Ultraperipheral heavy-ion collisions

Valerie Lang
On behalf of the large LHC experiments

LHCP Conference, Boston, US
4 June 2024
Or: News from nearly empty detectors?
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Standard (central) heavy ion collision
Ultraperipheral heavy ion collision
Features of ultraperipheral collisions

Interaction of Pb-nuclei via electromagnetic fields for impact parameters $b > 2R_{Pb}$

- Production of new particles from interaction of photons
  - Cross section enhanced by $Z^4 = 4.5 \cdot 10^7$ w.r.t. proton-proton
    - Large Hadron Collider (LHC) acts as photon collider!
- Also interaction of photon with nucleus possible → Photonuclear events
- Study various categories of produced particles and their properties
  - Di-lepton production: $e^+e^−, \mu^+\mu^−, \tau^+\tau^−$
  - Charged hadron production: Pions, strange mesons, charm mesons, jets, etc.
  - Light-by-light scattering

→ Disclaimer: Only show (personal) selection of results from ultraperipheral collisions
→ Consider as a teaser → Feel free to dive in deeper into many interesting results

\[ \text{Diagram showing Pb-nuclei interaction via photons} \]
Understanding the photon flux

Investigate production of $e^+e^-$ pairs

- Equivalent photon approximation (EPA):
  - Total cross section = convolution of photon flux with elementary production cross-section
- Break-up of Pb-nuclei possible → Electromagnetic dissociation
  - Induced by additional photon exchanges → Higher likelihood for smaller impact parameters → More forward neutrons
- Suppress or enhance through selections in very-forward calorimeters (ZDC)
- In addition: Backgrounds:
  - $\Upsilon$ and $\tau^+\tau^-$ production and single-dissociative process
  - Dissociation of emitting nucleus, if origin of the photons from substructure of nucleon (proton, neutron) → Largest background → Determined from fit to acoplanarity:
    $$\alpha = 1 - |\Delta \phi|/\pi \rightarrow 0 \rightarrow \text{Back-to-back configuration}$$
    $$\rightarrow 1 \rightarrow \text{Collinear configuration}$$
Understanding the photon flux

Investigate production of $e^+e^-$ pairs

- Measurement of differential cross sections, e.g. as function of invariant mass $m_{ee}$

Inclusive

Zero neutrons on either side in ZDC: 0n0n

→ Comparison to two generators with different photon flux modelling: STARlight and SuperChic

→ STARlight: Photon flux from point-like sources, restricting impact parameter $b > R_{Pb}$

→ SuperChic: Photon flux from nuclear form factor, impact parameters down to $b = 0$

→ Similar shapes as in data, but slight (different) offsets
Study τ-lepton properties

Investigate production of $\tau^+\tau^-$ pairs

- Select events with one τ-lepton decay involving muon, the other hadronically (or involving electron)

$\gamma\gamma \to \tau\tau$ clearly observed

Extract anomalous magnetic moment of τ-lepton: $a_\tau$

→ Use fit to decay muon $p_T$ distribution (ATLAS)
→ Use cross-section dependence on $a_\tau$ (CMS)
Study $\tau$-lepton properties

Investigate production of $\tau^+\tau^-$ pairs

- Select events w/ one $\tau$-lepton decay involving muon, the other hadronically (or involving electron)

$\gamma\gamma \to \tau\tau$ clearly observed

Extract anomalous magnetic moment of $\tau$-lepton: $a_\tau$

Very new: $\gamma\gamma \to \tau\tau$ in pp collisions!

$\Rightarrow$ Larger statistics beats lower cross sections

$\Rightarrow$ Heavy ion UPC measurements need to catch up
Investigate photon interactions with nucleus

Charged hadron production in direct and resolved photonuclear interactions

- Direct interaction of photon with parton in nucleus, or fluctuation of photon to vector-meson (VM), e.g. $\rho$

- Determine charged particle yield

$$ Y(\eta, p_T) = \frac{1}{N_{ev}} \frac{dN_{ch}^2}{dp_T d\eta} $$

- While selecting 0nXn topology in ZDC

→ Positive $\eta$: photon-going direction
→ Negative $\eta$: Pb-going direction
Investigate photon interactions with nucleus

Charged hadron production in direct and resolved photonuclear interactions

- Direct interaction of photon with parton in nucleus, or fluctuation of photon to vector-meson (VM), e.g. $\rho$

- Determine charged particle yield
  \[ Y(\eta, p_T) = \frac{1}{N_{\text{rec}}} \frac{d^2 N_{\text{ch}}}{d\eta dp_T} \]

- Less charged particles in photon-going direction, more in Pb-going direction
- Consistent with lower photon energy compared to per-nucleon energy of Pb

- While selecting 0nXn topology in ZDC

- Positive $\eta$: photon-going direction
- Negative $\eta$: Pb-going direction

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Investigate photon interactions with nucleus

Charged hadron production in direct and resolved photonuclear interactions

- Direct interaction of photon with parton in nucleus, or fluctuation of photon to vector-meson (VM), e.g. $\rho$
- Determine charged particle yield
  - While selecting 0nXn topology in ZDC

Comparison to MC generator in separate-\(\eta\) bins
Important to improve simulation to understand potential collective flow effects

Number of selected events

\(\rightarrow\) Positive \(\eta\): photon-going direction
\(\rightarrow\) Negative \(\eta\): Pb-going direction

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Exclusive four pion production

Elastic scattering of a photon-generated VM of the target nucleus (coherently)

- Coherent scattering usually leaves the nucleus intact → Dominated by $\rho$-meson photoproduction
- Experimental hints for excited $\rho$-resonance with decay to $\pi^+\pi^-\pi^+\pi^−$ → Which resonance?
- Select events with 4 tracks, and veto activity in scintillator-based forward detectors V0 and AD

Estimation of combinatorial background

Fit with interfering resonances with mixing angle

ALICE 5.02 TeV, 0.62 nb⁻¹

arXiv:2404.07542
Exclusive four pion production

Elastic scattering of a photon-generated VM of the target nucleus (coherently)

- Coherent scattering usually leaves the nucleus intact \(\rightarrow\) Dominated by \(\rho\)-meson photoproduction
- Experimental hints for excited \(\rho\)-resonance with decay to \(\pi^+\pi^-\pi^+\pi^-\) \(\rightarrow\) Which resonance?
- Select events with 4 tracks, and veto activity in scintillator-based forward detectors V0 and AD

\[\text{ALICE, } \sqrt{s_{\text{NN}}} = 5.02 \text{ TeV, } |y| < 0.5\]

\[\chi^2/\text{ndf} = 51 / 47\]

\[\text{Data (zero net charge)}\]

\[\text{Combinatorial BG (Pol4)}\]

\[\text{Coherent STARlight MC}\]

\[\text{Incoherent STARlight MC}\]

\[\text{Data compatible with two resonances } \rho(1450) \text{ and } \rho(1700) \text{ observed at slightly lower masses, and compatible widths compared to those reported by PDG}\]
Coherent (a) vs. incoherent (b) production of $c\bar{c}$ mesons

- Pomeron ($\geq 2$ gluons) exchange w/ full nucleus (a) or particular nucleon only (b)
- Selection through decays $J/\psi \rightarrow \mu^+\mu^-$ and $\psi(2S) \rightarrow \mu^+\mu^-$
- Enhance coherent production and UPC through forward activity suppression in scintillating-pad (SPD) and forward shower counters (HeRScheL)

Cross section ratio as function of rapidity measured for the first time in PbPb collisions
Characteristics of J/ψ production

Coherent production enhanced through suppression of forward activity in V0 & AD

- J/ψ reconstruction via muonic decays: 2 opposite sign muons in muon-spectrometer range (−4.0 < η < −2.5)
- Helicity frame: z-axis in flight direction of J/ψ, y-axis perpendicular to plane by collision axis & J/ψ direction

Extraction of signal yield in bins of cos(θ) and φ

→ Fitting angular distribution of decay muons from J/ψ signal using 3 polarisation parameters with properties:
  → (λ_θ, λ_φ, λ_θφ) = (0,0,0) → Isotropic
  → (λ_θ, λ_φ, λ_θφ) = (1,0,0) → Transversely polarized
  → (λ_θ, λ_φ, λ_θφ) = (−1,0,0) → Longitudinally polarized

<table>
<thead>
<tr>
<th>λ_θ</th>
<th>λ_φ</th>
<th>λ_θφ</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.75 ± 0.25 ± 0.24</td>
<td>0.03 ± 0.03 ± 0.02</td>
<td>0.10 ± 0.05 ± 0.06</td>
</tr>
</tbody>
</table>

→ Consistent with transversely polarized J/ψ mesons from coherent production
→ Consistent with s-channel helicity conservation
J/ψ’s as probe of the nucleus

Coherent production proportional to square of gluon density functions (at LO)

- Resolve ambiguity between photon emitter and target nucleus through electromagnetic dissociation (EMD) of ion

→ Determine nuclear suppression factor:

\[ R_g^{Pb} = \sqrt{\frac{\sigma_{meas}}{\sigma_{IA}}} \] (IA = impulse approximation, i.e. scaled from proton interactions + nuclear form factor)

- Neutron emission from EMD detected in ZDC/ZN:
  Categorize as 0n0n, 0nXn and XnXn

- Relation between rapidity and gluon momentum fraction

\[ x = \frac{M_{J/\psi}}{\sqrt{S_{NN}}} \cdot e^{\pm y} \] → Resolve ambiguity between ±y through simultaneous extraction from 3 neutron categories
J/ψ’s as probe of the nucleus

Coherent production proportional to square of gluon density functions (at LO)

- Resolve ambiguity betw. photon emitter and target nucleus through electromagnetic dissociation (EMD) of ion
- Neutron emission from EMD detected in ZDC/ZN
- Categorize as 0n0n, 0nXn and XnXn
- Relation between rapidity and gluon momentum fraction

\[ x = \frac{M_{J/\psi}}{\sqrt{S_{NN}}} \cdot e^{\pm y} \] 

- Determine nuclear suppression factor:
  \[ R_{g,Pb}^{Pb} = \sqrt{\frac{\sigma_{meas}}{\sigma_{IA}}} \] (IA = impulse approximation, i.e. scaled from proton interactions + nuclear form factor)

\( \rightarrow \) Both, gluon saturation (red) and shadowing (green) models provide reasonable description of data at high energies (low \( x \))
J/ψ’s as probe of the nucleus

Incoherent production: Sensitive to variance of spatial gluon distribution

- Variance related to quantum fluctuations of subnucleon degrees of freedom
  - Small variance at small momentum fractions \( x \) = possible sign of gluon saturation
- Contribution of incoherent J/ψ production grows with larger momentum transfers |\( t \)|
  → Measurement of cross section as function of |\( t \)|
- Use J/ψ transverse momentum as proxy: |\( t \)| ≈ \( p_T^2 \)
  → Veto any other activity through V0 and AD detectors

→ No prediction simultaneously describes absolute normalization and |\( t \)| dependence
→ Models including quantum fluctuations (purple, light-blue, green) provide better description of |\( t \)| dependence

ALICE 5.02 TeV, 0.23 nb\(^{-1}\) PRL 132, 162302 (2024)
A light to new physics?

Scattering of photons to photons through loop or axion-like mediator

• Large photon-photon luminosities in UPC PbPb collisions provide access to rare processes
  • Selection of two photons → Suppression of any other neutral or charged particles, less than 3 neutrons in both ZDCs

→ Determine differential cross section for $\gamma\gamma \rightarrow \gamma\gamma$
→ Consistent with prediction

→ Extract limits in mass-coupling plane

CMS 5.02 TeV, 1.65 nb$^{-1}$ ATLAS 5.02 TeV, 2.2 nb$^{-1}$
CMS-PAS-HIN-21-015 JHEP 03 (2021) 243

universität freiburg

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Summary

Ultraperiperal (UPC) heavy ion collisions $\rightarrow$ Provide unique physics potential

- LHC as photon-photon and photon-nucleus collider
- Photon-induced di-lepton production
  - Study photon flux, properties of $\tau$-lepton
- Photonuclear interactions
  - Charged hadron production as probe to potential collective flow effects
  - Light or heavy vector-meson production to study resonances, helicity conservation, nuclear gluon densities, incl. gluon saturation
- Rare processes through charge-enhanced cross sections with Pb ions
  - Probe photophilic interaction of axion-like particles

$\rightarrow$ Proof of extraordinary experimental versatility of LHC experiments!

$\rightarrow$ Lots of trigger improvements in Run 3 $\rightarrow$ Let’s stay curious!
Thank you for your attention.
Additional interesting publications

New measurements that did not make it into the talk anymore (non-complete list):

- ALICE: Impact parameter dependence in coherent $\rho^0$ production: [https://arxiv.org/abs/2405.14525](https://arxiv.org/abs/2405.14525)

Earlier measurements on some of the topics included in my talk (non-complete):

- ALICE: Coherent $J/\psi$ and $\psi'$ at midrapidities: [EPJC 81 (2021) 712](https://link.springer.com/article/10.1140/epjc/s10052-021-09727-9)

Interesting further reading:

ATLAS including ZDC

ZDC coverage: $|\eta| > 8.3$

CMS including ZDC

ZDC coverage: $|\eta| > 8.3$

ALICE with forward detectors

V0 coverage: $-3.7 < |\eta| < -1.7, 2.8 < |\eta| < 5.1$

AD (ALICE Diffractive) coverage: $-6.9 < |\eta| < -4.9, 4.7 < |\eta| < 6.3$

https://cerncourier.com/a/alice-the-heavy-ion-challenge/

LHCb with forward detectors

LHCb coverage: $2 < |\eta| < 5$

HeRSCheL coverage: $5 \lesssim |\eta| \lesssim 10$

https://cds.cern.ch/record/2300319/?ln=de

https://lhcb.web.cern.ch/lhcb_page/infrastructure/lhcb-geom/
Understanding the photon flux

Investigate production of $e^+e^-$ pairs

- Systematic uncertainties
Study τ-lepton properties

Investigate production of $\tau^+\tau^-$ pairs – in heavy ion collisions

• For signal strength of $\gamma\gamma \rightarrow \tau\tau$

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>Impact on $\mu_{\tau\tau}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>muon Level-1 trigger (sys)</td>
<td>1.0</td>
</tr>
<tr>
<td>$\tau$ decay modeling</td>
<td>1.0</td>
</tr>
<tr>
<td>tracking eff. (overall ID material)</td>
<td>0.9</td>
</tr>
<tr>
<td>muon Level-1 trigger (stat)</td>
<td>0.7</td>
</tr>
<tr>
<td>topocluster reco. eff.</td>
<td>0.6</td>
</tr>
<tr>
<td>muon reco. eff. (stat)</td>
<td>0.6</td>
</tr>
<tr>
<td>tracking eff. (PP0 material)</td>
<td>0.6</td>
</tr>
<tr>
<td>topocluster energy calib.</td>
<td>0.5</td>
</tr>
<tr>
<td>muon reco. eff. (sys)</td>
<td>0.5</td>
</tr>
<tr>
<td>photonuclear template var. ($\mu$1T-SR)</td>
<td>0.5</td>
</tr>
<tr>
<td>Total systematic</td>
<td>2.6</td>
</tr>
</tbody>
</table>

For $a_\tau$

\[ Pre-fit impact on $a_\tau$: \]
\[
\theta = \theta + \Delta \theta
\]
\[
\theta = \theta - \Delta \theta
\]
\[ Post-fit impact on $a_\tau$: \]
\[
\theta = \theta + \Delta \theta
\]
\[
\theta = \theta - \Delta \theta
\]

- $\Delta \theta$
- Nuis. Param. Pull

\[ ATLAS \]

$Pb+Pb \sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}, 1.44 \text{ nb}^{-1}$

\[ Phys. Rev. Lett. 131 (2023) 151802 \]
Study \( \tau \)-lepton properties

Investigate production of \( \tau^+ \tau^- \) pairs – in pp collisions

The observed (expected) significance is 5.3 (6.5) s.d. for the exclusive \( \gamma \gamma \to \tau \tau \) process. This constitutes the first observation of this process in pp collisions. The corresponding significances per final state are 2.3, 3.0, 2.1, and 3.4 (3.2, 2.1, 3.9, and 3.9) s.d. in the \( e\mu, e\tau, \mu\tau, \) and \( \tau_+ \tau_- \) final states, respectively. The most sensitive channel in terms of expected significance is \( \mu\tau \).
Study \( \tau \)-lepton properties

Investigate production of \( \tau^+ \tau^- \) pairs – in pp collisions

\[ \rightarrow \text{For the fit of the signal strength of } \gamma \gamma \rightarrow \tau \tau : \]

\[\text{CMS Preliminary} \quad 138 \text{ fb}^{-1} (13 \text{ TeV}) \]

\[ \mu = 0.75^{+0.20}_{-0.18} \]

- OPAL
  - PLB 431 (1998) 188
- L3
  - PLB 434 (1998) 169
- ARGUS
  - PLB 485 (2000) 37
- Belle
  - JHEP 04 (2022) 110

This result

\[d_c \text{ (e cm)} \]

\[0 \quad 0.1 \quad 0.2 \quad 0.3 \quad 0.4 \quad 0.5 \]

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**Exclusive four pion production**

**Singe resonance fit**

![Graph showing singe resonance fit](ALICE_Pb+Pb→Pb+Pb+π+π−π− m_{π+π−π−} (GeV/c^2))

- ALICE, Pb + Pb → Pb + Pb + π⁺π⁻π⁻
- |S_NN = 5.02 TeV, |y_{π⁺π⁻π⁻}| < 0.5
- χ²/ndf = 48 / 25
- Prob = 0.4 %

### Systematic uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background subtraction</td>
<td>1.5</td>
</tr>
<tr>
<td>Angular distribution</td>
<td>6.5</td>
</tr>
<tr>
<td>Total uncorrelated</td>
<td>6.7</td>
</tr>
<tr>
<td>Angular distribution</td>
<td>12.0</td>
</tr>
<tr>
<td>Signal extraction</td>
<td>1.7</td>
</tr>
<tr>
<td>Track selection</td>
<td>1.5</td>
</tr>
<tr>
<td>Track matching</td>
<td>4.0</td>
</tr>
<tr>
<td>Incoherent contribution</td>
<td>1.5</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>1.0</td>
</tr>
<tr>
<td>Pileup</td>
<td>3.8</td>
</tr>
<tr>
<td>Luminosity</td>
<td>2.6</td>
</tr>
<tr>
<td>Total correlated</td>
<td>13.7</td>
</tr>
</tbody>
</table>

- **→** Azimuthal angular distribution betw. 2 positive pions reweighted to match flat (isotropic) distribution
- **→** Propagated to re-calculate $A \times \epsilon$ corrections

**→** Bad chi²/ndf → not a good fit to the data
Characteristics of heavy VM production

Systematic uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>Relative uncertainty [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\sigma_{J/\psi}^{\text{coh}}$</td>
</tr>
<tr>
<td>Tracking efficiency</td>
<td>0.5–2.0</td>
</tr>
<tr>
<td>PID efficiency</td>
<td>0.9–1.6</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>2.7–3.7</td>
</tr>
<tr>
<td>HERSCHEL efficiency</td>
<td>1.4</td>
</tr>
<tr>
<td>Background estimation</td>
<td>1.2</td>
</tr>
<tr>
<td>Momentum resolution</td>
<td>0.9–34</td>
</tr>
<tr>
<td>Branching fraction</td>
<td>0.6</td>
</tr>
<tr>
<td>Luminosity</td>
<td>4.4</td>
</tr>
</tbody>
</table>

→ Largest momentum resolution uncertainties from $p_T^*$ interval: 140-160MeV with very small event yields

→ Starred notation indicates definition in nucleus-nucleus centre-of-mass frame

→ Account for the non-zero crossing angle between two Pb beams in lab frame

LHCb 5.02 TeV, 0.23 nb$^{-1}$ JHEP 06 (2023) 146
Characteristics of J/ψ production

Systematic uncertainties

<table>
<thead>
<tr>
<th>Systematics</th>
<th>$\lambda_\theta$</th>
<th>$\lambda_\phi$</th>
<th>$\lambda_{\theta\phi}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\cos \theta$ range</td>
<td>0.142</td>
<td>0.002</td>
<td>0.056</td>
</tr>
<tr>
<td>signal extraction</td>
<td>0.026</td>
<td>0.002</td>
<td>0.008</td>
</tr>
<tr>
<td>unfolding</td>
<td>0.019</td>
<td>0.004</td>
<td>0.004</td>
</tr>
<tr>
<td>response matrix</td>
<td>0.009</td>
<td>0.008</td>
<td>0.004</td>
</tr>
<tr>
<td>single muon $p_T$ threshold</td>
<td>0.196</td>
<td>0.022</td>
<td>0.019</td>
</tr>
<tr>
<td>Total</td>
<td>0.244</td>
<td>0.023</td>
<td>0.060</td>
</tr>
</tbody>
</table>

Table 1: Summary of the systematic uncertainty contributions, presented as absolute values. The $\cos \theta$ range systematic uncertainty refers to the fitted range variation, the signal extraction to the choice of the description of the J/ψ, the unfolding systematic uncertainty is due to the choice of the number of iterations, the response matrix refers to the input distribution in generating the matrix, and the trigger systematic uncertainty is associated to the single muon $p_T$ selection used for the trigger efficiency calculation.
J/ψ’s as probe of the nucleus

Systematic uncertainties

- Study of energy dependence

<table>
<thead>
<tr>
<th>Source</th>
<th>Type</th>
<th>0σn</th>
<th>0σn+Xn0n</th>
<th>XnXn</th>
<th>0σn</th>
<th>0σn+Xn0n</th>
<th>XnXn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal extraction</td>
<td>U</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Incoherent fraction</td>
<td>U</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Coherent shape</td>
<td>C</td>
<td>0.1</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
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</tr>
<tr>
<td>Feed-down</td>
<td>C</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>Branching ratio</td>
<td>C</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Luminosity</td>
<td>C</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Trigger live time</td>
<td>C</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>ITS-TPC matching</td>
<td>C</td>
<td>2.8</td>
<td>2.8</td>
<td>2.8</td>
<td>2.8</td>
<td>2.8</td>
<td>2.8</td>
</tr>
<tr>
<td>TOF trigger</td>
<td>C</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
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</tr>
<tr>
<td>SPD trigger</td>
<td>C</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>ϵ_{pu}</td>
<td>C</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>ϵ_{emd}</td>
<td>C</td>
<td>0</td>
<td>3.2</td>
<td>3.5</td>
<td>3.2</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>Migrations</td>
<td>A</td>
<td>-3.9</td>
<td>3.4</td>
<td>-3.6</td>
<td>3.1</td>
<td>1.1</td>
<td>1.1</td>
</tr>
</tbody>
</table>

Table 1. Summary of the systematic uncertainties, given in percent, related to the measurements performed with the central barrel detectors. The minus sign in the entry for migrations in the 0σn class signifies that this uncertainty is anti-correlated with those from migrations in the 0σn+Xn0n and XnXn classes. The second column identifies the type of uncertainty (U=uncorrelated, C=correlated, A=anticorrelated) as used in eq. (6.1).

<table>
<thead>
<tr>
<th>Source</th>
<th>Type</th>
<th>2.5 &lt;</th>
<th>3.0 &lt;</th>
<th>3.5 &lt;</th>
<th>4.0 &lt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal extraction</td>
<td>U</td>
<td>0.2</td>
<td>1.3</td>
<td>0.8</td>
<td>0.7</td>
</tr>
<tr>
<td>Incoherent fraction</td>
<td>U</td>
<td>0.4</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>Coherent shape</td>
<td>C</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Feed-down</td>
<td>C</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>Branching ratio</td>
<td>C</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>Luminosity</td>
<td>C</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Tracking</td>
<td>C</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Trigger</td>
<td>C</td>
<td>6.2</td>
<td>6.2</td>
<td>6.2</td>
<td>6.2</td>
</tr>
<tr>
<td>Matching</td>
<td>C</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>ϵ_{pu}</td>
<td>C</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>ϵ_{emd}</td>
<td>C</td>
<td>0</td>
<td>1.1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Migrations</td>
<td>A</td>
<td>-0.3</td>
<td>3.8</td>
<td>-0.2</td>
<td>3.6</td>
</tr>
</tbody>
</table>

Table 2. Summary of the systematic uncertainties, given in percent, related to the measurements performed with the muon spectrometer. The minus sign in the entry for migrations in the 0σn class signifies that this uncertainty is anti-correlated with those from migrations in the 0σn+Xn0n and XnXn classes. The second column identifies the type of uncertainty (U=uncorrelated, C=correlated, A=anticorrelated) as used in eq. (6.1).
J/\psi’s as probe of the nucleus

Systematic uncertainties for incoherent production

TABLE II. Summary of the identified systematic uncertainties to the cross section. The numbers in parentheses denote a range of values in the different |t| intervals. Except for the first two uncertainties, all others are correlated in |t|.

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal extraction</td>
<td>(1.0,2.9)</td>
</tr>
<tr>
<td>Selection on</td>
<td>z_{vtx}</td>
</tr>
<tr>
<td>f_C</td>
<td>(0.0,0.4)</td>
</tr>
<tr>
<td>f_D</td>
<td>(0.2,6.5)</td>
</tr>
<tr>
<td>Integrated luminosity</td>
<td>2.9</td>
</tr>
<tr>
<td>Veto inefficiency due to pileup</td>
<td>3.0</td>
</tr>
<tr>
<td>Veto inefficiency due to dissociation</td>
<td>3.8</td>
</tr>
<tr>
<td>ITS-TPC tracking</td>
<td>2.8</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>1.3</td>
</tr>
<tr>
<td>Branching ratio</td>
<td>0.6</td>
</tr>
<tr>
<td>Photon flux</td>
<td>2.0</td>
</tr>
</tbody>
</table>
A light to new physics?

Light-by-light cross section determination: Background estimation and systematic uncertainties

CMS 5.02 TeV, 1.65 nb⁻¹
CMS-PAS-HIN-21-015

→ CEP MC scaled to data in region $A^\gamma_\phi > 0.015$
→ Extrapolated to signal region $A^\gamma_\phi > 0.01$

Signal process
Breit-Wheeler
$\gamma\gamma \rightarrow e^+ e^-$

Central exclusive diphoton production (CEP) $gg \rightarrow \gamma\gamma$

Table 7: Summary of relative systematic uncertainties in the measurement of the LbL scattering cross section.

<table>
<thead>
<tr>
<th>Uncertainity</th>
<th>Relative Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background normalisation</td>
<td>15%</td>
</tr>
<tr>
<td>Background shape</td>
<td>14%</td>
</tr>
<tr>
<td>Exclusive diphoton efficiencies</td>
<td>12.5%</td>
</tr>
<tr>
<td>Luminosity</td>
<td>1.5%</td>
</tr>
<tr>
<td>Total (statistical/nonstatistical)</td>
<td>24% (15%/19%)</td>
</tr>
</tbody>
</table>

Figure: Diphoton acoplanarity distribution over $A^\gamma_\phi = 0-0.1$ in events passing the fiducial criteria of Table 1 (except the $A^\gamma_\phi < 0.01$ one) measured in data (black dots) compared with the predictions for the LbL signal (orange histogram), the B-W process (yellow histogram), and the CEP (blue histogram, normalised to data as explained in the text) backgrounds. Error bars on the data points show statistical uncertainties, and dashed bands on the stacked histograms (and at unity in the data/MC ratio) represent systematic uncertainties.
Light-by-light cross section determination: Background estimation and systematic uncertainties

\[ \sigma_{\text{fid}} = \frac{N_{\text{data}} - N_{\text{bkg}}}{C \times \int L \, dt} \]

**Figure 6.** The diphoton acoplanarity distribution for events satisfying the signal region selection, but before applying the \( A_\phi < 0.01 \) requirement. Data are shown as points with statistical error bars, while the histograms represent the expected signal and background levels. The CEP \( gg \rightarrow \gamma \gamma \) background is normalised in the \( A_\phi > 0.01 \) control region. The signal prediction is normalised to the same integrated luminosity as the data. The shaded band represents the uncertainties in signal and background predictions, excluding the uncertainty in the luminosity.

→ Uncertainty in background estimation gives 6% uncertainty in integrated fiducial cross section

Table 1. The detector correction factor, \( C \), and its uncertainties for the integrated fiducial cross-section measurement. The second row lists the numerical value of \( C \) together with the total uncertainty. The total uncertainty on \( C \) is a quadratic sum of systematic and statistical components.
\( \gamma \gamma \rightarrow \mu \mu \) with non-UPC configuration

Muon pairs as electromagnetic probes of the quark-gluon plasma

- Consider transverse momentum scale: \( k_{\perp} = 1/2(p_{T1} + p_{T2})(\pi - |\phi_1 - \phi_2|) \)
  - \( k_{\perp} \approx 0 \), if leptons are back-to-back in \( \phi \)
  - \( k_{\perp} \approx \) factor \( \times \) average \( p_T \), where factor is larger if leptons are more aligned in \( \phi \)

→ Dependence on collision centrality

→ Influence of magnetic field effects?

→ More central collisions have on average broader \( k_{\perp} \)-distribution, but not an effect from magnetic fields