Inclusive quarkonium photoproduction at the LHC

Kate Lynch
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& Ronan McNulty (UCD)

DIS, Grenoble 2024

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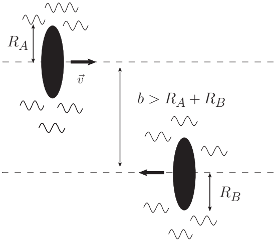
Part I

Introduction

Photon-induced interactions @ the LHC



- Accelerated charged particles emit photons

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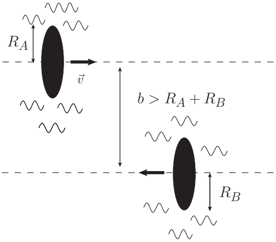

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- Photoproduction usually studied in *ep* colliders
  → clean photoproduction environment
- However, the LHC is an excellent source of photons
  → can reach extremely large $W_{\gamma p}$

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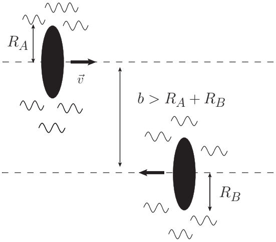

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- Energies available at the LHC:
  - pp @ $\sqrt{s} = 13$ TeV $\rightarrow W_{\gamma p}^{max} \approx 5$ TeV $\rightarrow x_{\gamma}^{\text{max}} \approx 0.14$
  - pPb @ $\sqrt{s_{NN}} = 8.16$ TeV $\rightarrow W_{\gamma p}^{max} \approx 1.5$ TeV $\rightarrow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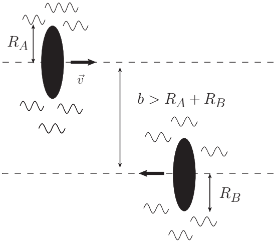

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- At hadron-hadron colliders: **Ultra Peripheral Collisions** select photoproduction
  - Done so far only for exclusive processes

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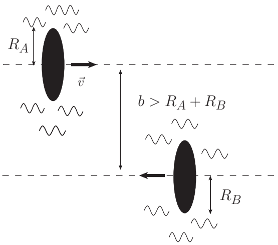

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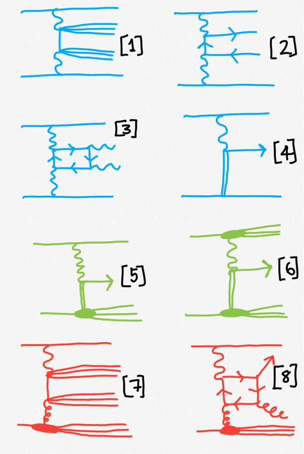
As I will show now: **inclusive quarkonium photoproduction**
can be measured via UPC at the LHC

Photon-induced interactions via UPC @ the LHC

- So far focus of UPCs @ LHC on exclusive processes (fully determined final state) **[1–4]**
- Recently there have been photoproduction studies with nuclear break up **[5,6*]**
- Only existing inclusive UPC study for di-jets **[7]** → not yet published!



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

[2] **Exclusive dilepton**: ATLAS, PRC 104 (2021) 024906, PLB 777 (2018) 303-323, PLB 749 (2015) 242-261; CMS, JHEP 01 (2012) 052

[3] **Light-by-light scattering**: ATLAS, Nature Phys. 13 (9) (2017) 852–858; CMS, PLB 797 (2019) 134826

[4] **Exclusive quarkonium**: ALICE, EPJC 79 (5) (2019) 402, PRL 113 (23) 232504; LHCb, JHEP 06 (2023) 146, JPG 40 (2013) 045001, JHEP 10 (2018) 167

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[6] **Peripheral* quarkonium photoproduction**: ALICE, PRL 116 (2016) 22, 222301, PLB 846 (2023) 137467; LHCb, PRC 105 (2022) L032201

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*non-UPC

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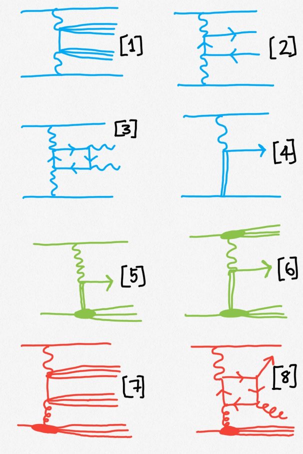

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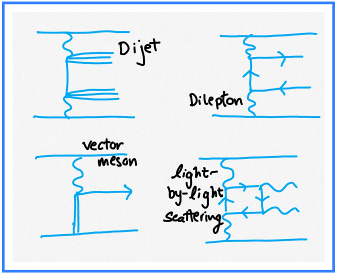
[8] **Inclusive quarkonium photoproduction: NOT YET MEASURED AT THE LHC!**

*non-UPC

Exclusive vs. inclusive photoproduction at the LHC

Exclusive: fully determined final state



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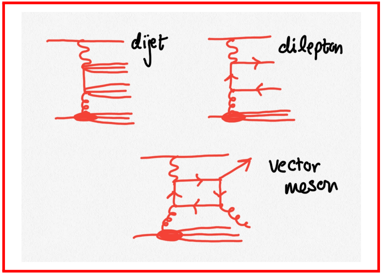

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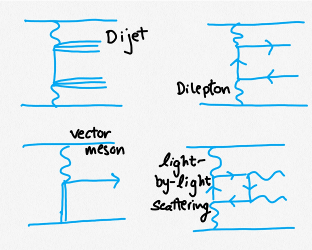
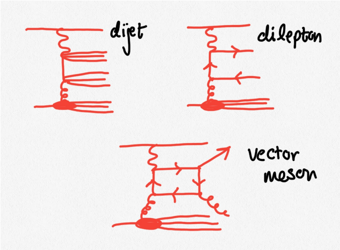


- Probe **G**eneralised **P**arton **D**istributions

Inclusive: **not** fully determined final state



- Probe **P**arton **D**istribution **F**unctions

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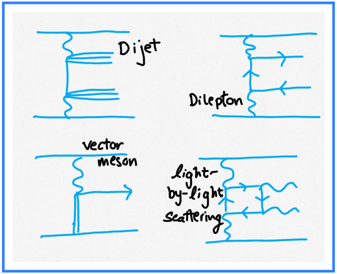

- Probe **G**eneralised **P**arton **D**istributions
- Colourless exchange

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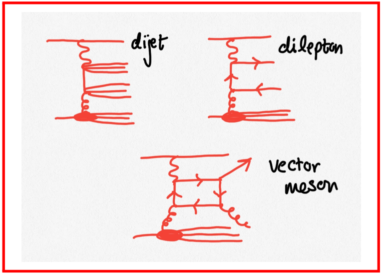

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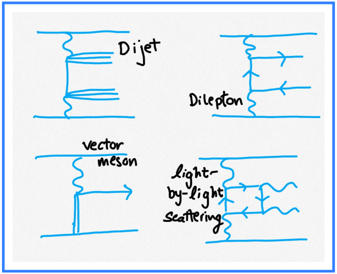
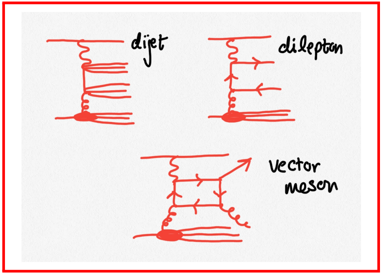


- Probe **G**eneralised **P**arton **D**istributions
- Colourless exchange
- Experimentally clean: even @ LHC

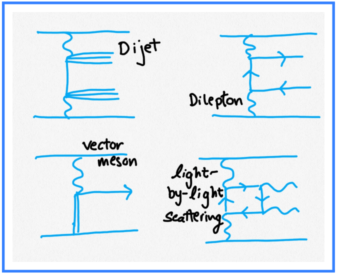
Inclusive: **not** fully determined final state



- Probe **P**arton **D**istribution **F**unctions
- Colourful exchange
- Challenging: large backgrounds

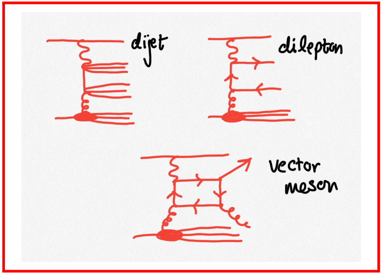
Exclusive vs. inclusive photoproduction at the LHC

Exclusive: fully determined final state



- Probe **G**eneralised **P**arton **D**istributions
- Colourless exchange
- Experimentally clean: even @ LHC
- Smaller rates

Inclusive: **not** fully determined final state



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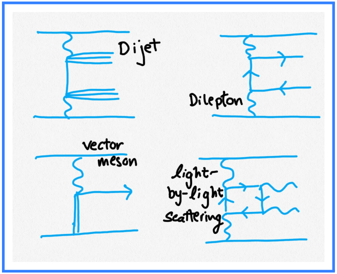

- Probe **G**eneralised **P**arton **D**istributions
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- Experimentally clean: even @ LHC
- Smaller rates
- Initial state kinematics **fully** determined by the final state

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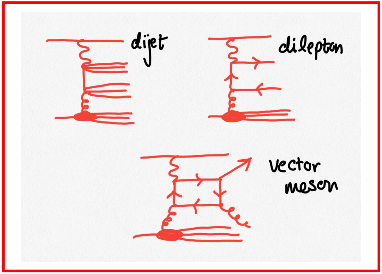

- Probe **P**arton **D**istribution **F**unctions
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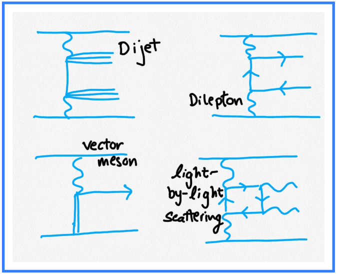
Exclusive vs. inclusive photoproduction at the LHC

Exclusive: fully determined final state



- Probe **G**eneralised **P**arton **D**istributions
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- Smaller rates
- Initial state kinematics **fully** determined by the final state
- Measured at the LHC

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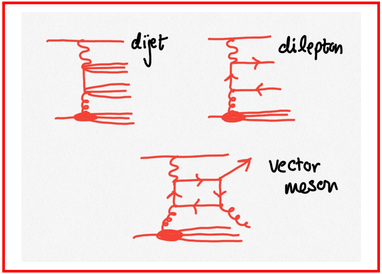

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- Initial state kinematics **partially** determined by the final state
- Should be measured at the LHC

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
  - × cannot simultaneously describe the photoproduction and polarisation data

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)	✗	✓	✓
Zhang et al.	✓($p_T > 6.5$ GeV)	✗	✓	✓
Gong et al.	✓($p_T > 7$ GeV)	✗	✓	✗
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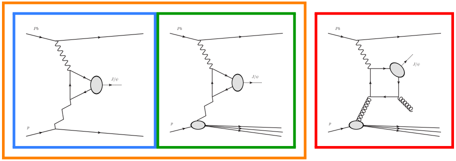
Want more inclusive photoproduction data → ~~EIC in 10 years~~ LHC today!

Existing J/ψ photoproduction measurements from HERA



- Data exists for **diffractive** (exclusive and proton-dissociative) & **inclusive/inelastic** photoproduction @ HERA $\sqrt{s} = 320$ GeV

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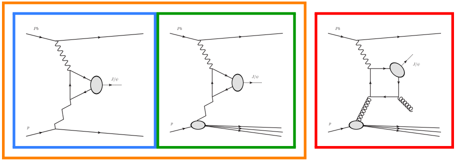

- Data exists for **diffractive** (exclusive and proton-dissociative) & **inclusive/inelastic** photoproduction @ HERA $\sqrt{s} = 320$ GeV
- Different contributions separated using experimental cuts on p_T and $z = \frac{P_p \cdot P_\psi}{P_p \cdot P_\gamma} \ldots$

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

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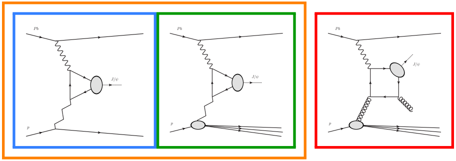

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- HERA result: $\sigma^{\mathrm{HERA}}_{\mathrm{exclusive}} \simeq \sigma^{\mathrm{HERA}}_{\mathrm{dissociative}} \simeq \sigma^{\mathrm{HERA}}_{\mathrm{inclusive}}$
- Expectation: $\sigma^{\mathrm{LHC}}_{\mathrm{exclusive}} \simeq \sigma^{\mathrm{LHC}}_{\mathrm{dissociative}} \simeq \sigma^{\mathrm{LHC}}_{\mathrm{inclusive}} \rightarrow$ only difference is photon flux!
- Exclusive and proton-dissociative photoproduction have been measured @ LHC
- Expect that inclusive yield is sufficently large we will demonstrate this

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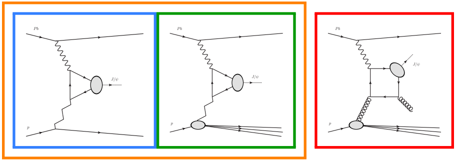

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- Exclusive and proton-dissociative photoproduction have been measured @ LHC
- Expect that inclusive yield is sufficently large we will demonstrate this
- As just discussed, measuring inclusive quarkonium photoproduction to understand the quarkonium hadronisation

Part II

Methodology

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

We must:

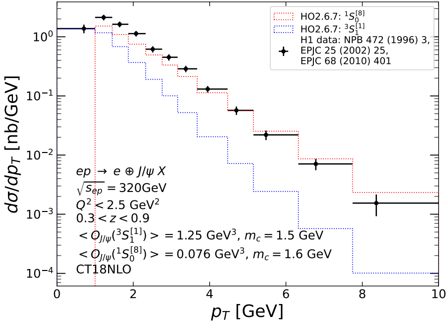
1. Evaluate yield & P_T reach: need reliable Monte Carlo (MC) sample

Problem:

- Only **LO MC** for quarkonia & Large QCD corrections to $d\sigma/dP_T$!

e.g. J.P.Lansberg Phys.Rept. 889 (2020) 1

- LO CS undershoots large P_T photoproduction data [Theory uncertainties not shown]
- LO CO captures large P_T photoproduction data [Theory uncertainties not shown]



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We must:

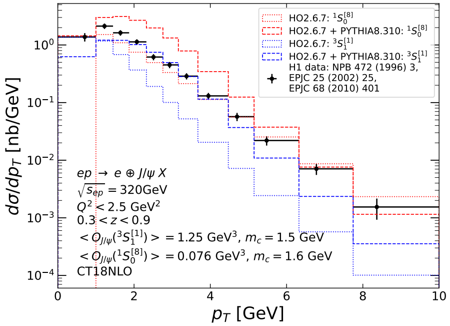
1. Evaluate yield & P_T reach: need reliable Monte Carlo (MC) sample

Problem:

- Only **LO MC** for quarkonia + QCD corrections are large!
  - LO CS + Parton Shower improved but not as good a NLO CS

    See e.g. C. Flore, JPL, H.S. Shao, Y. Yedelkina, PLB 811 (2020) 135926

  - LO CO + Parton Shower overshoots low P_T data



P_T tune necessary, especially to assess P_T reach

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

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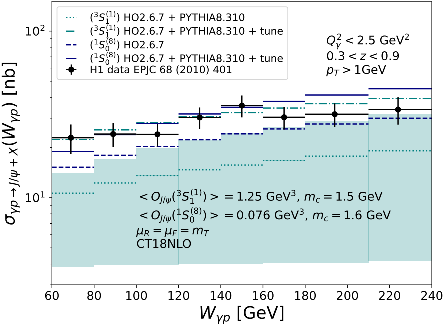
Solution: perform tune in P_T to H1 data + $W_{\gamma p}$ and y dependence from photon flux



$W_{\gamma p}$ dependence ok with P_T tune

2. Reconstructibility of z and $W_{\gamma p}$? [In pPb, no ambiguity on γ emitter but E_γ not measured in UPC]
3. Reject background: reliable background MC + background reduction strategy

Background Monte Carlo: hadroproduction P_T distribution

- Just as for photoproduction we tune our hadroproduction background MC to LHC data
- Tune to 5 TeV y-integrated LHCb data (up to $P_T = 20$ GeV) under the assumptions:

LHCb, JHEP 11 (2021) 921 181

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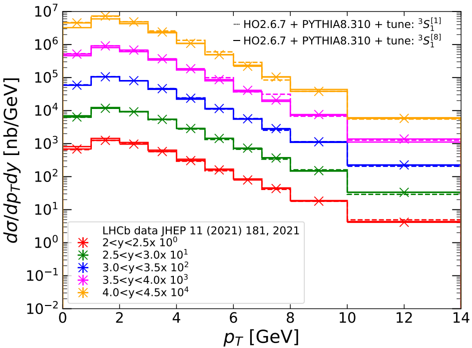
1. Tuning is y independent

Validation 1: $d\sigma/dy$ @ 5 TeV.



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LHCb, JHEP 11 (2021) 921 181

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

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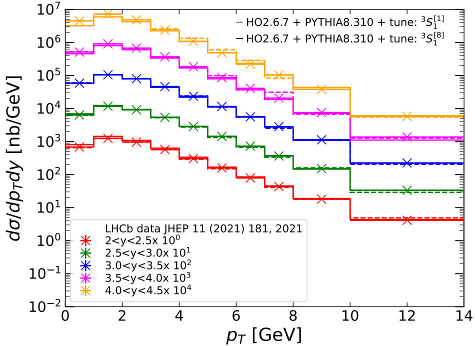
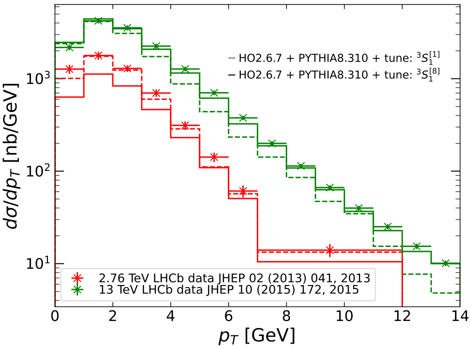
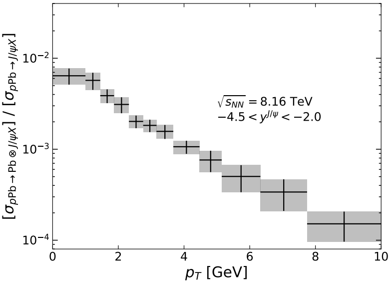


Validation 2: $\sqrt{s} = 13$ and 2.76 TeV

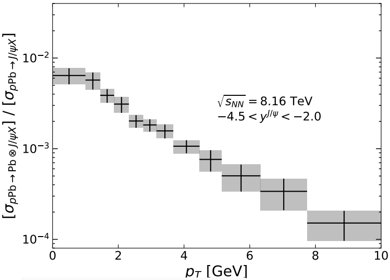


Background-reduction techniques



- 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

Background-reduction techniques



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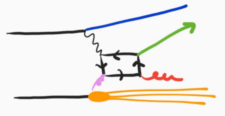
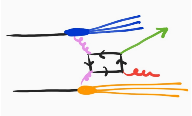
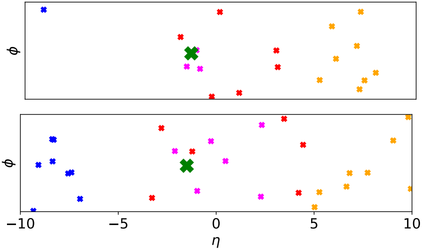
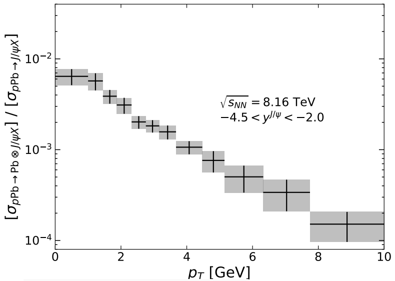






- 3 background-reduction techniques based on different detector acceptances

Background-reduction techniques



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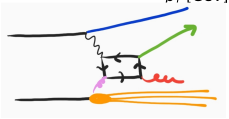
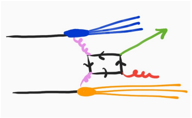
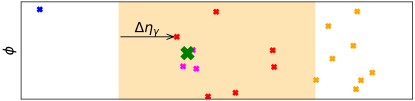
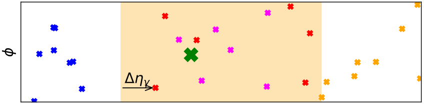


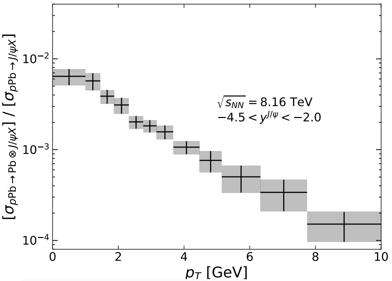




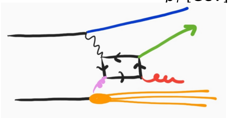


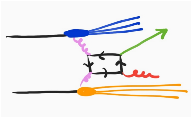
- 3 background-reduction techniques based on different detector acceptances:
  I central $\Delta\eta_\gamma$: distance in rapidity between main detector on photon-going side and closet particle activity

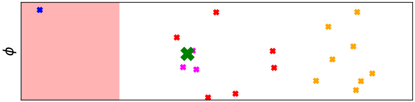
Background-reduction techniques

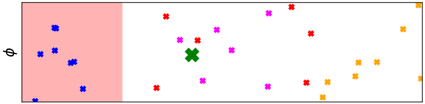


- Large yields but huge backgrounds!
- Background reduction critical at large P_T
- Background J/ψ are associated with more detector activity than photoproduced J/ψ



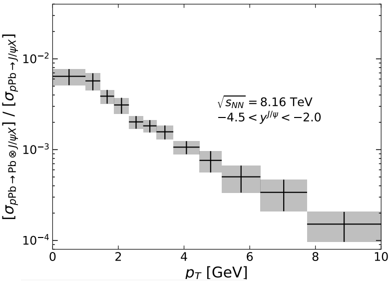




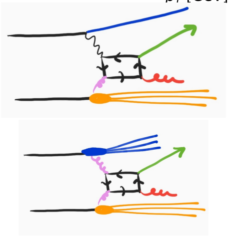


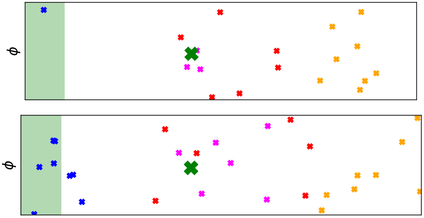
- 3 background-reduction techniques based on different detector acceptances: I central II forward

Background-reduction techniques



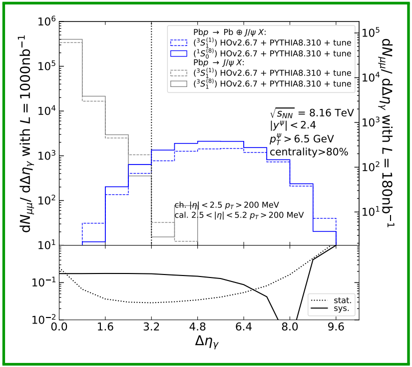
- Sufficient yields but huge backgrounds!
- Background reduction becomes more critical at larger P_T
- Hadroproduced J/ψ are associated with more detector activity than photoproduced J/ψ





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

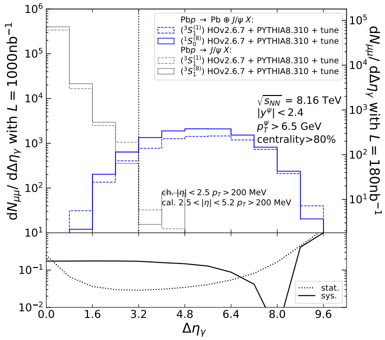
CMS-like detector



Wide $(\Delta\eta < 10)$ rapidity coverage: clean separation between photoproduction (signal) and hadroproduction (background) events

Method I: Rapidity gaps in CMS- and LHCb-like detectors

CMS-like detector



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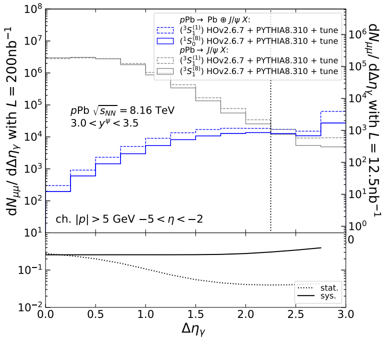
LHCb-like detector



Narrow $(\Delta\eta < 3)$ rapidity coverage:
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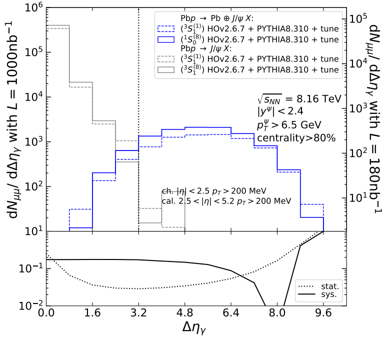

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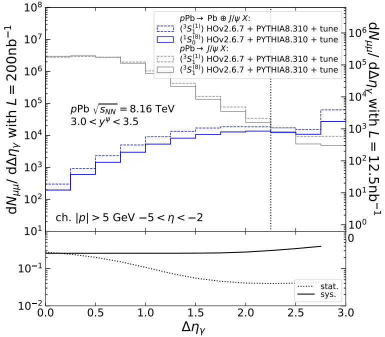
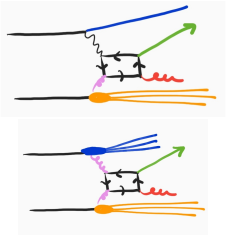
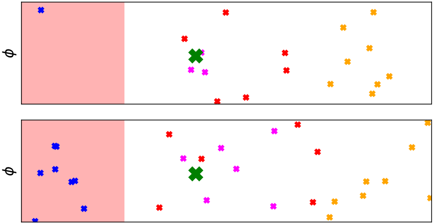


Narrow $(\Delta\eta < 3)$ rapidity coverage:
less clean separation between photoproduction and hadroproduction events

- 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

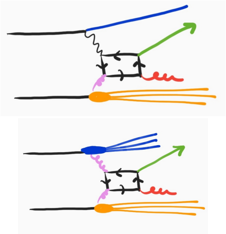


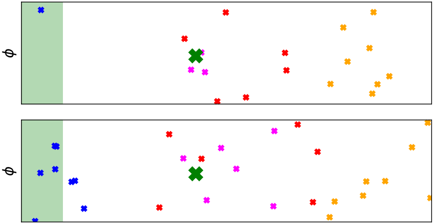


Method II: forward activity with HeRSCheL at LHCb

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

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 *p*Pb collisions: ALICE, JHEP 02 (2021) 002]

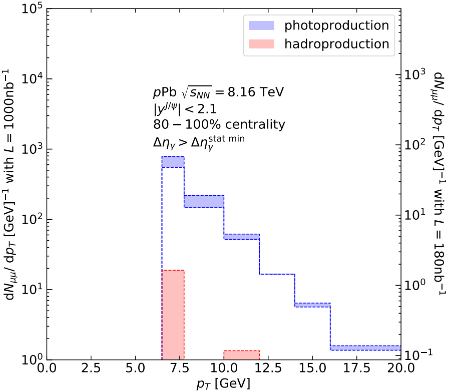
- Selecting events with **0 neutrons** in ZDC can further enhance signal purity

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

Part III

Results

Photoproduction yields



- Possible to isolate photoproduction with CMS and ATLAS using methods I & III
- With Run3+4 lumi, possible to extend the P_T reach from 10 GeV (HERA data) to 20 GeV
- Expect ψ' yield to be $\sim 1/20$ of J/ψ yield no P_T differential data from HERA!

detector	CMS-like	LHCb-like	CMS-like	LHCb-like
	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

Kinematic reconstruction: $W_{\gamma p}$ and z

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

- What about $d\sigma/dz$ and as a function of $W_{\gamma p}$?
  - Fully equivalent to *ep* measurements

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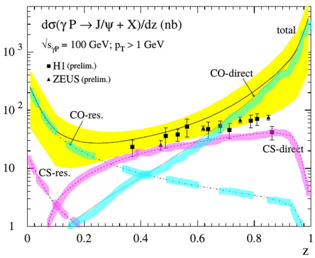
  - Study quarkonium hadronisation

octet vs. singlet

Kramer, hep-ph/016120



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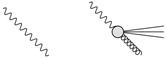
direct and resolved photons



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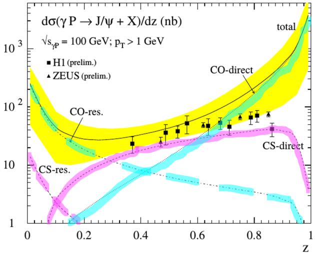

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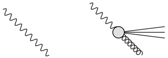

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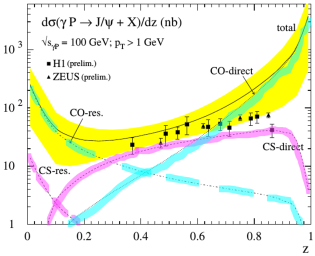

- Let us reconstruct the photon kinematics from the final state :

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

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

- In fact, we only need to measure $(P_X \cdot P_p)$ 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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- This results in the following biases;
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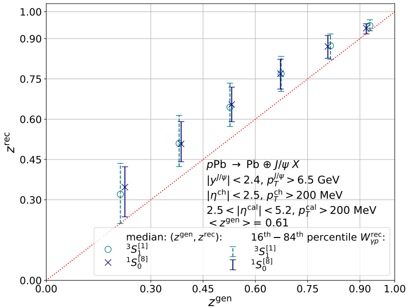

Kinematic reconstruction: results

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- This results in the following biases;
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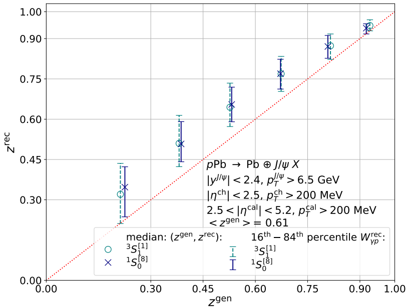
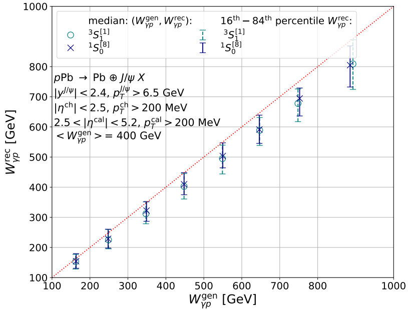




- For CMS and ATLAS: z reconstruction allows for $\mathcal{O}(5-6)$ bins (similar to HERA)

  improves with increasing values of z

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

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

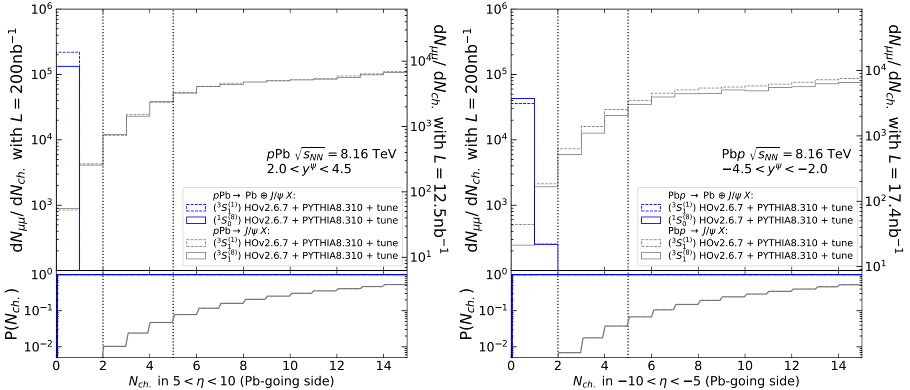
Summary and outlook

- The LHC can 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

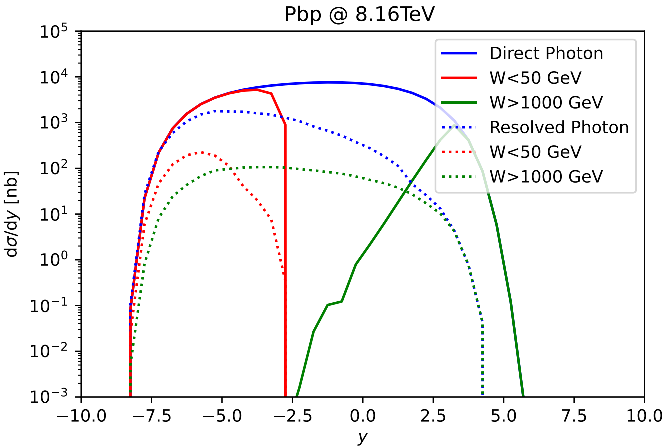
  (CMS has additional advantage of measuring $P_T \rightarrow 0$ GeV)
- Possible to make measurements at ALICE and LHCb too!
- Despite the impossibility to measure the intact Pb ion, possible to reconstruct z and $W_{\gamma p}$
  - Binning competitive with HERA, confirms the reach in $W_{\gamma p}$ up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

Backup

Activity in HeRSCeL



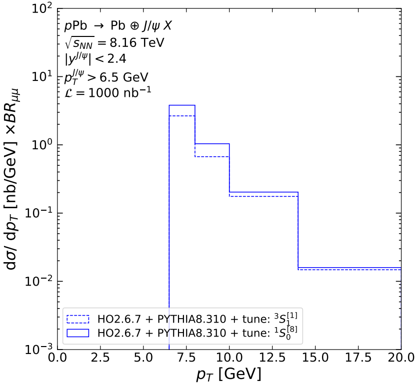
Direct and resolved photon rapidity comparison

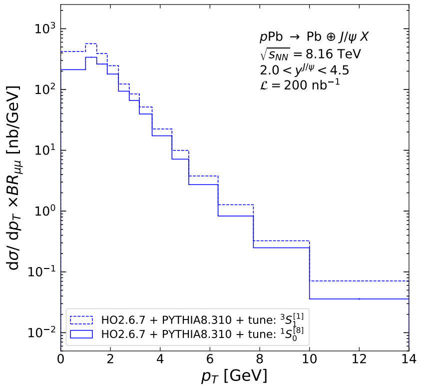


Resolved photon contribution increases with increasing photon energy ($W_{\gamma p}$); however, at most forward rapidities is suppressed.

Results: photoproduction P_T distributions and yields

	CMS-like detector	LHCb-like detector





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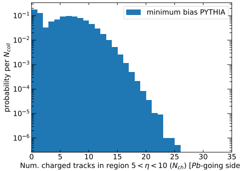
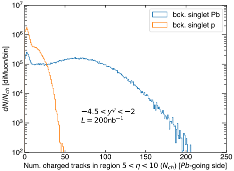
Run 2 lumi:		
yield	$\mathcal{O}(10^3 - 10^5)$	$\mathcal{O}(10^3 - 10^4)$
P_T reach	14 GeV	8 GeV
Run 3+4 lumi:		
yield	$\mathcal{O}(10^4 - 10^6)$	$\mathcal{O}(10^4 - 10^5)$
P_T reach	20 GeV	14 GeV

From p to Pb in the HeRSCheL region

- The background is modelled by generating pA events with HELAC-Onia and passing them through PYTHIA; PYTHIA reads these as pp events.
- In a pp collision $N_{coll.} = 1$; whereas in a pA collision there are many more nucleons and therefore it is possible to have $N_{coll.} > 1$ [typically modelled using Glauber-type models].
- Using minimum bias events generated by PYTHIA, one can obtain a probability distribution for the number of charged tracks in the HeRSCheL region. **[bottom left]**
- To model the HeRSCheL signal using the PYTHIA events (i.e., converting pp to pA) events are randomly assigned a centrality class and then assigned $N_{coll.}$ based on ALICE results. **[bottom centre arXiv:1605.05680]**
- For a given event, the total number of charged tracks in the HeRSCheL region is given by throwing $i = 1, .., N_{coll.} - 1$ points into the probability distribution, and summing over $N_{coll.}$.
- The transformation from pp to pA HeRSCheL distribution. **[bottom right]**



Centrality class	$\langle N_{\rm coll}\rangle_{\rm opt.}$	$\langle N_{\rm coll}\rangle_{\rm ALICE}$	b [fm]
2–10%	14.7	$11.7 \pm 1.2 \pm 0.9$	4.14
10–20%	13.6	$11.0 \pm 0.4 \pm 0.9$	4.44
20–40%	11.4	$9.6 \pm 0.2 \pm 0.8$	4.94
40–60%	7.7	$7.1 \pm 0.3 \pm 0.6$	5.64
60–80%	3.7	$4.3 \pm 0.3 \pm 0.3$	6.29
80–100%	1.5	$2.1 \pm 0.1 \pm 0.2$	6.91



Kinematics: z and $W_{\gamma p}$ reconstruction

$$\text{Pb}(P_{\text{Pb}}) + p(P_p) \to \text{Pb}(P'_{\text{Pb}}) + J/\psi(P_\psi) + X(P_X)$$

- By momentum conservation $P_\gamma = P_\psi + P_X - P_p$
  - $P_{\text{Pb}} \simeq \frac{1}{2} P^-_{\text{Pb}} \eta_+$: lead-ion moving backward with negative rapidity
  - $P_p \simeq \frac{1}{2} P^+_p \eta_-$: proton moving forward with positive rapidity
  - $P_X = \sum_i^N P_i$: sum over particle momenta

$$z = \frac{P_p \cdot P_\psi}{P_p \cdot \underbrace{(P_\psi + P_X - P_p)}_{P_\gamma}} \simeq \frac{P^-_\psi}{P^-_X + P^-_\psi}$$

$$W_{\gamma p} \simeq \sqrt{2(P_\psi + P_X - P_p) \cdot P_p} \simeq \sqrt{(P^-_X + P^-_\psi) P^+_p}$$

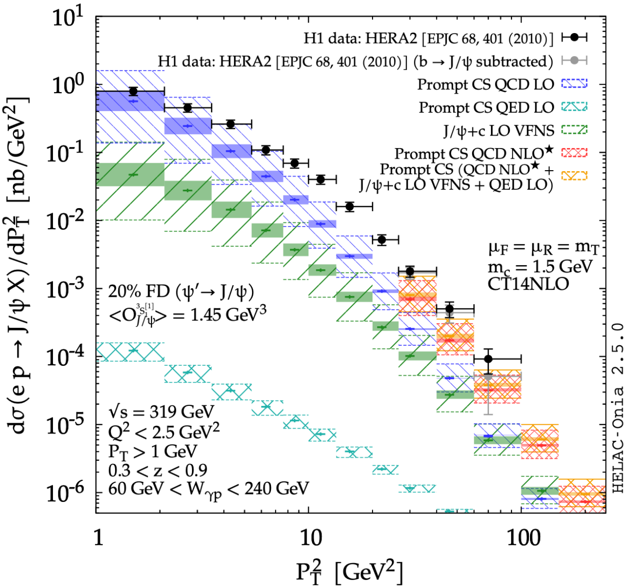
- A particle i **collinear to the proton** has $P^-_i = 0$ and does not contribute to z
  - Exclusive case: $P^-_X = 0 \to z = 1$
- A particle i **collinear to the photon emitter** has a large P^-_i
  - As we expect a rapidity gap between the **photon emitter** and the produced particles, much of the produced particles can be captured by the main LHC detectors

Lightcone four-vector representation

1. Choose two vectors along an axis such that,
$$\eta^{\pm} \cdot \eta^{\pm} = 0 \quad \& \quad \eta^{\mp} \cdot \eta^{\pm} = 2. \tag{1}$$
2. A particle's four-momentum can be written as,
$$p = (E, p_x, p_y, p_z) = [P^+, P^-, \mathbf{p}]. \tag{2}$$
3. The scalar product of two four-momenta is given as,
$$p \cdot q = \frac{1}{2}\left(P^+Q^- + P^-Q^+\right) - \mathbf{p} \cdot \mathbf{q}. \tag{3}$$
4. If p lies along the vector η^-, then the scalar product reduces to,
$$p \cdot q = \frac{1}{2}\left(P^-Q^+\right). \tag{4}$$
5. Consider some massless particle q,
   - If q lies on the vector η^+: $p \cdot q$ is maximised $\rightarrow p \cdot q = A$.
   - If q is perpendicular to the vectors $\eta^{\pm}$: $p \cdot q = A/2$.
   - If q lies on the vector η^-: $p \cdot q$ is minimised $\rightarrow p \cdot q = 0$.

NLO inclusive J/ψ photoproduction at HERA

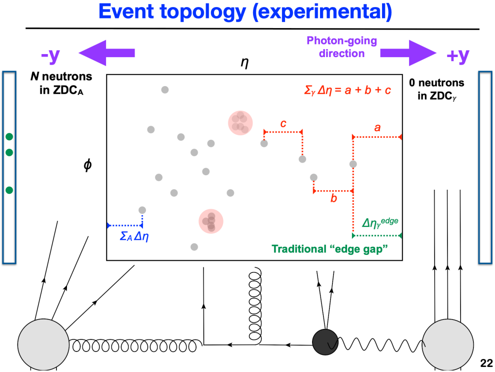
"NLO inclusive J/ψ photoproduction at large P_T at HERA and the EIC", Flore et. al. 2021

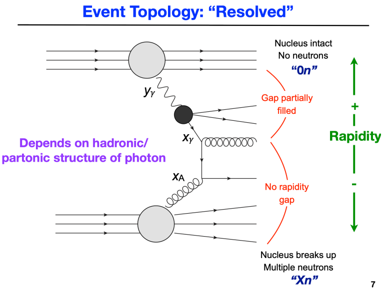


ATLAS UPC dijet Study

ATLAS-CONF-2022-021

- Pb-Pb @ $\sqrt{s_{NN}} = 5.02$ TeV
  - 0nXn requirement [$E_{ZDC} < 1$ TeV]
  - $\sum_{\gamma} \Delta\eta$ requirement [instead of $\Delta\eta_{\gamma}^{edge}$]
    - Include resolved photon in analysis
    - What is the effect of higher order corrections on choice of gap definition?





Slides from A. Angerami

Luminosity targets

From LHC programme coordination meeting; *p*Pb and PbPb targets are for Run 3 and 4 and *pp* targets are for Run 3 only.

	ATLAS	CMS	ALICE	LHCb
pp	160 fb^{-1}		200 pb^{-1}	25 fb^{-1}
PbPb	13 nb^{-1}			2 nb^{-1}
*p*Pb	1 pb^{-1}		0.5 pb^{-1}	0.2 pb^{-1}

Pb-Pb inclusive dijets

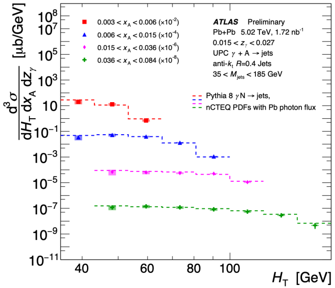
ATLAS-CONF-2017-011, ATLAS-CONF-2022-021

- Triply differential cross section in,

$$z_\gamma = \frac{m_{jets}}{\sqrt{s_{NN}}} e^{+y_{jets}}, \quad x_A = \frac{m_{jets}}{\sqrt{s_{NN}}} e^{-y_{jets}}, \quad H_T = p_T^{jet1} + p_T^{jet2} \tag{5}$$

- Jets defined using anti-k_T with $R = 0.4$; $p_T^{jet1(2)} > 15(20)$ GeV and $|\eta^{jet}| < 4.4$.

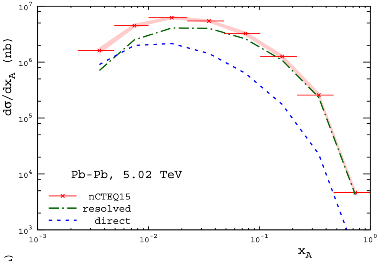
- selection of events:
  - $\Delta\eta_A < 3$ [hadro.] and $\sum_\gamma \Delta\eta > 2.5$ [photo.]
  - sum-of-gaps retains high efficiency for the resolved-photon contribution
  - 0nXn biases towards lower impact parameter collisions



Pb-Pb inclusive dijets

Guzey, Klasen, PHYSICAL REVIEW C 99, 065202 (2019)

- Resolved contribution dominant in region $x_A > 0.01$ [equivalently, resolved-photon contribution dominant for J/ψ in most forward region]
- Resolved and direct contributions comparable in region $x_A < 0.01$
- LO results (PYTHIA 8 + EPPS16 nPDF) quantitatively similar
- However, resolved contribution is larger @ NLO [this statement is scheme and scale dependant]



Set-up: generating samples

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

- Use MC samples generated by HELAC-Onia in the NRQCD framework to model the photoproduction and hadroproduction
  - Signal $[\gamma g \rightarrow J/\psi({}^3S_1^1)g\ ]$ and $[\gamma g \rightarrow J/\psi({}^1S_0^8)g\ ]$
  - Background $[gg \rightarrow J/\psi({}^3S_1^1)g\ ]$ and $[gg \rightarrow J/\psi({}^3S_1^8)g]$
- Use PYTHIA to shower partonic events
- The P_T distribution is not well described by leading order NRQCD or leading order NRQCD + Parton shower
- Perform a tune of leading order NRQCD + Parton shower MC to experimental data to correctly describe the P_T shape
  - photoproduction signal H1 *ep* 320 GeV data **10.1140/epjc/s10052-010-1376-5**; **10.1007/s10052-002-1009-8**
  - hadroproduction background LHCb 5 TeV *pp* data **10.1007/JHEP11(2021)181**