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Phenomenological NLO analysis of η_c production at the LHC in the collider and fixed-target modes

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Abstract

In view of the good agreement between the LHCb prompt- η_c data at $\sqrt{s} = 7$ and 8 TeV and the NLO colour-singlet model predictions –*i.e.* the leading v^2 NRQCD contribution–, we provide predictions in the LHCb acceptance for the forthcoming 13 TeV analysis bearing on data taken during the LHC Run2. We also provide predictions for $\sqrt{s} = 115$ GeV for proton-hydrogen collisions in the fixed-target mode which could be studied during the LHC Run3. Our predictions are complemented by a full theoretical uncertainty analysis. In addition to cross section predictions, we elaborate on the uncertainties on the $p\bar{p}$ branching ratio –necessary for data-theory comparison– and discuss other usable branching fractions for future studies.

1. Introduction

In 2014, LHCb released the first experimental study of prompt- η_c hadroproduction at the LHC [1] at $\sqrt{s} = 7$ and 8 TeV. It was found that the cross section measured by LHCb was compatible with a negligible contribution of Colour-Octet (CO) transitions. More quantitatively, this observation combined with Heavy-Quark-Spin Symmetry (HQSS) yielded severe constraints on the corresponding CO transitions at work on J/ψ production [2–5]. These are so stringent that only one fit [2] currently survives these constraints at the expense of a slight tension with the CDF polarisation data [6]¹. For reviews on quarkonium production, the reader is referred to Refs. [8–14]

In this paper, we provide predictions for prompt- η_c hadroproduction at $\sqrt{s} = 13$ TeV to further test the compatibility between the Colour-Singlet (CS) contributions and the data and then in turn to refine the constraints on the Long-Distance Matrix Elements (LDMEs) associated with

¹The recent IHEP analysis where λ_ϕ and $\lambda_{\phi\phi}$ were computed for the first time at NLO [7] also does not comply with the η_c data.

the dominant CO contributions. See [15] for a recent similar study for the η'_c case for which forthcoming data will also be invaluable. Since such constraints need to be extracted by taking a proper account of both theoretical and experimental uncertainties, we also elaborate on our knowledge of the branching fractions of the decay channels which can be used by LHCb as well as on the scale, the charm-quark mass and the Parton-Distribution Function (PDF) uncertainties of the CS cross-section predictions.

The structure of the article is as follows. Section 2 is devoted to the discussion on the decay channels. Section 3 explains the theory framework we have used to provide CS NLO predictions and gathers our predictions both for the collider kinematics and for the fixed-target kinematics. Section 4 gathers our conclusion.

2. Discussion on the decay channels

The decays of non- 1^{--} charmonium states to the experimentally clean di-muon channel are strongly suppressed and hence these states can only be reconstructed using decays to hadrons or their radiative transitions to underlying charmonium states. In this section we discuss possible decay channels to study η_c , h_c and η'_c , which cannot be accessed using their decays to $\mu^+\mu^-$ or $J/\psi\gamma$. The known branching fractions [16] of the decays discussed below are summarised in Tab. 1. Many of these branching fractions can be measured more precisely at Belle, Belle II, BES III, or the super tau-charm experiments.

	$\mathcal{B} \times 10^3$								
	$p\bar{p}$	$\phi\phi$	$\phi K^+ K^-$	$\phi\pi^+\pi^-$	$\Lambda\bar{\Lambda}$	$\Xi^+\Xi^-$	$\Lambda(1520)\bar{\Lambda}(1520)$	$\eta_c\gamma$	$p\bar{p}\pi^+\pi^-$
η_c	1.52 ± 0.16	1.79 ± 0.20	2.9 ± 1.4	unknown	1.09 ± 0.24	0.90 ± 0.26	-	-	5.3 ± 1.8
J/ψ	2.12 ± 0.03	forbidden	0.83 ± 0.12	0.87 ± 0.09	1.89 ± 0.08	0.97 ± 0.08	unknown	17 ± 4	6.0 ± 0.5
χ_{c0}	0.22 ± 0.01	0.80 ± 0.07	0.97 ± 0.25	unknown	0.33 ± 0.02	0.48 ± 0.07	0.31 ± 0.12	forbidden	2.1 ± 0.7
h_c	< 0.15	forbidden	unknown	unknown	unknown	unknown	unknown	510 ± 60	unknown
χ_{c1}	0.076 ± 0.003	0.42 ± 0.05	0.41 ± 0.15	unknown	0.11 ± 0.01	0.08 ± 0.02	< 0.09	forbidden	0.50 ± 0.19
χ_{c2}	0.073 ± 0.003	1.06 ± 0.09	1.42 ± 0.29	unknown	0.18 ± 0.02	0.14 ± 0.03	0.46 ± 0.15	forbidden	1.32 ± 0.34
η'_c	0.07^2	unknown	unknown	unknown	unknown	unknown	unknown	forbidden	unknown
ψ'	0.29 ± 0.01	forbidden	0.07 ± 0.02	0.12 ± 0.03	0.38 ± 0.01	0.29 ± 0.01	unknown	3.4 ± 0.5	0.60 ± 0.04

Table 1: The branching fractions ($\times 10^3$) of charmonium decays to hadrons and radiative decays to $\eta_c\gamma$.

The $p\bar{p}$ decays of charmonia have been investigated as a possible channel to measure charmonium production at the LHC [17]. The measurement of the η_c production at the LHCb experiment has been performed using the $\eta_c \rightarrow p\bar{p}$ decay [1], which demonstrated that the $p\bar{p}$ final state is powerful to reconstruct the η_c state and measure the η_c production rate relative to that of the J/ψ , even though the η_c hadroproduction rate is measured only for η_c with transverse momenta (P_T) larger than 6.5 GeV due to the available trigger bandwidth. Also, this decay is used to study exotic candidates decaying to $\eta_c\pi^-$ [18]. The branching fraction of the $\eta_c \rightarrow p\bar{p}$ is known to

²Indirect determination

about 10% precision [16]. The studies of the η_c would benefit from a more precise measurement of $\mathcal{B}(\eta_c \rightarrow p\bar{p})$ or $\mathcal{B}(\eta_c \rightarrow p\bar{p})/\mathcal{B}(J/\psi \rightarrow p\bar{p})$. Branching fractions of $\chi_{cJ} \rightarrow p\bar{p}$ decays and $\psi' \rightarrow p\bar{p}$ have been measured to about 3-5% precision. Recently, LHCb has observed the decay $\eta'_c \rightarrow p\bar{p}$ using a data sample of exclusive $B^+ \rightarrow p\bar{p}K^+$ decays [19]. Together with the measurement of $\mathcal{B}(B^+ \rightarrow \eta'_c K^+)$ by Belle [20], the branching fraction of $\eta'_c \rightarrow p\bar{p}$ is indirectly determined to be about 0.7×10^{-4} . Therefore, the decay $\eta'_c \rightarrow p\bar{p}$ is promising for the η'_c hadroproduction measurement.

The other promising final state to study prompt production of charmonium is $\phi\phi$. The 1^- charmonium states are forbidden to decay to $\phi\phi$. LHCb measured the $\chi_{c0,1,2}$ and η'_c production in inclusive b -hadron decays using the $\phi\phi$ final state with the first evidence of the $\eta'_c \rightarrow \phi\phi$ decay [21]. In the latter analysis, a possible problem was highlighted, namely the PDG fit value of $\mathcal{B}(\eta_c \rightarrow \phi\phi)$ differs from the PDG average value [16] by a factor close to 2. In addition, the ratio of the branching fractions $\mathcal{B}(\eta_c \rightarrow \phi\phi)/\mathcal{B}(\eta_c \rightarrow p\bar{p})$ was measured. More measurements are needed to establish a robust value of the $\mathcal{B}(\eta_c \rightarrow \phi\phi)$. Also, due to the evidence of the $\eta'_c \rightarrow \phi\phi$, this channel is promising to measure the hadroproduction of the η'_c . Similarly, the $\phi K^+ K^-$ and the $\phi\pi^+\pi^-$ final states could be used.

The branching fractions of charmonium decays to long-lived baryons such as $\Lambda\bar{\Lambda}$ and $\Xi^+\Xi^-$ are measured for most charmonium states. The reconstruction of these decay channels is challenging for LHCb due to the large lifetimes of these baryons such that they escape the Vertex Locator (VELO), which cause a small reconstruction and trigger efficiency. Decays involving short-lived baryons are reconstructed by LHCb with better efficiency.

The decays $\chi_{c0,2} \rightarrow \Lambda(1520)\bar{\Lambda}(1520)$ have been observed by the BES III collaboration [22] while the $J/\psi \rightarrow \Lambda(1520)\bar{\Lambda}(1520)$ decay is not observed so far. This channel becomes another candidate to measure hadroproduction of charmonium states [23].

The least studied charmonium state is the h_c meson, and not many of h_c decays have been observed so far. The h_c meson is expected to decay to $p\bar{p}$, however, the upper limit on the $\mathcal{B}(h_c \rightarrow p\bar{p})$ reported by the BES III collaboration [24] is more than one order of magnitude smaller than the theoretical prediction [17]. Also, the h_c can be measured using its radiative transition $h_c \rightarrow \eta_c\gamma$ with branching fraction about 50%, which requires reconstruction of the η_c state. Recently, LHCb observed the very clean decays $\chi_{c1,2} \rightarrow J/\psi\mu^+\mu^-$, and precisely measured the χ_{c2} mass and its natural width [25]. The $h_c \rightarrow \eta_c\mu^+\mu^-$ decay can be searched similarly. Also, the BES III has observed the $h_c \rightarrow p\bar{p}\pi^+\pi^-$ decay and measured its branching fraction [26] to be $(2.89 \pm 0.32 \pm 0.55) \times 10^{-3}$, which is promising for searches by LHCb.

3. Framework and results

3.1. Framework

The present NLO analysis was performed thanks to the FDC framework [27, 28]³ which generates the Born, real-emission and virtual contributions, ensures the finiteness of their sum, performs the partonic-phase-space integration and that over the PDFs. As announced, we performed a full study of the scale uncertainty by varying both μ_R and μ_F about the default value $\mu_0 = \sqrt{m_{\eta_c}^2 + P_T^2}$ as $(\mu_R, \mu_F) = \mu_0 \times (1, 1; 0.5, 0.5; 2, 2; 0.5, 1; 1, 0.5; 1, 2; 2, 1)$. We have also studied the mass uncertainty by varying the charm quark mass m_c by 0.1 GeV about a default value of 1.5 GeV.

As for the CS LDME, we have taken $\langle \mathcal{O}^{\eta_c}(^1S_0^{[1]}) \rangle = 0.39 \text{ GeV}^3$ which corresponds to $|R(0)|^2 = 0.81 \text{ GeV}^3$ for the radial wave function at the origin. In order to study the impact of the PDF uncertainties at NLO, we have used the CT14 set [29] which is included in LHAPDF5 [30]. The corresponding uncertainties follow from the 57 eigensets of CT14.

3.2. Results for the collider mode at $\sqrt{s} = 13 \text{ TeV}$

Our predictions at $\sqrt{s} = 13 \text{ TeV}$ follow from the expected kinematical range of the forthcoming LHCb study performed on data taken during the Run2 in 2015-2016. They correspond to 2 fb^{-1} of data at $\sqrt{s} = 13 \text{ TeV}$. We have therefore considered the same rapidity acceptance as that used for the first LHCb analysis [1], namely $2 < y_{\text{cms}} < 4.5$ without any additional fiducial cuts on the decay product of the η_c .

Fig. 1a displays our predictions for the P_T -differential prompt- η_c cross section at NLO accuracy along with their associated scale, mass and PDF uncertainties. It is clear that the latter are negligible in this energy range as compared to those from the scales. Fig. 1b shows the ratio of the NLO/LO cross sections with the scale and mass uncertainties only and points at a K factor slightly increasing with P_T . This is the expected behaviour with leading P_T channels opening up at α_s^4 . It also shows that the scale uncertainty is as large as 50%, whereas the mass uncertainty is rather on the order of 25% in the P_T region which we considered.

Assuming a recorded luminosity of 2 fb^{-1} , $\mathcal{B}(\eta_c \rightarrow p\bar{p}) = 1.52 \times 10^{-3}$ and an efficiency on the order of 2 %, the 100-count limit per GeV correspond to 2 pb and is located around $P_T \simeq 20 \text{ GeV}$. Without any surprise, the increase in the energy should allow LHCb to push their measurements at 13 TeV to slightly larger P_T compared to 7 and 8 TeV. Limitations may come from the range

³The FDC (standing for Feynman Diagram Calculation) package have been developed to automated HEP computations. It is based on the LISP symbolic programming language in order to produce FORTRAN codes. The Lagrangian are formed by the code, following the user requirement, from which are derived the corresponding Feynman rules. The package generates all possible Feynman diagrams contributing to a given process up to one loop in a given model. It can in particular deal quarkonium production within NRQCD. The amplitude of the process are analytically manipulated to generate FORTRAN codes of the squared amplitudes up to one loop. Numerical results for the (differential) cross sections are then computed by performing the phase-space integrals using the phase-space slicing method. We refer to [28] for explanations relevant to quarkonium-production applications.

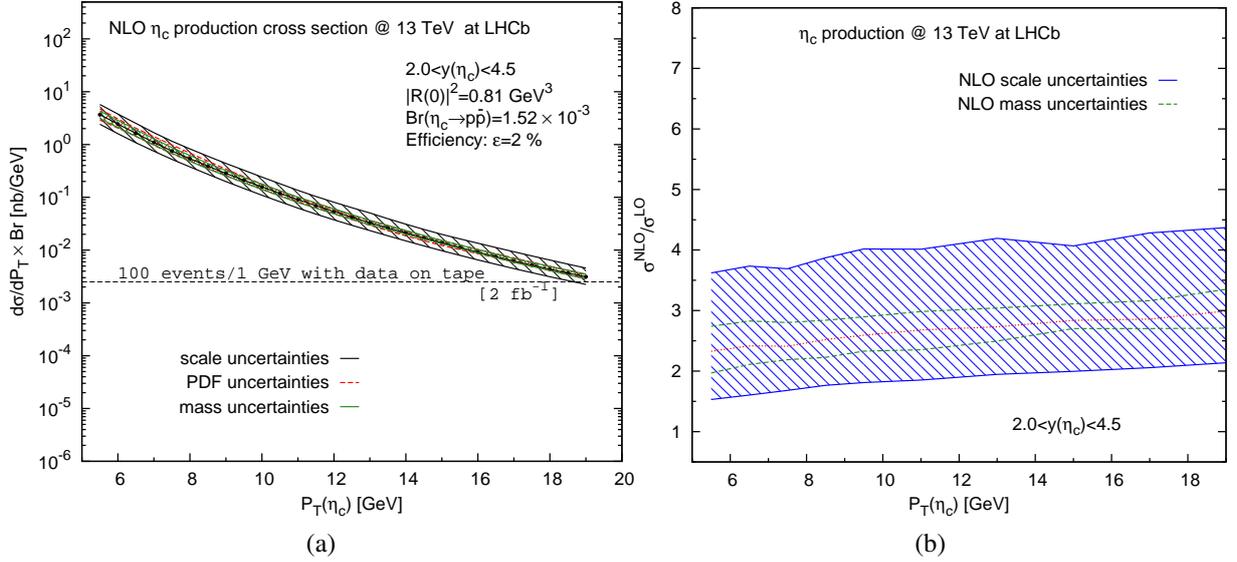


Figure 1: (a) NLO P_T -differential cross section in the LHCb acceptance at 13 TeV. The black (green, red) hatched band denotes the scales (mass, PDF) uncertainties; (b) NLO/LO cross-section ratio as a function of P_T where only the scale and mass uncertainties on the NLO cross section are shown.

where the $J/\psi \rightarrow p\bar{p}$ yield is measured as well as from systematical uncertainties. In view of the other branching fractions on Table (1), let us add that other decays are also within the reach of LHCb measurements.

3.3. Results for the fixed-target mode at $\sqrt{s} = 115$ GeV

The use of the proton LHC beam in the fixed-target mode has lately been the object of intense investigation both in terms of feasibility and in terms of physics reach, see *e.g.* [31–53]. In particular, a wide variety of measurements in different possible implementations were discussed in [31]. We will limit ourselves here to a few statements on the kinematics. First, 7 TeV protons impinging fixed targets release a center-of-mass system (cms) energy close to 115 GeV ($\sqrt{s} = \sqrt{2E_p m_N}$). Second, the boost between the cms and the laboratory is $\gamma_{\text{cms}}^{\text{lab}} = \sqrt{s}/(2m_p) \simeq 60$ yielding a rapidity shift as large as $\tanh^{-1} \beta_{\text{cms}}^{\text{lab}} \simeq 4.8$. As such, the nominal acceptance of the LHCb detector in the cms approximates to $-2.8 < y_{\text{cms}} < -0.3$. Physics wise, the LHCb detector probes backward physics in the fixed-target mode.

Nowadays, the first analysed fixed-target data based on the SMOG LHCb system –initially designed to improve the luminosity determination in LHCb, now used as a low-density-unpolarised-gas target– are coming in [54, 55] and confirm that the particle multiplicity in the LHCb detector is such that its performance in the fixed-target mode remains intact. One can thus consider that similar decay channels of the η_c as those discussed for the collider mode could be studied if sufficient luminosities can be achieved.

Until now, the LHCb-SMOG statistical samples for J/ψ taken with different noble gases (He, Ar, Ne) remain too small –on the order of hundreds– to expect any η_c counts. The situation could significantly get better in the future with proposed SMOG2 system [56, 57] with achievable yearly luminosities on the order of 10 pb^{-1} during the LHC Run3. It is however crucial to further constrain NRQCD LDMEs –as we propose here– to have a H target available as opposed as to nuclear –noble gas– targets. For the LHC Run4, yearly luminosities as high as few fb^{-1} will be within experimental reach as discussed in [31].

Fig. 2a displays the P_T -differential η_c cross section at $\sqrt{s} = 115 \text{ GeV}$ in the expected acceptance of LHCb in the fixed-target mode. As above, we separated out the uncertainties from the scale variations (μ_F and μ_R), from the charm-quark mass and from the PDFs which are a little larger here since one probes slightly larger x values. As a matter of fact, dedicated rapidity-differential measurements at very negative y_{cms} could provide specific constraints on the gluon PDFs [31, 52, 53]. Fig. 2b shows the ratio of the NLO/LO cross sections with the mass and scale uncertainties only and points at a K factor slightly increasing with P_T . This is the expected behaviour with leading P_T channels opening up at α_s^4 . It also shows that the scale uncertainty is as large as 5 at low energies, whereas that from the mass remains on the order of 25% like at LHC-collider energies.

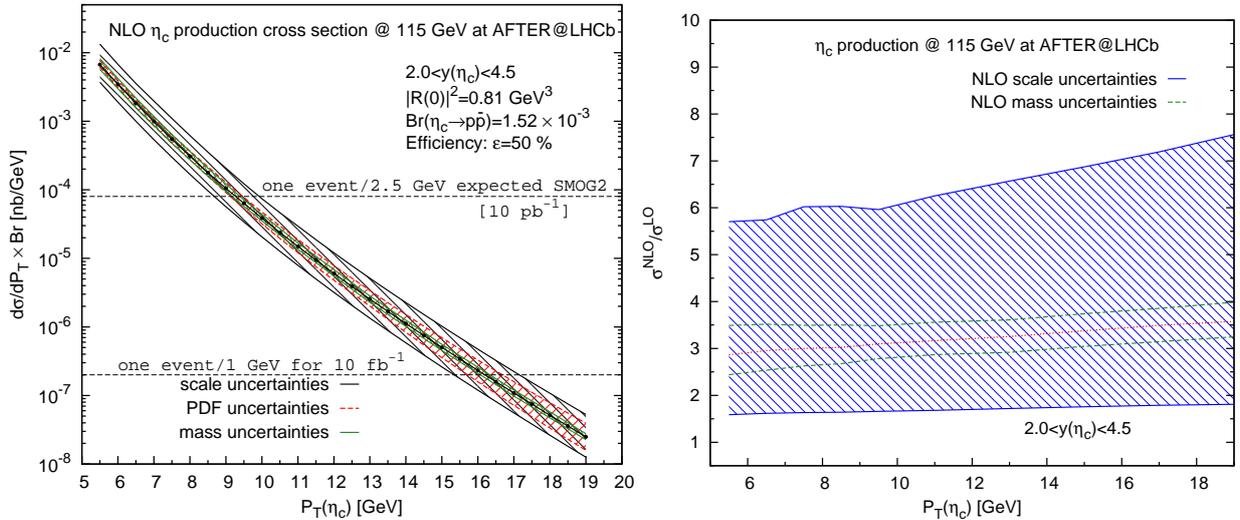


Figure 2: (a) NLO P_T differential cross section in the LHCb acceptance at 115 GeV in the fixed-target mode. The black (green,red) hatched band denotes the scales (mass,PDF) uncertainties; (b) NLO/LO cross-section ratio as a function of P_T where only the scale and mass uncertainties on the NLO cross section are shown.

Assuming an integrated luminosity of 10 pb^{-1} , $\mathcal{B}(\eta_c \rightarrow p\bar{p}) = 1.52 \times 10^{-3}$ and an efficiency on 50 %, the one-count limit per 2.5 GeV for $d\sigma/dP_T$ is on the order 0.08 pb, which corresponds according to our results to a P_T upper limit of $8.5 \div 10 \text{ GeV}$. It precisely happens to be the range accessed at 7 and 8 TeV. With 10 fb^{-1} , the reach would simply be equivalent to that of the collider

mode. We further note that, thanks to the reduced multiplicities in the fixed-target mode, lower P_T 's should be accessible. This would allow one to measure the gluon Transverse-Momentum-Dependent functions (TMDs) along the lines of [58–60].

4. Conclusions and outlook

We have computed the prompt η_c -production cross section at one loop accuracy in QCD and in the CSM (LO in v^2 of NRQCD) for the LHCb kinematics in the collider mode at $\sqrt{s} = 13$ TeV and in the fixed-target mode at $\sqrt{s} = 115$ GeV. In addition, we have provided an up-to-date discussion of the possible decay channels to be used for such studies and performed an original analysis of the theoretical analysis including that from the factorisation and renormalisation scales, from the charm quark mass and from the PDFs.

In addition, let us stress that the understanding and the measurements of η_c production go well beyond the determination of NRQCD LDMEs. Its production in proton-nucleus collisions (see [61] for predictions of the corresponding nuclear modification factors at LHC energies) can provide complementary means to probe the distribution of gluons inside nuclei along the lines of [62, 63]. In proton-deuteron collisions at extreme x_F , it can also give us some handle on the gluon distribution in the deuteron at very large x [64].

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