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Prospects for quarkonium studies at the high-luminosity LHC

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Prospects for quarkonium-production studies accessible during the upcoming high-luminosity phases of the CERN Large Hadron Collider operation after 2021 are reviewed. Current experimental and theoretical open issues in the field are assessed together with the potential for future studies in quarkonium-related physics. This will be possible through the exploitation of the huge data samples to be collected in proton-proton, proton-nucleus and nucleus-nucleus collisions, both in the collider and fixed-target modes. Such investigations include, among others, those of: (i) J/ψ and Υ produced in association with other hard particles; (ii) $\chi_{c,b}$ and $\eta_{c,b}$ down to small transverse momenta; (iii) the constraints brought in by quarkonia on gluon PDFs, nuclear PDFs, TMDs, GPDs and GTMDs, as well as on the low- x parton dynamics; (iv) the gluon Sivers effect in polarised-nucleon collisions; (v) the properties of the quark-gluon plasma produced in ultra-relativistic heavy-ion collisions and of collective partonic effects in general; and (vi) double and triple parton scatterings.

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141 1. Introduction

142 The Large Hadron Collider (LHC) accelerator and detector systems are being upgraded to enable their
143 optimal exploitation after 2027 with a ten-fold increase in its instantaneous luminosity in the proton-proton
144 (pp) running mode with respect to the nominal design values [1]. The ultimate high-luminosity phase of
145 the collider (referred to as HL-LHC) will lead to the collection of huge data samples of pp collisions from
146 total integrated luminosities reaching $\mathcal{L} = 3 \text{ ab}^{-1}$ at ATLAS and CMS, and around $\mathcal{L} = 0.3 \text{ ab}^{-1}$ at LHCb,
147 by the end of the LHC operation in 2035. In addition, integrated luminosities of about 13 nb^{-1} , 13 nb^{-1} , and
148 2 nb^{-1} of PbPb data as well as 1.2 pb^{-1} , 0.6 pb^{-1} , and 0.6 pb^{-1} of pPb data are expected to be obtained by
149 each of the ATLAS/CMS, ALICE, and LHCb experiments until 2030, respectively [2]. Such unprecedented
150 data sets will open up new exciting physics opportunities in the study of the Standard Model [3], and in
151 particular its heavy-flavour sector [4]. This phase will also offer the possibility to collect data using the
152 LHC proton and ion beams on Fixed Targets (FT). The corresponding physics programme [5, 6] of the LHC
153 in the FT mode (referred to as FT-LHC) relies on extremely high *yearly* luminosities. The FT mode is under
154 study for ALICE and LHCb, where up to 10 fb^{-1} in pp , 300 pb^{-1} in proton-nucleus (pA), and 30 nb^{-1} in
155 lead-nucleus (PbA) collisions are expected.

156 The aim of this review is to highlight the impact that the upcoming operations of the LHC, in partic-
157 ular the HL-LHC and FT-LHC, will have on various sectors of quarkonium-production studies in pp , pA ,
158 and nucleus-nucleus (AA) collisions. Not only is the mechanism underlying the inclusive production of
159 quarkonia (Q) still an outstanding problem in hadroproduction [7], but quarkonia can also serve as tools
160 for the study of many other aspects of Quantum Chromodynamics (QCD). To name a few, charmonia and
161 bottomonia can be used to probe the proton gluon content in terms of various parton densities such as parton
162 distribution functions (PDFs, see e.g. [8–12]), transverse-momentum densities (TMDs, see e.g. [13–23]),
163 and generalised parton densities (GPDs, see e.g. [24–27]); the gluon content of heavy nuclei through nu-
164 clear PDFs (see e.g. [28–32]). More generally, they allow the study of the initial stages of ultra-relativistic
165 heavy-ion collisions (see e.g. [33]) and at the same time, they offer new ways to investigate the dynamics
166 of hard multi-parton interactions (see e.g. [34–37]) or to measure the properties of the quark-gluon plasma
167 (see e.g. [33, 38, 39]).

168 The interested reader will find it useful to consult the following reviews [40–44] addressing HERA
169 and Tevatron results, and more recent ones [7, 33] concerning recent advances in the field with the
170 RHIC and LHC data. With regards to existing experimental results, the reader is guided to the HEPData
171 database (<https://www.hepdata.net/>), to a dedicated repository of quarkonium measurements up to
172 2012 (<http://hepdata.cedar.ac.uk/review/quarkonii/>) documented in [45] and to a recent review
173 on RHIC results [46].

174 The document is organised as follows. Section 2 focuses on the studies accessible in pp collisions. Sec-
175 tion 3 discusses quarkonium production in exclusive and diffractive interactions, while Section 4 is devoted
176 to the impact on studies involving transverse-momentum-dependent observables. Quarkonium studies in
177 pA and AA collisions are respectively covered in Sections 5 and 6. Finally, Section 7 addresses quarkonium
178 production in double parton scattering (DPS) and triple parton scattering (TPS). Following the structure of
179 similar previous prospective quarkonium studies at the LHC, such as [47], each chapter starts with a short
180 summary of the current state-of-the-art and open experimental and theoretical issues, followed by a succinct
181 list of HL-LHC studies that should further improve the understanding of all quarkonium-related physics.
182 Anywhere relevant we have indicated when higher luminosities are needed or when similar luminosities
183 to those already collected during the previous runs will be sufficient with dedicated triggers for these new
184 studies.

2. Proton-proton collisions⁹

2.1. Introduction: status and prospects

The production of quarkonium in high-energy particle collisions has been linked to longstanding challenges in our understanding of quark confinement in QCD. The study of quarkonium production provides not only valuable information on non-perturbative QCD physics, but also crucial and often novel signatures for the exploration of new phenomena, multi-quark spectroscopy, probes of proton structure, and double parton scattering interactions, amongst other subjects.

Various theoretical treatments tackling the production of quark-antiquark pairs and their subsequent formation of a quarkonium bound state have been proposed and confronted with experimental data. The most notable and used of these are the Colour Evaporation Model (CEM) [48–52], the Colour-Singlet Model (CSM) [53–55], and non-relativistic QCD (NRQCD) [56] factorisation, which extends the CSM by the introduction of the Colour Octet (CO) mechanism. As regards their application to hadroproduction, in particular at the LHC, these are often employed within the framework of collinear factorisation, High-Energy (HE) factorisation¹⁰ or even Colour Glass Condensates (CGC). Even though most of the discussion in this section focuses on NRQCD used with collinear factorisation, the proposed measurements are also relevant to test most of the theoretical models discussed in the literature.

No single approach has been able to simultaneously describe all experimental observables collected to date, but the NRQCD approach is the most rigorous and thus has had greatest success. However, the predictive power of NRQCD relies heavily on the universality of the non-perturbative long-distance matrix elements (LDMEs) protected by the so-called factorisation approach. These LDMEs characterise the transition rates for various colour-spin states of a produced heavy-quark pair to become a physical quarkonium and should be process-independent. Despite the success of NRQCD in many phenomenological applications (see, e.g., [43]), there are still challenges to understand the single-inclusive quarkonium production mechanism at colliders, notably a unified description of their cross section in different production modes, the polarisation of the vector states, the constraints set by the production of pseudoscalar mesons via NRQCD Heavy-Quark-Spin Symmetry (HQSS), not to mention further puzzles in associated production. Differences between various sets of LDMEs extracted from the accumulated data [57–64] persist, and there is a long way to go to confirm the universality of these LDMEs [7, 65]. Hence, a coherent physical picture to interpret quarkonium production data is still missing today.

This impasse in our understanding of quarkonium production, and its subsequent limitations on the use of quarkonium data as a tool for other physics processes, has motivated the critical need to establish novel observables that can serve to advance both goals. The study of various new final states containing quarkonia, and measurements of novel quarkonium observables in hadron-hadron collisions, e^+e^- , lepton-hadron, photon-hadron, photon-photon and nuclear collisions, can provide complementary sensitivity to different combinations of LDMEs (see [7] and references therein) as well as insight into a wide range of phenomena.

The large pp collision data sets expected to be collected at the HL-LHC for inclusive quarkonium production will provide a compelling setting for these investigations. In the following sections, we outline the potential that the HL-LHC experiments have to explore these topics, and highlight priorities for study. In Section 2.2.1, we begin by reviewing how measurements of the J/ψ and Υ transverse-momentum (P_T) distributions and polarisations is central to our understanding of their production and outline expectations for the HL-LHC period. Section 2.3 explains how studies of the surrounding hadronic activity in collision events containing quarkonia provide new insights to various QCD topics. In Section 2.4, we address physics opportunities opened up through the study of unconventional quarkonium states, e.g. the C -even η_Q and χ_Q states. Section 2.5 examines how data on associated production of quarkonium with other heavy states provides a rich opportunity to explore topics as diverse as searches for new phenomena and multi-parton interactions at the HL-LHC. Finally, in Section 2.6 we outline how quarkonium data in the HL-LHC era can be a compelling tool for precision PDF determinations both at low x and low scale, and at high x .

⁹Section editors: Darren Price, Hua-Sheng Shao.

¹⁰also referred to as k_T factorisation.

2.2. J/ψ and Υ conventional measurements: P_T spectra and polarisation

2.2.1. P_T spectra: going higher

The study of P_T distributions of heavy-quarkonium states produced at hadron colliders has played a critical role in the development of our understanding of the underlying production mechanism. The drastically different P_T dependence observed between the Tevatron [66, 67] data and the leading order (LO) theoretical predictions for J/ψ and $\psi(2S)$ production at mid and high P_T led to tremendous improvements in our understanding on how a produced heavy-quark pair at a large P_T transmutes itself into a physical quarkonium state, and to the development of the NRQCD-factorisation approach for the production of heavy quarkonia [56, 68].

For a given heavy-quark mass, m_Q , heavy-quarkonium production in hadron-hadron collisions can be divided into three kinematic regimes: $P_T^2 \gg m_Q^2$, $P_T^2 \sim m_Q^2$, and $P_T^2 \ll m_Q^2$, which provide tools sensitive to very different, but often complementary, physics issues. For heavy-quarkonium production, QCD factorisation connects the colliding hadron(s) to the underlying quark-gluon scattering that produces a heavy-quark pair while NRQCD factorisation matches the pair, produced with various colour-spin states, to a physical quarkonium through the corresponding LDMEs. For both QCD and NRQCD factorisations, calculating quarkonium production in these three kinematic regimes requires different approximations and treatments.

When $P_T^2 \gg m_Q^2$, quarkonium production is ideal to isolate the non-perturbative hadronisation part. Since the produced heavy-quark pair at high P_T is so separated in phase space from the colliding hadron beams, one can thereby pin down the uncertainty associated to the LDMEs. However, the production involves two very different momentum scales, and resummation of large $\log(P_T^2/m_Q^2)$ terms is necessary [69–71].

Although reliable factorisation formalisms have been derived for, at least, the first two regimes where $P_T^2 \gg m_Q^2$ and $P_T^2 \sim m_Q^2$, a smooth matching between these two regimes is needed to be able to compare theoretical calculations with experimental data. For example, when $P_T^2 \gg m_Q^2$, theoretical calculations are organised in terms of QCD collinear factorisation of the leading power and next-to-leading power contributions in the $1/P_T^2$ expansion [69–71]. Since no QCD collinear factorisation is valid beyond the first subleading power contribution [72], QCD factorisation formalisms in this regime can only include the leading $1/P_T^4$ and the first subleading $1/P_T^6$ factorised partonic hard parts. On the other hand, for the regime where $P_T^2 \sim m_Q^2$, the leading term in the power of the strong coupling constant, α_s , and heavy-quark relative velocity, v , in the NRQCD factorisation approach contains $1/P_T^6$ or $1/P_T^8$ terms depending on the colour-spin states of the pair. Clearly, the two factorisation approaches lead to different P_T dependencies and a consistent matching between these two regimes is clearly needed, especially for fitting the LDMEs [73, 74].

On the experimental side, the Run 1 & 2 LHC data already allow one to push further the reachable P_T domain for J/ψ and Υ production compared to the Tevatron range. The latter already reached $P_T \simeq 25$ GeV for ψ but this was barely sufficient to assume $P_T^2 \gg m_Q^2$. Moreover, the Tevatron data sample was clearly insufficient for the Υ states. Thanks to the extended LHC P_T reach and to the advent of NLO NRQCD computations [57–64], one could set novel constraints on the NRQCD LDMEs needed to fit the ψ data since high- P_T data prefer a dominance of $^1S_0^{[8]}$ rather than the $^3S_1^{[8]}$ state that was compatible with mid- P_T data at the Tevatron using LO estimates. Yet, there is still a debate about whether large $\log(P_T^2/m_Q^2)$ could affect the determination of the LDMEs. In this context, data at even higher P_T will not be superfluous, especially for $\psi(2S)$ for which constraints from other colliding systems are very limited. Such data will also be useful in confirming the inability of the CEM to account for this high- P_T regime [75, 76]. The reader is guided to a recent review [7] where the impact of the current LHC data on the phenomenology is explained in details. For the three Υ states, data at higher P_T , probably above 100 GeV, are certainly also welcome to be sure to reach the fragmentation limit. These are certainly within the reach of HL-LHC.

2.2.2. Polarisation: going further

The most studied quarkonia are the vector states, $\psi(nS)$ and $\Upsilon(nS)$, because they are easily produced in e^+e^- annihilation but also because they are easily detectable via their di-lepton decay channels. This also offers the possibility to directly measure their polarisation, also referred to as spin alignment, via the analysis of

282 the angular distribution of their decay products, which can be parameterised as:

$$\frac{d^2N}{d\cos\theta d\phi} \propto 1 + \lambda_\theta \cos^2\theta + \lambda_\phi \sin^2\theta \cos 2\phi + \lambda_{\theta\phi} \sin 2\theta \cos\phi, \quad (1)$$

283 where θ is the polar angle between the positively charged lepton momentum in the quarkonium rest frame,
 284 p_{ℓ^+} , and the spin-quantisation axis (z axis) and ϕ is the azimuthal angle between the projection of p_{ℓ^+} on
 285 the xy plane (thus orthogonal to the spin-quantisation axis) and the x axis. The decay angular coefficients,
 286 λ_θ (also known as α), λ_ϕ and $\lambda_{\theta\phi}$ are related to specific elements of the spin density matrix but are frame
 287 dependent. They obviously depend on the choice of the spin-quantisation axis. The reader is guided to [7]
 288 for an up-to-date discussion of the predicted values of these parameters in different production models and
 289 to [33] for an exhaustive list of the existing measurements up to 2015.

290 It had been hoped that such polarisation measurements could verify the smoking-gun prediction of
 291 NRQCD according to which vector quarkonia are produced transversely polarised [77, 78], i.e. $\lambda_\theta = +1$, in
 292 the helicity frame¹¹ at large P_T . However, when Tevatron data (see e.g. [79]) became precise enough, it be-
 293 came clear that this prediction was wrong. At the same time, NRQCD results at NLO were found to deviate
 294 from this seemingly fundamental NRQCD result obtained at LO¹². From a smoking gun in the 1990's, the
 295 polarisation turned, in the 2010's, into a mere constraint via NRQCD fits. Indeed, the complex interplay
 296 between the different CO contributions at NLO renders NRQCD predictions for polarisation sensitive to
 297 tiny details of the fits.

298 In this context, we would like to provide several recommendations:

- 299 • In the currently studied kinematic region, clear-cut theory predictions should not be expected. Leav-
 300 ing aside the feed-down effects, which however constitute a serious source of complications, the
 301 polarisation in fact essentially depends on a linear combination of LDMEs. New types of data, such
 302 as those discussed in the following sections are needed. In fact, even at extremely high P_T and for the
 303 feed-down-free $\psi(2S)$, it is not clear that a simple picture will emerge. Yet, it remains important to
 304 consolidate the current measurements especially for the excited states, which admittedly remain very
 305 limited.
- 306 • Precise polarisation measurements at low P_T in the collider mode certainly remain useful, especially
 307 in the central rapidity region, to get a more global view including RHIC and Tevatron measurements.
 308 Along the same lines, measurements in the FT mode in the 100 GeV range, as can be realised at the
 309 FT-LHC, will be critical to complete the picture.
- 310 • It is essential to measure the three angular coefficients in order to avoid relying on theoretical and/or
 311 experimental assumptions. This also allows one to compute frame-invariant quantities [83–88], which
 312 can serve, by using determination of these invariants in multiple frames, as consistency checks of the
 313 experimental procedure. For further checks, it would also be interesting to measure the other angular
 314 distribution coefficients beyond Eq. (1) like the $\lambda_\phi^\perp \sin^2\theta \sin 2\phi$ and $\lambda_{\theta\phi}^\perp \sin 2\theta \sin\phi$ terms, which are
 315 predicted to be exactly zero from parity invariance.
- 316 • Beside the extraction of these invariants from combinations of the angular coefficients, it is possible
 317 to extract them directly as functions of the lepton momenta [86, 88, 89]. We encourage attempts in
 318 this direction.
- 319 • We encourage theorists to compute the 3 angular coefficients and the related invariants. We note that
 320 the first calculation of $\lambda_{\theta\phi}$ at NLO in NRQCD was only computed in 2018 [90] for the J/ψ meson.

¹¹In the helicity frame, the quantisation axis is the Q momentum in the c.m.s. frame and the xz plane contains the latter and the momenta of the colliding particles.

¹²For the record, the first NLO polarisation computations were performed in the CSM back in 2008 [80, 81] showing a longitudinal yield at NLO instead of the transverse LO yield. The NLO NRQCD studies date back to 2012 by the Hamburg [82], PKU [58, 61] and IHEP [59] groups and their interpretations differ much. The Hamburg and IHEP NLO fits show increasingly transverse ψ yields with increasing P_T in the helicity frame (at variance with Tevatron and LHC data). The PKU NLO fit –including Tevatron polarisation data at the beginning [58] but excluding them later [61]– shows a quasi unpolarised yield at high P_T .

321 • Polarisation measurements also remain very important in quantifying the acceptance corrections to be
 322 applied to pass from experimental cross-section measurements performed in a fiducial region to the
 323 inclusive ones. Even though the currently available results show no significant polarisation, it should
 324 be kept in mind that, in specific kinematic conditions, the polarisation could drastically change. Ide-
 325 ally, experiments should publish fiducial cross-section results, which would free their results from this
 326 additional source of uncertainty. However, it should be clear that advancing the theoretical predictions
 327 to higher precision (we are not even yet at NNLO in α_s) and, at the same time, providing predictions
 328 for the di-lepton angular distribution in designated fiducial regions, may not be possible due to the
 329 computational complexity. This certainly calls for a concerted effort between both experimental and
 330 theoretical communities.

331 2.3. Characterisation of Q events

332 2.3.1. Q in jets

333 In the past few years, quarkonium production within jets has been attracting increasing attention as a probe
 334 of heavy-quark hadronisation and quarkonium production mechanisms. At the LHC, such a process has
 335 been measured by the LHCb [91] and CMS [92] collaborations. Both collaborations have observed striking
 336 deviations of data from Monte Carlo simulations, which use LO NRQCD complemented with subsequent
 337 parton showering. The observable measured in both experiments is the transverse momentum fraction, $z =$
 338 $P_T^\psi/P_T^{\text{jet}}$, carried by the quarkonium state J/ψ inside the corresponding jet. This observable is indicative of
 339 the fragmenting-parton momentum carried by the quarkonium state. Theoretical predictions for the LHCb
 340 data have been provided in [93] by using the fragmentation-jet functions (FJF) and the Gluon Fragmentation
 341 Improved PYTHIA (GFIP), which correspond to a modified parton shower approach, where the quarkonium
 342 fragmentation is only implemented at the end of the shower

343 As shown in Fig. 1, the predictions reproduce many important features of the data. One however notes
 344 that the agreement depends both on the values of LDMEs (compare the bands between the 3 plots) and
 345 the fragmentation modelling (compare the red and grey bands in each plot). In principle, to get a better
 346 discriminating power of the data on the LDMEs, it is important not to integrate over P_T^{jet} and to look at
 347 how the probability to produce a J/ψ at fixed z varies with P_T^{jet} . Even though these exploratory studies have
 348 shown that these new observables can provide deeper insights into quarkonium production at large P_T ,
 349 more detailed studies are necessary to obtain a more comprehensive picture. The reader is guided to the
 350 review [7] for a discussion of the theoretical caveats, and in particular that all the current predictions rely
 351 on LO fragmentation functions (FF). As such, NLO corrections may be very large and diminish sensitivity
 352 to the LDMEs.

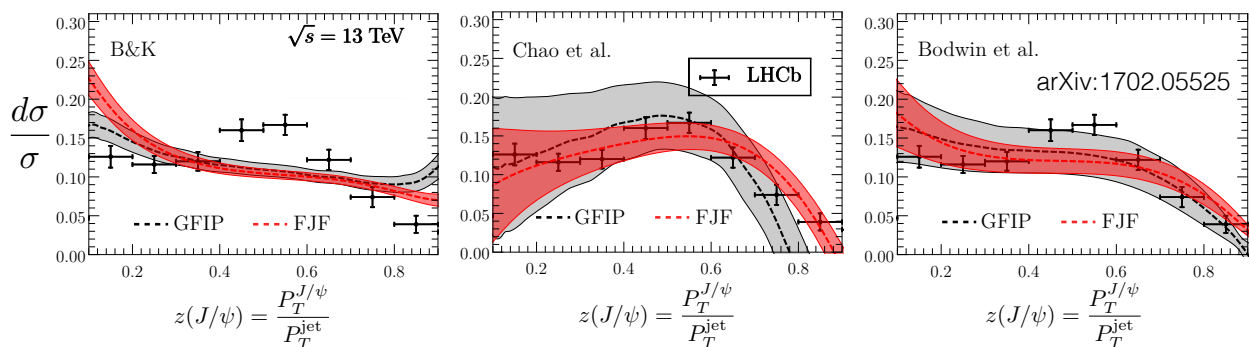


Figure 1: Comparisons of the $z(J/\psi)$ LHCb measurements to the predicted $z(J/\psi)$ distribution using FJF (red) and GFIP (gray) for three choices of LDMEs (left, centre, right). [Plots adapted from [93]]

353 There are significant opportunities to expand these existing studies of J/ψ (and other quarkonia) in jets.
 354 Quarkonia in jets can be selected by data collected via leptonic triggers from the decay of the quarkonium or
 355 through the use of high- P_T hadronic triggers to select the jet candidate, potentially providing data spanning
 356 hundreds of GeV in jet transverse momenta. As events of interest will necessarily be characterised by
 357 leptons surrounded by significant hadronic activity, care will be needed to ensure such events are not vetoed
 358 by standard online or offline lepton- or jet-reconstruction algorithms optimised for HL-LHC conditions.

359 At the HL-LHC, we identify the following major subsequent studies with significant phenomenological
360 impact:

- 361 • The transverse momentum fraction, z , should be measured with finer binning and for a wider range
362 of jet transverse momentum. The transverse momentum of the jet, that sets the hard scale of the
363 process, controls the size of evolution. This will allow the test of various aspects of the quarkonium
364 fragmentation mechanisms, and their relative contributions. In addition, a detailed study of the regime
365 $1 - z \ll 1$ will give insights into the non-perturbative aspects of quarkonium hadronisation where the
366 process is particularly sensitive to soft radiation.
- 367 • To decouple modelling of the jet transverse momentum dependence from modelling of the fractional
368 momentum associated with quarkonium states, we encourage experiments to perform measurements
369 such as those illustrated in Fig. 1 in narrow intervals of jet transverse momentum, or ultimately
370 as multi-differential measurements in jet P_T and z . As well as providing additional information to
371 explore the observed discrepancies, this will allow for more detailed comparisons and combinations
372 of data between experiments accessing complementary P_T ranges at HL-LHC.
- 373 • Jet substructure observables, such as thrust and other angularities, will give access to details of the
374 radiation surrounding the quarkonium within the jet. The distribution of radiation in the jet is sensitive
375 to the production mechanisms of quarkonium and could offer an additional handle on the numerical
376 values of the LDMEs. A theoretical investigation of observables of this type has been performed
377 in [94].
- 378 • Multi-differential measurements of quarkonium energy fractions and transverse momentum with re-
379 spect to the jet axis [95, 96] can provide a three-dimensional picture of quarkonium fragmentation.
- 380 • Studies should be expanded to include measurement of other quarkonia, such as $\psi(2S)$ in jets or
381 $\Upsilon(nS)$ in jets for the first time. Such measurements are critical to provide a complementary way to
382 constrain all LDMEs used in production modelling.

383 Compared to light hadrons, quarkonium production is anticipated to be less affected by background
384 contributions from multi-parton interactions and underlying event activity. However, at the HL-LHC, the
385 use of jet-grooming techniques might also be helpful in further removing contributions of soft radiation,
386 and allow for an improved convergence of experimental studies and theoretical calculations. In particular, it
387 is important to keep under control the impact of DPS, whereby a quarkonium is produced in one scattering
388 simultaneously with a dijet from another, with one of these jets being so close to the quarkonium that the
389 quarkonium is considered to belong to this jet.

390 2.3.2. \mathcal{Q} as a function of the particle multiplicity

391 Multiplicity-dependent studies of quarkonium production give insights into the correlations between hard
392 (heavy-quark production) and soft (charged-particle multiplicity) processes, and improve our understanding
393 of multi-parton interactions (MPI) and initial-state effects. Figures 2 and 3 show the normalised yields
394 of quarkonium production at mid- and forward-rapidity as a function of the charged-particle multiplicity,
395 measured at mid-rapidity $dN_{ch}/d\eta$ for pp collisions at $\sqrt{s} = 5.02$ and 13 TeV, respectively [97]. The results
396 at forward rapidity (Fig. 3) include Υ states as well as $\psi(2S)$ and J/ψ , whereas the central rapidity ones
397 (Fig. 2) show only inclusive J/ψ .

398 The quarkonium normalised yield increases linearly as a function of the multiplicity at forward rapidity,
399 while at mid-rapidity a faster-than-linear increase is observed both for the P_T -integrated and P_T -differential
400 J/ψ cases. Several theoretical models predict a correlation of the J/ψ normalised yield with the normalised
401 event multiplicity that is stronger than linear. These include a coherent particle production model [99], the
402 percolation model [100], the EPOS3 event generator, a CGC+NRQCD model [101], the PYTHIA 8.2 event
403 generator [103], and the 3-Pomeron CGC model [102]. In all these models, the predicted correlation is the
404 result of a (N_{ch} -dependent) reduction of the charged-particle multiplicity. This can be an effect due to the
405 colour string reconnection mechanism as implemented in PYTHIA, but the initial-state effects as implemented
406 in the percolation or CGC models lead to a similar reduction in the particle multiplicity. Concerning the
407 excited-over-ground yield ratios, recent results by the ALICE collaboration on charmonium production at

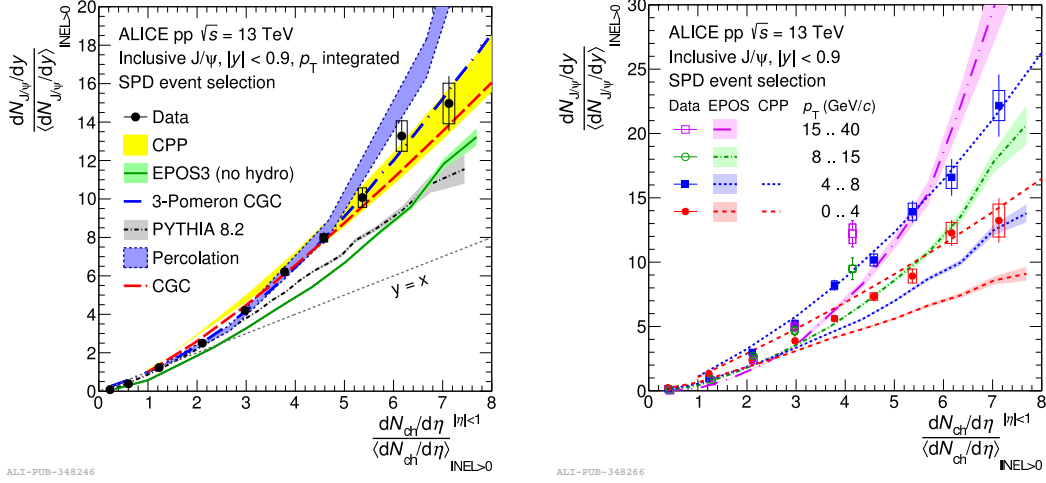


Figure 2: Normalised inclusive J/ψ yield at mid-rapidity as a function of the normalised charged-particle pseudorapidity density at mid-rapidity for the P_T -integrated (left) and P_T differential (right) cases. The data [97] are compared to theoretical predictions from EPOS-3 [98], the coherent particle production model (CPP) [99], the percolation model [100], the CGC model [101], the 3-Pomeron CGC model [102], and PYTHIA 8.2 [103]. [Plots taken from [97]]

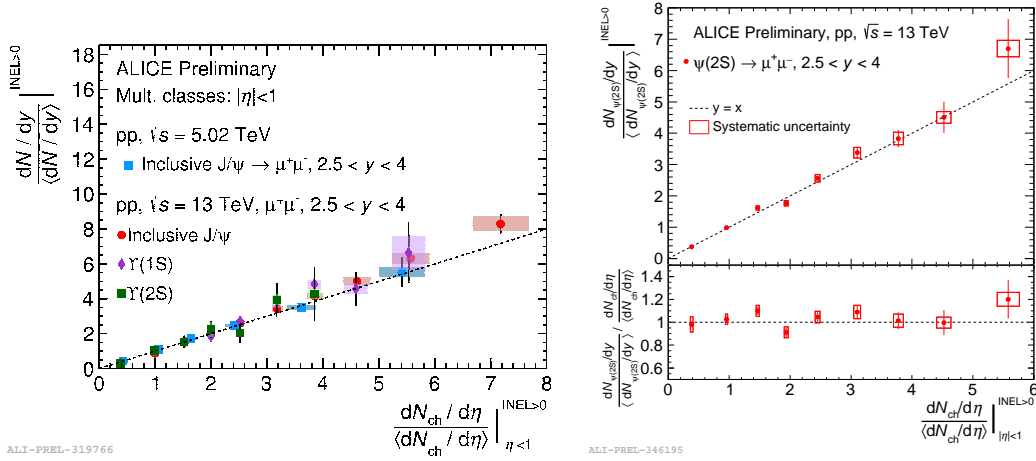


Figure 3: Normalised yields of inclusive quarkonia at forward rapidity as a function of the charged-particle multiplicity at mid-rapidity $dN_{ch}/d\eta$ in pp collisions at $\sqrt{s} = 5.02$ (left) and 13 TeV (right). Both quantities are normalised by the corresponding value for minimum bias pp collisions ($dN_{Q\bar{Q}}/dy$, $dN_{ch}/d\eta$). The error bars represent the statistical uncertainty on the relative quarkonium yields, while the point-to-point systematic uncertainties on the relative quarkonium yield are depicted as boxes. The dotted linear line ($y = x$) is drawn to visualise the deviation from linearity of the data points. [Plots taken from [97]]

408 forward rapidity are consistent with unity within the systematic uncertainties, while pointing at a possible
 409 reduction for an increasing normalised multiplicity [104]. Moreover, the preliminary results on the Υ and
 410 $\Upsilon(2S)$ normalised yields versus the normalised multiplicity [105] point at a stronger departure from linearity
 411 for the excited state when compared to the ground state, which would lead to a reduction of the ratio
 412 $\Upsilon/\Upsilon(2S)$ at high multiplicities.

413 The measurements outlined here are currently limited by systematic uncertainties that will be reduced
 414 with the upcoming HL-LHC quarkonium data. With the expected much larger data samples and enlarged
 415 rapidity coverage, LHC experiments have good prospects to perform multi-differential studies among dif-
 416 ferent kinematic variables, also at forward rapidity. This will enable focused studies of the dependence in
 417 specific regions of the phase space and precision analyses of the higher-excited quarkonium states, such as
 418 the $\Upsilon(3S)$.

419 2.4. Production of unconventional states

420 2.4.1. Production of η_c and $\eta_c(2S)$ states

421 Studies of the η_c and $\eta_c(2S)$ states, as spin partners of the J/ψ and $\psi(2S)$, provide independent constraints on
 422 the LDMEs of the spin-triplet family based on HQSS, following the velocity-scaling rule of NRQCD. Next-
 423 to-leading order (NLO) NRQCD calculations [106–108] show that there are only two relevant channels,
 424 a CO channel and the leading- v^2 CS channel, while the feed-down contribution is negligible. This greatly
 425 simplifies the corresponding theoretical analysis. On the other hand, all S - and P -wave CO channels, as well
 426 as significant feed-down contributions in the J/ψ case, compete with each other in the ψ hadroproduction
 427 processes.

428 At the LHC, two LHCb measurements of η_c exist [109, 110], via the hadronic decay channel $\eta_c(1S) \rightarrow$
 429 $p\bar{p}$ [111] with a branching fraction of about $1.45 \cdot 10^{-3}$ [112]. The current trigger at the LHCb detector allows
 430 only the measurement of the P_T spectrum of η_c with $P_T > 6.5$ GeV. Nevertheless, such measurements have
 431 already presented surprises that indicate that the CS channel alone is already sufficient to account for the
 432 experimental data within the range $6.5 < P_T < 14$ GeV. Therefore, the data substantially constrain one
 433 CO LDME of the J/ψ by using HQSS, essentially ruling out most of the LDME sets from the world data
 434 fits. With the much larger data samples anticipated at the HL-LHC, the extensions of the P_T range in the
 435 measurements will be beneficial at, at least, two levels. On the one hand, the low- P_T data will be very
 436 useful to extract the low- x gluon PDF in the proton as discussed in Sec. 2.6, given the dominance of the CS
 437 channel in this regime. The same measurement in the fixed-target mode [6] at the HL-LHC would allow a
 438 probe of the high- x regime of the gluon density [113]. On the other hand, the higher- P_T data will improve
 439 the sensitivity to the CO LDME, thanks to the harder P_T spectrum of the CO compared to the CS channel.

440 For the same reasons, the study of the $\eta_c(2S)$ state is interesting to understand the $\psi(2S)$ production
 441 mechanism based on HQSS. Its feasibility at the LHC has been explored in [114] via several decay channels.
 442 Figure 4 shows that the P_T -differential cross section strongly depends on the choice of the CO LDME set.
 443 A measurement, with a dedicated trigger, of $\eta_c(2S)$ at the HL-LHC will impact the final theoretical
 444 interpretation of the charmonium production data. Equivalent measurements with bottomonium are also
 445 feasible: prospects for η_b studies at the LHC have recently been discussed in [12].

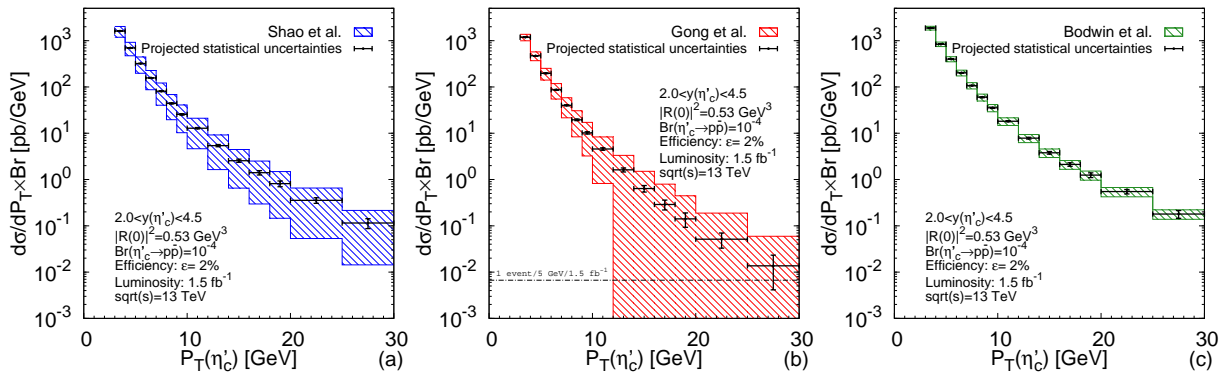


Figure 4: Differential- P_T cross section for $\eta_c(2S)$ production times $\mathcal{B}(\eta_c(2S) \rightarrow p\bar{p})$ for the three CO LDME sets [59, 61, 62] along the projected statistical uncertainties using the central theoretical values in each case, with an assumed efficiency of 2% and a luminosity of (1.5 fb^{-1}) by the LHCb detector at $\sqrt{s} = 13$ TeV. [Plots taken from [114]]

446 2.4.2. Polarisations of χ_{c1} and χ_{c2} states

447 It has been advocated in [115, 116] that the measurement of the polarisations of the χ_{c1} and χ_{c2} mesons
 448 at the LHC would uncover how the P -wave states are produced at hadron colliders. These states contribute
 449 to around 30% of the prompt J/ψ yields via the radiative decays $\chi_c \rightarrow J/\psi + \gamma$ (see [7] for an up-to-
 450 date discussion on the feed-down component). Such studies are also motivated by the simplicity of these
 451 states from the NRQCD perspective with the HQSS relation. Indeed, only a single CO LDME needs to be
 452 determined from the experimental data compared to three for the S -wave states to reach a comparable
 453 precision, and thereby NRQCD has a stronger predictive power for the P -wave states.

454 A first measurement by the CMS collaboration with 19.1 fb^{-1} of data in pp collisions at $\sqrt{s} = 8$ TeV
 455 appeared recently [117]. Such a measurement is very challenging at both ATLAS and CMS because the

456 photons from these radiative transitions have to be measured through their conversions to e^+e^- [118, 119]
 457 to achieve a high precision measurement. The analysis is thus limited by the large systematic uncertainty
 458 associated to muon and photon detection efficiencies. Consequently, only the difference between the χ_{c1}
 459 and χ_{c2} polarisations, from the angular dependence of the χ_{c2}/χ_{c1} yield ratio, is available. In other words,
 460 the χ_{c1} and χ_{c2} polarisations are not yet known separately.

461 Figure 5 displays the coefficient λ_θ in the decay chain $\chi_c \rightarrow J/\psi\gamma \rightarrow \mu^+\mu^-\gamma$, which follows the form
 462 $1 + \lambda_\theta \cos^2 \theta$ [85, 120, 121], where θ is the polar angle of μ^+ in the rest frame of the J/ψ meson. The
 463 left panel shows the polarisation pattern of χ_{c2} when assuming unpolarised χ_{c1} . The right panel compares
 464 data with a NLO NRQCD prediction [115, 116] for χ_{c2} polarisation after fixing the χ_{c1} polarisation to the
 465 corresponding NRQCD values.

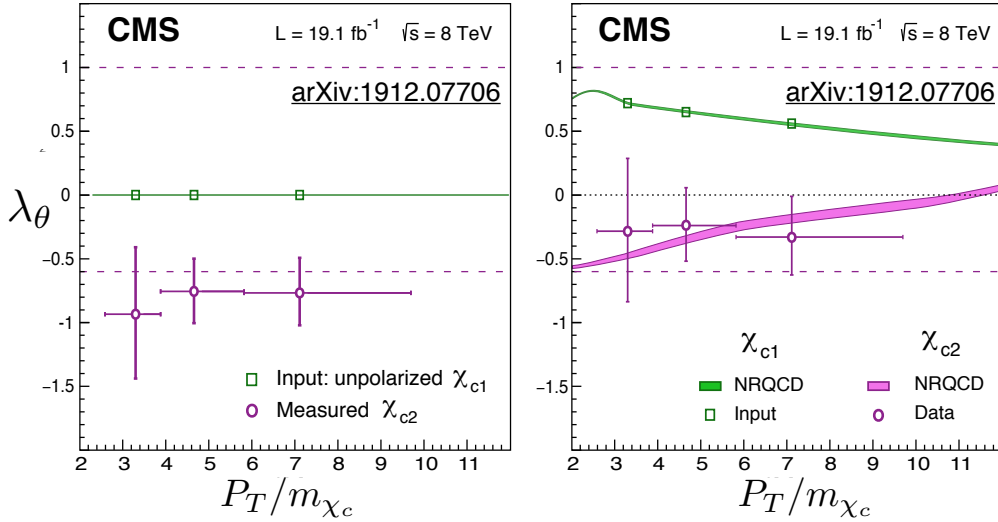


Figure 5: Measurements of the polarisation parameter λ_θ versus P_T/m_{χ_c} for χ_{c1} and χ_{c2} production in pp collisions at $\sqrt{s} = 8$ TeV measured by the CMS collaboration compared to NRQCD predictions. [Plots adapted from [117]]

466 At the HL-LHC, the limitation of measuring only the χ_{c1} and χ_{c2} polarisation difference can be lifted,
 467 with the much larger data samples and a better control of systematic uncertainties. This will require a
 468 commitment to collect high-statistics calibration data at low P_T for the determination of muon and photon
 469 conversion efficiencies. It is thus very desirable to measure the independent polarisation for each P -wave
 470 state in the future. The equivalent measurements for the χ_b states will also be useful for understanding the
 471 corresponding bottomonium sector. In fact, these measurements are also necessary for a proper interpretation
 472 of the J/ψ and Υ polarisation measurements to properly account for the effect of the χ_Q feed-down
 473 component.

474 2.4.3. Production of the exotic X , Y and Z states

475 Many X , Y and Z states have been found following the $X(3872)$ observation [122], but their underlying
 476 (multi-quark or hadron-molecular) nature is still unclear. Studying the production of X , Y and Z states,
 477 both theoretically and experimentally, can provide important information to understand the formation and
 478 properties of multi-quark states.

479 Let us take as an example the $X(3872)$, now also referred to as $\chi_{c1}(3872)$. Its prompt production rate
 480 has been estimated within the NRQCD factorisation approach [123] assuming that it is a pure charm-meson
 481 molecule. In order to be able to adequately describe measurements of its production rate from the CDF col-
 482 laboration, the charm-meson rescattering mechanism was introduced in [123]. However, the LO calculation
 483 with the non-perturbative matrix element determined from the CDF data leads to much bigger yields than
 484 experimentally measured by the CMS collaboration [124], as shown in Fig. 6 (left). On the contrary, the au-
 485 thors of [125] suggested that the $X(3872)$ is a mixture of $\chi_{c1}(2P)$ and $D^0\bar{D}^{0*}$ states, and the hadroproduction
 486 proceeds dominantly through its $\chi_{c1}(2P)$ component. The cross section through the charm-meson molecular
 487 component has been assumed to be negligible in [125], and the fraction of the charmonium component in
 488 $X(3872)$ has been tuned to the CMS data.

489 Once the overall normalisation of the cross section from CMS observations was fit by fixing this char-
 490 monium fraction, the NRQCD approach was found to describe the data across a much larger range of P_T
 491 as observed by ATLAS [126] (Fig. 6, right). It is worth noting that the NRQCD calculations plotted in both
 492 panels of Fig. 6 have very different underlying assumptions. The LO NRQCD curve [123] in the left (CMS)
 493 plot assumes $X(3872)$ to be a pure loosely bound charm-meson molecular state and the model includes
 494 the charm-meson rescattering mechanism, whereas the NLO NRQCD curve in the right (ATLAS) panel,
 495 takes the $X(3872)$ as a mixed state of charmonium and charm-meson molecule and assumes its production
 496 via the charmonium component is dominant. On the other hand, the non-prompt $X(3872)$ production rate
 497 measured by ATLAS [126] was found to be poorly described by fixed-order next-to-leading-log (FONLL)
 498 predictions [127] in contrast to the good agreement observed for the charmonium $\psi(2S)$ case. Analysis of
 499 the non-prompt $X(3872)$ lifetime distribution indicated the presence of an anomalously large short-lifetime
 500 component consistent with decays via the B_c , which has yet to be fully understood. Given the unclear nature
 501 of the $X(3872)$, and different model/theoretical assumptions in various existing cross-section calculations,
 502 it is not yet conclusive which picture can successfully reproduce the world data on the $X(3872)$.

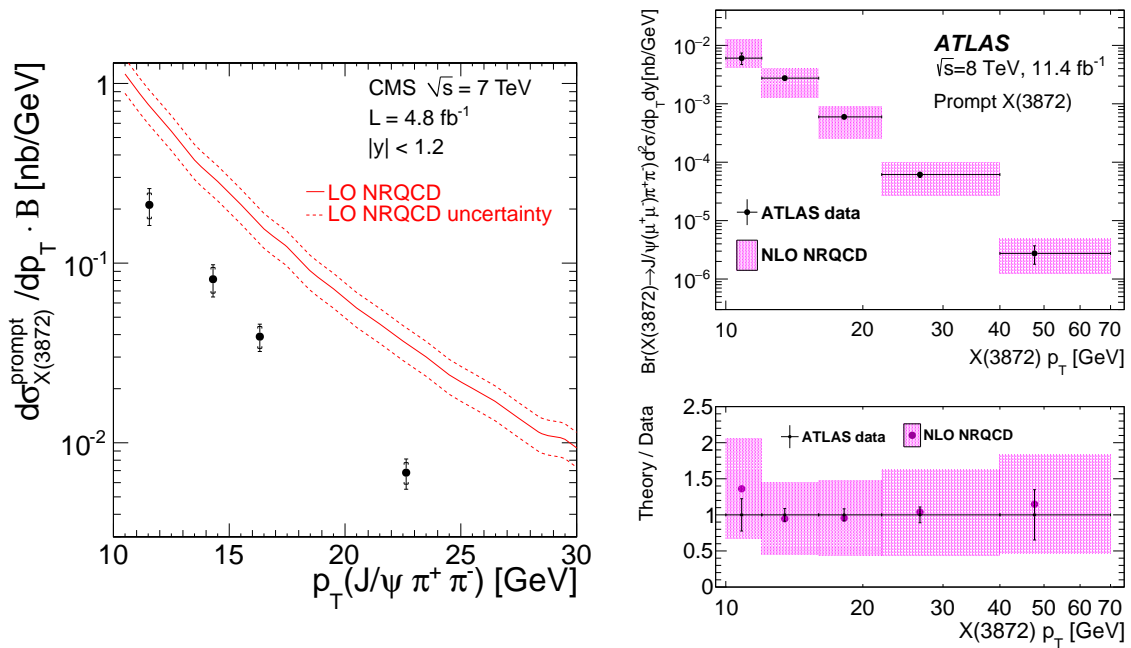


Figure 6: P_T differential cross section times branching fraction as a function of P_T for the prompt production of the $X(3872)$ state, measured by the CMS collaboration [124] (left), and by the ATLAS collaboration [126] (right), compared to the theoretical predictions from [123] and [125], respectively. [Plots taken from [124, 126]]

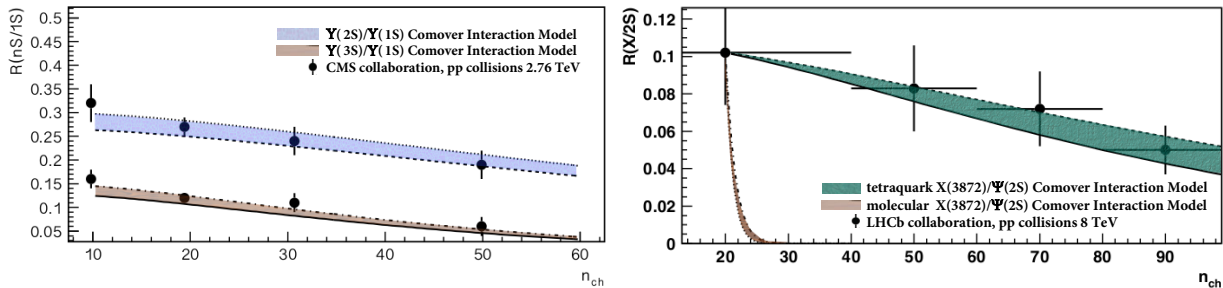


Figure 7: (Left) Relative yields of excited-to-ground-state Υ mesons as a function of event multiplicity in pp collisions at $\sqrt{s} = 2.76$ TeV at central rapidities as measured by the CMS collaboration [128]. (Right) Relative yields of $X(3872)$ over $\psi(2S)$ as a function of charged-particle multiplicity at $\sqrt{s} = 8$ TeV in the forward region as measured by the LHCb collaboration [129] (right). The bands represent the CIM results [130, 131], while the points refer to the experimental data. In the right panel, the brown band assumes $X(3872)$ is a molecular state with a radius of 5 fm, while the green band assumes it is a compact tetraquark state with a radius of 0.65 fm.

503 The study of the relative production of $X(3872)$ over conventional quarkonium states as a function of

504 particle multiplicity, as performed by the LHCb collaboration [129] in pp collisions at 8 TeV, can help
 505 to discriminate the nature of this exotic state. The preliminary LHCb data on the relative yields of the
 506 exotic $X(3872)$ over $\psi(2S)$ meson show a similar behaviour to the relative yields of excited-over-ground-
 507 state Υ mesons reported by the CMS collaboration [128] in pp collisions at 2.76 TeV, pointing to a possible
 508 common origin. Both data sets have been studied in the framework of the comover interaction model (CIM),
 509 i.e. including final-state interactions with the comoving medium [130, 131]. The results are shown in Fig. 7.
 510 Within this approach, the radius of the $X(3872)$ is about twice that of the $\psi(2S)$. This finding supports the
 511 $X(3872)$ being a tetraquark state and disfavours the molecular interpretation that would need a much larger
 512 radius, close to 5 fm.

513 With the data delivered by the HL-LHC, many more rare X , Y and Z states are likely to be collected.
 514 These future datasets offer the opportunity to measure their double differential production cross section as
 515 functions of transverse momentum and rapidity, or set much more stringent upper limits on their hadropro-
 516 duction cross sections. In addition, the polarisations of some X , Y and Z states in pp collisions, e.g. as
 517 proposed in [132] for the $X(3872)$, can also be measured, as done recently by the CMS collaboration for the
 518 $\chi_{c1,2}$ mesons [117] (see also the discussion in Sec. 2.4.2).

519 2.5. Q -associated-production processes

520 2.5.1. Associated production of Q and vector bosons

521 The study of associated-production processes, such as the combined production of quarkonia with a vector
 522 boson, provides a new tool to study perturbative and non-perturbative QCD, novel approaches to searches
 523 for new phenomena for both light and heavy states [133, 134], and an additional probe of multiple-parton-
 524 scattering interactions complementary to W + jet, WW , and di-quarkonium-production processes, which are
 525 discussed in Section 7.

526 Associated $J/\psi + Z$ and $J/\psi + W$ production have both been observed [135–137] by the ATLAS col-
 527 laboration. These are extremely rare processes, with only approximately one in every 10^6 W or Z boson-
 528 production events also producing a J/ψ in the fiducial volume of the ATLAS detector. Yet they can provide
 529 rich physics opportunities well-suited to precision studies with the large data-sets at the HL-LHC. The pres-
 530 ence of a vector boson allows for more efficient event triggering than that would be possible for inclusive
 531 quarkonium processes. The resulting relatively high- P_T multi-lepton signatures mean that selections are
 532 resilient to the expected high instantaneous luminosities (and correspondingly large numbers of multiple
 533 simultaneous pp pileup interactions) anticipated at the HL-LHC. Based on existing selections, this means
 534 that the ultimate HL-LHC data-sets of 8 500 prompt $J/\psi + Z$ events and 30 000 prompt $J/\psi + W$ events, and
 535 double as many non-prompt events, can be expected to be recorded for study by each of the general purpose
 536 detectors. Similar measurements of $J/\psi + \gamma$ associated production, as well as equivalent processes with
 537 bottomonium production and with excited quarkonium states, together provide a rich laboratory for future
 538 exploration.

539 Fig. 8 shows an example of the measured differential $J/\psi + Z$ rates for prompt J/ψ production compared
 540 with CO and CS NLO NRQCD predictions and data-driven estimates of the double parton scattering (DPS)
 541 contribution. Existing measurements point to discrepancies that can in part be explained by: enhanced
 542 DPS rates inconsistent with measurements from inclusive vector boson and hadronic jet processes; non-
 543 trivial correlations in DPS interactions; or enhanced contributions to single parton scattering (SPS) rates
 544 that become particularly important at large transverse momenta.

545 The limited data currently available implies that the existing DPS extractions are approximate (see de-
 546 tailed discussions in Section 7). Data from the HL-LHC will enable more detailed studies of DPS dynamics
 547 necessary to decouple DPS from SPS interactions at low momentum transfer. Current J/ψ measurements
 548 are limited to differential rates versus P_T , but measurements of other observables and two-dimensional dif-
 549 ferential distributions, such as the difference in the azimuthal angle between the boson and the quarkonium,
 550 $\Delta\phi(Z, J/\psi)$, versus $P_T(J/\psi)$, are recommended in the future to decouple SPS and DPS dynamics and allow
 551 precision studies and reinterpretation of these data. First studies in this direction have been produced by the
 552 ATLAS collaboration, that observed [138] no strong $P_T(J/\psi)$ dependence on the distribution of $\Delta\phi(W, J/\psi)$.

553 At high P_T , SPS can be expected to dominate over DPS processes. As J/ψ produced in association
 554 with a vector boson have been observed to be produced with harder P_T spectra than inclusive J/ψ (a two-
 555 to three-orders of magnitude drop from 10–100 GeV in the former compared to a six-order of magnitude

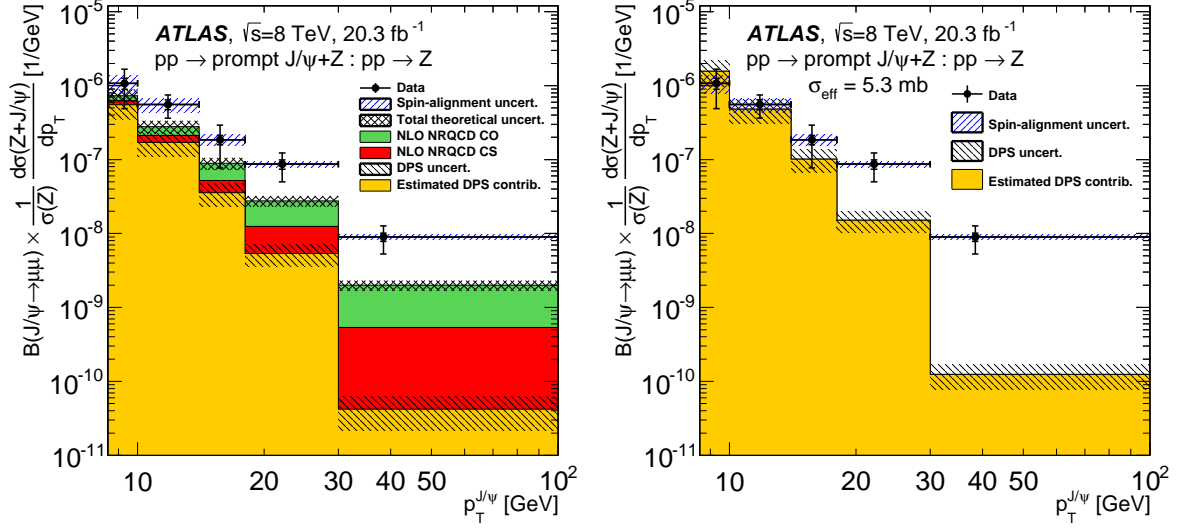


Figure 8: Measured differential prompt $J/\psi + Z$ rates as a function of J/ψ P_T compared to SPS predictions and a DPS rate normalised to $\sigma_{\text{eff}} = 15$ mb (left), where the normalisation is fit to data at low $\Delta\phi(Z, J/\psi)$ resulting in a preferred $\sigma_{\text{eff}} = 5.3$ mb (right). [Plots taken from [136].]

drop [139, 140] in the latter), data at the HL-LHC are expected to provide a comparable high- P_T reach to current inclusive measurements for detailed testing of perturbative QCD calculations.

Fig. 9 (Left) illustrates how rates of $J/\psi + W$ production can be described by NLO CEM predictions together with a DPS contribution with an effective cross section of $\sigma_{\text{eff}} = 6.1^{+3.3+0.1}_{-1.9-0.3}$ mb [141], compatible with the minimum of 6.3 ± 1.9 mb determined by ATLAS [137] and with the lower (68% C.L.) limit of 5.3 mb determined in the $J/\psi + Z$ process [136]. However, new data, shown in Fig. 9 (right), illustrate that challenges remain in describing associated production in the high- P_T regime, where perturbative calculations underestimate the data by an order of magnitude.

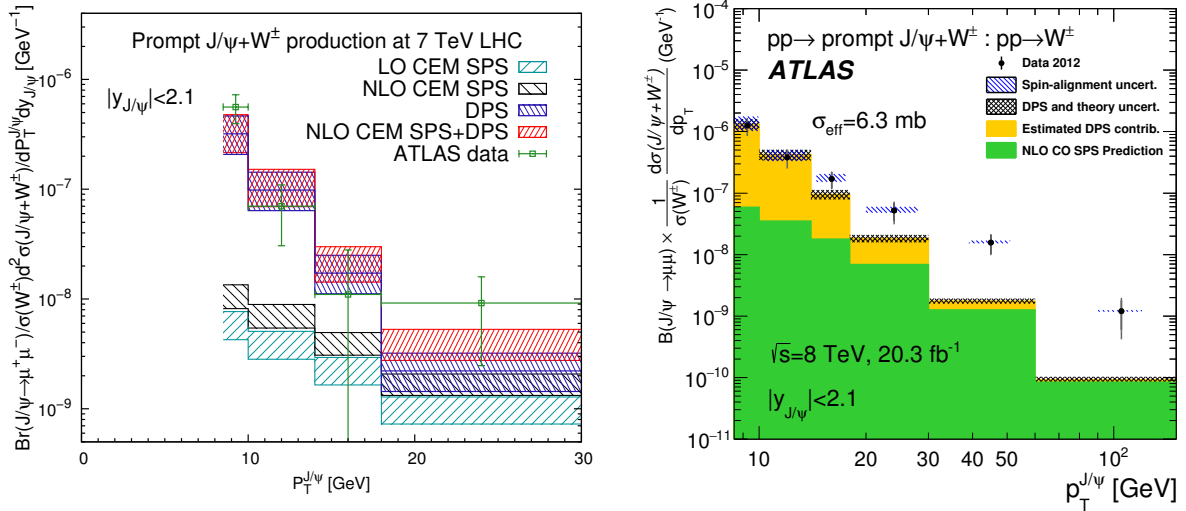


Figure 9: (Left) Measured differential prompt $J/\psi + W$ rates as a function of J/ψ P_T in pp collisions at 7 TeV and (Right) at 8 TeV extending to $P_T(J/\psi) > 100$ GeV compared to CEM SPS and DPS predictions. The data–theory agreement is good on the left, but the data exceed the predictions in the right distribution. [Plots and data taken from [141] and [135, 137].]

Studies of other observables such as the spin alignment of quarkonia in associated production are only expected to become possible in the HL-LHC era, and will provide additional information on the underlying production mechanisms. The NLO CS contributions, which are expected to dominate at high P_T , predict the polar anisotropy of direct J/ψ and Υ produced in association with a Z boson to become strongly longitudinal ($\lambda_\theta < 0$) as the P_T of the quarkonium increases [142]. This stands in contrast to observations of very weak spin alignment in inclusive-production modes [143, 144] and so it is an area where even measurements of

570 limited precision can provide useful inputs.

571 Associated production of a photon and a quarkonium state offers an additional new probe of production
572 dynamics. This process has yet to be observed, although these final states have been the subject of study
573 for both P -wave quarkonium states [118, 145–148] and exclusive H^0 boson decays [149, 150]. The non-
574 resonant production of $\gamma + Q$ is challenging to distinguish due to low photon-reconstruction efficiencies or
575 large experimental backgrounds at low transverse momenta. These processes are however predicted to have
576 large SPS NLO cross-sections [151] that make them well-suited for future study, in particular to constrain
577 gluon TMDs (see Section 4.5.3). Expected DPS rates are not well-known, a fact that can compound the
578 interpretation of measurements at low P_T in a similar fashion to the existing $J/\psi + W/Z$ measurements. The
579 requirement of a high- P_T photon in experimental measurements will likely suppress DPS contributions and
580 enable excellent prospects for study at the HL-LHC if photons can be reliably associated to the quarkonium-
581 production vertex.

582 Similarly, associated vector-boson processes involving bottomonium states have yet to be observed.
583 This is in part due to lower expected production rates and the (slightly) larger combinatorial backgrounds
584 (from leptonic B meson decays) present in the $\Upsilon(nS) \rightarrow \mu^+\mu^-$ invariant mass region.

585 Such processes may be sensitive to heavy-quark-gluon-fusion contributions, in addition to the gluon-
586 gluon and light-quark-gluon processes present for the charmonium-production modes, and provide further
587 complementary tools with which to study SPS and DPS dynamics.

588 Associated $Q + W/Z/\gamma$ production provides a new opportunity to study heavy-flavour production in
589 association with a vector boson, which has to-date otherwise been predominantly tested in hadronic jet
590 final states [152–154]. Quarkonium-production modes provide an opportunity to test theoretical predictions
591 of $W/Z/\gamma + b(c)$ in a complementary regime at low transverse momentum and at small opening angles
592 sensitive to gluon splitting contributions. Open-heavy-flavour states have begun to be exploited for the
593 study of charm [155, 156], and $J/\psi + b$ final states have demonstrated their effectiveness for study of heavy-
594 flavour modelling [157] in topologies that are challenging to study with hadronic jet final states. Existing
595 measurements of non-prompt $J/\psi + Z$ production [136] have established these processes as having relatively
596 high production rates and small DPS contributions. Non-prompt $J/\psi + Z$ production has been found [158]
597 to be a sensitive probe of $Z + b$ production which is complementary to b -jet identification approaches and
598 that will, in particular, benefit from the enlarged acceptances and increased datasets at the HL-LHC.

599 Prompt- $Q + V$ processes also represent a tool and an opportunity to study a variety of potentially new
600 phenomena. Prompt- $Q + V$ production has been proposed as a compelling prospect for the study of rare
601 decays of the H^0 boson [159–161], or new heavy states [133, 162–164]. Such searches have begun to be
602 explored experimentally [134, 149, 165], but the potential of such searches will only be fully realised in
603 the HL-LHC era. In addition to searches for resonant phenomena decaying into $Q\bar{Q} + V$ final states, such
604 measurements can be re-purposed in the search for new light-mass states produced in association with a
605 vector boson. A study [133] using initial $J/\psi + W$ -observation data [135] was able to set competitive limits
606 on the production of a light scalar near the J/ψ mass, exceeding constraints both from dedicated low-mass
607 di-lepton searches at the LHC, as well as from searches via radiative Υ decays from e^+e^- experimental data.
608 A dedicated programme of searches for new phenomena in $Q\bar{Q} + V$ final states has yet to be performed
609 within the LHC collaborations but has fruitful prospects. The potential inclusion of Z -boson associated-
610 production modes, and its extension to include higher di-lepton masses, up to and beyond the Υ , $\Upsilon(2S)$
611 and $\Upsilon(3S)$ resonances, together with the large HL-LHC datasets, offer the opportunity for the LHC to far
612 surpass [133] the current bounds from LEP data.

613 2.5.2. Q -pair production

614 The production of pairs of quarkonia also offers rich opportunities for the study of both SPS and DPS as well
615 as of searches for rare decays and for new particles. Unlike for inclusive quarkonium production, which
616 is presumably dominated by quarkonium plus jet(s) or minijet(s) final states (see, e.g., [47, 81, 166, 167]),
617 the quarkonium pair production processes, including double charmonia, double bottomonia and charmo-
618 nium+bottomonium, can in principle provide independent handles to investigate the SPS quarkonium pro-
619 duction mechanism at LHC energies. Such measurements are, however, contaminated by sizeable DPS
620 contributions. Conversely, the measurements of these processes are also strongly motivated [34, 35] by
621 their potential for study of DPS interactions in their own right (see Section 7), and as a probe of the lin-

622 early polarised gluons inside the proton [16, 22] (see Section 4), as well as for the search for new exotic
 623 states predicted in QCD [168, 169] and in beyond the Standard Model theories, and for searches for rare
 624 decay modes of H^0 and Z bosons [170]. The di- J/ψ final state has proven the potential of such searches
 625 with the large datasets beginning to become available at the LHC with the recent observation by the LHCb
 626 collaboration of a new state [169] at a mass of 6.9 GeV, widely interpreted as a fully-charm tetraquark state.

627 Due to their rare but distinctive four-lepton signatures, di-quarkonia are excellent candidates for pre-
 628 cision studies with the large datasets expected at the HL-LHC. The experimental challenge will be to en-
 629 sure wide kinematic coverage and high event-selection efficiency in the complex HL-LHC environment.
 630 Searches for their production in the decay of H^0 bosons [170, 171], or other high-mass states, will benefit
 631 from Lorentz boosts in systems with large invariant mass. However, for new particle searches below the
 632 Z boson peak (and particularly below the $B\bar{B}$ threshold) [172, 173], an effective use of the unprecedented
 633 luminosities delivered in the HL-LHC programme requires that the experiments (in particular, the gen-
 634 eral purpose detectors) maintain a high efficiency for reconstruction of low transverse-momentum leptons,
 635 $O(2 - 4 \text{ GeV})$, in four-lepton signature events containing one or more quarkonium candidates.

636 The di- J/ψ final states have been the focus of significant theoretical study [16, 22, 34, 35, 76, 174–
 637 189], reflected in the concentration of measurements from the LHC so far into the same final state [190–
 638 194]. The experimental picture has been recently broadened with measurements of di- Υ production by
 639 CMS [173, 195], and a study of $J/\psi + \Upsilon$ [196] production by $D\bar{O}$ at the Tevatron.

640 From the theoretical perspective, di- Υ production is more-or-less similar to the di- J/ψ process, while
 641 both are significantly different with respect to $J/\psi + \Upsilon$. The bulk of SPS events can be accounted for by
 642 the leading- v^2 CS channel in the former ones, while, for the latter, the complete study of [197] reveals that
 643 the contributions from CO plus the feed-down contribution from excited quarkonium states are larger than
 644 the CS channel in SPS production of $J/\psi + \Upsilon$. Given this, $J/\psi + \Upsilon$ would be a priority for study from the
 645 viewpoint of investigating the CO mechanism. Although plagued by a significant fraction of events from
 646 DPS interactions, the CO contributions can potentially be determined at the HL-LHC through measurement
 647 of their invariant mass distribution as shown in Fig. 10. Such a process has never been observed experimen-
 648 tally, while the $D\bar{O}$ collaboration only found 3σ evidence at the Tevatron for the inclusive process, which
 649 should be expected to be composed of SPS and DPS components. It is thus desirable to carry out an analysis
 650 at the LHC to establish observation and decouple the SPS component for further study.

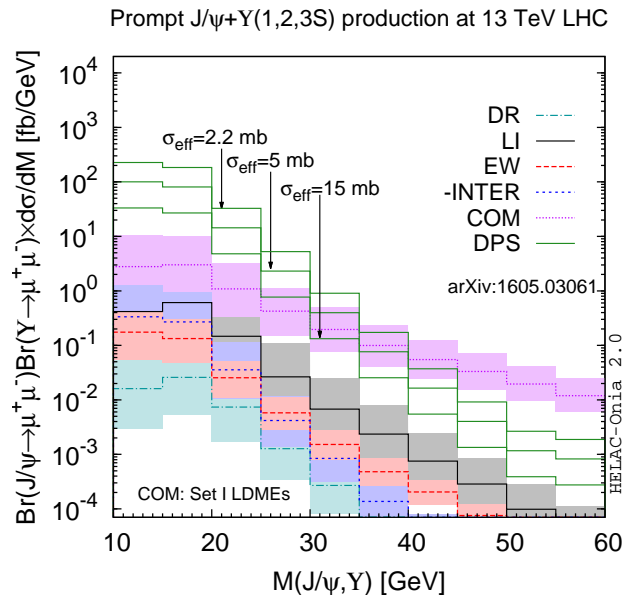


Figure 10: Prediction for the invariant mass distribution of $J/\psi + \Upsilon$ production in pp collisions at $\sqrt{s} = 13 \text{ TeV}$ within the fiducial volume $2 < y_{J/\psi}, y_{\Upsilon} < 4.5$. [Plot taken from [197]]

651 Besides the continuing measurements on $J/\psi + J/\psi$ and $\Upsilon(1S) + \Upsilon(1S)$, it would be difficult to achieve a
 652 coherent picture without a survey of all the excited states, and mapping the different production modes will
 653 require the large datasets in the HL-LHC era. Measurements of these excited states are eagerly anticipated:
 654 different combinations of quarkonia provide independent tests for the existence of new anticipated [198–
 655 200] and unanticipated states, and will not only provide information on feed-down contributions to existing

656 production measurements but also provide a direct probe of their own production mechanisms.

657 2.5.3. Associated production of Q and jets

658 The production mechanisms for high- P_T quarkonium-production result in the production of one or more
659 hadronic jets accompanying the quarkonium state. The multiplicity of these jets and the radiation patterns
660 relative to the produced state (or the similar J/ψ -hadron azimuthal correlation studies carried out e.g. by
661 STAR [201]) provide valuable insights into the underlying production mechanisms of quarkonia, and are
662 sensitive to CS/CO contributions as well as to higher-order quantum corrections.

663 We encourage the HL-LHC experimental collaborations to measure the production cross section of
664 quarkonium states as functions of both jet multiplicity (for jets above some fixed transverse momentum
665 scale, $P_T > Q_0$) and quarkonium transverse momentum. Ideally, these measurements should be matched
666 to corresponding measurements of inclusive jet production in the same fiducial volume. As well as serving
667 as an alternative tool for the study of single parton production, such datasets can find further application
668 as an additional probe of DPS through measurements of angular correlations and P_T balance observables,
669 analogous to those performed in V + jets [202, 203] and other quarkonium final states (see Section 7.3).

670 Although initial studies can already be performed with the existing LHC data, high- P_T Q + inclu-
671 sive jets signatures can be efficiently recorded at the HL-LHC, where the large datasets will enable access
672 to events with high jet multiplicities as well as the hadronic activity accompanying very high- P_T (100–
673 300 GeV) quarkonium, a regime that inclusive production measurements are now starting to probe [204].
674 Such studies would be complementary to measurements of quarkonium produced *in* jets (Section 2.3.1) as
675 well as studies of quarkonium correlations with soft hadronic activity at low P_T (Section 2.3.2).

676 The high performance of jet flavour tagging at ATLAS/CMS offers the potential for novel studies of
677 associated quarkonium and heavy-flavour production in final states with hadronic jets. Measurements of
678 such processes have not yet been performed. The P_T dependence of the production rates of J/ψ + c -jet or
679 Υ + b -jet events is sensitive to the CS and CO contributions. Measurements of the topology of such events
680 would provide valuable information, with CS transitions expected to dominate for quasi-collinear J/ψ + c
681 or Υ + b production, while CO contributions would dominate in topologies with two heavy-flavour jets
682 recoiling against the quarkonium state. Production rates [205] for these processes are sufficiently large at
683 high $P_T^Q > 20$ GeV (needed to ensure jets can be adequately reconstructed and tagged), and thereby there
684 are good prospects for study of these processes at the HL-LHC. Assuming a combined trigger and dimuon
685 efficiency of approximately 50% [206] and low- P_T c -tagging and b -tagging efficiencies of 25% and 50%,
686 respectively [207, 208], estimated yields of J/ψ + $c\bar{c}$ and Υ + $b\bar{b}$ (with at least one identified heavy-flavour
687 jet) of 7 500 and 150 000 can be expected at both ATLAS and CMS detectors with the HL-LHC dataset, *if*
688 the current efficiencies for triggering on quarkonium states down to $P_T \approx 20$ GeV can be maintained.

689 2.6. Constraining the gluon PDF in the proton using Q

690 The progressive accumulation of large amounts of experimental data at the LHC, with associated increas-
691 ingly reduced statistical uncertainties, requires a parallel effort to decrease the theoretical uncertainties of
692 the corresponding predictions. Theoretical hadronic cross sections exhibit dependencies on intrinsic scales
693 such as the factorisation and renormalisation scales. The inclusion of higher-order perturbative QCD cor-
694 rections in calculations of partonic cross sections, mostly at NLO accuracy today, will lead to a reduction
695 of such scale uncertainties. For many theoretical calculations, the PDF uncertainties are often the leading
696 uncertainty today. In particular, the gluon density in the small- x domain ($x \lesssim 10^{-4}$), extrapolated from
697 larger- x regions, is essentially unconstrained by experimental data, and affects quarkonium cross sections in
698 the low- P_T and/or forward regimes. Low- x studies are also relevant in searches for phenomena beyond the
699 DGLAP linear QCD evolution equations [209–211], such as those driven by Balitsky-Fadin-Kuraev-Lipatov
700 (BFKL) [212–215] or non-linear parton saturation [216–218].

701 It is thus helpful to exploit new paths to perform PDF fits, by trying to incorporate new precise data
702 already available, which are not traditionally considered in PDF global fits. A possibility in this direction is
703 offered by the LHC data on hidden and open-heavy-flavour production, characterised by very high statistical
704 precision. There are recent small- x gluon constraints, though not yet in the global analyses, from inclusive
705 open-charm production [219–222] and from J/ψ in exclusive reactions [223] (see section 3.3.2 for details).
706 These data probe the very low x , down to $x \approx 3 \cdot 10^{-6}$, and low scale (a few GeV^2) domain. However,

707 tensions arise between the open charm and the exclusive J/ψ extractions. It would therefore be valuable
708 to have new insights from additional independent determinations with similar inputs, such as from the
709 inclusive quarkonium data.

710 Given the lack of consensus on the production mechanisms, the inclusion of inclusive quarkonium pro-
711 duction data in the PDF global fits, which was initially proposed in the 1980s [9, 10], has been abandoned.
712 In addition, the ψ and Υ hadroproduction processes suffer from large LDME uncertainties from several
713 competitive CO channels. These non-perturbative CO LDMEs could be largely determined from the cor-
714 responding experimental data for each PDF choice. The, the usage of the ψ and Υ data in a PDF fit, albeit
715 still lacking the coherent picture, could be taken correlated with the corresponding LDME determinations,
716 which is analogous to the role of the strong coupling α_s in other PDF analysis.

717 The situation could be radically improved if, for a given quarkonium observable, one is able to iden-
718 tify a single dominant channel or mechanism. One typical example is η_c hadroproduction at the LHC at
719 $P_T \lesssim 12$ GeV (see also discussions in Section 2.4.1), where it is understood that only the leading- v^2 CS
720 channel is relevant. The remaining obstacle in using the quarkonium data to pin down the small- x gluon
721 density in the proton is the large intrinsic theoretical uncertainties in the cross section calculations, that are
722 at NLO accuracy today. Similar to the open-charm case, these scale uncertainties can be largely mitigated
723 by looking at ratios of (differential) cross sections (such as the ratios of two independent measurements at
724 different centre-of-mass energies [224] or of cross sections in two different rapidity bins [219]). These ratios
725 have the extra advantage of cancellation of some of the systematic uncertainties, such as those related to the
726 (single) LDME in theoretical calculations and the correlated systematical errors in experimental measure-
727 ments. Exploiting the η_c LHCb Run-2 measurement [110] is however not competitive as it is dominated
728 by large statistical uncertainties. The HL-LHC is clearly able to significantly increase the precision of the
729 measurement. All such inclusive quarkonium data are able to improve our knowledge of the proton PDFs
730 lying in the low x ($x < 10^{-5}$) and low scales (a few GeV^2) regime, which are expected to be hard to constrain
731 in general.

732 In addition, the collider mode, FT-LHC [6] will allow one to probe the high- x range of the proton
733 PDFs. In such a colliding configuration, the probed x range of the parton (gluon, charm and valence quarks)
734 densities can reach $x \simeq 0.5$, if not larger, by using various final states, including open-heavy-flavour hadrons
735 and quarkonia.

736 For further aspects on the experimental side, the experimental collaborations should provide all infor-
737 mation needed to include their data with the appropriate uncertainties in PDF fits. In particular, informa-
738 tion [225] on bin-by-bin correlations of systematic uncertainties, in the form of covariance error matrices
739 in differential distributions, as well as those on correlations between different distributions, are essential
740 to perform a fully meaningful statistical analysis and extraction of best-fit PDFs accompanied by reliable
741 uncertainty estimates. Moreover, it is obvious that the quarkonium data used in a standalone way are not
742 enough to perform PDF fits at all values of x and scale. Therefore, it is ideal to use them in conjunction
743 with all other data traditionally already used in PDF global fits, in particular those on inclusive and semi-
744 inclusive Deep-Inelastic-Scattering (DIS), as a complementary tool to extend the (x , scale) coverage of the
745 latter.

746 The last considerations of this section regard recent theory progresses. It has been known for a long
747 time that, for some choices of parameterisation, where gluon PDFs are rather flat, the open-charm and
748 charmonium P_T -integrated cross sections at low scales can become negative [226–230] at high \sqrt{s} . Such
749 pathological behaviours appear at (N)NLO for open charm and at NLO for charmonium. Hence, imposing
750 the positivity of these cross sections, assuming that the missing higher order QCD corrections do not com-
751 pletely change the picture, would add additional constraints on the gluon PDF. This would also go along the
752 lines of a recent exploratory study on the positivity of the $\overline{\text{MS}}$ PDF itself [231].

753 However, it was recently found in [12] that the unphysical behaviour of the η_c cross section at NLO
754 for increasing \sqrt{s} (but not necessarily for extremely large \sqrt{s}) could efficiently be tempered by a specific
755 factorisation-scale choice. The resulting cross section indeed then shows a reduction of the renormalisation
756 scale uncertainty while remaining very sensitive to the gluon PDF at low scales. If a similar scale choice
757 can be used for J/ψ for which numerous P_T -integrated cross sections have been measured, it could certainly
758 be used in the future to fit the gluon PDF at NLO.

759 3. Exclusive and diffractive production¹³

760 The diffractive production of quarkonia differs from inclusive production, discussed in the previous section,
761 by the presence of colourless particle exchanges that lead to rapidity gaps, devoid of any hadronic activity, in
762 the final state of the event. Diffractive processes are called exclusive if the final state, including the forward
763 scattered protons, is fully determined. In hadron-hadron collisions, such events are generally characterised
764 by two large rapidity gaps with a centrally produced object, which can consist of a single particle or a pair
765 of particles.

766 Diffractive quarkonium production at hadron colliders offers a unique tool to study the nature of both C -
767 even pomerons and C -odd odderons, multi-gluon colourless systems exchanged in scatterings with hadrons,
768 which are fundamental to the understanding of soft hadron interactions. In the perturbative regime, the
769 pomeron and odderon can roughly be interpreted as consisting of two and three gluons, respectively, though
770 in general these are non-perturbative objects.

771 Diffractive processes can provide an improved understanding of the production of quarkonium states.
772 Different Feynman diagrams contribute in inclusive, diffractive, and exclusive quarkonium production,
773 which can be accessed through a comparison of results; e.g. in exclusive J/ψ production, CO contribu-
774 tions are entirely absent. In addition, exclusive production presents a particularly clean experimental envi-
775 ronment and, sometimes, a simpler theoretical domain, which may assist with the identification of exotic
776 quarkonia. In the large c.m.s. energy limit, diffractive processes serve as a special testing ground for the
777 BFKL resummation of HE logarithms entering at all orders of the perturbative expansion.

778 One of the most fruitful applications of exclusive quarkonium production is their use as probes of the
779 partonic structure of the colliding objects. Exclusive measurements are the only way to probe the 3D
780 distribution of partons as functions of their longitudinal momentum and transverse position (through single-
781 particle production), and their 5D distribution in terms of transverse position, longitudinal, and transverse
782 momentum (through the production of pairs of particles or jets). These 5D distributions are related to
783 Generalised Transverse Momentum Distributions (GTMDs), which are Fourier transforms of Wigner distri-
784 butions. They are known as the “mother distributions”, since they contain the most complete information on
785 the nucleon structure. Integrating them over the parton transverse momentum gives the generalised parton
786 distributions (GPDs) and taking the forward limit of the GPDs results in the PDFs.

787 Selected experimental results on exclusive and diffractive quarkonium measurements are presented in
788 Section 3.1.1, with some discussion of open questions for theory and experiment. A measurement of diffrac-
789 tive quarkonium production for the study of BFKL resummation is introduced in Section 3.2. In Section 3.3,
790 the physics accessible in single vector-quarkonium production is discussed under three headings. Firstly,
791 Section 3.3.1 presents processes in hadron-hadron interactions useful for the extraction of GPDs: unlike
792 DIS data, which have been extensively used to constrain GPDs, hadron-hadron collider data have not yet
793 been exploited. Secondly, exclusively-produced quarkonia can, with certain approximations, provide infor-
794 mation on PDFs, but until now such measurements have not been included in global PDF fits. Section 3.3.2
795 discusses the theoretical framework and proposes a method for the extraction of PDFs from exclusive J/ψ
796 production. Thirdly, with FT-LHC, a kinematic region complementary to that in the collider mode could
797 be accessed, as discussed in Section 3.3.3. The exclusive production of pairs of quarkonia (and jets) is
798 discussed in Section 3.4. Until recently, it was not known how to access GTMDs, but now it has been
799 shown that they can be extracted from pairs of particles or jets both in DIS and photoproduction. DIS mea-
800 surements await the future Electron-Ion Collider (EIC) [229], but for photoproduction in hadron-hadron
801 collisions, the LHC is the ideal machine. A discussion of some of the most favourable experimental chan-
802 nels at the HL-LHC is provided in Section 3.4.

803 As already discussed, three main distinct modes of operation are foreseen for HL-LHC: pp , pA and AA
804 collisions¹⁴ where A is an ion, usually lead. Compared to previous LHC running, data taken in HL-LHC pp
805 collisions will be difficult to use for exclusive measurements because of the high number of pp interactions
806 per beam collision. Measurements in such an environment may still be possible using proton taggers that
807 could allow identification of the separate pp primary vertices, or through dedicated data collection with a
808 lower number of interactions per beam collision.

¹³Section editors: Charlotte Van Hulse, Ronan McNulty.

¹⁴Collisions using O, Ar, Kr and Xe beams may also be envisioned.

809 Collisions in the pA mode offer several advantages for the study of the nucleon, and have been under-
 810 utilised to date, due to the low integrated luminosities taken thus far. For HL-LHC, a nearly tenfold increase
 811 of data is foreseen [2]. This will not result in many multiple interactions per beam crossing and will provide
 812 a more appropriate channel to perform photoproduction measurements, exploiting the enhanced photon flux
 813 from the nucleus (which goes approximately as Z^2). Compared to pp collisions (in the absence of a proton
 814 tagger), pA collisions also have the advantage of identifying the photon emitter. In addition, they might
 815 offer a handle on constraining nuclear distributions, through photoproduction on the nucleus in the nucleus-
 816 going direction. While the foreseen tenfold increase in luminosity is important for a wide range of physics,
 817 exclusive measurements would clearly benefit from even higher luminosities in order to exploit their full
 818 potential (e.g. for Υ and charmonium-pair production, as discussed later).

819 Access to nuclear distributions (PDFs, GPDs, and Wigner distributions) is best provided through the
 820 study of ion-ion (AA) collisions. A nearly tenfold increase of data collection in PbPb collisions is fore-
 821 seen for the HL-LHC. For photoproduction processes, the ambiguity in the identity of the photon emitter
 822 can in part be lifted through the detection of neutrons emitted by one of the Pb ions, e.g. in zero-degree
 823 calorimeters [232].

824 3.1. Experimental results

825 3.1.1. Selected experimental results

826 Exclusive and diffractive production has been studied in lepton-hadron interactions, both at the FT experi-
 827 ments HERMES [233–245], COMPASS [246–253], and the experiments at Jefferson Lab [254–266], and
 828 at the collider experiments H1 (see, among others, [267–283]) and ZEUS (see, among others, [284–296]).
 829 It has also been studied in hadron-hadron collisions at the Tevatron, RHIC, and LHC. While lepton-hadron
 830 interactions offer the advantage of high-precision measurements by using a point probe to study hadrons,
 831 hadron colliders can reach a higher c.m.s. energy, hence providing access to lower values of the parton
 832 fractional momentum, x .

833 Future experiments are envisaged with expanded possibilities for exclusive and diffractive measure-
 834 ments. For the study of lepton-hadron interactions, the EIC construction is in development [297]. The EIC
 835 will allow the collection of large samples of data at variable c.m.s. energies, thus making possible high-
 836 precision, multi-differential measurements with a vast kinematic coverage. Moreover, measurements with
 837 polarised nucleons and (unpolarised) nuclear-ion beams will allow one probing the nucleon spin structure
 838 and nuclear matter, respectively. Stepwise upgrades for the LHC and the LHC experiments are also ongoing
 839 and planned, on a time scale preceding the EIC, at c.m.s. energies about 50 times larger than those acces-
 840 sible at the EIC. Such a programme has the potential to access rarer diffractive and exclusive processes. In
 841 addition, there exists the possibility to perform measurements with FT collisions at the LHC, covering c.m.s.
 842 energies similar to those at the EIC. These provide access to the high- x region. Also, ideas and studies for
 843 measurements with a polarised target at the LHC, sensitive to spin-related physics, are underway [6, 298].
 844 Furthermore, planned data collection with a heavy-ion beam and nuclear targets provides the possibility to
 845 study the nuclear parton density.

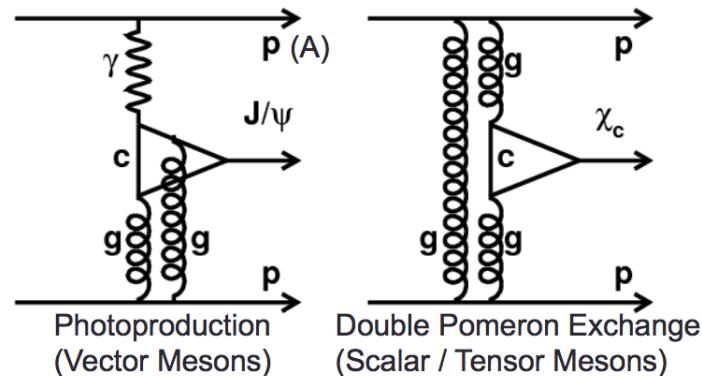


Figure 11: Photoproduction (Left) and double-pomeron exchange production (Right) of charmonium at hadron colliders.

846 Exclusive quarkonium production at hadron colliders is commonly studied in ultra-peripheral collisions

847 (UPCs) [299–302]. In such collisions, impact parameters are typically larger than the sum of the nuclear
848 radii, so strong interactions are suppressed, while electromagnetic interactions are favoured. Exclusive
849 meson production has been studied at the Tevatron in $p\bar{p}$ collisions, at RHIC in AuAu and p Au collisions,
850 and at the LHC in proton-proton, p Pb, and PbPb collisions. The measurements cover light vector-meson
851 production, such as single- ρ production [303–312], and heavier single and pair-produced quarkonia J/ψ ,
852 $\psi(2S)$, χ_c and Υ [312–319]. In heavy-quarkonium production, the charm and bottom quarks provide the
853 hard scale that makes possible a theoretical perturbative expansion, and the interpretation of the results in
854 terms of PDFs, GPDs, or Wigner distributions. The majority of the measurements so far were performed
855 using unpolarised hadrons, but preliminary measurements with a transversely polarised proton have been
856 performed at RHIC and these allow access to spin-dependent PDFs, GPDs, and Wigner distributions [320].
857 Differential cross-sections have been measured as functions of quarkonium rapidity and the Mandelstam
858 variable t , which can be approximated by the P_T^2 of the produced meson system.

859 Single vector-meson production involves a single-pomeron exchange (SPE), and is the most studied
860 process so far in central exclusive production, while scalar and tensor quarkonium are produced through
861 double-pomeron exchange (DPE); the different production mechanisms are shown in Fig. 11. Since only
862 gluon propagators are present in DPE, central exclusive production is a fertile hunting ground for glueballs,
863 tetraquarks, and quark-gluon hybrid states, with the potential advantage of a lower background contamina-
864 tion compared to non-exclusive measurements. Such gluon-rich media are also a good environment to study
865 the odderon, predicted in QCD but not unambiguously observed [321, 322]. A very promising channel that
866 would provide strong evidence for the existence of the odderon is exclusive photoproduction of C+ quarko-
867 nia, which can only be produced if the photon fuses with another C- propagator. Searches for the exclusive
868 production of scalar [323, 324] or tensor quarkonia in pA or AA collisions are therefore of great interest and
869 require high luminosity. Exclusive, in comparison to inclusive, measurements can also give insight into the
870 production mechanisms of charmonia and could indirectly help to distinguish between different frameworks
871 used for inclusive production.

872 The HL-LHC operation warrants a future programme of work for experimentalists and theorists in
873 which the different frameworks can be better disentangled through the comparison of suitably chosen high-
874 precision observables in exclusive, diffractive, and inclusive reactions. For example, in exclusive reactions,
875 CO states are absent and, in non-exclusive processes, it is plausible that, as the produced quarkonium
876 becomes more isolated, the CO contributions become more suppressed.

877 By virtue of the Landau-Yang theorem [325, 326], which states that a spin-1 particle cannot couple to
878 two identical massless vector particles, the exclusive production of χ_{c1} is expected to be heavily suppressed
879 compared to its spin partners, the χ_{c0} and χ_{c2} . In inclusive production, this suppression may not be as pro-
880 nounced because of the CO contributions. If the initial gluons are allowed to be off-shell or if a third gluon is
881 emitted, this suppression is lifted but the χ_{c1} rates remain partly suppressed [327, 328] compared to the χ_{c2} .
882 In the exclusive case, CO contributions are absent and any gluon emission is forbidden. Thus, measuring
883 the yield ratio χ_{c2}/χ_{c1} here would directly probe the degree of off-shellness of the gluons compared to the
884 inclusive mode discussed in Section 4.6.

885 Such investigations can be further expanded by measuring quarkonium polarisation. The first study on
886 polarisation of prompt χ_{c1} and χ_{c2} in inclusive production [117] uncovered a significant difference in polar
887 anisotropy, λ_θ , in agreement with NRQCD. Measurements that avoid the need to detect photon conversions
888 are expected to improve the experimental resolution [329]. This may in fact be possible in the exclusive
889 mode where the polarisation invariants (see Section 2.2.2) can reach their extremal values.

890 While photoproduction of quarkonia at heavy-ion colliders is typically studied in UPCs, there are now
891 indications of contributions from photoproduced J/ψ in peripheral collisions (with partial hadronic overlap),
892 both at LHC by the ALICE experiment [330], and at RHIC by the STAR experiment [331]. At low P_T , an
893 excess of J/ψ yields compared to that expected from hadroproduction is observed, which can be explained
894 by contributions from photon-induced J/ψ production. In this context, it would be extremely useful to
895 study the polarisation of the J/ψ , since it is measured to be unpolarised in hadroproduction and transversely
896 polarised in photoproduction, as inherited from the parent (real) photon. This study could be expanded to
897 include $\psi(2S)$ and Υ .

898 Contradictory results have been found for the ratio of coherently photoproduced $\psi(2S)$ to J/ψ . While
899 the data at central rapidity in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV showed a ratio almost twice that in pp
900 collisions [332], new data at forward rapidity in PbPb collisions at 5.02 TeV give a ratio consistent with the

901 pp results [333].

902 Studying diffractive processes where the probed beam hadron breaks up provides some sensitivity to
 903 the non-uniformity of the gluon distribution in the transverse impact-parameter space (see [334, 335] and
 904 references therein). Cross sections and cross-section ratios of coherent and incoherent J/ψ and Υ photopro-
 905 duction are a valuable tool to study the nucleon shape [334, 336–338].

906 The identification of diffractive processes in general and the separation of diffractive processes where
 907 the beam particles break up or stay intact are experimentally and theoretically challenging, especially in
 908 collider experiments. Some aspects involved in the identification of exclusive and non-exclusive diffractive
 909 processes are discussed next.

910 3.1.2. Experimental identification of diffractive processes

911 The experimental identification of diffractive events usually relies on the identification of a large rapidity
 912 gap, found by ordering all charged particles in pseudorapidity and noting the largest difference, $\Delta\eta$, between
 913 adjacent particles. There are at least two practical problems with this approach, due to the fact that detectors
 914 are not hermetic. Firstly, how big a gap is required to identify an event as diffractive? Secondly, how does
 915 one deal with the dissociation of the projectiles, which occurs within a few units of rapidity of the beams
 916 and often enters uninstrumented regions? Both these issues are briefly discussed below: neither is fully
 917 resolved and each is difficult to approach both theoretically and experimentally.

918 One way to investigate the size of the gap required to tag an event as diffractive is to look at the (back-
 919 ground) gap sizes in inclusive events. However, modelling this in generators is difficult as the results
 920 depend on non-perturbative effects: a single soft particle can destroy the gap. It was shown in [339] that, if
 921 the threshold for detecting tracks is relatively high ($P_T > 1$ GeV), similar results are obtained with cluster
 922 hadronisation and string fragmentation models. However, order-of-magnitude differences occur at lower
 923 transverse momenta: the probability of $\Delta\eta > 4$ in minimum bias pp events at $\sqrt{s} = 7$ TeV was found to
 924 be about 0.1 using a cluster hadronisation model [340] and 0.02 for string fragmentation [341]. A recent
 925 measurement by ATLAS [342], comparing the largest gap in pp events at $\sqrt{s} = 8$ TeV with PYTHIA [343]
 926 and HERWIG++ [344] (Fig. 12, Left), shows that the data exhibit fewer large gaps than the models predict.

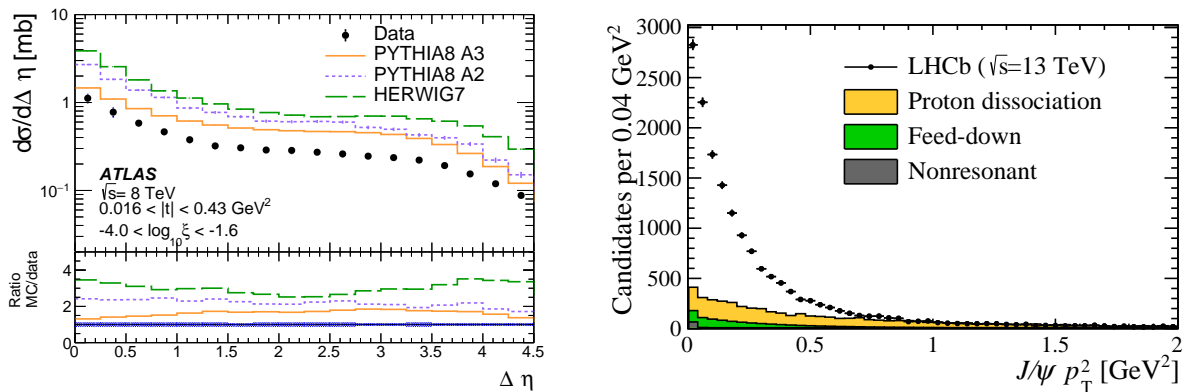


Figure 12: Left: Hadron-level differential single-diffractive cross section as a function of $\Delta\eta$, comparing the measured data with PYTHIA and HERWIG++ 7 predictions. Right: Transverse momentum squared distribution of J/ψ candidates showing estimated fractions of exclusive, feed-down, and proton-dissociation contributions. [Figures taken from [342] and [315].]

927 A related problem occurs in central exclusive production, where large gaps should exist on either side of
 928 the central system (e.g. $pp \rightarrow p \oplus J/\psi \oplus p$ as discussed further in Section 3.3.2). Various methodologies have
 929 been employed in such systems to determine whether the candidate events are truly isolated or whether the
 930 proton dissociates. A simple approach, taken in the analysis of exclusive $\pi\pi$ production by CMS [304], is
 931 to fit additional neutral energy deposits in known non-exclusive events, and extrapolate to the signal region,
 932 assuming similar behaviour for like-sign and unlike-sign combinations. Another approach, by LHCb, in
 933 the analysis of exclusive J/ψ production [315], uses Regge theory to fit the P_T distribution in known non-
 934 exclusive events to model the dissociative process and combines this with the signal shape to determine the
 935 purity of a sample of candidate exclusive events (Fig. 12, Right). A more complex approach was presented
 936 in a recent H1 analysis of the photoproduction of ρ mesons [345]. Dissociative events are not well described

937 either at generator level or in the detector simulation. Therefore, a sophisticated re-weighting of the DIFVM
 938 generator [346] was employed, tuned using control samples from data.

939 An elegant solution to the problem of identifying exclusive events is found if the intact protons can
 940 be reconstructed. This requires dedicated detectors installed at very low angles to the beam, typically
 941 in Roman pots located several hundred metres from the interaction point. Both ATLAS (through the AFP
 942 spectrometer [347]) and CMS-TOTEM (using CT-PPS [348]) use such technology, which has the additional
 943 advantage of providing an independent measurement of the mass of the central system.

944 3.2. Forward J/ψ + backward jet production

945 In Section 2.5.3, experimental studies were motivated towards the measurement, in inclusive reactions,
 946 of quarkonia associated with jets, following the first proposal of [7]. Motivations for studying them in
 947 diffractive reactions are now considered.

948 Diffractive reactions featuring a semi-hard scale hierarchy [216], i.e. $\sqrt{s} \gg \{Q\} \gg \Lambda_{\text{QCD}}$, with \sqrt{s} the
 949 centre-of-mass energy and $\{Q\}$ a (set of) characteristic hard scale(s), serve as a special testing ground for the
 950 dynamics of strong interactions in the High-Energy (HE) limit. Here, a genuine Fixed-Order (FO) treatment
 951 based on collinear factorisation fails, since large energy logarithms enter the perturbative series in the strong
 952 coupling, α_s , with a power that increases with the order. In particular, large final-state rapidities (or rapidity
 953 distances), typical of single forward emissions (or double forward/backward emissions) with colourless
 954 exchanges in the t -channel, directly enhance the weight of terms proportional to $\ln(s)$. The HE factorisation
 955 based on the BFKL equation performs an all-order resummation of these large energy logarithms both in the
 956 leading-logarithmic approximation (LL), which means inclusion of all terms proportional to $\alpha_s^n \ln(s)^n$, and
 957 in the next-to-leading-logarithmic approximation (NLL), including all terms proportional to $\alpha_s^{n+1} \ln(s)^n$.

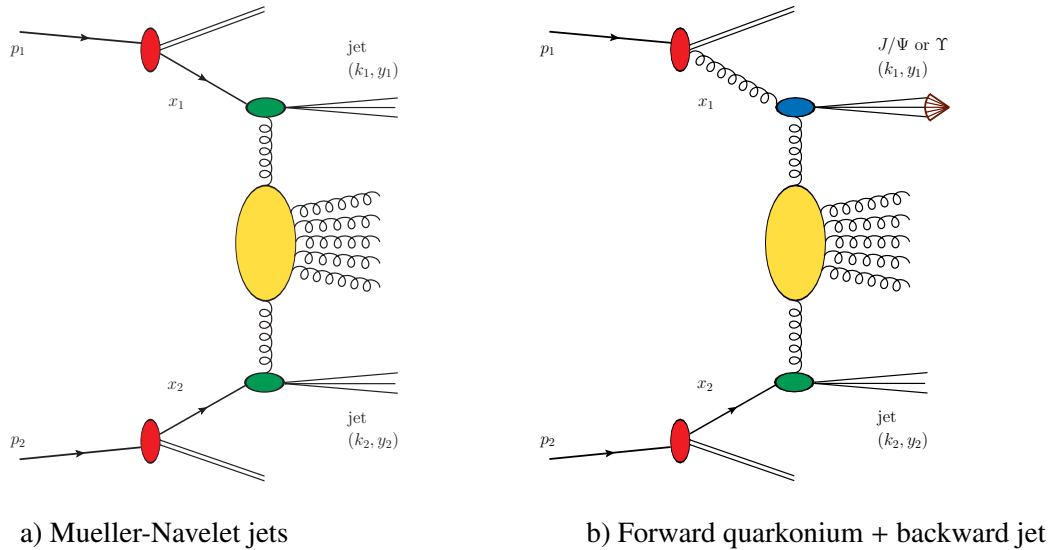


Figure 13: Pictorial representation of two semi-hard reactions in the hybrid “HE + collinear” factorisation. Red blobs denote collinear PDFs, whereas green (blue) ones refer to the hard part of impact factors accounting for jet (quarkonium) emissions. They are connected to the BFKL gluon Green’s function, schematically represented in yellow, via pomeron lines.

958 Over the last few years, predictions for observables in a wide range of semi-hard final states have been
 959 proposed [349–366]. Among them, azimuthal correlations between two Mueller-Navelet jets [367] have
 960 been identified as favourable observables in the discrimination between BFKL- and FO-inspired calcula-
 961 tions [368–370]. This channel, depicted in Fig. 13 (a), is characterised by hadroproduced jets with high
 962 transverse momenta, a large difference in rapidity, and a secondary undetected gluon system.¹⁵

963 Several phenomenological studies have been conducted so far [372–384] and have been found to be in
 964 fair agreement with data collected by the CMS collaboration [385]. The theoretical description relies on the
 965 so-called *hybrid factorisation*, where DGLAP ingredients are elegantly combined with the HE resummation.

¹⁵Although featuring secondary gluon emissions in the final state, this reaction can be classified as a diffractive one. Indeed, the imaginary part of its cross section, dominant with respect to the real part in the HE limit, can be directly linked to the forward elastic-scattering amplitude via the optical theorem.

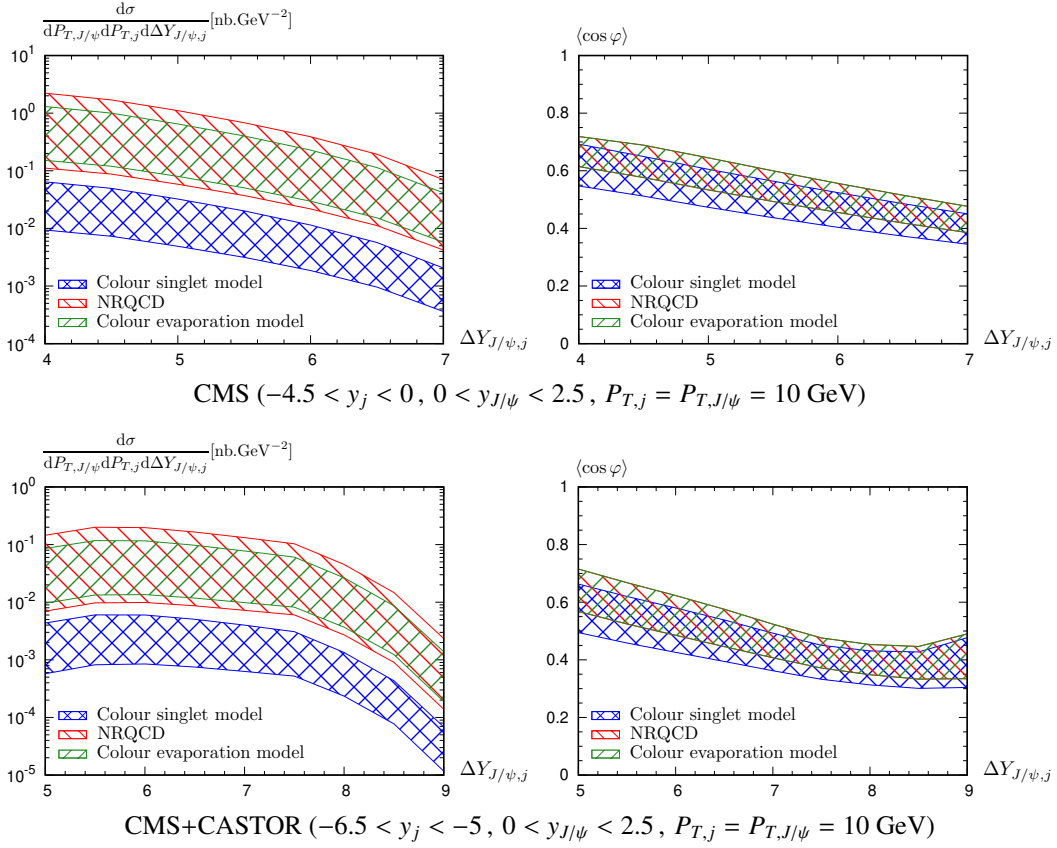


Figure 14: Cross section (Left) and $\langle \cos \varphi \rangle$ (Right) at $\sqrt{s} = 13$ TeV as a function of the rapidity distance $\Delta Y_{J/\psi,j}$ between the J/ψ and the jet as obtained in the BFKL approach in [371], for three different J/ψ hadronisation models. [Figures adapted from [371]]

966 On the one hand, longitudinal momentum fractions of the two jets are assumed to be large enough so that
 967 the collinear factorisation applies, thus permitting a description of the incoming partons in terms of the
 968 usual PDFs. On the other hand, transverse momenta exchanged in the t -channel are not negligible due to
 969 the large rapidity interval in the final state, thus calling for a HE-factorised treatment, genuinely afforded by
 970 the BFKL approach.

971 In line with these studies, the inclusive detection of a forward J/ψ and a very backward jet in hadronic
 972 collisions at the LHC was recently proposed [371] as a novel semi-hard channel (Fig. 13, b). Here, at vari-
 973 ance with most of the previous analyses, calculations are done in a hybrid HE + collinear factorisation with
 974 partial NLL BFKL accuracy, while different quarkonium production mechanisms are at work. This study
 975 allows a probe of the dynamics of the HE resummation, its effect being emphasised by the smaller values
 976 of transverse momentum at which identified mesons can be tagged with respect to jets (thus heightening
 977 the weight of secondary, undetected gluons). At the same time, it offers an intriguing and complementary
 978 opportunity to probe different approaches for the description of the production of quarkonium states.

979 Predictions for the differential cross section and for the azimuthal correlation, $\langle \cos \varphi \rangle$, with $\varphi = \varphi_{J/\psi} -$
 980 $\varphi_j - \pi$, the difference of the azimuthal angles of both emitted objects, are presented in Fig. 14 as a function
 981 of the rapidity interval, $\Delta Y_{J/\psi,j}$, between the J/ψ and the jet at $\sqrt{s} = 13$ TeV. The meson is detected in
 982 the forward rapidity region of the CMS detector, $0 < y_{J/\psi} < 2.5$, while two possibilities are considered
 983 for the backward-jet emission: it can be tagged a) by CMS $-4.5 < y_j < 0$, or b) inside the ultra-backward
 984 CASTOR detector [386], $-6.5 < y_j < -5$. Notably, case b) compensates for the smaller rapidities at
 985 which mesons can be detected (which represents a major drawback in the detection of a J/ψ instead of a
 986 jet), thus restoring the rapidity intervals typical of the Mueller-Navelet jet production. Both the J/ψ and
 987 jet P_T are required to be above 10 GeV. The uncertainty bands combine the effect of the variation of the
 988 renormalisation and the factorisation scales, together with the running of the non-perturbative constants
 989 related to the hadronisation of the J/ψ . In particular, the CS LDME $\langle O_{J/\psi}^{3S_1^{[1]}} \rangle$ is varied between 1.16 and 1.32
 990 GeV^3 , as obtained in [387] and [388] respectively. The CO LDME $\langle O_{J/\psi}^{3S_1^{[8]}} \rangle$ is varied between 0.224×10^{-2}

991 and $1.1 \times 10^{-2} \text{ GeV}^3$ [57, 58, 60].¹⁶ In the CEM, the parameter $F_{J/\psi}$ represents the fraction of the $c\bar{c}$ pairs
 992 produced in the invariant mass range $[2m_c, 2m_D]$ hadronising into J/ψ mesons and it is varied between 0.02
 993 and 0.04 [389] (see also [75]).

994 The inspection of results in Fig. 14 leads to significant cross sections that can be studied at the HL-LHC.
 995 In the NRQCD approach, the CO contribution prevails over the CS one [371], while the CEM exhibits a
 996 behaviour similar to the NRQCD (CS+CO) result. Azimuthal correlations show patterns very similar to the
 997 ones obtained for the Mueller-Navelet dijet and, in general, for all the semi-hard channels investigated so
 998 far: large rapidity intervals enhance the weight of undetected hard-gluon radiation, thus leading to a loss of
 999 correlation between the two final-state particles in the azimuthal plane.

1000 Future studies will extend this work to: (i) a full NLL BFKL analysis, (ii) the integration of transverse
 1001 momenta of the J/ψ and the jet over kinematic ranges accessible at the LHC, (iii) the evaluation of possible
 1002 DPS effects [390].

1003 3.3. Single vector- Q exclusive photoproduction

1004 Measurements of quarkonia in UPCs allow one to probe various parton distributions. In general, as dis-
 1005 cussed in Section 3.3.1, exclusive processes provide access to GPDs. At very low values of x and t , the
 1006 GPD can be related to the conventional integrated PDF, via the Shuvaev transform, as discussed in Sec-
 1007 tion 3.3.2. While data collected at the LHC in the collider mode probes the low- x region, data collected
 1008 with a FT, as presented in Section 3.3.3, can constrain GPDs at high x . In both the low- and high- x regions,
 1009 measurements are scarce and hence the distributions currently suffer from large uncertainties.

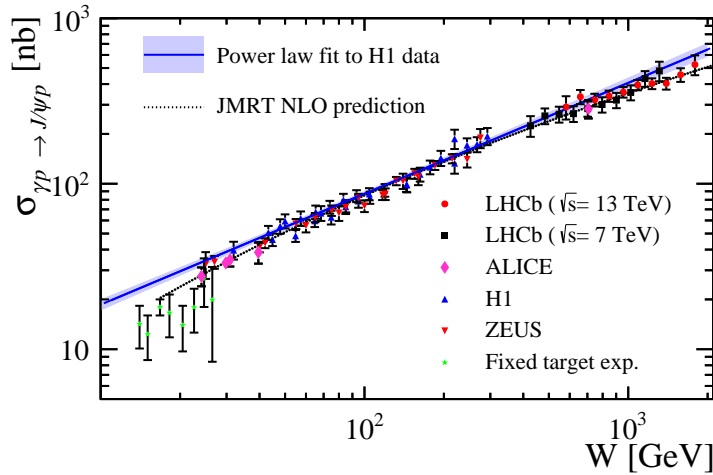


Figure 15: Cross section for exclusive J/ψ production as a function of the photon-proton c.m.s. energy, W , extracted from data collected in proton-proton collisions by LHCb (red circles and black squares), proton-lead collisions by ALICE (magenta diamonds), ℓp collisions by H1 and ZEUS (triangles), and FT experiments. [Figure taken from [315].]

1010 Exclusive production of J/ψ and $\psi(2S)$ has been measured in pp [314, 315, 391], $p\text{Pb}$ [392, 393], and
 1011 PbPb [332, 333, 394–397] collisions by the experiments at the LHC, in AuAu collisions at RHIC [318], and
 1012 in $p\bar{p}$ collisions at the Tevatron [398]. Exclusive production of Υ has also been analysed in pp [316] and
 1013 in $p\text{Pb}$ [317] collisions at the LHC. Fig. 15 presents the γp cross section for exclusive J/ψ production as a
 1014 function of the γp c.m.s. energy, W , extracted by the LHCb [315], ALICE [392], H1 [271], ZEUS [399], and
 1015 FT experiments. Good consistency over two orders of magnitude in energy is seen between photoproduction
 1016 in diverse experimental conditions, which hints at the universality of the underlying physics.

1017 Exclusive production of vector quarkonia also has sensitivity to odderon production. In addition to
 1018 the photon-pomeron fusion process shown in Fig. 11, vector quarkonia can be produced through odderon-
 1019 pomeron fusion. It was shown in [400] that the odderon contribution may be significant at the LHC and that
 1020 it may dominate at large transverse momenta. The two production mechanisms can therefore potentially be

¹⁶Note that the NRQCD result presented in [371] only takes into account the $3S_1^{[1]}$ CS and $3S_1^{[8]}$ CO states and it should be kept in mind that the other CO states could also give a sizeable contribution.

1021 separated through the transverse momentum distribution. Although the precise shape of each spectrum is
 1022 somewhat uncertain, an excess of events at high P_T could be evidence for the odderon. One possibility for
 1023 HL-LHC would be to measure the P_T spectrum precisely in pA collisions, where any odderon production
 1024 is heavily suppressed with respect to photoproduction, and then to compare that to the spectrum obtained
 1025 in pp collisions. The presence of proton-taggers would greatly assist this measurement as it would allow
 1026 the major background in the high- P_T region due to proton dissociation (see Fig. 12, Right) to be heavily
 1027 suppressed.

1028 3.3.1. Accessing GPDs from data collected in UPCs

1029 Introduced more than 20 years ago [401–403], GPDs have been since studied both theoretically and exper-
 1030 imentally. They provide access to the quark and gluon orbital angular momenta [404], the 3D distribution
 1031 of quarks and gluons as a function of their longitudinal momentum and transverse position [405, 406], and
 1032 the distribution of pressure and shear forces inside the nucleon [407, 408].

1033 The channels to experimentally access GPDs are exclusive processes with a hard scale. Their extraction
 1034 requires a measurement that is doubly differential in x and t . So far GPDs have mainly been constrained
 1035 in the high-to-medium x region from measurements of deeply virtual Compton scattering (DVCS) [233–
 1036 239, 241, 242, 252, 254, 255, 257–259, 261, 265, 266, 275, 277, 290] and exclusive meson production in
 1037 DIS [240, 243–249, 251, 253, 256, 260, 262–264, 267, 268, 274, 287, 292, 294], where the hard scale is
 1038 provided by the large virtuality, Q , of the photon exchanged between the incoming lepton and nucleon. Each
 1039 of these processes provides complementary information, with a sensitivity to different types and flavour
 1040 combinations of the GPDs.

1041 Instead of requiring a highly virtual incoming photon, a real photon can be used as a probe if the final-
 1042 state particle is a heavy quarkonium (ideally Υ), where now the hard scale is provided by the large mass of
 1043 the quarkonium. Alternatively, GPDs can be probed in timelike Compton scattering (TCS), triggered by a
 1044 real incoming photon and producing a highly virtual outgoing photon that provides the hard scale. The ep
 1045 collider experiments H1 and ZEUS measured the photoproduced heavy quarkonia, J/ψ and Υ [271, 288,
 1046 289, 296], but did not have sufficiently large data samples to measure TCS.

1047 Hadron-hadron UPCs can also photoproduce quarkonia and TCS. The large c.m.s. energy at the LHC
 1048 offers the unique advantage of providing access to the very low- x region, down to $x \approx 10^{-6}$ (for photon
 1049 virtualities of 1 GeV^2). In the case of heavy-ion UPCs, there is a further benefit compared to pp or ℓp
 1050 collisions of an increased photon flux, since it is proportional to Z^2 . The cleanest extraction of GPDs at the
 1051 HL-LHC would be obtained in pA collisions, which necessitates a high luminosity for this collision mode
 1052 due to the double-differential nature of the measurement.

1053 Exclusive production of quarkonia (Fig. 11, Left) is an ideal channel in UPCs to study gluon GPDs,
 1054 since it is already sensitive to gluons at LO. In contrast, access to quark GPDs in UPCs is provided at
 1055 LO by the TCS process [409, 410]. At the same time, TCS shows some sensitivity to gluons due to NLO
 1056 contributions, which are sizeable at the LHC [411]. In the FT mode, with polarised and unpolarised targets,
 1057 exclusive quarkonium production and TCS [412] provide additional information to constrain gluon and
 1058 quark GPDs, respectively. Exclusive quarkonium measurements in FT collisions are discussed in more
 1059 detail in Section 3.3.3.

1060 In general, exclusive measurements in pp collisions allow the study of nucleon GPDs, while the analysis
 1061 of AA collisions gives access to nuclear GPDs. pA collisions can access both nucleon and nuclear GPDs.
 1062 Indeed, depending on the rapidity of the final-state particles, γp or γA interactions dominate [413]. Hence,
 1063 with a non-central detector, as for example LHCb, measurements in pA and in $A p$ collisions offer important
 1064 complementary information.

1065 Some caveats regarding the study of GPDs in UPCs should also be kept in mind. At present, there is still
 1066 no all-order factorisation proof of exclusive quarkonium production. In addition, higher-twist, higher-order,
 1067 and mass corrections could play a sizeable role when evaluating the process amplitude.

1068 3.3.2. Probing the low- x and low-scale gluon PDF with exclusive Q production

1069 In [27, 414], the utility of the exclusive J/ψ data, measured recently by the LHCb collaboration in the
 1070 forward rapidity interval $2 < y_Q < 4.5$, as a means of probing and ultimately determining the low- x and
 1071 low- Q gluon PDF is discussed. To date, the exclusive data have not been included in global PDF analyses

1072 for two reasons. First, the underlying theory prediction within collinear factorisation at NLO for exclusive
 1073 J/ψ production suffered from a large scale uncertainty and exhibited poor perturbative stability. Second,
 1074 one could not readily extract a PDF to compare to the $\overline{\text{MS}}$ collinear distributions determined in the global
 1075 fits due to the off-forward kinematics and the description of the process via GPDs with the skew parameter
 1076 ξ . However, both of these problems have recently been overcome and the reader is pointed to [26, 415]
 1077 and [416] for more details.

1078 At small x and skewness ξ values, one may relate the conventional collinear PDFs to the GPDs via
 1079 the Shuvaev transform [416]. This approach exploits the observation that the evolution of the conformal
 1080 moments of GPDs is similar to that of the Mellin moments of PDFs. The polynomiality in the series of ξ of
 1081 the conformal moments of the GPDs allows an identification of the leading term as the Mellin moments of
 1082 the PDFs. In turn, one may then systematically construct all the conformal moments of the GPDs at small ξ
 1083 with an accuracy of $O(\xi^2)$ at LO. At NLO, the evolution becomes non-diagonal and the accuracy is lowered
 1084 to $O(\xi)$. Still, for the diffractive processes of interest, this is more than adequate. Therefore, by virtue of the
 1085 exclusive J/ψ process sitting at low x and at a low Q scale, one can relate the underlying GPD inputs to the
 1086 conventional PDFs.

1087 After a systematic taming within the NLO result, amounting to a resummation of a class of large log-
 1088 arithms and implementation of a low Q_0 cut within the NLO coefficient function, the cross-section pre-
 1089 dictions utilising state-of-the-art NLO global parton fits describe the data well in the HERA region, yet
 1090 produce vastly different results in the LHCb region, see Fig. 16 (Left) and [27]. This large uncertainty
 1091 *between* the global predictions is tantamount to the lack of data constraints for $x < 10^{-3}$, where the global
 1092 parton behaviour in the low (x, Q^2) domain is based on extrapolating the input PDF Ansatz from larger x .
 1093 As shown in the right panel of Fig. 16, the propagation of this, currently large, uncertainty at small x to
 1094 the exclusive J/ψ cross section demonstrates the sizeable uncertainty for any given parton function set and
 1095 provides support for the claim that the exclusive J/ψ data are in a position to reliably constrain the low- x
 1096 gluon.

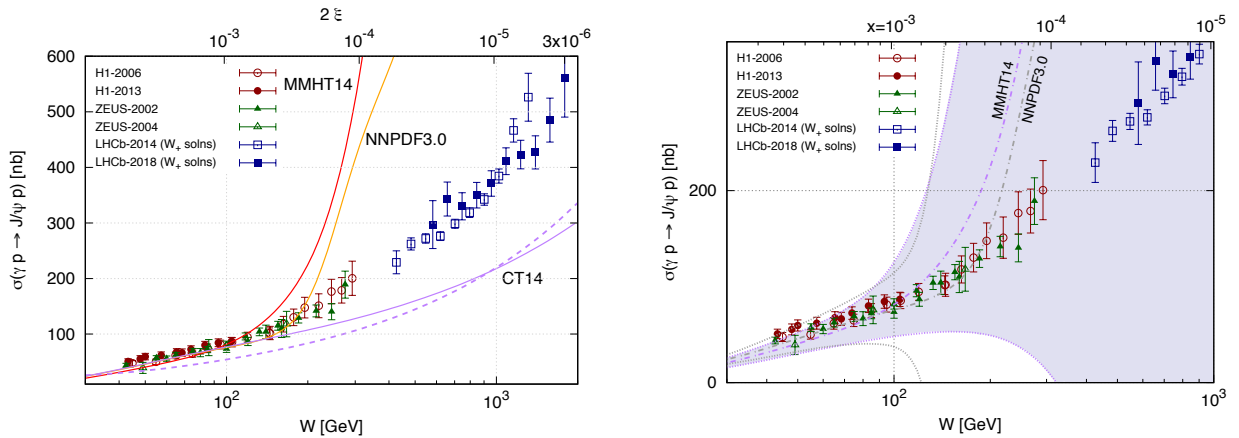


Figure 16: Cross sections for exclusive J/ψ photoproduction in ep and pp collisions as a function of γp c.m.s. energy. Left: Data compared to predictions using three distinct sets of global PDFs with scales $\mu_F^2 = \mu_R^2 = m_c^2$ (solid lines). Also shown for CT14 is the prediction with scales $\mu_F^2 = \mu_R^2 = 2m_c^2$ (dashed line), demonstrating the stability of the theory with respect to scale variations. Right: Data compared to two sets of global PDFs, showing the global PDF 1σ uncertainty, which greatly exceeds the experimental uncertainty. The data are from [271, 296, 399, 417] and the LHCb W_+ solutions are constructed from [314, 315]. [Plots taken from [414].]

1097 For the future, there are three points of note regarding exclusive J/ψ production via UPCs and the
 1098 extraction of low- x gluon PDFs. Firstly, there is no indication of gluon density saturation down to $x = 10^{-5}$
 1099 – the data are compatible with a rising power law. With increasing data quality and statistics in the upcoming
 1100 HL-LHC phase together with, in time, higher collision energies, some sensitivity to the effects of saturation
 1101 might be seen. Secondly, there is a need to reconcile the differing behaviour of the low- x gluon PDF obtained
 1102 from independent analyses using the inclusive (D -meson) [220] and exclusive (J/ψ) [223] sectors. It is
 1103 unclear whether this is a question of data quality or whether the theory framework needs improving. Thirdly,
 1104 measurements of the inclusive forward C -even charmonia ($\chi_{c0}, \chi_{c2}, \eta_c$) production, (and indeed bottomonia)
 1105 integrated over P_T are of high value. The NLO gluon can be probed down to approximately the same x and
 1106 Q values as in exclusive J/ψ , but now in the conventional inclusive mode. From a phenomenological

standpoint, it would be interesting to compare the low- x gluons obtained from fits to scalar, vector, and tensor charmonia.

The same methodology applies to making NLO predictions for $\psi(2S)$ and Υ production. For the latter, the scale dependencies are significantly reduced and the predictions are more robust (see [316]). However, the experimental precision for both is poorer due to lower statistics. This situation can be remedied at the HL-LHC. The ideal situation is to measure both these processes in high-luminosity pA collisions. At present, though, the anticipated integrated luminosity for this phase of running is probably not sufficient to make a competitive measurement. Further studies are required in order to determine whether pp collisions could be used. The increase in luminosity at HL-LHC means an increased pileup of pp interactions, but it may still be possible to select exclusive $\psi(2S)$ and Υ production through their characteristic signals of precisely two muons consistent with a primary interaction point and/or using forward proton tagging.

3.3.3. FT measurements of Q photoproduction

UPCs are not only unique tools to study photoproduction processes with hadron beams in the collider mode, but also in the FT mode. LHC FT collisions can release a c.m.s. energy of $\sqrt{s} = 115$ GeV with the LHC 7 TeV proton beam [5], giving access to the high- x range of the parton distributions. FT collisions have already been achieved by the LHCb collaboration, thanks to its System for Measuring Overlap with Gas (SMOG) [418]. In the upcoming Run 3 of the LHC, a new system (SMOG2) will be installed, consisting of a target cell, in which gas is injected in the centre and pumped out at both ends [419, 420]. The HL-LHC plans to have an upgraded polarised SMOG system. It is worth noting that the ALICE collaboration is also studying the feasibility to conduct a FT programme after Run 3 using a solid target coupled to a bent crystal to deflect the beam halo [421].

FT measurements with an unpolarised target in general access spin-independent (TMD) PDFs, GPDs, and Wigner distributions, while polarised targets access different spin-dependent objects. Exclusive quarkonium measurements in polarised FT collisions are discussed in [422]. With transversely polarised protons, the measurement of exclusive photoproduction of vector quarkonia is sensitive to the gluon GPD, E_g , which in turn allows, in principle, a determination of the gluon orbital angular momentum, L_g . Both L_g and E_g are currently essentially unknown.

With an integrated yearly luminosity of only 150 pb^{-1} foreseen for Run 3 at the LHC, one could expect to produce about 3000 J/ψ in the LHCb acceptance to perform preliminary studies of the multi-dimensional gluon content of the proton. Similar studies can in principle be conducted with a Pb beam on a H gas target but would only produce a few tens of J/ψ [422].

Fig. 17 shows projections for HL-LHC, for an LHCb-like detector. These assume an integrated luminosity of 10 fb^{-1} , corresponding to the maximum luminosity that can be obtained in a year of running at the LHC in pH collisions using a storage cell gas target with a longitudinal dimension of 1 m. The left panel shows the differential cross section as a function of y_ψ in the laboratory frame before and after applying kinematic cuts for the LHCb region, covering a rapidity between 2 and 5. The top x axis shows the photon-proton c.m.s. energy, $W_{(\gamma p)}$, while the right y axis shows the yearly yield per 0.1 rapidity unit. A yearly yield of about 2×10^5 in the di-muon decay channel is expected. The right panel of Fig. 17 shows the projection of the single transverse-spin asymmetry (STSA) (A_N) of the J/ψ as a function of Feynman x_F , for two ranges in P_T and one year of FT-LHC data taking in pH collisions. The asymmetry can be measured with an absolute precision ranging from 1 to 4%, making possible a first measurement sensitive to E_g in FT mode at the LHC with a polarised target, likely before the EIC.

Projections also exist for the ALICE detector operated in the FT mode for HL-LHC, assuming the usage of a polarised gas system with a storage cell technology. The maximum yearly integrated luminosities considered are mainly limited by the detector rate capabilities and amount to 260 pb^{-1} in pH collisions (polarised or unpolarised), leading to a photoproduced J/ψ yield of about 1300 J/ψ in the ALICE muon spectrometer. The statistics are even more scarce in the ALICE central barrel, which is covering the very backward rapidity region, at the edge of the J/ψ phase space.

3.4. Accessing Wigner functions through Q -pair production

The 1D PDFs, and the 3D TMDs and GPDs, each describing different aspects of the non-perturbative structure of hadrons, can all be derived from the more general GTMDs [424, 425]. There are several com-

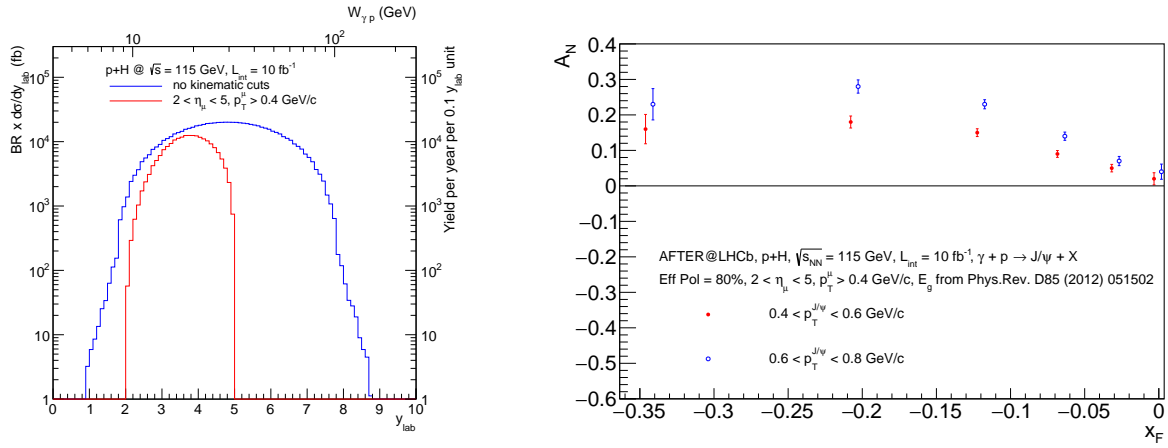


Figure 17: Rapidity-differential J/ψ photoproduction cross section predicted by the STARLIGHT Monte Carlo generator [423] (Left), and projected J/ψ A_N distribution as a function of x_F (Right), for FT pH collisions at $\sqrt{s} = 115$ GeV, assuming the performances of an LHCb-like detector and a polarised target with 80% effective polarisation. [Figures taken from [422].]

1158 pelling reasons to study GTMDs. Firstly, they contain more physics content than that encoded in the TMDs
 1159 and GPDs, and thus allow an exploration of physics that is lost in taking the TMD/GPD kinematic limits.
 1160 Secondly, GTMDs can be related, via Fourier transformations, to Wigner functions, which are the quantum-
 1161 mechanical version of classical phase-space distributions encountered in statistical physics. Partonic Wigner
 1162 functions may allow for a hadron tomography in 5D phase space [426, 427]. Thirdly, certain GTMDs can
 1163 unravel unique correlations between the parton orbital motion and the spin of hadrons [428–430]. Fourthly,
 1164 there is a particular GTMD that is related to the Sivers TMD (see also Section 4.7). By establishing the
 1165 equivalence between GTMDs and QCD-odderns at small x , the authors in [321] have shown that it is possi-
 1166 ble to access the gluon Sivers TMD through exclusive π^0 production in *unpolarised* ep scattering. This
 1167 finding goes against the traditional belief that the Sivers function can only be accessed via a transversely
 1168 polarised target.

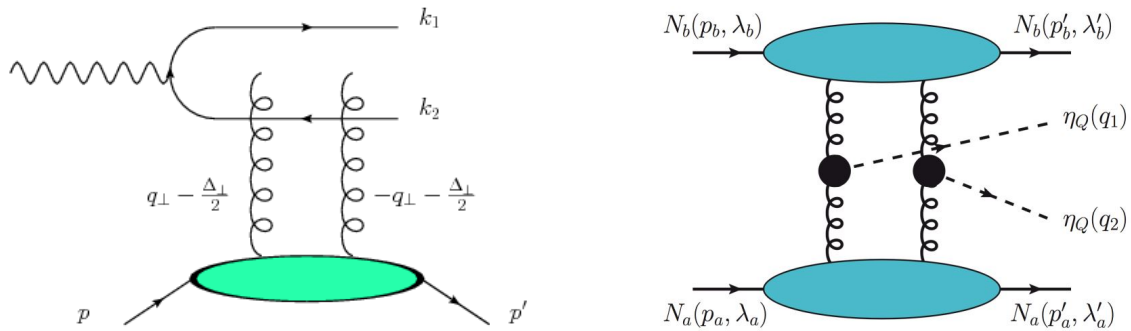


Figure 18: Left: Leading-order Feynman diagram for exclusive dijet production in lepton-nucleon/nucleus scattering. Right: Leading-order Feynman graph for the exclusive double quarkonium production in nucleon-nucleon collisions. The perturbative subprocess $gg \rightarrow \eta_Q$ is computed in the CSM. The η_Q meson has a transverse momentum that is determined by the (intrinsic) transverse momentum of the gluons through which it is produced.

1169 For a long time, it was questionable whether GTMDs could be measured at all. The authors of [431]
 1170 were the first to suggest the measurement of gluon GTMDs through exclusive dijet production in lepton-
 1171 nucleon/nucleus collisions at small x (Fig. 18, Left). Given that the GTMDs depend on the transverse
 1172 vectors \vec{q}_T (partonic transverse momentum) and $\vec{\Delta}_T$ (the Fourier transform of the impact-parameter \vec{b}_T), it is
 1173 possible to parameterise the angular correlation between these two vectors by a symmetric and an antisym-
 1174 metric part. The latter, known as the elliptic distribution, has a characteristic $\cos(2\phi)$ angular modulation,
 1175 where ϕ is the angle between the relative transverse momenta of the dijets and the recoiling nucleon/nucleus.
 1176 This angular modulation is similar to the observed elliptic flow phenomenon in relativistic heavy-ion colli-
 1177 sions [432–434]. This pioneering work gave impetus to the field of GTMDs and subsequently many other
 1178 interesting ideas were put forward [435–438], among which is the ability to access gluon GTMDs in exclu-
 1179 sive photoproduction in pA collisions.

1180 In [439] it was shown that the production of two pseudoscalar quarkonia (e.g. $\eta_c\eta_c$, $\eta_c\eta_b$ or $\eta_b\eta_b$) in
 1181 exclusive hadronic collisions, where both hadrons remain intact, is a direct probe of GTMDs for gluons
 1182 at moderate x (Fig. 18, Right). In that work, an observable sensitive to gluon (canonical) orbital angular
 1183 momentum was identified. A similar idea came out in [440], where the authors proposed to access gluon
 1184 GTMDs at small x via the production of pairs of $C = +1$ quarkonia (η_c or χ_{cJ}) in exclusive pp collisions,
 1185 where one of the protons breaks up after the collision. Although the latter has a larger count rate, there may
 1186 be contamination from NRQCD CO contributions. An alternative suggestion would be to consider either
 1187 a combination of a J/ψ and a C -even quarkonium [441], or possibly the associated production of two J/ψ
 1188 in pp collisions at the LHC, as opposed to two C -even quarkonium states. The production mechanisms for
 1189 these processes with one or two J/ψ , in the GTMD-type of kinematics, is expected to be more complicated.
 1190 Nonetheless, given the experimental ease with which J/ψ states can be detected, theoretical efforts in this
 1191 direction are surely warranted.

1192 From the experimental side, exclusive pairs of charmonia have been studied in pp collisions by the
 1193 LHCb experiment [313], but the statistical precision is insufficient to extract the cross section as a function
 1194 of the P_T of the quarkonia. The CMS collaboration recently performed [442] a preliminary measurement
 1195 of exclusive dijets in PbPb collisions: the $\cos(2\phi)$ modulation between the sum of the transverse momenta
 1196 of the jets and their difference was extracted, which for the first time provides the information relevant
 1197 for the determination of the GTMDs. This first experimental access to GTMDs can be extended in the
 1198 future to similar measurements but for pairs of quarkonia. As discussed for PDFs and GPDs, dedicated
 1199 measurements during the HL-LHC should thus provide access to the Wigner distributions of the proton.

1200 4. Transverse-Momentum-Dependent effects in inclusive reactions¹⁷

1201 The multi-dimensional structure in momentum space of a nucleon has recently attracted much interest,
 1202 as a possible source of many observable effects in hadronic interactions and, more generally, as a way
 1203 of improving our understanding of QCD. This structure can be parameterised in terms of several objects,
 1204 which encode different correlations between the momentum and spin of a parton and its parent nucleon.
 1205 In simple terms, these are three-dimensional generalisations of the usual one-dimensional, collinear PDFs
 1206 or FFs, but with a dependence on the parton transverse momentum, k_T . The way to introduce and define
 1207 such generalisations is a subject of intense investigations, and debates, within the community [443]. What
 1208 is at stake here is a crucial step in our understanding of the nucleon 3D structure (in momentum space), and
 1209 hence in our understanding of colour confinement in QCD. In what follows, we will discuss four approaches
 1210 that address transverse-momentum-dependent and/or spin effects and are all relevant for quarkonium studies
 1211 at the HL-LHC:

- 1212 • The TMD factorisation framework, applicable both in unpolarised and polarised collisions, in which
 1213 the TMDs have a concrete definition in terms of gauge-invariant operators and properties such as
 1214 QCD evolution;
- 1215 • The High-Energy (HE) or k_T factorisation framework, designed to account for HE effects (large
 1216 \sqrt{s}). Besides the transverse momentum of the initial partons, k_T , this formalism also considers their
 1217 virtualities, which naturally becomes relevant in this limit;
- 1218 • The collinear twist-3 (CT3) factorisation framework, which is an extension of collinear factorisation
 1219 to treat polarised parton/nucleon collisions, and which matches TMD factorisation in the large- k_T
 1220 limit;
- 1221 • The Generalised Parton Model (GPM), a phenomenological model meant to extend collinear factori-
 1222 sation with functions accounting for the Sivers effect both in the quark and gluon sectors.

1223 It should be clear to the reader that these approaches are not meant to be considered on an equal foot-
 1224 ing: the GPM computations are restricted to polarised collisions, but more importantly they are essentially
 1225 descriptive. Yet, they can be very useful to check various hypotheses about the underlying phenomena

¹⁷Section editors: Miguel G. Echevarria, Vato Kartvelishvili.

1226 generating the spin asymmetries. CT3 predictions go further with a deeper connection to the QCD proper-
 1227 ties but are based on collinear considerations where the transverse-momentum effect are integrated over in
 1228 higher-twist correlators. HE factorisation, only applied to unpolarised collisions so far, is first designed to
 1229 treat new effects at large \sqrt{s} . As such, care should be taken when using its predictions when \sqrt{s} is not very
 1230 large, in particular for systems or conditions where TMD factorisation is a priori not applicable. Indeed, the
 1231 latter, while being probably the most inclusive in terms of phenomena generated by the k_T of the partons, is
 1232 also the most restrictive in terms of applicability owing to its ambition to be the most rigorous.

1233 The purpose of this section is to outline the recent progress regarding quarkonium production in pro-
 1234 cesses where the transverse-momentum-dependent gluon effects enter, and how the HL-LHC can contribute
 1235 to this emerging research domain.

1236 The TMD factorisation framework is briefly introduced in Section 4.1, followed by a discussion in
 1237 Section 4.2 on several specificities and open issues related to the treatment of quarkonium production, while
 1238 HE factorisation is treated in Sections 4.3 and 4.4. Section 4.5 focuses on various-quarkonium production
 1239 processes in unpolarised pp collisions within the TMD factorisation framework, with a special focus on the
 1240 unpolarised and the linearly-polarised gluon TMDs, f_1^g and $h_1^{\perp g}$. In Section 4.6, we address the complex
 1241 issue of factorisation-breaking effects or, more generally, effects beyond TMD and HE factorisations, and
 1242 discuss some easily measurable processes where they can be studied. Finally, in Section 4.7, collisions with
 1243 polarised nucleons are considered; these become measurable at the HL-LHC with a polarised target in the
 1244 FT mode, allowing one to measure STSAs in quarkonium production to probe e.g. the gluon Sivers effect
 1245 accounted by the TMD and CT3 factorisations and the GPM.

1246 4.1. TMD factorisation in the gluon sector

1247 In the last few years, the field of TMDs has taken a large leap forward. Both the theoretical framework [444–
 1248 450] and the phenomenological analyses (see e.g. [451–459]) have developed, including new, higher-order
 1249 perturbative calculations (see e.g. [460–466]). This progress, however, has been made mainly in the quark
 1250 sector, with the gluon sector lagging behind due to the difficulty in cleanly probing gluons in high-energy
 1251 processes.

1252 Gluon TMDs at the leading twist, first analysed and classified in [467], are shown in Table 1, in terms of
 1253 both the polarisation of the gluon itself and of its parent hadron. The distribution of unpolarised gluons in-
 1254 side an unpolarised hadron, f_1^g , and of circularly polarised gluons inside a longitudinally polarised hadron,
 1255 g_1^g , correspond (i.e. are matched at large k_T through an operator product expansion) to the well-known
 1256 collinear unpolarised and helicity gluon PDFs respectively. The distribution of linearly-polarised gluons in
 1257 an unpolarised parton, $h_1^{\perp g}$, is particularly interesting, since it gives rise to spin effects even in collisions
 1258 of unpolarised hadrons, like at the LHC. The Sivers function, $f_{1T}^{\perp g}$, which encodes the distribution of unpo-
 1259 larised gluons in a transversely-polarised nucleon, has a very important role in the description of STSAs.
 1260 There is a classification analogous to Table 1 for quark TMDs, and also for both quark and gluon TMD
 1261 FFs, which are as relevant as TMD distributions for processes which are sensitive to the role of transverse
 1262 dynamics of partons in the fragmentation process.

		gluon polarisation		
		U	circular	linear
nucleon polarisation	U	f_1^g		$h_1^{\perp g}$
	L		g_1^g	$h_{1L}^{\perp g}$
	T	$f_{1T}^{\perp g}$	g_{1T}^g	$h_1^g, h_{1T}^{\perp g}$

Table 1: Gluon TMD (PDFs) at twist 2. U, L, T describe unpolarised, longitudinally polarised and transversely-polarised nucleons. U , ‘circular’, ‘linear’ stand for unpolarised, circularly polarised and linearly-polarised gluons. Functions in blue ($h_1^{\perp g}, g_{1T}^g$) are T -even. Functions in black (f_1^g, g_1^g) are T -even and survive integration over the parton k_T . Functions in red ($h_{1L}^{\perp g}, f_{1T}^{\perp g}, h_1^g, h_{1T}^{\perp g}$) are T -odd.

1263 As is the case for quark TMDs, gluon TMDs contain information on the initial- and/or final-state QCD

1264 interactions of the incoming hadron. Different types of gluon TMDs exist, distinguished by the precise struc-
 1265 ture of the gauge links in their operator definition, which depends on the hard process under consideration:
 1266 the two most common are the so-called Weizsäcker-Williams (WW) and dipole (DP) types [15, 468, 469].
 1267 The WW type involves either initial- or final-state interactions, while the DP type involves both, so different
 1268 processes probe different types of gluon TMDs. Incidentally, the WW type is the gluon TMD which, in
 1269 the proper choice of gauge, can be written as the gluon number operator acting on the hadron Fock state,
 1270 implying the physical interpretation of the TMD as a number density.

1271 Exploratory analyses on gluon TMD distributions [467, 470, 471] were done in the so-called *spectator-*
 1272 *model* approach. Originally developed for studies in the quark-TMD sector [472–477], this relies on the
 1273 assumption that the struck nucleon emits a gluon, after which the remnants are treated as a single spectator
 1274 particle, taken on-shell. The power of the spectator-model framework lies in the possibility to concurrently
 1275 generate all TMD densities at twist-2 (Table 1). In this context, a novel parameterisation for T -even dis-
 1276 tributions has been recently proposed in [478]. At variance with previous studies, the spectator mass is
 1277 allowed to take a continuous range of values weighted by a flexible spectral function, which allows one to
 1278 effectively reproduce both the small- and the moderate- x behaviour of the TMDs. Furthermore, it embodies
 1279 the effect of $q\bar{q}$ contributions, which are generally neglected by standard spectator models. These results
 1280 on the 3D tomography of (un)polarised gluons inside (un)polarised nucleons are part of the effort to gain a
 1281 deeper understanding of observables sensitive to gluon TMD dynamics.

1282 So far, quarkonium-production observables are one of the most promising tools at our disposal to access
 1283 gluon TMDs, since they are directly sensitive to gluons. These processes are quite challenging from the
 1284 theoretical point of view, because they involve several momentum scales and require dealing with different
 1285 aspects of QCD, from the formation of heavy-quark bound states to soft-gluon resummation. For this reason,
 1286 they represent a wonderful testing ground of our knowledge of QCD. Indeed, the interest has grown lately,
 1287 with a number of LO analyses assuming TMD factorisation (see e.g. [13, 15–17, 19, 22, 23, 479–491]) and
 1288 others that perform NLO calculations (see e.g. [492–494]).

1289 Experimental information on gluon TMDs is however very limited. The first attempt [16] to fit unpo-
 1290 larised gluon TMD PDF, f_1^g , was only made in 2017 and was performed using J/ψ pairs. So far nothing is
 1291 known on $h_1^{\perp g}$. The possible extension of this first fit with forthcoming LHC data as well as other quarko-
 1292 nium channels of interest will also be discussed.

1293 4.2. TMD factorisation in Q production: challenges and opportunities

1294 As discussed in Section 2, besides NRQCD, other approaches have been proposed to describe quarkonium
 1295 production, like the CSM [53–55] or the CEM [48, 495, 496], and their variations and extensions [497–500].
 1296 All these frameworks have been routinely used along with collinear factorisation. Whereas a factorisation
 1297 proof exists for NRQCD and collinear factorisation, it does not exist at present for the other approaches.
 1298 Their combination with TMD factorisation is then potentially even more delicate. This is why, in this
 1299 section, we only consider the combination of the NRQCD and TMD factorisations and some adjustments
 1300 are needed to properly deal with the low- P_T region.

1301 If one wishes to predict P_T spectra, NRQCD factorisation is only applicable when the quarkonium is
 1302 produced with a relatively large $P_T \gtrsim 2m_Q$. Intuitively, in this kinematic regime, emissions of soft and
 1303 ultra-soft gluons from the heavy-quark pair cannot alter the large P_T of the quarkonium. Ignoring these
 1304 soft emissions, the quarkonium P_T is then determined by the short-distance reactions. At the same time,
 1305 the infrared (IR) divergences that remain from the hard scattering are absorbed into the non-perturbative
 1306 LDMEs and collinear PDFs. However, when quarkonia are produced with small P_T , large double logarithms
 1307 arise and need to be resummed. Indeed, the observed (low) P_T distribution of Υ production at the Tevatron
 1308 and LHC was found to be consistent with the prediction from a TMD factorisation Ansatz with resummation
 1309 of the large double logarithms [501–503] (even if a simple NLO treatment seems to provide fairly good
 1310 results as well [81]).

1311 In any case, the key point here is that, at low P_T , the soft-gluon factorisation assumption must be
 1312 abandoned. In [504–506], the quarkonium production in ℓp collisions and e^+e^- annihilation was studied in
 1313 the endpoint region, which is sensitive to soft radiations exactly where NRQCD factorisation breaks down.
 1314 It was found that promoting the LDMEs into quarkonium shape functions is necessary to accurately account
 1315 for soft radiation from the heavy-quark pair. Similarly, for the TMD spectrum of quarkonia, TMD-shape

1316 functions are needed to be able to rigorously derive the relevant factorisation theorems at low P_T .

1317 The degrees of freedom for studying such low- P_T processes were introduced in the context of soft-
1318 collinear effective theory in [507, 508], where it was shown that the cross section for quarkonium production
1319 at low P_T involves a new kind of non-perturbative object besides the TMDs, which can be seen as the 3D
1320 extension of the well-known NRQCD LDMEs. These TMD-shape functions, like the LDMEs, scale with
1321 the relative velocity, v , of the heavy quark-antiquark pair in the quarkonium rest frame. Therefore, the
1322 factorisation turns out to be a simultaneous expansion in the relative quark-pair velocity v and $P_T/(2m_Q)$.

1323 Currently, a few of open questions remain with regard to the factorisation:

- 1324 • The double expansion in $P_T/(2m_Q)$ and the heavy-quark pair relative velocity, v , allows for a priori
1325 sub-leading contributions in one expansion parameter, which might be enhanced in the other. Thus
1326 the reorganisation of terms in the cross section becomes non-trivial, and a potential contribution of
1327 higher-twist TMDs and TMD-shape functions cannot be discarded.
- 1328 • This approach involves a summation over the various colour and angular-momentum configurations
1329 that contribute to the formation of the bound state. This might spoil the factorisation in pp collisions
1330 when CO states are produced. This is due to the so-called Glauber or Coulomb exchanges, which are a
1331 subset of soft gluons that can entangle initial and final states and thus prevent the factorisation. At the
1332 moment, such a factorisation has only been established for η_Q production [507], where the CS state
1333 dominates the production process, following the NRQCD velocity-scaling rules. It might be extended
1334 to other processes dominated by the CS channel, like di-quarkonium or associated production. This
1335 represents an opportunity to study effects in QCD that connect long and short distance physics.
- 1336 • In addition to these issues specific to quarkonium production, one should keep in mind that, in
1337 hadronic collisions, the final state must not explicitly involve coloured objects for TMD factorisation
1338 to apply [509–514]. Thus, it is not supposed to hold for ψ or Υ hadroproduction in the CSM
1339 where the quarkonium is necessarily produced along with a hard gluon. On the one hand, if this
1340 hard gluon is not observed, the connection between the quarkonium P_T and the initial-parton k_T is
1341 lost. On the other, if, instead, one proposes to measure the associate production of ψ or Υ with a
1342 jet (or hadron), the observed final state is coloured, and the colour flow arising from the reaction
1343 becomes so entangled that it prevents one from deriving a factorised form for the cross section (see
1344 however [515]). In other words, and as already mentioned in the first point, Glauber exchanges play
1345 a role and spoil the factorisation.

1346 4.3. The HE factorisation framework

1347 The aim of High-Energy (HE) factorisation –also called k_T factorisation or the Parton Reggeisation Ap-
1348 proach (PRA)– is to go beyond collinear factorisation by resumming corrections to the hard-scattering
1349 coefficient which are enhanced by powers of $\log(1/z_{\pm})$ when z_{\pm} gets small. As $z_{\pm} = q_{\pm}/k_{\pm}$, with q_{\pm} the
1350 light-cone components of the momentum of the studied final state and k_{\pm} those of the initial parton, such
1351 corrections indeed get large at high \sqrt{s} . The general HE factorisation formula for the inclusive cross sec-
1352 tion $d\sigma$ of a hard process in pp collisions [216, 516, 517] can be outlined as a double convolution (in the
1353 momentum fraction x_i and in the transverse momentum k_{T_i} of both incoming partons) of a partonic cross
1354 section $d\hat{\sigma}_{ij}$ with two unintegrated PDFs (UPDFs) or gluon densities (UGDs).

1355 When one refers to uPDFs, one considers that they are obtained from the convolution of an evolution
1356 factor C_{ij} , which performs the resummation and satisfies some version of the BFKL equation [212–215],
1357 and a collinear PDF $f_{j/p}$. The complete cancellation of the μ_F dependence will happen only if the collinear
1358 PDFs with small- x -resummed DGLAP evolution are used, see e.g. [518, 519]. This however does not
1359 prevent one from using the usual PDFs if the observable under consideration shows more sensitivity to the
1360 transverse momenta $k_{T1,2}$ than to the x dependence of the UPDF.

1361 On the contrary, as far as the concept of UGD is concerned, no collinear input is implied. These are
1362 written as a convolution of the BFKL gluon Green’s function and a non-perturbative proton *impact fac-*
1363 *tor* which is meant to be determined by data. They have been the subject of intense studies since the
1364 early days both in exclusive and inclusive channels. Originally employed in the study of DIS structure
1365 functions [520, 521], the UGD has been studied through exclusive diffractive vector-meson leptonproduc-
1366 tion [522–529] measured at HERA [274, 530], single-bottom-quark production [531] at the LHC, inclusive

1367 forward Drell–Yan di-lepton production [532–535] measured by LHCb [536], and exclusive ψ , $\psi(2S)$ and
 1368 Υ photoproduction [537–539]. Recent analyses on the diffractive electroproduction of ρ mesons [525, 529]
 1369 have corroborated the underlying assumption [540] that the small-size dipole-scattering mechanism is at
 1370 work, thus validating the use of the UGD formalism, which holds when the observable P_T is large.

1371 In contrast to TMD factorisation, HE factorisation has the advantage not to be limited to the low- q_T
 1372 region (compared to the relevant hard scale of the process). Indeed, large values of P_T also contribute
 1373 to the region $z_{\pm} \ll 1$ if additional radiation is highly separated in rapidity from the observed system.
 1374 Radiative corrections of this kind become important with increasing \sqrt{s} , since more phase space for such
 1375 emissions opens up. This difference in their range of applicability is often a source of confusion and debate,
 1376 especially because sometimes the acronym TMD is also used outside the scope of TMD factorisation. In
 1377 our discussion, when such objects are discussed we will always use their names like f_1^s or $h_1^{\perp s}$.

1378 However, HE factorisation has its own theoretical shortcomings compared to TMD factorisation. In
 1379 general, not all corrections beyond Next-to-Leading Logarithmic approximation¹⁸ can be taken into account
 1380 by the standard HEF formulation. This can be traced back to the fact that, even at the leading power in the
 1381 HE limit, $z_{\pm} \ll 1$, QCD amplitudes only admit a factorisation in terms of matrix elements of multiple
 1382 light-like Wilson lines with a complicated colour structure or, equivalently, in terms of multi-Reggeon
 1383 exchanges in the \hat{t} -channel (see e.g. [541] for a review). In order to take all such contributions arising from
 1384 multi-Reggeon exchanges into account, results from the CGC formalism can be incorporated [542] in a
 1385 factorised formula inspired by TMD factorisation. However, in the phenomenology at the leading twist, it
 1386 is usually assumed that the largest $N^{k \geq 1}$ LL-corrections can still be represented by an effective UPDF that
 1387 takes into account both DGLAP and BFKL effects. Numerous recipes to obtain such UPDF can be found in
 1388 the literature, such as Kimber–Martin–Ryskin–Watt (KMRW) UPDF [543–545], Collins–Ellis–Bluemlein
 1389 UPDF [516, 546], Parton-Branching Method [547] and many more.

1390 The coefficient function $d\hat{\sigma}$ at LO in α_s and at leading-power in z_{\pm} can be understood as a partonic
 1391 cross section involving off-shell (Reggeised) initial-state partons with virtualities $k_{1,2}^2 = -\mathbf{k}_{T1,2}^2$. For simple
 1392 processes, such as $g^*(k_1) + g^*(k_2) \rightarrow Q\bar{Q}$, it can be computed by usual QCD Feynman Rules with the
 1393 following replacement for the polarisation vectors of initial-state gluons: $\varepsilon^\mu(k_{1,2}) \rightarrow k_{T1,2}^\mu / |\mathbf{k}_{T1,2}|$. However,
 1394 there is no analogous simple rule for off-shell quarks in the initial state. In addition, for more general QCD
 1395 processes, such coefficient function will not be gauge-invariant. The coefficient function for any subprocess
 1396 can be computed to any order in α_s using the effective field theory (EFT) for multi-Regge processes in
 1397 QCD [548–550] and its gauge invariance is guaranteed by construction within the EFT. The formalism
 1398 of [551–553] is equivalent to the EFT at tree level. Hereafter we will refer to all these approaches, like k_T
 1399 factorisation and Parton Reggeisation Approach (PRA) [554], as HE factorisation.

1400 4.4. High-Energy factorisation in \mathcal{Q} production: challenges and opportunities

1401 The HE factorisation coefficient functions for inclusive heavy-quarkonium production in NRQCD at LO
 1402 were first computed in [555–558] and the relevance of the gluon off-shellness in χ_{c1} production to lifting
 1403 the Landau–Yang suppression was first highlighted in [555]. LDMEs from recent fits on hadroproduction
 1404 data [559–562] are comparable to those obtained at NLO in collinear factorisation, especially for the LDME
 1405 of the $^3S_1^{(8)}$ state, while the LDMEs of $^3P_J^{[8]}$ and $^1S_0^{[8]}$ states turn out to have the same order of magnitude as
 1406 in collinear factorisation, but often with an opposite sign. This is because LO HE factorisation calculations
 1407 do not take into account NLO corrections due to final-state radiation effects.

1408 Recently, HE factorisation has been used together with the formalism of CS Light-Front Wave Functions
 1409 (LFWFs) [563, 564] and the Improved CEM (ICEM) [565–567] to describe the bound-state formation.
 1410 The CS LFWF calculation shows an interesting discrepancy with the strict non-relativistic approximation
 1411 (see e.g. Figs. 10 and 11 of [563]), which points towards potentially large relativistic corrections. The
 1412 ICEM calculation somewhat counter-intuitively predicts mostly unpolarised production of charmonia [565]
 1413 and bottomonia [566] at high P_T , unlike e.g. the NRQCD-factorisation-based predictions of [568]. This
 1414 disagreement uncovers some interesting aspects of the physics of heavy-quarkonium polarisation in the
 1415 ICEM and its interplay with HE factorisation that deserve further study.

1416 All the calculations mentioned above have been performed at LO. So far, no NLO quarkonium studies
 1417 exist in HE factorisation, which are far more complex than in collinear or TMD factorisations. However,

¹⁸The N^k LL-approximation in the context of HEF is defined as the resummation of terms $\sim \alpha_s^{n+k} \log^n(1/z_{\pm})$.

1418 such NLO computations would be in some respects equivalent to an NNLO accuracy for collinear factori-
 1419 sation, which are in fact not yet available for heavy-quarkonium production in none of the aforementioned
 1420 production models. With such NLO computations at our disposal, it will also become possible to quanti-
 1421 tatively characterise the region of applicability of HE factorisation in quarkonium production, where NLO
 1422 corrections would under control.

1423 As regards advances towards first NLO computations, the reader is guided to [569] for progress in the
 1424 computations of loop corrections, where the recent progress towards the automation of the computation of
 1425 gauge-invariant HE factorisation amplitudes reported in [570] would certainly be beneficial for the com-
 1426 pletion of the real-emission-correction computations. Exploratory NLO calculations have recently been
 1427 successfully performed [571, 572] and these show that one can overcome the problem of large unphysical
 1428 NLO corrections found, for instance, in BFKL-based computations. All these developments make NLO HE
 1429 factorisation calculations possible in the near future, with the aim of describing more accurately a variety
 1430 of observables related to single and associated production of heavy quarkonia in different quarkonium-
 1431 production models. Confronting the results of these calculations with HL-LHC data, which will briefly be
 1432 discussed in Section 4.6, will allow one to learn more about, on the one hand, the quarkonium-production
 1433 mechanisms and, on the other, the relevance of HE phenomena in these reactions.

1434 4.5. Unpolarised TMD studies with \mathcal{Q} at the HL-LHC

1435 As already mentioned, inside an unpolarised proton one can define two independent gluon TMD densities:
 1436 the unpolarised f_1^g and the linearly-polarised $h_1^{\perp g}$ distributions [467, 477, 573]. Being time-reversal even
 1437 (T -even), these TMDs can be nonzero even in (sub)processes where neither initial-state nor final-state
 1438 interactions are present. However, like all other TMDs, they are affected by such interactions, which can
 1439 render them process-dependent and even hamper factorisation.

1440 The distribution of linearly-polarised gluons has attracted much attention in the last few years. It cor-
 1441 responds to an interference between $+1$ and -1 gluon helicity states, which can be different from zero if
 1442 the gluon k_T is taken into account. If sizeable, this TMD can affect the P_T distributions of scalar and pseu-
 1443 doscalar particles produced in the final state, such as, for instance, H^0 bosons or C -even charmonium and
 1444 bottomonium states. Interestingly, it turns out that at small x , the linearly-polarised distribution may reach
 1445 its maximally allowed size, bounded by the unpolarised-gluon density [467]. Moreover, linearly-polarised
 1446 gluons can also be generated perturbatively from unpolarised quarks and gluons inside the proton [574, 575].
 1447 This determines the large- k_T tail of the distribution [576].

1448 From the experimental point of view, in contrast to quark TMDs, almost nothing is known about gluon
 1449 TMDs, due to the lack of processes, like single-inclusive DIS (SIDIS) and Drell–Yan pair production,
 1450 that directly probe them. A Gaussian-shape extraction of the unpolarised gluon TMD has recently been
 1451 performed, based on the LHCb measurement of the P_T spectra of J/ψ pairs [16], the first of its kind.

1452 Many proposals have been put forward to access TMDs in pp collisions, mainly by looking at azimuthal
 1453 asymmetries and P_T distributions for quarkonium production.

1454 The quarkonium processes for which one can hope TMD factorisation to hold – with NRQCD properly
 1455 modified – are

- 1456 • $pp \rightarrow \eta_{c,b} + X$ [13],
- 1457 • $pp \rightarrow J/\psi + \gamma + X$ and $pp \rightarrow \Upsilon + \gamma + X$ [14],
- 1458 • $pp \rightarrow J/\psi + \ell \bar{\ell} + X$ and $pp \rightarrow \Upsilon + \ell \bar{\ell} + X$ [17],
- 1459 • $pp \rightarrow \eta_c + \eta_c + X$ [482],
- 1460 • $pp \rightarrow J/\psi + J/\psi + X$ and $pp \rightarrow \Upsilon + \Upsilon + X$ [16, 22],

1461 at LO in v , thus only considering the CS contributions. The reason to focus on these CS processes is to
 1462 avoid the presence of final-state interactions which, together with the initial-state interactions present in pp
 1463 collisions, would lead to the breakdown of TMD factorisation [509–514]. The case of $pp \rightarrow \chi_{0c,b} + X$ or
 1464 $pp \rightarrow \chi_{2c,b} + X$ [13] is particular since CS and CO appear at the same order in v , which is a likely source
 1465 of complication. As such, we will come back to it in Section 4.6 when discussing considerations beyond
 1466 the strict TMD factorisation.

1467 Among these quarkonium reactions, we should make a distinction between single and associated pro-
1468 duction. Whereas the former is probably simpler to analyse, it does not allow the scale of the process to be
1469 tuned by increasing the invariant mass of the produced system. Consequently, there is not much room for
1470 TMD factorisation to apply as one is forced to be in the region $P_T \lesssim 2m_Q$. In addition, single-quarkonium
1471 production only provides an indirect way to probe $h_1^{\perp g}$ through P_T modulations, as it does not offer the pos-
1472 sibility of accessing the azimuthal asymmetries generated by the linearly-polarised gluons. Finally, during
1473 the HL-LHC period, these single-quarkonium cross sections, though much larger than for associated pro-
1474 duction, will be extremely complicated to measure with the ATLAS and CMS detectors in the applicability
1475 region of TMD factorisation. In contrast, the increased luminosity available at the HL-LHC will make the
1476 associated-production channels more accessible. However, single low- P_T quarkonia can probably be stud-
1477 ied in the much less hostile environment of FT-LHC by the LHCb and ALICE detectors. All these aspects
1478 will be addressed in the following three subsections.

1479 At this stage, it is important to note that the unpolarised and linearly-polarised gluon distributions to
1480 be extracted from the above-mentioned reactions, which correspond to the WW distributions in the small- x
1481 limit, are expected [577] to be the same as those entering (open and closed) heavy-quark-pair production
1482 in ep collisions. This represents an important test of the universality of the gluon TMDs inside unpolarised
1483 protons, which can only be performed by comparing data from pp and ep colliders. On the other hand,
1484 the consideration of processes where the TMD factorisation is not supposed to hold can be very valuable
1485 in advancing our understanding of long-distance correlations in QCD, by quantifying the actual role of the
1486 expected factorisation-breaking contributions. This will also be addressed in Section 4.6.

1487 4.5.1. Single low- P_T C -even Q production

1488 Single-quarkonium production offers the possibility of constraining both unpolarised and linearly-polarised
1489 gluon TMDs [13], even if the hard scale is set by the mass of the bound state and thus the room for TMD
1490 factorisation to work is limited. Leaving aside the complications of TMD-shape functions pointed out
1491 in [507, 508], which should be properly taken into account to perform quantitatively consistent phenom-
1492 ological analyses, the analysis of their (low) P_T spectra up to roughly half their mass can of course give
1493 information about the k_T dependence of the unpolarised TMD f_1^g at the scale 3 GeV (10 GeV) for the char-
1494 monium (bottomonium), but also on the distribution of the linearly-polarised gluons, $h_1^{\perp g}$, which modulate
1495 the quarkonium P_T spectrum. Estimations of these modulations and of the x range where they can be ac-
1496 cessed at the LHC in the collider and FT modes are given in Table 2. Estimated rates are also given to
1497 illustrate that they can be measured, provided that the detectors can cope with the background at low P_T .

Q	expected yield ($\sqrt{s} = 115$ GeV)	expected yield ($\sqrt{s} = 14$ TeV)	x_2 range ($\sqrt{s} = 115$ GeV)	x_2 range ($\sqrt{s} = 14$ TeV)	Low- P_T modulation
η_c	$\mathcal{O}(10^{5\div 6})$	$\mathcal{O}(10^{6\div 7})$	$0.02 \div 0.5$	$10^{-6} \div 3 \cdot 10^{-5}$	$0 \div 80\%$ [13, 578]
η_b	$\mathcal{O}(10^{1\div 2})$	$\mathcal{O}(10^{3\div 4})$	$0.1 \div 1$	$5 \cdot 10^{-6} \div 10^{-4}$	$0 \div 80\%$ [13, 449, 578]
$\chi_{c0}(1P)$	$\mathcal{O}(10^{3\div 4})$	$\mathcal{O}(10^{4\div 5})$	$0.02 \div 0.5$	$10^{-6} \div 3 \cdot 10^{-5}$	$0 \div 80\%$ [13]
$\chi_{c2}(1P)$	$\mathcal{O}(10^{5\div 6})$	$\mathcal{O}(10^{6\div 7})$	$0.02 \div 0.5$	$10^{-6} \div 3 \cdot 10^{-5}$	$< 1\%$ [13]
$\chi_{b0}(nP)$	$\mathcal{O}(10^{1\div 2})$	$\mathcal{O}(10^{3\div 4})$	$0.1 \div 1$	$5 \cdot 10^{-6} \div 10^{-4}$	$0 \div 80\%$ [13]
$\chi_{b2}(nP)$	$\mathcal{O}(10^{2\div 3})$	$\mathcal{O}(10^{4\div 5})$	$0.1 \div 1$	$5 \cdot 10^{-6} \div 10^{-4}$	$< 1\%$ [13]

Table 2: Expected P_T modulations generated by $h_1^{\perp g}$ for a selection of quarkonium-production observables, along with the expected yields and x_2 ranges derived from $x_2 = Me^{-y_{c.m.s.}}/\sqrt{s}$ for a rapidity coverage $-2.8 < y_{c.m.s.} < 0.2$ for FT mode at $\sqrt{s} = 115$ GeV and $2 < y_{c.m.s.} < 5$ for collider mode at $\sqrt{s} = 14$ TeV.

1498 However, we should stress that, in principle, TMD factorisation is only supposed to hold for η_Q pro-
1499 duction. The measurement of scalar and tensor $\chi_{c,b}$ states is essential to get a complete picture, but their
1500 low- P_T spectra are subject to specific factorisation-breaking effects [493] (see Section 4.6).

1501 4.5.2. $Q + Q$ production

1502 Pair-production of quarkonia at the LHC is in large majority from gluon fusion [176, 179], even down to
 1503 the energy of the FT mode [6, 182]. Thus, they enable the study of the gluon content of the proton with
 1504 low contamination from quark-induced contributions. As seen in Section 2 and to be discussed again in
 1505 Section 7, the hadroproduction of quarkonium pairs can be initiated [7, 34, 35] by SPS or by DPS.

1506 Only the SPS component is of interest here to probe TMDs in gluon fusion. It is thus important to
 1507 control the potential contamination from DPS. At low rapidity separations, Δy_{QQ} , and when the invariant
 1508 mass of the pair, M_{QQ} , increases, the relative contribution of DPS gets so low that it becomes a minor source
 1509 of uncertainty. Near the threshold, i.e. the region so far measured by LHCb [194], the DPS contribution
 1510 should be subtracted, which calls for a good understanding of its kinematic distribution.

1511 In addition, increasing M_{QQ} , as in the data samples of ATLAS [193] and CMS [192], allows one to
 1512 probe higher transverse-momentum of the pair, P_{QQ_T} , while remaining in the region of applicability of
 1513 TMD factorisation. J/ψ -pair and Υ -pair production were already studied several times by LHC collabora-
 1514 tions with various setups, although these studies were not designed for the extraction of information regard-
 1515 ing gluon TMDs (see Section 2.5.2). Increasing the samples of J/ψ pairs would allow for the measurement
 1516 of double- or even triple-differential cross sections, which are much more suitable for the extraction of
 1517 gluon TMDs without diluting their effects. More data on di- Υ production would allow one to probe gluon
 1518 TMDs at similar masses of the pair, but in a different system with different feed-down, DPS or ν -correction
 1519 contamination.

To highlight the importance of measuring azimuthal modulations, it is instructive to note that the differ-
 ential cross section of the process of QQ production via gluon-gluon fusion has the general form [16]:

$$\frac{d\sigma}{dM_{QQ}dY_{QQ}d^2\mathbf{P}_{QQ_T}d\Omega} \propto \frac{\sqrt{M_{QQ}^2 - 4M_Q^2}}{sM_{QQ}^2} \times \left\{ F_1 C[f_1^g f_1^g] + F_2 C[w_2 h_1^{\perp g} h_1^{\perp g}] + \cos(2\phi) \left(F_3 C[w_3 f_1^g h_1^{\perp g}] + F_3' C[w_3' h_1^{\perp g} f_1^g] \right) + \cos(4\phi) F_4 C[w_4 h_1^{\perp g} h_1^{\perp g}] \right\}, \quad (2)$$

1520 where the angular variables in $d\Omega = d\cos\theta d\phi$ are defined in the Collins–Soper frame and describe the
 1521 spatial orientation of the back-to-back pair in this frame. For vector-quarkonium-pair production, the hard-
 1522 scattering coefficient F_2 remains negligible over the whole phase space ($F_2/F_1 < 0.01$). Thus, $d\sigma/dP_{QQ_T}$
 1523 is not modulated by $h_1^{\perp g}$ and its measurement gives direct access to f_1^g .

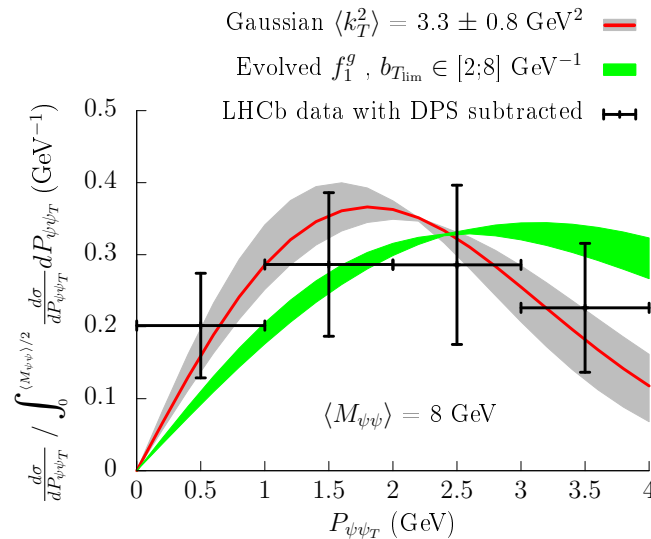


Figure 19: Comparison of the *normalised* $P_{\psi\psi_T}$ -spectrum for J/ψ -pair production at $M_{\psi\psi} = 8 \text{ GeV}$ computed using two models of the gluon TMDs with that measured by LHCb. [Figure taken from [22]]

1524 As for the azimuthal asymmetries, they can be conveniently studied by defining

$$\langle \cos(n\phi_{CS}) \rangle = \frac{\int d\phi_{CS} \cos(n\phi_{CS}) d\sigma}{\int d\phi_{CS} d\sigma}. \quad (3)$$

1525 In fact, $\langle \cos(2, 4\phi_{CS}) \rangle$ represent half the relative magnitude of the corresponding ϕ_{CS} -asymmetries in Eq. (2)
 1526 with respect to the azimuthally-independent part, and thus they are directly connected to $h_1^{\perp g}$.

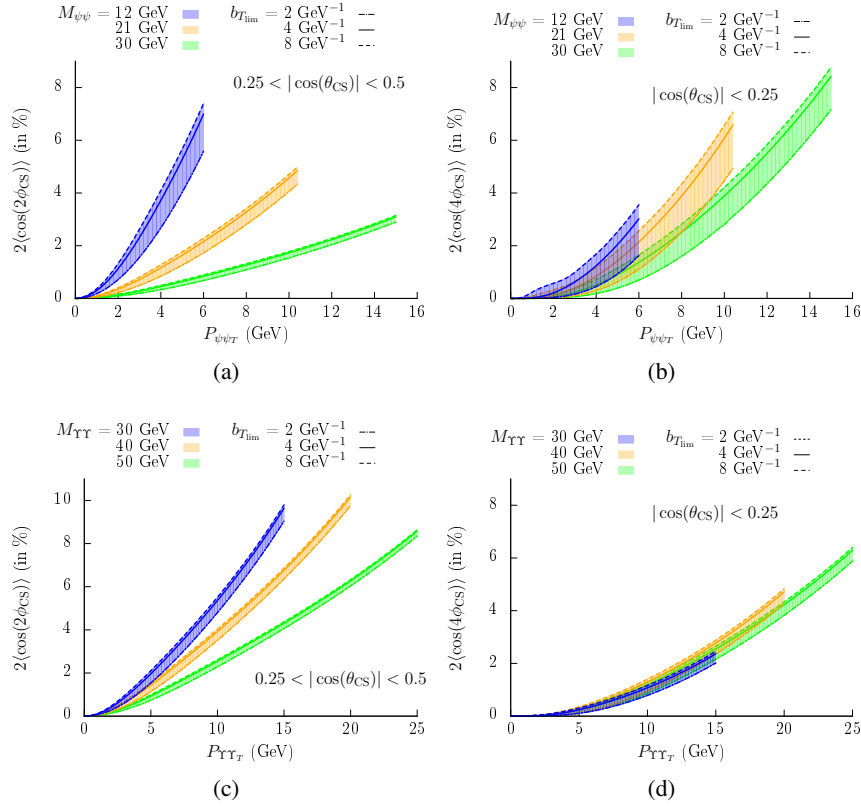


Figure 20: Azimuthal asymmetries for di- J/ψ (a,b) and di- Υ (c,d) production as functions of P_{QQ_T} : (a,c) $2\langle \cos(2\phi_{CS}) \rangle$ for $0.25 < |\cos(\theta_{CS})| < 0.5$, and (b,d) $2\langle \cos(4\phi_{CS}) \rangle$ at $|\cos(\theta_{CS})| < 0.25$. The results are presented for $M_{\psi\psi} = 12, 21$ and 30 GeV and for $M_{\Upsilon\Upsilon} = 30, 40$ and 50 GeV, for $b_{Tlim} = 2, 4$ and 8 GeV^{-1} . [Figure taken from [22]]

1527 The normalised $P_{\psi\psi_T}$ spectra for di- J/ψ production computed using a Gaussian-based TMD model [16]
 1528 or using an evolved TMD [22] are compared on Fig. 19 to the LHCb data [194], from which the DPS
 1529 is subtracted assuming that they are fully uncorrelated. The data considered are for $P_{\psi\psi_T} < M_{\psi\psi}/2$ with
 1530 $\langle M_{\psi\psi} \rangle \simeq 8$ GeV. The Gaussian-based TMD model fits the data best with a width $\langle k_T^2 \rangle$ of the order of
 1531 3 GeV^2 . Such a large value is a consequence of TMD evolution increasing the intrinsic momentum of
 1532 the gluons entering the hard scattering. The spectrum using evolved TMDs is plotted for widths b_{Tlim} of
 1533 a Gaussian nonperturbative Sudakov factor between 2 and 8 GeV^{-1} . The lower bound corresponds to the
 1534 conventional limit with the perturbative region, while the higher bound matches the diameter of the proton.
 1535 While the computation with evolution can account for the LHCb spectrum, the lack of a double differential
 1536 measurement in $P_{\psi\psi_T}$ and $M_{\psi\psi}$ does not allow the TMD evolution to be constrained.

1537 The relative size of azimuthal asymmetries in J/ψ - and Υ -pair production are presented in Fig. 20 as a
 1538 function of $P_{\psi\psi_T}$, for two ranges of rapidity difference ($|\cos(\theta_{CS})| < 0.25$ corresponds to central production,
 1539 while $0.25 < |\cos(\theta_{CS})| < 0.5$ corresponds to forward production), different values of $M_{\psi\psi}$ and for b_{Tlim} in
 1540 the range $[2;8]$ GeV^{-1} . Asymmetries reach magnitudes of 8 to 10% at larger P_{QQ_T} at central rapidities for
 1541 both J/ψ - and Υ -pair production.

1542 Much larger data samples to be collected at the HL-LHC will measure P_{QQ_T} distributions, allowing
 1543 for a proper fit of f_1^g at different scales. Additionally, they will allow for a measurement of the azimuthal
 1544 asymmetries, which could be as large as 10% and which would tell if indeed $h_1^{\perp g}$ is non-zero. Other studies
 1545 of quarkonium-pair production are discussed in Section 4.6.

1546 4.5.3. $Q + \gamma$ production

1547 Besides vector-quarkonium-pair production, the study of a vector quarkonium produced in association with
 1548 an isolated photon is another very promising way to access the distribution of both the k_T and the polar-
 1549 isation of the gluon in an unpolarised proton in pp collisions at the LHC [14]. Despite its likely smaller

1550 cross section compared to quarkonium-pair production, it is likely to be less prone to factorisation breaking
 1551 effects (see Section 4.6), while it shows a very similar capability in accessing $h_1^{\perp g}$.

The differential cross section for the production of $Q + \gamma$ ($Q = J/\psi, \Upsilon$) via gluon-gluon fusion has the same general form as for di-onia:

$$\frac{d\sigma}{dM_{\gamma Q} dY_{\gamma Q} d^2q_T d\Omega} \propto \frac{M_{\gamma Q}^2 - M_Q^2}{sM_Q^3 M_{\gamma Q}^3} \left\{ F_1 C[f_1^g f_1^g] + \cos(2\phi) F_3 C[w_3 f_1^g h_1^{\perp g}] + \cos(4\phi) F_4 C[w_4 h_1^{\perp g} h_1^{\perp g}] \right\}, \quad (4)$$

1552 where q_T is the transverse momentum of the quarkonium-photon pair and the angular variables in $d\Omega =$
 1553 $d\cos\theta d\phi$ are defined in the Collins-Soper frame [14]. Exactly as for di-onia, the first term in the curly
 1554 brackets corresponds to the contribution from unpolarised gluons described by f_1^g , while the second and
 1555 third terms contain the linearly-polarised gluon TMD function $h_1^{\perp g}$ and bring in some azimuthal modula-
 1556 tions.

1557 While in [14] the amplitudes of 2ϕ and 4ϕ modulation terms were found to be of comparable size, more
 1558 realistic simulations suggest that it may be safer to concentrate on the 4ϕ term, which is less likely to be
 1559 mimicked by typical acceptance requirements of the general-purpose LHC detectors on muons and photons.
 1560 It was found that the 4ϕ modulation is larger at small values of $\cos^2\theta$, and a cut at $\cos^2\theta = 0.1$ allows one
 1561 to separate the low- $\cos^2\theta$ area where the 4ϕ modulation is enhanced from the high- $\cos^2\theta$ area where it is
 1562 suppressed.

1563 In the absence of experimental data, we have found it useful to perform some feasibility studies to
 1564 extract the 4ϕ modulation. In what follows, the process is simulated for pp collisions at 13 TeV using
 1565 the PYTHIA 8 generator, with $h_1^{\perp g} = 0$. In order to emulate the effects of a possible non-zero $h_1^{\perp g}$, each
 1566 event is assigned a weight proportional to the expression in the curly bracket in Eq. (4)). For such pi-
 1567 oneering investigations, it is sufficient to mimic evolution effects by assuming a simple Gaussian depen-
 1568 dence of the unpolarised gluon distribution f_1^g on the transverse momentum of the gluon k_T [16, 579],
 1569 $f_1^g(x, k_T^2) = G(x)/\pi\langle k_T^2 \rangle \exp(-k_T^2/\langle k_T^2 \rangle)$, where the collinear gluon distribution function is given by $G(x)$,
 1570 and $\langle k_T^2 \rangle$ is assumed to be independent of x . A model-independent positivity bound is used to restrict pos-
 1571 sible parameterisations for $h_1^{\perp g}$ [467]: $k_T |h_1^{\perp g}(x, k_T^2)| \leq 2M^2 f_1(x, k_T^2)$. Following Refs. [16, 579], ‘Model 1’
 1572 is defined by $h_1^{\perp g}(x, k_T^2) = \frac{M^2 G(x)}{\pi\langle k_T^2 \rangle^2} \exp(1 - k_T^2/r\langle k_T^2 \rangle)$, while in ‘Model 2’ $h_1^{\perp g}(x, k_T^2)$ is chosen to saturate the
 1573 positivity bound.

1574 According to Eq. (4)), for an ideal experiment with full acceptance, the dependence on ϕ in the absence
 1575 of gluon polarisation is expected to be flat, while in the case of non-zero gluon polarisation, a ϕ modulation
 1576 appears with the magnitude proportional to the magnitude of $h_1^{\perp g}$. However, the kinematics of a typical
 1577 general-purpose LHC detector such as ATLAS or CMS suggests that the minimum P_T of an identified
 1578 muon is around 4 GeV, which implies $P_T^{J/\psi} > 8$ GeV and hence requires a cut $P_T^\gamma > 8 - 9$ GeV to produce
 1579 a P_T -balanced final state where q_T is smaller than, say, $M_{Q\gamma}/2$. These cuts cause a significant non-trivial
 1580 distortion of the observed ϕ distribution, which complicates the extraction of the ϕ -modulated terms. It
 1581 was observed that this distortion is almost independent of $\cos\theta$, and one can use the ratio of the differential
 1582 cross sections with low and high $\cos^2\theta$ to largely eliminate the kinematic distortion and help to extract the
 1583 4ϕ -modulated contribution.

1584 The comparison between unweighted and weighted distributions of the ratio of differential cross sections
 1585 with low $\cos^2\theta < 0.1$ and high $\cos^2\theta > 0.1$ is shown in Fig. 21. The distributions are fitted with a Fourier
 1586 series truncated after $\cos 4\phi$. The dashed blue line shows the unweighted result, which assumes $h_1^{\perp g} = 0$,
 1587 while the solid red lines in Fig. 21a and Fig. 21b correspond, respectively, to Model 1 and Model 2 defined
 1588 above.

1589 For the level of statistics of this Monte Carlo sample, which roughly corresponds to an integrated
 1590 luminosity of 100/fb at 13 TeV (with no account for detection efficiency), the change in the coefficient
 1591 of the $\cos 4\phi$ modulation term relative to the unweighted case, ΔP_4 , is non-significant for Model 1 at
 1592 $\Delta P_4(M1) = (9 \pm 6)10^{-3}$, but should be reliably measured if the gluon TMDs are described by Model 2,
 1593 with $\Delta P_4(M1, 2) = (50 \pm 6)10^{-3}$. An increase in the integrated luminosity by a factor of 100 should allow
 1594 one to reach the sensitivity needed for Model 1 even for a detection efficiency of $\sim 20\%$. A similar picture
 1595 is expected to be obtained for prospects with the CMS detector, whereas dedicated simulations are clearly
 1596 needed to assess whether one could venture to even lower P_T values with the LHCb detector.

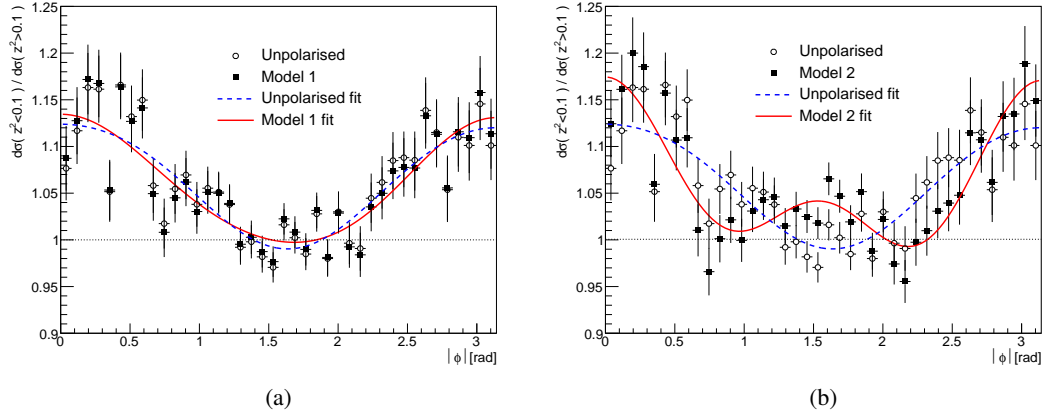


Figure 21: The ratios of differential cross sections for events with $z^2 \equiv \cos^2 \theta < 0.1$ over the events with $\cos^2 \theta > 0.1$. On both plots, the open points describe the unweighted distribution, corresponding to $h_1^{\perp g} = 0$, with the fit shown as the dashed blue line. The solid points describe the weighted distributions, with the fits shown as solid red lines, for Model 1 (a) and Model 2 (b) described in the text.

1597 4.6. Beyond and in between TMD and HE factorisations

1598 Quarkonia are nearly always produced by gluons at the LHC and, as such, their P_T spectra is, more or less
 1599 directly, sensitive to the gluon distribution in the transverse plane. However, even in unpolarised hadronic
 1600 collisions, many phenomena come into play when one wishes to study this connection. Depending on the
 1601 theoretical formalism one employs to approach this relationship between the dynamics of the gluon and that
 1602 of quarkonia, different effects are emphasised.

1603 As was previously alluded to, TMD factorisation is expected to have a restrictive range of applicability,
 1604 both in terms of kinematics (P_T should be smaller than the hard scale, the usual invariant mass of the
 1605 observed system) and processes (no colour flow in the final state in hadronic collisions). On the contrary,
 1606 HE factorisation is much more inclusive in terms of processes but, being designed to account for HE effects,
 1607 it may be inaccurate or simply miss some phenomena when the collision energy is finite. When put in the
 1608 context of quarkonium production, for which the mechanisms at work are not even an object of consensus, it
 1609 is not surprising that the situation quickly gets intricate. In this section, we will simply attempt to correlate
 1610 some possible future measurements at the HL-LHC with theoretical objectives. It should be clear that these
 1611 are not necessarily absolutely rigorous, completely achieved nor objects of consensus.

1612 Let us first start with ideas of quarkonium measurements inspired by considerations from TMD factori-
 1613 sation with NRQCD for which specific factorisation-breaking effects can be identified. The first on the list
 1614 of course is that of single J/ψ or Υ as a function of P_T , which have been routinely measured at colliders for
 1615 thirty years. These have been investigated assuming the validity of TMD factorisation within NRQCD with
 1616 CO contributions [486] as well as the CEM [484].

1617 There are two issues here concerning why TMD factorisation should in principle not apply. First, if
 1618 one focuses on the leading- v contributions, thus to the CSM, both J/ψ and Υ are produced with a gluon. If
 1619 its momentum is integrated over, the connection between the final-state measured momenta and the initial-
 1620 state ones is lost. Second, if one considers the sub-leading v contributions from CO, which at low P_T are
 1621 enhanced by one power of α_s , the colour flow is so entangled that one cannot expect to derive a factorised
 1622 formula for the hadronic cross section. However, it does not prevent the analysis of data along the lines
 1623 of what a would-be TMD factorised cross section predicts and, then, to attempt to extract information
 1624 on TMDs. Along these lines, it would be very interesting to compare the low- P_T spectra of the vector
 1625 and pseudoscalar states, i.e. for $P_T < M_Q/2$. Such data exist for the vector states, but not yet for the
 1626 pseudoscalar ones. If they are found to be different, caution will be needed before attributing this difference
 1627 either to P_T modulations from $h_1^{\perp g}$ or, simply, to factorisation-breaking effects beyond factorised TMDs
 1628 expected for these processes.

1629 The same remark can be made for the χ_Q states. Different P_T modulations from $h_1^{\perp g}$ are expected [13]
 1630 between the scalar and the tensor states. They are however also subject to factorisation-breaking effects
 1631 owing to their CO content [493]. It may nevertheless happen that these effects could be related by HQSS

1632 between both these χ_Q states. As what regards the pseudovector state, χ_{Q1} , according to NRQCD, its
 1633 arbitrary¹⁹ CO content would normally allow its production by the fusion of two on-shell gluons. LHCb
 1634 data however show [580] a χ_{c2}/χ_{c1} ratio steadily rising when P_T approaches zero in accordance with the
 1635 Landau–Yang theorem but in disagreement with the NRQCD expectations. In other words, the impact of
 1636 CO is not as expected. In view of this, one should certainly not refrain from incorporating the χ_Q states in
 1637 a global TMD survey for fear of factorisation-breaking effects due to their CO content.

1638 The HE factorisation framework provides further motivations for such studies of low- P_T χ_Q states and,
 1639 particularly, of ratios such as χ_{c2}/χ_{c1} . At the LHC, according to HE factorisation, this should also not show
 1640 the observed Landau–Yang enhancement, this time not because of CO, but because the pseudo-vector χ_{c1}
 1641 can be produced by two gluons when at least one is off-shell²⁰. Similarly, one may also want to compare
 1642 the pseudoscalar and tensor P_T spectra. Clearly, what is at stake then is the correlation between the off-
 1643 shellness of the initial gluons and their fractional momenta, rather than their possible linear polarisation.
 1644 This illustrates how a single observable can highlight two different phenomena in two different formalisms.
 1645 Of course, if observed, the question on how they are connected could be asked.

1646 Similarly there remain further aspects of the connection between the virtualities and the k_T of the initial
 1647 gluons that can be studied in associated production of quarkonia. Calculations in HE factorisation for
 1648 inclusive double charmonium hadroproduction are for instance discussed in Section 7 and provide, even
 1649 at LO, a reasonable account of the $P_{\psi\psi_T}$ spectra, which is connected to f_1^g as shown in Section 4.5.2. In
 1650 TMD factorisation, a first attempt to connect the size of the azimuthal modulations generated by $h_1^{\perp g}$
 1651 to the quarkonium polarisations was made in [581]. It would be interesting to see how, in HE factorisation,
 1652 the quarkonium polarisation evolves with energy and understand how it is correlated to the initial-gluon
 1653 virtualities. More generally, quarkonium-pair production, which should be studied even more widely at the
 1654 HL-LHC, likely represents a very versatile laboratory in which to analyse possible dualities between HE
 1655 and TMD factorisations.

1656 4.7. Single transverse-spin asymmetries at the HL-LHC in FT mode

1657 STSAs, or A_N , are defined as²¹

$$A_N = \frac{1}{\mathcal{P}_{\text{eff}}} \frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow}, \quad (5)$$

1658 where $\sigma^{\uparrow(\downarrow)}$ is a differential cross section produced with a nucleon polarised upwards (downwards) and \mathcal{P}_{eff}
 1659 is the effective polarisation. Large STSAs were observed for the first time in 1976, in Λ^0 production in
 1660 FT $p\text{Be}$ scattering at Fermilab [583], and have been seen in many other experiments since then. When
 1661 considering only the scattering of quarks or gluons, STSAs are expected to scale with the quark mass and
 1662 the c.m.s. energy as $A_N \sim m_q/\sqrt{s}$, as was shown in the seminal paper [584]. This prediction is many orders
 1663 of magnitude smaller than the experimental observation, hence the explanation for large STSAs has to be
 1664 found beyond the perturbative realm of QCD.

1665 Two different theoretical mechanisms have been proposed, both relating STSAs to the structure of
 1666 hadrons in terms of QCD. The first mechanism, called the collinear twist-3 (CT3) approach [585–587],
 1667 is valid in the presence of one hard scale. An example would be the single inclusive production of a light
 1668 meson in pp scattering, where the hard scale is provided by the large P_T of the meson. The STSAs is
 1669 then due to quark-gluon-quark or triple-gluon correlators, which are the sub-leading (in the scale) twist-3
 1670 extensions of the usual collinear PDFs (fragmentation type twist-3 correlators also being relevant [588]).

1671 The second mechanism takes place within TMD factorisation, and is therefore valid in the presence
 1672 of two ordered hard scales: a small and a large one. In this framework, large STSAs are caused by the
 1673 distribution of unpolarised partons inside the transversely-polarised hadron, parameterised by the Sivvers
 1674 TMD PDF f_{1T}^\perp [589] or by the fragmentation of a transversely-polarised parton into an unpolarised light
 1675 meson, as parameterised by the Collins TMD FF H_1^\perp [590]. Note that in the kinematic region where P_T
 1676 approaches the hard scale M , the TMD framework maps smoothly to the collinear regime, see e.g. [591–
 1677 593].

¹⁹The trade-off between the CO and CS component in a P -wave quarkonium is set by the unphysical NRQCD scale.

²⁰We recall that the gluon virtuality is expected to increase for decreasing x according to HE factorisation.

²¹Note that another direction, such as the transverse momentum of the produced particles, is needed. (see e.g. [582] for more details).

1678 Finally, a phenomenological approach is the Generalised Parton Model (GPM) [594], in which the
 1679 Siverson and Collins mechanisms are applied even in single-scale processes, keeping track of the transverse-
 1680 momentum exchanges in the partonic scattering. This approach has proven to be quite successful in phe-
 1681 nomenological analyses, although one should be careful when extracting conclusions about the involved
 1682 TMDs and the underlying physics. In any case, it can be used to give a fair estimate of STSAs in single-
 1683 scale processes, where the analysis in the proper twist-3 framework becomes a real challenge, due to the
 1684 many involved and still unconstrained twist-3 functions.

1685 Below STSAs in different quarkonium-production processes are discussed, in the context of a future FT
 1686 experiment at the HL-LHC [6], which could perform these measurements by polarising a target.

1687 4.7.1. Vector Q production

1688 In this subsection, STSAs in the $p^\dagger p \rightarrow Q + X$ process are discussed. As was previously discussed, such
 1689 processes are strictly speaking not TMD factorisable and do not therefore directly probe the TMD $f_{1T}^{\perp g}$ [595],
 1690 which encapsulates the Siverson effect believed to generate these STSAs, in the absence of Collins effect from
 1691 the fragmentation of the hadron.

1692 However, within the GPM, which is an effective model where spin and intrinsic transverse-momentum
 1693 effects are taken into account, such STSAs are treated as if they were factorisable in terms of an analogous
 1694 object which is denoted, in what follows, as the Gluon Siverson function (GSF), in order to account for the
 1695 gluon Siverson effect.

1696 A more sophisticated extension of the GPM, the Colour-Gauge-Invariant GPM (CGI-GPM) [488, 596],
 1697 can also be considered, where effects from initial-state and final-state interactions, in the one-gluon approx-
 1698 imation, are encapsulated in the GSF modelling. Within the CGI-GPM, there are two independent GSFs,
 1699 acting as phenomenological counterparts to the previously mentioned WW and DP $f_{1T}^{\perp g}$ in Section 4.1,
 1700 here denoted by f - and d -type, respectively. In this respect, one can in principle also address the process
 1701 dependence of the GSF.

1702 Concerning the quarkonium-production mechanism, both the CSM and NRQCD can be considered
 1703 since factorisation-breaking effects are put aside. All details about such phenomenological studies can be
 1704 found in [488, 491, 597]. In what follows, some selected results which support future experimental studies
 1705 at the LHC will be shown.

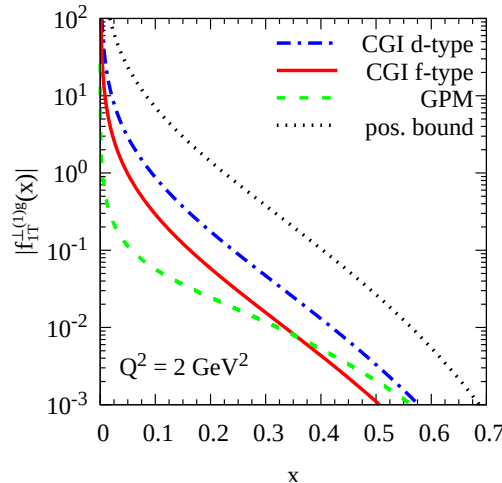


Figure 22: Upper values for the first k_T moments of the GSFs at $Q^2 = 2 \text{ GeV}^2$ [598].

1706 A first attempt to constrain these effective GSFs both within the GPM and the CGI-GPM approaches,
 1707 from mid-rapidity pion and D -meson STSA data from RHIC [599, 600], was presented in [598, 601].
 1708 Fig. 22 shows the extracted upper bounds of the first k_T moment of the GSFs. Note that this quantity is a
 1709 necessary ingredient for the evolution of the GSF itself. As a matter of fact, the obtained GSF allows for
 1710 a fairly good description of the available J/ψ STSA data (almost compatible with zero) [602], even if no
 1711 definite conclusion can be drawn owing to the possible presence of non-factorisable contributions, the feed-
 1712 down from states that could depend in a different manner on the GSF, and the still rather large experimental

1713 uncertainties in a restricted domain in x . It is thus extremely important to extend this analysis to more
 1714 quarkonium states and to the kinematics reachable at the FT-LHC as discussed in [6, 298].

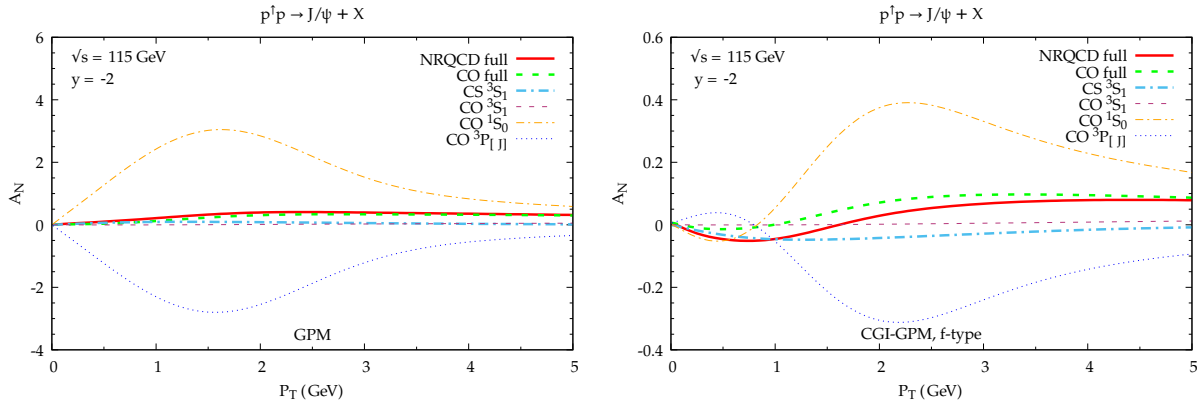


Figure 23: Maximised values for A_N vs. P_T for the process $pp^\uparrow \rightarrow J/\psi + X$ at $\sqrt{s} = 115$ GeV and $y_{cm} = -2$ within the GPM (left panel) and the CGI-GPM (right panel) approaches [491, 597]. The full result (red solid lines) together with its wave decomposition (see legend) are shown.

1715 Fig. 23 shows estimates for the STSA in the FT mode at the LHC, A_N , obtained by *maximising* the Siverts
 1716 effect within the GPM (left panel) and the CGI-GPM f -type (right panel) approaches. The maximised quark
 1717 contributions as well as those from the d -type GSF (not shown) are compatible with zero. For completeness,
 1718 the contribution from each wave to the full result is shown (see legend). Notice that some contributions
 1719 within the GPM are larger than one. Since the denominator of the STSA includes all terms (entering with
 1720 relative signs), while the numerator considers only a specific wave state. The overall result (red solid lines)
 1721 is, as expected, smaller than one. A full comparison between two different mechanisms for quarkonium
 1722 production (CSM vs. NRQCD) and two effective TMD schemes (GPM vs. CGI-GPM) for the maximised
 1723 A_N is presented in Fig. 24. These results, where no previous information on the GSF has been used, illustrate
 1724 the potential role of such a dedicated phenomenological study.

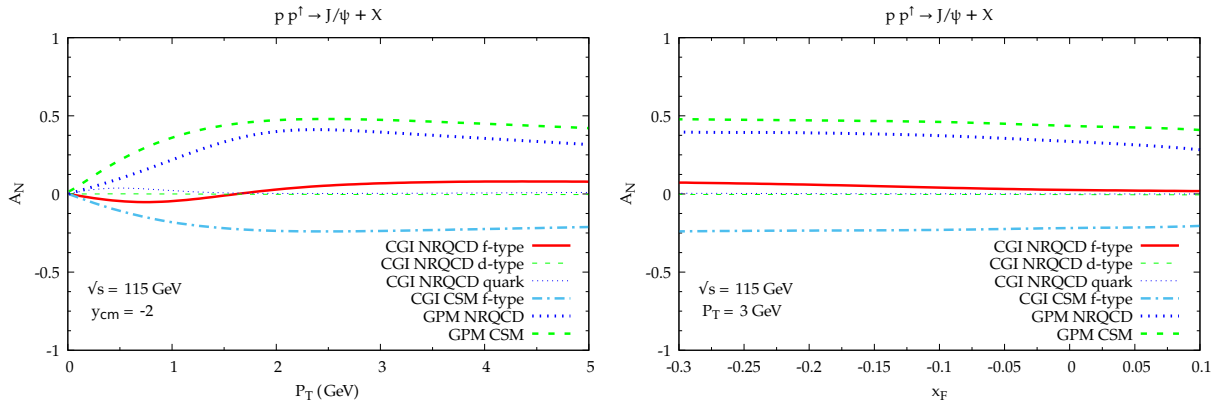


Figure 24: Maximised values for A_N for the process $pp^\uparrow \rightarrow J/\psi + X$ at $\sqrt{s} = 115$ GeV at fixed $y_{cm} = -2$ vs. P_T (left panel) and at fixed $P_T = 3$ GeV vs. x_F (right panel), obtained adopting the CGI-GPM and GPM approaches, within the CSM and NRQCD [491, 597].

1725 In [6, 298], first studies of the projected uncertainties on A_N were performed. Fig. 25 shows the esti-
 1726 mated statistical uncertainties at the FT-LHC for A_N as a function of x_F in Υ production in pp^\uparrow collisions
 1727 at $\sqrt{s} = 115$ GeV for an LHCb-like detector with 10 fb^{-1} of luminosity, while Fig. 26 shows the ex-
 1728 pected statistical precision for A_N in J/ψ production with an ALICE-like detector for pp^\uparrow collisions with 45
 1729 pb^{-1} of luminosity. The expected Υ , J/ψ and background yields were extrapolated from the J/ψ -rapidity
 1730 spectrum and the signal-to-background ratios of [605] with the procedure described in [298]. The signal-
 1731 to-background ratio at 115 GeV is 1.2 and an efficiency of 13% was assumed [606]. The projected uncer-
 1732 tainties, on the order of a few percent, can certainly help in constraining the GSF and the related twist-3
 1733 correlators, investigating different phenomenological approaches and entering a more quantitative phase in
 1734 the study of gluon TMDs.

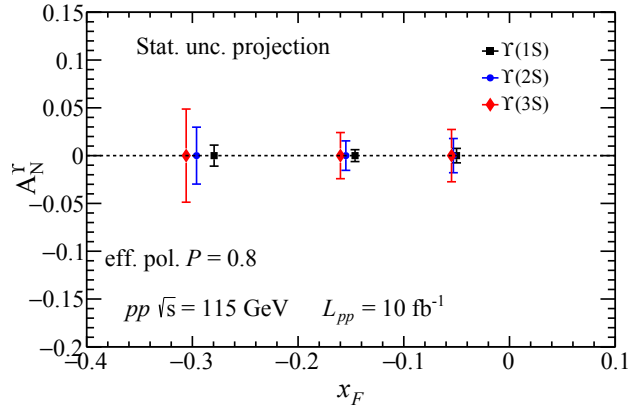


Figure 25: Statistical-precision projections for $\Upsilon(nS)$ A_N as a function of x_F . The quarkonium states are assumed to be measured in the di-muon channel with a LHCb-like detector. The signal and the background are calculated in fast simulations that take into account the performance of the LHCb detector [298, 603]. [Figure taken from [6]]

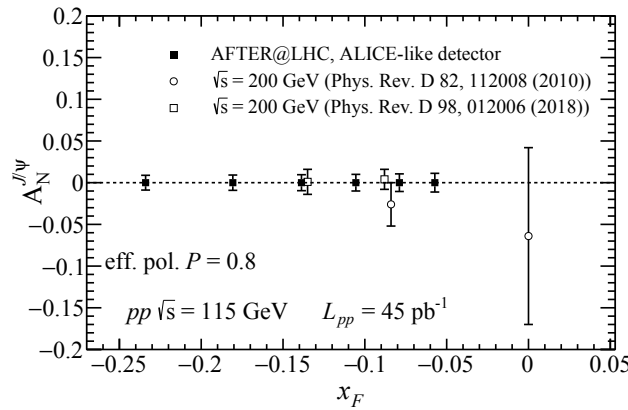


Figure 26: Statistical-precision projections for J/ψ A_N as a function of x_F compared to the existing measurements [602, 604]. The J/ψ di-muon spectrum is assumed to be measured in the Muon Spectrometer of the ALICE detector, with the target located at the nominal interaction point ($z_{\text{target}} \approx 0$). The signal and the background are extrapolated at $\sqrt{s_{NN}} = 115$ GeV from the ALICE measurements in [605]. [Figure taken from [6]]

1735 4.7.2. C -even Q states

1736 The production of C -even quarkonium states has recently attracted great attention both theoretically and
 1737 experimentally (see Section 2). With a detector similar to LHCb, STSAs for χ_c , χ_b and η_c could be measured
 1738 at low P_T in the FT mode, as suggested by several studies of χ_c states in the busier collider mode down to a
 1739 P_T as low as 2 GeV [146, 607]. The first study of inclusive η_c production above $P_T = 6$ GeV was performed
 1740 by LHCb together with non-prompt $\eta_c(2S)$ production [608]. Such prompt studies can clearly be carried
 1741 out by LHCb [114]. Indeed, given the lower combinatorial background at lower energies and the fact that
 1742 the cross section for pseudoscalar charmonium production is similar to that of the vector ones, the low- P_T
 1743 region should be in reach. It may also be the case for η_b production [12], which offers a slightly wider range
 1744 of applicability for TMD factorisation in terms of the P_T range.

1745 The measurement of STSAs of C -even quarkonium states would give a clean access not only to CT3
 1746 tri-gluon correlators [609], but also to $f_{1T}^{\perp g}$ and the GSF of the GPM if the low- P_T region can be measured.
 1747 Such processes would offer an opportunity for comparisons between these frameworks. Estimations of both
 1748 η_Q and χ_Q STSAs from the CT3 formalism are however not yet available, nor is any robust information on
 1749 $f_{1T}^{\perp g}$. Table 2 presents some yield estimations and the expected x ranges that can be accessed.

1750 4.7.3. STSAs in associated Q production

1751 Associated-production channels [14, 15, 22, 515, 578, 610, 611], where a quarkonium is produced along
 1752 with another particle (e.g. another quarkonium, a photon, a lepton-pair, etc.), represent a very useful tool
 1753 to access $f_{1T}^{\perp g}$ of TMD factorisation, the GSF of the (CGI-)GPM and the related tri-gluon correlators for

1754 CT3 factorisation. With the possibility to scan over the invariant mass of the observed system, one gets an
 1755 interesting handle on the scale evolution of the Siverson effect. In addition, these associated-production chan-
 1756 nels enlarge the range of processes (with gluon-sensitive colourless final states) where TMD factorisation
 1757 is expected to apply, offering various options to verify the universality of the extracted TMDs. A problem
 1758 however is that such processes usually have small cross sections at RHIC and FT-LHC energies, and this
 1759 makes their study very challenging and probably requires high luminosity.

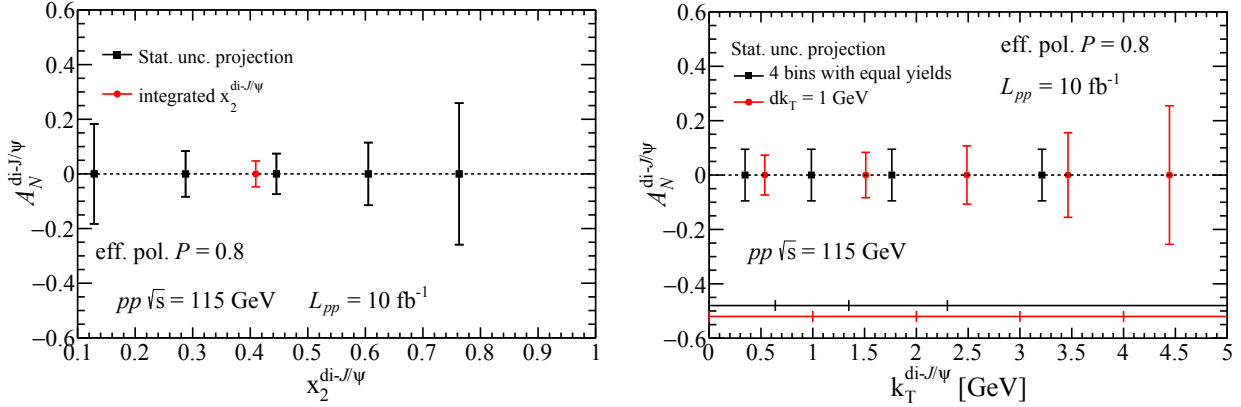


Figure 27: Statistical-precision projections for di- J/ψ A_N as a function of (a) x_F and (b) the pair k_T with a LHCb-like detector. The horizontal lines in (b) denote the width of the k_T bins used for the calculations. [Figure taken from [6].]

1760 Di- J/ψ production is certainly one of the most promising channels since the yields are not too small at
 1761 the FT-LHC [182] and the measurement is clearly feasible (unlike, for example, di- γ studies). Furthermore,
 1762 the feed-down contamination is limited to $\psi(2S)$ [35, 182], which probe $f_{1T}^{\perp g}$ in the same way. Fig. 27 shows
 1763 the expected statistical precision for A_N obtainable from di- J/ψ production at the FT-LHC with the LHCb
 1764 detector as a function of the transverse momentum of the pair, k_T , and the corresponding x_2 . Two scenarios
 1765 are considered for the analysis of A_N as a function of k_T : bins with a fixed width of 1 GeV ($dk_T = 1 \text{ GeV}$, red
 1766 points) and bins containing equal yields (black points). Here, the k_T dependence is modelled as a Gaussian
 1767 distribution with width $\sigma = 2 \text{ GeV}$. The x_2 -integrated A_N will allow for the determination of the STSA with
 1768 a few percent precision, and the $A_N(k_T)$ will give access to the k_T -dependence of the gluon Siverson TMD up
 1769 to $k_T \approx 4 \text{ GeV}$, which is not accessible anywhere else.

1770 5. Proton-nucleus collisions²²

1771 5.1. Introduction

1772 Quarkonium production in pA collisions is studied in several contexts at the LHC. Traditionally, it is used as
 1773 a baseline for the investigation of quarkonium production in AA collisions, where the production of heavy
 1774 quark-antiquark bound states with different binding energies contains information about the properties of
 1775 the final-state deconfined medium (Section 6). In the absence of any other initial- or final-state effects, any
 1776 changes to the yield in pA collisions compared to pp collisions is attributable to intrinsic modifications of
 1777 the PDFs in the nucleus with respect to the free proton PDFs. Quarkonium production at the LHC is thereby
 1778 an interesting probe of the nPDFs in both the collider and FT operations. Quarkonium production in the
 1779 collider mode gives access to very low parton momentum fractions, down to below $x \approx 10^{-5}$, up to still
 1780 relatively large energy scales (Fig. 28). This extreme kinematic region has not been constrained by accurate
 1781 measurements at any heavy-ion facility so far, and hence deserves further attention. The FT mode allows
 1782 probing large partonic momentum fractions $x > 0.3$, another region where only loose constraints exist at
 1783 present.

1784 In addition, pA collisions provide an ideal arena to explore the dynamics of heavy-quarks in cold-nuclear
 1785 matter. At collider energies, the non-perturbative hadronisation of the heavy-quark pair is factorisable
 1786 from its production [33], allowing the study of some universal features of cold-nuclear effects. Initial-state

²²Section editors: Michael Winn, Bertrand Ducloué.

1787 multiple interactions of a colliding parton inside a heavy ion together with final-state multiple scatterings of
 1788 the produced heavy-quark pair before it exits the nucleus can interfere, which also modifies the yield in pA
 1789 collisions compared to pp collisions (Sec. 5.2.1). However, the soft-gluon interaction between the produced
 1790 heavy-quark pair and the parton spectators of the colliding beams in both pp and pA collisions could break
 1791 the factorisation between the production and the bound-state formation that dominates at lower P_T . Such
 1792 a factorisation breaking can be studied using the CIM (see Sections 2.4.3 & 5.4.1). Systematic theoretical
 1793 treatments of the multiple scattering between the heavy-quark pair and the traversed nucleus are urgently
 1794 needed for predictions for the HL-LHC pA programme [30, 31].

1795 Furthermore, the heavy-ion-physics programme at the LHC has shown smooth system-size evolutions
 1796 of various key QGP signatures. They appear for large final-state particle multiplicities, but they extend also
 1797 towards lower particle-multiplicity environments in pPb and pp collisions. Quarkonium is interesting due
 1798 to its role as a signature of the QGP creation, as well as its heavy mass providing an additional dimension
 1799 in the investigation of these phenomena. Strong nuclear modifications of quarkonium production were
 1800 observed in pA collisions at the LHC [33], but whether or not they can be ascribed to the modification
 1801 of the nuclear wave function [612, 613], or to energy loss, or to other mechanisms including final-state
 1802 phenomena associated usually to AA collisions, is not yet resolved. Hence, the question is open as to
 1803 whether quarkonium and heavy-flavour observables are a tool to constrain the hadronic wave function or
 1804 whether they inform us about final-state parton collectivity: it may also depend on the specific observable.

1805 In addition to collider data, quarkonium production in the LHC FT mode, pioneered by LHCb [418],
 1806 implemented for higher luminosity in Run 3 for LHCb and investigated for further upgrades in LHCb and
 1807 ALICE, opens up new possibilities to study QCD phenomena at large x in nuclei with unprecedented detail
 1808 and precision [5, 6, 603, 614, 615].

1809 All the open questions outlined above need to be addressed in order to deepen our understanding of
 1810 the QGP properties and of hadron structure at high energies. New quarkonium studies, enabled by higher
 1811 luminosities in pA data at the HL-LHC and related theory progress, are reported in the following.

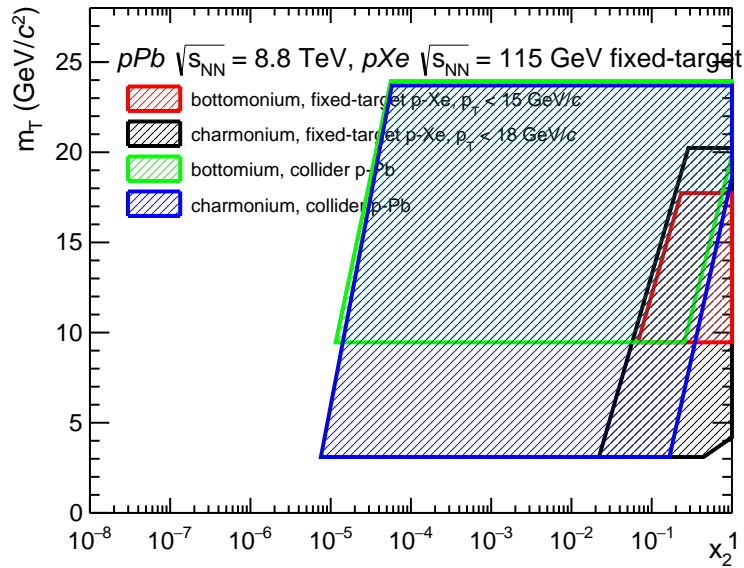


Figure 28: Kinematic plane M_T vs x_2 at the LHC in collider and FT mode. The P_T range is limited to kinematic regions where large enough data samples can be collected. For simplicity, small gaps within the experimental acceptance at small momentum in the collider mode are omitted. FT coverages are taken from [6].

1812 5.2. Cold nuclear matter effects in Q production

1813 In view of using pA collisions as a baseline for AA collisions or as a testing ground for the initial-state par-
 1814 tonic structure of the nucleus –i.e. using nuclear modifications in pPb collisions compared to pp collisions
 1815 to study the so-called cold nuclear matter effects–, one relies on several theoretical models to capture the
 1816 origin of these effects based on different assumptions.

1817 5.2.1. Theoretical models: setting the scene

1818 **Collinear factorisation and nPDFs.** The use of nuclear PDFs (nPDFs) for calculations involving pA
1819 collisions rely on the assumption that one can factorise pA scattering cross sections into a hard component
1820 –the partonic cross section– and soft components –the PDFs and FFs. These soft components are supposed
1821 to be universal, meaning in particular that the nPDFs would not depend on the process under study or the
1822 collision system (e.g. ℓA or pA). Even though there is still no proof that factorisation is applicable to
1823 collisions involving nuclei, there are few doubts that it applies for processes like Drell–Yan pair production
1824 in pA collisions. Yet, this remains the first and probably most important assumption made when performing
1825 nPDF fits using pA data, and it indeed deserves further dedicated studies. In addition, it is assumed that the
1826 nPDFs encapsulate all the nuclear effects at play. At FT energies, it is very possible that the energy loss can
1827 play a visible role in Drell–Yan production whereas, at collider energies, this effect is negligible.

1828 Existing data usable to fit nPDFs are limited and the resulting uncertainties are significant, which makes
1829 it difficult to perform tests of the factorisation hypothesis. Future LHC pA data for processes probing
1830 different scales and incoming parton flavours can be crucial in this respect: since the DGLAP equation
1831 governs the evolution from low to high scales and couples quarks with gluons, the inclusion of a given data
1832 set in global fits would also have an impact on the description of another. However, disentangling the impact
1833 of a possibly violated factorisation assumption is not trivial at the moment, due to the fact that we have not
1834 reached yet an accurate comprehensive description of all cold-nuclear-matter effects. The simultaneous
1835 analysis of future LHC data, as well as of those that will be available at the EIC, will certainly help to
1836 develop a more complete picture in this respect.

1837 While proton PDF fits have reached a high level of sophistication and precision [229], modern nPDF
1838 fits [616–622] are not yet as precise, for basically three reasons:

- 1839 (i) much less data are available from ℓA and pA collisions compared to from ℓp and pp , and these data
1840 cover more restricted ranges in x and the scale;
- 1841 (ii) nPDFs require the further determination of their A dependence, where A is the atomic number of the
1842 nucleus, and consequently more data to obtain a similar precision;
- 1843 (iii) since the physics of pA collisions is more complex than that of pp collisions, due to the possible
1844 presence of multiple nuclear matter effects, one has to be more cautious when enlarging the data sets
1845 used in fits to new reactions.

1846 Whereas the accuracy of proton PDF fits is at NNLO (and further work has started towards N³LO accuracy),
1847 a similar level of accuracy for unpolarised nPDF fits is desirable, but so far has only been achieved in fits
1848 exploiting nuclear DIS data [621, 622]. In the NNLO fit of [620], besides DIS data, FT pA Drell–Yan
1849 data have been used, covering larger x values, up to $x \approx 1$. Unfortunately, data on FT ℓA DIS can only
1850 constrain nPDFs down to $x \approx 6 \cdot 10^{-3}$. In contrast, the minimum x probed in pA collisions at the LHC
1851 extends to significantly lower values, depending on the c.m.s., the kinematic cuts, and the measured final
1852 states. Therefore, the tendency to use collider data obtained in pA collisions to constrain nPDFs has recently
1853 increased, mainly thanks to newly available hard-scattering high-precision measurements from the pPb runs
1854 at the LHC.

1855 **The Colour-Glass Condensate.** At high collision energy (or small x values), parton densities inside
1856 hadrons become so large that non-linear effects such as gluon recombination become important, which
1857 can lead to a saturation of the gluon density. The CGC effective field theory [218, 623–628] provides a
1858 convenient framework to describe processes in this regime. In this formalism, a pA collision can be seen as
1859 the scattering of a dilute projectile (the proton) on a dense target (the nucleus). Because the gluon density
1860 in a nucleus scales roughly like $A^{1/3}$, such non-linear effects are enhanced in pA compared to pp colli-
1861 sions. The Nuclear Modification Factor (NMF) R_{pA} is thus a useful observable to study saturation effects.
1862 In particular, the CGC provides a natural explanation for the decreasing behaviour of R_{pA} as a function
1863 of rapidity observed in forward J/ψ production at the LHC, which probes very small x values: since at a
1864 given x the gluon density in a nucleus is larger than in a proton and thus closer to saturation, R_{pA} will not
1865 increase as quickly with decreasing x (or increasing rapidity). While this general trend was present in the
1866 first predictions for this process at the LHC in the CGC formalism [629] and was subsequently confirmed
1867 experimentally [630], it turned out that the measured R_{pA} was much larger than the predicted one. The
1868 origin of this discrepancy can be attributed to approximations related to the initial conditions for the gluon

1869 density. Indeed, while in the CGC formalism the evolution of the gluon density as a function of x is fully
 1870 (perturbatively) determined by the Balitsky–Kovchegov equation [631, 632], the initial conditions of this
 1871 evolution, expressed at moderate $x_0 \approx 0.01$, involves non-perturbative dynamics that cannot be computed.
 1872 The initial conditions for a proton target can be extracted by a fit to HERA DIS data, but the lack of similar
 1873 high-precision low- x data for nuclei makes some modelling mandatory in the case of proton-nucleus col-
 1874 lisions. In [629], this was done by taking $Q_{s0,A}^2 = cQ_{s0,p}^2$, where $Q_{s0,p}$ and $Q_{s0,A}$ are the initial saturation
 1875 scales of the proton and nucleus, respectively, and $c \sim A^{1/3}$. In practice, the value of c was varied between 4
 1876 and 6. However a study looking at the A dependence of F_2 measured by the NMC collaboration [633] found
 1877 that that data is best described with c values between 1.5 and 3 [634]. Another way to extrapolate the initial
 1878 condition of a proton to a nucleus is to use, as in [635], the optical Glauber model, which assumes that at
 1879 $x = x_0$ the high-energy probe scatters independently off the nucleons, which are distributed according to
 1880 the standard Woods-Saxon distribution [636]. These two methods were shown to lead to results in good
 1881 agreement with experimental data [637–639].

1882 **Coherent energy loss.** Another possible nuclear effect is medium-induced gluon radiation via multiple
 1883 scatterings of an incoming probe in the target nucleus. In [640], it was shown that, for long formation
 1884 times, the interference between initial- and final-state emissions can lead to an energy loss which is propor-
 1885 tional to the incoming particle energy. This is in contrast with the Landau–Migdal–Pomeranchuk (LPM)
 1886 effect [641], at play for short formation times, that shows an energy dependence that is at most logarithmic
 1887 and is expected to be small at LHC energies. This fully coherent energy loss (the coherent action of all scat-
 1888 tering centres in the medium at large formation times) requires both initial and final states to be coloured
 1889 (in this model, quarkonium production is assumed to proceed via the splitting of an incoming gluon into
 1890 a quark-antiquark pair in a colour octet state). Under these assumptions the energy-loss spectrum is found
 1891 to depend only on one free parameter, the transport coefficient of the nuclear medium \hat{q} . A fit to E866
 1892 data [642] leads to a value of $\hat{q} = 0.075 \text{ GeV}^2/\text{fm}$ [643] which can then be used to make predictions for
 1893 other energies. The main output of the calculation is the energy loss probability distribution that, when
 1894 convoluted with the pp cross section (evaluated at a shifted energy corresponding to the energy loss), leads
 1895 to the pA cross section. To reduce the number of assumptions and parameters (especially in the case of
 1896 quarkonia for which the production mechanism is not well understood), in [643] the cross section in pp
 1897 collisions is not calculated but instead obtained by fitting experimental data using a simple functional form.
 1898 However, it is not clear how such an energy loss depends on the production mechanism or on the quantum
 1899 numbers of the produced quarkonia. Under these assumptions, the resulting prediction for the NMF of J/ψ
 1900 production was later found to be in good agreement with the measurements at the LHC, both at forward and
 1901 backward rapidities.

1902 **Global view.** As shown in Fig. 29, several calculations, based on different theoretical models, are able to
 1903 describe the experimental measurements of the J/ψ NMF as a function of rapidity in $p\text{Pb}$ collisions at the
 1904 LHC. The question of which physical mechanisms are responsible for these observed nuclear modifications
 1905 is still under debate, noting that these effects are not all mutually exclusive. In particular, the suppression
 1906 of quarkonium production at forward rapidities can be caused by shadowing, or by coherent energy losses,
 1907 or by heavy-quark absorption in the nucleus, or by a combination of more than one of these effects. To
 1908 ascertain which effects are responsible for the observations, simultaneous measurements of different heavy-
 1909 flavour probes in pA and AA collisions covering the same small x values, in collisions at the same $\sqrt{s_{NN}}$,
 1910 can help to disentangle them.

1911 It is also worth noting some essential issues in the model calculations. Firstly, the fundamental mecha-
 1912 nisms of the heavy-quark pair production in pA collisions could be quite different from that in pp collisions.
 1913 In particular, when $P_T \lesssim m_Q$, and when one specifically addresses P_T -dependent quantities as opposed to
 1914 integrated ones, the perturbative QCD collinear factorisation approach for quarkonium production is not
 1915 necessarily the most reliable theoretical approach (see e.g. [7, 43] for a review). As discussed in Secs. 2.2.1
 1916 and 4, the transverse momentum dependent (TMD) factorisation framework should take over the collinear
 1917 factorisation for heavy-quark pair production when $P_T \ll m_Q$, which makes the nPDFs effect unclear.

1918 For evaluating nuclear effects in the TMD factorisation approach, one must clarify how to include
 1919 nuclear size or $A^{1/3}$ -enhanced power corrections [651–653] into the leading-twist TMD factorisation ap-
 1920 proach [654] although, in general, the power corrections in hadronic collisions cannot be factorised beyond

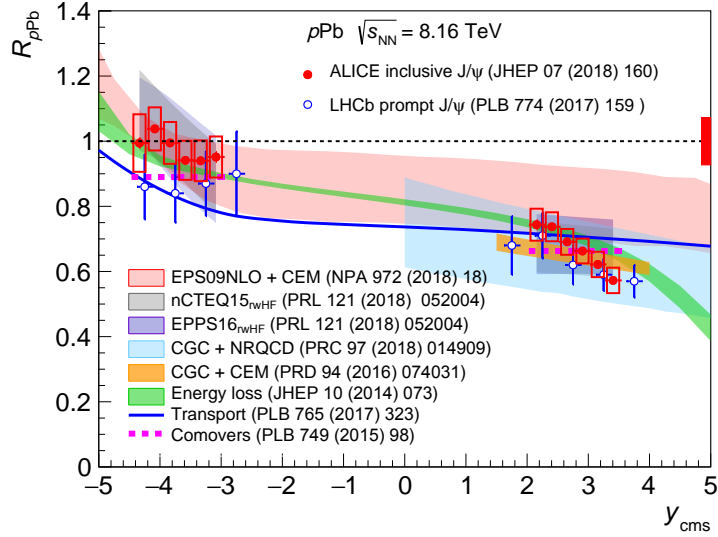


Figure 29: Comparison of the ALICE [644] and LHCb [645] measurements of the NMF of J/ψ production in p Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV with several model calculations [31, 32, 646–650]. Note that the curves labelled nCTEQ15 and EPPS16 are obtained after reweighting the corresponding nuclear PDF sets using LHC heavy-flavour data. [Figure taken from [644].]

1921 the sub-leading power [72, 655]. Besides, one must understand how to incorporate the nuclear dependence
 1922 into the non-perturbative TMD distributions [656]. Interestingly, it has been clarified that the leading-twist
 1923 TMD factorisation framework can be recovered by getting rid of higher body scattering corrections in the
 1924 CGC framework [542, 657, 658]. Therefore, some precautions are required to compare nPDFs with parton
 1925 saturation effects. Higher-twist effects can be studied by considering “clean” processes, such as Drell–Yan
 1926 process in pA collisions, and semi-inclusive nuclear DIS at the EIC. See Section 5.2.5 for experimental
 1927 prospects.

1928 It has been argued that if the quarkonium is produced at a very forward rapidity, the hadronisation of the
 1929 pair takes place outside of the colliding heavy ion (see e.g. [659] and references therein). Multiple scattering
 1930 of the produced pair in the nuclear medium could enhance its invariant mass so much (beyond the $D\bar{D}$ or
 1931 $B\bar{B}$ mass threshold) to prevent the pair from binding and leading to threshold-sensitive suppression [660].
 1932 Some model calculations have been carried out along this line in the CGC framework [647]. This threshold-
 1933 sensitive suppression could be caused by multiple scattering of the pair in the colliding ion or by exchanging
 1934 soft gluons with co-moving spectator partons of the beam, also known as the comover mechanism. One
 1935 could investigate this threshold suppression effect on top of the energy loss effect. So, a careful examination
 1936 is required in order to distinguish the modification of the hadronisation mechanism in nuclear medium from
 1937 the modification of the initial PDFs, or higher twist effects, and so forth. See Section 5.4 for a discussion
 1938 about hadronisation.

1939 5.2.2. Improved constraints on nPDFs from LHC data

1940 Given the caveats related to possible confounding factors involved in pA collisions already discussed, the
 1941 usage of quarkonium to improve our knowledge on nPDFs depends on whether or not the nPDF effect is the
 1942 dominant one. Even though such a dominance may not be straightforward to establish, one should note that
 1943 the quarkonium data sets are large, relatively precise and thus constraining under this working hypothesis
 1944 that can be falsified if tensions with other data sets appear.

1945 The first p Pb LHC data included into global nPDF fits [619] are from inclusive W and Z boson produc-
 1946 tion measurements, constraining valence and sea quarks down to $x \approx 10^{-3}$ at high scale, and di-jet data,
 1947 with direct sensitivity to the gluon distribution (whereas inclusive DIS is sensitive to gluons only indirectly,
 1948 through scale violations) down to $x \approx 5 \cdot 10^{-3}$. Including data on charmonium and bottomonium production,
 1949 as well as open-charm production in the LHC kinematics, can further extend the range in x and the scale.
 1950 In particular, in [32], it was shown that, using LHC heavy-flavour data at c.m.s. energies up to 8 TeV to
 1951 reweight two nPDF fits (EPPS16 and nCTEQ15), led to evidence for shadowing effects at $x \approx 10^{-5}$ and for
 1952 antishadowing at $x \approx 10^{-1}$. It was also shown that the inclusion of these data has a strong impact on the
 1953 gluon nPDF uncertainties, with a reduction of at least a factor of two with respect to the nominal values.

1954 This first very promising analysis encourages further developments. In particular, the matrix-elements
 1955 that have been used in the study correspond to a purely phenomenological parametrisation, instead of a
 1956 calculation from a Lagrangian. It would be interesting to check to which extent the results of the study are
 1957 confirmed by adopting a more sound theoretical description of the considered processes, once it becomes
 1958 available. This development is not straightforward because of the present limitations of the NRQCD frame-
 1959 work, which has not been able to explain all charmonium observables simultaneously. In addition, it was
 1960 stressed in [32, 661, 662] that the nPDF constraints set by the LHC p Pb heavy-flavour data crucially de-
 1961 pend on the value of the factorisation scale, μ_F , at which the reweighting is performed. This should always
 1962 be kept in mind when these constraints are discussed, especially for the charm(onium) cases, where the
 1963 constraints are stringent, while the ambiguity from the scale choice is significant.

1964 Moreover, since the analysis of [32] is based on a reweighting technique, the compatibility with other
 1965 data (e.g. Drell–Yan data and DIS data) included in the original nPDF fits has only been assessed a posteriori,
 1966 by verifying that the goodness-of-fit (χ^2) is not worsened by the inclusion of the additional heavy-flavour
 1967 data. It would be desirable to go beyond this approach, by including all the data at the same time, i.e. from
 1968 the very beginning, in the nPDF fit. This would allow an homogeneous treatment of all parameters in the
 1969 theory predictions, ensure they are fully consistent with each other, and keep track of correlations between
 1970 different sets of data. In this first reweighting study, the data from D , J/ψ , B and Υ were considered
 1971 separately. In the case of D and J/ψ , it was however noted that the constraints for strong shadowing were
 1972 very similar, which is a first sign of the universality expected if the nPDF factorisation holds [32] (See
 1973 also [663]).

1974 It remains an open question if the antishadowing effect obtained in [32] is a consequence of the data
 1975 included, or simply depends on having imposed the momentum sum rule. In order to explore this further, it is
 1976 important to consider data at various x values, e.g. in different rapidity ranges, including the antishadowing
 1977 peak region, as well as overlaps between different data sets, covering slightly different x ranges.

1978 It was also noted [32] that LHC bottomonium data (as well as B data) are affected by much smaller scale
 1979 uncertainties but that the current very large experimental uncertainties do not yet allow the gluon nPDF to be
 1980 constrained. It is expected that with forthcoming data, in particular those on bottomonium production, the
 1981 nPDF constraints will further improve [2]. The statistical uncertainties for ALICE and LHCb from Run-3
 1982 and -4 data will shrink by about a factor of 5 compared to the 2016 data at $\sqrt{s_{NN}} = 8.16$ TeV, systematic
 1983 uncertainties will also improve due to the better precision with which control channels can be determined.
 1984 ATLAS and CMS will reduce the statistical uncertainties by about a factor of 2 or 3. These numbers do not
 1985 include further improvements that may be achieved due to better resolution, acceptances, or efficiencies.

1986 The high-luminosity phase of the LHC should also allow for precise measurements of the feed-down
 1987 contributions from χ_c and $\psi(2S)$ states to J/ψ , and from χ_b , $\Upsilon(2S)$ and $\Upsilon(3S)$ to Υ , that are fundamental
 1988 aspects for reliable predictions of the absolute cross sections for J/ψ and Υ production and to control the
 1989 impact of final-state effects.

1990 5.2.3. pA collisions at the FT-LHC: high-precision input for global nPDF fits

1991 In addition to collider-mode data, FT data at the LHC, using various nuclear targets (He, Ar, Ne, Xe,
 1992 ...) at relatively low $\sqrt{s_{NN}}$, can provide crucial constraints for global nPDF fits, especially in the large-
 1993 x region. These data can be regarded as complementary to the pA collider measurements because they
 1994 allow for the study of NMFs down to small values of A . Using relatively light targets is very important
 1995 not only to understand nuclear-matter effects for increasing system sizes, but also for high-energy-cosmic-
 1996 ray astrophysical applications [222, 664], bearing in mind that the extrapolation from the region of large
 1997 $A = 208$ (for Pb) to the region of $A \lesssim 20$ is delicate at large x . Along the same lines, a high-luminosity
 1998 collider run with oxygen will be particularly useful [2].

1999 In the LHC FT kinematics, one is sensitive to the EMC effect (see e.g. [633]), which is seen to be linked
 2000 to short-range nucleon correlations [665]. These are strongly nucleus-dependent, and thus one cannot rely
 2001 on a simple A -dependent parameterisation like $\sigma_{pA} = \sigma_{pp} \times A^\alpha$ is indeed not suitable in the EMC region.
 2002 We also stress the fundamental importance of having a H target to derive a precise enough pp baseline
 2003 reference at $\sqrt{s_{NN}} = 115$ GeV in order to extract R_{pA} , which can then be compared to theoretical models.

2004 The high-intensity LHC beams offer unique opportunities for HL pA data taking in the FT mode as

2005 detailed in [6]. In the kinematic regime accessible with ALICE²³ and LHCb²⁴, the x_2 region to be probed
 2006 by charmonium and bottomonium production spans from 0.02 up to 1. Quarkonium production in this energy
 2007 range may be subject to several effects besides those of the nPDFs. One effect is the energy loss (see
 2008 e.g. [666]); another is the dissociation of quarkonium due to secondary interactions within the nucleus that
 2009 could explain the suppression patterns at the SPS and partially at RHIC [28, 667–669]. The separate quan-
 2010 tification of these nuclear modifications will require a systematic study of open-heavy flavour, quarkonium,
 2011 and Drell-Yan production over the kinematically available phase space accessible via measurements with
 2012 large integrated luminosity and varying nuclear targets. Once these ambiguities are lifted based on a careful
 2013 analysis of the various dependencies, quarkonium production offers unique access to parton densities in the
 2014 EMC-effect region of the nuclei, where strong nuclear effects were observed for quark degrees of freedom,
 2015 but where the gluonic modifications remain largely *terra incognita*.

2016 In the collider mode, this region can also be probed with top quark production [670], which is severely
 2017 statistically limited, and more promisingly, with di-jet measurements as already started with CMS
 2018 data [2, 671, 672]. Compared to these collider-mode data, FT quarkonium data probe very different hard
 2019 scales and energies but similar x values. These measurements are thus complementary since, as explained in
 2020 Section 5.2.1, their description in the collinear factorisation is connected via DGLAP evolution. Performing
 2021 both kinds of measurements would thus lead to more stringent constraints on nPDFs and potentially allow
 2022 one to test the factorisation hypothesis.

2023 Several possible experimental setups will allow for high-luminosity pA data-taking in ALICE and
 2024 LHCb [6]. Gaseous targets as pioneered with the upgraded SMOG setup [673], starting operation in 2021,
 2025 will enable the collection of high-luminosity pp data. Fig. 30 illustrates the constraining power of J/ψ and
 2026 Υ production for the nPDFs in the EMC region based on the yearly luminosities achievable with LHCb
 2027 and a gaseous FT setup, assuming that nPDF effects are the dominant mechanism behind nuclear modifi-
 2028 cations or that other nuclear effects are subtracted, which *de facto* means that various probes are measured
 2029 altogether to disentangle these different effects.

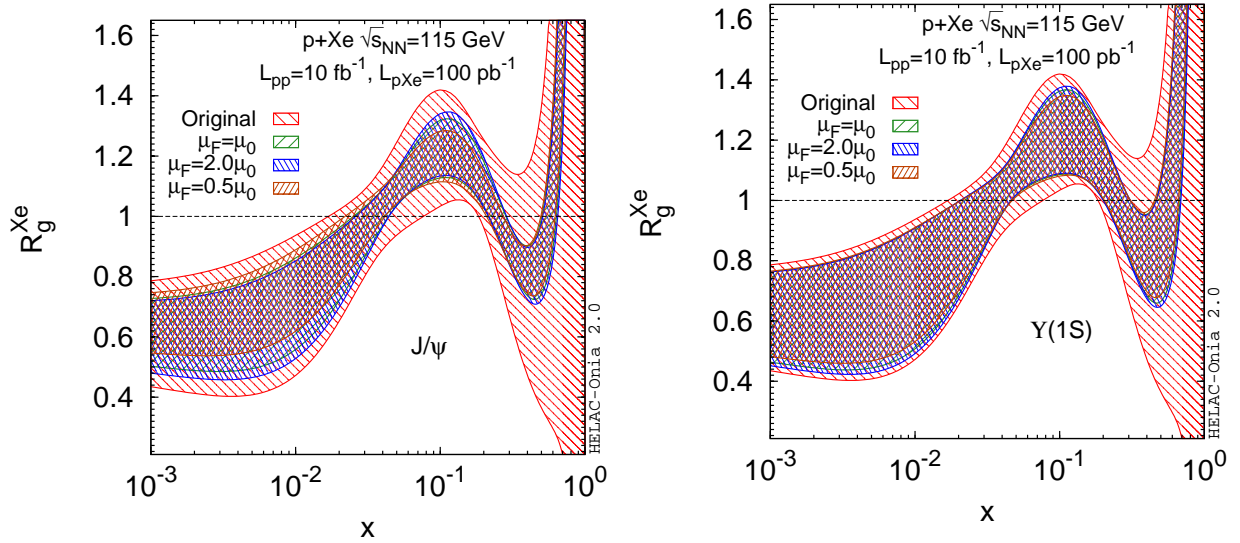


Figure 30: Ratio of the xenon nuclear over the proton PDFs, showing the impact of a nPDF reweighting according to generated pseudodata for prompt J/ψ production (Left) and Υ (Right) for integrated luminosities of 10 fb^{-1} (for pp collisions) and 100 pb^{-1} (for pXe collisions) in a LHCb-like setup. A strong reduction in the nPDF uncertainty is visible in the EMC region $0.3 < x < 0.7$. [Figures taken from [6]].

2030 5.2.4. Developments in theory and phenomenology of QCD at low x and its connection to \mathcal{Q} produc- 2031 tion

2032 Most phenomenological studies in the CGC formalism performed recently have relied on the LO ap-
 2033 proximation, with a subset of NLO corrections related to the running of the α_s coupling. In particular,

²³for which a FT upgrade is under consideration.

²⁴for which a FT programme exists with an ongoing upgrade.

2034 this includes calculations of forward J/ψ production in pA collisions that have been compared to LHC
2035 data [629, 637, 638]. Given that α_s is not very small, especially at the low scales probed in J/ψ production,
2036 theoretical uncertainties on cross sections are large which is one of the reasons why many studies focus on
2037 ratios such as the NMF. The full NLO corrections are expected to be sizeable and must be taken into ac-
2038 count for realistic applications and reliable comparisons with experimental data, not only on ratios but also
2039 on cross sections. Calculations in this formalism rely on factorisation into a process-dependent hard part,
2040 or impact factor, which can be computed perturbatively, and unintegrated gluon distributions, whose x evo-
2041 lution is governed by the Balitsky-Kovchegov (BK) equation, and are assumed to be process-independent
2042 (although not all processes probe the same distributions [468]). Intense efforts are ongoing to extend the
2043 accuracy of the CGC framework to NLO, which requires the NLO expressions of both the BK equation and
2044 process-dependent impact factors.

2045 The NLO BK equation was first presented in [674], and the first numerical solution to this equation
2046 showed that it is unstable because of very large and negative NLO corrections enhanced by collinear loga-
2047 rithms [675]. This instability was not unexpected since it already appeared with the NLO BFKL equation
2048 (the linearised version of the BK equation) and was cured by resumming these logarithms to all orders,
2049 restoring the convergence of the perturbative expansion. Similar resummations were proposed in the non-
2050 linear BK regime [676, 677], apparently leading to a stable evolution [678–680]. However, it was later
2051 found that while the evolution itself is stable, it is affected by a very large resummation scheme dependence
2052 that spoils the predictability of the calculations [681]. This was traced back to the fact that the studies
2053 in [676, 677] considered the evolution as a function of the projectile rapidity and not the target rapidity,
2054 which is the natural variable in this context and simply corresponds to $\ln 1/x_{Bj}$ in the case of DIS. Consid-
2055 ering the evolution as a function of target rapidity, and performing the resummation in this variable leads to
2056 a stable evolution, a small resummation-scheme dependence, and a good agreement with HERA DIS data
2057 at small x [682, 683].

2058 The other important source of higher-order corrections is the process-dependent impact factor. The first
2059 process for which the NLO impact factor, necessary for saturation studies, was derived is single inclusive
2060 light-hadron production [684, 685]. The numerical implementation of these expressions [686] showed that
2061 the NLO cross section turns negative when the produced-particle P_T is on the order of the saturation scale,
2062 which is precisely the regime where the CGC formalism should apply. A new formulation of the factorisa-
2063 tion at NLO [687], which relaxes some approximations made in [686] and which leads to a factorisation that
2064 is non-local in rapidity, was shown to lead to physical results [688]. It was also found that a very similar
2065 problem appears with the recently-derived NLO impact factor for inclusive DIS [689] and that it can be
2066 solved in the same way [690].

2067 Despite recent progress in the two directions (evolution and impact factors), there is at the moment
2068 no phenomenological study taking into account both sources of NLO corrections in pA collisions, which
2069 would be necessary for more reliable comparisons with data. In addition only a few impact factors have been
2070 computed up to NLO, and these only consider massless quarks as additional complications arise due to finite
2071 mass effects. Therefore it is difficult to expect comparisons of NLO calculations with LHC quarkonium data
2072 in the near future. However there are better prospects for relatively simpler processes such as forward light
2073 hadron [684–688, 691] or isolated photon [692, 693] production, which can also probe very small x values
2074 in the target.

2075 The experimental study of a wider variety of processes at the LHC is also important in view of the
2076 current limitations related to the modelling of the initial conditions for a nucleus (see the discussion in
2077 Sec. 5.2.1). Future pA data on isolated photon and Drell–Yan production would provide direct constraints
2078 on the nuclear wave function, and allow one to test whether these various processes can be described with
2079 a single set of parameters. Theoretical calculations for these processes are also under better control, as they
2080 are not affected by the uncertainties related to the hadronisation mechanism of quark-antiquark pairs into
2081 quarkonia.

2082 Future data on light hadrons production would also be valuable. While absolute cross sections for
2083 this process are affected by rather large fragmentation functions uncertainties [694], the NMF is a more
2084 robust observable and the comparison with other processes could help to discriminate between different
2085 nuclear suppression mechanisms. For instance, in the CGC approach, the suppression at forward rapidities
2086 is similar for light hadrons and Drell–Yan production [695, 696]. On the other hand, in the coherent energy
2087 loss model, the first process shows a sizeable suppression [697, 698] while the NMF for Drell–Yan is unity

2088 at forward rapidity since one considers the production of a colourless object [699]. The comparison between
 2089 quarkonium and Drell-Yan suppression was advocated in [699] as a possible way to discriminate between
 2090 initial- and final-state effects (see the discussion in the following section). However light hadrons production
 2091 may be a more reliable example than quarkonium of a process sensitive to coherent energy loss, since it is
 2092 generally better understood.

2093 5.2.5. Discrimination of different nuclear effects with new measurements

2094 In order to resolve the ambiguity between the energy loss and the nuclear modification of the nuclear
 2095 wave function, electromagnetic measurements, like Drell-Yan pair [700] or photon [701] production, in
 2096 particular at forward rapidities, involving hard scales similar to quarkonium production can be crucial. The
 2097 authors of [699] proposed to study the ratio of the NMFs of J/ψ over Drell-Yan production as a function
 2098 of rapidity. They showed that this ratio has a very different behaviour in calculations employing nPDFs,
 2099 where it remains close to or above unity, and in the coherent energy loss model, where it decreases quickly
 2100 (see Fig. 31). However, it should be noted that a full cancellation of the scale uncertainties is assumed
 2101 in these different processes, which may not be justified and needs to be investigated with further studies.
 2102 A calculation of this ratio in the CGC formalism shows that it is relatively flat and close to unity [696].
 2103 Therefore this observable could help to discriminate between models based on the energy loss and on
 2104 nuclear modifications of parton densities, with or without saturation. The NMF of Drell-Yan production
 2105 itself is also of great interest: since this process is not subject to coherent energy loss, this ratio is unity
 2106 in the energy-loss model at forward rapidities, where isospin effects are negligible [699]. On the contrary,
 2107 recent nPDF fits such as nCTEQ15 [618] and EPPS16 [619] show a rather strong shadowing at small x
 2108 values, which would lead to a NMF significantly below unity. This can be seen for example in Fig. 31
 2109 (Left), where the central value for the LHCb projection was obtained using the EPPS16 NLO set. It has to
 2110 be emphasised that here the nPDF parameterisations for the gluon distribution assume the same functional
 2111 shape as for the sea quarks, which is currently difficult to test with the limited data available. Future,
 2112 more accurate data could invalidate this assumption and show the need for new nPDF fits with more flexible
 2113 parameterisations. In view of this, one is entitled to question the discriminative power of such ratios of NMF
 2114 advocated in [699]. Yet, a measurement as precise as possible of the Drell-Yan process in this kinematic
 2115 regime is welcome as an important and clean probe of the nPDFs in a range where gluons dominate the
 2116 partonic content.

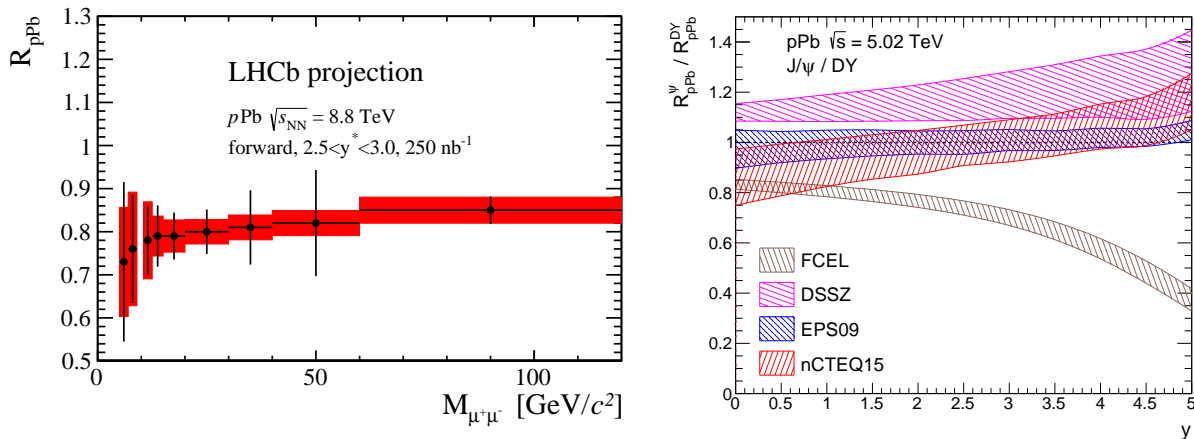


Figure 31: Left: Projection for the measurement of R_{pPb} for Drell-Yan pair production with the anticipated integrated luminosity for Run 3 and Run 4 at LHCb, see [700] for details. [Figure taken from [700]]. Right: Double ratio of the NMFs for Drell-Yan and quarkonium production in $p\text{Pb}$ collisions for various nPDFs (see the text for the assumptions used). [Figure adapted from [699]].

2117 Since these measurements access an uncharted domain of the nuclear wave function at low x , clearly
 2118 beyond the reach of the future EIC, they should be pursued with high priority for the quest of non-linear
 2119 parton evolution, as pointed out in the CERN Yellow Report [2]. Such measurements would also provide
 2120 new data to be included in global fits of nPDFs, which are at present poorly constrained at low x
 2121 and scales due to a lack of existing data in this region. This would help to reduce the corresponding theoretical
 2122 uncertainties and thus lead to a better discrimination with other models.

2123 The studies performed for Drell-Yan measurements illustrate the need for large data samples, as can
 2124 be seen from the relatively large error bars in Fig. 31 (Left), in all bins that containing the Z boson. The
 2125 systematic uncertainties, dominated by the knowledge of the background, in particular at low invariant
 2126 masses, could also be further reduced by improved precision. The CMS collaboration recently made a step
 2127 in this direction, extending the Drell-Yan measurement down to $M_{\mu\mu} \approx 15$ GeV requiring a P_T greater
 2128 than 15 GeV for the muon and 10 GeV for the sub-leading muon in the central rapidity acceptance of
 2129 CMS ($|\eta_\mu| < 2.4$) [702]. The current precision of the measurement cannot discriminate between different
 2130 scenarios in this central rapidity region and at still rather high lepton-pair momenta. In order to make full use
 2131 of the pA measurements at the HL-LHC, it will also be necessary to improve the theory in order to tame the
 2132 impact of the factorisation-scale uncertainty that can become the largest of all the theoretical uncertainties,
 2133 in particular in the regime of charm production [32, 662].

2134 Our discussion of the aforementioned models has, until now, only concerned vector quarkonium states.
 2135 In parallel, specific efforts are needed both on the theory and experimental sides to compare these models to
 2136 measurements of e.g. χ_c and η_c . This would allow one to further test the underlying theoretical assumptions.
 2137 LHCb pioneered the measurement of the hidden-over-open-charm ratio [703], but with uncertainties that
 2138 were too large to see differences with the value obtained in pp collisions. More precise measurements
 2139 are therefore required and could provide information on the magnitude of effects that act differently on
 2140 quarkonium and open-charm production²⁵. These measurements are also of prime interest in the context of
 2141 heavy-ion-like suppression patterns observed for the excited states as well as considerations related to their
 2142 azimuthal anisotropies.

2143 In addition, a comprehensive set of precise quarkonium measurements in pA collisions including polar-
 2144 isation data may provide better constraints than when considering only pp data in data-theory comparisons
 2145 and allow for additional consistency checks. For example, in the CGC+NRQCD approach, each intermedi-
 2146 ate state is suppressed in a different way [638]. Including R_{pA} data in global fits could be a way to try to set
 2147 more stringent constraints on the LDMEs and to further test NRQCD, although this, of course, would be at
 2148 the expense of the predictivity of the CGC+NRQCD approach in pA collisions of course.

2149 5.3. Flow-like phenomena in Q production

2150 5.3.1. Theoretical prospects

2151 Traditionally, pA collisions were considered to produce final states without any QGP, and were therefore
 2152 used as a tool to study cold-nuclear-matter effects as well as a baseline reference for QGP effects in AA col-
 2153 lisions. However, the discovery of collective phenomena in high-multiplicity pp [704] and pPb [705–707]
 2154 collisions at the LHC has led to a change of paradigm. The presence of long-range azimuthal correla-
 2155 tions observed for particles produced in such events, quantified by the second harmonic coefficient v_2 with
 2156 respect to the reaction plane, were found to be similar to those found in AA collisions, where they are con-
 2157 ventionally interpreted as a signature of an anisotropic hydrodynamic flow built up in the QGP. Various
 2158 mechanisms have been proposed to explain the experimental observations. These include the formation of
 2159 a hydrodynamically expanding mini-QGP and a initial-state gluon saturation within the CGC formalism.

2160 In this context, the case of quarkonia is of particular interest. Precise measurements in PbPb collisions
 2161 at the LHC showed a significant J/ψ flow [708–712]. Even though the experimental data are not entirely
 2162 consistent with the predictions of a parton-transport model [713], the observed flow is believed to originate
 2163 from the recombination of thermalised charm quarks within the QGP volume or at the phase boundary at
 2164 low P_T , and from the path-length-dependent colour screening and energy loss at high P_T . Within the QGP
 2165 scenario, the J/ψ flow is expected to be practically negligible in pPb collisions. At low P_T , the incomplete
 2166 thermalisation of the charm quarks during the short-lived QGP phase and the small number of initially pro-
 2167 duced $c\bar{c}$ pairs would result in negligible recombination effects. The small system size is not expected to
 2168 produce significant path-length dependent effects either. The ALICE and CMS collaborations performed
 2169 measurements of the inclusive and prompt J/ψ flow in pPb collisions [714, 715]. The J/ψ mesons are
 2170 reconstructed via their di-muon decay channel. The flow measurements are performed using associated
 2171 mid-rapidity charged-particle yields per J/ψ trigger. The contribution from recoil jets are suppressed by a

²⁵However, the interpretation of such ratios should always be made while considering the possible non-cancellation of theoret-
 ical uncertainties such as those from the unphysical renormalisation and factorisation scales.

2172 subtraction of the yields in low-multiplicity collisions from those in high-multiplicity collisions. The sec-
 2173 ond harmonic coefficient of the azimuthal distribution of the produced J/ψ is then extracted assuming a
 2174 factorisation of the flow coefficients of the J/ψ and of the associated charged particles. The ALICE and
 2175 CMS data clearly indicate significant J/ψ v_2 values approaching the values measured in central PbPb col-
 2176 lisions, while the transport model predict smaller values (Fig. 32, Left). Alternative calculations developed
 2177 withing the CGC approach (see Section 5.3.3) result in J/ψ v_2 values consistent with the experimental data.
 2178 Nevertheless, it is worth noting that in this scenario the heavy-quark momentum space anisotropy is not
 2179 correlated with the spatial anisotropy of the initial state of the collisions, while the measurements of J/ψ v_2
 2180 are done with respect to the charged-particle bulk, and the various LHC and RHIC measurements in small
 2181 and large collisions indicate that the flow coefficients of the bulk are driven by the initial-state collision
 2182 geometry [716].

2183 5.3.2. Experimental prospects

2184 The future LHC data from Runs 3 and 4 will allow one a significant improvement in the precision of the
 2185 J/ψ flow measurement in p Pb collisions. Fig. 32 (Right) shows the projection of the expected precision of
 2186 the ALICE measurement using an integrated luminosity of 500 nb^{-1} . The Muon Forward Tracker (MFT)
 2187 detector [717, 718], which is part of the 2020–21 ALICE upgrade, will allow the separation of the prompt
 2188 J/ψ contribution from the feed-down of B -hadron decays. A comparable precision is likely to be reachable
 2189 also in the dielectron channel at mid-rapidity, because of the upgraded central-barrel readout system that
 2190 will allow one to record basically the same integrated luminosity as the MFT system. The CMS experiment
 2191 will also be able to improve significantly the precision of the measurement due to a more than six-fold
 2192 increase of the integrated luminosity compared to that in Run 2. The wide combined rapidity coverage
 2193 of these measurements will shed light on the origin of the significant J/ψ v_2 . At the same time, more
 2194 differential theory predictions are needed.

2195 The parton-transport model predicts higher $\psi(2S)$ v_2 values compared to those of J/ψ (Fig. 32, Left),
 2196 while within the CGC-based model, $\psi(2S)$ and J/ψ v_2 values are expected to be practically the same. Taking
 2197 into account the charmonium-signal significance, the expected statistical uncertainty of $\psi(2S)$ v_2 is at least
 2198 one order of magnitude larger than for J/ψ , and thus significantly larger than the $\psi(2S)$ v_2 enhancement
 2199 predicted by the transport model. Nevertheless, given the sizeable suppression of $\psi(2S)$ with respect to
 2200 J/ψ in the Pb-going direction, the measurement of $\psi(2S)$ v_2 at forward and backward rapidities is quite
 2201 interesting in itself.

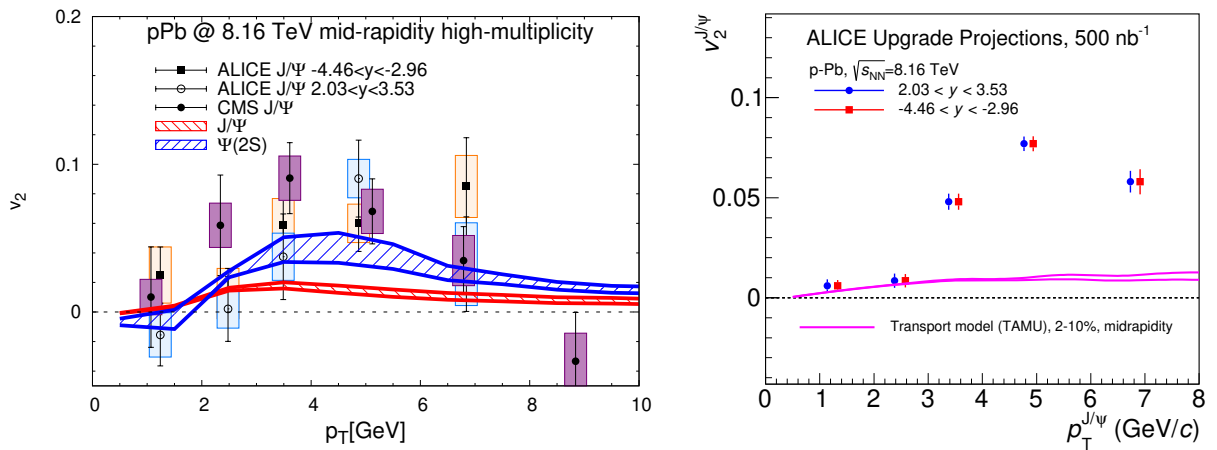


Figure 32: Left: Comparison between parton-transport-model calculations of the J/ψ and $\psi(2S)$ azimuthal flow versus P_T (curves) and published ALICE [714] and CMS [715] data on J/ψ flow (data points) [Figure taken from [713]]. Right: Projection of the expected precision of J/ψ v_2 to be measured by ALICE in p Pb collisions with an integrated luminosity of 500 nb^{-1}) [2]. [Figure taken from [719]].

2202 The measurement of Υ flow will be of particular interest, but a realistic extrapolation of the expected
 2203 precision with the upcoming luminosities awaits the first measurements by CMS or ATLAS which are better
 2204 positioned than ALICE for these measurements thanks to larger acceptances and partially better resolutions.

2205 5.3.3. Azimuthal anisotropies from initial-state effects

2206 As can be seen from Fig. 32, current calculations based on parton-transport models seem to not be able
 2207 to generate enough flow to match the data on J/ψ v_2 at the LHC due to the large particle mass and the
 2208 short-lived system. On the other hand, a recent calculation based on the CGC framework has shown that
 2209 momentum space anisotropies for heavy mesons can directly be generated by the p Pb collision process
 2210 itself, without the need for a QGP-droplet phase [720, 721], leading to a good agreement with LHC data
 2211 (Fig. 33). This requires that the gluon density in the nucleus be large enough for non-linear QCD dynamics
 2212 to be relevant, which is the case in high-multiplicity collisions at the LHC. By contrast with the heavy-ion-
 2213 like flow paradigm, these anisotropies are not connected to the initial spatial anisotropies of the system.

2214 In this model, one considers that both a quark (which serves as a reference to evaluate the v_2) and a
 2215 gluon (which then splits into a $Q\bar{Q}$ pair) from the projectile proton participate in the interaction with the
 2216 nucleus. The quark and gluon are assumed to be initially independent, but they can become correlated due
 2217 to colour interference arising when they interact with the dense gluonic-background fields in the nucleus.
 2218 In this initial-state-effect-only picture, the mass dependence of these intrinsic QCD anisotropies is not the
 2219 same for quarkonia and open production, due to completely different production mechanisms. In the first
 2220 case, the Q and \bar{Q} must be produced close to each other in order to form a quarkonium state, and therefore
 2221 the correlation of the $Q\bar{Q}$ pair with the reference quark is driven by the kinematics of the gluon before
 2222 the $g \rightarrow Q\bar{Q}$ splitting. On the other hand, in the case of open production, one of the heavy quarks is
 2223 integrated over and the distance between the Q and \bar{Q} can be arbitrarily large, which allows for some
 2224 mass dependence. Along the same lines, it was predicted that the azimuthal anisotropies for open bottom
 2225 would be much smaller than for open charm, which was confirmed by experimental data [722], but that the
 2226 azimuthal anisotropies for Υ would be essentially identical to those for J/ψ because both are directly driven
 2227 by the gluon kinematics. A future measurement of the Υ v_2 at the LHC to either confirm or invalidate this
 2228 prediction would therefore provide an important test for this model and could give more insight into the
 2229 origin of azimuthal anisotropies in quarkonia produced in pA collisions.

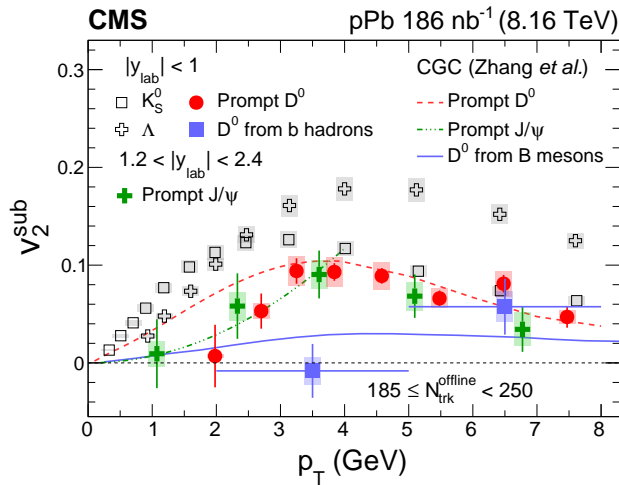


Figure 33: Comparison of the CGC calculation of J/ψ and open-heavy-flavour v_2 coefficients versus P_T [720] with CMS data [722]. [Figure taken from [722]].

2230 5.4. Q -hadronisation studies

2231 5.4.1. Theoretical status

2232 When studying effects on quarkonium production, an extended analysis must include both initial- and final-
 2233 state effects. However, it is probably more phenomenologically appropriate to distinguish between effects
 2234 that impact the whole charmonium (or bottomonium) family with the same magnitude from those which are
 2235 expected to impact differently the ground and the excited states. Among those effects equally affecting all
 2236 the states of a given family, one naturally finds the initial-state effects, since they act on a pre-quarkonium
 2237 state, which is not yet fixed when the effects are at work. On the contrary, final-state effects can affect each
 2238 quarkonium state differently.

Former measurements of the production rates of excited and ground charmonia in pA collisions at lower energies by the E866/NuSea [642] and NA50 [723] collaborations revealed a stronger suppression of the excited state near $x_F \approx 0$. At such low energies, this dissimilarity has been straightforwardly interpreted as the effect of a stronger breakup of the $\psi(2S)$ meson in interactions with the primordial nucleons contained in the colliding nucleus, the so-called nuclear absorption.

However, at higher energies, the quarkonium formation time is expected to be larger than the nucleus radius. This is due to the large boost between the nucleus (and its nucleons) and the pair. At rest, a $c\bar{c}$ or $b\bar{b}$ pair takes 0.3–0.4 fm to hadronise, but this time has to be considered in the rest frame of the nucleus. The formation time is thus dilated by a large Lorentz-boost factor, which at LHC energies²⁶ results in times orders-of-magnitude-longer than the Pb nucleus radius. In other words, the spectator nucleons of the nucleus cannot discriminate ground and excited quarkonium states, since they cross each others too early.

An alternative explanation has been proposed to be at play in pA collisions, based on the interaction of the nascent quarkonia with some particles that are produced in the collision and which happen to travel along with the heavy-quark pair. This implies that such *comovers*, those particles with a similar rapidity as the quarkonium state, can continue to interact well outside of the nuclear volume up to the moment where the quarkonium is fully formed. Since the excited states are larger, the comover dissociation affects them more strongly than the ground states, which explains the observed difference between them even at high energies. This effect is naturally more important when the densities of particles are larger. As such, it increases with the centrality and, for asymmetric collisions such as pA , it will be stronger in the nucleus-going direction. Along the same lines, the same effect should be at work for any colliding system. In particular, the excited states should also dissociate more in high-multiplicity pp collisions (see Section 2.4.3).

In the CIM [646], initial-state and final-state effects are treated separately, respectively via nPDFs and the aforementioned interaction with comoving particles. The behaviour of the excited-over-ground-state ratio is then naturally driven by the comover suppression since the nPDF effects cancel in the ratio. The rate equation that governs the density of quarkonia is just a Boltzmann equation that depends on the density of particles and their break-up cross section. It has been proposed in [130] that the break-up can be evaluated using an empirical formula that accounts for the geometrical size and the binding energy of the different states. It can be applied to all the states and yields a natural explanation for the experimental data on excited-over-ground states (Fig. 34).

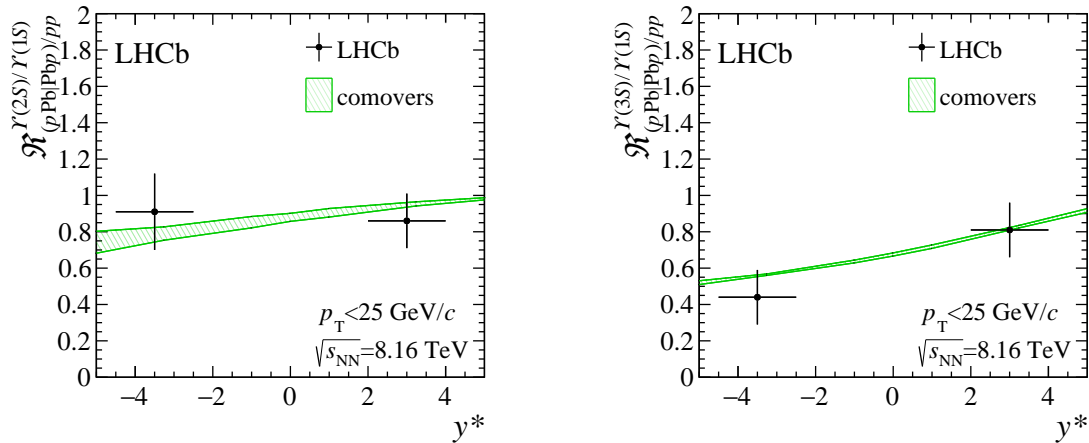


Figure 34: Double ratios for $Y(2S)$ (Left) and $Y(3S)$ (Right) as a function of laboratory rapidity in pPb collisions at $\sqrt{s} = 8.16$ TeV. The bands correspond to the theoretical prediction for the CIM [130] compared to LHCb data [724]. [Figures taken from [724]].

In [647], the breaking of factorisation was examined for J/ψ and $\psi(2S)$ production at forward rapidities in the CGC framework by modelling the threshold-sensitive suppression due to the comover interactions. The factorisation effectively holds for J/ψ production in minimum bias pA collisions, but it may break in high-multiplicity events, even though the J/ψ is a strongly-bound system. The multiple rescattering effects in the CGC framework can describe high-multiplicity events due to the sizeable semi-hard saturation scale [101, 725], although the underlying physics behind such phenomena is still not very clear

²⁶except for extremely large Pb-going rapidities.

(Section 2.3.2). In high-multiplicity pA collisions, the nuclear-enhanced-comover-rescattering effect could lead to the modification of the J/ψ production rate due to a threshold-sensitive suppression [660]. For larger quarkonium states, like $\psi(2S)$ and χ_c , both the semi-hard and soft comover rescatterings before the bound-state formation should be essentially of the same size in high-multiplicity pp collisions. Further investigations are thus welcome to examine the duality between the CIM and these qualitative expectations from the CGC framework.

With the increased luminosity available in the upcoming HL-LHC, the measurement of production rates for multiple quarkonium states, with different physical sizes and binding energies, offers an excellent tool for probing the time scale of the evolution of heavy quark-antiquark pairs into bound colourless quarkonium states. The study of the yields of excited-over-ground quarkonia as a function of the charged-particle multiplicity, both in pp and pA collisions, will help to clarify the hadronisation mechanism at play. In particular, the measurement of different quarkonium states with good precision should lead to better model constraints that test its applicability. Estimates of the precision with which the yields can be determined in the different experiments are given in the following section.

In addition, much progress in heavy-meson spectroscopy has taken place in the last years at the LHC. Recently, the LHCb collaboration presented results on the relative production rates of promptly produced $X(3872)$ over $\psi(2S)$ as a function of particle multiplicity, given by the total number of charged particle tracks reconstructed in the VELO detector for the forward pseudorapidity region, $2 < \eta < 5$ in pp collisions at 8 TeV [129]. This ratio is found to decrease with increasing multiplicity. Hadronisation mechanisms, as described above, can provide insights on the nature of these exotic states [131].

5.4.2. Experimental prospects

The NMFs of excited vector-meson states in pA collisions show significantly stronger suppression than for the ground states, as measured by the ALICE [630, 726–733], ATLAS [734], CMS [735, 736], and LHCb [724, 737–739] collaborations at the LHC. In order to solidify the experimental findings, it will be crucial to analyse larger statistical samples.

The ratio between two different quarkonia is a useful quantity to directly compare the relative suppression of both states between various experiments as a function of different kinematic variables since many systematic uncertainties, both in experiments and theory predictions, cancel in the ratio. We focus here on the expectations for $\psi(2S)/J/\psi$ and $\Upsilon(nS)/\Upsilon(1S)$ ratios in pPb collisions in ALICE. These kinds of ratios have already been measured at the LHC [724, 726, 740], but the statistical uncertainties are 20% or larger. All projections use a total integrated luminosity of 500 nb^{-1} of pPb collisions, split in two sub-samples of equal size for the two possible beam orientations.

The left panel of Fig. 35 shows the projection for the $\psi(2S)/J/\psi$ ratio as a function of $y_{\text{c.m.s.}}$ with the pPb data expected to be collected at $\sqrt{s} = 8.8 \text{ TeV}$ at the HL-LHC, compared to the current Run-2 results at $\sqrt{s} = 8.16 \text{ TeV}$. This $\psi(2S)/J/\psi$ ratio is currently found to have a significance (in units of standard deviations) of 2.9σ and 0.9σ below the same ratio measured in pp collisions at $\sqrt{s} = 8.16 \text{ TeV}$ at backward and forward rapidity, respectively. The statistical uncertainty is reduced by a factor of ~ 5 using the same luminosity increase assumed for other ALICE projections shown in [2]. Similar expectations for the $\Upsilon(2S)/\Upsilon(1S)$ and $\Upsilon(3S)/\Upsilon(1S)$ ratios as a function of $y_{\text{c.m.s.}}$ are shown in Fig. 35 (Right). The $\Upsilon(2S)/\Upsilon(1S)$ ratio is found, at backward and forward rapidity, to be respectively 1σ and 0.8σ below the same ratio measured in pp collisions at $\sqrt{s} = 8 \text{ TeV}$ [741]. Correspondingly, the $\Upsilon(3S)/\Upsilon(1S)$ ratio is respectively 0.4σ and 1.6σ below the pp ratio. The statistical uncertainty is reduced by a factor of ~ 5 .

The systematic uncertainties on the signal extraction, which are most relevant for the ratio measurements, are also expected to decrease significantly with the improved knowledge of the background distributions, but precise numbers are difficult to estimate at the moment. The reduction of uncertainties will allow one to clearly establish the suppression of the excited states and to perform precise model comparisons to advance our understanding of the physical origin of the observed nuclear modifications. Similar improvements of statistical precision can be expected for LHCb thanks to a similar luminosity ratio between the already available data and the planned luminosity for the 2030s in pPb collisions. For ATLAS and CMS, a reduction of the statistical uncertainties by about a factor 2 can also be expected according to [2]. The estimates provided here are purely statistical: further improvements can be expected from better instrumentation in terms of acceptances, efficiencies, and resolution thanks to the foreseen upgrades that will be fully

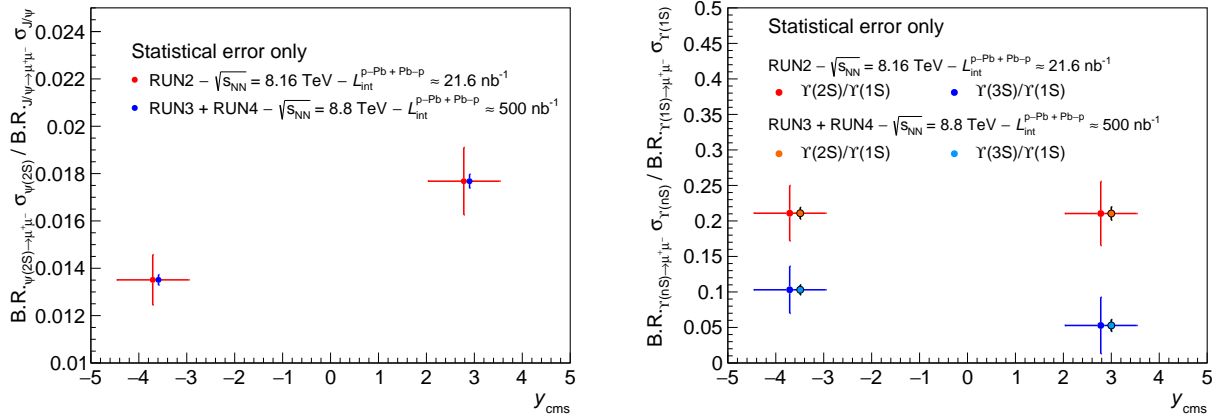


Figure 35: Projections for the $\psi(2S)/J/\psi$ (Left) and $\Upsilon(nS)/\Upsilon(1S)$ (Right) ratios as a function of the c.m.s. rapidity $y_{c.m.s.}$ in pPb collisions at $\sqrt{s} = 8.8$ TeV compared to the current Run-2 results at $\sqrt{s} = 8.16$ TeV. [Figures taken from [742]].

2326 beneficial for detector-occupancy conditions in pA collisions, which are well below those of the pp data
 2327 with orders-of-magnitude-larger pileup.

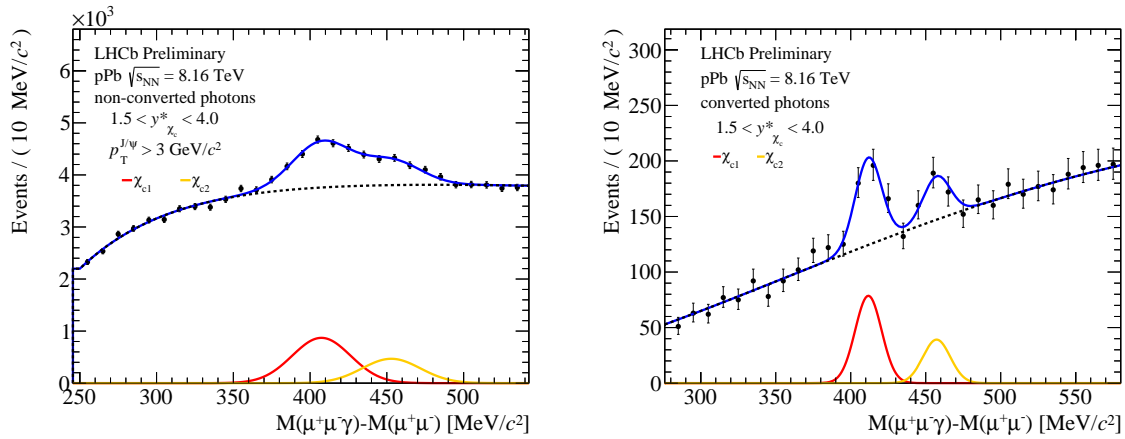


Figure 36: Mass difference $\Delta M = M(\mu^+\mu^-\gamma) - M(\mu^+\mu^-)$ measured at forward rapidity by LHCb in the 2016 pPb data (integrated luminosity $13.6 \pm 0.3 \mu b^{-1}$) [743]. Left: Reconstruction via calorimetric photons for $P_T^{J/\psi} > 3$ GeV. Right: Reconstruction via converted photons, integrated over P_T . The distributions are integrated over $1.5 < y^* < 4$ where y^* is the laboratory rapidity. These plots demonstrate the feasibility of first measurements at the LHC in pA collisions. [Figures taken from [743]].

2328 In addition to the vector states, the P -wave states of charmonium, χ_c , could provide complementary in-
 2329 formation to that shown in [744] based on the models outlined in [745, 746], in particular due to their strong
 2330 suppression predicted in AA collisions. In pp collisions, LHCb carried out measurements of χ_{c1}/χ_{c2} pro-
 2331 duction ratios [146] and of the χ_c to J/ψ cross section ratio [580] based on an integrated luminosity of
 2332 36 pb^{-1} at 7 TeV. Similar measurements were performed by CMS [147] and ATLAS [118] at $\sqrt{s} = 7$ TeV
 2333 with an integrated luminosity of $\sim 4.5 \text{ pb}^{-1}$. The LHCb measurements appear complementary for the study
 2334 of nuclear modifications in pPb collisions, given the lower P_T region explored compared to the CMS
 2335 ($7 < P_T < 25$ GeV) and ATLAS ($10 < P_T < 30$ GeV) ones. All these measurements are based on the
 2336 decay channel $\chi_c \rightarrow J/\psi\gamma$ reconstructing the J/ψ in the di-muon channel and the photon in the calorimeter.
 2337 Measurements of cross-section ratios of χ_c production have been performed based on the reconstruction
 2338 of the converted photon in the tracker [580]. The planned increased pPb integrated luminosity at the HL
 2339 LHC should allow measurements in these decay channels with similar precision as in pp collisions. The
 2340 data already recorded demonstrate the reconstructibility of the decay channels of interest [743] as shown
 2341 in Fig. 36. Recently, LHCb [329] and the BESIII [747] collaboration observed the decay of $\chi_c \rightarrow J/\psi\mu\mu$.
 2342 With the upcoming very high-luminosity data takings beyond Run 3, this decay channel could be used as
 2343 well for cross section measurements despite its very small branching fraction of 10^{-4} for χ_{c1}
 2344 and χ_{c2} [747].

2345 6. Nucleus-nucleus collisions²⁷

2346 6.1. Introduction and context

2347 A hot and dense state of matter, the quark gluon plasma (QGP), is created in PbPb collisions at the LHC.
 2348 The quarkonia provide natural probes to study its properties, since the heavy quarks are created early in
 2349 the collision and, as bound states, they are sensitive to a large variety of initial- to final-state effects. The
 2350 in-medium modifications to the fundamental force between two static colour charges can be investigated
 2351 via changes in the quarkonium spectroscopy. The heavier, looser bound states should typically be the most
 2352 suppressed in heavy-ion collisions. In the cooling of the fireball, the quarkonia can also be “(re)generated”
 2353 through the recombination of individual heavy quarks and antiquarks in the medium. Such an effect is more
 2354 pronounced for charmonia than bottomonia due to the larger number of $c\bar{c}$ pairs present in the QGP.

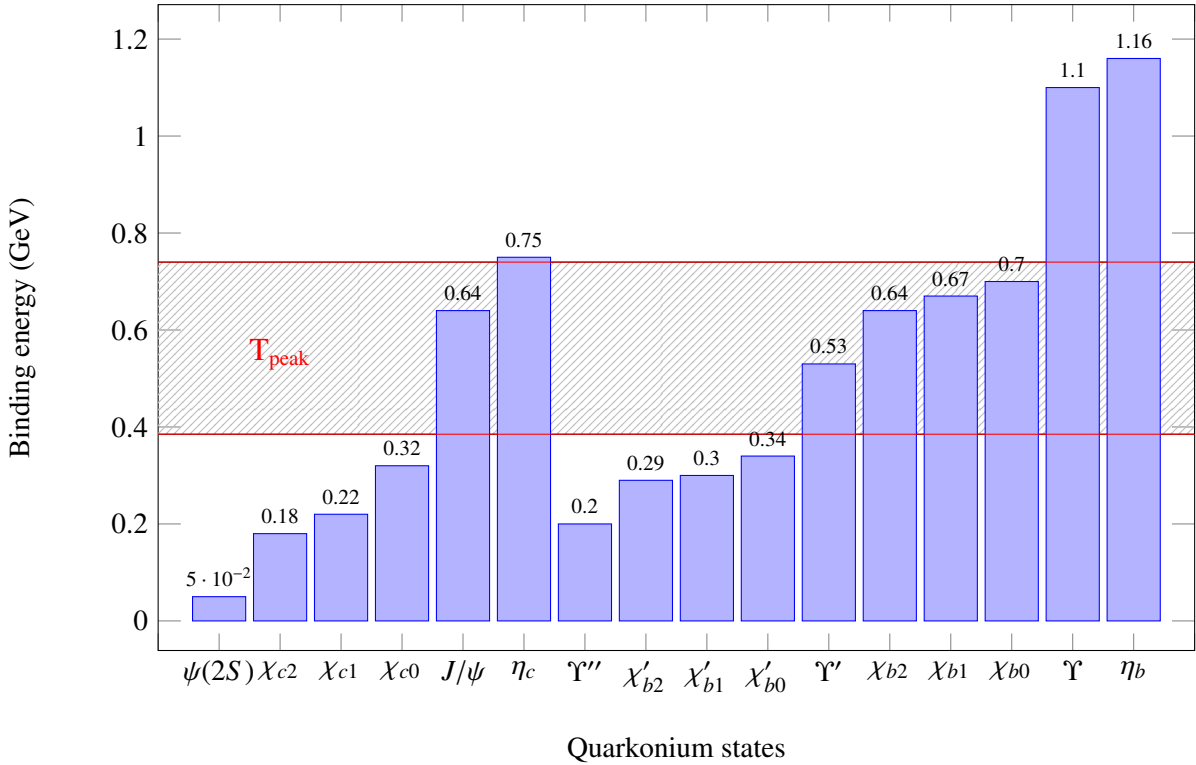


Figure 37: Binding energies of several quarkonium states in the vacuum [668] along with an estimation for the QGP peak temperature, T_{peak} , in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [748] (shaded area).

2355 The quarkonium production in heavy-ion collisions has long been proposed to be directly related to
 2356 the temperature of the produced QGP [749]. Fig. 37 illustrates the power of quarkonium spectroscopy in
 2357 measuring the medium temperature, compared to conventional methods using the slope of photon yields at
 2358 intermediate $P_T \approx 1\text{--}4$ GeV [750, 751]. The peak temperature from the thermal-photon spectrum strongly
 2359 relies on the unknown QGP formation time assumed in the model estimations. The reported direct-photon
 2360 spectra may also include a large contribution from meson bremsstrahlung [752]. Some caveats should be
 2361 kept in mind when using quarkonia as a QGP thermometer:

- 2362 (i) for a given family, the measurement of the relative quarkonium yields is supposed to be insensitive to
 2363 initial-state effects, but a validation is desirable via the measurements of the quarkonium modification
 2364 versus rapidity, in order to scan over the fractional momentum x , in a controlled particle-multiplicity
 2365 and collision-energy environment;
- 2366 (ii) it is still a question which temperature the quarkonium states probes: the peak temperature, the initial
 2367 temperature or some average temperature;
- 2368 (iii) it is also under debates how important the quarkonium breaking during the hadronic phase is;

²⁷Section editors: Émilien Chapon, Pol-Bernard Gossiaux.

2369 (iv) for the charmonia, the recombination competes with the suppression in heavy-ion collisions and these
 2370 effects should be disentangled.

2371 It is also useful to take the opposite approach: fix the temperature to a value favoured by other measure-
 2372 ments, and test the quarkonium dynamics and interactions given this assumed thermodynamic properties of
 2373 the bulk.

2374 The main features of the nuclear modification factor (R_{AA}), the ratio of production in AA to pp account-
 2375 ing for the amount of nuclear overlap, for J/ψ mesons at the LHC are already well measured after ten years
 2376 of operation. A smaller suppression relative to the lower RHIC collision energies has been found [753]
 2377 especially at low P_T (below approximately 5 GeV) [754, 755] and has been attributed to regeneration. A
 2378 greater suppression is observed at higher P_T [756, 757], which is consistent with stronger dissociation ef-
 2379 fects from the bigger, longer-lived QGP at the LHC. The behaviour of R_{AA} at high P_T at the LHC (up to
 2380 50 GeV or beyond), on the other hand, is still uncertain. There are hints of an increasing trend in R_{AA} from
 2381 ATLAS [756] and CMS [757] with the Run-2 data. Data from the HL-LHC will allow one to improve
 2382 the precision and push to even higher P_T [758], which will confirm (or disprove) this trend which could
 2383 be related to parton energy loss [759] or to jet quenching [760]. Further studies are needed, however, as
 2384 the energy-loss phenomenology yields tensions with the hierarchy of nuclear modifications of ground and
 2385 excited states [761]. A projection of the high P_T reach from CMS is shown in Fig. 38.

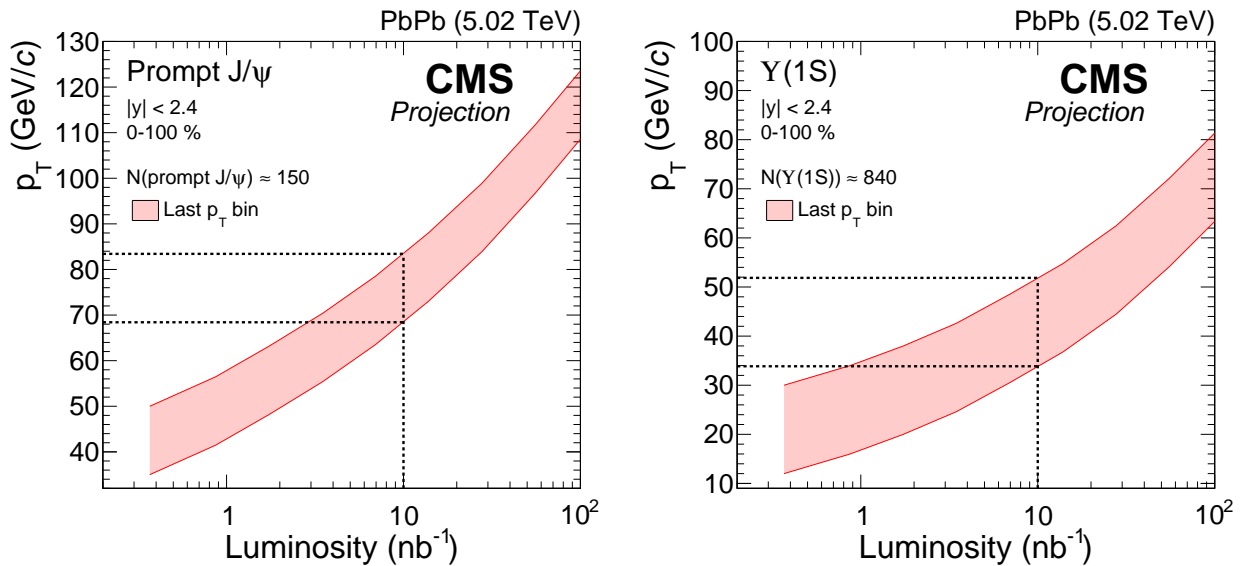


Figure 38: Prompt J/ψ (Left) and Υ (Right) [P_T^{low}, P_T^{up}] boundaries for the highest P_T bin as a function of the luminosity in the CMS experiment [758]. The boundaries are chosen in such a way that the number of quarkonia in the bin for the corresponding luminosity equals the number of mesons found in the last P_T bin of the analysis with a luminosity of $368 \mu\text{b}^{-1}$, as used for existing measurements [757, 762], keeping the width of this last P_T bin fixed. The projection for the expected luminosity of 10 nb^{-1} , roughly matching the expectation for the HL-LHC (see Table 3), is highlighted with dashed lines. [Figure from [758]]

2386 In particular, information about excited-quarkonium production in heavy-ion collisions is very limited
 2387 at the moment [332, 756, 762–764], and further data on the excited states will be crucial. Given the large
 2388 feed-down contributions, corresponding to about half of the Υ yield at large P_T for instance [7, 33, 765],
 2389 the yield of excited states is difficult to determine and this directly reflects on the precision of the model
 2390 predictions for J/ψ or Υ . In addition, the charmonium ground state, η_c , remains unmeasured.

2391 Anisotropic pressure gradients in the QGP, which are a consequence of the non-spherical (elliptic, to
 2392 first order) shape of the overlap region between the colliding nuclei, induce anisotropies in the azimuthal
 2393 distribution of the final particle momenta, including the so-called elliptic flow. This flow is characterised by
 2394 the second order v_2 of the Fourier expansion of this distribution. The v_2 of J/ψ mesons has been measured
 2395 to be non-zero [711, 712], which is qualitatively well reproduced by the transport models at low P_T where
 2396 the J/ψ v_2 relates to the thermalisation of the charm quarks and their interaction with the hydrodynamic
 2397 expansion of the medium. However, at higher P_T , the agreement is not good. As shown in Fig. 39, a precise
 2398 measurement of J/ψ v_2 up to higher P_T , complementary to $R_{AA}(P_T)$, will be instrumental in understanding
 2399 the charmonium-production mechanisms in heavy-ion collisions. It will allow their behaviour at high P_T
 2400 to be related to the energy loss via a path-length dependence effect, by distinguishing between the long and

2401 short axes of the ellipsoid-like medium. Higher orders of the anisotropic flow of quarkonia are becoming
 2402 accessible, such as v_3 [712], and more precise measurements of these will provide further information about
 2403 quarkonium production and transport at low P_T .

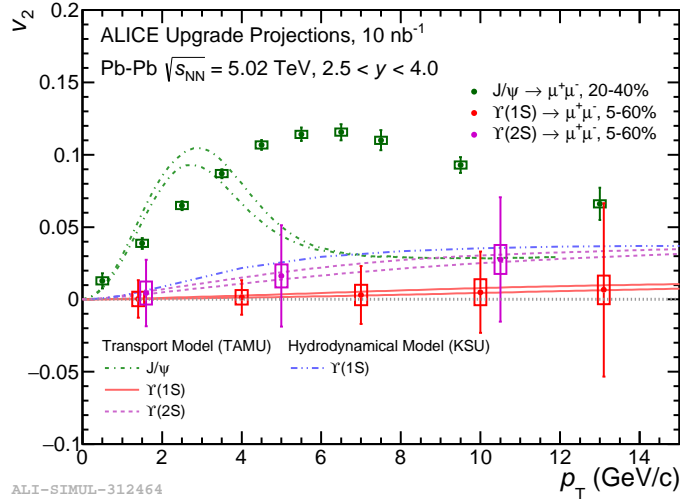


Figure 39: Projections for the v_2 coefficient as a function of P_T for the J/ψ , Υ and $\Upsilon(2S)$ mesons in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in the ALICE experiment, assuming the predictions from the transport model of [766] and compared to an alternative model [767]. [Figure from [2]]

2404 Measurements of other charmonium states than J/ψ are currently limited to the $\psi(2S)$ meson, though
 2405 these have poor precision. The production of $\psi(2S)$ mesons is found to be much more suppressed than J/ψ ,
 2406 even at relatively high P_T (up to 30 GeV) [756, 763]. Data from the HL-LHC will help to better understand
 2407 $\psi(2S)$ production in PbPb collisions, though a v_2 measurement may remain challenging. In particular,
 2408 a precise measurement of the $\psi(2S)/J/\psi$ ratio (Fig. 40) will test the validity of the statistical hadronisation
 2409 model [768] compared to dynamical models [769]. The measurement of the P -wave states, such as χ_c ,
 2410 would help complete the picture, but it is experimentally challenging due to the difficulty of reconstructing
 2411 very-low- P_T photons in a heavy-ion environment. A possible option would be to look at $\chi_c \rightarrow J/\psi\mu\mu$
 2412 decays. Similarly, the η_c states only have large branching fractions to hadrons, usually with a rather large
 2413 number of final-state particles, and thus will be very challenging to measure in heavy-ion collisions.

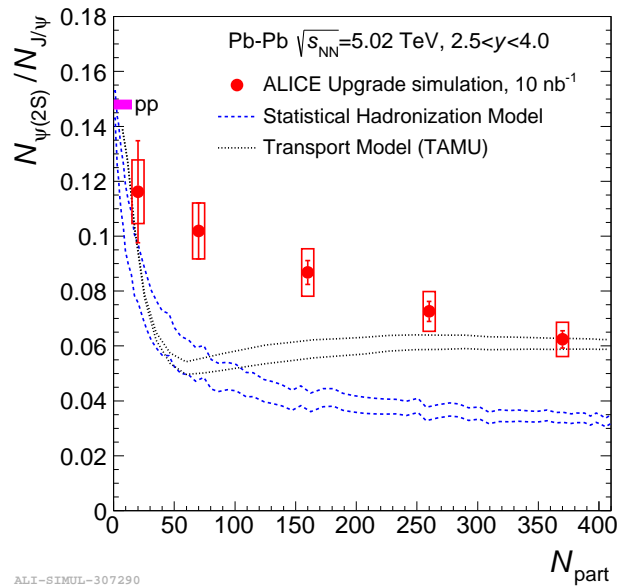


Figure 40: Ratio of the $\psi(2S)/J/\psi$ production yields vs. N_{part} in PbPb collisions measured by ALICE over $2.5 < y < 4$ [717, 744]. Model predictions in the transport approach [769] and from the statistical hadronisation [768] are included. The values of the ratio used for the projections are quasi-arbitrary. [Figure from [2]]

2414 Due to the much smaller number of $b\bar{b}$ compared to $c\bar{c}$ pairs produced in PbPb collisions, regeneration

2415 is thought to play a much smaller role in the dynamical models for bottomonia than for charmonia, though
 2416 it may still be significant for the strongly suppressed excited states [766, 770]. Indeed, R_{AA} for the Υ states
 2417 does not feature a significant P_T or rapidity dependence [762]. In addition, there is a strong centrality
 2418 dependence (with smaller R_{AA} in central collisions), as well as a sequential ordering in the suppression of
 2419 the different states, with the $\Upsilon(3S)$ being so suppressed that it has not yet been measured significantly in
 2420 heavy-ion collisions. Data from the HL-LHC will provide higher precision measurements (Fig. 41), up to
 2421 high P_T , enabling better model discrimination: smaller uncertainties may reveal structures in R_{AA} , which
 2422 appears flat as a function of P_T with current experimental precision. The v_2 of Υ mesons in PbPb collisions
 2423 has recently been measured for the first time [771, 772], though with limited precision. Such studies will be
 2424 continued at the HL-LHC. Finally, similar comments to their charmonium counterparts above, can be made
 2425 for χ_b (and η_b) mesons.

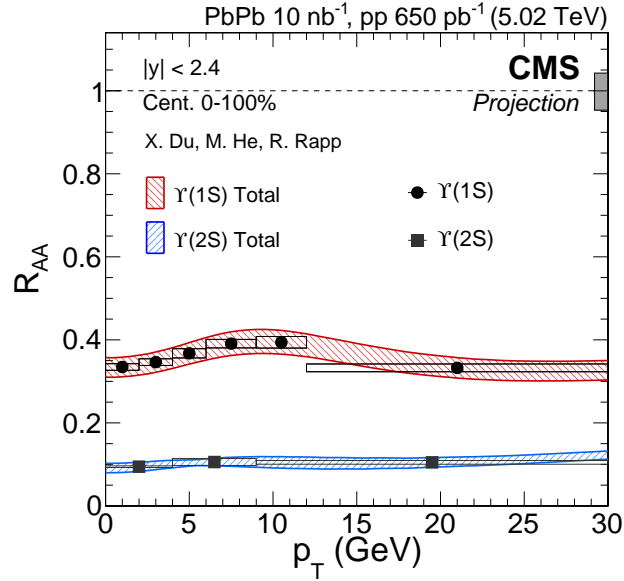


Figure 41: Projected R_{AA} as a function of P_T for Υ and $\Upsilon(2S)$ yields expected at the CMS [758] experiment, with 10 nb^{-1} of PbPb data and 650 pb^{-1} of reference pp data. [Figure from [758]]

2426 The possible complications due to the different production mechanisms in AA collisions (the suppression
 2427 of the direct production, and the recombination from correlated pairs or the regeneration in the plasma from
 2428 uncorrelated pairs) could be circumvented by comparing data at several collision energies, i.e. running at
 2429 lower energies than the nominal one. This is one of the advantages of taking data in the FT mode [6], as
 2430 mentioned in Section 6.3.1.

2431 A running scenario for the HL LHC, starting with Run 3 (2021) and the major upgrades of the ALICE
 2432 and LHCb detectors for heavy-ions, has been proposed in the corresponding CERN Yellow Report (Work-
 2433 ing Group 5) [2] and is given in Table 3. The listed integrated luminosities have not yet been endorsed by
 2434 the experiments, the LHC, or CERN. They are reported indicatively in order to give the reader the order
 2435 of magnitude of what can be expected. The interested reader may refer to [773] for a recent study of the
 2436 expected future performances of the LHC for heavy-ion beams. There is also an interest in running with ion
 2437 beams in Run 5 and beyond, possibly with lighter ions (such as argon or krypton), to reach higher luminosities
 2438 and reduce combinatorial background, giving access to rarer states such as $\chi_b(1P)$. The ALICE [774]
 2439 and LHCb [775] experiments have started planning upgrades supporting this scenario.

2440 Further discussion of the physics case and prospects for quarkonium measurements in heavy-ion collisions
 2441 at the HL-LHC is given in Section 7 of the aforementioned CERN Yellow Report [2]. A few selected
 2442 topics are discussed below.

2443 6.2. Recent theory developments

2444 Although some concrete predictions for quarkonium yields can be made assuming they are produced ac-
 2445 cording to the laws of statistical physics at the pseudo-transition temperature, most approaches on the mar-
 2446 ket attempt to implement the suppression and (re)generation of quarkonia, advocated in the introduction,

Year	Systems, $\sqrt{s_{NN}}$	Duration	$\int \mathcal{L}$
2021	PbPb 5.5 TeV	3 weeks	2.3 nb ⁻¹
	<i>pp</i> 5.5 TeV	1 week	3 pb ⁻¹ (ALICE), 300 pb ⁻¹ (ATLAS, CMS), 25 pb ⁻¹ (LHCb)
2022	PbPb 5.5 TeV	5 weeks	3.9 nb ⁻¹
	OO, <i>pO</i>	1 week	500 μ b ⁻¹ and 200 μ b ⁻¹
2023	<i>pPb</i> 8.8 TeV	3 weeks	0.6 pb ⁻¹ (ATLAS, CMS), 0.3 pb ⁻¹ (ALICE, LHCb)
	<i>pp</i> 8.8 TeV	few days	1.5 pb ⁻¹ (ALICE), 100 pb ⁻¹ (ATLAS, CMS, LHCb)
2027	PbPb 5.5 TeV	5 weeks	3.8 nb ⁻¹
	<i>pp</i> 5.5 TeV	1 week	3 pb ⁻¹ (ALICE), 300 pb ⁻¹ (ATLAS, CMS), 25 pb ⁻¹ (LHCb)
2028	<i>pPb</i> 8.8 TeV	3 weeks	0.6 pb ⁻¹ (ATLAS, CMS), 0.3 pb ⁻¹ (ALICE, LHCb)
	<i>pp</i> 8.8 TeV	few days	1.5 pb ⁻¹ (ALICE), 100 pb ⁻¹ (ATLAS, CMS, LHCb)
2029	PbPb 5.5 TeV	4 weeks	3 nb ⁻¹
Run-5	Intermediate AA	11 weeks	e.g. Ar–Ar 3–9 pb ⁻¹ (optimal species to be defined)
	<i>pp</i> reference	1 week	

Table 3: Indicative running scenarios for different heavy-ion runs at the HL-LHC, with the expected integrated luminosity, as proposed in the CERN Yellow Report [2] (but subject to review by the experiments, LHC, and CERN). The years in the table do not account for modifications of the schedule after the publication of the report, which include a delay of the start of Run 4 (2027 → 2028) and a delay of the start of Run 3 because of the COVID-19 pandemic (2021 → 2022).

2447 through dedicated dynamical transport models. While early approaches were formulated in terms of ki-
2448 netic equations making use of dissociation rates and cross sections obtained from pQCD calculations or
2449 effective models, more recent developments have profited from the concept of imaginary potentials that,
2450 in approaches like potential NRQCD (pNRQCD), makes the bridge between those coefficients used in the
2451 transport models and lattice QCD (lQCD) calculations. These new developments enable more solid links
2452 between the experimental observables to be measured with better precision at HL-LHC runs and the basic
2453 fundamental properties of the in-medium $Q\bar{Q}$ interactions.

2454 In parallel, the formalism of open quantum systems (OQS) is nowadays considered, by an increasing
2455 part of the theoretical community, as the emerging paradigm that should either supersede semi-classical
2456 approaches or, at least, provide the methods to generate corrections to these approaches. This prospect
2457 is particularly appealing for HL-LHC runs as well, as the experimental precision needs to be matched by
2458 an increased control of the theoretical models. In Section 6.2.1, we provide a description of progresses
2459 achieved with the OQS formalism as well as its links to Boltzmann transport.

2460 Among the various theoretical challenges, the correct quantum treatment of the regeneration of low-
2461 P_T charmonia, due to numerous $c\bar{c}$ pairs, is a key question for the most central PbPb collisions at LHC
2462 energies and beyond. In Section 6.2.2, we discuss a recent approach stemming from a direct reduction of
2463 the Von Neumann equation, which provides an alternative to semi-classical algorithms deduced for instance
2464 in [776, 777] and yields preliminary predictions for R_{AA} and v_2 of J/ψ .

2465 The production of quarkonia at high P_T is another key issue in the global landscape, as the few present
2466 v_2 predictions from transport models fail to reproduce the experimental data at intermediate P_T , leaving the
2467 door open for other mechanisms like that involving energy loss of the $Q\bar{Q}$ pair. However, the modelling
2468 of such a situation requires knowledge of the in-medium interaction of a $Q\bar{Q}$ pair at finite velocity, which
2469 is still not fully known. In Section 6.2.3, we present a summary of recent progresses made in one of the
2470 state-of-the-art approaches.

2471 6.2.1. Semi-classical transport and open quantum system

2472 Modern phenomenological studies of quarkonium production in heavy-ion collisions require consistency in
 2473 considering static screening, dissociation and recombination in the treatment of hot-medium effects. Semi-
 2474 classical transport equations such as the Boltzmann equation and the rate equation, which is obtained from
 2475 the Boltzmann equation by integrating the quarkonium distribution over phase space, have been applied
 2476 widely and shown to be phenomenologically successful [130, 766, 778–793].

2477 Such a phenomenological success of the semi-classical Boltzmann equation has been explained by
 2478 deriving the transport equation under systematic expansions that are closely related to a hierarchy of scales
 2479 $M \gg Mv \gg Mv^2 \gtrsim T$ [777, 794], where M is the heavy-quark mass, v the typical relative velocity between
 2480 the heavy quark-antiquark pair in a quarkonium state and T the temperature of the plasma. Under this
 2481 separation of scales, pNRQCD [795–797] can be used to simplify the calculations. The starting point of the
 2482 derivation is the OQS formalism that has recently been used to study quarkonium transport [776, 798–812].
 2483 In this formalism, the quarkonium is an open subsystem interacting with the thermal QGP. Integrating out
 2484 the degrees of freedom of the thermal bath results in a non-unitary and time-irreversible evolution equation,
 2485 which further leads to a Lindblad equation in the Markovian approximation. The Lindblad equation can
 2486 be shown to become the semi-classical Boltzmann equation in the semi-classical limits after a Wigner
 2487 transform is applied to the subsystem density matrix (a Gaussian smearing is required to maintain positivity).
 2488 The Markovian approximation can be justified when the subsystem is weakly interacting with the thermal
 2489 bath, which is true in our power counting since the quarkonium size is small $rT \sim \frac{T}{Mv} \lesssim v \ll 1$. A schematic
 2490 diagram of the various approximations and resulting equations is shown in Fig. 42. The derivation clearly
 2491 demonstrates the validity condition of the semi-classical transport equations. Essentially, what should be
 2492 preserved is the non-relativistic nature of the heavy quarks from the QGP viewpoint. As the P_T of the
 2493 quarkonium increases, the energy of the medium excitation in the rest frame of the quarkonium is boosted,
 2494 which could ruin the nonrelativistic expansion. Furthermore, the derivation provides a way of systematically
 2495 including the quantum corrections to the semi-classical transport equation. Alternatively, one can directly
 2496 solve the Lindblad equation for the quarkonium phenomenology, which in principle is a quantum system.
 2497 Improvements towards a full quantum phenomenological treatment are still needed.

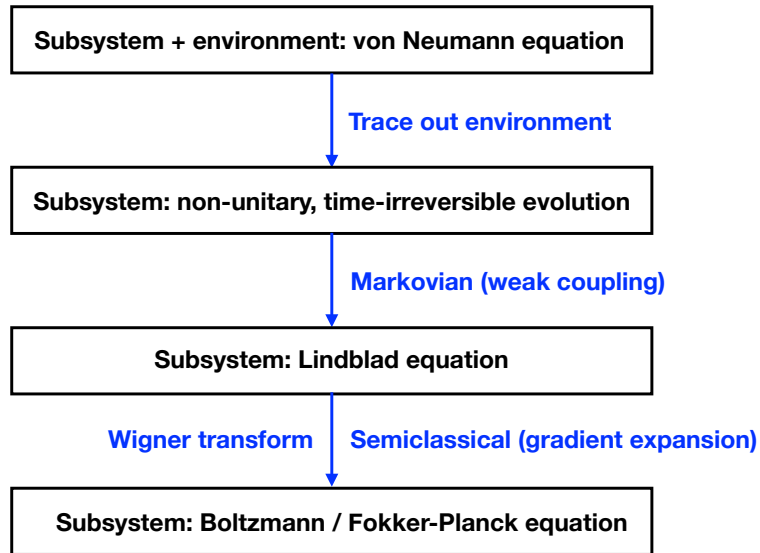


Figure 42: Various approximations made and evolution equations obtained in the derivation of the semi-classical transport equation for quarkonium from the von Neumann equation of closed quantum systems.

2498 To explore the limits of the semi-classical transport approaches and find solid experimental evidence
 2499 of quantum effects in the quarkonium transport, experimental data with high precision are needed. For
 2500 example, precise measurements of the azimuthal angular anisotropy and of R_{AA} of excited quarkonium
 2501 states such as $\chi_b(1P)$ and $\Upsilon(3S)$ will be very helpful in distinguishing different semi-classical transport
 2502 calculations. A precise measurement of R_{AA} of $\chi_b(1P)$ is of particular interest [793] since, if the dissociation
 2503 is the only hot medium effect, then one expects R_{AA} of $\Upsilon(2S)$ and of $\chi_b(1P)$ to be similar (with the value for
 2504 $\chi_b(1P)$ slightly higher) [786] since the binding energies and sizes of the two states are comparable. However,

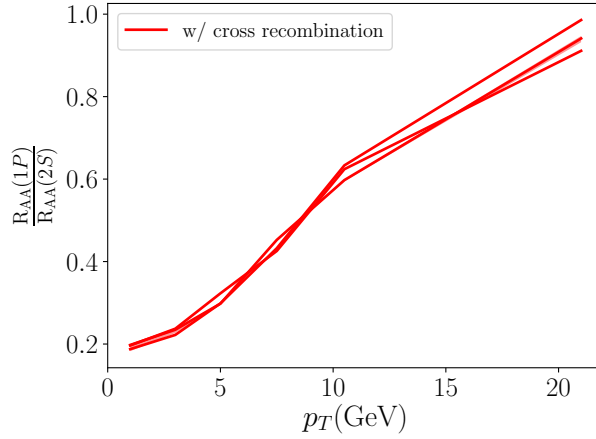


Figure 43: Ratios of $R_{AA}(\chi_b(1P))$ and $R_{AA}(\Upsilon(2S))$ as a function of p_T predicted in [793]. Different lines correspond to different choices of parameters. Nuclear PDF effects largely cancel in the ratio.

2505 it is known from recent studies using the OQS formalism that the dissociation is a result of the wave-
 2506 function decoherence. Due to the decoherence of the original state, say $\Upsilon(2S)$, a non-vanishing overlap can
 2507 be developed with other states that exist in the medium (i.e. the local temperature is below their melting
 2508 temperature), say $\chi_b(1P)$. This gives a probability to form another quarkonium state from a dissociating
 2509 state. This recombination process (known as “correlated recombination” [793]) involves a heavy quark-
 2510 antiquark pair from the same hard vertex (a dissociating quarkonium) and is different from the traditional
 2511 concept of recombination, which comes from heavy quarks and antiquarks initially produced from different
 2512 hard vertices. The existence of such a correlated recombination is mandatory for theory consistency and
 2513 is well-motivated from OQS studies. With correlated recombination, an initial $\Upsilon(2S)$ state may dissociate
 2514 first and then recombine as a $\chi_b(1P)$ state and vice versa. The probabilities of both these processes are
 2515 similar since $\Upsilon(2S)$ and $\chi_b(1P)$ have similar binding energies and sizes. However, primordially many
 2516 more $\chi_b(1P)$ mesons are produced, which leads to less suppressed yields of the $\Upsilon(2S)$ than the $\chi_b(1P)$
 2517 state. Consequently, it is of great interest to measure the ratio between the R_{AA} suppression factors of
 2518 $\chi_b(1P)$ and $\Upsilon(2S)$. Calculations that include correlated recombination (which requires some information
 2519 of the two-particle distribution function of the heavy quark-antiquark pairs) such as [793], predict the ratio
 2520 to be about 1/3 in central collisions while calculations such as [786], which do not include correlated
 2521 recombination, give a ratio larger than unity. The contrast is dramatic (for example, compare Fig. 1 of [786]
 2522 and Fig. 7 of [793]). If it is possible to measure this ratio in future experiments, its power for discriminating
 2523 between models will be high. This ratio calculated in [793] also depends on p_T , and approaches unity as
 2524 p_T increases, as shown in Fig. 43.

2525 The correlated recombination discussed above is not an intrinsic quantum effect and can be accounted
 2526 for in semi-classical transport equation calculations. With high precision data, it may also be possible
 2527 to find a common inconsistency between all semi-classical approaches and experimental data, which then
 2528 hints at the importance of quantum effects in quarkonium in-medium dynamics. In view of the discussion
 2529 in Section 5.2 on nPDF effects, one expects these to largely cancel in such a ratio and, in any case, to be
 2530 negligible compared to the variation shown in Fig. 43.

2531 6.2.2. A density-operator model for Q production in AA collisions

2532 In this section, a newly developed model is introduced that aims to offer a better understanding of heavy-
 2533 quarkonium formation in the presence of many $Q\bar{Q}$ pairs (that is, in the LHC conditions) while offering a
 2534 different approach to the existing ones. In this model, the formation of heavy quarkonia is conceived as a
 2535 coalescence in phase space, based on composite particle cross sections, following Remler’s formalism [813,
 2536 814] directly deduced from the Von Neumann’s equation.

2537 By computing an effective production rate (including both dissociation and recombination processes),
 2538 the model is able to keep track of the inclusive formation probability of the quarkonium system with time,
 2539 taking into account the heavy-quark kinematics and their interaction with medium particles. For a given

2540 $\{Q, \bar{Q}\}$ pair $\{1, 2\}$, the contribution to the rate is

$$\Gamma(t) = \sum_{i=1,2} \sum_{j \geq 3} \delta(t - t_{ij}(v)) [W_{Q\bar{Q}}(t + \epsilon) - W_{Q\bar{Q}}(t - \epsilon)], \quad (6)$$

2541 where the sum j reflects the sum over all particles from the bulk, while the δ factor only acts when one
 2542 of the members of a given pair ($i = 1$ or $i = 2$) undergoes a collision with a particle ($j \geq 3$). The rate
 2543 expression relies on the Wigner distribution of the quarkonium vacuum states, through the gain $W_{Q\bar{Q}}(t + \epsilon)$
 2544 and loss $W_{Q\bar{Q}}(t - \epsilon)$ terms. While the expression only shows the rate contribution from one pair, it can easily
 2545 be extended to all pairs in the medium by summing over all combinations. In this way, both recombination
 2546 and dissociation are taken into account inside both the gain and loss terms, which represent the overall
 2547 contribution of the recombination and dissociation at any given time. The time evolution of the probability
 2548 P for a quarkonium state formation thereby follows:

$$P(t) = P(t_0) + \int \Gamma(t) dt. \quad (7)$$

2549 In this approach, the heavy quarks do not need to be considered at thermal (or chemical) equilibrium at any
 2550 stage of the collision. This feature makes it possible to apply it, not only to large systems like AA collisions,
 2551 but to small systems as well. It also offers concrete perspectives to deal with several particles ($Q\bar{Q}$ pairs)
 2552 in real-time dynamics. Finally, the model is also quite sensitive to key ingredients of the quarkonium
 2553 production such as: the primordial, or initial, $Q\bar{Q}$ pair production (with cold nuclear matter effects); the
 2554 $Q\bar{Q}$ interaction; and the local medium temperature field which is modelled according to the EPOS event
 2555 generator [98] in the present implementation. In Fig. 44, preliminary predictions are provided for R_{AA} and
 2556 v_2 as a function of the J/ψ P_T obtained within this operator model, both with and without screened binding
 2557 interactions.

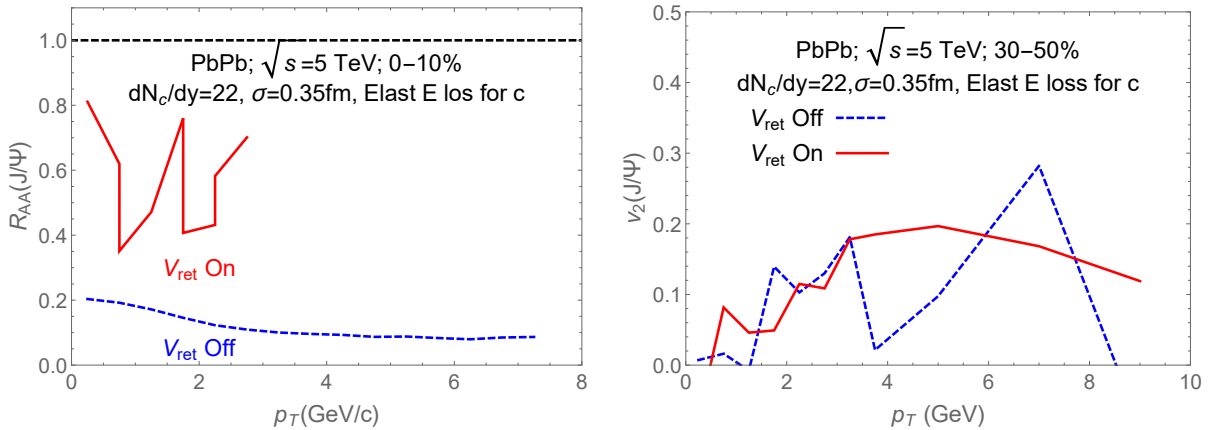


Figure 44: Prediction for R_{AA} (Left) and v_2 (Right) of the J/ψ with the density-operator model for PbPb collisions at $\sqrt{s_{NN}} = 5$ TeV. The solid lines corresponds to $c\bar{c}$ interactions modelled following screened binding potential, while the dashed curves correspond to c and \bar{c} solely interacting with the light quarks and the gluons through elastic scatterings. [The observed oscillations result from numerical fluctuations.]

2558 In the future, both IQCD calculations and HL-LHC data on R_{AA} and v_2 of J/ψ will be brought together to
 2559 constrain the interactions among Q , \bar{Q} , and medium partons, and then explore in detail the consequences of
 2560 the model for excited states and higher harmonics like v_3 , which start to be accessible experimentally [815].

2561 6.2.3. An advanced EFT for Q in matter

2562 In recent years, significant progress in understanding subatomic particle propagation in matter has been
 2563 reached using modern effective field theories (EFTs). First developed for light partons [816–818], the
 2564 Soft-Collinear Effective Theory with Glauber gluons (SCET_G) was applied to describe the suppression
 2565 of inclusive hadrons and jets as well as the modification of jet substructure [819–821]. This approach
 2566 was subsequently extended to open heavy-flavour [822, 823] to understand the production of D mesons,
 2567 B mesons, and heavy-flavour-tagged jets [824, 825]. A logical next step is to start with the theory of

2568 quarkonium production, NRQCD and its modern formulations [56, 795, 826], and to introduce interactions
 2569 with the background nuclear medium [761].

2570 The hierarchy of ground and excited quarkonium suppression emphasises the need for such an EFT
 2571 approach. In order for the traditional energy-loss phenomenology [759] to contribute significantly to the
 2572 modification of quarkonium cross sections in QCD matter, the quarkonium formation must happen outside
 2573 of the medium and be expressed as the fragmentation of partons into the various J/ψ and Υ states. This
 2574 is possible in the recently developed Leading-Power (LP) factorisation approach to QCD [60] (see also
 2575 Section 2) although we stress that it is only in the high- P_T range that this LP factorisation is thought to
 2576 work well.

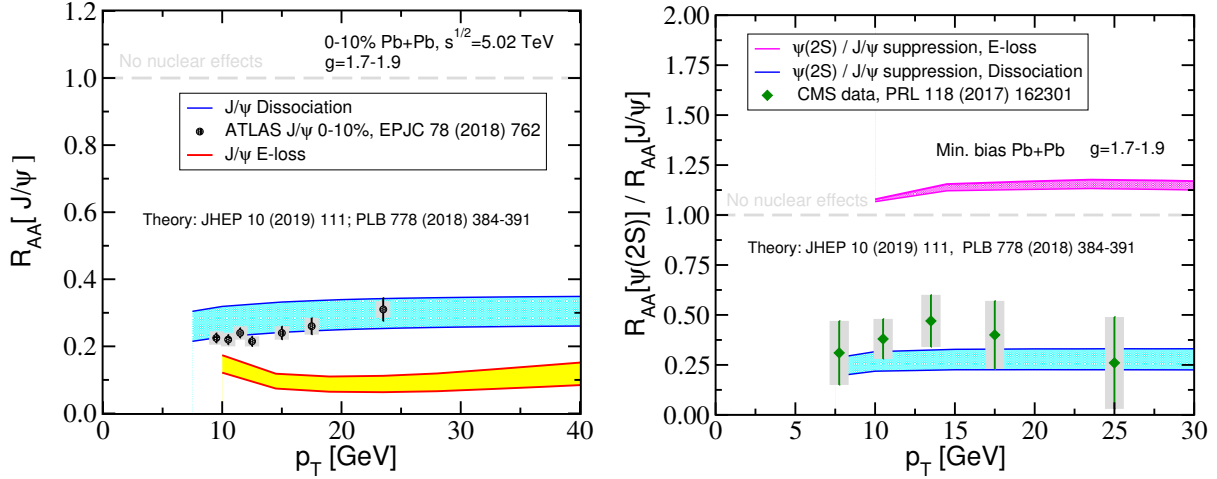


Figure 45: Left: Suppression of the J/ψ production in central PbPb collisions at ATLAS compared to the energy loss (yellow) and EFT (blue) quarkonium dissociation calculations. Right: The double ratio of $\psi(2S)$ to J/ψ suppression as a measure of the relative significance of QCD matter effects on ground and excited states (CMS) compared to the same energy loss (purple) and EFT (blue) theoretical models.

2577 As an example, we calculate the baseline J/ψ and $\psi(2S)$ cross sections from LDMEs extracted using
 2578 LP factorisation in PbPb collisions at the LHC (Fig. 45). The energy-loss evaluation is carried out in the
 2579 soft-gluon-emission limit of the full in-medium splitting kernels [823, 827], and is well constrained by light-
 2580 hadron quenching [819, 828]. The energy loss approach overpredicts the suppression of J/ψ measured by
 2581 ATLAS [756] in the range $P_T > 10$ GeV where the computation starts to be applicable. The discrepancy
 2582 is a factor of 2 to 3 in both minimum bias and central collisions (yellow band in Fig. 45 Left). The most
 2583 important discrepancy, however, is in the relative medium-induced suppression of $\psi(2S)$ to J/ψ as shown
 2584 in the right panel of Fig. 45 (purple band). The energy-loss model predicts smaller suppression for the $\psi(2S)$
 2585 state compared to J/ψ and $R_{AA}[\psi(2S)]/R_{AA}[J/\psi] \approx 1.1$. The CMS experimental results [763] show that
 2586 the suppression of the weakly bound $\psi(2S)$ is 2 to 3 times larger than that of J/ψ .

2587 Such a tension between the data and the energy-loss calculations shows that a formulation of a general
 2588 microscopic theory of the quarkonium interactions in matter [761, 829, 830] is necessary. When an energetic
 2589 particle propagates in a hot or cold nuclear medium, the interaction with its quasi-particles is typically
 2590 mediated by off-shell-gluon exchanges – Glauber or Coulomb gluons. Their typical momenta depend on
 2591 the source of in-medium interactions – collinear, static, or soft. We construct the Lagrangian of NRQCD_G
 2592 by adding to the velocity-renormalisation-group NRQCD (vNRQCD) Lagrangian the terms that include the
 2593 interactions with medium sources through virtual Glauber/Coulomb gluons exchanges. It takes the form:

$$\mathcal{L}_{\text{NRQCD}_G} = \mathcal{L}_{\text{vNRQCD}} + \mathcal{L}_{Q-G/C}(\psi, A_{G/C}^{\mu,a}) + \mathcal{L}_{\bar{Q}-G/C}(\chi, A_{G/C}^{\mu,a}), \quad (8)$$

2594 where, in the background field method, the effective $A_{G/C}^{\mu,a}$ incorporate the information about the sources.
 2595 Here, ψ and χ are the heavy quark and antiquark fields respectively. The leading and subleading correction
 2596 to the NRQCD_G Lagrangian in the heavy-quark sector from virtual (Glauber/Coulomb) gluon insertions,
 2597 i.e. $\mathcal{L}_{Q-G/C}$, are derived using three different methods yielding the same results. We find that at LO the
 2598 modification in the leading Lagrangian, $\mathcal{L}_{Q-G/C}^{(0)}$, is independent of the nature of the quasiparticles of the

2599 QCD medium:

$$\mathcal{L}_{Q-G/C}^{(0)}(\psi, A_{G/C}^{\mu,a}) = \sum_{\mathbf{p}, \mathbf{q}_T} \psi_{\mathbf{p}+\mathbf{q}_T}^\dagger (-gA_{G/C}^0) \psi_{\mathbf{p}} \quad (\text{collinear/static/soft}). \quad (9)$$

2600 As the quarks (and antiquarks) couple to the time like component of the Glauber/Coulomb field, it is easy to
 2601 implement the interactions in a background-field approach. In contrast, at NLO, the distinction is manifest
 2602 in the subleading Lagrangian, $\mathcal{L}_{Q-G/C}^{(1)}$ [761].

2603 The dissociation rates for the various quarkonium states in the QGP can be obtained from NRQCD_G
 2604 and incorporated into the rate equations first developed to describe the propagation of open heavy-flavour
 2605 states in matter [831, 832]. Under the approximation where the transition between states is neglected, the
 2606 quarkonium transport takes the form derived in [784, 789]. The EFT predictions are also shown in Fig. 45
 2607 (blue bands), and give a much better description of the data than the energy-loss approach. Furthermore, in
 2608 this limit, the surviving quarkonia are expected to retain the polarisation acquired from their initial produc-
 2609 tion. A measurement that the HL-LHC might explore is that of quarkonium polarisation in nucleus-nucleus
 2610 collisions (see Section 6.3.3).

2611 On the theory side, it will be important to extend such predictions to higher P_T , on the order 100 GeV.
 2612 The increased data sample at the HL-LHC should in principle allow one to check whether the LP factori-
 2613 sation limit and the energy-loss dominance are reached. Furthermore, as J/ψ and Υ data becomes more
 2614 precise, in particular with smaller uncertainties on the relative suppression of excited to ground states, it
 2615 will be possible look for effects of medium-induced transition between quarkonium states [761].

2616 6.3. Opportunities at HL-LHC

2617 6.3.1. Studying the collision-energy dependency of Q production

2618 The LHC high-luminosity program will have the opportunity to explore different collision energies. One
 2619 of the most interesting possibilities is to explore the current maximum PbPb energy of $\sqrt{s_{NN}} = 5.02$ TeV
 2620 and low-energy collisions in the FT mode, similar to the RHIC c.m.s. energy range. The current energy
 2621 achieved in the FT mode by the LHCb experiment, using the nominal 2.5 TeV Pb beam energies, is $\sqrt{s_{NN}} =$
 2622 69 GeV. Quarkonium total cross-sections decrease by approximately a factor 15 in pp collisions between
 2623 $\sqrt{s} = 5$ TeV and $\sqrt{s} = 69$ GeV. Large integrated luminosities in this mode are desirable to compensate for
 2624 such a difference in yields. The expected integrated luminosities, $\int \mathcal{L}$, for the FT mode in LHCb, SMOG2,
 2625 is 20 nb^{-1} in one year of PbAr collisions at $\sqrt{s_{NN}} = 72$ GeV [420], nearly 100 times larger than what was
 2626 recorded by the same experiment in PbPb collisions at 5 TeV. Similar estimations have been obtained by the
 2627 AFTER@LHC study group for different techniques (gas target, solid target with bent-crystal beam splitting
 2628 or with a dedicated beam line) [6, 614, 833] using both the LHCb and ALICE detectors.

2629 Whereas the freeze-out temperatures are nearly constant in the aforementioned collision energy range,
 2630 the peak temperature is expected to change by roughly a factor of three when comparing the estimated
 2631 peak temperatures obtained from direct-photon-yield slopes measured at RHIC [751] and at the LHC [748].
 2632 The same factor is obtained for charged-particle multiplicities as reported in [834]. It is noteworthy in
 2633 these publications that the peak temperature also depends on the collision centrality. However, the peak
 2634 temperature shows a more modest variation of around 50% from peripheral to central events. It would
 2635 be relevant to measure the modification of the quarkonium spectrum at the same particle multiplicity but
 2636 distinct collision energies. Such a measurement, made preferably with the same detector, would have a
 2637 stringent constraint on models that consider the quarkonium breaking by co-moving hadrons [6].

2638 The contribution from charmonium (re)generation strongly depends on the collision energy. More than
 2639 100 $c\bar{c}$ pairs are produced in a single central PbPb collision at $\sqrt{s_{NN}} = 5$ TeV according to the charm
 2640 cross section published in [835]. This large number of uncorrelated $c\bar{c}$ pairs is an abundant source for the
 2641 charmonium (re)generation process, which could explain the enhancement of low- P_T J/ψ yields [754], and
 2642 to a lesser extent the elliptic flow [709–711] observed in PbPb collisions at LHC.

2643 Taking the FONLL computation [836] of the charm cross section at $\sqrt{s_{NN}} = 69$ GeV, less than one
 2644 charm pair per collision is expected on average, leaving no room for charmonium (re)generation. This
 2645 feature alone makes high-luminosity, low-energy collisions at the FT-LHC a significant opportunity to use
 2646 (re)generation-free charmonium states to probe the QGP temperature.

2647 Bottomonia are expected not to be affected by (re)generation (from uncorrelated $b\bar{b}$ pairs) given that,
 2648 even at the maximum-energy PbPb collisions at LHC, less than one $b\bar{b}$ pair is produced on average per
 2649 collision. Looking at quarkonium suppression as a function of rapidity and system size (another asset of
 2650 the versatile FT mode) would permit searches for the onset of QGP effects, and hence put constraints on the
 2651 in-medium modification of the quarkonium potential.

2652 The current status of the implementation of a FT operation mode within the LHCb detector, and the
 2653 ongoing technical developments performed towards the achievement of an extended FT physics programme
 2654 during HL-LHC, both in LHCb and potentially with the ALICE detector, have been discussed in Sec-
 2655 tion 3.3.3. Conventional detectors with a coverage of the forward rapidities in the laboratory frame, such
 2656 as LHCb or the ALICE muon arm, allow scanning of the mid to backward c.m.s. rapidity region. With the
 2657 HL-LHC luminosities in the FT mode, the yearly charmonium yields in PbXe collisions are expected to
 2658 be very large, of the order of $\sim 10^7$ J/ψ mesons in LHCb (Fig. 46, left) and of the order of a few 10^6 J/ψ
 2659 mesons in the ALICE muon spectrometer.

2660 The understanding of the (dynamical) charmonium suppression (given the negligible (re)generation
 2661 expected at low c.m.s. energy) in the QGP would highly benefit from systematic and precise studies of all
 2662 excited states. This includes direct χ_c measurement, which becomes less challenging at low energy and
 2663 backward rapidity, thanks to a low-background environment. Projections with an LHCb-like detector of the
 2664 $\psi(2S)$ nuclear modification factor indicate, for instance, that a statistical precision of a few percent could be
 2665 reached at mid rapidity in the c.m.s. [6]. In addition to the $\psi(2S)$ and χ_c measurements, novel observables,
 2666 such as quarkonium-pair ($J/\psi + J/\psi$) or quarkonium-heavy-quark correlations ($J/\psi + D$), which require a
 2667 larger luminosity and acceptances than that achieved in the past at the SPS and RHIC, could be explored for
 2668 the first time in this energy regime. As can be seen in Fig. 46 (Left), the low level of background in the J/ψ
 2669 region supports the feasibility of the aforementioned studies, especially in the most backward region where
 2670 backgrounds are smallest.

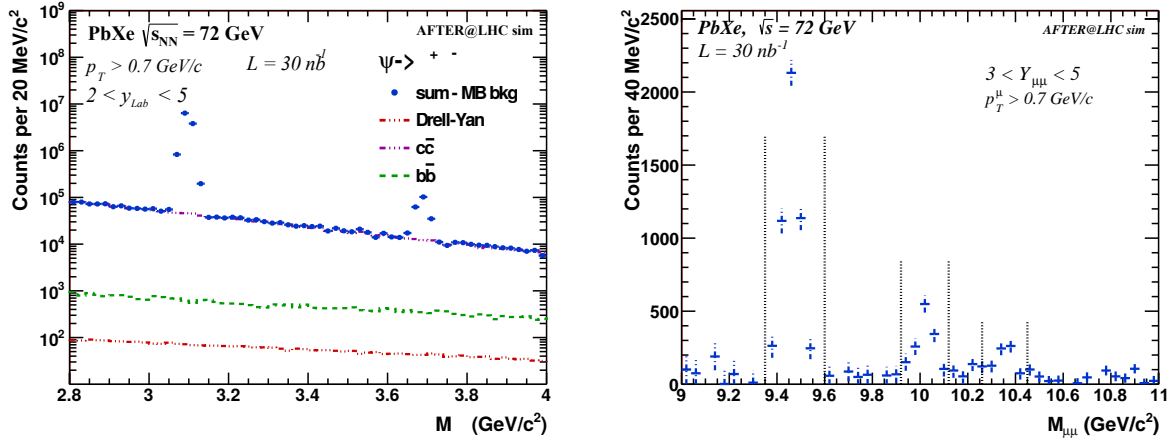


Figure 46: Di-muon invariant mass distribution in the J/ψ , $\psi(2S)$ (Left) and $\Upsilon(nS)$ (Right) regions, expected in PbXe FT collisions at $\sqrt{s_{NN}} = 72$ GeV, for an LHCb-like detector ($2 < y_{lab} < 5$). The combinatorial background is subtracted using like-sign pairs. No nuclear modification are assumed. The integrated luminosity of $\int \mathcal{L} = 30nb^{-1}$ corresponds to one LHC-year of data-taking for ions (i.e. typically one month of data taking), with an LHCb-like detector equipped with a gaseous storage-cell of 1-m length. The maximum luminosity achieved has been limited such that no more than 15% of the Pb beam is removed by the interaction with the target. [Plots taken from [6]].

2671 Figure 46 (Right) shows projections for the $\Upsilon(nS)$ invariant-mass region, in the di-muon-decay channel,
 2672 after the combinatorial-background subtraction, in PbXe collisions, with an LHCb-like detector. The yearly
 2673 Υ , $\Upsilon(2S)$ and $\Upsilon(3S)$ yields are about 4×10^3 , 10^3 and 5×10^2 mesons, respectively. Given the excellent res-
 2674 olution of LHCb, the three states are well separated. The expected statistical precision on the measurements
 2675 of R_{AA} of each of the three states will be about 7%, 20% and 30% for the Υ , $\Upsilon(2S)$ and $\Upsilon(3S)$, respectively.
 2676 Yield projections in the bottomonium sector also exists for the ALICE muon arm. Typically a few hundred
 2677 Υ mesons will be collected in PbXe collisions in one year of LHC data taking. The study of the excited
 2678 states, even for several data-taking years, will remain rather limited with ALICE in the FT mode. Such
 2679 studies of $\Upsilon(nS)$ suppression, especially with the LHCb detector, will therefore bring crucial new inputs
 2680 to our understanding of the nature of the hot medium created in this energy regime, complementary to the

2681 studies already performed at the LHC (see CMS results [837–839]). This will allow tests of the different
 2682 approaches discussed in sections 6.1 and 6.2 and comparisons with effective models, such as the CIM, that
 2683 deals with quarkonium suppression and accounts for Landau damping [130].

2684 6.3.2. Prospects for $X(3872)$ studies

2685 About 20 years after its discovery [122], the question of whether $X(3872)$ is a molecule, a compact
 2686 tetraquark, or a hybrid state is still a subject of intense debate. It is thus worth wondering whether heavy-ion
 2687 experiments can help us understand its nature, in addition to the other exotic XYZ states. Such investigations
 2688 with heavy ions are needed in parallel to the recent experimental [129] and theoretical [131] work related to
 2689 high-multiplicity pp collisions mentioned in Section 5.4.1 (see also Section 2.4.3 for a general discussion
 2690 of the production in pp collisions). To advance our understanding using heavy ions, two inputs are needed:
 2691 precise measurements of the $X(3872)$ yields in heavy-ion collisions and solid theoretical calculations that
 2692 lead to different results for different underlying structures. Neither is an easy task.

2693 On the theory side, many phenomena may affect the production of the $X(3872)$. For example, for
 2694 low- P_T production, the dissociation and recombination of the $X(3872)$ similar to those of charmonium can
 2695 happen in the hot QGP (for a compact tetraquark state) or in the hadronic gas (for a molecule). These
 2696 processes in the hadronic gas are also connected with similar processes in pp and pA collisions, though
 2697 the background hadronic gas densities are different. These reaction rates are poorly understood from first
 2698 principles. Furthermore, the recombination is sensitive to the total number of charm quarks produced in one
 2699 event, which has not been precisely determined in heavy-ion collisions.

2700 At larger P_T , energy loss may also affect the $X(3872)$ yields. Moreover, in order to convert calculations
 2701 to phenomenology, one needs precise knowledge of the branching ratio of the decay channel of the $X(3872)$
 2702 used in the measurement (for example, $J/\psi\pi\pi$), which is also not well known but may be improved with
 2703 future measurements at B factories. Though the task is difficult, one still hopes that one can do some analy-
 2704 ses with precise data. So far, only the ratio between the production yields of the $X(3872)$ and the $\psi(2S)$ has
 2705 been measured by the CMS collaboration in the $P_T = 10\text{--}50$ GeV range [840]. Since the suppression mech-
 2706 anism of $\psi(2S)$ is not well understood, it is preferable if the direct yield (rather than the ratio) of $X(3872)$
 2707 can be measured as a function of P_T in the soft regions. This would indicate how significant recombination
 2708 is to the production of the $X(3872)$, since recombination is sensitive to the particle wave function. This
 2709 idea is motivated by the important contribution from recombination in charmonium production at low P_T .
 2710 On the experimental side, the size of the $X(3872)$ data samples needs to be increased in order to carry out
 2711 more differential measurements. At the same time, phenomenological calculations assuming different struc-
 2712 tures of the $X(3872)$ have to be carried out. Using the $X(3872)$ production yields in heavy-ion collisions to
 2713 understand its structure may not be fully successful by itself, but provides complementary information to
 2714 measurements in other collision systems.

2715 6.3.3. ψ polarisation in PbPb collisions

2716 The question of whether the J/ψ meson is polarised in AA collisions has been addressed by only a few
 2717 authors [841–843], who have advocated that a modification of the J/ψ polarisation in AA (as compared to
 2718 pp) could be due to either the disappearance of feed-down from higher states due to the suppression of
 2719 these states in QGP, or the modification of the $c\bar{c} \rightarrow J/\psi$ conversion mechanism, which would be altered in
 2720 those collisions, through a modification of the LDMEs at freeze-out. To quantify the χ_c suppression in AA
 2721 collisions, in [843], it is considered that the feed-down from χ_c results in the “blurring” of the direct J/ψ
 2722 production in pp , which would then be recovered in AA .

2723 However, the first measurement of J/ψ polarisation in AA collisions by ALICE [844], although still
 2724 affected by sizeable uncertainties, does not show a significant modification of the J/ψ polarisation param-
 2725 eters, λ_θ , λ_ϕ and $\lambda_{\theta\phi}$. At present, the first question to be answered is indeed whether the polarisation differs
 2726 in the pp and AA samples, rather than the actual size of the polarisation in AA collisions. In this context, it
 2727 would be helpful to look at R_{AA} as a function of the cosine of the di-lepton polar angle, $\cos\theta$, since the po-
 2728 larisation directly affects the $\cos\theta$ distribution: this measurement may have greater experimental precision
 2729 than a direct measurement of λ_θ .

2730 Details of the quarkonium formation can also be addressed in AA collisions. From the viewpoint of the
 2731 theoretical modelling, the SCET_G approach described in Section 6.2.3 is an ideal candidate to investigate the

2732 polarisation at large P_T , a regime where each directly produced charmonium is expected to have the same
 2733 polarisation as in pp collisions, due to helicity quasi-conservation in the energy loss process, but where the
 2734 energy loss and suppression affect their relative yields and their subsequent contribution to the lower-lying
 2735 states. At smaller P_T , the interactions with the QGP, neglected in most of the previous studies, and the
 2736 large fraction of the J/ψ yield due to recombination are expected to partly wash away the polarisation of
 2737 the $c\bar{c}$ state. On the contrary, the strong magnetic field created in the early QGP stage could enforce a spin
 2738 alignment of the J/ψ perpendicular to the event plane [845]. Experimental investigations should therefore
 2739 be supported by quantitative theoretical predictions that include all these ingredients, and are based on
 2740 state-of-the-art understanding of J/ψ polarisation in pp collisions.

2741 An alternate strategy could consist in measuring the polarisation of prompt $\psi(2S)$ in AA collisions,
 2742 which do not receive any feed-down, in kinematic regions where the yield is found to be polarised in pp
 2743 collisions. One may reasonably anticipate a gradual reduction of the polarisation in AA collisions for an
 2744 increasing centrality due to interactions with the QGP constituents. The issue is that, for now, the $\psi(2S)$ has
 2745 only been found to be (longitudinally) polarised for $P_T > 10$ GeV at forward rapidities [846]. In addition,
 2746 this represents a genuine experimental challenge: the $\psi(2S)/J/\psi$ ratio in PbPb in the di-muon channel is
 2747 about 1–2% (3–5% in pp) [763]. The published ALICE results in PbPb [844] use $750 \mu\text{b}^{-1}$ of data, while
 2748 10nb^{-1} are expected after Runs 3–4. This means that naively a $\psi(2S)$ polarisation in PbPb at the end of
 2749 Run 4 will still be less precise than the Run-2 J/ψ measurement (not accounting for the much lower signal-
 2750 over-background for $\psi(2S)$ compared to J/ψ , nor for improvements due to detector upgrades). The situation
 2751 may be different with lighter ions (which may be available for Run 5 or beyond), providing more integrated
 2752 luminosity, and for which less suppression is expected with respect to pp . Finally, if such a measurement
 2753 was to be done by the ATLAS or CMS experiments, the gain in acceptance in rapidity may be compensated
 2754 by a larger P_T threshold.

2755 7. Double and triple parton scatterings²⁸

2756 7.1. Introduction

2757 The extended nature of hadrons and their large parton densities when probed at the HL-LHC collision
 2758 energies, make it very likely to produce simultaneously two or more quarkonium states alone or together
 2759 with other heavy particles via separate multi-parton interactions in pp [35], pA [847–850], and AA [849,
 2760 851] collisions. Double, triple, and in general n -uple parton scatterings (DPS, TPS, and NPS, respectively)
 2761 depend on the degree of transverse overlap of the matter densities of the colliding hadrons, and give access
 2762 to the phase space distributions of partons inside the proton or nucleus. The study of NPS provides thereby
 2763 valuable information on the hadronic wave functions describing the correlations among partons in space,
 2764 momentum, flavour, colour, spin, etc., and their corresponding evolution as a function of collision energy.
 2765 In addition, understanding double and triple parton scatterings is of relevance in the study of backgrounds
 2766 for the associated production of quarkonia plus other hard particles (Section 2.5), for rare Standard Model
 2767 (SM) decays, and/or for searches for new physics in final states with multiple heavy particles.

The pQCD-factorised expression to compute the cross section of a given double parton scattering process in hadron collisions reads

$$\sigma_{\text{DPS}} = \left(\frac{m}{2}\right) \sum_{a_1 a_2 b_1 b_2} \sum_R [{}^R\hat{\sigma}_{a_1 b_1} {}^R\hat{\sigma}_{a_2 b_2}] \otimes \int d^2\mathbf{y} {}^R F_{b_1 b_2}(x_i, \mathbf{y}) {}^R F_{a_1 a_2}(\bar{x}_i, \mathbf{y}), \quad (10)$$

2768 where m is a combinatorial factor to avoid multiple counting of the same process, \otimes denotes a convolution
 2769 over longitudinal momentum fractions, $\hat{\sigma}_{ab}$ is the partonic cross section for the interaction between partons
 2770 a_i and b_i , while $F_{a_1 a_2}$ is the double parton distribution function (dPDF) of two partons inside a proton [852],
 2771 separated by a distance \mathbf{y} and each carrying a longitudinal momentum fraction x_i . The sum over a_i and b_i
 2772 runs over parton flavours and spin, while R runs over the allowed colour representations [853, 854].

2773 Section 7.2 describes the current status of the theoretical DPS calculations based on Eq. (10). Often,
 2774 however, rather than the full calculations, a useful simplistic approximation is employed to estimate the

²⁸Section editors: David d’Enterria, Tomas Kasemets.

2775 cross sections for the DPS production of two hard particles H_1 and H_2 from the product of their correspond-
 2776 ing single-parton-scattering (σ_{SPS}) values normalised by an effective cross section σ_{eff} to warrant the proper
 2777 units of the final result, namely

$$\sigma_{\text{DPS}}^{hh' \rightarrow H_1 + H_2} = \left(\frac{m}{2}\right) \frac{\sigma_{\text{SPS}}^{hh' \rightarrow H_1} \cdot \sigma_{\text{SPS}}^{hh' \rightarrow H_2}}{\sigma_{\text{eff}}} . \quad (11)$$

2778 This so-called ‘‘pocket formula’’ encapsulates the intuitive result that, in the absence of any partonic cor-
 2779 relations, the probability to have two parton-parton scatterings producing two heavy or high- P_T particles
 2780 (e.g. quarkonium states) in a given inelastic hadron-hadron collision should be proportional to the product
 2781 of probabilities to independently produce each one of them. In the extreme case where one assumes that (i)
 2782 the dPDF factorises as the product of transverse and longitudinal densities, (ii) the longitudinal components
 2783 themselves reduce to the product of independent single PDFs, (iii) the transverse profile is the same for all
 2784 partons, and (iv) no other parton correlations are present, the effective cross section is [855, 856]

$$\sigma_{\text{eff}} \equiv \sigma_{\text{eff,DPS}} = \left[\int d^2b T^2(b) \right]^{-1} . \quad (12)$$

2785 Consequently, σ_{eff} can be written as a function of the pp overlap $T(b)$ at impact parameter b , computable
 2786 from the transverse parton-density profile of the proton $\rho(b)$ in a Glauber approach [636]. For conventional
 2787 transverse parton $\rho(b)$ distributions of the proton, such as those typically implemented in the modern pp
 2788 Monte Carlo (MC) event generators PYTHIA 8 [857], and HERWIG++ [858], one expects values of $\sigma_{\text{eff}} \approx$
 2789 15–25 mb. These σ_{eff} values are smaller than the purely geometric ‘‘soft’’ pp cross section of $\sigma_{\text{inel}} \approx 35$ mb,
 2790 derived from the electromagnetic radius of the proton, because of the inherent ‘‘centrality bias’’ that appears
 2791 when one or more hard enough parton scatterings is required.

2792 The pocket formula (Eq. (11)) can be used for pp , pA , and AA collisions, and its generalisation for
 2793 the hard production of n sets of particles, denoted H_i , in n parton scatterings from the corresponding single
 2794 parton values can be expressed as the n^{th} -product of the corresponding SPS cross sections for the production
 2795 of each single final-state particle, normalised by the $(n^{\text{th}} - 1)$ power of an effective NPS cross section [856]:

$$\sigma_{\text{nps}}^{hh' \rightarrow H_1 + \dots + H_n} = \left(\frac{m}{n!}\right) \frac{\prod_i \sigma_{\text{SPS}}^{hh' \rightarrow H_i}}{(\sigma_{\text{eff,NPS}})^{n-1}}, \quad \text{with } \sigma_{\text{eff,NPS}} = \left\{ \int d^2b T^n(b) \right\}^{-1/(n-1)}, \quad (13)$$

2797 where, again, the second equality holds in the strong assumption of absence of any parton correlations
 2798 and $\sigma_{\text{eff,NPS}}$ bears a simple geometric interpretation in terms of powers of the inverse of the integral of the
 2799 hadron-hadron overlap function $T(b)$ over all impact parameters.

2800 The expressions based on Eq. (13) applied to quarkonium production in DPS and TPS processes be-
 2801 low provide baseline (purely ‘‘geometric’’) order-of-magnitude estimates of their expected cross sections
 2802 by combining (i) SPS cross sections σ_{SPS} , which are either experimentally measured or computed within
 2803 perturbative QCD e.g. at NLO or NNLO accuracy today, plus (ii) a value of $\sigma_{\text{eff,NPS}}$, theoretically derived
 2804 in a Glauber geometric approach, or extracted from experimental measurements. The comparisons of ex-
 2805 perimental data, and/or more complete theoretical predictions with reduced number of approximations, to
 2806 the simple cross sections expected from the pocket formula, allow one to assess the corresponding size and
 2807 impact of parton correlations in the proton (or nuclear) wave functions. Since DPS and TPS cross sections
 2808 depend on the square and cube of the corresponding SPS cross sections, perturbative processes with large
 2809 enough SPS cross sections are needed in order to have a visible number of events at the HL-LHC: this is the
 2810 advantage of using multiple production of quarkonia, over more rare heavy particles such as electroweak
 2811 bosons, in NPS studies.

2812 7.2. Theoretical status of Double Parton Scattering

2813 7.2.1. Factorisation of DPS cross sections

2814 The theoretical predictions for DPS cross sections rely on the factorisation of the underlying dynamics as
 2815 a convolution of parton-parton cross sections and dPDFs, as described by Eq. (10). A first vital question
 2816 is whether this factorisation actually holds, up to power-suppressed corrections. A starting point is to look
 2817 at the production of two colourless systems, e.g. of (pairs of) W , Z or H^0 bosons since, for their SPS

2818 production, factorisation was proven for both the total and TMD cross sections in the 1980s [448, 859–
 2819 861]. In recent years, it has been established that DPS factorisation also holds for the double Drell–Yan
 2820 (DDY) process both for the case of the total cross section, and for the case where the transverse momenta
 2821 of the bosons are measured (double TMD, or DTMD, case) [462, 853, 862–865]. The steps that need to be
 2822 taken to demonstrate factorisation for the latter case are schematically shown in Fig. 47.

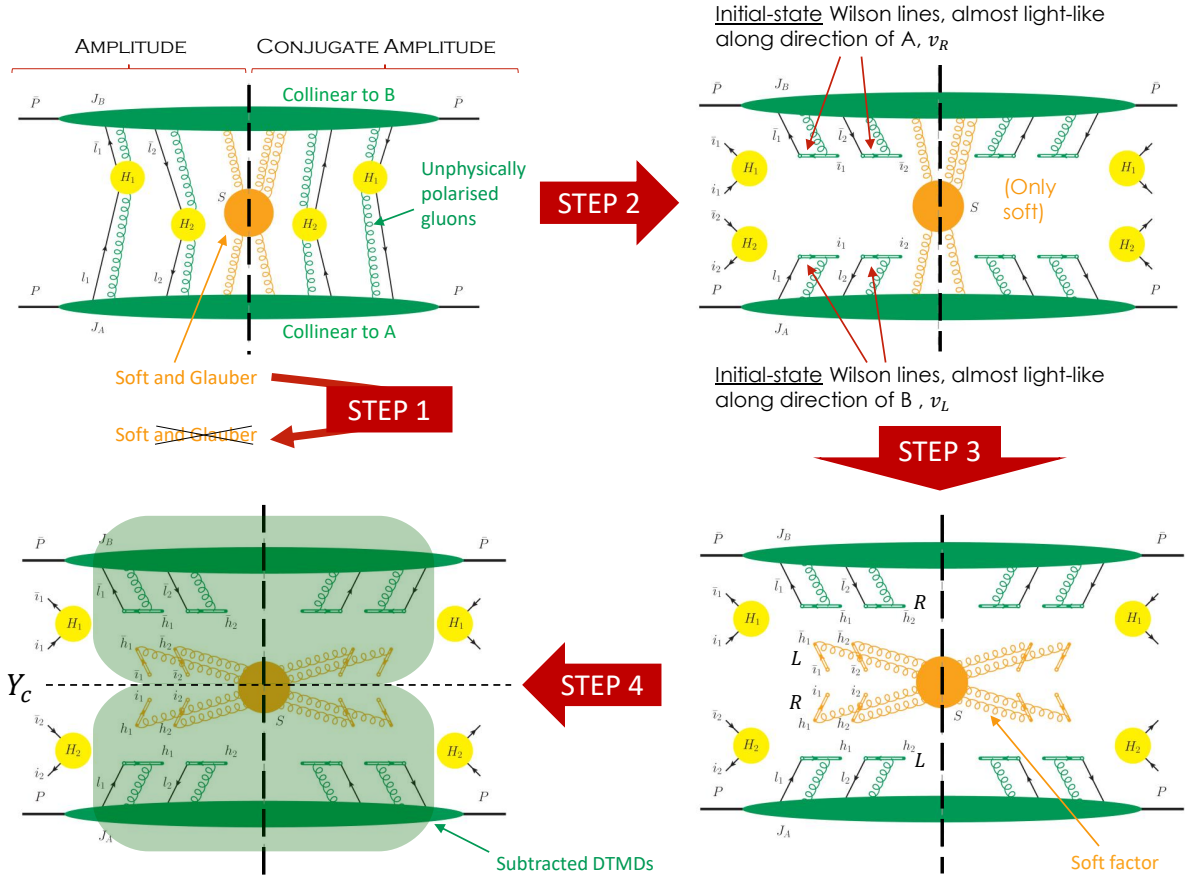


Figure 47: Diagrammatic illustration of the steps to achieve a proof of factorisation for the double Drell–Yan cross sections at a given transverse momentum. The green blobs represent the right and left moving proton, yellow blobs the hard interactions and orange blob the soft interactions. The graph is for the cross section, with the vertical line indicating the final state cut. [Figure modified from [864]].

2823 Certain contributions to DPS overlap with (loop) contributions to single scattering, and yet others over-
 2824 lap with other more-exotic scattering mechanisms such as higher twist contributions, or DPS-SPS interfe-
 2825 rence. A consistent factorisation framework for DPS should avoid double counting between DPS, single
 2826 scattering, and other mechanisms. A framework that achieves this, and maintains a description of the DPS
 2827 part in terms of separate rigorously defined dPDFs for each hadron, was developed in [854] (other propos-
 2828 als were made earlier [866–869], although these did not have this last property). The application of the
 2829 approach of [854] to the DTMD case is described in [853, 865]. Whether factorisation holds for other DPS
 2830 processes, including those involving quarkonium production, is less clear. Whatever factorisation-breaking
 2831 complications apply for SPS of quarkonium, via the CO channel at a given P_T (Section 4.2), are expected
 2832 to be carried over to the DPS case.

2833 7.2.2. Evolution of dPDFs

Apart from DPS factorisation, a second key element for the computation of double parton cross sections via Eq. (10) is to control the phase space evolution of dPDFs. Double parton distributions $F_{ab}(x_i, y, \mu_i)$, with $i = 1, 2$, enter the DPS factorised cross section through the parton luminosities $\mathcal{L}_{a_1 a_2 b_1 b_2} = \int d^2 \mathbf{y} F_{a_1 a_2}(y) F_{b_1 b_2}(y)$, where \mathbf{y} is the transverse separation between the two partons. A measurement of the dPDFs functional form is at present not yet available, and DPS phenomenological studies

rely on model Ansätze. However, their scale dependence is well known [866, 870–873] and is analogous to the familiar one for PDFs. Double PDFs evolve in energy scale μ_i according to generalised DGLAP equations

$$\frac{d}{d \log \mu_1^2} F_{a_1 a_2}(x_i, y, \mu_i) = \left(P_{a_1 c}^{(1)} \otimes_1 F_{c a_2} \right)(x_i, y, \mu_i) \quad \& \quad \frac{d}{d \log \mu_2^2} F_{a_1 a_2}(x_i, y, \mu_i) = \left(F_{a_1 c} \otimes_2 P_{c a_2}^{(2)} \right)(x_i, y, \mu_i), \quad (14)$$

2834 where $P_{ab}^{(1,2)}$ are the splitting functions, $y = |y|$ and the convolution \otimes is performed in x_1 or x_2 . This set of
 2835 equations is valid for the y -dependent dPDFs: integration over y introduces an additional inhomogeneous
 2836 term in Eq. (14).

2837 Given their dependence on many parameters, and their $O(N_f^2)$ multiplicity, dPDFs are complex to han-
 2838 dle numerically, both in terms of memory occupation and computational time. The LO double-DGLAP
 2839 evolution for the y -integrated dPDFs was first studied in [871], and a publicly available dPDF set (GS09
 2840 [874]) was provided based on a product Ansatz $F_{ab} = f_a \cdot f_b \cdot \Phi$, where $f_{a,b}$ are regular PDFs, and Φ is
 2841 a suppression factor. Recent progress has been made with a new tool called ChiliPDF [875, 876]. This
 2842 tool can solve the double-DGLAP equations up to NNLO, including $O(\alpha_s^2)$ matching at the flavour transi-
 2843 tion scales, in a fast and relatively lightweight way, with a working numerical precision below $O(10^{-4})$ for
 2844 $x_1 + x_2 < 0.8$ that is safely far beyond theory uncertainties on dPDFs (Fig. 48, Left). Quark-mass effects
 2845 can be sizeable for dPDFs. Considering as boundary condition for Eq. (14) the perturbative splitting from
 2846 PDFs into dPDFs (denoted as “1”, as opposed to the product Ansatz “2” [854]), the inclusion of the heavy-
 2847 quark masses by matching at the flavour-transition scales introduces large scale uncertainties on the evolved
 2848 dPDFs (Fig. 48, centre). The insertion of the gluon splitting into massive quarks in the “1” dPDFs visibly
 2849 reduces the uncertainties even at LO, as shown in Fig. 48 (Right) [877].

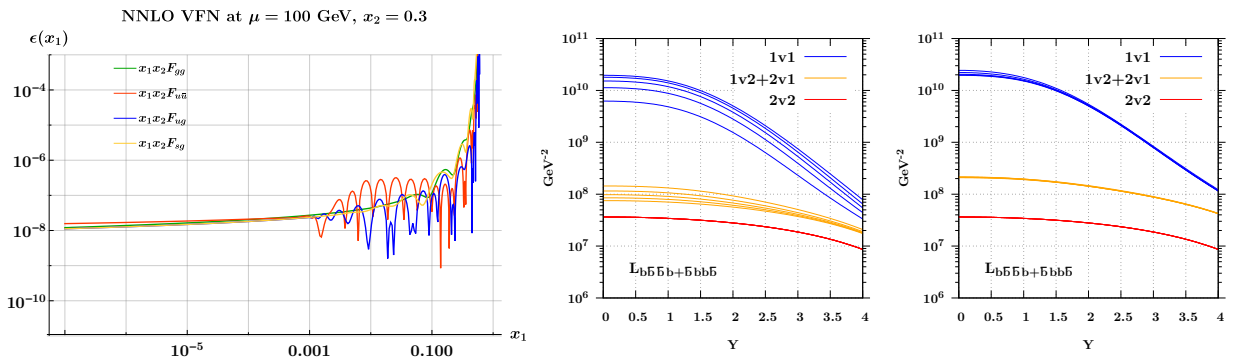


Figure 48: Left: Relative accuracy reached by ChiliPDF for a set of dPDFs (F_{gg} , F_{uu} , F_{ug} , F_{sg}) evolved to $\mu_1 = \mu_2 = 100$ GeV at NNLO in the variable-flavour-number (VFN) scheme, as a function of x_1 at fixed $x_2 = 0.3$. Centre: LO symmetrised luminosity $\mathcal{L}_{b\bar{b}b\bar{b}}$ for pure splitting (“1v1”), pure product (“2v2”), and mixed (“1v2+2v1”) combinations of dPDF Ansätze, at $\mu_1 = \mu_2 = 25$ GeV, and with the two final system rapidities $Y_1 = 0$ and $Y_2 = Y$. The lines correspond to variations of the matching scales $\mu_{c,b} = (1 \dots 5) \cdot m_{c,b}$ in the splitting Ansatz. Right: Same as centre plot, but with the inclusion of the gluons splitting into massive $c\bar{c}$ and $b\bar{b}$ pairs. [Left and centre figures are taken from [875]].

2850 7.2.3. Impact of parton correlations on σ_{eff}

The pocket formula (Eq. (11)) provides the baseline purely geometric DPS cross section expected in the absence of any parton correlations. Obviously, longitudinal, transverse, and spin correlations, among others, are present at the parton level, and are expected to modify the σ_{eff} value extracted from the ratio of squared SPS over DPS cross sections [878–880]. The role of these effects in digluon distributions, fundamental in gluon initiated processes such as those relevant for quarkonium production, has been covered in [881] in the covariant relativistic Light-Front (LF) approach adopted to calculate the dPDFs. In this case, rotations between the canonical and the LF spin induce model-independent correlations that prevent a factorisation between the (x_1, x_2) - b_\perp dependence (Fig. 49, Left), where b_\perp is the transverse partonic distance. By properly considering general features of moments of dPDFs, the following relationship has been derived for σ_{eff} [881, 882]:

$$\frac{\sigma_{\text{eff}}}{3\pi} \leq \langle b_\perp^2 \rangle \leq \frac{\sigma_{\text{eff}}}{\pi}. \quad (15)$$

2851 The right panel of Fig. 49 shows how data on σ_{eff} can thereby constrain the mean transverse distance
 2852 between two partons.

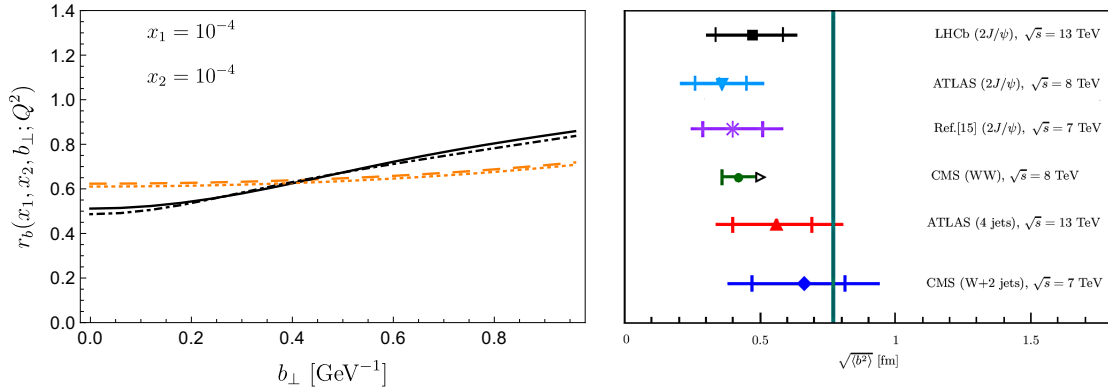


Figure 49: Left: Ratio $r_b(x_1, x_2, b_\perp, Q^2)$ quantifying the impact of relativistic correlations on digluon distributions [881]. This quantity would be equal to 1 if parton correlations were absent. Black and yellow curves shown the results of different models of double parton distribution functions for $Q^2 = m_H^2$ (full and dashed) and $Q^2 = 4m_c^2$ (dot-dashed and dotted). Right: Range of allowed transverse partonic distances obtained from the extracted mean values of σ_{eff} . [Figure adapted from [882].]

2853 Since correlations between the spin of partons have direct consequences on the angular distribution of
 2854 the particles produced in the final state, it has been proposed to study various asymmetries in DPS processes
 2855 to extract information on correlated quantum properties of two partons inside a proton. A calculation of
 2856 double same-sign W -boson production cross sections has recently demonstrated that spin correlations can
 2857 have large effects on the distribution of particles, and that the HL-LHC phase (if not before) opens up
 2858 the possibility to measure them [883, 884]. A promising variable for spin correlation measurements is
 2859 the asymmetry between the DPS cross section for the case when the leptons from the W -boson decay go
 2860 towards the same or opposite hemispheres. The rightmost panel of Fig. 50 shows the estimated significance
 2861 of a possible observation of such an asymmetry as a function of the integrated luminosity collected. Even
 2862 a *null measurement*, i.e. a precisely measured zero asymmetry, would be interesting, as it would severely
 2863 constrain the spin correlations inside the proton.

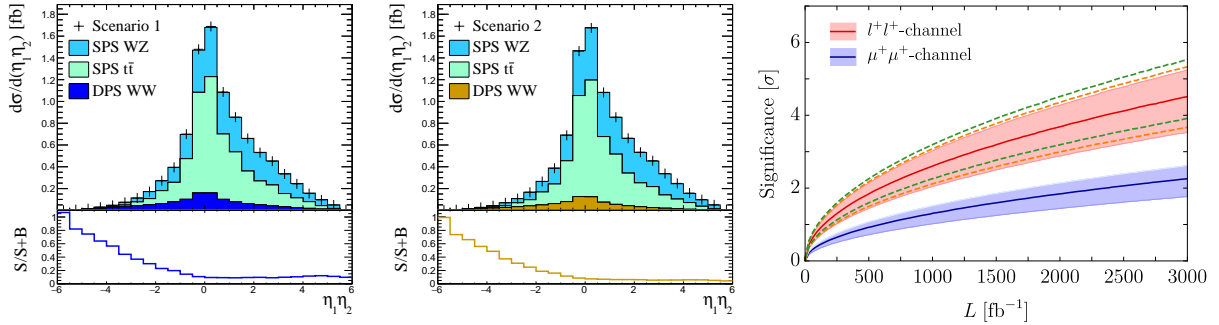


Figure 50: Results of template fits in Scenario 1 (correlated DPS with uncorrelated extraction, Left) and Scenario 2 (uncorrelated DPS with correlated extraction, centre) for the product of pseudorapidity densities of same-sign leptons from the decay of DPS $W + W$ production. Right: Estimate of the significance (in standard deviations) of an assumed asymmetry of 0.11 for a signal cross section of 0.29 fb. Blue line/band corresponds to $\mu^+\mu^+$ only, while the red line/band includes all positively charged combinations of e^+ and μ^+ . Dashed curves show the sensitivity of the central red curve to changes in the asymmetry of $\pm 20\%$ (orange dashed curves) and the magnitude of the DPS cross section by a factor of 3/2 or 3/4 (green dashed curves). [Plots are taken from [883]].

2864 Fig. 50 (Left and Centre) shows two template fits to a combination of DPS signal and backgrounds.
 2865 In Scenario 1 (Fig. 50, Left) partons are assumed to be correlated, but the extraction assumes uncorrelated
 2866 DPS. In Scenario 2 (Fig. 50, centre) the roles are reversed. Assuming an underlying effective cross section
 2867 of $\sigma_{\text{eff}} = 15$ mb, the values for the fiducial cross sections and associated σ_{eff} derived after analyses of
 2868 the angular distributions in the two scenarios are: $\sigma_{\text{DPS}} = 0.59$ fb, $\sigma_{\text{eff}} = 12.2$ mb, and $\sigma_{\text{DPS}} = 0.44$ fb,
 2869 $\sigma_{\text{eff}} = 16.4$ mb, respectively. As one can see, the 30% span of the DPS production cross section and the cor-
 2870 responding variation of σ_{eff} , found in this simple treatment, illustrate the danger of neglecting correlations
 2871 in DPS measurements in general, and of using correlation-sensitive variables in template fits in particular.

2872 Quantum number correlations will also be present in DPS involving one or more quarkonium states.

2873 The size of these effects are largely unknown, and the lessons learned from double- W production can be
 2874 directly applied to DPS quarkonium production. The smaller momentum fractions probed tend to decrease
 2875 the relevance of correlations, but the corresponding lower energy scale tends to increase their effects. If
 2876 difficulties in isolating the DPS contribution in quarkonium production can be overcome, the large DPS
 2877 cross sections provide unique possibilities to study interparton correlations.

2878 7.3. DPS studies with Q

2879 7.3.1. Current status

2880 Thanks to their large production yields in hadronic collisions, multiple measurements exist now of the
 2881 cross sections for the production of two quarkonium states, or a quarkonium plus another high- P_T or heavy
 2882 particle, in proton-(anti)proton collisions at the LHC and Tevatron. The corresponding SPS studies, as tools
 2883 to understand the quarkonium production mechanism itself, are discussed in Sec. 2.5. The measurements
 2884 can be generally categorised as diquarkonium processes: $J/\psi + J/\psi$ [190–194], $J/\psi + \Upsilon$ [196], and $\Upsilon +$
 2885 Υ [173, 195], quarkonium in association with a vector boson: $J/\psi + W^\pm$ [135, 137] and $J/\psi + Z$ [136],
 2886 or with an open heavy-flavour hadron: $J/\psi + \text{open-charm hadron}$ [885], $\Upsilon + \text{open-charm hadron}$ [886]. All
 2887 these processes have recently been reviewed in [7].

2888 The standard DPS measurements proceed as follows. Since DPS are by nature more kinematically un-
 2889 correlated than single scattering processes, the DPS contribution preferentially populates the regions with
 2890 larger azimuthal and rapidity separations between the two produced objects, compared to the SPS produc-
 2891 tion mechanisms. The y and ϕ differential cross sections measured in data are compared to the expectations
 2892 of SPS models, and any excess with respect to the SPS predictions is attributed to DPS contributions. An ex-
 2893 ample of a differential production cross section in bins of rapidity difference (of two J/ψ mesons), is shown
 2894 in Fig. 51 (Left). This plot also illustrates a typical misconception of theoretical uncertainties in which the
 2895 shapes of the extremal curves of an uncertainty band are assumed to give the shape of all the possible theory
 2896 curves. Theory uncertainty bands rather indicate where one expects to find curves computed at a higher
 2897 precision; these may not follow the same shape. In the present case, such an approximation artificially un-
 2898 derestimates the SPS uncertainty and overestimates the discriminating power of the $|\Delta y|$ spectrum between
 2899 the DPS and SPS contributions.

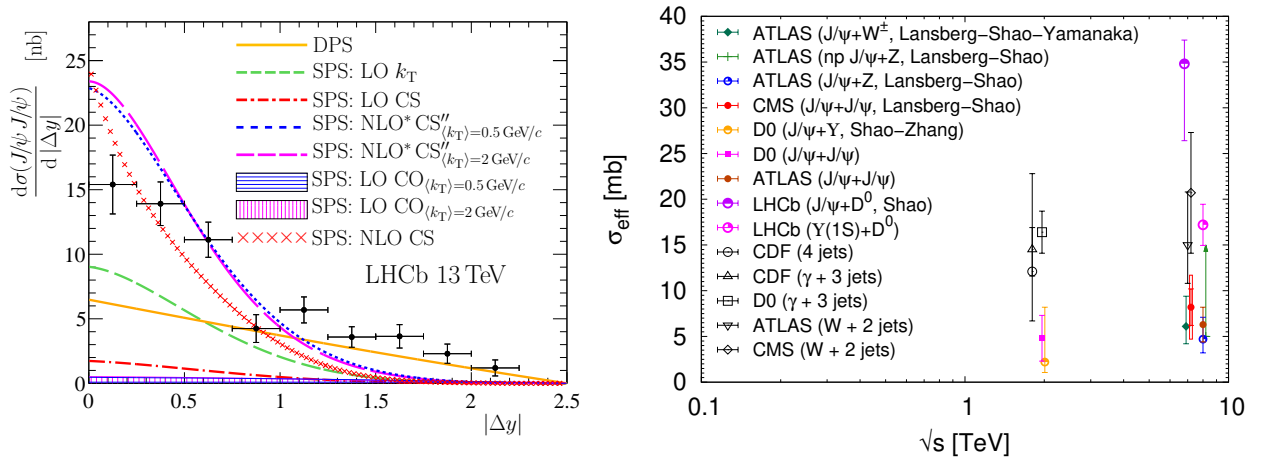


Figure 51: Left: Differential J/ψ -pair production cross section as a function of rapidity difference $|\Delta y|$ of two J/ψ mesons measured by LHCb in pp collisions at $\sqrt{s} = 13$ TeV, compared to SPS (various models, without uncertainties) and DPS predictions. Right: Comparison of σ_{eff} values extracted with different processes in pp and $p\bar{p}$ collisions. [Left plot is from [194], and right plot is from [887].]

2900 From the derived value of σ_{DPS} , one can then usually derive the associated effective cross section taking
 2901 its ratio to the product of corresponding SPS cross sections as per Eq. (11), $\sigma_{\text{eff}} \propto (\sigma_{\text{SPS}}^{H_1} \sigma_{\text{SPS}}^{H_2}) / \sigma_{\text{DPS}}^{H_1+H_2}$.
 2902 Smaller values of σ_{eff} correspond to larger DPS cross sections. Fig. 51 (Right) summarises the current
 2903 status of σ_{eff} extractions, based on the DPS pocket formula, with different final states [35, 75, 141, 158,
 2904 191, 193, 197, 202, 203, 885, 886, 888–891]. Values of $\sigma_{\text{eff}} \approx 2\text{--}30$ mb have been derived, though with
 2905 large errors, with a simple (unweighted) average giving $\sigma_{\text{eff}} \approx 15$ mb. This summary plot indicates that σ_{eff}
 2906 is smaller when derived from measurements of quarkonium processes in the ATLAS and CMS experiments,

2907 which typically cover central rapidities and require J/ψ mesons with relatively large P_T in order to ensure
 2908 the decayed muons can reach the muon chambers. On the contrary, the other (forward) quarkonium-based
 2909 extractions lead to larger σ_{eff} values, indicating smaller DPS contributions.

2910 Such differences can be interpreted as indicative of the non-universality of σ_{eff} when measured in differ-
 2911 ent kinematic ranges (LHCb vs ATLAS/CMS), (e.g. due to the different relative weight of gluon vs. quark
 2912 initial states), of non-universal parton correlations, and/or attributed to poorly controlled subtractions of
 2913 SPS contributions. One typical example for the last point is the process of production of a J/ψ meson in
 2914 association with a D^0 meson discussed in [891]. This more recent and more refined analysis with improved
 2915 SPS calculations yields a factor of two larger σ_{eff} value than the one presented in the original LHCb pa-
 2916 per [885], where the SPS contribution was assumed to be negligible. Similar caution is necessary when
 2917 using associated production of Υ plus open-flavour to extract DPS cross sections, as done by LHCb Col-
 2918 laboration with the $\Upsilon + D$ final state [886]. As shown in [554], taking into account NRQCD CO processes,
 2919 feed-down decays, and $g \rightarrow D$ fragmentation contributions, one can obtain SPS cross section values of the
 2920 same order as observed in the data. Moreover, the initial-state radiation effects, considered in [554] within
 2921 the HE factorisation, lead to kinematic distributions very similar to those observed in the experiment (with
 2922 the notable exception of the $\Delta\phi$ distribution, which has a hard-to-explain enhancement towards $\Delta\phi \rightarrow 0$ in
 2923 the data). Therefore, the conclusion that $\Upsilon + D$ production is dominated by DPS is significantly weakened.

2924 The importance of appropriately controlling the SPS production mechanism before attempting to extract
 2925 any DPS cross section is further illustrated in Fig. 52 for double- J/ψ production. In NRQCD factorisation,
 2926 the total cross section of (direct) J/ψ pair production is dominated by double CS $^3S_1^{[1]}$ contribution as
 2927 confirmed both in the collinear factorisation up to NLO accuracy [35, 179, 181, 188] and in HE factori-
 2928 sation [189] discussed in Section 4.3. On the other hand, in the CEM with collinear factorisation at LO
 2929 and NLO accuracy, such a contribution is absent, thereby leading to an underestimation of the SPS cross
 2930 sections in the whole Δy range [76] (Fig. 52, Left). If the CEM prediction was to be trusted, then practically
 2931 the whole double- J/ψ production cross section should be attributed to DPS, which would lead to a corre-
 2932 sponding reduced value of σ_{eff} and would require unrealistically strong partonic correlations to describe the
 J/ψ momenta distributions observed in data.

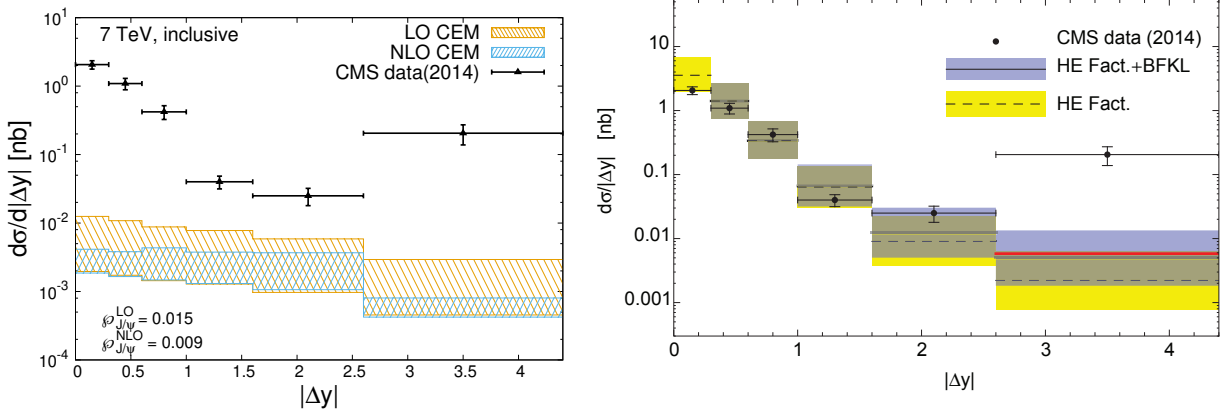


Figure 52: Differential J/ψ -pair production cross section as a function of the rapidity difference between the two J/ψ mesons, $|\Delta y|$, measured by the CMS experiment in pp collisions at $\sqrt{s} = 7$ TeV [192], compared to the predictions of the LO and NLO CEM (Left) and of the HE factorisation (Right). [Left plot is from [76], and right plot adapted from [189]].

2933 In addition to the effects related to unknowns arising in the SPS cross section, further caution must
 2934 be exercised with the assumptions on the DPS cross section itself. In particular, as discussed above, the
 2935 shape of the DPS signal is unknown in the presence of parton correlations and can have an impact on the
 2936 extractions of the DPS cross section.

2937 In the next section, we discuss how upcoming measurements, in particular with the new opportunities
 2938 opened up at the HL-LHC, can help to clarify the aforementioned experimental and theoretical issues and
 2939 thereby improve our understanding of DPS processes with quarkonium-based studies.

2941 7.3.2. HL-LHC prospects

2942 A first step to exploit quarkonium DPS measurements in order to extract quantitative information on the
2943 hadronic wave functions (in particular, on the various underlying sources of partonic correlations) and their
2944 energy evolution, is to understand the wide span of σ_{eff} extractions shown in Fig. 51 (Right). As mentioned
2945 above, leading sources of confusion are the different techniques used in each measurement to determine
2946 and remove the contamination from SPS contributions in the DPS signal region. Key to the ability to
2947 impose more stringent cuts and to better probe different corners of phase space are, firstly the very large
2948 data samples, and secondly, the upgraded charged-particle tracking over a wide pseudorapidity, $|\eta| \lesssim 5$,
2949 (with muon acceptance extended by half a unit, up to $|\eta| \lesssim 3$) in the ATLAS and CMS detectors during
2950 the HL-LHC phase. Both advantages will allow a better study of the azimuthal and rapidity separations
2951 between quarkonium states simultaneously produced in SPS and DPS processes. The following concrete
2952 experimental proposals are suggested for DPS studies at HL-LHC:

- 2953 • In order to better extract the DPS signal from the data, rather than simple standard cut-based analyses
2954 used so far, more advanced multi-variate analyses of the relevant quarkonium pair kinematic variables
2955 ($y_{ij}, \phi_{ij}, P_{Tij}, \dots$) should be carried out. SPS predictions with the highest order of accuracy (ideally, at
2956 least, NLO plus resummation and/or parton showering) should be used only, and effects of variations
2957 in the shape of the DPS cross section should be explicitly investigated. The theoretical uncertainty as-
2958 sociated with the SPS cross sections should be properly propagated into any experimentally extracted
2959 DPS cross section and σ_{eff} value.
- 2960 • Final states with $\psi(2S)$ mesons, free of feed-down contributions in contrast to the J/ψ mesons com-
2961 monly studied so far, should be considered. High-statistics measurements of the $\Delta\phi$ -differential dis-
2962 tribution of $Q\bar{Q}$ -pair production at $|\Delta y| \gtrsim 2.5$, where all SPS models tend to fail, should be performed.
2963 The $J/\psi + \psi(2S)$ and $J/\psi + \chi_c$ final states are of particular interest as they can provide new ways to dif-
2964 ferentiate the SPS and DPS contributions since their feed-down fraction to J/ψ pairs are significantly
2965 different when they are produced by SPS and DPS [7, 35].
- 2966 • The production of charmonium (e.g. $\psi(2S)$ as an essentially feed-down-free state) plus a B -meson (or
2967 a non-prompt J/ψ) is an interesting candidate for future DPS studies, since the leading v contribution
2968 from the CSM is suppressed at LO [7] and the B fragmentation function is better controlled than that
2969 of the D .
- 2970 • Beyond the first study of the associated production of a J/ψ with a charmed meson carried out by
2971 LHCb [885], it will be instructive to perform precise comparisons of the P_T spectra associated with
2972 different charm hadrons and those produced alone. With more precise measurements, it will be pos-
2973 sible to confirm the hint of a slight difference in the P_T spectrum of the J/ψ produced alone or with
2974 a charmed hadron. Such a confirmation would go against the DPS dominance, thus along the lines
2975 of [891]. Obviously, this could be complemented by the extraction of the DPS yields using data from
2976 control regions and DPS MC simulations.
- 2977 • The unique feature of the ALICE detector for quarkonium studies is a forward muon system, covering
2978 $2.5 < \eta < 4$, combined with a central-barrel tracking/PID system ($|\eta| < 0.9$) to achieve pseudorapidity
2979 differences $|\Delta\eta|$ up to 4.9, exceeding the capabilities of ATLAS and CMS. With an expected pp -
2980 collision data set corresponding to $\sim 0.2 \text{ fb}^{-1}$, measurements of D or B mesons in the central region,
2981 associated with a quarkonium in the forward region, become possible with very low limits on P_T for
2982 both objects. Compared to ATLAS and CMS, the relatively low integrated luminosity of ALICE will
2983 be compensated by the much smaller pileup probability (and lower P_T).
- 2984 • During Run-2, the LHCb experiment collected around 6 fb^{-1} of pp collisions at $\sqrt{s} = 13 \text{ TeV}$
2985 which, for double- J/ψ production, translates into data samples 20 times larger than in previous DPS
2986 measurements. This data sample remains to be analysed and will make it possible to study doubly
2987 differential production cross sections, e.g. in two-dimensional bins of J/ψ -pair transverse momentum
2988 and invariant mass, especially probing the momentum distribution of linearly polarised gluons inside
2989 unpolarised protons [16, 22] (Section 4.5.2). Using the data sets expected at the HL-LHC, one can
2990 carry out a similar programme of measurements for rarer processes, such as those, for example,
2991 involving $\psi(2S)$, Υ or even η_c [179].

2992 • In all the above cases, quarkonium polarisation measurement can be instrumental in disentangling
 2993 DPS from SPS. If the former are dominant, the quarkonium polarisation should be identical in both
 2994 single and associated production.

2995 • J/ψ -pair production could also be studied at the FT-LHC at $\sqrt{s} = 115$ GeV with large enough yields
 2996 to look for possible DPS contributions [182]. This would provide a possibly unique measurement of
 2997 σ_{eff} in this energy range.

2998 On the theoretical side, the following developments, among others, are needed to fully exploit the
 2999 experimental data made available:

3000 • The theoretical SPS cross sections (“subtracted” from the experimental data in order to identify the
 3001 DPS contributions) need to include the largest number of perturbative corrections possible, both for
 3002 FO and resummed logarithms terms. Additionally, and particularly relevant for quarkonium pro-
 3003 duction, efforts to significantly reduce the model dependence will be crucial to isolate the DPS cross
 3004 section. Predictions with limited theoretical accuracy should be avoided as they consequently degrade
 3005 the DPS cross-section extraction.

3006 • Progress towards full-NLO corrections for the DPS cross sections for double-quarkonium production,
 3007 including pQCD-induced partonic correlations, computed via Eq. (10), must be made.

3008 • Studies should be undertaken of the impact of perturbative and non-perturbative effects on gluon-
 3009 gluon double parton distribution functions calculated within phenomenological models, such as con-
 3010 stituent quark models.

3011 • A consistent treatment of heavy-quark-mass thresholds and the evaluation of their numerical effect in
 3012 DPS cross sections is required.

3013 • Cross-section calculations should be performed for double quarkonium production including explic-
 3014 itly the effects of parton correlations of (i) kinematic (momentum fractions, transverse separation),
 3015 (ii) quantum (flavour, spin, colour, fermion number), and (iii) mixed (involving interplay between the
 3016 two) origins.

3017 • Explicit studies of the x -dependence of the effective cross section σ_{eff} , and identification of experi-
 3018 mental observables sensitive to such an evolution, are required.

3019 7.4. TPS studies with Q in pp collisions

3020 As discussed in the previous Section, the wide span of σ_{eff} extractions based on the DPS pocket formula
 3021 for double-quarkonium measurements (Fig. 51, right) calls for alternative studies that can shed light on the
 3022 origin of the ranges of derived values. In [36], it was pointed out for the first time that the study of triple
 3023 parton scatterings (TPS) can further help to independently improve our understanding of the transverse
 3024 proton profile and estimate the impact of parton correlations. The pocket formula for triple parton scattering
 3025 reads, based on Eq. (13),

$$\sigma_{\text{TPS}}^{hh' \rightarrow H_1+H_2+H_3} = \left(\frac{m}{3!}\right) \frac{\sigma_{\text{SPS}}^{hh' \rightarrow H_1} \cdot \sigma_{\text{SPS}}^{hh' \rightarrow H_2} \cdot \sigma_{\text{SPS}}^{hh' \rightarrow H_3}}{\sigma_{\text{eff,TPS}}^2}, \quad \text{with} \quad \sigma_{\text{eff,TPS}}^2 = \left[\int d^2b T^3(b) \right]^{-1}. \quad (16)$$

3026 In this purely geometric approach, it was demonstrated that for a wide range of proton transverse profiles
 3027 (encoded in the cube of the overlap function $T^3(b)$), the effective triple and double effective cross sections
 3028 are actually proportional and very similar numerically [36]:

$$\sigma_{\text{eff,TPS}} = k \times \sigma_{\text{eff}}, \quad \text{with} \quad k = 0.82 \pm 0.11. \quad (17)$$

3029 Therefore, from the $\sigma_{\text{eff,TPS}}$ values extracted from the data, one can derive independent values of σ_{eff} .
 3030 However, since TPS cross sections depend on the cube of the corresponding SPS cross sections, a triple
 3031 hard process $pp \rightarrow H_i + H_i + H_i$, with SPS cross sections $\sigma_{\text{SPS}}^{pp \rightarrow H_i} \approx 1 \mu\text{b}$, has a very small TPS cross
 3032 section $\sigma_{\text{TPS}}^{pp \rightarrow H_i+H_i+H_i} \approx 1 \text{fb}$, and perturbative processes with large enough SPS cross sections are needed

3033 in order to have visible number of events. The very large yields of quarkonium expected at the HL-LHC
 3034 allow one to carry out triple parton scattering (TPS) studies for the first time [36].

3035 As TPS is a priori of subleading power with respect to single and double parton scattering, its theoretical
 3036 investigation is challenging. As one goes to high scale Q , TPS contributions will rapidly diminish as
 3037 $\Lambda_{\text{QCD}}^4/Q^4$ compared to SPS. On the other hand, if one goes to few-GeV-scale observables, usually the
 3038 theoretical predictions are plagued with very large intrinsic theoretical uncertainties. In addition, extracting
 3039 TPS contributions requires an accurate control, not only of the SPS but also, of the SPS+DPS contributions,
 3040 as sources of the same final states. These three facts may reduce the eventual potential of TPS studies
 3041 at the LHC. Production modes that have been studied in the literature are the triple- J/ψ [37] and triple
 3042 $D\bar{D}$ -mesons [892] production, while other processes, like J/ψ +two same-sign open charm, and $J/\psi + J/\psi$
 3043 plus open charm production [35], are also worth pursuing. We will focus here on the triple- J/ψ production
 3044 process.

3045 A complete study on triple- J/ψ production in pp collisions at 13 TeV has been carried out in [37], by
 3046 computing SPS, DPS, and TPS contributions simultaneously for the first time based on the event generator
 3047 HELAC-ONIA [893, 894]. The study shows that the process receives a suppressed SPS contribution with
 3048 respect to the DPS and TPS ones. Thus, it becomes a golden channel for the first-ever observation of TPS
 3049 processes, and to provide new valuable insights into double-quarkonium production by comparing the value
 3050 of σ_{eff} obtained from the DPS contribution measured directly in the process to that derived from the TPS
 3051 yields via Eq. (17). The cumulative cross section $\sigma(pp \rightarrow 3J/\psi) \times \text{BR}^3(J/\psi \rightarrow \mu^+\mu^-)$ after imposing
 3052 the $P_T^{J/\psi} > P_{T,\text{min}}$ cut and the rapidity gap cut $|\Delta y(J/\psi, J/\psi)| > |\Delta y|_{\text{min}}$ on each J/ψ pair can be found in
 3053 Figs. 53a and 53b, respectively. By assuming 100% event-reconstruction efficiency, the horizontal lines in
 3054 the two plots indicate the cross sections at which 100 events are collected for several integrated luminosities.
 3055 In particular, with the nominal HL-LHC luminosity of 3 ab^{-1} , 100 events are anticipated with $P_T^{J/\psi} > 7 \text{ GeV}$.
 3056 Moreover, Fig. 53b shows that the minimal rapidity gap cut between J/ψ pairs can be used to improve the
 3057 purity of the TPS signal. Such a study was carried out by assuming zero correlation between the partonic
 3058 scatterings following Eq. (16) above. The measurement of this novel process with HL-LHC data should
 3059 definitely clarify whether such a simple geometric hypothesis is justified.

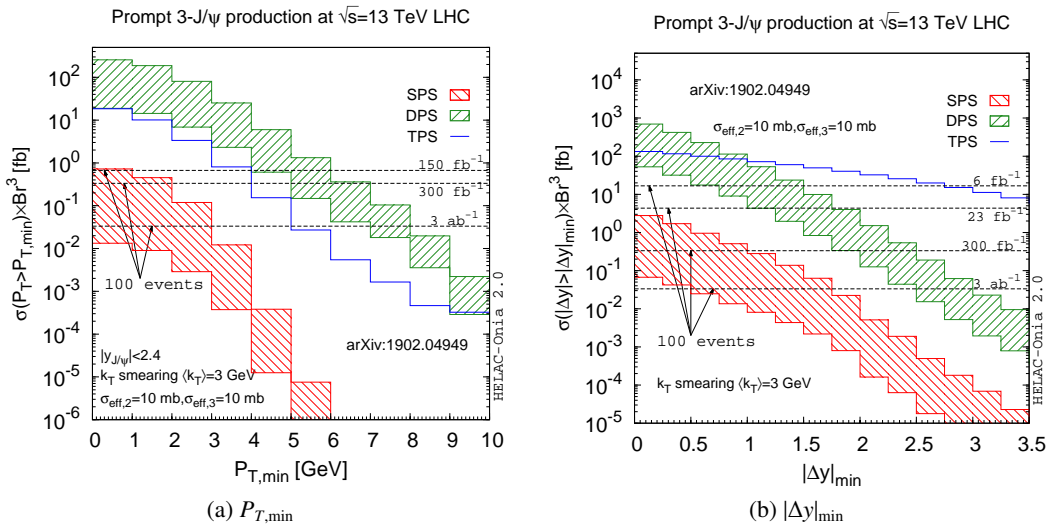


Figure 53: Cumulative cross section of the dependence of the triple- J/ψ production ($\sigma(pp \rightarrow 3J/\psi) \times \text{BR}^3(J/\psi \rightarrow \mu^+\mu^-)$, in fb) on the minimal transverse momentum cut $P_T^{J/\psi} > P_{T,\text{min}}$ (Left) and of the minimal rapidity gap cut $|\Delta y(J/\psi, J/\psi)| > |\Delta y|_{\text{min}}$ (Right) among three J/ψ 's in pp collisions at $\sqrt{s} = 13 \text{ TeV}$.

3060 7.5. DPS and TPS studies with Q in pA collisions

3061 pA and AA collisions also provide new handles on improving our understanding of DPS, and in general
 3062 NPS, processes. DPS [847, 848, 895] and TPS [850] are significantly enhanced in pA collisions compared
 3063 to pp collisions thanks to the (much) larger transverse parton density of nuclei compared to protons. As
 3064 discussed in the pp case, final states with quarkonia benefit from large production yields that have lead to
 3065 the first measurements of DPS processes, and to future more detailed analyses, as discussed below.

3066 In the case of DPS, the cross section receives contributions from interactions where the two partons of
 3067 the nucleus belong to the same nucleon ($\sigma_{\text{DPS},1}$), and two different nucleons ($\sigma_{\text{DPS},2}$). The pocket formula
 3068 for the DPS cross section of particles H_1, H_2 in pA collisions can be written as a function of the elementary
 3069 proton-nucleon (pN) SPS cross sections to produce H_1 and H_2 separately as [895]

$$\sigma_{\text{DPS}}^{pA \rightarrow H_1 + H_2} = \left(\frac{m}{2}\right) \frac{\sigma_{\text{SPS}}^{pN \rightarrow H_1} \cdot \sigma_{\text{SPS}}^{pN \rightarrow H_2}}{\sigma_{\text{eff,DPS},pA}}, \quad (18)$$

3070 where the effective DPS pA cross section in the denominator, $\sigma_{\text{eff,DPS},pA}$, depends on the standard σ_{eff}
 3071 parameter measured in pp collisions, Eq. (11), and on a pure geometric quantity, $T_{AA}(0)$, that is directly
 3072 derivable from the well-known nuclear transverse profile via a Glauber model [636]. The overall expected
 3073 DPS enhancement in pA compared to pp collisions is $\sigma_{\text{eff,DPS}}/\sigma_{\text{eff,DPS},pA} \approx [A + A^{4/3}/\pi]$ which in the case
 3074 of $p\text{Pb}$ amounts to a factor of ~ 600 relative to pp , i.e. a factor of $[1 + A^{1/3}/\pi] \approx 3$ higher than the naive ex-
 3075 pectation assuming the same A -scaling of the single parton cross sections [895]. The relative weights of the
 3076 two DPS contributions are $\sigma_{\text{DPS},1} : \sigma_{\text{DPS},2} = 0.7 : 0.3$ (for small mass number A), and $0.33 : 0.66$ (for large
 3077 A) [895]. One can thus exploit such large expected DPS signals over the SPS backgrounds in pA collisions
 3078 to study double parton scatterings in detail and, in particular, to extract the value of $\sigma_{\text{eff,DPS}}$ independently
 3079 of measurements in pp collisions. In addition, recent studies that incorporate impact-parameter-dependent
 3080 nPDF effects [896], have pointed out that the study of DPS processes in heavy-ion collisions provide useful
 3081 information on the (unknown) spatial-dependence of nuclear parton densities.

3082 In the case of triple parton scatterings, a similar formula to Eq. (18) has been derived [36], that includes
 3083 now three types of contributions from interactions where the three partons of the nucleus belong to the same
 3084 nucleon ($\sigma_{\text{DPS},1}$), two ($\sigma_{\text{DPS},2}$) and three different nucleons ($\sigma_{\text{DPS},3}$). For $p\text{Pb}$ collisions, the three TPS terms
 3085 are $\sigma_{\text{TPS},1} : \sigma_{\text{TPS},2} : \sigma_{\text{TPS},3} = 1 : 4.54 : 3.56$, and their sum amounts to 9.1, namely the TPS cross sections
 3086 are nine times larger than the naive expectation based on an A scaling of the corresponding proton-nucleon
 3087 TPS cross sections. Generic pocket formulas exist that allow the determination of the cross sections for
 3088 any combination of three final-state particles, including quarkonium states in pA collisions [856]. Using
 3089 NNLO predictions for single heavy-quark production, the authors of [36] have shown that three $D\bar{D}$ -pairs
 3090 are produced from separate parton interactions in about 10% of the $p\text{Pb}$ events at the LHC. The study of
 3091 TPS in pA scattering at the HL-LHC will provide novel experimental and theoretical handles to understand
 3092 double and triple parton scatterings, constrain the parton transverse profile of the proton, and clarify the role
 3093 of partonic correlations in the proton and ion wave functions.

3094 7.5.1. Current status

3095 The first-ever experimental study of DPS in pA collision has been carried out by LHCb, measuring the
 3096 like-sign $D + D$ ($D^0 + D^0$, $D^0 + D^+$ and $D^+ + D^+$) and $J/\psi + D$ production in $p\text{Pb}$ collisions at $\sqrt{s_{NN}} =$
 3097 5.02 TeV [897]. The azimuthal angle between the two charm hadrons in a pair, $\Delta\phi$, is measured to be flat,
 3098 independent of a cut on the charm transverse momentum for DD pairs, while that of $D\bar{D}$ pairs tends to
 3099 peak at $\Delta\phi \approx 0$ for higher charm P_T . The ratio of cross sections between DD and $D\bar{D}$ pairs is shown in
 3100 Fig. 54 (Left), with a magnitude of about 0.3, while the measurement in pp collisions is about 0.1 [885].
 3101 The forward-backward ratio (R_{FB}) quantifying the production at positive rapidities over that at negative
 3102 rapidities in the common range $2.7 < |y(D)| < 3.7$, is measured for $D\bar{D}$ pairs to be $R_{\text{FB}}(D\bar{D}) = 0.61 \pm$
 3103 0.04 (stat) ± 0.12 (syst), which is consistent with that of inclusive charm production $R_{\text{FB}}(D)$ [898], but that
 3104 of DD pairs is $R_{\text{FB}}(DD) = 0.40 \pm 0.05$ (stat) ± 0.10 (syst) $\approx R_{\text{FB}}^2(D\bar{D})$. Since the forward-backward ratio
 3105 being lower than unity is explained by the modification of nuclear PDF, the value for like-sign DD pairs
 3106 is consistent with two pairs of partons participating in the hard scattering. These observations support a
 3107 significant contribution of DPS in the like-sign DD production while the opposite-sign $D\bar{D}$ production has
 3108 a large component of SPS, namely the inclusive production of a single charm quark pair.

3109 The $\sigma_{\text{eff},pA}$ parameter is obtained using $D^0 + D^0$ and $J/\psi + D^0$ production assuming solely DPS con-
 3110 tribution (Fig. 54, Right). The LHCb derivation of $\sigma_{\text{eff},pA}$ results in a value that is (arbitrarily) normalised
 3111 to be $A^2 = 208^2$ times larger than that defined in Eq. (18). The theoretical prediction, shown as the grey
 3112 band in the plot, amounts to $\sigma_{\text{eff},pA} \approx 1$ b, and is supported by the data. This result confirms the predicted
 3113 factor of three enhancement for DPS compared to a simple A scaling [847, 848, 895]. Looking in more
 3114 detail, the positive-rapidity data exhibit a higher $\sigma_{\text{eff},pA}$ value compared to the negative rapidity one, which

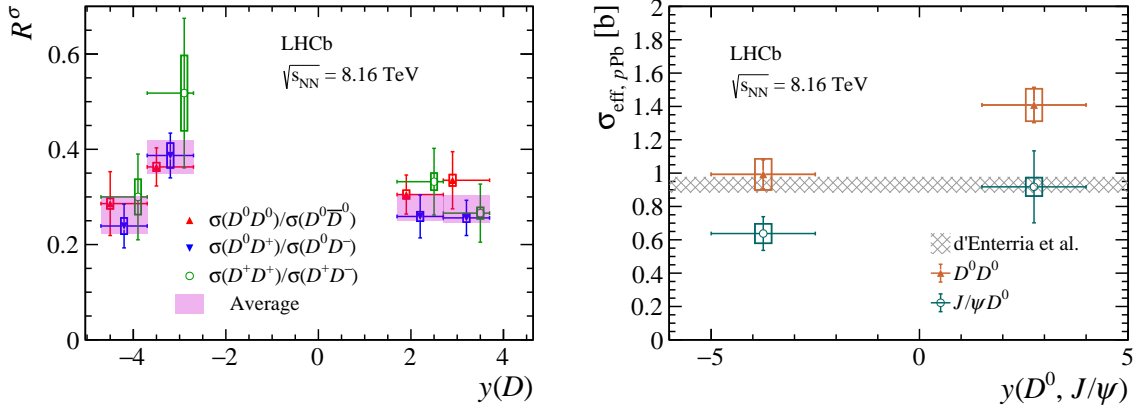


Figure 54: Left: Ratios of cross sections between like-sign and opposite-sign open charm pairs for different rapidity regions of charm hadrons [897]. The weighted average of ratios for different pairs is shown as a shaded magenta box. Right: σ_{eff} parameter derived using $D^0 + D^0$ and $J/\psi + D^0$ production for both negative and positive rapidities. The shaded area corresponds to the prediction from [895] scaled by A^2 , which predicts around a factor of three relative enhancement for DPS production compared to a naive scaling from pp collisions. Vertical bars (boxes) are statistical (systematic) uncertainties.

3115 implies the necessity of considering the impact-parameter dependence in nPDFs [896] (see below). The
 3116 $\sigma_{\text{eff}, pA}$ parameter measured for $J/\psi + D^0$ production hints at smaller values than that derived from $D^0 + D^0$
 3117 production, and the same behaviour was observed in pp data [885]. This is suggestive of a non-negligible
 3118 contribution of SPS in $J/\psi + D^0$ production [891] which is not subtracted in the LHCb analysis. Due to
 3119 limited statistics, the kinematic correlation between J/ψ and D^0 , e.g. the $\Delta\phi$ distribution, does not provide
 3120 yet enough information to identify the SPS component.

3121 The LHCb observation of non-identical $\frac{\sigma_{pPb \rightarrow D^0}^2}{2\sigma_{pPb \rightarrow D^0 + D^0}}$ values in the forward and backward regions indicates
 3122 the presence of more effects beyond the expected geometrical DPS enhancement in pp compared to pA
 3123 collisions. Assuming the same test function of the transverse spatial dependence $G(x) \propto x^a$ in the nuclear
 3124 PDF modifications suggested in [896], Fig. 55 shows that the LHCb data supports exponent values $a > 1.5$,
 3125 which however suffer from the uncertainty of $\sigma_{\text{eff}, pp}$. A smaller $\sigma_{\text{eff}, pp}$ value in fact requires stronger impact-
 3126 parameter dependence (i.e. larger a). The nuclear modification factors of single inclusive D^0 production in
 3127 the two rapidity intervals are from independent measurements of the single inclusive process. This example
 3128 corroborates the conclusion of [896] that DPS in pA collisions can be used to probe the impact-parameter-
 3129 dependent nPDFs.

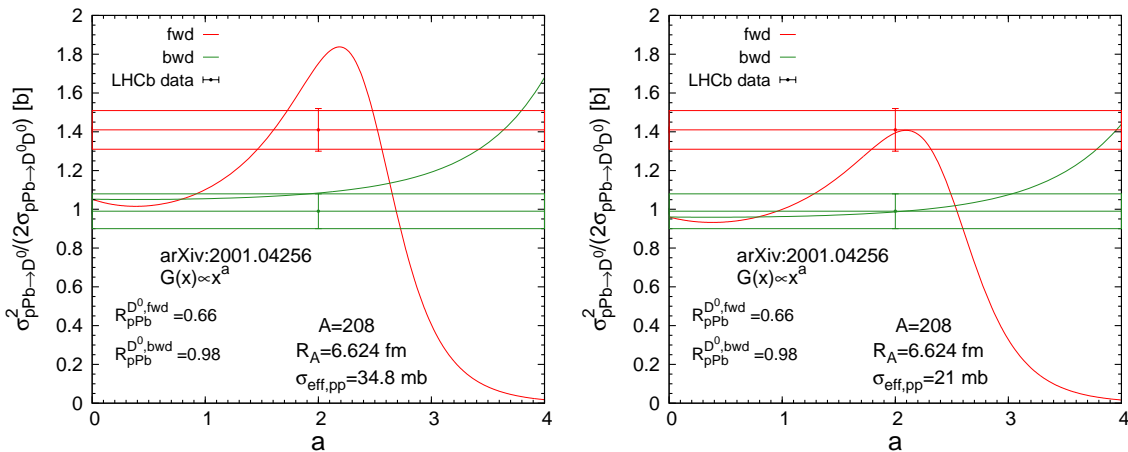


Figure 55: Comparison of the ratio $\sigma_{pPb \rightarrow D^0}^2 / (2\sigma_{pPb \rightarrow D^0 + D^0})$ between the impact-parameter-dependent DPS calculation [896] and the LHCb data [897] in both forward ($1.5 < y(D^0) < 4.0$) and backward ($-5.0 < y(D^0) < -2.5$) rapidity intervals. Two different $\sigma_{\text{eff}, pp}$ values are shown in the left and right plots respectively.

3130 7.5.2. HL-LHC prospects

3131 At the HL-LHC, with the size of $p\text{Pb}$ data samples increased by about a factor of ten compared to Run-2,
 3132 one can exploit the large expected DPS signals over the SPS backgrounds in quarkonium final states as a
 3133 means to scrutinise double and triple parton scatterings and, in particular in the purely geometric picture
 3134 neglecting parton correlations, to extract the value of the effective DPS cross section σ_{eff} independently of
 3135 (and complementarily to) measurements in pp collisions. First off, measurements in fine bins of final-state
 3136 kinematics can be obtained for $J/\psi + D^0$ pairs in order to understand the possible difference of the $\sigma_{\text{eff},pA}$
 3137 parameter derived from $J/\psi + D^0$ and $D^0 + D^0$ data, and shed light on the varying values at negative and
 3138 positive rapidities (Fig. 54).

3139 Table 4 collects the expected DPS cross sections for the combined production of quarkonia ($J/\psi, \Upsilon$)
 3140 and/or electroweak bosons (W, Z) in $p\text{Pb}$ collisions at the nominal LHC energy of $\sqrt{s_{NN}} = 8.8$ TeV. The
 3141 individual SPS pN cross sections have been derived in [849] at NLO accuracy with the colour evapora-
 3142 tion model (CEM) [899] for quarkonia, and with mCFM for the electroweak bosons, using the CT10 [900]
 3143 proton and EPS09 [616] nPDFs. The EPS09 nPDF does not include any impact-parameter dependence of
 3144 nuclear effects, i.e. it ignores the effects discussed in Fig. 55. The DPS cross sections are estimated with
 3145 the factorised expression for pA collisions, Eq. (18) with $\sigma_{\text{eff,DPS},pA} = 22.5 \mu\text{b}$. The visible DPS yields
 3146 ($N_{\text{DPS},p\text{Pb}}$ values quoted) are estimated taking into account the relevant di-lepton decay branching fractions
 3147 $\text{BR}(J/\psi, \Upsilon, W, Z) = 6\%, 2.5\%, 11\%, 3.4\%$, plus simplified acceptance and efficiency losses. For J/ψ , the
 3148 following value $(\mathcal{A} \times \mathcal{E})_{J/\psi} \approx 0.01$ was assumed over merely one unit of rapidity at $|y| = 0$, and $|y| = 2$,
 3149 corresponding to ATLAS/CMS central, and ALICE/LHCb forward, acceptances. For Υ and W, Z , the fol-
 3150 lowing values $(\mathcal{A} \times \mathcal{E})_{\Upsilon} \approx 0.2$ and $(\mathcal{A} \times \mathcal{E})_{W,Z} \approx 0.5$ were assumed over $|y| < 2.5$. The quoted numbers
 3151 were evaluated for an integrated luminosity amounting to $\mathcal{L}_{\text{int}} = 1 \text{ pb}^{-1}$. The quoted $N_{\text{DPS},p\text{Pb}}$ values are
 3152 conservative for two reasons. First, ATLAS/CMS may ultimately integrate about $\mathcal{L}_{\text{int}} = 2 \text{ pb}^{-1}$ $p\text{Pb}$ colli-
 3153 sions (although ALICE/LHCb should record half this value, see Table 3) [2]. Second, for final states with
 3154 J/ψ , the expected number of visible events can be easily multiplied by a factor of 3–5, taking into account
 3155 the full rapidity acceptance (enlarged after Run-2, in some cases) of the ALICE/LHCb and ATLAS/CMS
 3156 detectors. All listed processes are therefore in principle observable in the LHC proton-lead runs. Rarer DPS
 3157 processes like $W + Z$ and $Z + Z$ have much lower cross sections and will require much higher integrated
 3158 luminosities at the HL-LHC and/or c.m.s. energies such as those reachable at the CERN Future Circular
 3159 Collider [901, 902].

Table 4: Estimated production cross sections at $\sqrt{s_{NN}} = 8.8$ TeV for SPS quarkonia and electroweak bosons in pN collisions, and for DPS double- J/ψ , $J/\psi + \Upsilon$, $J/\psi + W$, $J/\psi + Z$, double- Υ , $\Upsilon + W$, $\Upsilon + Z$, and same-sign $W + W$, in $p\text{Pb}$. DPS cross sections are obtained via Eq. (18) for $\sigma_{\text{eff,DPS},pA} = 22.5 \mu\text{b}$ (uncertainties, not quoted, are of the order of 30%), and the associated yields for 1 pb^{-1} integrated luminosity, after di-lepton decays and acceptance+efficiency losses [849, 903]. We note that the J/ψ yields quoted are only *per unit of rapidity* at mid- or forward- y .

$p\text{Pb}, \sqrt{s_{NN}} = 8.8 \text{ TeV}$	final states			
	$J/\psi + J/\psi$	$J/\psi + \Upsilon$	$J/\psi + W$	$J/\psi + Z$
$\sigma_{\text{SPS}}^{pN \rightarrow a}, \sigma_{\text{SPS}}^{pN \rightarrow b}$	$45 \mu\text{b} (\times 2)$	$45 \mu\text{b}, 2.6 \mu\text{b}$	$45 \mu\text{b}, 60 \text{ nb}$	$45 \mu\text{b}, 35 \text{ nb}$
$\sigma_{\text{DPS}}^{p\text{Pb}}$	$45 \mu\text{b}$	$5.2 \mu\text{b}$	120 nb	70 nb
$N_{\text{DPS}}^{p\text{Pb}} (1 \text{ pb}^{-1})$	~ 65	~ 60	~ 15	~ 3
	$\Upsilon + \Upsilon$	$\Upsilon + W$	$\Upsilon + Z$	ss $W + W$
$\sigma_{\text{SPS}}^{pN \rightarrow a}, \sigma_{\text{SPS}}^{pN \rightarrow b}$	$2.6 \mu\text{b} (\times 2)$	$2.6 \mu\text{b}, 60 \text{ nb}$	$2.6 \mu\text{b}, 35 \text{ nb}$	$60 \text{ nb} (\times 2)$
$\sigma_{\text{DPS}}^{p\text{Pb}}$	150 nb	7 nb	4 nb	150 pb
$N_{\text{DPS}}^{p\text{Pb}} (1 \text{ pb}^{-1})$	~ 15	~ 8	~ 1.5	~ 4

3160 8. Summary

3161 Quarkonium measurements at the LHC are not only motivated by the intrinsic goal of advancing our under-
 3162 standing of their underlying production mechanisms, which are still not fully understood today, but also by

3163 the broad and unique opportunities they offer to perform a wide range of studies. In this document, we have
3164 reviewed the prospects for quarkonium studies in the upcoming high-luminosity phases of the LHC, with
3165 proton-proton (pp), proton-nucleus (pA), and nucleus-nucleus (AA) collisions. Among the research topics
3166 highlighted are: opportunities in multi-quark spectroscopy; in new probes of the proton parton distributions
3167 including transverse-momentum dependent and spin effects; in sensitive observables for the study of dou-
3168 ble parton scattering interactions; in nuclear PDFs or other nuclear effects; and in studies to determine the
3169 properties of the quark-gluon plasma.

3170 Section 2 surveyed the prospects for measurements of quarkonium production in pp collisions in the
3171 coming years and into the HL-LHC era. The motivations for future measurements of the quarkonium P_T
3172 spectra and polarisation were discussed, as well as the possibilities for more detailed characterisations of the
3173 properties of quarkonium-production events, in particular for J/ψ and Υ . Such investigations can be under-
3174 taken through the study of (i) the hadronic activity accompanying scatterings where quarkonia are produced,
3175 (ii) the formation of quarkonia within high-energy jets, and (iii) their associated production alongside highly
3176 energetic objects such as jets, vector bosons, or other quarkonium states. We have highlighted where such
3177 measurements can provide new insights into broader fields such as in the search for new physics phenomena
3178 and in the study of multi-parton interactions, and where such measurements have already shown significant
3179 promise. The potential for the study of C -even quarkonia as well as multi-quark and molecular states was
3180 presented. Opportunities for HL-LHC quarkonium data to provide constraints on proton PDFs in the low- x
3181 and low-scale regime were also outlined.

3182 Section 3 addressed diffractive and, mainly, exclusive photoproduction of quarkonia in hadron-hadron
3183 collisions. After a short description of selected experimental results and the discussion of open points in ex-
3184 periment and theory, this section focused on measurements possible at the HL-LHC, both in the collider and
3185 fixed-target modes, that either have not yet been performed or that have not yet been sufficiently exploited.
3186 In particular, the study of forward J/ψ production in combination with a backward jet and the study of ex-
3187 clusive single-quarkonium and quarkonium-pair production, which provide access to the multi-dimensional
3188 nucleon and nucleus partonic structure, have been discussed. Here, the advantage of pA collisions in the
3189 collider data-taking mode, and the need for high integrated luminosities, have been highlighted in order to
3190 fully exploit the potential of exclusive measurements.

3191 Section 4 focused on studies of the transverse-momentum-dependent and spin dynamics in quarkonium
3192 production in pp collisions. Having first reviewed the two main frameworks that account for transverse-
3193 momentum-dependent effects, i.e. TMD factorisation and HE factorisation, a discussion followed on their
3194 applicability to quarkonium production along with potential challenges, open issues, and opportunities. In
3195 particular, the discussion covered those quarkonium-production processes that can be used to study the im-
3196 pact of factorisation-breaking effects and the region of applicability of these frameworks. Single transverse-
3197 spin asymmetries, believed to be generated in quarkonium production by the gluon Sivers effect, that arises
3198 from the correlation between the proton spin and the gluon motion, were also addressed. Three approaches
3199 which can account for this correlation have been discussed, as well as a selection of experimental projections
3200 for the HL-LHC in unpolarised collisions, and in polarised collisions in the LHC FT mode.

3201 Section 5 focused on inclusive quarkonium studies in pA collisions at the LHC. First, a survey of the
3202 different phenomena at play was given. This was followed by an overview of the current status of the use
3203 of quarkonium data to constrain nPDFs in the collider and FT modes, and of low- x parton saturation calcu-
3204 lations applied to quarkonium production. Second, experimental observables used to compare quarkonium
3205 production in pA and pp collisions were discussed. The section concluded with a discussion of the sta-
3206 tus and prospects for the understanding of flow-like phenomena observed in pA collisions, as well as of
3207 the experimental and theoretical status of quarkonium-hadronisation modifications in pA compared to pp
3208 collisions.

3209 Section 6 focused on quarkonium production in AA collisions. The main physics phenomena at play in
3210 quarkonium physics in heavy-ion collisions were introduced, as well as the theoretical state-of-the-art and
3211 experimental prospects for the HL-LHC. Recent theory developments were been discussed, including the
3212 semi-classical transport in open quantum systems, a density-operator model, and an advanced effective-
3213 field-theory model. A selection of opportunities offered by the HL-LHC was presented, including the
3214 investigation of the collision-energy dependence of various observables through comparisons of FT and
3215 collider data, and prospects for studies of the $X(3872)$ state and for measurements of the J/ψ polarisation.

3216 Section 7 discussed the current theoretical and experimental status of the physics of double and triple

parton scatterings (DPS and TPS) in pp and pA collisions, with an emphasis on the role of measurements of the production of multiple quarkonia, or quarkonia plus electroweak gauge boson, as a means to clarify the multiple open issues in the field. Detailed theoretical perspectives and experimental prospects of relevance for the HL-LHC operation, including expected number of events for various DPS and TPS final states with quarkonia, were provided.

Overall, this document reviewed how the HL-LHC will, on the one hand, help to understand quarkonium production better and, on the other, help to advance the use of quarkonia as tools for multiple aspects of QCD physics.

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