Photonuclear production of vector mesons in ultra-peripheral Pb-Pb collisions at the LHC

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Photoproduction in ultra-peripheral collisions

The EM fields correspond to an equivalent flux of photons.

These can lead to two-photon or photonuclear interactions in collisions where no hadronic interactions occur ($b > 2R$).

Exclusive vector meson production ($\gamma + A \rightarrow V + A$) of particular interest as a probe of the gluon distribution $g(x, Q^2)$.

Exclusive photoproduction of heavy vector mesons is calculable from pQCD, at LO:

$$\frac{d\sigma}{dt}\Big|_{t=0} = \frac{\alpha_s^2 \Gamma_{ee}}{3\alpha M_V^5} 16\pi^3 \left[ xg(x, \frac{M_V^2}{4}) \right]^2$$

Ryskin 1993
Nuclear gluon distribution and the photoproduction cross section

Uncertainty in nuclear gluon distribution translates into different cross section for photoproduction of J/ψ at mid-rapidity (dσ/dy ∝ [g(x,Q^2)]^2).

$$R_G = g_A(x, Q^2)/[A \cdot g_p(x, Q^2)]$$

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Exclusive J/ψ production studied previously:
New results at Quark Matter 2014

New results presented here:

Exclusive $\rho^0$, $\psi(2S)$ production and $\gamma\gamma \rightarrow e^+e^-$. 
The ALICE Experiment at the LHC

- A central tracking system with particle identification.
- Acceptance $|\eta| \leq 0.9$, $p_T > 100$ MeV/c
- Trigger from SPD and TOF
- A muon arm at forward rapidities $-4.0 < \eta < -2.5$.
- Triggering, tracking and identification of muons.
- VZERO counters for triggering; used here as veto detectors to define rapidity gaps ($-3.7 < \eta < -1.7$) and ($2.8 < \eta < 5.1$).
- Zero-Degree Calorimeters (ZDC) – 114 m from interaction point.
ALICE triggers and event selection for UPC

2010 Pb-Pb at $\sqrt{s_{\text{NN}}} = 2.76$ TeV:
Central barrel trigger based on TOF, SPD, VZERO. Sensitive to exclusive $\rho^0$ production and $\gamma\gamma\rightarrow e^+e^-$.  

2011 Pb-Pb at $\sqrt{s_{\text{NN}}} = 2.76$ TeV:
Central barrel trigger based on TOF, SPD, VZERO. Back-to-back topology requirement. Sensitive to exclusive $J/\psi$ and $\psi(2S)$ production and to $\gamma\gamma\rightarrow e^+e^-$.  

Studied decay modes:

$\rho^0 \rightarrow \pi^+\pi^-$  
$J/\psi \rightarrow e^+e^-, \mu^+\mu^-$  
$\psi(2S) \rightarrow e^+e^-, \mu^+\mu^-$  
$J/\psi \pi^+\pi^- \ (J/\psi \rightarrow e^+e^-, \mu^+\mu^-)$.  

All tracks reconstructed in the central barrel.

Exclusive production of light vector mesons ($\rho^0$)

$\text{Pb}+\text{Pb} \rightarrow \text{Pb}+\text{Pb}+\pi^++\pi^-$.  
- Pions identified by TPC $dE/dx$  
- Coherent events selected by $p_T < 0.15$ GeV/c.  
- Corrected for incoherently produced $\rho$ (5%).  
- $\text{Acc x Eff correction applied in each } m_{\text{inv}} \text{-bin.}$

$M_\rho = 761.6 \pm 2.3 \text{ (stat.)} +6.1/-3.0 \text{ (syst.) MeV/c}^2 \quad \text{(PDG 769 – 775 MeV/c}^2\text{)}$

$\Gamma = 150.2 \pm 5.5 \text{ (stat.)} +12.0/-5.6 \text{ (syst.) MeV/c}^2 \quad \text{(PDG 148 – 152 MeV/c}^2\text{)}$

$|B/A| = 0.50 \pm 0.04 \text{ (stat.)} +0.10/-0.04 \text{ (syst.)} \quad \text{(GeV/c}^2\text{)}^{1/2}$

Fit to Breit-Wigner resonance + continuum term (Söding 1966).

\[
\frac{d\sigma}{dM_{\pi\pi}} = A \sqrt{\frac{M_{\pi\pi}M_\rho^0\Gamma(M_{\pi\pi})}{M_{\pi\pi}^2 - M_\rho^0 + iM_\rho^0\Gamma(M_{\pi\pi})}} + B
\]

\[
\Gamma(m_{\pi\pi}) = \Gamma_\rho^0 \frac{m_\rho^0}{m_{\pi\pi}} \left(\frac{m_{\pi\pi}^2 - 4m_\pi^2}{m_\rho^0 + 4m_\pi^2}\right)^{3/2}
\]
Exclusive production of light vector mesons ($\rho^0$)

Cross section obtained by integrating the resonance contribution over $[2m_{\pi^\rho}, M + 5\Gamma]$. Same range in $M_{inv}$ as used by STAR and ZEUS.

$$\left. \frac{d\sigma(\rho^0)_{coh.}}{dy} \right|_{y=0} = \left( 420 \pm 10 \text{(stat.)} ^{+39}_{-55} \text{(sys.)} \right) \text{mb}$$

**GDL:** Proper QM Glauber calculation for scaling $\sigma(\gamma p) \Rightarrow \sigma(\gamma A)$, uses Donnachie-Landshoff model for $\sigma(\gamma p)$.

**GM:** Based on the color dipole model with saturation implemented by the Color Glass Condensate formalism.

**STARLIGHT:** Scales the experimentally measured $\gamma p$ cross section using a Glauber model, neglecting the elastic nuclear cross section.


Joakim Nystrand, Quark Matter 2014, Darmstadt, Germany, 19-24 May 2014.
Exclusive production of light vector mesons ($\rho^0$)

- Total cross section obtained by integrating over all rapidities.
- Enables comparison with STAR results.
- Additional systematic error on the shape of $d\sigma/dy$ from the difference between GM and STARLIGHT models.

$$\sigma(\rho^0)_{\text{coh.}} = \left(4.3 \pm 0.1(\text{stat.})^{+0.6}_{-0.5}(\text{sys.})\right) b$$
Exclusive production of light vector mesons ($\rho^0$)
- The strong fields associated with heavy-ions lead to large probabilities for exchanging additional photons when a $\rho^0$ is produced at small impact parameters.
- These photons will excite one or both of the nuclei (typically GDR excitations) and lead to break up.

Break up scenarios:

0N0N  – no neutrons emitted in any direction
XN    – at least one neutron emitted in any direction
0NXN  – at least one neutron emitted in one direction and no neutron in the other
XNXN  – at least one neutron emitted in both directions.

The neutrons are detected in the ZDCs.

<table>
<thead>
<tr>
<th></th>
<th>STARLIGHT</th>
<th>RSZ</th>
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<tr>
<td>All events</td>
<td>7293</td>
<td></td>
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<tr>
<td>0N0N</td>
<td>6175</td>
<td>79% (-2.9σ)</td>
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<tr>
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<td>21% (+2.2σ)</td>
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<td>958</td>
<td>16% (+2.9σ)</td>
</tr>
<tr>
<td>XNXN</td>
<td>231</td>
<td>5.2% (+4.5σ)</td>
</tr>
</tbody>
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Exclusive production of heavy vector mesons ($\psi(2S)$)

- Decay mode: $\psi(2S) \to J/\psi\pi^+\pi^- (J/\psi \to e^+e^-, \mu^+\mu^-)$.
- Two “hard” tracks with $p_T > 1$ GeV/c ($e^+e^-$ or $\mu^+\mu^-$ from $J/\psi$ decay).
- Two “soft” tracks from the $\pi^+\pi^-$.
- Typically only the hard tracks reach TOF to produce a trigger.
- Dilepton decay channel $\psi(2S) \to e^+e^-, \mu^+\mu^-$ also used as cross check.

See Poster G-07 by Michal Broz.
Exclusive production of heavy vector mesons ($\psi(2S)$)

4-track channel provides a very clean, nearly background free sample.

$$\psi(2S) \rightarrow \pi^+\pi^- \mu^+\mu^-$$

See Poster G-07 by Michal Broz for signal extraction, cross section calculation, and comparison between different decay channels.
Exclusive production of heavy vector mesons ($\psi(2S)$)

- Photonuclear $\psi(2S)$ production may probe nuclear gluon shadowing.
- However, to correctly interpret the nuclear effects, one has to understand the underlying $\gamma+p \to V+p$ baseline. Here the uncertainties are much larger for $\psi(2S)$ than for $J/\psi$.

Data from HERA and fixed target experiments; ALICE preliminary from UPC p-Pb; LHCb from exclusive production in p-p collisions.

For references: See backup slides.
Exclusive production of heavy vector mesons ($\psi(2S)$)

ALICE preliminary $d\sigma/dy = 0.83 \pm 0.19$ (stat+syst) mb

No nuclear effects. Big difference between STARLIGHT No Nucl. Eff. and AN-MSTW08 reflects the uncertainty in the baseline.

Hadronic models (STARLIGHT) or color dipole models.

Moderate shadowing $\approx$ EPS09.

Strong shadowing $\approx$ EPS08.

See Poster G-07 by Michal Broz for ratio between $\psi(2S)$ and $J/\psi$ photoproduction cross section.
Two-photon production of $e^+e^-$ pairs in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV.

Topology cut in trigger implied that only $M_{ee} > 2.2$ GeV/c$^2$ could be studied.

ALICE Collaboration, EPJC 73 (2013) 2617 (Central Barrel).
Two-photon production of $e^+e^-$ pairs in Pb-Pb

With the 2010 data this can be extended down to $M_{ee} = 0.6$ GeV/$c^2$.

Data

\[
\begin{align*}
\sigma(0.6 \leq M_{ee} \leq 2.0 \text{ GeV}/c^2, |\eta_{1,2}| \leq 0.9): & \quad 9.8 \pm 0.6\text{(stat)} +0.9/-1.2\text{(syst)} \text{ mb} \\
\sigma(2.2 \leq M_{ee} \leq 2.6 \text{ GeV}/c^2, |\eta_{1,2}| \leq 0.9): & \quad 154 \pm 11\text{(stat)} +17/-11\text{(syst)} \mu\text{b} \\
\sigma(3.7 \leq M_{ee} \leq 10.0 \text{ GeV}/c^2, |\eta_{1,2}| \leq 0.9): & \quad 91 \pm 10\text{(stat)} +11/-8\text{(syst)} \mu\text{b}
\end{align*}
\]

STARLIGHT

\[
\begin{align*}
\sigma(0.6 \leq M_{ee} \leq 2.0 \text{ GeV}/c^2, |\eta_{1,2}| \leq 0.9): & \quad 9.7 \text{ mb} \\
\sigma(2.2 \leq M_{ee} \leq 2.6 \text{ GeV}/c^2, |\eta_{1,2}| \leq 0.9): & \quad 128 \mu\text{b} \\
\sigma(3.7 \leq M_{ee} \leq 10.0 \text{ GeV}/c^2, |\eta_{1,2}| \leq 0.9): & \quad 77 \mu\text{b}
\end{align*}
\]

And the results can be combined to cover the range $M_{ee} = 0.6 – 10.0$ GeV/$c^2$.
Two-photon production of $e^+e^-$ pairs in Pb-Pb

Transverse momentum distribution well described by the Monte Carlo (STARLIGHT).
Conclusions

- ALICE has made the first measurement of coherent photoproduction of \( \rho^0 \), \( J/\psi \), and \( \psi(2S) \) in Pb+Pb collisions at the LHC.

- Cross section for the \( J/\psi \) earlier found to be in agreement with models with moderate nuclear gluon shadowing (EPS09).

- The measured cross section for the \( \psi(2S) \) disfavours models with no nuclear effects and models with strong gluon shadowing. The experimental and theoretical uncertainties prevent any stronger conclusion from the \( \psi(2S) \) measurement at the moment.

- Cross section for \( \rho^0 \) is in agreement with STARLIGHT and GM, about a factor of 2 below GDL. Similar to what was observed at RHIC.

- Two photon cross section in good agreement with STARLIGHT Monte Carlo (leading order QED). Result sets constraints on contribution from higher order terms from the \( \sqrt{\alpha} \) Z coupling.
Backup
References

Models $\rho^0$ production:


Models $\Upsilon(2S)$ production:

References

Data $\gamma + p \rightarrow V + p \ (V = \rho^0, J/\Psi \text{ or } \Psi(2S))$:


Models $\gamma + p \rightarrow V + p \ (V = J/\Psi \text{ or } \Psi(2S))$:

http://starlight.hepforge.org/