First energy-dependent measurement of incoherent J/ψ photoproduction in PbPb UPCs

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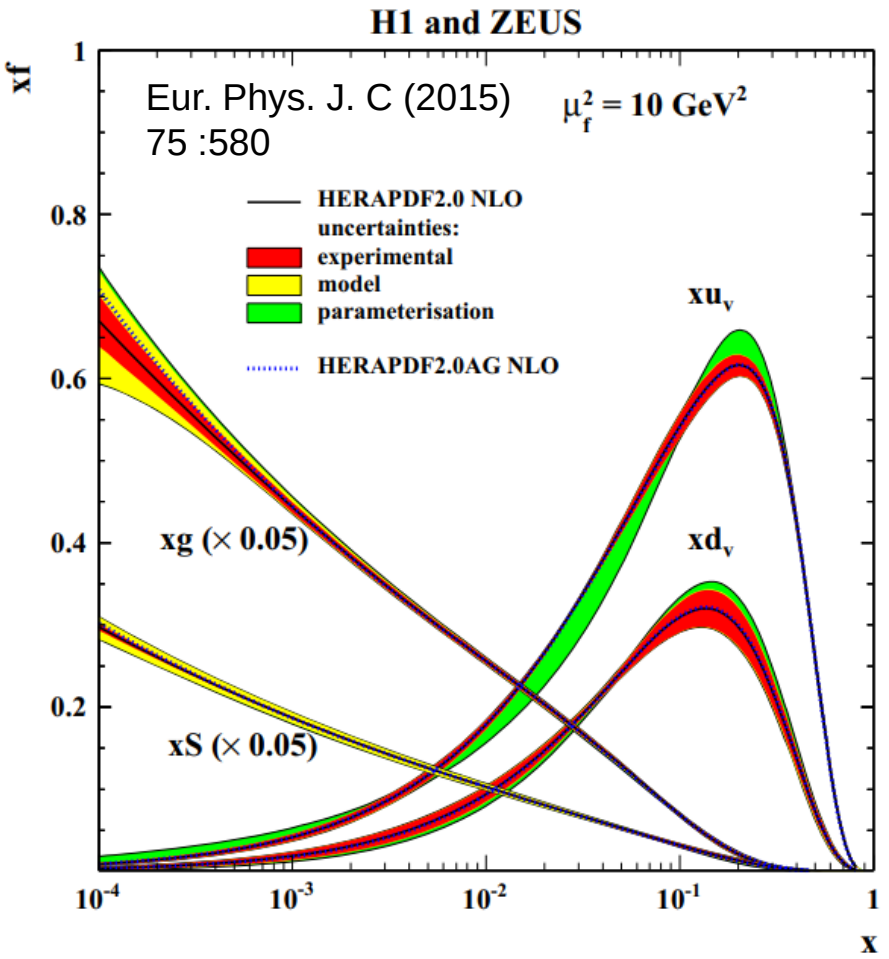
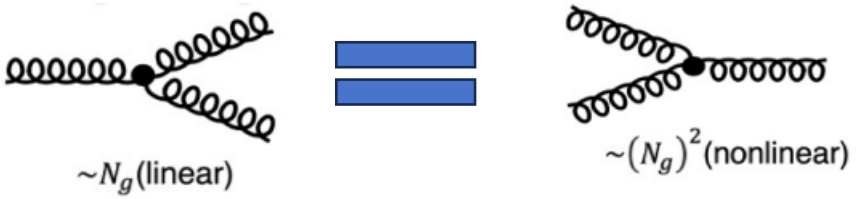
Bjorken-x Evolution of Gluon Fields in Nuclei

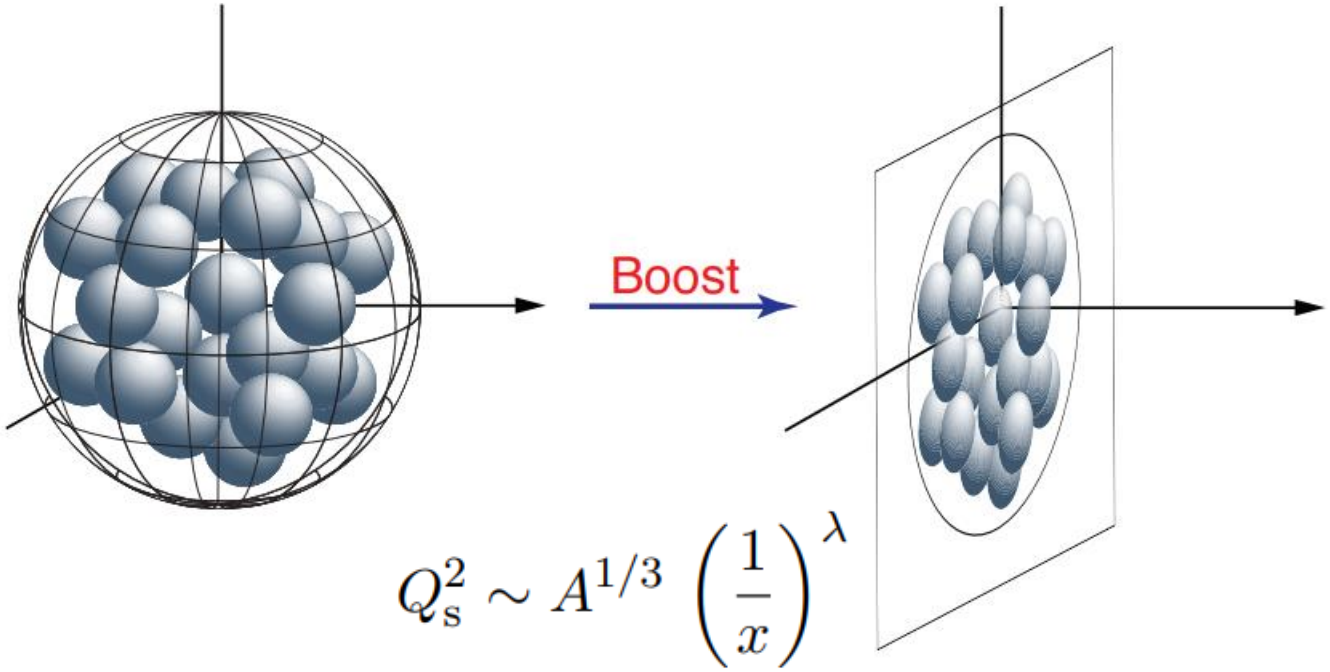
- Rapid growth in gluon density at small x shown by HERA
- Unitarity imposes a limit on the growth
- Fate of gluons at extreme densities?
- Mechanism of the potential flatten of PDF?



Gluon Saturation at Small x



gluon saturation?

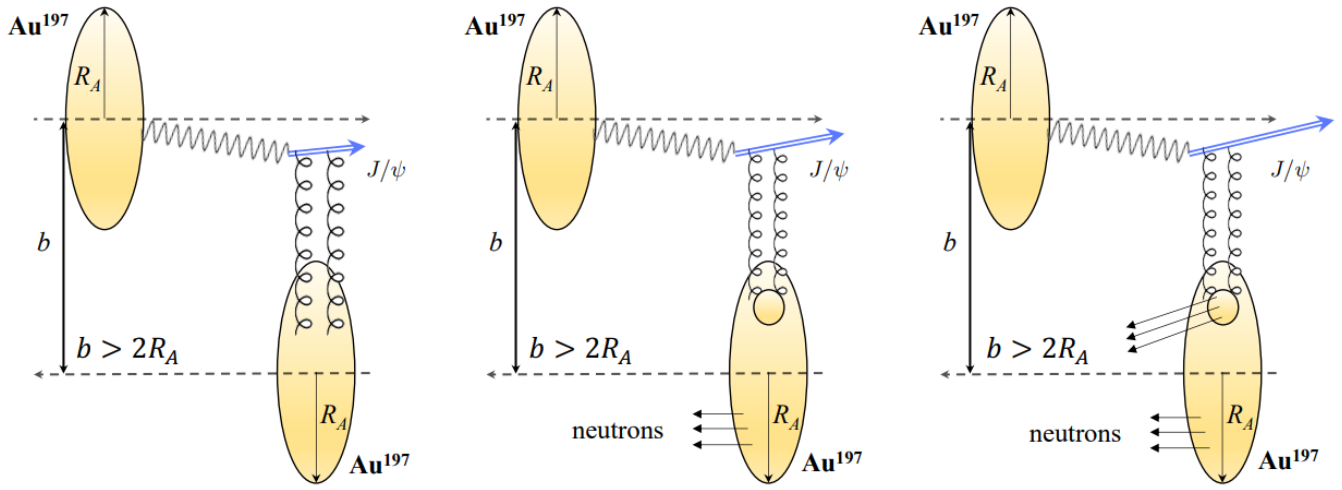


No evidence of gluon saturation found in protons yet

$A^{\frac{1}{3}}$-enhanced gluon density in an ultrarelativistic nucleus

Gluon saturation is expected to be more easily reached in relativistic heavy nuclei

Vector Meson Photoproduction in UPCs



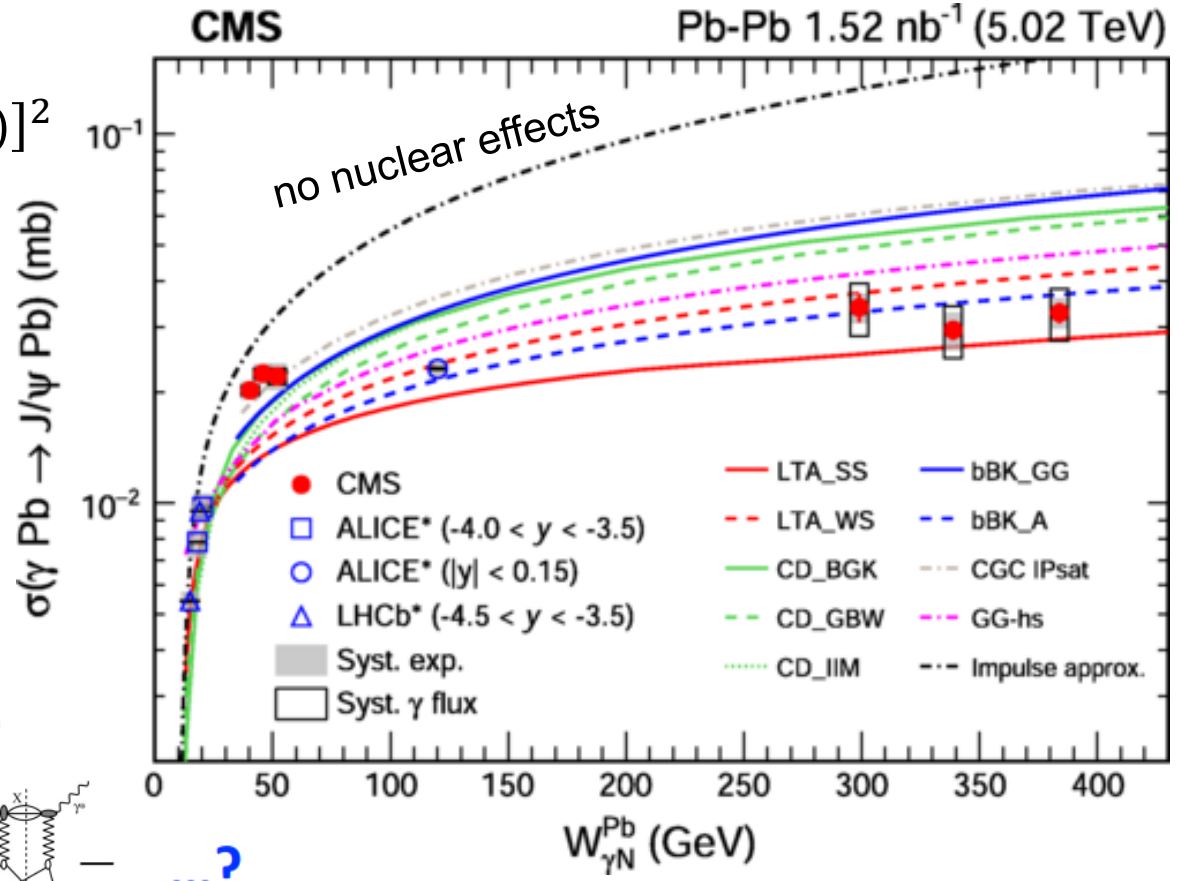
(a) Coherent, nucleus stays intact (b) Incoherent with elastic nucleon (c) Incoherent with nucleon dissociation

- Coherent: entire target nucleus interacts, which remains intact
- Incoherent: nucleon or sub-nucleon interacts; target nucleus can remain intact or **break up** (~85% probability V. Guzey et al. EPJC 74 (2014) 2942)

Energy-Dependent Coherent J/ψ Photoproduction

$$\sigma \propto [xG(x, Q^2)]^2$$

- **Average gluon density** probed
- Strongly saturated cross section
- Not described by any model

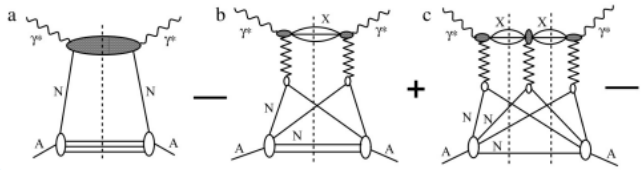


CMS, PRL 131, 26201 (2023)

Gluon Saturation?

F. Gelis et al. Annu. Rev. Nucl. Part. Sci. 60 (2010) 463

Nuclear shadowing?

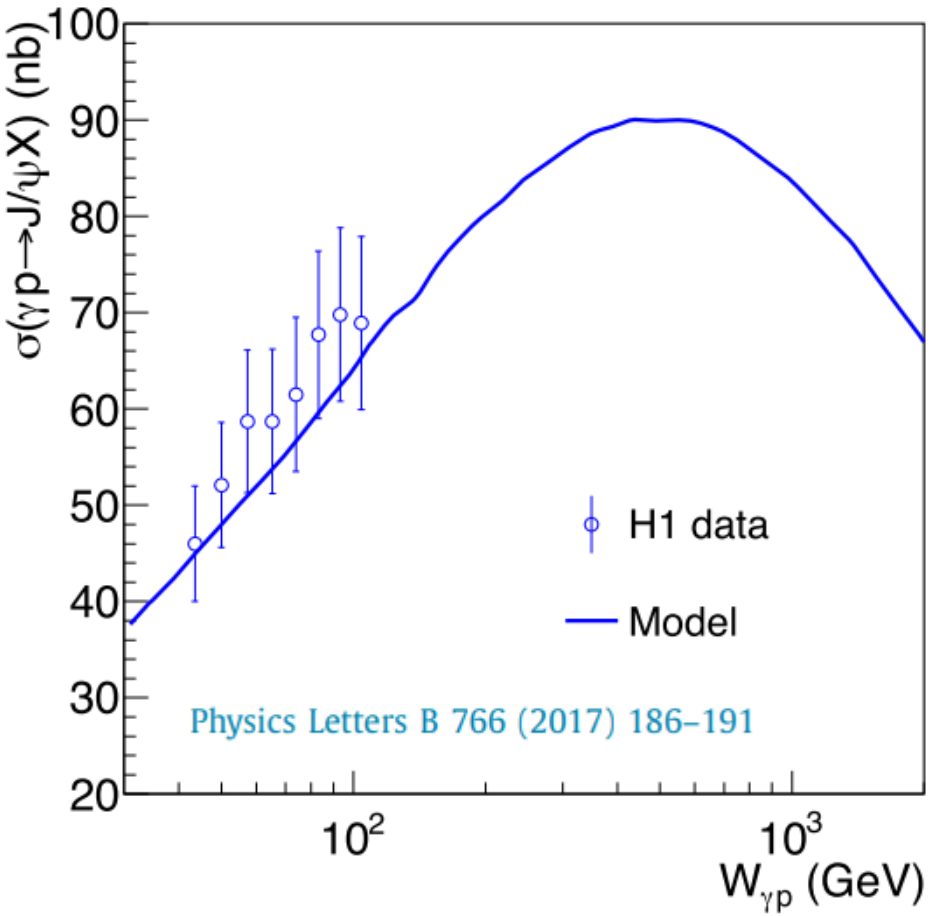


V. Guzey et al. EPJC 74 (2014) 2942

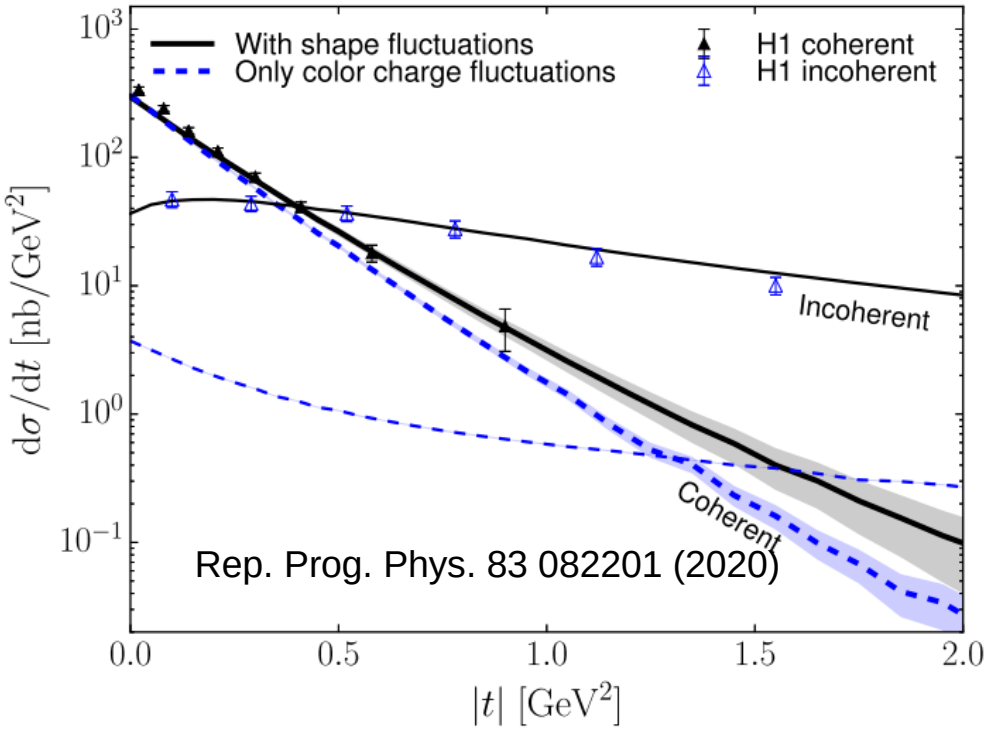
...?

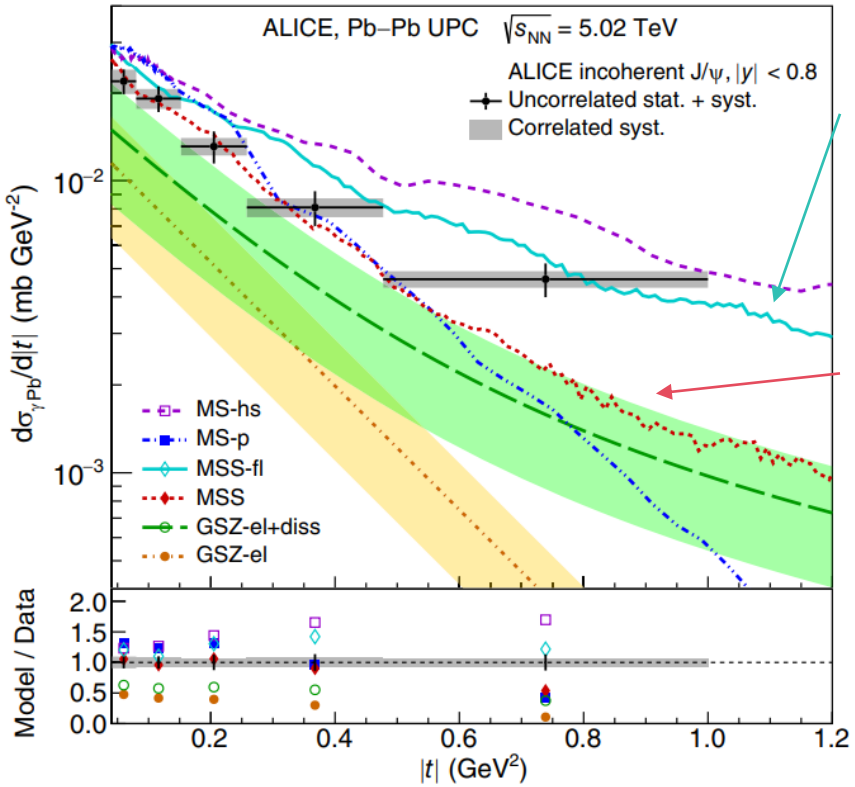
Energy-Dependent Incoherent Photoproduction

- Probing **gluon density fluctuations**
- Expected to diminish as approaching saturation
- γA never measured, maybe reach saturation earlier?



|t|-Dependent Incoherent J/ψ Photoproduction





CGC with sub-nucleon fluctuations

CGC w/o sub-nucleon fluctuations

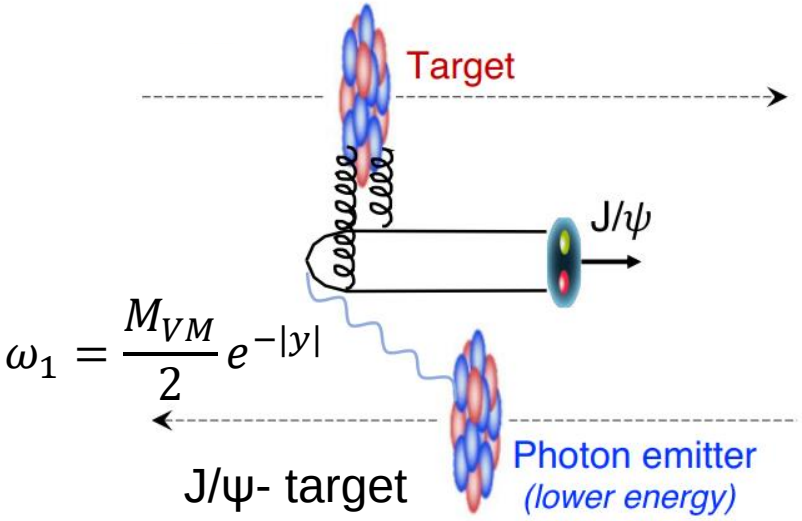
PRL 132, 162302 (2024)

CGC – Color Glass Condensate

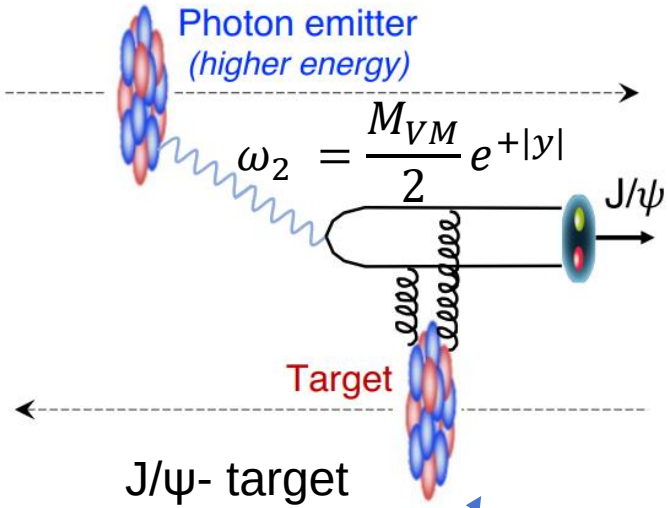
- HERA data and ALICE data slope described by **CGC with sub-nucleon fluctuations**
- However, ALICE data **magnitude overestimated**

Still not fully understood!

“Two-Way Ambiguity” in A-A UPCs



J/ψ- target same direction



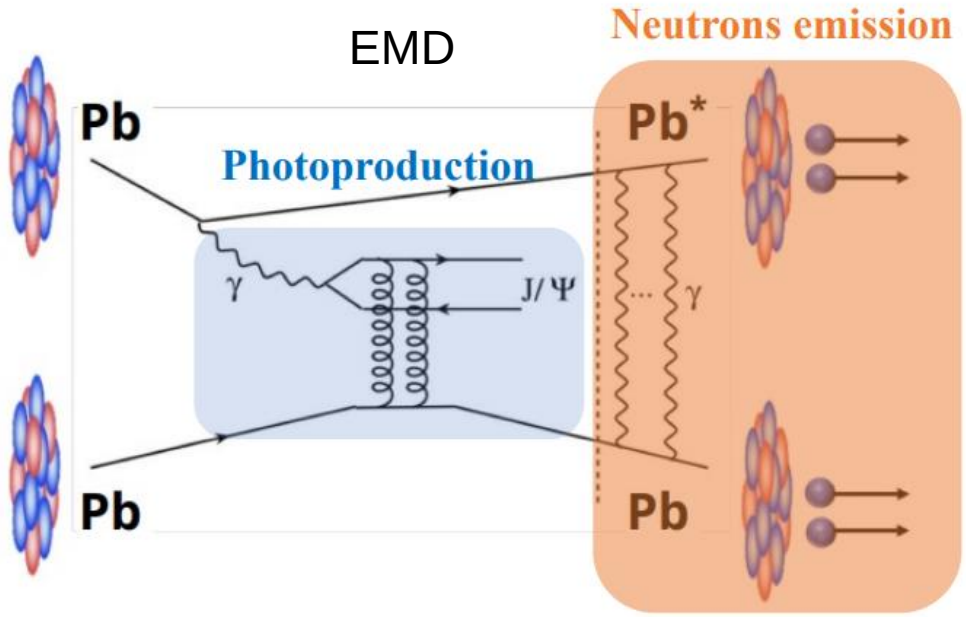
J/ψ- target opposite direction

$$\frac{d\sigma_{\mathrm{PbPb}\to\mathrm{PbPb'J/\psi}}(y)}{dy} = n_{\gamma/\mathrm{Pb}}(\omega_1)\sigma_{\gamma\mathrm{Pb}\to\mathrm{J/\psi Pb'}}(\omega_1) + n_{\gamma/\mathrm{Pb}}(\omega_2)\sigma_{\gamma\mathrm{Pb}\to\mathrm{J/\psi Pb'}}(\omega_2)$$

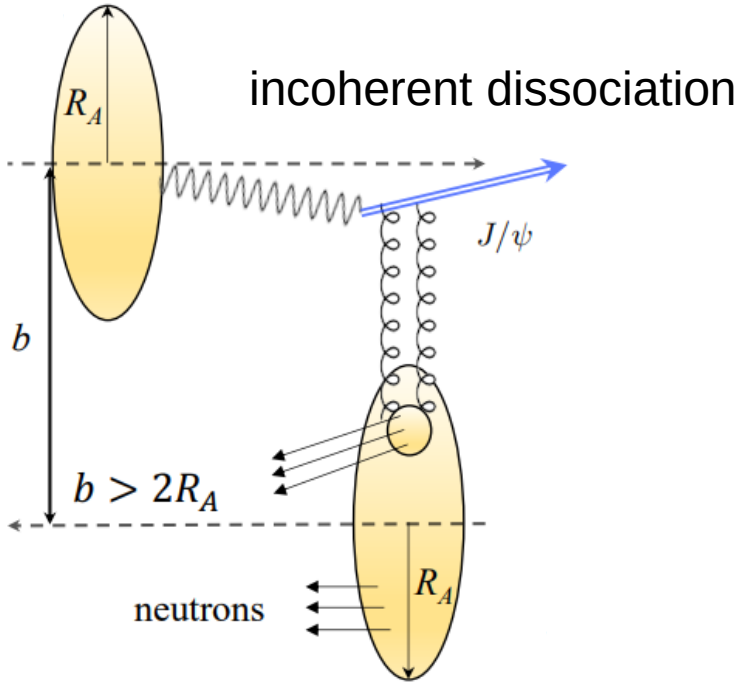
neutron tagging?

Neutron Emission in UPCs

EMD



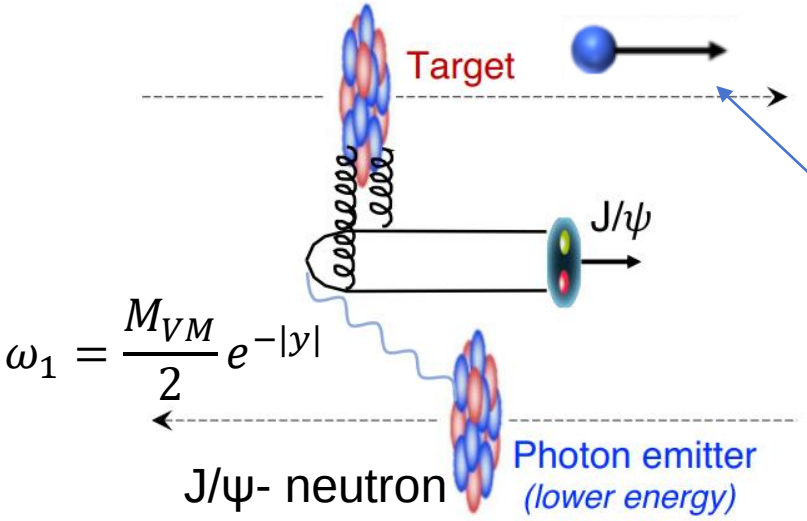
incoherent dissociation



Neutron emission from:

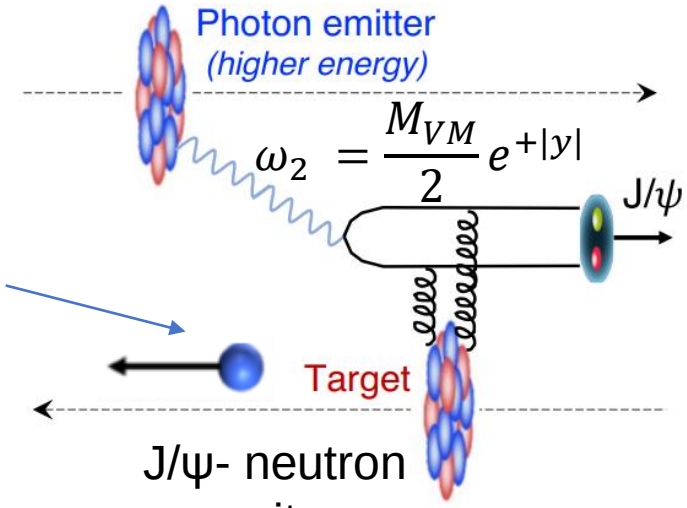
- Electromagnetic dissociation (EMD): independent of photoproduction
- Incoherent dissociation: large momentum transfer leads to neutron emission **from target** (**incoherent only**)

Neutron Tagging for Incoherent Photoproduction



$$\omega_1 = \frac{M_{VM}}{2} e^{-|y|}$$

emitted neutrons



$$\omega_2 = \frac{M_{VM}}{2} e^{+|y|}$$

J/ψ- neutron same direction

$$\frac{d\sigma_{\mathrm{PbPb}\to\mathrm{PbPb'J/\psi}}(y)}{dy} = n_{\gamma/\mathrm{Pb}}(\omega_1)\sigma_{\gamma\mathrm{Pb}\to\mathrm{J/\psi Pb'}}(\omega_1)$$

J/ψ- neutron opposite direction

$$\frac{d\sigma_{\mathrm{PbPb}\to\mathrm{PbPb'J/\psi}}(y)}{dy} = n_{\gamma/\mathrm{Pb}}(\omega_2)\sigma_{\gamma\mathrm{Pb}\to\mathrm{J/\psi Pb'}}(\omega_2)$$

Target direction tagged by neutron

J/ψ-Neutron Direction Correlation

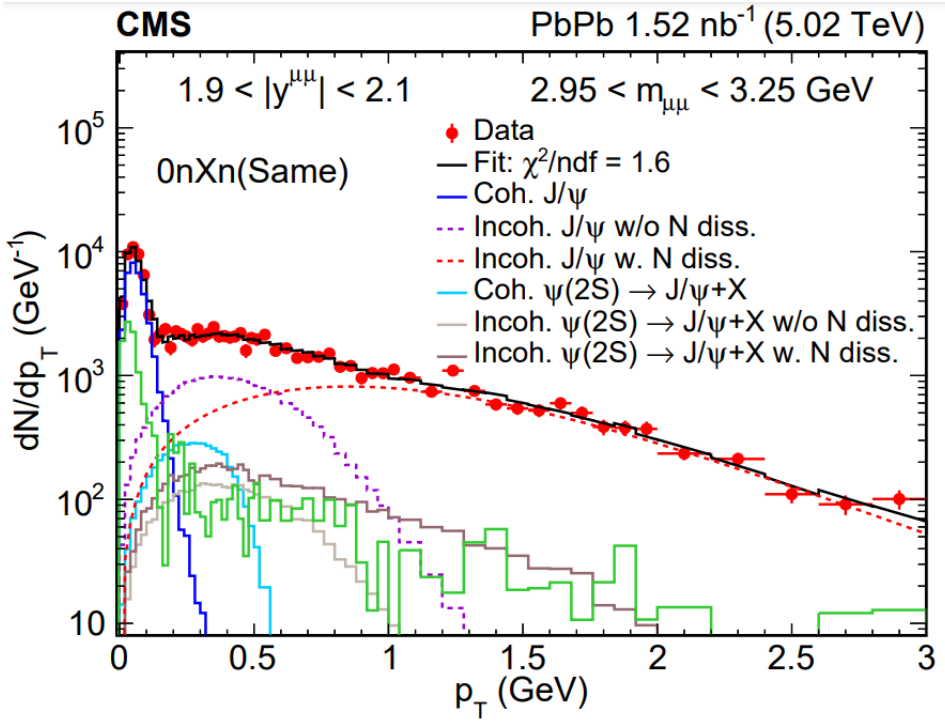
J/ψ-Xn Same Direction

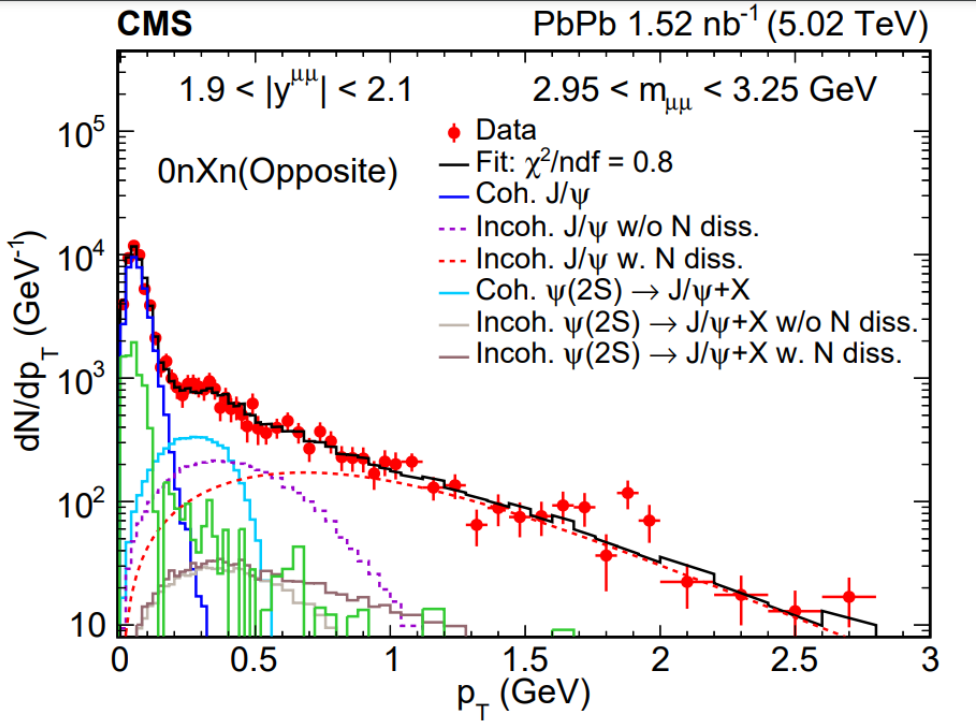
$$\omega = \frac{M_{VM}}{2} e^{-|y|}$$

0nXn divided into two

J/ψ-Xn Opposite Direction

$$\omega = \frac{M_{VM}}{2} e^{+|y|}$$





$$\frac{d\sigma_{\mathrm{PbPb}\to\mathrm{PbPb'J/\psi}}(y)}{dy} = n_{\gamma\mathrm{Pb}}(\omega)\sigma_{\gamma\mathrm{Pb}\to\mathrm{J/\psi Pb'}}(\omega)$$

Cross Section Calculation

- 15% incoherent are elastic: accounted for in 0nAn* V. Guzey et al. EPJC 74 (2014) 2942

$$\frac{d\sigma^{0nAn*}_{PbPb\to PbPb'J/\psi}}{dy} = \frac{d\sigma^{0nXn}_{PbPb\to PbPb'J/\psi}}{dy} + \frac{d\sigma^{0n0n}_{PbPb\to PbPb'J/\psi}}{dy}$$

relative fractions at (+y) and (-y) in 0n0n assumed to be same as 0nXn

- Photon flux only available for EMD

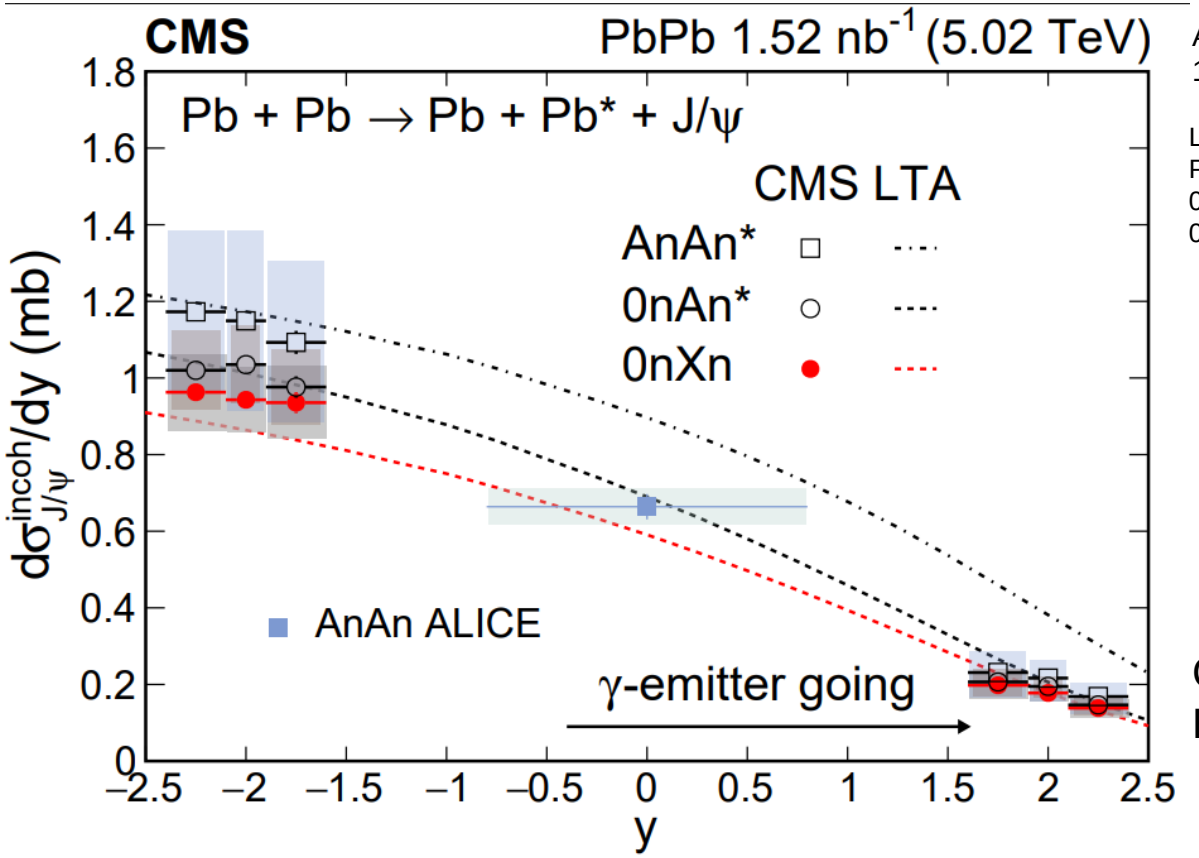
$$n^{0nAn^*}_{\gamma/Pb}(\omega) = n^{0n0n(EMD)}_{\gamma/Pb}(\omega) + \frac{1}{2} n^{0nXn(EMD)}_{\gamma/Pb}(\omega)$$

0n0n: 0n0n(incoh) + 0n0n(EMD)
0nXn: 1. 0nXn(incoh) + 0n0n(EMD)
2. 0nXn(incoh) + 0nXn(EMD), Xn aligning in the same direction

EMD and incoh are independent → 50% align/oppose

$$\sigma_{\gamma Pb\to J/\psi Pb'}(W) = \frac{d\sigma^{0nAn^*}_{PbPb\to PbPb'J/\psi}(y)}{dy} / n^{0nAn^*}_{\gamma/Pb}(\omega)$$

InCoh. J/ψ Differential Cross Sections



ALICE: PRL 132, 162302 (2024)

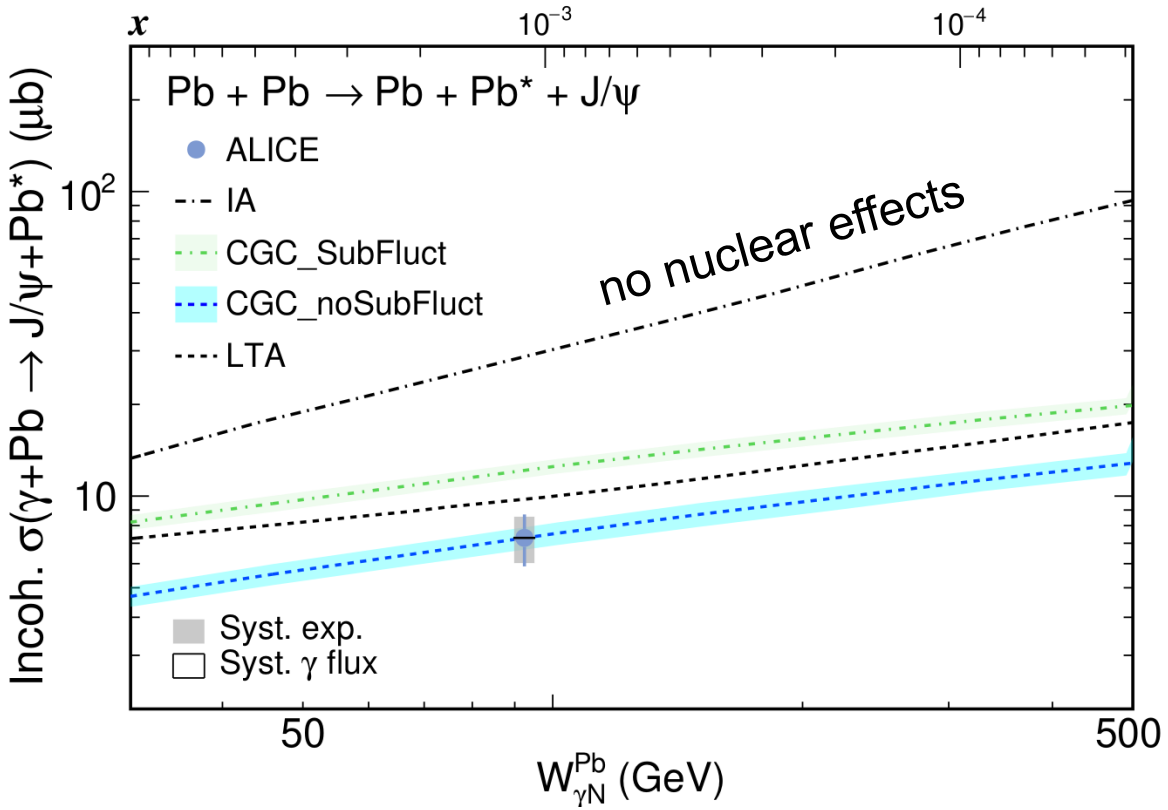
LTA: V. Guzey et al. PRC 108 (2023) 024904, PRC 99 (2019) 015201

CMS-PAS-HIN-23-009

$$\sigma_{\gamma Pb\to J/\psi Pb'}(W) = \frac{d\sigma^{0nAn^*}_{PbPb\to PbPb'J/\psi}(y)}{dy} / n^{0nAn^*}_{\gamma/Pb}(\omega)$$

- $\pm y$ asymmetry → strong incoh. J/ψ-neutron correlation
- LTA (nuclear shadowing model) cannot describe the data in different neutron categories simultaneously

InCoh. J/ψ Cross Section per γPb Interaction



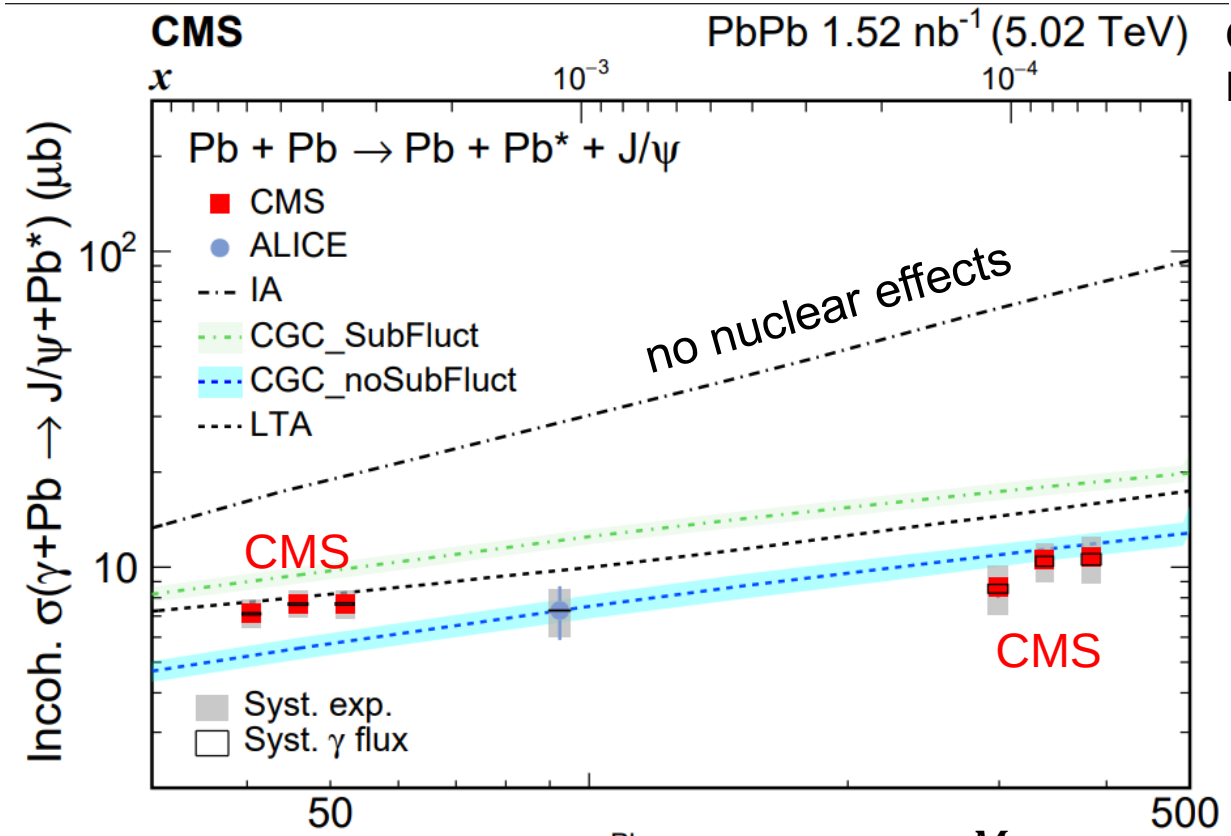
- ALICE data strongly suppressed compared to Impulse Approx. (IA)
- CGC without sub-nucleonic fluctuations seems to best describe the data

ALICE: PRL 132, 162302 (2024)

LTA: V. Guzey et al. PRC 108 (2023) 024904, PRC 99 (2019) 015201

CGC: PRD 109 (2024) 7, L071504, PRD 106 (2022) 7, 074019

InCoh. J/ψ Cross Section per γPb Interaction



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ALICE: PRL 132, 162302 (2024)

LTA: V. Guzey et al. PRC 108 (2023) 024904, PRC 99 (2019) 015201

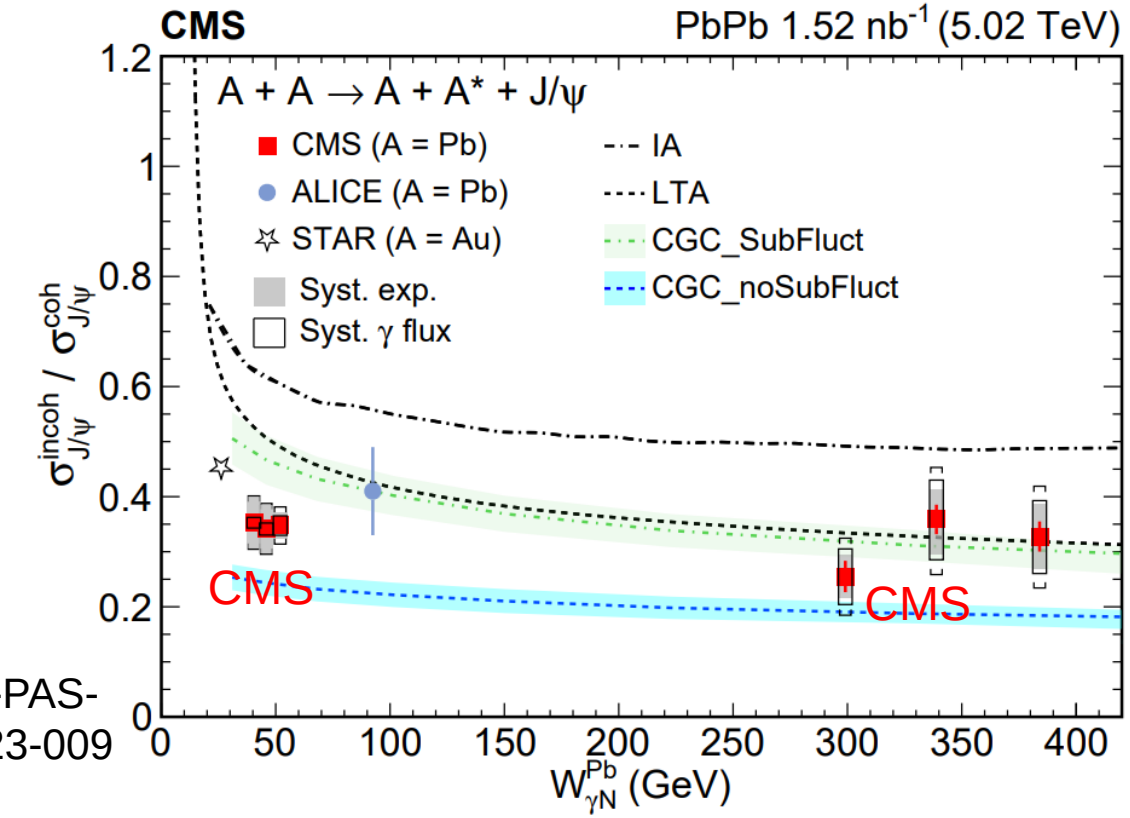
CGC: PRD 109 (2024) 7, L071504, PRD 106 (2022) 7, 074019

- Strong suppression relative to IA
- Stronger suppression towards higher W
- Models can only partially describe the data

$$W = \sqrt{\sqrt{s_{NN}} M_{J/\psi} e^{-y}} \qquad \omega = \frac{M_{VM}}{2} e^{y}$$

$$\sigma_{\gamma Pb \to J/\psi Pb'}(W) = \frac{d\sigma^{0nAn^*}_{PbPb \to PbPb' J/\psi}(y)}{dy} / n^{0nAn^*}_{\gamma/Pb}(\omega)$$

InCoh.-Coh. Cross Section Ratio

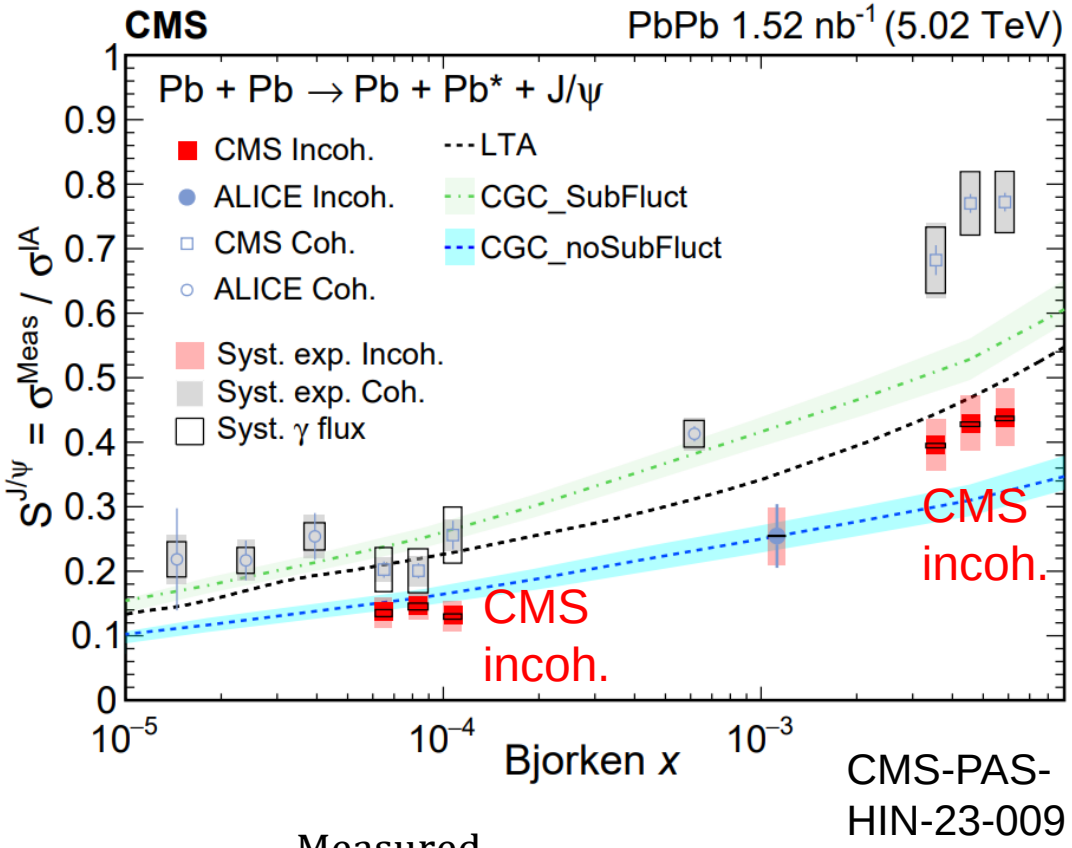


CMS-PAS-HIN-23-009

- No clear W dependent (40<W<400GeV)
  - No support Black Disk Limit reached
- Slightly rising trend towards lower W
- LTA and CGC with sub-nucleon fluctuations qualitatively describe data trend

Theoretical uncertainties from **VM wave function, nuclear density, nuclear form factor, free nucleon PDFs, photon flux, and J/ψ formation probability** are largely cancelled

Nuclear Suppression

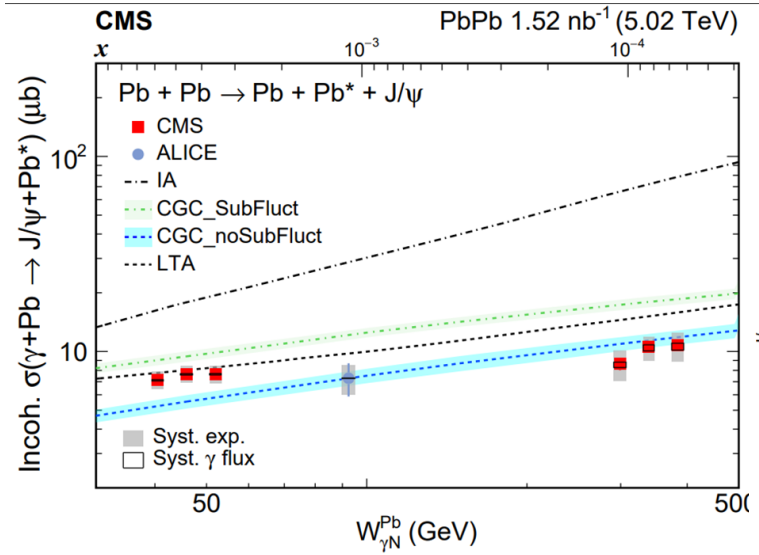


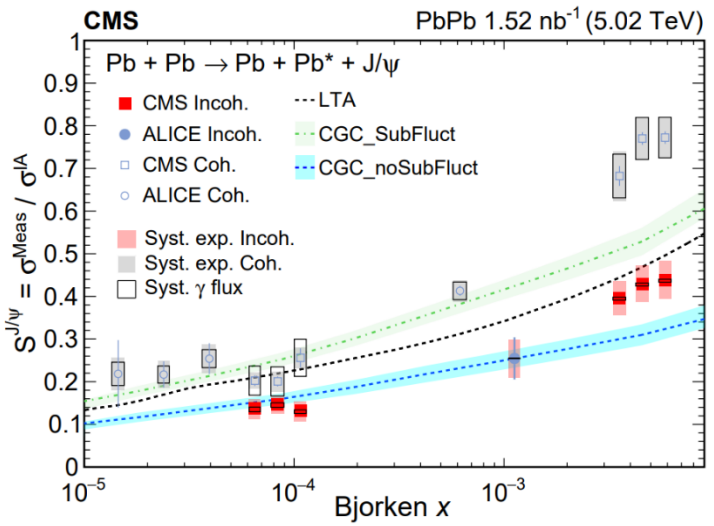
$$S^{\mathrm{J}/\psi} = \frac{\sigma^{\mathrm{Measured}}_{\gamma\mathrm{Pb}\to\mathrm{J}/\psi\mathrm{Pb}'}}{\sigma^{\mathrm{IA}}_{\gamma\mathrm{Pb}\to\mathrm{J}/\psi\mathrm{Pb}'}}$$

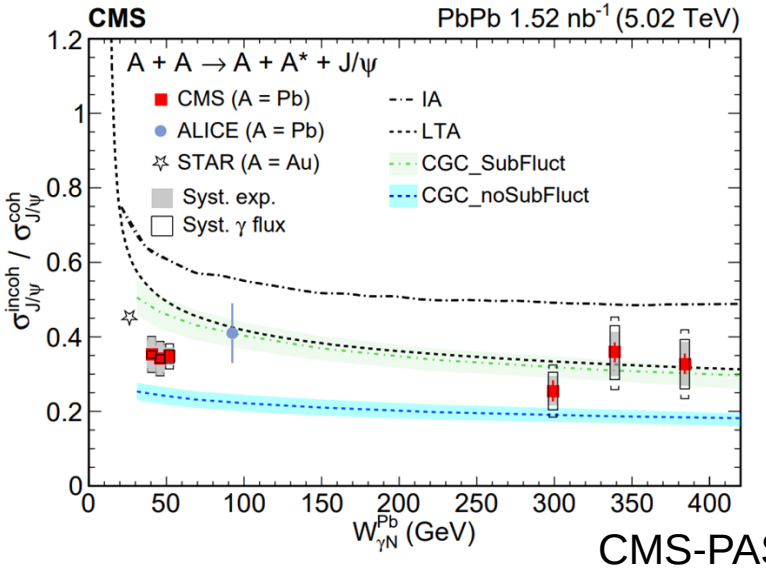
no nuclear effects

- Stronger suppression towards smaller x
- flattens at $x \sim 10^{-4}$
- InCoh. more suppressed than Coh. And gets close at $x \sim 10^{-4}$
- No model can describe the data

Summary







CMS-PAS-HIN-23-009

- **First energy-dependent** incoherent J/ψ photoproduction off nucleus measurement
- No model fully describes all results
- Stronger suppression than coherent J/ψ and tend to converge at small x
- No clear energy-dependent incoh./coh. ratio indicates black disk limit not reached

Thank you!