Charmonium photoproduction in ultra-peripheral Pb-Pb collisions with ALICE at LHC

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Overview

- LHC as $\gamma$Pb and $\gamma$p collider (ultra-peripheral collisions)
- Physics motivation (gluon distribution in nuclei and nucleons)
- ALICE and UPCs (detector and trigger description)
- $J/\psi$ and $\psi(2S)$ cross section (forward and mid-rapidity)
- Results and comparison with models (gluon shadowing)
- $\gamma\gamma$ cross section (constraint on QED processes)
- Conclusions
LHC as $\gamma$Pb and $\gamma$p collider

- heavy ions are accelerated towards each other at ultra relativistic energies
- charged particles $\rightarrow$ accompanied by an electromagnetic field
- the EM field can be viewed as a beam of quasi-real photons
- intensity of the photon beam proportional to $Z^2$
- photon flux described in Fermi-Weizsäcker-Williams approximation
- hadronic processes strongly suppressed when $b > R_1 + R_2$
- high $\sigma$ for $\gamma$-induced reactions e.g. vector meson photoproduction

Virtuality of the photon dependent on the radius of the emitting particle:

$$Q^2 \approx \left( \frac{\hbar c}{R} \right)^2$$

$\gamma$ from $p \rightarrow Q^2 \approx (250 \text{MeV})^2$

$\gamma$ from Pb $\rightarrow Q^2 \approx (30 \text{MeV})^2$
Physics motivation

- quarkonia photo-production allows to study the gluon density $G(x,Q^2)$ in Pb

$$d\sigma(\gamma N \to VN) \bigg|_{t=0} \approx \frac{\alpha_s \Gamma_{ee}}{3\alpha_e M_V^5} 16\pi^3 \left(xG(x,Q^2)\right)^2$$

- Bjorken-$x$ accessible at LHC $x = (M_V/\sqrt{s_{NN}})\exp(\pm y) \sim 10^{-2} - 10^{-5}$

- vector meson photo-production as tool to measure nuclear gluon shadowing and saturation

$$R_g^A(x,Q^2) = \frac{G_A(x,Q^2)}{G_p(x,Q^2)}$$

Physics motivation

✓ coherent vector meson production:
   ✷ photon couples coherently to all nucleons
   ✷ $<p_T> \sim 1/R_{Pb} \sim 60$ MeV/c
   ✷ no neutron emission in ~80% of cases

✓ incoherent vector meson production:
   ✷ photon couples to a single nucleon
   ✷ $<p_T> \sim 1/R_p \sim 500$ MeV/c
   ✷ target nucleus normally breaks up

✓ an interesting physics case is also $\gamma\gamma$ interactions to provide informations on QED processes when the vertex $\sqrt{\alpha}$ is replaced by $Z\sqrt{\alpha}$

$\gamma p$ cms energy $W_{\gamma p}$ beyond previous experiments (talk by E. Scapparone)

LHeC Study group ArXiv: 1211.4831
ACORDE (cosmics)  
VZERO scint. (centrality)  
-3.7 < \eta < -1.7, 2.8 < \eta < 5.1  
T0 (timing)  
ZDC (centrality)  
FMD (N_{ch} -3.4 < \eta < 5)  
PMD (N_{\gamma}, N_{ch})  

Central Barrel  
2 \pi tracking & PID  
|\eta| < 1  

muon spectrometer  
-2.5 > \eta > -4  

Detector:  
Length: 26 meters  
Height: 16 meters  
Weight: 10,000 tons
ALICE and UPCs ($J/\psi \rightarrow \mu^+\mu^-$)

UPC forward trigger

- single muon trigger with $p_T > 1$ GeV/c ($-4<\eta<-2.5$)
- hit in VZERO-C ($-3.7<\eta<-1.7$)
- no hits in VZERO-A ($2.8<\eta<5.1$)

integrated luminosity $\sim 55 \mu b^{-1}$

✓ offline event selection:
- beam gas rejection with VZERO
- hadronic rejection with ZDC and SPD

✓ track selection:
- muon tracks: $-3.7 < \eta < -2.5$
- matching with the trigger
- radial position for muons at the end of absorber: $17.5 < R_{abs} < 89.5$ cm
- $p_T$ dependent DCA cut
- opposite sign dimuon: $-3.6 < y < -2.6$
ALICE and UPCs \((J/\psi \rightarrow \mu^+\mu^- \text{ and } J/\psi \rightarrow e^+e^-)\)

UPC mid-rapidity trigger

✧ ≥ 2 hits in SPD
✧ 2 ≤ TOF hits ≤ 6 and back-to-back topology
✧ veto on VZERO-C and VZERO-A

integrated luminosity \(\sim 23 \mu b^{-1}\)

✓ offline event selection:

✧ rejection with VZERO and FMD
✧ primary vertex
✧ \(\max (p_{T1}, p_{T2}) > 1 \text{ GeV/c}\)
✧ \(dE/dx\) consistent with e/µ
✧ opposite sign tracks
✧ ZDC cut on number of neutrons emitted in coherent events
ALICE and Ultra-Peripheral Collisions

central Pb-Pb collision

UP Pb-Pb collision at mid-rapidity

UP Pb-Pb collision at forward rapidity

2 (or 4) tracks in an otherwise empty detector
detailed studies done to understand the noise and the emptiness of the detector
\[ \gamma \text{Pb processes (Pb-Pb collisions)} \]

shedding light on the nucleus
**J/ψ measurement (coherent at forward rapidity)**

First measurement of J/ψ photo-production done at LHC

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**p_T distribution fitted using MC samples representing several components:**
- coherent and incoherent J/ψ
- ψ' feed down
- γγ → μ⁺μ⁻

Distribution peaked at low momentum as expected from coherent production

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J/ψ photo-production probes the gluon distribution in Pb at x~10⁻²
J/ψ measurement (mid-rapidity)


Decay channels separation by looking at the dE/dx in TPC

electrons

muons
J/ψ measurement (coherent and incoherent at mid-rapidity)

dimuon channel


\[ \text{Eur. J. Phys. C73, 2617 (2013)} \]

\[ \text{coherent and incoherent J}/\psi \]

\[ \text{(coherent and incoherent) } \psi' \text{ feed down} \]

\[ \gamma\gamma \rightarrow \mu^+\mu^- \]

\[ \text{hadronic} \]

\[ \rho_T \text{ distribution fitted using MC samples representing several components:} \]

- coherent and incoherent J/ψ
- (coherent and incoherent) \( \psi' \) feed down
- \( \gamma\gamma \rightarrow \mu^+\mu^- \)
- hadronic

\[ \rho_T < 200 \text{ MeV/c and } < 6 \text{ neutrons} \]

emitted by nuclei to separate

coherent from incoherent production

distribution peaked at low momentum as expected from coherent production

- \( \text{J}/\psi \) photo-production probes the gluon distribution in Pb at \( x \sim 10^{-3} \)
- incoherent processes provide further constraints on the different models

05/12/2014

D. De Gruttola (Centro Ferm Roma and Salerno INFN) – IS 2014 3-7 December 2014 Napa Valley, California (USA)
J/ψ measurement (coherent and incoherent at mid-rapidity)

dielectron channel


\[ p_T < 300 \text{ MeV/c and } < 6 \text{ neutrons} \]

- emitted by nuclei to separate coherent from incoherent production

\[ \rho_T \text{ distribution fitted using MC samples representing several components:} \]

- coherent and incoherent J/ψ
- \( (\text{coherent and incoherent) } \psi' \text{ feed down} \)
- \( \gamma\gamma \to e^+e^- \)
- hadronic

\[ \text{distribution peaked at low momentum as expected from coherent production} \]

- J/ψ photo-production probes the gluon distribution in Pb at \( x \approx 10^{-3} \)
- incoherent processes provide further constraints on the different models
Results and comparison with models


\[
\begin{align*}
\left|y\right| & < 0.9 \quad \rightarrow d\sigma^{\text{coh}}_{J/\psi} / dy = 2.38^{+0.34}_{-0.24} (\text{stat} + \text{syst}) \text{ mb} \\
-3.6 < y < -2.6 \rightarrow d\sigma^{\text{coh}}_{J/\psi} / dy = 1.00 \pm 0.18 (\text{stat})^{+0.24}_{-0.26} (\text{syst}) \text{ mb}
\end{align*}
\]

Data are closer to models incorporating nuclear gluon shadowing.

- **AB**: Adeluyi and Bertulani, PRC85 (2012) 044904
  - These models use LO pQCD scaled by an effective constant to correct for missing contributions.
  - MSTW08 assumes no nuclear effects, EPS08/09 incorporate nuclear effects according to different parametrizations.
- **CSS**: Cisek, Szczurek, Sch.fer PRC86 (2012) 014905
  - Color dipole model based on unintegrated gluon distribution of the proton.
- **STARLIGHT**: Klein, Nystrand PRC60 (1999) 01493
  - GVDM coupled to a Glauber approach and using HERA data to fix the $\gamma p$ cross section.
- **GM**: Goncalves, 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.

Measured cross section in good agreement with the calculation using the EPS09 nuclear gluon prediction.
Results and comparison with models

none of the three existing models predicts the incoherent cross section correctly

STARLIGHT predicts a correct incoherent-to-coherent ratio (0.41)

ALICE measurement $0.41^{+0.10}_{-0.08} (\text{stat} + \text{syst})$


\[ d\sigma_{J/\psi}^{inc} / dy = 0.98^{+0.19}_{-0.17} (\text{stat} + \text{syst}) \text{ mb} \]

incoherent processes provide further constraints on the treatment of the nuclear modifications implemented in the different models

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STARLIGHT: Klein, Nystrand PRC60 (1999) 01493
GVDM coupled to a Glauber approach and using HERA data to fix the $\gamma p$ cross section

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, Mantysaari, PRC87 (2013) 032201
color dipole model based with Glauber approach and a saturation prescription
$\psi(2S)$ measurements (mid-rapidity)

first exclusive photonuclear production of $\psi(2S)$

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

- Clear coherent contribution at very low $p_T$
- Moderate number of candidates in 4-lepton channels, but very clear signal

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ψ'/ψ ratio

first exclusive photonuclear production of ψ(2S)

\[
\frac{d\sigma}{dy} = 0.83 \pm 0.19 \text{ (stat+syst) mb}
\]

- data disfavor models using impulse approximation and strong nuclear shadowing
- difficult to give a preference between models with mild shadowing (EPS09) or Glauber nuclear treatment (STARLIGHT, GDGM, LM)
many sources of systematic uncertainties will cancel in the measured ratio

\[ R[\sigma(\psi(2S))/\sigma(J/\psi)] = 0.34^{+0.08}_{-0.07} \text{ (stat+syst)} \]

change of R from pp to Pb-Pb may indicate that nuclear effects affect 1S and 2S states differently

models predict the ratio for pp correctly

the same models that reproduced correctly the pp ratio, fail in describing the Pb-Pb ratio

the AN EPS09 model describes in a satisfactory way this ratio (although it assumes the same functional form for J/\psi and \psi(2S))
\( \gamma \gamma \) processes (\( \text{Pb-Pb collisions} \))

sheding light on...light
the $\gamma\gamma$ cross section measurement provides important constraints on QED calculations when the vertex $\sqrt{\alpha}$ has to be replaced by $Z\sqrt{\alpha}$

due to the large Pb charge, giving $Z\sqrt{\alpha} \sim 0.6$, the inclusion of higher order terms is not straightforward $\rightarrow$ the models* including higher order terms predict a reduction of the cross section up to 30%

the measured values for the $\gamma\gamma$ cross sections are 20% above but fully compatible within 1.0 $\sigma$ and 1.5 $\sigma$ with the STARLIGHT (LO) prediction for the low and high invariant mass intervals (128 $\mu$b and 77 $\mu$b)

the models predicting a strong contribution of higher-order terms (not included in STARLIGHT) are not favored

\[ \sigma_{\gamma\gamma}^{e^+e^-} = 154 \pm 11(stat)_{-10.8}^{+16.6}(syst) \mu b \quad \text{precision 12%} \]

\[ \sigma_{\gamma\gamma}^{e^+e^-} = 91 \pm 10(stat)_{-8.0}^{+10.9}(syst) \mu b \quad \text{precision 16%} \]

* Baltz Phys. Review 80 2009 034-901
\(\gamma\gamma\) cross section

using 2010 Pb-Pb data this measurement can be extended down to \(M_{ee} = 0.6\) GeV/c\(^2\) and the results can be combined to cover the range \(M_{ee} = 0.6 - 10\) GeV/c\(^2\)

\[
\begin{array}{l|c|c}
\sigma(|\eta_{1,2}| \leq 0.9) & \text{data} & \text{STARLIGHT} \\
\hline
(0.6 \leq M_{ee} \leq 2.0\) GeV/c\(^2\)) & 9.8 \pm 0.6(\text{stat}) +0.9/-1.2(\text{syst})\) mb & 9.7\) mb \\
(2.2 \leq M_{ee} \leq 2.6\) GeV/c\(^2\)) & 154 \pm 11(\text{stat}) +17/-11(\text{syst})\) \(\mu\)b & 128\) \(\mu\)b \\
(3.7 \leq M_{ee} \leq 10.0\) GeV/c\(^2\)) & 91 \pm 10(\text{stat}) +11/-8(\text{syst})\) \(\mu\)b & 77\) \(\mu\)b \\
\end{array}
\]
Conclusions

LHC as $\gamma\text{Pb}$, $\gamma\text{p}$ and $\gamma\gamma$ collider to study:

- (Pb-Pb) measurement of exclusive vector meson ($J/\psi$) cross sections to investigate the gluon distribution in the nuclei

- (Pb-Pb) results agree with EPS09 gluon distribution, favoring the presence of gluon shadowing

- (Pb-Pb) $\psi'$ vector meson photoproduction measured

- (Pb-Pb) $\gamma\gamma$ cross section to set constraint on QED processes

- three ALICE papers:
  - Eur. J. Phys. C73, 2617 (2013) ($J/\psi$ and $\gamma\gamma$ at mid-rapidity)
  - arxiv:1406.7819, accepted for publication in PRL ($p$-Pb - talk by E. Scapparone)
back-up
γγ cross section

transverse momentum distribution well described by the Monte Carlo (STARLIGHT)
$J/\psi$ $p_T$ distributions (linear scale)

$p_T$ distribution fitted using MC samples representing several components:

- coherent and incoherent $J/\psi$
- (coherent and incoherent) $\psi'$ feed down
- $\gamma \gamma \rightarrow \mu^+\mu^-$
- hadronic

distribution peaked at low momentum as expected from coherent production
Feed down ($\psi' \to J/\Psi + \text{anything}$)

- fraction $f_D$ of $J/\Psi$ coming from the decay of $\psi' \to J/\Psi + \text{anything}$ estimated by simulating a sample of coherently produced $\psi'$ with STARLIGHT, using PYTHIA to simulate their decay into $J/\Psi$

- contribution from incoherent $\psi'$ expected to be negligible for the enriched coherent $J/\Psi$ samples → not considered

- $\psi'$ polarization can be shared between $J/\Psi$ and the other daughters → $\psi'$ decay simulated assuming no polarization, full transverse and full longitudinal polarization for the $J/\Psi$

for a given polarization $P$:

$$f_D^P = \frac{\sigma_{\psi'} \cdot BR(\psi' \to J/\psi + \text{anything}) \cdot (\text{Acc} \times \varepsilon)^P_{\psi' \to J/\psi}}{\sigma_{J/\Psi} \cdot (\text{Acc} \times \varepsilon)_{J/\psi}}$$

see table in the next slide for the results
Feed down ($\psi' \rightarrow J/\Psi + \text{anything}$)

alternatively the ratio $\psi'$ over $J/\Psi$, used to compute the feed-down $f_D$, can be extracted from the data

due to the limited statistics the two decay channels were combined:

$$N_{\psi'} = 17 \pm 10 \text{ and } N_{J/\psi} = 505 \pm 48$$

$\rightarrow f_D$ ranges from 11.0$\pm$6.5% for transverse $\psi'$ polarization to 15$\pm$9% for longitudinal $\psi'$ polarization

the average of these estimates is $f_D = 0.10^{+0.05}_{-0.06}$

invariant mass distribution for combined dimuon and dielectron channels