J/ψ inclusive photoproduction in ultra peripheral collisions

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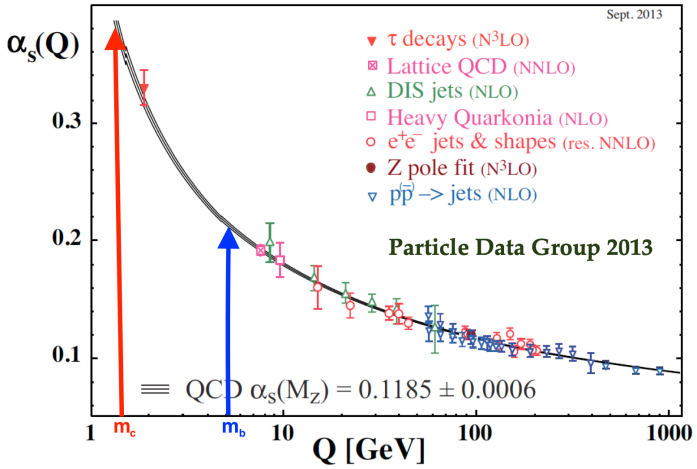
Quarkonium Production

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.

The current situation ...

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

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- Colour-Singlet Model (CSM) long thought to be insufficient

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[large NLO and NNLO correction to the P_T spectrum ; but not perfect $\rightarrow$ need a full NNLO]

P.Artoisenet, J.Campbell, JPL, F.Maltoni, F. Tramontano, PRL 101, 152001 (2008); JPL EPJC 61 (2009) 693; H.S. Shao JHEP 1901 (2019) 112

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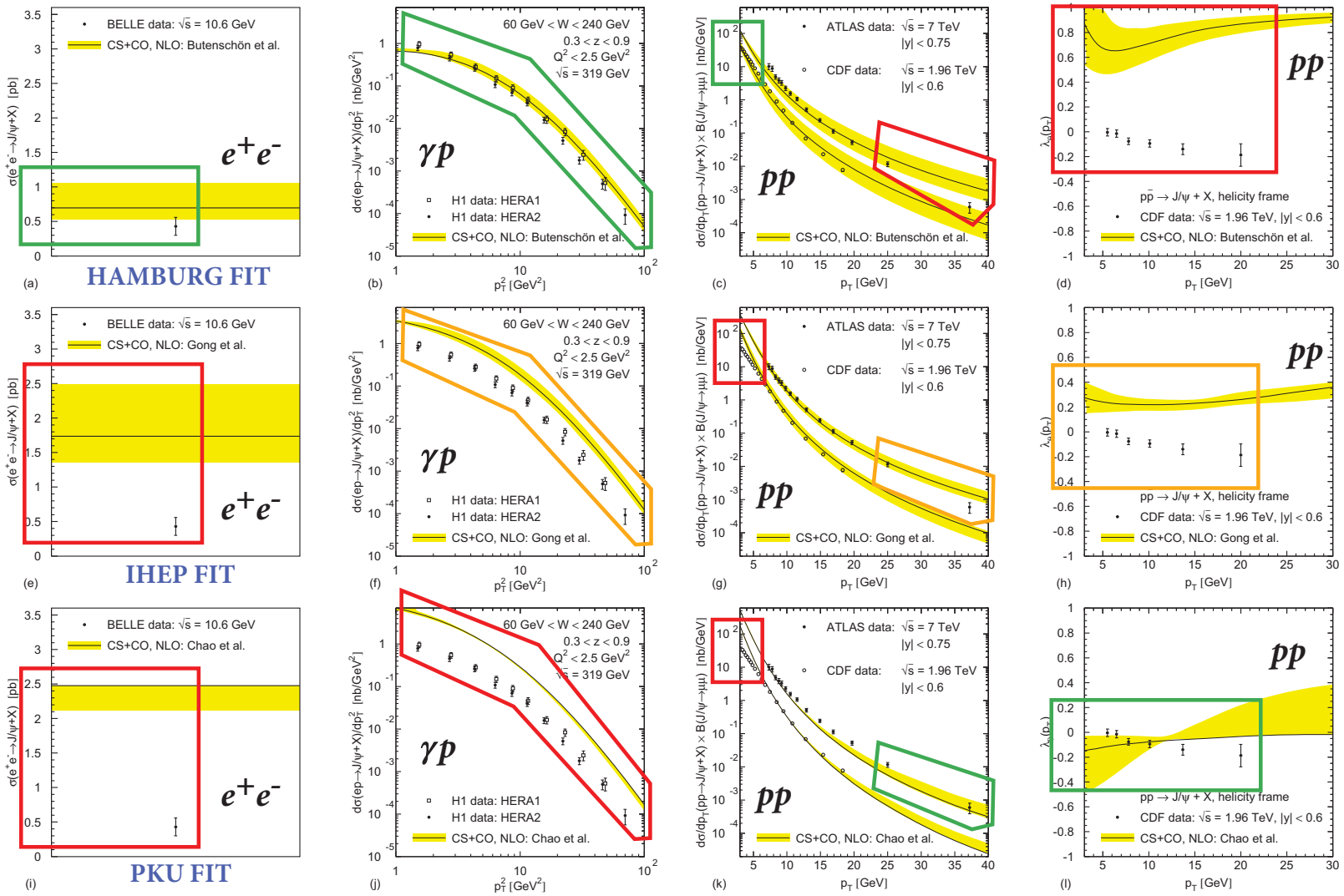
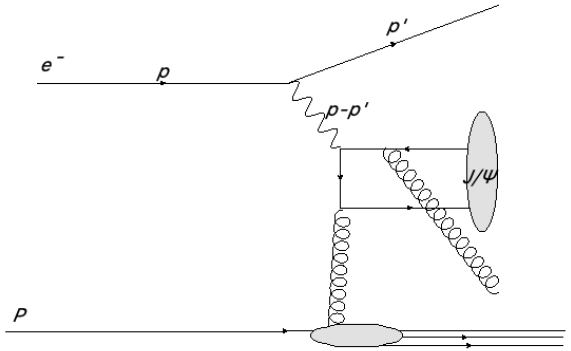
- Each approach has trouble describing all of the data.
- This motivates the study of new observables

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



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

- 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, DE) was shut down in 2007.
  - EIC (BNL, US) ∼10 years from data collecting.

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

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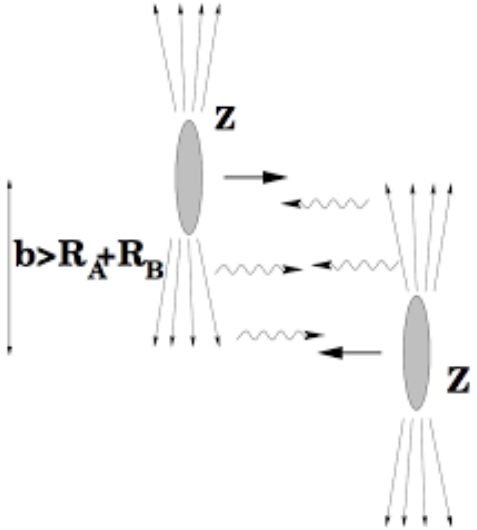
- A UPC is an interaction where $b > R_A + R_B$, we assume photon induced reactions dominate.



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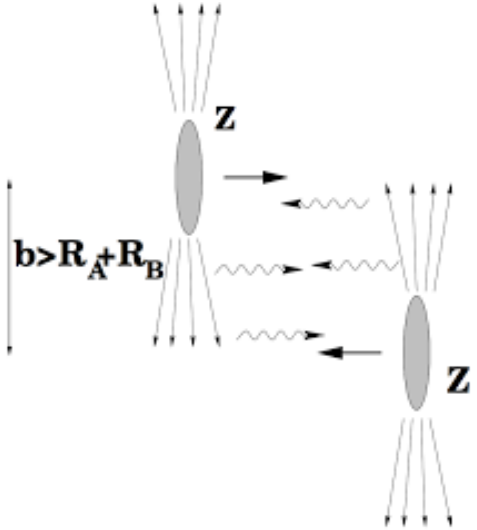

- Consider $\sqrt{s}$ large enough to produce new particles.

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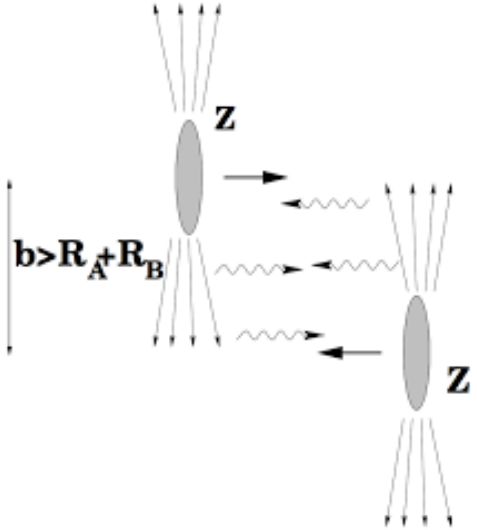

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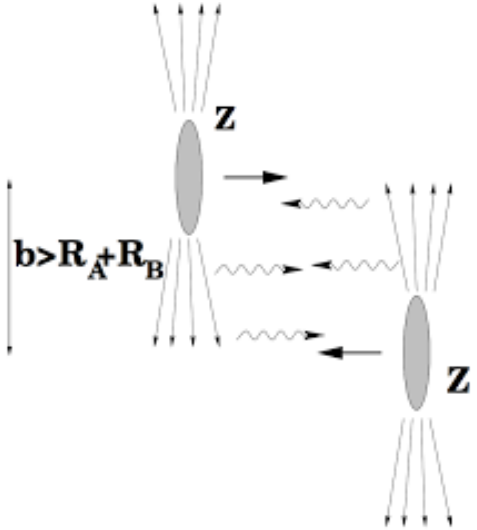
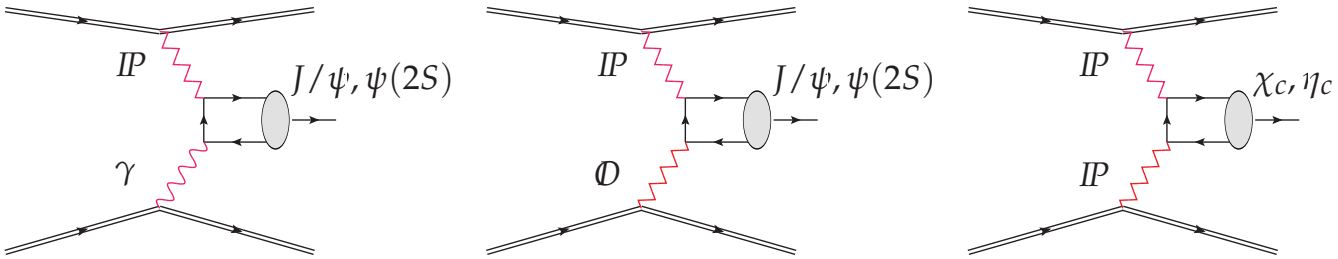


- Consider $\sqrt{s}$ large enough to produce new particles.
- Expect photon-induced reactions with fewer particles produced.

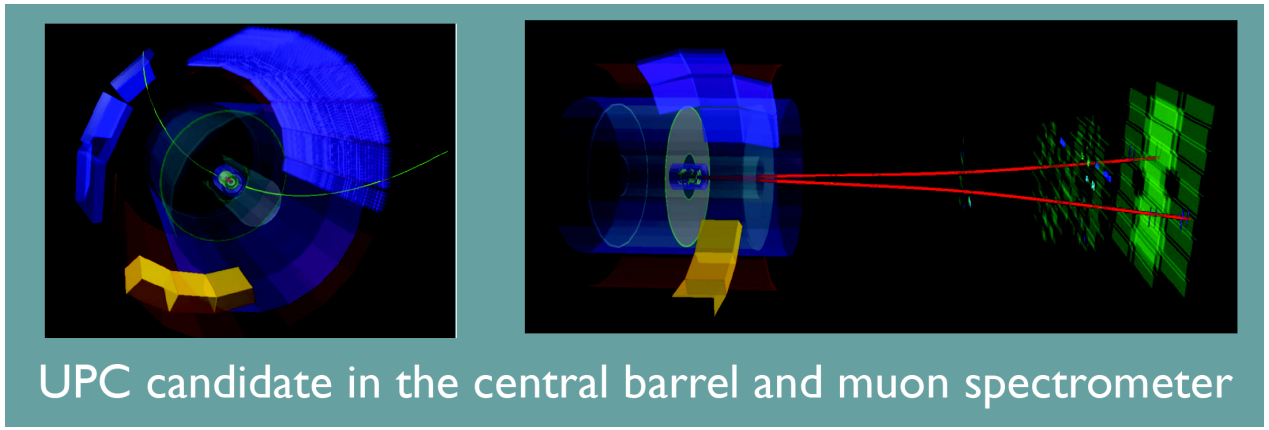
$\rightarrow$ The photon probes the contents of the hadron.

Exclusive J/ψ production in pp collisions

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



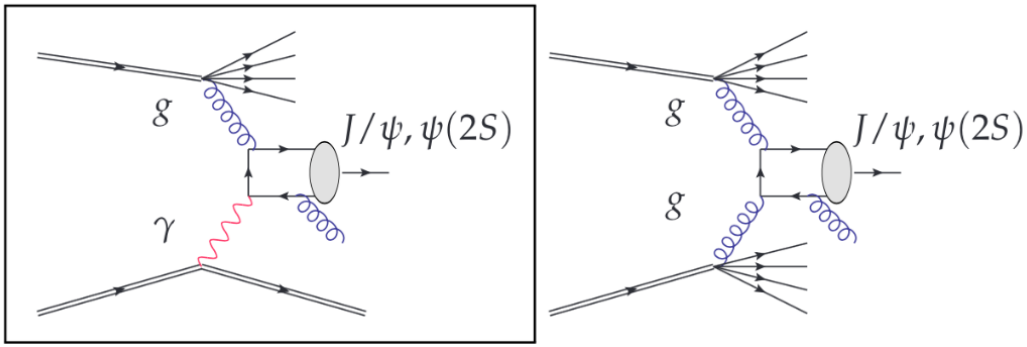
- Clean signal
  - **only** quarkonia and its decay products are produced.
  - protons stay intact



ALICE candidate signal for exclusive J/ψ production via UPC

Inclusive J/ψ production in pp collisions

Inclusive reactions

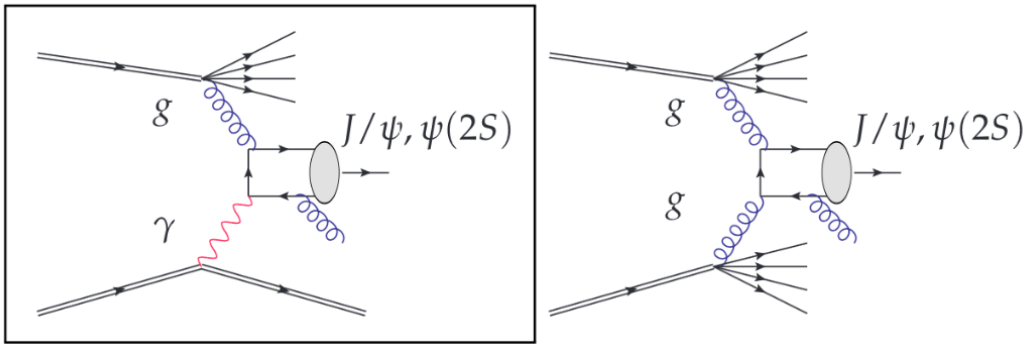


(a) Photoproduction (b) hadroproduction

- 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.

Inclusive J/ψ production in pp collisions

Inclusive reactions



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- Inclusive photoproduction $[\gamma + p \to J/\psi + X]$ can be distinguished by requiring;
  1. The photon emitting proton stays intact.
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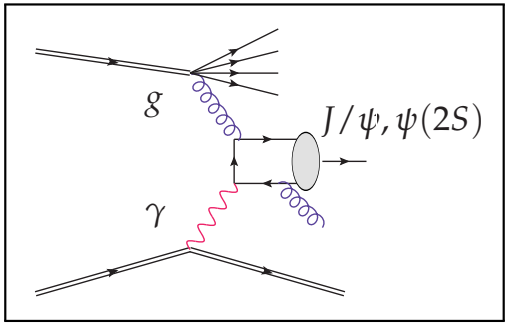
Question: can we distinguish these processes in practice? Or do the particles emitted by the inclusive hard reaction pollute the region where the intact proton emerges?

Why inclusive UPC ?

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

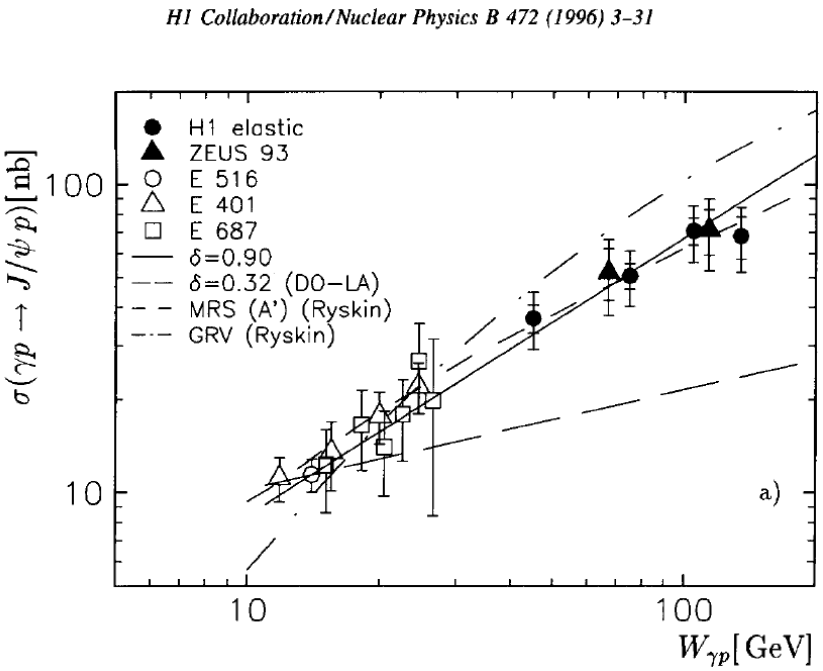
It offers new ways to test the mechanisms of inclusive production (octet vs singlet, etc ...).

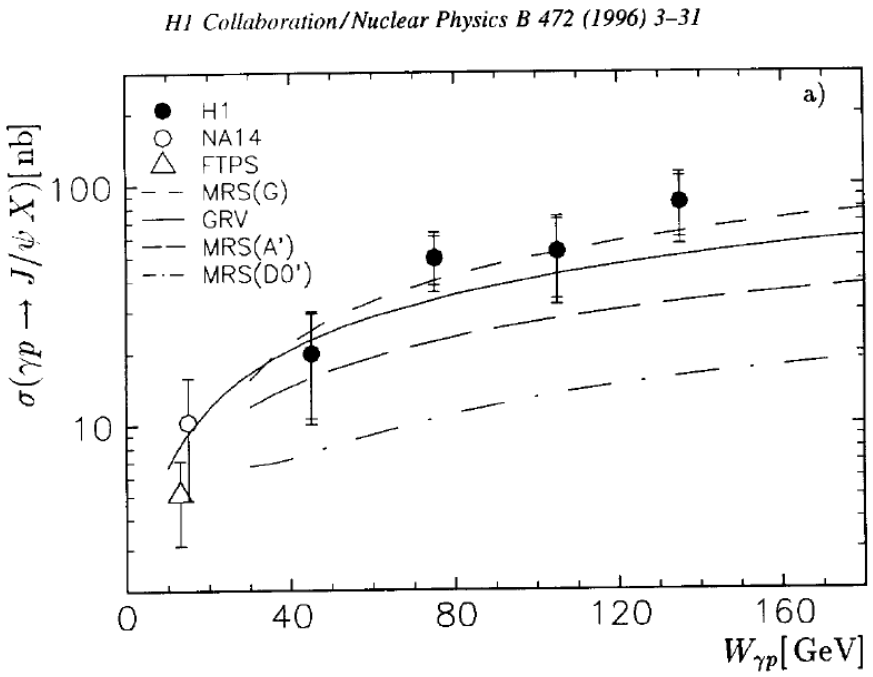


Also allows one to study J/ψ inclusive photoproduction which probes the gluon PDFs

As will be discussed by Liza.

Supporting data





Exclusive and Inclusive J/ψ photoproduction data from H1 *ep* collsions (left and right).

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

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

LHCb JHEP10(2018)167;

Goal

- To understand inclusive photoproduction mechanism in UPCs.
- To characterise inclusive J/ψ 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.

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>
```

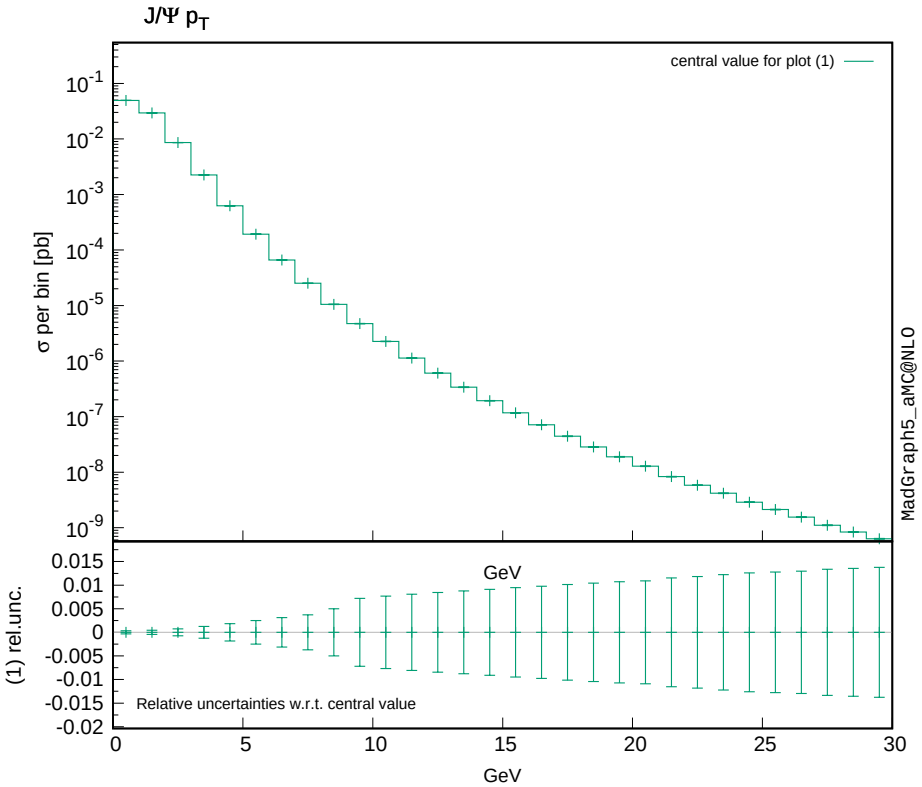
Results

- Used HELAC-Onia to generate the partonic event $[\gamma + g \rightarrow J/\psi + g]$ (*pp* photoproduction mode colpar=10).
- J/ψ 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	ALICE	CMS	ATLAS
$p_T^{J/\psi}$	<0 GeV	<0 GeV	<6.5 GeV	<8.5 GeV
$y^{J/\psi}$	(2,4.5)	(2.5,4)	< 2.4*	<2.1*
η^{μ}	(2,4.5)	(2.5,4)	<2.4*	<2.5*

*absolute value

Process without cuts



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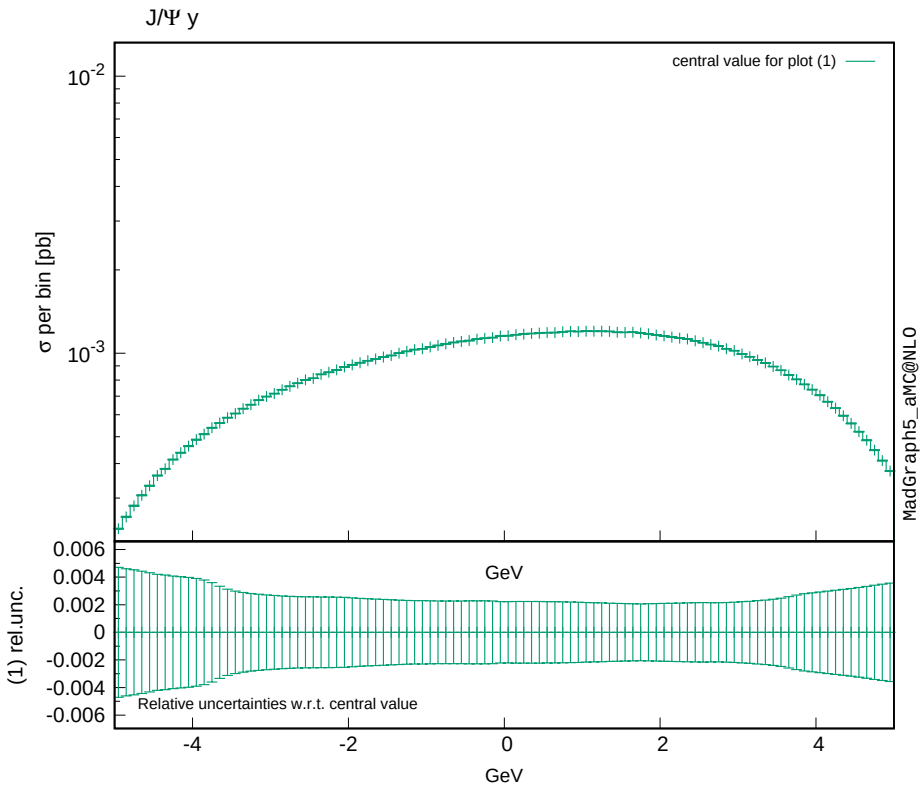
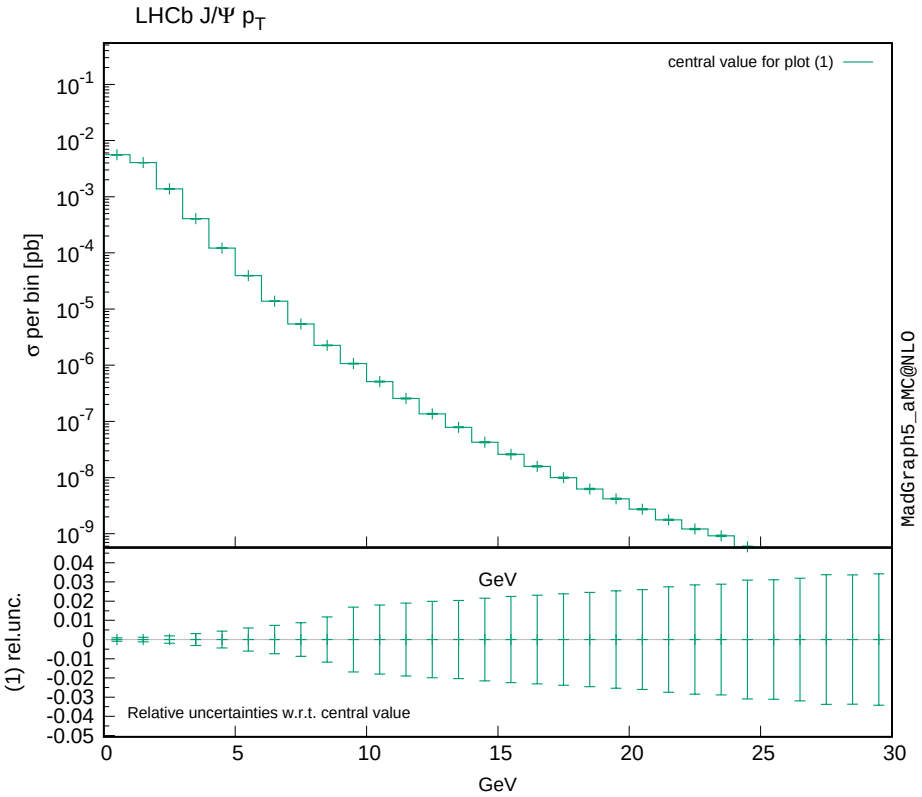


(b) J/ψ y

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

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

LHCb



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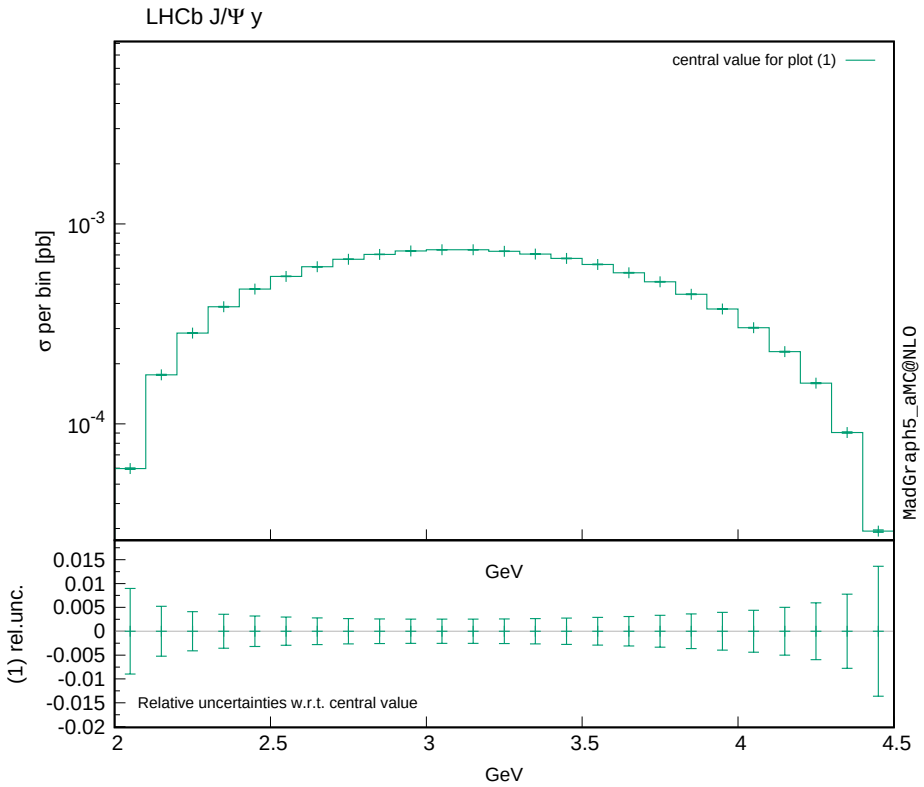
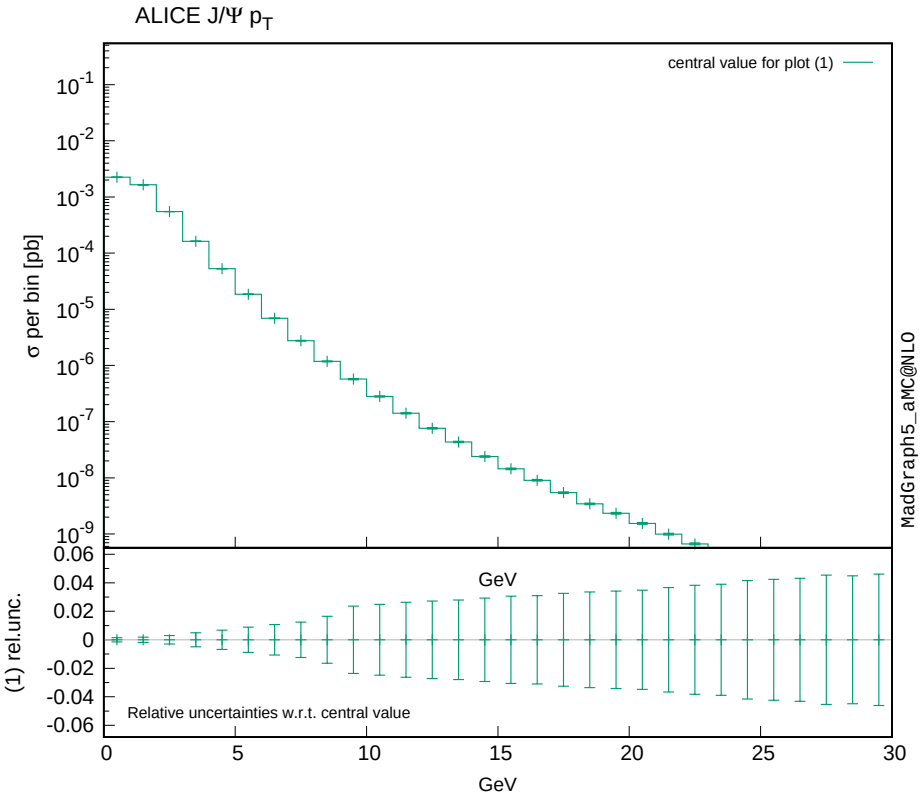


(b) J/ψ y

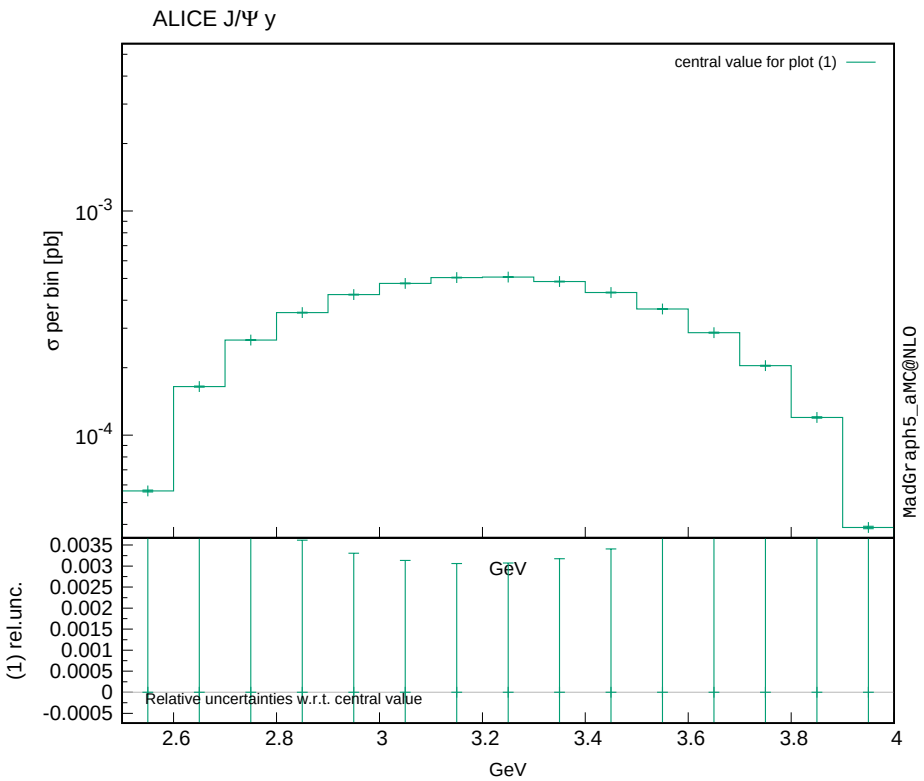
LHCb detector acceptance ($\sim 16\%$) : $2 < \eta^{\mu} < 4.5$ and $p_T^{\mu} > 0.4$ GeV, $2 < y^{J/\psi} < 4.5$ and $p_T^{J/\psi} > 0$ GeV.

.

ALICE



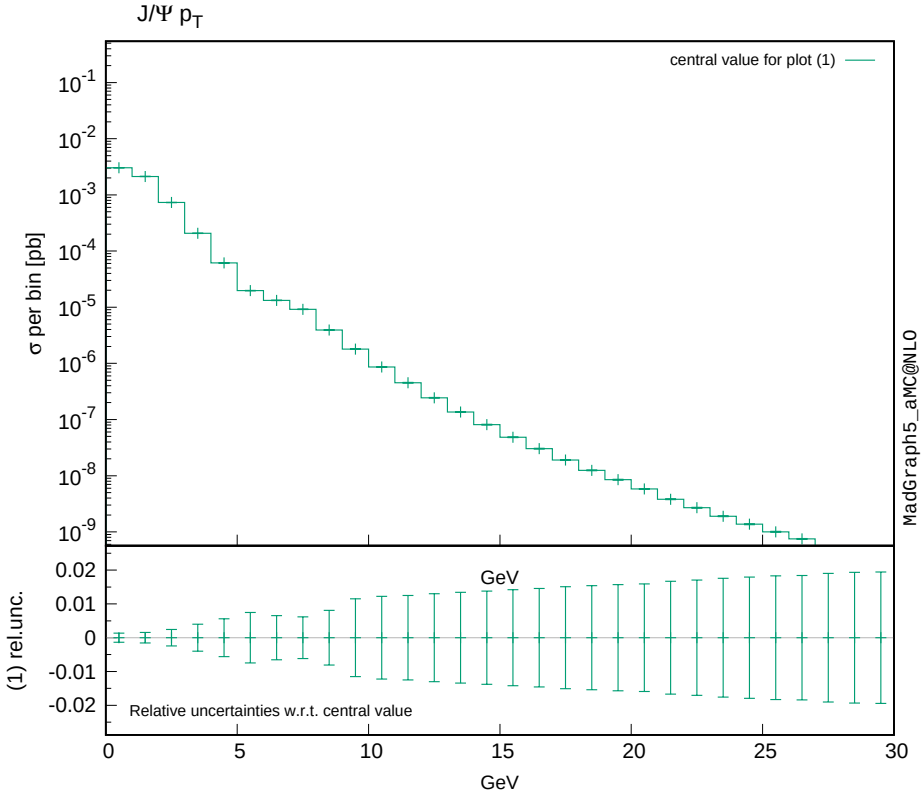
(a) $J/\psi \quad p_T$



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

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

CMS with low p_T



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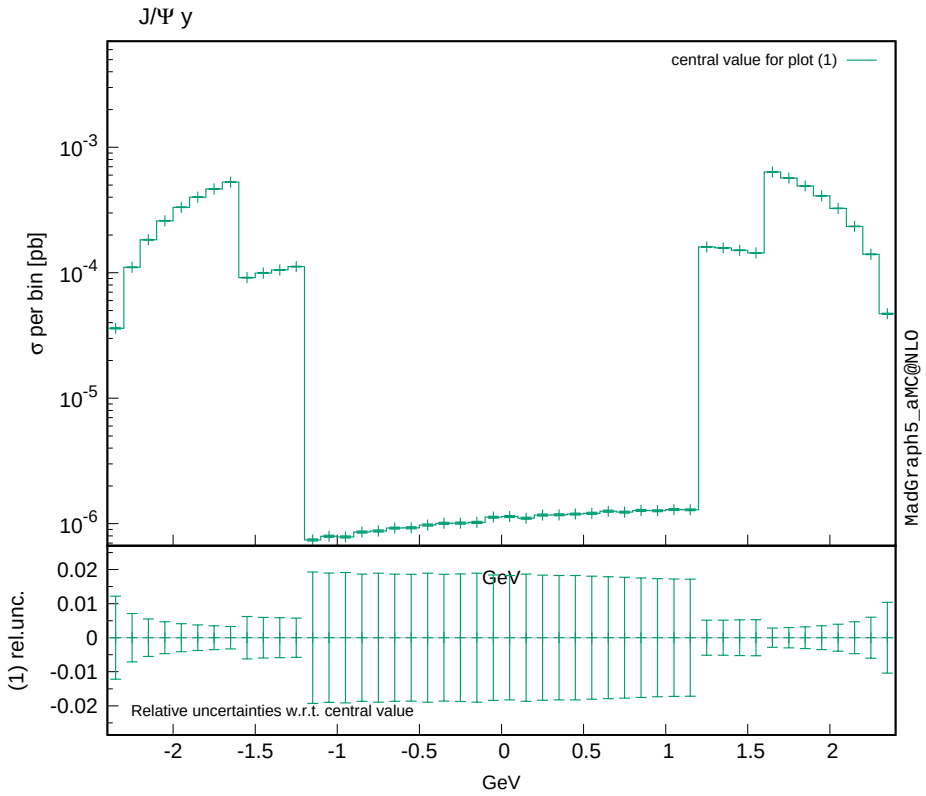
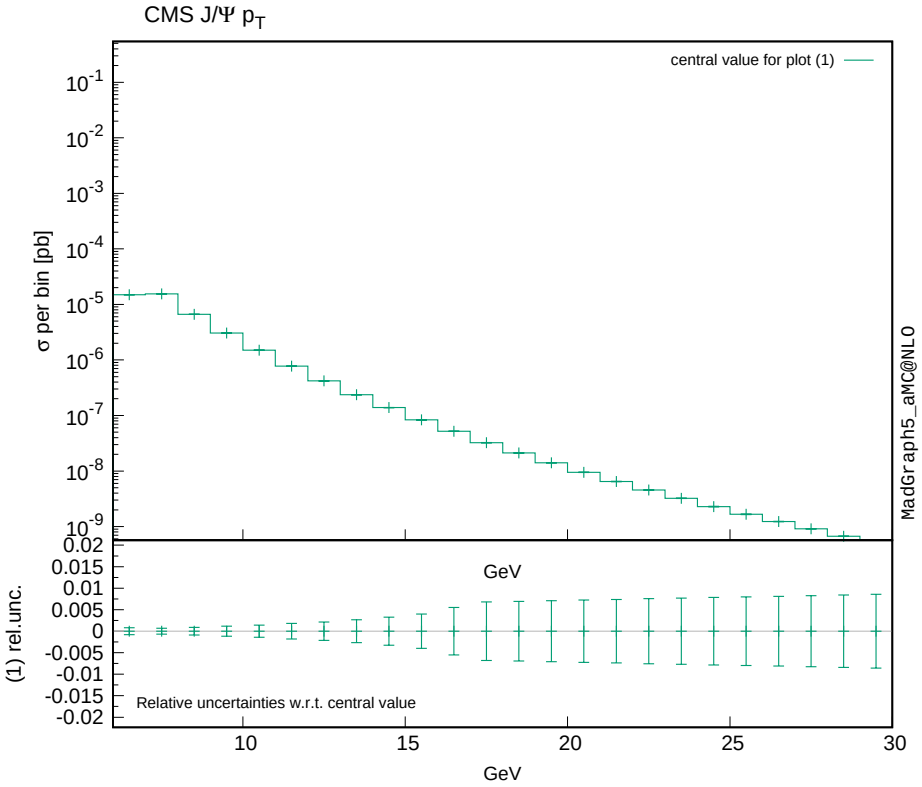


(b) J/ψ y

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 $1.6 < |y^{J/\psi}| < 2.4$.

CMS



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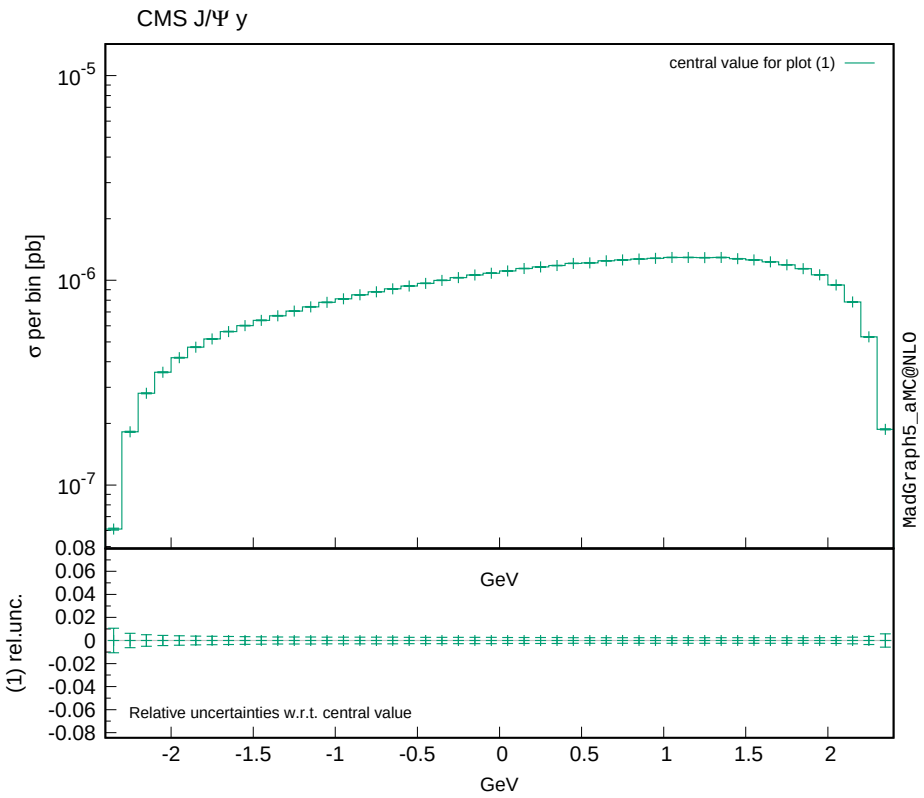
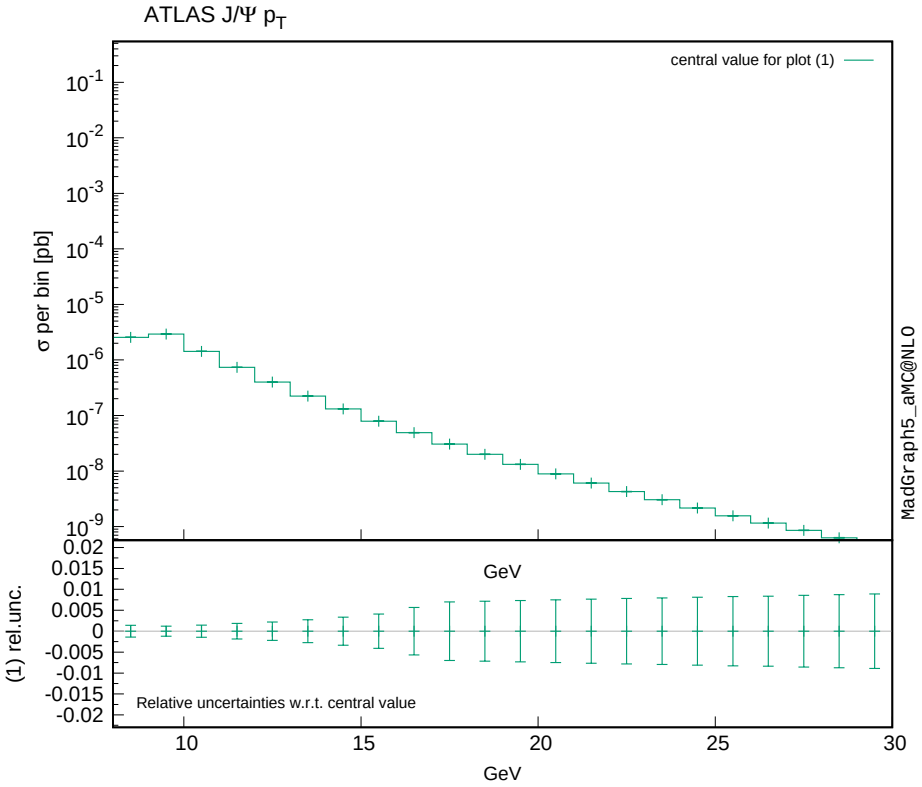


(b) J/ψ y

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

ATLAS



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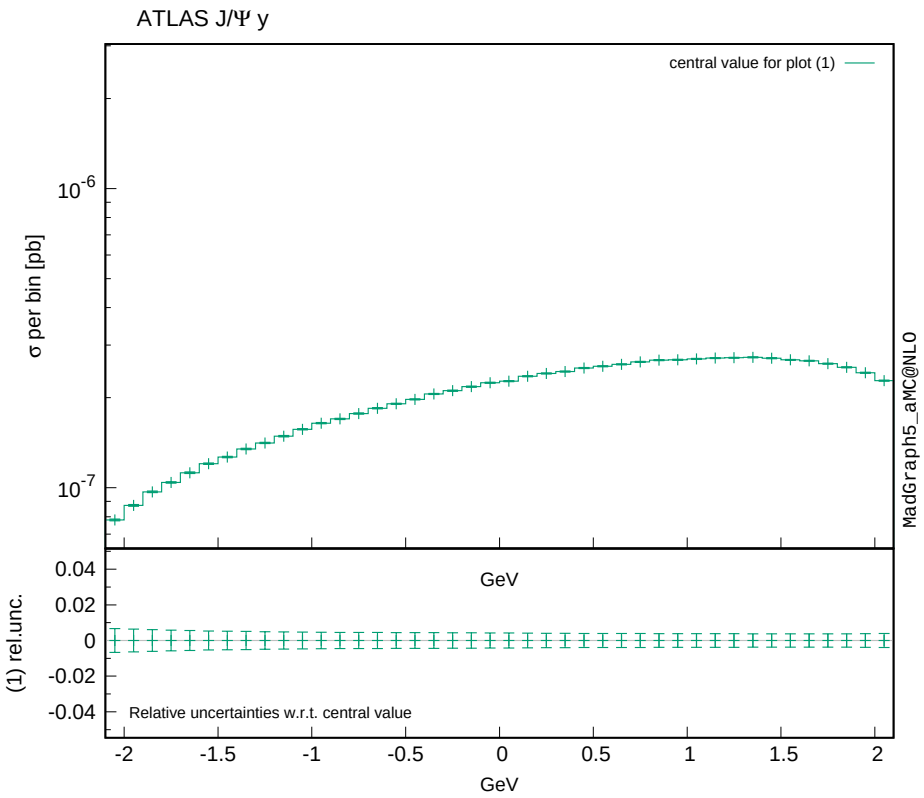
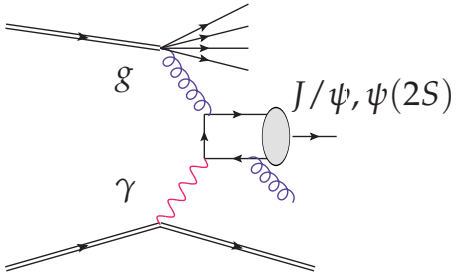


(b) J/ψ y

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

Outlook

- Aim to learn the mechanism of quarkonium production through studying inclusive J/ψ 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

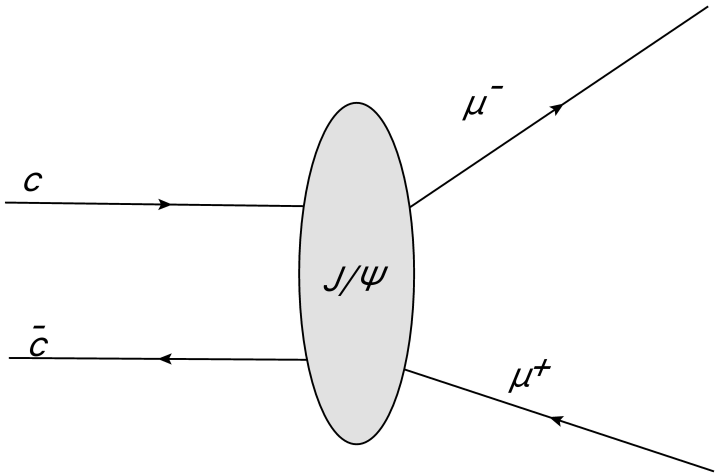
Summary

- ALICE* and LHCb are sensitive in the forward rapidity region with low p_T, which has good statistics.
- CMS and ATLAS are sensitive in the central rapidity 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.
- Currently working on understanding the output of PYTHIA 8 to see if it is in fact possible to tag J/ψ 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 aforementionned experimental set ups.

*ALICE can detect low p_T central electrons, not considered here.

J/ψ ; 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%.



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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-perterbative parameter for each fock state is related to HQSS