J/ψ photoproduction results from ALICE

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Introduction
• Active search for **saturation** at low $x$!

• Debate about current results remains open
• **Nuclear shadowing effects** on gluon PDFs at low $x$

\[ R_g^A(x, Q^2) = \frac{g_A(x, Q^2)}{g_p(x, Q^2)} < 1 \]

• Onset of saturation is expected to depend on the atomic mass number

→ **Saturation may contribute to nuclear shadowing!**
• Hadronic interactions are suppressed

Photon-induced reactions can be measured at the LHC!

• Photon-induced reactions also contribute at $b < 2R$:
  • $J/\psi$ excess at very low $p_T$ – ALICE$^1$


Photoproduction in hadronic collisions
7 Apr 2022, 09:20, Alexandra Neagu
https://indico.cern.ch/event/895086/contributions/4724130/
Photoproduction

- LHC is a **Light-Hadron Collider** at the highest available energies
- Many photoproduction processes can be studied in ALICE  ➔  Vector meson production
- Bjorken-$x$ evolution of the parton distribution
  \[ x = \frac{M_{VM}}{\sqrt{S_{NN}}} e^{\pm y} \]
- Centre-of-mass energy of the photon–target system
  \[ W_{\gamma p,Xe,Pb}^2 = 2E_{p,Xe,Pb}M_{VM}e^{\mp y} \]
- Transverse-plane distribution of the partons
  2D Fourier transform to the $|t|$ ($\sim p_T^2$) dependence

\[ W_{\gamma p,Xe,Pb}^2 \]

\[ p^0, J/\psi, \psi'(y,p_T^2) \]

\[ p, Xe, Pb \]
ALICE: $J/\psi$ measurement at midrapidity

**Time-of-Flight (TOF)**
- Multigap resistive plate chambers
- Triggering and particle identification

**L3 Magnet**
$B = 0.5 \, \text{T or} \, 0.2 \, \text{T}$

**Time Projection Chamber (TPC)**
- Drift volume with multiwire proportional chambers end caps
- Tracking and particle identification

**Inner Tracking System (ITS)**
- Silicon detector
- Triggering and tracking
ALICE: $J/\psi$ measurement at forward rapidity

Muon Tracker
- Resistive plate chambers
- Triggering

Muon Wall

Muon Trigger
- Resistive plate chambers
- Triggering

Muon Tracker
- Cathode pad chambers
- Tracking

Absorber

Dipole Magnet
ALICE: Vetoes to enforce exclusivity condition

Zero-Degree Calorimeter (ZDC)
- Sampling calorimeters
- Luminosity determination

V0
- Scintillator counter
- Veto activity
- Luminosity determination

ALICE Diffractive (AD)
- Scintillator counter
- Veto activity
Pb-Pb UPC Results
Coherent $J/\psi$ cross section: $y$ - dependence

- **Nuclear suppression factor**: for $x \in (0.3, 1.4) \cdot 10^{-3}$

$$S_{Pb} = \sqrt{\left(\frac{d\sigma}{dy}\right)_{\text{data}} / \left(\frac{d\sigma}{dy}\right)_{\text{IA}}} = 0.65 \pm 0.03$$

- Models with **shadowing** (EPS09, LTA) and **saturation** (GG-HS):
  - Describe central and forward data
  - Underestimate semi-forward data
  - Other models describe either the central or the forward rapidity region

- **No model describes the full rapidity dependence**
Coherent $\psi'$ cross section: $y$ - dependence

- **Nuclear suppression factor:** for $x \in (0.3,1.6) \cdot 10^{-3}$

  $$S_{Pb} = 0.66 \pm 0.06$$

  Consistent with the $J/\psi$ result

- **Models with shadowing:**
  - EPS09 - agrees
  - LTA - agrees

- **Models with saturation:**
  - b-BK - agrees
  - GG-HS - overpredicts

- Other models overpredict the results
Coherent $J/\psi$ cross section: $|t|$ - dependence

- From $p_T^2$-dependent photoproduction to $|t|$-dependent photonuclear production:
  - $p_T^2$ to $|t|$ transition with two different unfolding methods
  - Correction on interference of photon sources
  - From UPC to photonuclear cross section using the photon flux

\[
\frac{d^2\sigma_{J/\psi}^{\text{coh}}}{dy dp_T^2} \bigg|_{y=0} = 2n_{\gamma\text{Pb}}(y = 0) \frac{d\sigma_{\gamma\text{Pb}}}{d|t|}
\]

→ Probing the transverse partonic structure of the nucleus at low $x$!
Coherent $J/\psi$ cross section: $|t|$ - dependence

- Difference from STARlight (driven by the nuclear form factor) in shape and magnitude

$|t|$ dependent QCD dynamical effects!

- Models based on pQCD describe data within current uncertainties:
  - Nuclear **shadowing** (LTA)
  - Gluon **saturation** (b-BK)
- Future measurements should allow to distinguish between the predictions

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Xe-Xe UPC Results
Coherent $\rho^0$ cross section: $A$ - dependence

- Measurement with Pb and Xe collisions

- Power-law fit: $\alpha = 0.96 \pm 0.02$
  - Below coherent  shadowing
  - Value close to incoherent is a coincidence caused by large shadowing effect
  - Black-disc limit distant at $W_{\gamma A} = 65$ GeV

- Models agree with the data:
  - GKZ - shadowing
  - CCKT - saturation
p-Pb UPC Results
$\gamma\gamma \rightarrow \mu\mu$ cross section

- $\gamma\gamma \rightarrow \mu\mu$ cross section in the **low mass** region!
- **STARlight:**
  - LO QED without final-state radiation or other NLO effects
  - No interactions within the radius of the targets

**Slight excess in data**

**agreement within 3 sigma**

- Can be used to improve current models
  - **Fix background** for VM or jet **photoproduction**
  - Improve predictions for **light-by-light scattering**

![Graph showing $d\sigma/dy$ for $\gamma\gamma \rightarrow \mu\mu$](image.png)
Energy dependence: Exclusive $J/\psi$ cross section

- Power law fit to ALICE data
  - Exponent: $\delta = 0.70 \pm 0.04$
- No change between HERA and LHC
- ALICE and LHCb are compatible
- Agreement with models:
  - JMRT NLO: DGLAP formalism with main NLO contributions
  - CCT: Saturation in an energy dependent hot spot model
Energy dependence: Dissociative J/ψ cross section

- First measurement of the dissociative cross section at the LHC!
  - Agreement with CCT, predicts maximum at $W_{γp} \approx 500$ GeV
  - Agreement with HERA results

**NEW**

**Energies ≈ 1 TeV available in Run 3!**
Outlook: LHC Runs 3 & 4

- $\mathcal{L}$ increase - 1 nb$^{-1}$ (Run 2) $\rightarrow$ 13 nb$^{-1}$ (Runs 3+4)
- Continuous readout $\rightarrow$ higher data collection efficiency
- Significant detector upgrades
- Proposed O-O run $\rightarrow$ new system size

Many more collisions to be recorded by ALICE!
Outlook: LHC Runs 3 & 4

• **Improvements** in **statistical** precision, **systematic** uncertainties and **efficiency**:
  
  → Increased precision on all previous measurements

• **New differential** measurements:
  
  • \( \frac{d^2\sigma}{dy|t|} \)

  • Angular dependences between \( l^+ l^- \)

  • Coherent \( \rho^0 \) evolution with \( A \) in O-O …

• **Completely new** measurements:
  
  • \( \Upsilon(1S) - Q^2 \) factor 10 larger than \( J/\psi \)

  • Interference effects

  • Incoherent \( \rho^0 \) production …

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Future UPC measurements in ALICE
6 Apr 2022, 18:38, Adam Matyja
https://indico.cern.ch/event/895086/contributions/4723698/
Conclusion
Conclusion

• Nuclear parton structure at Bjorken $x \in (0.3, 1.4) \cdot 10^{-3}$:
  • $S_{\text{Pb}} \approx 0.65$
  • $|t|$ dependence sensitive to parton distribution in the transverse plane
  • Models with shadowing or saturation describe data within uncertainties

• Proton parton structure at Bjorken $x \in (0.5, 2) \cdot 10^{-2}$:
  • Exclusive cross section agrees with previous results
  • For the first time dissociative and low mass $\gamma\gamma \to \mu\mu$ cross sections!

• Major improvements for Runs 3 & 4:

  → Plenty of new results anticipated!
Thank you for your attention!
Backup
Photoproduction

\[ \gamma \rightarrow \rho^0, J/\psi, \psi' \ (y, p_t^2) \]
Photoproduction

**Photoproduction**

- Flux intensity $\sim Z^2$
- Photon energy given by Pb boost

**J/ψ, ψ’**

- Perturbative QCD $Q^2 \sim \frac{M^2}{4}$
- Clear experimental signal:
  - Large lepton branching ratios
  - Small decay width
  - Exclusive production

**Photon emission**

- In LO collinear pQCD:
  $$\frac{d\sigma_{\gamma p+\rightarrow J/\psi+A}}{dt} \bigg|_{t=0} = \frac{M_{J/\psi}^3 \Gamma ee \pi^3 \alpha_s(Q^2)}{48 \alpha_{em} Q^8} [xg_A(x, Q^2)]^2$$

Photoproduction $p_T$ signature

- Photon interacts with the **whole nucleus**: $p_T \approx 60$ MeV/c $\sim 1/R_{\text{Pb}}$
  - **Coherent** (Pb-Pb) - Target ion stays intact

- Photon interacts with **single nucleon**: $p_T \approx 300$ MeV/c $\sim 1/R_{\text{N}}$
  - **Incoherent** (Pb-Pb) - Target ion breaks, nucleon stays intact
  - **Exclusive** (p-Pb) - Target proton stays intact

- Photon interacts with **single nucleon and excites it**: $p_T \approx 1$GeV/c
  - **Dissociative** (p-Pb) - Target proton breaks
  - **Dissociative** (Pb-Pb) - Target nucleon breaks as well as the ion
Coherent $J/\psi$ cross section

- Very clear signal
  - Measured in 3 decay channels: $\mu^+\mu^-, e^+e^-, p\bar{p}$
Coherent $\psi'$ cross section

- Clear signal even with less events

- Measured in 3 decay channels:
  $\mu^+ \mu^- \pi^+ \pi^-$, $e^+ e^- \pi^+ \pi^-$, $l^+ l^-$
Coherent $J/\psi$ cross section: $y$ - dependence

- **Impulse approximation (IA):** Photoproduction data from protons, does not include nuclear effects except coherence

- **STARlight:** Photoproduction data from protons + Vector Meson Dominance model, includes multiple scattering but no gluon shadowing

- **EPS09 LO:** Parametrization of nuclear shadowing data

- **LTA:** Leading Twist Approximation of nuclear shadowing

- **IIM BG, IPsat, BGK-I:** Color dipole approach coupled to the Color Glass Condensate formalism with different assumptions on the dipole-proton scattering amplitude

- **GG-HS:** Color dipole model with hot spots nucleon structure

- **b-BK:** Color dipole approach coupled with impact-parameter dependent Balitsky-Kovchegov equation
Exclusive and Dissociative $J/\psi$ signal extraction

- Simultaneous unbinned fit of mass and $p_T$ spectra of $\mu^+\mu^-$ pairs
Run 1 ALICE Pb-Pb UPC at $\sqrt{s_{NN}} = 2.76$ TeV

Pb+Pb $\rightarrow$ Pb+Pb+$J/\psi$  
$\sqrt{s_{NN}} = 2.76$ TeV  

- ALICE Coherent $J/\psi$  
- Reflected

ALI-PUB-66209
Run 1 ALICE p-Pb UPC at $\sqrt{s_{NN}} = 5.02$ TeV

Outlook: Impact of ALICE and LHC UPC results

- Reweighted EPPS16 nPDFs with LHC results
  - Run 2: ALICE + LHCb
  - Run 1: ALICE + CMS

→ Decrease in EPPS16 uncertainties!