Inclusive quarkonium photoproduction in ultra-peripheral collisions

Kate Lynch

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QCD evolution

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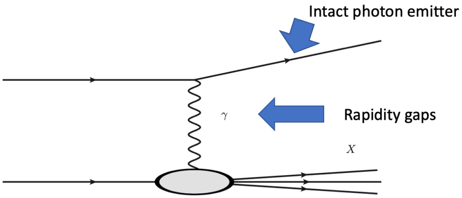

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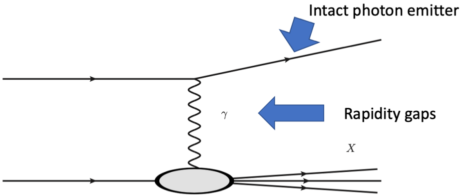

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  - Scattered lepton detected $\rightarrow$ photon energy is known
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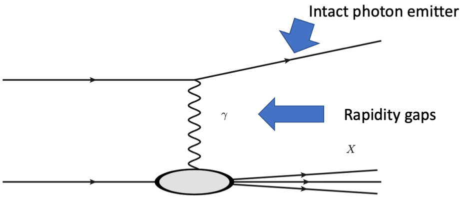
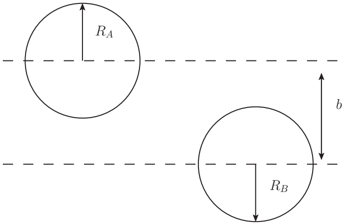


- In **electron proton** collisions...
  - Scattered lepton detected → photon energy is known
  - Scattered lepton **not** detected (i.e. small photon virtuality) → photon energy can only be determined by reconstructing final states
- In **proton-proton**, **proton-ion**, or **ion-ion** collisions...
  - **Cannot** detect scattered beam particle → can we reconstruct photon energy at the LHC? (Later...)
  - Require the photon emitter is intact = **coherent photoproduction** (i.e. photon emitted outside charge radius →**UPC**)

Ultra peripheral collisions...



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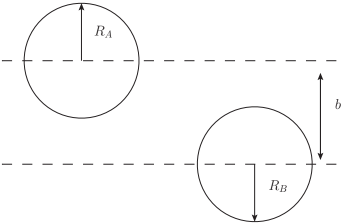

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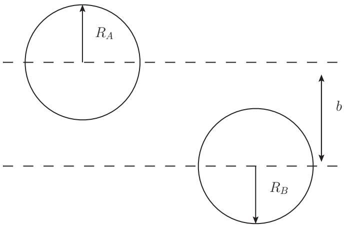

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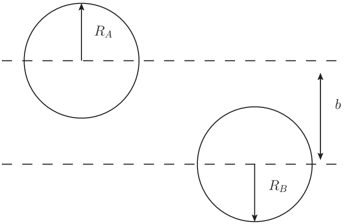

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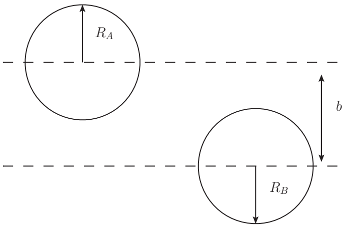

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  - proton-lead: $\sqrt{s_{NN}} = 8.16$ TeV $\rightarrow$ $\boxed{W_{\gamma N}^{max} \approx 1.4 \text{ TeV}}$
  - electron-proton:
    - HERA: $\sqrt{s_{ep}} = 320$ GeV
    - EIC: $\sqrt{s_{ep}} = 45 - 140$ GeV

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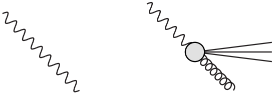

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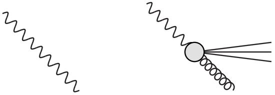
- Bound states of heavy quarks $c\bar{c}$ or $b\bar{b}$
- Production mechanism remains an open question... Colour Singlet Model vs. Colour Octet Mechanism and NRQCD vs. Colour Evaporation Model



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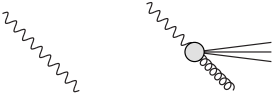
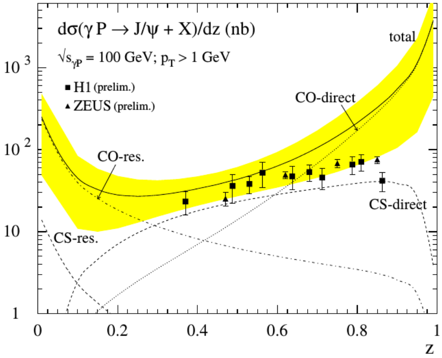


direct and resolved photons

Discriminant variable?

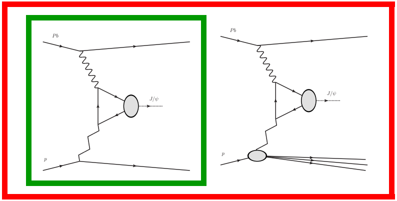
- Elasticity $z = \frac{P_\psi \cdot P_p}{P_\gamma \cdot P_p}$



KRAMER, hep-ph/016120

Diffractive vs. inclusive photoproduction

Diffractive production



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- **exclusive**: **only** J/ψ decay products

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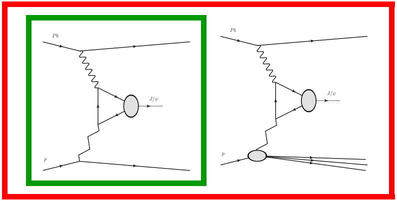

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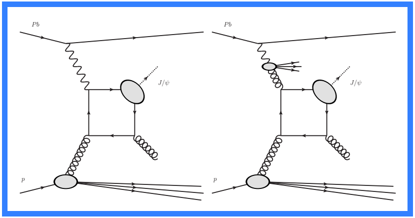

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- Resolved vs. direct contribution
- Test production mechanism
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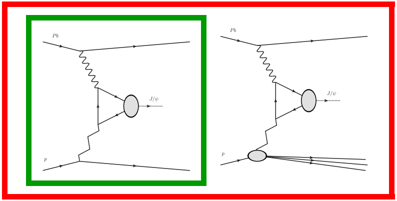

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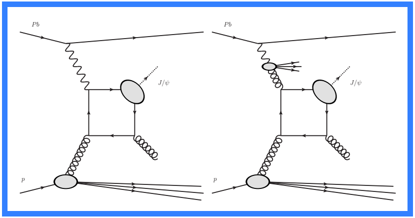

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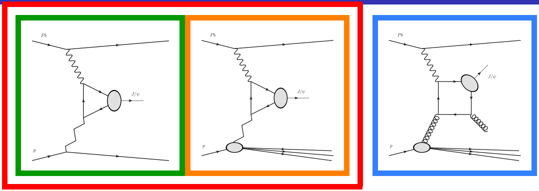
We propose inclusive photoproduction is measured at the LHC; opportunity to extend p_T- & $W_{\gamma p}$-reach, capture a variety of quarkonium species & improve statistical accuracy of existing data

Photoproduction measurements at HERA in e-p collisions



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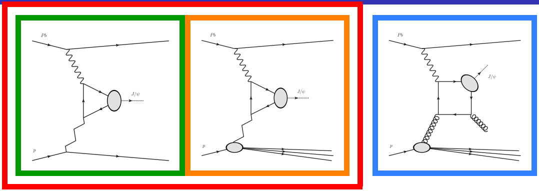

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  - different contributions separated using experimental cuts ...
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      additional constraints on activity separate exclusive and proton-disassociative
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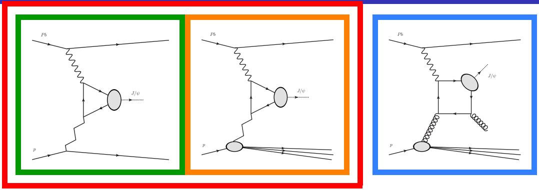

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- Each contribution is found to be comparable $\sigma \simeq \sigma \simeq \sigma$

... exclusive measurements have been made at the LHC therefore we expect there is an inclusive signal...

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Why? Next *e*-*p* data taking possible at the EIC ($\sim$10 years)

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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*]

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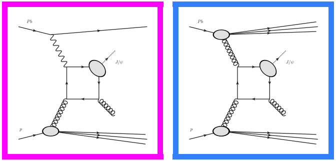

- Hadroproduction contribution is greater than photoproduction; $\sigma > \sigma$
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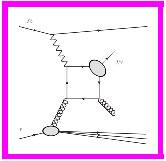

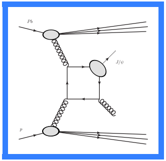

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- In order to make a measurement we must be able to reduce the hadroproduction contribution... we will call this background

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Generating samples

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

- Use HELAC-Onia to generate MC samples [in the NRQCD framework]
- Use octet- and singlet-contributions to model the signal and background
  - Signal $[\gamma g \rightarrow J/\psi(^3S_1^1)g\ ]$ and $[\gamma g \rightarrow J/\psi(^1S_0^8)g\ ]$
  - Background $[gg \rightarrow J/\psi(^3S_1^1)g\ ]$and $[gg \rightarrow J/\psi(^3S_1^8)g\ ]$
- 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
  - hadroproduction background LHCb 5 TeV *pp* data **10.1007/JHEP11(2021)181**
  - photoproduction signal H1 *ep* 320 GeV data **10.1140/epjc/s10052-010-1376-5**;**10.1007/s10052-002-1009-8**

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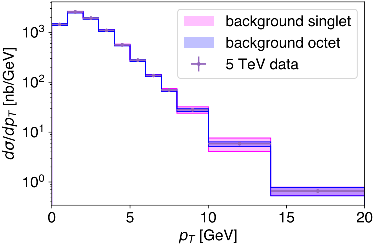
Validation: hadroproduction background

Reweight MC to data;
rapidity integrated
LHCb data @ 5 TeV



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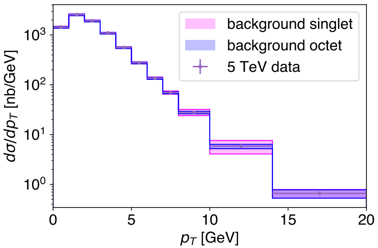

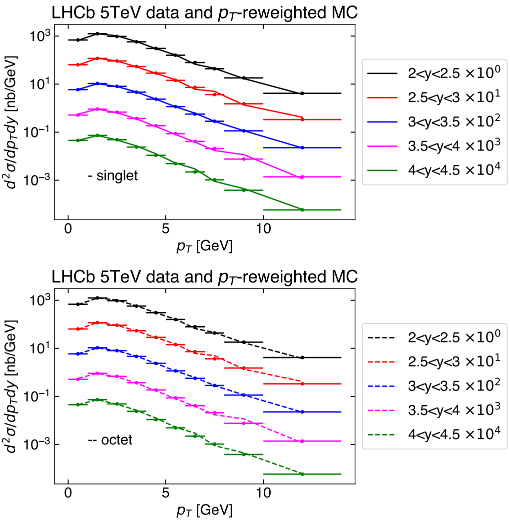

Validation: hadroproduction background

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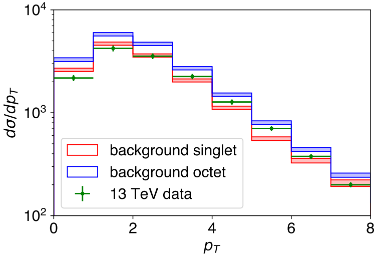
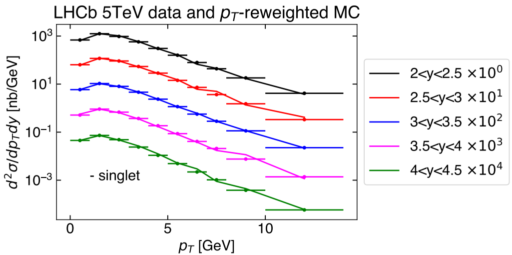
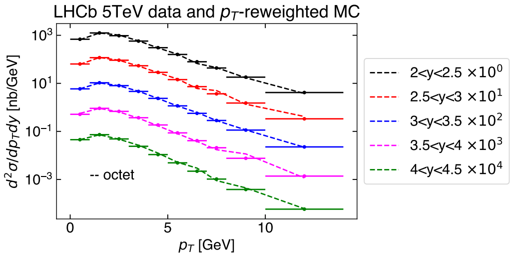
- Compare RW MC to rapidity-differential data
- Compare RW MC to data at 13 TeV







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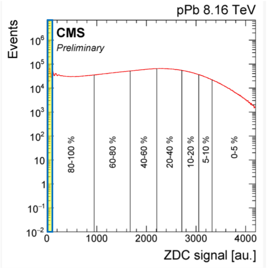
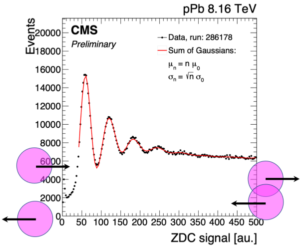
Method I: far-forward activity; zero degree calorimeter

- Far-forward detectors close to beam-pipe; used to classify centrality
- No interference with quarkonium production mechanism





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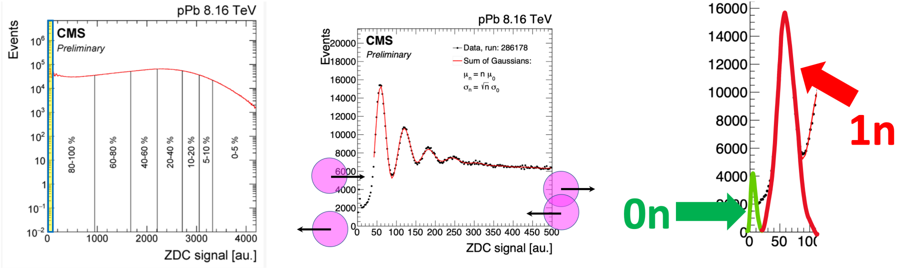

Minimum bias data ($\geq$7 GeV in forward calorimeter) **CMS 10.1088/1748-0221/16/05/P05008**

- Can resolve single to few neutron emissions
- All of the signal is in the 0-neutron bump [signal with neutron emission is negligible]
- Background is in the $\geq$ 1-neutron region

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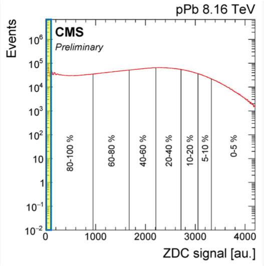

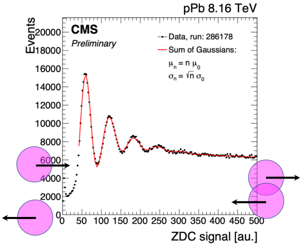

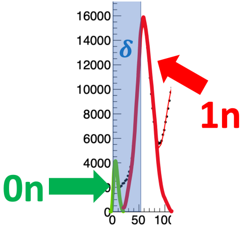

Minimum bias data (≥7 GeV in forward calorimeter) **CMS 10.1088/1748-0221/16/05/P05008**

- If we fix the ZDC cut value such that we keep a proportion (δ) of events which contains $\mathcal{O}(100\%)$ of the signal ($\delta = \hat{s} + x\hat{b}$)
- Then we retain a fraction x of the background; where $x = 1 - (1-\delta)(1+\frac{\hat{s}}{\hat{b}})$
- Choosing $E_{zdc} = 20$ a.u. $\rightarrow \delta = 10^{-3}$ and assuming sig. over bkg. $\frac{\hat{s}}{\hat{b}} = 10^{-3}$
- The sig. over bkg. in our sample moves to $\frac{\hat{s}}{x\hat{b}} = 10^{3}$
- This can be done in ALICE, CMS & ATLAS

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

- HeRSCheL detectors at forward and backward rapidity in the region $5 < |\eta| < 10$
- Expect some interference with quarkonium production mechanism

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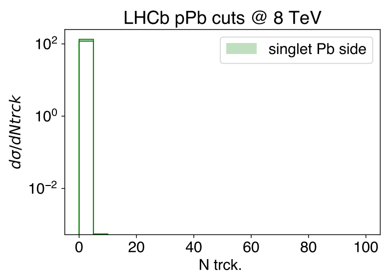
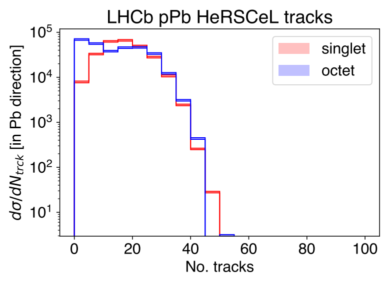
- HeRSCheL detectors at forward and backward rapidity in the region $5 < |\eta| < 10$
- Expect some interference with quarkonium production mechanism
- Use MC samples to count the number of charged tracks in HeRSCheL region

Illustrative **Preliminary**



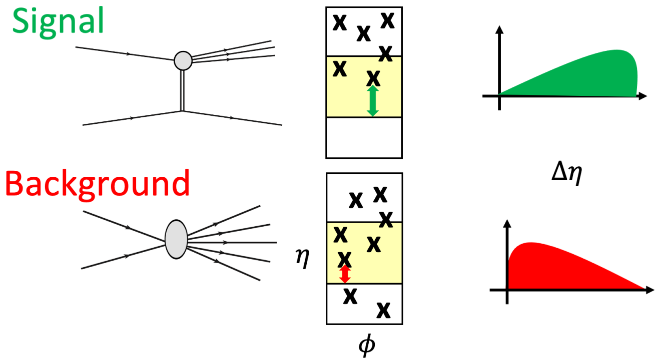


If we take 5 tracks as our cut value; we expect to retain $\mathcal{O}(100\%)$ of the signal and remove $\mathcal{O}(80 - 95\%)$ the background.

Method III: central activity; rapidity gaps

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

- Larger rapidity gaps in signal events due to less activity
- Smaller rapidity gaps in background events due to more activity



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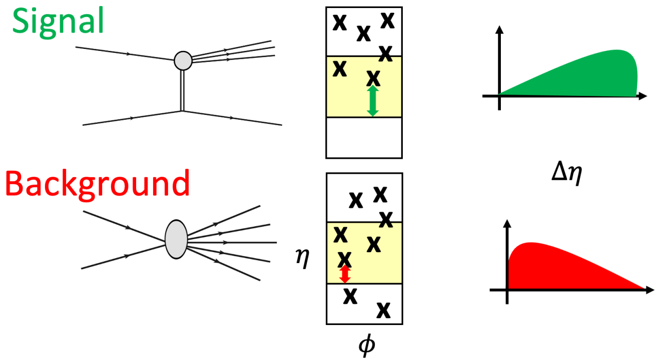
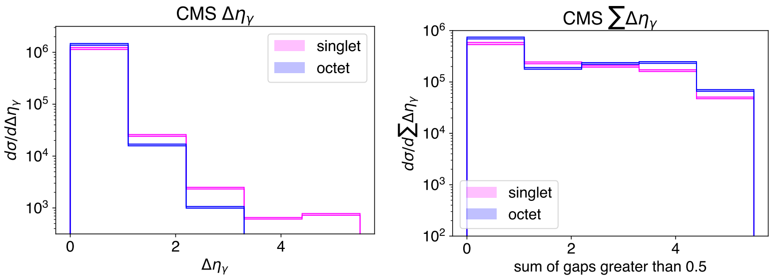


- Production-mechanism dependant observable; i.e. colour singlet and colour octet yield different gap distributions

Method III: Gap distributions in CMS acceptance

- Rapidity-gap-type observables are ideal where there is a wide rapidity coverage, i.e., CMS and ATLAS
- Different rapidity gap definitions have...
  - different efficiencies
  - sensitivity to description of quarkonium production

Preliminary



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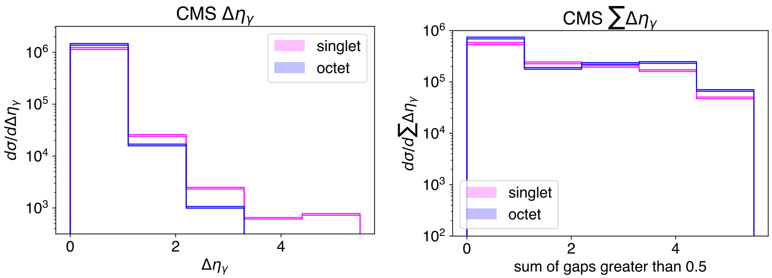

- Gap size can be chosen to achieve desired purity and statistics in a given sample

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Kinematic reconstruction

We are interested in reconstructing...

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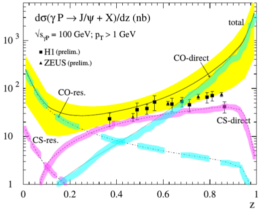
Both variables depend on exchange photon energy!

KRAMER, hep-ph/016120



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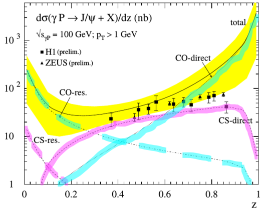

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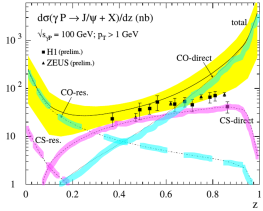

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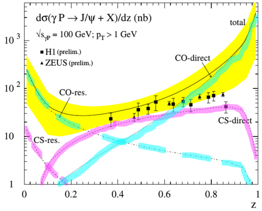

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  - **measured** the photon energy is known
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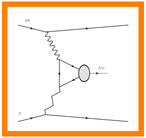
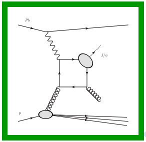
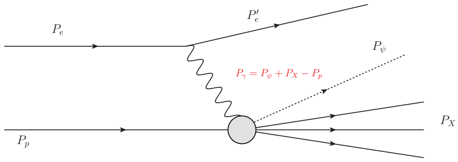
- At the LHC the scattered photon-emitter **cannot** be measured therefore to know the photon energy we must reconstruct the final state
  - In the exclusive case this is simple; final state particle gives the photon energy
  - This is **not** true for the inclusive case... how well can we reconstruct the final state?





z Reconstruction at HERA

Nucl.Phys.B 472 (1996) 3-31



Electron moving forward with positive rapidity

Proton moving backward with negative rapidity

$$z = \frac{P_p \cdot P_\psi}{P_p \cdot (P_\psi + P_X - P_p)}$$

$$= \frac{(E + p_z)_\psi}{(E + p_z)_\psi + \sum (E + p_z)_X}$$

$$= \frac{1}{1 + \frac{\sum (E+p_z)_X}{(E+p_z)_\psi}} = \frac{1}{1 + \frac{P_X^+}{P_\psi^+}}$$

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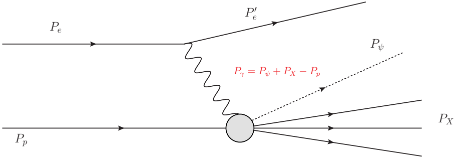

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- Anything collinear to the proton $(E + p_z = 0)$ does not contribute to the denominator of z!
  - In the exclusive case, there is nothing, $P_X^+ = 0$; z=1
  - In the diffractive proton break-up case, $P_X^+ \to 0$; $z \simeq 1$

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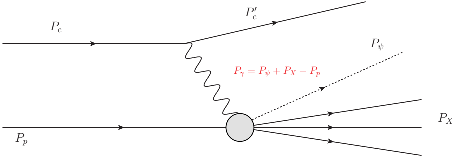

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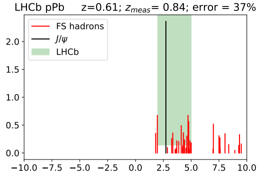
  - In the diffractive proton break-up case, $P_X^+ \to 0$; $z \simeq 1$
- The most forward tracks contribute most $(E + p_z = m_T e^y)$
  - In the resolved photon case $z \to 0$

z Reconstruction at the LHC

← **proton direction**



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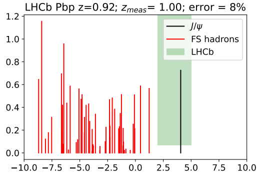

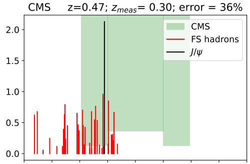

	CMS		**LHCb**
Charged	no	yes	no
p_T	$p_T > 200$ MeV	$p_T > 400$ MeV	$p_T > 100$ MeV
η	$2.5 < \|\eta\| < 5$	$\|\eta\| < 2.5$	$2 < \eta < 5$

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

z Reconstruction at the LHC

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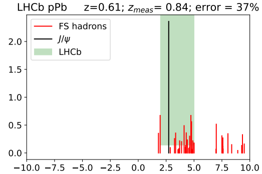

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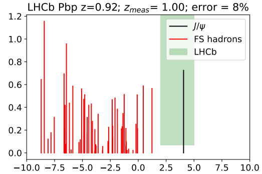

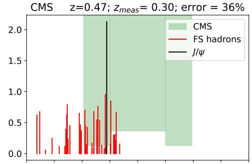

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  - $z_{measured} \geq z_{theoretical}$ due to missed particles

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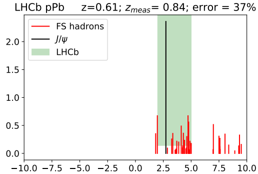

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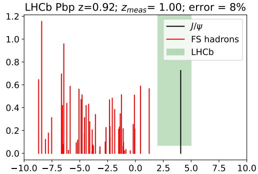

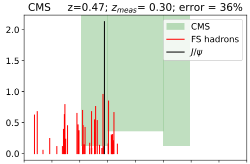

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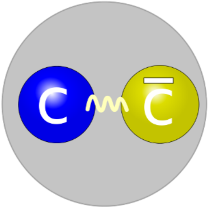
- Only measure particles **in** the **detector acceptance**
  - $z_{measured} \geq z_{theoretical}$ due to missed particles
- z resolution ($\sigma_{\Delta z}$) improves with increasing z
- $< z >$ increases with rapidity and $W_{\gamma p}$
- The z-reconstruction is best in the large $W_{\gamma p}$/most forward region

Summary and outlook

- Measuring inclusive photoproduction at the LHC appears feasible which is complimentary to the HERA measurements
- In *Pb*-*p* collisions at CMS, ATLAS and ALICE the ZDC is sufficient to suppress backgrounds
- For LHCb a combination of gap and HeRSCheL are likely sufficient to suppress background
- Increasing the size of the rapidity gap cut will enhance the purity of the sample
- z and $W_{\gamma p}$ reconstruction appears possible at large energy which will allow control of the resolved contribution and offer the possibility to learn about the quarkonium production mechanism

What are Quarkonia

- Bound states of heavy quarks $c\bar{c}$ or $b\bar{b}$



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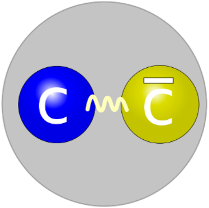

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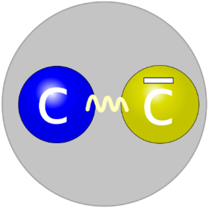

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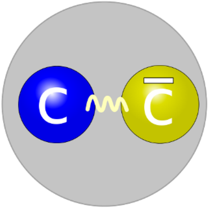

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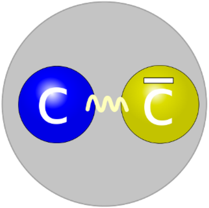

- Quarkonium production is separated into two energy regimes
  - Heavy quark pair production $m_Q >> \Lambda_{QCD}$
  - Hadronisation is non-perturbative
- **Factorisation** between short and long distance physics
- Production mechanism remains an open question!

Status today ...?

1. Colour Singlet Model
    - problems in p_T spectrum at large p_T
    - improved by NLO corrections
    - describes η_c data @ NLO

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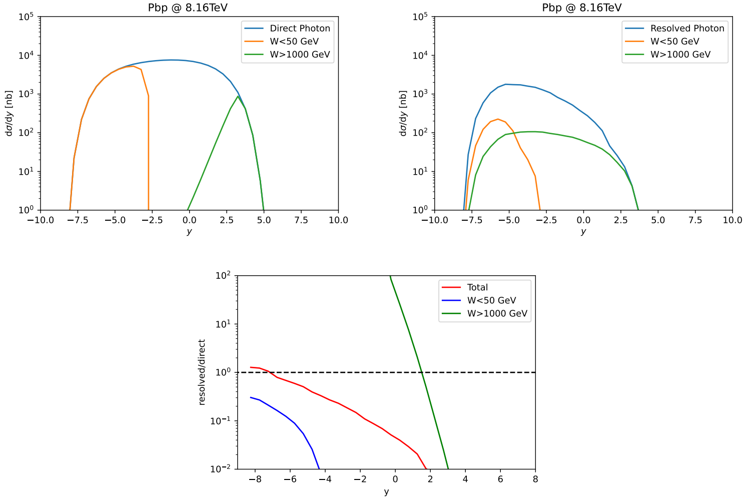
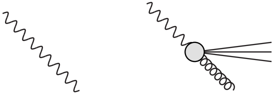
3. Colour Evaporation Model
   - tends to overshoot the data at large p_T
   - fails for $J/\psi J/\psi$ data

Rapidity distribution with slices in $W_{\gamma p}$



(Quasi)on-shell or off-shell photon...

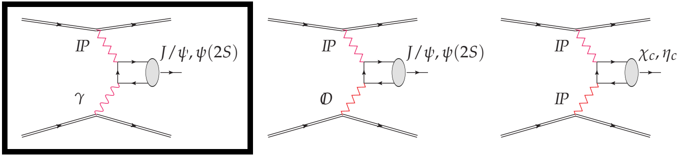
- **Photoproduction** quasi-real photon $Q^2 << m^2_{J/\psi}$
  - Bulk of the cross-section
  - easy to compute (hard scale)
  - resolved component!
- **Leptoproduction** virtual photon γ^* $Q^2 > m^2_{J/\psi}$
  - Smaller cross-section
  - difficult to compute (introduce new scale)
  - **NO** resolved component



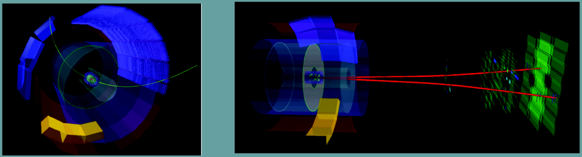
direct and resolved photons

Exclusive J/ψ production

Colourless exchanges via $\mathbb{P}$,$\mathbb{O}$ or γ emission.

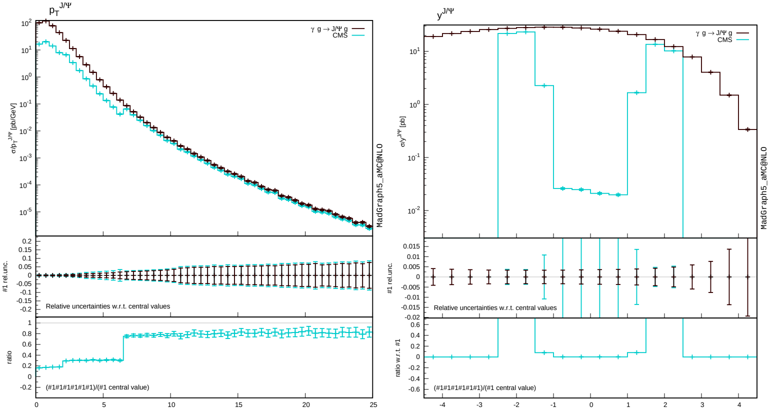


- only **colour singlet** contributions
- Clean signal
  - **only** quarkonia and its decay products are produced.
  - **both** colliding particles stay intact



UPC candidate in the central barrel and muon spectrometer

Photoproduction cross section

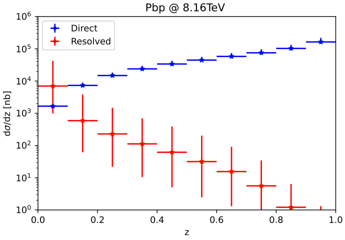


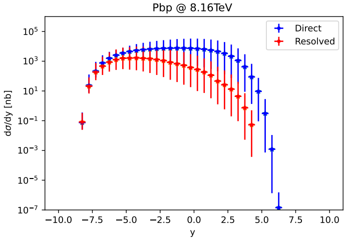
8.16 TeV photoproduction in Pbp

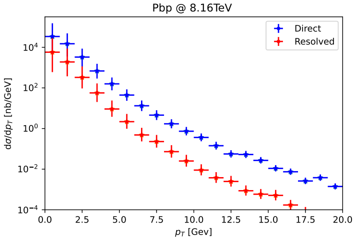
CMS cuts

- Cross-section steeply falling in p_T

Photoproduction cross section: resolved vs. direct

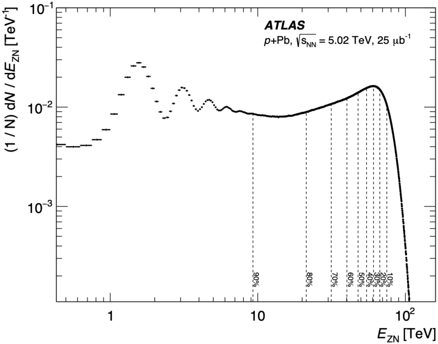






Cutting background: zero degree calorimeter

ATLAS CERN-EP-2022-086

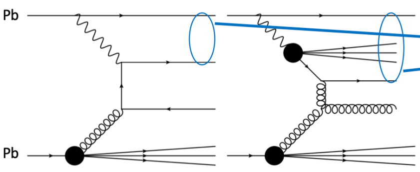


Selecting Photo-nuclear Dijet Events

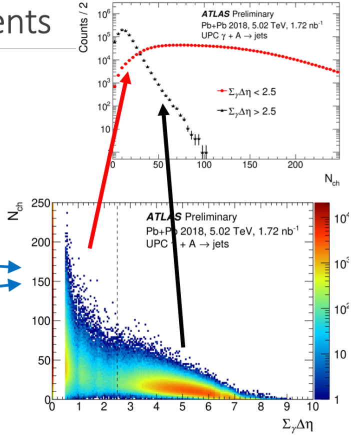
Event Selections → Raw Yields → Unfolding → Systematic Uncertainties → Final Results

<u>Event Selections</u>

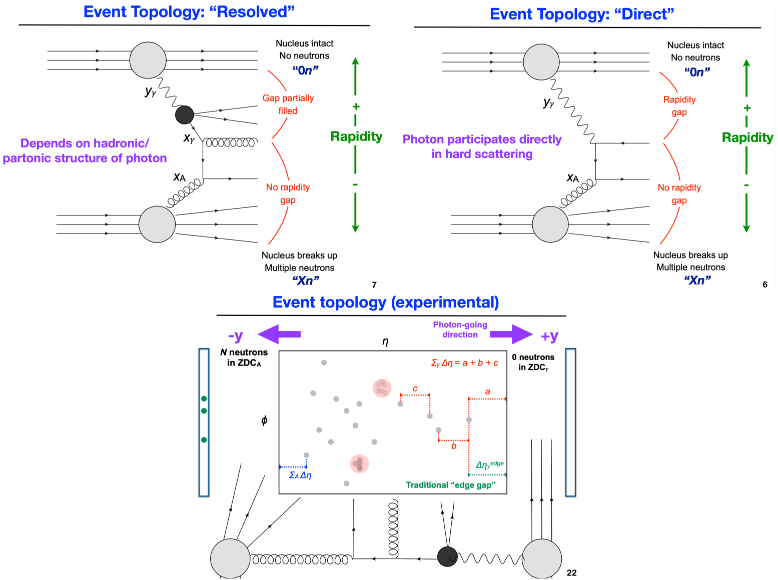
- 0nXn requirement for nuclear breakup in exactly <u>one</u> ATLAS Zero-Degree Calorimeter (ZDC)
- Large rapidity gaps on one side of the detector
  - To veto $\gamma\gamma \rightarrow q\bar{q}$, we also require $\Delta\eta_A^{edge} > 3$



Direct   Resolved



Slide from Ben Gilbert



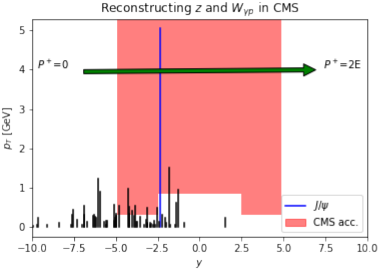
Slides from A. Angerami

z and $W_{\gamma p}$ exclusive vs. inclusive...

$$z = \frac{P_p \cdot P_\psi}{P_p \cdot (P_\gamma = P_\psi + P_X - P_p)} \qquad W_{\gamma p} = \sqrt{(P_\gamma + P_p)^2} = \sqrt{(P_p^- P_\psi^+)\frac{2}{z}}$$

EXCLUSIVE: $P_p \cdot P_\psi \quad \rightarrow z = 1 \qquad \rightarrow W_{\gamma p} = \sqrt{4E_p(m_T e^y)_\psi}$

INCLUSIVE: $P_p \cdot (P_\psi + P_X) \quad \rightarrow z = \frac{1}{1+\frac{P_X^+}{P_\psi^+}}$



through direct photon processes are

$$\gamma + g \;\rightarrow\; c\bar{c}\left[1,{}^3S_1;\, 8,{}^3S_1;\, 8,{}^1S_0;\, 8,{}^3P_J\right] + g, \tag{17}$$

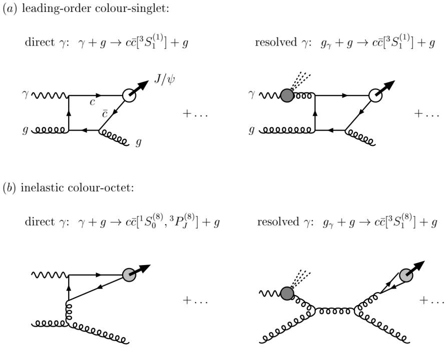
$$\gamma + q/\bar{q} \;\rightarrow\; c\bar{c}\left[8,{}^3S_1;\, 8,{}^1S_0;\, 8,{}^3P_J\right] + q/\bar{q}, \tag{18}$$

where the initial-state parton originates from the target proton. For resolved photon processes, the subchannels are

$$g + g \;\rightarrow\; c\bar{c}\left[1,{}^3S_1;\, 8,{}^3S_1;\, 8,{}^1S_0;\, 8,{}^3P_J\right] + g, \tag{19}$$

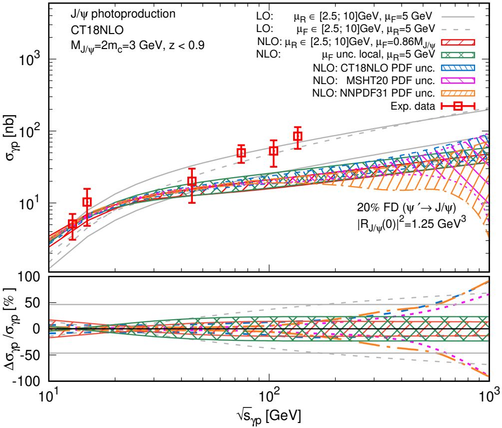
$$g + q/\bar{q} \;\rightarrow\; c\bar{c}\left[8,{}^3S_1;\, 8,{}^1S_0;\, 8,{}^3P_J\right] + q/\bar{q}, \tag{20}$$

$$q + \bar{q} \;\rightarrow\; c\bar{c}\left[8,{}^3S_1;\, 8,{}^1S_0;\, 8,{}^3P_J\right] + g, \tag{21}$$



NLO computation for inclusive photoproduction

Colpani Serri, Feng, Flore, Lansberg, Ozcelik,Shao,Yedelkina, PLB835 (2022) 137556



NLO computation for $\gamma p \rightarrow J/\psi X$.

At the LHC can extend the measurement to $\sim 10^3$ GeV.

ATLAS UPC dijet Study

ATLAS-CONF-2022-021

- Pb-Pb @ $\sqrt{s_{NN}} = 5.02$ TeV
  - 0nXn requirement [$E_{ZDC} < 1$ TeV]

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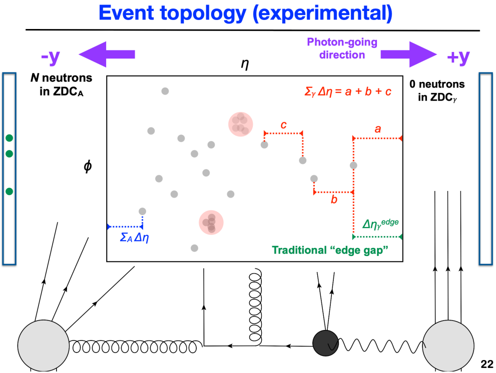
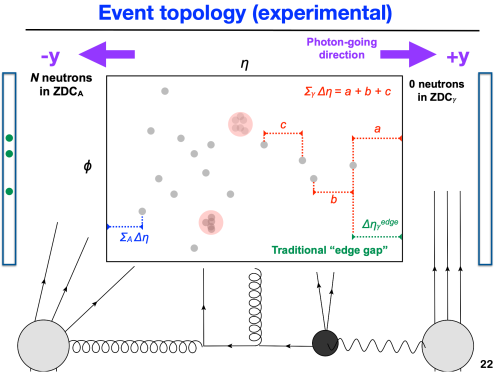
  - $\sum_\gamma \Delta\eta$ requirement [instead of $\Delta\eta_\gamma^{edge}$]

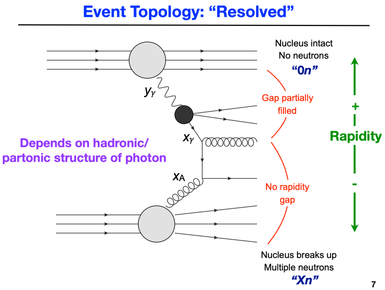


Slides from A. Angerami

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

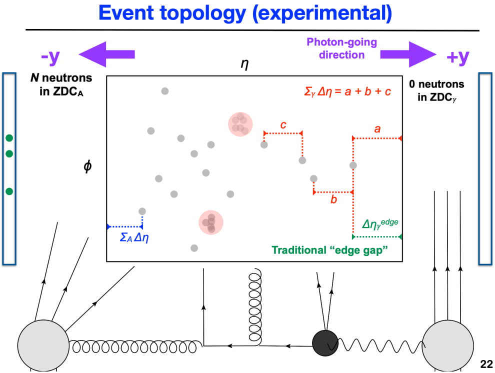


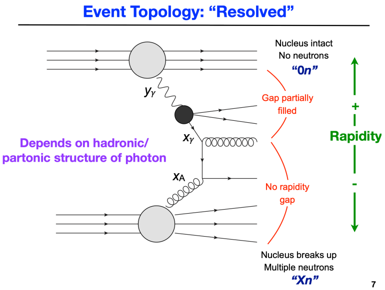


Slides from A. Angerami

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?





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Quarkonium Production

1. Colour Singlet Model
   - $Q\bar{Q}$ pair produced with the same quantum numbers as $\mathcal{Q}$
   - **NO** gluon emissions during hadronisation
   - $d\sigma(\mathcal{Q} + X) = d\sigma(Q\bar{Q} + X)\langle\mathcal{O}^{\mathcal{Q}}\rangle$

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   - $Q\bar{Q}$ pairs with different quantum numbers contribute
   - Higher Fock states are v-suppressed
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3. Colour Evaporation Model
   - Quantum numbers of $Q\bar{Q}$ decorrelated from $\mathcal{Q}$
   - Semi-soft gluon emissions during hadronisation
   - $\mathrm{d}\sigma(\mathcal{Q}+X) \propto \int_{2m_Q}^{2m_H} \frac{d\sigma(Q\bar{Q}+X)}{dm_{Q\bar{Q}}} dm_{Q\bar{Q}}$