Inclusive quarkonium photoproduction in ultra-peripheral collisions

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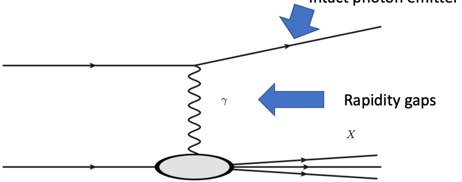

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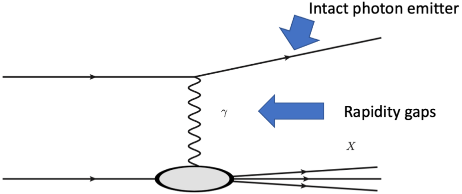

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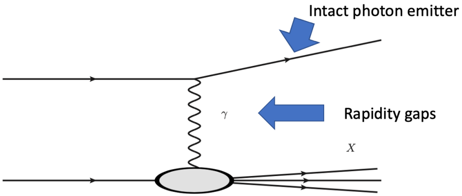

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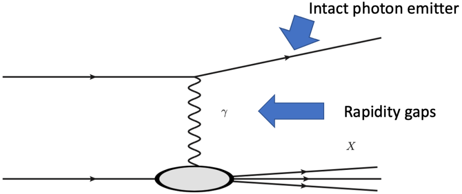

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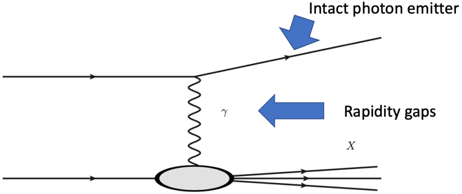

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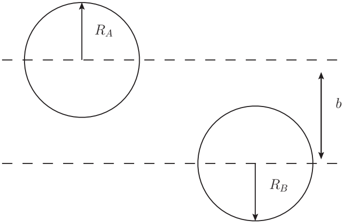
- In ultra-peripheral collisions, interactions are mediated over distances larger than charge radius and so, electromagnetic exchange becomes dominant

Photoproduction @ the LHC via ultra-peripheral collisions...

UPC: interaction mediated over distances larger than charge radius ($b > R_A + R_B$)



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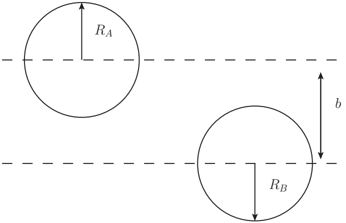

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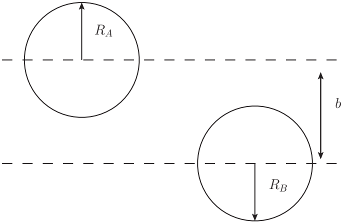

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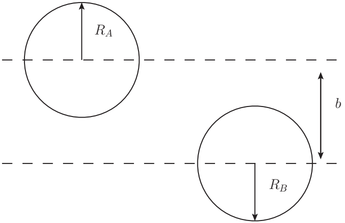

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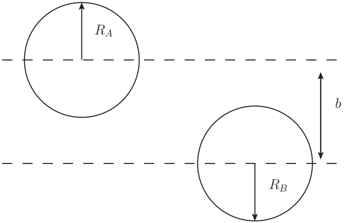

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  - electron-proton:
    - HERA: $\sqrt{s_{ep}} = 320$ GeV
    - EIC: $\sqrt{s_{ep}} = 45 - 140$ GeV

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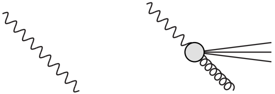

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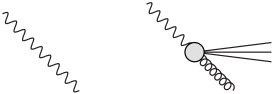

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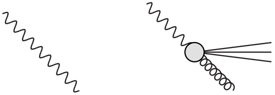

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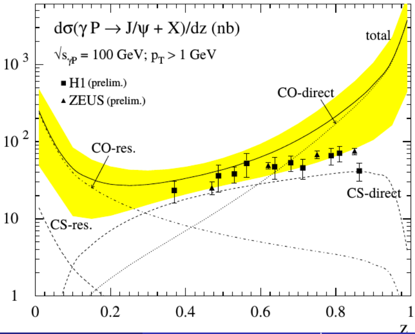
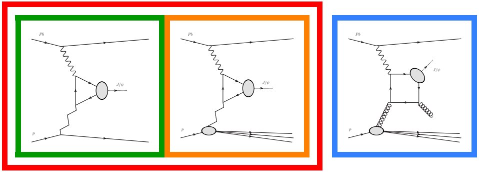


Photoproduction measurements at HERA in e-p collisions



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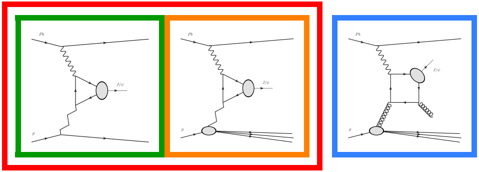

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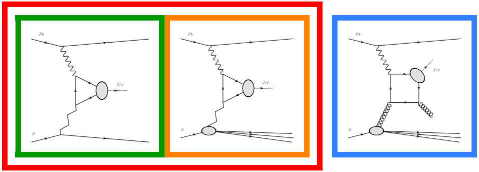

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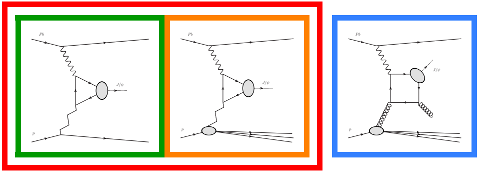

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- Different contributions separated using experimental cuts ...
  - Diffractive region: $p_T < 1$ GeV $z > 0.9$
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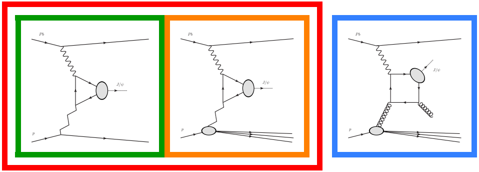

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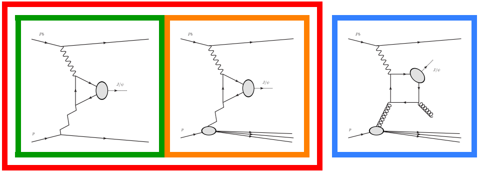

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We propose inclusive **photoproduction** is measured at the LHC; opportunity to extend p_T- & $W_{\gamma p}$-reach, capture a variety of quarkonium species & improve statistical accuracy of existing data

Table of Contents

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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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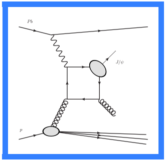
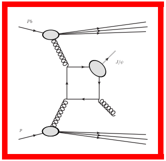
How do **intact** (photoproduction) vs. **broken lead-ion** (hadroproduction) contributions compare?





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

Table of Contents

Generating samples

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

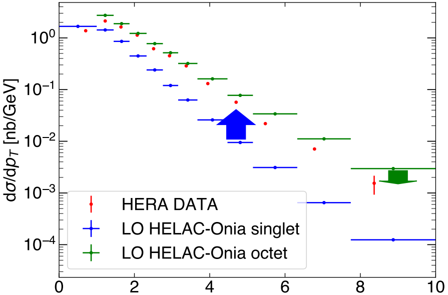
- Use HELAC-Onia to generate MC samples [in the NRQCD framework]
- Use MC samples to model the signal and background
  - Signal $[\gamma g \to J/\psi(^3S_1^1)g\ ]$ and $[\gamma g \to J/\psi(^1S_0^8)g\ ]$
  - Background $[gg \to J/\psi(^3S_1^1)g\ ]$ and $[gg \to J/\psi(^3S_1^8)g\ ]$
- Use PYTHIA to shower partonic events
- The p_T distribution is not well described by leading order NRQCD so we tune the samples to experimental 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**

Table of Contents

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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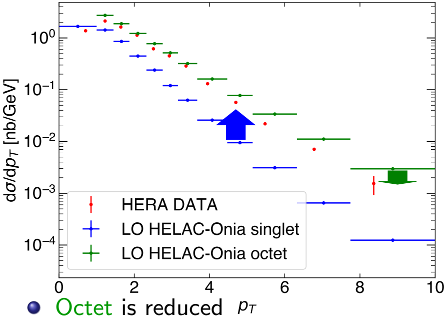

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$1.0 < p_T < 1.45$	1.5	0.8
$1.45 < p_T < 1.87$	1.9	0.9
$1.87 < p_T < 2.32$	2.5	0.9
$2.32 < p_T < 2.76$	2.6	0.8
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$3.16 < p_T < 3.67$	4.6	0.9
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$4.47 < p_T < 5.15$	6.0	0.7
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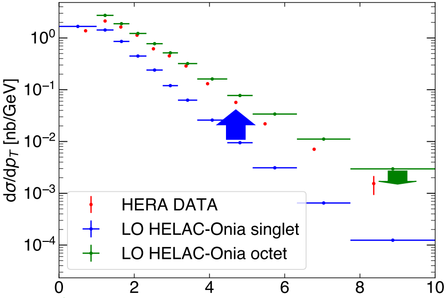

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NOTE: no tuning factor for octet in $0 < p_T < 1$ GeV as cross section is divergent. However, tuning factors can be computed using distributions from PYTHIA where events are smeared into the $0 < p_T < 1$ GeV region.

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

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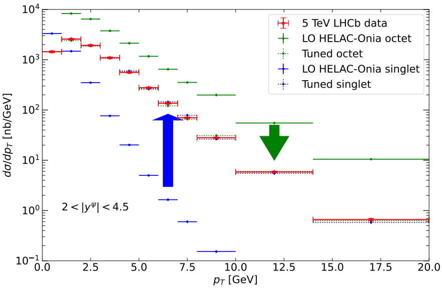

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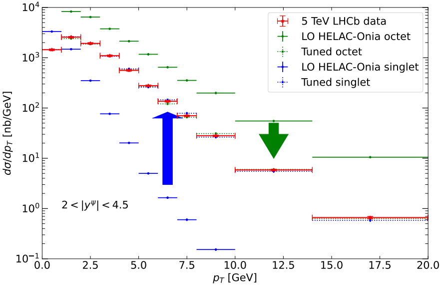

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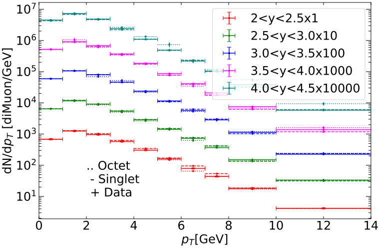

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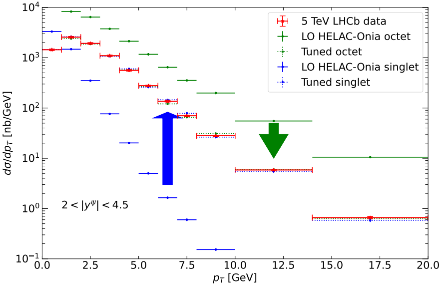

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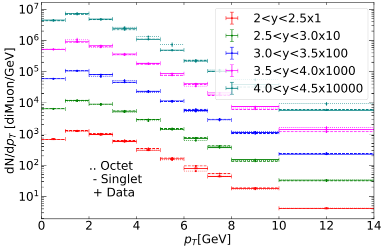
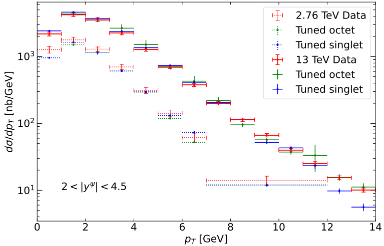


Validation 2: tune vs. 13- and 2.76 TeV data.



Signal-over-background in detector acceptance

	LHCb	**CMS** typical	**CMS** low p_T	**ATLAS**	**ALICE**
detector acceptance:					
	$2 < y^\psi < 4.5$	$\|y^\psi\| < 2.1$	$1.2 > \|y^\psi\|$ $p_T^\psi > 6.5$	$\|y^\psi\| < 2.1$	$2.5 < \|y^\psi\| < 4$
		$p_T^\psi > 6.5$	$1.2 < \|y^\psi\| < 1.6$ $p_T^\psi > 2$	$p_T^\psi > 8.5$	
			$1.6 < \|y^\psi\| < 2.4$ $p_T^\psi > 0$		
Signal-over-background:					
Pbp	$3 \cdot 10^{-3}$	$9 \cdot 10^{-4}$	$1 \cdot 10^{-2}$	$6 \cdot 10^{-4}$	$3 \cdot 10^{-3}$
pPb	$1 \cdot 10^{-2}$	$9 \cdot 10^{-4}$	$1 \cdot 10^{-2}$	$6 \cdot 10^{-4}$	$1 \cdot 10^{-2}$

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:		
Pbp	$3 \cdot 10^{-3}$	$9 \cdot 10^{-4}$	$1 \cdot 10^{-2}$	$6 \cdot 10^{-4}$	$3 \cdot 10^{-3}$
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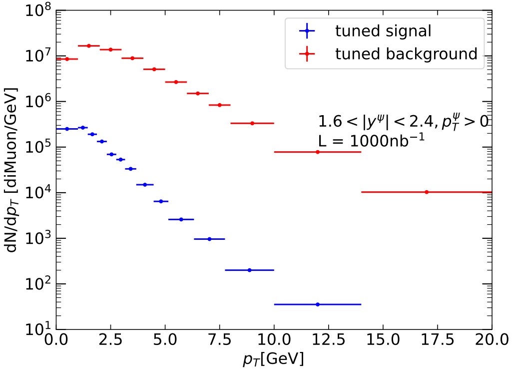

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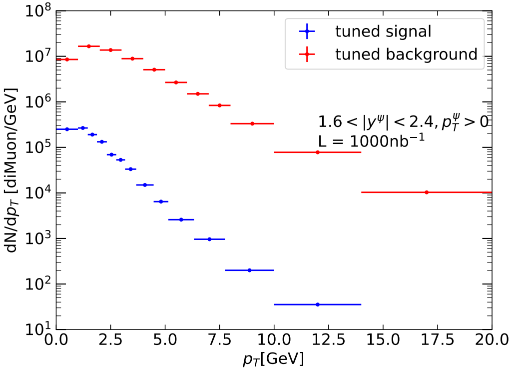

Must impose cuts to enhance signal with respect to background!

Table of Contents

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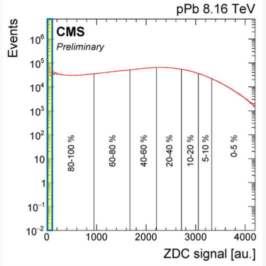
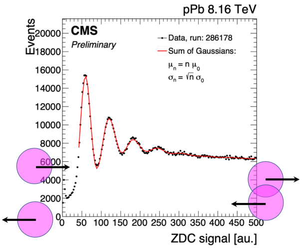
- Far-forward detectors close to beam-pipe; used to classify centrality





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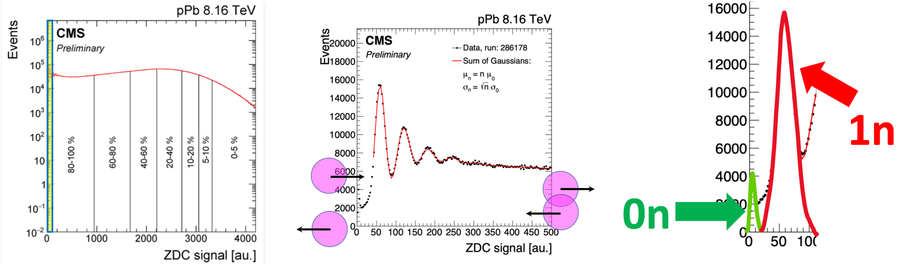

Minimum bias data ($\geq$7 GeV in forward calorimeter) **CMS 10.1088/1748-0221/16/05/P05008**

- 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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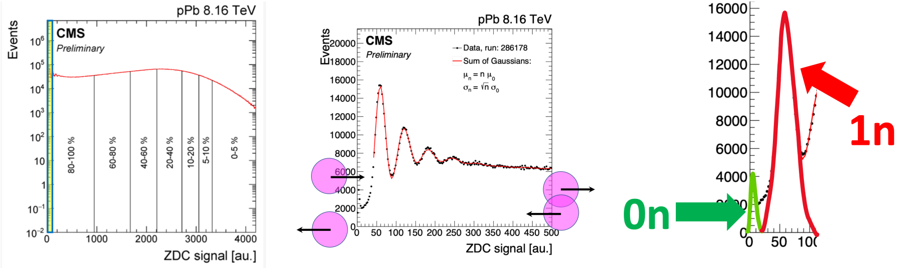

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  - Therefore maximally 2% of 1n events look like 0n events

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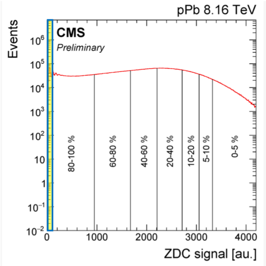

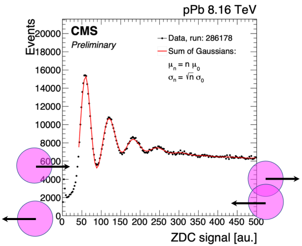

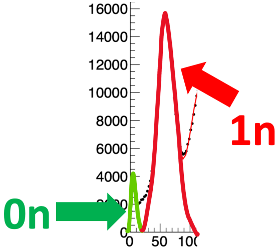

Minimum bias data ($\geq$7 GeV in forward calorimeter) **CMS 10.1088/1748-0221/16/05/P05008**

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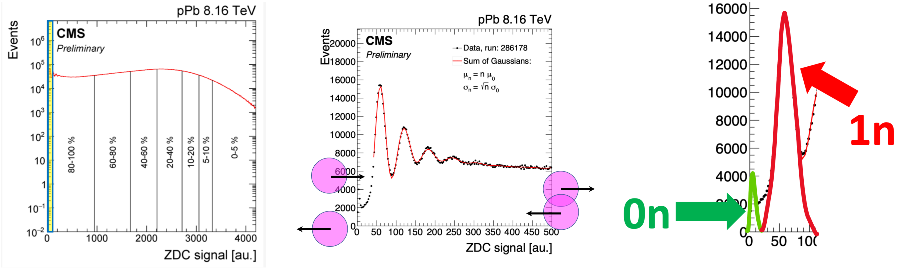

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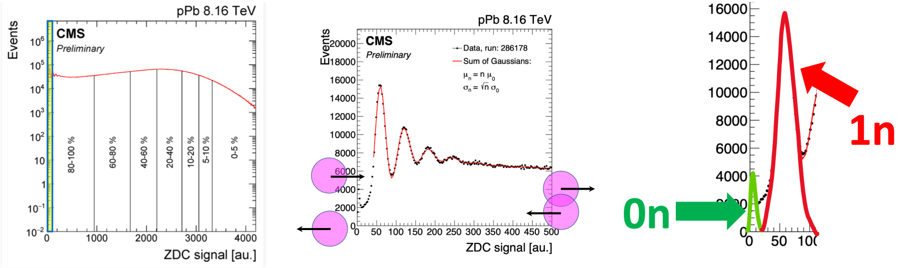

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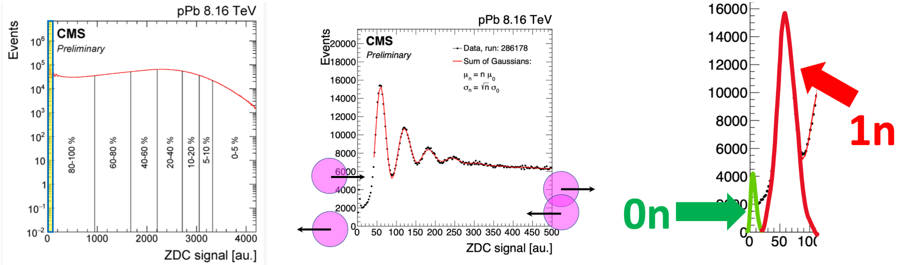

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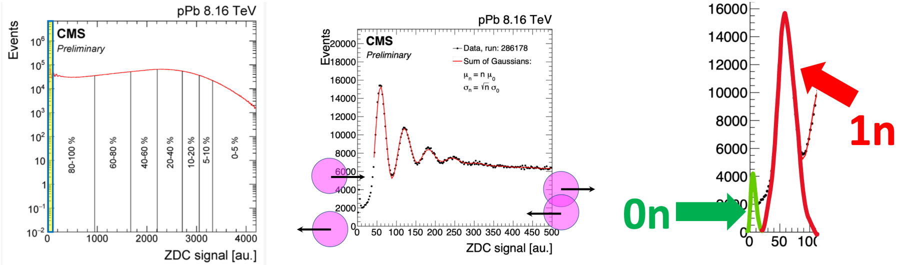

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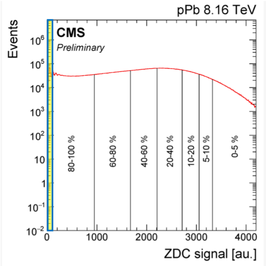

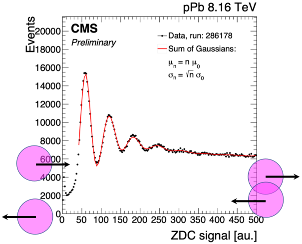

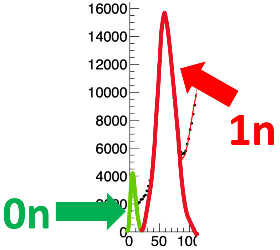

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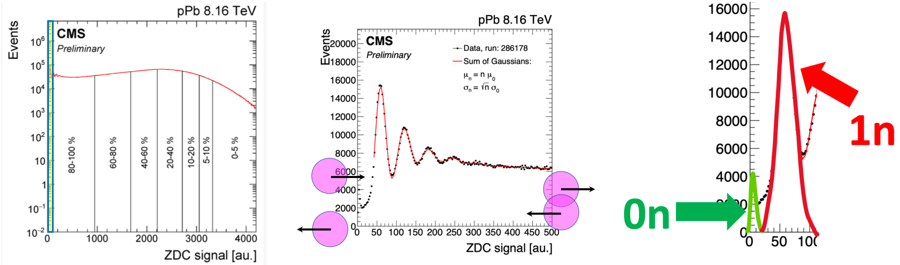

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  - 3 with $\epsilon = 0.02$ and 7 with $\epsilon = 0.01$
- This background reduction technique can be used in CMS, ALICE & ATLAS.

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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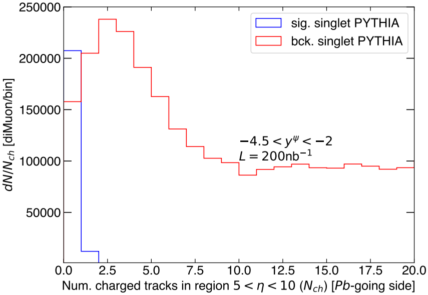

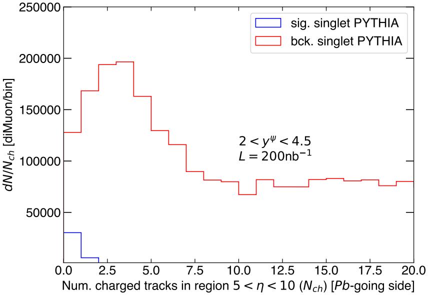

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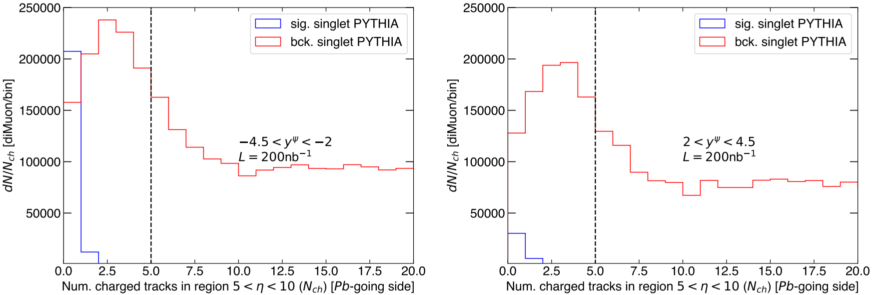

If we take 5 tracks as our cut value; we expect to retain $\mathcal{O}(100\%)$ of the signal and remove $\mathcal{O}(95\%)$ the background.

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
- **Background**: more events with smaller gaps

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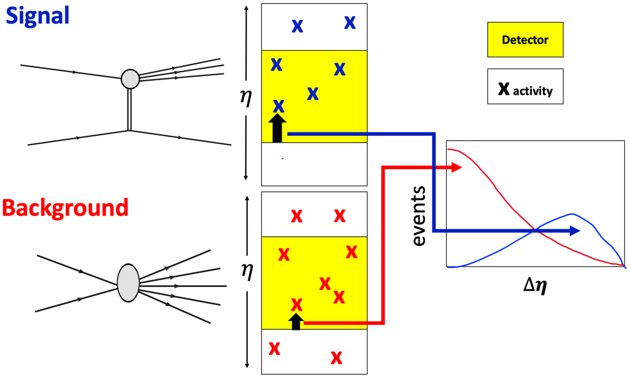

Method III: Rapidity gap distributions in CMS acceptance

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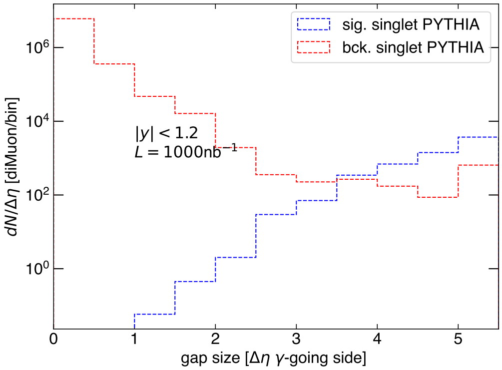

Most background events have a small gap size.
Most signal events have large gap size.

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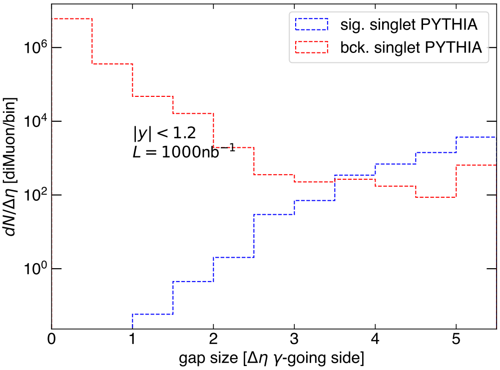

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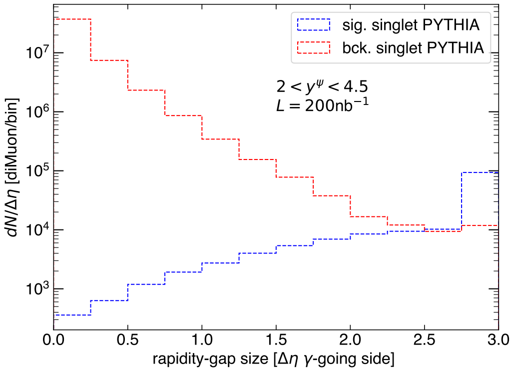
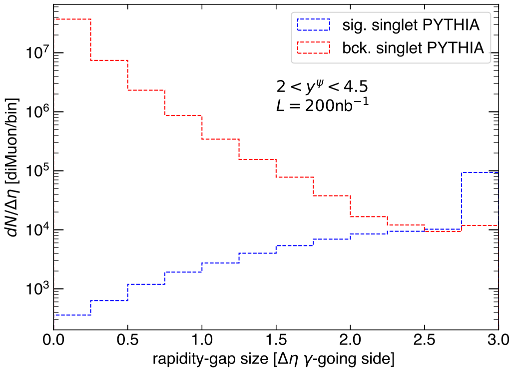
If we take a cut value of $\Delta\eta = 2$; we expect to retain $\mathcal{O}(99\%)$ of the signal and remove $\mathcal{O}(99\%)$ the background.

Method III: Rapidity gap distributions in LHCb acceptance



If we take a cut value of $\Delta\eta = 2$; we expect to retain $\mathcal{O}(40-80\%)$ of the signal and remove $\mathcal{O}(99\%)$ the background.



If we take a cut value of $\Delta\eta = 2$; we expect to retain $\mathcal{O}(40 - 80\%)$ of the signal and remove $\mathcal{O}(99\%)$ the background.

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

Signal-over-background in detector acceptance after cuts

	LHCb		CMS low p_T
	Pbp	pPb	
Signal-over-background:			
	$3 \cdot 10^{-3}$	$1 \cdot 10^{-2}$	$1 \cdot 10^{-2}$

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Method III	2	8	2

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Method I	-	-	6
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Method III	2	8	2
Method I-III	14	80	1400

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Kinematic reconstruction

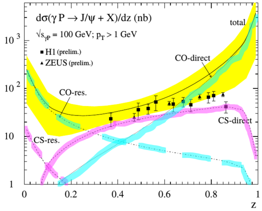
We are interested in reconstructing...

$W_{\gamma p}$ **:** 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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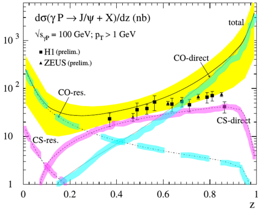

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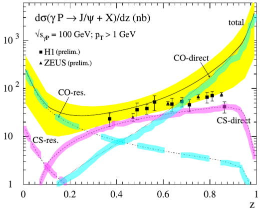

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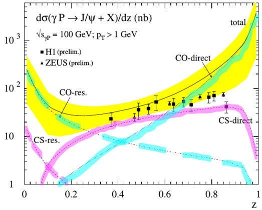

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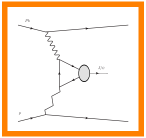
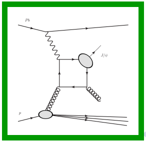
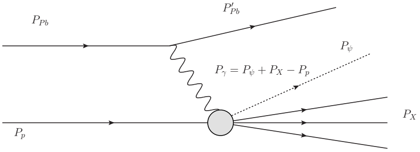
- At the LHC the scattered photon-emitter is in the beam-pipe and **cannot** be measured. To learn about the photon energy must examine the final-state system.
  - In the exclusive case this is simple; detected particle gives the photon energy
  - This is **not** true for the inclusive case... how well can we reconstruct the final state?





z Reconstruction



- Lead-ion moving forward with positive rapidity $\left(P_{Pb} \simeq \frac{1}{2} P^+_{Pb} \eta_-\right)$
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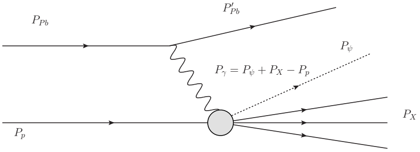

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- By momentum conservation $P_\gamma = P_\psi + P_X - P_p$

$$z = \frac{P_p \cdot P_\psi}{P_p \cdot \underbrace{(P_\psi + P_X - P_p)}_{P_\gamma}} \simeq \frac{P^+_\psi}{P^+_X + P^+_\psi}$$

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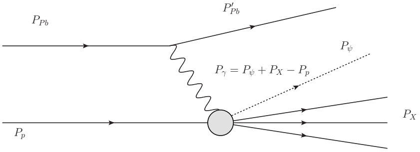

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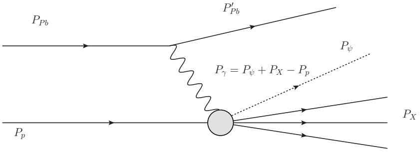
- A particle i **collinear to the proton** does not contribute to z since $P^+_i = 0$

z Reconstruction



- Lead-ion moving forward with positive rapidity $(P_{Pb} \simeq \frac{1}{2} P^+_{Pb} \eta_-)$
- Proton moving backward with negative rapidity $(P_p \simeq \frac{1}{2} P^-_p \eta_+)$
- P_X is a sum over particle momenta $\left(P_X = \sum_i^N P_i\right)$

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

$$z = \frac{P_p \cdot P_\psi}{P_p \cdot \underbrace{(P_\psi + P_X - P_p)}_{P_\gamma}} \simeq \frac{P^+_\psi}{P^+_X + P^+_\psi}$$

- A particle i **collinear to the proton** does not contribute to z since $P^+_i = 0$
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  - Diffractive proton-break-up case: $P^+_X \to 0 \to z \simeq 1$

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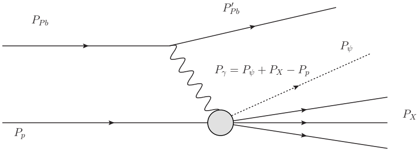

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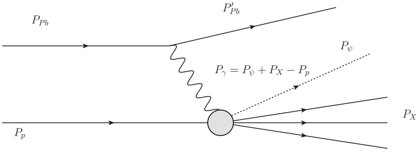

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  - Resolved photon case: at a given photon energy, increase amount of radiation in the photon direction $\rightarrow P^+_{X\text{res.}} > P^+_{X\text{dir.}} \rightarrow z_{\text{dir.}} > z_{\text{res.}}$

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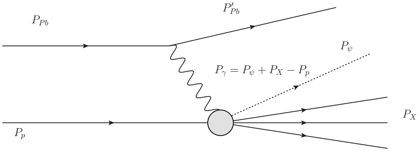

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Analogously, $W_{\gamma p} \simeq \sqrt{2 P_p \cdot P_\gamma} \simeq \sqrt{P^-_p (P^+_\psi + P^+_X)}$ is only dependent on plus-component momenta.

Per event z reconstruction

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

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CMS requirements

Charged	no	yes
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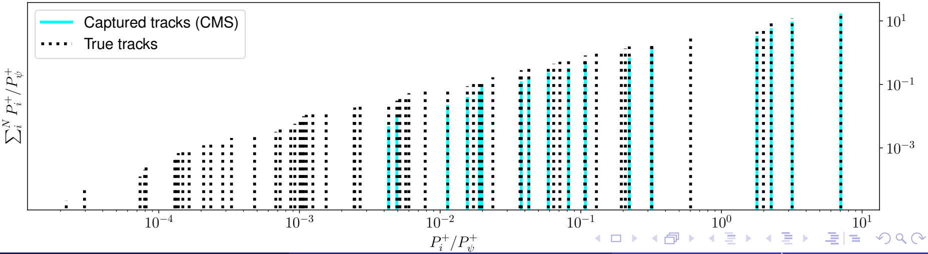

z Reconstruction at the LHC: summary

$$z = \frac{1}{1 + \frac{P_X^+}{P_\psi^+}}$$

- Only measure particles **in** the **detector acceptance**
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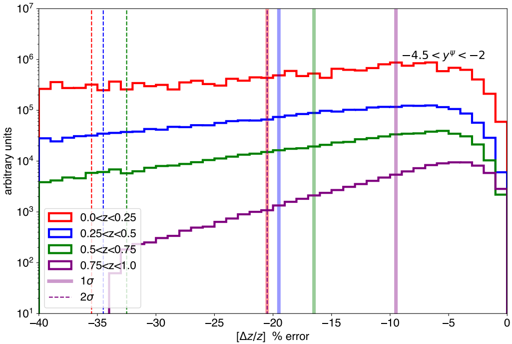

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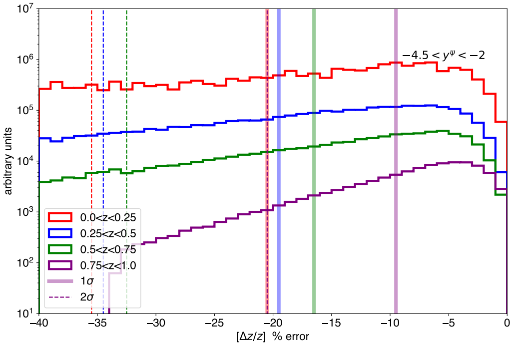

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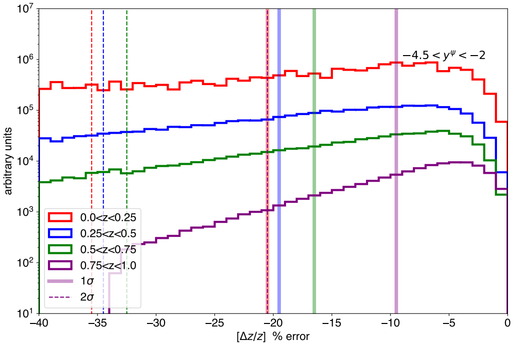


- z res. $(\sigma_{\Delta z})$ improves with increasing z
- $< z >$ increases with y^ψ and $W_{\gamma p}$
- z-reconstruction in the region... in **CMS** and **LHCb**
  - $0.20 < z < 0.45$... reconstructed within **30%** **25%**
  - $0.45 < z < 0.70$... reconstructed within **25%** **30%**
  - $0.70 < z < 0.90$... reconstructed within **10%** **20%**
  - $0.90 < z < 1.0$... reconstructed within **5%** **10%**

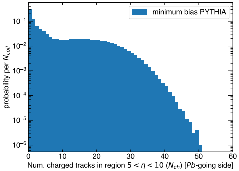
Summary and outlook

- 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 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.

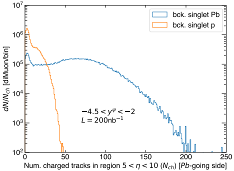
Backup

From p to Pb in the HeRSCheL region

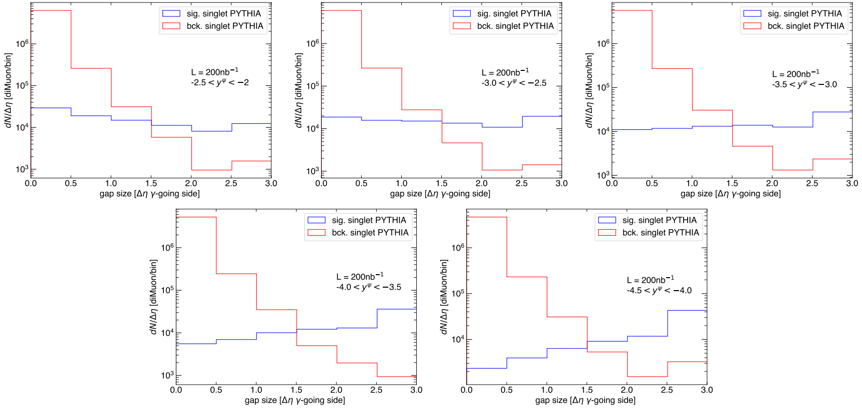
- The background is modelled by generating pA events with HELAC-Onia and passing them through PYTHIA; PYTHIA reads these as pp events.
- In a pp collision $N_{coll.} = 1$; whereas in a pA collision there are many more nucleons and therefore it is possible to have $N_{coll.} > 1$ [typically modelled using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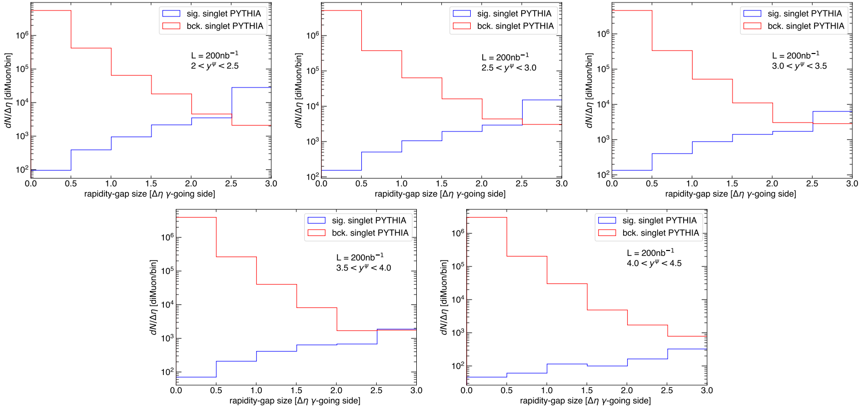


z Reconstruction at the LHC: summary

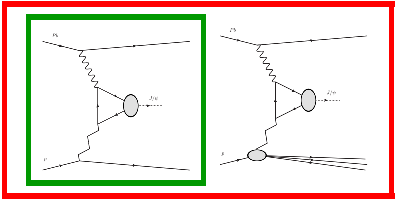
In a given kinematic region, the percentage error on z-reconstruction at one standard deviation.

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

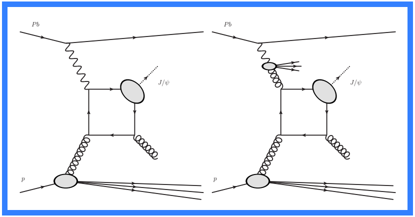
Diffractive vs. inclusive photoproduction

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,

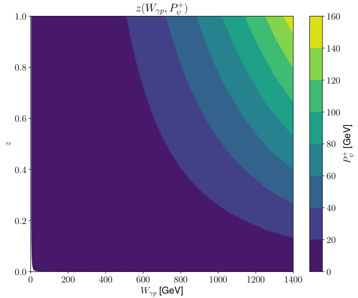
$$p \cdot q = \frac{1}{2}\left(P^+Q^- + P^-Q^+\right) - \mathbf{p} \cdot \mathbf{q}. \tag{3}$$

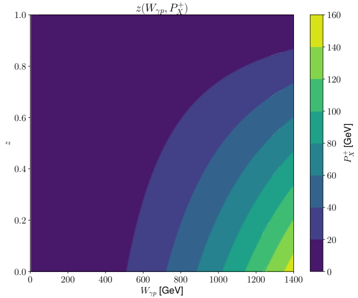
4. If p lies along the vector η^-, then the scalar product reduces to,

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

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 $\rightarrow p \cdot q = 0$.

Resolution of reconstructed variables





$$\frac{\delta z}{z} = z\frac{P_X^+}{(P_\psi^+)^2}\delta P_\psi^+ \oplus z\frac{\delta P_X^+}{P_\psi^+}$$

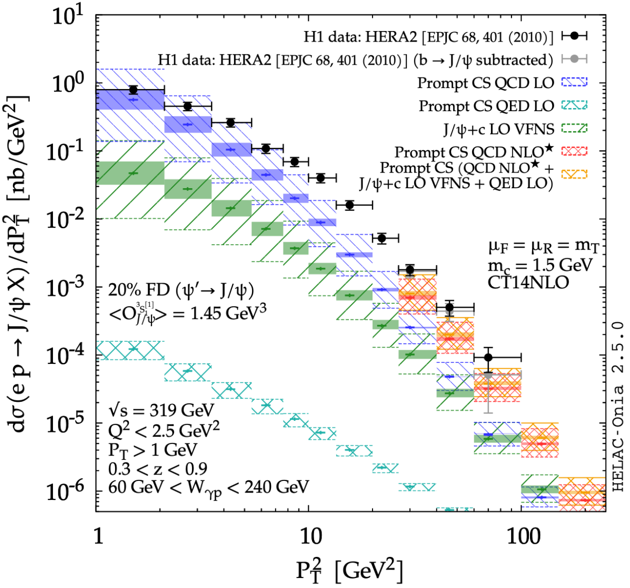
- Poor z resolution at small P_ψ^+

$$\frac{\delta W_{\gamma p}}{W_{\gamma p}} = \frac{P_p^-}{2W_{\gamma p}^2}\delta P_\psi^+ \oplus \frac{P_p^-}{2W_{\gamma p}^2}\delta P_X^+$$

- Poor $W_{\gamma p}$ resolution at small $W_{\gamma p}$

NLO inclusive J/ψ photoproduction at HERA

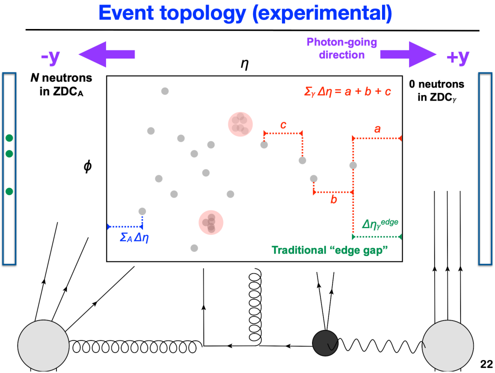
arXiv:2107.13434

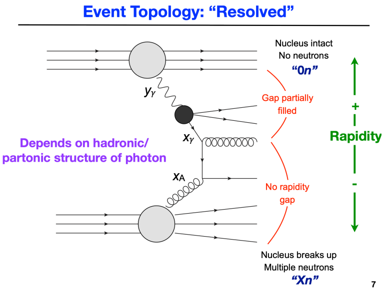


ATLAS UPC dijet Study

ATLAS-CONF-2022-021

- Pb-Pb @ $\sqrt{s_{NN}} = 5.02$ TeV
  - 0nXn requirement [$E_{ZDC} < 1$ TeV]
  - $\sum_\gamma \Delta\eta$ requirement [instead of $\Delta\eta_\gamma^{edge}$]
    - Include resolved photon in analysis
    - What is the effect of higher order corrections on choice of gap definition?





Slides from A. Angerami

LHC @ 13 TeV **slide from Leif Lonnblad**

Total	100 mb
Non-diffractive	56 mb
Elastic	22 mb
Diffractive	22 mb
Jets $p_\perp > 150$ *GeV*	220 nb
W+Z	200 nb
Top	600 pb
Higgs	30 pb

Luminosity targets taken from LHC programme coordination meeting; pPb 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}
pPb	1 pb^{-1}		0.5 pb^{-1}	0.2 pb^{-1}