Inclusive quarkonium photoproduction at the LHC

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& Ronan McNulty (UCD)

Synergies between LHC and EIC for quarkonium physics
Trento

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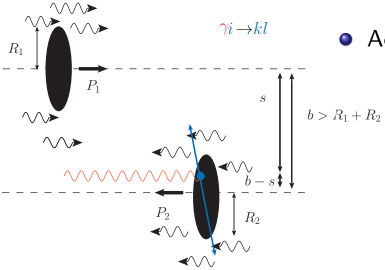
Part I

Introduction

Photon-induced interactions @ the LHC



- Accelerated charged particles emit photons

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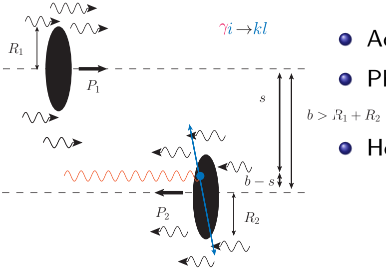

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  $\rightarrow$ clean photoproduction environment
- However, the LHC is an excellent source of photons
  $\rightarrow$ can reach extremely large $W_{\gamma p}$

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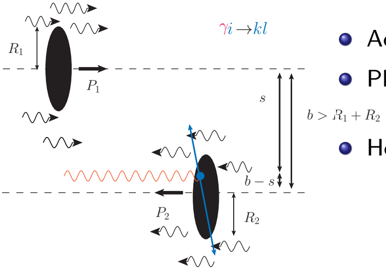

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- Energies available at the LHC:
  - pp @ $\sqrt{s} = 13$ TeV $\rightarrow W_{\gamma p}^{max} \approx 5$ TeV $\rightarrow x_{\gamma}^{\text{max}} \approx 0.14$
  - pPb @ $\sqrt{s_{NN}} = 8.16$ TeV $\rightarrow W_{\gamma p}^{max} \approx 1.5$ TeV $\rightarrow x_{\gamma}^{\text{max}} \approx 0.03$
- Energies available at *ep* colliders:
  - $W_{\gamma p}^{\text{max HERA}} \approx 240$ GeV
  - $W_{\gamma p}^{\text{max EIC}} \approx 100$ GeV

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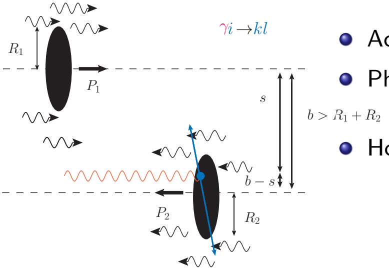

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- At hadron-hadron colliders: **Ultra Peripheral Collisions** select photoproduction
  - Done so far only for exclusive processes

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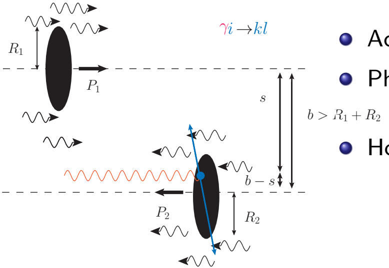

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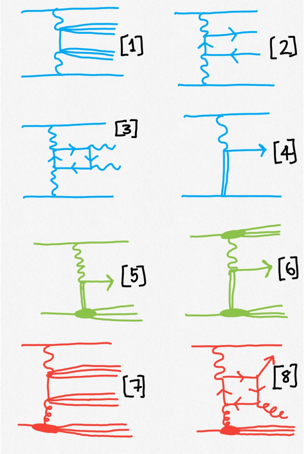
We will show:

Inclusive quarkonium photoproduction can be measured via UPC at the LHC

Photon-induced interactions via UPC @ the LHC

- So far focus of UPCs @ LHC on exclusive processes (fully determined final state) **[1–4]**
- Recently there were photoproduction studies with nuclear break up **[5]** (non-UPC [6*])
- Only published inclusive UPC study in PbPb: two-particle azimuthal correlations
  ATLAS, PRC 104, 014903 (2021)
- Coming soon: inclusive photonuclear dijets in PbPb **[7]**



[1] **Exclusive dijet**: CMS, PRL 131 (2023) 5, 051901

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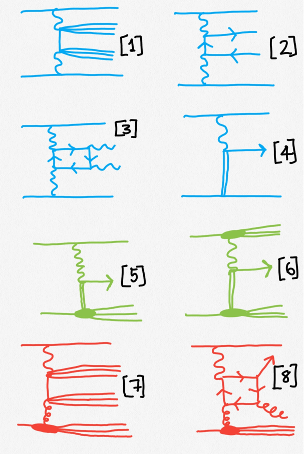

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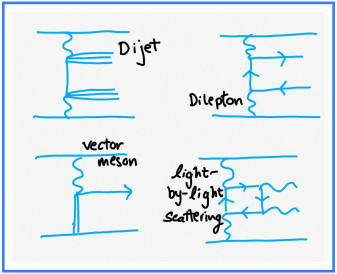
[8] **Inclusive quarkonium photoproduction: NOT YET MEASURED AT THE LHC!**

Exclusive vs. inclusive photoproduction at the LHC

Exclusive: fully determined final state



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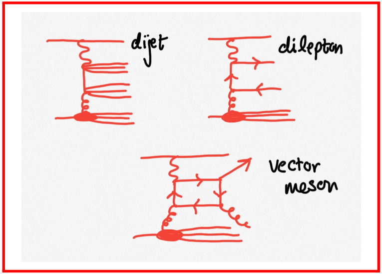

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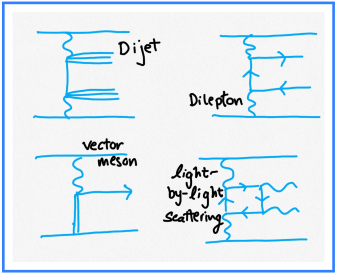

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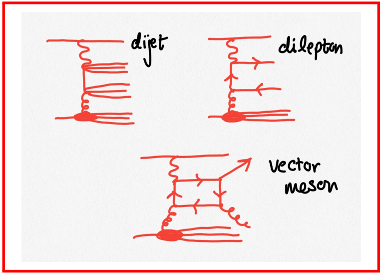

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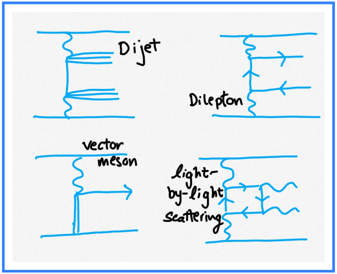

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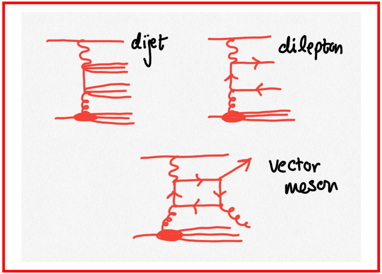

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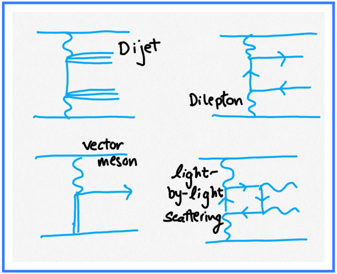

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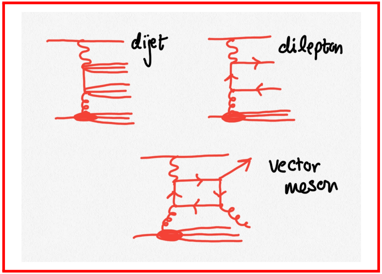

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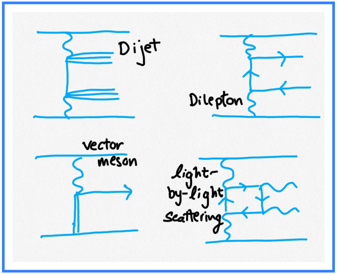

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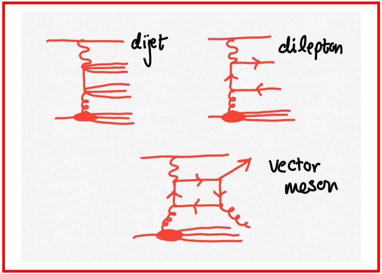

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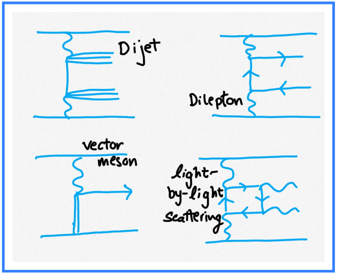

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- Initial state kinematics **fully** determined by the final state

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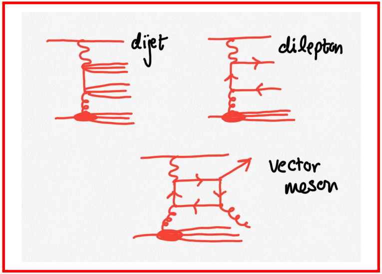

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Exclusive vs. inclusive photoproduction at the LHC

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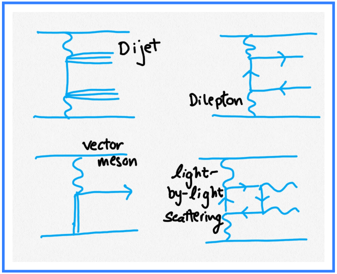

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- Initial state kinematics **fully** determined by the final state
- Measured at the LHC

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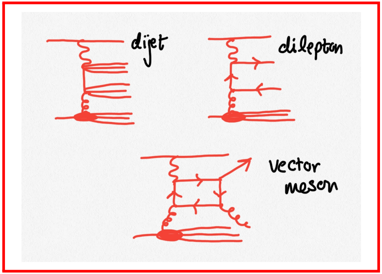

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- Initial state kinematics **partially** determined by the final state
- Can and should be measured at the LHC

Quarkonium production status

- Discovered 50 years ago quarkonia are bound states of heavy quarks
- To date there is **no theoretical mechanism** that can **describe all of the data**
- Different models make different assumptions of the hadronisation
    - **Colour Evaporation model**: 1 free parameter per meson
    - × fails to describe di-J/ψ data
    - **Colour Singlet model**: no free parameters
    - × tends to undershoot large p_T data
    - **Colour Octet mechanism** (extension to CSM via non-relativistic QCD): free parameters
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Maxim Nefedov, QaT 2023

LDME fit	J/ψ hadropr.	J/ψ photopr.	J/ψ polar.	η_c hadropr.
Butenschön et al.	✓($p_T > 3$ GeV)	✓	✗	✗
Chao et al. + η_c	✓($p_T > 6.5$ GeV)	✗	✓	✓
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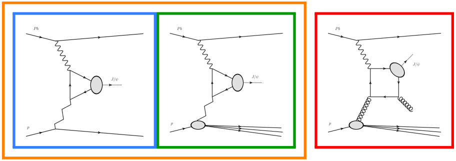
More inclusive photoproduction data → possible at ~~EIC in 10 years~~ LHC today!

Existing J/ψ photoproduction measurements from HERA



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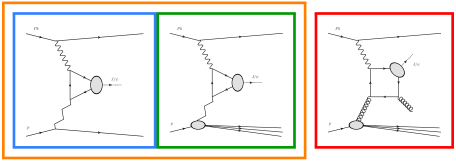

- Data exists for **diffractive** (exclusive and proton-dissociative) & **inclusive/inelastic** photoproduction @ HERA $\sqrt{s} = 320$ GeV
- Different contributions separated using experimental cuts on p_T and $z = \frac{P_p \cdot P_\psi}{P_p \cdot P_\gamma} \ldots$

diffractive region: $p_T < 1$ GeV, $z > 0.9$; inclusive region: $p_T > 1$ GeV, $z < 0.9$

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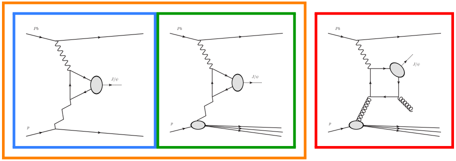

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- HERA result: $\sigma^{\text{HERA}}_{\text{exclusive}} \simeq \sigma^{\text{HERA}}_{\text{dissociative}} \simeq \sigma^{\text{HERA}}_{\text{inclusive}}$
- Expectation: $\sigma^{\text{LHC}}_{\text{exclusive}} \simeq \sigma^{\text{LHC}}_{\text{dissociative}} \simeq \sigma^{\text{LHC}}_{\text{inclusive}} \rightarrow$ only difference is photon flux!
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- Expect that inclusive yield is sufficently large we will demonstrate this

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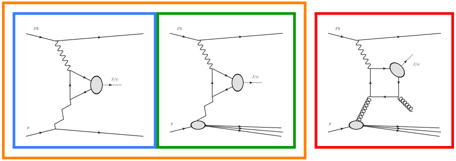

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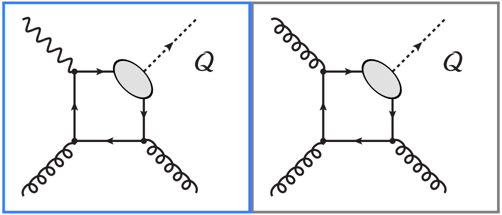
- Exclusive and proton-dissociative photoproduction have been measured @ LHC
- Expect that inclusive yield is sufficently large we will demonstrate this
- Measuring inclusive quarkonium photoproduction to

  understand the quarkonium hadronisation

Is it feasible to measure inclusive quarkonium photoproduction at the LHC?

- Anticipate sizeable photoproduction yield
- Large hadronic background must be shown to be suppressed



Proton-lead is the ideal collision system

- Enhanced photon flux w.r.t. *pp*: $\propto Z^2$
- No ambiguity as to the photon emitter: reconstruction of z and $W_{\gamma p}$
- Less pileup than *pp*

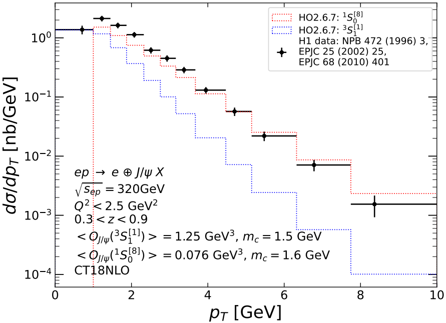
Part II

Methodology

Building a Monte Carlo sample

We must:

1. Evaluate yield & P_T reach: need reliable Monte Carlo (MC) sample
   Problem:
   - Only **LO MC** for quarkonia + QCD corrections are large!
     - LO CS undershoots undershoots large P_T data
     - LO CO captures large P_T data



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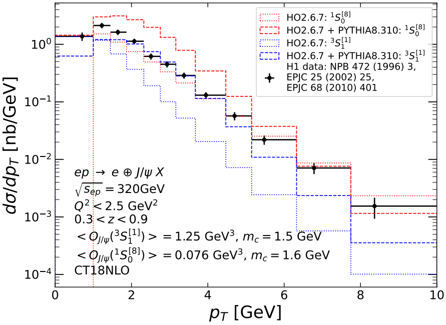
   Problem:
   - Only **LO MC** for quarkonia + QCD corrections are large!
     - LO CS + PS undershoots improved but still undershoots
     - LO CO + PS captures overshoots low P_T data



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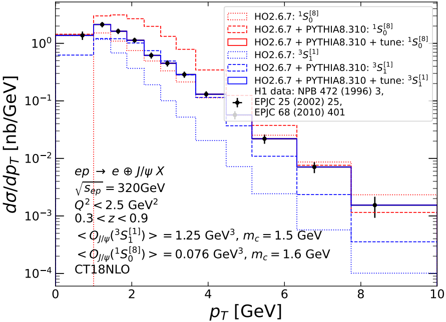
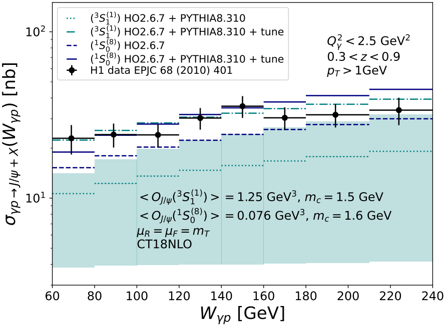
   Solution: perform tune in P_T to HERA data + keep $\sqrt{s}$ and y dependence from photon flux





2. Reject background: reliable background MC + background reduction strategy

Background Monte Carlo: hadroproduction P_T distribution

- Just as for photoproduction we tune our background Monte Carlo to data
- Compute tune factors using 5 TeV rapidity-integrated LHCb data under the assumptions:

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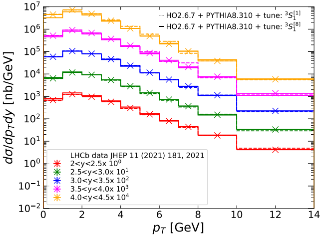
Validation 1: tune vs. y-diff. data @ 5 TeV.



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  2. Tuning is $\sqrt{s}$ independent

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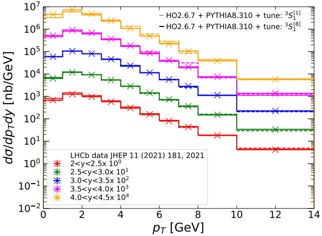
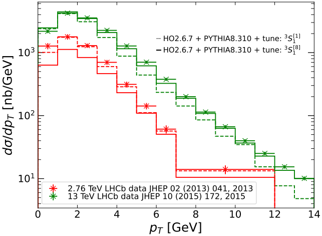
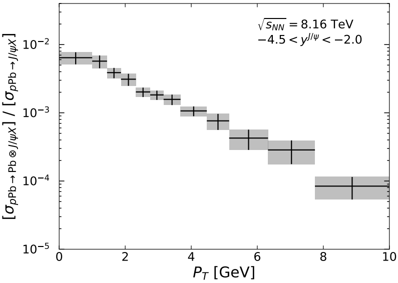


Validation 2: tune vs. 13- and 2.76 TeV data.



Background-reduction techniques



- Large yields but huge background!
- Background reduction critical at large P_T
- Hadroproduced J/ψ are associated with more detector activity than photoproduced J/ψ

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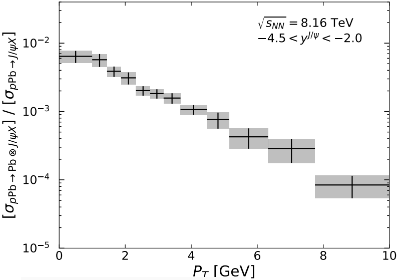

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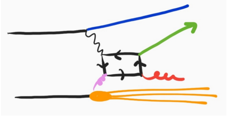

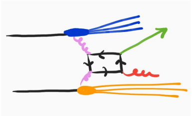

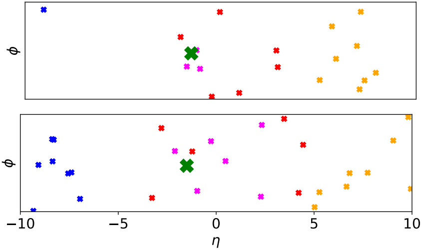

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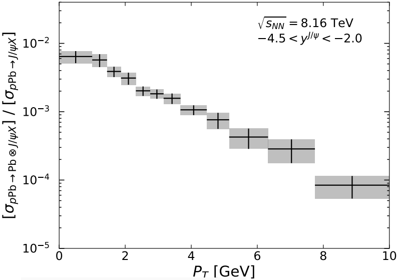

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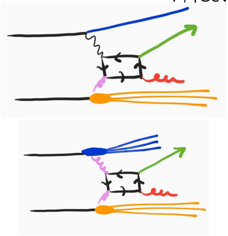
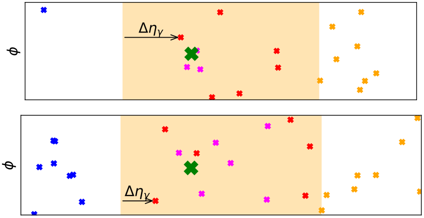
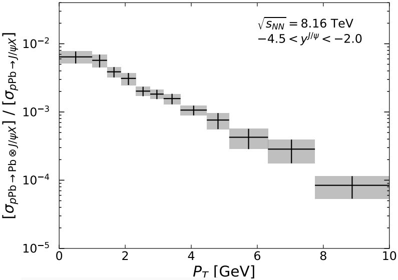




- 3 background-reduction techniques based on different detector acceptances:
  I central $\Delta\eta_\gamma$: distance in rapidity between main detector on photon-going side and closet particle activity



- Large yields but huge backgrounds!
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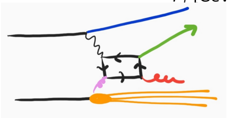
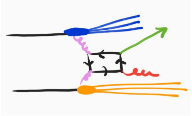
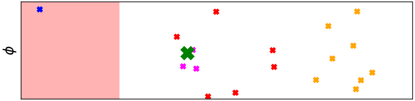
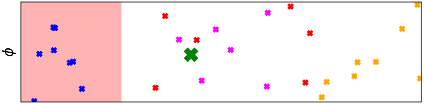


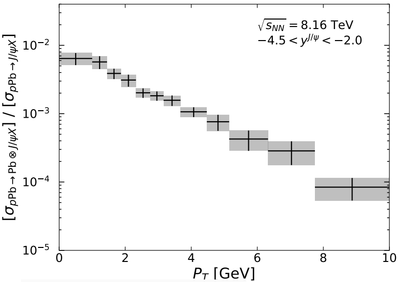




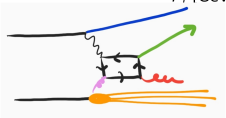


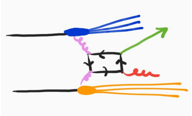
- 3 background-reduction techniques based on different detector acceptances:
  I central II forward

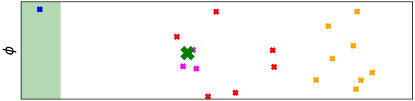
Background-reduction techniques

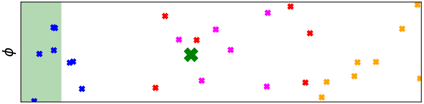


- Sufficient yields but huge backgrounds!
- Background reduction becomes more critical at larger P_T
- Hadroproduced J/ψ are associated with more detector activity than photoproduced J/ψ









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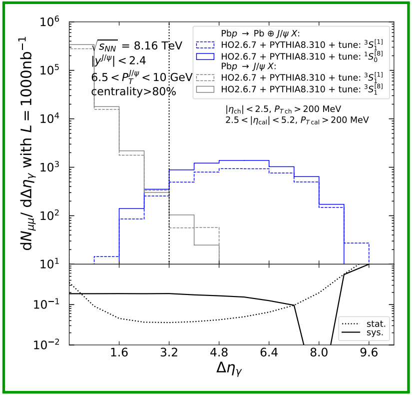
Method I: Rapidity gaps in LHC detectors

General purpose detector [ATLAS, CMS]



Broad rapidity coverage:

CMS/ATLAS 10 units

clean separation between photoproduction and hadroproduction

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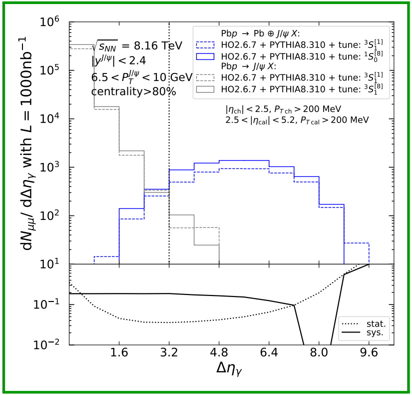

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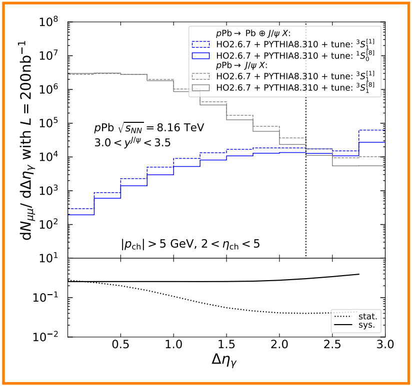

Narrow rapidity coverage:

LHCb 3 units, ALICE 1.8 units

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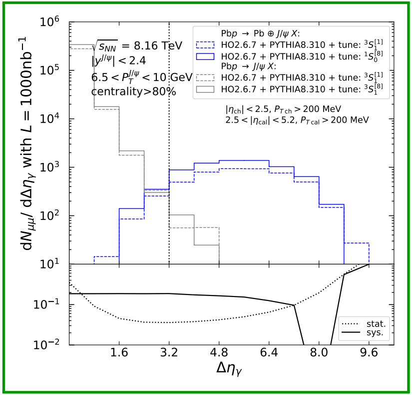

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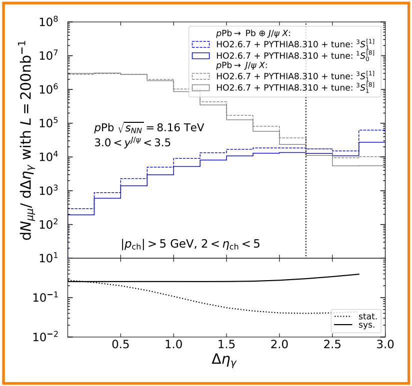

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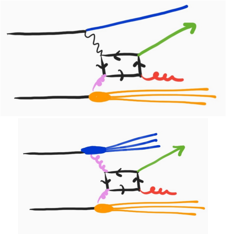
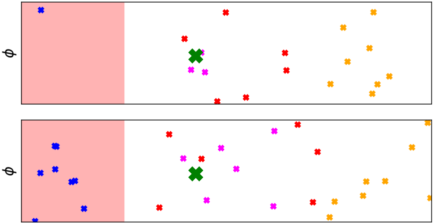
less clean separation between photoproduction and hadroproduction

- Selecting a cut value that minimises that statistical uncertainty: $\rightarrow$ **removes** $\mathcal{O}(99.99\%)$ ($\mathcal{O}(99.9\%)$) of background events $\rightarrow S/B \gtrsim \mathcal{O}(1)$

Background-reduction techniques

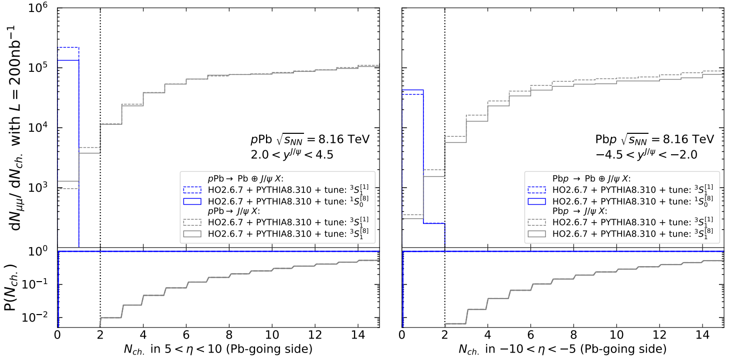




Method II: forward activity with HeRSCheL at LHCb

- forward scintillator sensitive to charged particle activity in the region $5 < |\eta| < 10$
- Photoproduction events identified with **no HeRSCheL activity**

- Differential yield w.r.t. the number of charged particles on the γ-emitter side within $5 < \eta < 10$ for photo- and hadroproduced J/ψ



Selecting events based on activity in HeRSCheL

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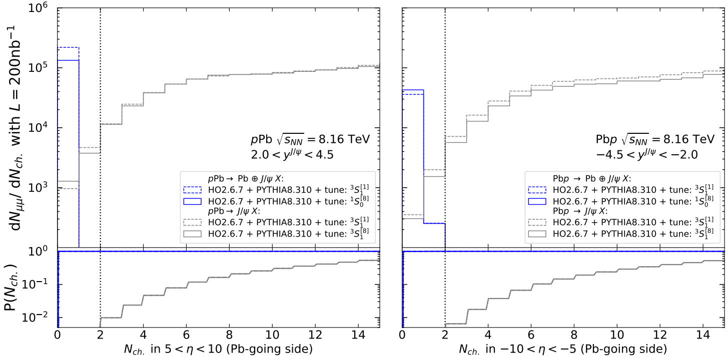
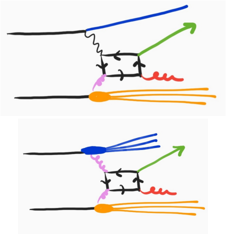
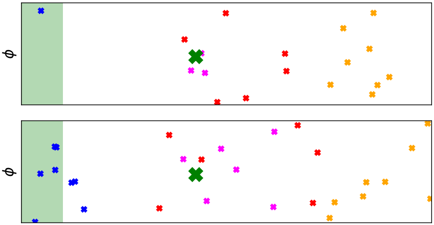


- We anticipate a clear distinction between photo- and hadroproduction
- Necessary to perform a full detector simulation to include HeRSCheL response

Background-reduction techniques





Method III: far-forward activity with zero-degree calorimeter at ALICE, ATLAS, & CMS

- Detector close to the beam pipe ($|\eta| \gtrsim 8$) sensitive to neutral particles
- UPCs identified as most peripheral events ($80 - 100\%$ centrality)

[Already done in pPb collisions: ALICE, JHEP 02 (2021) 002]

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[We expect $\mathcal{O}(100\%)$ of the signal with no neutron emission]

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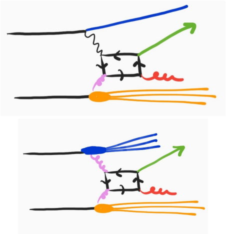

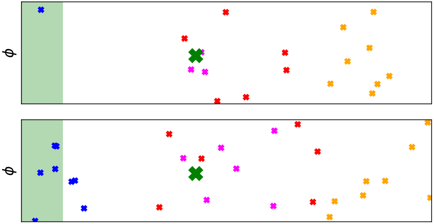

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  - This would **not** be possible in PbPb where there is a non-negligible photoproduction cross section with neutron emissions $\mathcal{O}(50\%)$
    - distentangling the photon emitter **CMS, Phys.Rev.Lett. 131 (2023) 26, 262301, PRC 93, 055206 (2016)**

Part III

Results

Comment on methods I–III in HL run

One of the advantages of pPb over pp is the significantly reduced pile-up. However, given the possibility of a pPb run with a sizeable μ value we should consider the efficacy of methods **I–III** under such conditions:

- Method **I**: rapidity gaps
  - **Calorimeter** based rapidity-gap definitions not possible
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  - Reduced $\Delta\eta$ reach for ATLAS and CMS 10$\rightarrow$ 5 units
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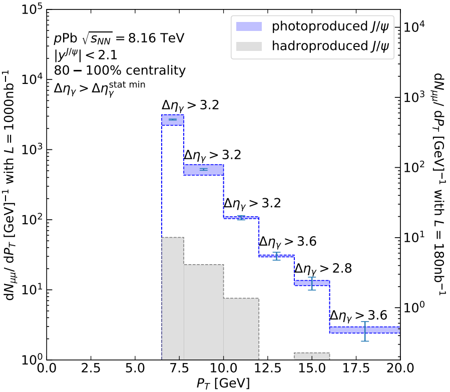
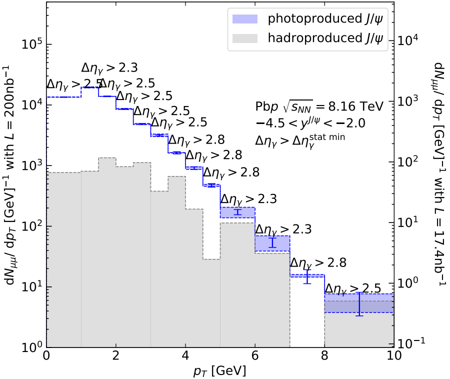
The same comments apply to exclusive UPCs

Photoproduction yields: ATLAS & CMS



- Possible to isolate photoproduction with CMS and ATLAS using methods I & III
- Possible to further enhance signal purity by selecting 0n events
- With Run3+4 lumi, possible to extend the P_T reach from 10 GeV (HERA data) to 20 GeV

detector	CMS	LHCb	CMS	LHCb
	Run 2 lumi:		Run 3+4 lumi:	
yield	$\mathcal{O}(10^3 - 10^5)$	$\mathcal{O}(10^3 - 10^4)$	$\mathcal{O}(10^4 - 10^6)$	$\mathcal{O}(10^4 - 10^5)$
P_T reach	14 GeV	8 GeV	20 GeV	14 GeV



- Possible to isolate photoproduction at LHCb using method I alone
- Combining with HeRSCheL information (method II) will improve background removal
- Expect ψ' yield to be $\sim 1/20$ of J/ψ yield no P_T differential data from HERA!

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We have shown that it is possible to measure P_T -differential inclusive photoproduction cross sections at the LHC without waiting for the EIC

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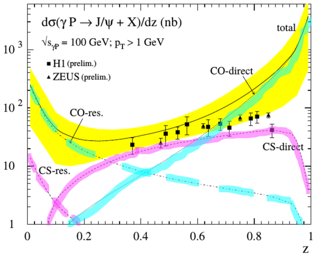
octet vs. singlet

Kramer, hep-ph/016120



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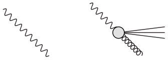

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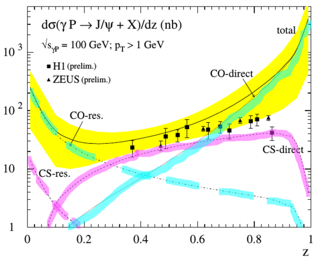

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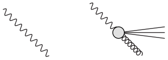

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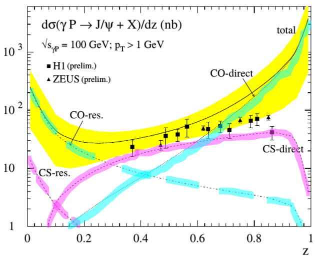

- Let us reconstruct the photon kinematics from the final state :

  $\mathrm{Pb}(P_{\mathrm{Pb}}) + p(P_p) \overset{\gamma(P_\gamma)}{\to} \mathrm{Pb}(P'_{\mathrm{Pb}}) + J/\psi(P_\psi) + X(P_X)$ thus $P_\gamma = P_\psi + P_X - P_p$

- $W_{\gamma p} \simeq (2\underbrace{(P_\psi + P_X - P_p)}_{P_\gamma}\cdot P_p)^{1/2}$ & $z = \frac{P_p \cdot P_\psi}{P_p \cdot (P_\psi + P_X - P_p)}$

- We only need to measure $(P_\psi \cdot P_p)$ & $(P_X \cdot P_p)$ or equivalently $P_X^- = E_X - P_{X,z}$
- NB: In the exclusive case, $P_X \simeq P'_p \Rightarrow P_\gamma + P'_p = P_\psi + P'_p$ and $W_{\gamma p} \simeq M_\psi e^{-y_\psi}$

Kinematic reconstruction: results

- Limited detector coverage $\Rightarrow P^{-}_{\text{reconstructed}} < P^{-}_{\text{generated}}$

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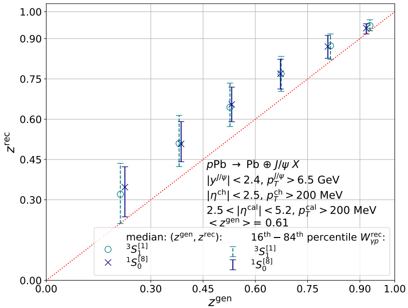

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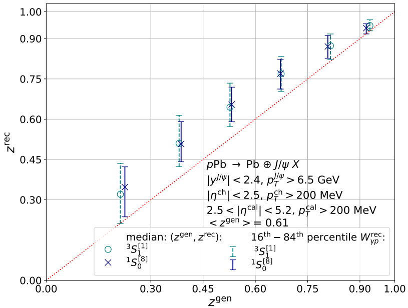
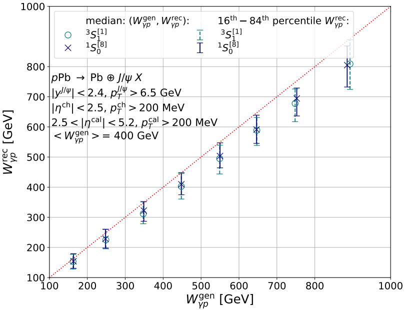




- For CMS and ATLAS: z reconstruction allows for $\mathcal{O}(5-6)$ bins (similar to HERA)

  improves with increasing values of z

- $W_{\gamma p}$ reconstruction allows for $\mathcal{O}(10)$ bins

  improves for decreasing values of $W_{\gamma p}$

Summary and outlook

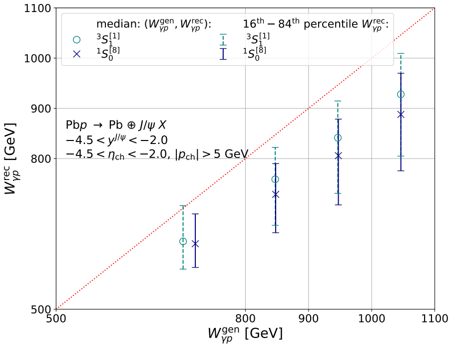
- A proton-lead collision system allows the LHC to be used as a photon-nucleon collider
  - Feasible to measure inclusive J/ψ, ψ' and Υ photoproduction at the LHC
  - Complementary to HERA measurements with a doubled P_T reach
  - It can be done now $\mathcal{O}(10)$ years before the EIC
- CMS and ATLAS are the **most favourable** experiments with the largest P_T reach and broadest psuedorapidity coverage

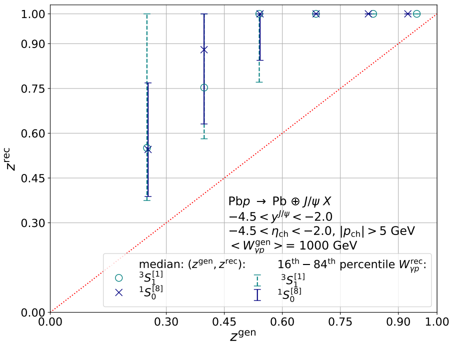
  (CMS has additional advantage of measuring $P_T \to 0$ GeV)
- Possible to make measurements at ALICE and LHCb too!
- Despite the impossibility to measure the intact Pb ion, possible to reconstruct z and $W_{\gamma p}$
  - Binning competitive with HERA, confirms the reach in $W_{\gamma p}$ up to 1 TeV !
  - Possibility to isolate resolved-photon contributions

Backup

Reconstruction of kinematic variable in LHCb

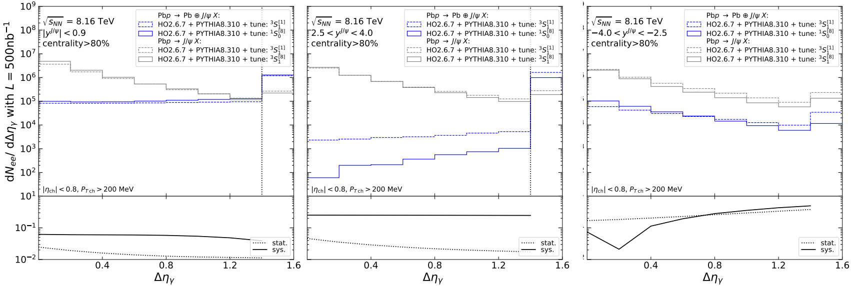
Owing to the narrow psuedorapidity gap coverage in LHCb ($2 < \eta < 5$), reconstruction of kinematics at LHCb is not possible.



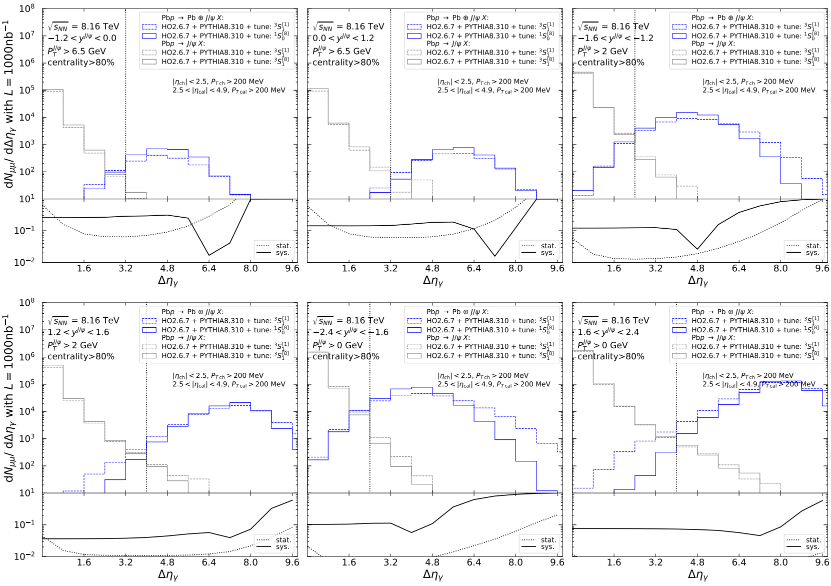


- When $z^{\rm rec} = 1$ only the J/ψ is captured!

$\Delta\eta_\gamma$-differential yield for J/ψ in the ALICE acceptance.



$\Delta\eta_\gamma$-y–diff. yield for J/ψ in CMS low-P_T acceptance

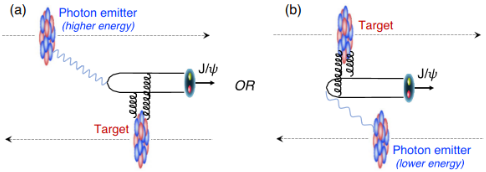


Neutron emission: disentangling the photon emitter

- For exclusive vector meson production in PbPb collisions there is as ambiguity as to which Pb ion is the photon emitter
- At a given rapidity either:

$$(a)\ x_\gamma = \frac{m_{T\,J/\psi}}{\sqrt{s}} e^{+y^{J/\psi}},\ x_{\mathbb{P}} = \frac{m_{T\,J/\psi}}{\sqrt{s}} e^{-y^{J/\psi}} \text{ or } (b)\ x_\gamma = \frac{m_{T\,J/\psi}}{\sqrt{s}} e^{-y^{J/\psi}},\ x_{\mathbb{P}} = \frac{m_{T\,J/\psi}}{\sqrt{s}} e^{+y^{J/\psi}}$$

ALICE, JHEP 10 (2023) 119;CMS, Phys.Rev.Lett. 131 (2023) 26, 262301 **PRC 93, 055206 (2016)**



- Neutron emissions (detected with ZDCs) serve as an impact parameter filter
- Larger photon energies are associated with smaller impact parameters
- 0nXn and XnXn select smaller impact parameter and larger x_γ compared to 0n0n