Inclusive Quarkonium Production at the EIC and at LHC via UPC

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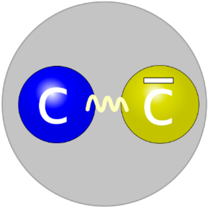
What are Quarkonia

- Bound states of heavy quarks $c\bar{c}$ or $b\bar{b}$



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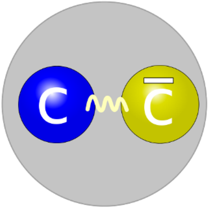

- Heavy quarks produced perturbativly $m_Q >> \Lambda_{QCD}$

  can be computed with Feynman diagrams

	m_Q	Λ_{QCD}/m_Q	$\alpha_s(m_Q)$
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b	4.75 GeV	0.05	0.18

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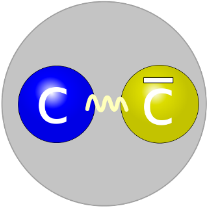

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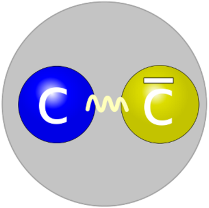

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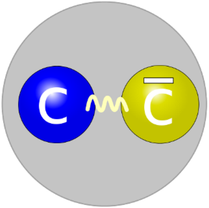

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- Their hadronisation is non-perturbative
- **Factorisation** between energy regimes
- Production mechanism remains an open question !

Quarkonium Production

1. Colour Singlet Model
   - $Q\bar{Q}$ pair produced with the same quantum numbers as $\mathcal{Q}$
   - **NO** gluon emissions during hadronisation
   - $d\sigma(\mathcal{Q} + X) = d\sigma(Q\bar{Q} + X)\langle \mathcal{O}^{\mathcal{Q}} \rangle$

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   - Higher Fock states with different quantum numbers contribute
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3. Colour Evaporation Model
   - Quantum numbers of $Q\bar{Q}$ decorrelated from $\mathcal{Q}$
   - Semi-soft gluon emissions during hadronisation
   - $\mathrm{d}\sigma(\mathcal{Q}+X) \propto \int_{2m_Q}^{2m_H} \frac{d\sigma(Q\bar{Q}+X)}{dm_{Q\bar{Q}}} dm_{Q\bar{Q}}$

Status today ...?

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   - problems in p_T spectrum at large p_T
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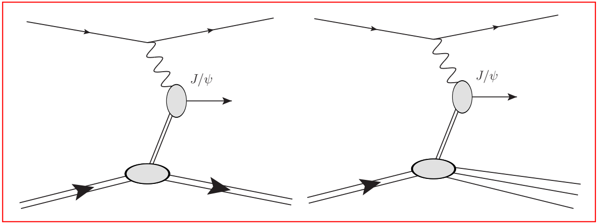
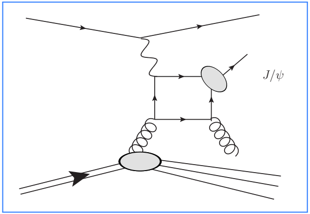
Quarkonium (J/ψ) production @ EIC





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- Exclusive (diffractive)

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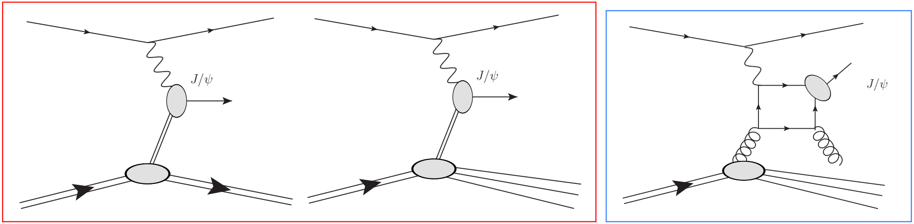

- Inclusive (inelastic)
- Want to study inclusive production...
  - Test mechanism of production .... Octet vs. Singlet
  - Probe gluon PDF
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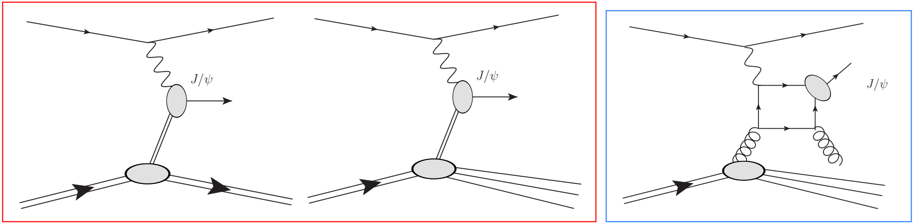

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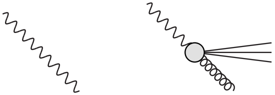
  extract GPDs

Quarkonium Production @ EIC

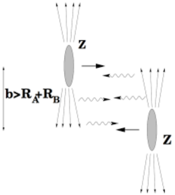
(Quasi)on-shell or off-shell photon...

- **Photoproduction** quasi-real photon $Q^2 << m^2_{J/\psi}$
  - Bulk of the cross-section
  - easy to compute (hard scale)
  - resolved component!
- **Leptoproduction** virtual photon γ^* $Q^2 > m^2_{J/\psi}$
  - Smaller cross-section
  - difficult to compute (introduce new scale)
  - **NO** resolved component



direct and resolved photons

Connection to the LHC: Photoproduction in UPC



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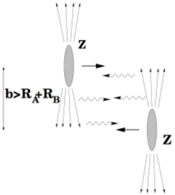

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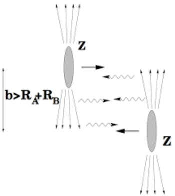

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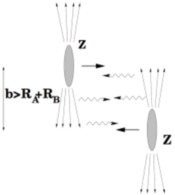

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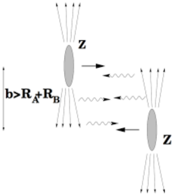

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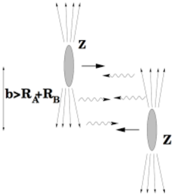

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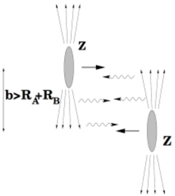

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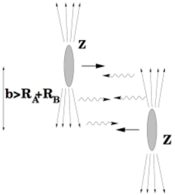

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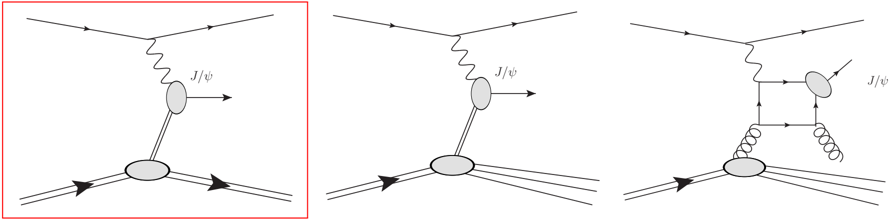
  - HERA $\sqrt{s_{\gamma p}^{max}} \approx 0.2$ TeV

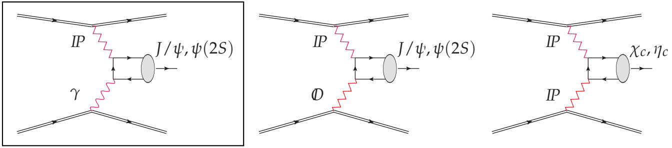
What has been measured...



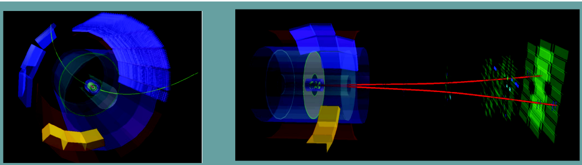
- **Exclusive** production in *pPb PbPb*, *dAu*, *ep*...

Exclusive J/ψ production

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



- only **colour singlet** contributions
- Clean signal
  - **only** quarkonia and its decay products are produced.
  - **both** colliding particles stay intact



UPC candidate in the central barrel and muon spectrometer

ALICE candidate signal for exclusive J/ψ production via UPC

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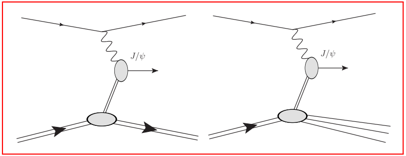

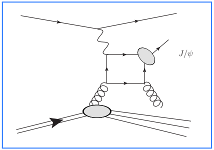

- Exclusive & inclusive production @ HERA $\sqrt{s} = 320$ GeV

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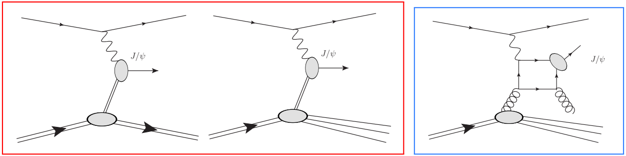

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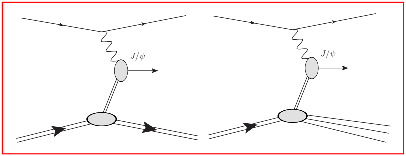

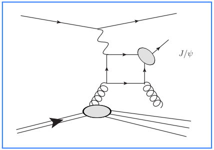

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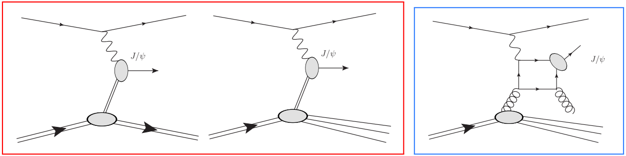

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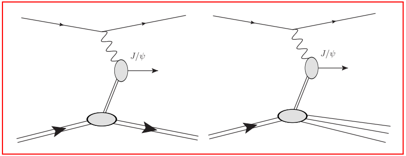

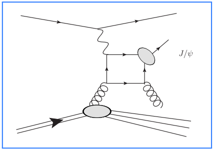

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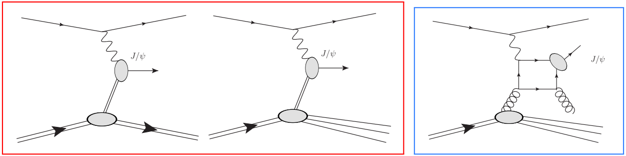

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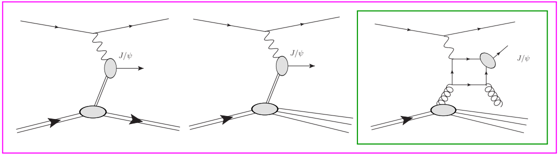
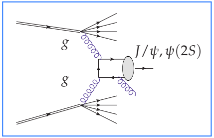
* enhanced photon flux (Z^2)

* less pileup than *pp* collisions

Inclusive UPC vs. Inclusive Production @ LHC





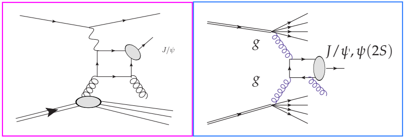
- Photon emitter reamins **intact**
- **Both** colliding nuclei break up

Can we distinguish these in practice??

OR

Does the hard gluon in the box pollute the region where we want to see the intact proton??

Signal vs. Background

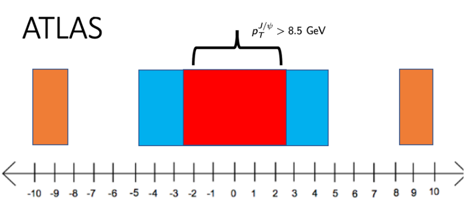


Back of the envelope calculation gives ...

$$R_{\text{sigback}} = \frac{\sigma_{sig}}{\sigma_{back}} \approx 1/50$$

- Need to use detectors to VETO background (p breakup) events

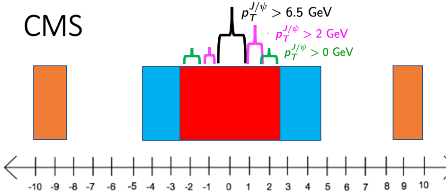
Detectors @ LHC



ZDC: $|\eta| > 8.3$

Cal.: $|\eta| < 4.9$ ($p_T > 200$ MeV)

Tracking: $|\eta| < 2.5$ ($p_T > 400$ MeV)



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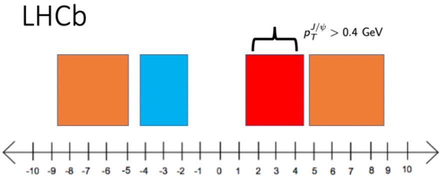
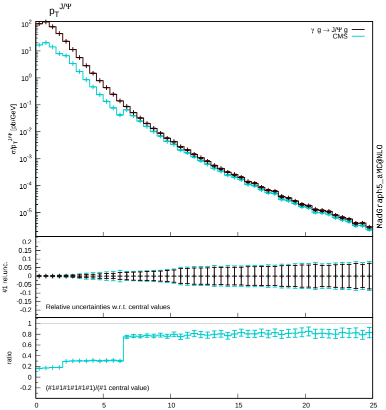


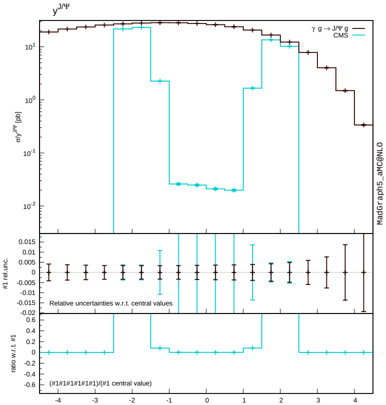
HeRSChel: $5 < |\eta| < 8.5$

VELO: $-4 < \eta < -1.5$ ($p_T > 0.1$ GeV)

LHCb: $2 < \eta < 5$ ($p_T > 0.1$ GeV)

Photoproduction cross section



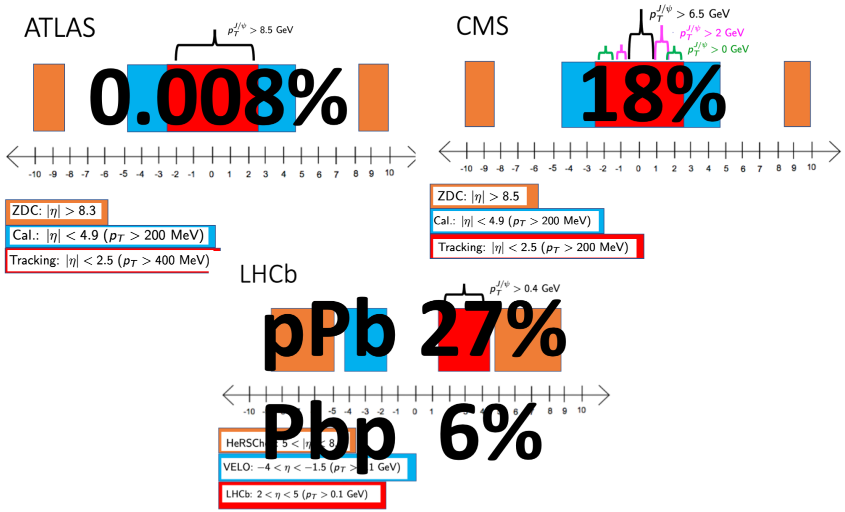


8.16 TeV photoproduction in Pbp

CMS cuts

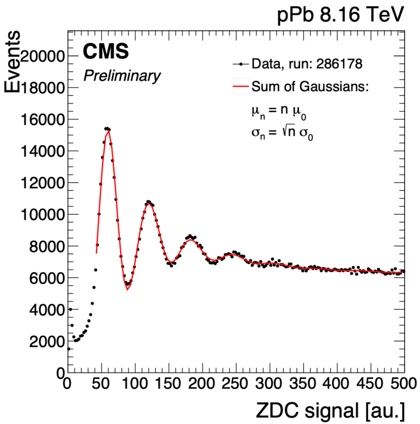
- Cross-section steeply falling in p_T

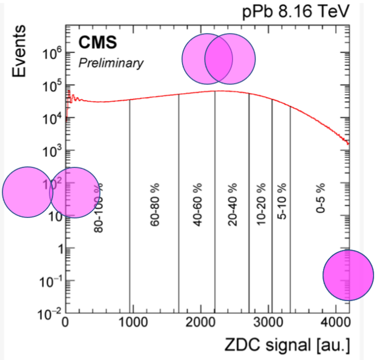
Detectors LHC @ 8.16 TeV acceptance



ZDC

Can remove ∼ 99.9 % of hadronic events !





Simulating events

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- HELAC-Onia to generate the partonic event $[\gamma + g \rightarrow J/\psi + g\ ]$

NLOAccess

Automated perturbative calculation with NLOAccess

HELAC-Onia Web

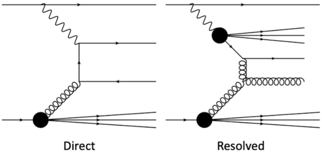
HELAC-Onia ia an automatic matrix element generator for the calculation of the heavy quarkonium helicity amplitudes in the framework of NRQCD factorization.
The program is able to calculate helicity amplitudes of multi P-wave quarkonium states production at hadron colliders and electron-positron colliders by including new P-wave off-shell currents. Besides the high efficiencies in computation of multi-leg processes within the Standard Model, HELAC-Onia is also sufficiently numerical stable in dealing with P-wave quarkonia and P-wave color-octet intermediate states.

- Pass Les Houches event file through PYTHIA
- Place detector cuts

	Background	Signal	$\frac{background}{signal}$
Cross section	14000 pb	270 pb	~ 50
CMS Acceptance	0.19	0.19	
ZDC cut	0.001	-	$\sim$0.05
ATLAS Acceptance	0.0001	0.0006	
ZDC cut	0.001	-	~ 0.008
LHCb Pbp Acceptance	0.18	0.05	
$>$ 5 tracks Hershel	0.04	0.99	~ 7
LHCb pPb Acceptance	0.24	0.30	
$>$ 5 tracks in Hershel	0.04	1.0	~ 2

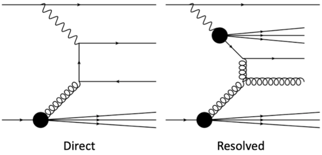
to further suppress background include some rapidity gap cuts however...

Still need to consider the resolved contribution...



- *Resolved photon contributions !*

Still need to consider the resolved contribution...



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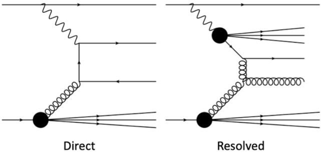
- In *ep* collisions cut $z > 0.3$

Small fraction of photon momentum in hard collision

Still need to consider the resolved contribution...



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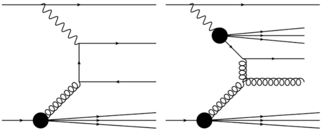

- *Resolved photon contributions !*
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- UPC @ LHC $\sqrt{s_{\gamma p}} \approx 1$ TeV vs. HERA $\sqrt{s_{\gamma p}} \approx 200$ GeV

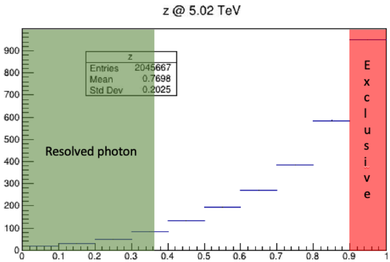
Summary

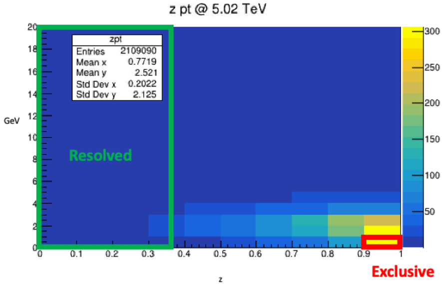
- Inclusive quarkonium allows us to discriminate production mechanisms
- It appears feasible to study this at the LHC **however** it is not clear what to do about the resolved contribution
- Study @ EIC has the advantage of placing kinematical cuts to isolate exclusive/resolved contributions

$\mathcal{L}_{CMS} \approx \mathcal{L}_{ATLAS} \approx 180nb^{-1}$
$\mathcal{L}_{LHCb_{pPb}} \approx 10nb^{-1}$; $\mathcal{L}_{LHCb_{Pbp}} \approx 20nb^{-1}$

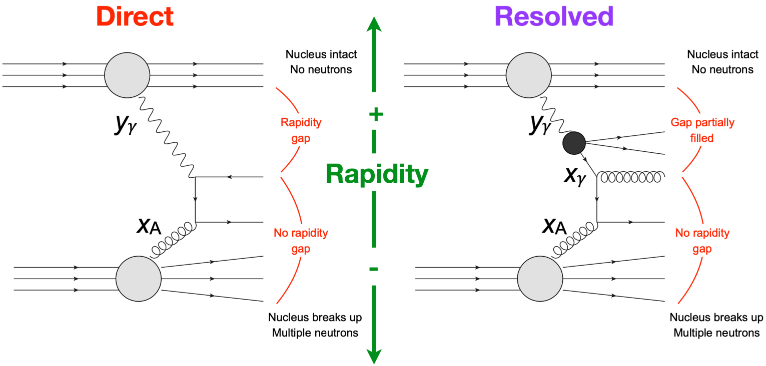
	Background	Signal	$\frac{background}{signal}$
Cross section	14000 pb	270 pb	~ 50
N_{cand}	2.5×10^9	5×10^7	
CMS Acceptance	0.19	0.19	
ZDC cut	0.001	-	$\sim$0.05
ATLAS Acceptance	0.0001	0.0006	
ZDC cut	0.001	-	~ 0.008
N_{cand}	2.8×10^8	5.4×10^6	
LHCb Pbp Acceptance	0.18	0.05	
>5 tracks Hershel	0.04	0.99	~ 7
N_{cand}	1.4×10^8	2.7×10^6	
LHCb pPb Acceptance	0.24	0.30	
>5 tracks in Hershel	0.04	1.0	~ 2

Kinematical cuts on the inclusive cross section





	Background	Signal	$\frac{background}{signal}$
Cross section	13996 pb	274.22 pb	~ 50
CMS Acceptance	0.194	0.1876	
ZDC cut	0.01	-	
$\Delta\eta_\gamma > 1$	0.012	0.94	
$\sum \Delta\eta_\gamma > 3.5$	0.08	0.97	~ 0.02
ATLAS Acceptance	0.000170	0.000619	
ZDC cut	0.01	-	
$\Delta\eta_\gamma > 1$	0.004	0.98	
$\sum \Delta\eta_\gamma > 3.5$	0.016	0.98	~ 0.001
LHCb Pbp Acceptance	0.18761	0.042	
$>$ 5 tracks Hershel	0.04	0.999	~ 7
LHCb pPb Acceptance	0.242	0.329	
$>$ 5 tracks in Hershel	0.04	1.0	~ 2


Direct
Resolved
Nucleus intact
No neutrons
y_γ
Rapidity
gap
x_A
No rapidity
gap
Nucleus breaks up
Multiple neutrons
+
Rapidity
-
Nucleus intact
No neutrons
y_γ
Gap partially
filled
x_γ
x_A
No rapidity
gap
Nucleus breaks up
Multiple neutrons

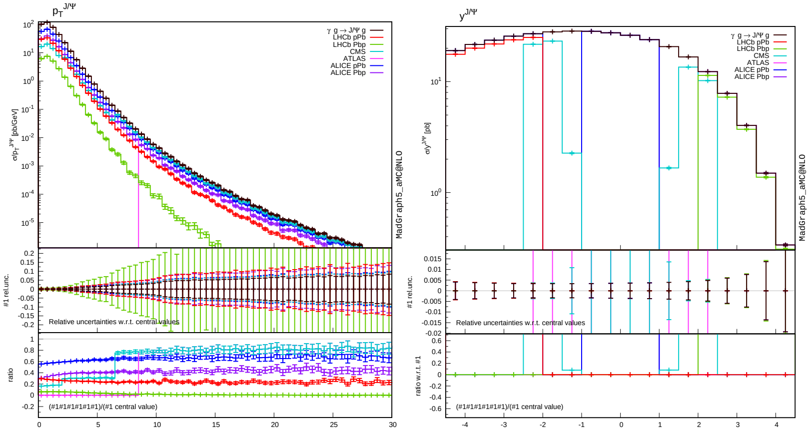


Figure: 8.16 TeV photoproduction in Pbp