Photoproduction of $J/\psi$ in UPCs accompanied by neutron emission

Luis F. Alcerro
(On behalf of the CMS Collaboration)

l.alcerro@cern.ch

Department of Physics & Astronomy
University of Kansas

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Motivation

● DIS experiments show gluons become rapidly dominant at high energies.
● Unitarity forbids this behavior go forever.
● New QCD regime: compensation between gluon splittings and recombinations.
● No conclusive evidence of saturation to date!
How are HI UPCs collisions useful?

- In UPCs \((b > R_1 + R_2)\), EM interactions dominate.
- Lorentz contracted EM fields produce fluxes of quasi-real photons.
- Photon fluxes enhanced \(\propto Z^2\).
- Saturation region is expected to be easier to be accessed \(Q_S \propto A^{1/3}\).
Photoproduction of vector mesons (VM)

- Photon quantum numbers \( J^{PC} = 1^{--} \) same for VM → photon fluctuates into a \( q\bar{q} \) dipole!
- VM photoproduction cross section
  \[ \propto (xg(x, Q^2))^2 \] at LO.
- Photoproduced VM cross section at small x can test gluon density.

\[
x = \left( \frac{M_{J/\psi}}{\sqrt{s_{NN}}} \right) e^{\mp y}
\]
Photoproduction of $J/\psi$ with protons

$$\gamma + p \rightarrow J/\psi + p$$

- Gluons inside a proton:
  - Investigated with ep, pPb and pp collisions by HERA and LHC
  - Consistent results between HERA and LHC data.
  - Data follow a power-law trend, consistent with the rapidly increasing gluon density.
  - No evidence for saturation!

EPJC 79 (2019) 402
Photoproduction of $J/\psi$ with heavy nuclei

$$\gamma + Pb \rightarrow J/\psi + Pb$$

- Gluons inside Pb:
  - $\sigma(J/\psi) < 1.\text{A} \rightarrow$ strong nuclear modification in nuclei.
  - Data challenge all existing models.
Photoproduction of $J/\psi$ with heavy nuclei

- **Ambiguity in symmetric collisions:** either ion can serve as the emitter or target.
- Each data point has contributions from low and high energy photons.

\[
\frac{d\sigma_{AA\rightarrow AA'/J/\psi}}{dy} = N_{Y/A}(y) \cdot \sigma_{Y\rightarrow J/\psi A'}(y) + N_{Y/A}(-y) \cdot \sigma_{Y\rightarrow J/\psi A'}(-y)
\]
Coherent $J/\psi$ photoproduction in UPC PbPb at 5.02 TeV

- Data from 2018 PbPb UPC, $L_{int} \sim 1.52 \text{ nb}^{-1}$
- Event selection:
  - Exactly two muons and nothing more!
  - Low energy depositions in hadronic calorimeter to suppress strong interactions.
  - Very clean events!
Signal extraction

- Invariant mass fits filter $J/\psi$ yields (coherent+incoherent) from QED background.
- Multi-template fits on $J/\psi$ transverse momentum allows to separate coherent and incoherent contributions.

![Graphs showing CMS data for $J/\psi$ signal extraction.](Image)

**CMS**

- $1.6 < |y^{\mu\mu}| < 1.9$
- $0 < p_T^{\mu\mu} < 0.2$ GeV

- **Data**
- **Fit:** $\chi^2/\text{ndf} = 1.0$
- **$J/\psi$ (6028 ± 90)**
- **$\psi(2S)$ (660 ± 58)**
- **$\gamma\gamma \rightarrow \mu\mu$**

- $R_N = 0.109 \pm 0.0095$
- $R = 0.232 \pm 0.0194$
- $f_D = 0.040 \pm 0.0033$

**PbPb 1.52 nb$^{-1}$ (5.02 TeV)**

- $1.6 < |y^{\mu\mu}| < 1.9$
- $2.95 < m_{\mu\mu} < 3.25$ GeV

- **Data**
- **Fit:** $\chi^2/\text{ndf} = 1.2$
- **Coherent $J/\psi$**
- **Incoherent $J/\psi$ w/o N dissociation**
- **Incoherent $J/\psi$ w. N dissociation**
- **Coherent $\psi(2S) \rightarrow J/\psi + X$**
- **(QED continuum) $\gamma\gamma \rightarrow \mu\mu$**

Total Coh. $J/\psi$ cross section

\[
\frac{d\sigma_{J/\psi}^{\text{coh}}}{dy} = \frac{N(J/\psi)}{(1 + f_I + f_D) \cdot e(J/\psi) \cdot \text{Acc}(J/\psi) \cdot \text{BR}(J/\psi \rightarrow \mu\mu) \cdot L_{\text{int}} \cdot \Delta y}
\]

- LHC experiments complement each others over a wide range of rapidity.
- CMS data covers a unique rapidity region, not previously accessed.
- CMS data follow ALICE forward rapidity trend.
- Two-way ambiguity unsolved so far... wait for next slides!

\[
\frac{d\sigma_{AA\rightarrow AA'J/\psi}}{dy} = N_{y/A}(y) \cdot \sigma_{Y/A\rightarrow J/\psi A'}(y) + N_{y/A}(-y) \cdot \sigma_{Y/A\rightarrow J/\psi A'}(-y)
\]

ALICE, EPJC 81 (2021) 712
LHCb, arXiv:2206.08221

CMS, PbPb 1.52 nb$^{-1}$ (5.02 TeV)

Pb + Pb → Pb + Pb + J/ψ

CMS
ALICE 2019
ALICE 2021
LHCb 2022

Pb + Pb → Pb + Pb + J/ψ

CMS
ALICE
LHCb

ALICE
LTA_SS
LTA_WS
CD_BGK
CD_GBW
CD_IIM

arXiv:2303.16984

arXiv:2303.16984
A solution to the two-way ambiguity puzzle

Control impact parameter of UPCs via forward neutron emissions

- Additional photon exchanges lead to neutron emissions via EMD.

- Analogous to centrality:
  \[ b_{XnXn} < b_{0nXn} < b_{0n0n} \]
Event classification via neutron multiplicity

- ZDC is used to detect neutrons $|\eta| > 8.3$ produced by nuclear dissociation/breakup.
Total Coh. $J/\psi$ cross section in neutron categories

ZDC allows to classify events in neutron categories.

First separation in different neutron categories.

arXiv:2303.16984
Coh. \( J/\psi \) photo nuclear cross section vs \( W \)

- **ALICE, LHCb vs I.A:**
  - Impulse approx. (IA) neglects all nuclear effects.
  - Data close to IA at low \( W \).
  - Data significantly lower than IA at \( W \sim 125 \) GeV.
  - Shadowing/saturation models predict larger suppression at higher \( W \).

- **First measurement by CMS:**
  - \( W < 40 \) GeV: rapidly increasing
  - \( 40 < W < 400 \) GeV: slowly raising -- underlying physics changed!
  - No models can describe the entire data distribution!
Nuclear suppression factor

$R_g^A = \left( \frac{g_A(x, Q^2)}{A \cdot g_p(x, Q^2)} \right)^{1/2}$

- Represents nuclear gluon suppression factor at LO.
- $x \sim 10^{-2} - 10^{-3}$: flat trend
- Quickly decrease towards lower $x$ region.

arXiv:2303.16984
Publicity: ZDC a protagonist in Run 3!

- **ZDC**: a critical detector for the forward physics program.
- Excellent performance during 2023 data taking.
- For the first time, it was used to trigger, allowing an improved event selection performance.
Summary

- Directly disentangled coh. $\sigma_{\gamma A \rightarrow J/\psi A}(W)$ in UPC for the first time.
- CMS measured coh. $\sigma_{\gamma A \rightarrow J/\psi A}(W)$ to a new unprecedentedly low-x gluon regime $(10^{-4} - 10^{-5})$.
- No model can completely describe the data at low and high $W$.
Backup slides
A solution to the two-way ambiguity puzzle

What is measured

\[
\begin{align*}
\frac{d\sigma_{AA\rightarrow AA'J/\psi}^{0n0n}}{dy} &= N_{Y/A}^{0n0n}(y) \cdot \sigma_{Y\rightarrow J/\psi A'}(y) + N_{Y/A}^{0n0n}(-y) \cdot \sigma_{Y\rightarrow J/\psi A'}(-y) \\
\frac{d\sigma_{AA\rightarrow AA'J/\psi}^{0nXn}}{dy} &= N_{Y/A}^{0nXn}(y) \cdot \sigma_{Y\rightarrow J/\psi A'}(y) + N_{Y/A}^{0nXn}(-y) \cdot \sigma_{Y\rightarrow J/\psi A'}(-y) \\
\frac{d\sigma_{AA\rightarrow AA'J/\psi}^{XnXn}}{dy} &= N_{Y/A}^{XnXn}(y) \cdot \sigma_{Y\rightarrow J/\psi A'}(y) + N_{Y/A}^{XnXn}(-y) \cdot \sigma_{Y\rightarrow J/\psi A'}(-y)
\end{align*}
\]

What we want

\[
\begin{align*}
\text{Dominant } b \text{ ranges of different neutron classes:} \\
&\text{0n0n: } b > 40 \text{ fm} \\
&\text{0nXn: } b \sim 20 \text{ fm} \\
&\text{XnXn: } b < 15 \text{ fm}
\end{align*}
\]

→ Solve for \( \sigma_{Y\rightarrow J/\psi A'}(y) \) and \( \sigma_{Y\rightarrow J/\psi A'}(-y) \), and \( x = \left( \frac{M_{VM}}{\sqrt{S_{NN}}} \right) e^{+y} \)

Entering a new regime of small \( x \sim 10^{-4} - 10^{-5} \) in nuclei!
Future opportunities

Exciting opportunities ahead
- Higher luminosities.
- A variety of ion species.
- Upgrades enabled by new technologies!

- **Various VM species in γPb with neutron tagging**
- **System size scan with different ion species**

When approaching the BDL
- Coh. cross section scales with $A^{2/3}$
- Incoh. cross section strongly suppressed; internal substructure becomes invisible
Comparison with new ALICE result since the CMS submission

arXiv:2305.19060
VM photoproduction kinematics

- A given $y \rightarrow$ Fixes $\omega, x, W$

- $\omega = \frac{M_{VM}}{2} e^{\pm y}$
  - $y$: Rapidity of the VM
  - $\omega$: Photon energy
  - $M_{VM}$: Mass of the VM

- $x = \left( \frac{M_{VM}}{\sqrt{s_{NN}}} \right) e^{\mp y}$

- $W^2 = M_{VM} \sqrt{s_{NN}} \cdot e^{\pm y}$
  - $W$: Centre-of-mass energy of the photon-target system

We study $J/\psi$

$\rho^0, J/\psi, \psi'(y, p_t^2)$

$w_{\gamma p, Xe, Pb}^2$

[p, Pb, Xe] [Pb, Xe] [p, Pb, Xe]
EMD pileup correction

Impact of dissociative PU corrected by measuring neutron multiplicity in events without any activity in CMS tracker.

\[ \gamma\gamma \rightarrow \mu^+\mu^- \text{ with/without neutron emitting} \]

Different collisions

EM dissociation without any \( \gamma\gamma \rightarrow \mu^+\mu^- \)

\[ \gamma\gamma \rightarrow \mu^+\mu^- \text{ with neutron multiplicity migration} \]