Feasibility of inclusive photoproduction and its interest for quarkonium and PDF constraints

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& Ronan McNulty (UCD)

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QCD Challenges from pp to AA collisions, Muenster

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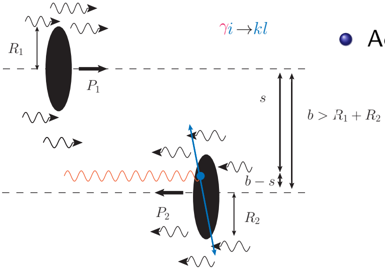
Part I

Introduction

Photon-induced interactions @ the LHC



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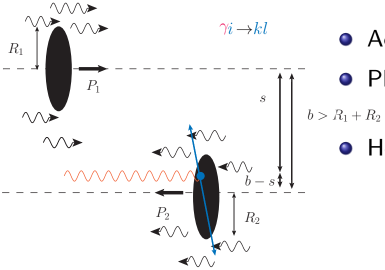
Photon-induced interactions @ the LHC



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

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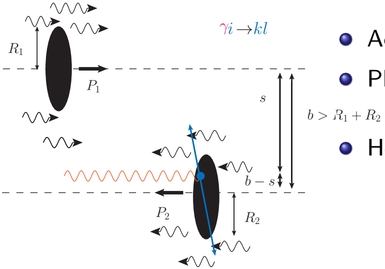

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- Energies available at the LHC:
  - pp @ $\sqrt{s} = 13$ TeV $\rightarrow W_{\gamma p}^{max} \approx 5$ TeV $\rightarrow x_{\gamma}^{\max} \approx 0.14$
  - pPb @ $\sqrt{s_{NN}} = 8.16$ TeV $\rightarrow W_{\gamma p}^{max} \approx 1.5$ TeV $\rightarrow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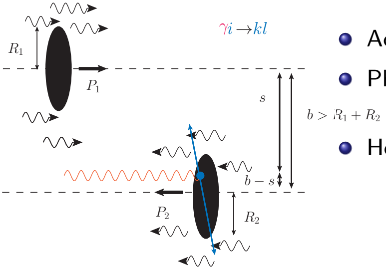

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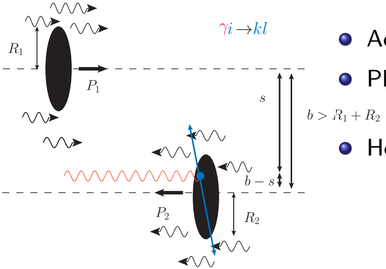

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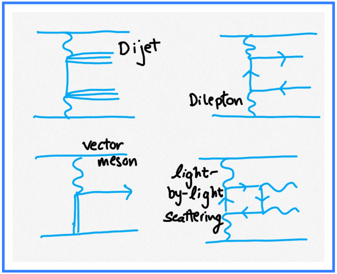
We will show:

Inclusive quarkonium photoproduction can be measured via UPC at the LHC

Exclusive vs. inclusive photoproduction at the LHC

Exclusive: fully determined final state



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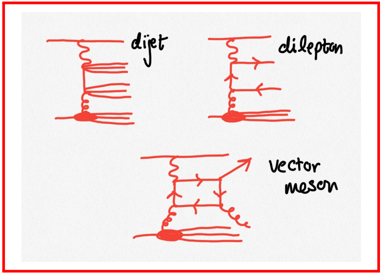

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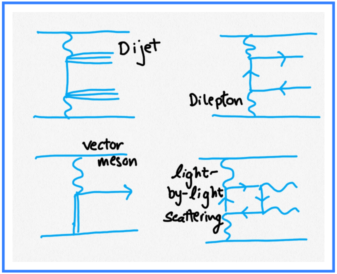

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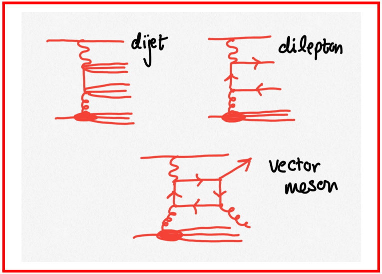

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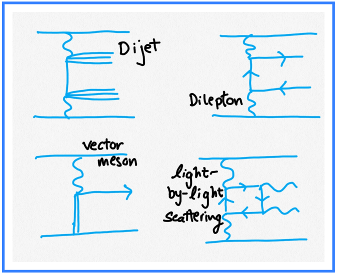

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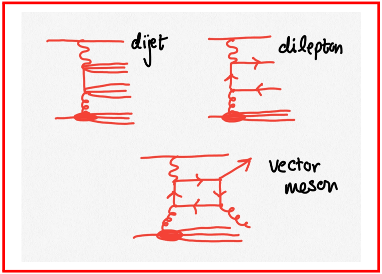

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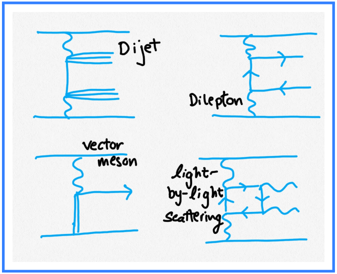

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- Experimentally clean: even @ LHC

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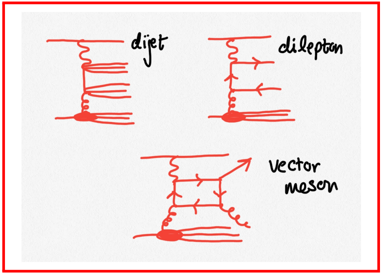

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- Challenging: large backgrounds

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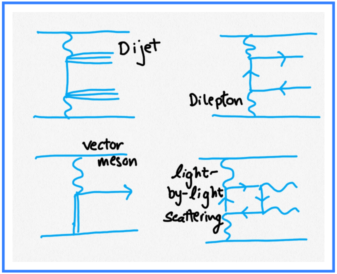

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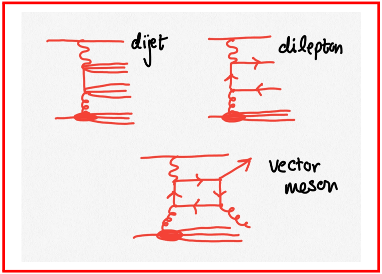

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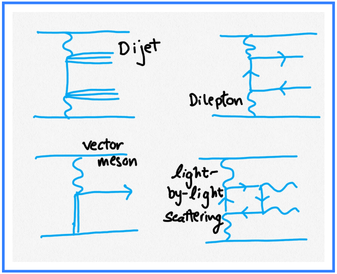

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- Initial state kinematics **fully** determined by the final state

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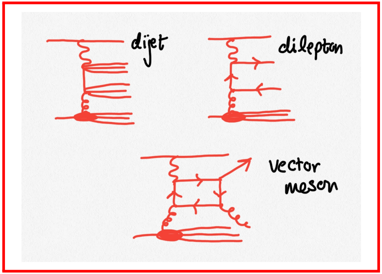

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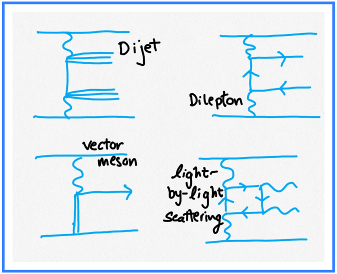

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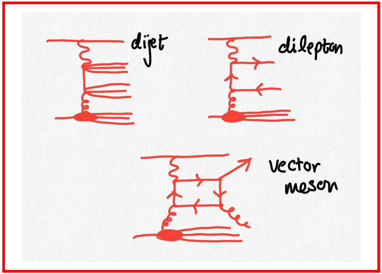

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- Colourful exchange
- Challenging: large backgrounds
- Larger rates
- Initial state kinematics **partially** determined by the final state
- Can and should be measured at the LHC

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
    - × 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)	✓	✗	✗
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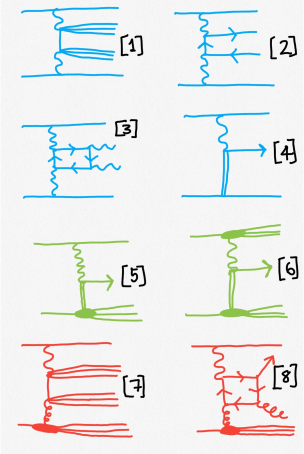
More inclusive photoproduction data → possible at ~~EIC in 10 years~~ LHC today!

Part II

Feasibility of inclusive quarkonium photoproduction measurements 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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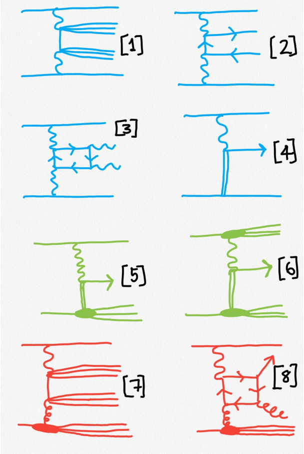

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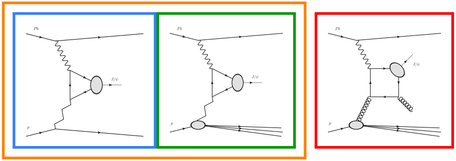
[8] **Inclusive quarkonium photoproduction: NOT YET MEASURED AT THE LHC!**

Existing J/ψ photoproduction measurements from HERA



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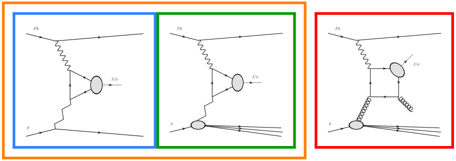

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- Different contributions separated using experimental cuts on p_T and $z = \frac{P_p \cdot P_\psi}{P_p \cdot P_\gamma} \ldots$

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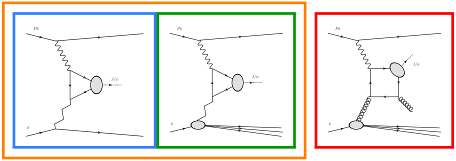

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- Expectation: $\sigma^{\text{LHC}}_{\text{exclusive}} \simeq \sigma^{\text{LHC}}_{\text{dissociative}} \simeq \sigma^{\text{LHC}}_{\text{inclusive}} \rightarrow$ only difference is photon flux!
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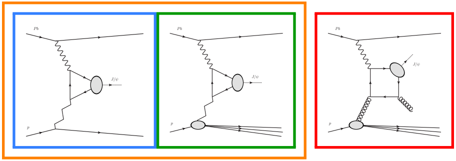

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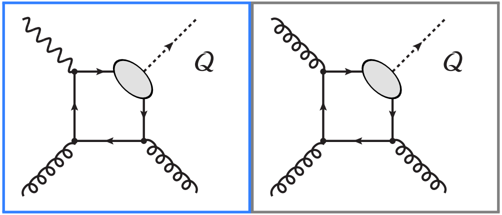
- Measuring inclusive quarkonium photoproduction to

  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*

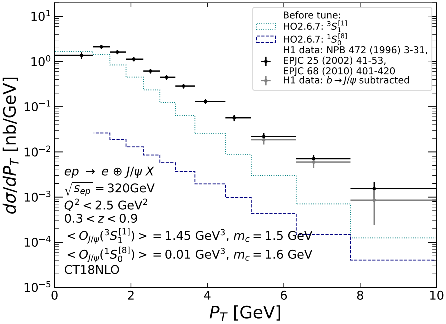
Part III

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 same slope as data at large P_T



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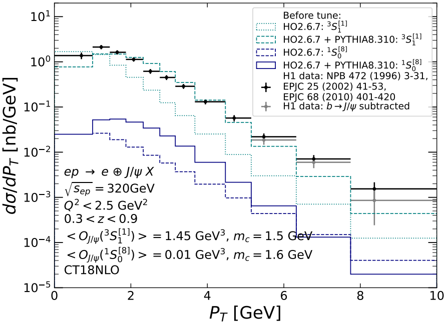
     - LO CS + PS improved but still undershoots at large P_T
     - LO CO + PS large P_T slope agreement is worse



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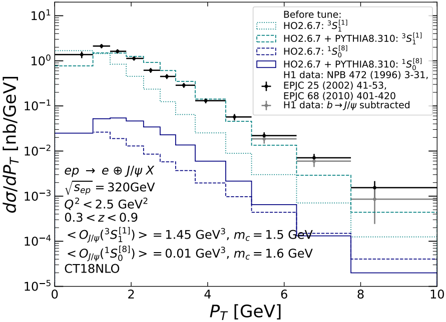

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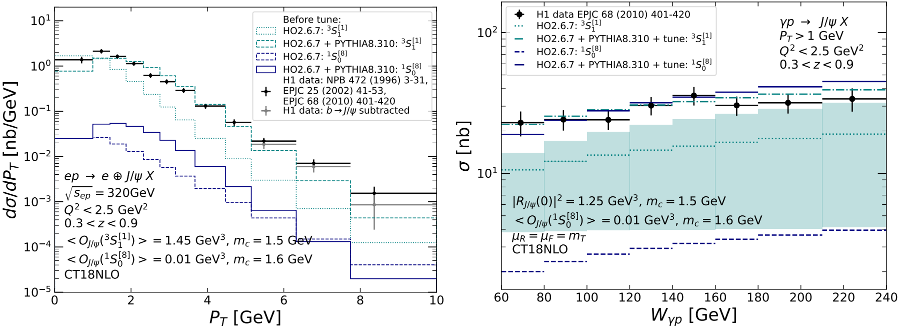

2. Reject background: reliable background MC + background reduction strategy

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 same assumptions:

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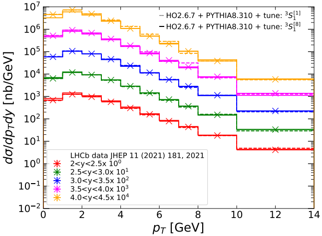

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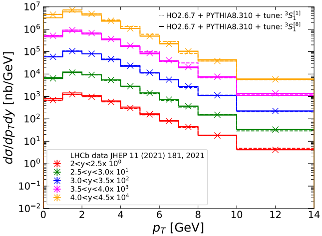
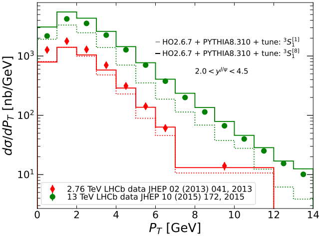
  1. Tuning is y independent
  2. Tuning is $\sqrt{s}$ independent

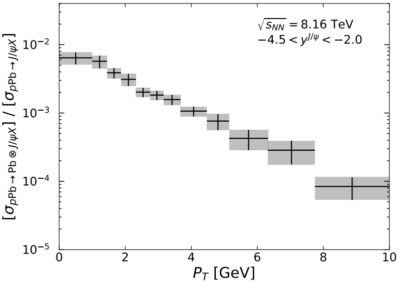
Validation 1: tune vs. y-diff. data @ 5 TeV.



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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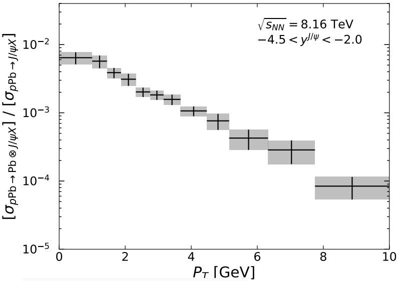

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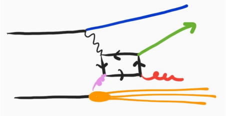
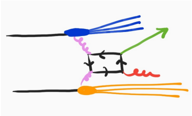
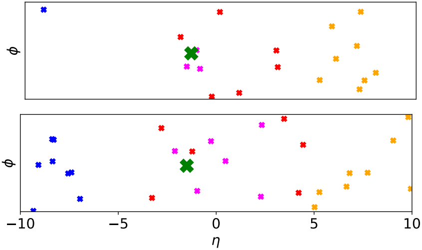
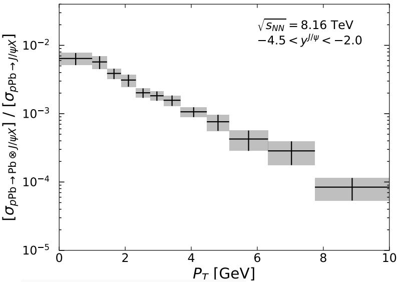






- 3 background-reduction techniques based on different detector acceptances

Background-reduction techniques



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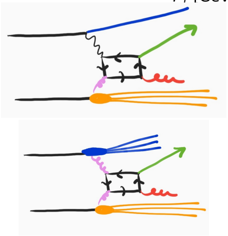
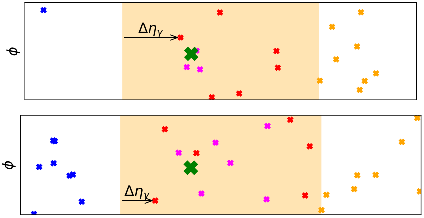
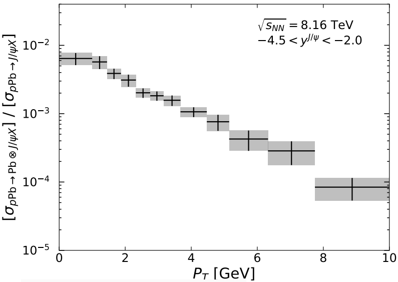


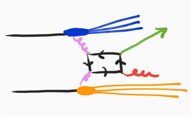


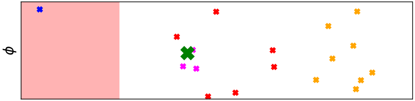
- 3 background-reduction techniques based on different detector acceptances:
  I central

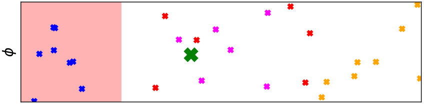
Background-reduction techniques



- 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

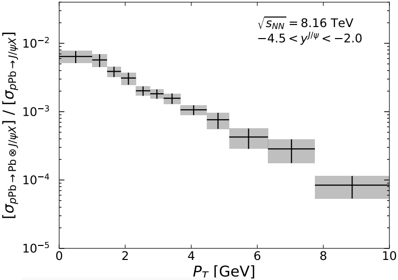




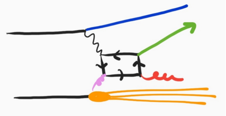


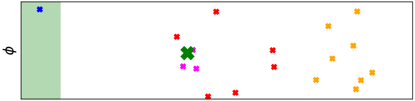
- 3 background-reduction techniques based on different detector acceptances: I central II forward

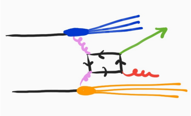
Background-reduction techniques

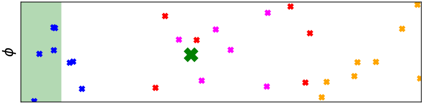


- Sufficient yields but huge backgrounds!
- Background reduction becomes more critical at larger P_T
- Hadroproduced J/ψ are associated with more detector activity than photoproduced J/ψ





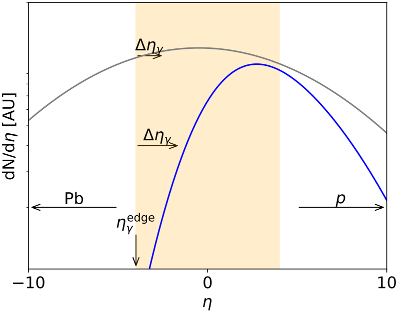




- 3 background-reduction techniques based on different detector acceptances: I central II forward III far-forward

Method I: Rapidity gap

- A rapidity gap exploits differences in event topologies
- Bulk of particle activity accompanying the J/ψ surrounds it and...
  - for photoproduced J/ψ skewed in the direction of the p
  - for hadroproduced J/ψ is symmetric in the direction of the Pb and p



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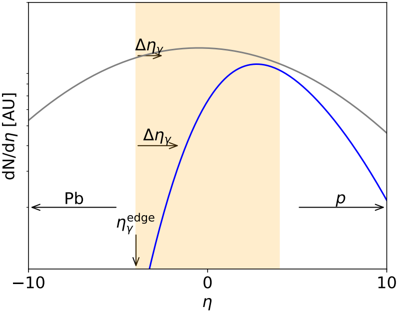
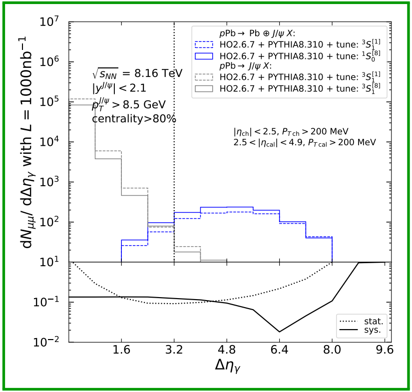


$\Delta\eta_\gamma$ definition

$\Delta\eta_\gamma = \min(\eta_\gamma^{\mathrm{edge}} - \eta_i)\ \forall\ i \neq J/\psi$ in the **detector acceptance**

Method I: Rapidity gaps in LHC detectors

General purpose detector [ATLAS, CMS]



Broad rapidity coverage:

CMS/ATLAS 10 units

clean separation between photoproduction

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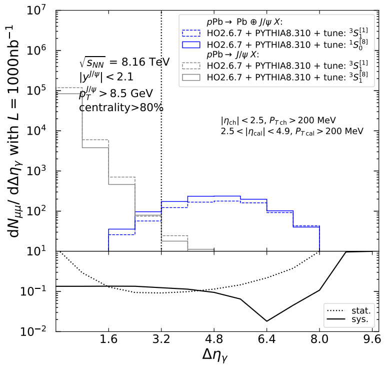

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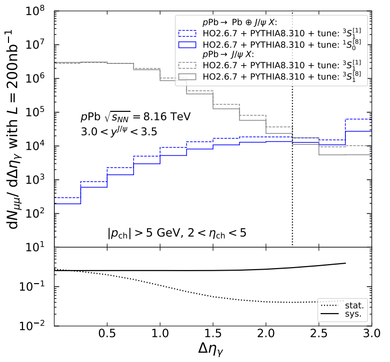

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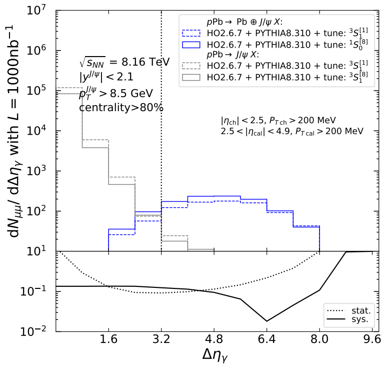

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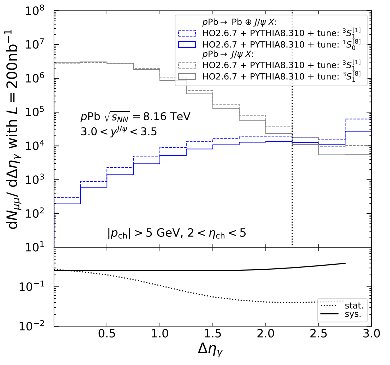

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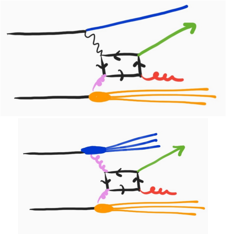
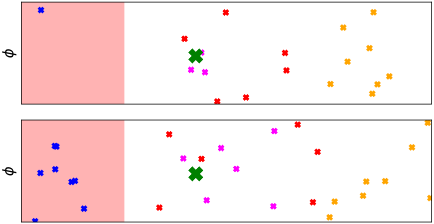
- Selecting a cut value that minimises that statistical uncertainty:
  → **removes** $\mathcal{O}(99.99\%)$ ($\mathcal{O}(99.9\%)$) of background events → $S/B \gtrsim \mathcal{O}(1)$

Background-reduction techniques



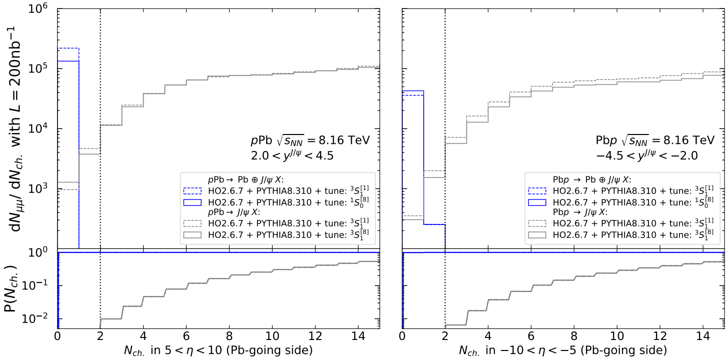


Method II: forward activity with HeRSCheL at LHCb

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

Selecting events based on activity in HeRSCheL

- 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



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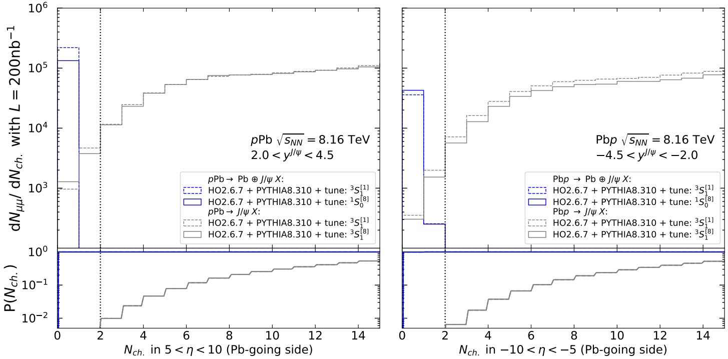
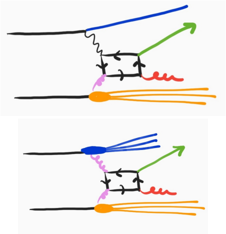
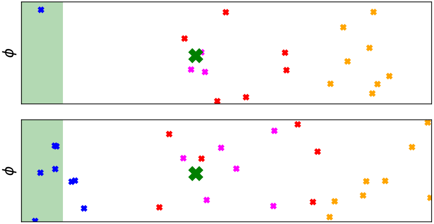


- Necessary to perform a full detector simulation to include HeRSCheL response
- We anticipate a clear distinction between photo- and hadroproduced events

Background-reduction techniques



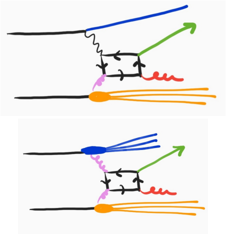


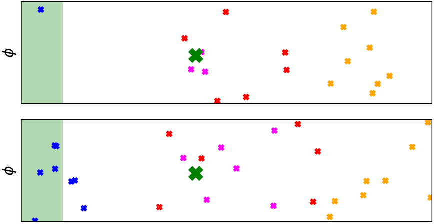
Method III: far-forward activity with zero-degree calorimeter at ALICE, ATLAS, & CMS

- Detector close to the beam pipe ($|\eta| \gtrsim 8$) sensitive to neutral particles
- UPCs identified as most peripheral events
  - Inclusive J/ψ as a function of centrality has been measured

    ALICE: JHEP 11 (2015) 127, JHEP 02 (2021) 002
  - The 80–100% centrality class removes 94% of all J/ψ events

Background-reduction techniques





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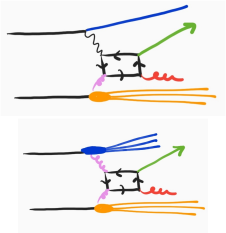

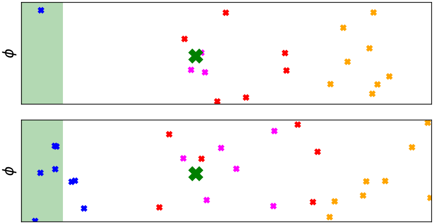

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  [We expect $\mathcal{O}$(99.99%) of the signal with no neutron emission]
  - In PbPb collision system there is a non-negligible photoproduction cross section with neutron emissions $\mathcal{O}(20\%)$
  - A **0 neutron** constraint biases the collision impact parameter: distentangling the photon emitter

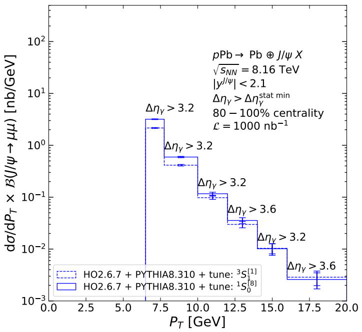
CMS, Phys.Rev.Lett. 131 (2023) 26, 262301, PRC 93, 055206 (2016)

Part IV

Results

Photoproduction yields

General purpose detector [ATLAS, CMS]



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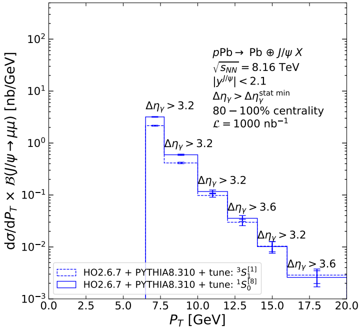

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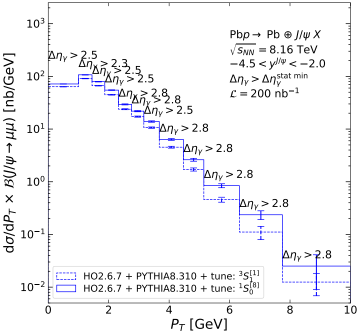

- Using GPD:
  - isolate photoproduction using $\Delta\eta_\gamma$ and selecting the 80–100% centrality class
  - With Run3+4 lumi extend the P_T reach from 10 GeV (HERA data)$\longrightarrow$ 20 GeV
  - Further enhance signal purity by selecting 0n events
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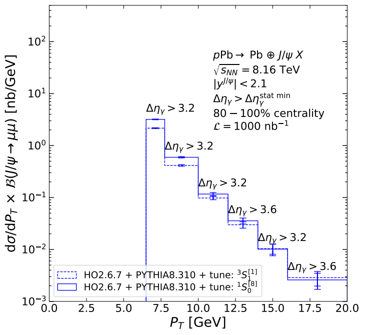

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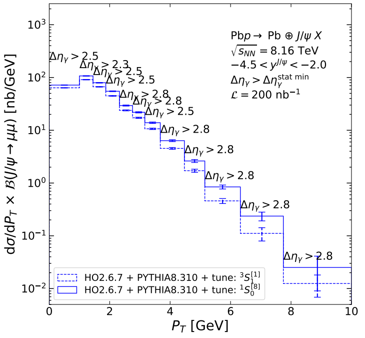

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- Using LHCb:
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  - Further enhance signal purity using HeRSCheL
- Expect ψ' yield to be $\sim 1/20$ of J/ψ yield no P_T differential data from HERA!

Part V

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

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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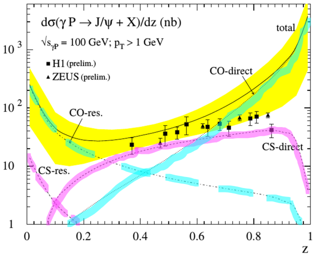
  - Study quarkonium hadronisation

octet vs. singlet

Kramer, hep-ph/016120



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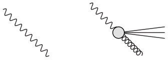

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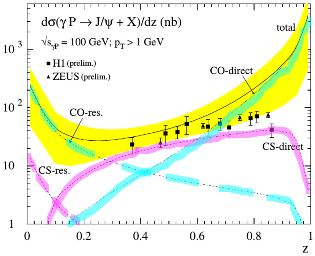

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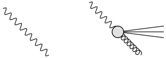

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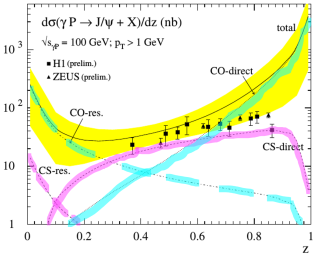

- Let us reconstruct the photon kinematics from the final state :

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

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

- 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: ATLAS/CMS results

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

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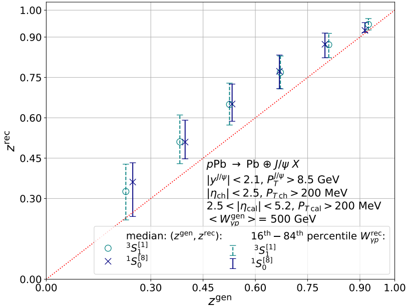

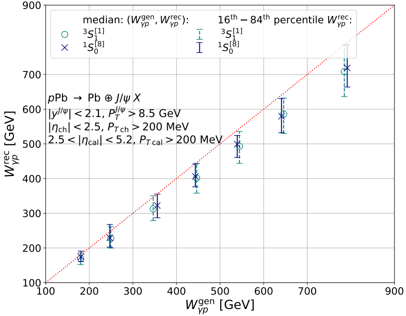

- The reconstruction is model independent ($^3S_1^{[1]} / {}^1S_0^{[8]}$)

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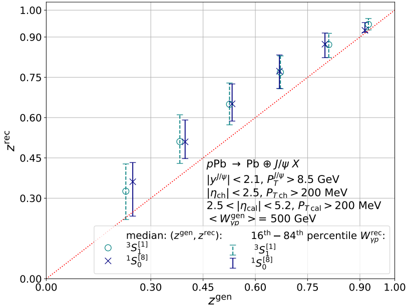
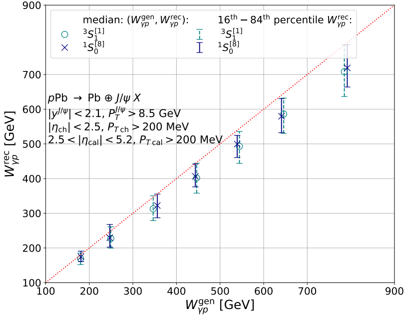
- This **can be corrected for** by determining the bias and spread of reconstructed values as a function of the generated values



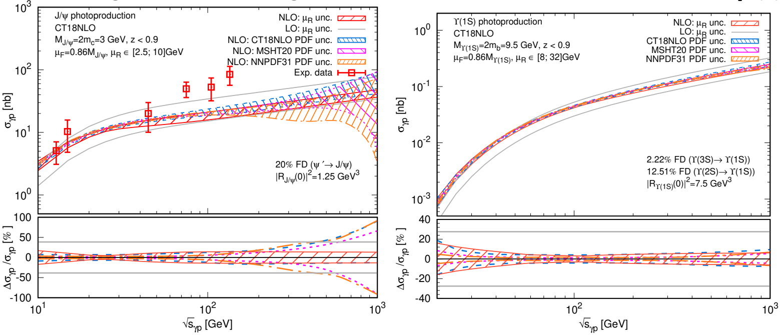


- The reconstruction is model independent ($^3S_1^{[1]}/^1S_0^{[8]}$)
- Using a bin size based on the spread and statistics:
  - z reconstruction allows for $\mathcal{O}(5-6)$ bins (similar to HERA)
  - $W_{\gamma p}$ reconstruction allows for $\mathcal{O}(7)$ bins

Prospects for PDF extraction using UPC data

Scale uncertainty for J/ψ and $\Upsilon(1S)$ as a function of $W_{\gamma p}$ using CSM and scale fixing procedure to cure perturbative instabilities that arise at $W_{\gamma p} \gg m_{\mathcal{Q}}$

A. Colpani Serri, Y. Feng, C. Flore, J.P. Lansberg, M.A. Ozcelik, H.S. Shao, Y. Yedelkina: arXiv:2112.05060 [hep-ph]



Exp. data: H1, Nucl.Phys.B 459(1996)3-50; FTPS, Phys.Rev.Lett. 52(1984)795-798; NAI- NA14Collaboration, Z.Phys.C 33(1987)505 **slide from Y. Yedelkina**

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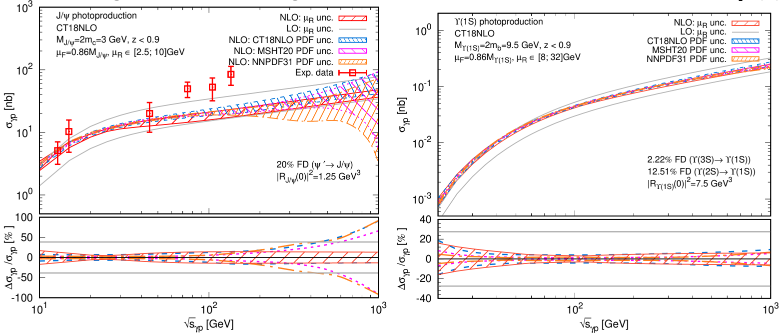

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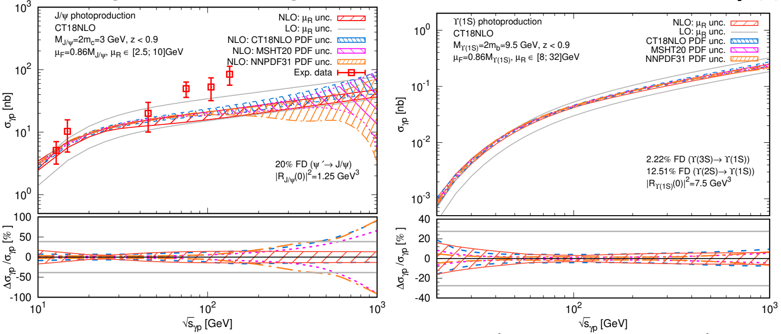

- Scale uncertainty increases at large $W_{\gamma p}$ $(=\sqrt{s_{\gamma p}})$ (equivalently small x)
  - Recall $W_{\gamma p}^{\text{max LHC}}$ is $\mathcal{O}(10^3\ \text{GeV})$

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Summary and outlook

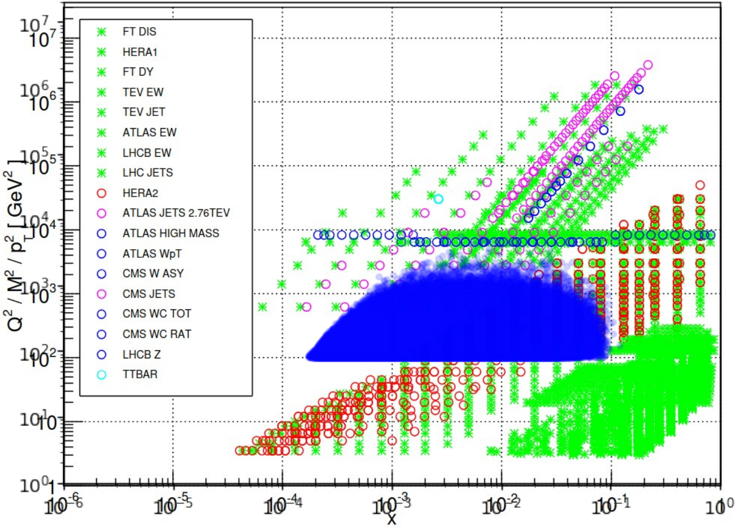
- A proton-lead collision system allows the LHC to be used as a photon-nucleon collider
  - Feasible to measure inclusive J/ψ, ψ' and Υ photoproduction at the LHC
  - Complementary to HERA measurements with a doubled P_T reach
  - It can be done now $\mathcal{O}(10)$ years before the EIC
- CMS and ATLAS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

Backup

Kinematic coverage of inclusive photoproduced J/ψ in ATLAS acceptance



Impact study: inclusion of **exclusive** J/ψ and $\Upsilon(1S)$ LHC data on PDF uncertainty

- **Exclusive** quarkomium production described with GPD, however in a kinematic region the GPD can be modelled by a PDF via the Shuvaev Transform up to corrections $\sim \mathcal{O}(x)$
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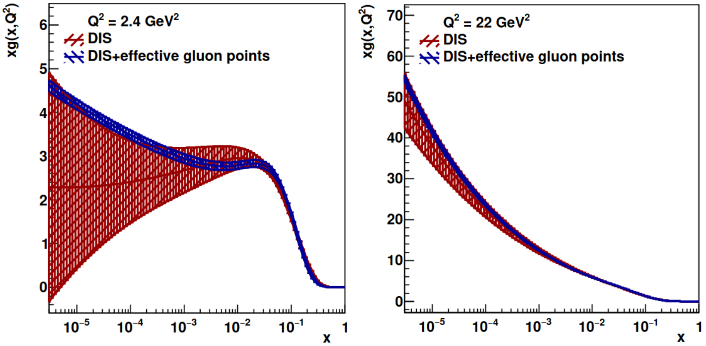
- Projection of inclusion of **exclusive** J/ψ and $\Upsilon(1S)$ LHC data in global analysis @ NLO accuracy shows a dramatic reduction in the low-x gluon PDF uncertainties

C. Flett, A. Martin, M. Ryskin, T. Teubner, arXiv:2408.01128



ATLAS UPC dijet in Pb-Pb @ $\sqrt{s_{NN}} = 5.02$ TeV

ATLAS-CONF-2022-021

- Triply differential cross section in,

$$z_\gamma = \frac{m_{jets}}{\sqrt{s_{NN}}} e^{+y_{jets}}, \quad x_A = \frac{m_{jets}}{\sqrt{s_{NN}}} e^{-y_{jets}}, \quad H_T = p_T^{jet1} + p_T^{jet2} \tag{1}$$

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

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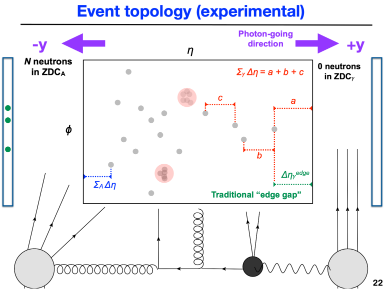
- Selection requirements:
  - Intact photon emitter: 0nXn [$E_{ZDC} < 1$ TeV]
  - Photon exchange: $\sum_\gamma \Delta\eta > 2.5$ [instead of $\Delta\eta_\gamma$]
  - Hadronic exchange: $\Delta\eta_A < 3$



Slide from A. Angerami

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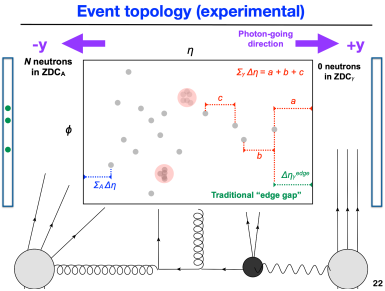

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  - Increased efficiency for retaining the resolved contribution

Slide from A. Angerami

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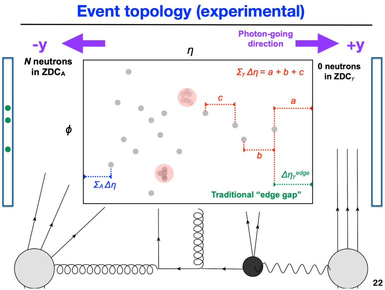

- $\sum_\gamma \Delta\eta$ vs. $\Delta\eta_\gamma$:
  - Reduced efficiency for removing hadroproduced events
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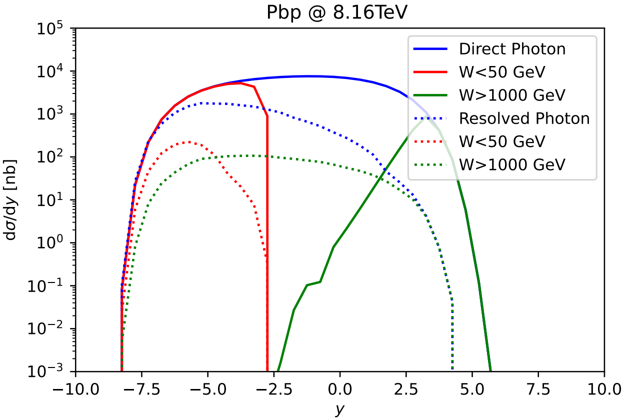
- Dijets: no clear handle on the size of the resolved photon contribution
- **Inclusive photoproduction**: a z-determination offers a handle on the size of the resolved photon contribution

Slide from A. Angerami

Leading order colour singlet prediction for rapidity distribution of direct and resolved photoproduction

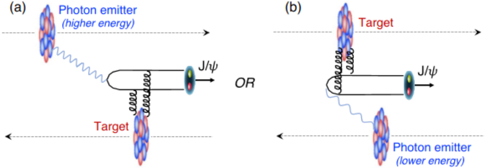


Neutron emission: disentangling the photon emitter

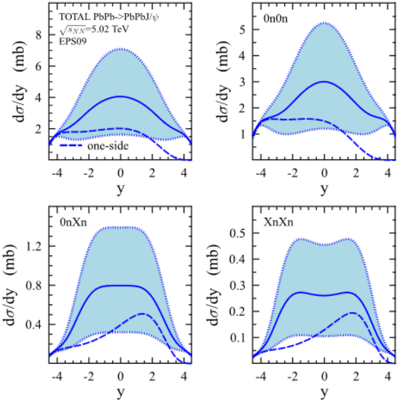
- For exclusive vector meson production in PbPb collisions there is as ambiguity as to which Pb ion is the photon emitter
- At a given rapidity either:

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

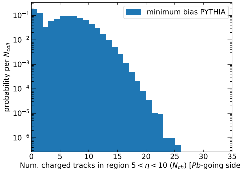


- Neutron emissions (detected with ZDCs) serve as an impact parameter filter
- Larger photon energies are associated with smaller impact parameters
- 0nXn and XnXn select smaller impact parameter and larger x_γ compared to 0n0n

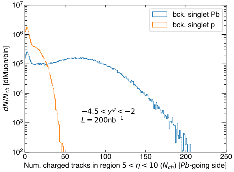


From p to Pb in the HeRSCheL region

- 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 $N_{\text{coll}} = 1$; whereas in a pA collision there are many more nucleons and therefore it is possible to have $N_{\text{coll}} > 1$ [typically modelled using a Glauber model].
- 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 $i = 1, .., N_{\text{coll}} - 1$ points into the probability distribution, and summing over N_{coll}.
- The transformation from pp to pA HeRSCheL distribution. **[bottom right]**



Centrality class	$\langle N_{\text{coll}} \rangle_{\text{opt.}}$	$\langle N_{\text{coll}} \rangle_{\text{ALICE}}$	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



Predicted rates

	CMS		LHCb	
	$\|y^{J/\psi}\| < 2.1$ $P_T^{J/\psi} > 6.5$ GeV	$P_T^{J/\psi} > 6.5$ GeV for $\|y^{J/\psi}\| < 1.2$ $P_T^{J/\psi} > 2$ GeV for $1.2 < \|y^{J/\psi}\| < 1.6$ $P_T^{J/\psi} > 0$ GeV for $1.6 < \|y^{J/\psi}\| < 2.4$	$2.0 < y^{J/\psi} < 4.5$	
J/ψ				
σ [nb]	4.8 ± 0.9	630.0 ± 1.1	880.0 ± 210.0	(200.0 ± 17.0)
Run 2 yields [$\times10^3$]	0.87 ± 0.16	110.0 ± 0.2	11.0 ± 2.7	(3.4 ± 0.3)
Run 3+4 yields [$\times10^5$]	0.048 ± 0.009	6.3 ± 0.011	1.8 ± 0.43	(0.4 ± 0.034)
$\psi(2S)$				
σ [nb]	0.24 ± 0.045	31.0 ± 0.055	44.0 ± 11.0	(9.9 ± 0.85)
Run 2 yields	43.0 ± 8.1	5600.0 ± 9.9	550.0 ± 130.0	(170.0 ± 15.0)
Run3+4 yields [$\times10^2$]	2.4 ± 0.45	310.0 ± 0.55	88.0 ± 21.0	(20.0 ± 1.7)
	$\|y^{\Upsilon}\| < 2.4$		$2.0 < y^{\Upsilon} < 4.5$	
$\Upsilon(1S)$				
σ [nb]	1.4		0.53	(0.054)
Run 2 yields	250.0		9.2	(0.67)
Run 3+4 yields	1400.0		110.0	(11.0)
$\Upsilon(2S)$				
σ [nb]	0.55		0.21	(0.021)
Run 2 yields	99		3.7	(0.27)
Run 3+4 yields	550		42.0	(4.3)
$\Upsilon(3S)$				
σ [nb]	0.4		0.16	(0.016)
Run 2 yields	74		2.8	(0.2)
Run 3+4 yields	410		32.0	(3.2)

Pile-up and effect on methods I–III

- **Advantage of *p*Pb over** *pp* is the significantly reduced **pile-up**
  - $\mu < 0.1 \Rightarrow \checkmark$
  - $\mu \sim \mathcal{O}(0.5) \Rightarrow$ reduced efficiency!
  - $\mu \gtrsim 1 \Rightarrow$ should reconsider the efficacy of methods I–III

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Efficacy of methods I–III with pile-up:

- Method I: rapidity gaps
  - **Calorimeter** based rapidity-gap definitions not possible
  - **Only** rapidity-gap definitions based on **charged tracks** possible
  - Reduced $\Delta\eta$ reach for ATLAS (and CMS) 10$\rightarrow$ 5 units
- Method II: HeRSCheL
  - Timing is insufficient
- Method III: ZDC
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These comments also apply to exclusive UPCs and to some extent to centrality determination

Riccardo Longo, Physics with high-luminosity p+A collisions at the LHC Workshop, CERN 2024

Method I: Rapidity-gap distribution feature

- Due to the skewed distribution of particle activity, there is a shift to larger values of $\Delta\eta_\gamma$ for photoproduced J/ψ with larger y

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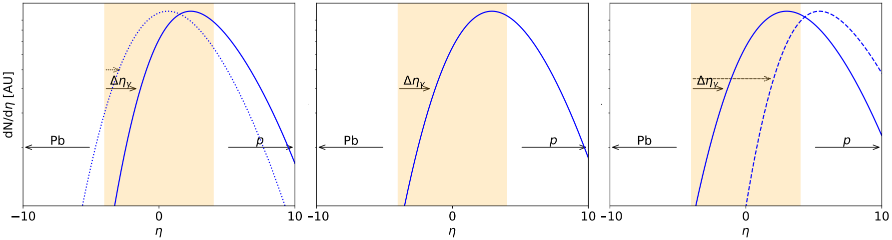

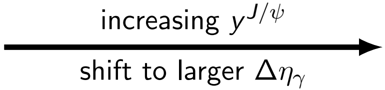

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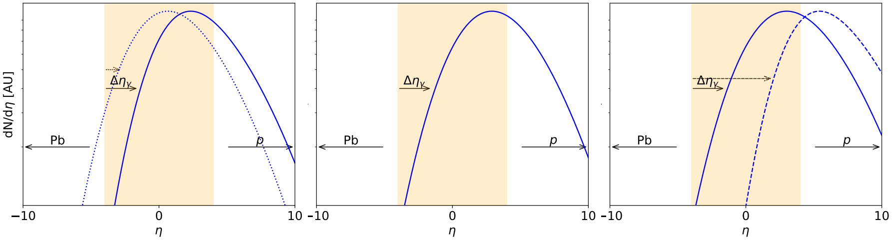
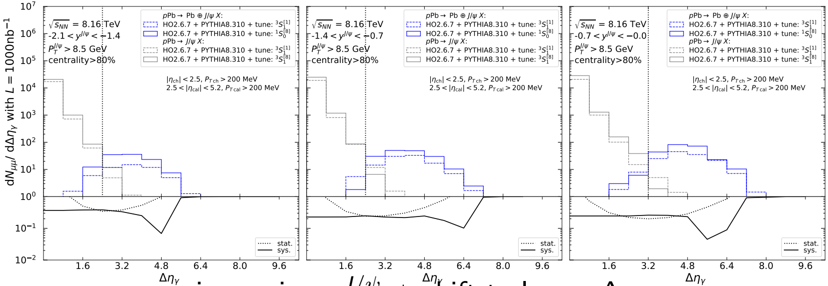


increasing $y^{J/\psi}$

shift to larger $\Delta\eta_\gamma$

- For hadroproduced J/ψ the $\Delta\eta_\gamma$-distribution is $y^{J/\psi}$ independent
- Therefore, the **greatest separation** between photo- and hadroproduced J/ψ is when $y^{J/\psi}_{\max}$ within the detector acceptance

Method I: Rapidity gaps in ATLAS



increasing $y^{J/\psi}$ + shift to larger $\Delta\eta_\gamma$