Probing Nuclear Gluonic Structure Via Photoproduced Vector Mesons in UPCs at CMS

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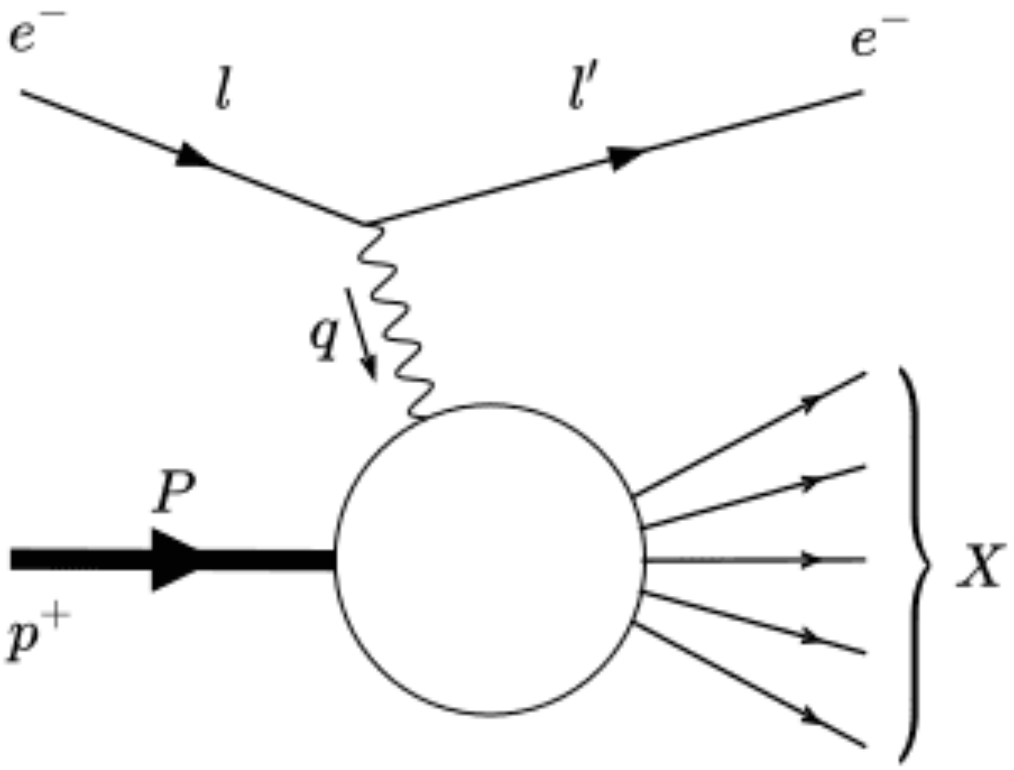
Oct 29 – Nov 02, 2025

CLHCP 2025, Henan Xinxiang

Understand Nucleon Structure via DIS

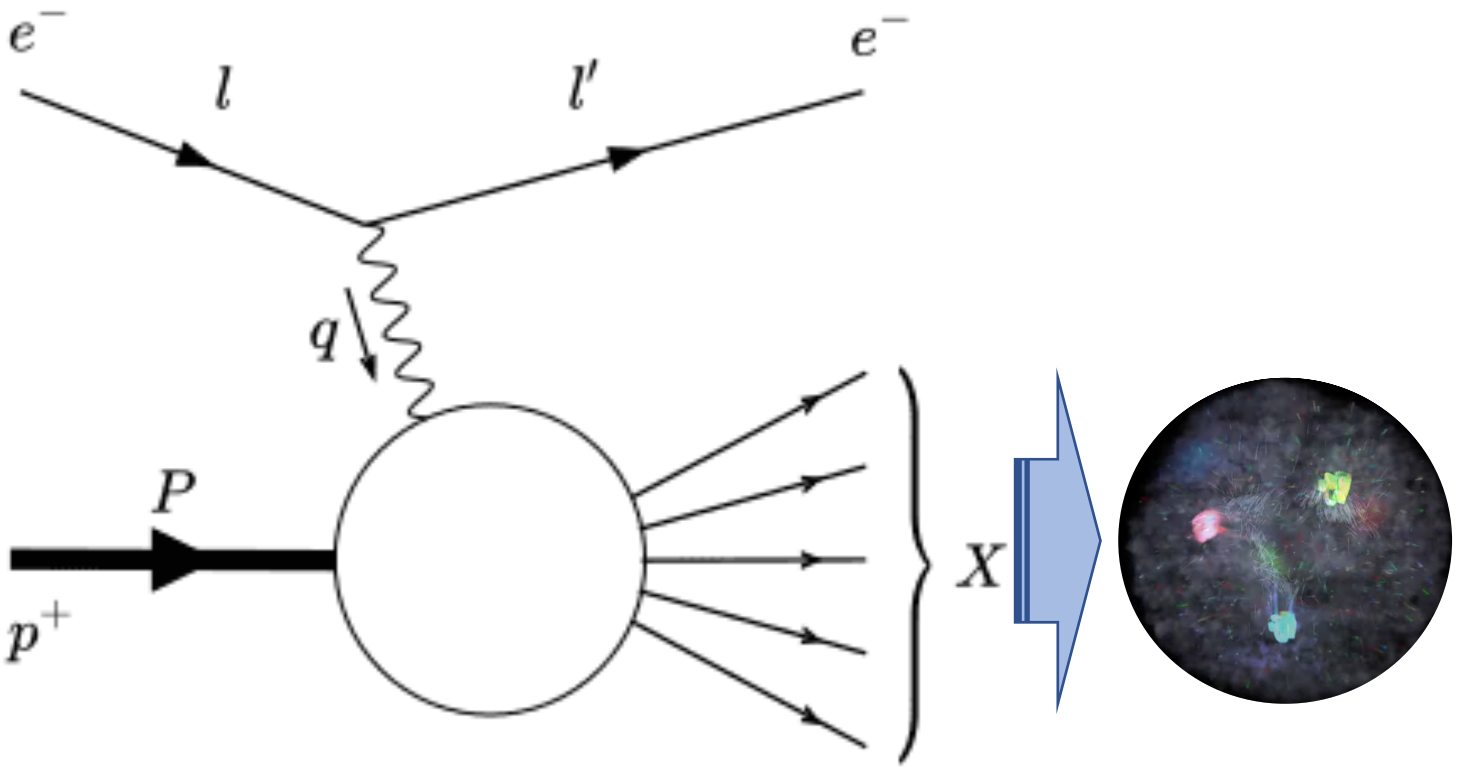
Smash them!!!



Deep Inelastic Scattering

Understand Nucleon Structure via DIS

Smash them!!!



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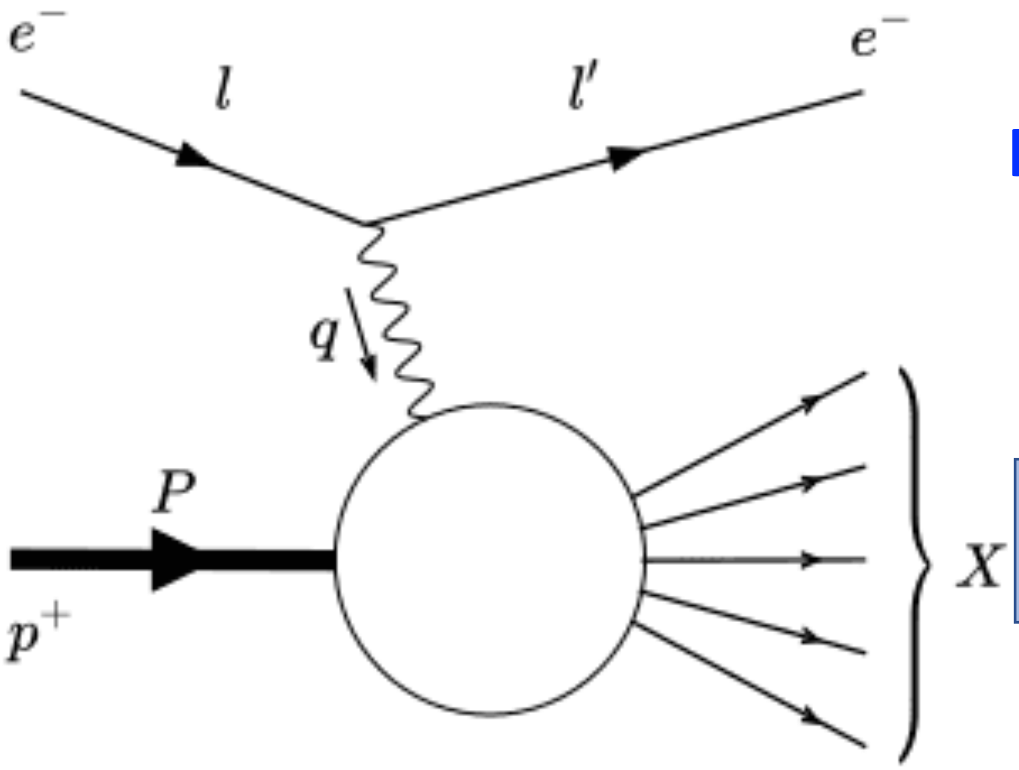
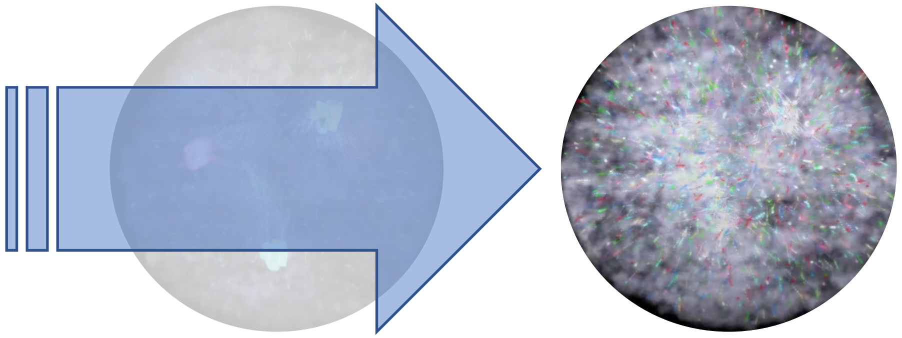


Higher energy, probing lower-x partons



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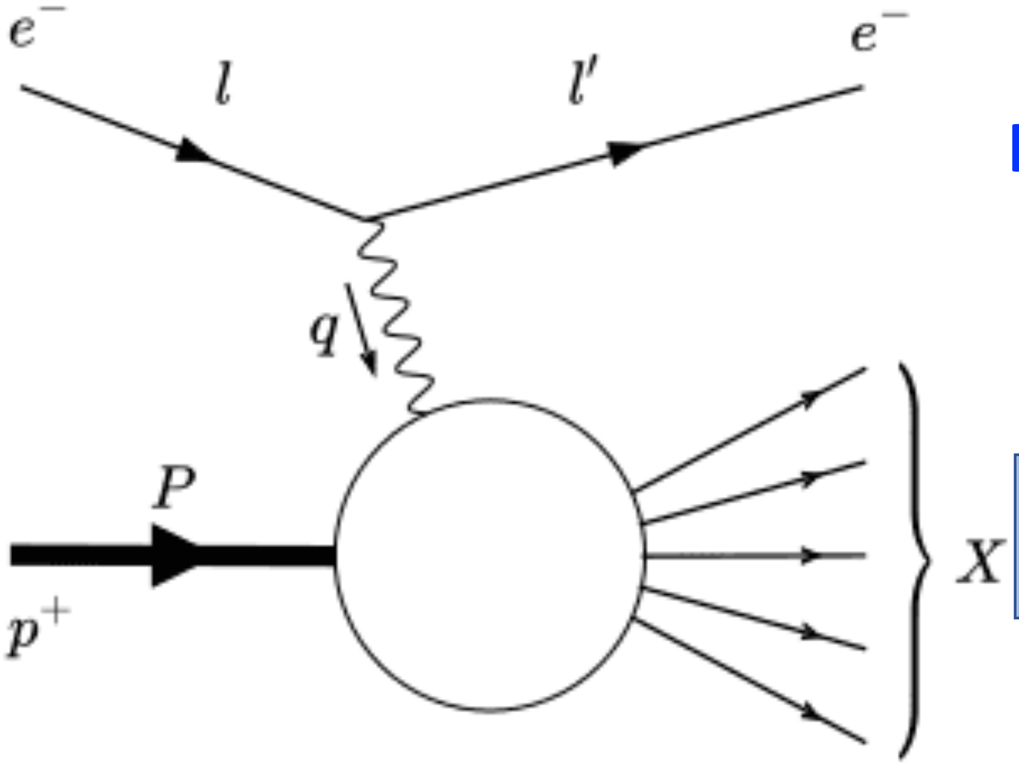

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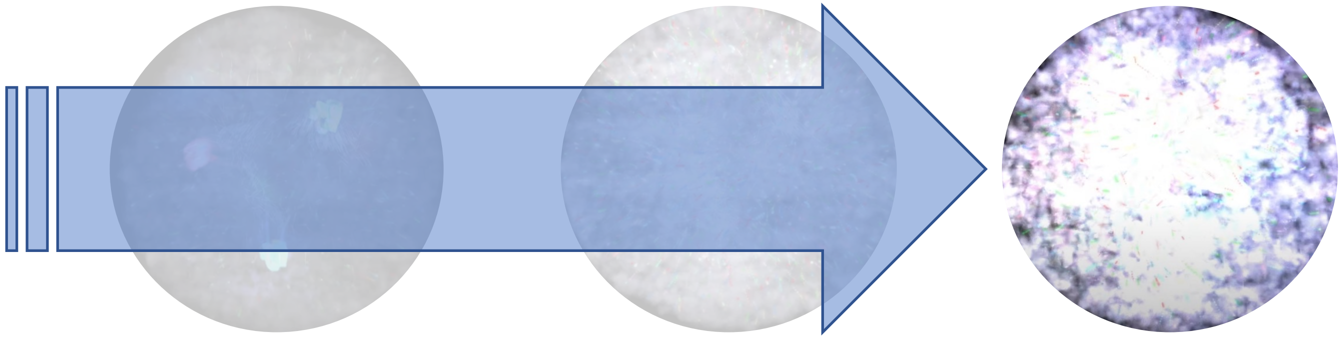
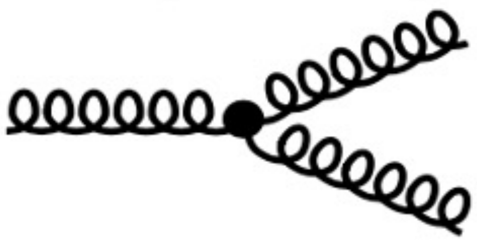


Deep Inelastic Scattering

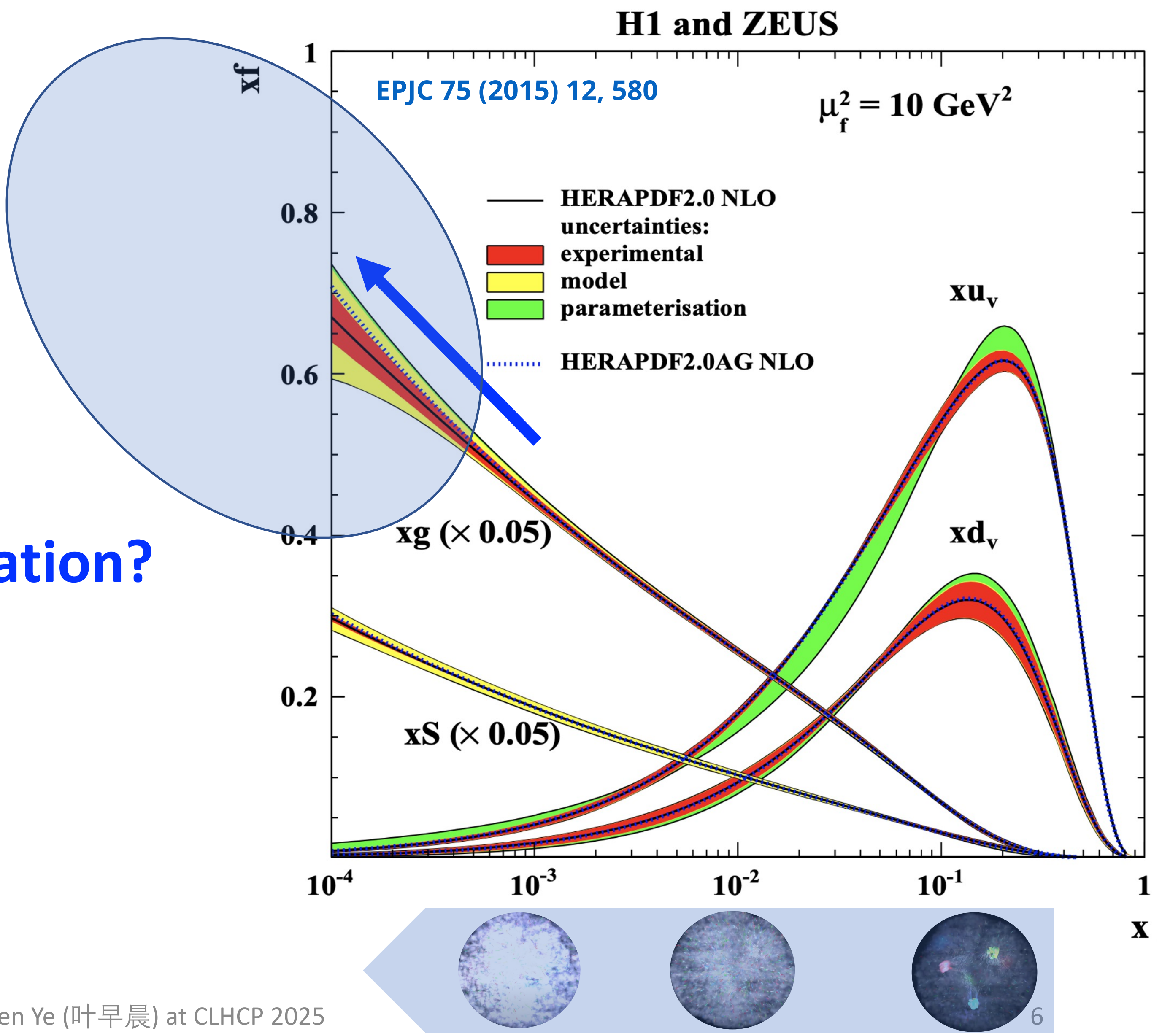
Understand Nucleon Structure

Splitting

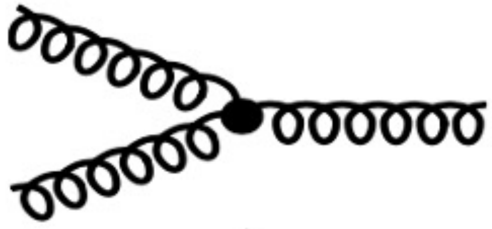


$\sim N_g$(linear)

Gluon Saturation?

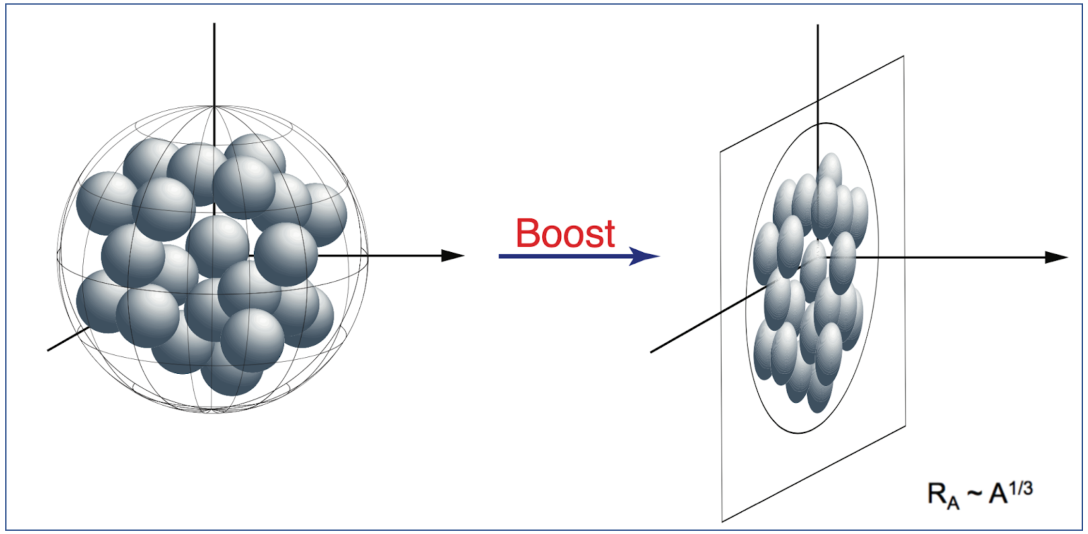


Recombination



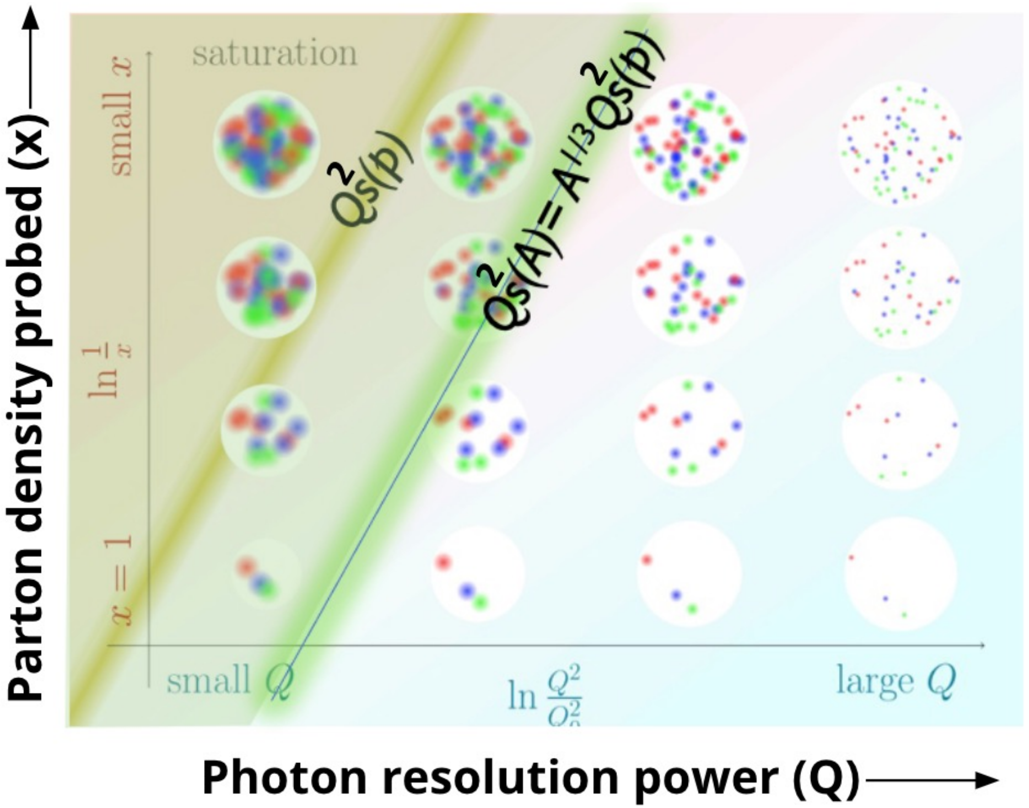
$\sim (N_g)^2$(nonlinear)

Advantages of Gluon Saturation Search in Nucleus



Gluons is **enhanced** by a factor of $A^{1/3}$ in **nucleus** compared to what in free nucleon

$$Q_s^2 \sim A^{1/3} \left(\frac{1}{x}\right)^{\lambda}$$

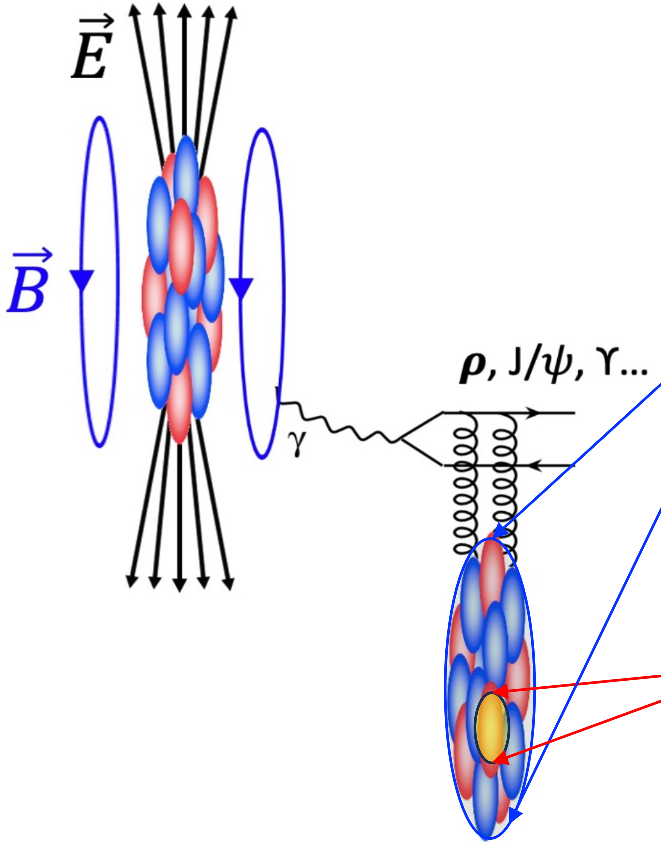


- **Gluon saturation can be more easily reached in heavy nuclei**

Probe Nuclear Gluonic Structure via VMs in UPCs

Vector meson photoproduction directly probes gluonic structure of nucleus/nucleon

At LO in pQCD, **cross section ∝** photon flux ⊗ **$[xG(x)]^2$**



Coherent production:

- Photon fluctuated dipole couples **coherently to entire nucleus**
- **Target** nucleus remains **intact** at ground state
- VM $<p_T>$ ~ **50 MeV**
- Probing the **average gluon density**

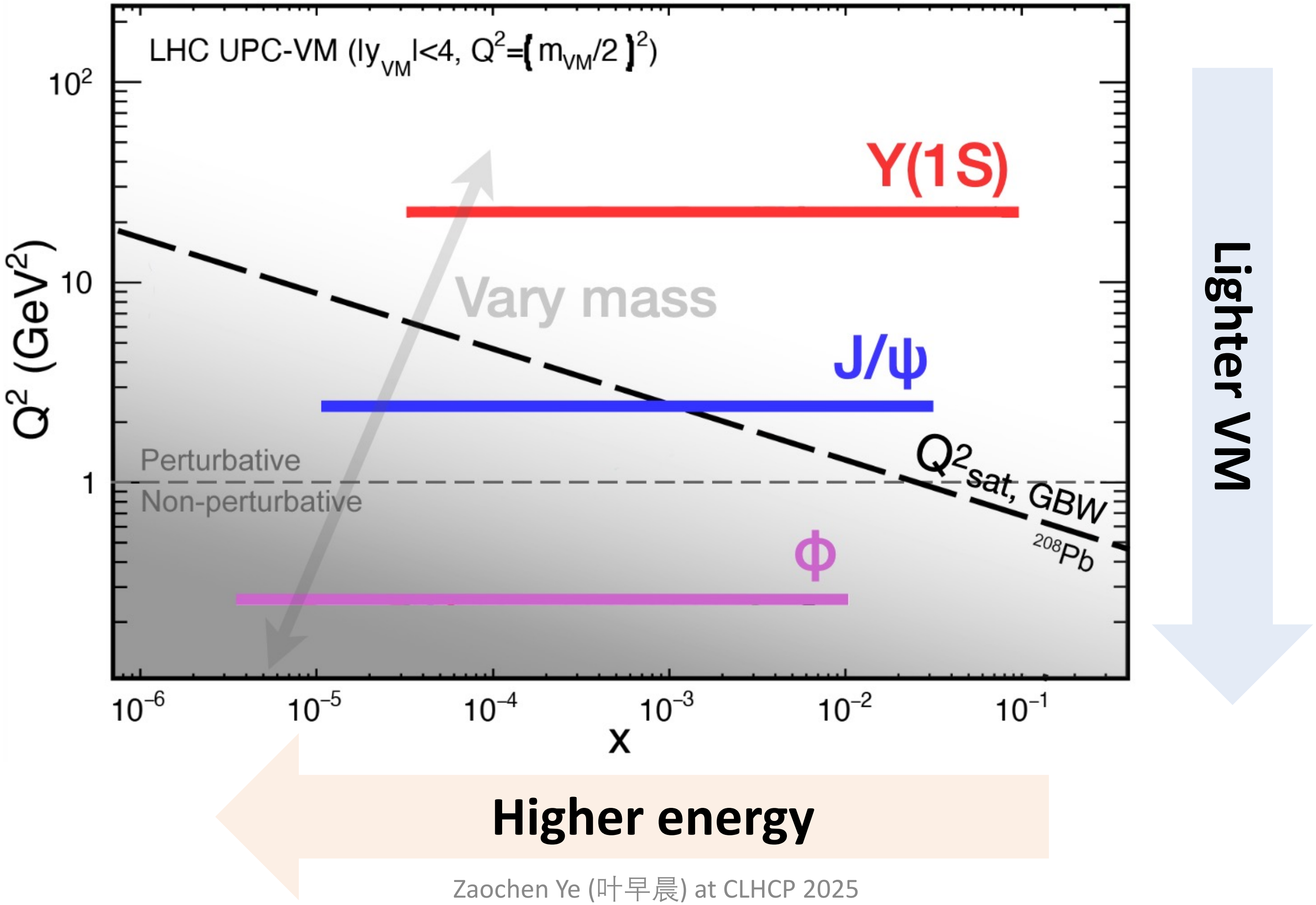
Incoherent production:

- Photon fluctuated dipole couples to **local gluonic hotspots**
- **Target** nucleus get excited, or **breaks (mostly)**
- VM $<p_T>$ ~ **500 MeV**
- Probing the **local gluon density** and **fluctuations**

$$\omega = \frac{M_{VM}}{2} e^{\pm y} \qquad x = \frac{M_{VM}}{\sqrt{s_{NN}}} e^{\mp y} \qquad W_{\gamma p} = 2\sqrt{\omega \cdot E_{beam}}$$

Probe Nuclear Gluonic Structure via VMs in UPCs

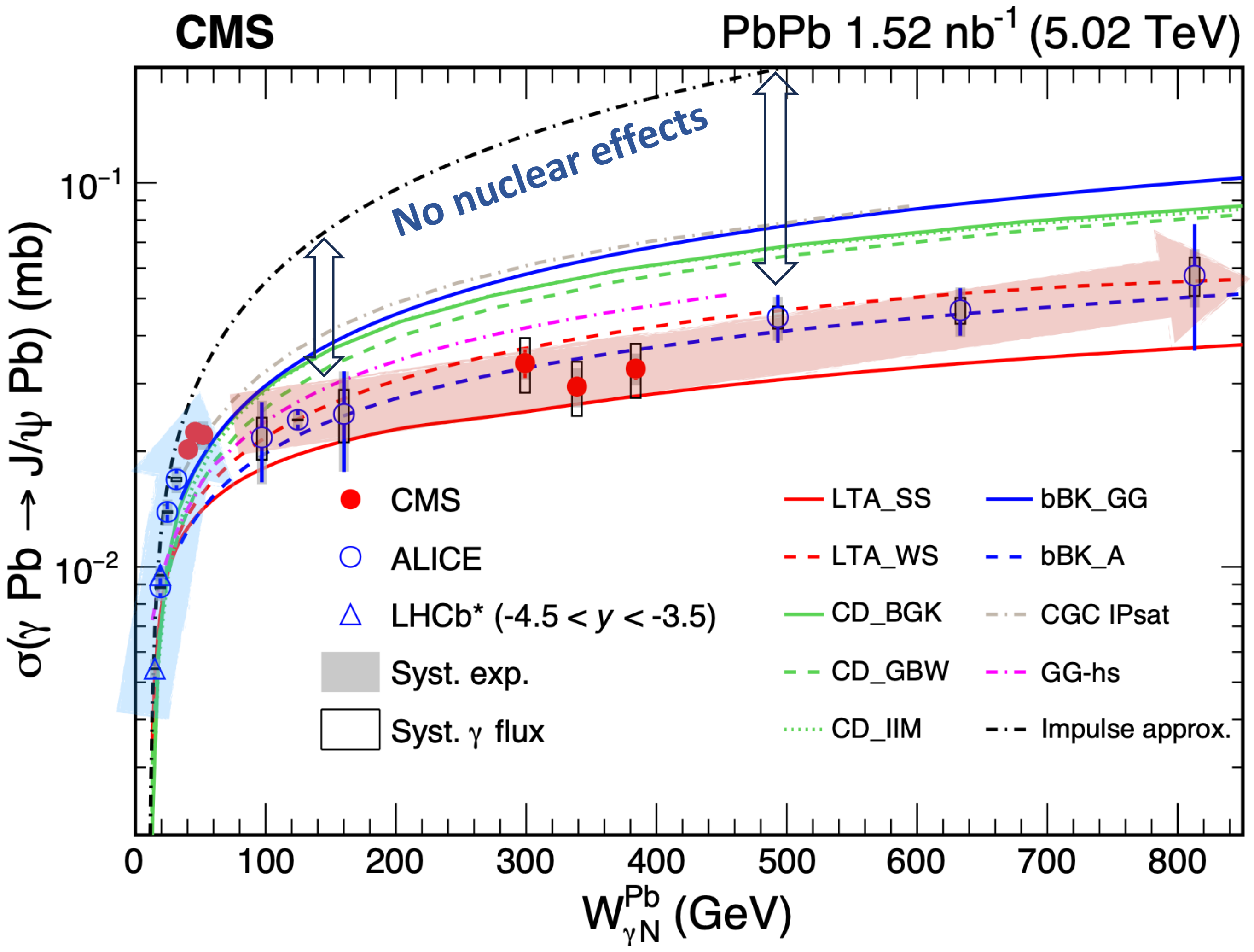
Explore in 2 dimensions: Q^2 vs. x



Coherent J/Ψ Cross Section of Per γ+Pb

CMS: PRL 131, 262301 (2023)

ALICE: JHEP 10 119 (2023)



Data show:

- **Rapid increase** at W < 40 GeV
- Turn into a **nearly flat** (**slower rising**) trend for W > 40 GeV

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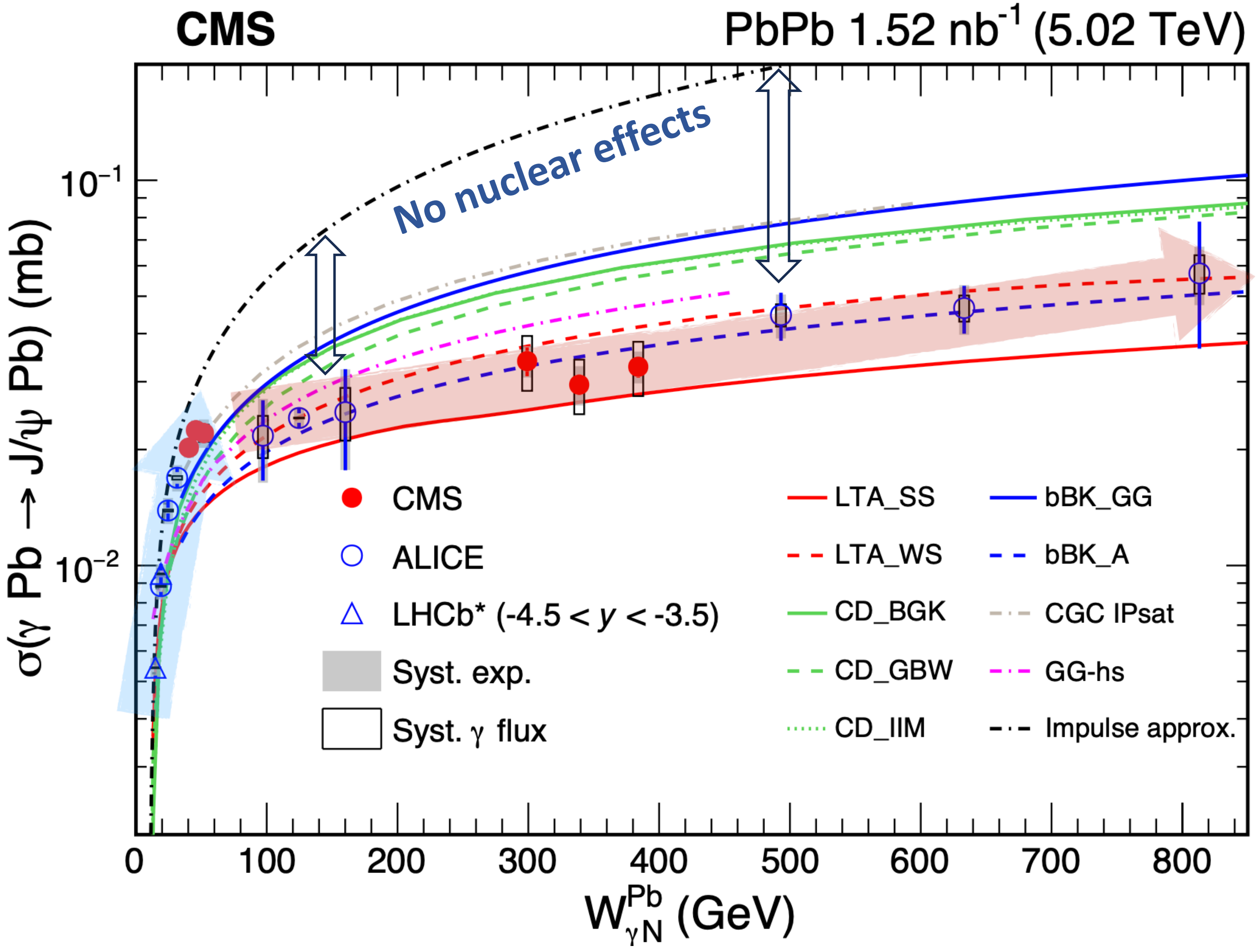

Data show:

- **Rapid increase** at W < 40 GeV
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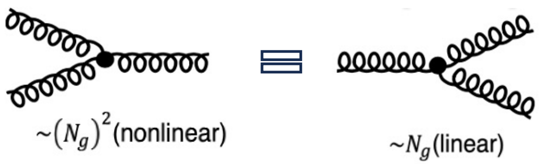
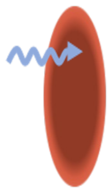
Strongly saturated cross sections

Gluon Saturation?

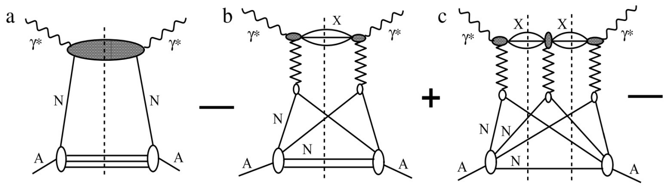


Black Disk Limit?



$$\hat{\sigma}^{\mathrm{inel}}_{\mathrm{PQCD}} \leq \hat{\sigma}_{\mathrm{black}} = \pi R^2_{\mathrm{target}}$$

Nuclear shadowing?

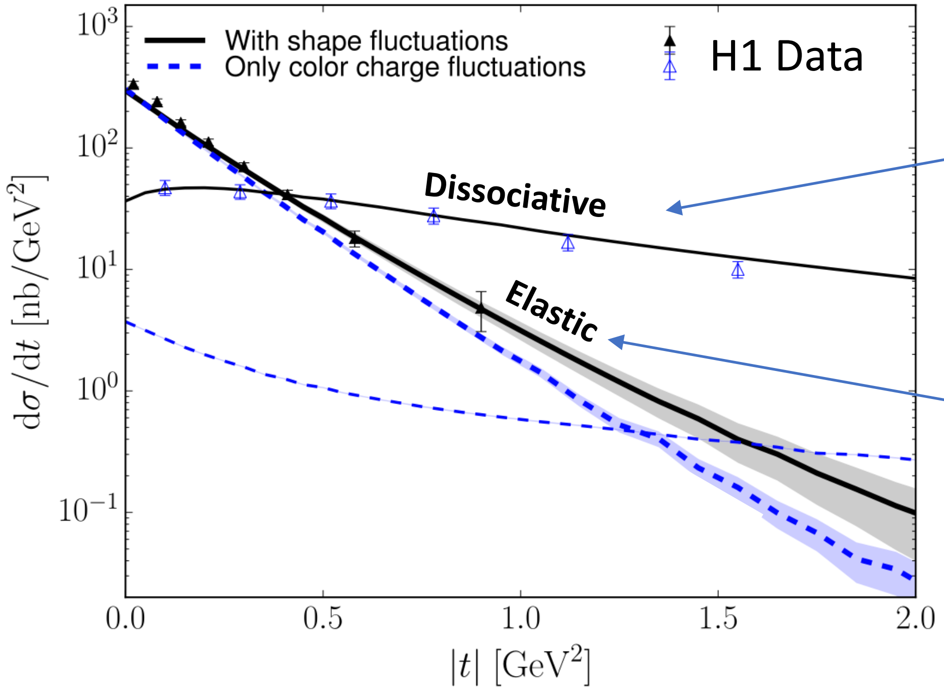


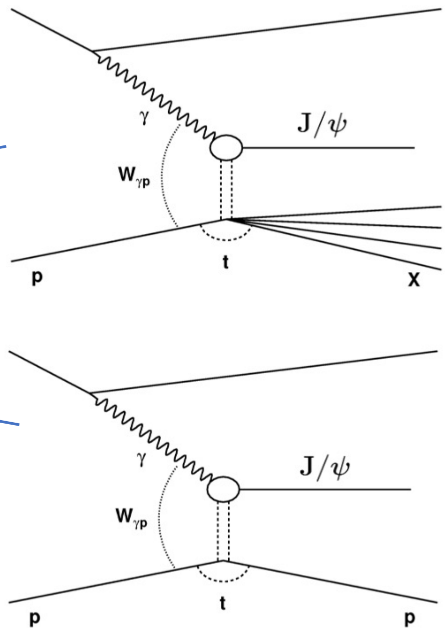
What's the underlying physics?

Fluctuating Gluons Probed via γ+p

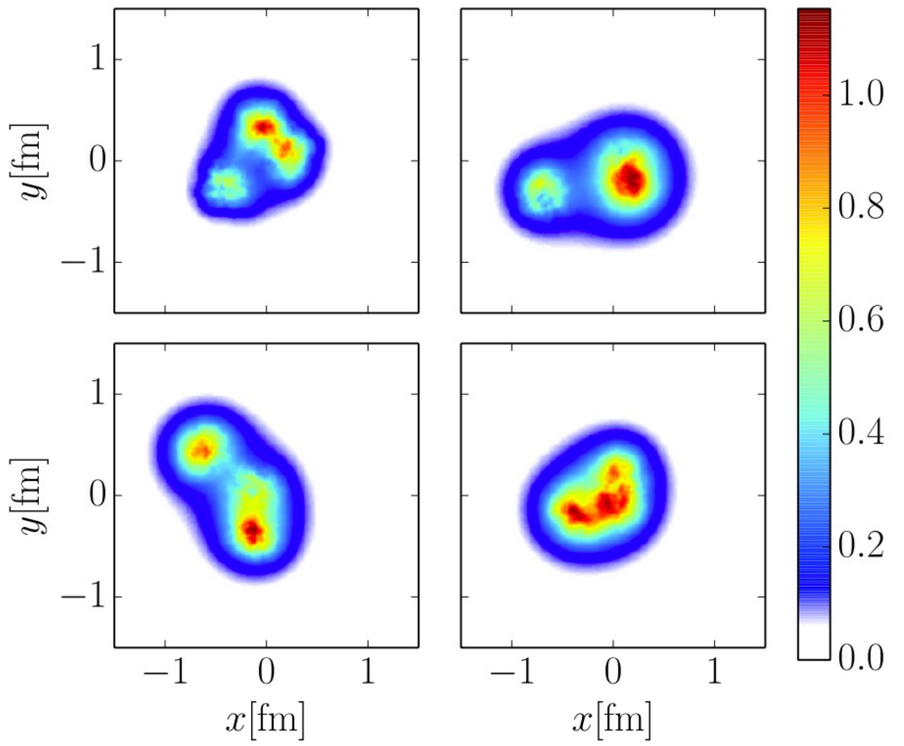
CGC IPsat considering the **fluctuations** of **geometry** (shape and size), **energy density**, **local saturation scale** and **color charge**, successfully describe the HERA data

J/Ψ Photoproduction at HERA



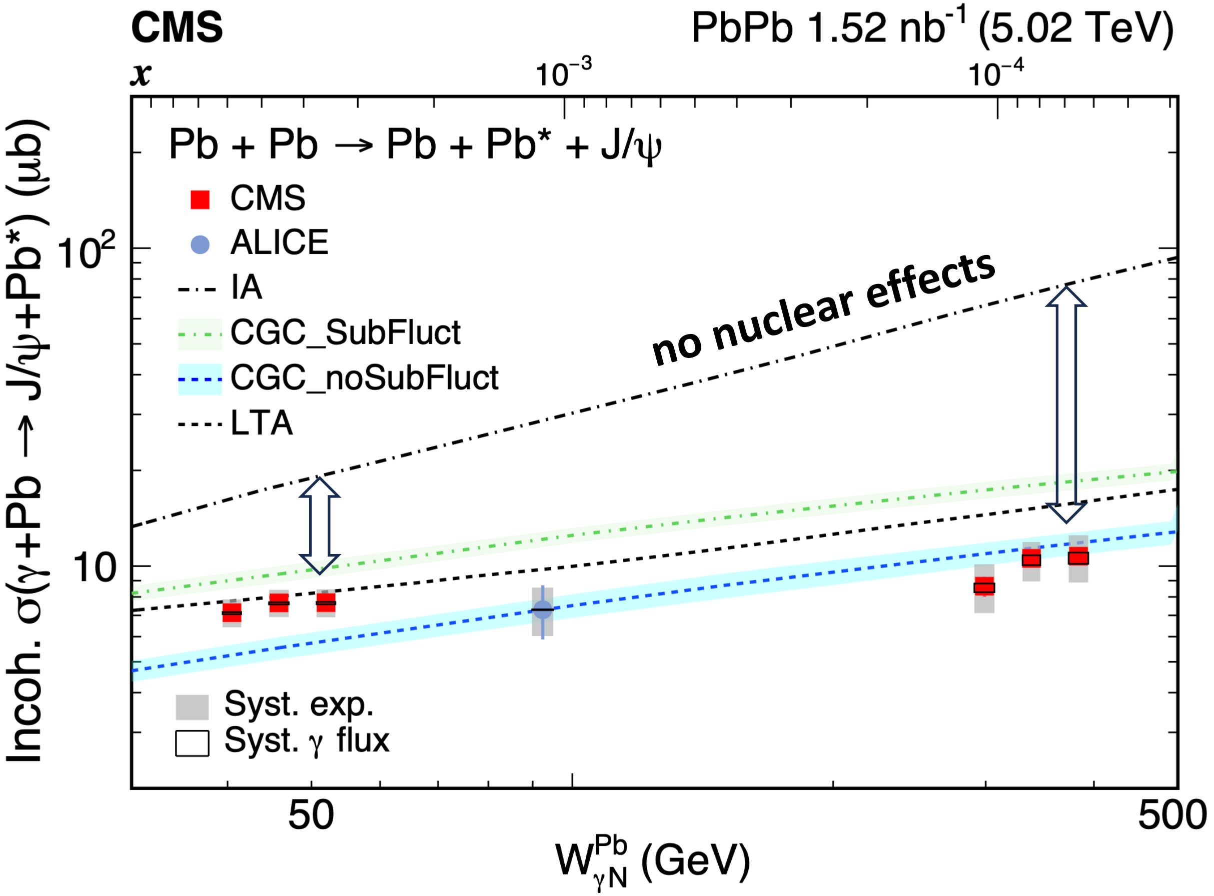


Rep. Prog. Phys. **83** (2020) 082201



CGC IPsat is a b-dependent saturation model under the Color-Glass Condensate framework

Incoh. J/Ψ Cross Section Per γ+Pb

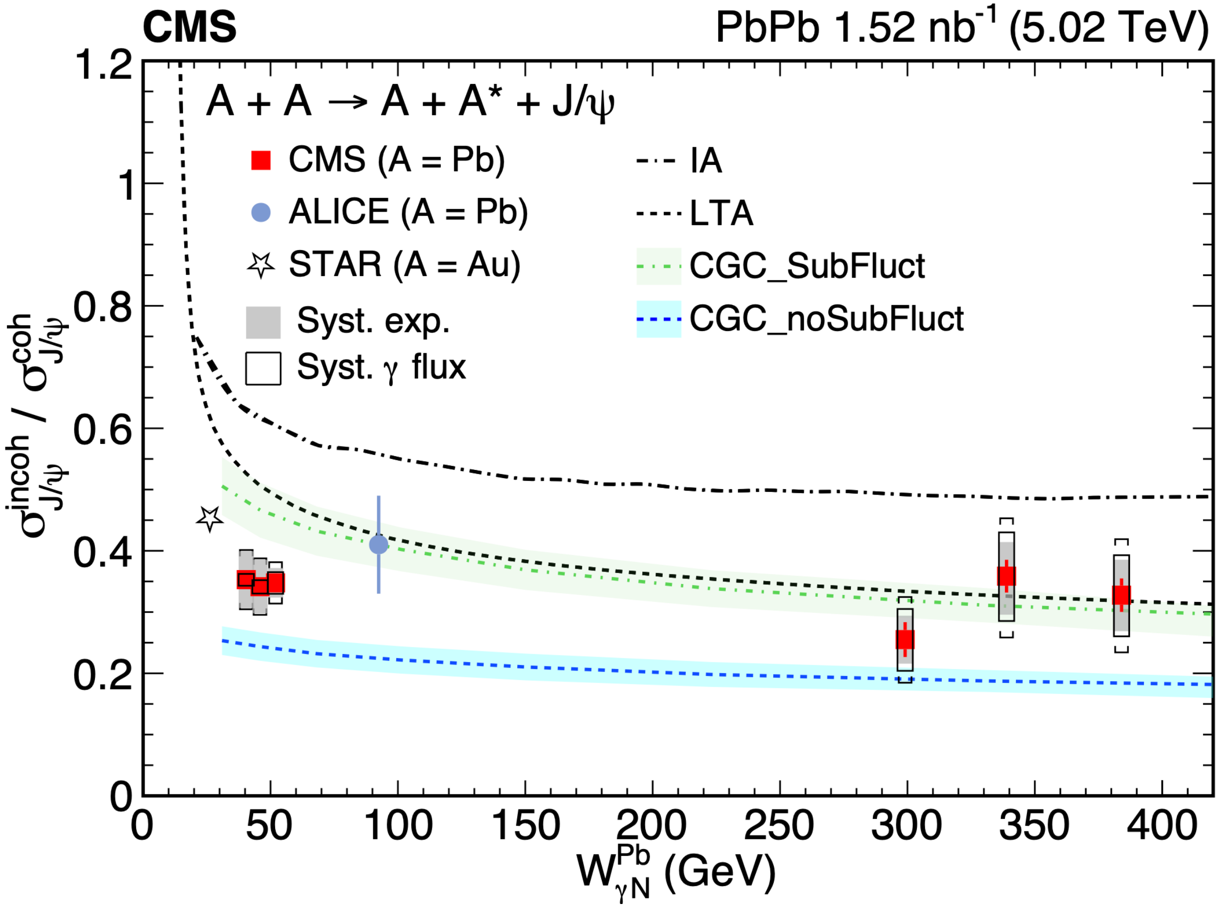


CMS, PRL 135, 112301 (2025), Editors' Suggestion

- **First energy-dependent** measurement of incoh. J/Ψ photoproduction
  - **Strongly saturated trend again**
- **Strong suppression** compared to Impulse Approximation (IA)
- **LTA** describe data at **W < 60 GeV**
- **CGC without** sub-nucleonic fluctuations better describe data at **W > 90 GeV**

CGC: PRD 109 (2024) 7, L071504, PRD 106 (2022) 7, 074019
LTA: V. Guzey et al. PRC 108 (2023) 024904, PRC 99 (2019) 015201
ALICE: EPJC 73 (2013) 2617

Cross Section Ratio of Incoh./Coh. J/Ψ

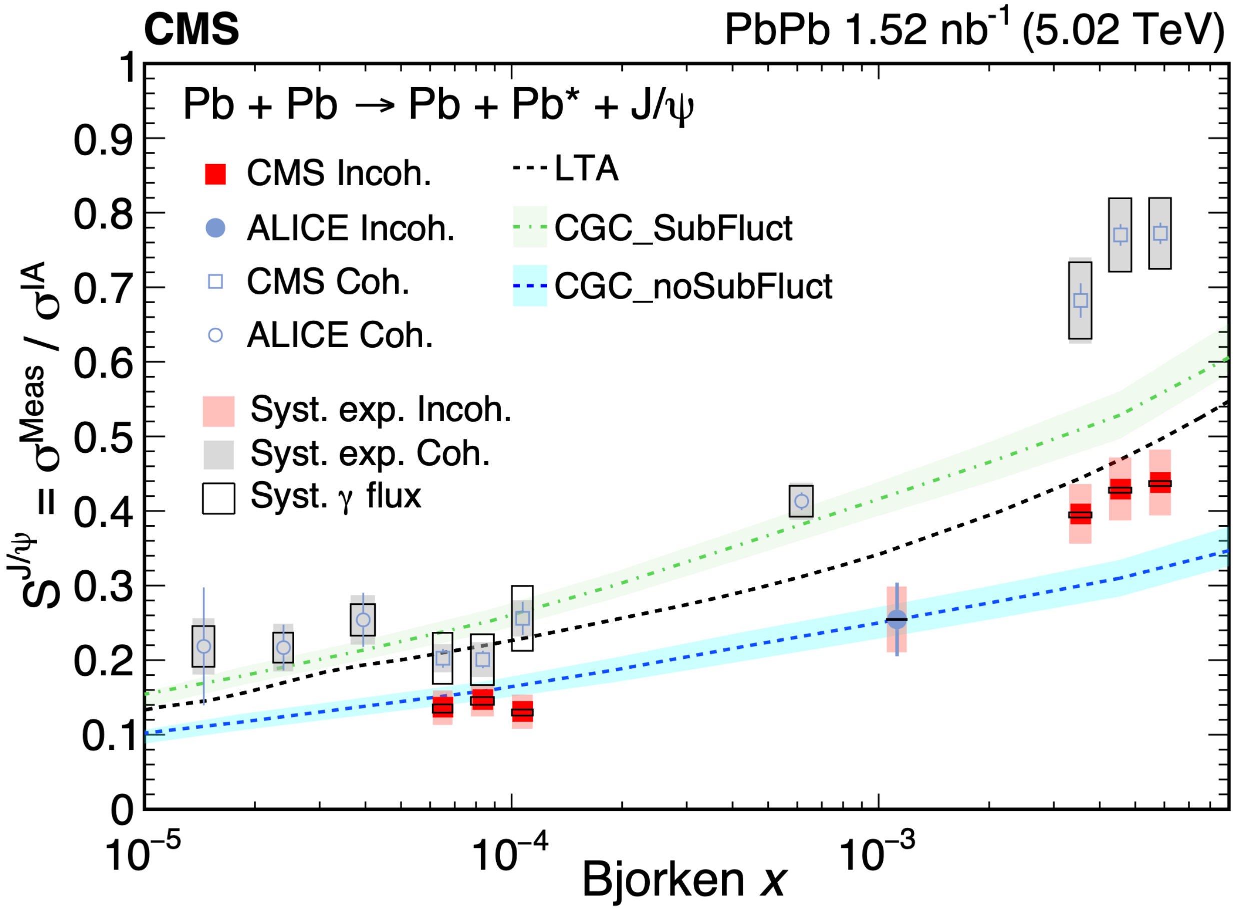


- **No clear W dependence (40 < W < 400 GeV)**
  - Not support Black Disk Limit is reached
- ALICE data agrees with CMS data, STAR data slightly rises towards lower W
- **LTA and CGC with sub-nucleonic fluctuation qualitatively describe data trend**

CMS, PRL 135, 112301 (2025), Editors' Suggestion

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

Nuclear Suppression Factor



CMS, PRL 135, 112301 (2025), Editors' Suggestion

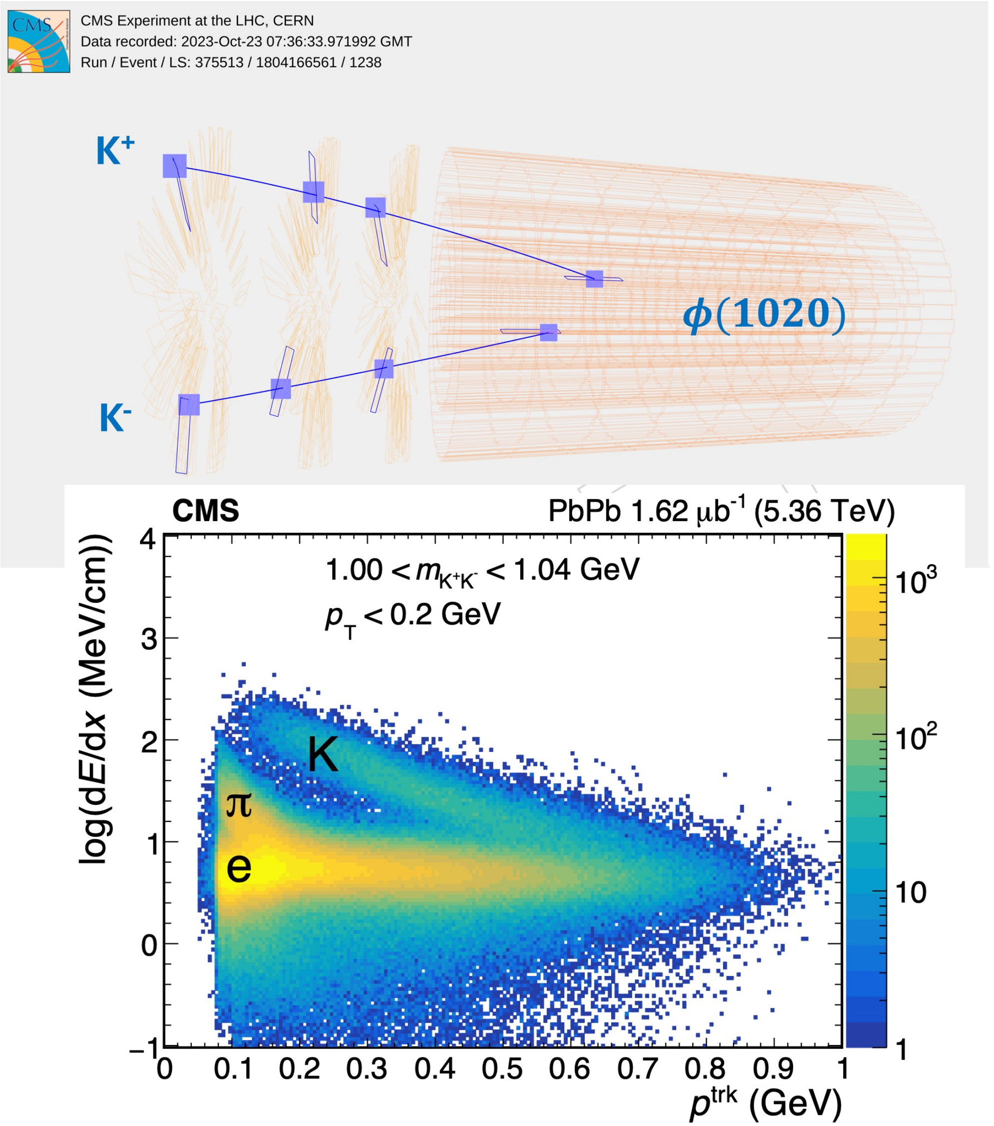
$$S_{\mathrm{coh}}^{J/\psi}(x,\mu^2) = (R_g)^2$$

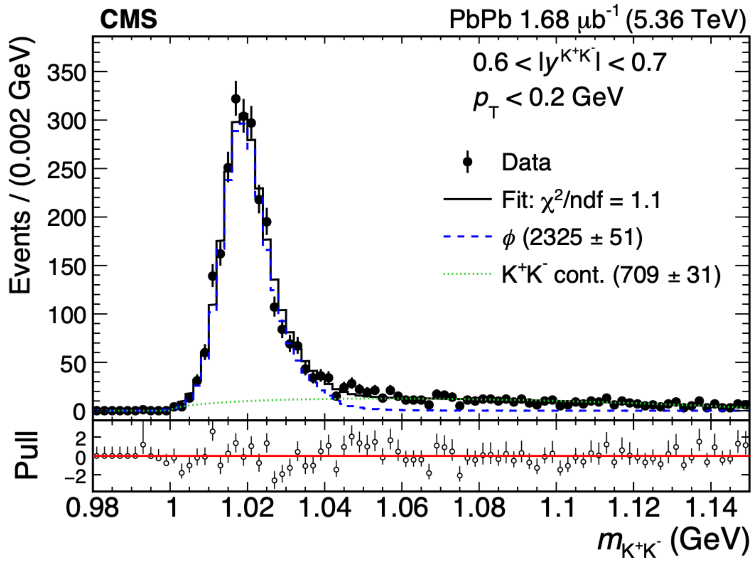
$$S^{J/\psi} = \frac{\sigma^{exp}_{\gamma Pb \to J/\psi Pb'}}{\boxed{\sigma^{IA}_{\gamma Pb \to J/\psi Pb'}}}$$

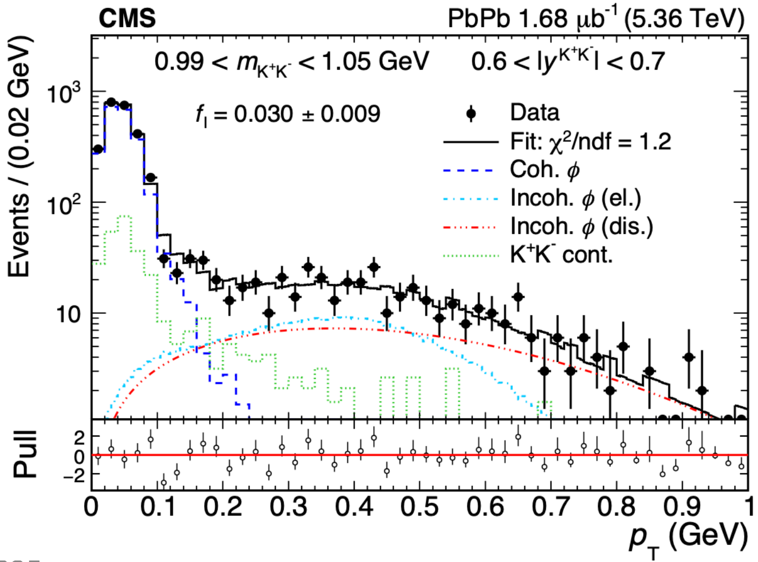
No nuclear effects

- Both Coh and Incoh J/Ψ show **stronger suppression towards lower *x*,** and eventually **flattens out**
- Incoh. is **more suppressed** than Coh. J/Ψ
- Incoh. J/Ψ get closer to Coh. J/Ψ for $x < 10^{-4}$

First Observation of ϕ Photoproduction in UPCs







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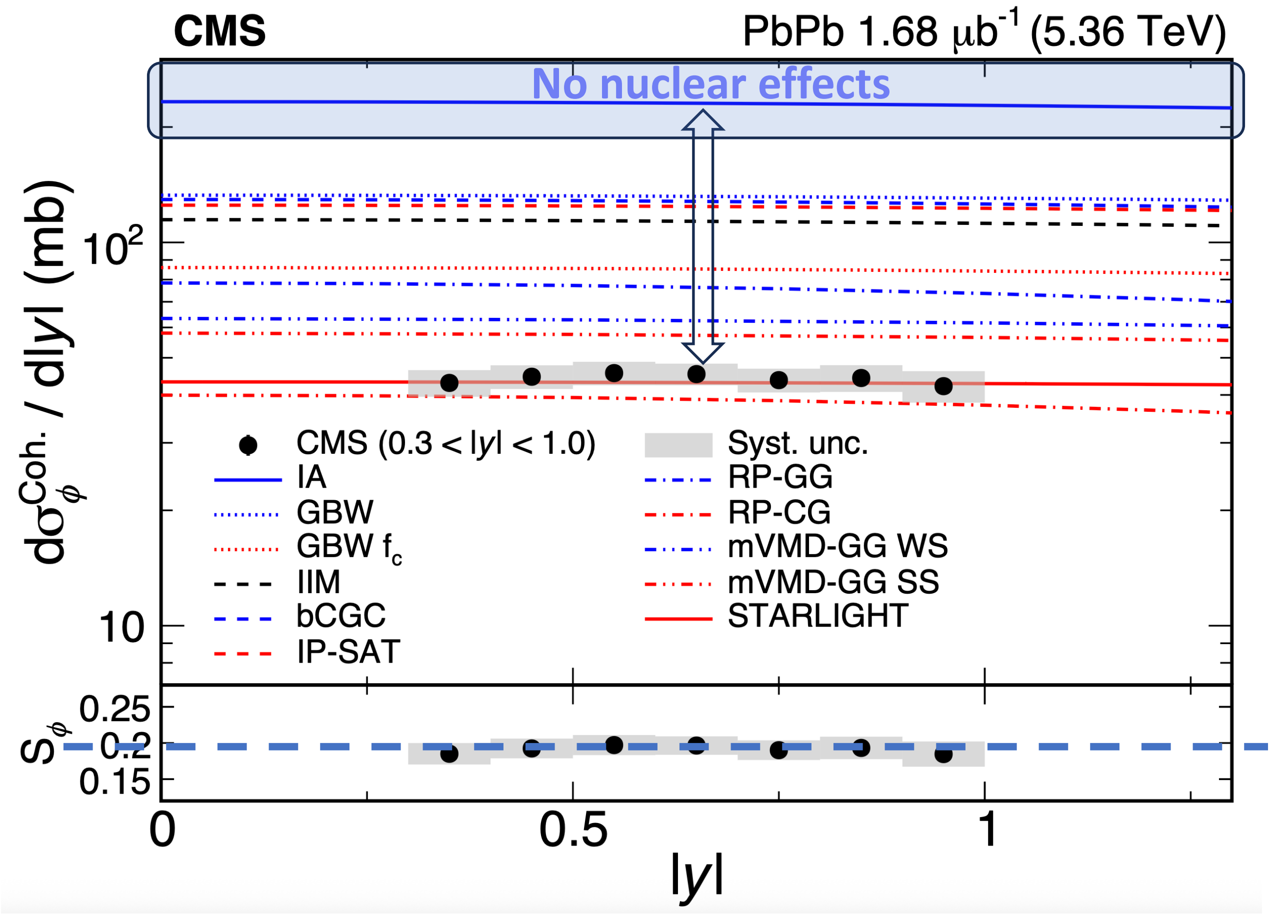
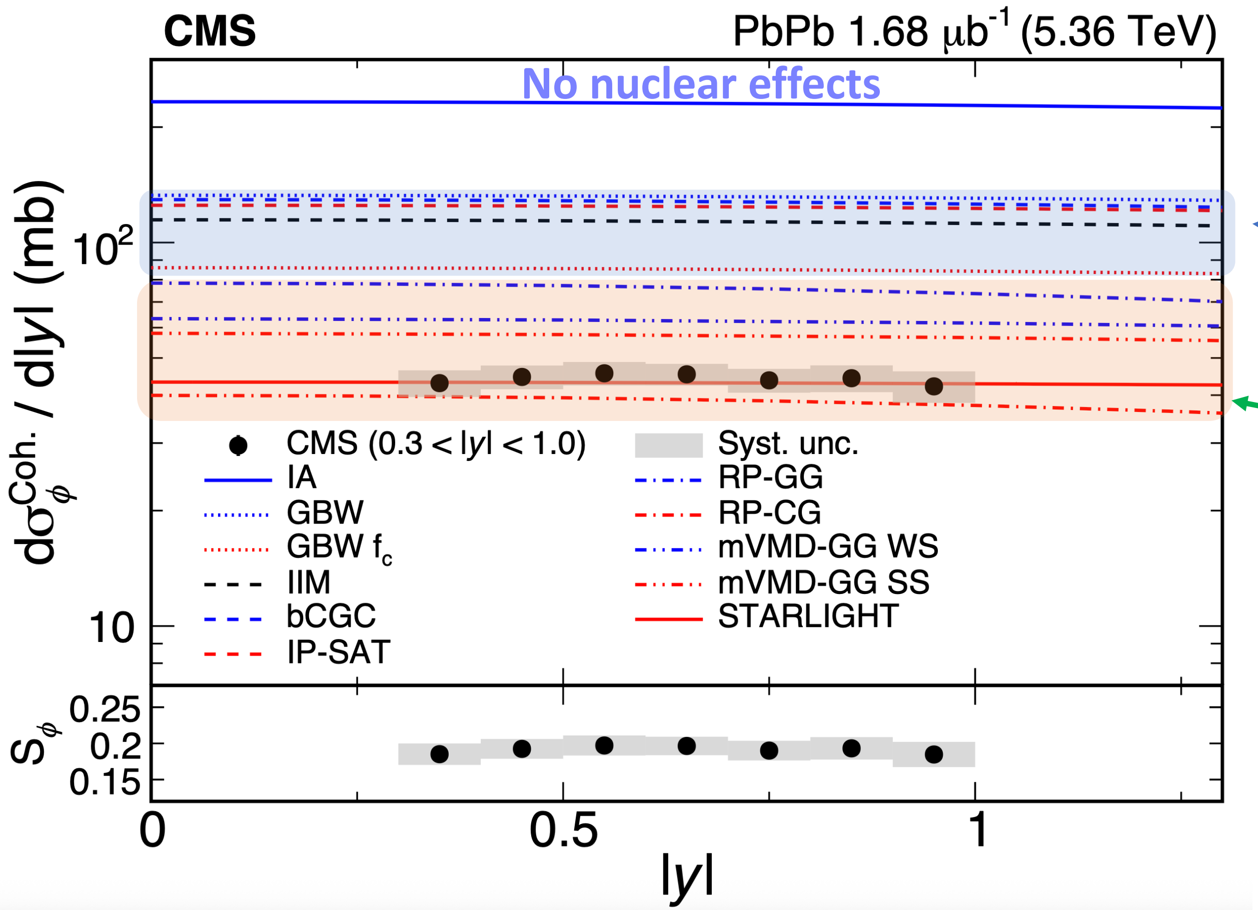


- **Strong (~5x) suppression is observed**

CMS, arXiv:2504.05193, submitted to PRL

First Observation of ϕ Photoproduction in UPCs

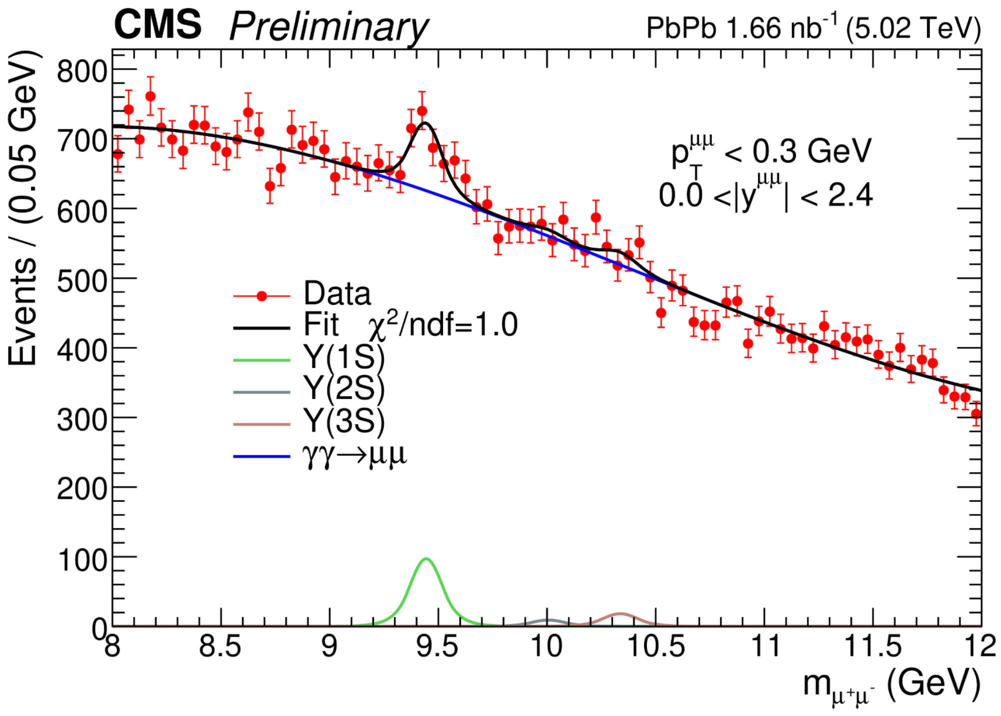


- **Strong (~5x) suppression is observed**
- **Gluon saturation models:**
  - Overpredicted data by a factor of **2-3**
- **Nuclear shadowing models:**
  - Generally better describe data
  - VMD + Gribov Glauber (GG) over predict data
  - VMD + Classical Glauber (CG) best describe data
    - STARLIGHT and RP-CG
      - But not describe J/Ψ and ***ρ*** results

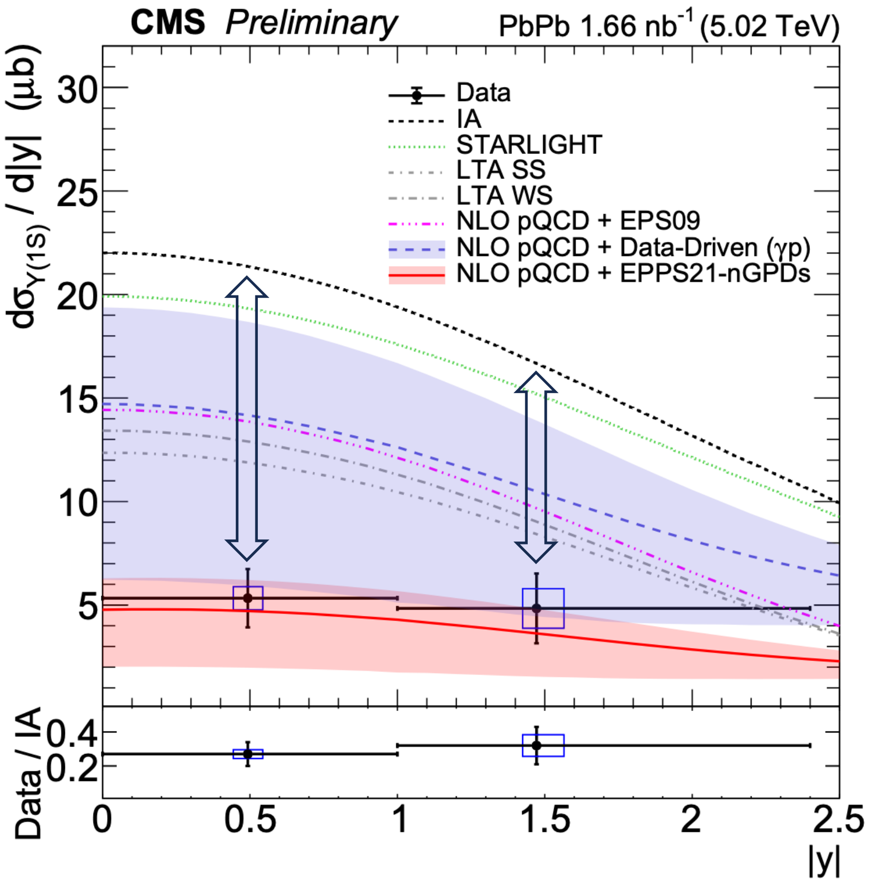
CMS, arXiv:2504.05193, submitted to PRL

First Observation of $\Upsilon(1S)$ Photoproduction in UPCs

Υ is expected to be less sensitive to the non-linear QCD effects



CMS-PAS-HIN-24-013



- **However, coherent $\Upsilon(1S)$ is observed to be strongly (~4x) suppressed!!!**

Summary

- **First energy-dependent Coh. and Incoh. J/Ψ are measured by CMS**
  - Both are strongly saturated at high energy
  - Ratio of Incoh/Coh J/Ψ stay constant ~0.3-0.5
  - Stronger towards lower x, eventually flattens out
  - Incoh. J/Ψ is more suppressed than Coh. J/Ψ
- **First Coh. ϕ photoproduction off heavy nuclei is observed by CMS:**
  - Nuclear suppression factor ~5
- **First $\Upsilon(1S)$ photoproduction off heavy nuclei is observed by CMS:**
  - Nuclear suppression factor ~4
- **Significant theoretical improvements are needed towards uncovering the underlying physics mechanisms at small x**

Thanks!

Special thanks to the theorists for their valuable discussions and insightful predictions:

CGC: B. Schenke , H. Mantysaari, F. Salazar, W. Zhao and J. Penttala

LTA: V. Guzey, M. Strikman, M. Zhalov and E. Kryshen

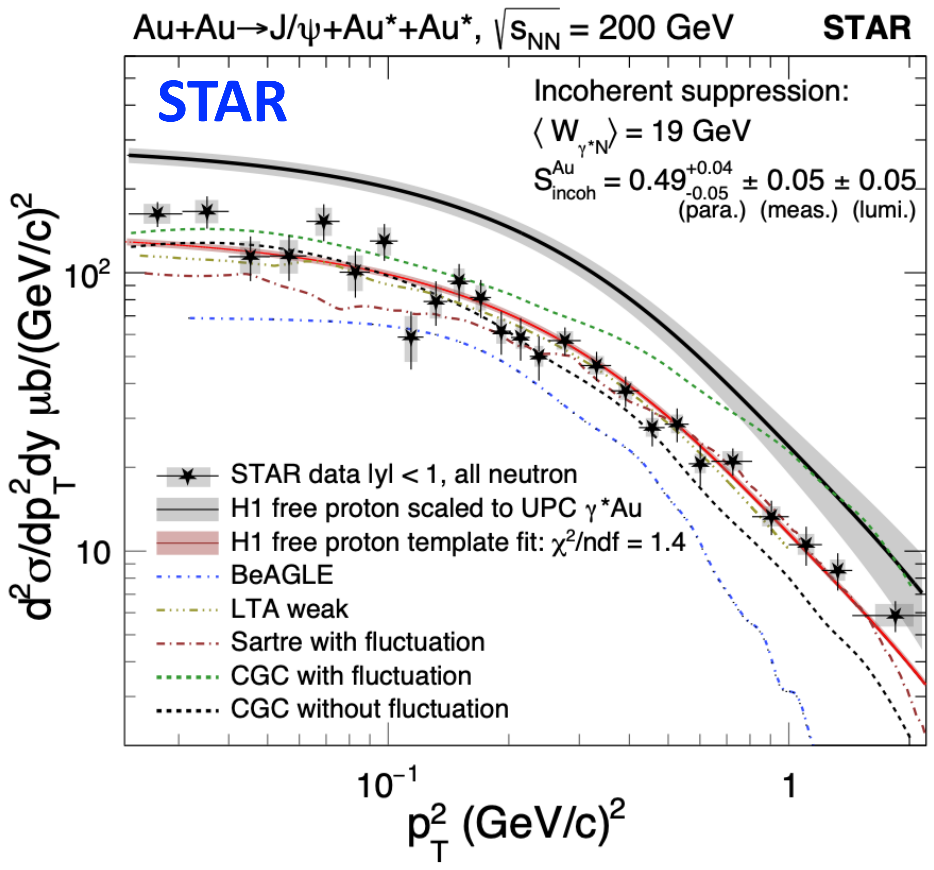
CD and GBW: V. P. Goncalves, B. D. Moreira, K. J. Golec-Biernat and M. Wusthoff

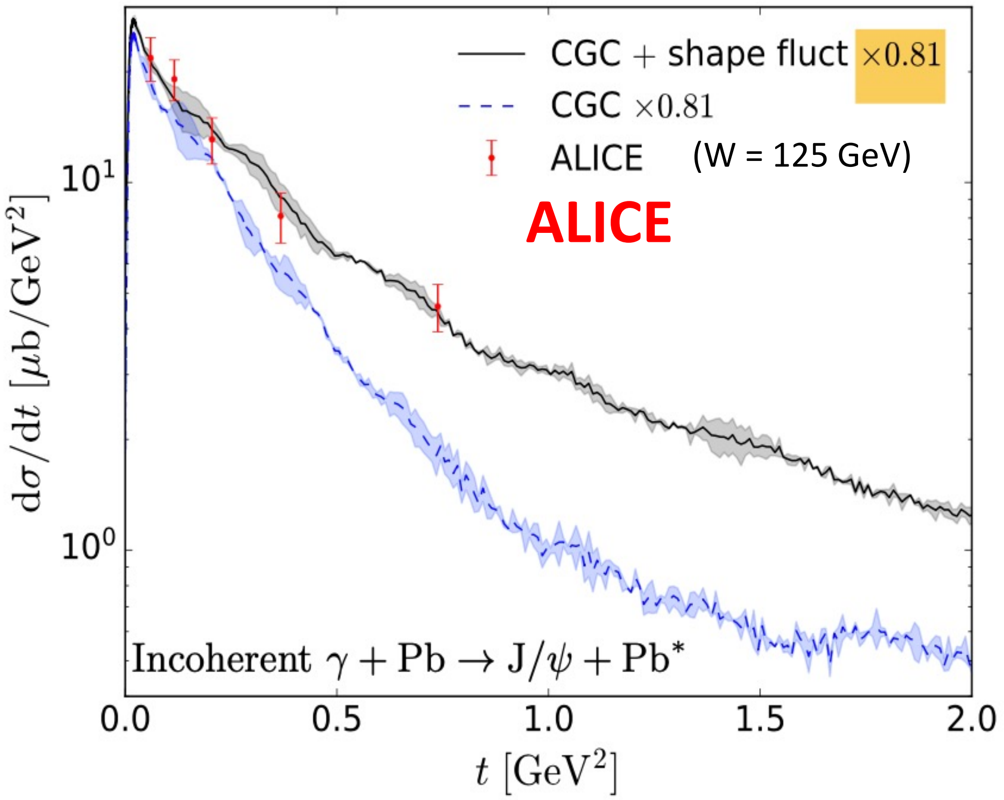
RP: M. V. T. Machado

STARLight: S. R. Klein

Backup Slides

Fluctuating Gluons Probed via Incoherent γ+Au/Pb





t distribution from STAR: well described by LTA, but in between two scenarios of CGC with and without sub-nucleonic fluctuations

t distribution from ALCIE: slope is well describe by CGC with sub-nucleonic fluctuations however, missed by a common scaling factor

CGC: PRD 109 (2024) 7, L071504
ALICE: PRL 132, 162302 (2024)
STAR: PRC 110 014911 (2024)

Photon Flux: **Point-like** vs. **Realistic**

CPC 277 (2022) 108388

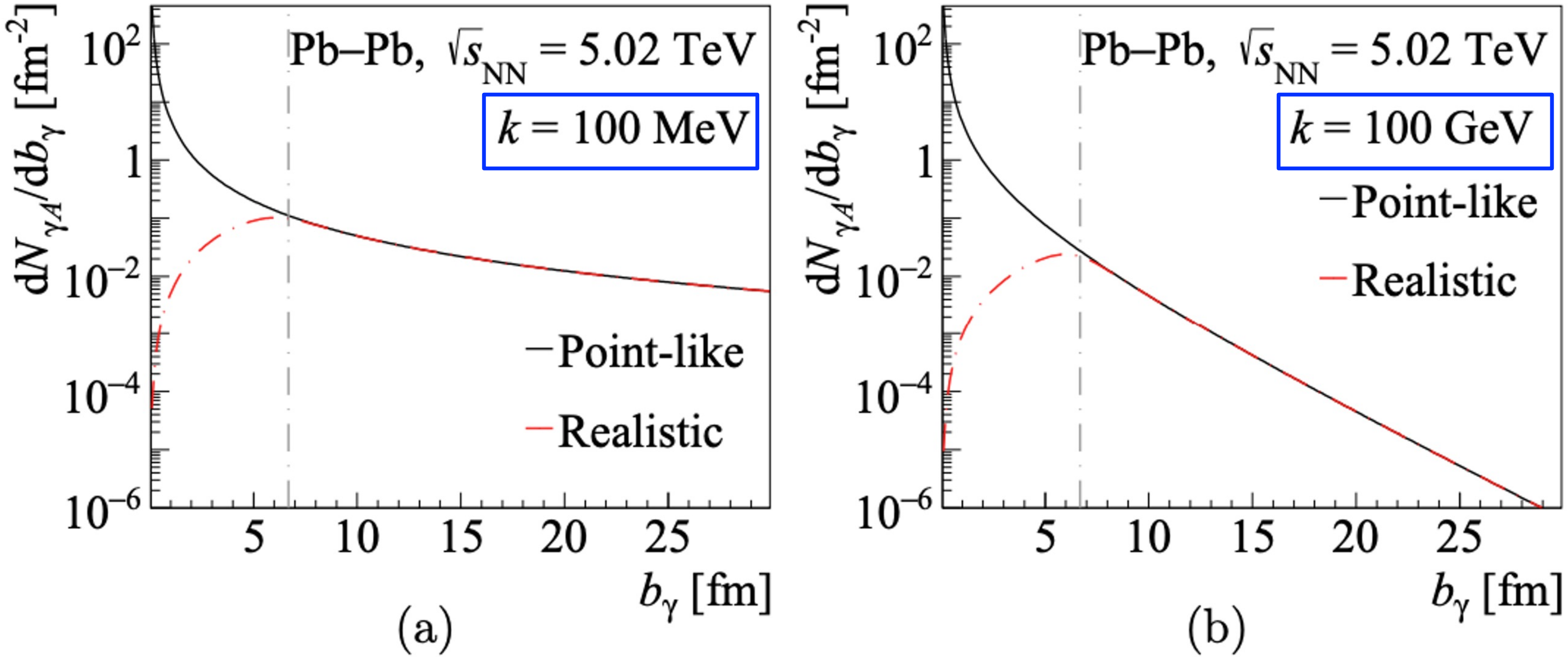
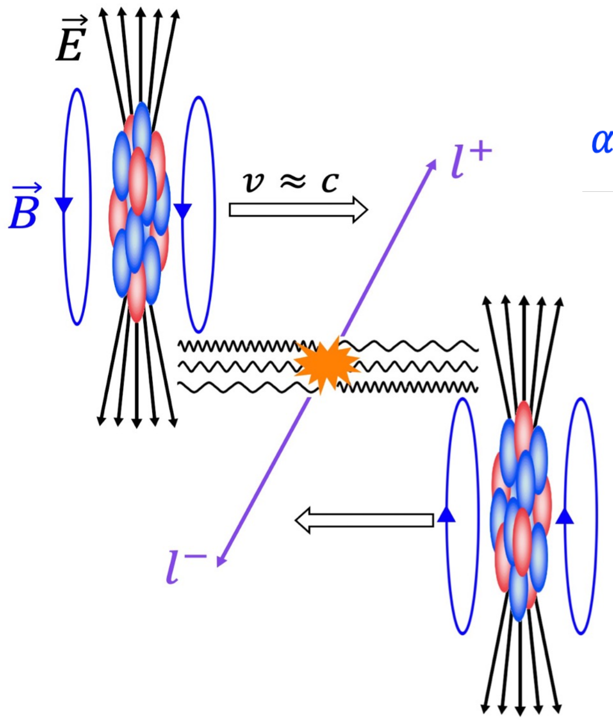


Figure 4: (Color online) Photon fluxes coming from a nucleus $N_{\gamma A}$ in the point-like source approximation and the realistic description as functions of impact parameter b_γ calculated at different photon energies: 100 MeV (a), 100 GeV (b).

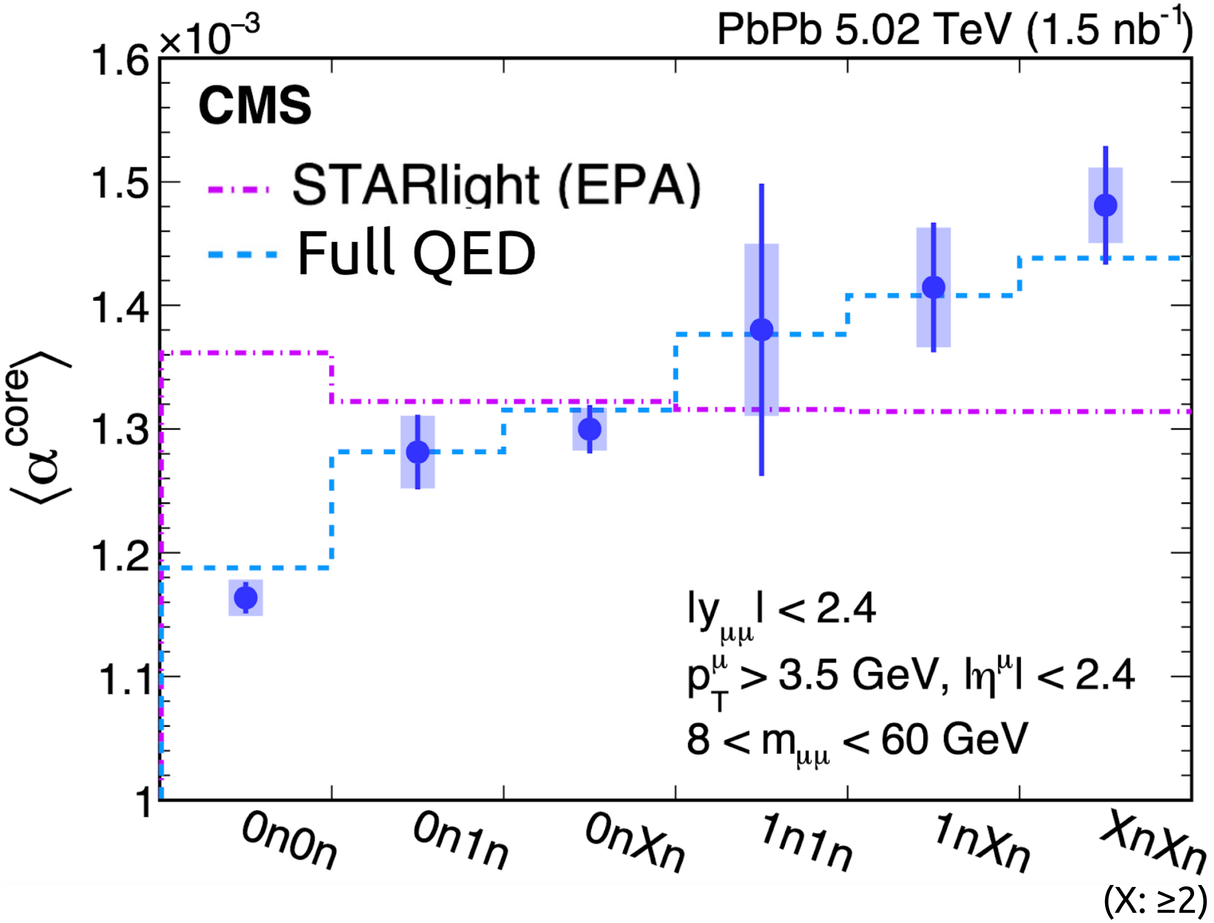
QED Dimuon with Neutron Tagging at CMS

PRL 127 (2021) 122001

$$\gamma\gamma \rightarrow \mu^+\mu^-$$

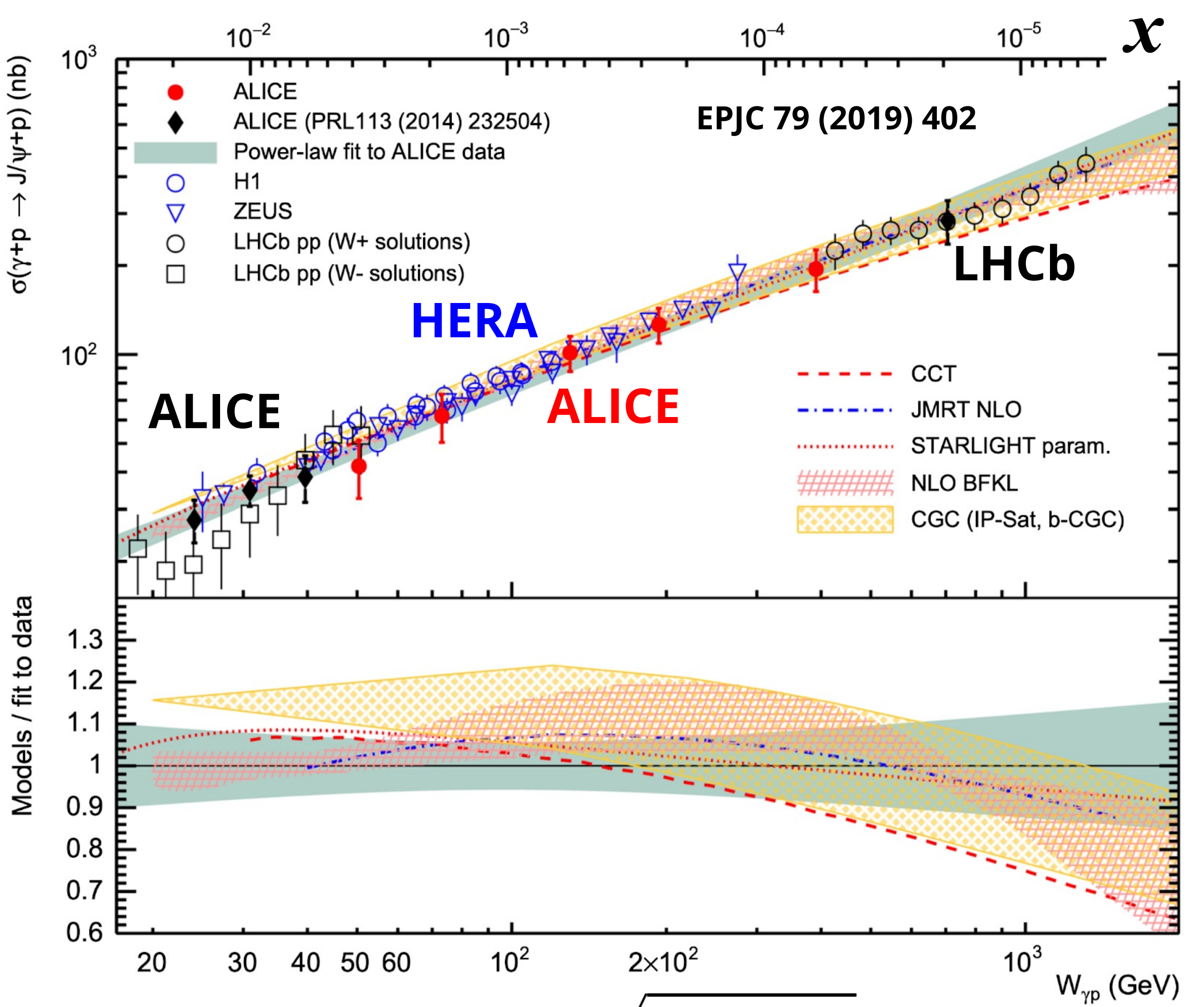


$$\alpha = 1 - \frac{|\phi^+ - \phi^-|}{\pi}, \alpha \propto p_T^{l^+l^-}$$



First direct evidence of b-dependent initial photon p_T, set strong base line for observe QGP EM effects in heavy ion collisions

Coherent J/Ψ Photoproduction via γ + p (Free Nucleon)



$$W_{\gamma p} = 2\sqrt{\omega \cdot E_{beam}}$$

$$\gamma + p \rightarrow J/\psi + p$$

- Data from **LHC** and **HERA** follow a **common** power-law trend, consistent with the expectation from the rapidly increasing gluon density in a proton

No clear indication of gluon saturation, even down to x~10^{-5} in a free nucleon!