Inclusive quarkonium photoproduction at the LHC

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& Ronan McNulty (UCD)

Physics with high-luminosity proton-nucleus collisions at the LHC
CERN

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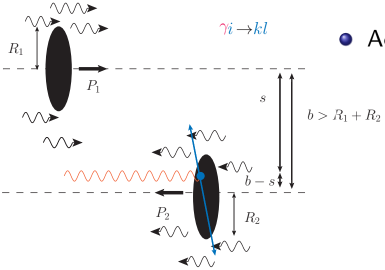
Part I

Introduction

Photon-induced interactions @ the LHC



- Accelerated charged particles emit photons

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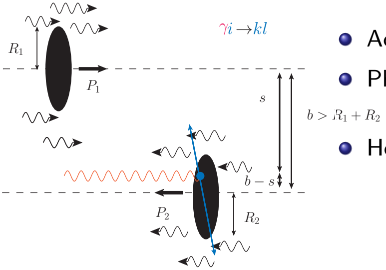

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  → clean photoproduction environment
- However, the LHC is an excellent source of photons
  → can reach extremely large $W_{\gamma p}$

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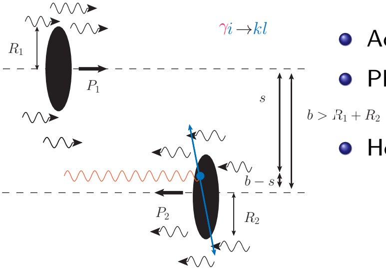

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- Energies available at the LHC:
  - pp @ $\sqrt{s} = 13$ TeV $\longrightarrow W_{\gamma p}^{max} \approx 5$ TeV $\rightarrow x_{\gamma}^{\text{max}} \approx 0.14$
  - pPb @ $\sqrt{s_{NN}} = 8.16$ TeV $\longrightarrow W_{\gamma p}^{max} \approx 1.5$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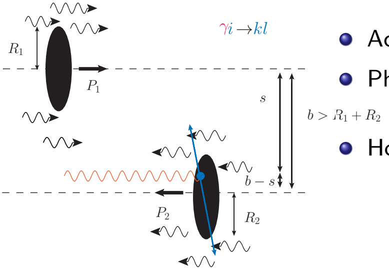

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  - Done so far only for exclusive processes

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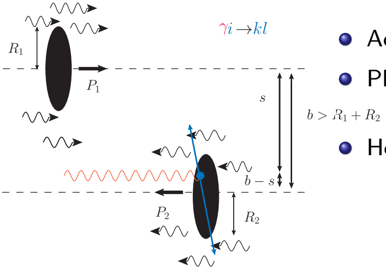

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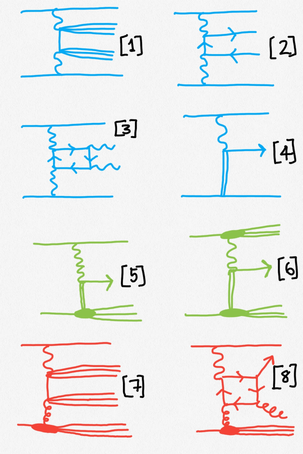
We will show: **inclusive quarkonium photoproduction**
can be measured via UPC at the LHC in **proton-lead** collisions

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

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

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[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

[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

[7] **Inclusive dijet**: Not yet published: ATLAS-CONF-2022-021, ATLAS-CONF-2017-011

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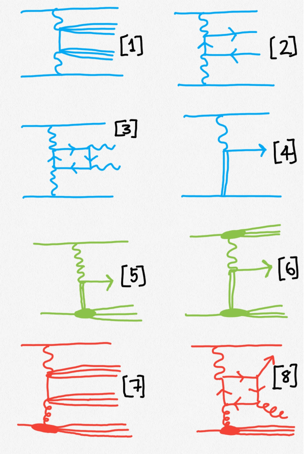

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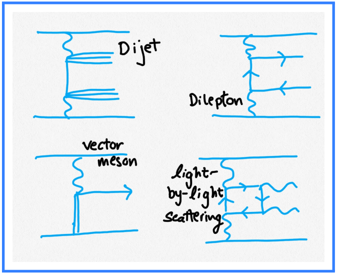
[8] **Inclusive quarkonium photoproduction: NOT YET MEASURED AT THE LHC!**

Exclusive vs. inclusive photoproduction at the LHC

Exclusive: fully determined final state



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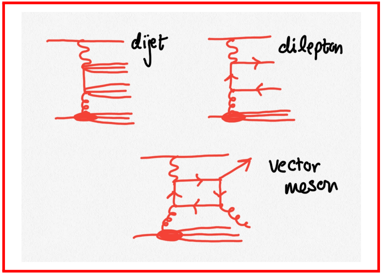

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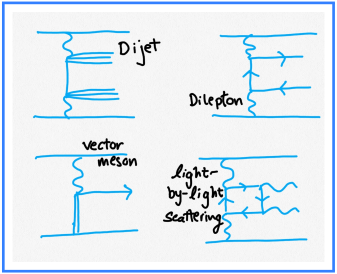

- Probe **G**eneralised **P**arton **D**istributions

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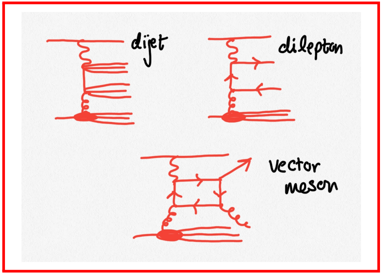

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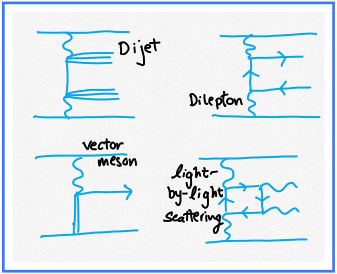

- Probe **G**eneralised **P**arton **D**istributions
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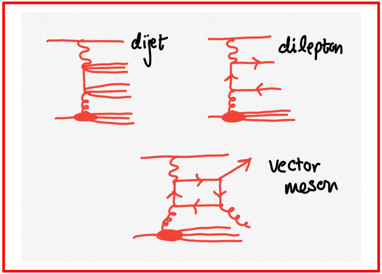

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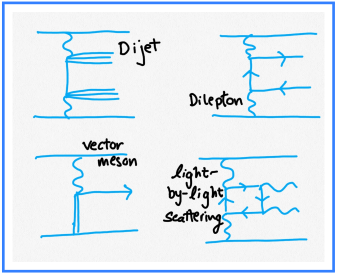

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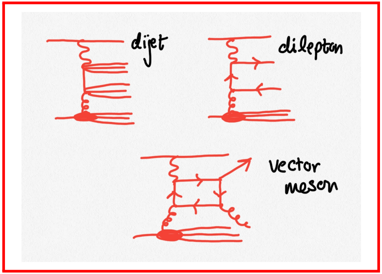
- Colourless exchange
- Experimentally clean: even @ LHC

Inclusive: **not** fully determined final state



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- Colourful exchange
- Challenging: large backgrounds

Exclusive vs. inclusive photoproduction at the LHC

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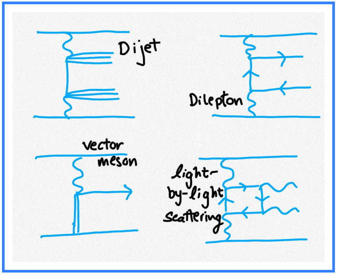

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- Colourless exchange
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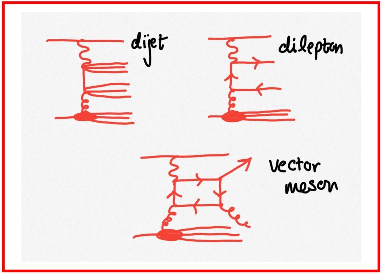

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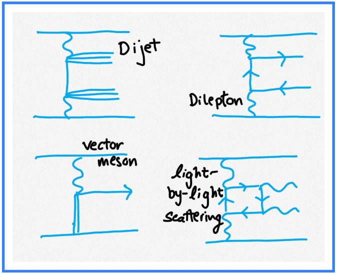

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- Initial state kinematics **fully** determined by the final state

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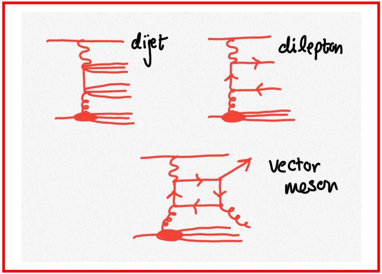

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Exclusive vs. inclusive photoproduction at the LHC

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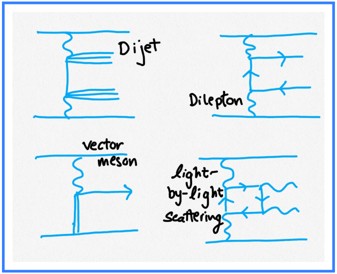

- Probe **G**eneralised **P**arton **D**istributions
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- Smaller rates
- Initial state kinematics **fully** determined by the final state
- Measured at the LHC

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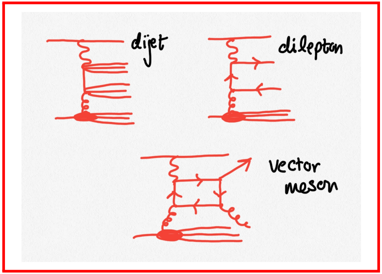

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- Initial state kinematics **partially** determined by the final state
- Can and should be measured at the LHC

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)	✓	✗	✗
Chao et al. + η_c	✓($p_T > 6.5$ GeV)	✗	✓	✓
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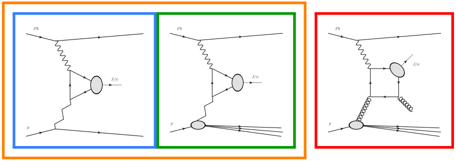
More inclusive photoproduction data → possible at ~~EIC in 10 years~~ LHC today!

Existing J/ψ photoproduction measurements from HERA



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

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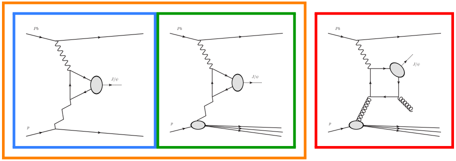

- Data exists for **diffractive** (exclusive and proton-dissociative) & **inclusive/inelastic** photoproduction @ HERA $\sqrt{s} = 320$ GeV
- Different contributions separated using experimental cuts on p_T and $z = \frac{P_p \cdot P_\psi}{P_p \cdot P_\gamma} \ldots$

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

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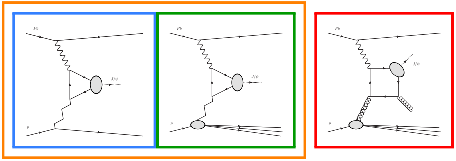

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- HERA result: $\sigma^{\mathrm{HERA}}_{\mathrm{exclusive}} \simeq \sigma^{\mathrm{HERA}}_{\mathrm{dissociative}} \simeq \sigma^{\mathrm{HERA}}_{\mathrm{inclusive}}$
- Expectation: $\sigma^{\mathrm{LHC}}_{\mathrm{exclusive}} \simeq \sigma^{\mathrm{LHC}}_{\mathrm{dissociative}} \simeq \sigma^{\mathrm{LHC}}_{\mathrm{inclusive}} \rightarrow$ 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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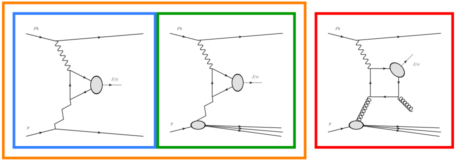

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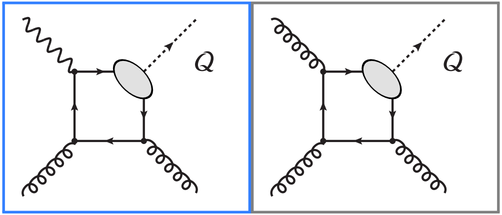
- Exclusive and proton-dissociative photoproduction have been measured @ LHC
- Expect that inclusive yield is sufficently large we will demonstrate this
- As just discussed, measuring inclusive quarkonium photoproduction to understand the quarkonium hadronisation

Part II

Feasibility of inclusive quarkonium photoproduction at the LHC

Inclusive quarkonium photoproduction at the LHC

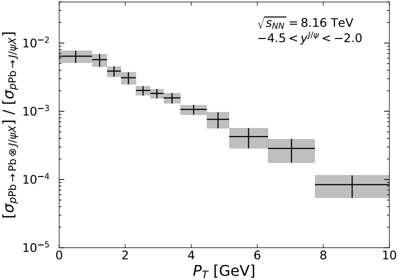
- Anticipate sizeable photoproduction yield
- Large hadronic background must be shown to be suppressed



Proton-lead is the ideal collision system

- No ambiguity as to the photon emitter
- Enhanced photon flux w.r.t. pp $\propto Z^2$
- Less pileup than pp

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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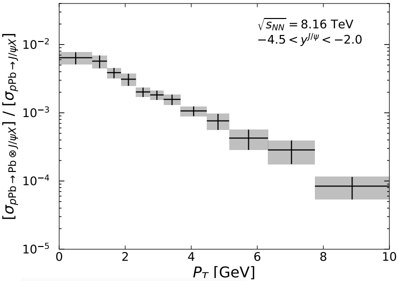

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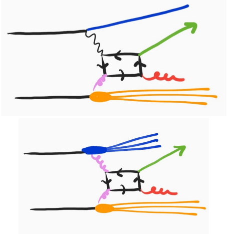
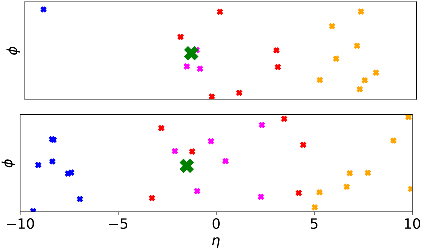
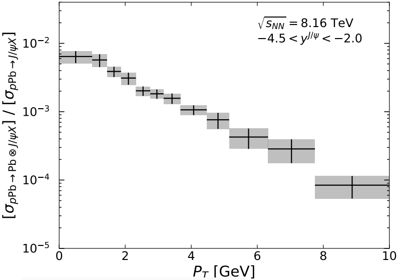




- 3 background-reduction techniques based on different detector acceptances

Background-reduction techniques



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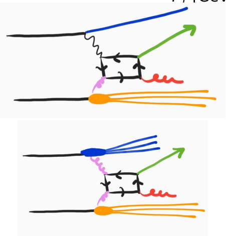

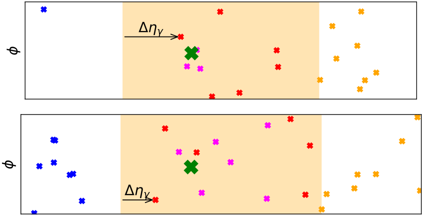

- 3 background-reduction techniques based on different detector acceptances:
  I central $\Delta\eta_\gamma$: distance in rapidity between main detector on photon-going side and closet particle activity

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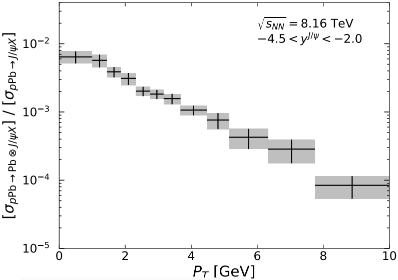
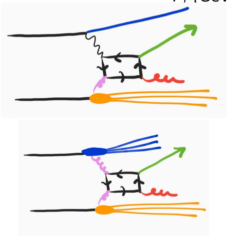
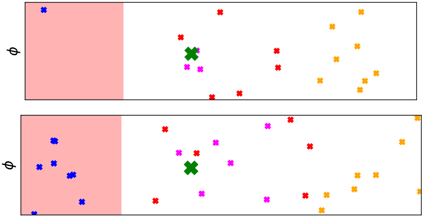
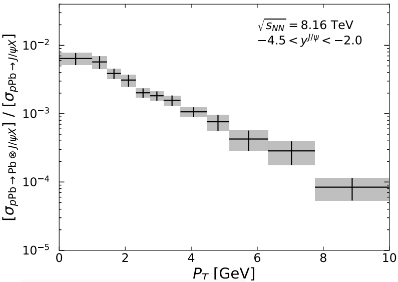


- Large yields but huge backgrounds!
- Background reduction critical at large P_T
- Background J/ψ are associated with more detector activity than photoproduced J/ψ

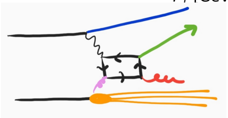


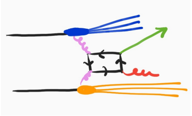


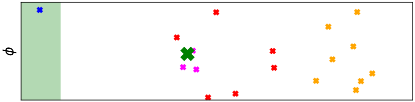
- 3 background-reduction techniques based on different detector acceptances: I central II forward

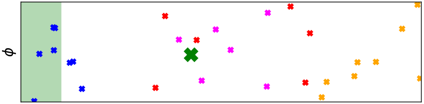


- Sufficient yields but huge backgrounds!
- Background reduction becomes more critical at larger P_T
- Hadroproduced J/ψ are associated with more detector activity than photoproduced J/ψ





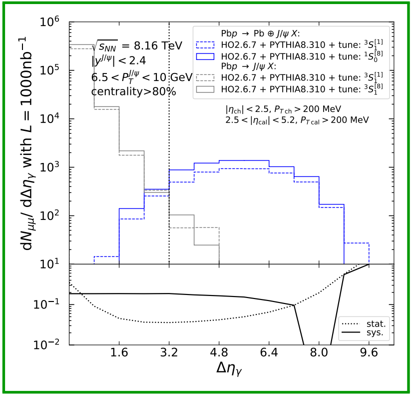




- 3 background-reduction techniques based on different detector acceptances:
  I central II forward III far-forward

Method I: Rapidity gaps in LHC detectors

General purpose detector [ATLAS, CMS]



Broad rapidity coverage:

CMS 10.4 units, ATLAS 9.8 units

clean separation between photoproduction and hadroproduction

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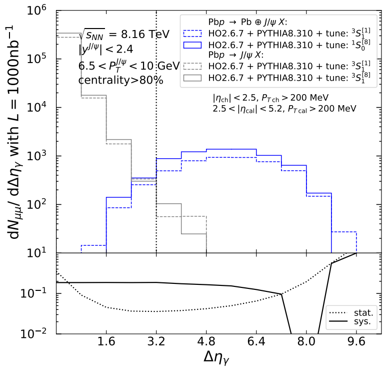

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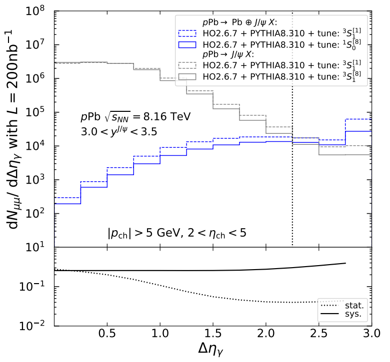

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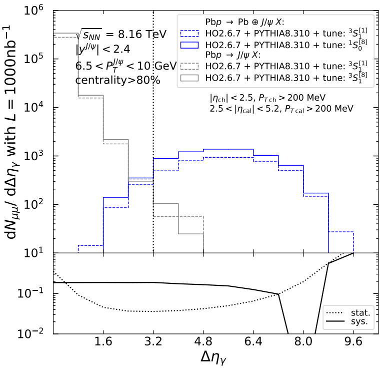

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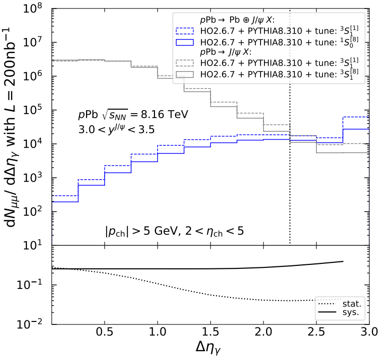

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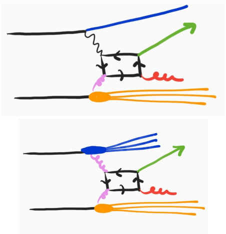
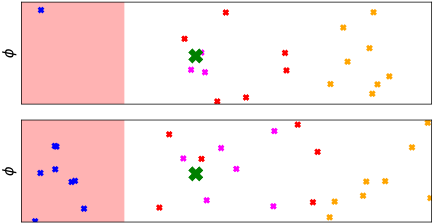
- Selecting a cut value that minimises that statistical uncertainty:
  $\rightarrow$ **removes** $\mathcal{O}(99.99\%)$ ($\mathcal{O}(99.9\%)$) of background events $\rightarrow S/B \gtrsim \mathcal{O}(1)$

Background-reduction techniques

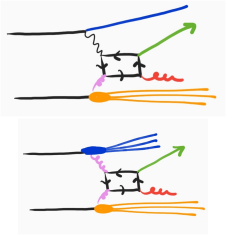


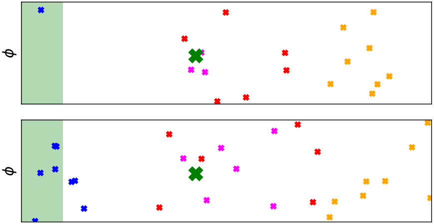


Method II: forward activity with HeRSCheL at LHCb

- 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

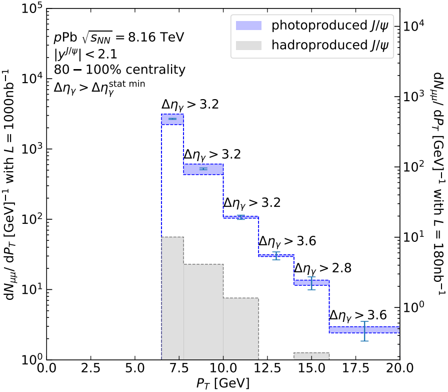
- detector close to the beam pipe ($|\eta| \gtrsim 8$) sensitive to neutral particles
- UPCs identified as most peripheral events ($80 - 100\%$ centrality)

[Already done in pPb 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]

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

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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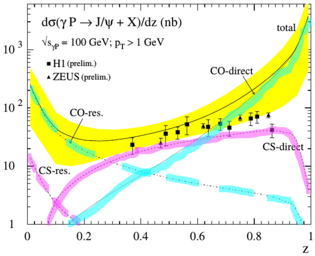
octet vs. singlet

Kramer, hep-ph/016120



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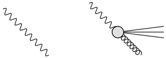
direct and resolved photons



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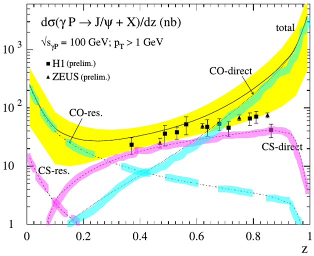

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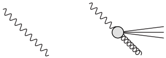

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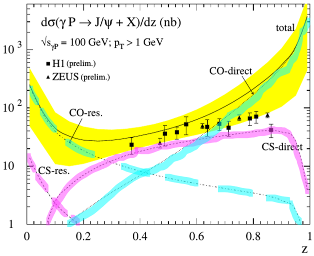

- Let us reconstruct the photon kinematics from the final state :

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

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

- 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 $W_{\gamma p} \simeq M_\psi e^{-y_\psi}$

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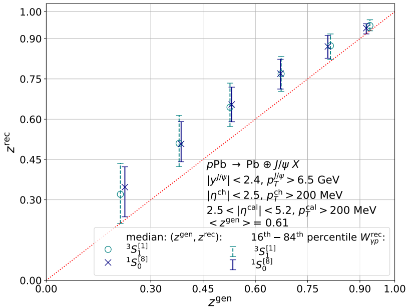

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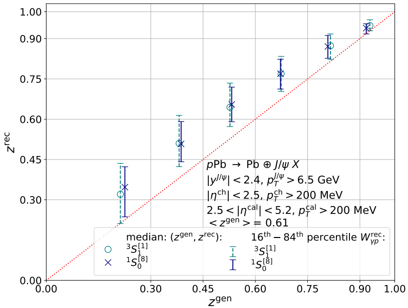

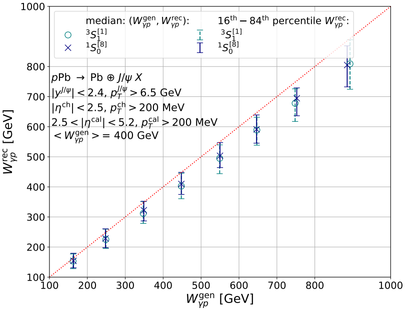

- For CMS and ATLAS: z reconstruction allows for $\mathcal{O}(5-6)$ bins (similar to HERA)

  improves with increasing values of z
- $W_{\gamma p}$ reconstruction allows for $\mathcal{O}(10)$ bins

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

Summary and outlook

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

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

Backup

Number of charged tracks in HeRSCheL on Pb going side