Inclusive quarkonium photoproduction in ultra-peripheral collisions

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GDR Orsay

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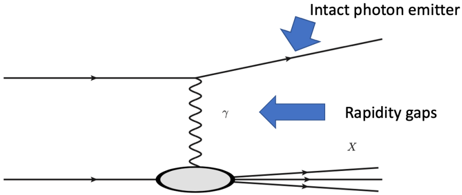

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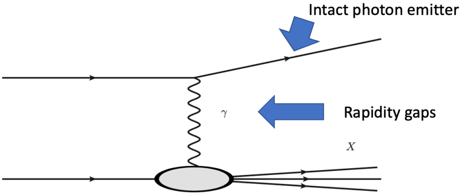

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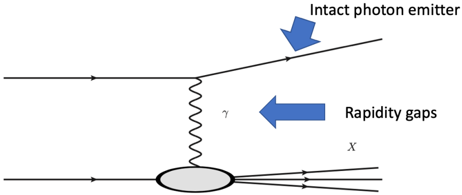

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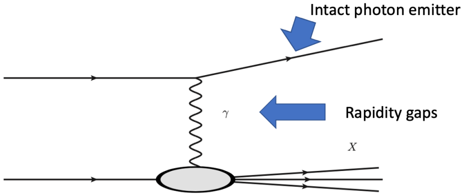

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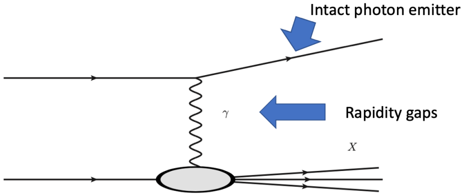

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- How do we isolate photon interactions at the LHC? ultra-peripheral collisions

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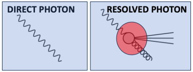

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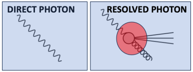

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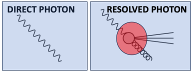

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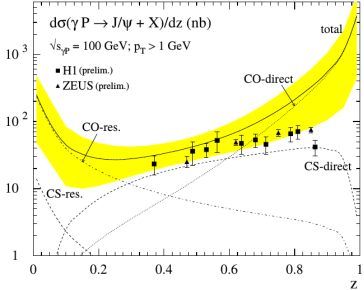
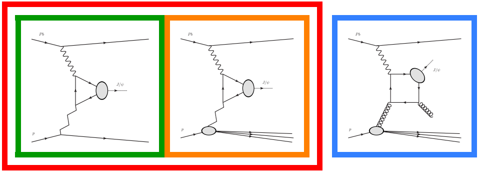
$$z = \frac{P_\psi \cdot P_p}{P_\gamma \cdot P_p}$$

- Different production models yield different distributions
- Gives handle on the resolved contribution



Photoproduction measurements at HERA in e-p collisions



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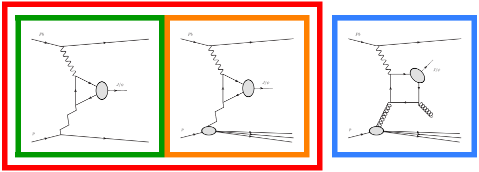

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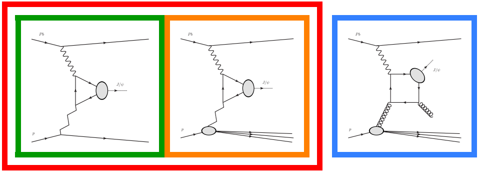

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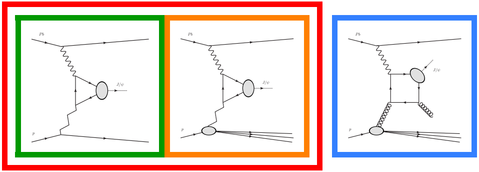

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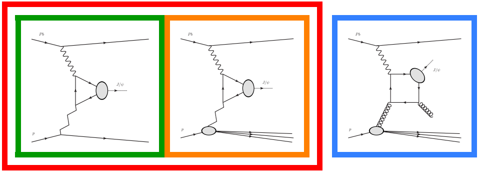

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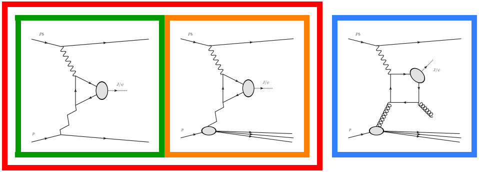

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We propose inclusive **photoproduction** is measured at the LHC; opportunity to extend p_T- & $W_{\gamma p}$-reach, capture a variety of quarkonium species & improve statistical accuracy of existing data

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- **no ambiguity** as to which beam particle emits the photon [*p-p* or *Pb-Pb*]
- **negligible neutron emission probability** from *Pb*-ion means a clean tag of the intact γ-emitter (later...) [$\mathcal{O}(0.5)$ in *Pb-Pb* **ATLAS-CONF-2022-021**]
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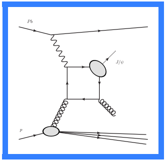
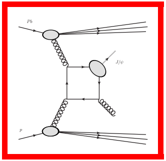
How do **intact** (photoproduction) vs. **broken lead-ion** (hadroproduction) contributions compare?





- Hadroproduction contribution is larger than photoproduction; $\sigma_{had.} \gg \sigma_{photo.}$
- In *p*-Pb the relative size of these contributions is rapidity-dependent
- In order to make a measurement we must be able to reduce the hadroproduction contribution... we will call this background

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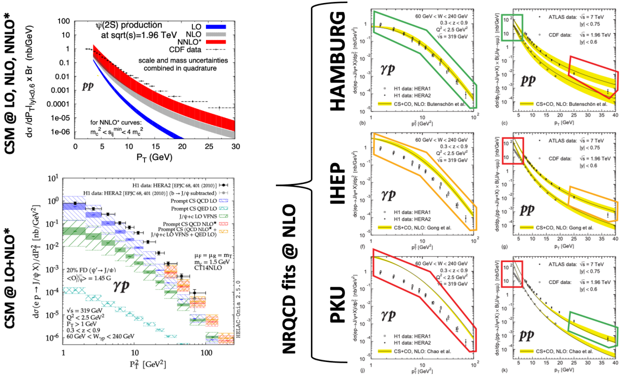
Set-up: tuning in p_T

- 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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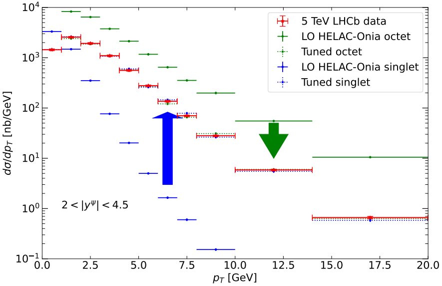

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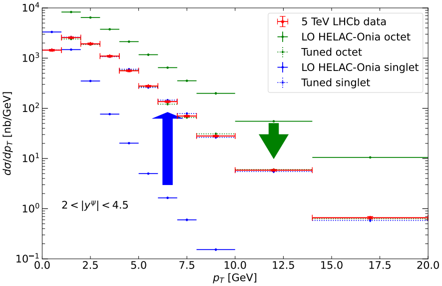

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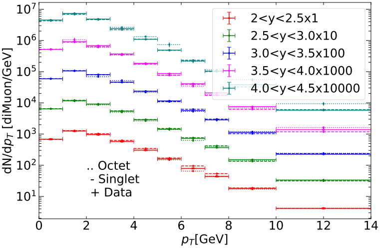

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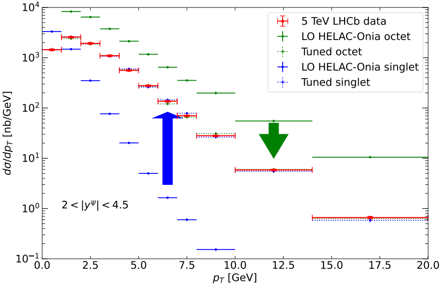

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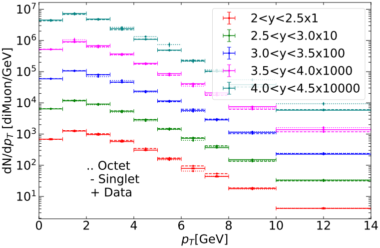
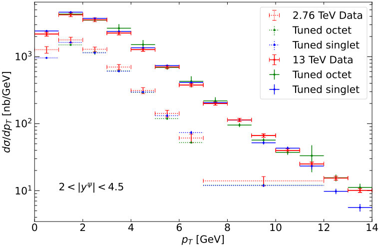


Validation 2: tune vs. 13- and 2.76 TeV data.



Signal-over-background in detector acceptance

	LHCb	**CMS** typical	**CMS** low p_T	**ATLAS**	**ALICE**
detector acceptance:					
	$2 < y^\psi < 4.5$	$\lvert y^\psi\rvert < 2.1$ $p_T^\psi > 6.5$	$1.2 > \lvert y^\psi\rvert$ $p_T^\psi > 6.5$ $1.2 < \lvert y^\psi\rvert < 1.6$ $p_T^\psi > 2$ $1.6 < \lvert y^\psi\rvert < 2.4$ $p_T^\psi > 0$	$\lvert y^\psi\rvert < 2.1$ $p_T^\psi > 8.5$	$2.5 < \lvert y^\psi\rvert < 4$
Signal-over-background:					
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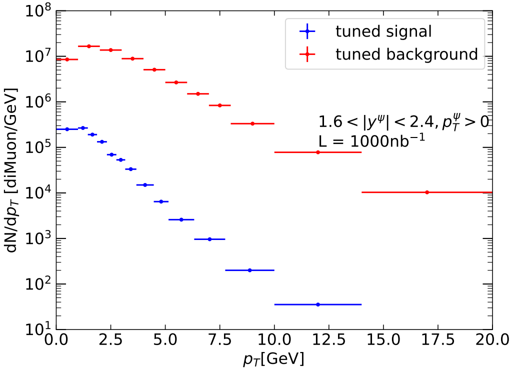

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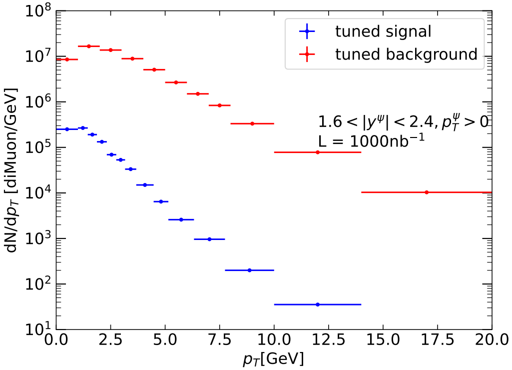

Must impose cuts to enhance signal with respect to background!

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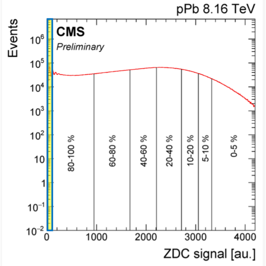
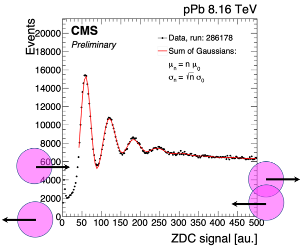
- Far-forward detectors close to beam-pipe; used to classify centrality





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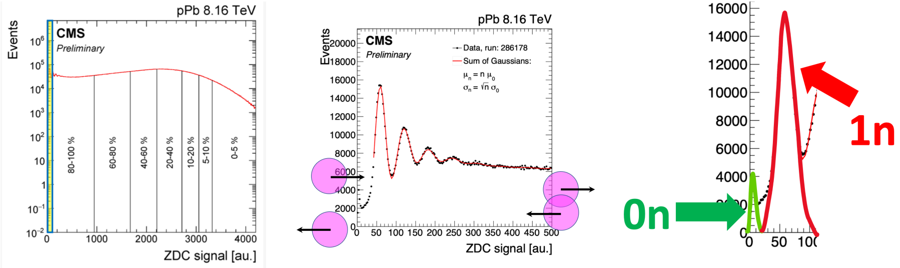

Minimum bias data ($\geq$7 GeV in forward calorimeter) **CMS 10.1088/1748-0221/16/05/P05008**

- Can resolve single to few neutron emissions
- All of the signal is in the 0-neutron bump [signal with neutron emission is negligible]
- $\geq$ 1-neutron region is all background
- Efficiency (ϵ) for detecting 1n is $>$ 98% **CMS, 2102.06640**; **ALICE, 1203.2436**

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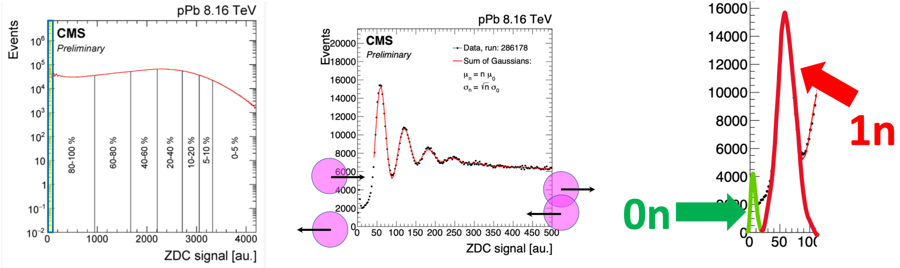

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    - Therefore maximally 2% of 1n events look like 0n events

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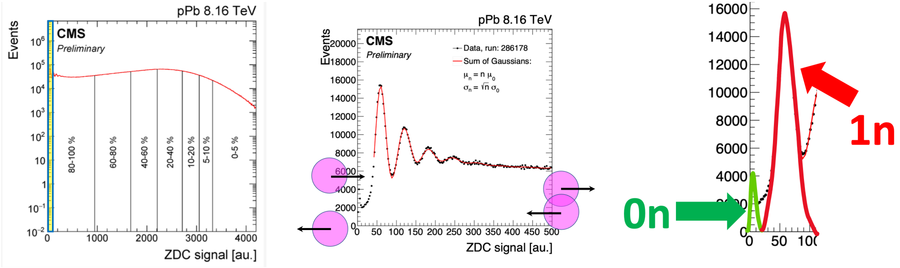

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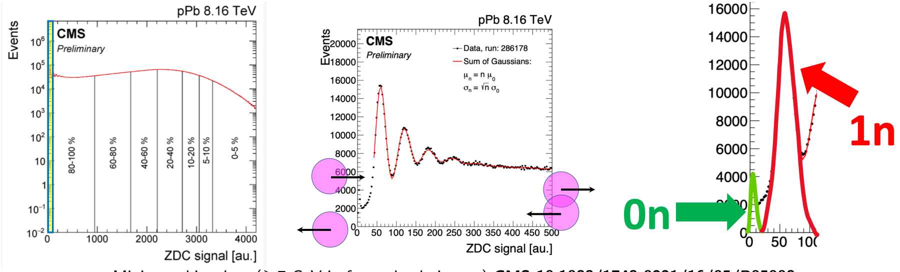

Minimum bias data (≥7 GeV in forward calorimeter) **CMS 10.1088/1748-0221/16/05/P05008**

Assume that the minimum bias and inclusive J/ψ ZDC spectra are similar.
So, let us use this to estimate the signal-over-background ratio in the 0n region!

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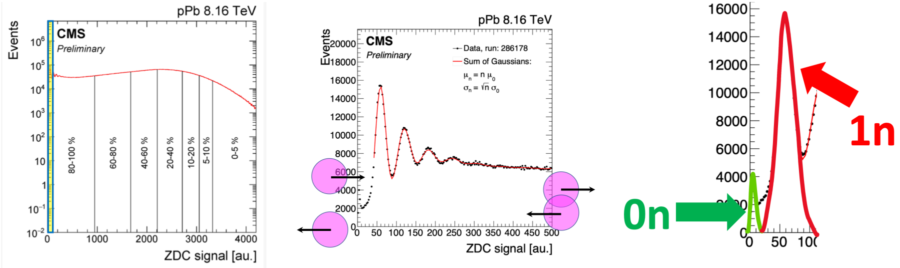

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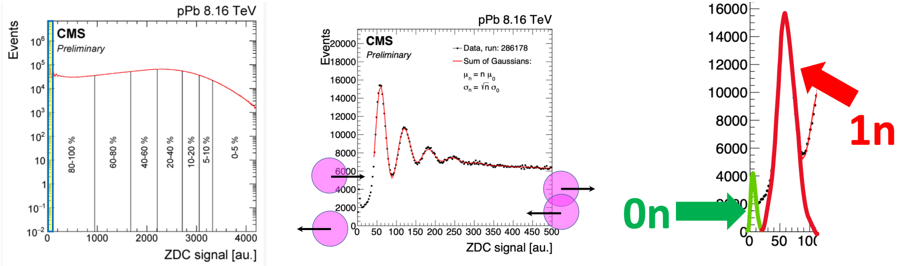

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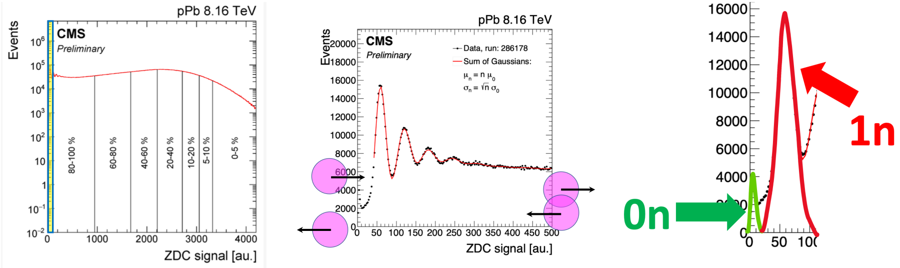

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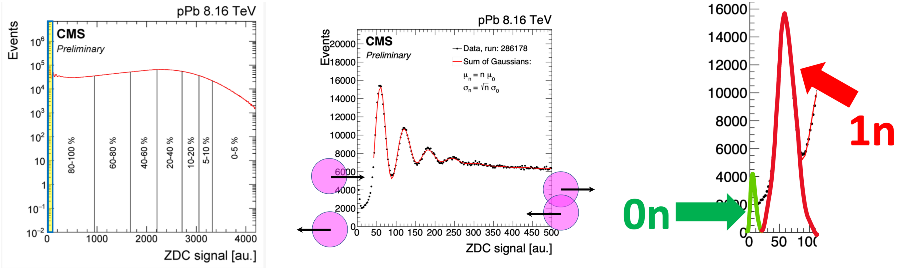

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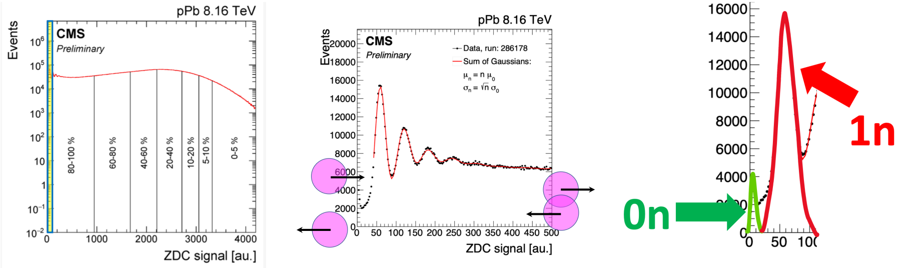

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- This background reduction technique can be used in CMS, ALICE & ATLAS.

Method II: forward activity; High Rapidity Shower Counter @ LHCb

- HeRSCheL detectors at forward and backward rapidity in the region $5 < |\eta| < 10$

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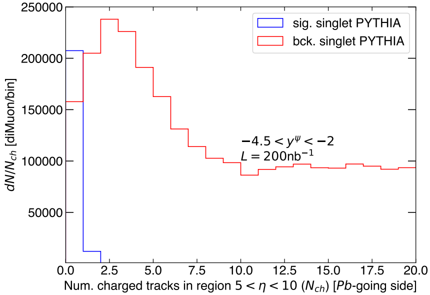

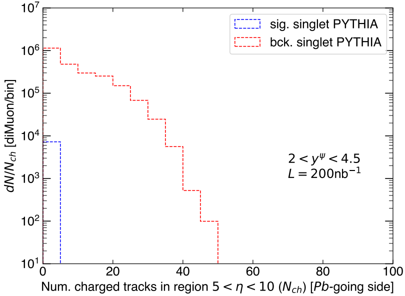

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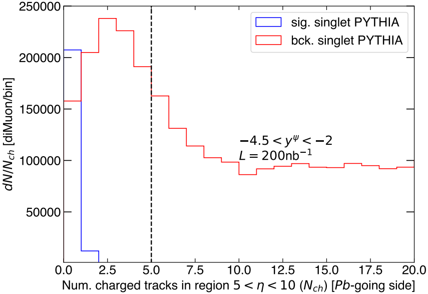

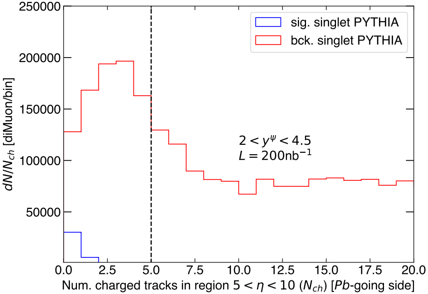

If we take 5 tracks as our cut value; we expect to retain $\mathcal{O}(100\%)$ of the signal and remove $\mathcal{O}(95\%)$ the background.

Method III: central activity; rapidity gaps

Characterise the central activity and exploit the difference between signal and background event topologies to cut background events

- **Signal**: more events with larger gaps
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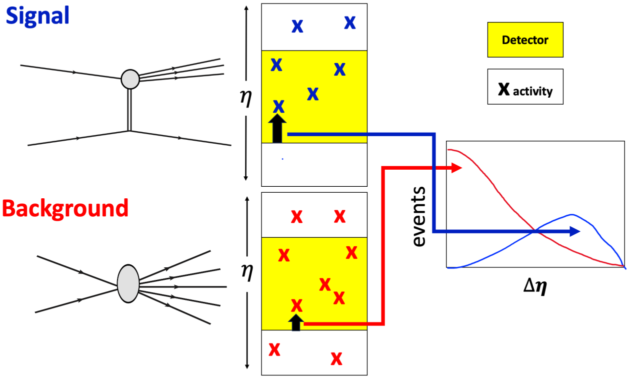

Method III: Rapidity gap distributions in CMS acceptance

- Rapidity-gap-type observables are ideal where there is a wide rapidity coverage, i.e., CMS and ATLAS
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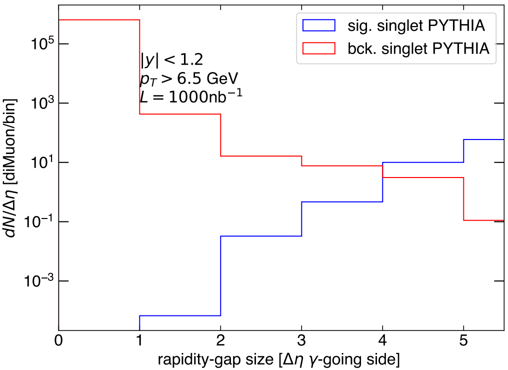

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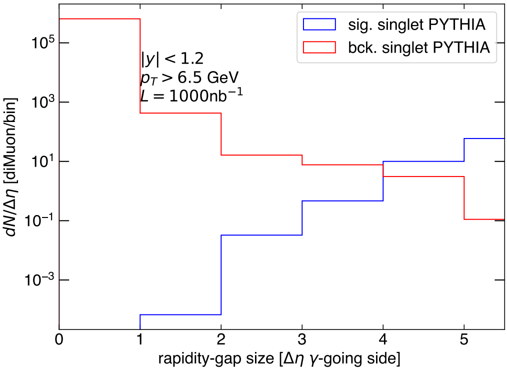

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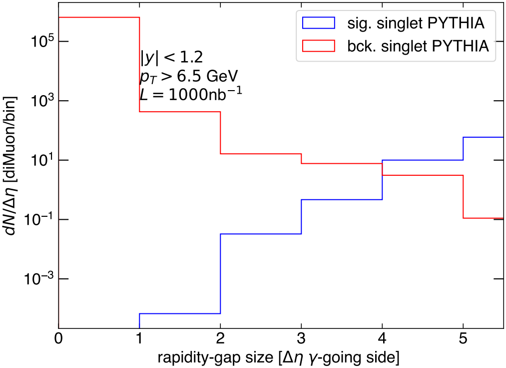

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- Gap size can be chosen to achieve desired purity and statistics in a given sample

Signal-over-background in detector acceptance after cuts

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	Pbp	pPb	
	Signal-over-background:		
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We are interested in reconstructing...

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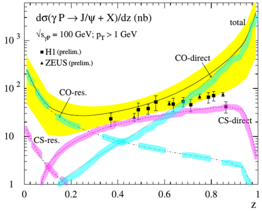
Both variables depend on exchanged photon energy!

KRAMER, hep-ph/016120



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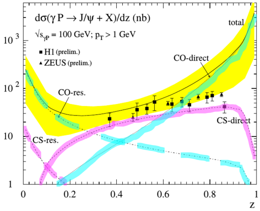

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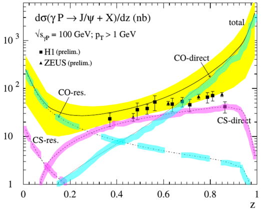

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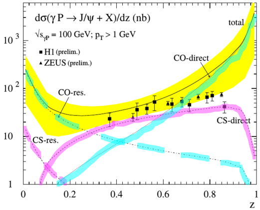

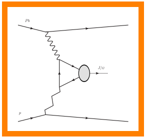

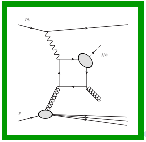

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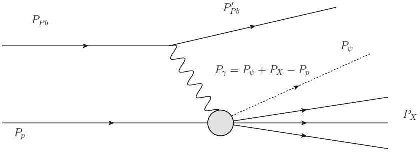

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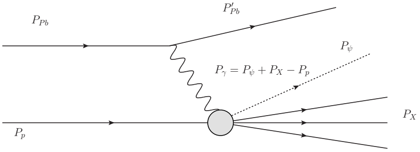

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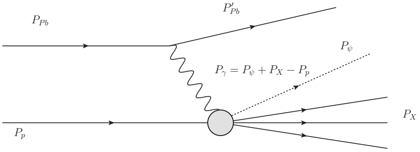

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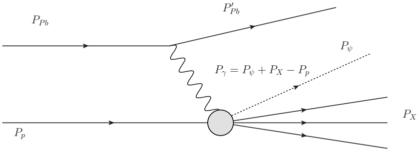

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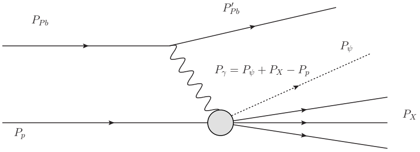

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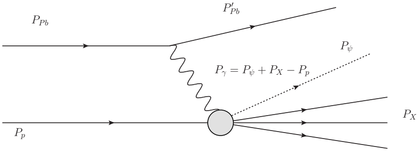

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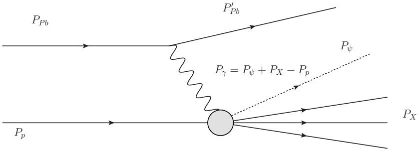

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Analogously, $W_{\gamma p} \simeq \sqrt{2P_p \cdot P_\gamma} \simeq \sqrt{P^-_p (P^+_\psi + P^+_X)}$ is only dependent on plus-component momenta.

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- $< z >$ increases with y^ψ and $W_{\gamma p}$
- z res. $(\sigma_{\Delta z})$ improves with increasing z

z Reconstruction at the LHC

z-reconstruction depends on; (i) **position of the detectors**; (ii) **kinematics of the event**.

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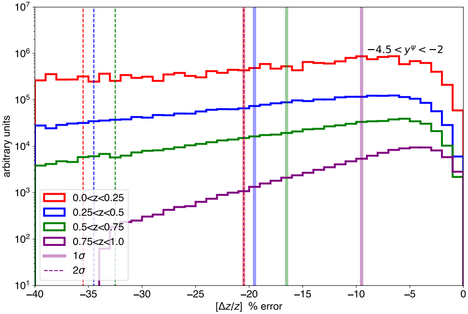

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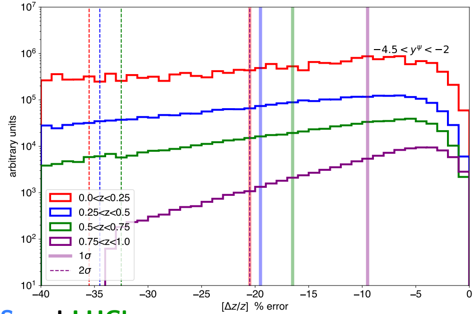


- z-reconstruction in the region... in **CMS and LHCb**
  - $0.20 < z < 0.45$... reconstructed within **30% 25%**
  - $0.45 < z < 0.70$... reconstructed within **25% 30%**
  - $0.70 < z < 0.90$... reconstructed within **10% 20%**
  - $0.90 < z < 1.0$... reconstructed within **5% 10%**

Summary and outlook

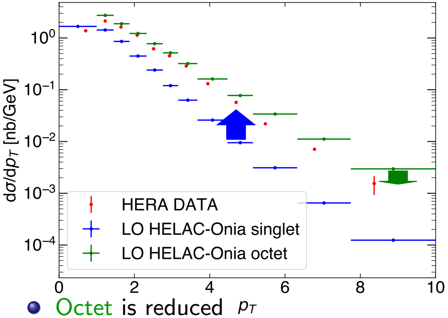
- Within QCD, non-perturbative interactions are not understood. Quarkonium offer the chance to examine the interplay between perturbative and non-perturbative strong interactions
- The LHC can be used as a photon-nucleon collider
  - measuring inclusive J/ψ photoproduction at the LHC appears feasible which is complimentary to existing HERA measurements
- In J/ψ photoproduction events in Pbp collisions
  - in CMS, ATLAS and ALICE the ZDC is sufficient to suppress background events
  - in each of these detectors rapidity gap constraints may be placed to further enhance the purity of the sample
  - 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

Tuning: photoproduction signal

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

- $60 < W_{\gamma p} < 240$ GeV
- $0.3 < z < 0.9$



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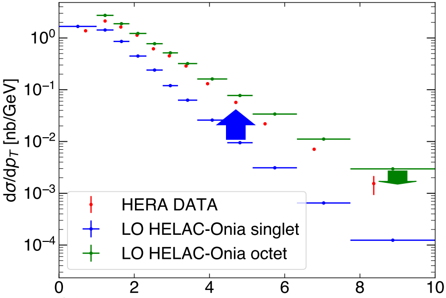

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p_T bin [GeV]	LO tuning factors $^3S_1^{(1)}$	$^1S_0^{(8)}$
$0.0 < p_T < 1.0$	0.8	-
$1.0 < p_T < 1.45$	1.5	0.8
$1.45 < p_T < 1.87$	1.9	0.9
$1.87 < p_T < 2.32$	2.5	0.9
$2.32 < p_T < 2.76$	2.6	0.8
$2.76 < p_T < 3.16$	3.8	0.9
$3.16 < p_T < 3.67$	4.6	0.9
$3.67 < p_T < 4.47$	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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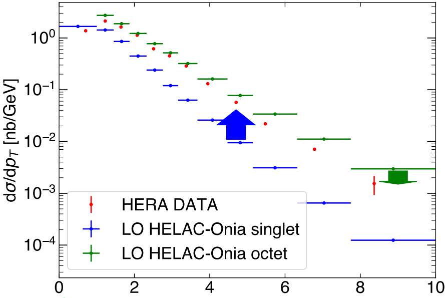

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NOTE: no tuning factor for octet in $0 < p_T < 1$ GeV as cross section is divergent. However, tuning factors can be computed using distributions from PYTHIA where events are smeared into the $0 < p_T < 1$ GeV region.

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- $\Delta z = z_{true} - z_{meas.} < 0$
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CMS requirements

Charged	no	yes
p_T	$p_T > 200$ MeV	$p_T > 400$ MeV
η	$2.5 < \|\eta\| < 5$	$\|\eta\| < 2.5$

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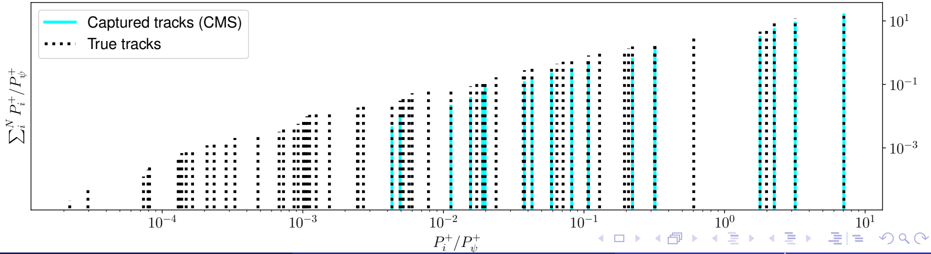

Quarkonium Production: theoretical models

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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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   - Higher Fock states (n) can contribute.
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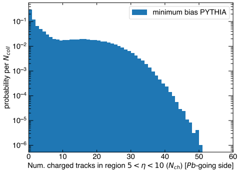
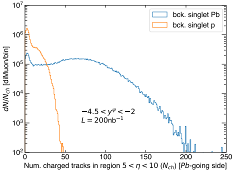
3. Colour Evaporation Model
   - Quantum numbers of $Q\bar{Q}$ decorrelated from $\mathcal{Q}$.
   - Only the invariant mass of the $Q\bar{Q}$ is constrained.
   - Semi-soft gluon emissions during hadronisation
   - $\sigma(\mathcal{Q}) = \int \frac{\sigma(Q\bar{Q})}{dm_{Q\bar{Q}}} dm_{Q\bar{Q}}$

From p to Pb in the HeRSCheL region

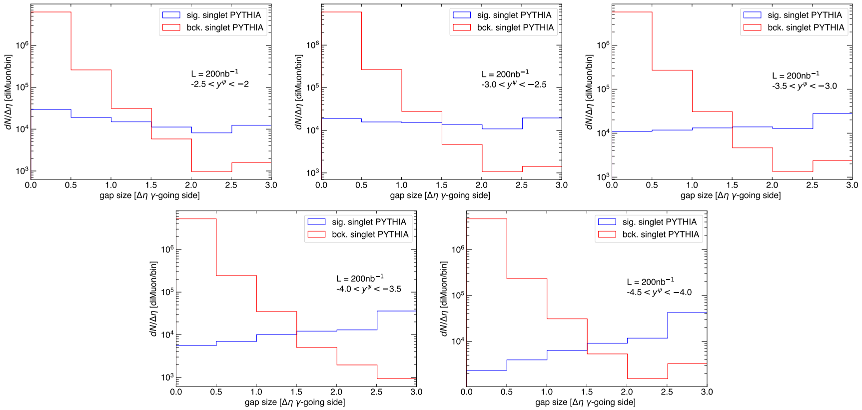
- The background is modelled by generating pA events with HELAC-Onia and passing them through PYTHIA; PYTHIA reads these as pp events.
- In a pp collision $N_{coll.} = 1$; whereas in a pA collision there are many more nucleons and therefore it is possible to have $N_{coll.} > 1$ [typically modelled using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



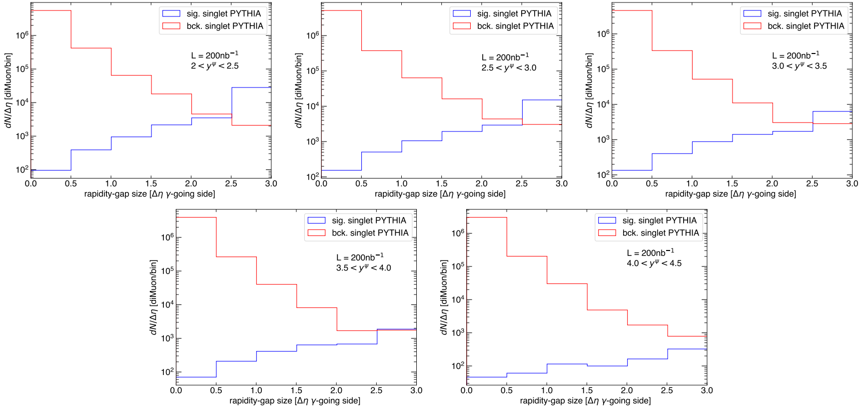
Centrality class	$\langle N_{\text{coll}} \rangle_{\text{opt.}}$	$\langle N_{\text{coll}} \rangle_{\text{ALICE}}$	b [fm]
2–10%	14.7	$11.7 \pm 1.2 \pm 0.9$	4.14
10–20%	13.6	$11.0 \pm 0.4 \pm 0.9$	4.44
20–40%	11.4	$9.6 \pm 0.2 \pm 0.8$	4.94
40–60%	7.7	$7.1 \pm 0.3 \pm 0.6$	5.64
60–80%	3.7	$4.3 \pm 0.3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



Rapidity-differential gap distributions in LHCb *p*Pb



Rapidity-differential gap distributions in LHCb Pbp



z Reconstruction at the LHC: summary

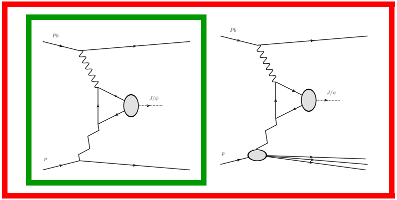
In a given kinematic region, the percentage error on z-reconstruction at one standard deviation.

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

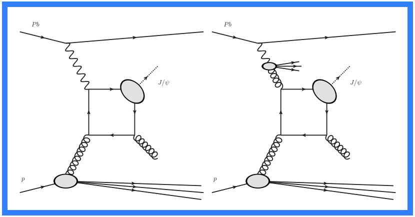
Diffractive vs. inclusive photoproduction

Diffractive production



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

Inclusive production



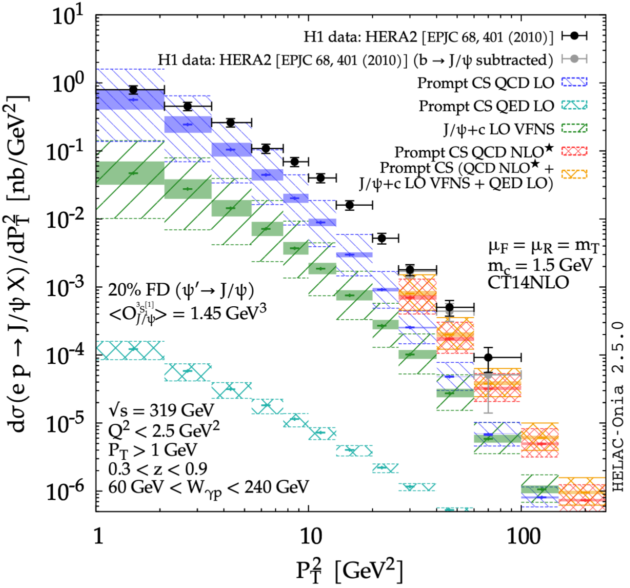
- Hard final state gluon
- Resolved vs. direct contribution
- Test production mechanism
- Probe gluon PDF

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

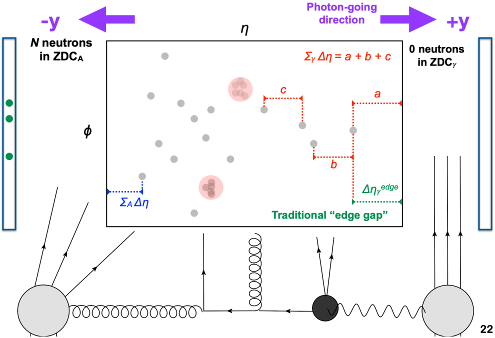
arXiv:2107.13434



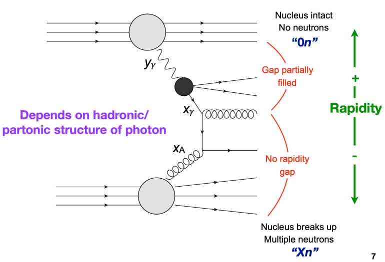
ATLAS-CONF-2022-021

- 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?

Event topology (experimental)



Event Topology: "Resolved"



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}