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► **To cite this version:**

Kate Lynch.  $J/\psi$  inclusive photoproduction in ultra peripheral collisions. Exploring QCD with Tagged Processes Workshop, Oct 2021, Orsay, France. <hal-03822226>

**HAL Id: hal-03822226**

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Submitted on 20 Oct 2022

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# $J/\psi$ inclusive photoproduction in ultra peripheral collisions

**Kate Lynch**

IJCLab & University College Dublin

in collaboration with Ronan McNulty, Charlotte Van Hulse, Carlo Flore,  
Jean-Philippe Lansberg & Hua-Sheng Shao, IJCLab (Orsay)

October 11<sup>th</sup> 2021



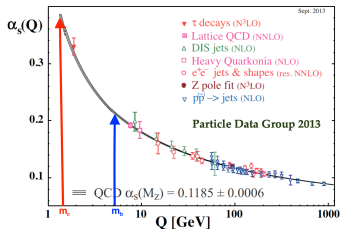
This project is supported by the European Union's Horizon 2020 research and innovation programme under Grant agreement no. 824093



# Quarkonium Production

J.-P. Lansberg, Phys.Rept. 889 (2020), 1-106;

- We are concerned with quarkonia which are bound states of heavy quarks.



- Because of its scale  $Q\bar{Q}$  production can be calculated perturbatively.
- However quarkonium production has two associated scales  
heavy-quark pair production (perturbative part) and hadronisation (non-perturbative part).
- Presently no consensus on the mechanism for quarkonium production.

# Quarkonium Production Model

See Phys.Rept. 889 (2020) 1-106 and EPJC (2016) 76:107 for reviews

Popular approaches assume a factorisation between the production of the heavy quark pair (**perturbative part**) and its hadronisation into a meson (**non-perturbative part**).

- No agreement on which mechanism is dominant
- Differences in the **treatment of the hadronisation**
- **3 common models:**
  - 1 COLOUR EVAPORATION MODEL: based on **quark-hadron duality**; only the invariant mass matters; semi-soft gluons emissions; colour-wise decorrelated  $c\bar{c}$  production and hadronisation;
  - 2 COLOUR SINGLET MODEL: hadronisation **w/o gluon emission**; colour and spin are preserved during the hadronisation
  - 3 NRQCD AND COLOUR OCTET MECHANISM: **higher Fock states** of the mesons taken into account;  $Q\bar{Q}$  can be produced in octet states with different quantum # to the meson.

# CEM vs. CSM vs. COM in a little more details

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## ① COLOUR EVAPORATION MODEL

- ▶ any  $Q\bar{Q}$  state contributes to a specific quarkonium state
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## ③ COLOUR OCTET MECHANISM

- ▶ one non-perturbative parameter per Fock State
- ▶ expansion in  $v^2$ ; series can be truncated
- ▶ the phenomenology partly depends on this
- ▶ The non-perturbative parameter for each fock state is related to HQSS

# The current situation in one slide ...

See JPL. arXiv:1903.09185 [hep-ph] (Phys.Rept. 889 (2020) 1)

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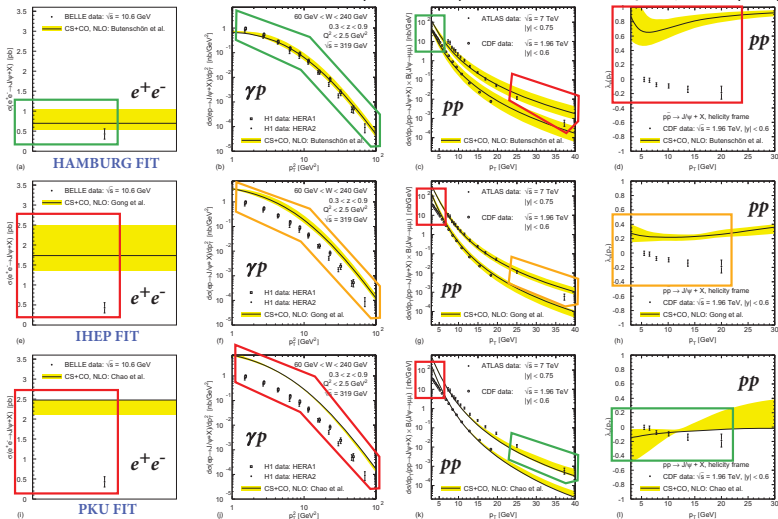
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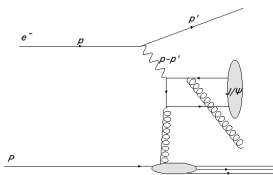
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- All approaches have troubles describing  $ep$  and  $pp$  polarisation and the  $\eta_c$  data
- This motivates the study of new observables

# Different colliding systems; different conclusions

Plot from M. Butenschön (ICHEP 2012); Discussion in JPL, Phys.Rept. 889 (2020) 1)



# Need for a new data set



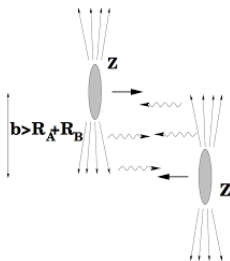
$$\gamma g \rightarrow J/\psi X$$

- This process is normally studied in lepton-proton colliders.
- Such a process is ideal because;
  - 1 Constraints can be placed on the lepton to ensure  $(p - p')^2 = Q^2$  is small.
  - 2 It is a clean environment; no difficulty in distinguishing inclusive and exclusive interactions.
- However, there are no high-energy lepton-proton colliders in function at present;
  - ▶ HERA at DESY (Hamburg, GE) was shut down in 2007.
  - ▶ EIC (BNL, US)  $\sim 10$  years from data collecting.

# Ultra peripheral collisions (UPCs) in ultra-relativistic hadron-hadron collisions.

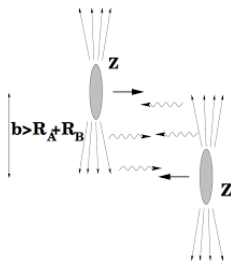
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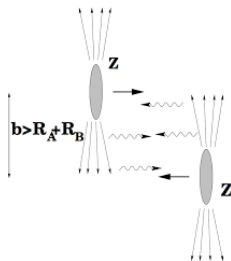
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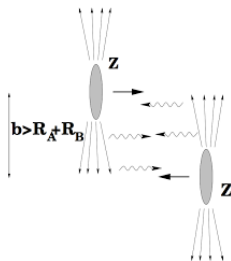
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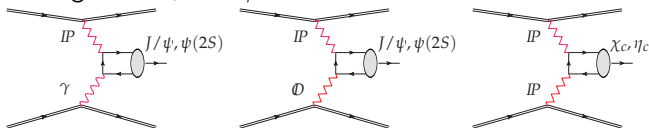
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- Consider  $\sqrt{s}$  large enough to produce new particles.
  - Expect photon-induced reactions with fewer particles produced.
- The photon probes the contents of the hadron.

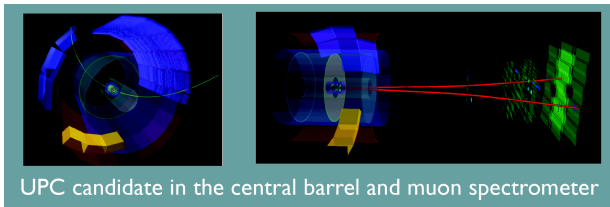
# Exclusive $J/\psi$ production in $pp$ collisions

Colourless exchanges via  $\mathbb{P}, \mathbb{O}$  or  $\gamma$  emission.



- Clean signal

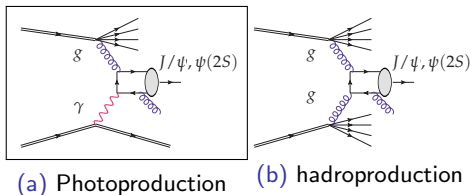
- ▶ **only** quarkonia and its decay products are produced.
- ▶ protons stay intact



ALICE candidate signal for exclusive  $J/\psi$  production via UPC

# Inclusive $J/\psi$ production in $pp$ collisions

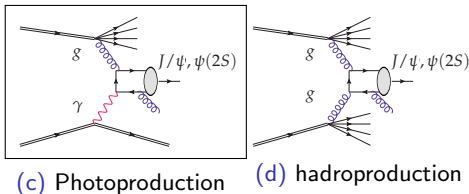
## Inclusive reactions



- Inclusive photoproduction [ $\gamma + p \rightarrow J/\psi + X$ ] can be distinguished by requiring;
  - 1 The photon emitting proton stays intact.
  - 2 The gluon emitting proton breaks up.

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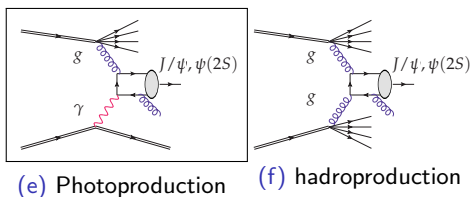
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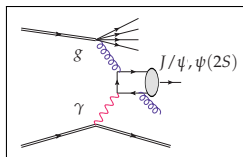
- Inclusive photoproduction [ $\gamma + p \rightarrow J/\psi + X$ ] can be distinguished by requiring;
  - 1 The photon emitting proton stays intact.
  - 2 The gluon emitting proton breaks up.

**Question:** can we distinguish these processes in practice? Or do the particles emitted by the inclusive hard reaction pollute the region where the intact proton emerges?

# Why inclusive UPC ?

See JPL, Phys.Rept. 889 (2020) 1

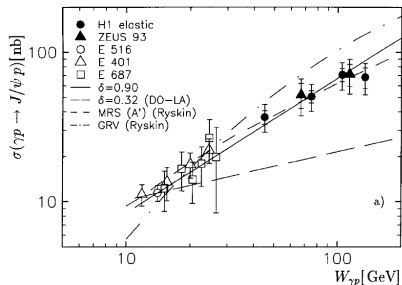
It offers new ways to test the mechanisms of inclusive production (octet vs singlet, etc ...).



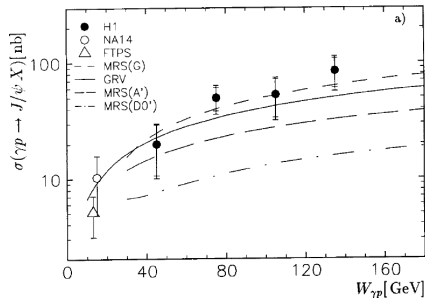
Also allows one to study  $J/\psi$  inclusive photoproduction which probes the gluon PDFs

# Supporting data

H1 Collaboration/Nuclear Physics B 472 (1996) 3–31



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Exclusive and Inclusive  $J/\psi$  photoproduction data from H1  $ep$  collisions (left and right).

- Similar rates for exclusive and inclusive photoproduction in  $ep$ .

LHCb have  $\sim 1400$   $J/\psi$  candidates for exclusive photoproduction in  $pp$  collisions with  $100 \text{ pb}^{-1}$  at  $\sqrt{s} = 13 \text{ TeV}$ .

LHCb JHEP10(2018)167;

# Goal

- To understand inclusive photoproduction mechanism in UPCs.
- To characterise inclusive  $J/\psi$  photoproduction in UPCs.
- This will be achieved by using HELAC-Onia and PYTHIA.

HELAC-Onia is a code that is able to calculate heavy quarkonium amplitudes.

- $\text{colpar} = 10$   $pp$  collision
- $a_g > c_{c\bar{c}}(3S11)$
- $c_{c\bar{c}}(3S11) > m_{c^+} m_{c^-} @ 0.06$

H. S. Shao; *Comput.Phys.Commun.* 184 (2013) 2562-2570

PYTHIA 8 is the tool that will be used to hadronise the outgoing gluon and proton remnants broken by the photon.

T. Sjöstrand et. al; *Comput.Phys.Commun.* 178 (2008), 852-867

# Les Houches event file

The Les Houches event file is produced by HELAC-Onia. It contains information about all of the particles involved in the partonic collision; particle Id, energy, momentum etc.

```
-->
<init>
  2212  2212  2.150000E+03  2.150000E+03  0  0  10042  10042  3  1
  9.0745309602E+01  6.5149826788E-01  1.0000000000E+00  81
</init>
<event>
  6  81  1.581755E-02  3.992994E+00  7.299270E-03  1.180000E-01
  22  -1  0  0  0  0  0.0000000000E+00  0.0000000000E+00  1.2833573788E+01  1.2833573788E+01  0.0000000000E+00  0.000000E+00  9.0000E+00
  21  -1  0  0  103  101  0.0000000000E+00  0.0000000000E+00  -1.9051513911E+00  1.9051513911E+00  0.0000000000E+00  0.000000E+00  9.0000E+00
  443  2  1  2  0  0  3.2190092539E+00  1.1830029049E+00  1.0285357824E+01  1.1249448965E+01  3.0000000000E+00  0.000000E+00  9.0000E+00
  21  1  1  2  103  101  -3.2190092539E+00  -1.1830029049E+00  6.4306457223E-01  3.4892762134E+00  0.0000000000E+00  0.000000E+00  9.0000E+00
  -13  1  3  0  0  0  -2.8263519350E-01  -5.5679434280E-01  1.8349445266E+00  1.9382786200E+00  0.0000000000E+00  0.000000E+00  9.0000E+00
  13  1  3  0  0  0  3.5016444474E+00  1.7397972477E+00  8.4504132978E+00  9.3111703455E+00  0.0000000000E+00  0.000000E+00  9.0000E+00
</event>
```

# Results

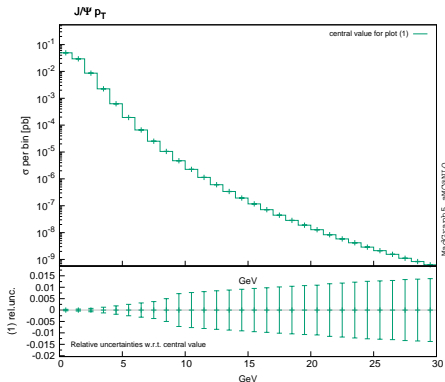
- Used HELAC-Onia to generate the partonic event [ $\gamma + g \rightarrow J/\psi + g$ ] from a  $pp$  collision.
- $J/\psi$  decays via the dimuon channel [ $cc \sim (3S11) > m^+ m^- @ 0.06$ ].
- Implemented cuts based on various experimental configurations (ATLAS, LHCb, ALICE and CMS) at the analysis level.

	LHCb	CMS	ATLAS	ALICE
$p_T^{J/\psi}$	<0.4 GeV	<6.5 GeV	<8.5 GeV	-
$y^{J/\psi}$	(2,4.5)	< 2.4*	<2.1*	(2.5,4)
$\eta^\mu$	(2,4.5)	<2.4*	<2.5*	(2.5,4)

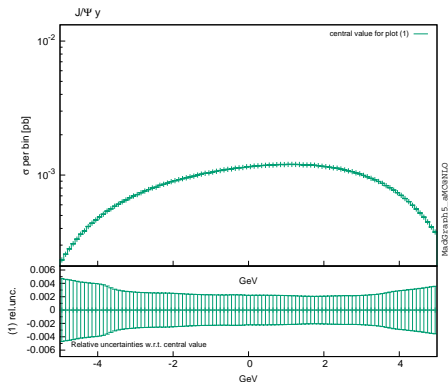
- Passed the Les Houches event file through PYTHIA to hadronise the outgoing gluon and proton remnants.

\*absolute value

# Process without cuts



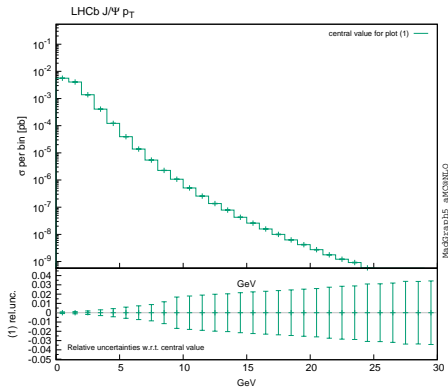
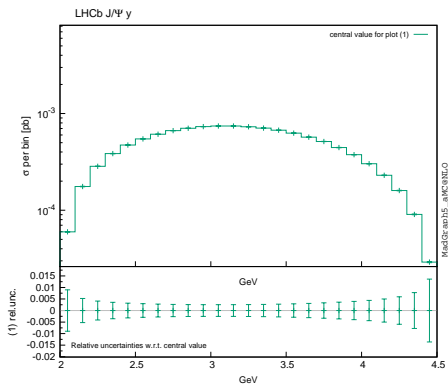
(g)  $J/\psi$   $p_T$



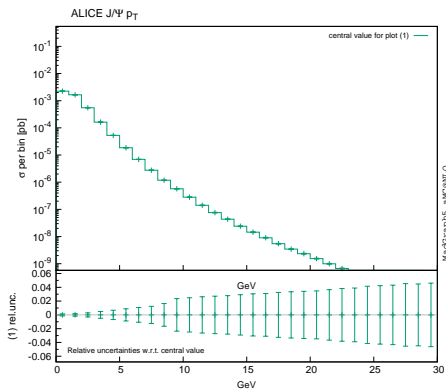
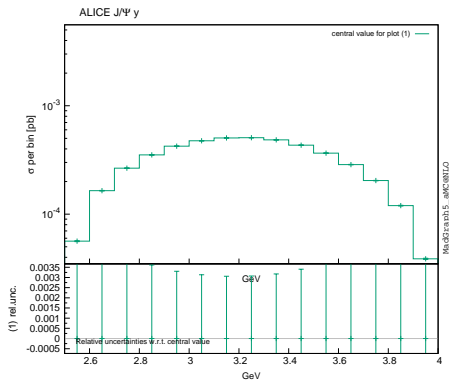
(h)  $J/\psi$   $y$

$\sqrt{s} = 7$  TeV in  $pp$  collision

- 1  $p_T$  of  $\sim 10$  GeV cross section reduced by a factor of  $10^5$ .
- 2 Asymmetry;  $J/\psi$  slightly favour moving in the direction of the  $\gamma$  emitting proton.

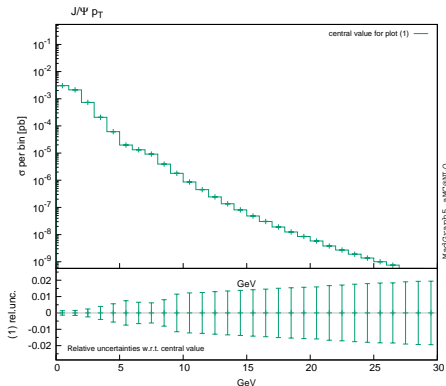
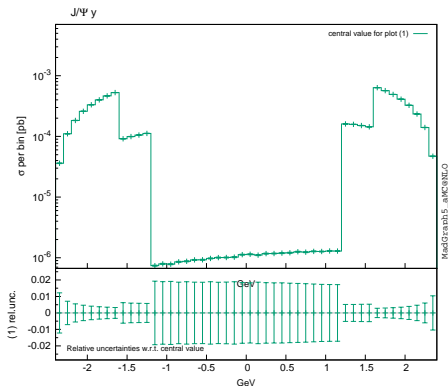
(a)  $J/\psi$   $p_T$ (b)  $J/\psi$   $y$ 

LHCb detector acceptance ( $\sim 16\%$ ) :  $2 < \eta^\mu < 4.5$  and  $p_T^\mu > 0.4$  GeV,  
 $2 < y^{J/\psi} < 4.5$  and  $p_T^{J/\psi} > 0$  GeV.

(a)  $J/\psi$   $p_T$ (b)  $J/\psi$   $y$ 

ALICE detector acceptance ( $\sim 5\%$ ):  $2.5 < \eta^\mu < 4$  and  $p_T^\mu > 0$  GeV,  
 $2.5 < y^{J/\psi} < 4$ .

## CMS 2010

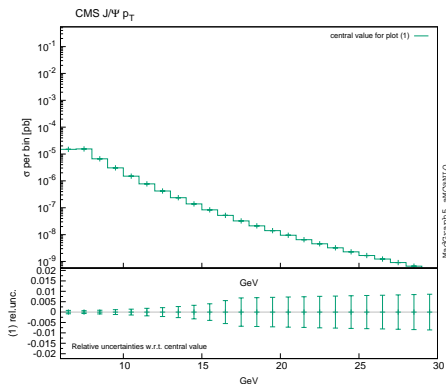
(a)  $J/\psi$   $p_T$ (b)  $J/\psi$   $y$ 

CMS detector acceptance ( $\sim 7\%$ ):  $|\eta^\mu| < 2.4$ ,

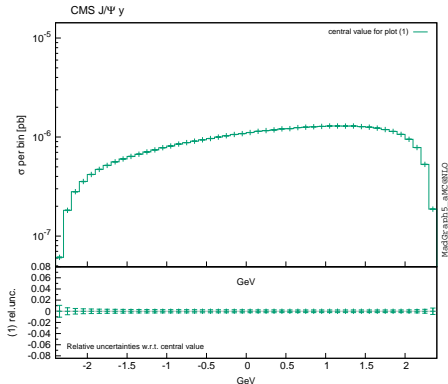
$p_T^{J/\psi} > 6.5$  GeV and  $|y^{J/\psi}| < 1.2$ ,

$p_T^{J/\psi} > 2$  GeV and  $1.2 < |y^{J/\psi}| < 1.6$ ,

$p_T^{J/\psi} > 0$  and  $1.6 < |y^{J/\psi}| < 2.4$ .

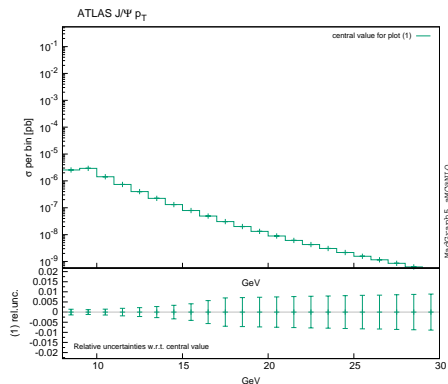
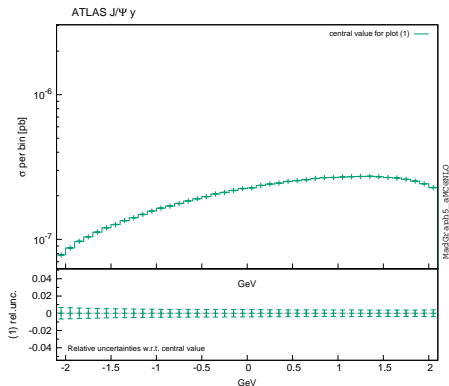


(a)  $J/\psi$   $p_T$



(b)  $J/\psi$   $y$

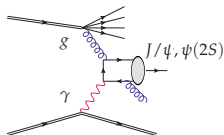
CMS detector acceptance ( $\sim 0.05\%$ ):  $|\eta^\mu| < 2.4$ ,  
 $p_T^{J/\psi} > 6.5$  GeV and  $|y^{J/\psi}| < 2.4$ .

(a)  $p_T$ (b)  $J/\psi$   $y$ 

ATLAS detector acceptance ( $\sim 0.01\%$ ):  $|\eta^\mu| < 2.5$ ,  
 $8.5 < p_T^{J/\psi} < 30$  GeV and  $|y^{J/\psi}| < 2.1$ .

# Outlook

- Aim to learn about quarkonium production mechanism through studying inclusive  $J/\psi$  photoproduction.



- The same study should be extended to the case of  $pPb$ .
- It has advantages over  $pp$ :
  - ▶  $\sim 95\%$  of photon emission is from the  $Pb$ .
  - ▶ Less pileup

# Summary

- ALICE and LHCb are sensitive in the forward region with low  $p_T$ , which has good statistics.
- CMS and ATLAS are sensitive in the central region but with large  $p_T$  constraint, reduced statistics but good tagging possibilities.
- CMS, ATLAS and ALICE all have a ZDC capable of vetoing an intact proton.
- In the LHCb the HeRSCHeL detector has been decommissioned.
- Presently working on understanding the output of PYTHIA 8 to see if it is in fact possible to tag  $J/\psi$  photoproduction.
- This preliminary study of the production rates with HELAC-Onia is encouraging.
- The study of the proton tagging remains to be done with PYTHIA 8 in the aforementioned experimental set ups.

## $J/\psi$ ; a mode to study quarkonium

- It is a vector meson,  $J^{PC} = 1^{--}$ , with same quantum numbers as a photon.
- Easy to detect via decay into a dimuon pair  $\rightarrow B(\mu^+\mu^-) \approx 6\%$ .

