Vector meson photoproduction in ultra-peripheral p-Pb collisions measured using the ALICE detector

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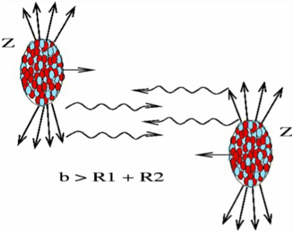
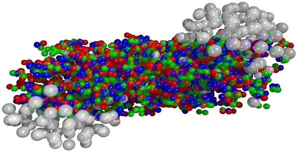
Ultra-peripheral collisions at the LHC

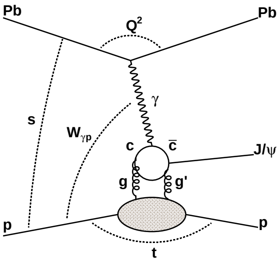




- The ultra-peripheral collision (UPC) is a collision at impact parameter greater than sum of nuclear radii $R1 + R2$
- Is mediated only by electromagnetic forces
- The electromagnetic field in UPC is described by flux of virtual photons (E. Fermi 1924)
- Generalization of virtual photons to relativistic case was done by Weizsäcker and Williams
- Intensity of the field is proportional to Z^2
- The LHC works as a photon-hadron collider
- Study of saturation phenomena and nuclear gluon shadowing in $\gamma \mathrm{p}$ and $\gamma \mathrm{Pb}$ interactions

Photoproduction of J/ψ in photon-proton interactions

- ALICE used p-Pb collisions, the lead-ion is most likely ($\sim$95%) the photon source



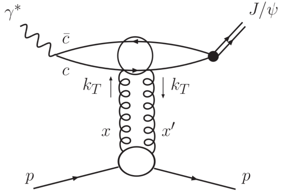
- Photon-proton cross section $\sigma(\gamma + \mathrm{p} \rightarrow J/\psi + \mathrm{p})$ is measured as a function of photon-proton center-of-mass energy $W_{\gamma\mathrm{p}}$
- Kinematics is constrained as:

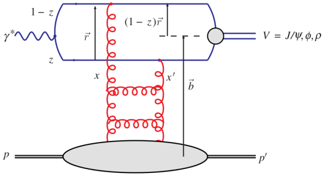
$$W_{\gamma\mathrm{p}}^2 = 2E_p M_{J/\psi} \exp(-y)$$

- Rapidity y of the J/ψ is measured along direction of proton beam of energy E_p
- LHC used both direction: $y > 0$ ($y < 0$) in p-Pb (Pb-p), yielding lower (higher) energy $W_{\gamma\mathrm{p}}$

Calculations of the photon-proton cross section $\sigma(\gamma+\mathrm{p} \rightarrow J/\psi+\mathrm{p})$

- High energy J/ψ production is modeled by the two-gluon exchange (left) or using the dipole approach (right)*





- Cross section in LO approximation is proportional to the square of the gluon distribution $xg(x, q^2)$ at the scale $q^2 = M^2_{J/\psi}/4$:

$$\left.\frac{\mathrm{d}\sigma}{\mathrm{d}t}(\gamma\mathrm{p} \rightarrow J/\psi\mathrm{p})\right|_{t=0} = \frac{\Gamma_{ee}\pi^3\alpha_s^2}{3M_{J/\psi}\alpha_{\mathrm{em}}}\left[xg(x, q^2)\right]^2$$

- Momentum fraction** of probed gluons is $x = (M_{J/\psi}/W_{\gamma\mathrm{p}})^2$
- In doing the experiment, each rapidity interval gives some $W_{\gamma\mathrm{p}}$ and hence the data at different x

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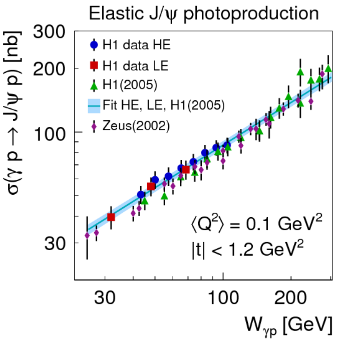
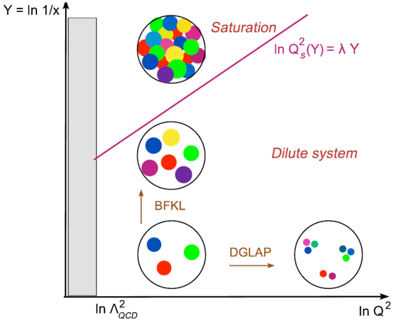
*Diagrams: two-gluon exchange: J. High Energy Phys. 11 (2013) 085, dipole approach: Phys. Rev. D 74, 074016 (2006)

**Actually there are two gluons at different momentum fractions $x' \ll x \ll 1$ and the cross section is in fact proportional to the *skewed* gluon distribution. It is dealt by the models on how to transform the diagonal distribution at x to the skewed distribution at $x_{1,2} = x \pm \xi$.

Gluon dynamics at small-x probed by J/ψ photoproduction

- Cross section at higher $W_{\gamma p}$ probes gluons at smaller x

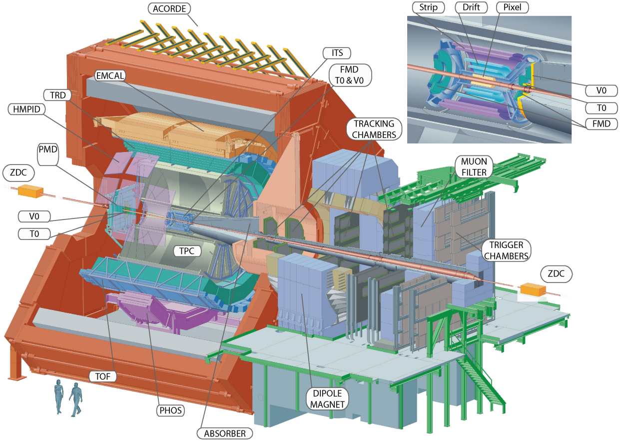




- Steady growth of the cross section $\sigma \propto W^{\delta}_{\gamma p}$ (HERA) indicates linear evolution with $Y = \ln 1/x$
- The gluon density is expected to saturate at small Bjorken-x
- Expected saturation should suppress the growth of the cross section beyond certain energy
- Finding the $W_{\gamma p}$ for onset of saturation is important experimental task

H1: Eur.Phys.J. C73, 2466 (2013), diagram: E. Iancu, CERN-2014-003.197

The ALICE experiment (A Large Ion Collider Experiment)

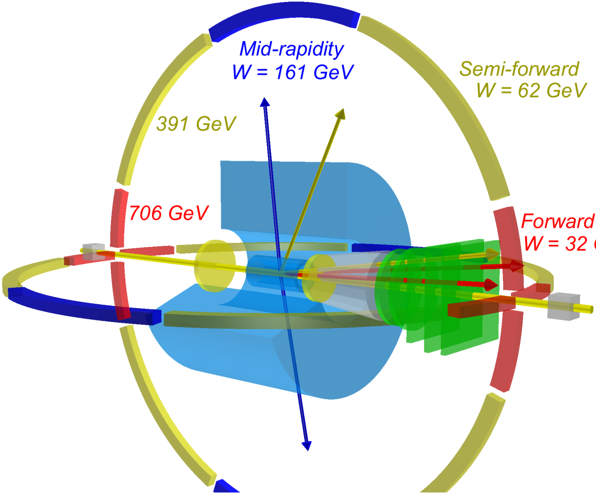


- Central detectors
  - Tracking in ITS+TPC
  - Acceptance $|\eta| < 0.9$
  - Trigger from SPD and TOF
- Muon spectrometer
  - $-4.0 < \eta < -2.5$
  - Tracking (MWPC), trigger (RPC)

- 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 $-9.7^\circ < \phi < 9.7^\circ$)

ALICE measurements of exclusive $J/\psi \to l^+ l^-$ in p-Pb UPC

- Just two tracks in an otherwise empty detector, combination of forward and central tracking
- Different laboratory rapidity y intervals, energy $W^2_{\gamma p} = 2E_p M_{J/\psi} \exp(-y)$



- Wider range in $W_{\gamma p}$ than any previous experiment, top energy two times larger than at HERA
- Results from forward rapidity in this talk, other intervals are being finalized for publication

Signal extraction for J/ψ in $\gamma \mathrm{p} \to J/\psi \mathrm{p}$

- Events within J/ψ mass peak are still a mixture of elastic, inelastic and dissociative production of the J/ψ and $\gamma\gamma \to \mu^+\mu^-$
- Templates to fit the p_T distribution, color notation (■ ■ ■ ■) will be followed in the fit

Two photon production $\gamma\gamma \to \mu^+\mu^-$

- Soft component of the p_T distribution, created by STARLIGHT*, folded by full detector simulation

Coherent γ-Pb interactions

- Part of the soft component, contributes to forward Pb-p
- STARLIGHT was normalized to ALICE measurement in Pb-Pb, folded by detector simulation

Exclusive $\gamma + \mathrm{p} \to J/\psi + \mathrm{p}$

- Process of interest, middle part of the p_T distribution
- Obtained using STARLIGHT + folding by simulation

Non-exclusive J/ψ and $\gamma\gamma \to \mu^+\mu^-$

- Process of proton dissociation or inelastic production, hard component of p_T distribution
- Taken from the data, increased energy deposition in VZERO or in ZDC in the direction of proton beam

* Phys.Rev. C60, 014903 (1999), hep-ph/9902259, https://starlight.hepforge.org/

Fine tuning of STARLIGHT template of exclusive $\gamma+\mathrm{p} \rightarrow J/\psi+\mathrm{p}$

- Shape of p_T distribution is expected to take the form

$$\frac{\mathrm{d}N}{\mathrm{d}p_T} = A \cdot p_T \exp(-b \cdot p_T^2)$$

- The slope parameter b depends on the energy $W_{\gamma\mathrm{p}}$ as*

$$b(W_{\gamma\mathrm{p}}) = b_0 + 4\alpha' \ln(W_{\gamma\mathrm{p}}/W_0)$$

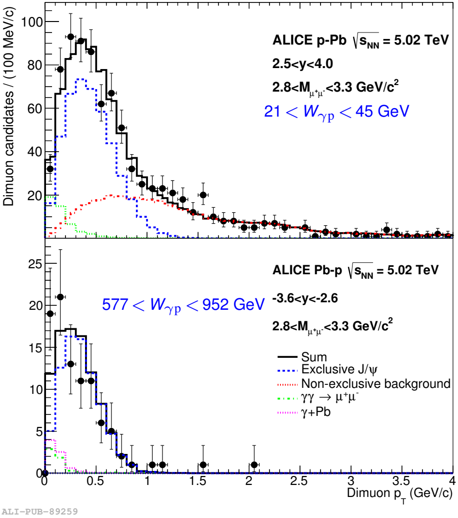
- STARLIGHT uses a constant b

- Special MC sample with b set in STARLIGHT for the energy at forward Pb-p was used for the p_T fit

* Eur. Phys. J. C 46, 585 (2006)

Fit to the p_T distribution in the forward rapidity

- Extraction of signal of exclusive J/ψ in p-Pb
- Model (black line) as a sum of the templates:
  - Exclusive J/ψ in γp
  - Elastic $\gamma\gamma \rightarrow \mu^+\mu^-$
  - Coherent γ-Pb interactions
  - Non-exclusive J/ψ and $\gamma\gamma \rightarrow \mu^+\mu^-$
- Fit using the model provides the number of J/ψ in $\gamma\mathrm{p} \rightarrow J/\psi\mathrm{p}$
- Normalization is free for J/ψ in γp and non-exclusive J/ψ
- Upper bound for $\gamma\gamma \rightarrow \mu^+\mu^-$ from fit to invariant mass
- Coherent contribution is fixed using the measured cross section in Pb-Pb



PRL 113 (2014) 232504

Experimental cross section of exclusive J/ψ photoproduction in p-Pb

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

$$\frac{\mathrm{d}\sigma}{\mathrm{d}y} = \frac{N^{exc}_{J/\psi}}{\varepsilon_{J/\psi}\cdot\mathcal{B}\cdot\mathcal{L}} \cdot \frac{1}{\Delta y}$$

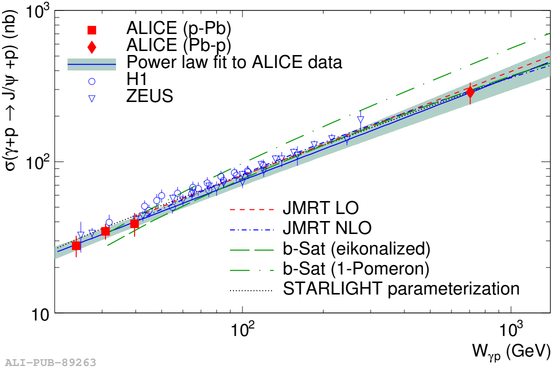
- $N^{exc}_{J/\psi} = \frac{N_{J/\psi}}{1+f_D}$ = yield of exclusive J/ψ
  - $N_{J/\psi}$ = number of elastic J/ψ from the fits to the p_T distribution
  - f_D: feed-down from $\psi' \to J/\psi + X$, follows from ratio of cross sections and efficiencies of direct J/ψ and J/ψ from ψ', effect of $\sim$10%
  - Case of forward Pb-p: $N^{exc}_{J/\psi}$ by event counting, subtraction of the $\gamma\gamma$, γPb and f_D components
- $\varepsilon_{J/\psi}$ = correction for detector acceptance and efficiency
- $\mathcal{B}$ = branching ratio of $J/\psi \to \mu^+\mu^-$ (PDG)
- $\mathcal{L}$ = luminosity of the data sample
- Δy = width of the rapidity bin
- Photon-proton cross sections is related via the photon spectrum $\mathrm{d}N_\gamma/\mathrm{d}k$ (distribution of photons carrying a momentum k) as

$$\frac{\mathrm{d}\sigma}{\mathrm{d}y}(\mathrm{p{+}Pb} \to \mathrm{p{+}Pb} + J/\psi) = k\frac{\mathrm{d}N_\gamma}{\mathrm{d}k}\sigma(\gamma{+}\mathrm{p} \to J/\psi{+}\mathrm{p})$$

- The average photon flux has been calculated from STARLIGHT
- Procedure is based on Weizsäcker-Williams method in impact parameter space

ALICE cross section of exclusive J/ψ photoproduction off protons

- Lower energies by forward p-Pb (3 bins), high energy by forward Pb-p
- A fit by power law $\sigma \propto W_{\gamma p}^{\delta}$ to the cross section as a function of energy $W_{\gamma p}$

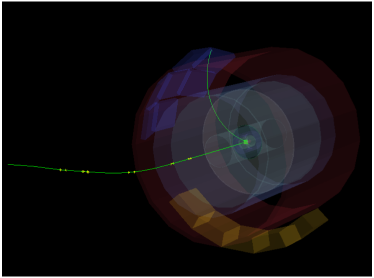


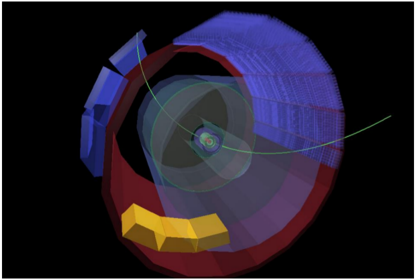
- Power-law fit to ALICE data alone gives $\delta_{\mathrm{ALICE}} = 0.68 \pm 0.06$
- Fits to HERA data give $\delta_{\mathrm{H1}} = 0.67 \pm 0.03$ and $\delta_{\mathrm{ZEUS}} = 0.69 \pm 0.04$, ALICE is compatible
- Models based on VDM, standard pQCD (LO and NLO like) and including saturation describe ALICE data

ALICE: PRL 113 (2014) 232504, H1: Eur.Phys.J. C73, 2466 (2013), ZEUS: Eur. Phys. J. C 24, 345 (2002)
JMRT: J. High Energy Phys. 11 (2013) 085, b-Sat: Phys. Rev. D 74, 074016 (2006), arXiv:1211.4831 (1-Pomeron)

Data from semi-forward and mid-rapidity intervals

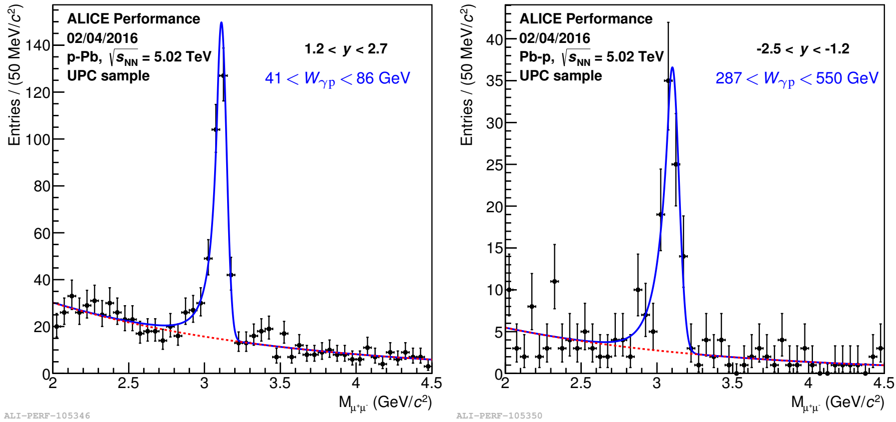
- Results are in final stages of paper preparation
- These new data will cover HERA range and also provide a new measurement beyond HERA energies





- Semi-forward rapidity
  - One muon in muon arm, one in central barrel
  - J/ψ rapidity $1.2 < |y| < 2.7$
  - $W_{\gamma p} \in [41, 86]$ GeV (p-Pb) and $[287, 550]$ (Pb-p)
- Mid-rapidity
  - Both muons or electrons in central barrel
  - J/ψ rapidity $|y| < 0.8$
  - $W_{\gamma p} \in [106, 235]$ GeV (p-Pb and Pb-p)

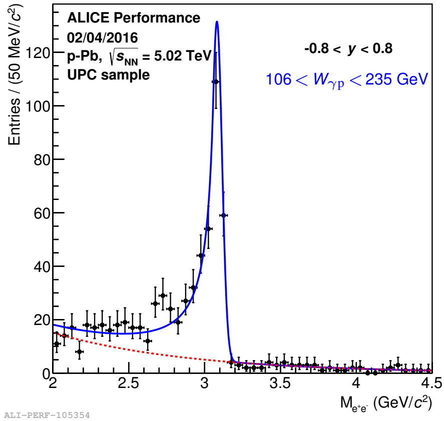
Invariant mass of selected candidates in semi-forward rapidity

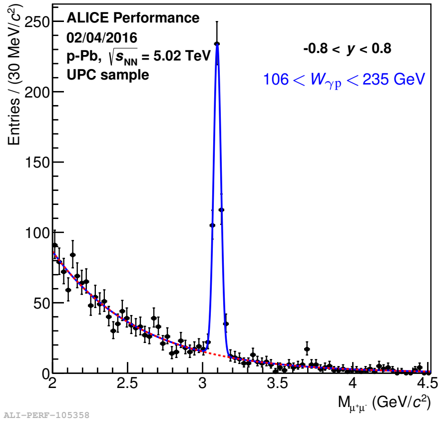


- Left: p-Pb at positive J/ψ rapidity, right: Pb-p at negative rapidity
- Clear signal of J/ψ, fit by Crystal Ball* and exponential for $\gamma\gamma \to \mu^+\mu^-$
- Parameters of the fit are compatible with MC expectations

* J. Gaiser, SLAC-R-255 (1982)

Invariant mass at mid-rapidity





- Common sample of p-Pb and Pb-p thanks to symmetry around $y = 0$
- Left: dielectron channel, right: dimuon channel
- Fit by Crystal Ball for J/ψ and exponential for $\gamma\gamma \to e^+e^-$ or $\gamma\gamma \to \mu^+\mu^-$

Conclusions

- ALICE has measured exclusive photoproduction of J/ψ beyond energies achieved at HERA
- In Run1 data, no significant change in behavior of gluon density going from HERA to LHC energy
- Large kinematics coverage of a single experiment (combination of ALICE forward and central tracking)
- Update by semi-forward and mid-rapidity intervals is in final stages of paper preparation
- New LHC p-Pb run this year
  - With 8 TeV, precision measurement over 30 GeV $\lesssim W_{\gamma\mathrm{p}} \lesssim$ 1300 GeV will be possible
  - Top energy is almost two times higher than in Run1
  - ALICE has new very forward ($5.5 < |\eta| < 7.5$) scintillators for stronger veto to non-UPC events
  - Cleaner sample, more luminosity and higher photon-proton energies
- Stay tuned!