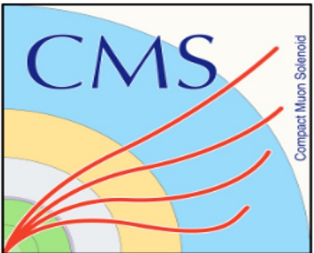


Probing Small- x Nuclear Gluonic Structure Via Vector Meson Photoproduction at CMS

Zaochen Ye (SCNU)

July 03, 2026

USTC, Hefei

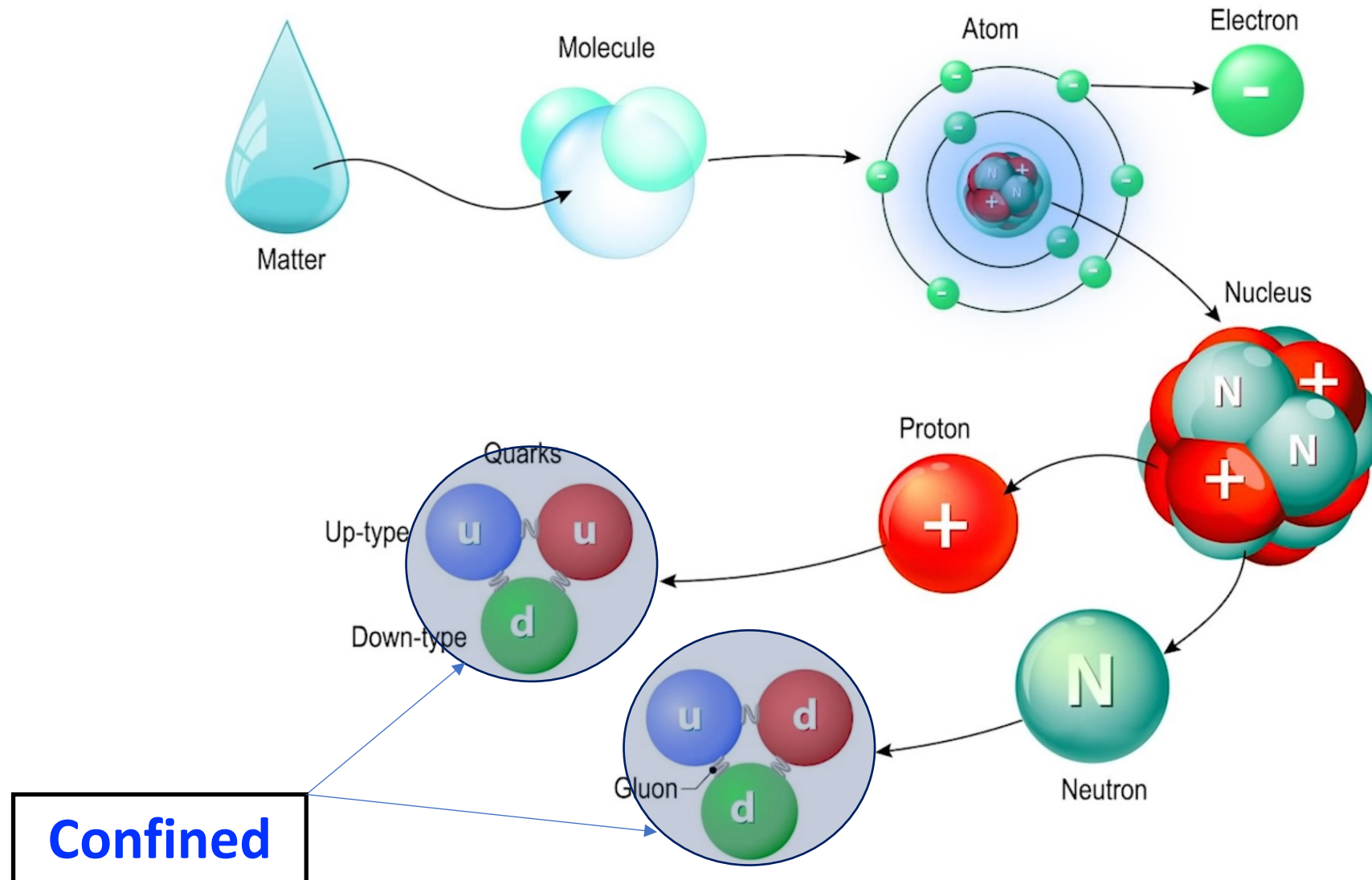


July 03, 2026



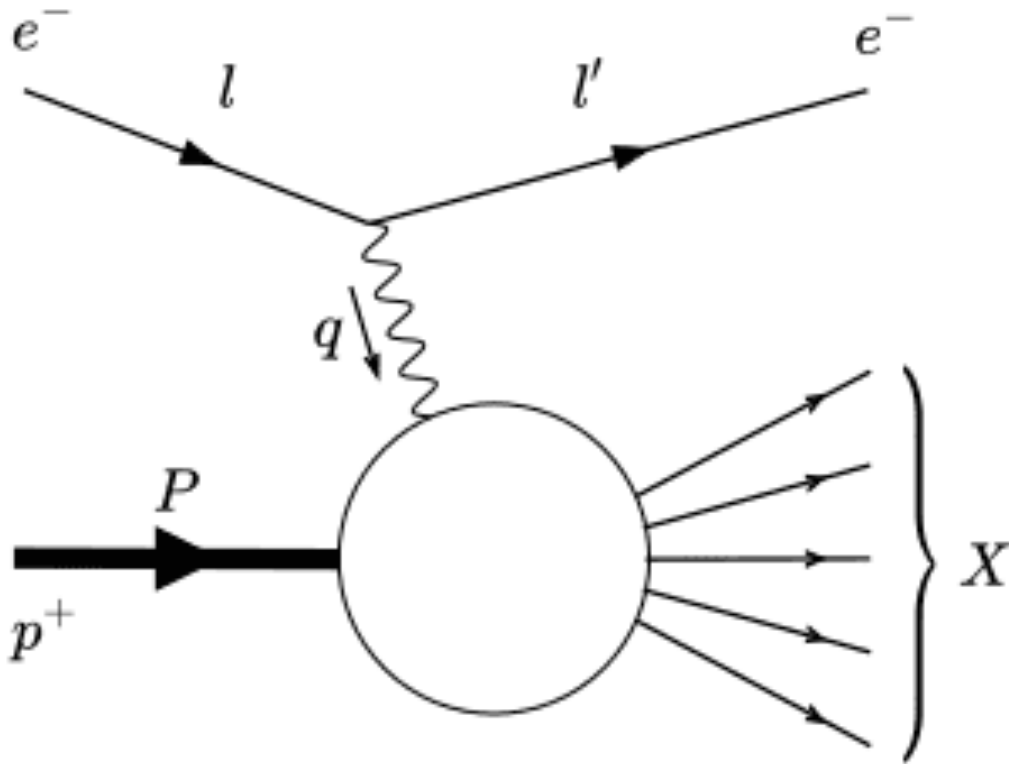
Zaochen Ye (叶早晨) at USTC

Understand Fundamental Structure of Matter



Understand Nucleon Structure via DIS

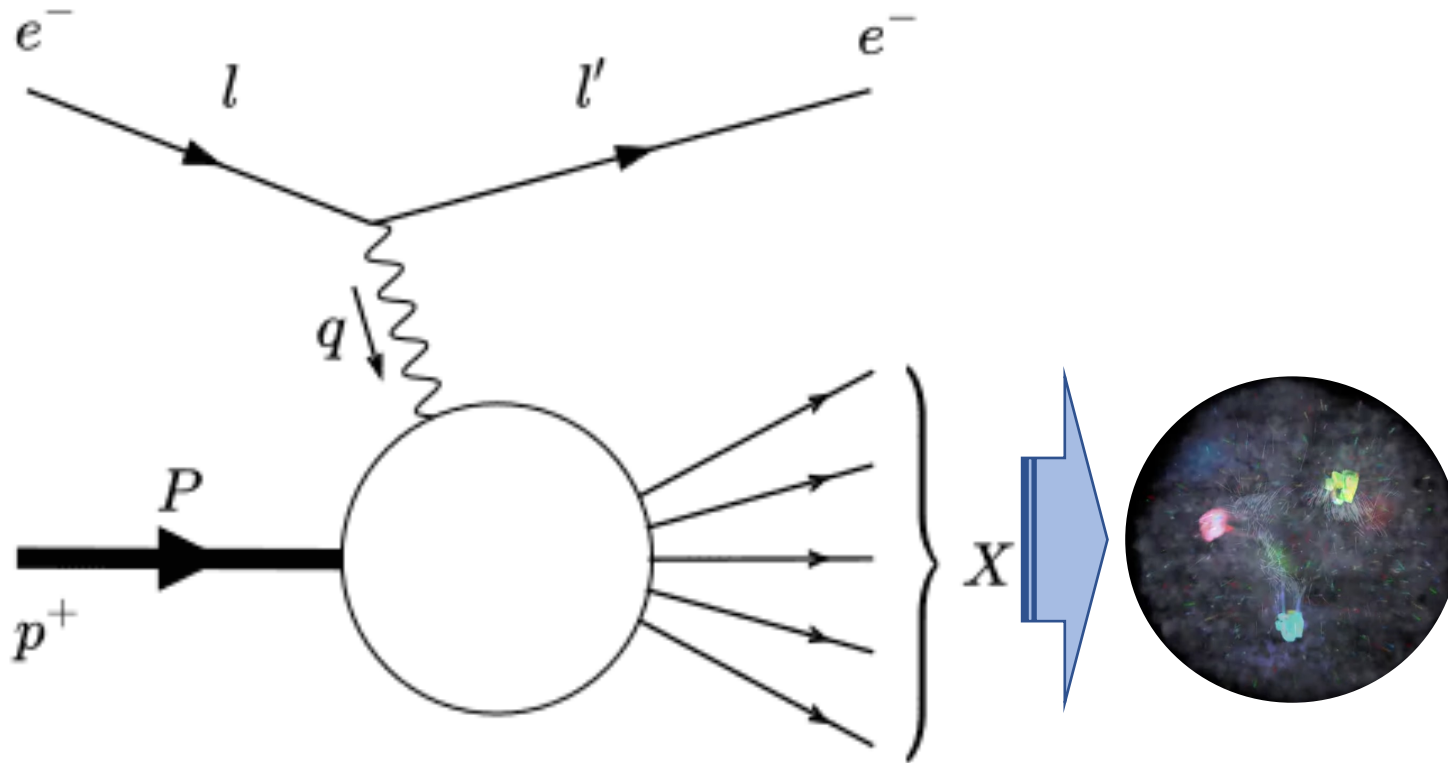
Smash them!!!



Deep Inelastic Scattering

Understand Nucleon Structure via DIS

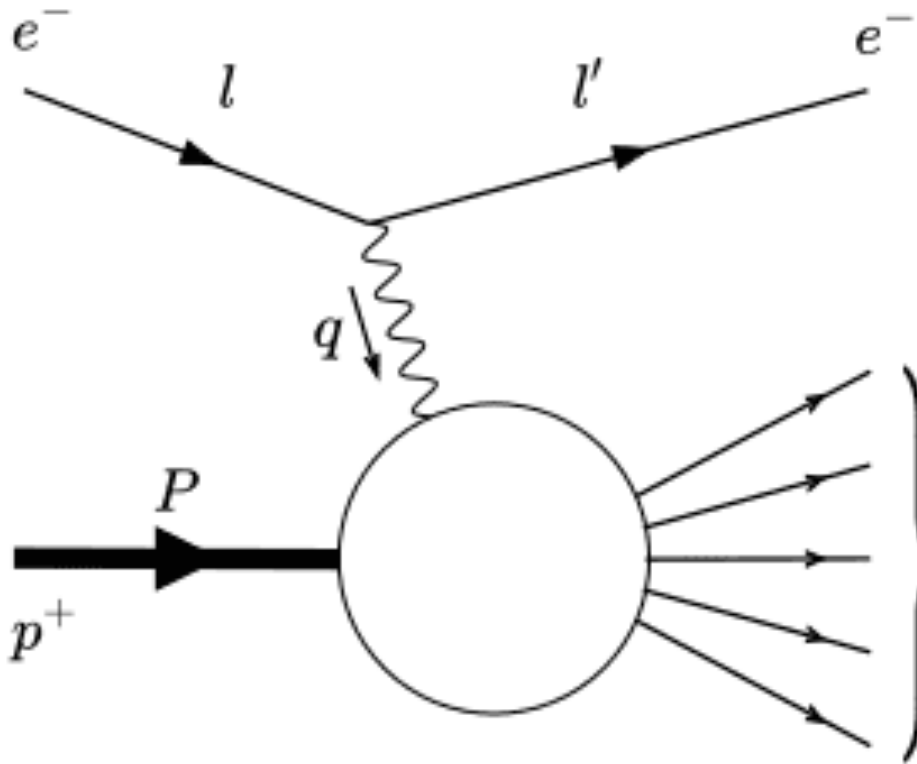
Smash them!!!



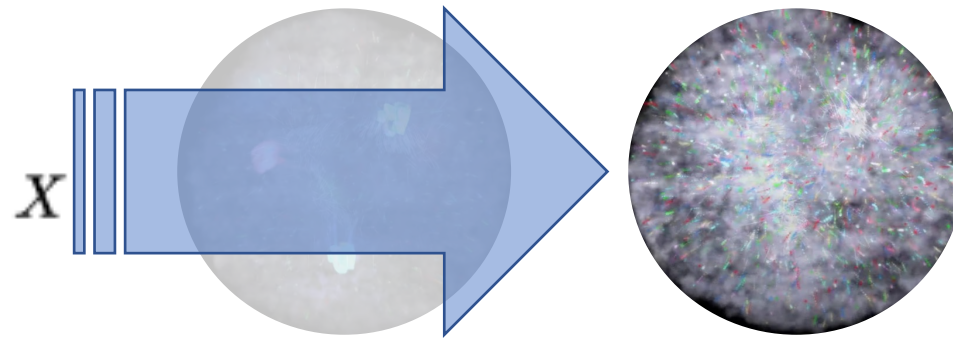
Deep Inelastic Scattering

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Smash them!!!



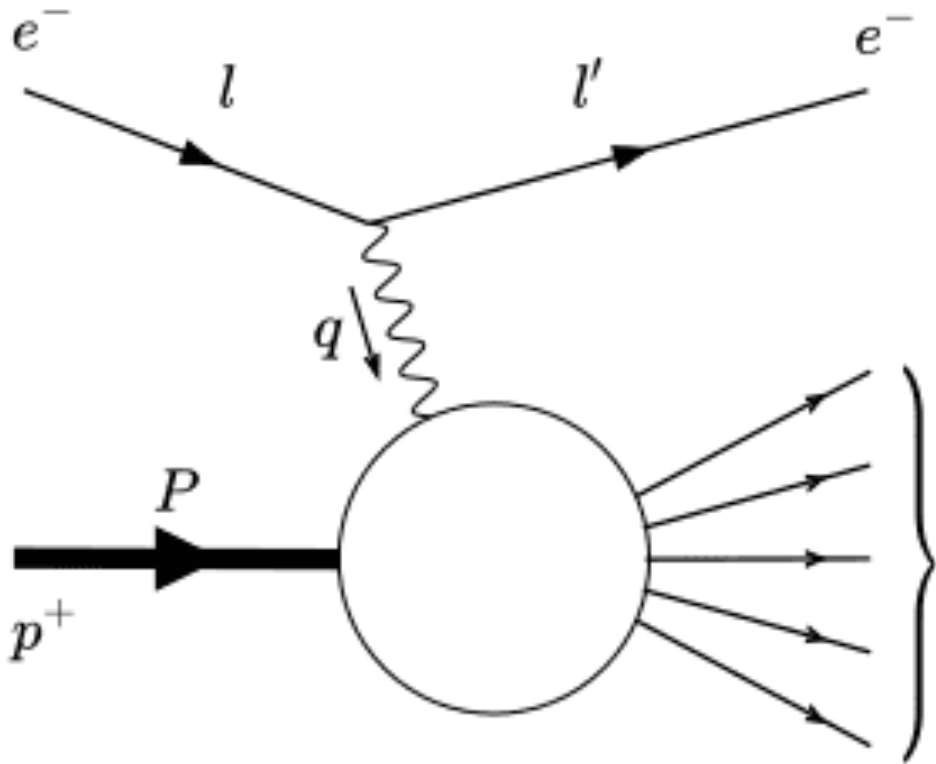
Higher energy, probing lower- x partons



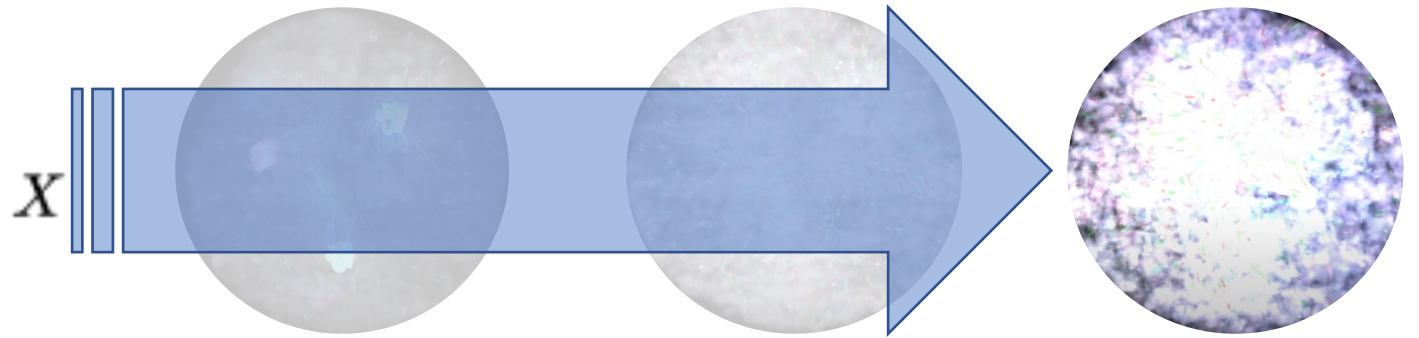
Deep Inelastic Scattering

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Smash them!!!



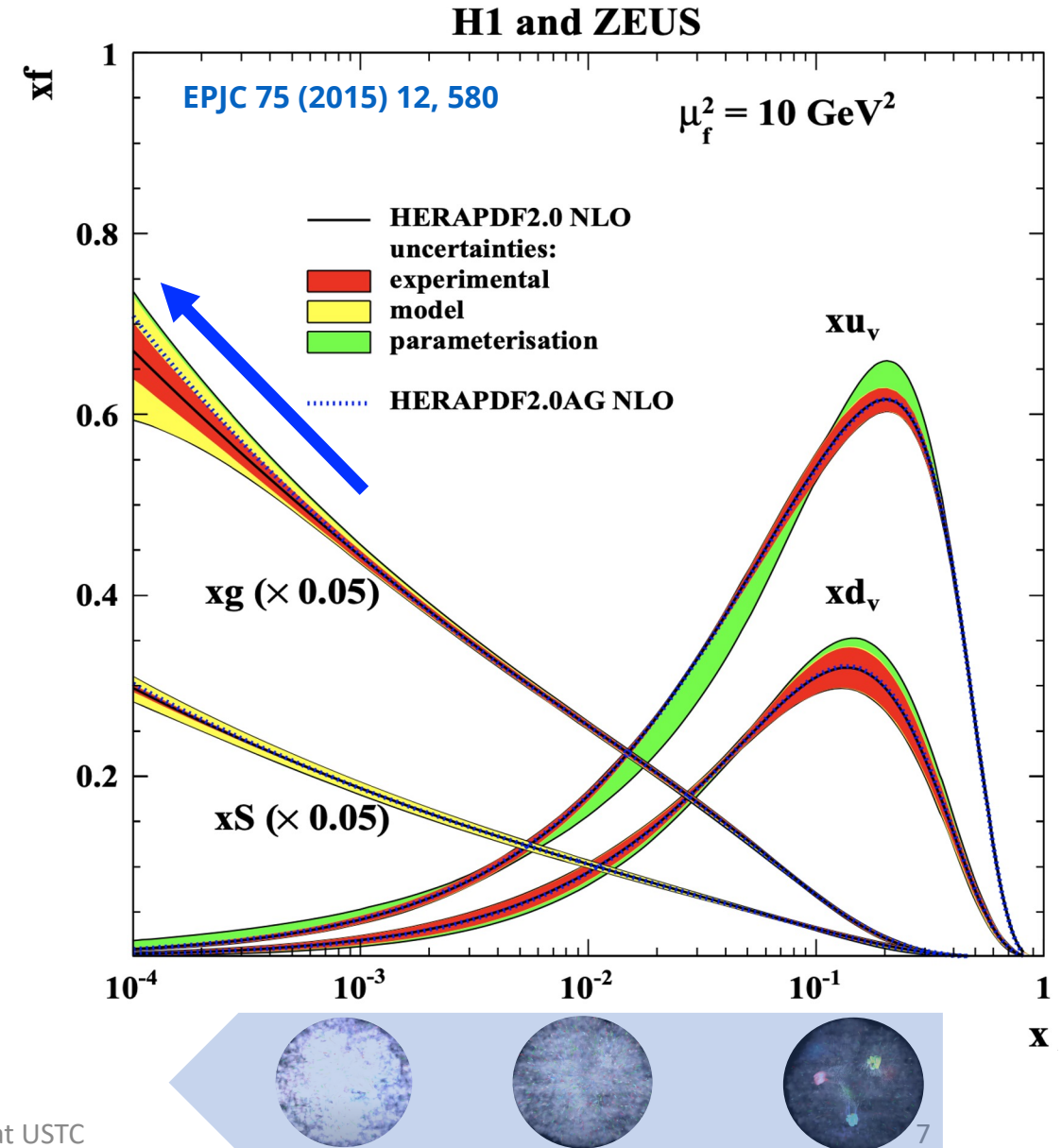
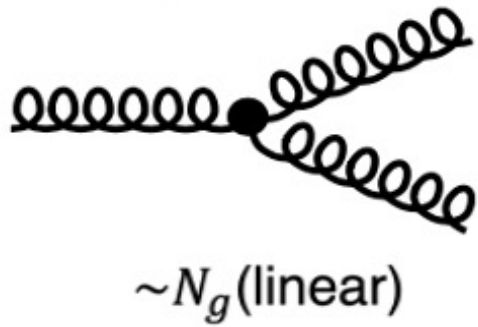
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Deep Inelastic Scattering

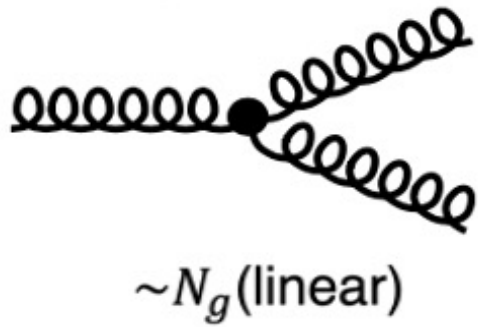
Understand Nucleon Structure

Splitting

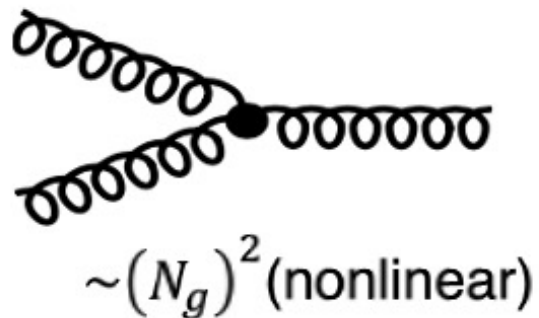


Understand Nucleon Structure

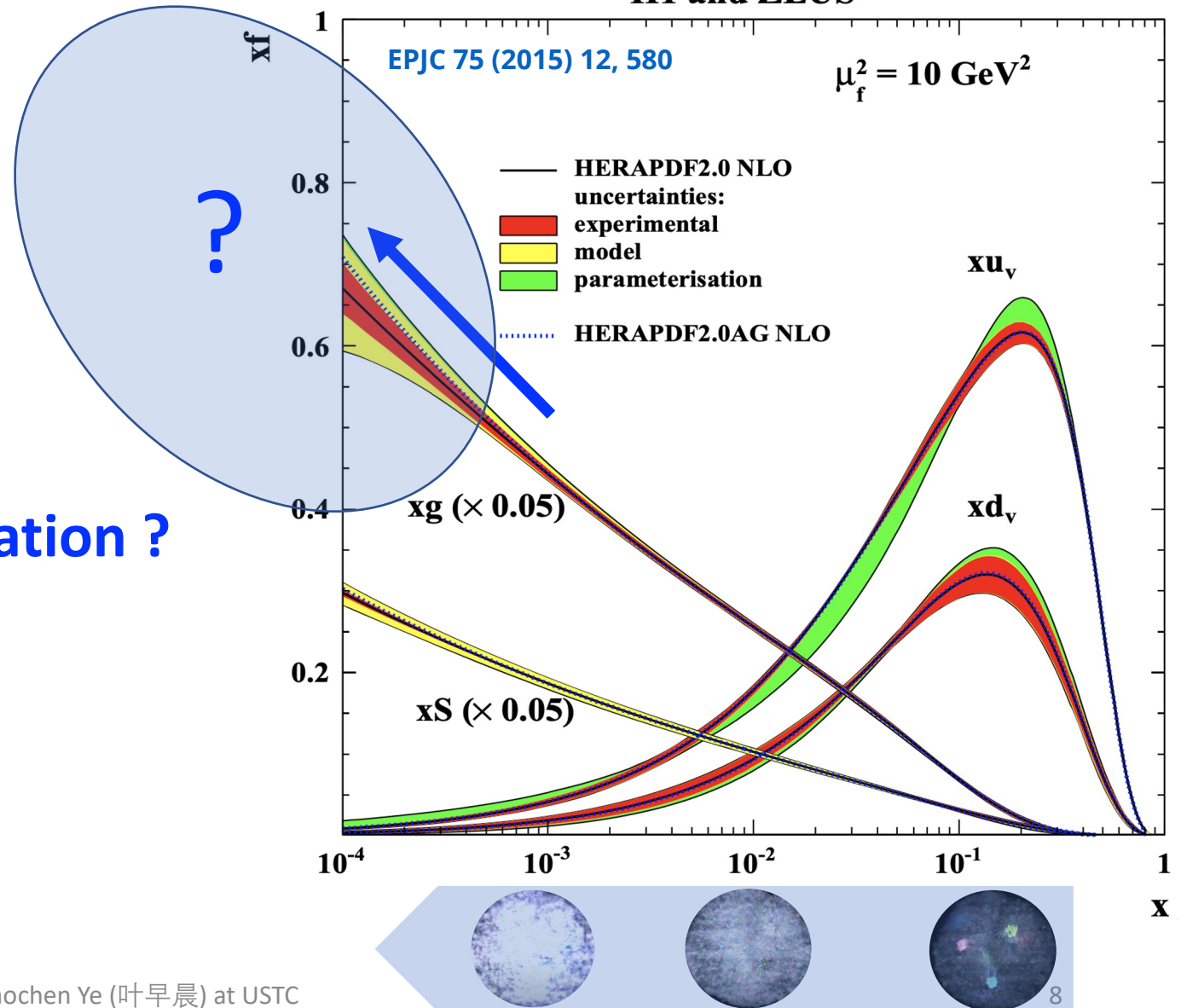
Splitting



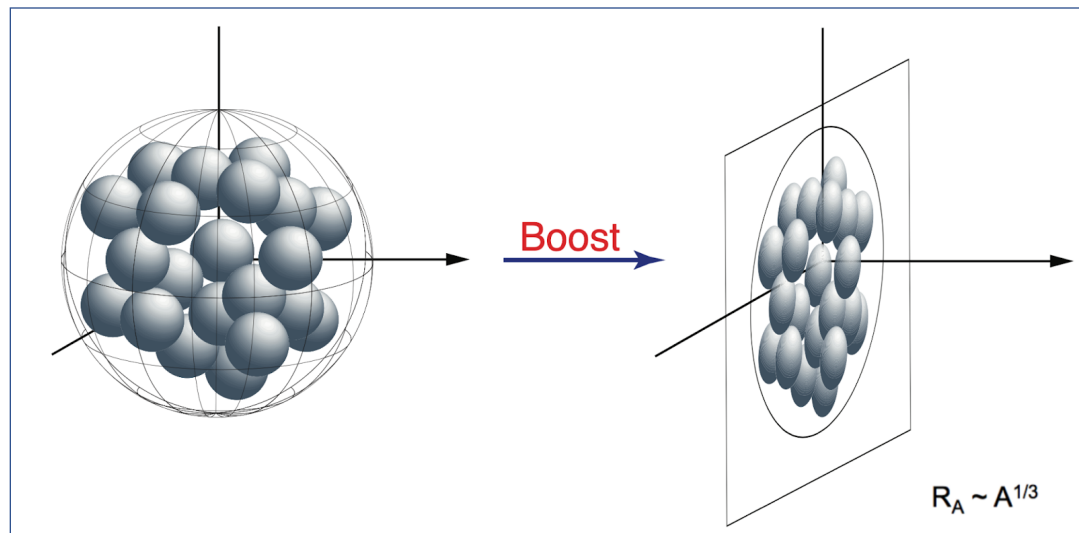
Recombination



Gluon Saturation ?



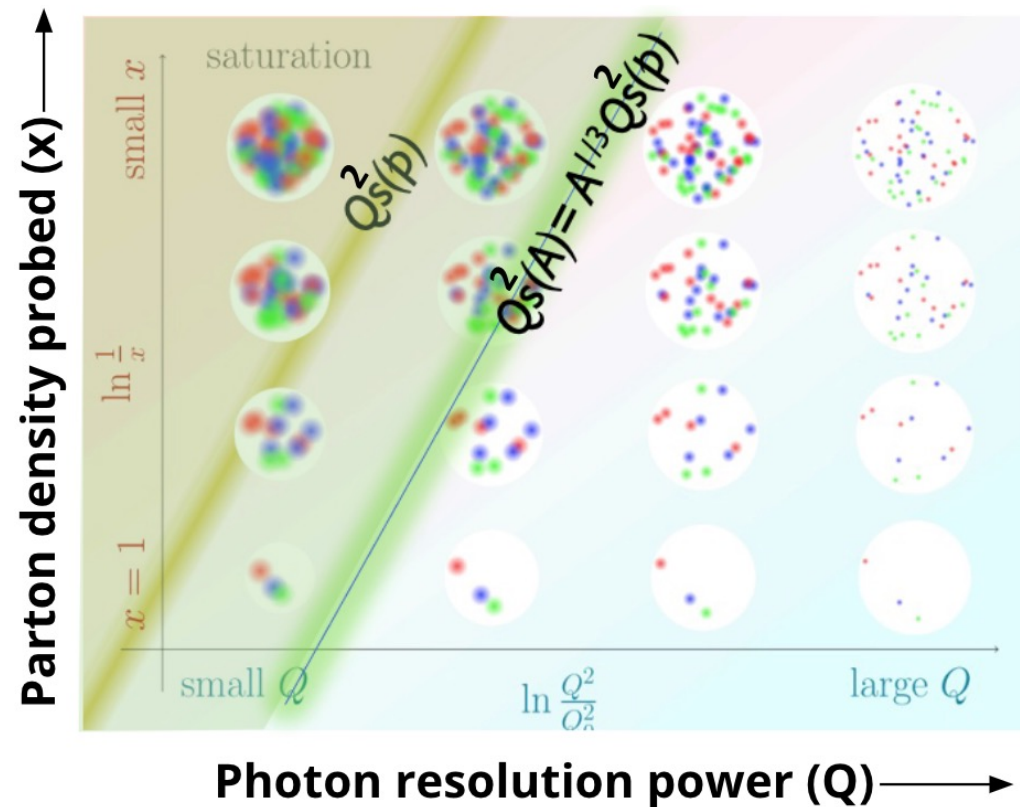
Advantages of Gluon Saturation Search in Nucleus



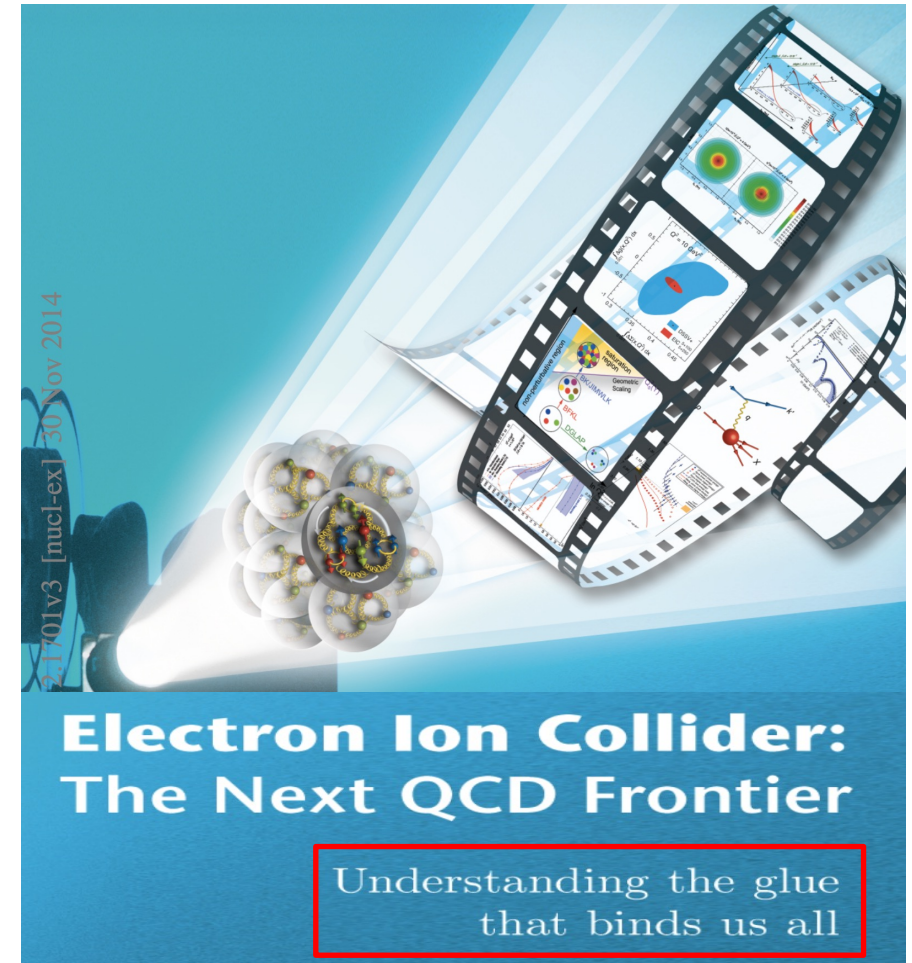
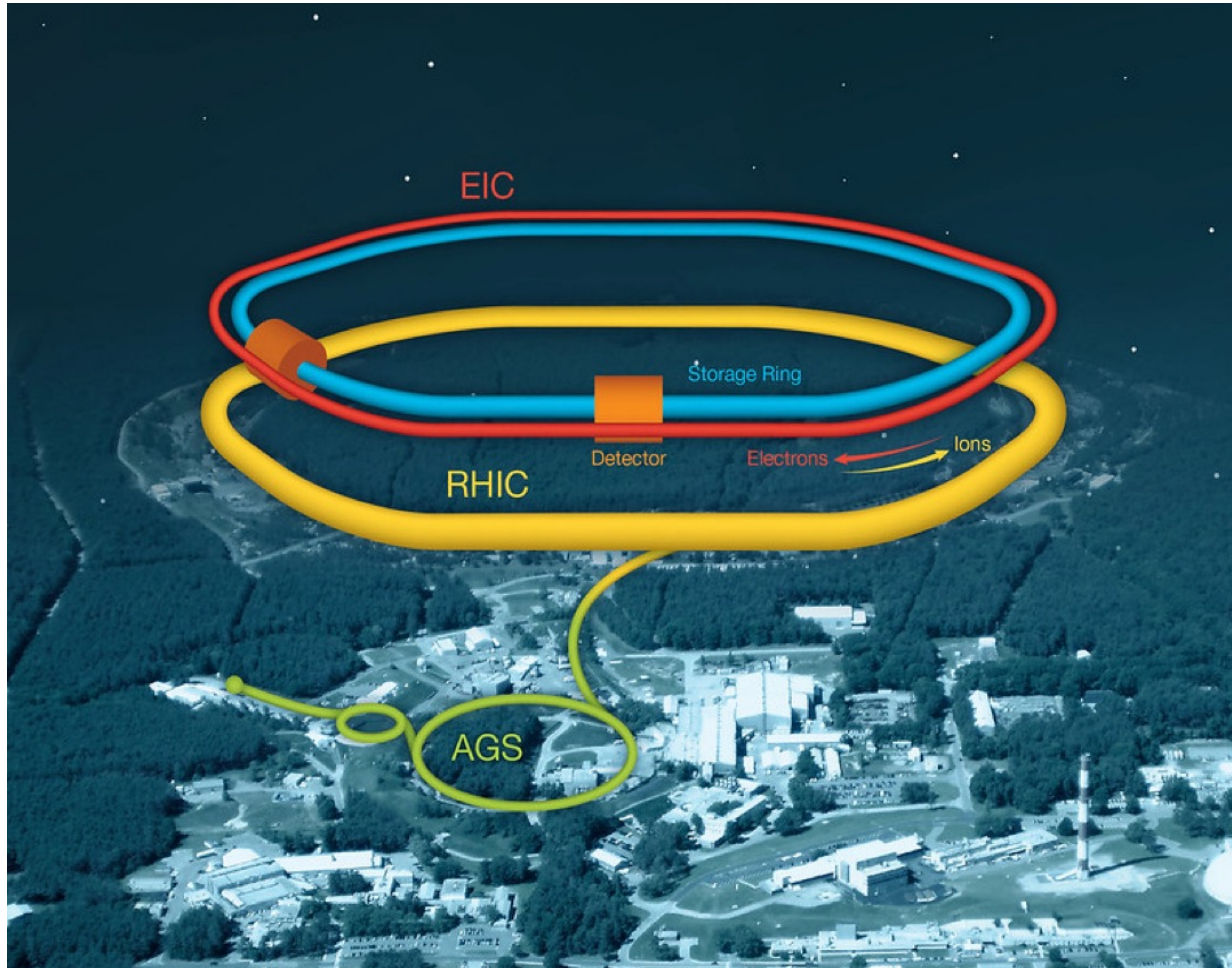
Gluons is **enhanced** by a factor of $A^{1/3}$ in **nucleus** compared to what in free nucleon

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

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



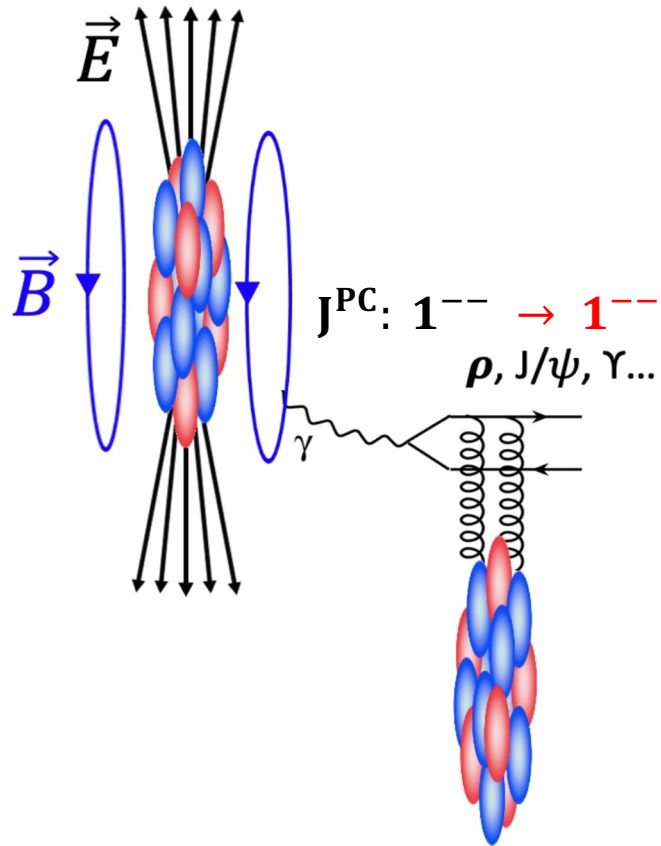
Key Goal of Future Electron Ion Collider



Probe Nuclear Gluonic Structure via VMs in UPCs

Vector meson photoproduction directly **probes gluonic structure** of nucleus/nucleon

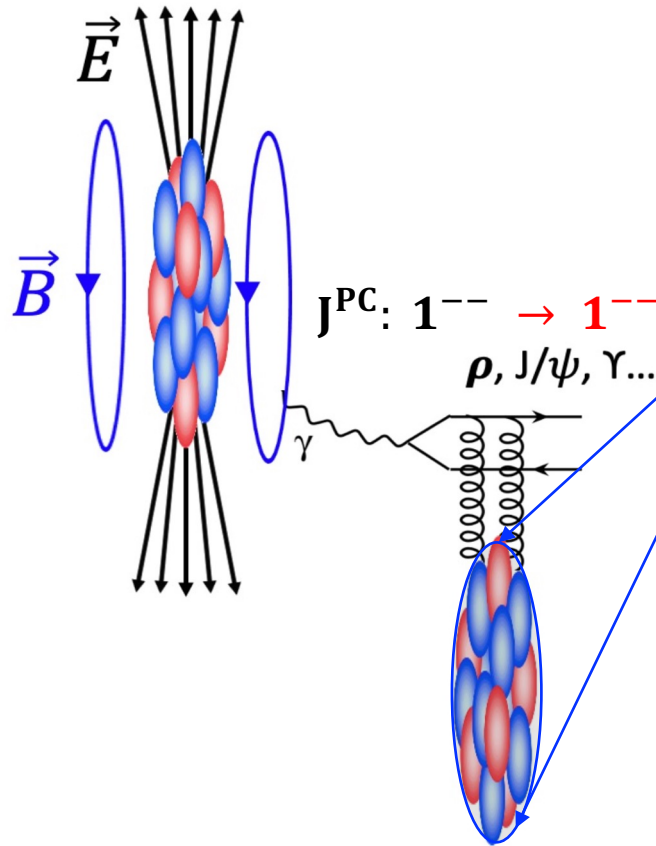
At LO in pQCD, **cross section** $\propto$ photon flux $\otimes$ **$[xG(x)]^2$**



Probe Nuclear Gluonic Structure via VMs in UPCs

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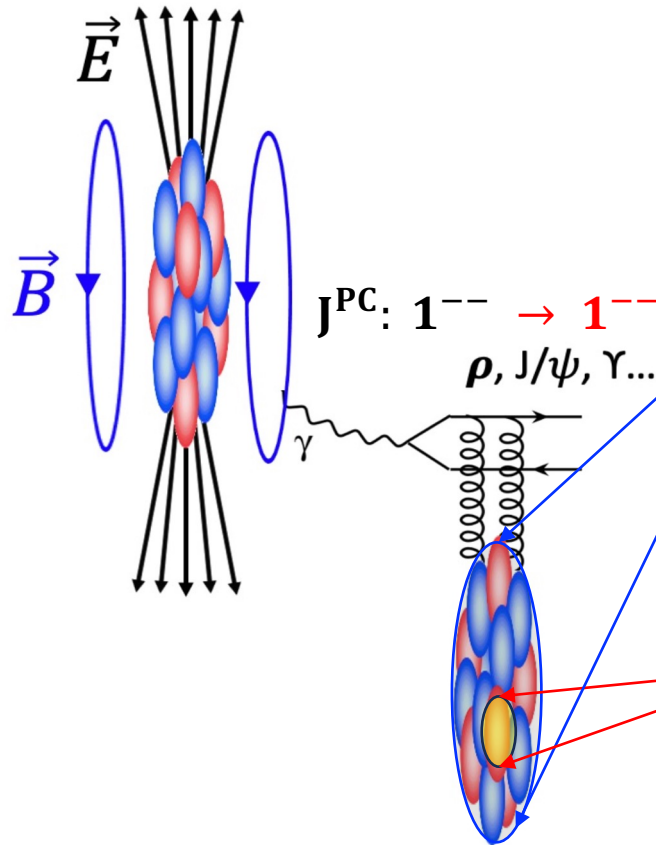
Coherent production:

- Photon fluctuated dipole couples **coherently to entire nucleus**
- **Target** nucleus remains **intact** at ground state
- VM $\langle p_T \rangle \sim 10^1$ MeV
- Probing the **average gluon density**

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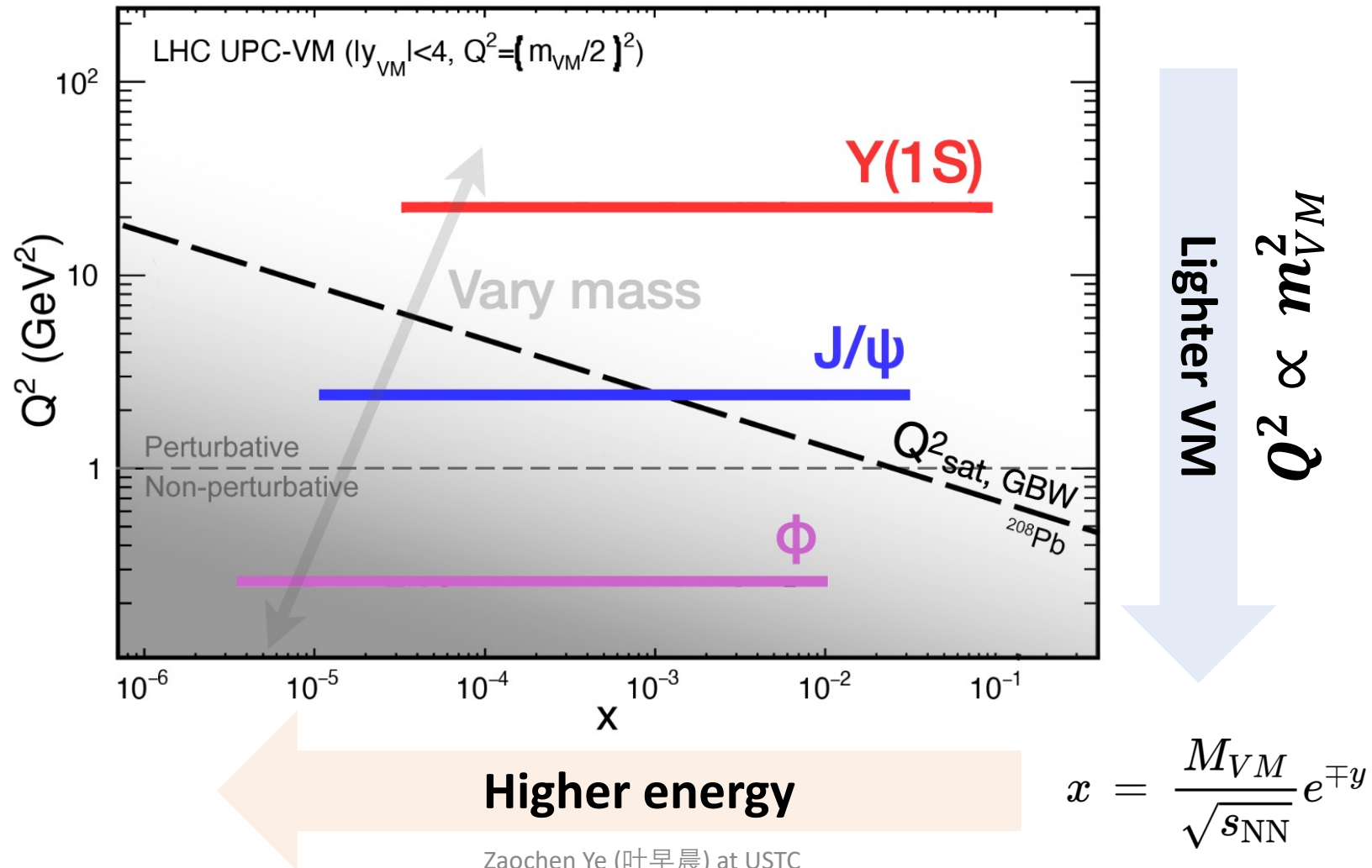
Incoherent production:

- Photon fluctuated dipole couples to **local gluonic hotspots**
- **Target** nucleus get excited, or **breaks (mostly)**
- VM $\langle p_T \rangle \sim 10^2$ - 10^3 MeV
- Probing the **local gluon density and fluctuations**

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

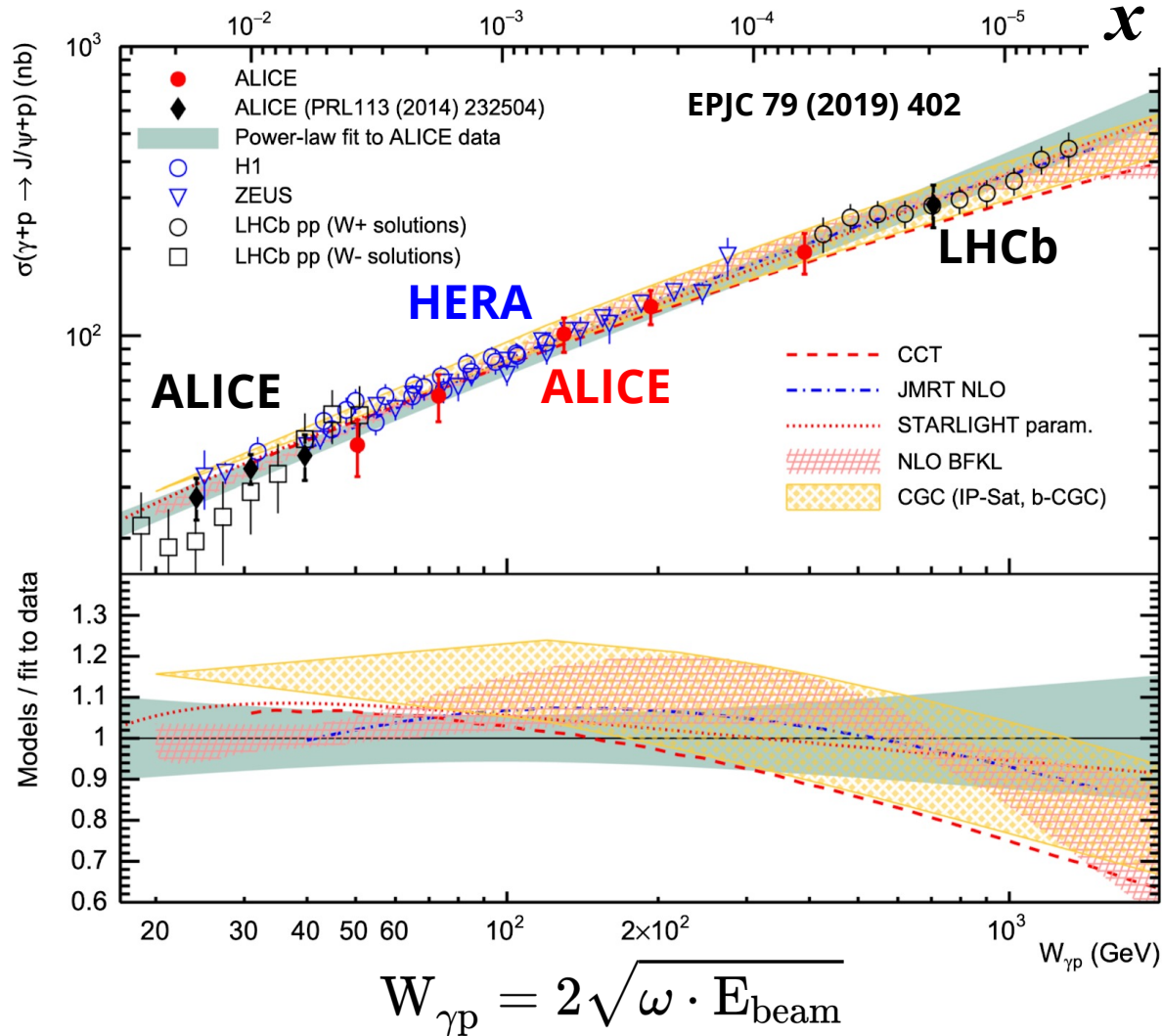
Probe Nuclear Gluonic Structure via VMs in UPCs

Explore in 2 dimensions: Q^2 vs. x



Coherent J/ψ Photoproduction via $\gamma + p$ (Free Nucleon)

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

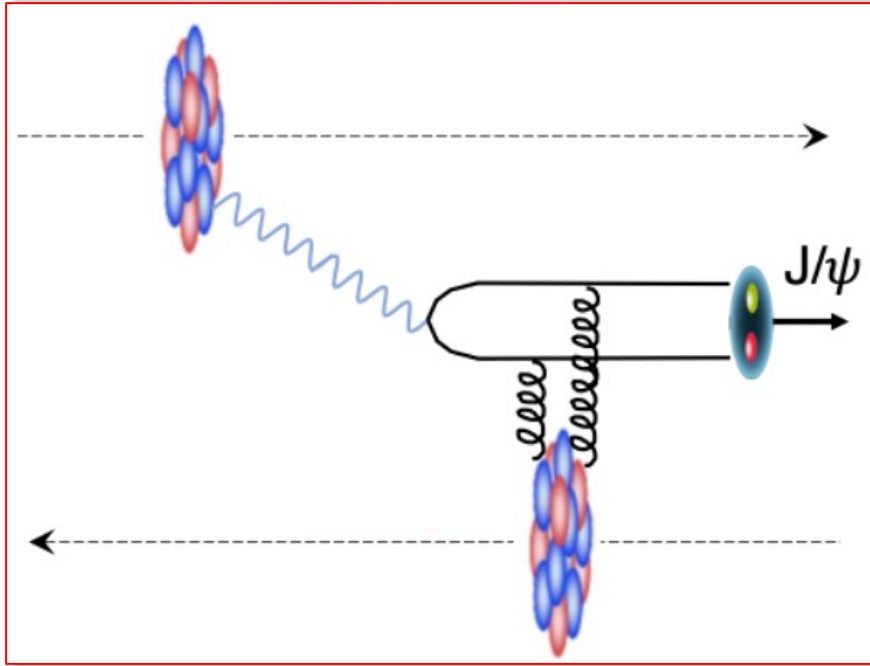


- Data from **LHC** and **HERA** follow a **common** power-law trend, consistent with the expectation from the rapidly increasing gluon density in a proton

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

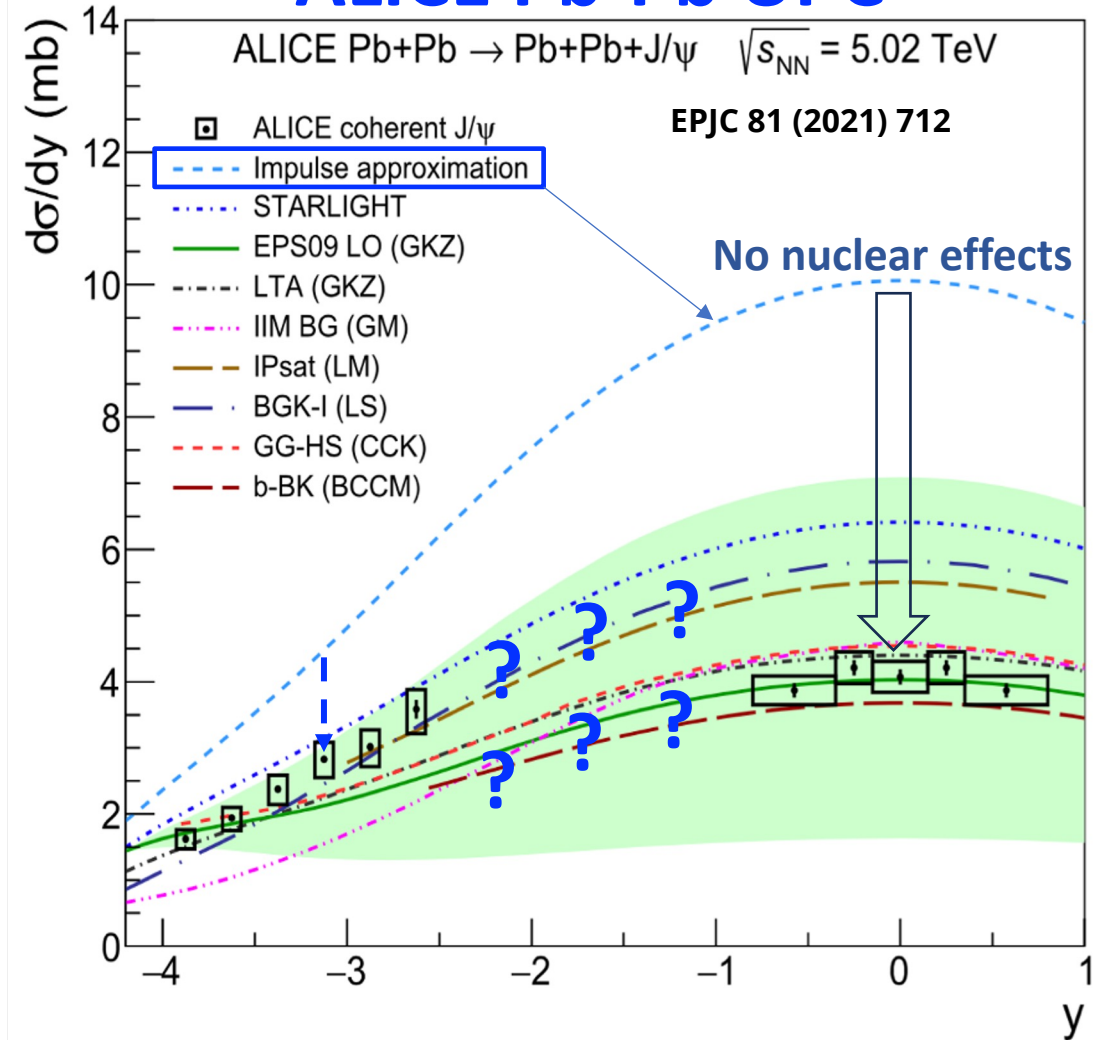
Coherent J/ψ Photoproduction in A-A UPCs

$$\gamma + \text{Pb} \rightarrow \text{J}/\psi + \text{Pb}$$



- **Strong suppression**, but the rapidity distribution was **a puzzle**

ALICE Pb-Pb UPC

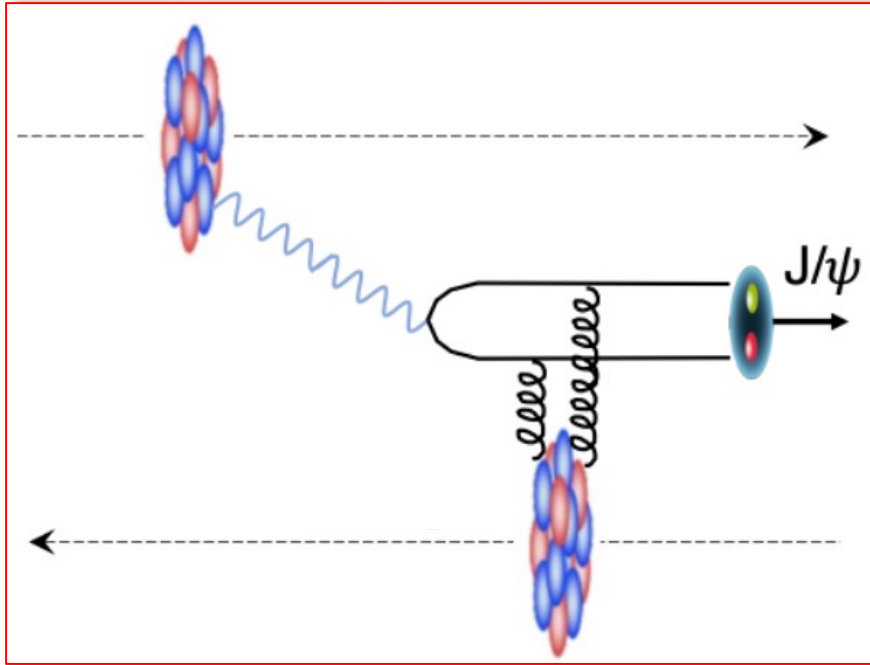


Coherent J/ψ Photoproduction in A-A UPCs

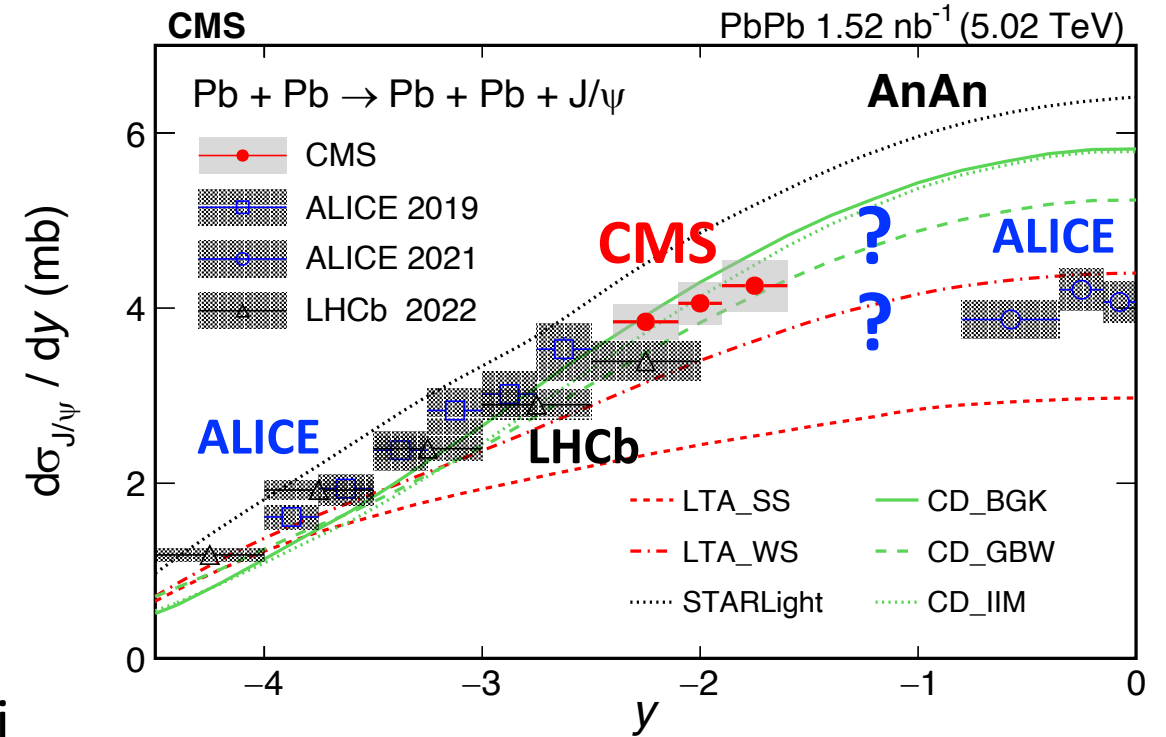
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CMS: PRL 131, 262301 (2023)

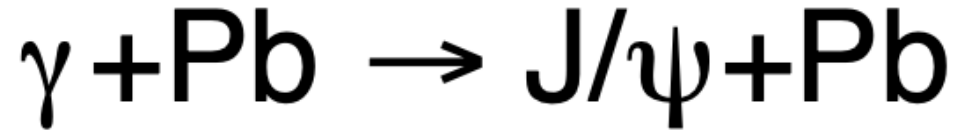
LHCb: JHEP 06 146 (2023)



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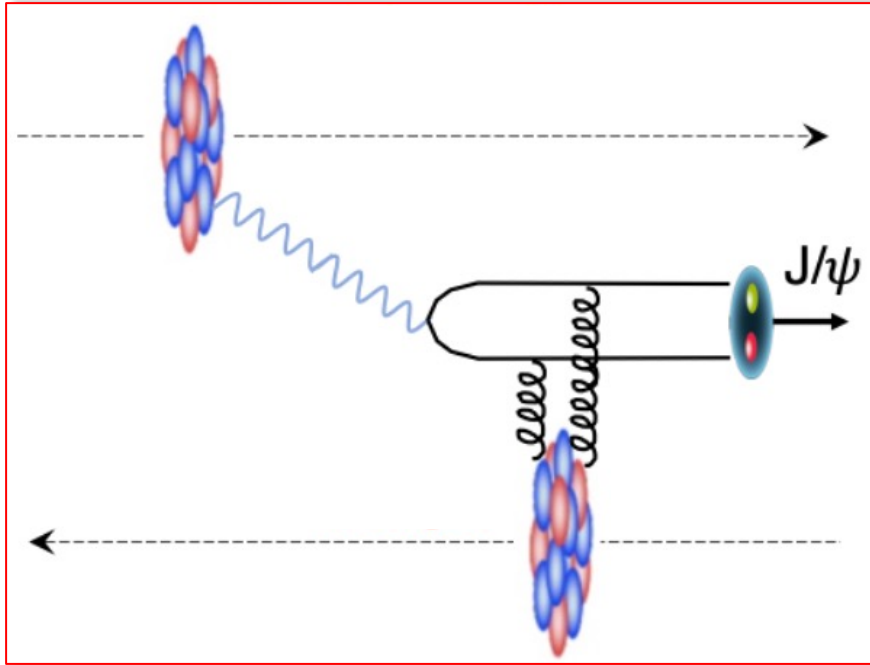


Coherent J/ψ Photoproduction in A-A UPCs

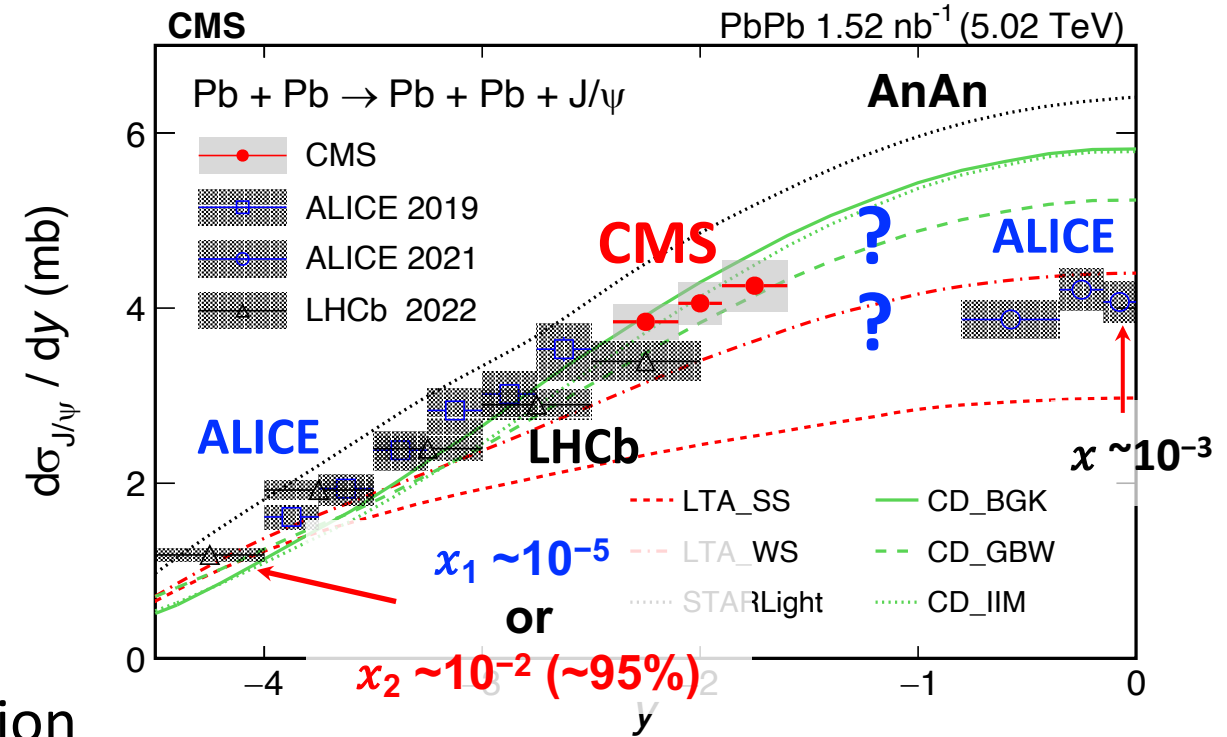


CMS: PRL 131, 262301 (2023)

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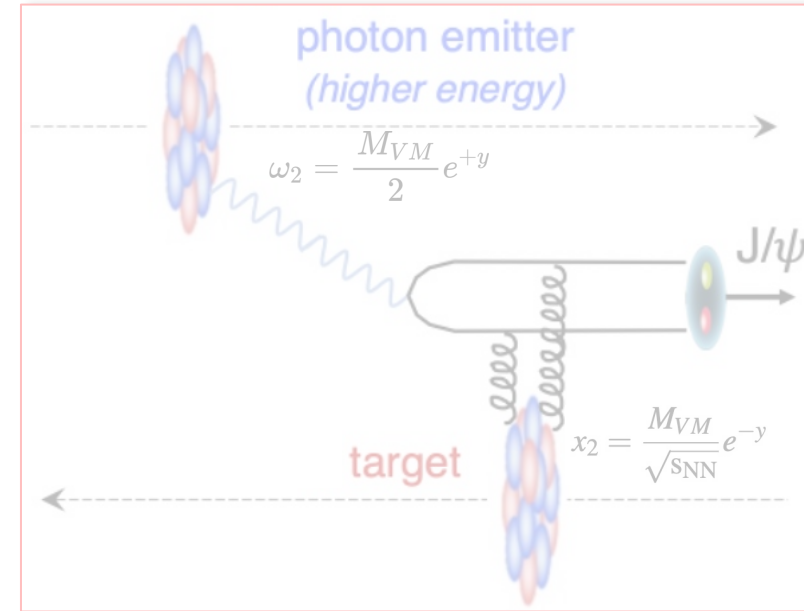
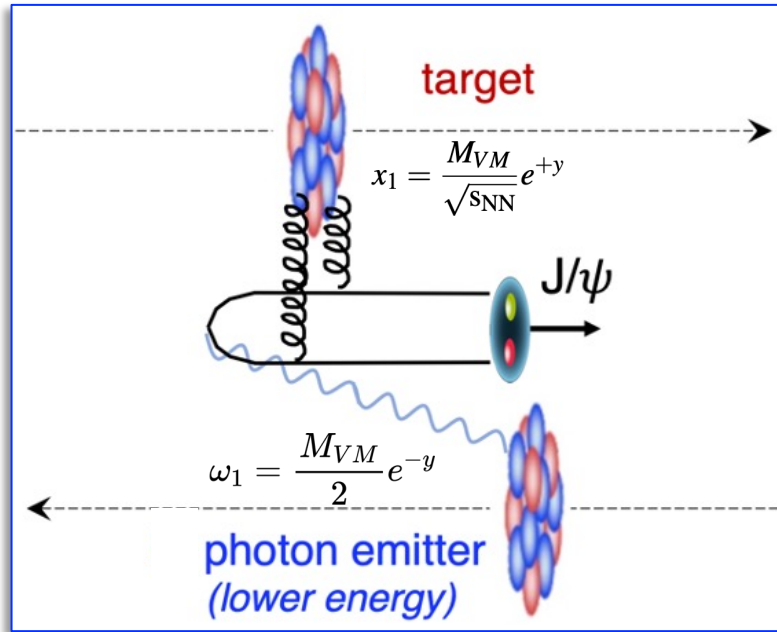


- **Strong suppression**, but the rapidity distribution was **a puzzle**



$$x = \frac{M_{V\psi}}{\sqrt{s_{NN}}} e^{\mp y} \quad \text{low-energy photons dominant}$$

Two-Way Ambiguity in A-A UPC

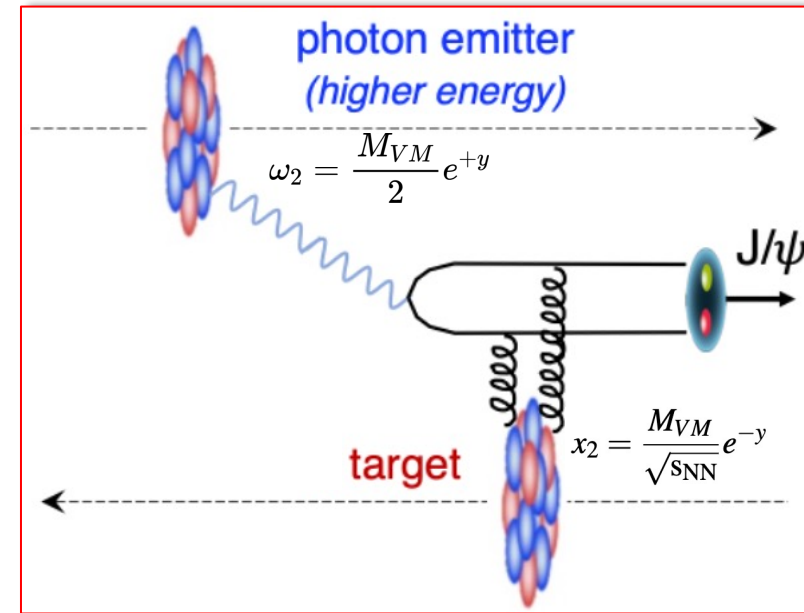
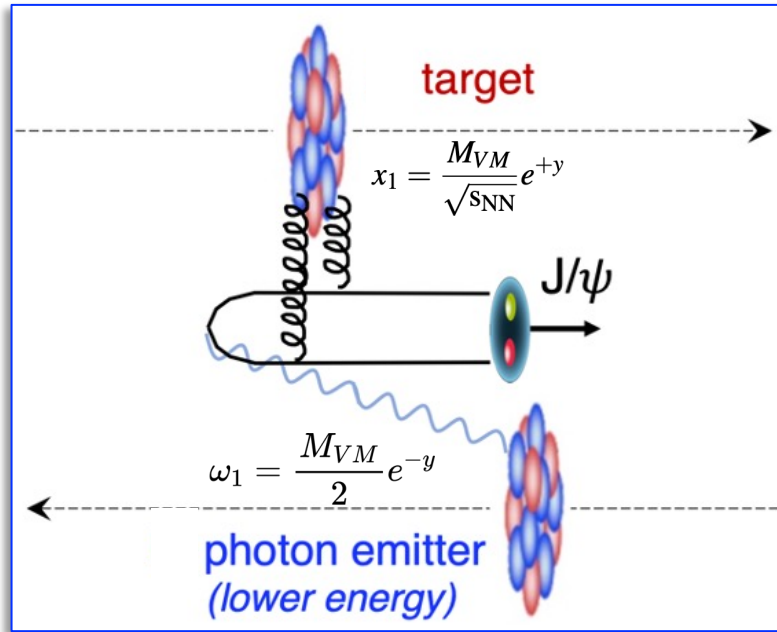


$$\frac{d\sigma_{AA \rightarrow AA' J/\psi}}{dy} = N_{\gamma/A}(\omega_1) \cdot \sigma_{\gamma A \rightarrow J/\psi A'}(\omega_1) + N_{\gamma/A}(\omega_2) \cdot \sigma_{\gamma A \rightarrow J/\psi A'}(\omega_2)$$

what we measure

- This ambiguity exists for both **coherent** and **incoherent** processes

Two-Way Ambiguity in A-A UPC



Smaller-x

$$\frac{d\sigma_{AA \rightarrow AA' J/\psi}}{dy} = N_{\gamma/A}(\omega_1) \cdot \sigma_{\gamma A \rightarrow J/\psi A'}(\omega_1) + N_{\gamma/A}(\omega_2) \cdot \sigma_{\gamma A \rightarrow J/\psi A'}(\omega_2)$$

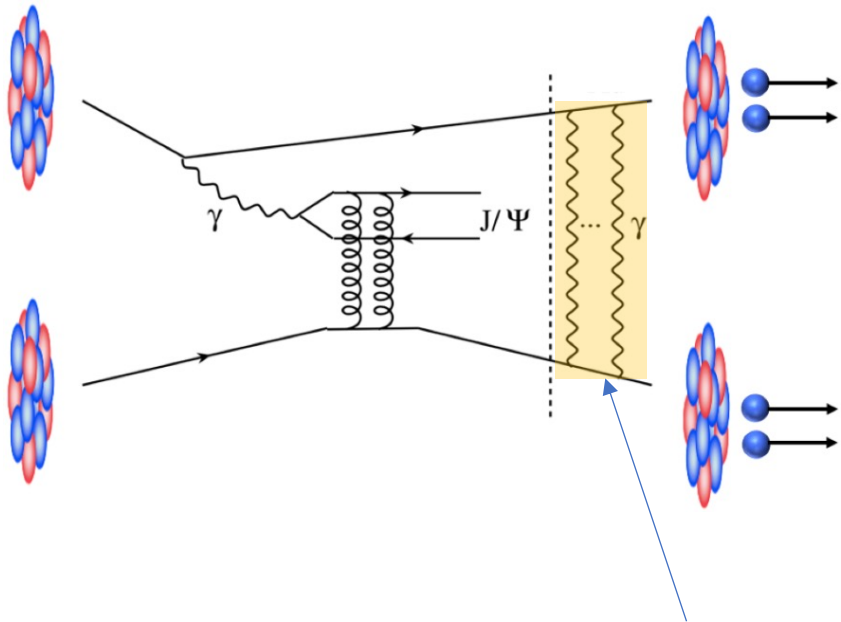
what we measure

- This ambiguity exists for both **coherent** and **incoherent** processes

Method to Solve Two-Way Ambiguity in A-A UPC

V. Guzey, M. Strikman, M. Zhalov, EPJC (2014) 72 2942

- Control/select the impact parameter of UPCs via forward emitted neutrons



- Analogous to centrality in hadronic collisions:

- $b_{XnXn} < b_{0nXn} < b_{0n0n}$ in UPC

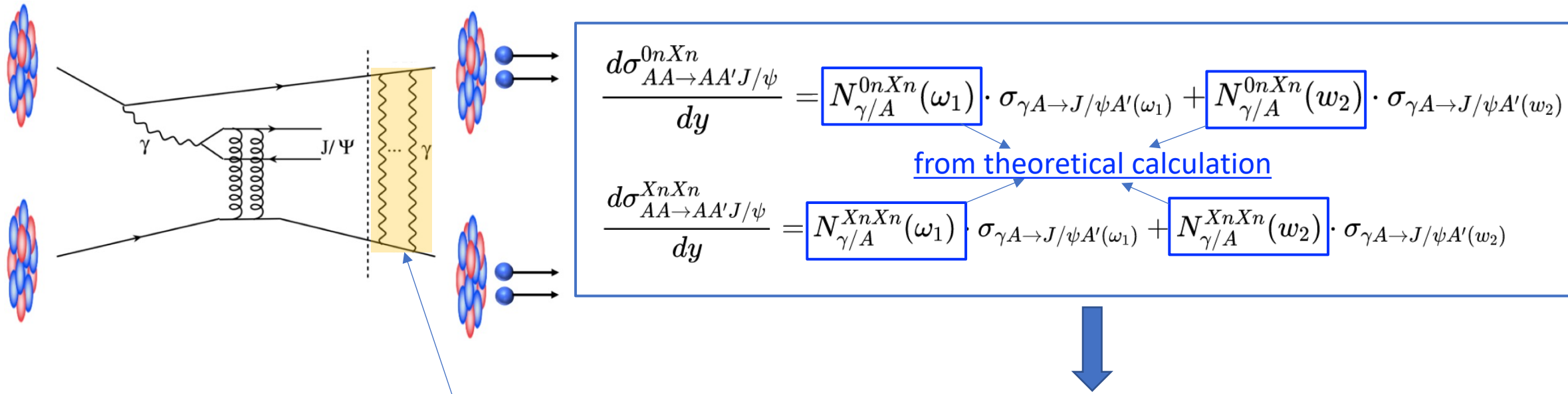
Neutron emission via EMD with additional photon exchange:

- Soft photons (energy ~ 10 s MeV)
- Independent of interested physics process
- Large cross section ~ 200 b (single EMD)
- The smaller $b \rightarrow$ the more neutrons

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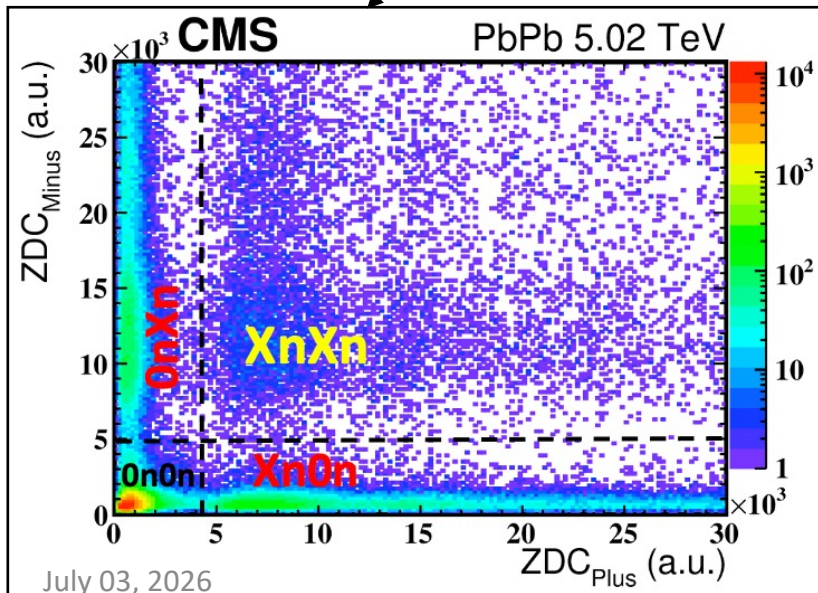
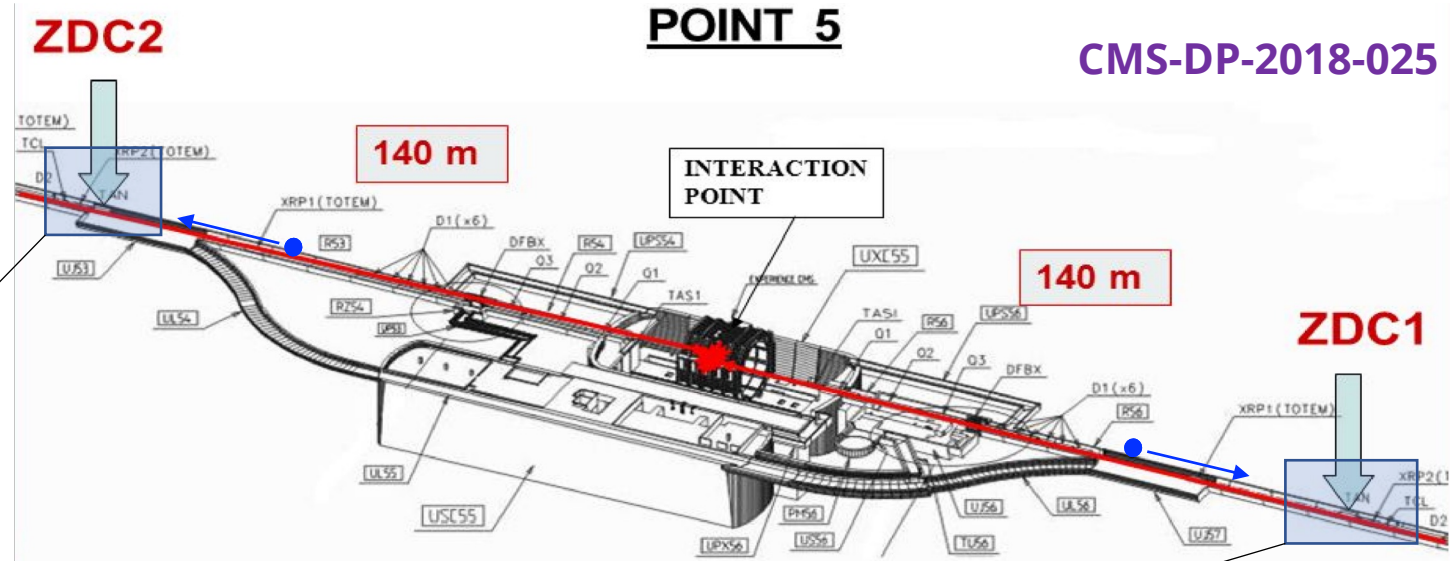
$$\sigma_{\gamma A \rightarrow J/\psi A'}(\omega_1)$$

Larger- x

$$\sigma_{\gamma A \rightarrow J/\psi A'}(\omega_2)$$

Smaller- x

Neutron Tag with Zero Degree Calorimeter



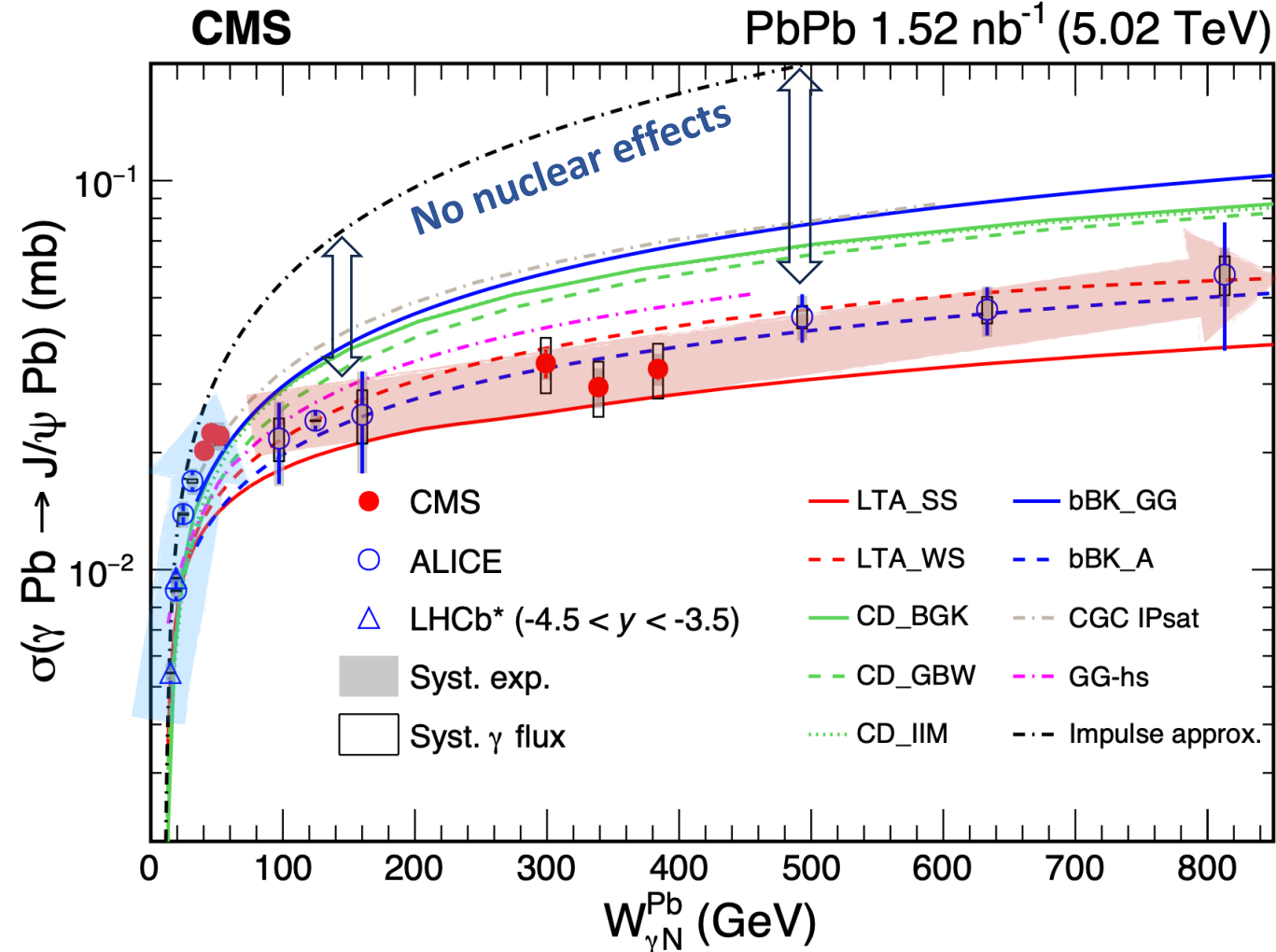
Tag events with **neutrons**:

- 0n0n, 0nXn, XnXn ($X: \geq 1$)

Coherent J/ψ Cross Section of Per γ+Pb

CMS: PRL 131, 262301 (2023)

ALICE: JHEP 10 119 (2023)



Data show:

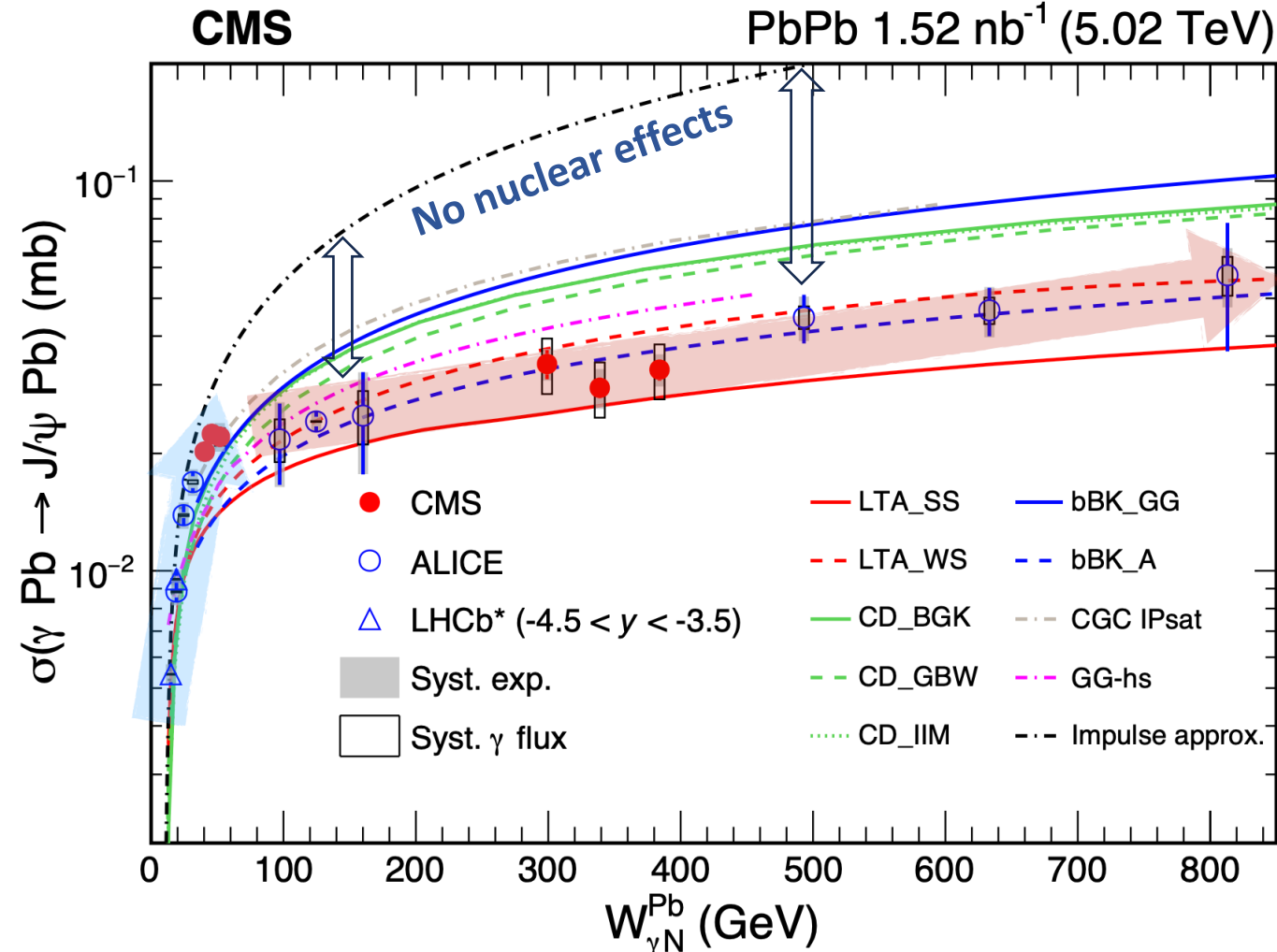
- **Rapid increase** at $W < 40$ GeV
- Turn into a **nearly flat** (slower rising) trend for $W > 40$ GeV

Strongly saturated cross sections

Coherent J/ψ Cross Section of Per γ+Pb

CMS: PRL 131, 262301 (2023)

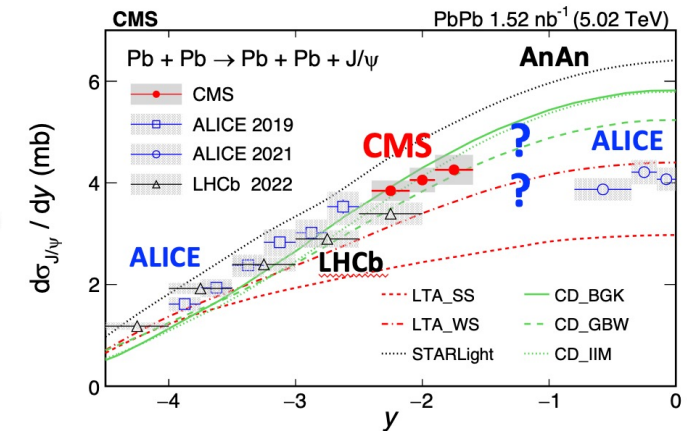
ALICE: JHEP 10 119 (2023)



Data show:

- Rapid increase at $W < 40 \text{ GeV}$
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- **y distribution puzzle is solved by studying the W dependence**
- Strong suppression

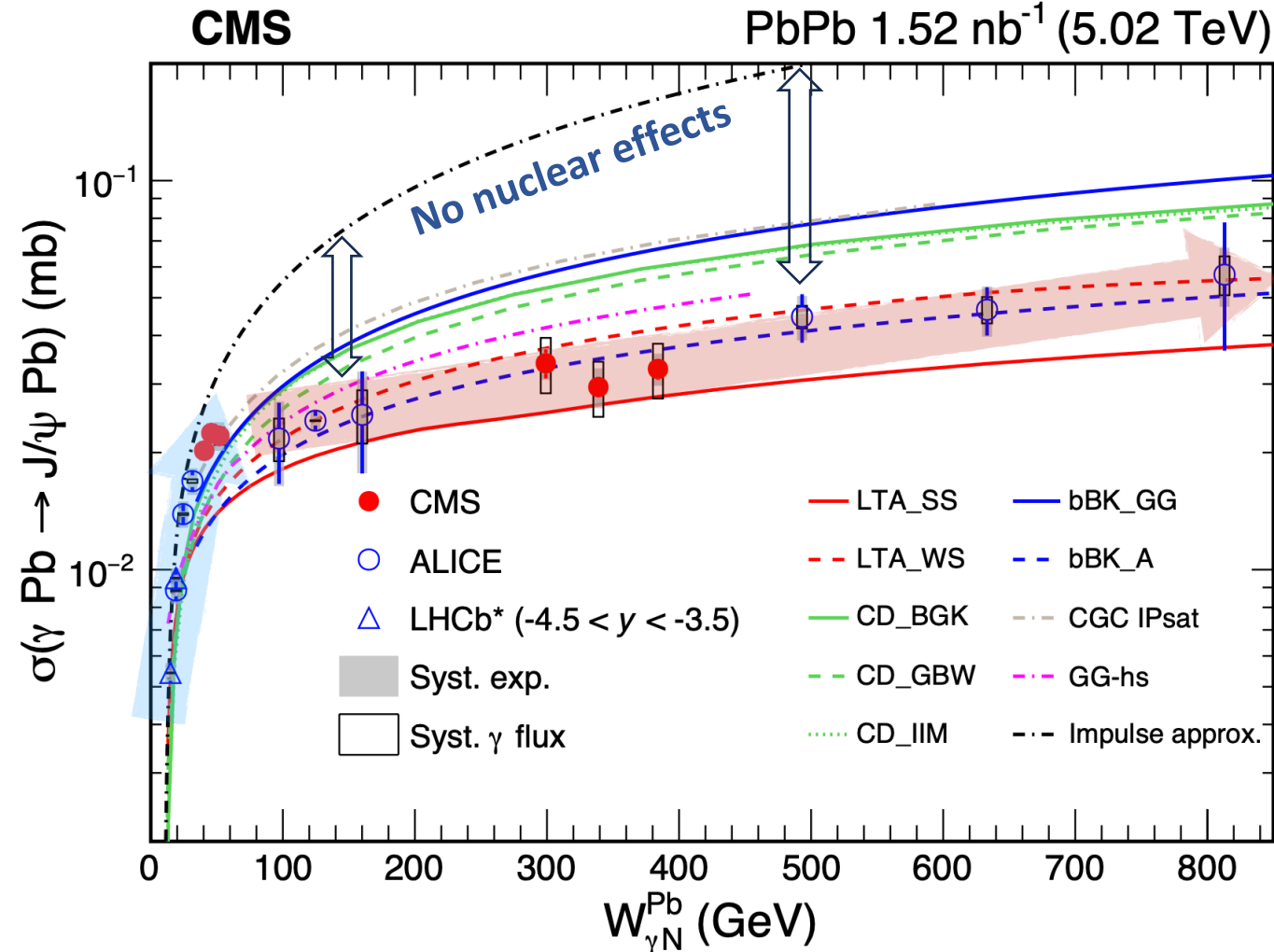
Strongly saturated cross sections



Coherent J/ψ Cross Section of Per γ+Pb

CMS: PRL 131, 262301 (2023)

ALICE: JHEP 10 119 (2023)

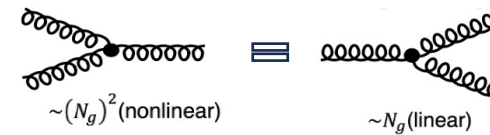


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Strongly saturated cross sections

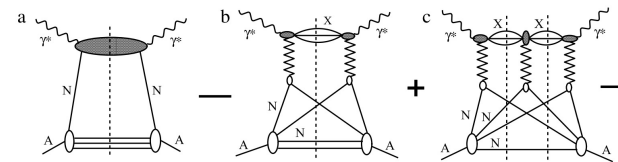
Gluon Saturation?



Black Disk Limit?

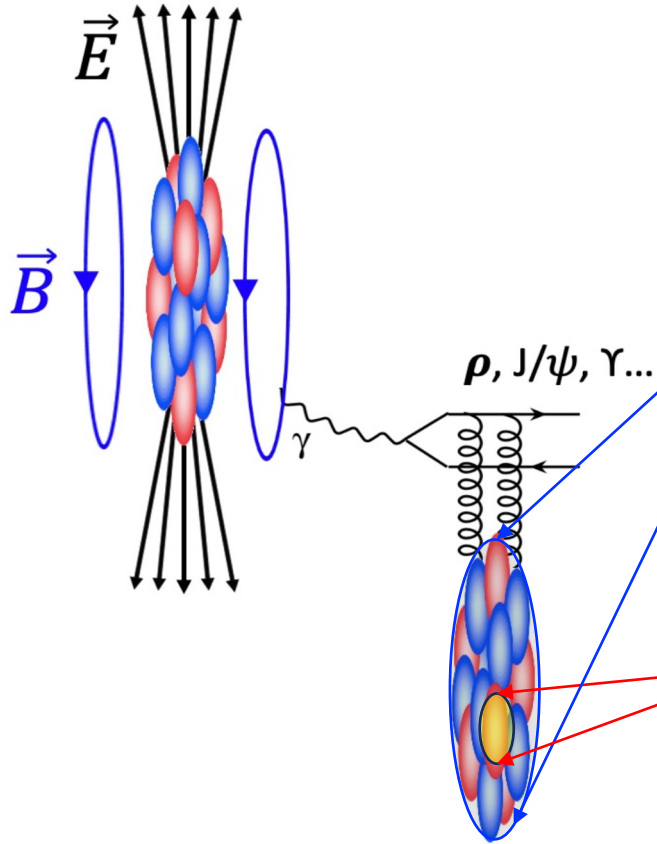
$$\hat{\sigma}_{\text{PQCD}}^{\text{inel}} \leq \hat{\sigma}_{\text{black}} = \pi R_{\text{target}}^2$$

Nuclear shadowing?



What's the underlying physics?

How About Incoherent J/ ψ Photoproduction?



Coherent production:

- Photon fluctuated dipole couples **coherently to entire nucleus**
- **Target** nucleus remains **intact**
- VM $\langle p_T \rangle \sim 10^1$ MeV
- Probing the **averaged gluon density**

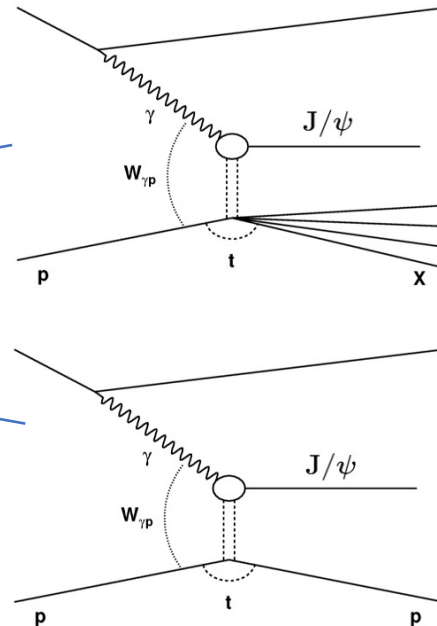
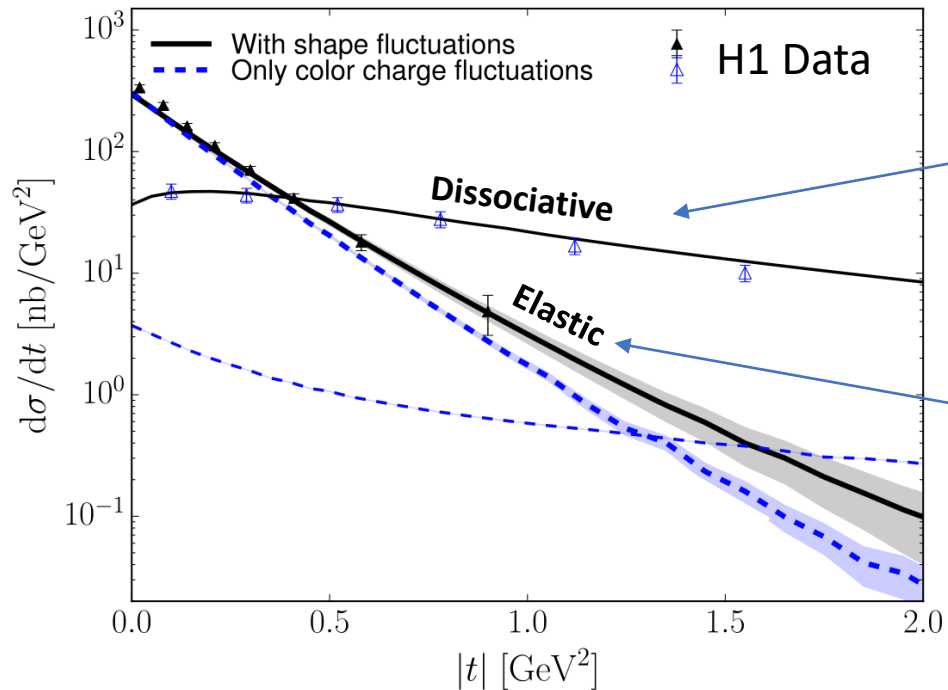
Incoherent production:

- Photon fluctuated dipole couples to **individual nucleon or sub-nucleon**
- **Target** nucleus usually **breaks**
- VM $\langle p_T \rangle \sim 10^2$ - 10^3 MeV
- Probing the **local gluon density** and **fluctuations**

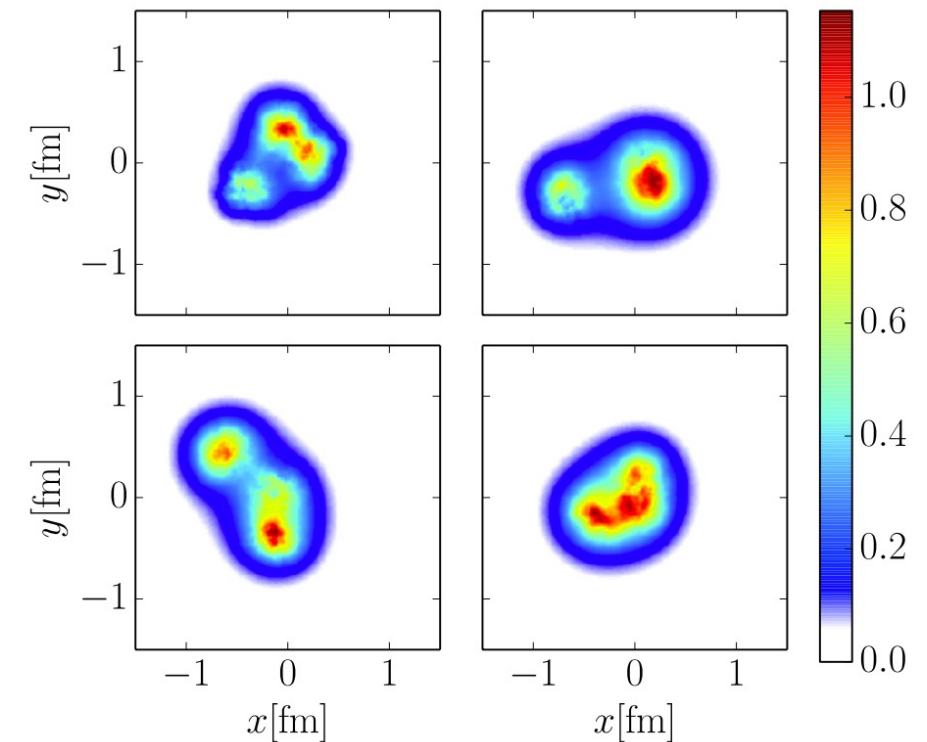
Fluctuating Gluons Probed via $\gamma+p$

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

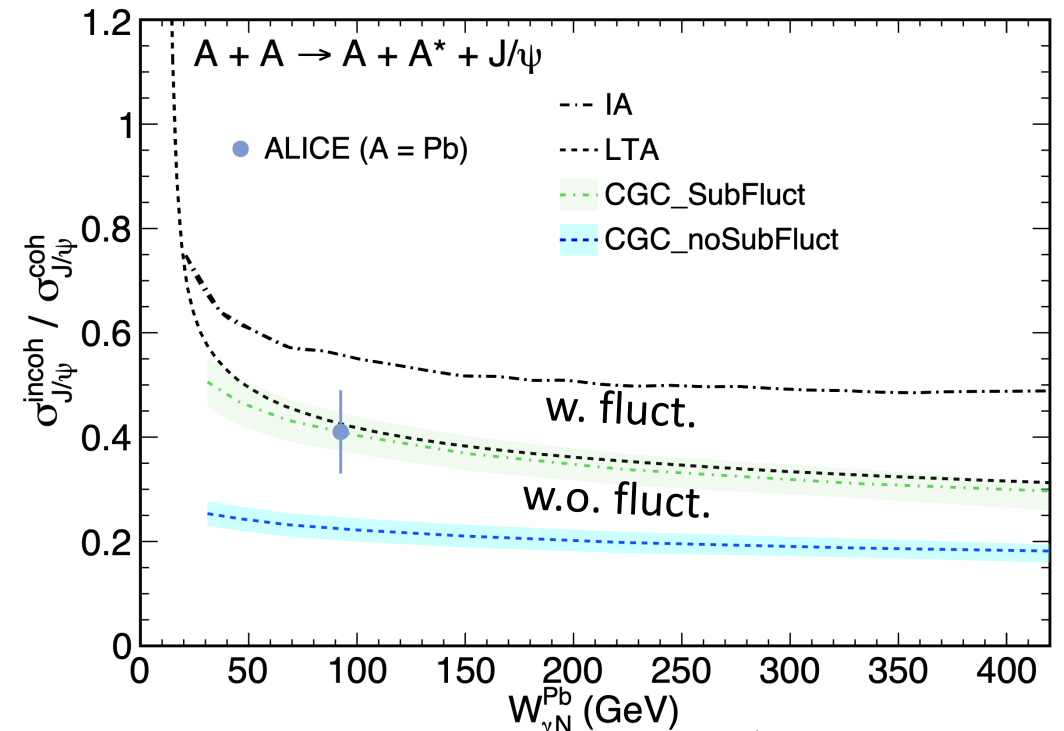
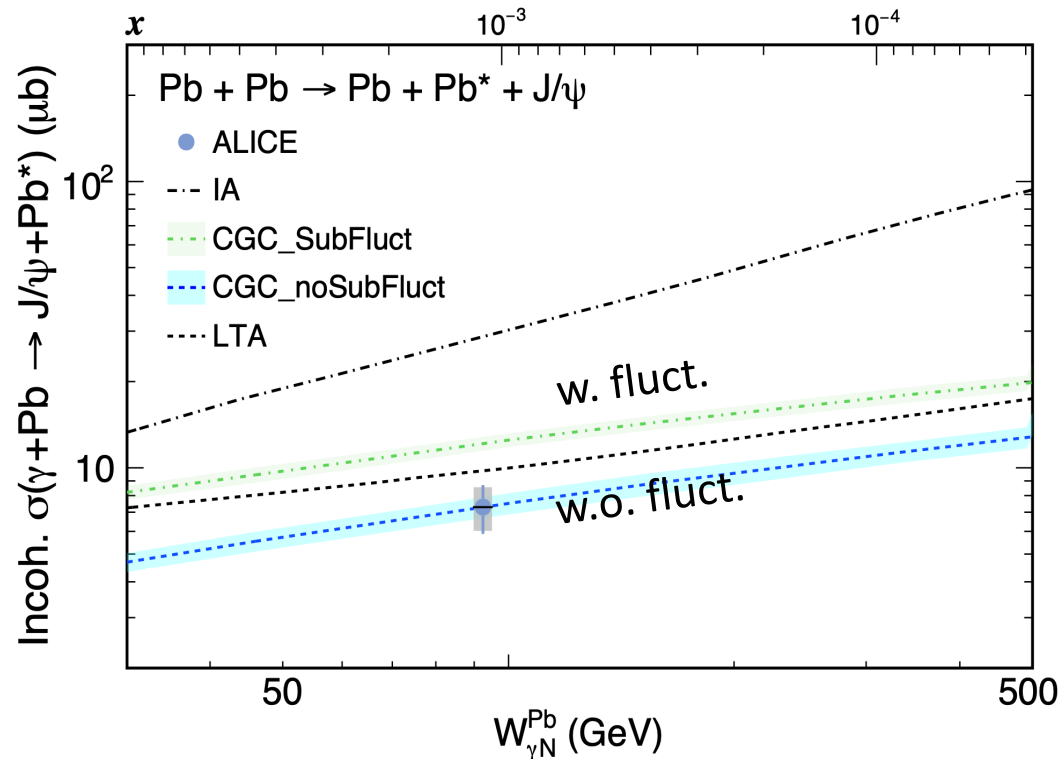


Rep. Prog. Phys. **83** (2020) 082201



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

Fluctuating Gluons and Energy Dependence

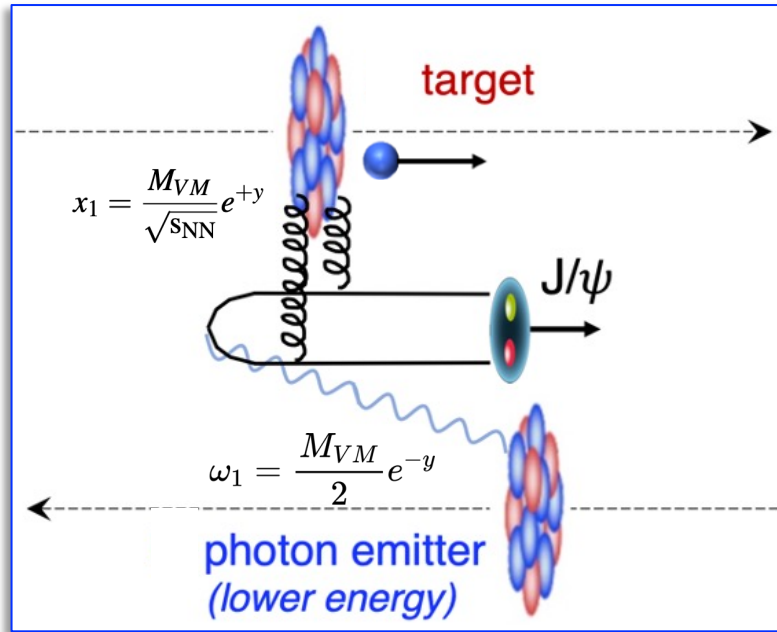


Increasing W (decreasing x)

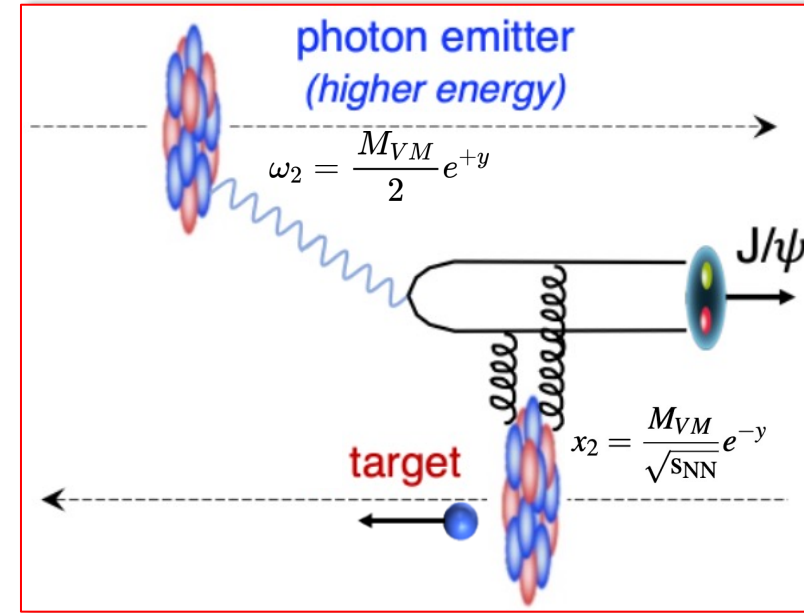
How the fluctuating gluons evolve, especially towards small- x limit?

- Would incoh. production vanish if black disk limit is reached?
- **Unfortunately, energy-dependent incoh. J/ψ has never been measured**

Solve “Two-Way Ambiguity” via Forward Neutrons



J/ψ-Xn (Same Direction)



J/ψ-Xn (Opposite Direction)

V. Guzey, M. Strikman, M. Zhalov, EPJC (2014) 72 2942

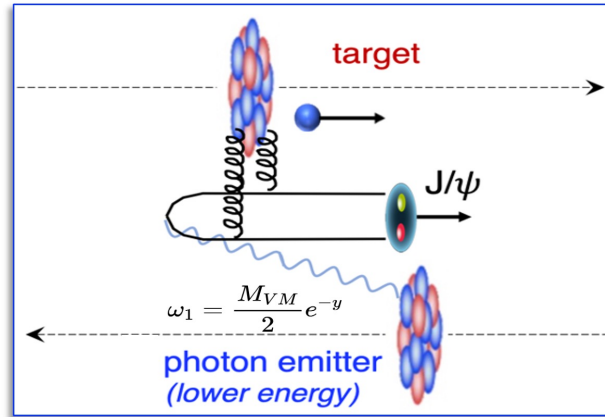
- **Incoh. J/ψ photoproduction itself has ~85% chance to induce the forward neutrons**
 - Detecting these neutrons will identify target nucleus
 - Help to solve the “Two-Way Ambiguity”

Example Signals (J/ψ-Xn Correlations)

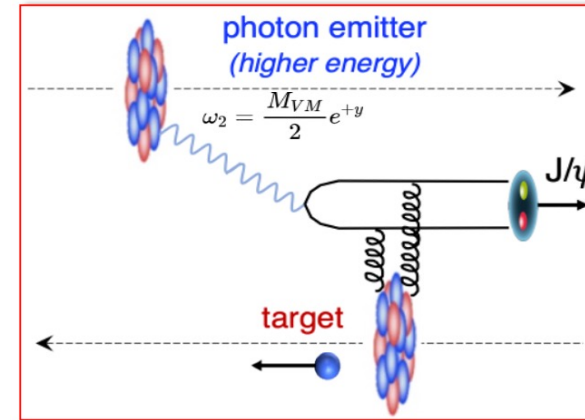
Low-W

$-\gamma$

J/ψ-Xn (Same Direction)

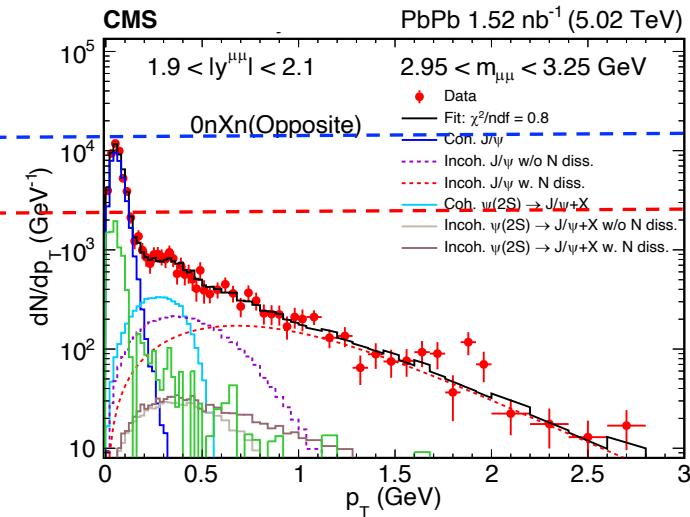
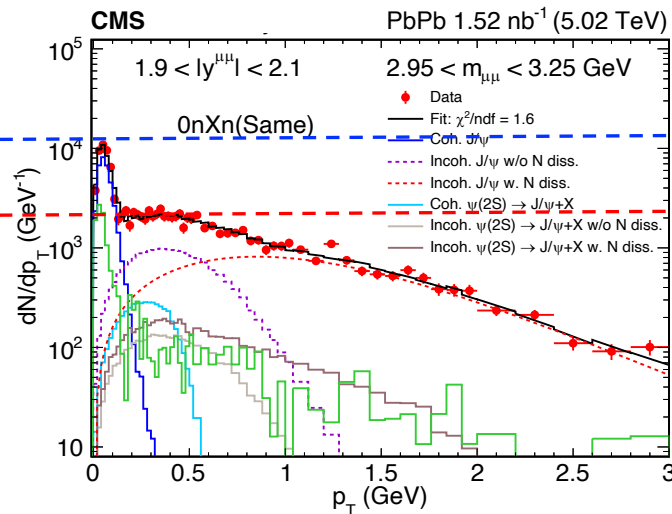


J/ψ-Xn (Opposite Direction)



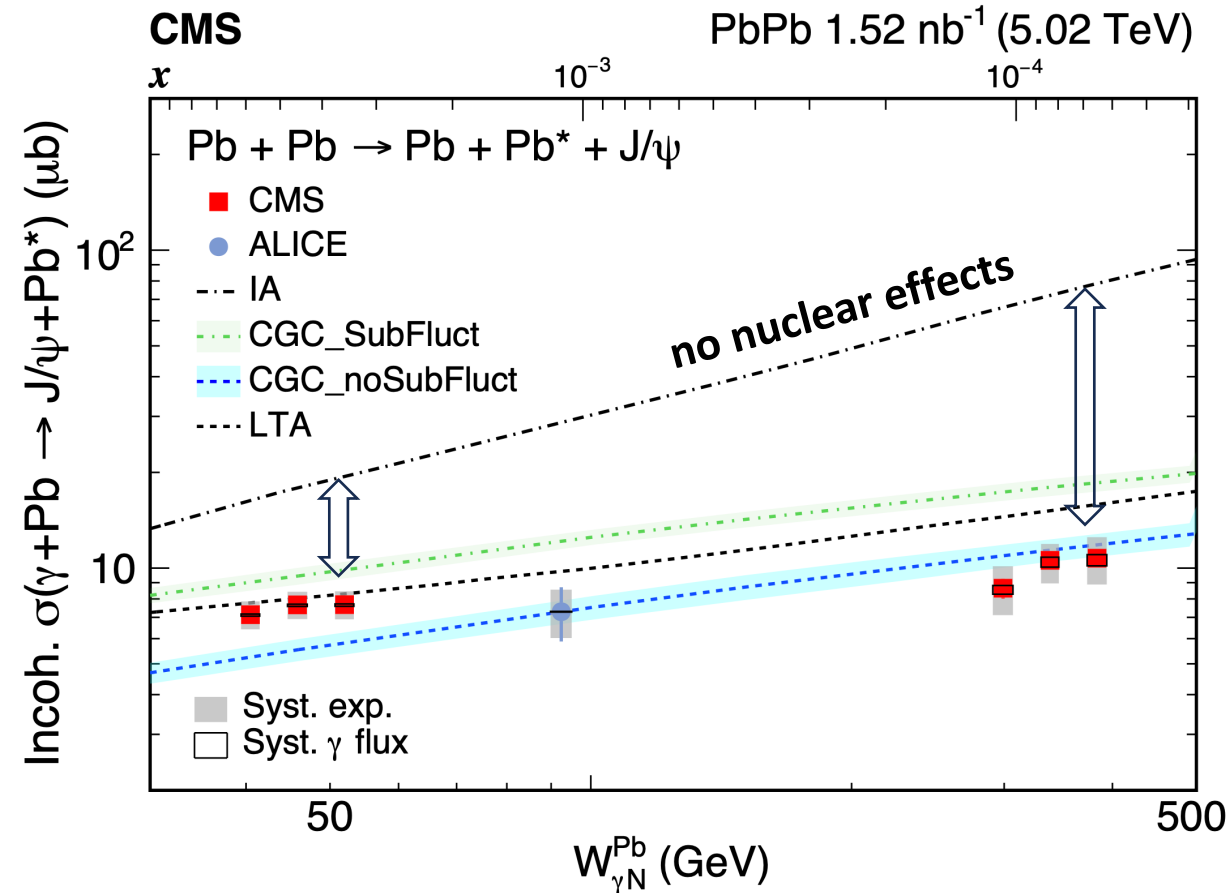
High-W

$+\gamma$



- **No correlation** between forward neutrons and coh. production
- **Strong correlation** between forward neutrons and incoh. production

Incoh. J/ψ Cross Section Per γ +Pb



- **First energy-dependent** measurement of incoh. J/ψ photoproduction
 - **Strongly saturated trend again**
- **Strong suppression** compared to Impulse Approximation (IA)

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

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

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

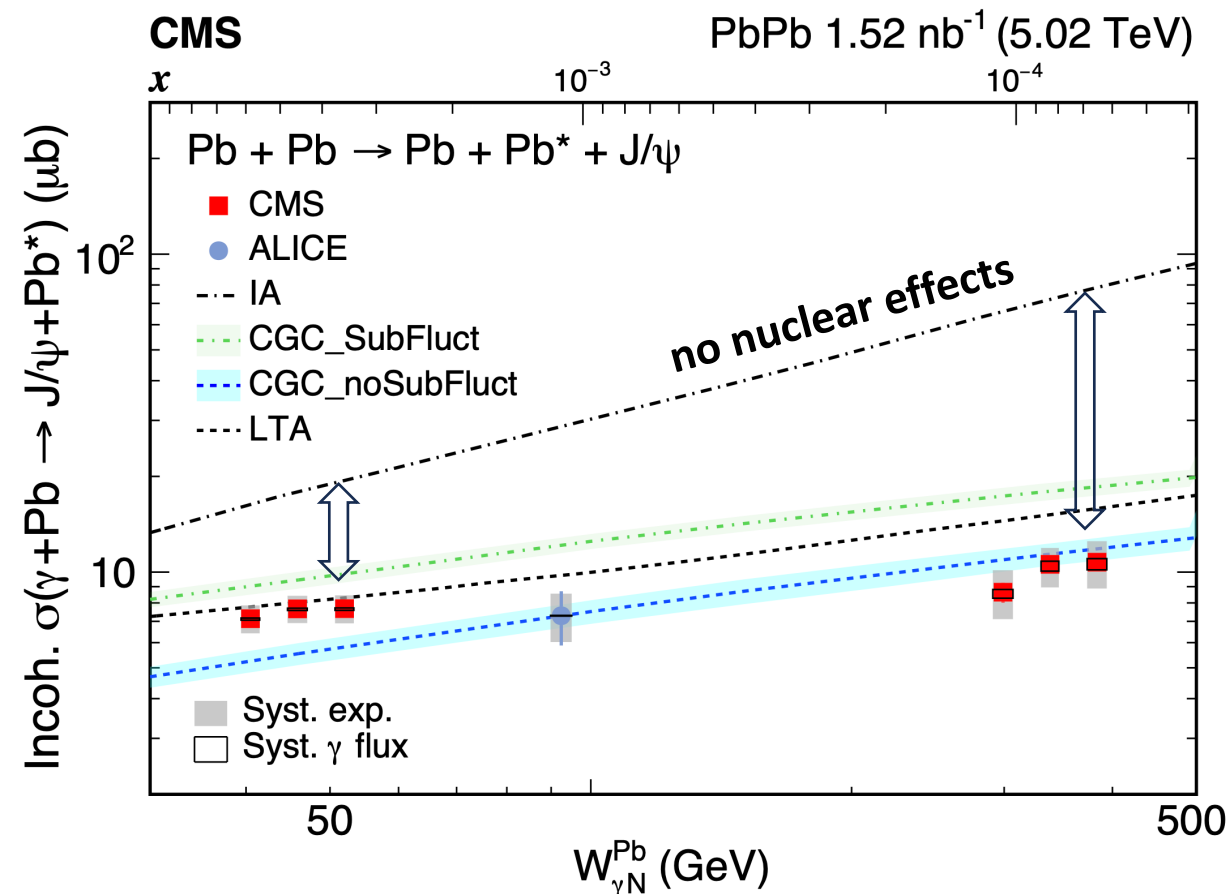
ALICE: EPJC 73 (2013) 2617

July 03, 2026

Zaochen Ye (叶早晨) at USTC

32

Incoh. J/ψ Cross Section Per γ +Pb



- **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**

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

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

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

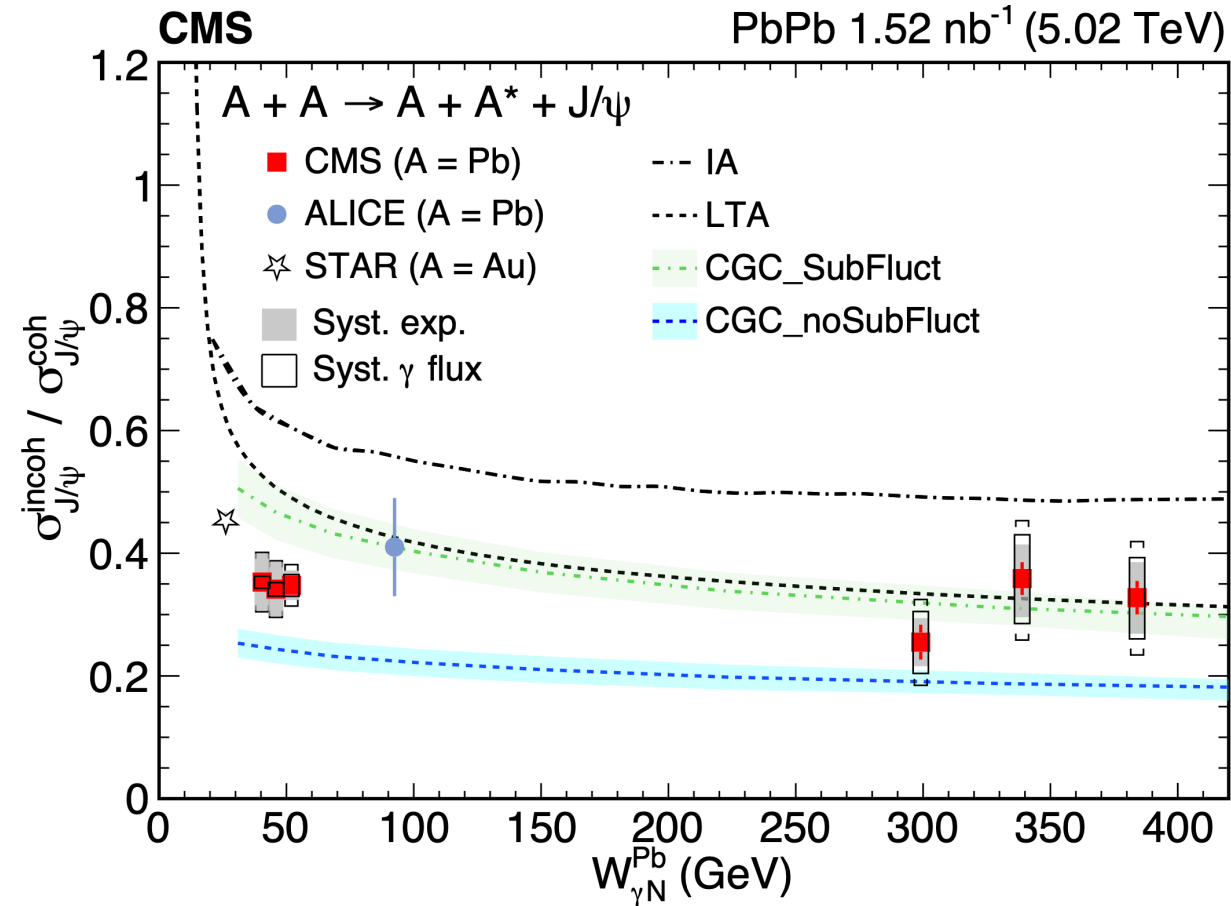
ALICE: EPJC 73 (2013) 2617

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



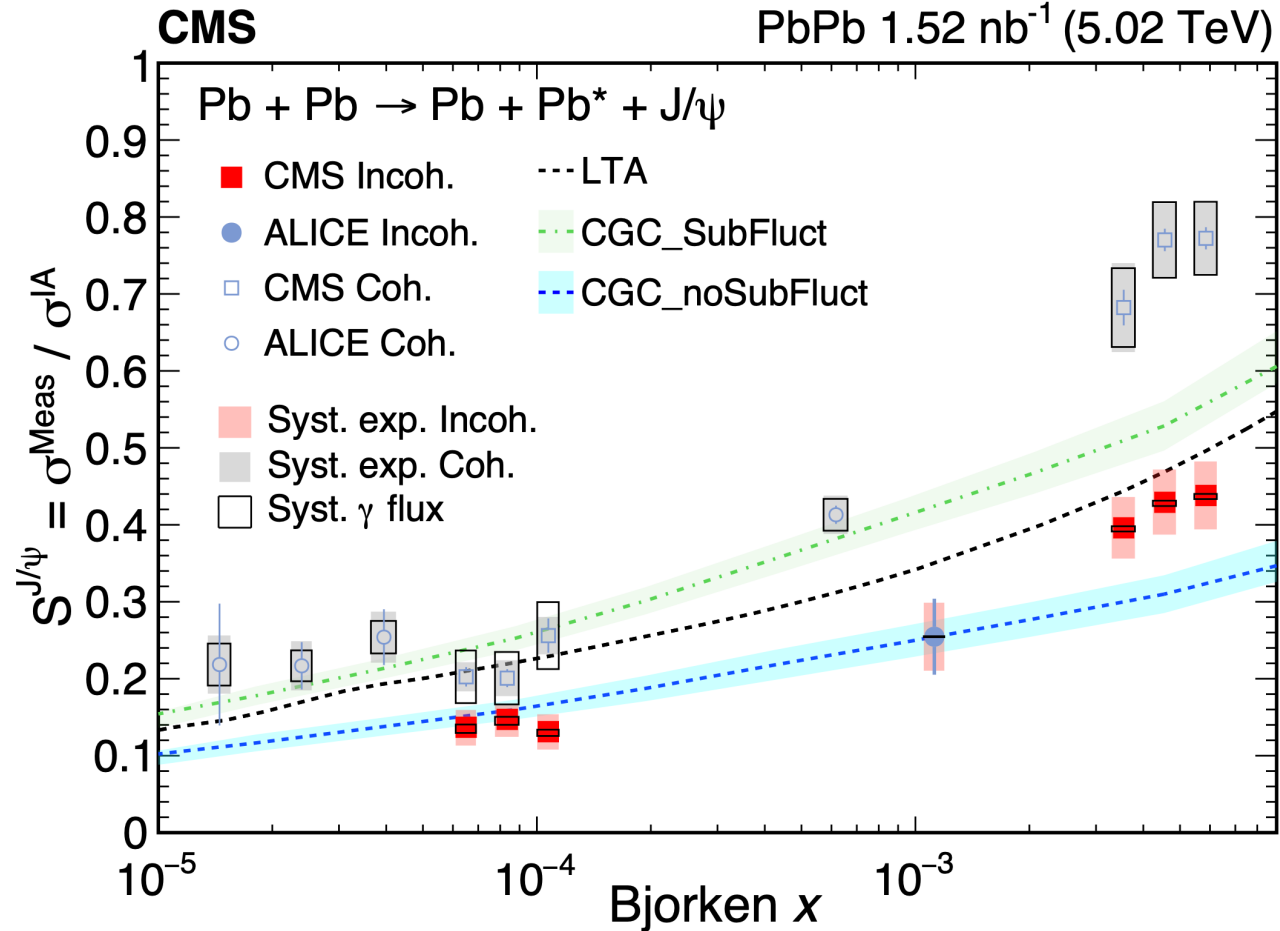
- **No clear W dependence ($40 < W < 400$ GeV)**
 - Not support Black Disk Limit is reached
- ALICE data agrees with CMS data, STAR data slightly rises towards lower W
- **LTA and CGC with sub-nucleonic fluctuation qualitatively describe data trend**

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

$$S_{J/\psi} = \frac{\sigma_{\gamma Pb \rightarrow J/\psi Pb'}^{exp}}{\sigma_{\gamma Pb \rightarrow J/\psi Pb'}^{IA}} \quad \text{No nuclear effects}$$

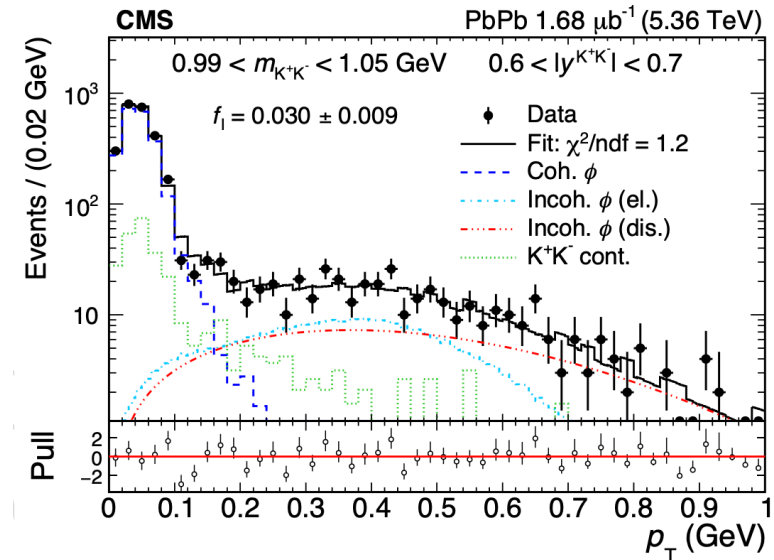
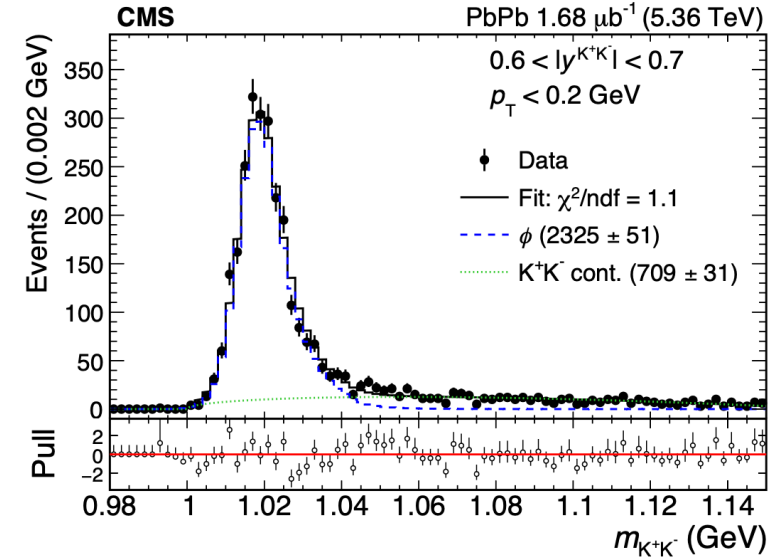
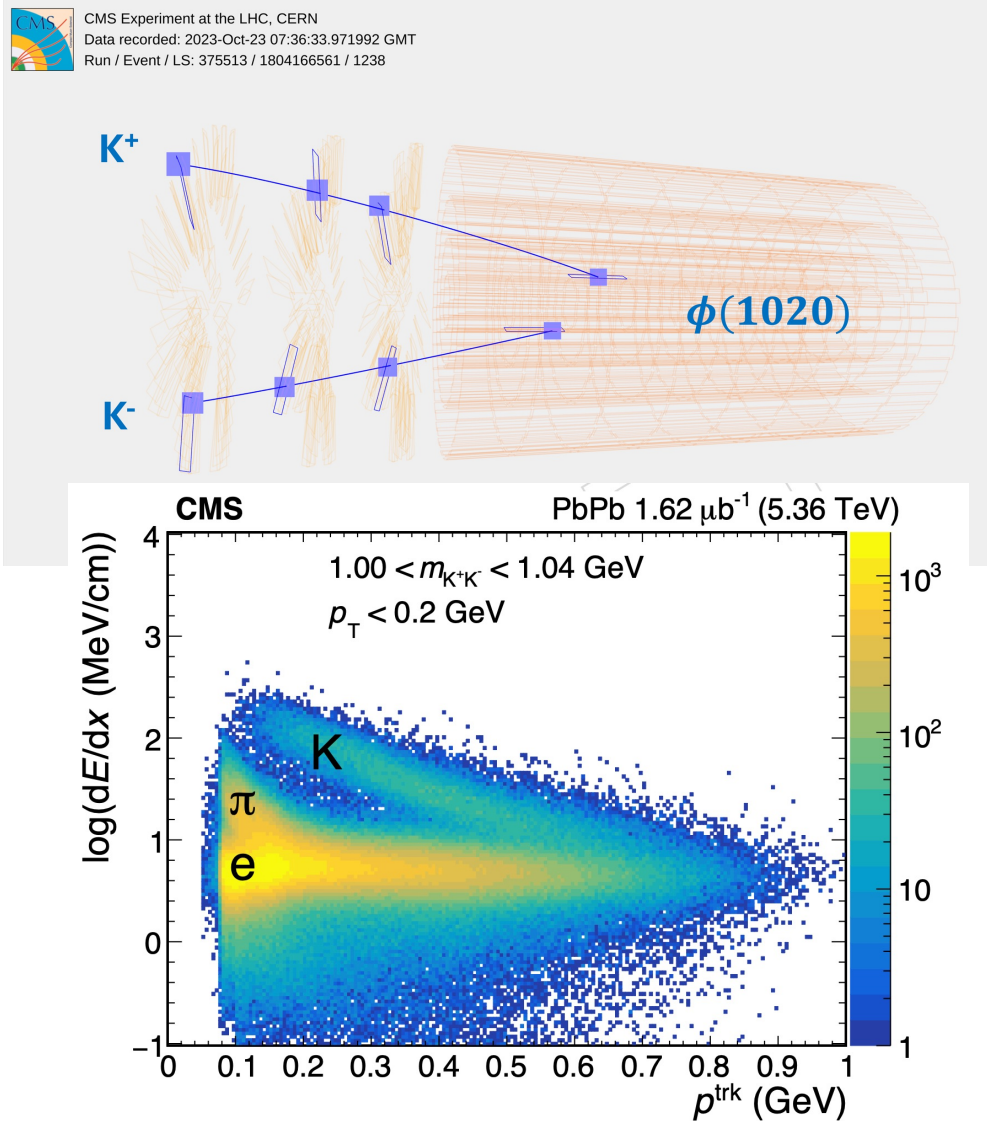


- Both Coh and Incoh J/ψ show **stronger suppression towards lower x** , and eventually **flattens out**
- Incoh. is **more suppressed** than Coh. J/ψ
- Incoh. J/ψ get **closer** to Coh. J/ψ for $x < 10^{-4}$

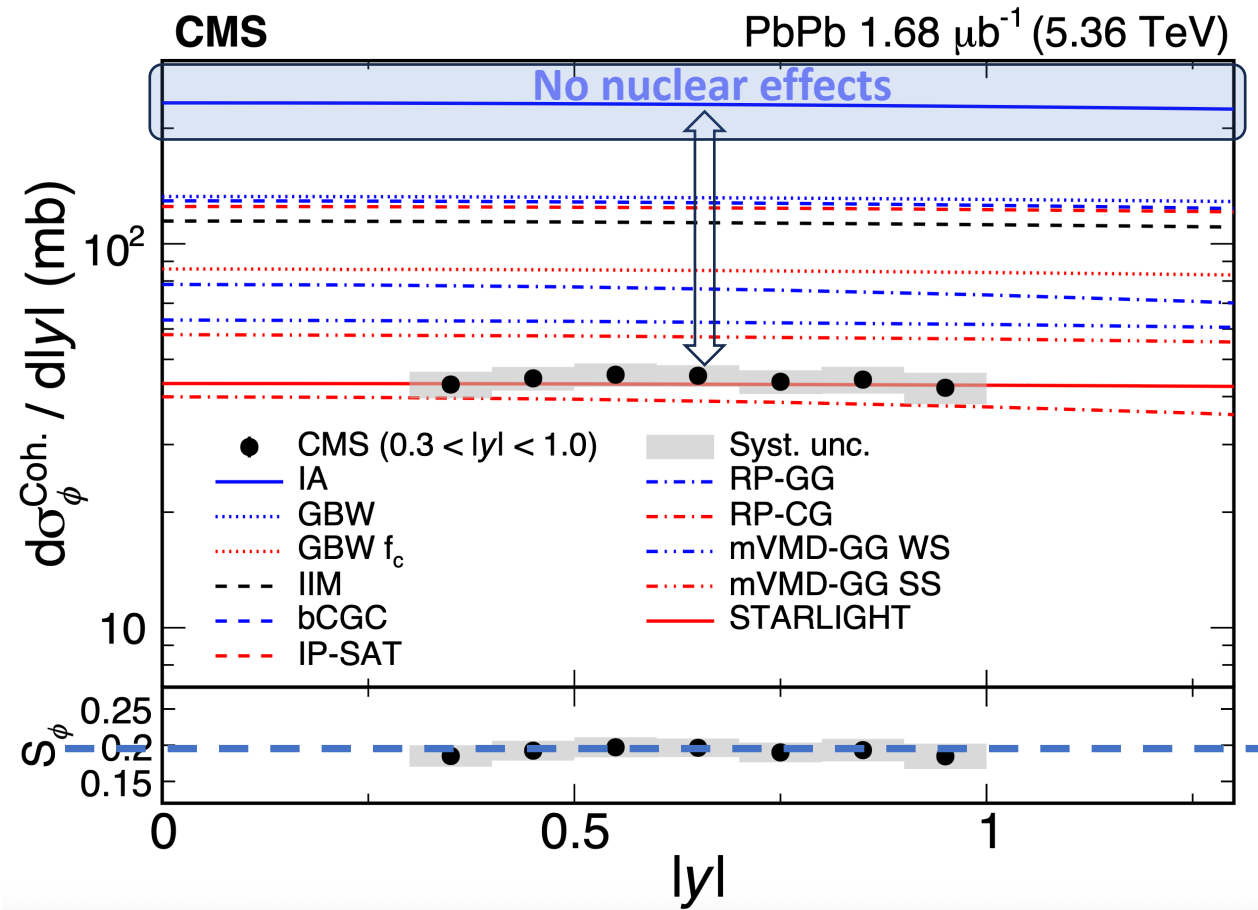
CMS, PRL 135, 112301 (2025), Editors' Suggestion

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

First Observation of ϕ Photoproduction in UPCs



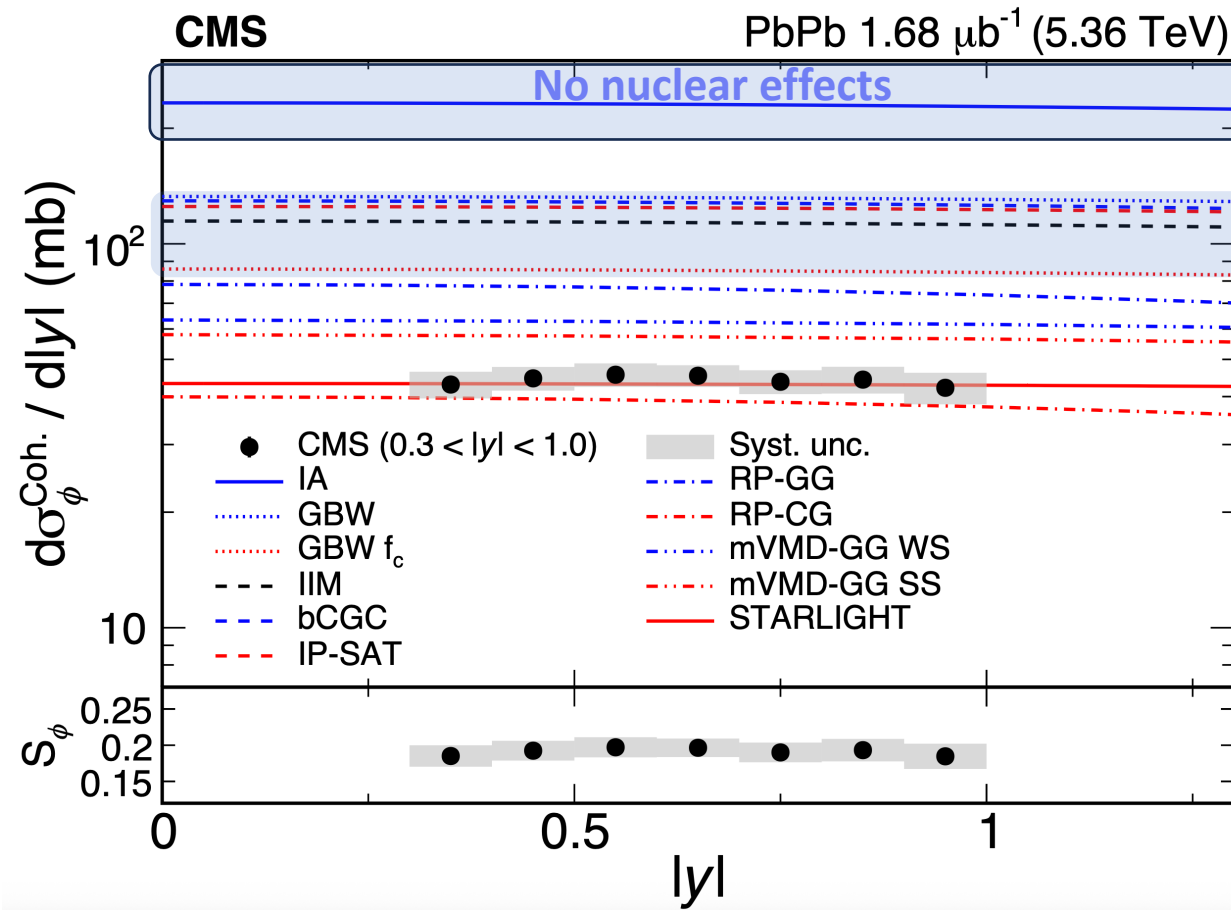
First Observation of ϕ Photoproduction in UPCs



- Strong ($\sim 5x$) suppression is observed

CMS, PRL 135, 262301 (2025)

First Observation of ϕ Photoproduction in UPCs



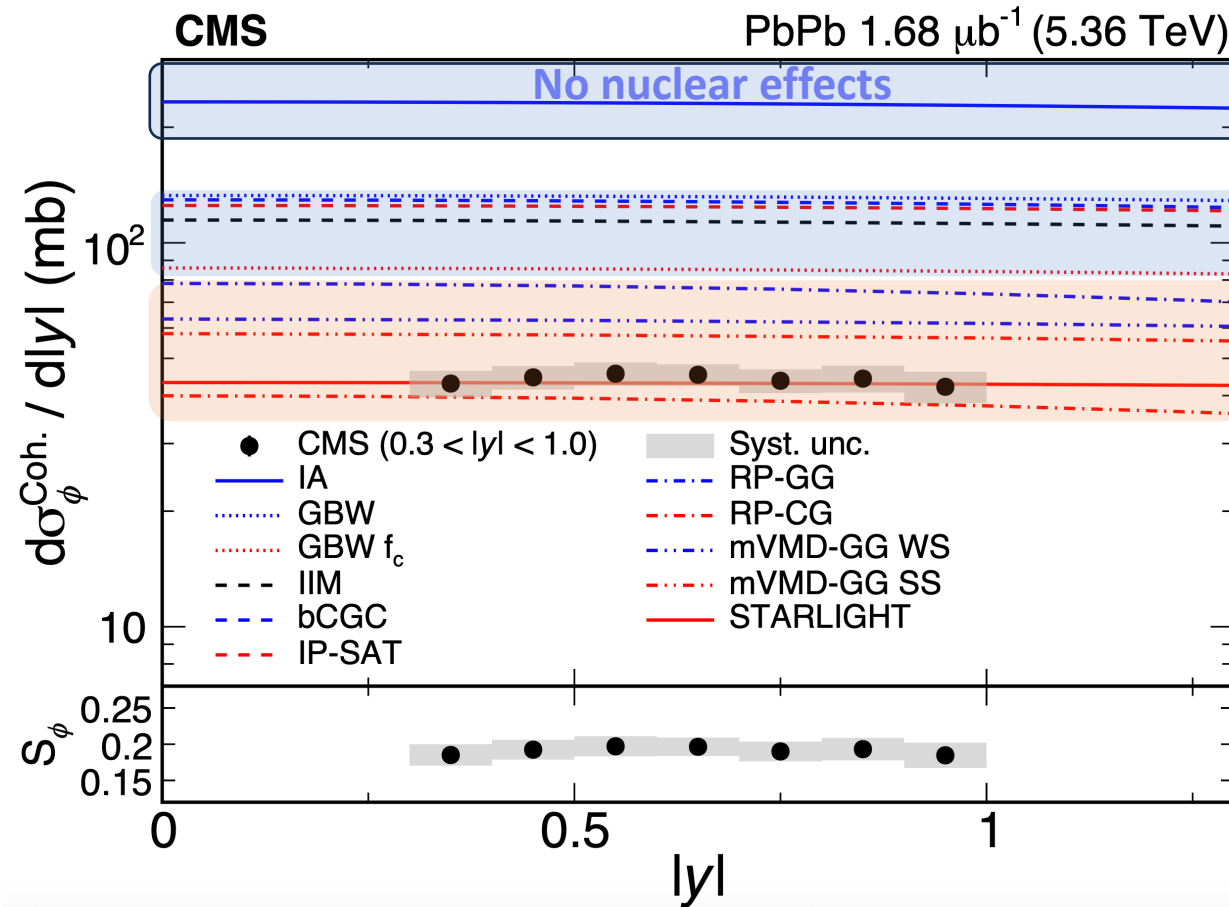
- Strong ($\sim 5x$) suppression is observed

- Gluon saturation models:

- Overpredicted data by a factor of 2-3

CMS, PRL 135, 262301 (2025)

First Observation of ϕ Photoproduction in UPCs

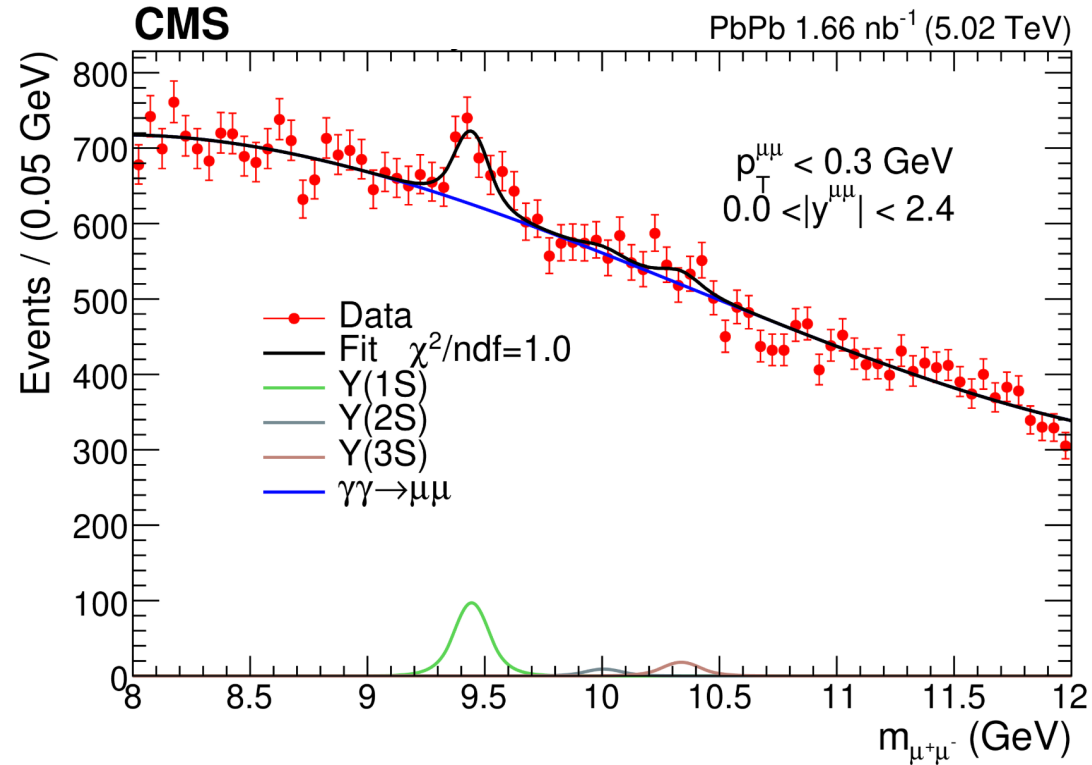


CMS, PRL 135, 262301 (2025)

- **Strong ($\sim 5x$) 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

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

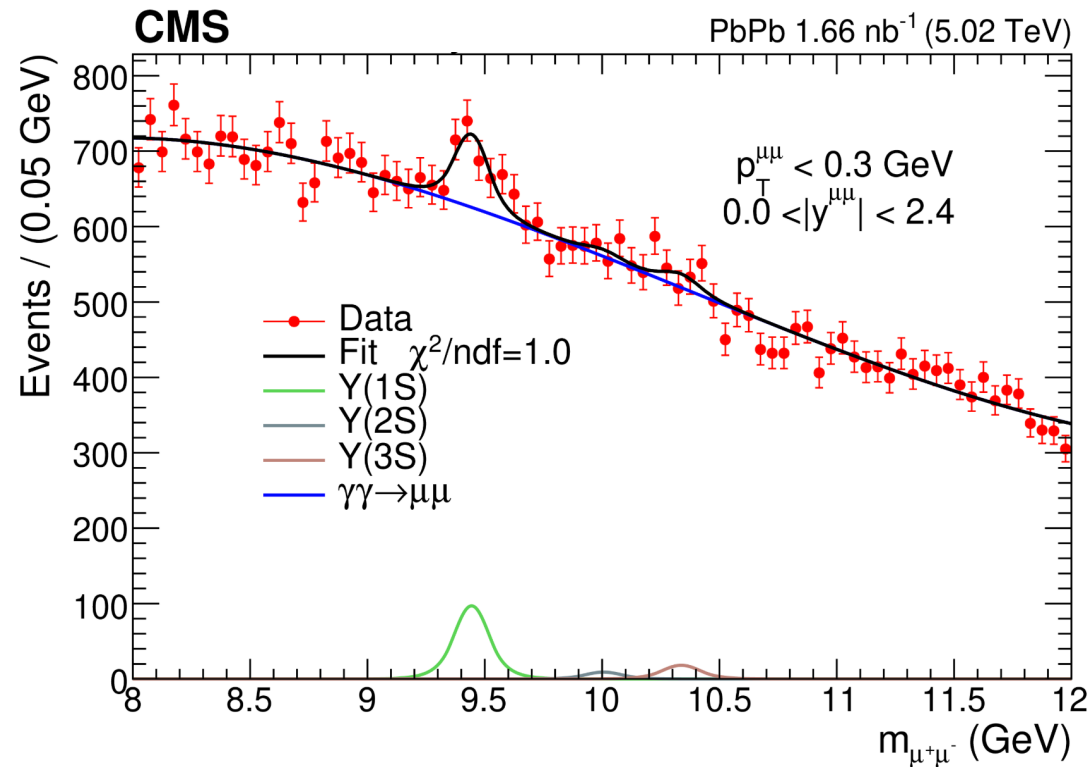
Υ is expected to be less sensitive to the non-linear QCD effects



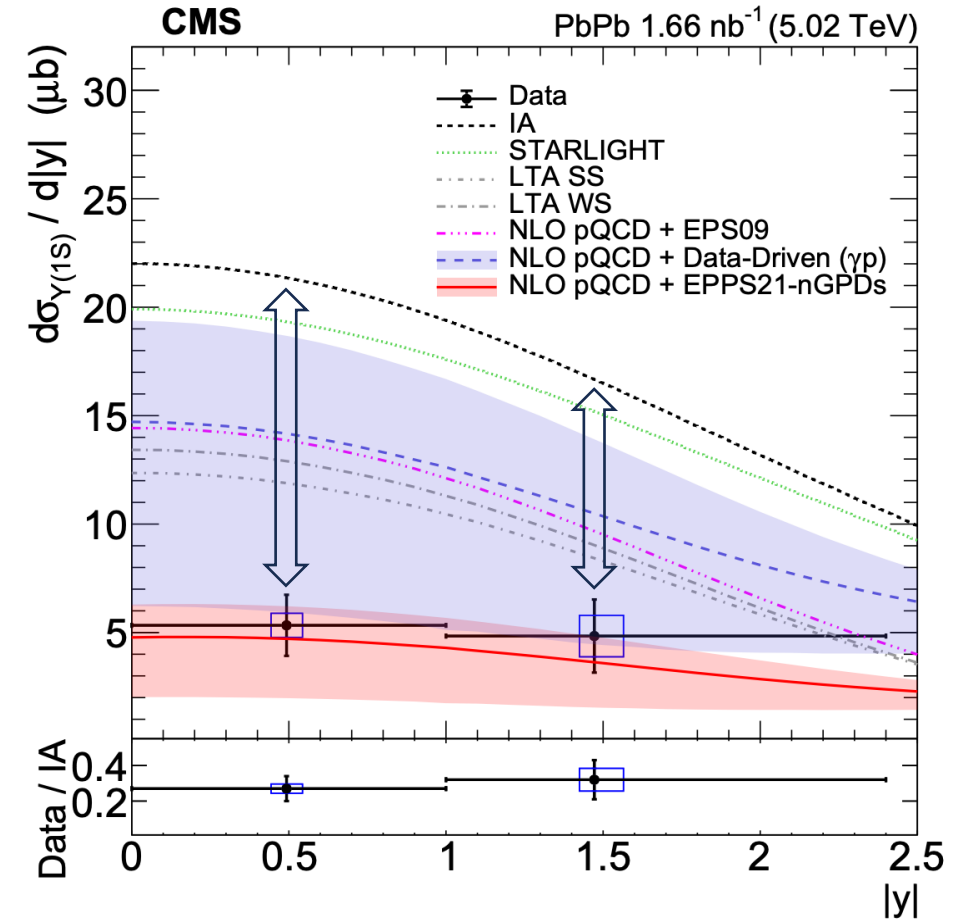
CMS: arXiv:2604.05814 , submitted to PRL

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

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



CMS: arXiv:2604.05814 , submitted to PRL



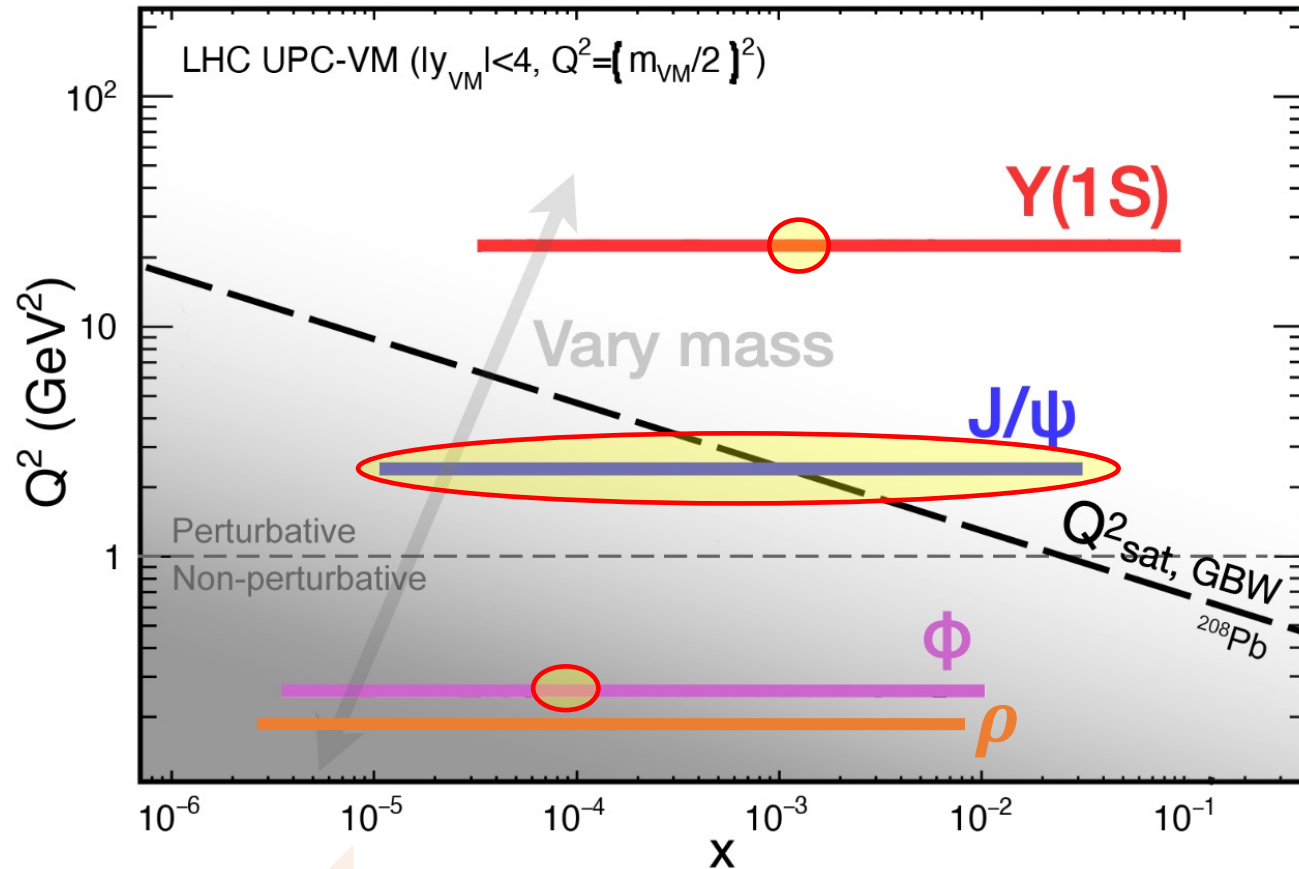
- However, coherent $\Upsilon(1S)$ is observed to be strongly ($\sim 4x$) suppressed!!!

Summary

- **First energy-dependent Coh. and Incoh. J/ψ are measured by CMS**
 - Both are strongly saturated at high energy or small x
 - Ratio of Incoh/Coh J/ψ stay at a constant
 - Stronger suppression 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 Coh. $\Upsilon(1S)$ photoproduction off heavy nuclei is observed by CMS:**
 - Nuclear suppression factor ~ 4
- **The fundamental physics mechanisms governing the small- x regime remain to be fully understood.**

Outlook

Explore nuclear gluonic structure in : x vs. Q^2 vs. Q_s^2

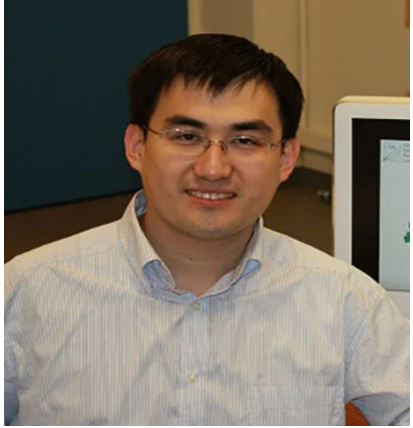


Various VMs in different nucleus-nucleus UPCs:

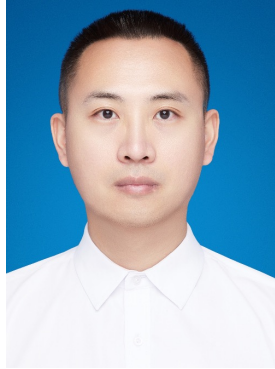
- **Coherent** and **Incoherent**
- Dipole sizes and **hard scales**
- Energy (x) dependence
- **A (saturation scale) dependences**
 - OO, NeNe, PbPb...

Thanks!

My major Collaborators at CMS:



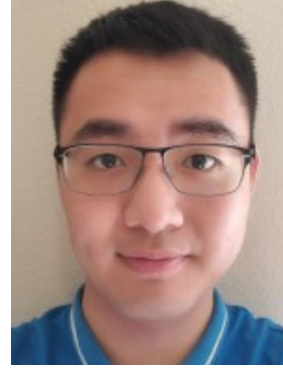
Wei Li



Shuai Yang



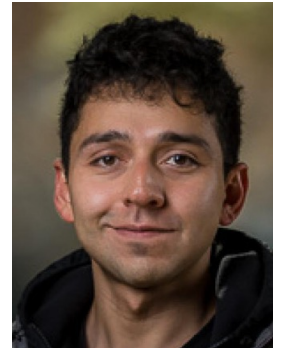
Andre Stahl



Jiazhao Lin



Xiao Huang



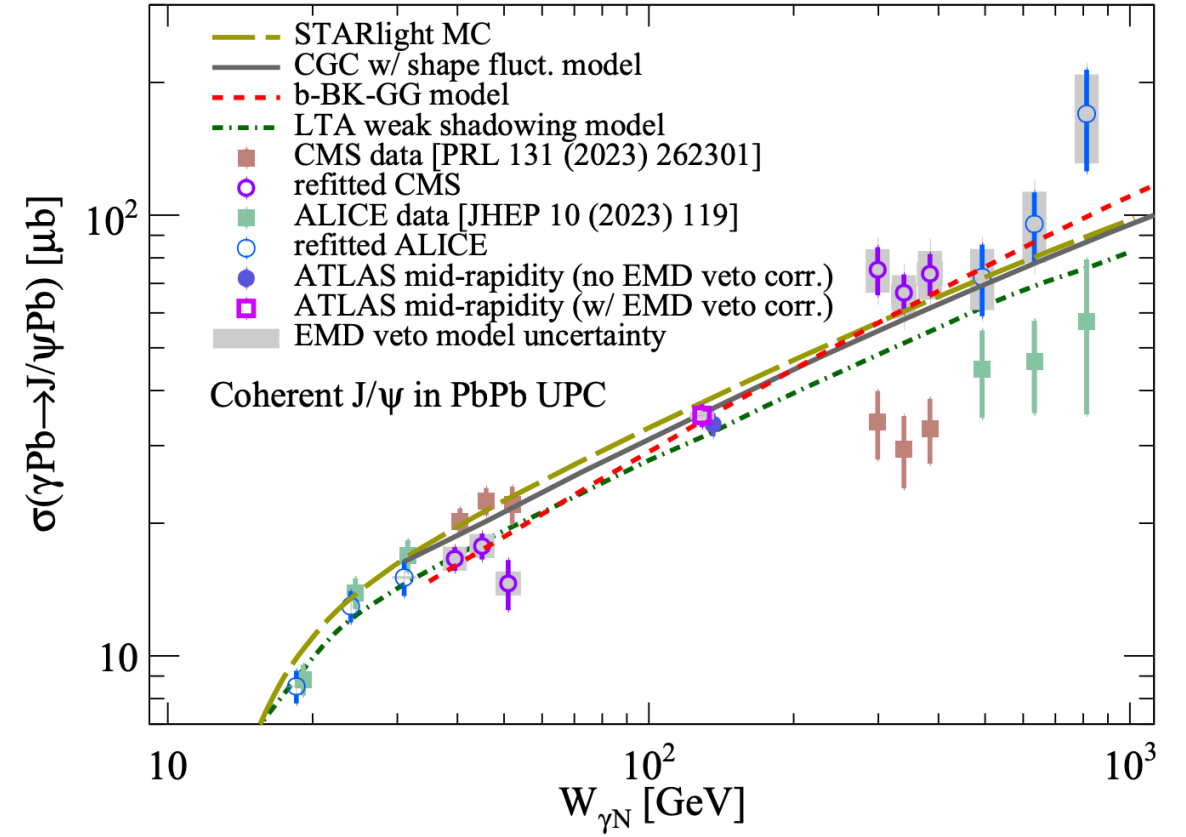
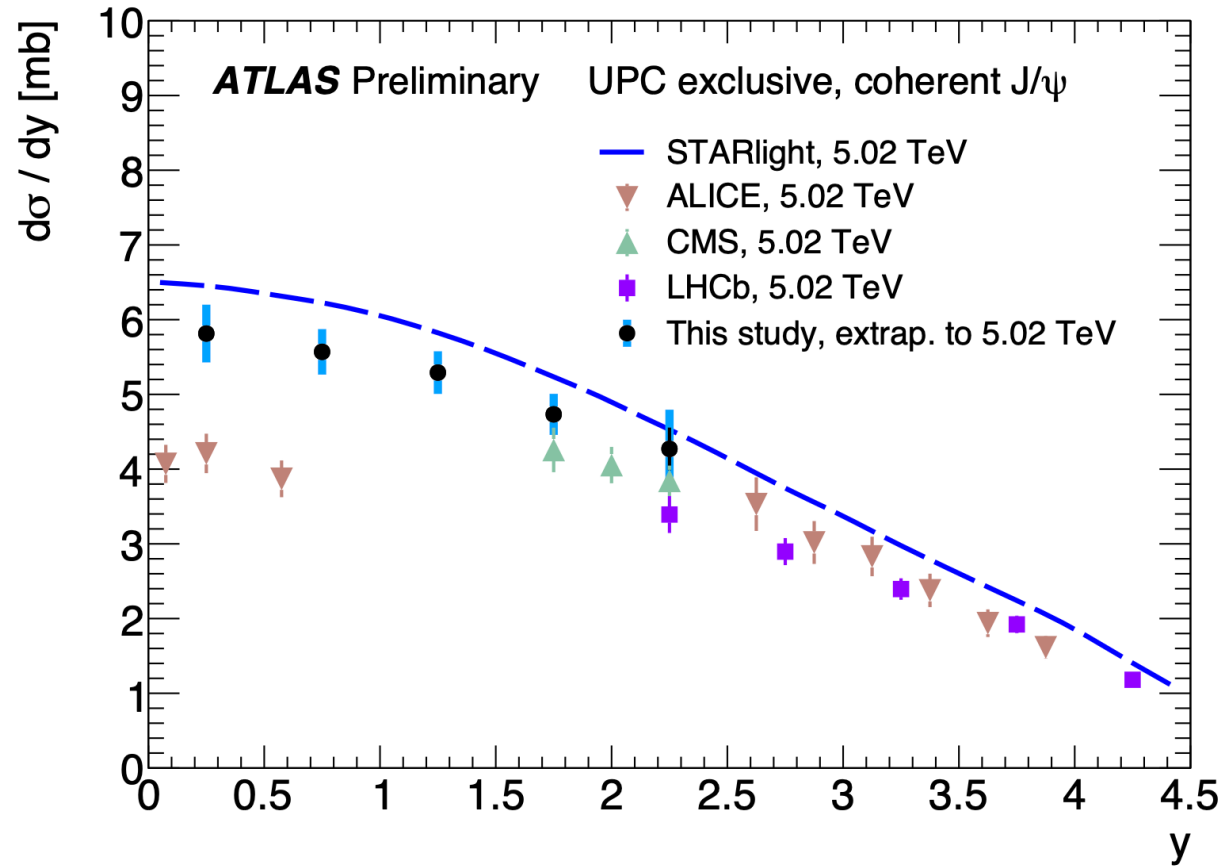
Luis Alcerro

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

Discussions



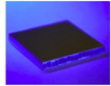
[arXiv:2604.19879](https://arxiv.org/abs/2604.19879)

Future Opportunities

MIP Timing Detector for PID

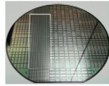
BTL: LYSO bars + SiPM readout:

- TK/ECAL interface: $|\eta| < 1.45$
- Inner radius: 1148 mm (40 mm thick)
- Length: ± 2.6 m along z
- Surface ~ 38 m², 332k channels
- Fluence at 4 ab⁻¹: $2 \times 10^{11} n_{\text{eq}}/\text{cm}^2$

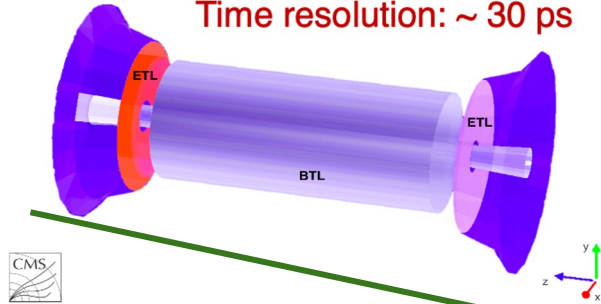


ETL: Si with internal gain (LGAD):

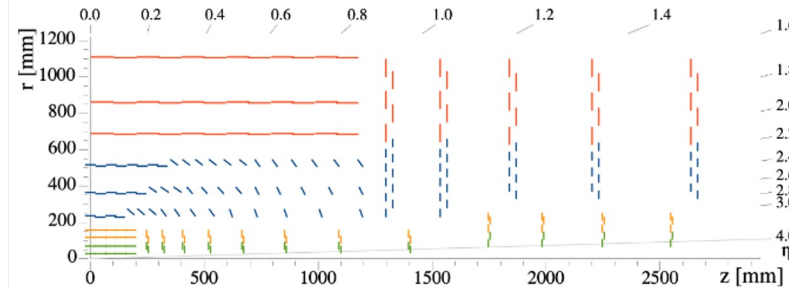
- On the CE nose: $1.6 < |\eta| < 3.0$
- Radius: $315 < R < 1200$ mm
- Position in z: ± 3.0 m (45 mm thick)
- Surface ~ 14 m², ~ 8.5 M channels
- Fluence at 4 ab⁻¹: up to $2 \times 10^{11} n_{\text{eq}}/\text{cm}^2$



Time resolution: ~ 30 ps



Tracker with $|\eta| < 4$ and better resolution, lighter materials

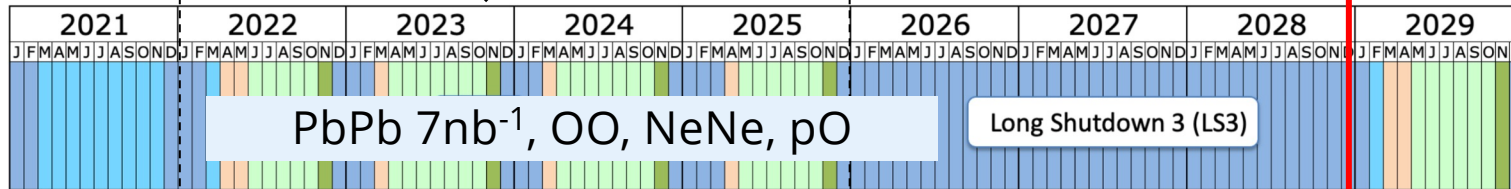


- Muon systems with $|\eta| < 2.8$
- Trigger and DAQ rate: $\sim 10\times$

↓ Run-3

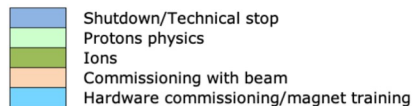
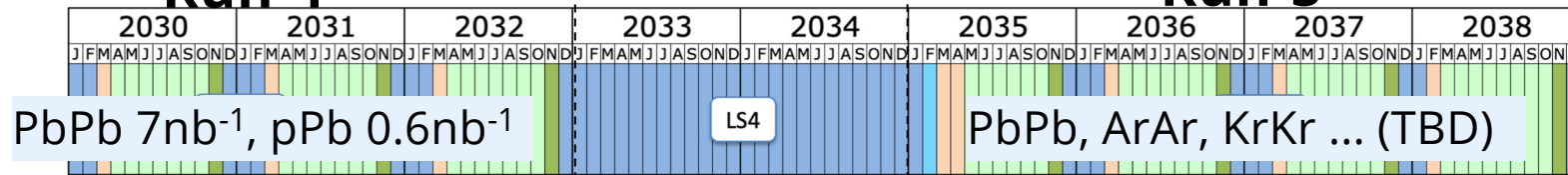
Phase-2 Upgrades

HL-LHC



Run-4

Run-5

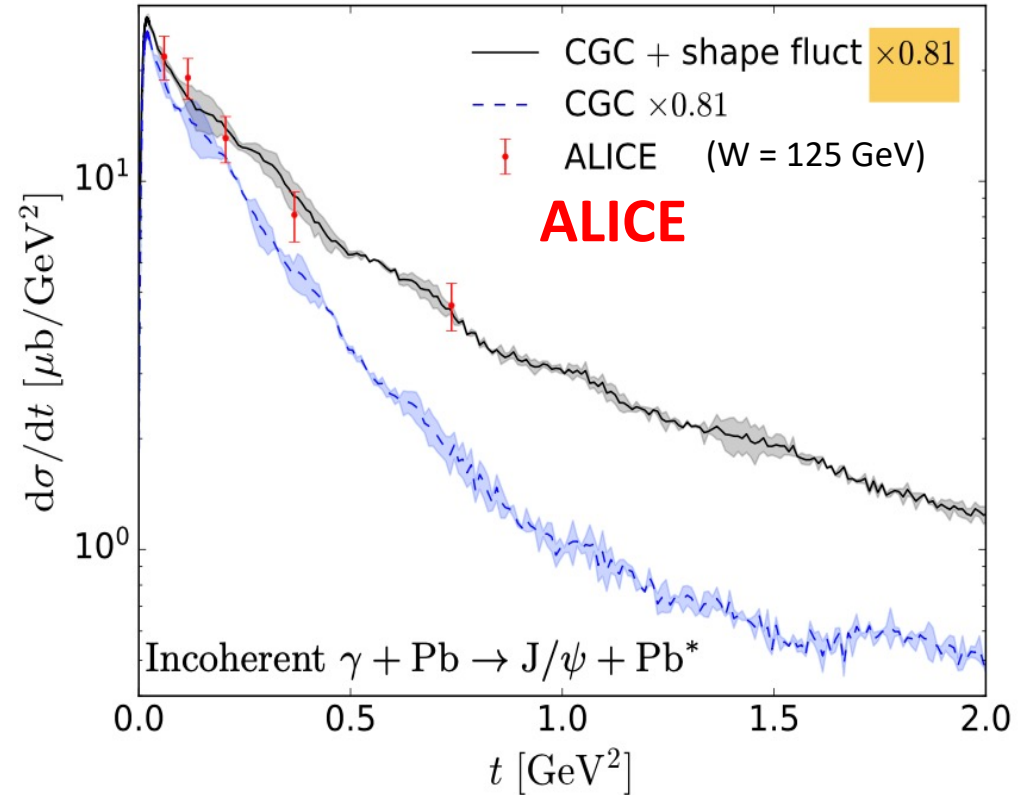
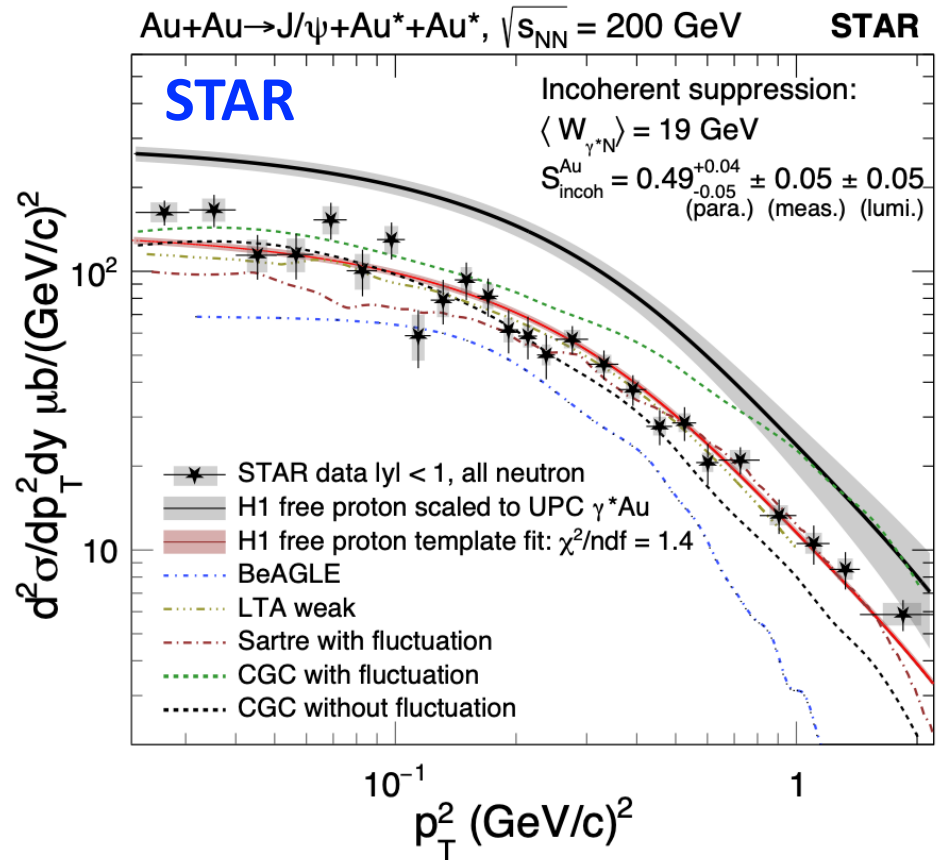


LHC schedule

Exciting opportunities ahead by:

- Higher luminosities.
- A variety of ion species.
- Upgrades enabled by new technologies!

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 ALICE: 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

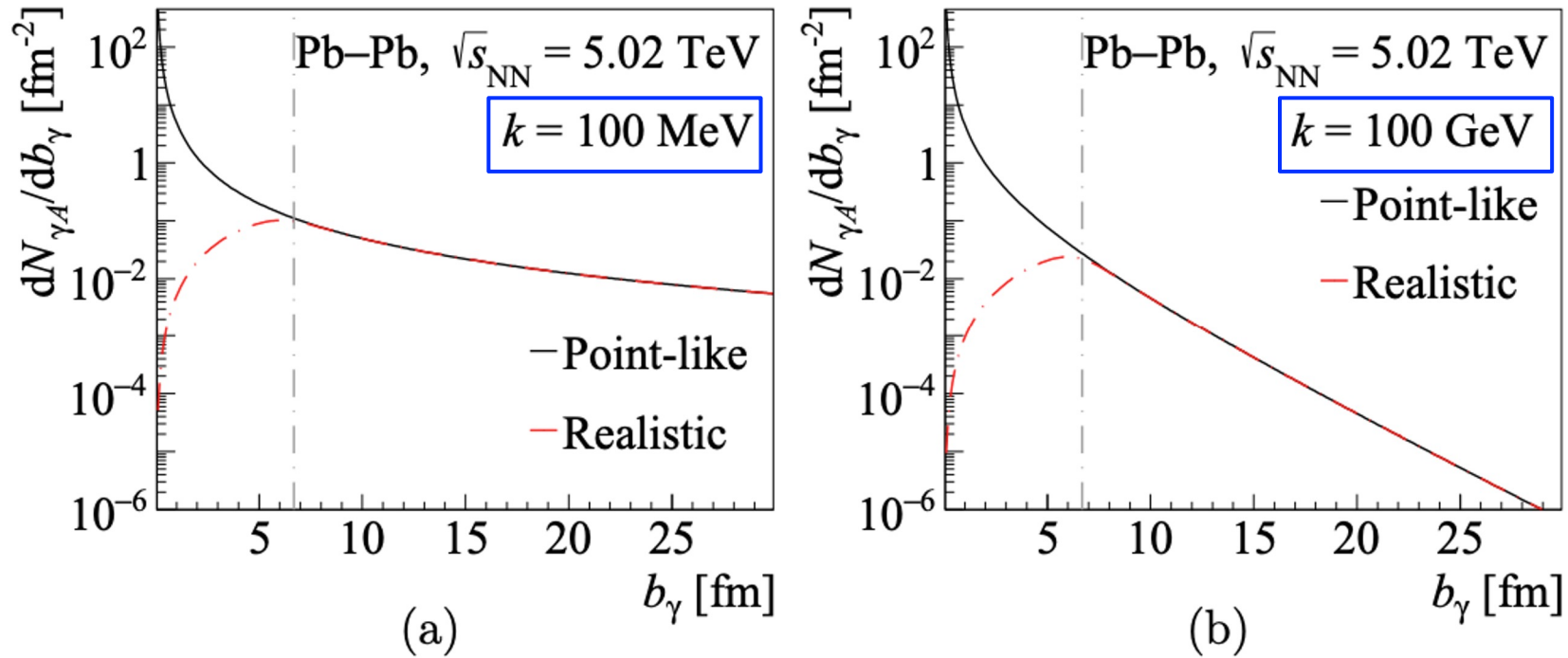


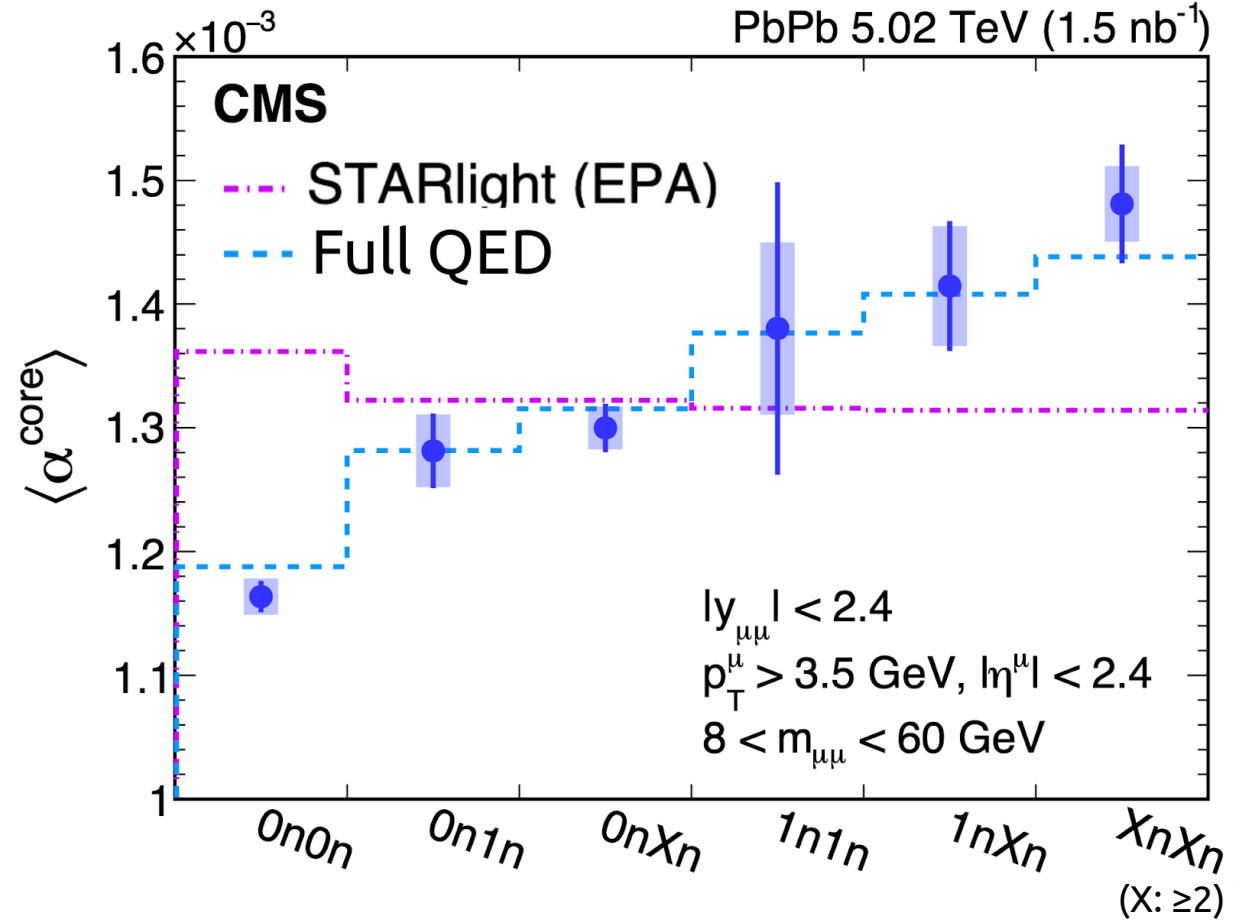
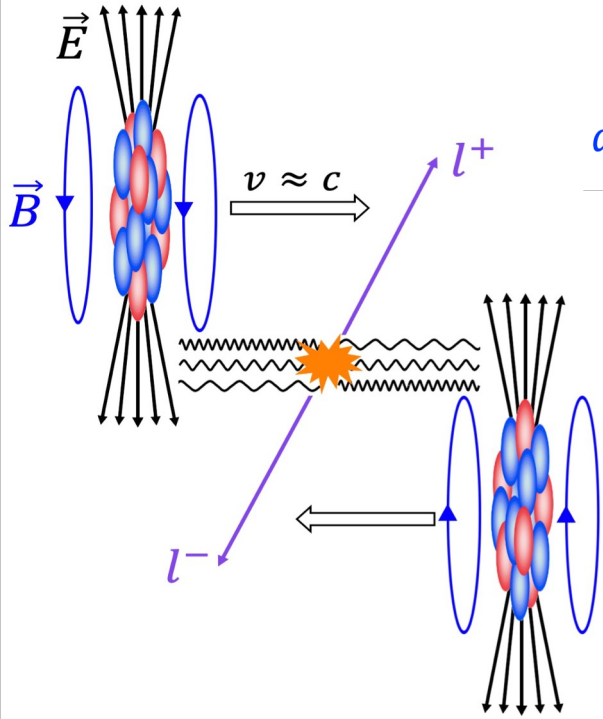
Figure 4: (Color online) Photon fluxes coming from a nucleus $N_{\gamma A}$ in the point-like source approximation and the realistic description as functions of impact parameter b_{γ} calculated at different photon energies: 100 MeV (a), 100 GeV (b).

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