Inclusive quarkonium photoproduction at the LHC

Kate Lynch
Jean-Philippe Lansberg (IJCLab), Charlotte Van Hulse (UAH)
& Ronan McNulty (UCD)

GDR, Tours 2024

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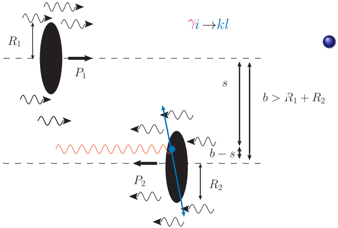
Part I

Introduction

Photon-induced interactions @ the LHC



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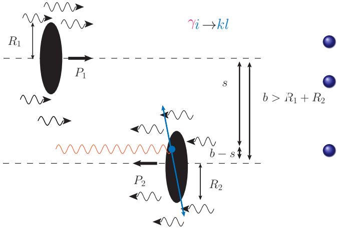
Photon-induced interactions @ the LHC



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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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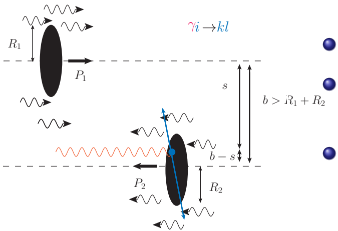

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- Energies available at the LHC:
  - pp @ $\sqrt{s} = 13$ TeV $\to W_{\gamma p}^{max} \approx 5$ TeV $\to x_{\gamma}^{max} = 0.14$
  - pPb @ $\sqrt{s_{NN}} = 8.16$ TeV $\to W_{\gamma p}^{max} \approx 1.5$ TeV $\to x_{\gamma}^{max} = 0.03$
- Energies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

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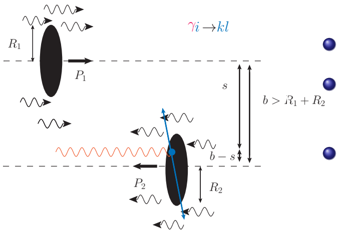

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  - Done so far only for exclusive processes

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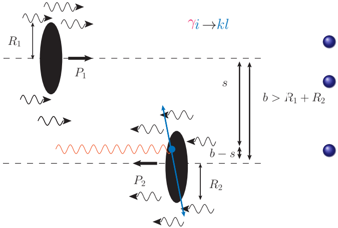

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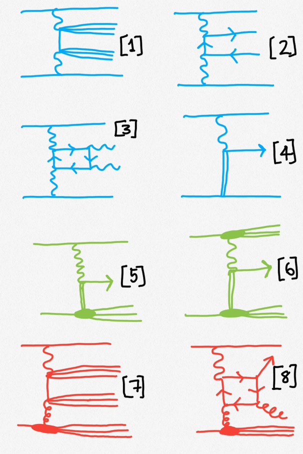
We advocate **inclusive quarkonium photoproduction** can be measured via UPC at the LHC

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 studies with nuclear break up **[5,6*]**
- Only existing inclusive UPC study **[7]**



[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

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[5] **Diffractive quarkonium with nuclear break up**: ALICE, PRD 108 (2023) 11

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

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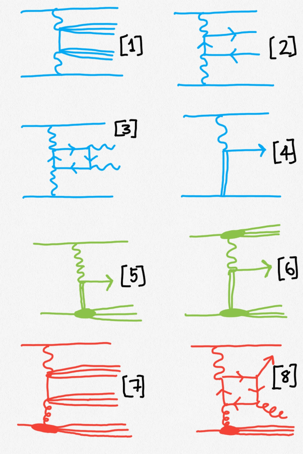

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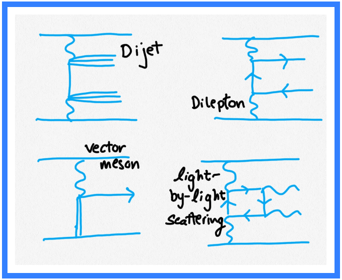
[8]**Inclusive quarkonium photoproduction:**
NOT YET MEASURED AT THE LHC!

*non-UPC

Exclusive vs. inclusive photoproduction at the LHC

Exclusive: fully determined final state



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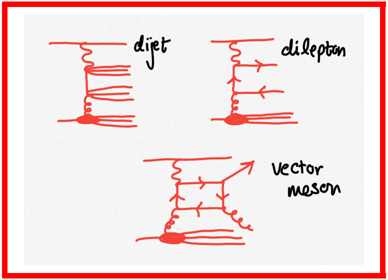

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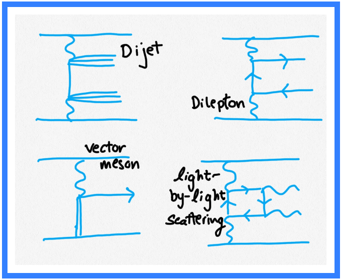

- Probe **G**eneralised **P**arton **D**istributions

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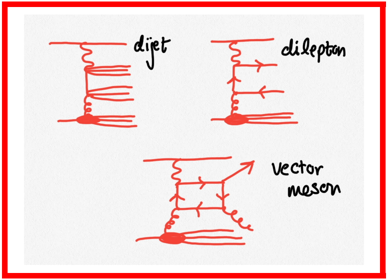

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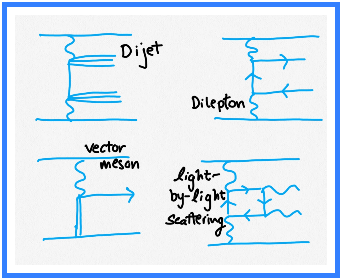

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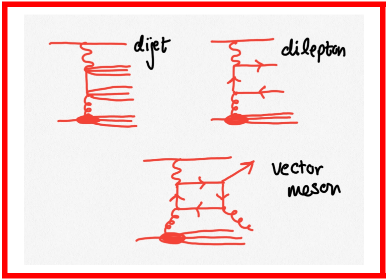

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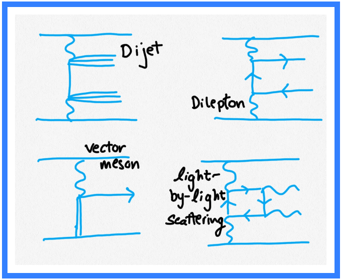

- Probe **G**eneralised **P**arton **D**istributions
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- Experimentally clean: even @ LHC

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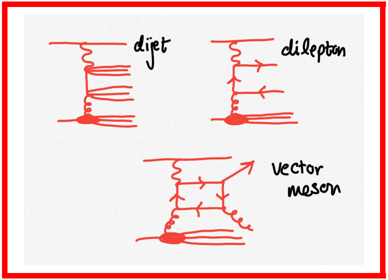

- Probe **P**arton **D**istribution **F**unctions
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- Experimentally challenging: large backgrounds

Exclusive vs. inclusive photoproduction at the LHC

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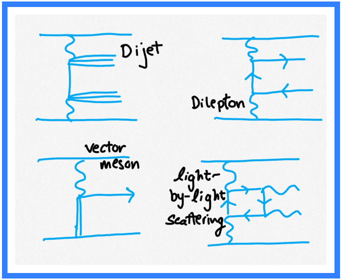
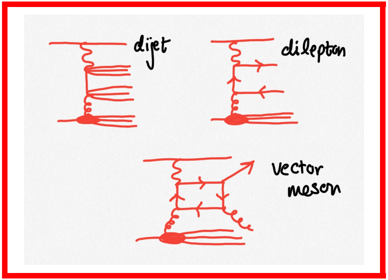


- Probe **G**eneralised **P**arton **D**istributions
- Colourless exchange
- Experimentally clean: even @ LHC
- Smaller rates

Inclusive: **not** fully determined final state



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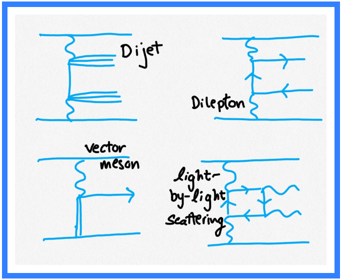

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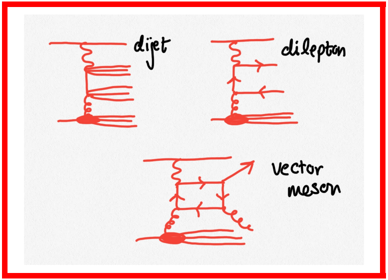

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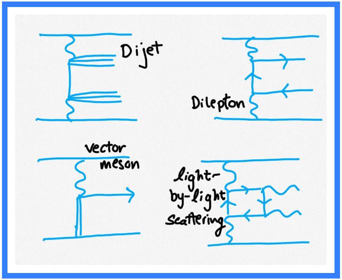

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- Smaller rates
- Initial state kinematics fully determined
- Measured at the LHC

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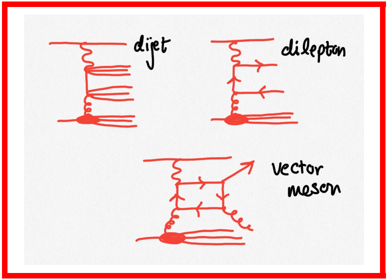

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- Colourful exchange
- Experimentally challenging: large backgrounds
- Larger rates
- Initial state kinematics **not** fully determined
- Should be measured at the LHC

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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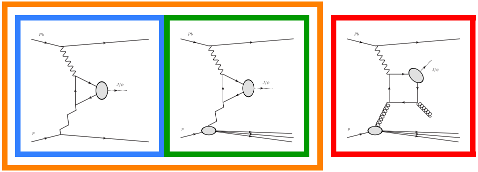
Want more inclusive photoproduction data → ~~EIC in 10 years~~ LHC today!

Existing J/ψ photoproduction measurements from HERA



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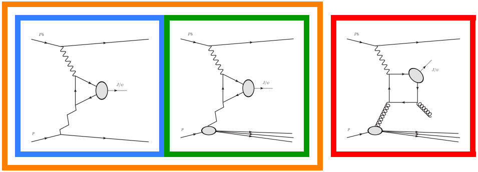

- Data exists for **diffractive** (exclusive and proton-dissociative) & **inclusive/inelastic** photoproduction @ HERA $\sqrt{s} = 320$ GeV
- Different contributions separated using experimental cuts on p_T and $z = \frac{P_p \cdot P_\psi}{P_p \cdot P_\gamma}$...

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

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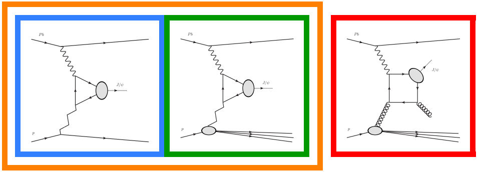

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- HERA result: $\sigma^{\mathrm{HERA}}_{\mathrm{exclusive}} \simeq \sigma^{\mathrm{HERA}}_{\mathrm{dissociative}} \simeq \sigma^{\mathrm{HERA}}_{\mathrm{inclusive}}$
- Expectation: $\sigma^{\mathrm{LHC}}_{\mathrm{exclusive}} \simeq \sigma^{\mathrm{LHC}}_{\mathrm{dissociative}} \simeq \sigma^{\mathrm{LHC}}_{\mathrm{inclusive}} \rightarrow$ only difference is photon flux!
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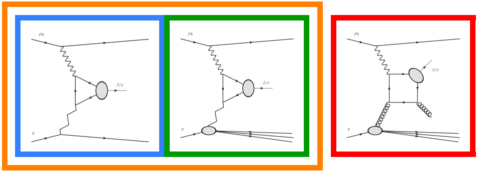

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- Exclusive and proton-dissociative photoproduction have been measured @ LHC
- Expect that inclusive yield is sufficently large we will demonstrate this
- Measuring inclusive quarkonium photoproduction presents the opportunity to understand the production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

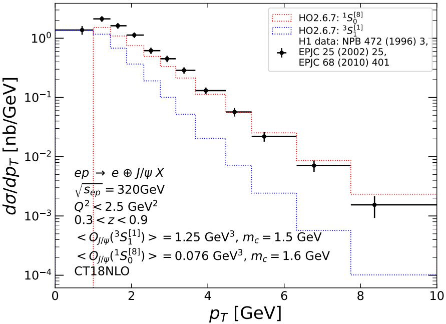
Part II

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 + QCD corrections are large!
     - LO CS undershoots undershoots large P_T data
     - LO CO captures large P_T data



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   Problem:
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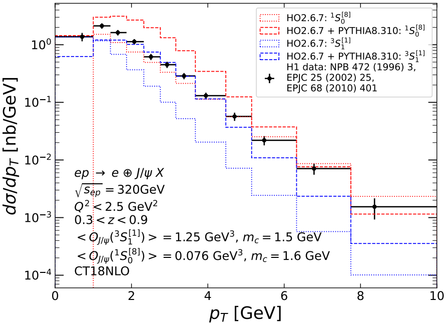
     - LO CS + PS undershoots improved but still undershoots
     - LO CO + PS captures overshoots low P_T data



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

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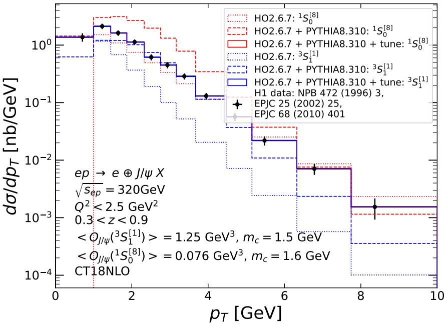
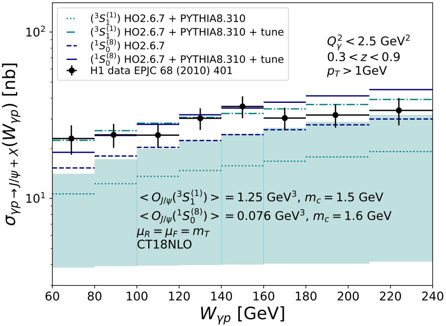
   Solution: perform tune in P_T to HERA data + keep $\sqrt{s}$ and y dependence from photon flux





2. pPb no ambiguity as to the photon emitter: allows for reconstruction of z & $W_{\gamma p}$
3. 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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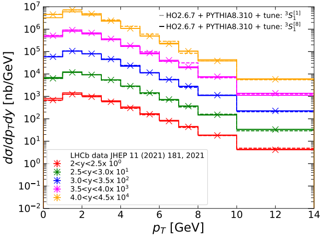

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  2. Tuning is $\sqrt{s}$ independent

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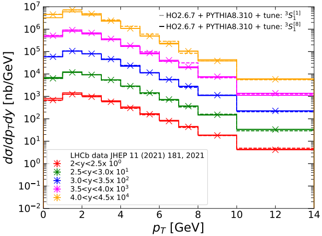
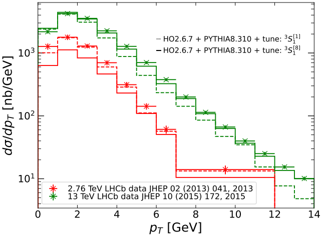
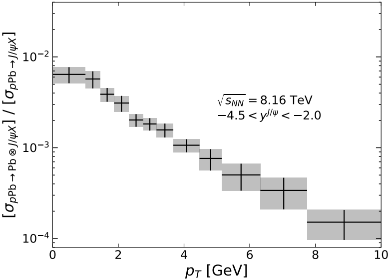


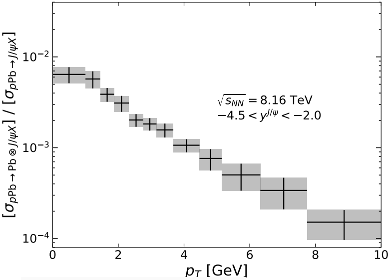
Validation 2: tune vs. 13- and 2.76 TeV data.



Background reducing techniques



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



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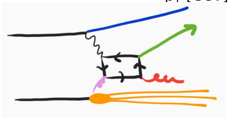
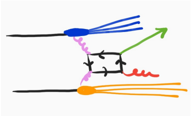
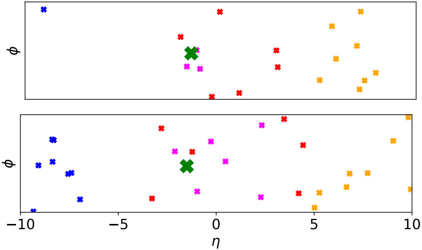
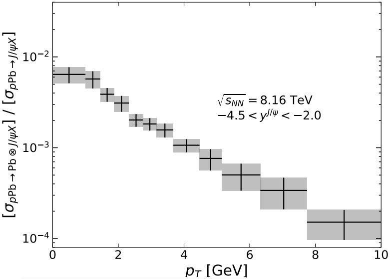






- We propose 3 background reduction techniques based on different regions of detector acceptance

Background reducing techniques



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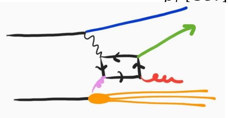
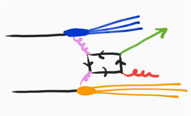
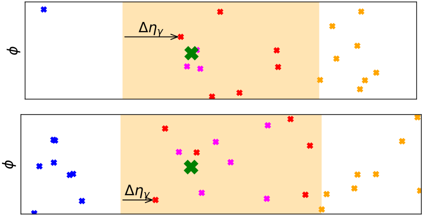
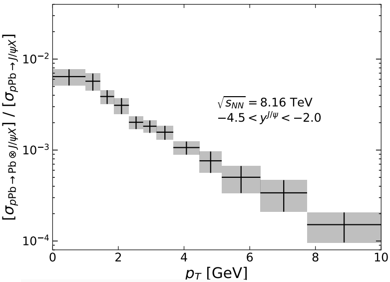






- We propose 3 background reduction techniques based on different regions of detector acceptance: I central $\Delta\eta_\gamma$: distance in rapidity between main detector on photon-going side and closet particle activity

Background reducing techniques



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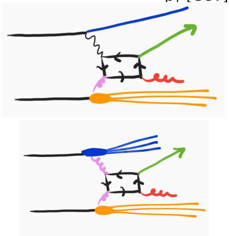
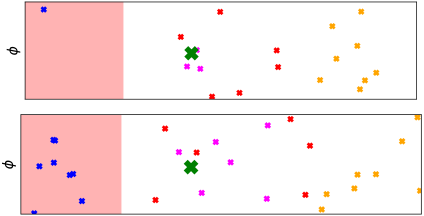
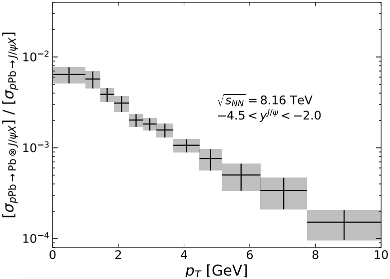


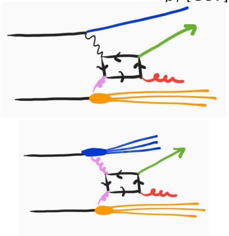


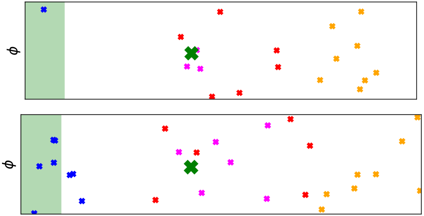
- We propose 3 background reduction techniques based on different regions of detector acceptance: I central II forward

Background reducing 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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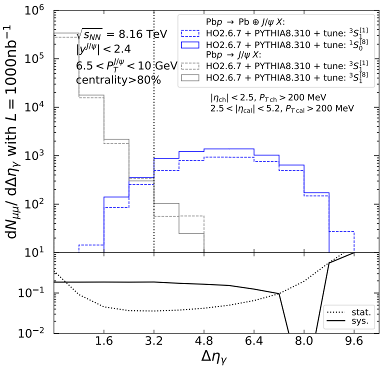
Method I: Rapidity gaps in CMS-, ATLAS-, and LHCb-like detectors

CMS/ATLAS-like detector



Wide rapidity coverage: clean separation between photo- and hadroproduction events

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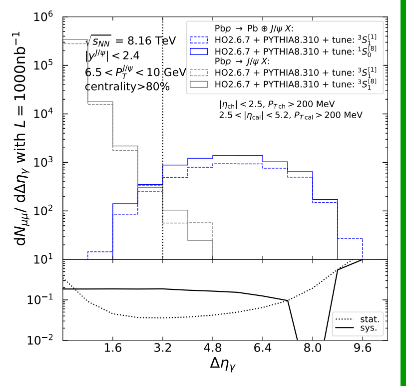

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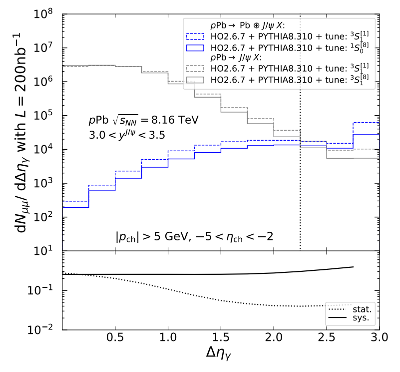

Narrow rapidity coverage: less pronounced separation between photo- and hadroproduction events

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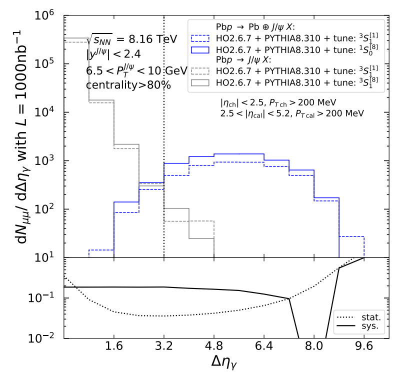

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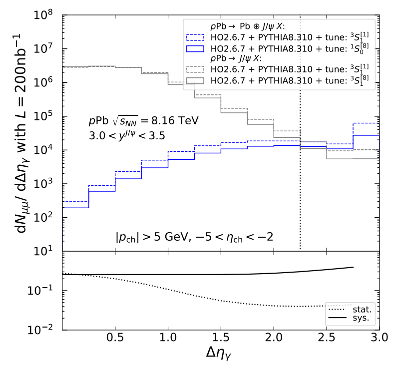
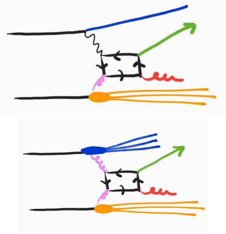
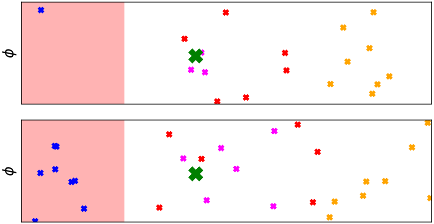


Narrow rapidity coverage: less pronounced separation between photo- and hadroproduction events

- Selecting a cut value that minimises that statistical uncertainty:
  → **removes** $\mathcal{O}(99.99\%)$ ($\mathcal{O}(99.9\%)$) of background events

Background reducing techniques

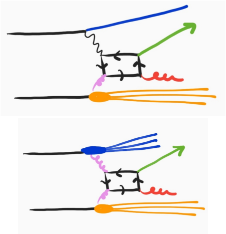


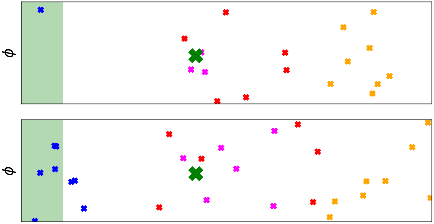


Method II: forward activity with HeRSCheL at LHCb

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

Background reducing techniques





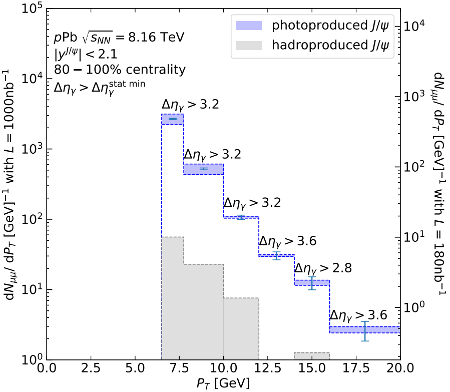
Method III: far-forward activity with zero-degree calorimeter at ALICE, ATLAS, & CMS

- detector close to the beam pipe ($|\eta| \gtrsim 8$) sensitive to neutral particles
- UPCs identified as most peripheral events ($80 - 100\%$ centrality)
- Selecting events with **0 neutrons** in ZDC can further enhance signal purity

Part III

Results

Photoproduction yields



- It is possible to isolate photoproduction in the CMS & ATLAS detectors using methods I & III
- With Run3+4 lumi it is possible to **double** the HERA P_T **reach** (10 GeV→20 GeV)
- pPb in Run 3?
  Workshop: `https://indico.cern.ch/e/pA_LHC_2024`

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 a P_T differential inclusive photoproduction cross section
- We would also like differential to be in $W_{\gamma p}$ and z:
  - complementary to HERA measurement

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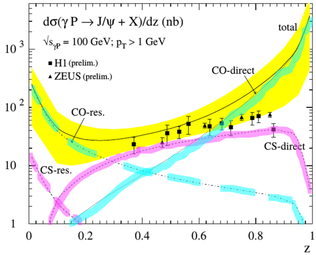
octet vs. **singlet**

KRAMER, hep-ph/016120



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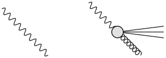
    octet vs. singlet
  - control the resolved-photon contribution

    direct and resolved photons



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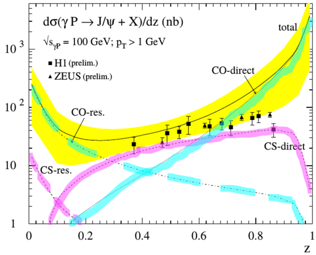

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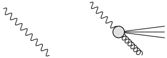

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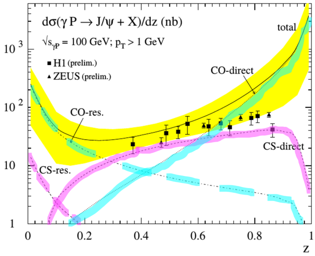

- Both variables are dependent on the photon energy!

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

- By momentum conservation $P_\gamma = P_\psi + P_X - P_p$

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

- In the exclusive case $z = 1$ and the rapidity of the J/ψ gives $W_{\gamma p}$
- In the inclusive case we have to examine the final state

? *How well can we capture P_X at the LHC?*

Kinematic reconstruction: results

- We remind that $P_X^- = \sum_i^N P_i^-$ and due to limited detector coverage $N_{\mathrm{meas}} < N_{\mathrm{true}}$

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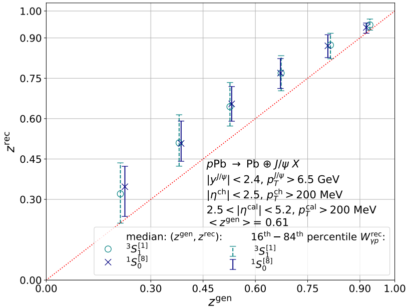

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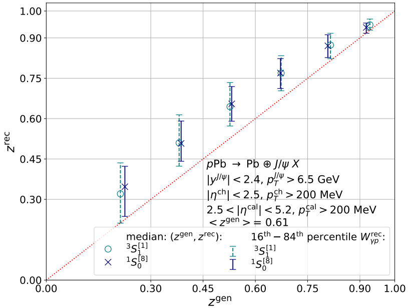
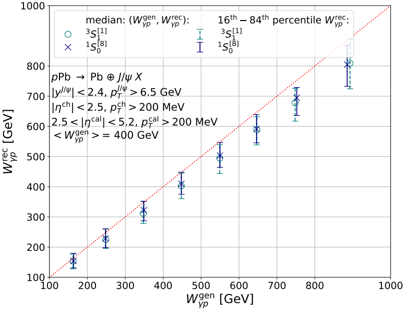




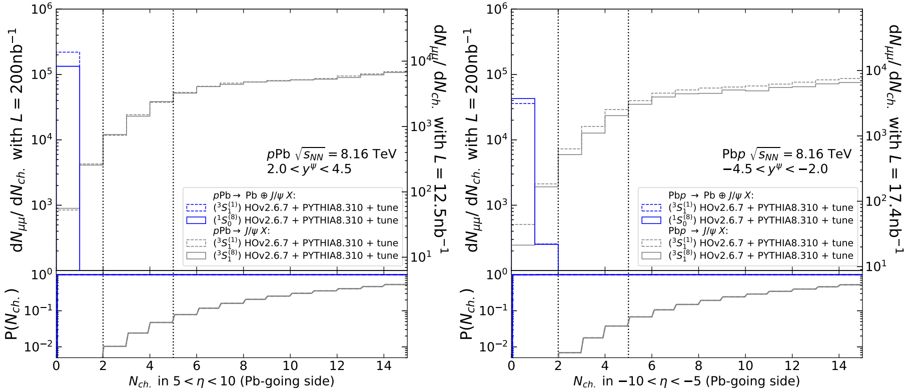
- z reconstruction improves with increasing values of z
- $W_{\gamma p}$ reconstruction improves for decreasing values of $W_{\gamma p}$

Summary and outlook

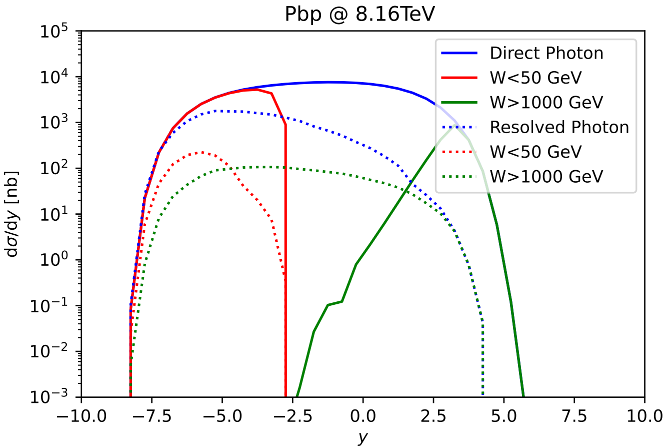
- The LHC can be used as a photon-nucleon collider
  - measuring inclusive J/ψ photoproduction at the LHC appears feasible which is complimentary to existing HERA measurements
- **CMS** is the **most favourable** experiment with the largest yield and P_T reach
- Possible to make a measurement at ALICE, ATLAS, and LHCb too!
- The $\Delta\eta_\gamma$ cut value allows for control over statistics and purity
- Both z and $W_{\gamma p}$ reconstruction appear possible with varying resolution which will allow control of the resolved contribution and offer the possibility to constrain the quarkonium production mechanism.
- Possible addition to the virtual access using: `https://nloaccess.in2p3.fr/`
- Possible extension of `gamma-UPC` to inclusive regieme **JHEP 09 (2022) 248**

Backup

Activity in HeRSCeL



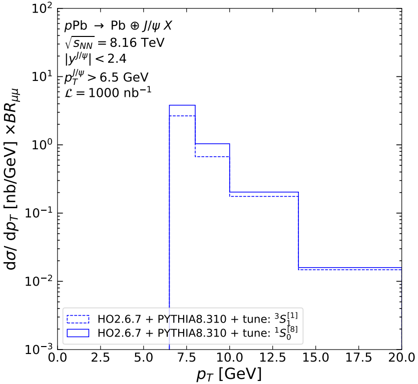
Direct and resolved photon rapidity comparison

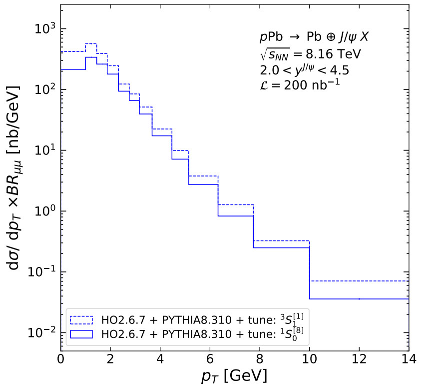


Resolved photon contribution increases with increasing photon energy ($W_{\gamma p}$); however, at most forward rapidities is suppressed.

Results: photoproduction P_T distributions and yields

CMS-like detector	LHCb-like detector

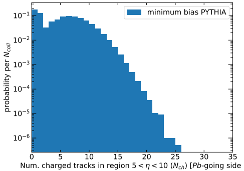




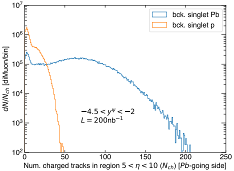
	CMS-like detector	LHCb-like detector
Run 2 lumi:		
yield	$\mathcal{O}(10^3 - 10^5)$	$\mathcal{O}(10^3 - 10^4)$
P_T reach	14 GeV	8 GeV
Run 3+4 lumi:		
yield	$\mathcal{O}(10^4 - 10^6)$	$\mathcal{O}(10^4 - 10^5)$
P_T reach	20 GeV	14 GeV

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,

$$p \cdot q = \frac{1}{2}\left(P^+Q^- + P^-Q^+\right) - \mathbf{p} \cdot \mathbf{q}. \tag{3}$$

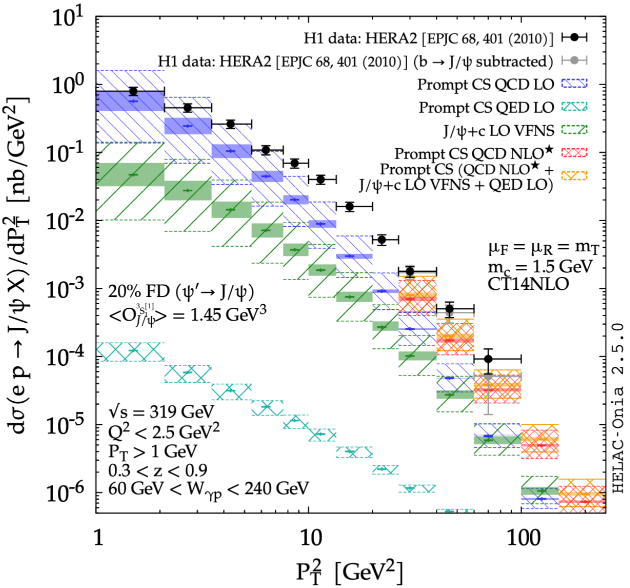
4. If p lies along the vector η^-, then the scalar product reduces to,

$$p \cdot q = \frac{1}{2}\left(P^-Q^+\right). \tag{4}$$

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

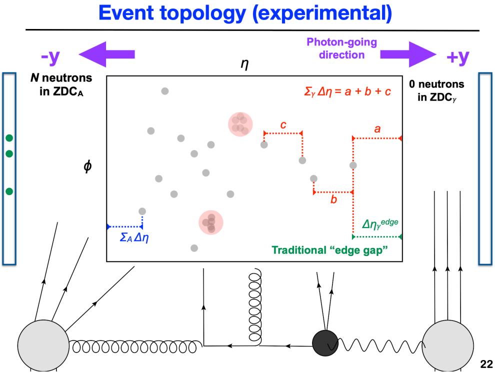
"NLO inclusive J/ψ photoproduction at large P_T at HERA and the EIC", Flore et. al. 2021

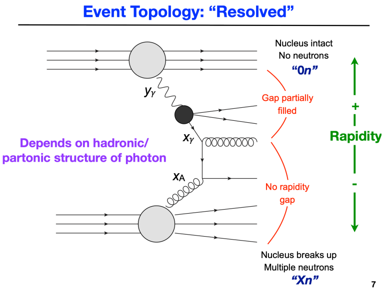


ATLAS UPC dijet Study

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}

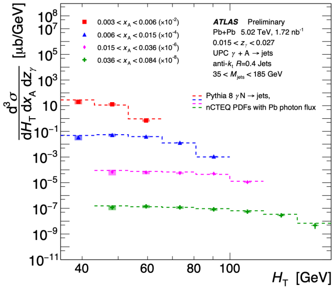
Pb-Pb inclusive dijets

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

- Triply differential cross section in,

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

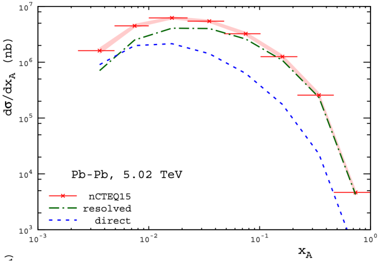
- Jets defined using anti-k_T with $R = 0.4$; $p_T^{jet1(2)} > 15(20)$ GeV and $|\eta^{jet}| < 4.4$.
- selection of events:
  - $\Delta\eta_A < 3$ [hadro.] and $\sum_\gamma \Delta\eta > 2.5$ [photo.]
  - sum-of-gaps retains high efficiency for the resolved-photon contribution
  - 0nXn biases towards 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 $[\gamma g \to J/\psi(^3S_1^1)g\ ]$ and $[\gamma g \to J/\psi(^1S_0^8)g\ ]$
  - Background $[gg \to J/\psi(^3S_1^1)g\ ]$ and $[gg \to J/\psi(^3S_1^8)g]$
- 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**