Photoproduction of vector mesons in ultra-peripheral collisions with ALICE

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Beams of quasi-real photons at the LHC
The EM field of protons and ions at the LHC can be viewed as a beam of quasi real photons

\[ R_1 + R_2 < b \rightarrow \text{UPC} \]

**Note 1:**
There are two potential sources, correspondingly two potential targets.

**Note 2:**
The photon is *coherently* emitted by the source and its virtuality is restricted by the radius of the emitting particle:

\[ Q^2 \approx \frac{hc}{(2\pi R)^2} \]

✓ \( \gamma \) from Pb: \( Q^2 \approx (30 \text{ MeV})^2 \)

**Note 3:**
The intensity of the photon beam is proportional to \( Z^2 \)

**Note 4:**
The max energy of the photons in the lab system is determined by the boost of the emitting particle

✓ Run2: larger energies possible

**Note 5:**
Interactions at large impact parameters are of electromagnetic origin.
Why Pb-ions as source of photons?

The LHC accelerates both protons and Pb nuclei

As mentioned before, the intensity of the photon beam depends on the square of the electric charge of the accelerated particle:

→ The intensity is orders of magnitude larger for Pb w.r.t. proton beams.

It is necessary to separate the collisions of hadrons, for which the LHC and its detectors were optimized, from the collisions involving quasi-real photons.

The strategy is to use the facts that

1. Strong interactions tend to produce particles at all rapidities, while electromagnetic interactions produce large rapidity gaps
2. Pb nuclei are very fragile objects, which break in all hadronic interactions ... and ALICE is able to detect with very high efficiency if a Pb nucleus breaks (by measuring in the very forward direction neutrons from the nuclear fragmentation)

→ Look for processes with large rapidity gaps and (almost) intact outgoing nuclei

These are called Ultra-Peripheral Collisions (UPC)
Exclusive photoproduction of vector mesons and ALICE
Exclusive vector meson production

- **Kinematics** completely determined:
  - ✔ **Rapidity** measures the *energy* of the photon-target interaction
  - ✔ The square of the *transverse momentum* of the vector meson is related to $\Delta$ the momentum transferred in the target vertex
- The only particles reaching the detector are the decay products of the vector meson

Very clean signature
What do we need?

1. To measure the decay products of a vector meson with very low transverse momentum:
   - $\rho$ to $\pi^+ + \pi^-$
   - $J/\psi$ to $\mu^+ + \mu^-$ or to $e^+ + e^-$
   - $\psi(2S)$ to $\mu^+ + \mu^-$, $e^+ + e^-$ or to $J/\psi + \pi^+ + \pi^-$

2. To make sure there is nothing else in the detector:
   Large rapidity coverage to veto particles

3. To make sure that the source/target do not break:
   neutron Zero Degree Calorimeters (ZDC)
Magnetic field of 0.5 T in the central region
New for Run2: The AD detector

- Modules of plastic scintillator read out with PMTs
- Time resolution 300 (500) ps in C (A) side, allows to reject out of time background
- Enlarges ALICE geometric rapidity coverage to
  - $-6.9 < \eta < -4.9$
  - $4.9 < \eta < 6.3$
- It increases ALICE capability to impose a veto on extra activity for exclusive processes in UPC
\( \gamma\text{-Pb: Results from Pb-Pb collisions in Run1} \)

Four topics:
① Coherent \( \rho \) production
② Coherent and incoherent \( J/\psi \) production
③ Coherent \( \psi(2S) \) production
④ A surprise!
Coherent $\rho$ production

- **Coherent**: photon couples to full nuclei: VM has **very** low transverse momentum
- **Incoherent**: photon couples to one nucleon: VM has low transverse momentum

- 2010 data
- Decay into $\pi^+\pi^-$

Distribution of transverse momentum for coherent $\rho$ is wider in STARLIGHT than in data
To be studied in Run2

Transverse momentum less than 150 MeV/c to reject incoherent contribution
Coherent $\rho$ production: cross section


- Agreement with STARLIGHT
- Disagreement with GDL model may be explained by inelastic nuclear shadowing (see Phys.Lett. B752 (2016) 51-58)

ALICE, JHEP 1509 (2015) 095
Coherent and incoherent $J/\psi$ production: cross sections


Direct observation of (moderate) gluon shadowing
Under some assumptions, ALICE measurements can be translated into LO pQCD constraints for gluon shadowing at small $x$.

Note: $R_{Pb}(x,\mu^2) = g_{Pb}(x,\mu^2)/(A_{Pb}g_p(x,\mu^2))$
Coherent $\psi(2S)$ production

- Measured decay channels: $\psi(2S) \rightarrow l^+l^-$ and $\psi(2S) \rightarrow J/\psi \pi^+\pi^-$

ALICE, PLB 751 (2015) 358

- Few signal events with almost no background
\( \psi(2S) \) wave function

- The wave function of excited states present so-called nodes (Nemchik et al, ZPC75 (1997) 71)

- These nodes have a negative contribution for large dipole sizes, where saturation effects are expected

- Measure \( J/\psi \) and \( \psi(2S) \) in the same kinematic region and compare them

\( (\alpha = z, \text{see diagram}) \)
Coherent $\psi(2S)$ production: cross section

Both impulse approximations should be equal ...

Strong shadowing is disfavoured ...

Do nuclear effects affect differently $1S$ and $2S$ states? Need more precise data!
For collisions at impact parameters smaller than the sum of radii of the interacting particles, the nuclei interact hadronically and they break.
Coherent $J/\psi$ production in peripheral collisions

Clear excess in the yield at low $p_T$ for peripheral collisions

And the excess is clearly from $J/\psi$
Coherent $J/\psi$ production in peripheral collisions

If the excess were from hadronic production, the $R_{AA}$ would reach up to 7! (Standard expectation is $R_{AA} \sim O(1)$)

If photoproduction is assumed as the underlying interaction we obtain

<table>
<thead>
<tr>
<th>Centrality class</th>
<th>Cross section ($\mu$b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-10 %</td>
<td>&lt;318</td>
</tr>
<tr>
<td>10-30%</td>
<td>&lt;290</td>
</tr>
<tr>
<td>30-50%</td>
<td>$73\pm44^{+26}_{-27}$</td>
</tr>
<tr>
<td>50-70%</td>
<td>$58\pm16^{+8}_{-10}$</td>
</tr>
<tr>
<td>70-90%</td>
<td>$59\pm11^{+7}_{-10}$</td>
</tr>
</tbody>
</table>

No theoretical calculations available for coherent photoproduction in peripheral collisions

(A first try is in PRC93 (2016) 044912)
γp: Results from p-Pb collisions in Run1

Exclusive J/ψ production:
① Published results
② Work in progress
The evolution of the gluon in the proton

- $J/\psi$ gives a fixed hard scale to use pQCD calculations
- Rapidity dependence of the $J/\psi$ gives the $\log(1/x)$ dependence
- Run2 data will provide a larger reach in $\log(1/x)$
Exclusive J/$\psi$ production in p-Pb

The photon source is known: it is the lead ion in > 95% of the cases $\rightarrow$ rapidity of the J/$\psi$ measures $W_{\gamma p}$, the center of mass energy of $\gamma p$ system

ALICE: PRL 113 (2014) 23, 232504

Clean signals, small background
exclusive $J/\psi$ production in p-Pb: cross sections

- ALICE data reaches more than twice the largest energy reached at HERA
- ALICE data alone compatible with a power law with exponent $\sim 0.67 \pm 0.06$
- Exponent is compatible with those from H1 (0.67$\pm$0.03) and ZEUS (0.69$\pm$0.02$\pm$0.03)

No change in the behavior of the cross section observed from HERA to LHC ... yet ...
**Work in progress**

**ALICE:** PRL 113 (2014) 23, 232504

\[ \sigma(y+p \rightarrow J/\psi + p)(nb) \]

\[ 10^3 \]

**ALICE (p-Pb)**

**ALICE (Pb-p)**

Power law fit to ALICE data

H1

ZEUS

\[ x \sim 10^{-2} \]

\[ x \sim 10^{-5} \]

\[ 10^2 \]

\[ 10^3 \]

\[ W_{\gamma p} (GeV) \]
Work in progress

ALICE will have soon measurements covering almost continuously three order of magnitude in x-Bjorken!

\( x \sim 10^{-5} \)

\( x \sim 10^{-2} \)
Some comments on Run 2 plans
**Pb-Pb Run2 data**

ALICE Performance 31/03/2016

Pb-Pb at $\sqrt{s_{NN}} = 5.02$ TeV

UPC Sample

$p_T < 0.3$ GeV/c

$-4.0 < y < -2.5$

**Pb-Pb center of mass energy twice larger**

- Larger photon flux
- Reach twice smaller Bjorken-x

**Improved detector and trigger capabilities**

- Cleaner samples, smaller systematic error
- Better use of detector acceptance

Central sample $\sim 6x$ larger than in Run1, and

**Forward sample $\sim 50x$ larger than in Run 1!**
p-Pb Run2 data

- Larger acceptance, more statistics, better trigger $\rightarrow$ improve current measurement!

- Reach energies above 1 TeV in $\gamma p$
The $L_\gamma HC$ (and $L_\gamma\gamma C$) are delivering very interesting physics.

Exciting times are ahead of us, so stay tuned!
References
Coherent $J/\psi$ photoproduction in ultra-peripheral Pb-Pb collisions at $\sqrt{s_{\text{NN}}}$ = 2.76 TeV
http://inspirehep.net/record/1185785?ln=en

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Phys. Rev. Lett. 113 (2014) no.23, 232504
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