Illuminating Quarkonium Production
Inclusive quarkonium photoproduction via UPC at the LHC

Kate Lynch

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& Ronan McNulty (UCD)

Forward Physics and QCD at the LHC and EIC

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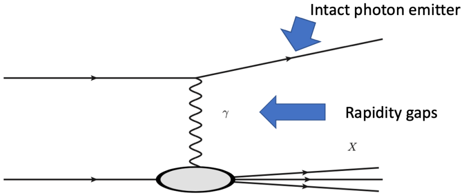

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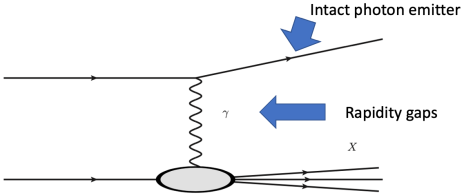

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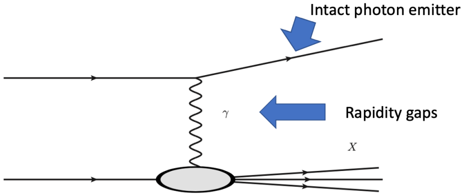

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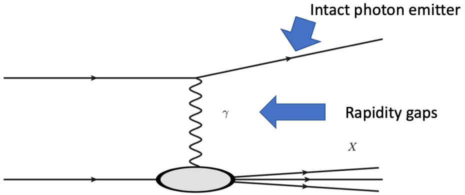

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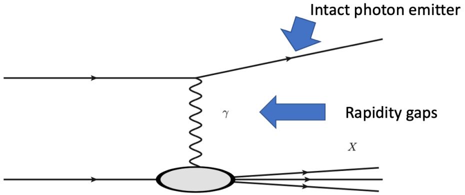

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- How do we isolate photon interactions at the LHC? ultra-peripheral collisions

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- Owing to the large mass of its constituents, quarkonia are in principle the simplest QCD bound states
  - however, production mechanism remains an open question; Colour Singlet Model Colour Octet Mechanism and NRQCD Colour Evaporation Model
- **Photoproduction** is generally **simpler** than hadroproduction
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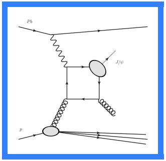
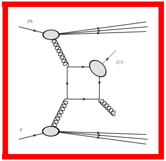
- How do photoproduction vs. hadroproduction contributions compare?





- Hadroproduction contribution is larger than photoproduction; $\sigma_{had.} \gg \sigma_{photo.}$
- In order to make a measurement we must be able to kill the hadroproduction

Signal vs. background in detector acceptance

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			detector acceptance:		
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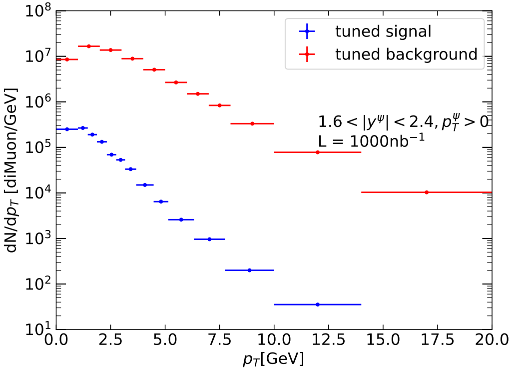

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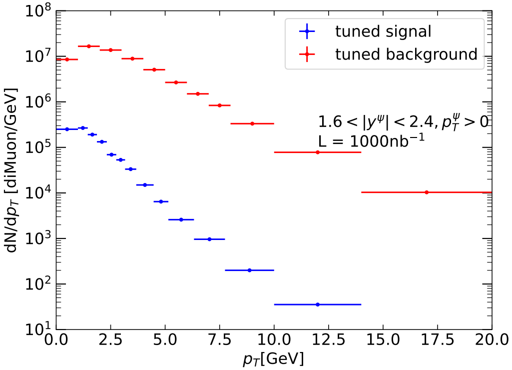
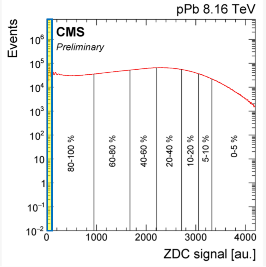
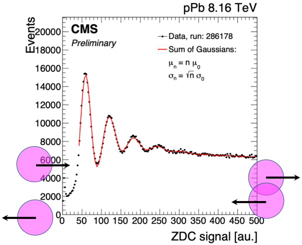


Must impose cuts to enhance signal with respect to background!

Killing background: searching for the intact photon emitter with ZDC

- Far-forward detectors close to beam-pipe; used to classify centrality





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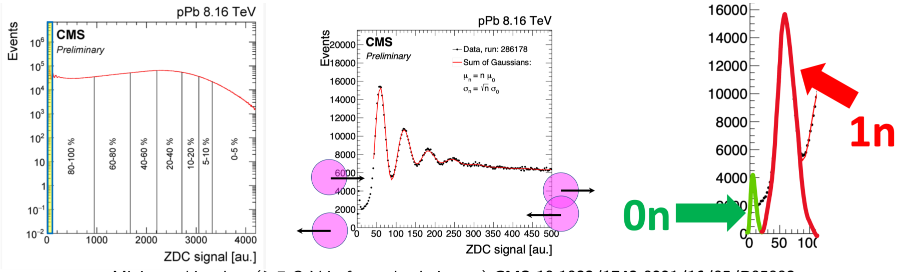

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- Can resolve single to few neutron emissions
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- $\geq$ 1-neutron region is all background
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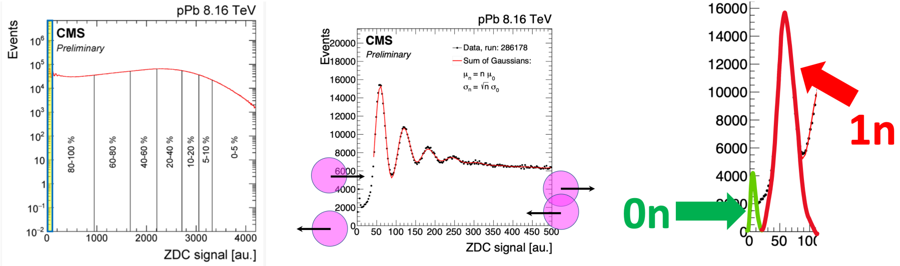

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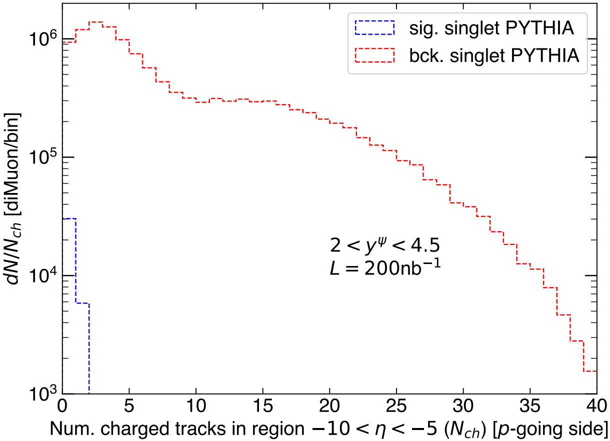

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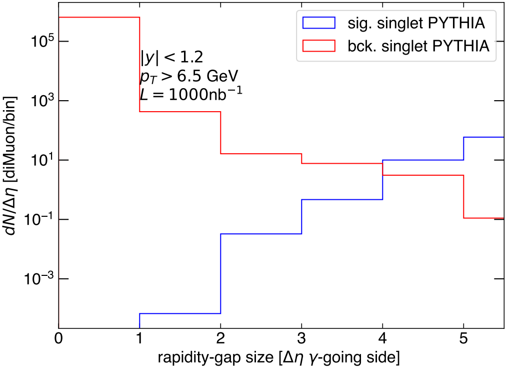

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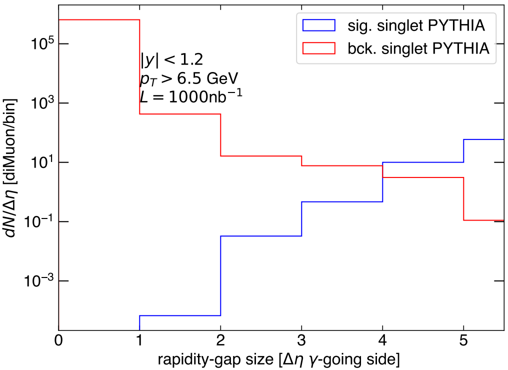

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Kinematic reconstruction

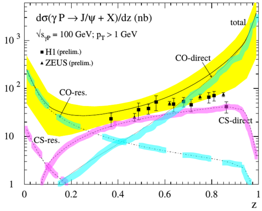
We are interested in reconstructing...

$W_{\gamma p}$ **:** to know the collision energy

z **:** discriminant variable for **quarkonium production mechanism** (singlet vs. octet) and allows us to **control the resolved-photon** contribution

Both variables depend on exchanged photon energy!

KRAMER, hep-ph/016120



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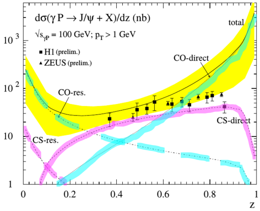

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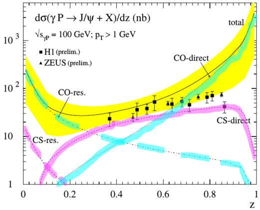

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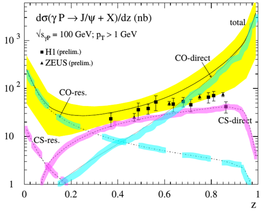

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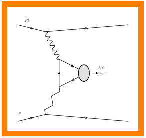
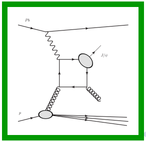
  - In the exclusive case this is simple; detected particle gives the photon energy
  - This is **not** true for the inclusive case... how well can we reconstruct the final state?





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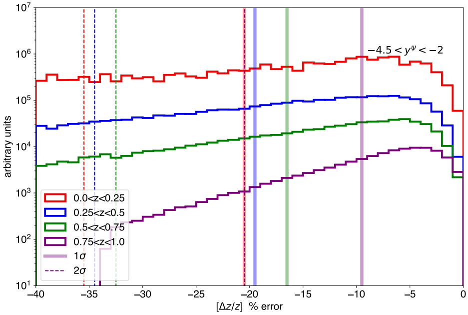


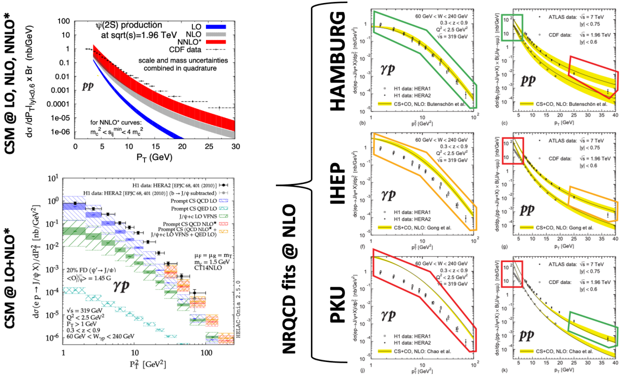
Summary and outlook

- Quarkonium offer the chance to examine the interplay between perturbative and non-perturbative regime of the strong interaction
- The LHC can be used as a photon-nucleon collider
  - measuring inclusive J/ψ photoproduction at the LHC appears feasible which is complementary to existing HERA measurements
- In J/ψ photoproduction events in Pbp collisions
  - in CMS, ATLAS and ALICE the ZDC is sufficient to suppress background events
  - in LHCb a combination of gap and HeRSCheL based cuts are likely sufficient to suppress background
- The $\Delta\eta$ value at which the cut is placed 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.

Backup

Set-up: tuning in p_T

- No single model can simultaneously describe the photo- and hadroproduction data



- A correct description of the p_T description require combining different contributions, including NLO ones: **not available in existing MC codes**
- In order to be accurate in our MC event distribution, we tune leading order colour singlet and colour octet spectra to data in other colliding systems and extrapolate by changing the photon flux and PDFs
- The objective of our MC simulation is not about rate predictions but the characterisation of inclusive events

Set-up: generating samples

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

- Use HELAC-Onia to generate MC samples [in the NRQCD framework]
- Use MC samples to model the signal and background
  - 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 [$gg \to J/\psi(^3S_1^8)g$]
- Tune to data;
  - 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**
- Use PYTHIA to shower partonic events
- Characterise the inclusive signal and background using showered events

Validation example: hadroproduction background

Tune MC to rapidity integrated data (LHCb data @ 5 TeV).
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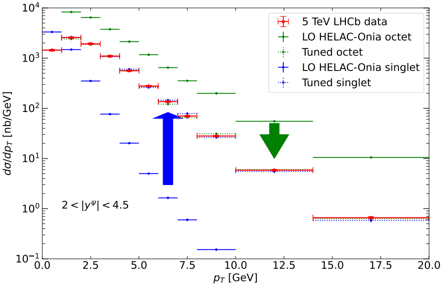

- Octet is reduced
- Singlet is increased

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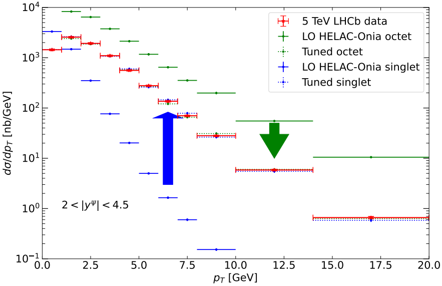

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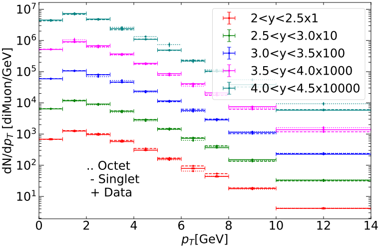

Validation example: hadroproduction background

Tune MC to rapidity integrated data (LHCb data @ 5 TeV). Assumptions:

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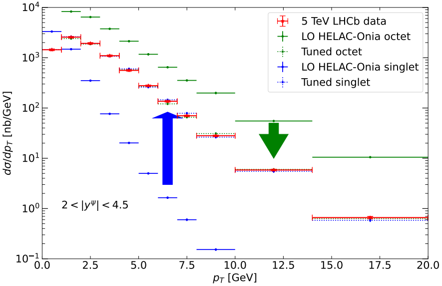

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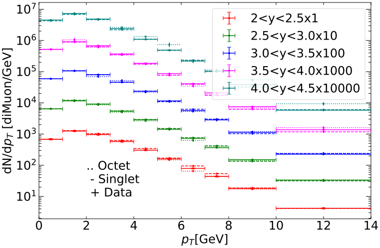
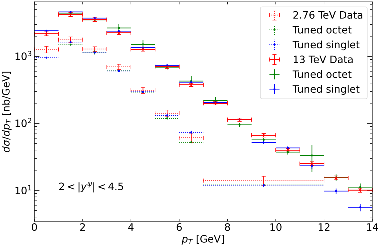


Validation 2: tune vs. 13- and 2.76 TeV data.



Tune MC to HERA data @ $\sqrt{s} = 320$ GeV;

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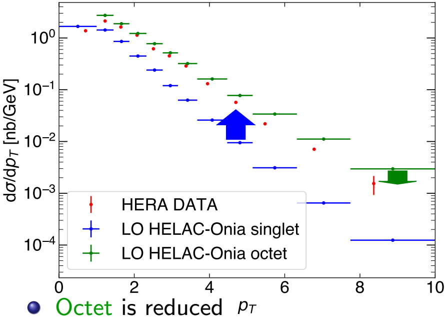

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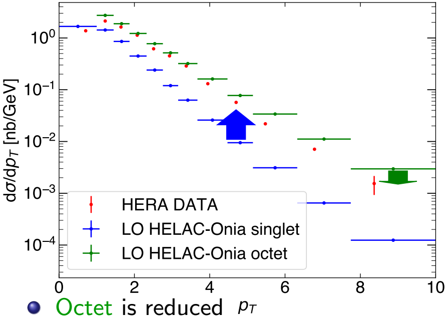

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p_T bin [GeV]	LO tuning factors $^3S_1^{(1)}$	$^1S_0^{(8)}$
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$1.0 < p_T < 1.45$	1.5	0.8
$1.45 < p_T < 1.87$	1.9	0.9
$1.87 < p_T < 2.32$	2.5	0.9
$2.32 < p_T < 2.76$	2.6	0.8
$2.76 < p_T < 3.16$	3.8	0.9
$3.16 < p_T < 3.67$	4.6	0.9
$3.67 < p_T < 4.47$	5.0	0.8
$4.47 < p_T < 5.15$	6.0	0.7
$5.15 < p_T < 6.32$	7.1	0.6
$6.32 < p_T < 7.75$	10.9	0.6
$7.75 < p_T < 10.0$	12.4	0.5

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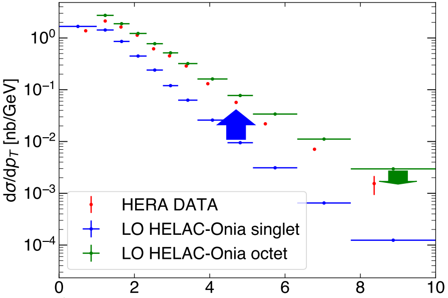

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NOTE: no tuning factor for octet in $0 < p_T < 1$ GeV as cross section is divergent. However, tuning factors can be computed using distributions from PYTHIA where events are smeared into the $0 < p_T < 1$ GeV region.

Per event z reconstruction

z-reconstruction depends on the... **position of the detectors** and **kinematics of the event**.

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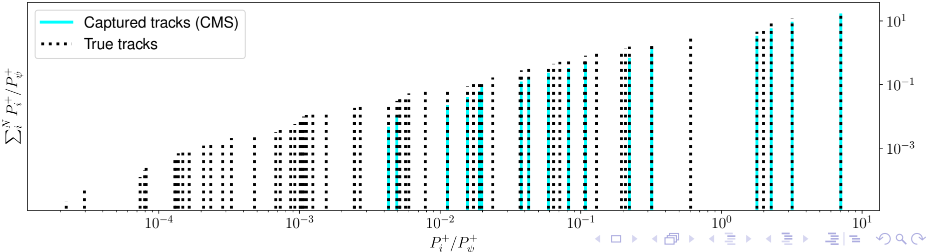
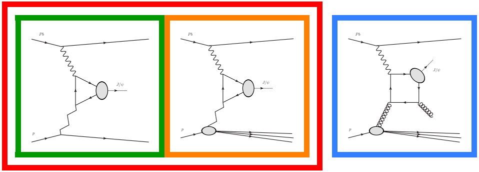


Photoproduction measurements at HERA in *e*-*p* collisions



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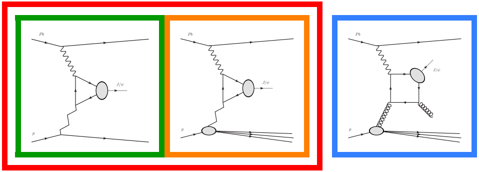

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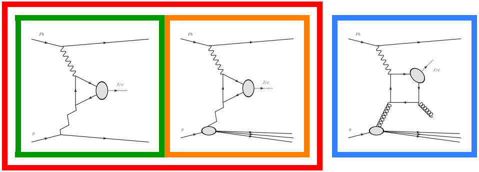

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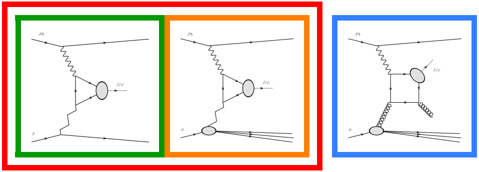

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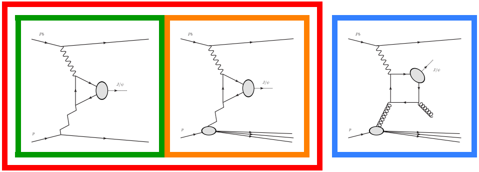

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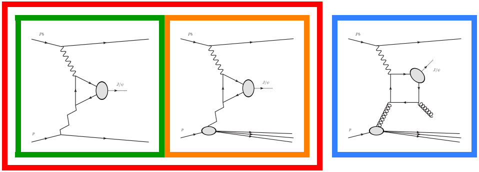

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We propose inclusive **photoproduction** is measured at the LHC; opportunity to extend p_T- & $W_{\gamma p}$-reach, capture a variety of quarkonium species & improve statistical accuracy of existing data

Quarkonium Production: theoretical models

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   - Heavy quarks ($Q\bar{Q}$) produced in the hard scattering have the same quantum numbers as the final quarkonium ($\mathcal{Q}$).
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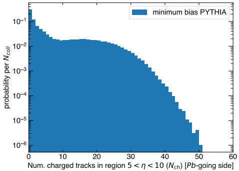
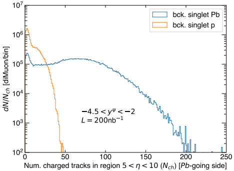
3. Colour Evaporation Model
   - Quantum numbers of $Q\bar{Q}$ decorrelated from $\mathcal{Q}$.
   - Only the invariant mass of the $Q\bar{Q}$ is constrained.
   - Semi-soft gluon emissions during hadronisation
   - $\sigma(\mathcal{Q}) = \int \frac{\sigma(Q\bar{Q})}{dm_{Q\bar{Q}}} dm_{Q\bar{Q}}$

From p to Pb in the HeRSCheL region

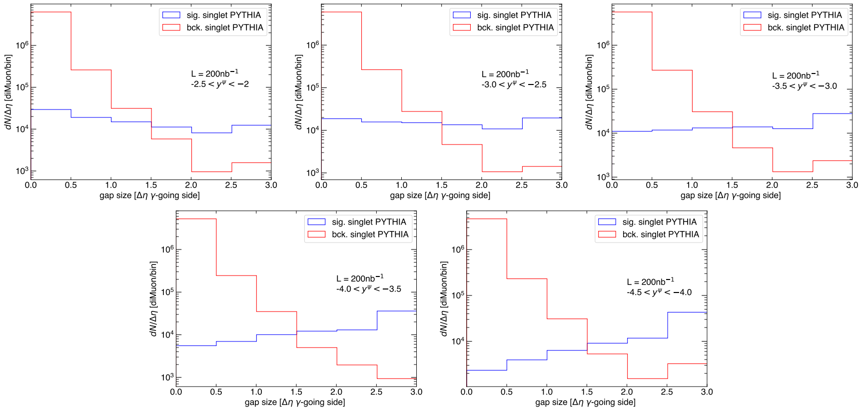
- The background is modelled by generating pA events with HELAC-Onia and passing them through PYTHIA; PYTHIA reads these as pp events.
- In a pp collision $N_{coll.} = 1$; whereas in a pA collision there are many more nucleons and therefore it is possible to have $N_{coll.} > 1$ [typically modelled using 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



Rapidity-differential gap distributions in LHCb pPb



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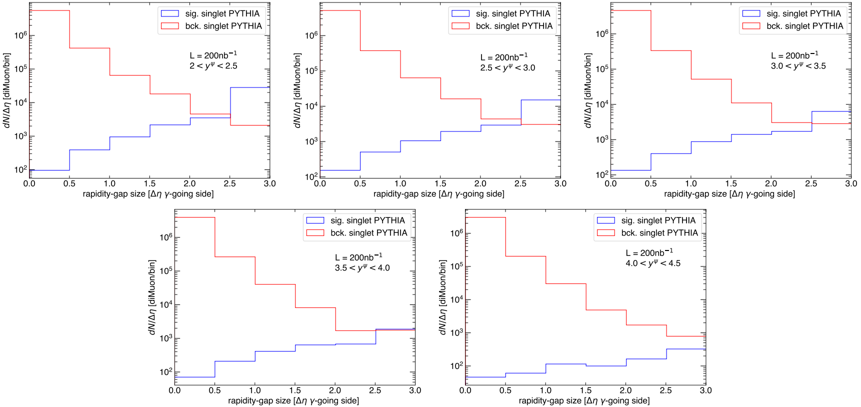


z Reconstruction at the LHC: summary

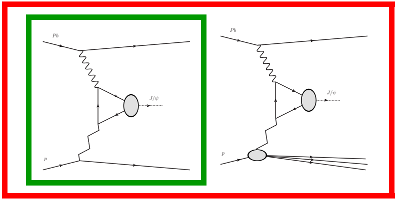
In a given kinematic region, the percentage error on z-reconstruction at one standard deviation.

	CMS						LHCb	
	$1.6 < y^{\psi} < 2.4$	$1.2 < y^{\psi} < 1.6$ $p_T^{\psi} > 2$ GeV	$0 < y^{\psi} < 1.2$ $p_T^{\psi} > 6.5$ GeV	$-1.2 < y^{\psi} < 0$ $p_T^{\psi} > 6.5$ GeV	$-1.6 < y^{\psi} < -1.2$ $p_T^{\psi} > 2$ GeV	$-2.4 < y^{\psi} < -1.6$ $-2.4 < y^{\psi} < -1.6$	$2 < y^{\psi} < 4.5$ $2 < y^{\psi} < 4.5$	$-4.5 < y^{\psi} < -2$ $-4.5 < y^{\psi} < -2$
$0.2 < z < 0.45$	-26%	-28%	-20%	-26%	-28%	-26%	-22%	-20%
$0.45 < z < 0.7$	-22%	-22%	-14%	-14%	-18%	-18%	-26%	-16%
$0.7 < z < 0.9$	-10%	-10%	-6%	-6%	-8%	-8%	-20%	-14%
$0.9 < z < 1$	-2%	-2%	-2%	-0%	-2%	-4%	-6%	-4%

Note: $\Delta z/z = (z - z_{exp.})/z < 0$.

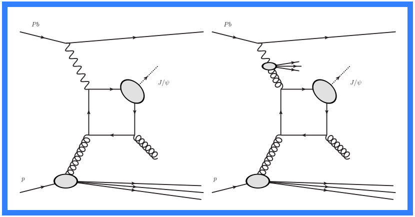
Diffractive vs. inclusive photoproduction

Diffractive production



- Colourless exchange
- Only CSM contributes
- **exclusive**: **only** J/ψ decay products

Inclusive production



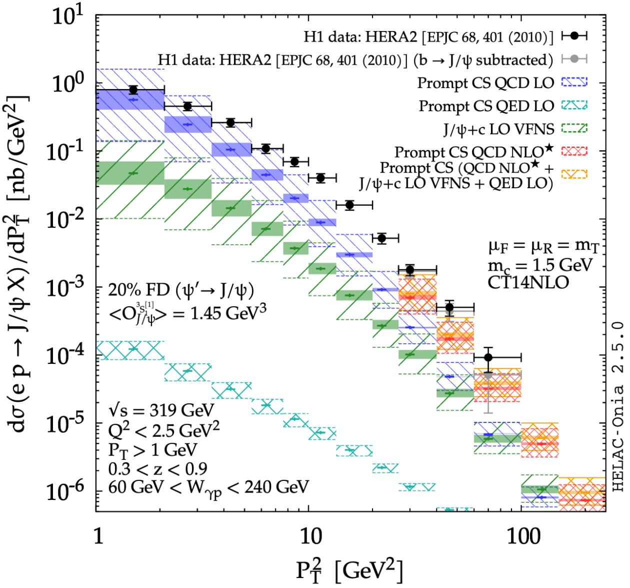
- Hard final state gluon
- Resolved vs. direct contribution
- Test production mechanism
- Probe gluon PDF

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 $\rightarrow p \cdot q = 0$.

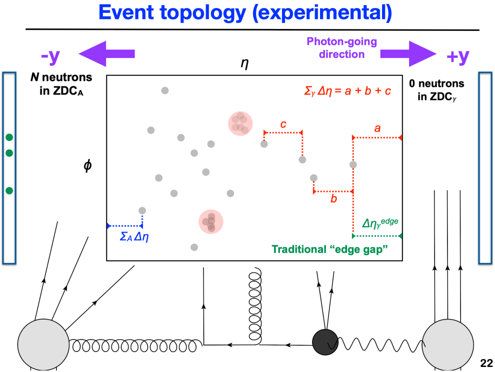
NLO inclusive J/ψ photoproduction at HERA

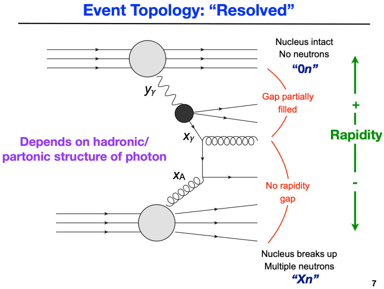
arXiv:2107.13434



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

Forecasted luminosity

Luminosity targets taken 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}