First measurement of the $|t|$-dependence of incoherent J/ψ photoproduction with ALICE at the LHC

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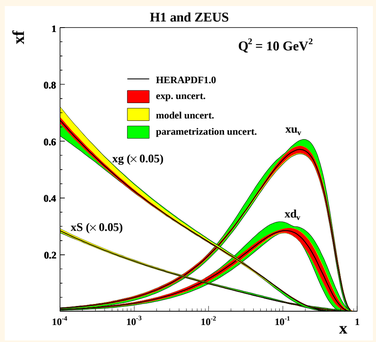
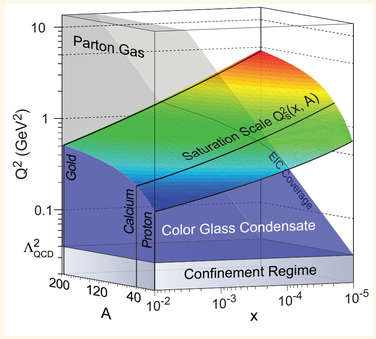
Physics motivation

- When seen with a high-energy probe, the structure of nucleons is dominated by **gluons**
- At some point, a **saturation** regime (a dynamic equilibrium between their production and annihilation) is expected to be reached
- For heavy nuclei, saturation is expected at lower energies (higher Bjorken-x)
- Experimental work is required to determine **if and when** the saturation occurs
- In order to answer such questions, the nuclear structure needs to be studied from various points of view:
  - What is the average gluon density?
  - How does the density **fluctuate event-by-event**?



Taken from [1]



Taken from [2]

Ultra-peripheral collisions (UPCs)

- To study the interior of nuclei, the ideal probes are **photons**
- EM fields of highly relativistic nuclei act as **light beams**, intensity of which $\propto Z^2$
- In UPCs, the nuclei collide at the impact parameter b larger than the sum of their radii:
  - Pure hadronic interactions are suppressed
  - Processes are induced by quasi-real photons

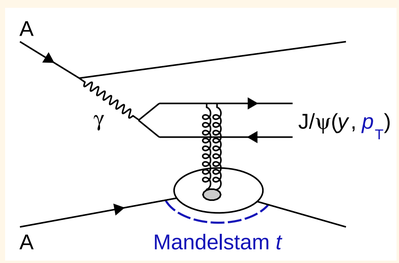
Diffractive J/ψ photoproduction

- The diffractive photoproduction of J/ψ in UPCs is sensitive to both the average and the variance of the gluon field spatial distribution
- An emitted photon fluctuates into a **color dipole** ($q\bar{q}$ pair) that **interacts strongly** with the target nucleus via an exchange of at least two gluons
- The γA interaction (the QCD part) is described by the photonuclear cross section, $\sigma_{\gamma A}$
- The process has two contributions:

Process	γ interacts with	$\sigma_{\gamma A}$ sensitive to (Good-Walker)	$\langle p_T \rangle$ of J/ψ
Coherent	The whole nucleus	The average	$\sim$ 50 MeV
Incoherent	A single nucleon	The variance	$\sim$ 400 MeV

- The Mandelstam t is related to the transverse structure of the target (through a Fourier transform)
- The smaller the scattering object, the larger the value of t
- If there are **significant geometrical fluctuations** at a sub-nucleon scale, we should observe an enhancement of the incoherent cross section at "large" t (~ 1 GeV^2)
- For the incoherent process, t can be obtained directly from the vector meson transverse momentum: $|t| = p_T^2$
- The vector meson rapidity gives us the energy (Bjorken-x) of the process:

$$x = \frac{M_{J/\psi}}{\sqrt{s_{NN}}} e^{-y}$$



(Diagram for incoherent photoproduction)

- From the experimental point of view, UPC events are **very clean**: only two back-to-back lepton tracks in an otherwise empty detector!

References

[1] **H1, ZEUS** Collaboration, F. D. Aaron *et al.*, "Combined Measurement and QCD Analysis of the Inclusive e$^{\pm}$p Scattering Cross Sections at HERA," *JHEP* **01** (2010) 109, arXiv:0911.0884 [hep-ex].

[2] A. Accardi *et al.*, "Electron Ion Collider: The Next QCD Frontier: Understanding the glue that binds us all," *Eur. Phys. J. A* **52** no. 9, (2016) 268, arXiv:1212.1701 [nucl-ex].

[3] A. Tauro, "ALICE Schematics," May, 2017. General Photo.

[4] **ALICE** Collaboration, S. Acharya *et al.*, "First measurement of the $|t|$-dependence of incoherent J/ψ photonuclear production," arXiv:2305.06169 [nucl-ex].

[5] S. R. Klein, J. Nystrand, J. Seger, Y. Gorbunov, and J. Butterworth, "STARlight: A Monte Carlo simulation program for ultra-peripheral collisions of relativistic ions," *Comput. Phys. Commun.* **212** (2017) 258–268, arXiv:1607.03838 [hep-ph].

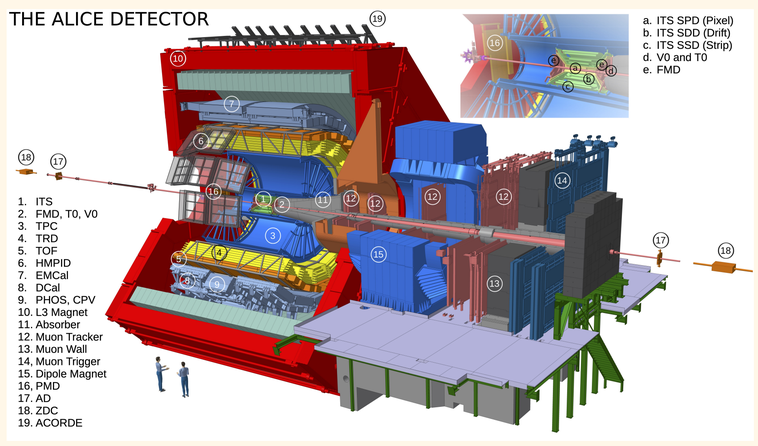
[6] H. Mäntysaari and B. Schenke, "Probing subnucleon scale fluctuations in ultraperipheral heavy ion collisions," *Phys. Lett. B* **772** (2017) 832–838, arXiv:1703.09256 [hep-ph].

[7] V. Guzey, M. Strikman, and M. Zhalov, "Nucleon dissociation and incoherent J/ψ photoproduction on nuclei in ion ultraperipheral collisions at the Large Hadron Collider," *Phys. Rev. C* **99** no. 1, (2019) 015201, arXiv:1808.00740 [hep-ph].

Brief analysis overview

- The **first measurement** of the dependence of the cross section for incoherent J/ψ photonuclear production on the Mandelstam t.
- Pb–Pb UPCs at $\sqrt{s_{NN}} = 5.02$ TeV
  $\Rightarrow$ probing **sub-nucleon fluctuations** in lead nuclei!
- Integrated luminosity of the data set $\mathcal{L} = (232 \pm 7)\ \mu b^{-1}$
- J/ψ reconstructed at midrapidity, requiring $|y| < 0.8$, from the decay into muon pairs
  $\Rightarrow$ corresponds to a Bjorken-x range (0.3–1.4) $\times 10^{-3}$
- The cross section reported in five $|t|$ intervals within $0.04 < |t| < 1$ GeV^2 and compared to the predictions of four different models

Participating ALICE detectors

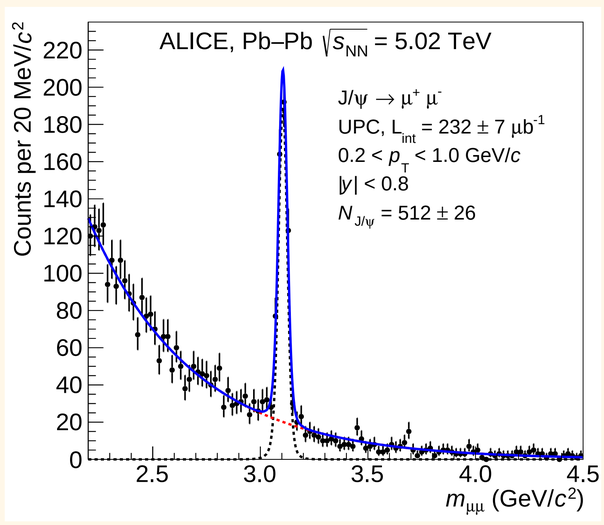


Taken from [3]

- Event selection: a central UPC trigger based on inputs from the Silicon Pixel Detector (SPD), Time-Of-Flight (TOF), ALICE Diffractive (AD) and V0
- Tracking: the Inner Tracking System (ITS) and the Time Projection Chamber (TPC) placed in a large solenoid magnet (0.5 T)
  - Looking at events with two oppositely-charged tracks, $|\eta| < 0.8$
- Particle identification: ionization energy loss measured in the TPC, compared to the muon hypothesis (a complete rejection of electrons in this kinematic range)
- Forward scintillation detectors AD & V0 operated as vetoes against unwanted hadronic activity

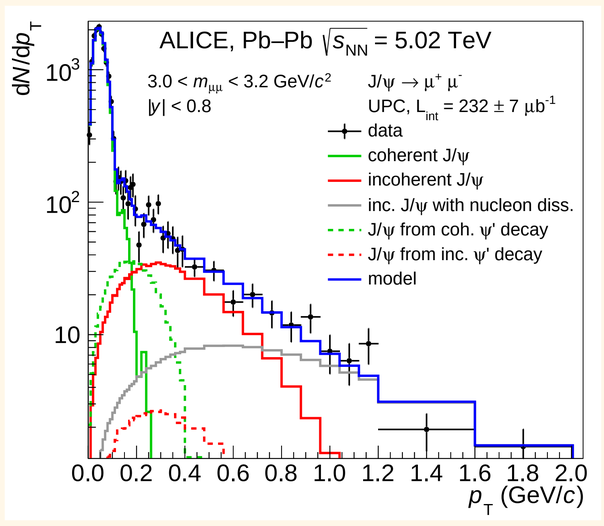
Signal extraction

- The raw J/ψ yield extracted by fitting the muon-pair invariant-mass distribution with a sum of a Crystal Ball function and an exponential
- Extracted yield for the total sample: 512 ± 26(stat.)



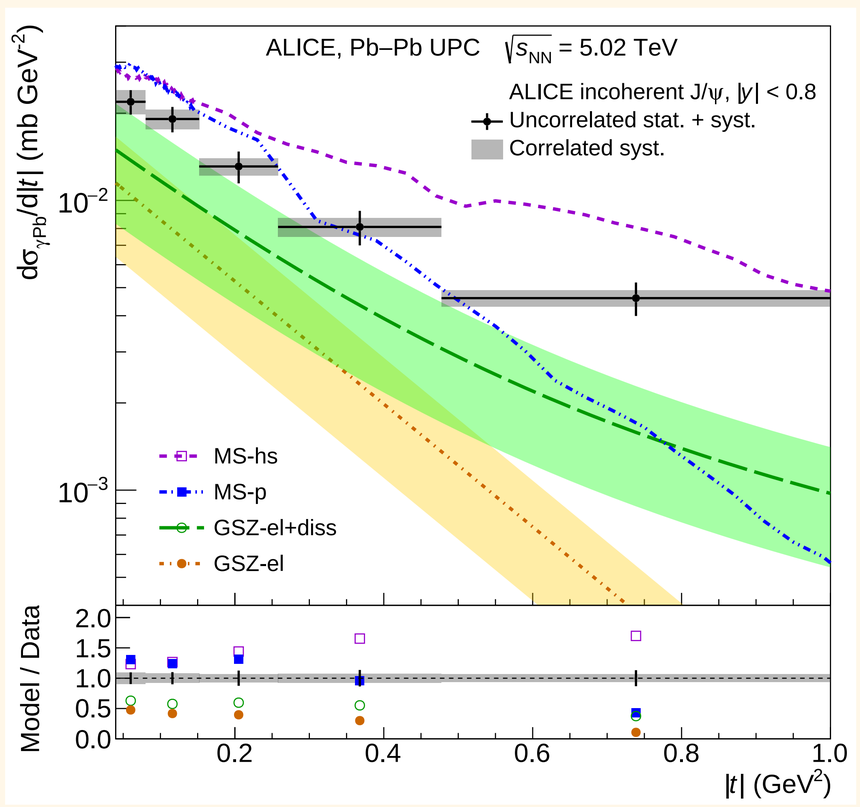
Taken from [4]

- Contribution of coherent J/ψ and of feed-down from the excited charmonium state ψ' determined from a fit to the transverse-momentum distribution of the J/ψ yields in the range $3.0 < m_{\mu\mu} < 3.2$ GeV/c^2



Taken from [4]. The anchored MC was generated with STARlight [5]

Results



Taken from [4]. The bottom panel represents the ratio of the integral of the predicted to that of the measured cross section in each $|t|$ range

- The measured $|t|$-dependence was compared to four phenomenological predictions:
  - **MS-p** [6]: no sub-nucleon fluctuations, the process depicted as an elastic interaction with a single nucleon
  - **MS-hs** [6]: the proton is composed of three spots of high gluon density (hot spots) whose positions in the impact-parameter plane change event-by-event + fluctuations in the saturation scale are introduced
  - **GSZ-el** [7]: elastic contribution only
  - **GSZ-el+diss** [7]: an extra dissociative-like component added, corresponding to sub-nucleon degrees of freedom (the bands reflect the uncertainties of the leading-twist approximation, LTA)
- The cross section integrated over $0.04 < |t| < 1$ GeV^2:
  - The data: $\sigma_{\gamma Pb} = (7.82 \pm 0.39(\text{stat.}) \pm 0.57(\text{syst.}))\ \mu b$
  - The models: 7.4, 11.8, 2.3 ± 1.0, and $4.1 \pm 1.8\ \mu b$ for MS-p, MS-hs, GSZ-el, and GSZ-el+diss, respectively
- There are two aspects of the data-model comparison:
  - The **normalization**: mainly linked to the scaling from proton to nuclear targets + the respective models must also describe the coherent cross section
  - The **slope** in $|t|$: driven by the size of the anticipated scattering object
- Models ignoring quantum fluctuations of the nuclear gluon density predict a $|t|$-dependence **much steeper** than the measured one
- Inclusion of such fluctuations in the same models softens the $|t|$-dependence and ensures **better agreement with the measurement**!

Conclusion

- ALICE at the LHC presents [4] the cross section for incoherent photoproduction of J/ψ off heavy ions, measured for the first time as a function of Mandelstam t, the square of the momentum transferred during the interaction
- The analysis was based on Pb–Pb UPCs at $\sqrt{s_{NN}} = 5.02$ TeV; the J/ψ was reconstructed at midrapidity, $|y| < 0.8$, corresponding to a Bjorken-x range of (0.3–1.4) $\times 10^{-3}$
- The cross section is reported in the range $0.04 < |t| < 1$ GeV^2 and compared to the predictions of four models:
  - None of the models describes correctly both the absolute normalization and the $|t|$-dependence observed in the data
  - When **fluctuations at a sub-nucleon scale** are introduced in the models, a reasonably good description of the measured $|t|$-slope is achieved, suggesting that the nuclear gluon density is not static at high energies