ALICE results on ultra-peripheral p-Pb and Pb-Pb collisions

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Ultra-peripheral collisions (UPC)

- Impact parameter \( b \) is larger than sum of nuclear radii
- Hadronic interactions are suppressed, only interactions mediated by the strong electromagnetic field behaving as a flux of virtual photons possible
- Field intensity is proportional to \( Z^2 \)
- LHC is used as a photon collider
- Study of saturation phenomena and nuclear gluon shadowing in \( \gamma p \) and \( \gamma Pb \) interactions

**ALICE results on p-Pb \( J/\psi \) photoproduction**
- PRL 113 (2014) 232504

**ALICE results on Pb-Pb \( J/\psi \) photoproduction**
- Eur. Phys. J. C73, 2617 (2013) central rapidities, also \( \gamma\gamma \rightarrow l^+l^- \) cross section

**ALICE results on Pb-Pb \( \rho^0 \) photoproduction**
- arXiv:1503.09177 [nucl-ex], submitted to JHEP
Central detectors
- Tracking in ITS+TPC
- Acceptance $|\eta| < 0.9$
- Trigger from SPD and TOF

Muon spectrometer
- $-4.0 < \eta < -2.5$
- Tracking (MWPC), trigger (RPC)

- VZERO scintillator arrays: VZERO-C ($-3.7 < \eta < -1.7$) on the muon arm side and VZERO-A ($2.8 < \eta < 5.1$) opposite to the muon arm
- Zero Degree Calorimeters (ZDC): detection of very forward neutrons ($|\eta| > 8.8$) and protons ($6.5 < |\eta| < 7.5$ and $-9.7^\circ < \phi < 9.7^\circ$)
$J/\psi$ in ultra-peripheral p-Pb collisions
**J/ψ photoproduction on a proton target**

- Photoproduction cross section is a probe to gluon distribution in the proton at low-$x$ with scale $q^2$, allows to search for saturation effects
  \[
  \frac{d\sigma}{dt}(\gamma^* p \rightarrow J/\psi p)|_{t=0} \propto [xg(x, q^2)]^2
  \]

- Smaller $x$ probed by higher photon-proton energy $W_{\gamma p}$
  \[
  x = (M_{J/\psi}/W_{\gamma p})^2
  \]

- Cross section of $\gamma p \rightarrow J/\psi p$ parametrized as power law of energy
  \[
  \sigma \propto W_{\gamma p}^\delta
  \]

- Empirical parametrization found at HERA ($ep$)

- Solutions of photon-proton cross section by LHCb ($pp$), power law had to be assumed due to ambiguity on photon source
ALICE measurement of $J/\psi$ photoproduction on a proton target

- In p-Pb collisions the lead-ion is most likely ($\sim$95%) the photon source
- Power law proportionality, $\sigma \propto W_\gamma^\delta p$, implies more gluons at lower $x$
- Any change in gluon behavior starting at some $W_\gamma p$ may affect the proportionality law
- Energy $W_\gamma p$ is given by $J/\psi$ rapidity $y$ measured vs. direction of proton beam of energy $E_p$

$$W_\gamma^2 = 2E_pM_{J/\psi}e^{-y}$$

- LHC switched the direction of the beams: for the MUON spectrometer $y > 0$ ($y < 0$) in p-Pb (Pb-p), yielding lower (higher) $W_\gamma p$
- Energy range of HERA extended by factor of $\sim$2, important connection between HERA and future facilities like LHeC

arXiv:1211.4831 (LHeC Study Group)
Possible ALICE configurations for $J/\psi \rightarrow l^+l^-$ in UPC

- Analysis criteria: *just two tracks in an otherwise empty detector*
- $J/\psi$ at low-$p_T$; different laboratory rapidity intervals

**Forward**
- Both tracks in muon arm
- $J/\psi$ rapidity $2.5 < |y| < 4.0$ GeV
- $W_{\gamma p} \in [21, 45]$ GeV (p-Pb) and [577, 952] (Pb-p)

**Mid-rapidity**
- Both muons or electrons in central barrel
- $J/\psi$ rapidity $|y| < 0.9$
- $W_{\gamma p} \in [100, 246]$ GeV (p-Pb and Pb-p)

**Semi-forward**
- One muon in muon arm, one in central barrel
- $J/\psi$ rapidity $1.2 < |y| < 2.7$
- $W_{\gamma p} \in [41, 86]$ GeV (p-Pb) and [287, 549] (Pb-p)
Two unlike-sign tracks in the muon spectrometer, tracks quality selection

Activity in VZERO-C compatible with expected muons from beam-beam interaction

No activity in SPD, VZERO-A and ZDCs

Trigger inputs from VZEROs and muon trigger

Selection on dimuon rapidity for a specific $\langle W_{\gamma p} \rangle$
Invariant mass distribution of the forward dimuons

- Dimuons passing the selection criteria
- Fit by Crystal-Ball ($J/\psi$) and exponential function (dimuon continuum)
- Parameters of the fit compatible with MC simulations
- Events within the $J/\psi$ mass peak are still a mixture of elastic or dissociative production of $J/\psi$ or $\gamma\gamma \rightarrow \mu^+\mu^-$:
  - The processes have different shapes of $p_T$, allowing one to separate the number of exclusive events from all $J/\psi$ candidates
Fit to the $p_T$ distribution

- Extraction of signal of exclusive $J/\psi$ in p-Pb
- $p_T$ of selected dimuons with inv. mass around the mass of $J/\psi$
- Spectrum of $p_T$ described by templates of the processes
  - Exclusive $J/\psi$ in $\gamma p$
  - Elastic $\gamma \gamma \rightarrow \mu^+ \mu^-$
  - Non-exclusive $J/\psi$ and $\gamma \gamma \rightarrow \mu^+ \mu^-$

The shapes for exclusive $J/\psi$ and $\gamma \gamma \rightarrow \mu^+ \mu^-$ were generated using STARLIGHT* and folded by detector simulation

Non-exclusive $J/\psi$ and $\gamma \gamma \rightarrow \mu^+ \mu^-$ contribution estimated from data, special sample of events with increased energy deposition in VZERO or in ZDC in the direction of proton beam

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Cross section of exclusive $J/\psi$ photoproduction in the forward p-Pb

- Differential cross section $\frac{d\sigma}{dy}(p + Pb)$ is measured to get the cross section of $\gamma p \rightarrow J/\psi p$

$$\frac{d\sigma}{dy} = \frac{N_{J/\psi}^{exc}}{(A \times \varepsilon) \times BR \times \mathcal{L} \times \Delta y}$$

- $N_{J/\psi}^{exc}$ = yield of exclusive $J/\psi$
  - p-Pb: $N_{J/\psi}^{exc} = N_{J/\psi}/(1 + f_D)$, where $N_{J/\psi}$ was obtained using the $p_T$ fit and $f_D$ is feed-down from $\psi'$
  - Pb-p: $N_{J/\psi}^{exc}$ taken by event counting followed by subtraction of the $\gamma\gamma$, $\gamma$Pb and $f_D$ components

- $f_D$: feed-down from $\psi'$, estimated using STARLIGHT, based on ratio of efficiency of $J/\psi$ from $\psi'$ and efficiency of prompt $J/\psi$ and corresponding cross sections and branching ratios. Numerical values are $f_D = 7.9^{+2.4}_{-1.9} \%$ (p-Pb) and $11^{+3.6}_{-2.8} \%$ (Pb-p)

- $A \times \varepsilon$ = detector acceptance and efficiency, calculated using MC
- $BR = $ branching ratio of $J/\psi \rightarrow \mu^+\mu^-$
- $\mathcal{L} = $ luminosity for a given UPC trigger
- $\Delta y = $ width of the rapidity bin
Relation of measured $\frac{d\sigma}{dy}(p + Pb)$ and photon-proton cross section

To get the cross section of $\gamma p \rightarrow J/\psi p$, we need to extract the photon-proton cross section $\sigma(\gamma+p)$ from the measured differential cross section $\frac{d\sigma}{dy}(p + Pb)$.

The cross sections are related via the photon spectrum $\frac{dN_\gamma}{dk}$ (distribution of photons carrying a momentum $k$)

$$\frac{d\sigma}{dy}(p+Pb \rightarrow p+Pb + J/\psi) = k \frac{dN_\gamma}{dk} \sigma(\gamma+p \rightarrow J/\psi+p)$$

The average photon flux has been calculated from STARLIGHT.

Procedure is based on Weizsäcker-Williams method and integration over impact parameter.

Corresponding energy $W_{\gamma p}$ given by rapidity of the $J/\psi$, the mean $\langle W_{\gamma p} \rangle$ for a given rapidity interval computed by weighting with photon flux and STARLIGHT cross section of $\gamma p \rightarrow J/\psi p$. 
ALICE cross section of exclusive $J/\psi$ photoproduction off protons

- A fit by power law $\sigma \propto W_{\gamma p}^{\delta}$ to the cross section as a function of energy $W_{\gamma p}$

<table>
<thead>
<tr>
<th></th>
<th>ZEUS</th>
<th>H1</th>
<th>ALICE</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta$</td>
<td>0.69 $\pm$ 0.04</td>
<td>0.67 $\pm$ 0.03</td>
<td>0.68 $\pm$ 0.06</td>
</tr>
</tbody>
</table>

- Parameter of ALICE fit in agreement with HERA, errors are (stat + syst)
- Models based on VDM, standard pQCD (LO and NLO like) and including saturation describe ALICE data
- LHCb solutions consistent with the power-law fit obtained from ALICE results
$J/\psi$ and $\psi(2S)$ in ultra-peripheral Pb-Pb collisions
Exclusive photoproduction of $J/\psi$ on heavy-ion target probes the nuclear gluon distribution. Momentum fraction carried by probed gluons varies with $y$ the rapidity of $J/\psi$:

$$x = \frac{M_{J/\psi}}{\sqrt{s_{NN}}} \exp(\pm y)$$

Ambiguity in $x$ by $\pm y$: each nucleus can act as photon source or target. At first approximation the nuclear density would scale with number of nucleons:

$$G^A(x, q^2) = A \cdot g(x, q^2)$$

Coherent photon coupling to the nucleus leads to coherent photoproduction, coupling to a single nucleon described as incoherent photoproduction. Coherently produced $J/\psi$ mesons characterized by very low $p_T$. Nuclear gluon shadowing: observed partial depletion of nuclear (w.r.t. nucleon) gluon density. Coherent production is sensitive to it.
Coherent $J/\psi$ results in Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV

- **AB**: Adeluyi, Bertulani, PRC85 (2012) 044904
  LO pQCD scaled by an effective constant to correct for missing contributions. MSTW assumes no nuclear effects, the other incorporate nuclear effects according different nuclear PDFs

- **CSS**: Cisek, Szczurek, Schäfer, PRC86 (2012) 014905
  Color dipole model based on unintegrated gluon distribution of the proton

- **STARLIGHT**: Klein, Nystrand, PRC60 (1999) 014903
  VDM coupled to a Glauber approach and using Hera data to fix the $\gamma p$ cross section

- **GM**: Gonçalves, Machado, PRC84 (2011) 011902
  Color dipole model, where the dipole nucleon cross section is from the IIM saturation model

- **RSZ**: Rebyakova, Strikman, Zhalov, PLB 710 (2012) 252
  Based on LO pQCD amplitude for two gluon exchange where the gluon density incorporates shadowing computed in leading twist approximation

- **LM**: Lappi, Mäntysaari, PRC87 (2013) 032201
  color dipole model + saturation

Nuclear suppression in Pb at small $x$

Best agreement with the model which incorporates nuclear gluon shadowing according to the EPS09 parameterization (AB-EPS09)
Coherent \( \psi(2S) \) photoproduction in Pb-Pb

- First measurement of \( \psi(2S) \) coherent photoproduction
- Tagging via decays (mid-rapidity)
  - \( \psi(2S) \to l^+ l^- \)
  - \( \psi(2S) \to J/\psi \pi^+ \pi^- \) and \( J/\psi \to l^+ l^- \)
- Clean signal despite moderate statistics

\[
\psi(2S) \to l^+ l^-
\]

\[
\psi(2S) \to J/\psi \pi^+ \pi^-
\]
Cross section of coherent $\psi(2S)$ photoproduction in Pb-Pb

- Agreement with models that include nuclear gluon shadowing consistent with the EPS09 parameterization
- Ratio $\sigma(\psi(2S))/\sigma(J/\psi)$ convenient because many experimental systematic uncertainties cancel
- Possibility of different nuclear effects to the 1S and 2S charmonia states
$\rho^0$ photoproduction in ultra-peripheral Pb-Pb collisions
$\rho^0$ photoproduction in ultra-peripheral Pb-Pb collisions

- Light vector meson photoproduction provides a probe to soft interactions at high energies
- ALICE measurement of mid-rapidity decays $\rho^0 \rightarrow \pi^+ \pi^-$
- Pions and electrons separation by $dE/dx$ in TPC
- Fit to the $p_T$ distribution using coherent and incoherent templates, data narrower than MC (same observation by STAR at RHIC)

Invariant mass of $\pi^+ \pi^-$ pairs

Fit to the $p_T$ distribution of $\rho_0$ candidates

Cross section of $\rho^0$ photoproduction in ultra-peripheral Pb-Pb collisions

- **GDL:** Glauber-Donnachie-Landshoff
  - Vector Meson Dominance Model in the Gribov-Glauber approach
  - $\sigma_{\rho N}$ using Donnachie-Landshoff model

- **GM:** Gonçalves, Machado
  - Based on the color dipole model in combination with saturation from a CGC-IIM model

- **STARLIGHT:** Klein, Nystrand
  - VDM coupled to a Glauber approach
  - HERA and fixed target data to fix the $\gamma p$ cross section

Prospects for Run 2

- Vector mesons in Run 1 Pb-Pb@2.76 TeV:

<table>
<thead>
<tr>
<th>Meson</th>
<th>Yield</th>
<th>$\mathcal{L}_{\text{int}}$</th>
<th>Error sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho_0$</td>
<td>$\sim 10^4$</td>
<td>0.26 $\mu$b$^{-1}$</td>
<td>stat error $\ll$ sys err</td>
</tr>
<tr>
<td>$J/\psi$ (mid-rapidity)</td>
<td>$\sim 500$</td>
<td>23 $\mu$b$^{-1}$</td>
<td>stat error $&lt; sys$ err</td>
</tr>
<tr>
<td>$J/\psi$ (forward)</td>
<td>$\sim 100$</td>
<td>55 $\mu$b$^{-1}$</td>
<td>stat error $&gt; sys$ err</td>
</tr>
<tr>
<td>$\psi(2S)$</td>
<td>$\sim 50$</td>
<td>23 $\mu$b$^{-1}$</td>
<td>stat error $\gg$ sys err</td>
</tr>
</tbody>
</table>

- Run 2 assumptions:

<table>
<thead>
<tr>
<th>System</th>
<th>$\sqrt{s}$</th>
<th>$\mathcal{L}_{\text{int}}$</th>
<th>Increase factor in $\mathcal{L}_{\text{int}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb-Pb</td>
<td>5.1 TeV</td>
<td>1 nb$^{-1}$</td>
<td>$\sim 7$</td>
</tr>
<tr>
<td>p-Pb</td>
<td>5.1 or 8 TeV</td>
<td>50 nb$^{-1}$</td>
<td>$\sim 2$</td>
</tr>
</tbody>
</table>

- Precision measurements of $J/\psi$, study of $\Upsilon$

- New forward scintillators
  - Two layers each, in coincidence
  - ADA: $5.5 < \eta < 7.5$
  - ADC: $-7.5 < \eta < -5.5$
  - Stronger veto to non-UPC events thanks to better coverage extending the range of existing VZEROs
Conclusions

- $J/\psi$ photoproduction in p-Pb
  - No significant change in gluon density behavior going from HERA to LHC energy

- Coherent $J/\psi$ in Pb-Pb
  - Models including nuclear gluon shadowing consistent with the EPS09 parametrization are favored

- Coherent $\psi(2S)$ in Pb-Pb
  - Models with no nuclear effects or with strong gluon shadowing disfavored

- $\rho^0$ photoproduction in Pb-Pb
  - Consistent with STARLIGHT and about a factor of 2 below the GDL Glauber calculation, similar to what was observed at lower energies by STAR

- Next LHC run
  - More luminosity
  - Higher CM energy of photon-target system
  - New forward detector for cleaner exclusive / coherent samples
  - Stay tuned!