Inclusive quarkonium production in ultra-peripheral collisions

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Heavy Flavours from small to large systems

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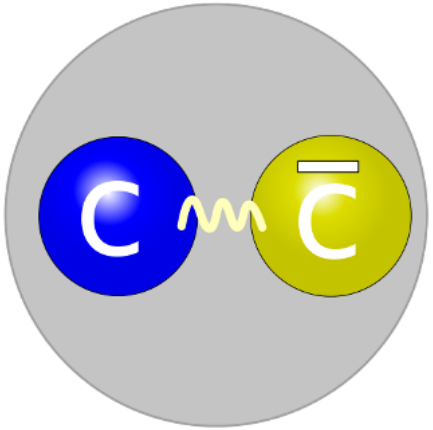
What are Quarkonia

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



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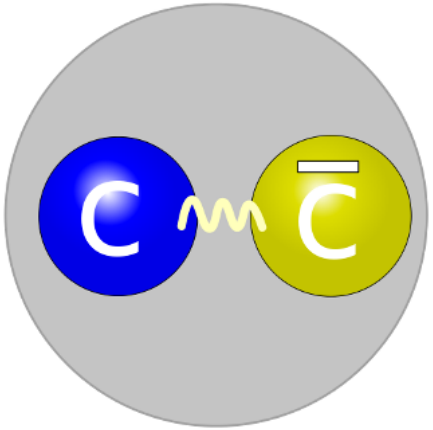

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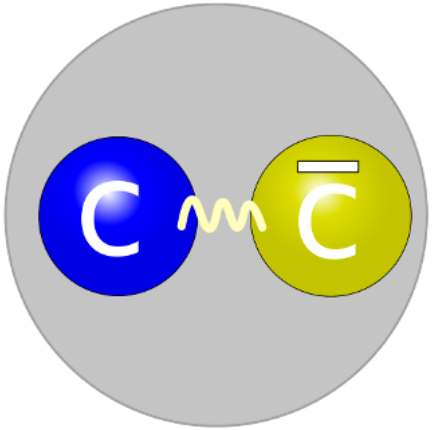

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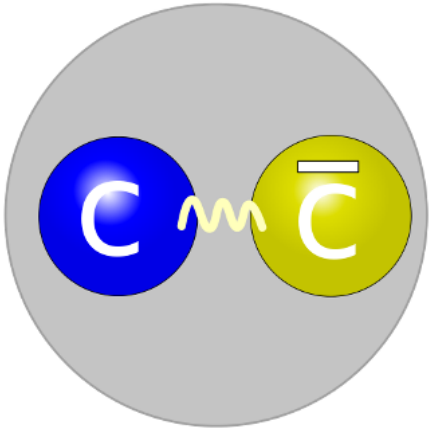

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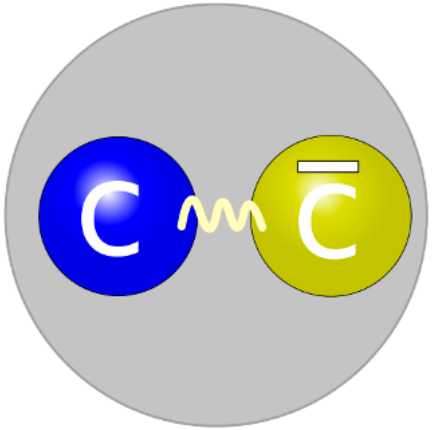

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- **Factorisation** between short and long distance physics
- Production mechanism remains an open question!

Quarkonium Production

1. Colour Singlet Model
   - $Q\bar{Q}$ pair produced with the same quantum numbers as $\mathcal{Q}$
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3. Colour Evaporation Model
   - Quantum numbers of $Q\bar{Q}$ decorrelated from $\mathcal{Q}$
   - Semi-soft gluon emissions during hadronisation
   - $\mathrm{d}\sigma(\mathcal{Q}+X) \propto \int_{2m_Q}^{2m_H} \frac{d\sigma(Q\bar{Q}+X)}{dm_{Q\bar{Q}}} dm_{Q\bar{Q}}$

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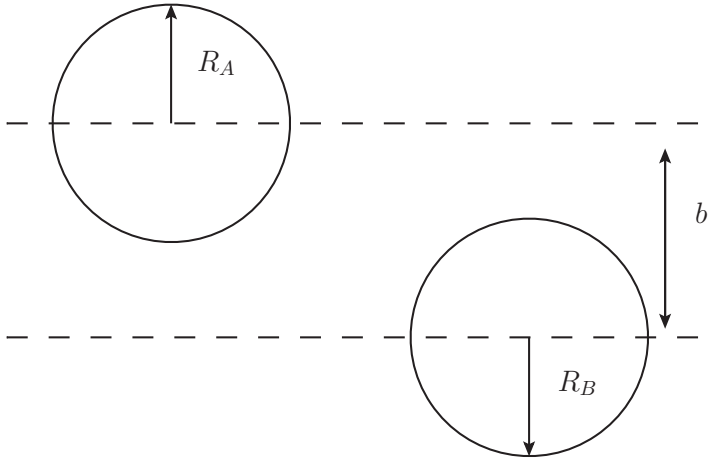
Ultra peripheral collisions...



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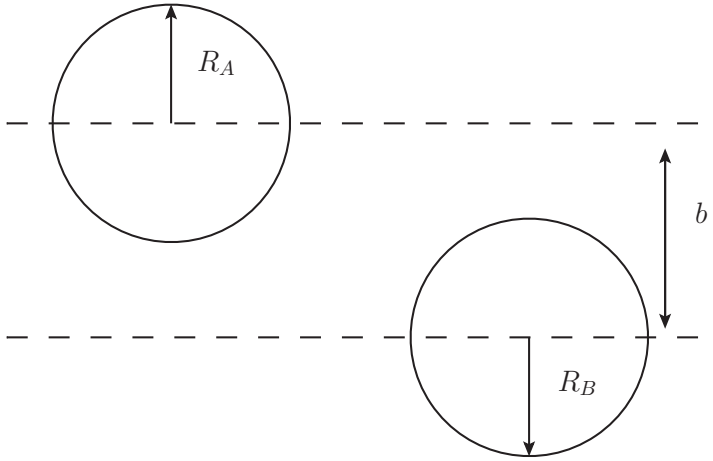

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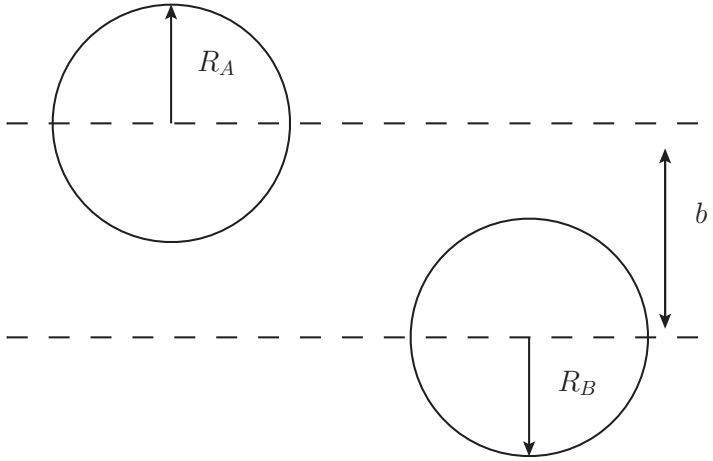

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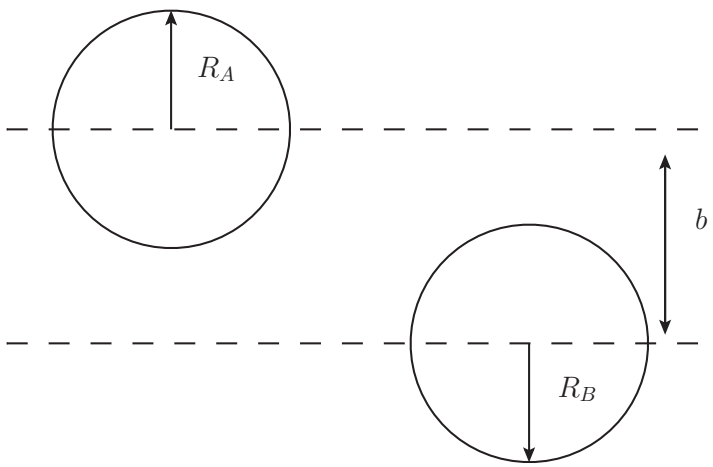

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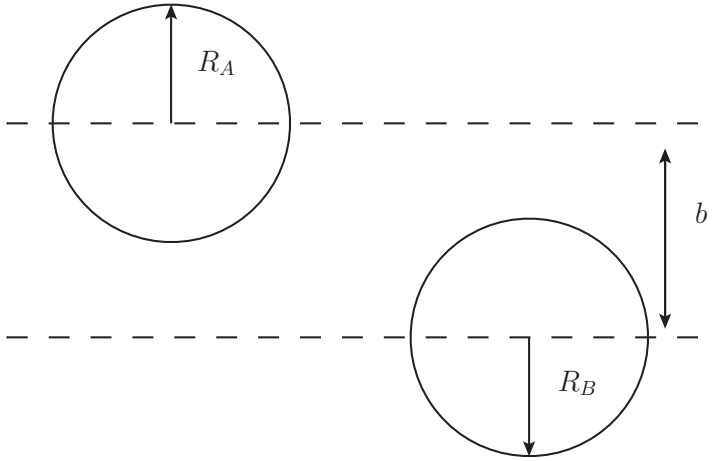

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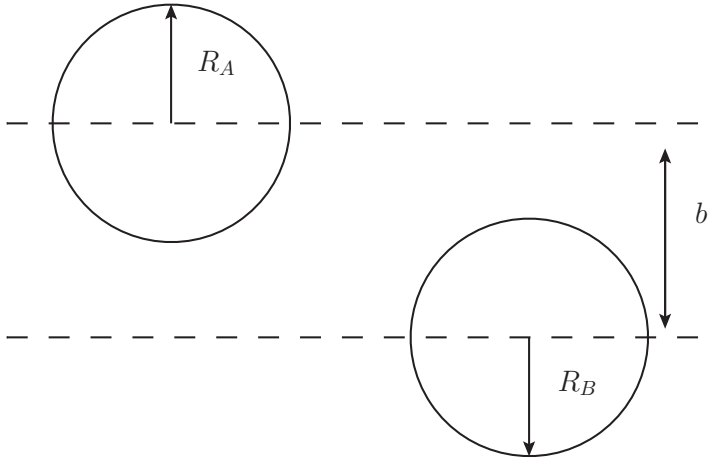

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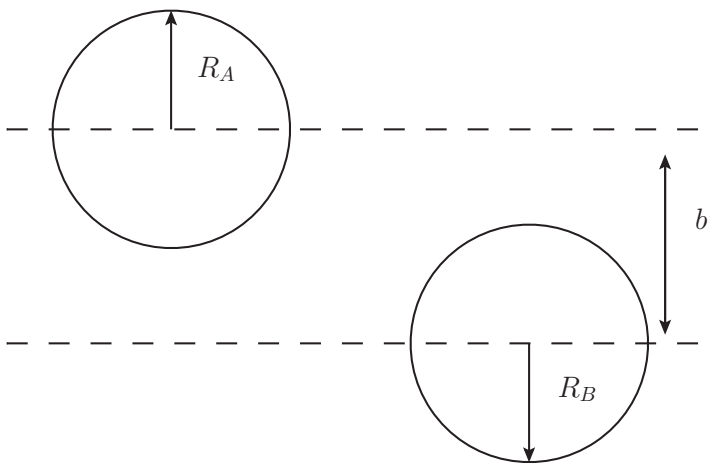

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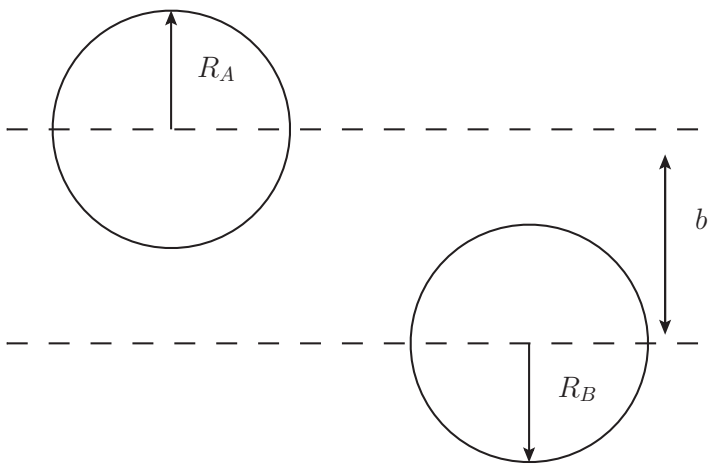

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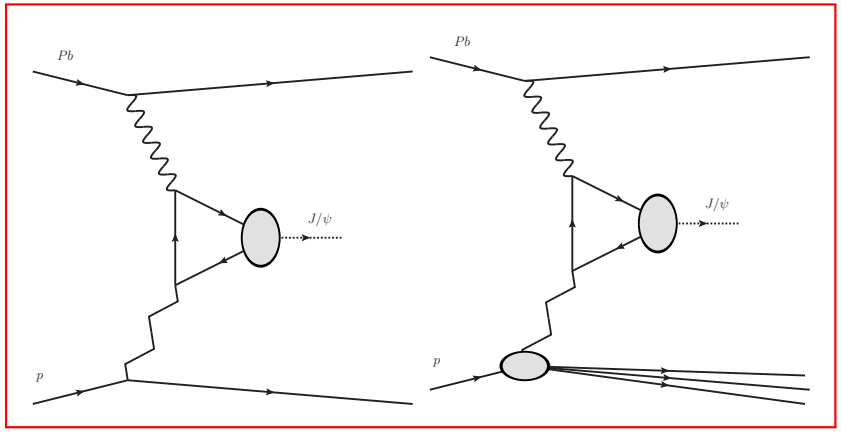
  - HERA $W_{\gamma N}^{max} \approx 0.2$ TeV

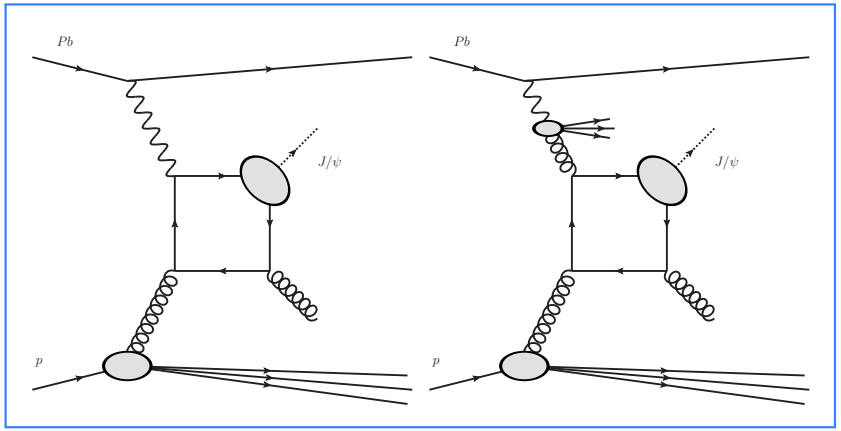
Inclusive vs. exclusive photoproduction

Exclusive production



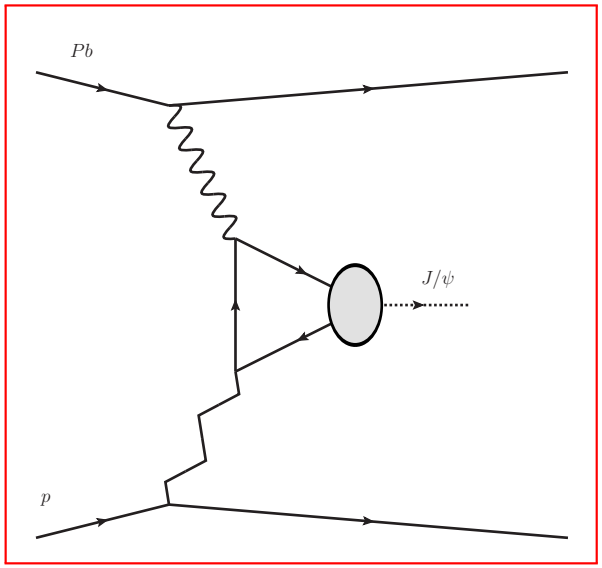
- **only** J/ψ decay products
- Colourless exchange
- Extract gluon GPDs

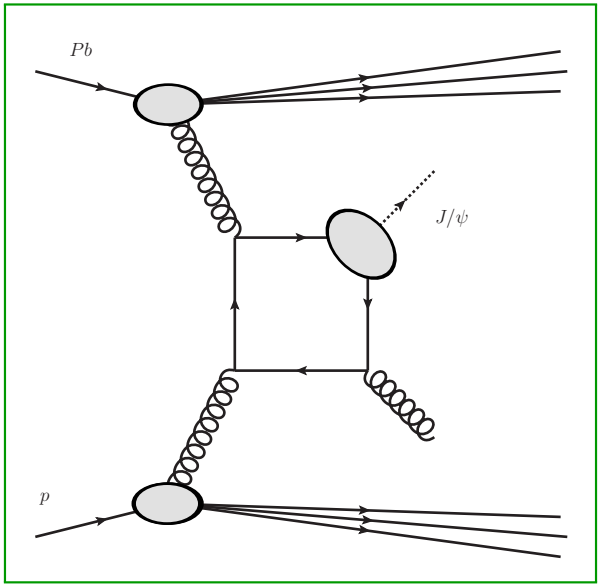
Inclusive production

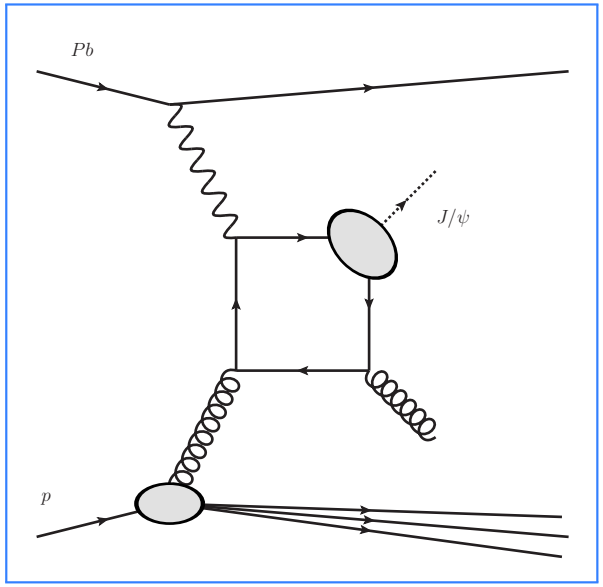


- Hard final state gluon
- Resolved vs. direct contribution
- Test production mechanism
- Probe gluon PDF

What has been measured...







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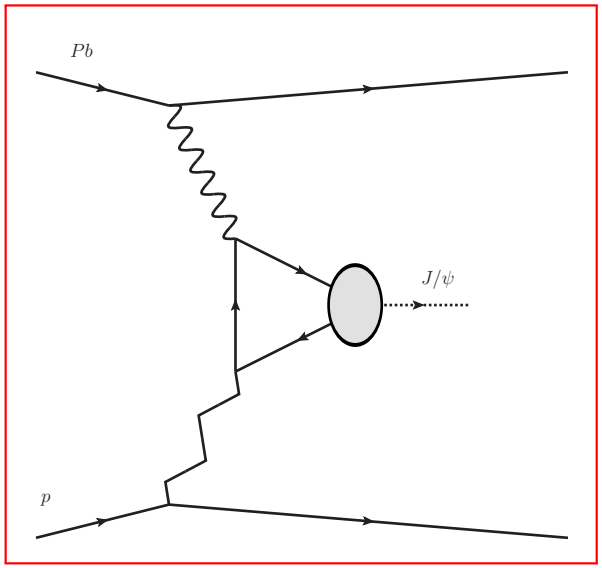

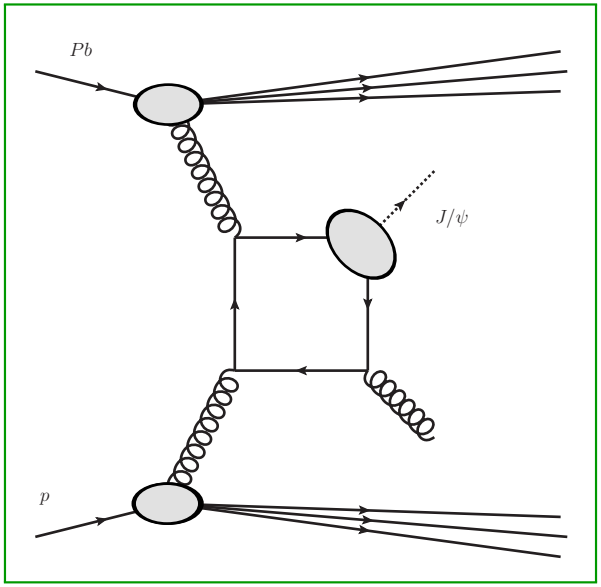

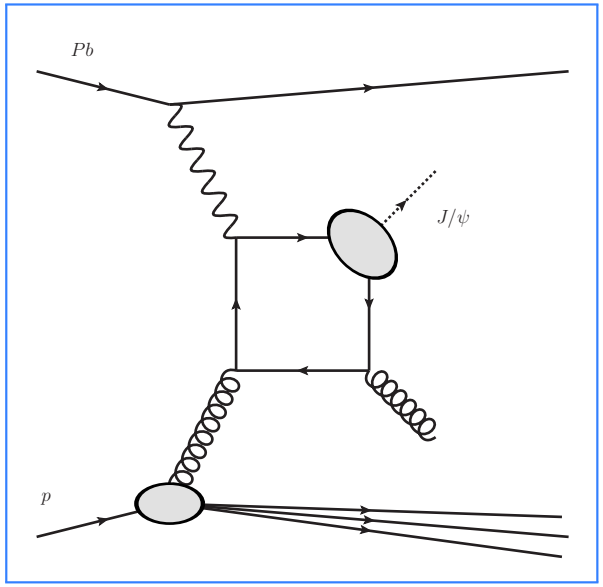

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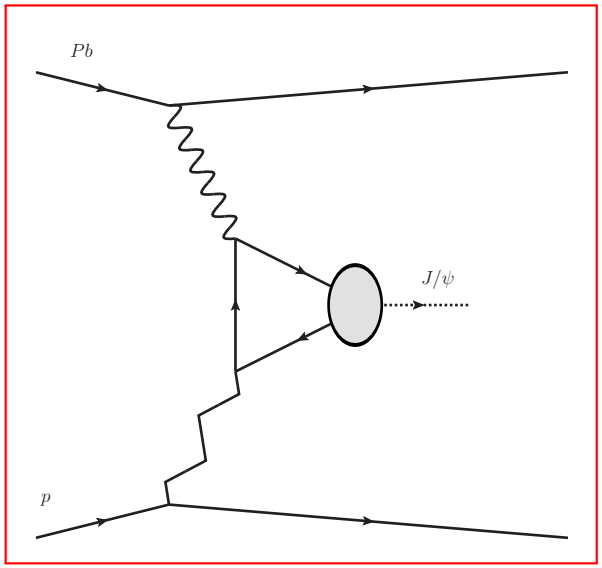

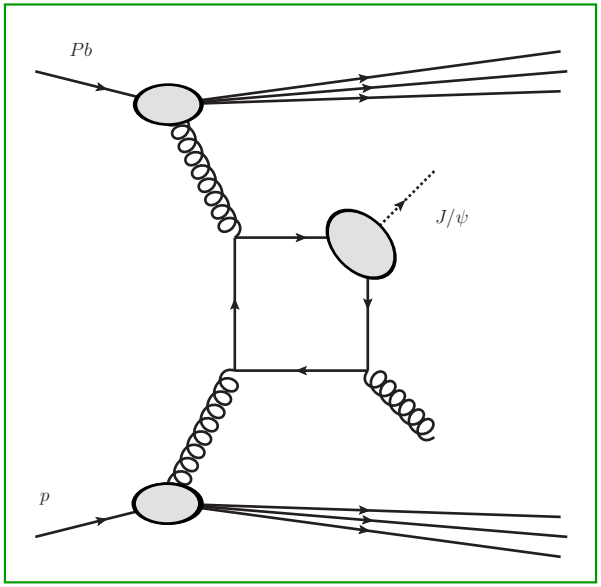

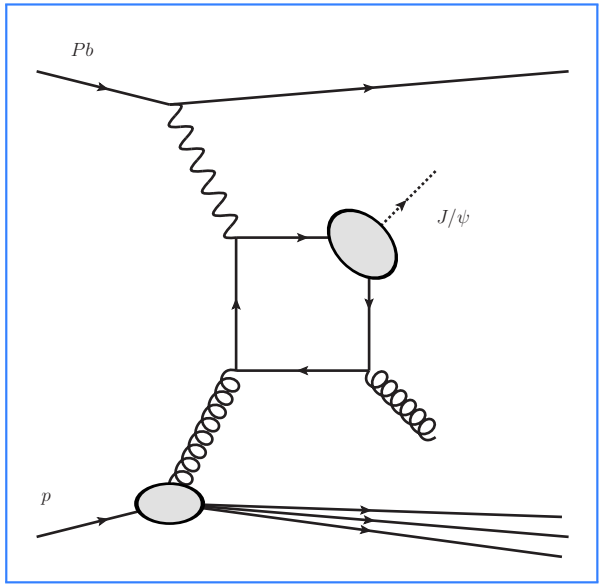

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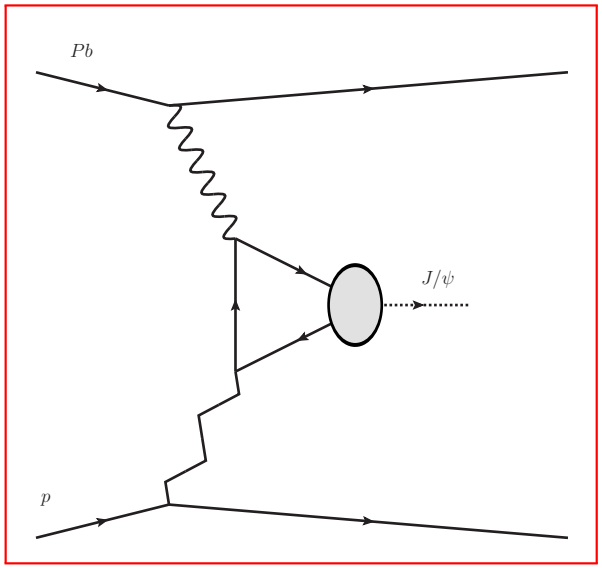

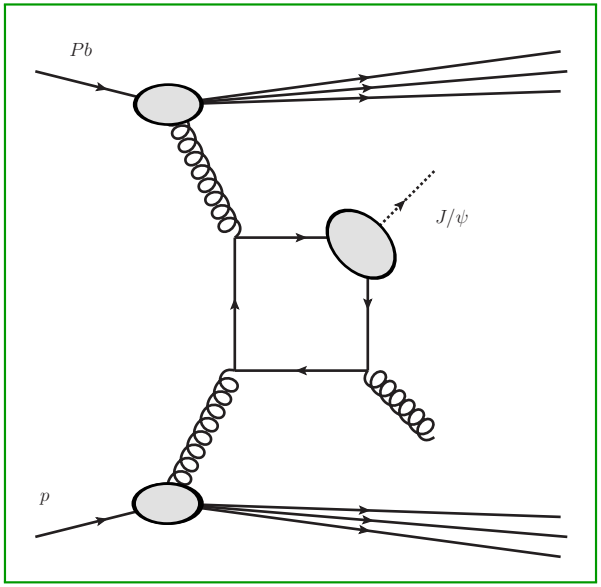

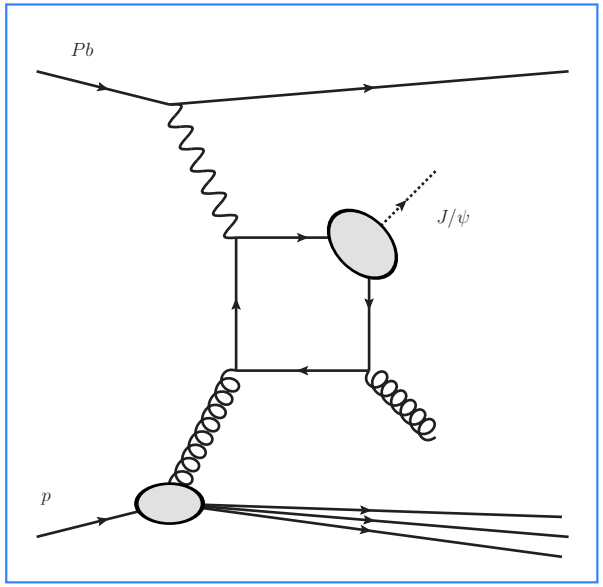

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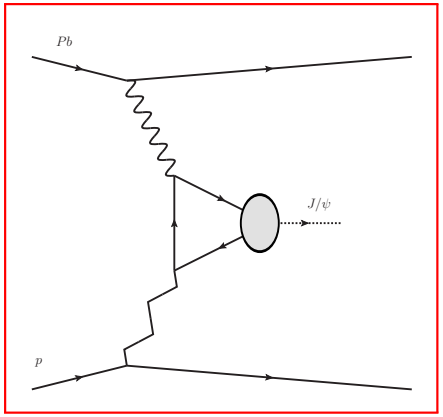
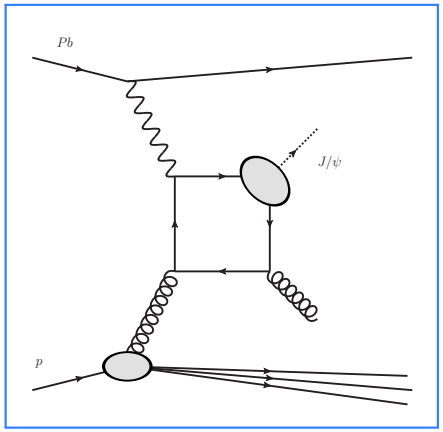
$\rightarrow$ Study in any system with a charged particle

What has been measured...at HERA





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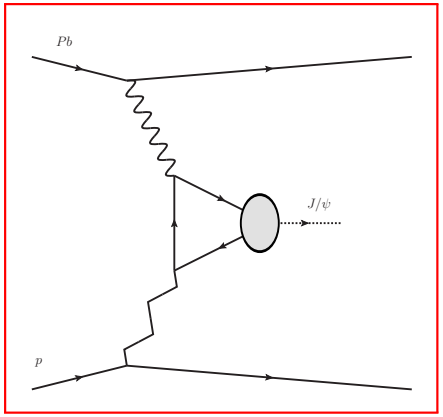

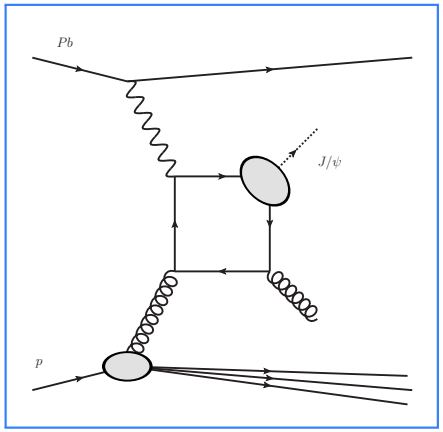

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  - separated using experimental cuts on ...
    - ★ $p_T > 1$ GeV
    - ★ $z = \frac{P_{J/\psi} \cdot P}{P_\gamma \cdot P} < 0.9$

* z is reconstructed experimentally

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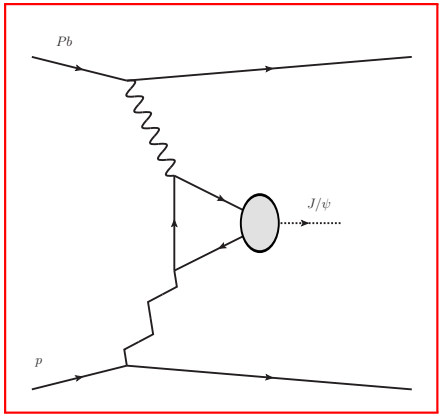

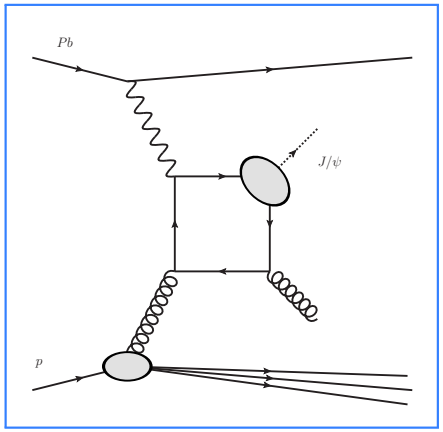

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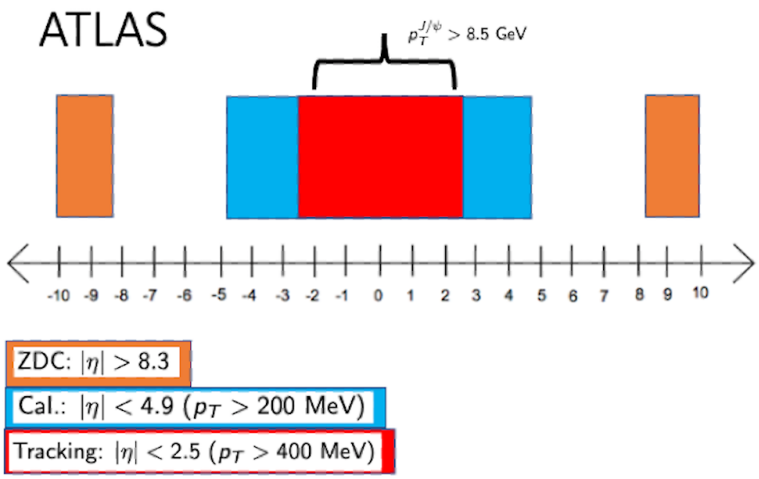
- Examine Pbp/pPb collisions

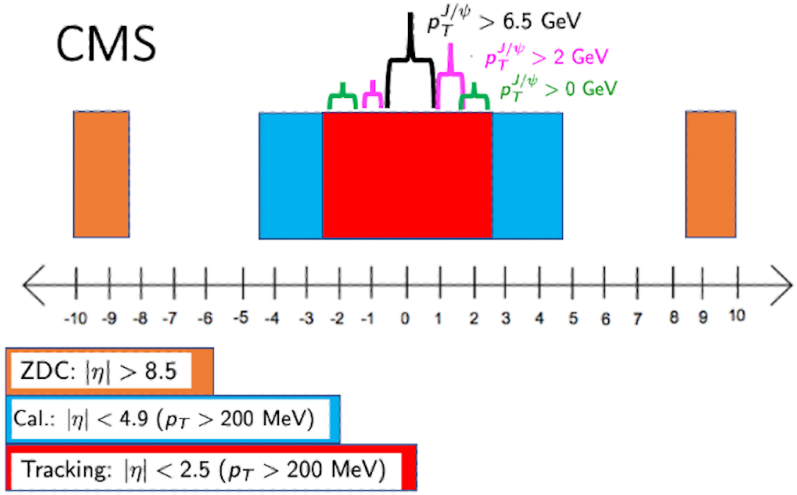
Feasibility: Detector Acceptance

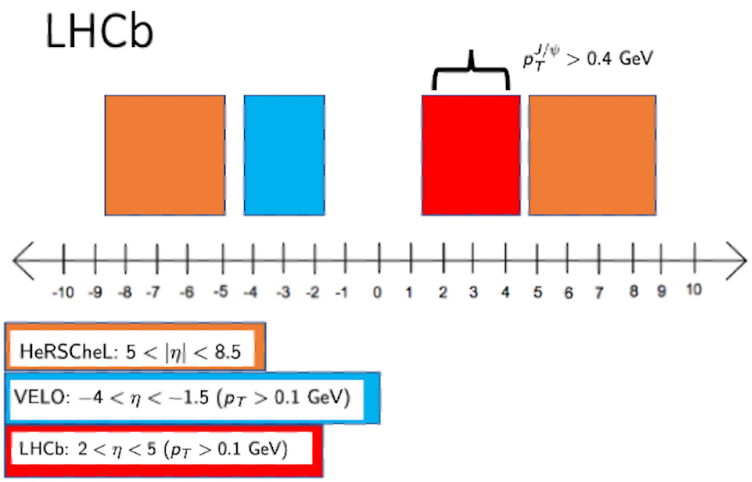
LHCb	**CMS** typical	**CMS** low p_T
$2 < y^\psi < 4.5$	$\lvert y^\psi \rvert < 2.1$	$1.2 > \lvert y^\psi \rvert$, $p_T^\psi > 6.5$
$p_T^\mu > 0.4$	$p_T^\psi > 6.5$	$1.2 < \lvert y^\psi \rvert < 1.6$, $p_T^\psi > 2$
		$1.6 < \lvert y^\psi \rvert < 2.4$, $p_T^\psi > 0$

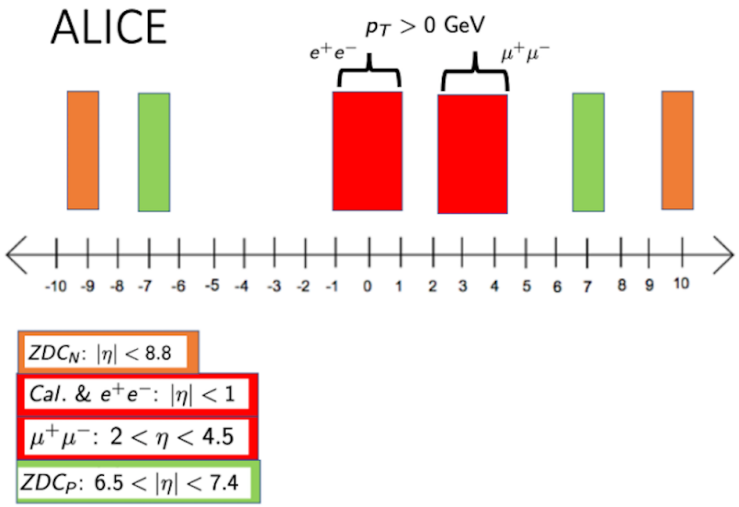
ALICE e^-e^+	**ALICE** $\mu^-\mu^+$	**ATLAS**
$\lvert y^\psi \rvert < 0.9$	$2.5 < y^\psi < 4$	$\lvert y^\psi \rvert < 2.1$
		$p_T^\psi > 8.5$

Detectors @ LHC

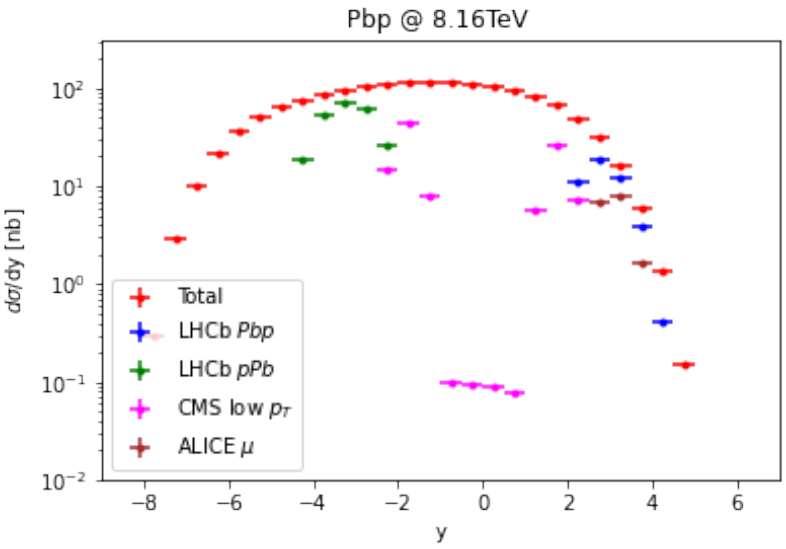


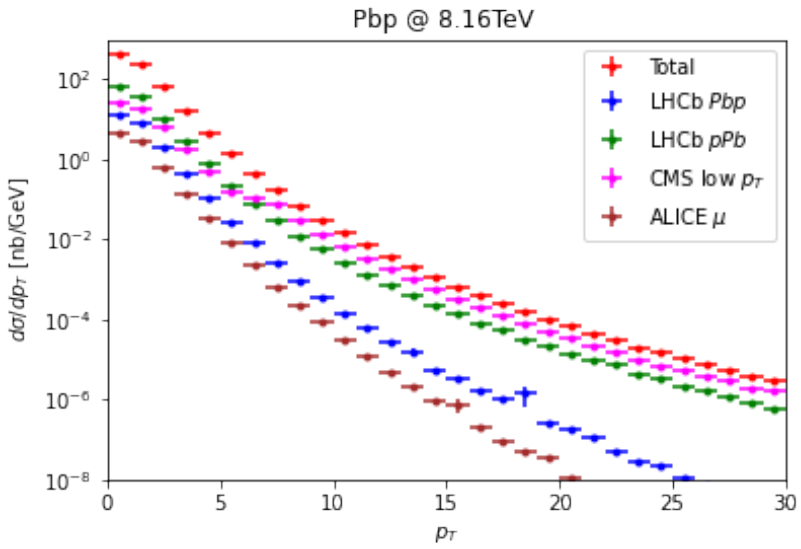






Detector acceptance: $\gamma g \to J/\psi(^3S_1^1)g$



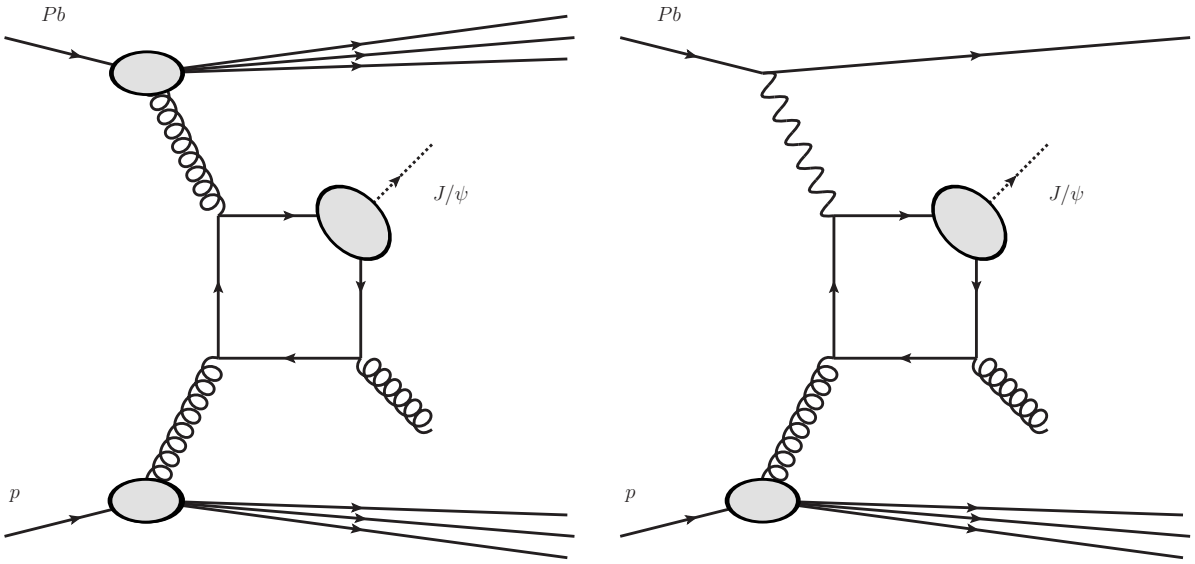


Detector acceptance:

LHCb	**CMS** typical	**CMS** low p_T	**ATLAS**	**ALICE** e^-e^+	**ALICE** $\mu^-\mu^+$
Pbp: 0.02 *pPb*: 0.1	0.0004	0.07	0.00007	0.2	*Pbp* : 0.01

Feasibility... can we distinguish it from backgrounds?

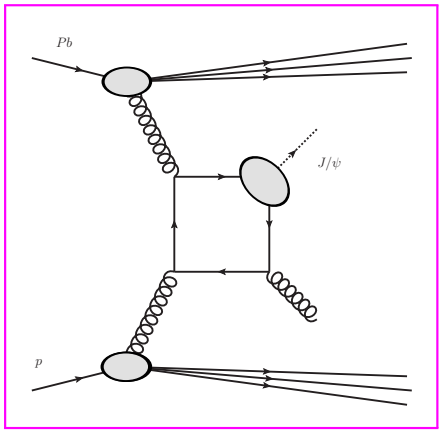
Can we distinguish these in practice ?

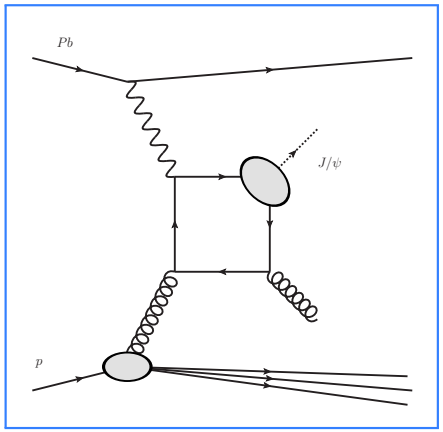


hadroproduction vs. photoproduction signal...

- γ emitter remains intact

Signal vs. Background

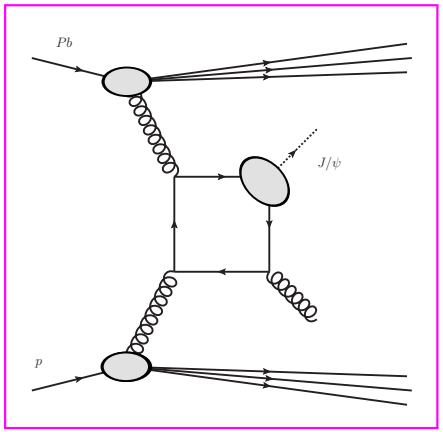


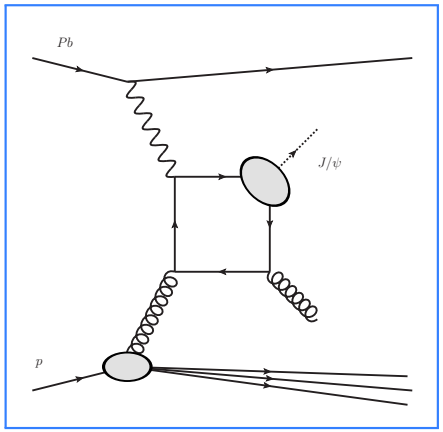


Back-of-the-envelope calculation gives ...

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

Signal vs. Background



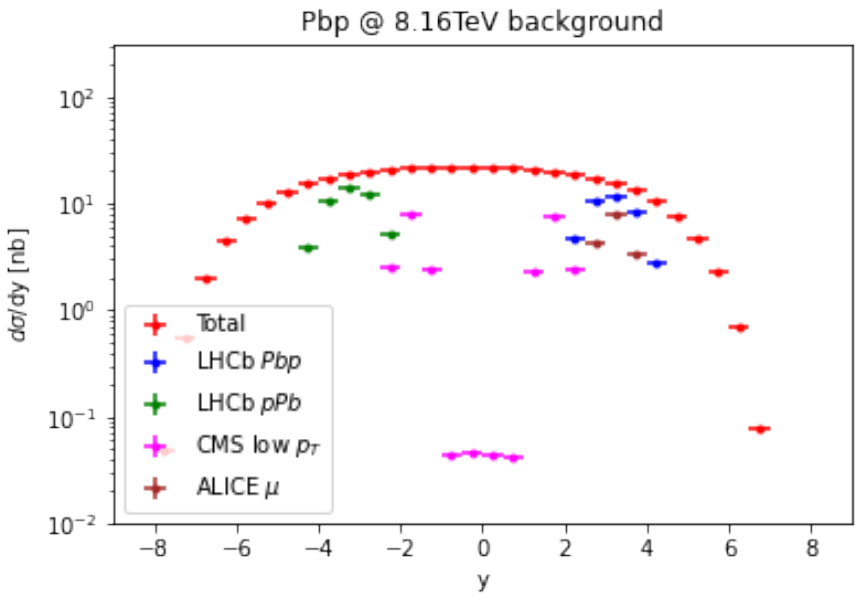


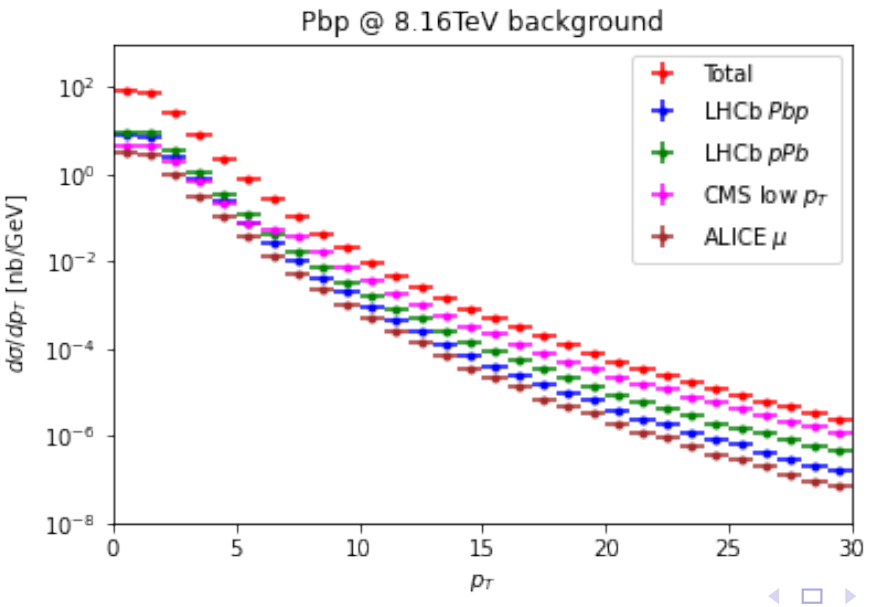
Back-of-the-envelope calculation gives ...

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

$\rightarrow$ Need to use detectors to reduce background contribution (Pb breakup)

Detector acceptance: $gg \to J/\psi(^3S_1^1)g$





Background/Signal ratio ...

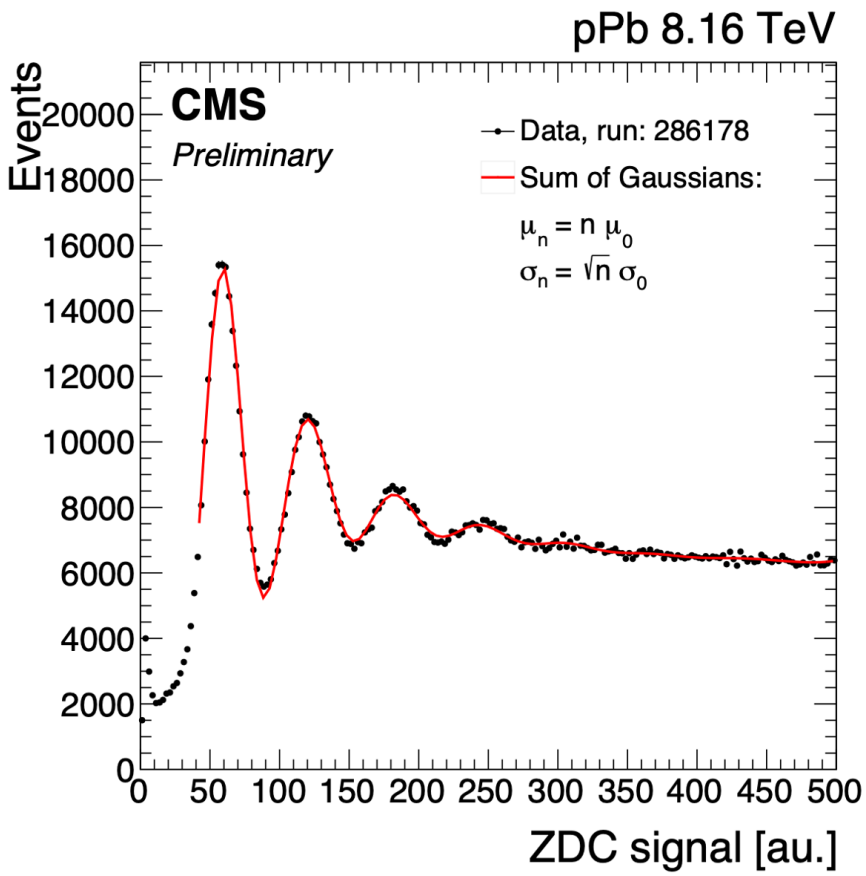
Background $(gg \to J/\psi(^3S_1^1)g)$: 19600 nb
Signal$(\gamma g \to J/\psi(^3S_1^1)g)$: 390 nb

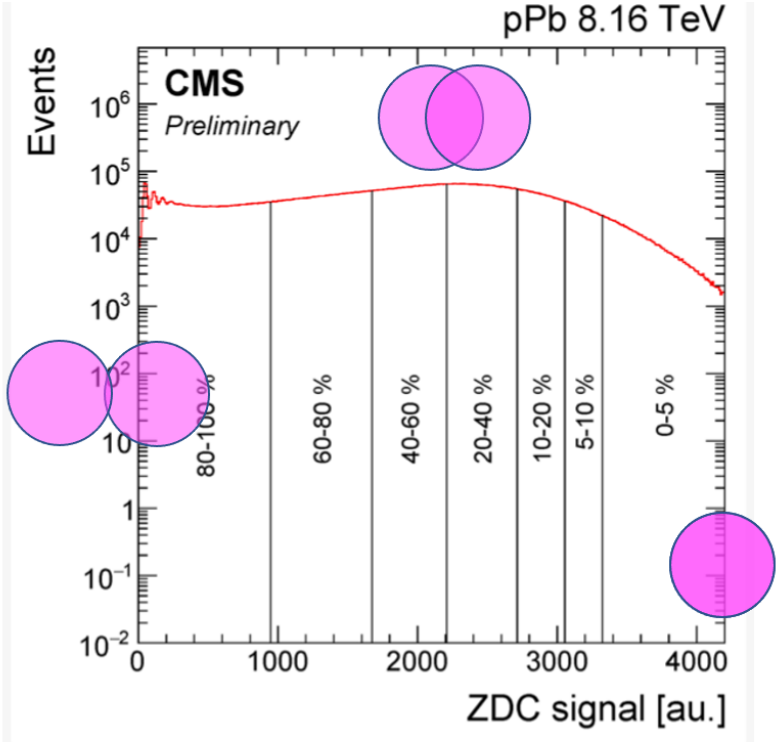
background/signal	50
LHCb *Pbp*	170
LHCb *pPb*	40
CMS typical	110
CMS low p_T	50
ALICE $\mu^+\mu^-$	190
ALICE e^+e^-	40

$\to$ need to remove experimental background

Cutting background: zero degree calorimeter

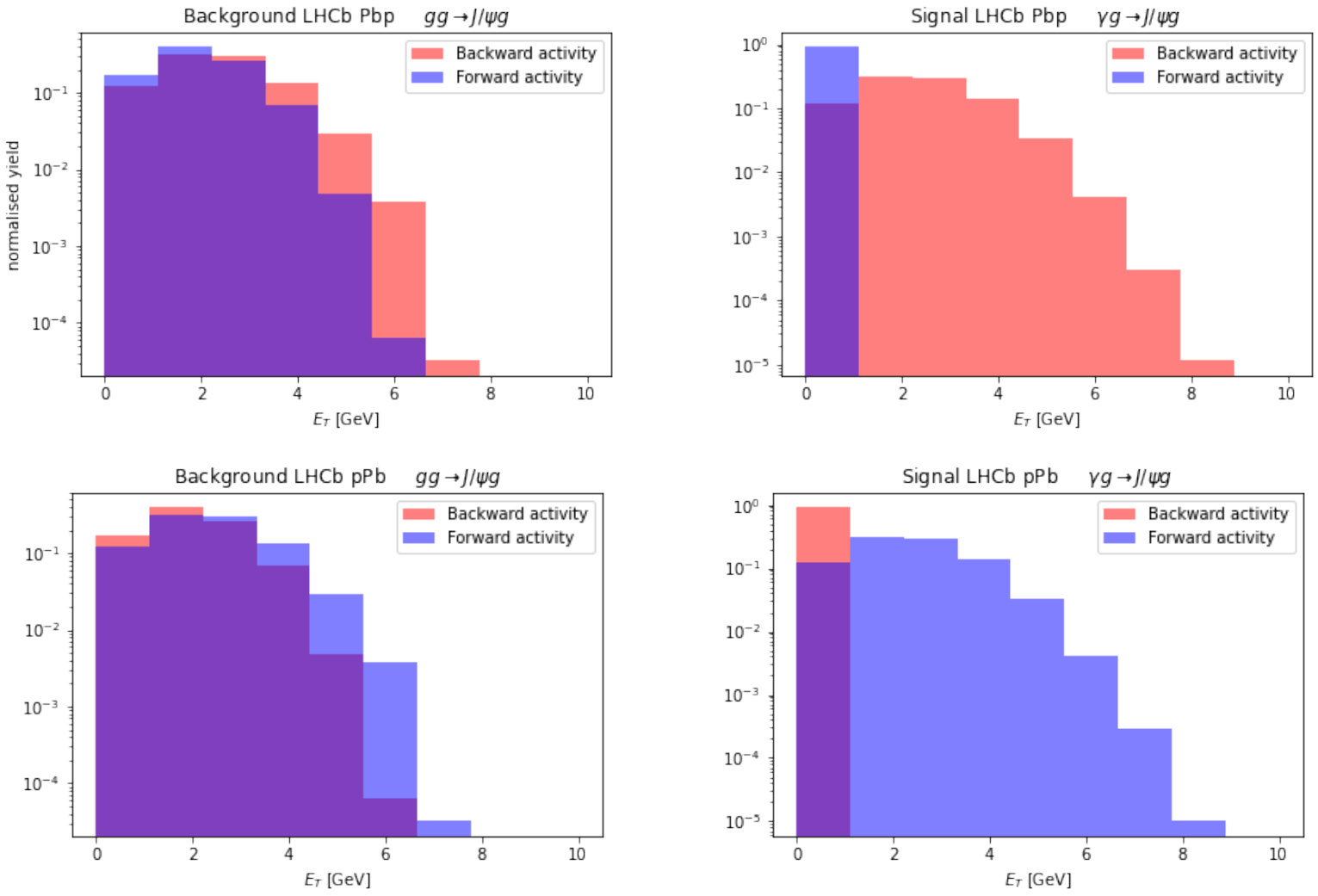
CMS 10.1088/1748-0221/16/05/P05008





Can remove $\sim$ 99.9 % of hadronic events !

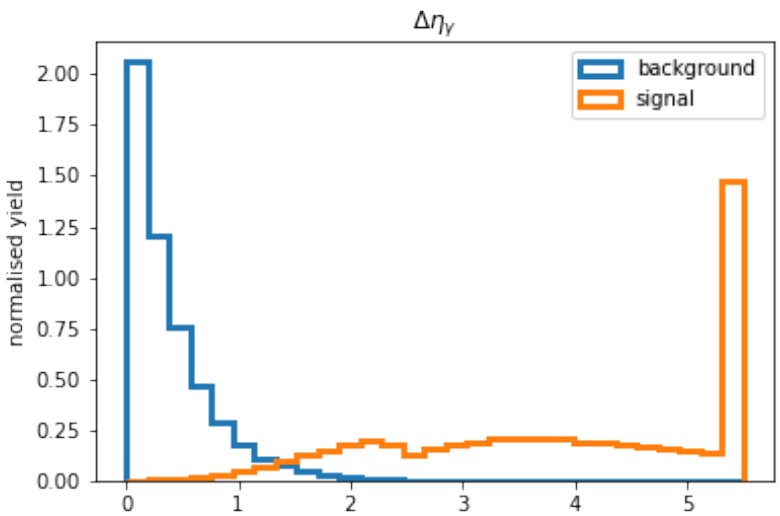
Cutting background: no ZDC ? HeRSCheL @ LHCb

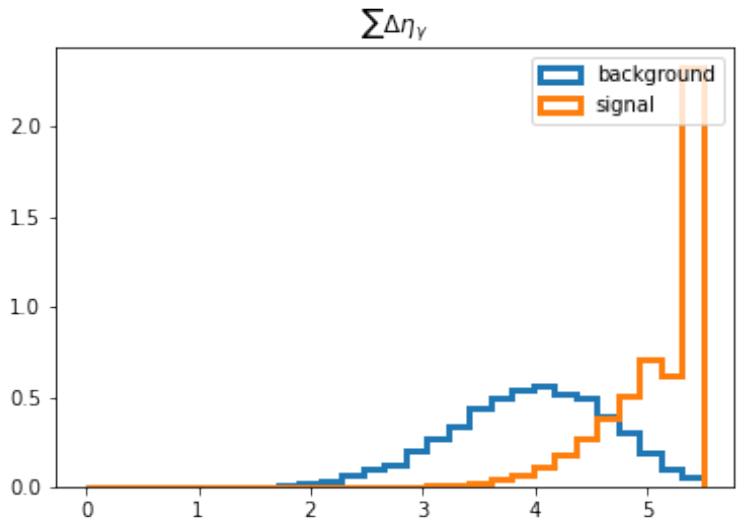


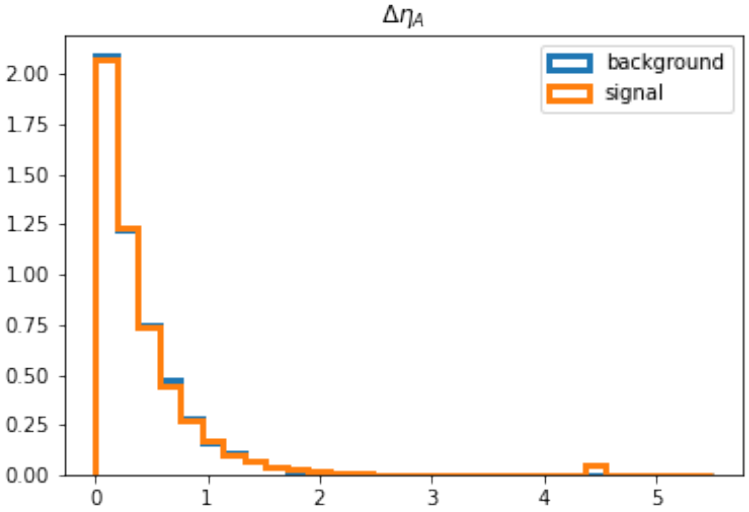
Cuts from forward activity

background/signal	50
LHCb *Pbp*	166
HeRSCheL	8.3
LHCb *pPb*	40
HeRSCheL	2
CMS typical	107
ZDC	0.32
CMS low p_T	48
ZDC	0.14
ALICE $\mu^+\mu^-$	189
ZDC	7.6
ALICE e^+e^-	41
ZDC	1.6

Rapidity gaps: CMS





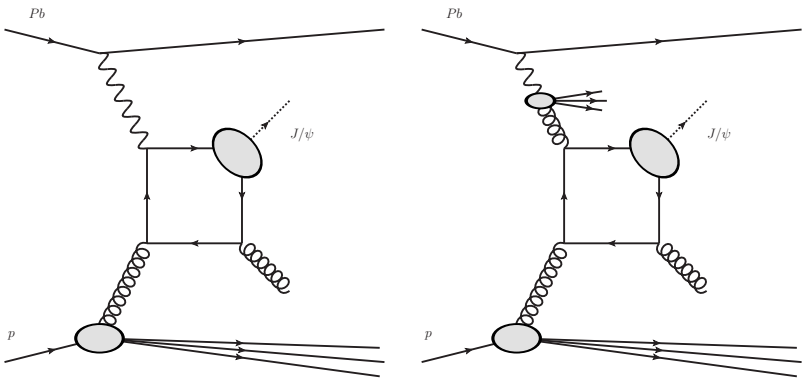


Cuts from forward activity and gaps

background/signal	50
LHCb *Pbp*	166
HeRSCheL $+ \sum \Delta\eta < 2$	0.94
LHCb *pPb*	40
HeRSCheL $+ \sum \Delta\eta < 1.5$	0.54
CMS typical	107
ZDC $+\Delta\eta_\gamma < 1$	0.04
ZDC $+ \sum \Delta\eta_\gamma < 4$	0.16
CMS low p_T	48
ZDC $+\Delta\eta_\gamma < 1$	0.02
ZDC $+ \sum \Delta\eta_\gamma < 4$	0.07

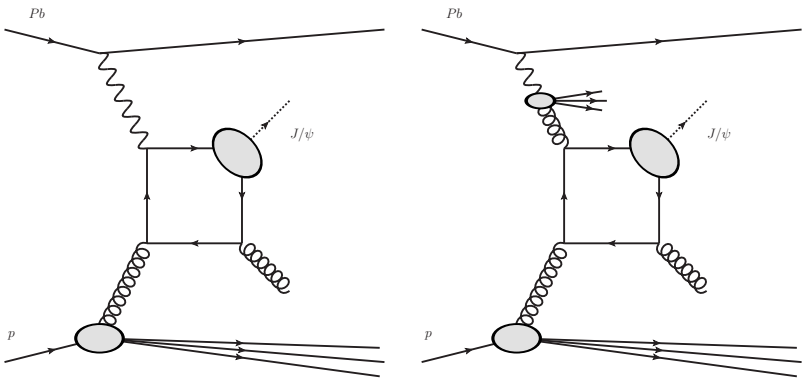
Can suppress background using cuts !!

Still need to consider the resolved contribution...



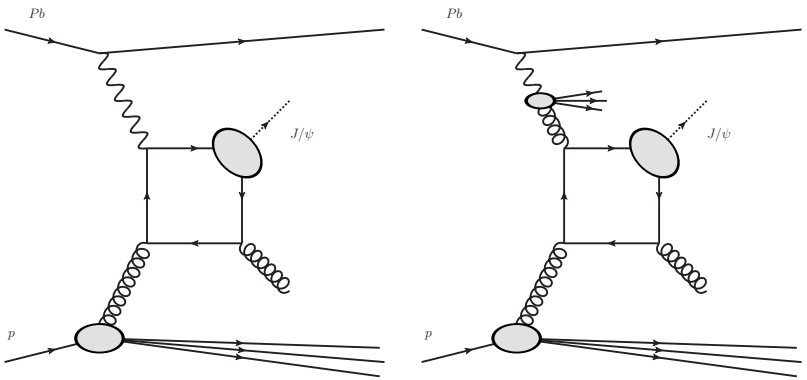
- *Photoproduction is simpler than hadroproduction* easier to extract PDFs...
- photon PDF not well known

Still need to consider the resolved contribution...



- *Photoproduction is simpler than hadroproduction* easier to extract PDFs...
- photon PDF not well known
- UPC @ LHC $\sqrt{s_{\gamma p}} \approx 1$ TeV vs. HERA $\sqrt{s_{\gamma p}} \approx 200$ GeV

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

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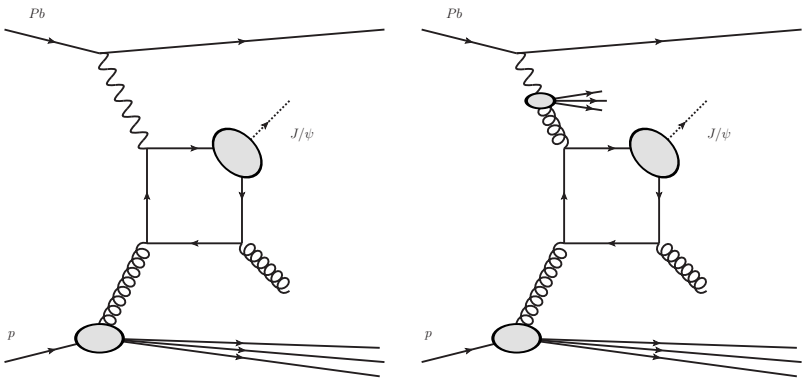

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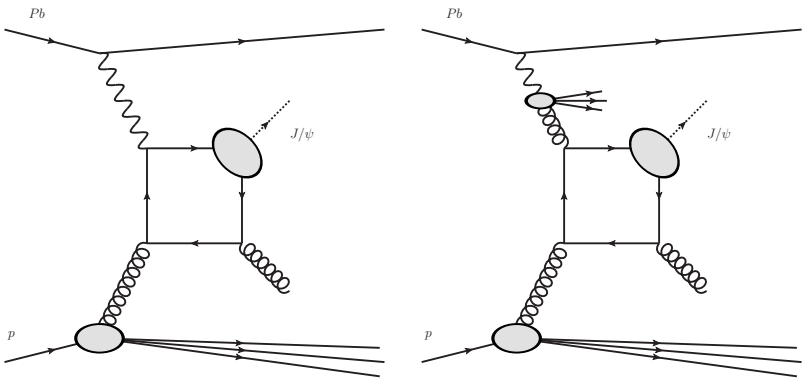
- In *ep* collisions cut $z > 0.3$ Small fraction of photon momentum in hard collision
- Recent inclusive UPC dijet analysis by ATLAS **do not cut** resolved photon contribution from analysis... **ATLAS-CONF-2022-021**

Still need to consider the resolved contribution...



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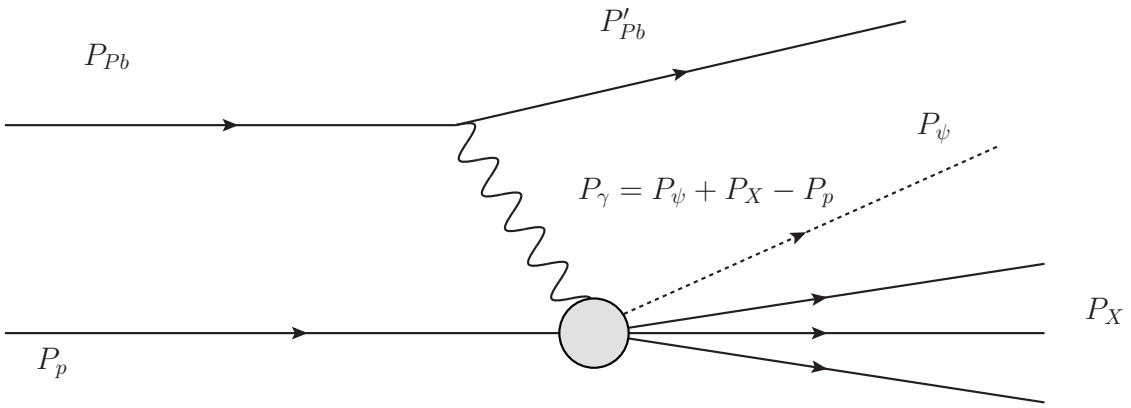
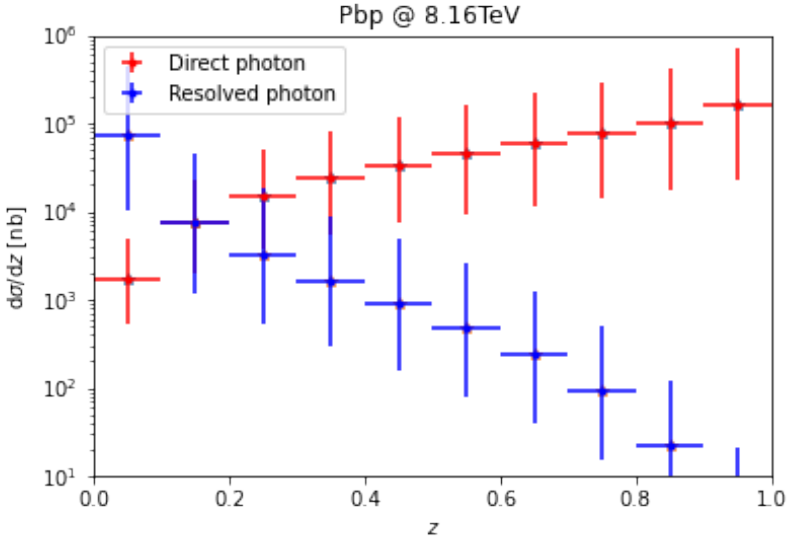
- In *ep* collisions cut $z > 0.3$ Small fraction of photon momentum in hard collision
- Recent inclusive UPC dijet analysis by ATLAS **do not cut** resolved photon contribution from analysis... **ATLAS-CONF-2022-021**
- Can we kinematically isolate regions where the resolved photon contribution is minimal?

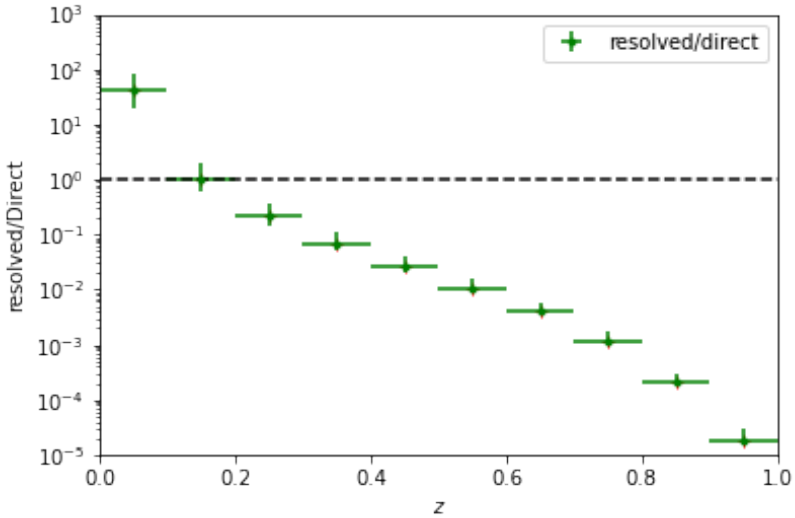
z and $W_{\gamma p}$...



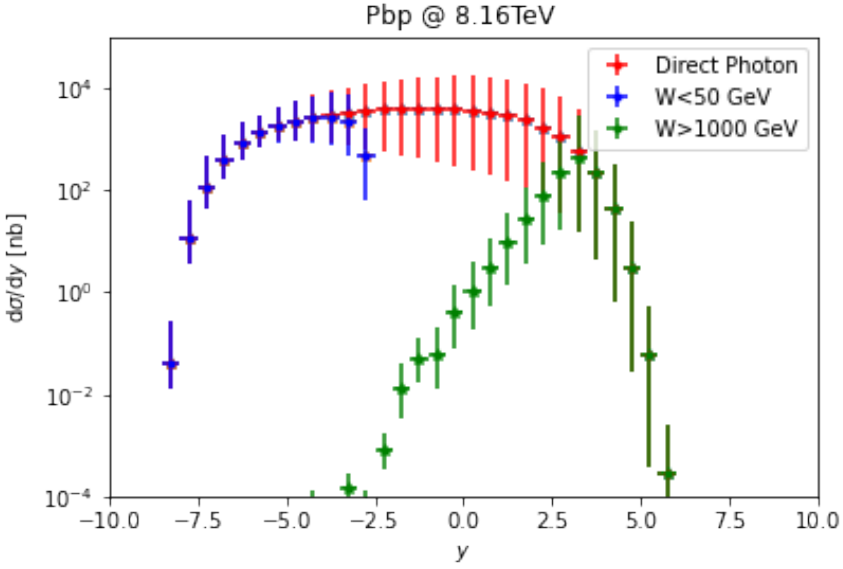
$$z = \frac{P_p \cdot P_\psi}{P_p \cdot P_\gamma} \qquad W_{\gamma p} = \sqrt{(P_\gamma + P_p)^2}$$

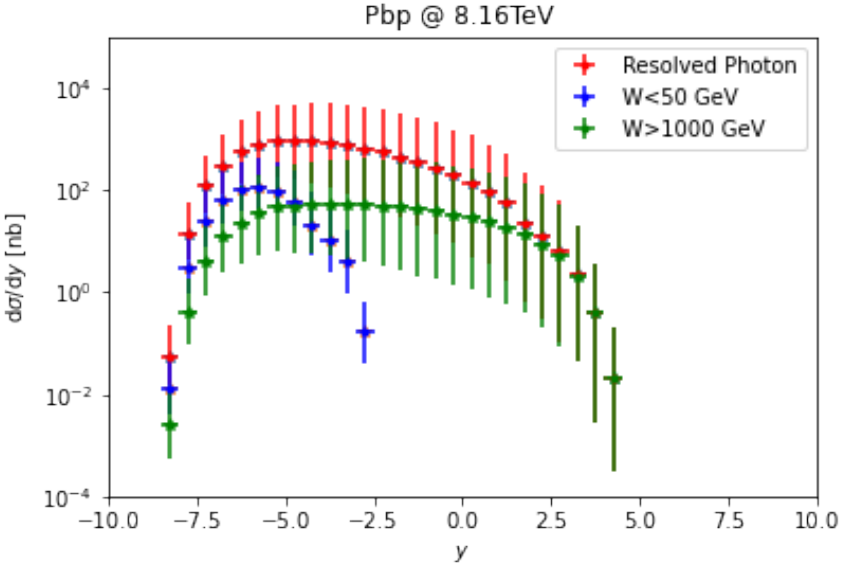
$$z = \frac{1}{1 + \frac{P_X^+}{P_\psi^+}} \qquad W_{\gamma p} = \sqrt{(P_p^- P_\psi^+)\frac{2}{z}}$$

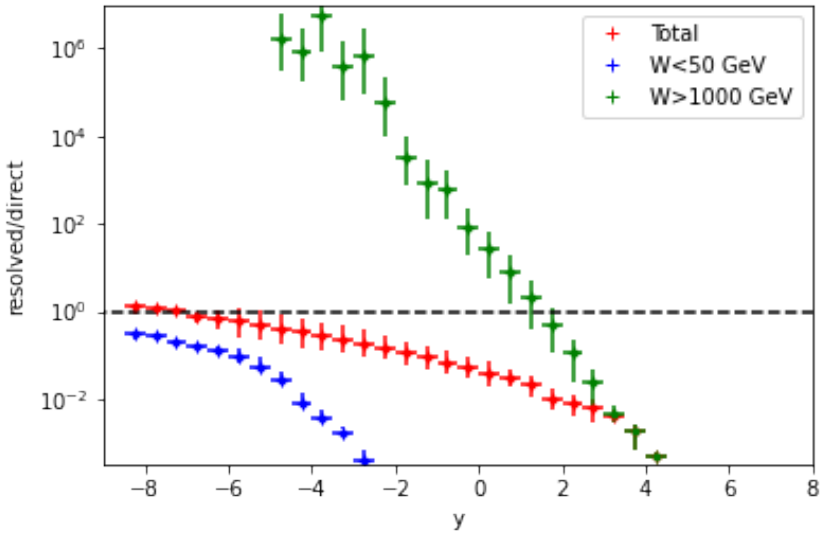




Direct and Resolved Photon Contributions with cuts on $W_{\gamma p}$.

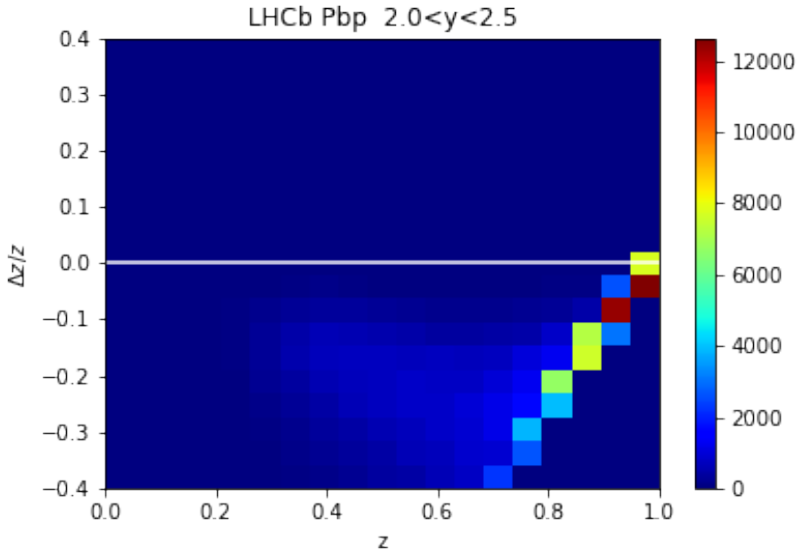


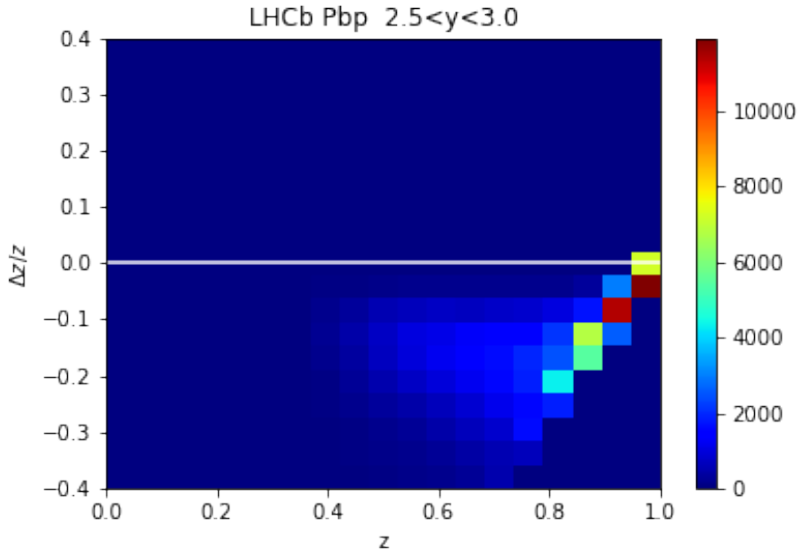


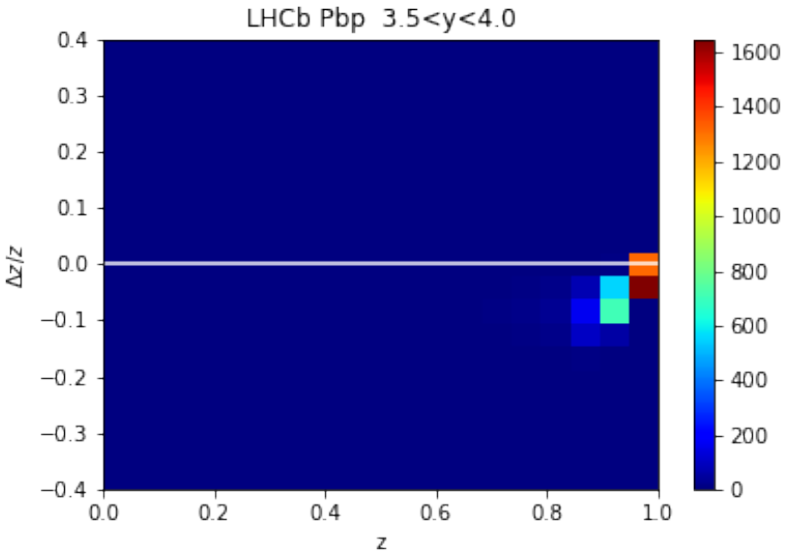


Direct and Resolved Photon Contributions with various cuts on $W_{\gamma p}$.

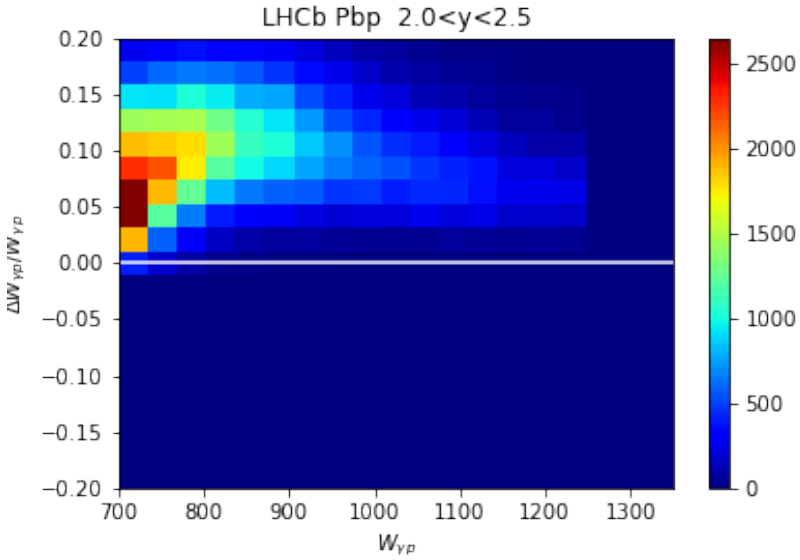
Reconstructing z @ LHCb *Pbp*...

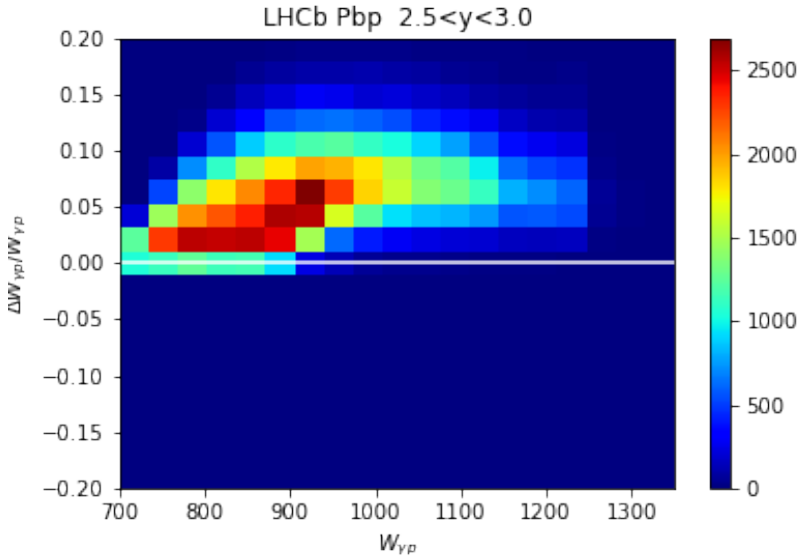


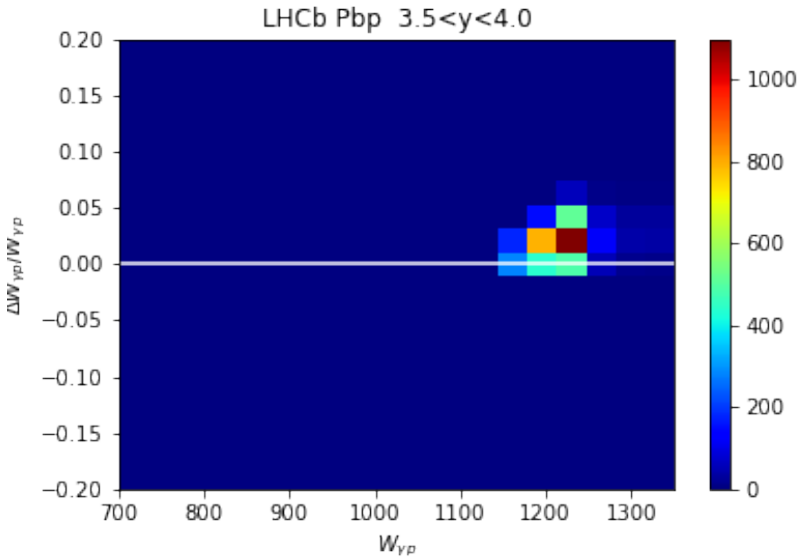




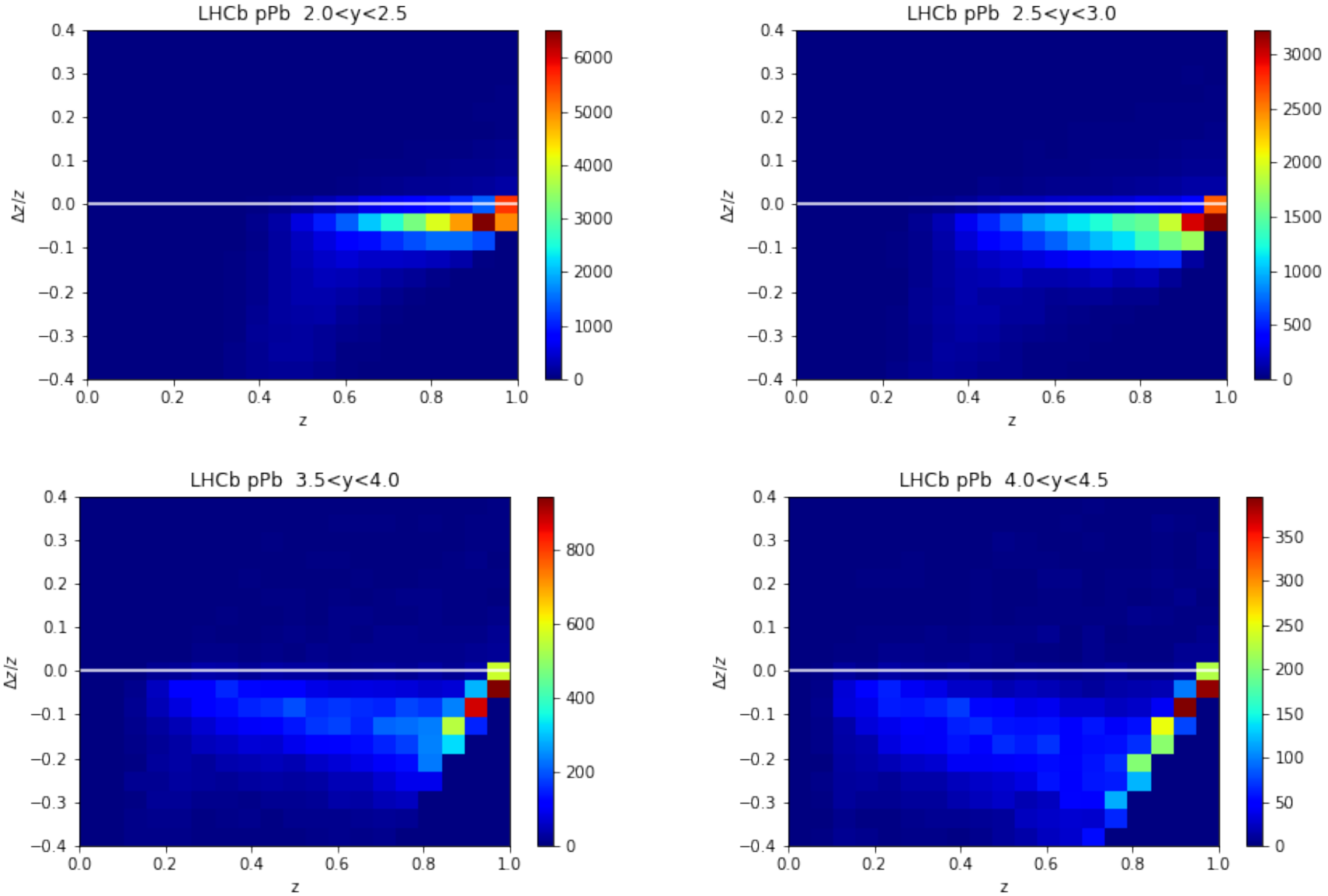
Reconstructing $W_{\gamma p}$ @ LHCb *Pbp*...



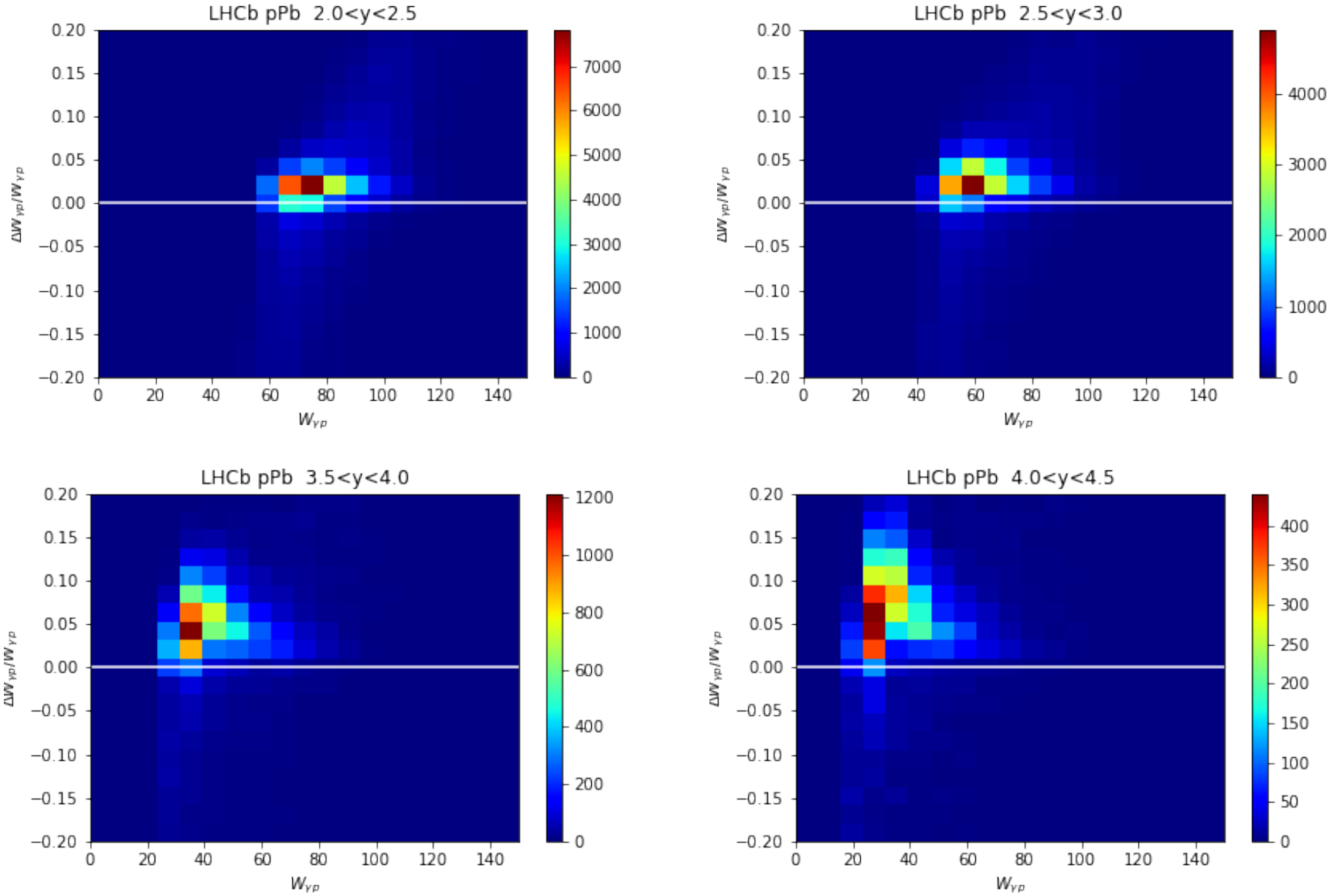




Reconstructing z @ LHCb pPb...

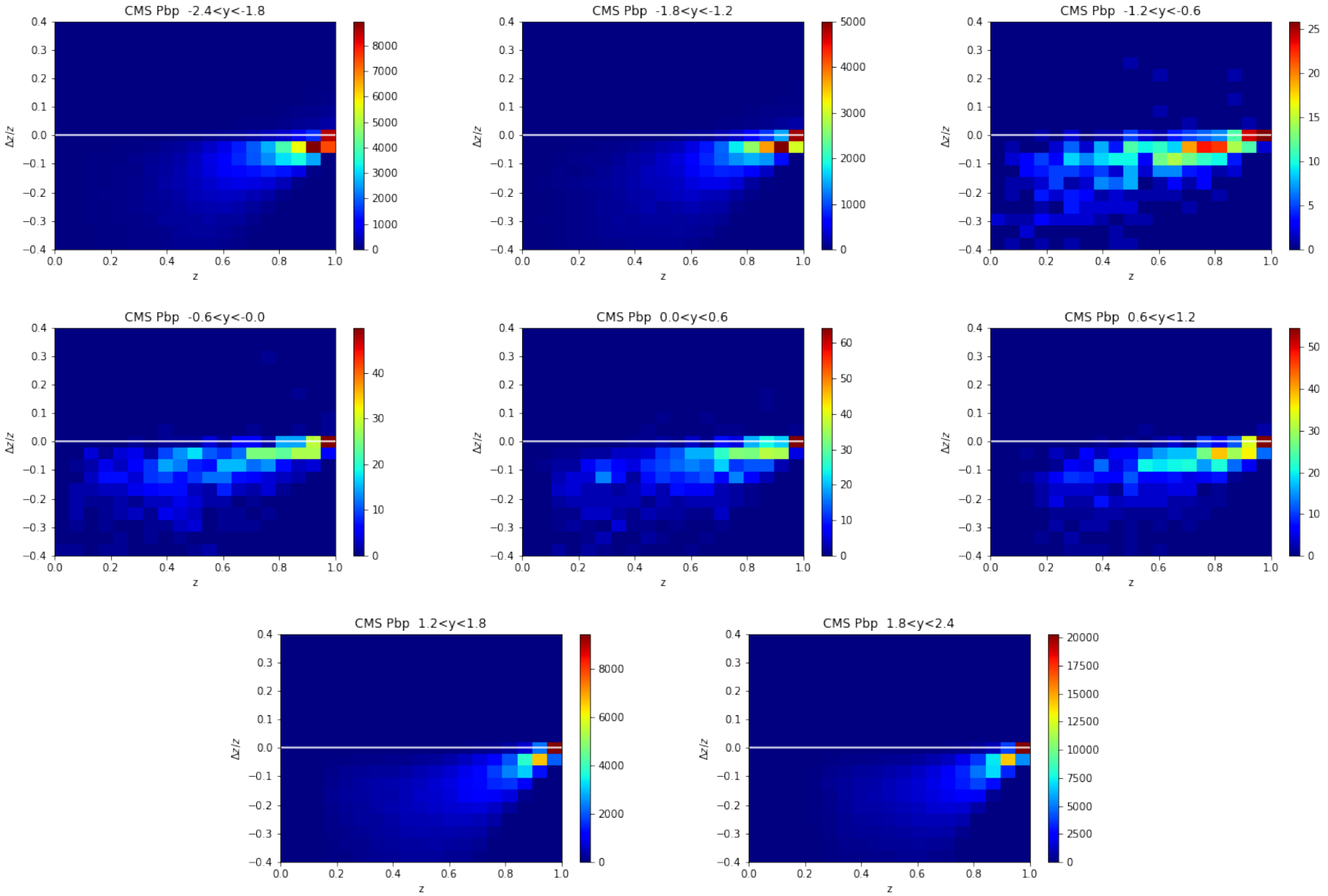


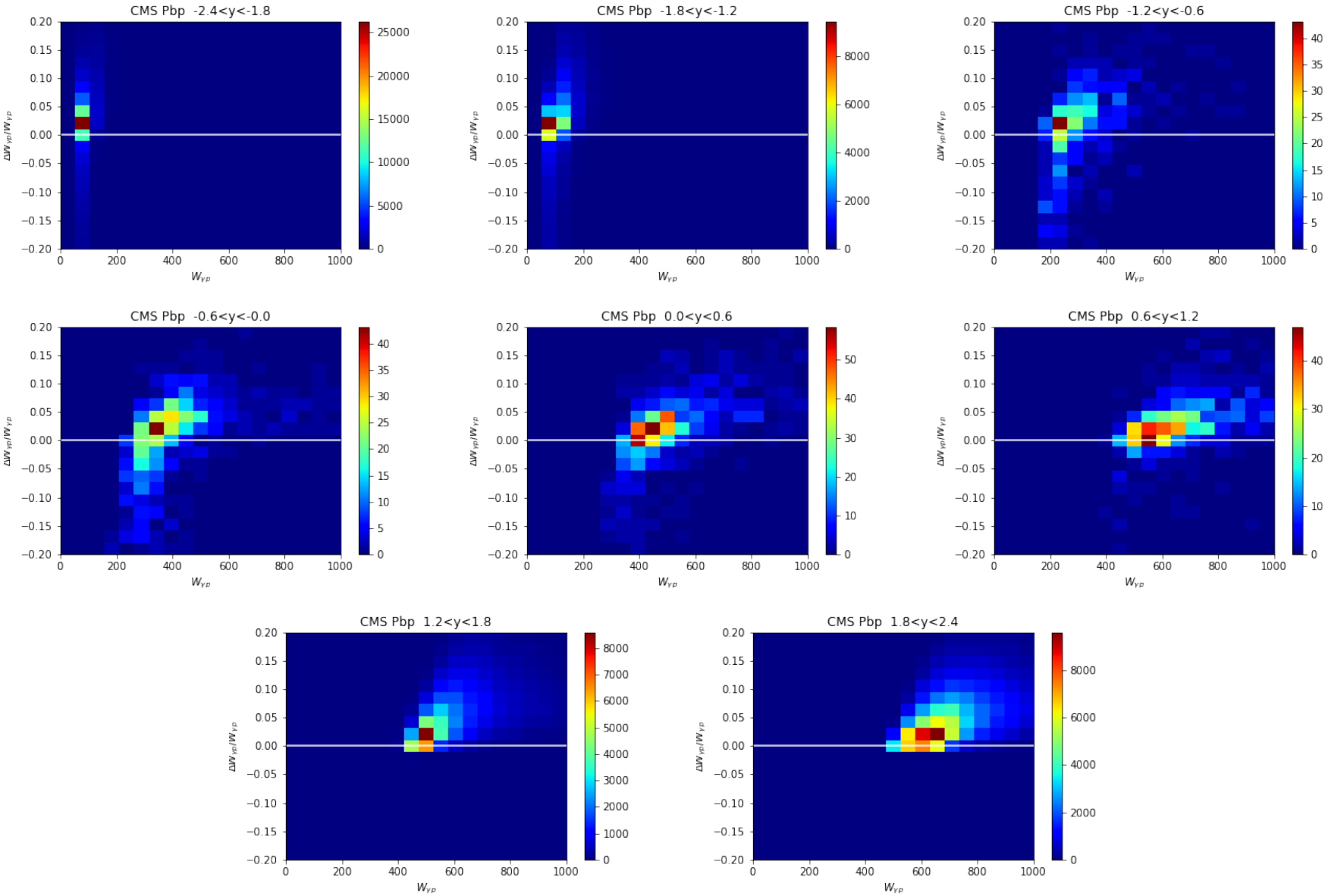
Reconstructing $W_{\gamma p}$ @ LHCb pPb...



Summary

- Study of inclusive quarkonium production allows us to discriminate production mechanisms
- It is feasible to study at the inclusive photoprodution at the LHC by making use of detector based cuts
- z and $W_{\gamma p}$ reconstruction seems possible in some kinematical regions which will allow control of the resolved contribution
- Future study @ EIC has the advantage of reduced resolved contributions


CMS Pbp -2.4<y<-1.8
CMS Pbp -1.8<y<-1.2
CMS Pbp -1.2<y<-0.6
CMS Pbp -0.6<y<-0.0
CMS Pbp 0.0<y<0.6
CMS Pbp 0.6<y<1.2
CMS Pbp 1.2<y<1.8
CMS Pbp 1.8<y<2.4
Δz/z
z


CMS Pbp -2.4<y<-1.8
CMS Pbp -1.8<y<-1.2
CMS Pbp -1.2<y<-0.6
CMS Pbp -0.6<y<-0.0
CMS Pbp 0.0<y<0.6
CMS Pbp 0.6<y<1.2
CMS Pbp 1.2<y<1.8
CMS Pbp 1.8<y<2.4
$W_{\gamma p}$
$\Delta W_{\gamma p}/W_{\gamma p}$

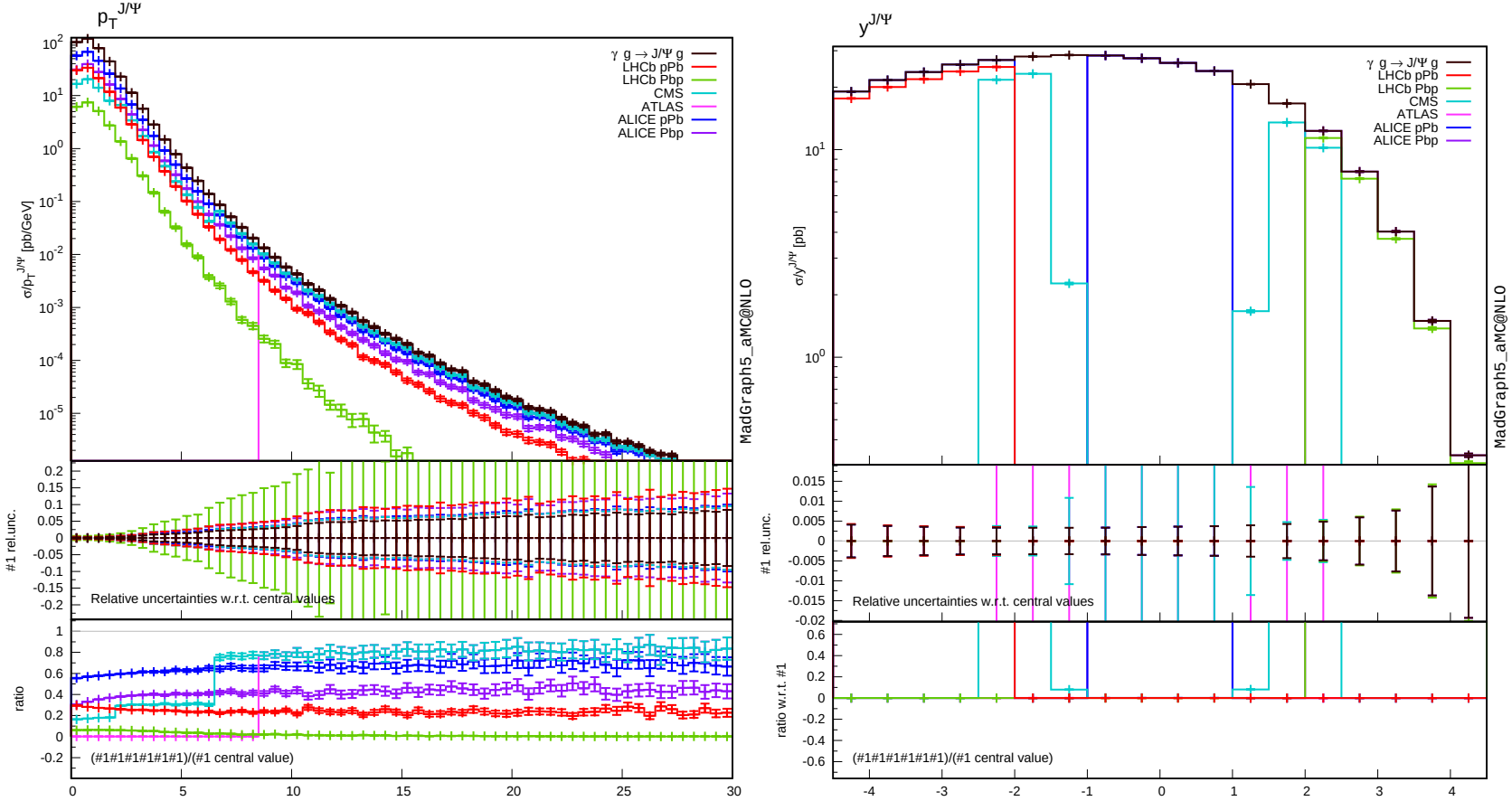
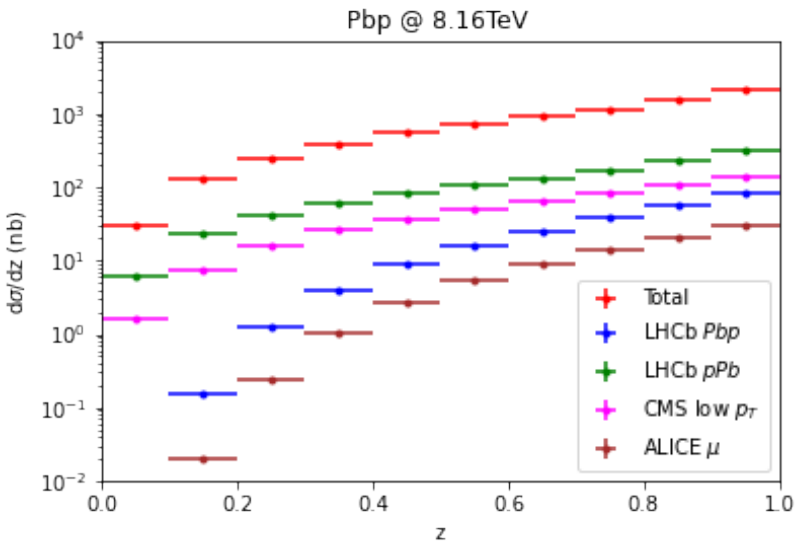
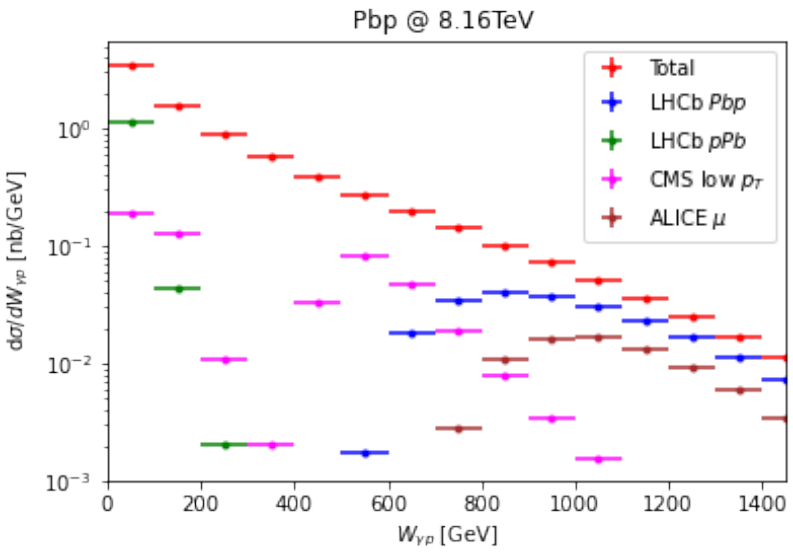


Figure: 8.16 TeV photoproduction in Pbp

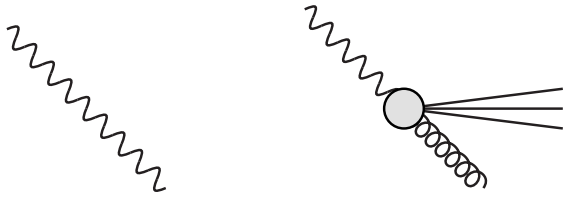

Pbp @ 8.16TeV
dσ/dz (nb)
z
Total
LHCb Pbp
LHCb pPb
CMS low p_T
ALICE μ


Pbp @ 8.16TeV
$d\sigma/dW_{\gamma p}$ [nb/GeV]
$W_{\gamma p}$ [GeV]
Total
LHCb Pbp
LHCb pPb
CMS low p_T
ALICE μ

Quarkonium Production @ EIC

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

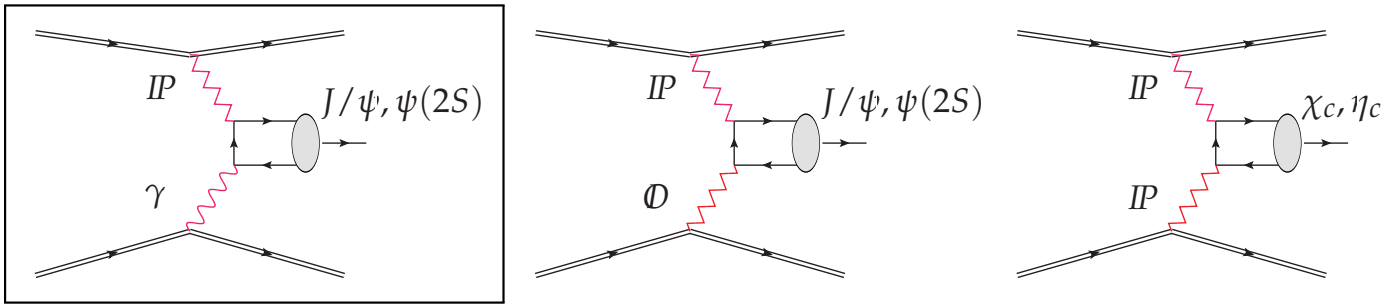
- **Photoproduction** quasi-real photon $Q^2 << m^2_{J/\psi}$
  - Bulk of the cross-section
  - easy to compute (hard scale)
  - resolved component!
- **Leptoproduction** virtual photon γ^* $Q^2 > m^2_{J/\psi}$
  - Smaller cross-section
  - difficult to compute (introduce new scale)
  - **NO** resolved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



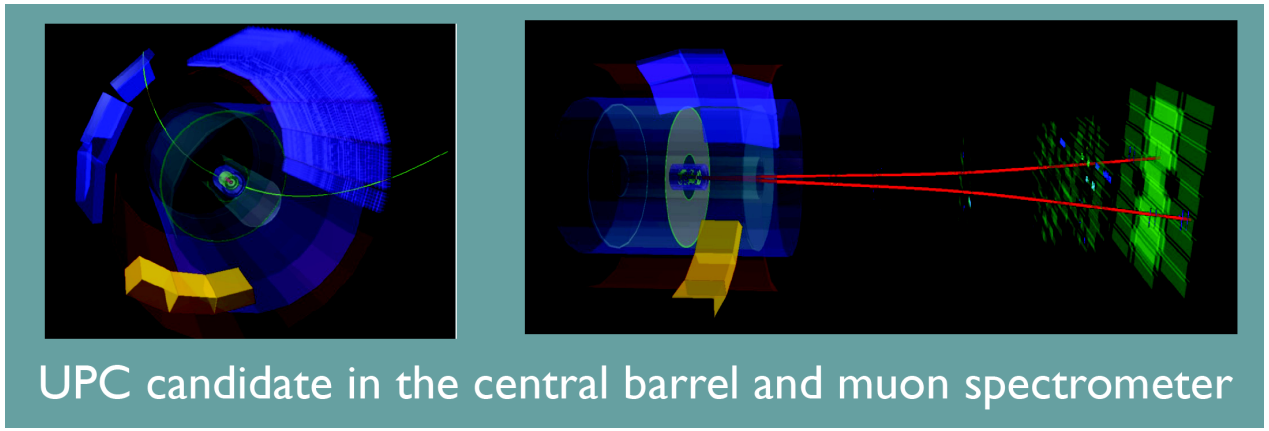
direct and resolved photons

Exclusive J/ψ production

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

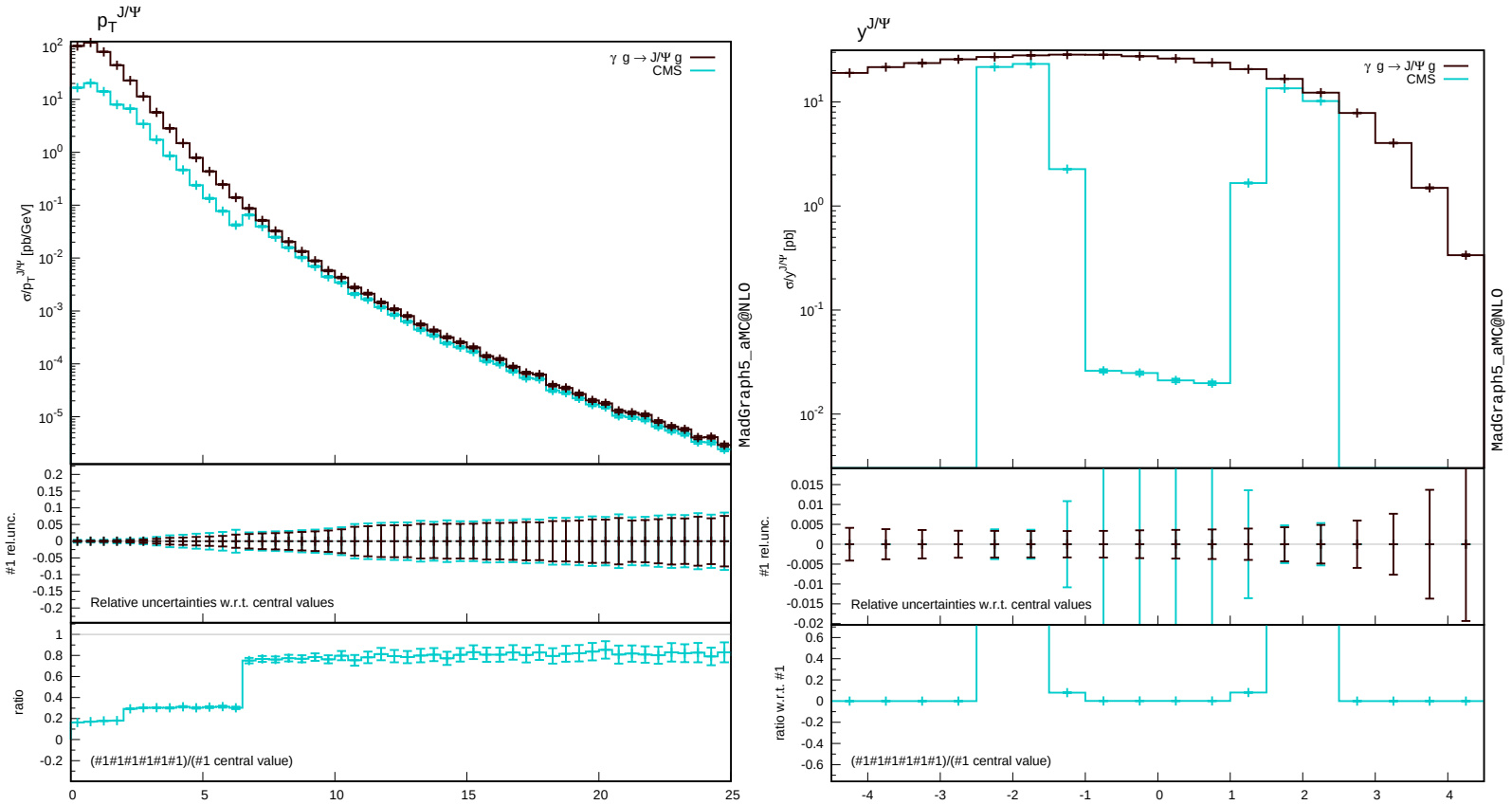


- only **colour singlet** contributions
- Clean signal
  - **only** quarkonia and its decay products are produced.
  - **both** colliding particles stay intact



ALICE candidate signal for exclusive J/ψ production via UPC

Photoproduction cross section

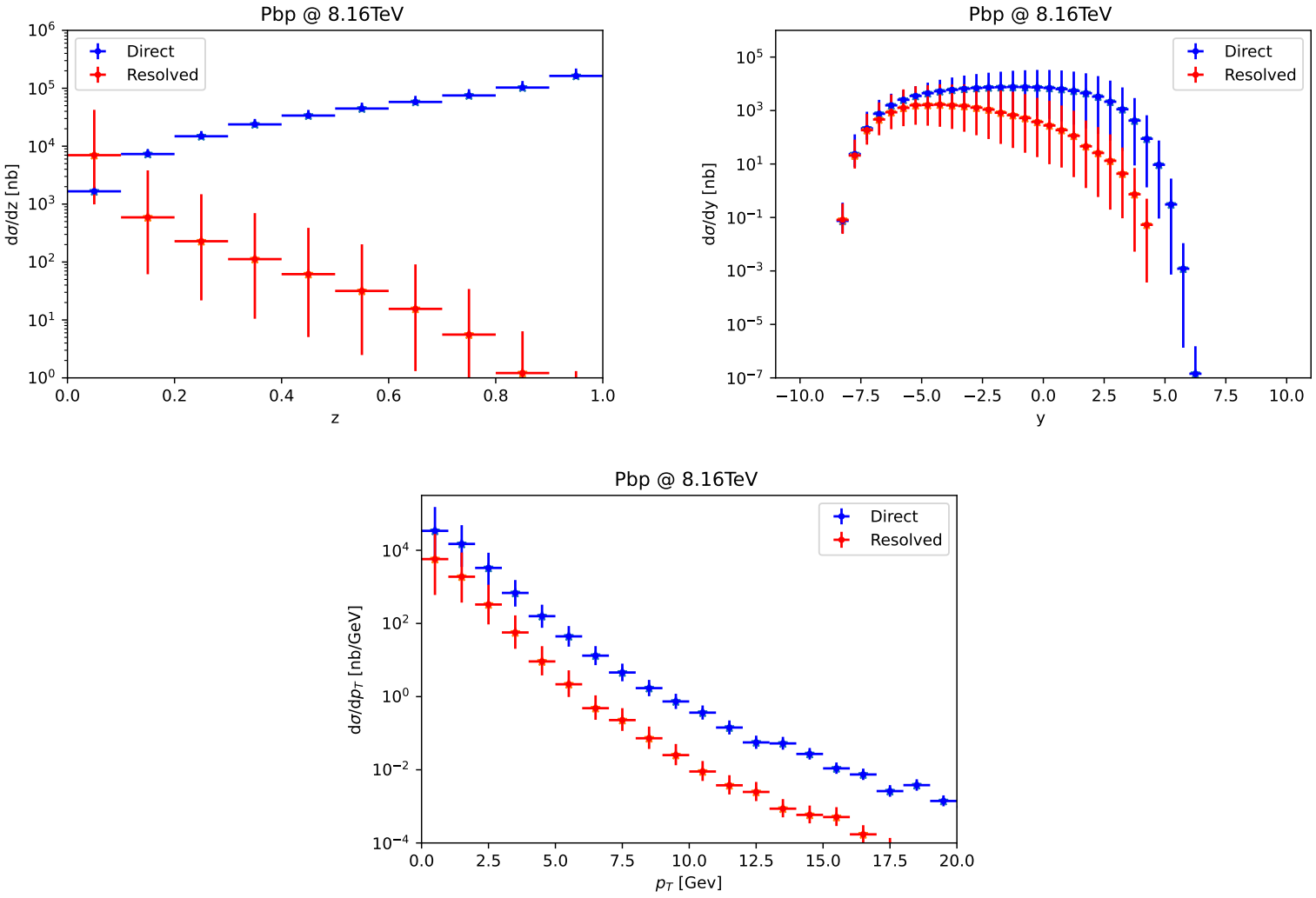


8.16 TeV photoproduction in Pbp

CMS cuts

- Cross-section steeply falling in p_T

Photoproduction cross section: resolved vs. direct



Simulating events

Comput.Phys.Commun. 184 (2013) 2562-2570

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

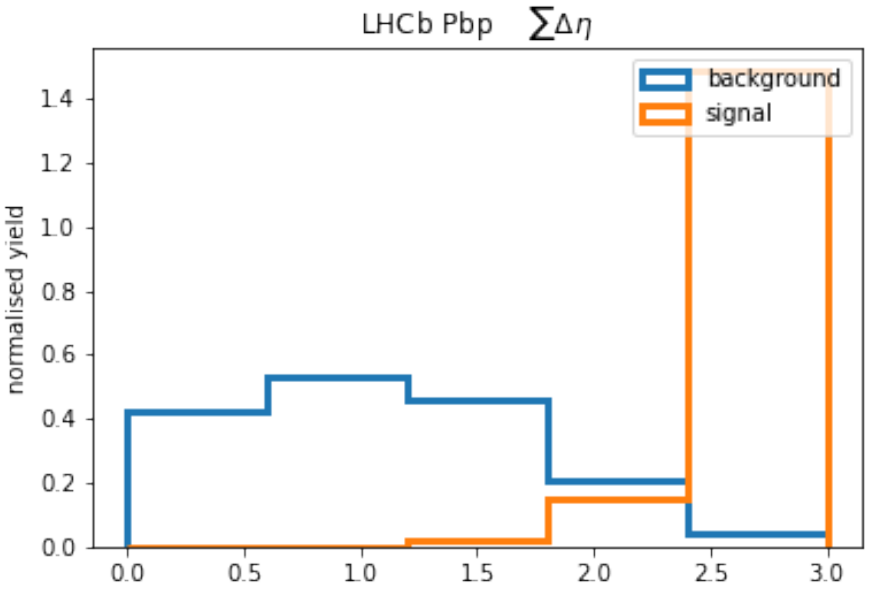
Automated perturbative calculation with NLOAccess

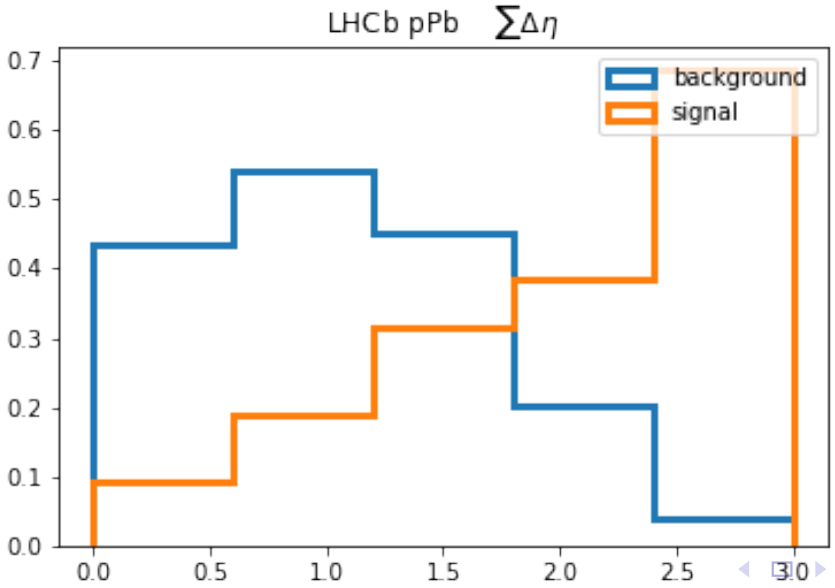
HELAC-Onia Web

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

Rapidity gaps: LHCb





Cutting background: zero degree calorimeter

ATLAS CERN-EP-2022-086