Recent results on ultra-peripheral collisions with the ALICE experiment

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Outline

• Introduction to UPC physics & diffractive photoproduction
• How ALICE detects UPCs
• Measurement of energy dependence of $J/\psi$ photoproduction
  • Coherent ($\gamma$Pb)
  • Exclusive + dissociative ($\gamma$p)
• Measurement of $|t|$-dependence of $J/\psi$ photoproduction
  • Coherent
  • Incoherent
• $J/\psi$ polarization
• Invitation to more ALICE UPC talks
Physics of ultra-peripheral collisions

Search for **gluon saturation**, study of nuclear effects such as **shadowing** of gluon PDFs

**Ultra-peripheral collisions (UPCs)**
- $b > 2R_A \Rightarrow$ pure hadronic interactions suppressed
- Photon-induced reactions with sizeable cross sections
- Flux $\propto Z^2$; low virtuality $Q^2$

**Vector meson diffractive production in UPCs**

- VM rapidity traces back the energy evolution
- **Clear experimental signature**, e.g. $J/\psi \to l^+l^-$ ⇒ two lepton tracks in an otherwise empty detector (except in a very forward direction)

<table>
<thead>
<tr>
<th>System</th>
<th>Process</th>
<th>$\langle p_T \rangle$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb–Pb</td>
<td>Coherent</td>
<td>$\sim 1/R_{nucleus} \sim 50$ MeV</td>
</tr>
<tr>
<td></td>
<td>Incoherent</td>
<td>$\sim 1/R_{nucleon} \sim 400$ MeV</td>
</tr>
<tr>
<td>p–Pb</td>
<td>Exclusive</td>
<td>$\sim 1/R_{proton} \sim 400$ MeV</td>
</tr>
<tr>
<td></td>
<td>Dissociative</td>
<td>$\sim 1$ GeV</td>
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</tbody>
</table>

**LO pQCD:** $d\sigma(\gamma + \text{Pb} \to \text{VM} + \text{Pb})/dt \propto [xg_A(x, Q^2)]^2$ 

*Z. Phys. C 57 (1993) 89-92*
How ALICE detects UPCs

Zero Degree Calorimeters (ZDCs)
Fwd neutrons & protons

ALICE Diffractive (AD)
Fwd scintillation counters, vetoing

V0
Fwd scintillation counters, vetoing

Status during Run 2 of the LHC: 2015–2018

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UPC analyses at midrapidity

$|\eta| < 0.9$
(often $|\eta| < 0.8$ to exclude border effects)

J/$\psi$ in Pb–Pb UPCs at $\sqrt{s_{_{NN}}} = 5.02$ TeV: $|y| < 0.8$ translates to $x \in (0.3, 1.4) \times 10^{-3}$

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J/ψ in Pb–Pb UPCs at \( \sqrt{s_{NN}} = 5.02 \) TeV: \(-4.5 < y < -2.5\) translates to either \(x \in (1.1, 5.1) \times 10^{-5}\) or \(x \in (0.7, 3.3) \times 10^{-2}\)
Energy dependence of coherent, exclusive and dissociative J/ψ production

- Energy dependence of coherent photonuclear production of J/ψ mesons in ultra-peripheral Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, *JHEP* 10 (2023) 119 NEW!

- Exclusive and dissociative J/ψ photoproduction, and exclusive dimuon production, in p–Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV, *arXiv:2304.12403* (accepted by PRD) NEW!
UPC cross section for photoproduction

\[ \frac{d\sigma_{PbPb}}{dy} = n_\gamma(y, \{b\})\sigma_{\gamma Pb}(y) + n_\gamma(-y, \{b\})\sigma_{\gamma Pb}(-y) \]

- **Forward** Pb–Pb: how to disentangle the contributions?
  \( n_\gamma = n_\gamma(b) \Rightarrow \) one needs to measure at the same rapidity but using **different impact parameters ranges**: \( \{b\}_1 \) and \( \{b\}_2 \)

- **Midrapidity in Pb–Pb:**
  \[ \frac{d\sigma_{PbPb}}{dy} = 2n_\gamma(y, \{b\})\sigma_{\gamma Pb}(y) \]

- **QCD enters here!**

- **QED**

- **p–Pb:**
  \[ \frac{d\sigma_{pPb}}{dy} = n_\gamma(y, \{b\})\sigma_{\gamma p}(y) \]

- UPC cross section = sum of the two contributions (photon flux \( \times \) photonuclear cross section):
Solving the photon direction ambiguity puzzle

\[
\frac{d\sigma^{(b)_1}_{\text{PbPb}}}{dy} = n_\gamma(y, \{b\}_1)\sigma_{\gamma\text{Pb}}(y) + n_\gamma(-y, \{b\}_1)\sigma_{\gamma\text{Pb}}(-y)
\]

\[
\frac{d\sigma^{(b)_2}_{\text{PbPb}}}{dy} = n_\gamma(y, \{b\}_2)\sigma_{\gamma\text{Pb}}(y) + n_\gamma(-y, \{b\}_2)\sigma_{\gamma\text{Pb}}(-y)
\]

• Two possible approaches:
  1) combining results from UPCs and peripheral collisions \((b < 2R)\)
  2) event tagging using forward neutrons [1] – an independent photon exchange may lead to electromagnetic dissociation (EMD) of a nucleus

• Event classification:
  • 0n0n: no neutrons on either side
  • 0nXn + Xn0n: neutrons on one side only
  • XnXn: forward neutrons on both sides

• Photon spectra corresponding to these fragmentation scenarios can be calculated [2]

We can measure \(d\sigma/dy\), calculate the photon fluxes, and then simply solve the system of linear equations (e.g. using a \(\chi^2\)-minimization)...

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Energy dependence of coherent J/ψ production

- Simultaneous analysis of mid- and forward-rapidity data
- Neutron classes ⇒ extraction of the dependence on $W_{γPb}$ + the nuclear shadowing factor $S_{γPb}$

Three bins at $−4 < y < −2.5$
Two bins at $|y| < 0.8$
Five $W_{γPb}$ values: 17 to 920 GeV!
Bjorken-$x$ range: $1 \times 10^{-5}$ to $3 \times 10^{-2}$

Example: 0n0n

ALICE Pb–Pb ($\sqrt{s}_{NN} = 5.02$ TeV) $\gamma \rightarrow F^-$
UPC, $L_x = 233 \pm 7$ mb$^{-1}$
$p_t < 0.2$ GeV/c
$0.1 < \gamma < 0.3$
$N_{cm} = 1744 \pm 49$
$\chi^2/\text{dof} = 0.96$

ALICE Pb–Pb ($\sqrt{s}_{NN} = 5.02$ TeV) $\gamma \rightarrow 0n0n$
UPC, $L_x = 233 \pm 7$ mb$^{-1}$
$p_t < 0.2$ GeV/c
$0.1 < \gamma < 0.3$
$N_{cm} = 2939 \pm 84$
$\chi^2/\text{dof} = 0.97$

ALICE Pb–Pb ($\sqrt{s}_{NN} = 5.02$ TeV) $\gamma \rightarrow Xn0n$
UPC, $L_x = 533 \pm 13$ mb$^{-1}$
$p_t < 0.25$ GeV/c
$2.5 < |y| < 4$
$N_{cm} = 2939 \pm 84$
$\chi^2/\text{dof} = 0.97$
Energy dependence

- **Unprecedented range** with the ALICE data
- Agreement with Run-1 ALICE results (UPC + peripheral)
- Good description of the **low-energy data**:  
  - Impulse approximation  
  - STARlight
- Good description of the **high-energy data**:  
  - GSZ: **EPS09-LO** parametrization of nuclear parton functions or leading twist approximation (LTA) of gluon shadowing  
    - GG-HS: colour-dipole approach, gluon saturation (hot spots)  
    - b-BK-A: solution to the impact-parameter dependent BK equation
- IA significantly above the data at low $x$  
  $\Rightarrow$ onset of nuclear shadowing
Nuclear suppression factor

- A quantitative measure of nuclear gluon shadowing

\[ S_{\gamma \text{Pb}} \approx 0.95 \text{ at low energies, then a large gluon depletion} \]
(down to 0.5) at high energies

Cross-check with the previous ALICE Run-2 results at midrapidity:

\[ S_{\gamma \text{Pb}} \approx 0.65 \]

\[ S_{\gamma \text{Pb}}(W_{\gamma \text{Pb},n}) = \frac{\sigma_{\gamma \text{Pb}}}{\sigma_{\gamma \text{Pb}}} \]

\( \sqrt{\frac{\sigma_{\gamma \text{Pb}}}{\sigma_{\gamma \text{Pb}}}} \)
Energy dependence of the photonuclear cross section

\[ \sigma(\gamma, Pb) = 5.02 \text{ TeV} \] (arXiv:2305.19060)
\[ \sigma(\gamma, Pb) = 5.02 \text{ TeV} \] (arXiv:2303.16984)
\[ \sigma(\gamma, Pb) = 2.76 \text{ TeV} \] (PLB 726 (2013) 290-295)
\[ \sigma(\gamma, Pb) = 2.76 \text{ TeV} \] (PRC 96 (2017) 015203)

- Impulse approximation
- STARlight
- EPS09 LO
- LTA
- GG-HS
- b-BK-A

ALICE alone explores (20, 900) GeV in \( W_{\gamma Pb} \) and \( x \) from \( 10^{-2} \) down to \( 10^{-5} \)

Recently, CMS performed a similar measurement in a narrower interval

CMS: arXiv:2303.16984 (accepted by PRL)

ALICE: JHEP 10 (2023) 119
Energy dependence of exclusive J/ψ production

- Asymmetric p–Pb system ⇒ photon can be assigned to the source ✓
- Beam configuration corresponds to the “low-energy” photon emitted from the nucleus

A power-law fit to the ALICE data: \( \delta = 0.70 \pm 0.04 \)

- Two bins within \(-4 < y < -2.5\) ⇒ two \(W_{\gamma\text{Pb}}\) values: 27 and 57 GeV
Energy dependence of dissociative J/ψ production

- First measurement of this process at a hadron collider
- The measurement is compatible with H1 results

The CCT model (hot spots) predicts maximum of the cross section at ≃ 500 GeV (“phase-space saturation”)

Probe to fluctuations of sub-nucleon structures inside the proton!

See the talk by Michael Winn: Monday at 16:30
Distribution of nuclear (Pb) matter in the transverse plane


- First measurement of the $|t|$-dependence of incoherent J/$\psi$ photonuclear production, arXiv:2305.06169 NEW!
Why to measure $|t|$-dependencies?

- Impact parameter $b$ and the VM transverse momentum $p_T$ are **Fourier conjugates**
- $|t|$-dependence of $\sigma_{Y\text{Pb}} \leftrightarrow$ matter distribution in the transverse plane

**Fourier tr.**

Good-Walker approach:
- coherent $\leftrightarrow$ **average**
- incoherent $\leftrightarrow$ **variation** (quantum fluctuations)

- Larger $|t| \leftrightarrow$ smaller scattering centers
- At $|t| \sim 1 \text{ GeV}^2$ we probe fluctuations at a sub-femtometer scale $\Rightarrow$ **gluons!**

**Pb + Pb $\rightarrow J/\Psi + \text{Pb} + \text{Pb, } \sqrt{s} = 5.02 \text{ TeV, } y = 0$**

**Geometric and $Q_s$ fluctuations in the nucleons**

**No subnucleon fluctuations**

**Graphs and plots**


**Phys.Rev.Lett.** 117 (2016) 5, 052301

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Photonuclear cross section extraction

- $J/\psi \rightarrow \mu\mu$ at midrapidity $\Rightarrow x \in (0.3, 1.4) \times 10^{-3}$
- Very clean $J/\psi$ signal over a relatively small background

\[
\frac{d^2\sigma_{J/\psi}}{dy dp_T^2} \bigg|_{y=0} = 2n_\gamma(y = 0) \frac{d\sigma_{\gamma Pb}}{d|t|}
\]

Coherent measurement
- unfolding to account for $p_T$ migration
- $p_T^2 \rightarrow |t|$ unfolding (photon $k_T$)

Incoherent measurement
- $p_T$ migration negligible
- $|t| = p_T^2$ (large transferred momentum)

Counts per 25 (MeV/c)$^2$

Coherent yields: $p_T < 0.11$ GeV/c (only a fit in one $p_T$ interval is shown)

Incoherent yields: $0.2 < p_T < 1$ GeV/c (the full sample is shown)

 Corrections for contamination

UPC cross section (measured)

PHYS.Lett.B 817 (2021) 136280

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arXiv:2305.06169
Coherent J/ψ

- Sensitive to the **average** of the target spatial distribution in the transverse plane

- **STARlight** – hadronic model based on the Glauber calculation
  - Gives a too high cross section
  - The $p_T$ spectrum determined from the nuclear (Pb) form factor

- **Dynamic effects from QCD important:**
  - **LTA** – leading twist approximation of nuclear shadowing (“low” prediction)
  - **b-BK** – color dipole approach, solution to the $b$-dependent BK equation (saturation effects)

New ALICE **Run-3 data** + improved tracking should help us distinguish which pQCD prediction is doing better!
Incoherent J/ψ

- The slope sensitive to **fluctuations** of the target transverse profile
- Each theory group provides two predictions:
  1) Elastic scattering on a **full nucleon** (**MS-p, MSS, GSZ-el**)
  2) **Sub-nucleon degrees of freedom**:
     - **MS-hs**: IPsat (hot spots + satu. scale fluct.)
     - **MSS-fl**: CGC-based, JIMWLK solution
     - **GSZ-el+diss**: extra dissociative component

  These models predict **steeper slopes** than in the data...

- **Sub-nucleon fluctuation region**

  These models are **favored by the data** at higher |t|

- The models fail to describe the **normalization** (scaling from proton to nuclear targets)

[Graph showing data points and model predictions with labels for MS-hs, MS-p, MSS-fl, GSZ-el, and GSZ-el+diss.]

**ALICE, Pb–Pb UPC √s_{NN} = 5.02 TeV**

**ALICE incoherent J/ψ, |y| < 0.8**

**Uncorrelated stat. + syst.**

**Correlated syst.**

**sub-nucleon fluctuation region**
Putting together coherent & incoherent data points

Three orders of magnitude in $|t|$ covered with a HERA-like accuracy!

arXiv:2305.06169

Other recent ALICE UPC results...

- First polarisation measurement of coherently photoproduced $J/\psi$ in ultra-peripheral Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. 

  arXiv:2304.10928

- Photoproduction of $K^+K^-$ pairs in ultra-peripheral collisions, 

  arXiv:2311.11792

- Measurement of the impact-parameter dependent azimuthal anisotropy in coherent $\rho^0$ photoproduction (preliminary)

- Exclusive four pion photoproduction in ultra-peripheral Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV (preliminary)
J/ψ polarization

- Angular distribution of J/ψ yields was unfolded in \( \phi \), corrected for \( A \times \varepsilon \), and fitted to (\( \lambda \) are polarization parameters):
  \[
  W(\cos \theta, \phi) \propto \frac{1}{3 + \lambda_\theta} (1 + \lambda_\theta \cos^2 \theta + \lambda_\varphi \sin^2 \theta \cos 2\phi + \lambda_{\theta\varphi} \sin 2\theta \cos \phi)
  \]

- **Helicity frame** used (z axis \( \parallel \) J/ψ momentum)

Results compatible with **transverse polarization**: 
\( (\lambda_\theta, \lambda_\varphi, \lambda_{\theta\varphi}) = (1,0,0) \)

- First experimental evidence for the s-channel helicity conservation (SCHC) hypothesis in J/ψ photoproduction off lead nuclei
- Spin-density matrix elements extracted & compared with HERA results:

  \[
  r_{00}^{04} = \frac{1 - \lambda_\theta}{3 + \lambda_\theta} \\
  r_{1,-1}^{04} = \frac{\lambda_\varphi}{2} (1 + r_{00}^{04})
  \]

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\[0.3 - 0.2 - 0.1 0.0 0.1 0.2 0.3 0.4 0.5\]

\[0.068 \pm 0.070 \pm 0.070\]
\[0.003 \pm 0.003 \pm 0.003\]
\[0.014 \pm 0.014 \pm 0.012\]
\[0.340 \pm 0.090 \pm 0.060\]

\[0.02 (\text{sys.}) \pm 0.03 (\text{stat.}) \pm 0.03 (\text{stat.})\]
\[0.03 \pm 0.03 (\text{stat.}) \pm 0.02 (\text{stat.})\]
\[0.01 \pm 0.01 (\text{stat.}) \pm 0.01 (\text{stat.})\]

\[0.10 \pm 0.05 (\text{stat.}) \pm 0.06 (\text{stat.})\]

\[\chi^2/\text{dof} = 127.4 / 74 = 1.7\]
Summary

Using data from Run 2 of the LHC, ALICE has recently presented many UPC measurements:

- Energy dependence of coherent, exclusive and dissociative J/ψ production
- Dependence of coherent and incoherent J/ψ production on |τ|
- J/ψ polarization
- K⁺K⁻ and exclusive four pion photoproduction
- Azimuthal anisotropies in ρ⁰ production

Some of these are, especially through comparison with phenomenological models, a probe into important effects in high-energy QCD:

- Gluon saturation
- Nuclear shadowing
- Fluctuations at sub-nucleon scale

With new data to come in Run 3 & 4, and thanks to detector upgrades, ALICE will be able improve the precision and conduct even more detailed measurements...

STAY TUNED!

See the talk by Anisa Khatun: Friday at 18:00
Reminder of ALICE contributions at UPC 2023

• Energy dependence of J/ψ in UPCs at the LHC
  Michael Winn, Monday at 16:30

• K⁺K⁻ photoproduction in ultra-peripheral Pb–Pb collisions with ALICE
  Minjung Kim, Monday at 18:45

• Measurement of the impact-parameter dependent azimuthal anisotropy in coherent ρ⁰ photoproduction with ALICE
  Andrea Riffero, Tuesday at 10:15

• Photoproduction of J/ψ and dileptons in events with nuclear overlap with ALICE
  Nicolas Bizé, Thursday at 17:30

• A Forward Calorimeter in ALICE
  Ionut Cristian Arsene, Friday at 16:30

• UPC physics with ALICE in Run 3
  Anisa Khatun, Friday at 18:00
Thank you for your attention!