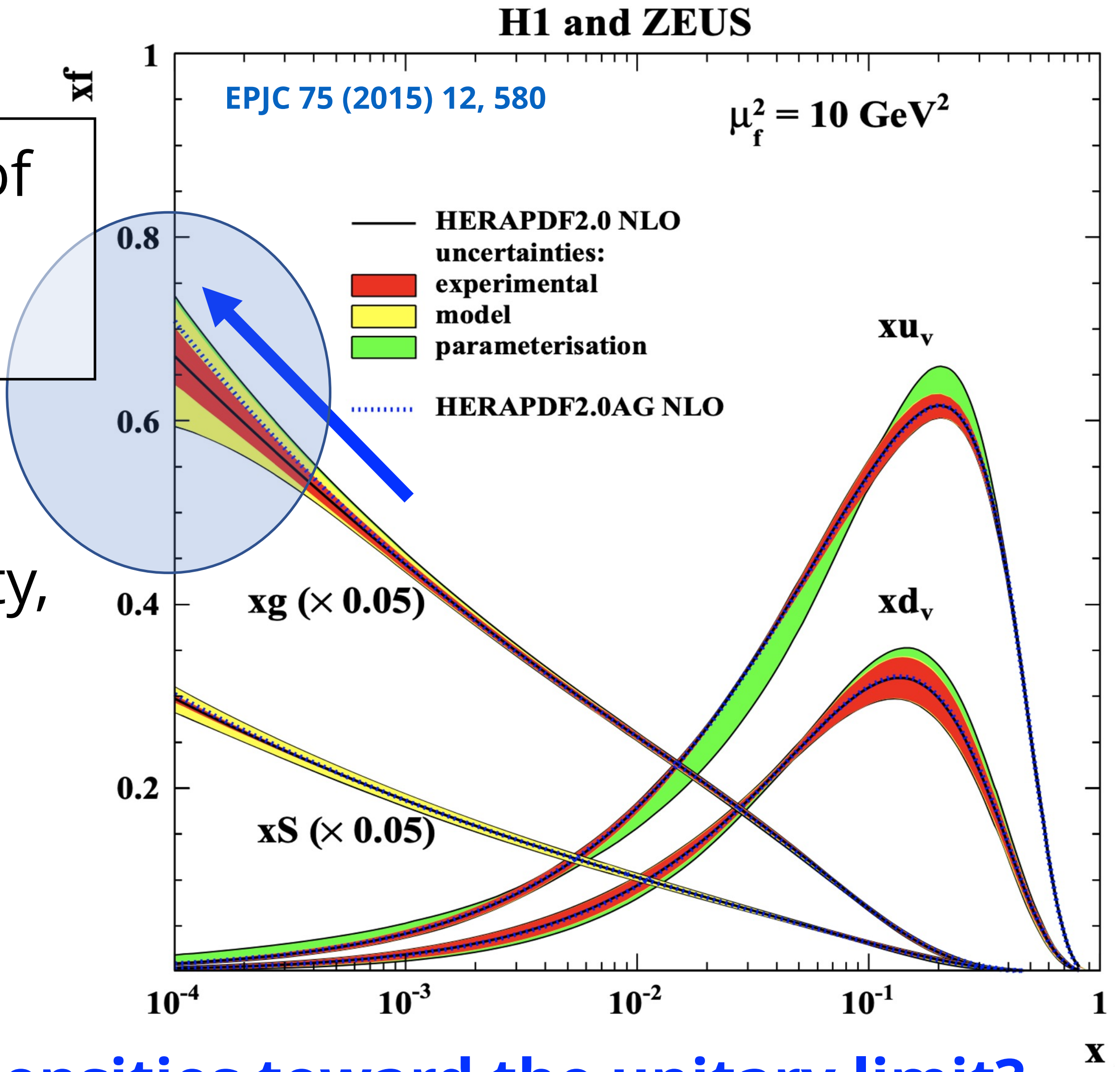
Heavy Quarkonium Photoproduction in Ultra-Peripheral Collision

Zaochen Ye (SCNU)

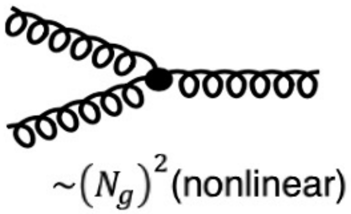
Understand Nucleon Structure

e-p collider

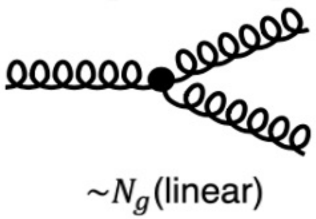
Rapid increase of gluon density towards small x



Indefinite growth at small-x violates unitarity, new mechanism is expected.

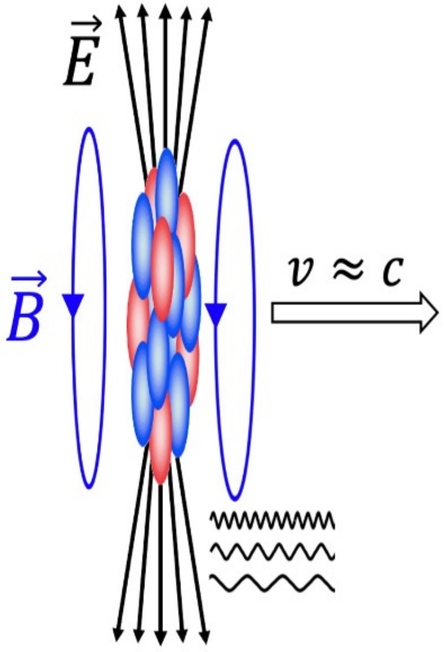


Saturation?



What is the fate of gluons at extreme densities toward the unitary limit?

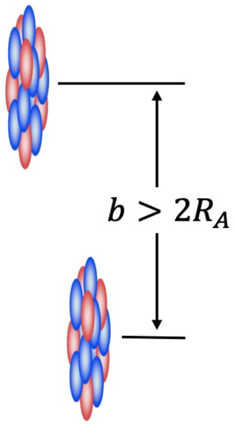
Ultra-Peripheral Collision (UPC)

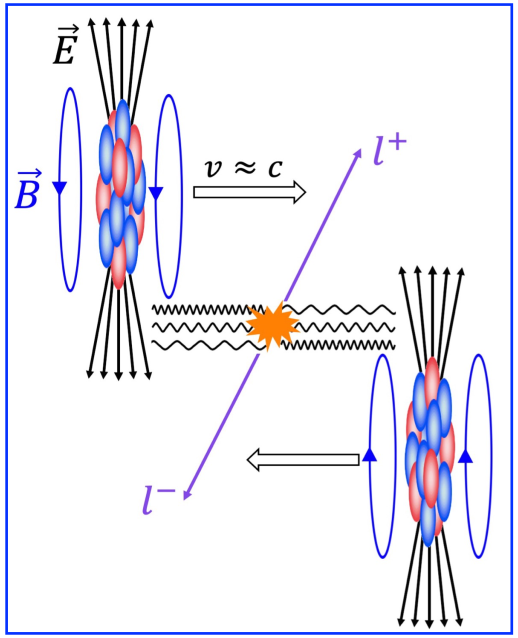


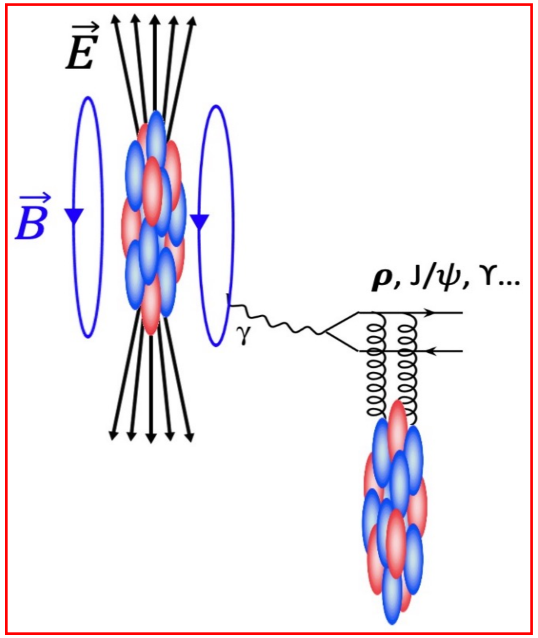
- **Lorentz contracted EM fields → flux of quasi-real photons ($Q^2 < \hbar^2/R^2$)**
- **The photon flux ∝ Z^2**
- **Photon kinematics: $p_T < \hbar/R_A$ ~ 30 MeV (E_{max} ~ 80 GeV) at LHC**

Heavy ion collider is also a Photon-Photon and Photon-Ion collider !!!

UPC:





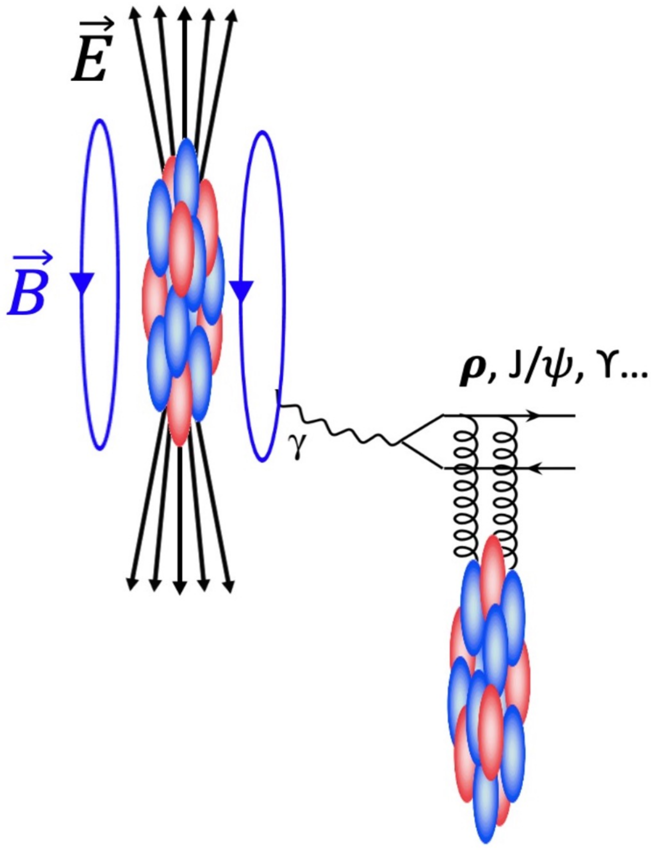


...

Quarkonium Photoproduction in UPC

Quarkonium (e.g., J/Ψ) photoproduction directly probes gluonic structure of nucleus/nucleon

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



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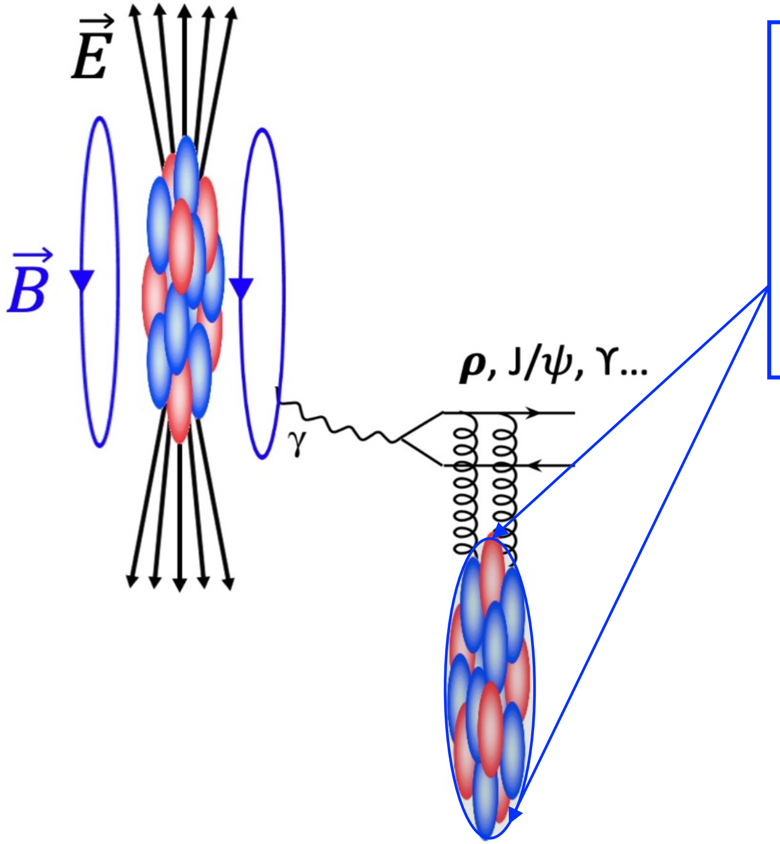

Coherent production:

- Photon fluctuated dipole couples **coherently to entire nucleus**
- **Target** nucleus remains **intact**
- VM $\langle p_T \rangle$ ~ **50 MeV**
- Probing the **averaged gluon density**

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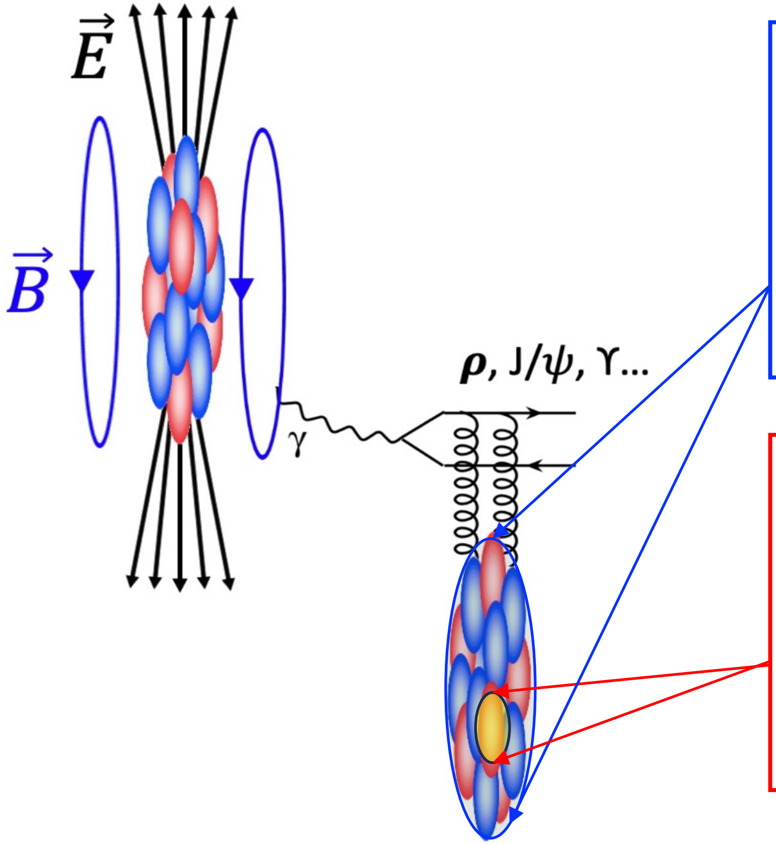

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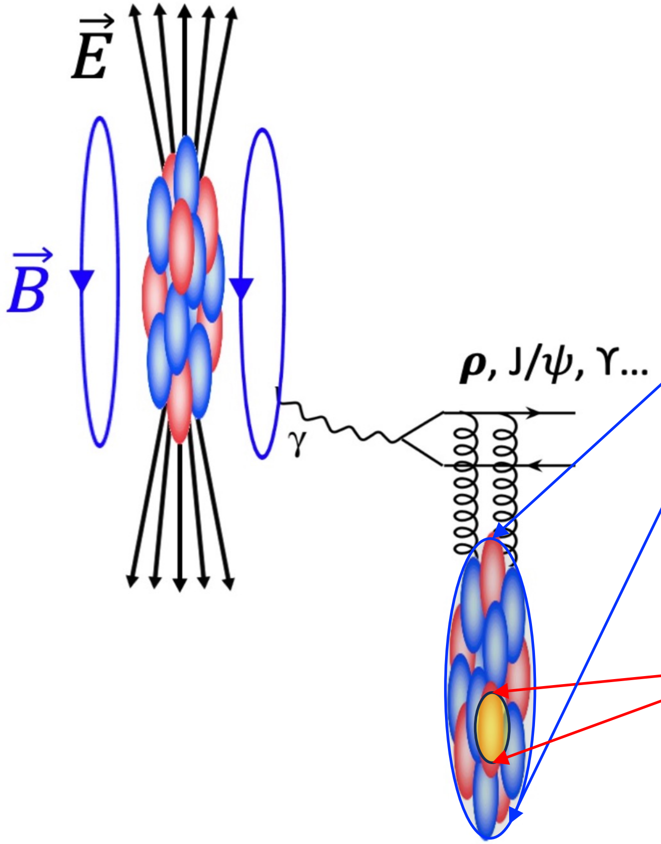

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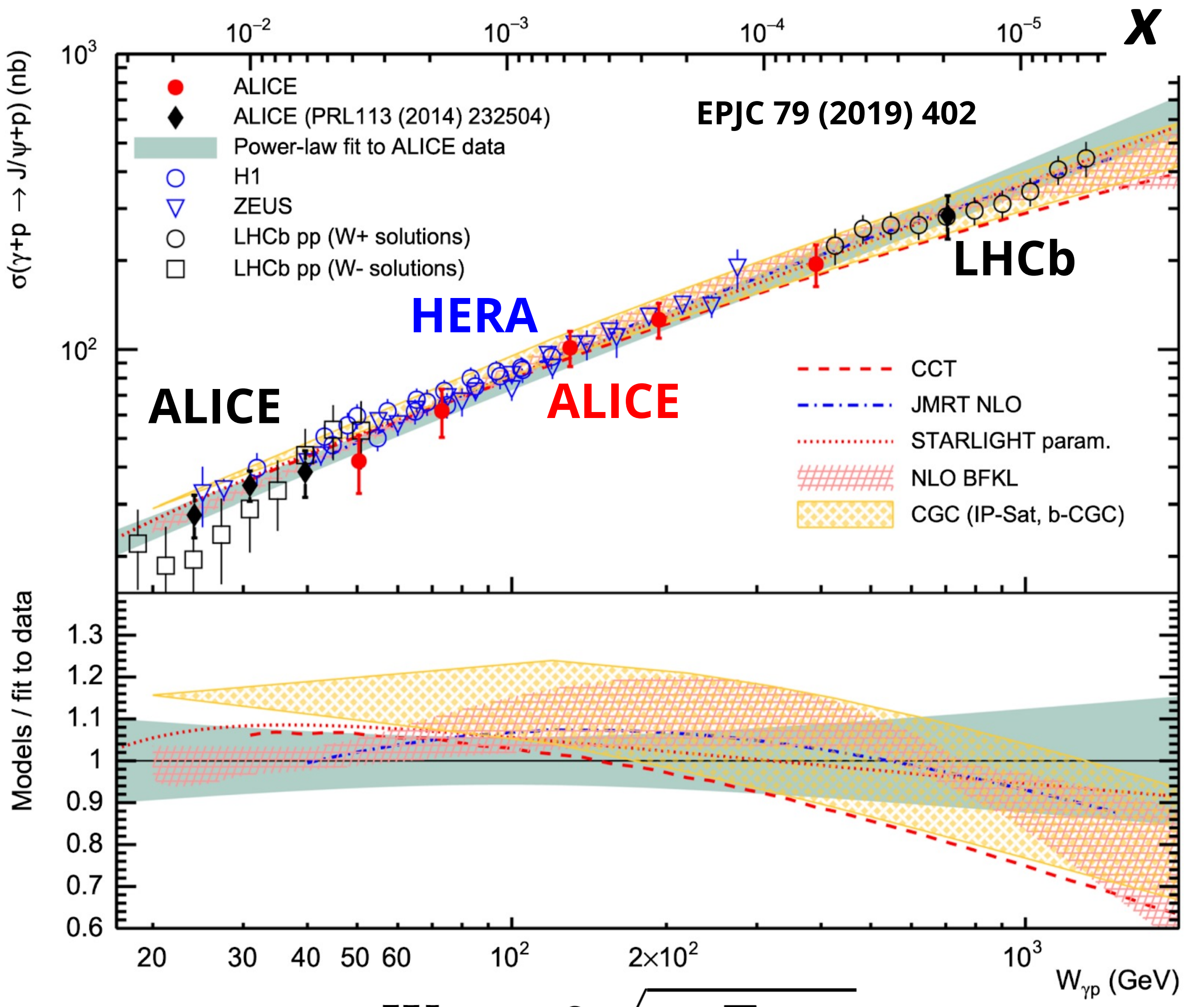
$$\omega = \frac{M_{VM}}{2} e^{\pm y} \qquad x = \frac{M_{VM}}{\sqrt{s_{NN}}} e^{\mp y} \qquad W_{\gamma p} = 2\sqrt{\omega \cdot E_{beam}}$$

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



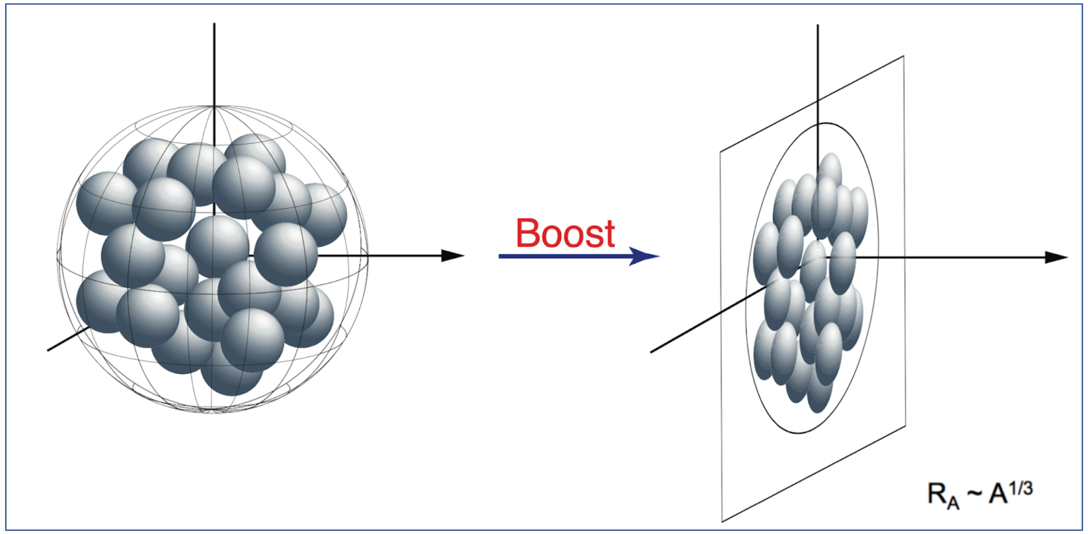
$$W_{\gamma p} = 2\sqrt{\omega \cdot E_{beam}}$$

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

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

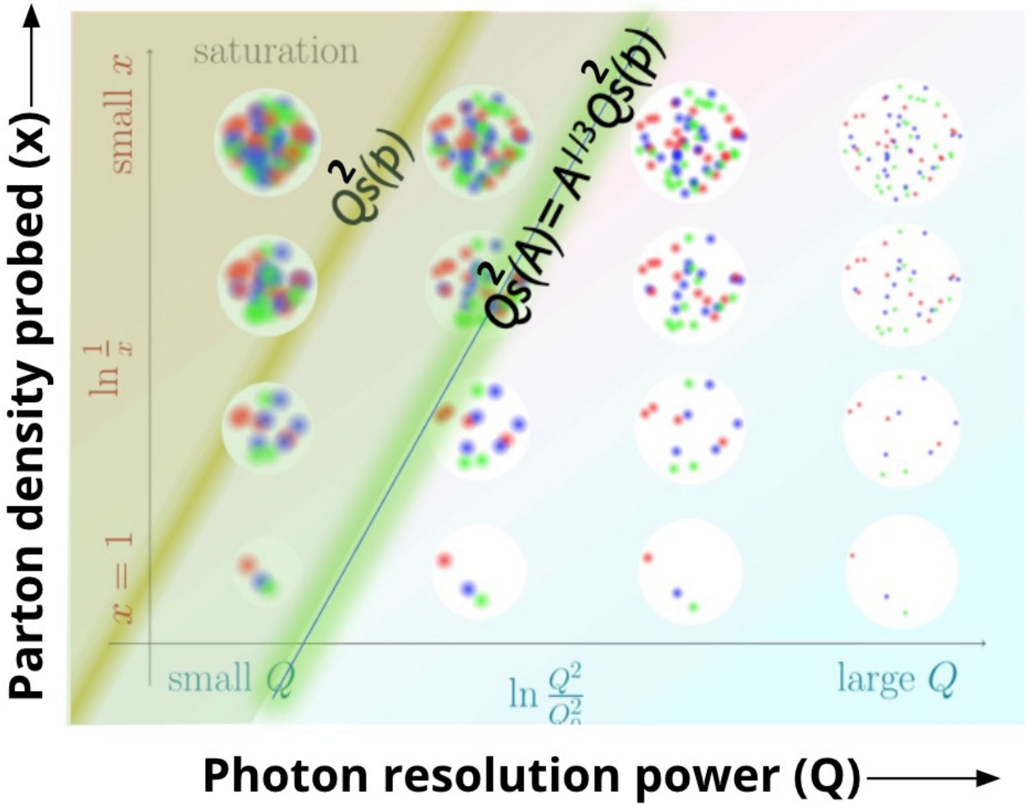
No clear indication of gluon saturation, even down to $x \sim 10^{-5}$ in a free nucleon!

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

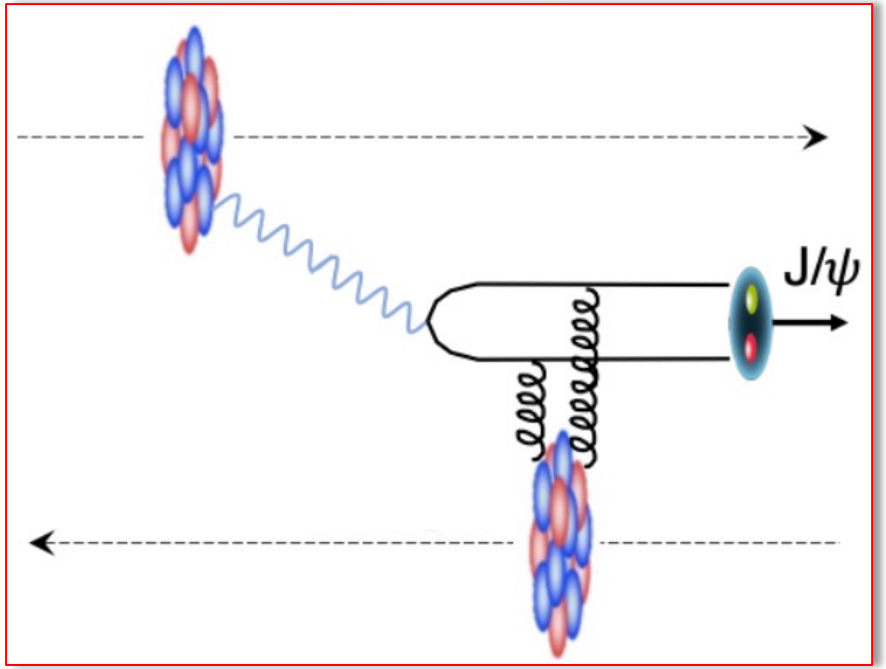
$$Q_s^2 \sim A^{1/3} \left(\frac{1}{x}\right)^{\lambda}$$



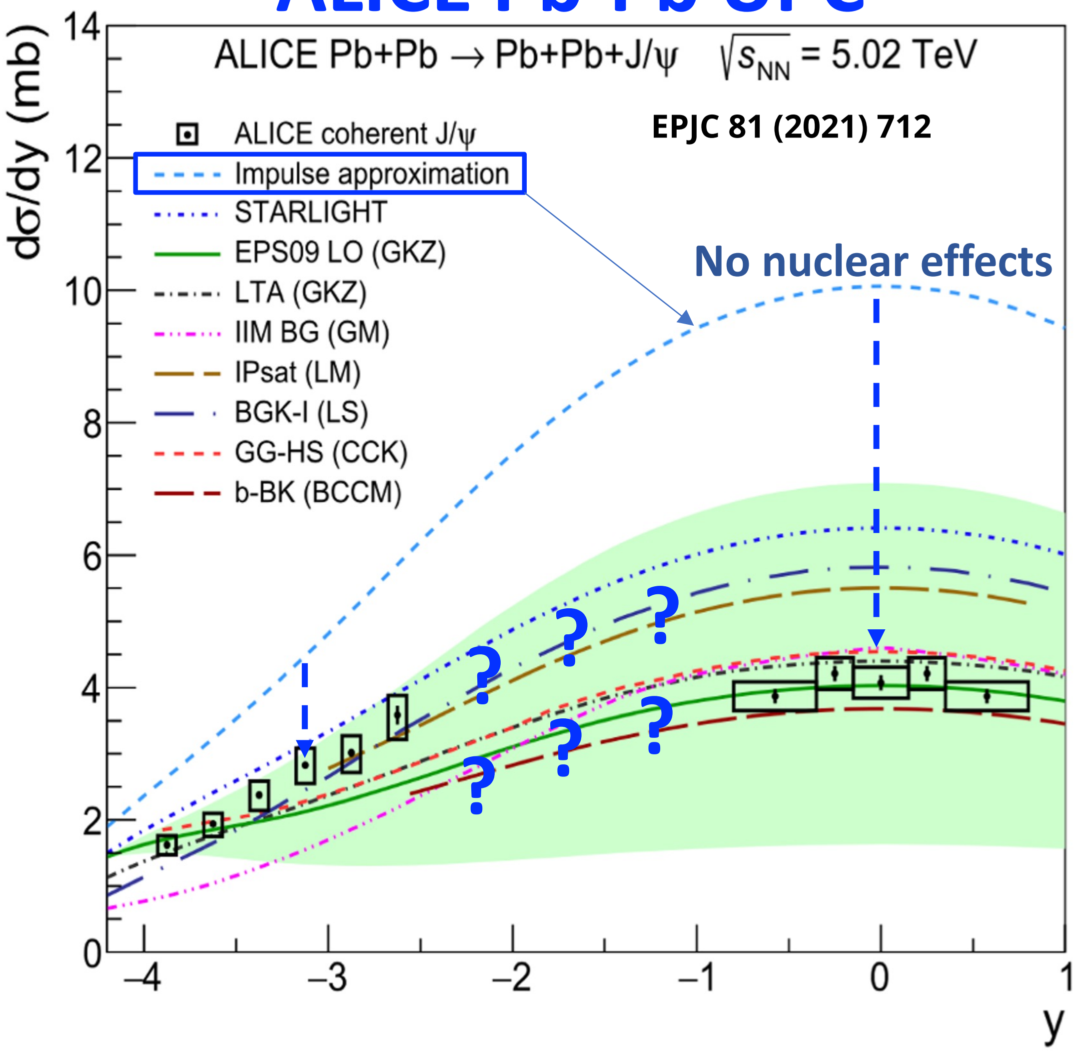
- **Gluon saturation is expected to be more easily reached in heavy nuclei**

Coherent J/Ψ Photoproduction in A-A UPCs

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



ALICE Pb-Pb UPC



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

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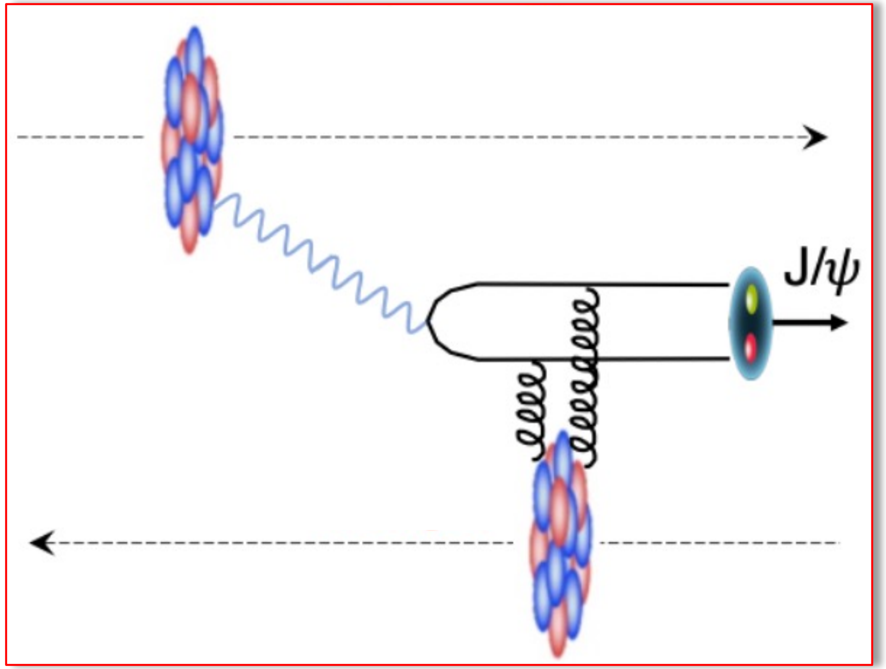
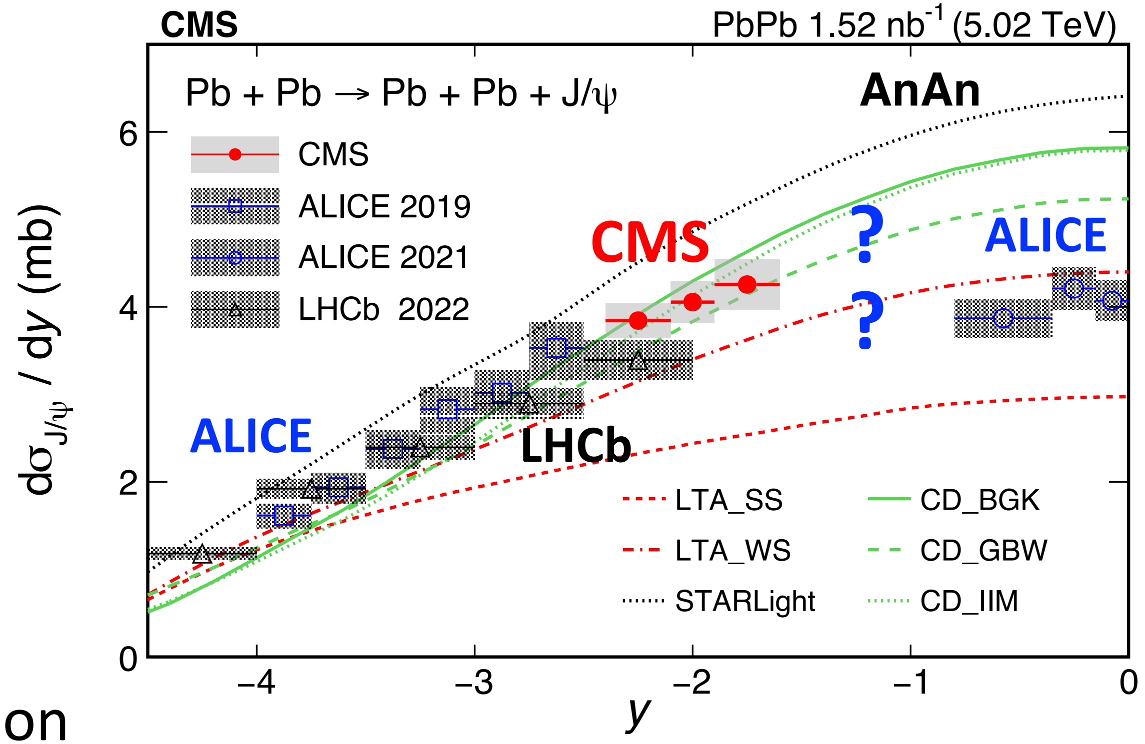


CMS: PRL 131, 262301 (2023)
LHCb: JHEP 06 146 (2023)



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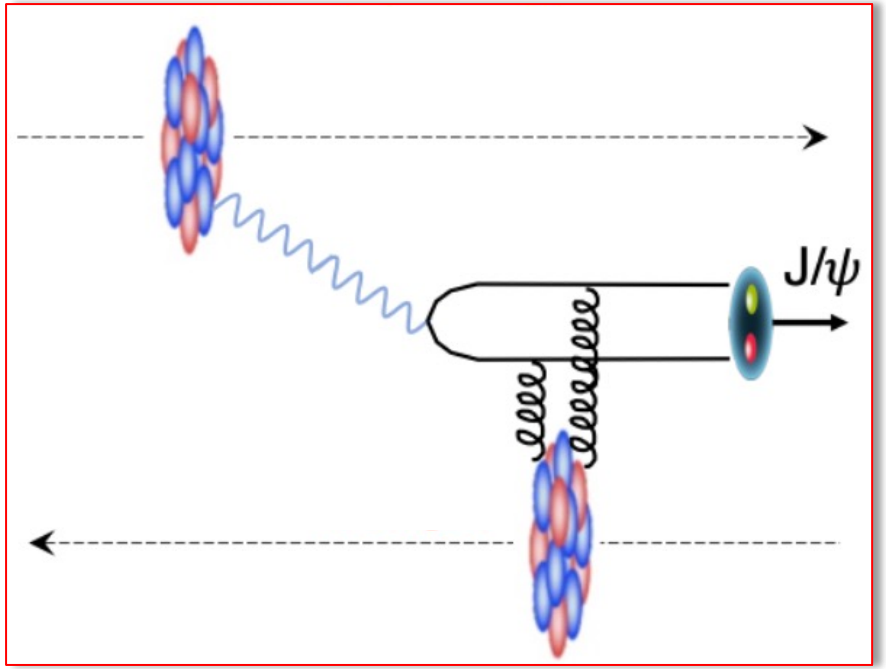
Coherent J/Ψ Photoproduction in A-A UPCs

γ+Pb → J/ψ+Pb



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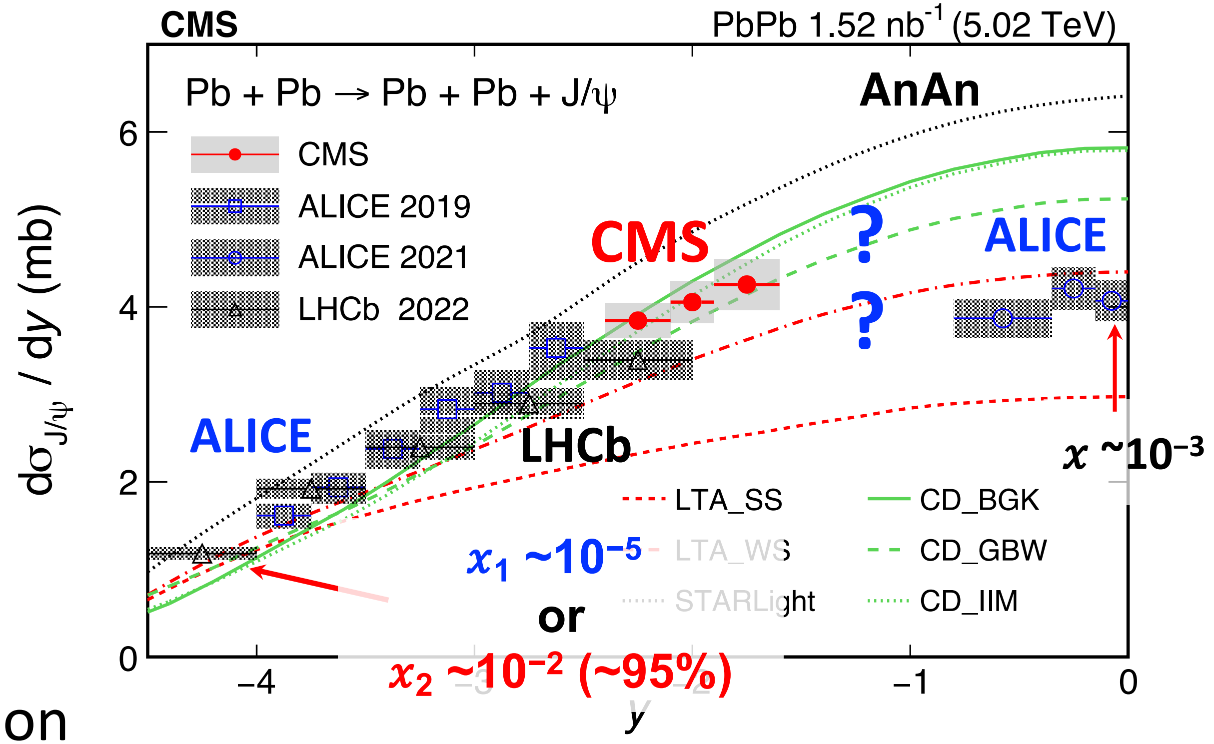
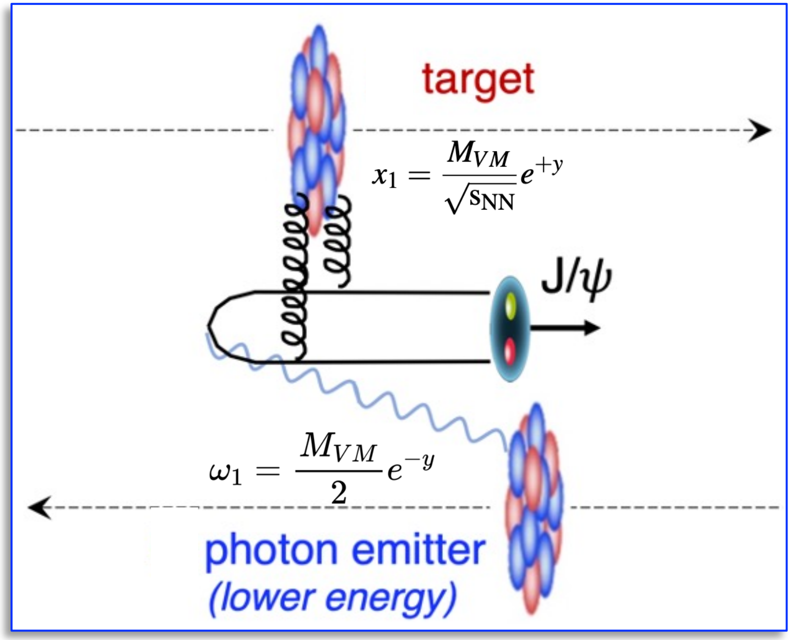
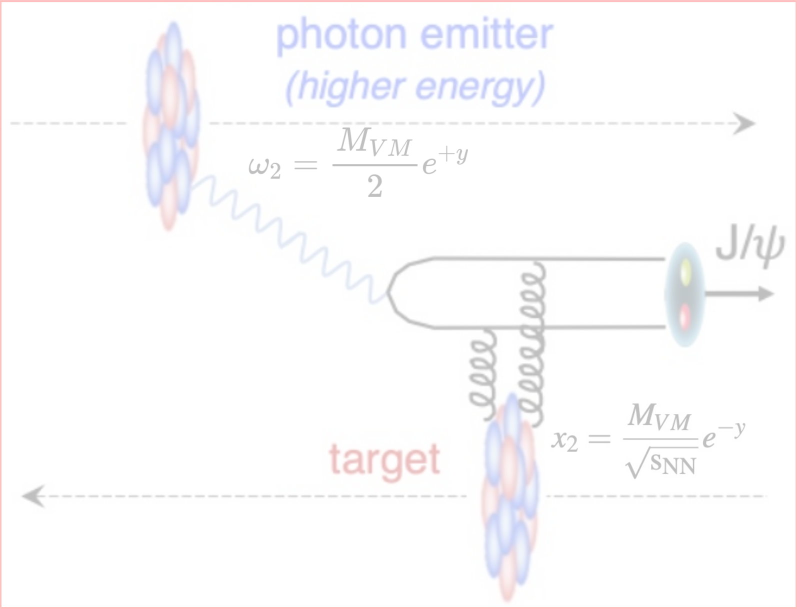


$$x = \frac{M_{VM}}{\sqrt{s_{NN}}} e^{\mp y}$$

low-energy photons dominant

Two-Way Ambiguity in A-A UPC





$$\frac{d\sigma_{AA\to AA'J/\psi}}{dy} = N_{\gamma/A}(\omega_1)\cdot\sigma_{\gamma A\to J/\psi A'}(\omega_1) + N_{\gamma/A}(w_2)\cdot\sigma_{\gamma A\to J/\psi A'}(w_2)$$

what we measure

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

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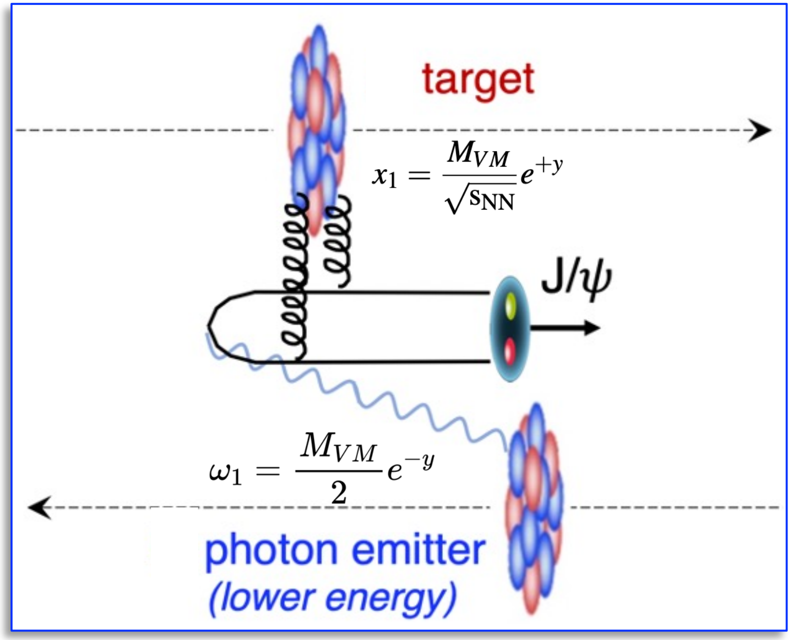

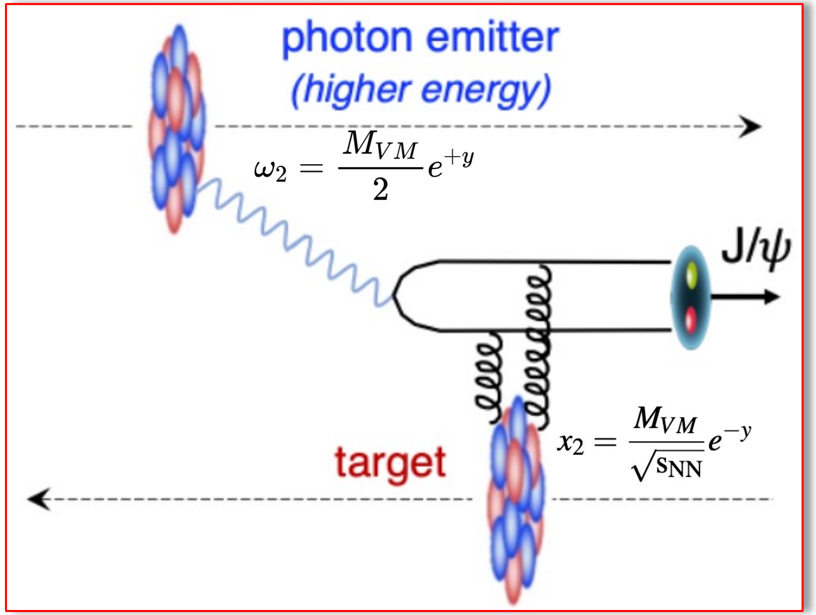

Smaller-x

$$\frac{d\sigma_{AA\to AA'J/\psi}}{dy} = N_{\gamma/A}(\omega_1)\cdot\sigma_{\gamma A\to J/\psi A'}(\omega_1) + N_{\gamma/A}(w_2)\cdot\sigma_{\gamma A\to J/\psi A'}(w_2)$$

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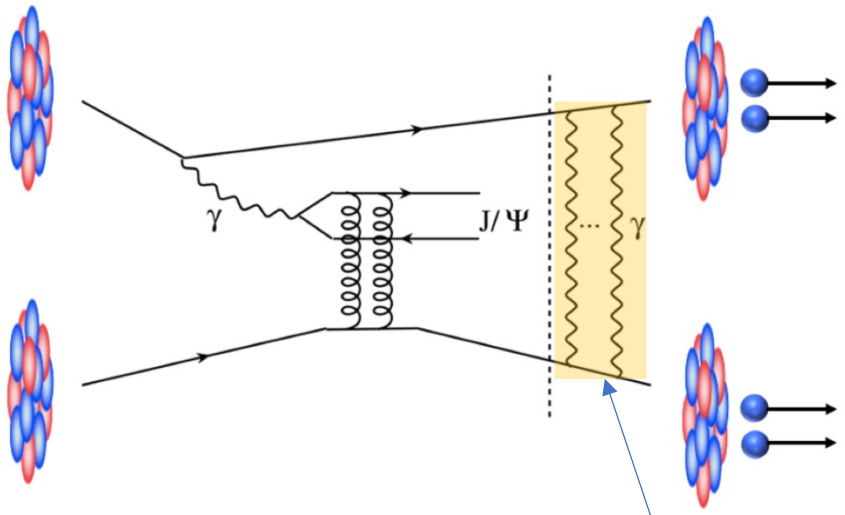
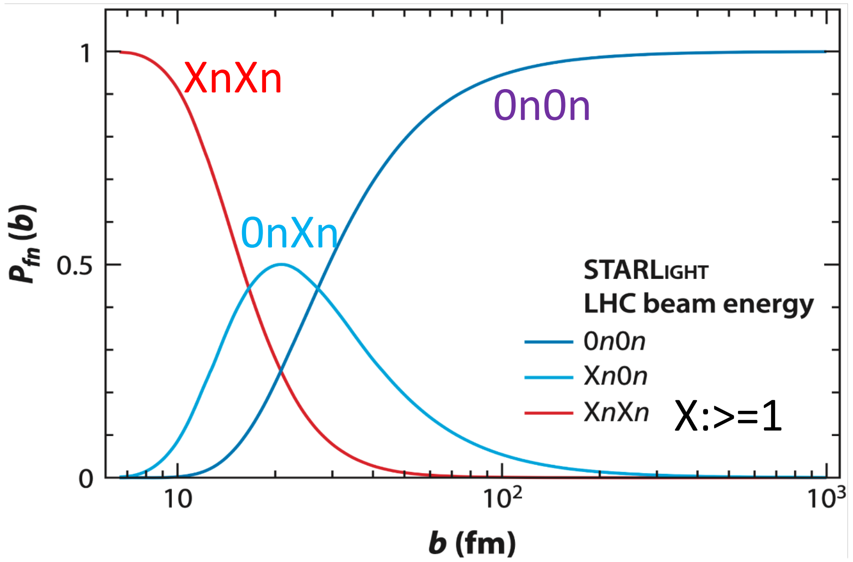
Method to Solve Two-Way Ambiguity in A-A UPC

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

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



Klein & Steinberg,
Ann. Rev. Nucl. Part. Sci. 70 (2020) 323



Neutron emission via EMD with additional photon exchange:

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

- Analogous to centrality:
  - $b_{XnXn} < b_{0nXn} < b_{0n0n}$ **in UPC**

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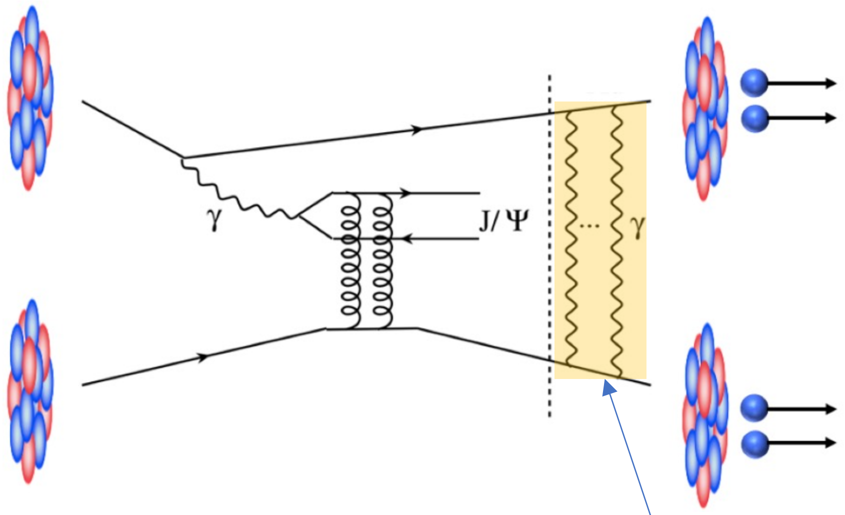

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from theoretical calculation

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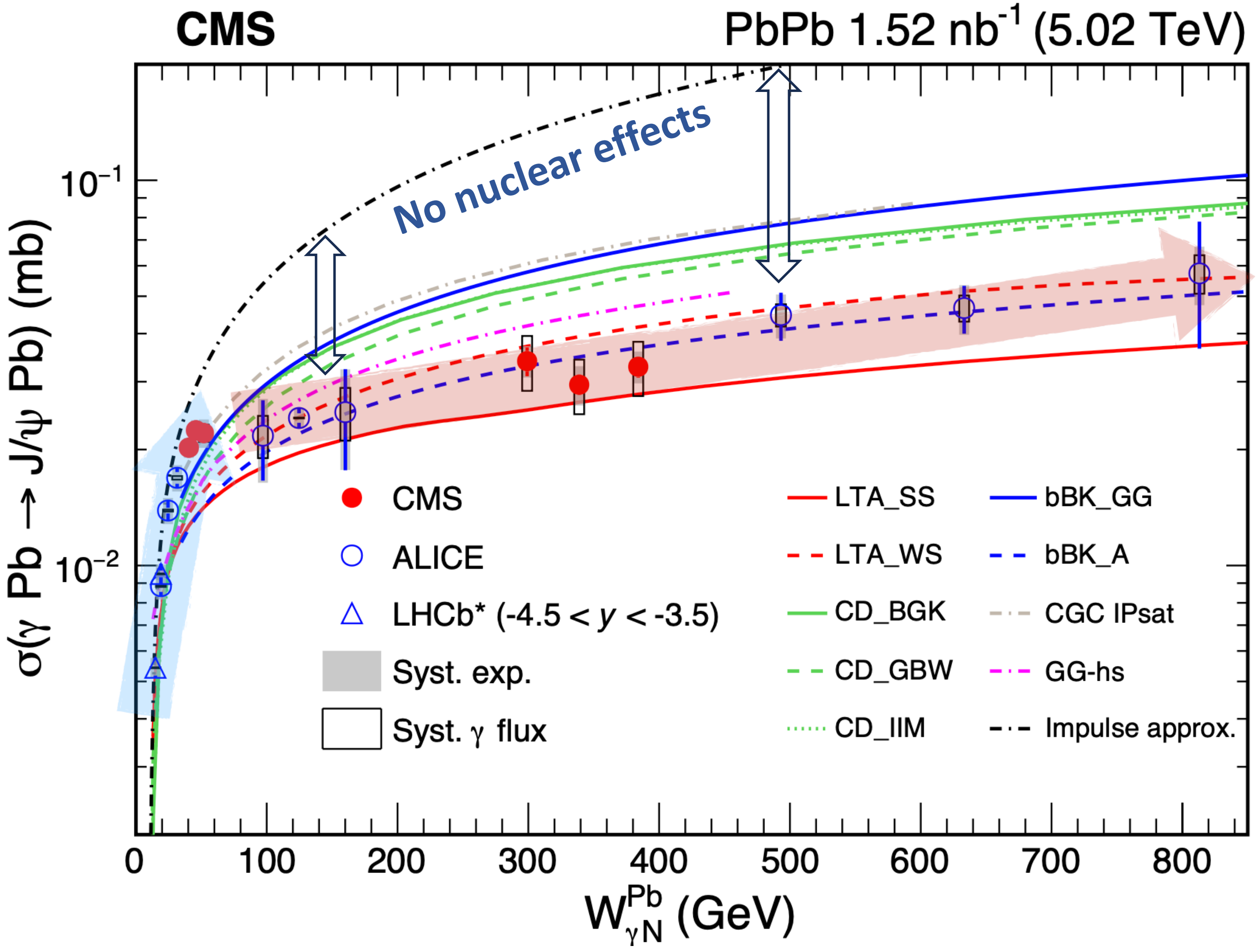
$\sigma_{\gamma A\to J/\psi A'(\omega_1)}$ **Larger-x**

$\sigma_{\gamma A\to J/\psi A'(w_2)}$ **Smaller-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

Strongly saturated cross sections

See Jani Penttala’s talk

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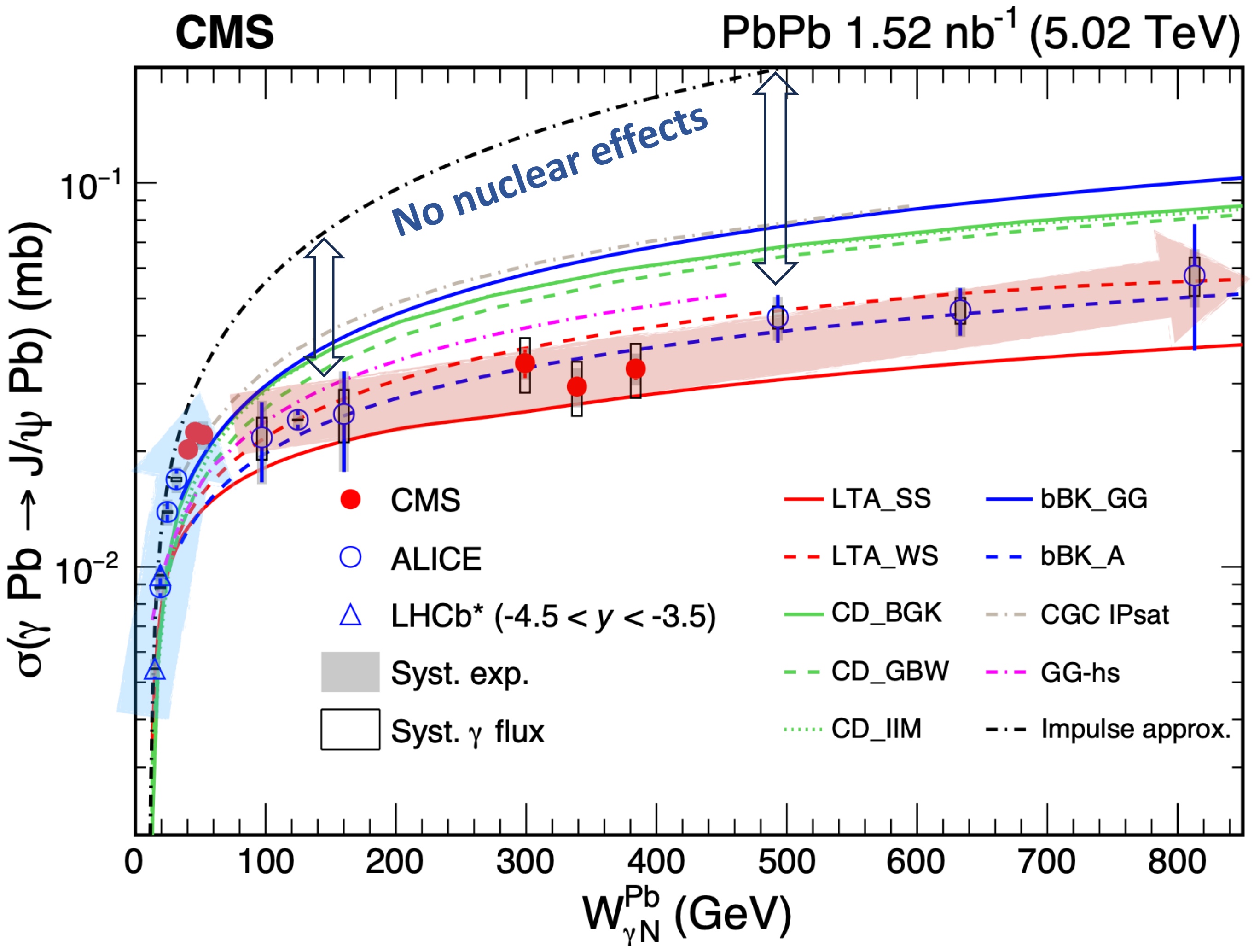

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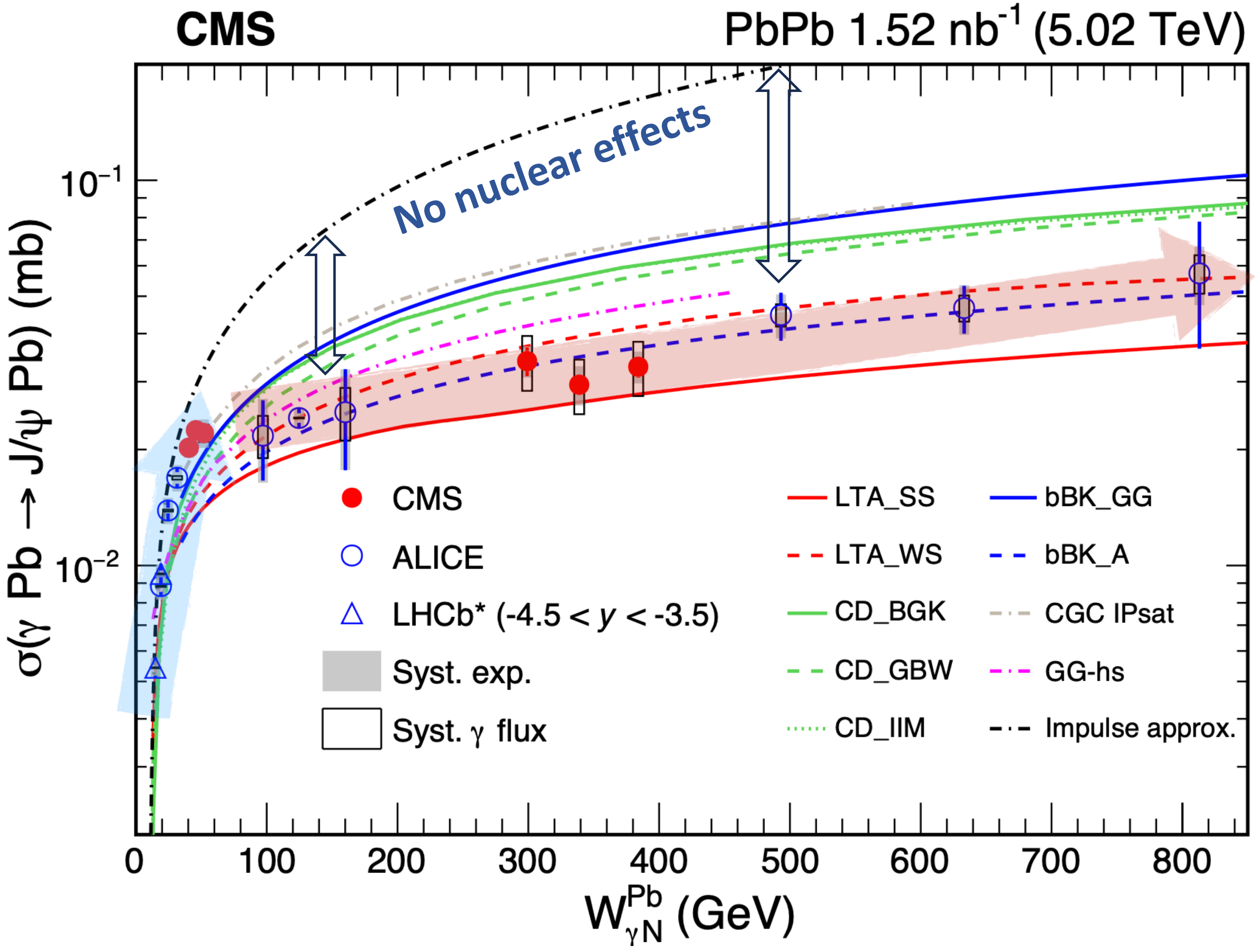

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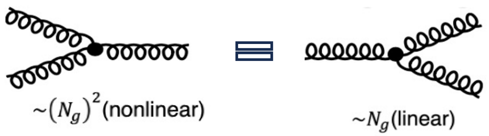
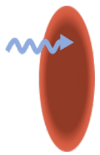
Gluon Saturation?

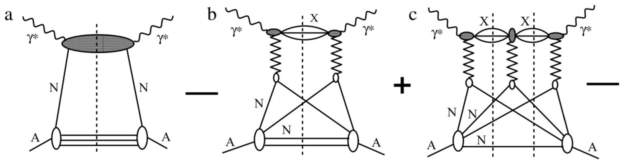


Black Disk Limit?



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

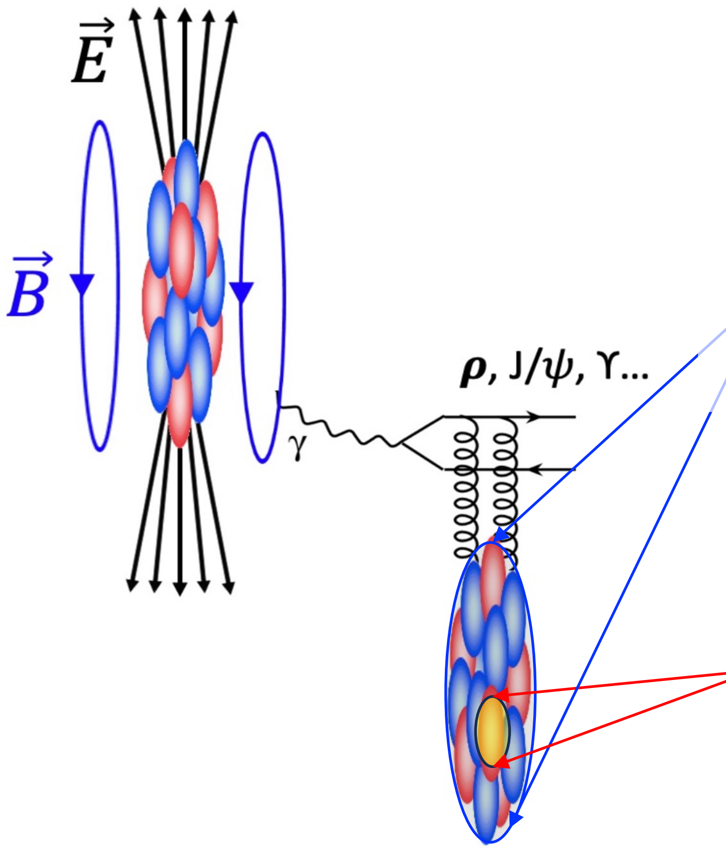
Nuclear shadowing?



What's the underlying physics?

See Jani Penttala's talk

How About Incoherent J/Ψ Photoproduction?



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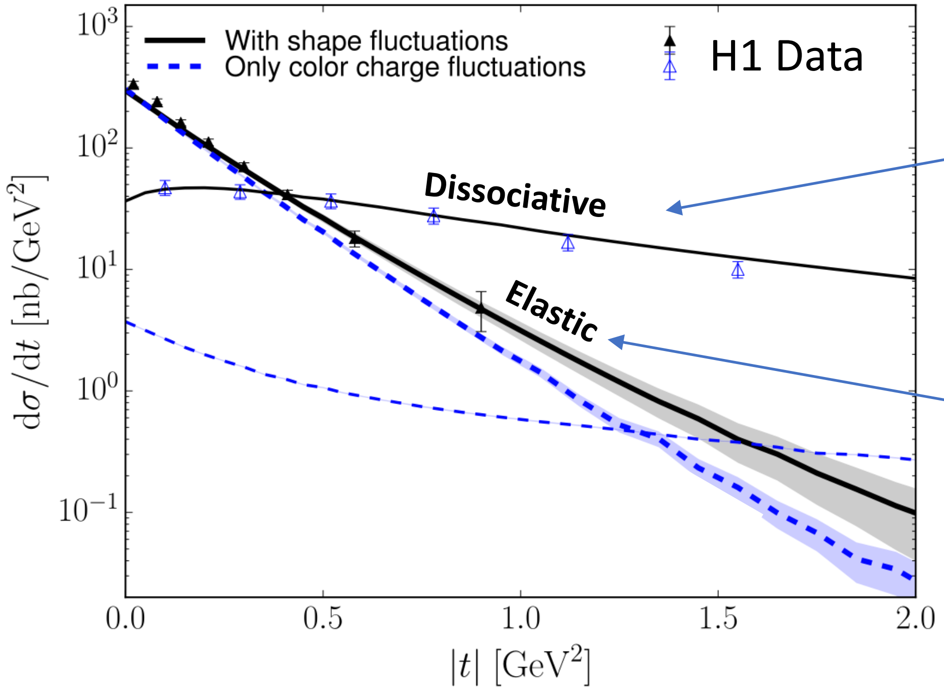
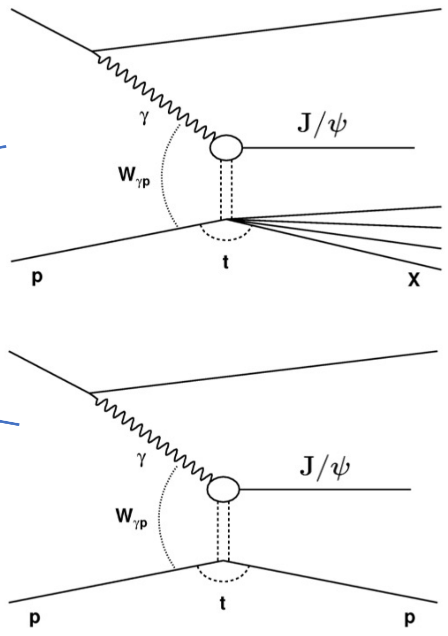
Fluctuating Gluons Probed via γ+p

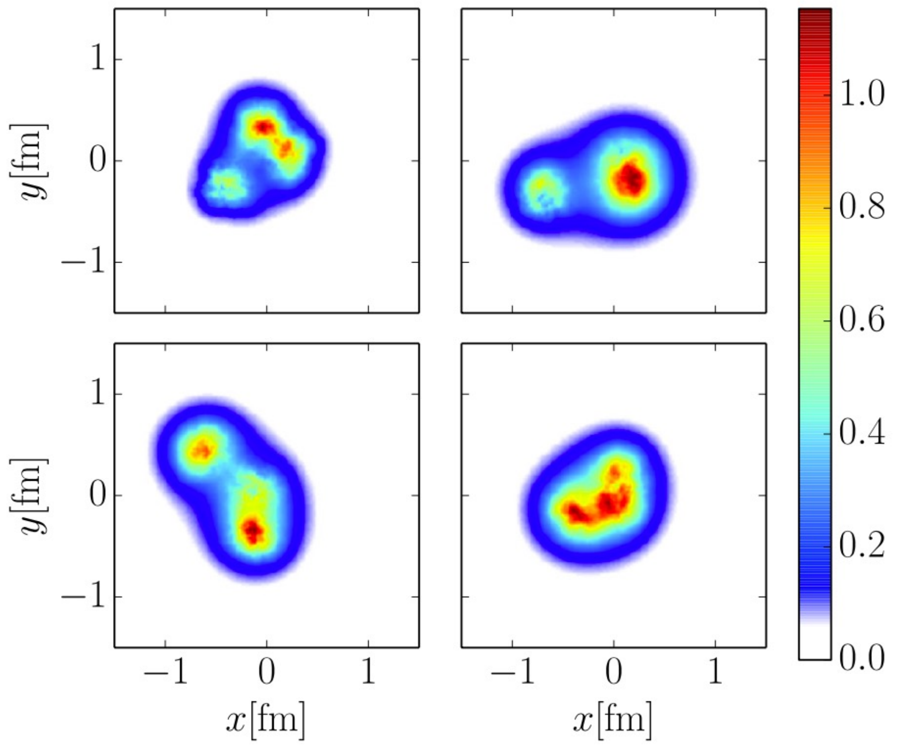
CGC IPsat considering the **fluctuations** of **geometry** (shape and size), **energy density**, **local saturation scale** and **color charge**, successfully describe the HERA data

J/Ψ Photoproduction at HERA



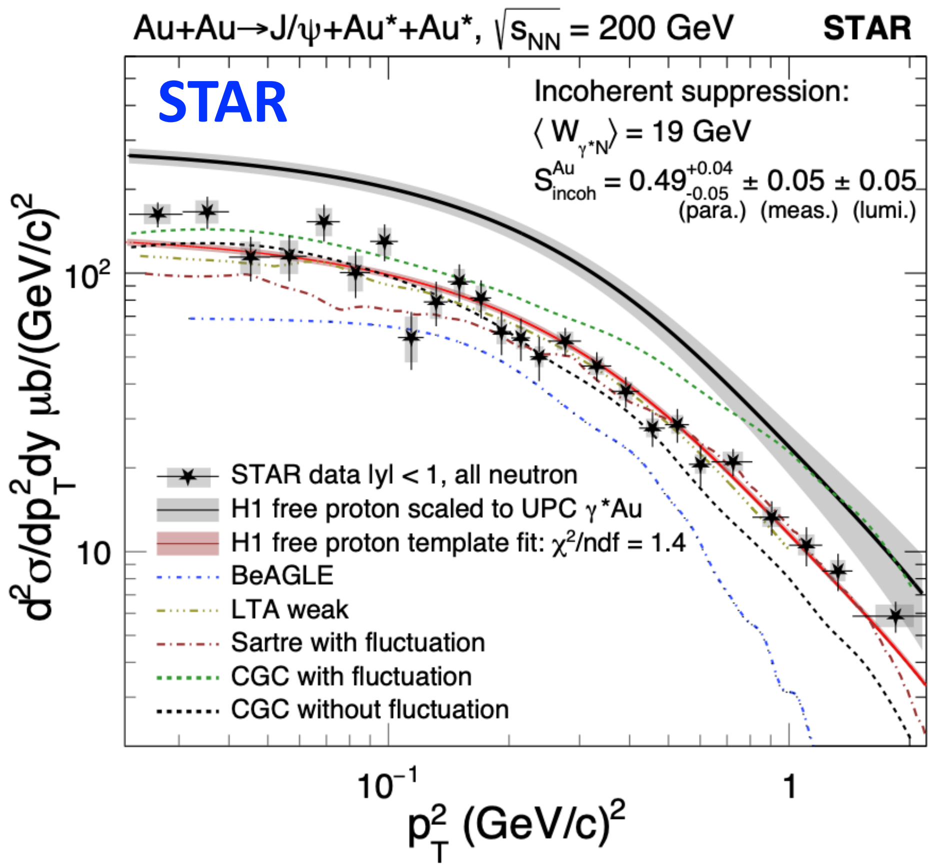


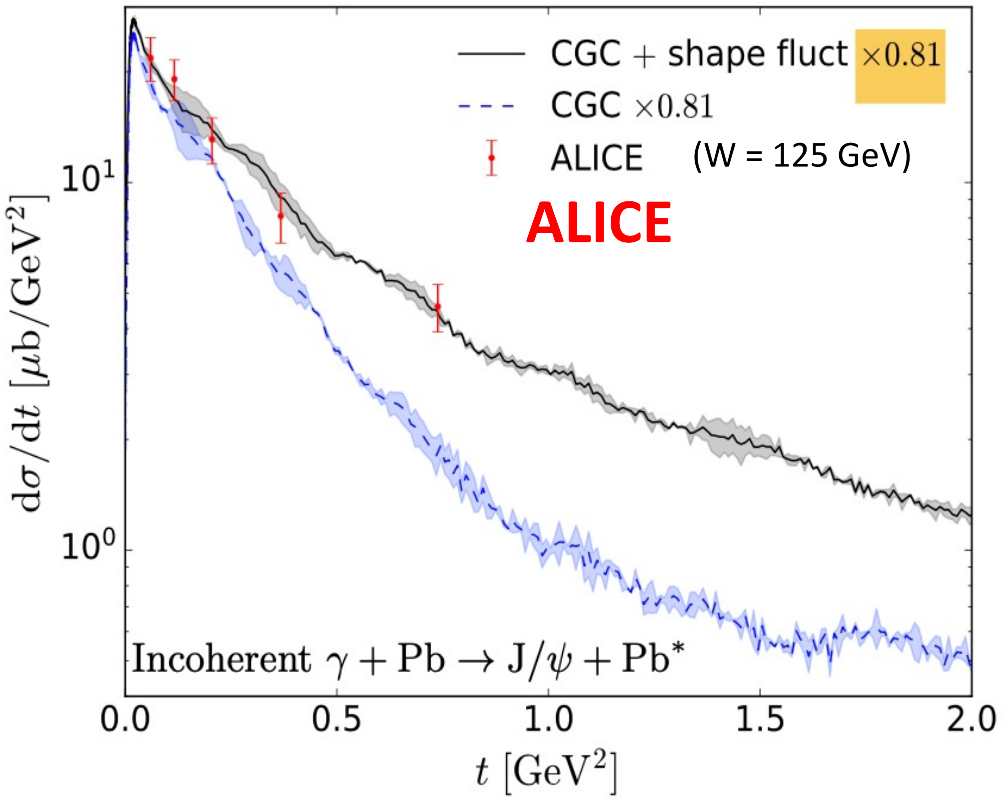
Rep. Prog. Phys. **83** (2020) 082201



CGC IPsat is impact parameter dependent saturation model under the Color-Glass Condensate framework

Fluctuating Gluons Probed via Incoherent γ+Au/Pb

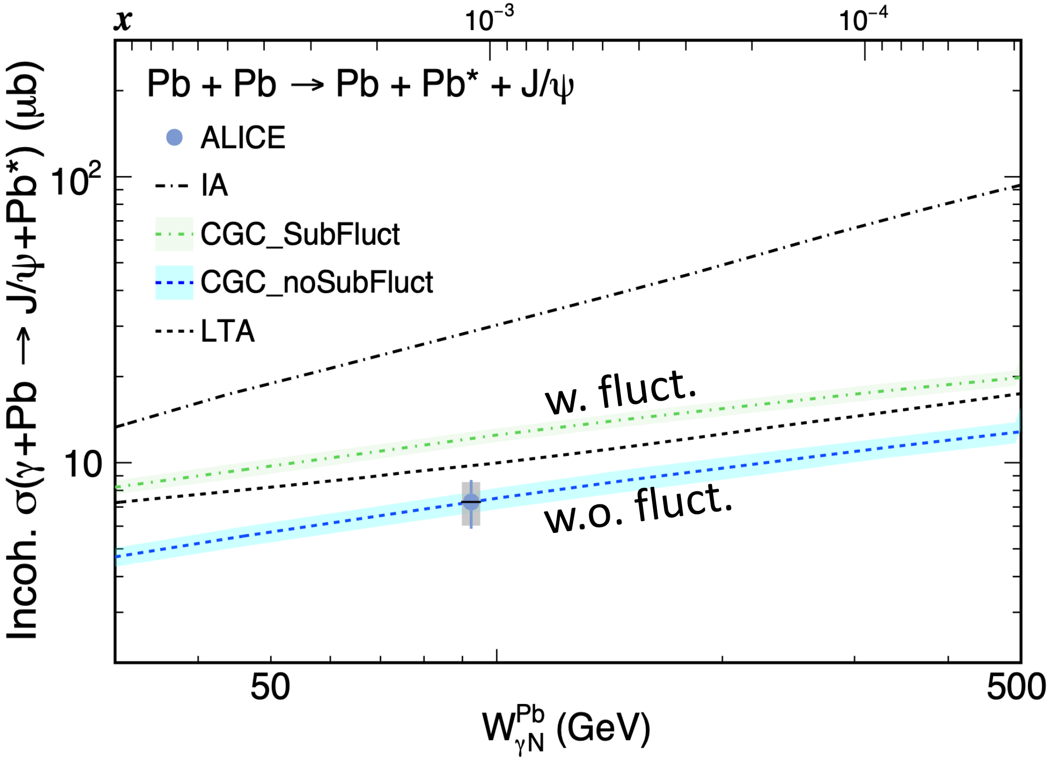


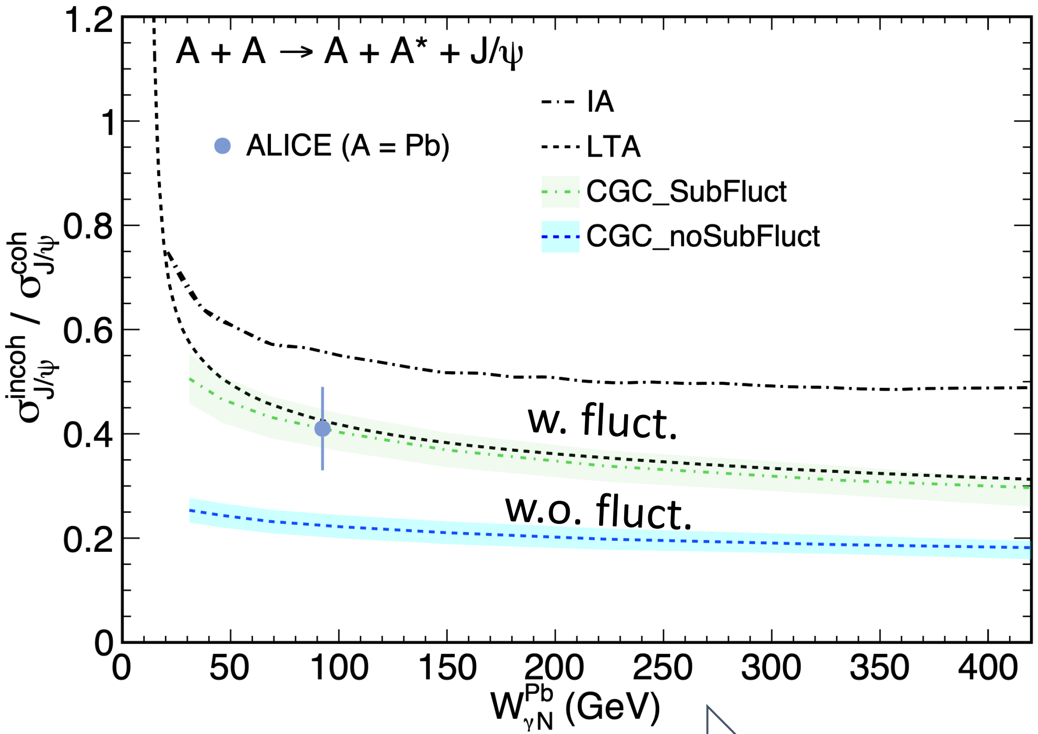


t distribution from STAR: well described by LTA, but in between two scenarios of CGC with and without sub-nucleonic fluctuations
t distribution from ALCIE: slope is well describe by CGC with sub-nucleonic fluctuations however, missed by a common scaling factor

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

Fluctuating Gluons and Energy Dependence



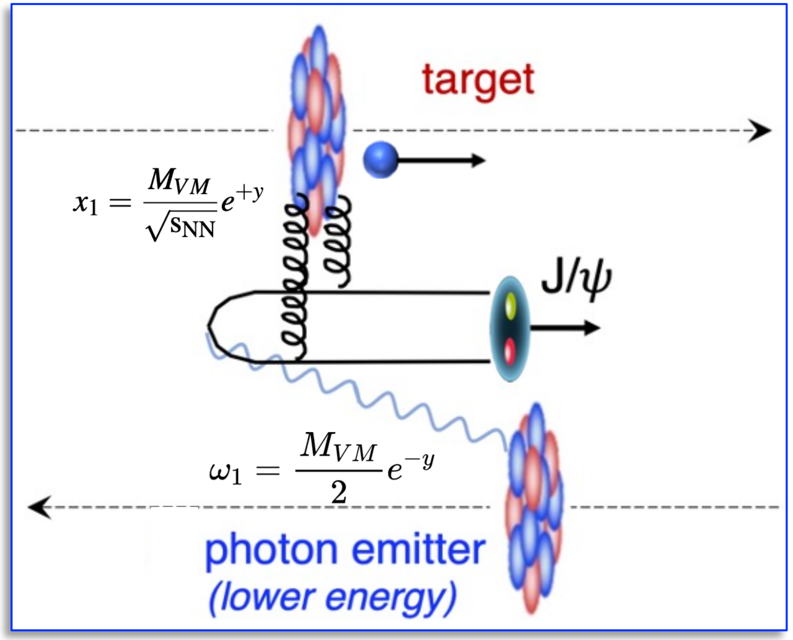


Increasing W (decreasing x)

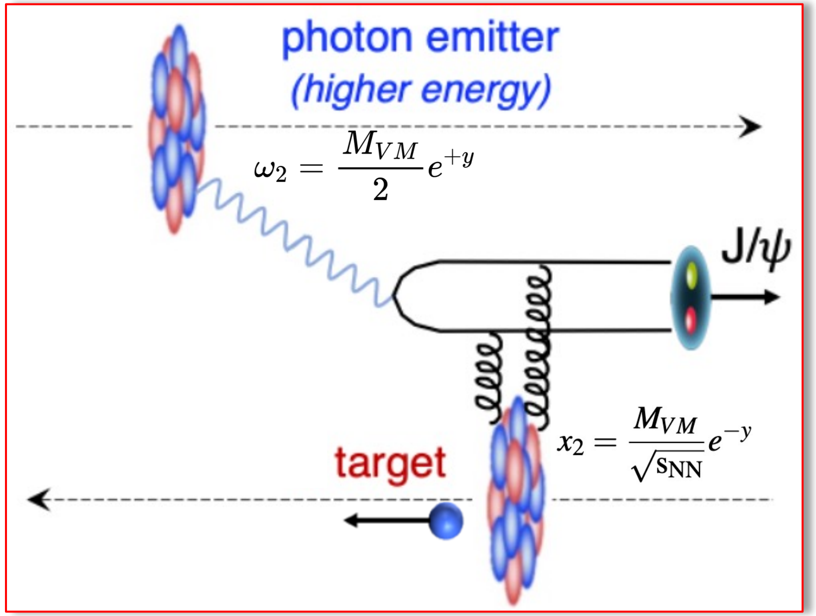
How the fluctuating gluons evolute, especially towards small-x limit?

- 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)

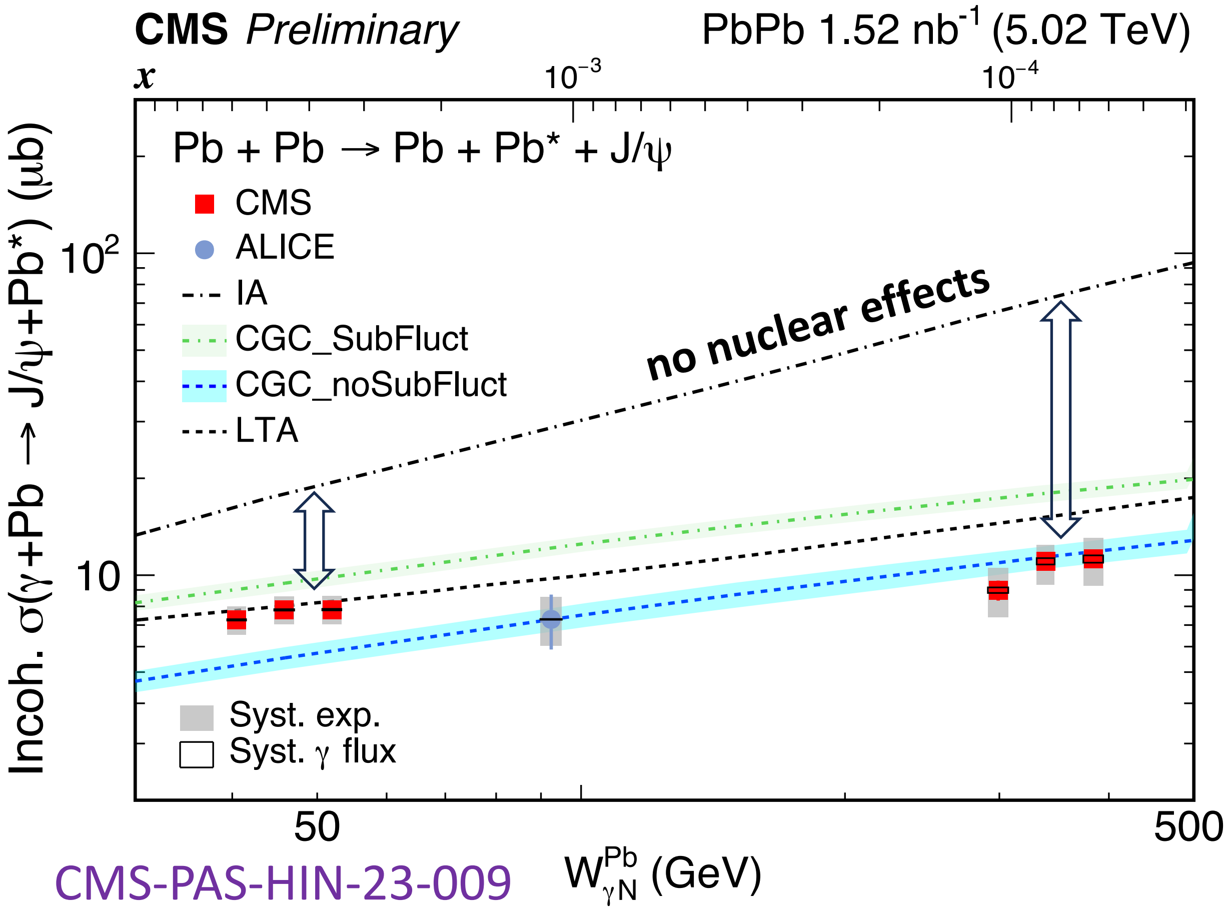


J/Ψ-Xn (Opposite Direction)

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"

Incoh. J/Ψ Cross Section Per γ+Pb

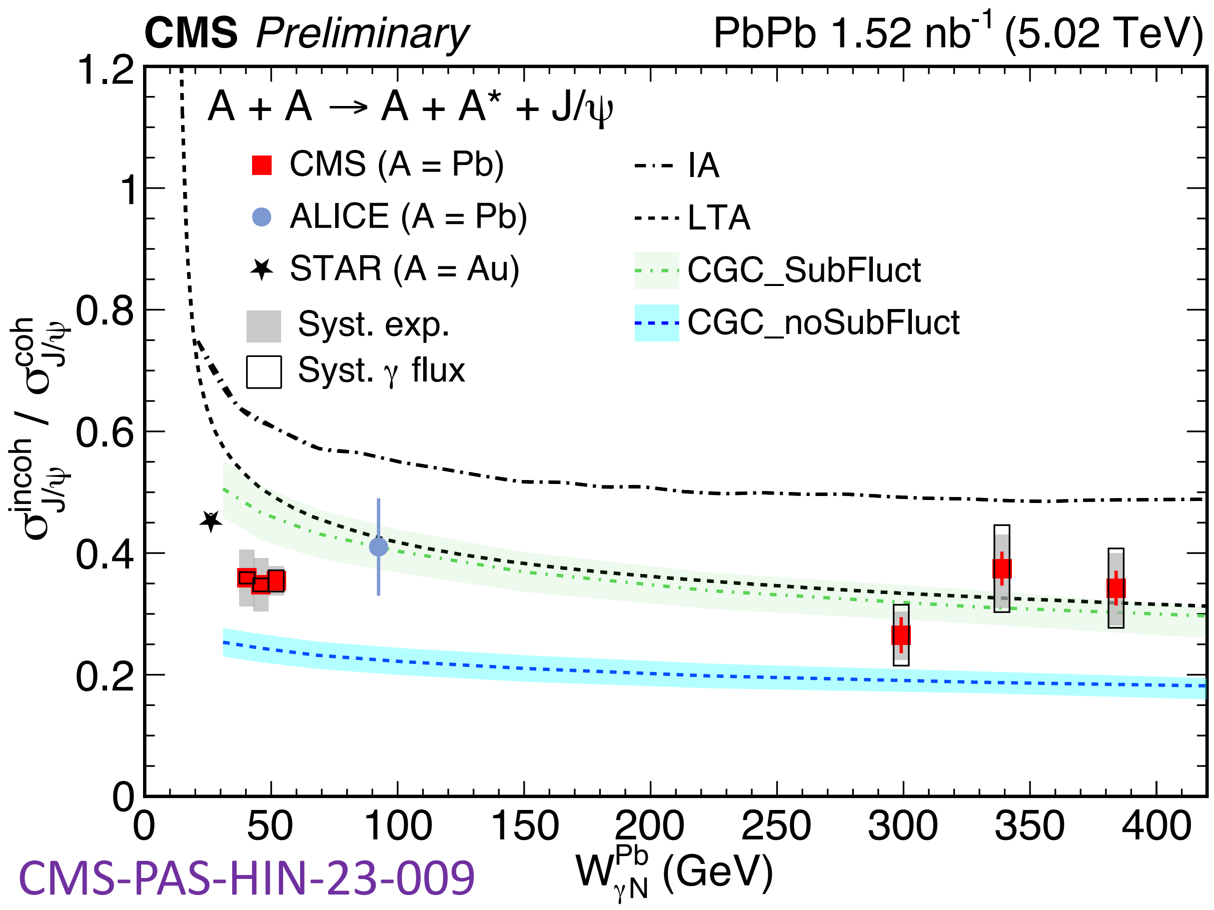


CMS-PAS-HIN-23-009

- **First energy-dependent** measurement of incoherent J/Ψ photoproduction
  - **Strongly saturated trend again**
- **Strong suppression** compared to Impulse Approximation (IA)
- LTA (nuclear shadowing) 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



CMS-PAS-HIN-23-009

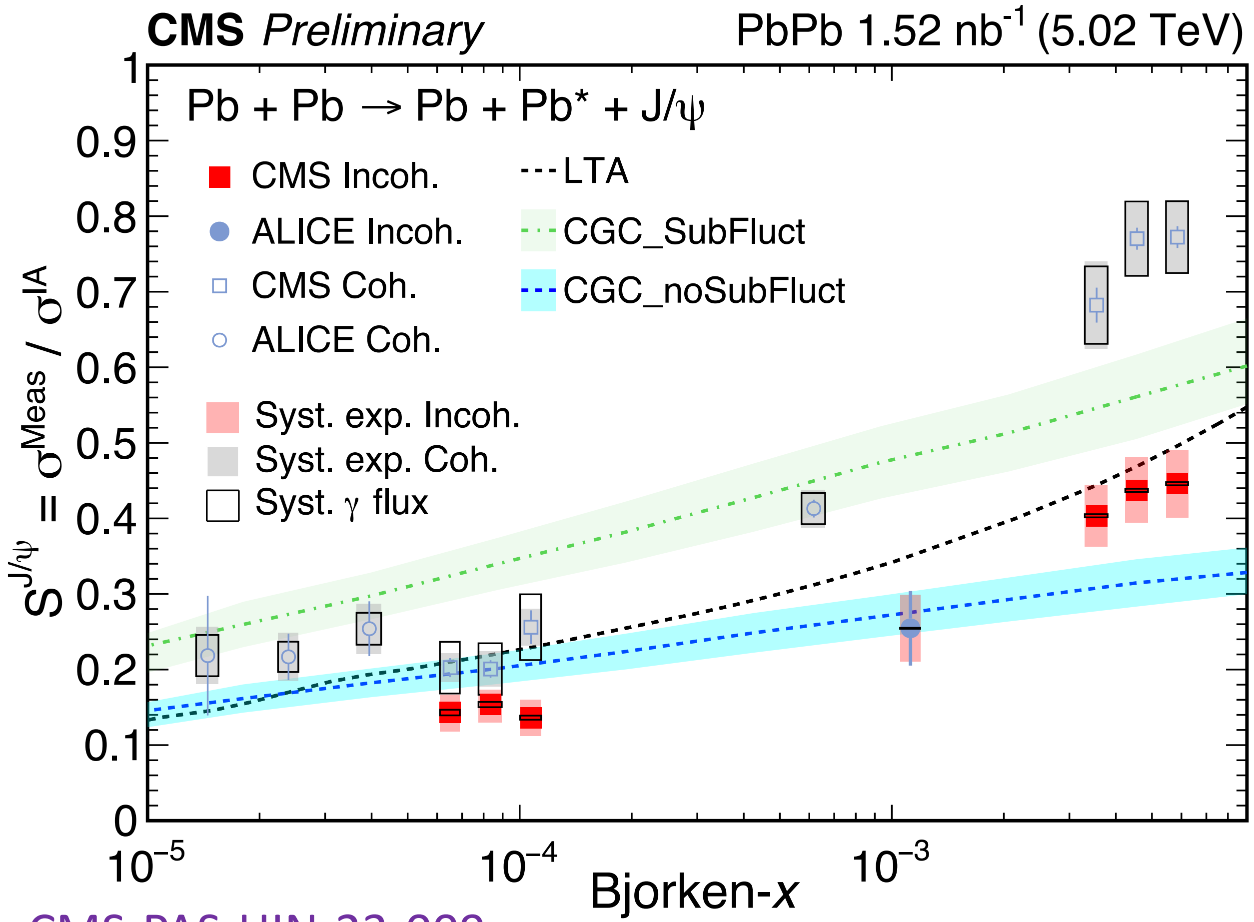
- **No clear W dependent (40 < W < 400 GeV)**
  - Not support Black Disk Limit is reached
- ALICE data agrees with CMS data, STAR data slightly rises towards lower W
- LTA and CGC with sub-nucleonic fluctuation qualitatively describe data trend

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

→

Cleanest test for theoretical assumptions on nuclear effects

Nuclear Suppression Factor



CMS-PAS-HIN-23-009

Coh: CMS, PRL 131, 26201 (2023); ALICE, JHEP 10, (2023) 119

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

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

→ 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 $x < 10^{-4}$
- No models can describe the data

Summary

- Both **Coh. and Incoh.** J/Ψ photoproduction in UPCs are observed to be **strongly saturated at high energy**
- Probing nuclear gluonic structure **over broad x interval**: **10^{-2} - 10^{-5}**
    - At scales of nucleus (coh.) and nucleon (incoh.)
- **Ratio of Incoh/Coh J/Ψ stay constant ~0.3-0.5** for $40 < W < 400$ GeV
    - Sub-nucleonic fluctuations are needed to describe data
    - Not support that black disk limit is reached
- **Nuclear suppression** factor of J/Ψ photoproduction via γ+Pb interaction:
    - **Stronger towards lower x, eventually flattens out**
    - Incoh. J/Ψ is **more suppressed** than Coh. J/Ψ photoproduction
- Theoretical models (saturation or shadowing) **only occasionally describe partial** measured observables
    - **Significant theoretical improvements are needed**

Future Opportunities

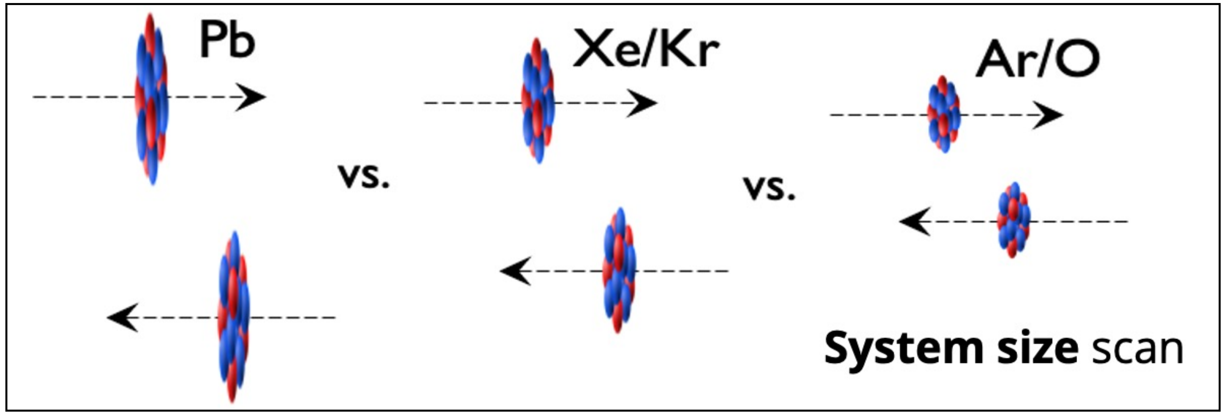
Various VMs in different nucleus-nucleus UPCs with **neutron taggings:**

- **Coherent and Incoherent** productions
- Control of **dipole sizes** and **hard scales**.
- **Test on the A dependences**
- Variation of **saturation scales**

$$\boldsymbol{x}\ vs.\ \boldsymbol{Q^2}\ vs.\ \boldsymbol{Q_S^2}$$

PbPb $L_{int} = 13\ nb^{-1}$

Meson	σ	All Total	Central 1 Total	Central 2 Total	Forward 1 Total 1	Forward 2 Total
$\rho \to \pi^+\pi^-$	5.2b	68 B	5.5 B	21B	4.9 B	13 B
$\rho' \to \pi^+\pi^-\pi^+\pi^-$	730 mb	9.5 B	210 M	2.5 B	190 M	1.2 B
$\phi \to K^+K^-$	0.22b	2.9 B	82 M	490 M	15 M	330 M
$J/\psi \to \mu^+\mu^-$	1.0 mb	14 M	1.1 M	5.7 M	600 K	1.6 M
$\psi(2S) \to \mu^+\mu^-$	30μb	400 K	35 K	180 K	19 K	47 K
$\Upsilon(1S) \to \mu^+\mu^-$	2.0 μb	26 K	2.8 K	14 K	880	2.0 K

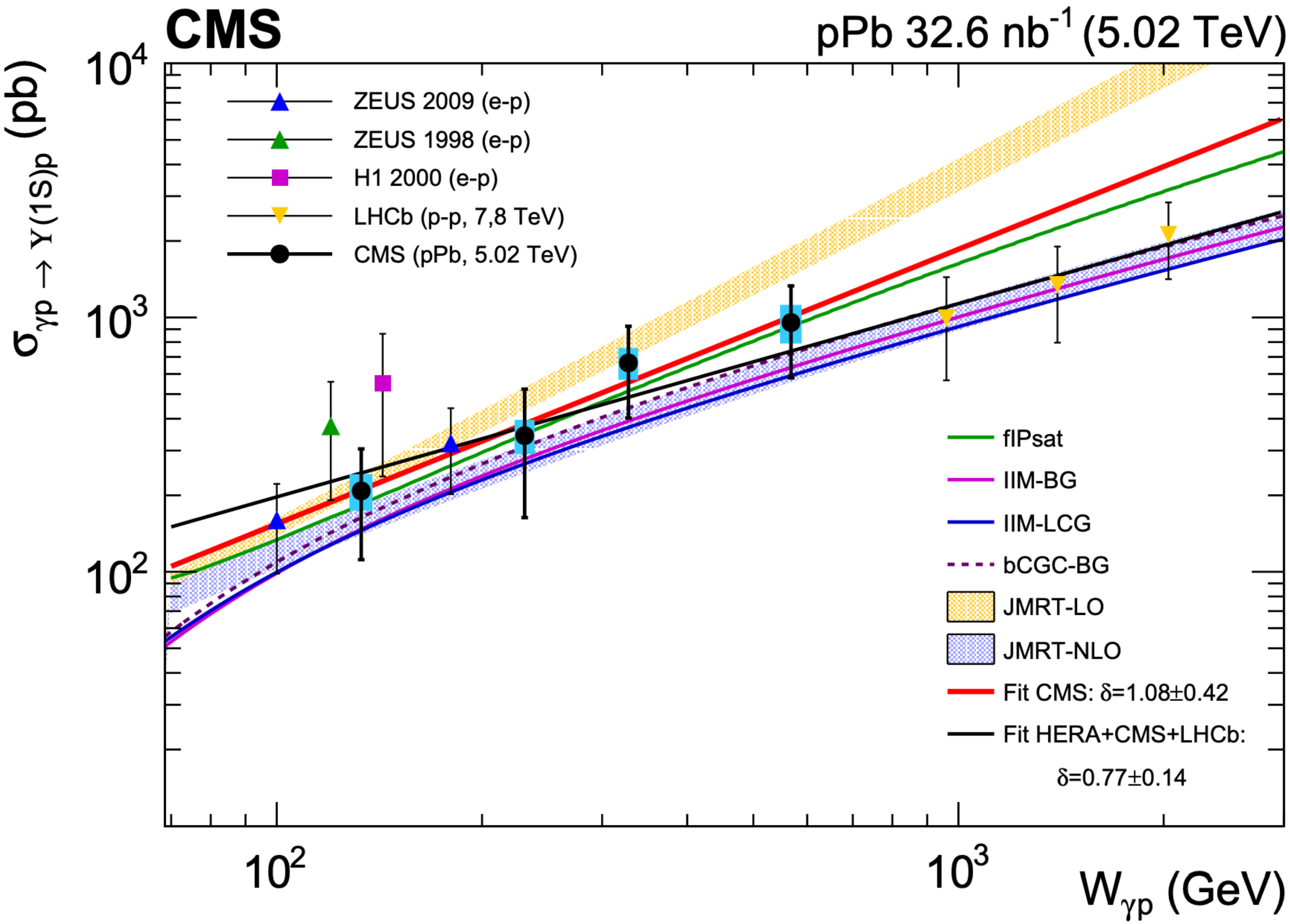


CERN Yellow Report, arXiv:1812.06772

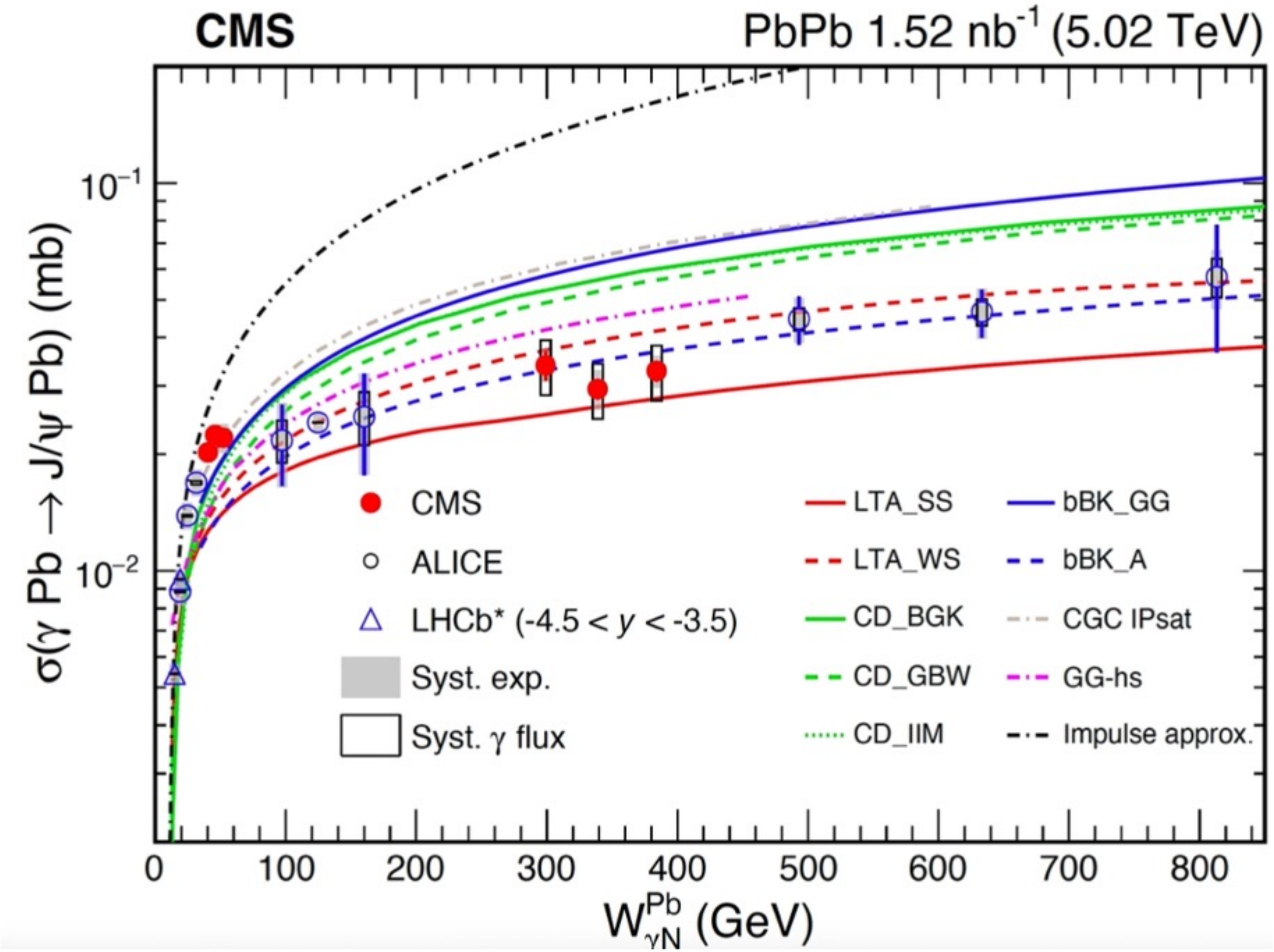
Thanks for your attention!
Welcome to Guangzhou!

Backup Slides

Exlusive Upsilon(1S) via γ+p Interactions



CMS and ALICE data follows the same trend



CMS: PRL 131, 262301 (2023) **ALICE: JHEP 10, (2023) 119**

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

CPC 277 (2022) 108388

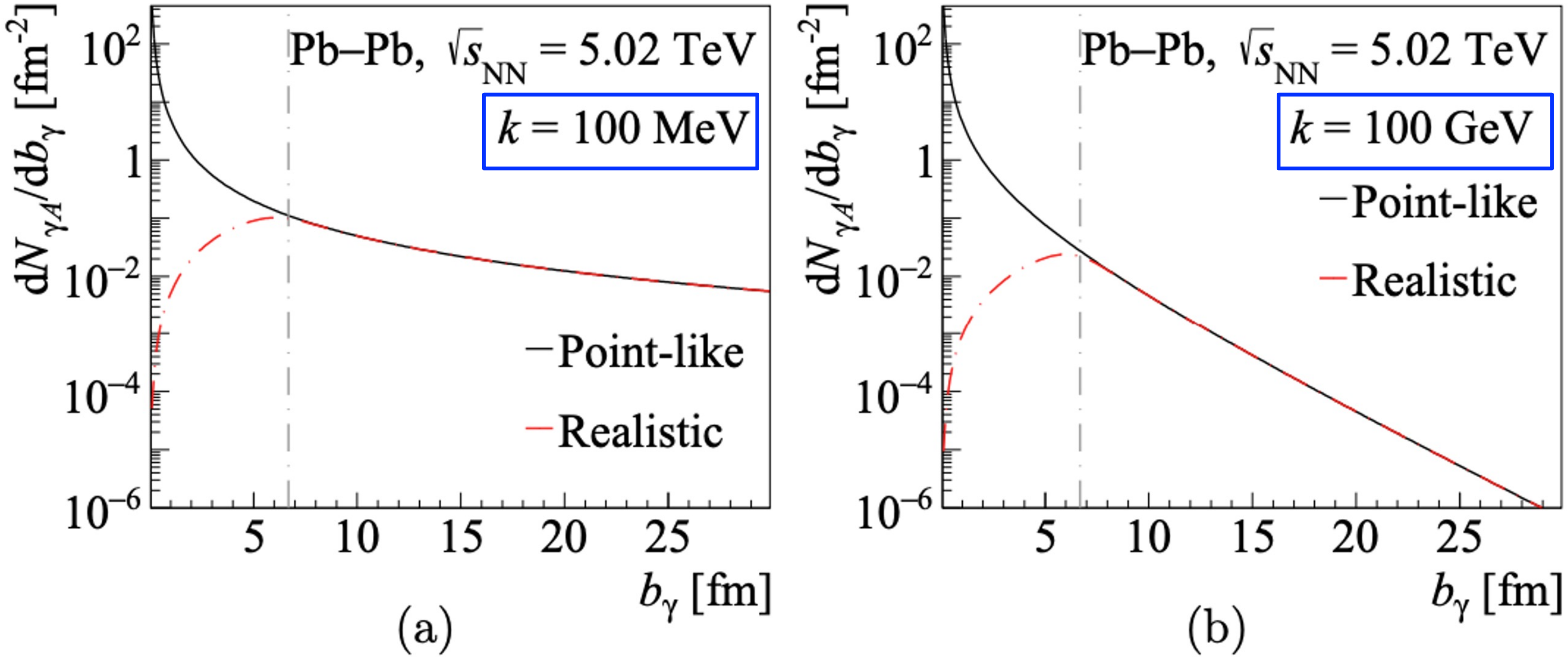
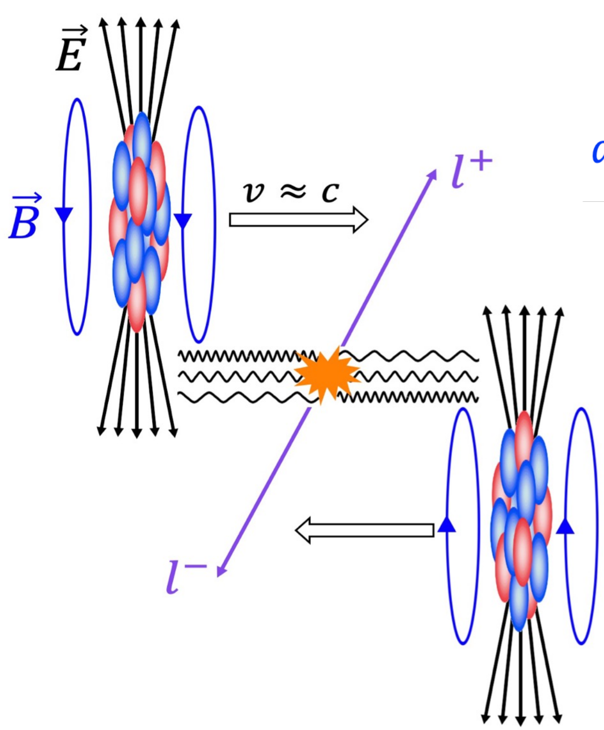


Figure 4: (Color online) Photon fluxes coming from a nucleus $N_{\gamma A}$ in the point-like source approximation and the realistic description as functions of impact parameter b_{γ} calculated at different photon energies: 100 MeV (a), 100 GeV (b).

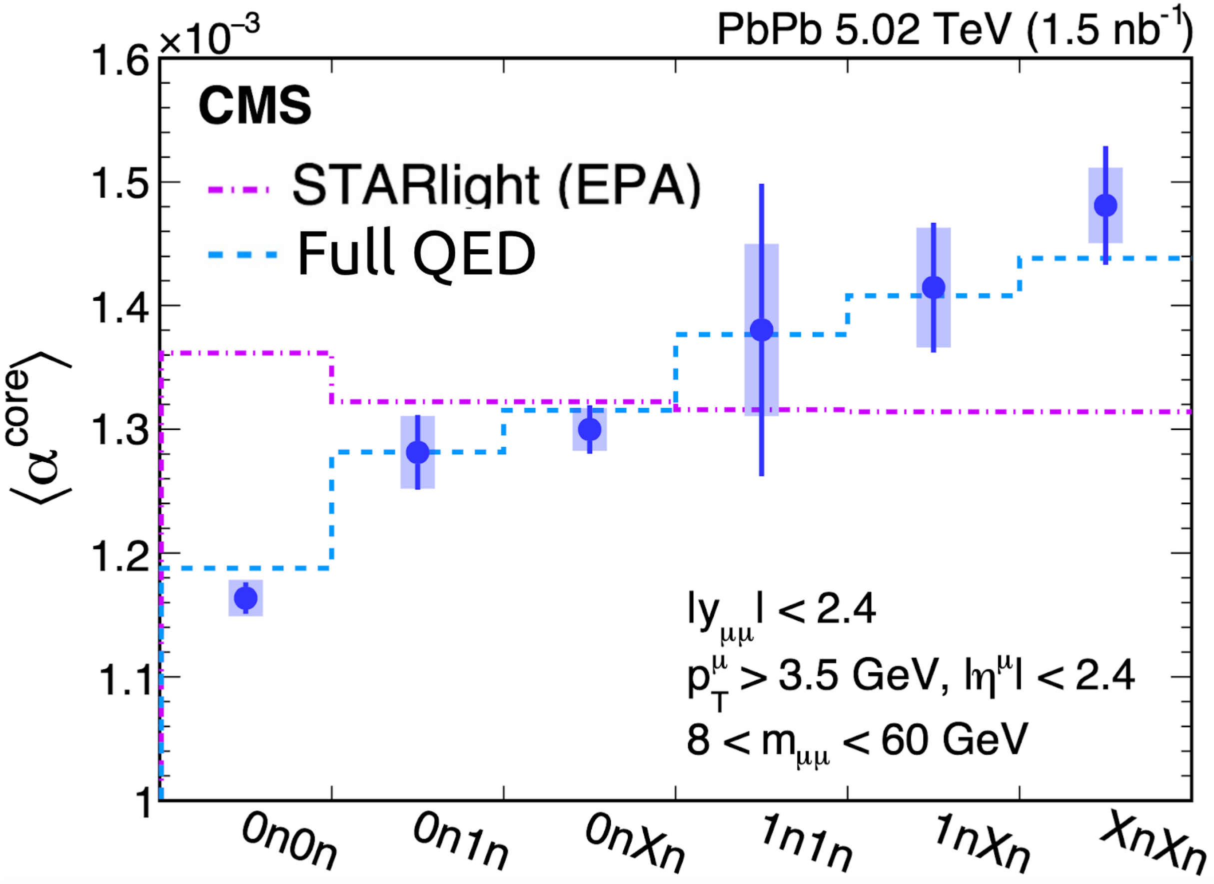
QED Dimuon with Neutron Tagging at CMS

PRL 127 (2021) 122001

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



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



(X: ≥2)

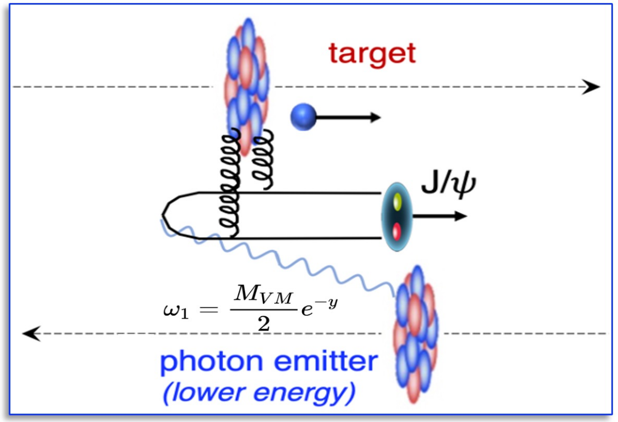
First direct evidence of b-dependent initial photon p_T, set strong base line for observe QGP EM effects in heavy ion collisions

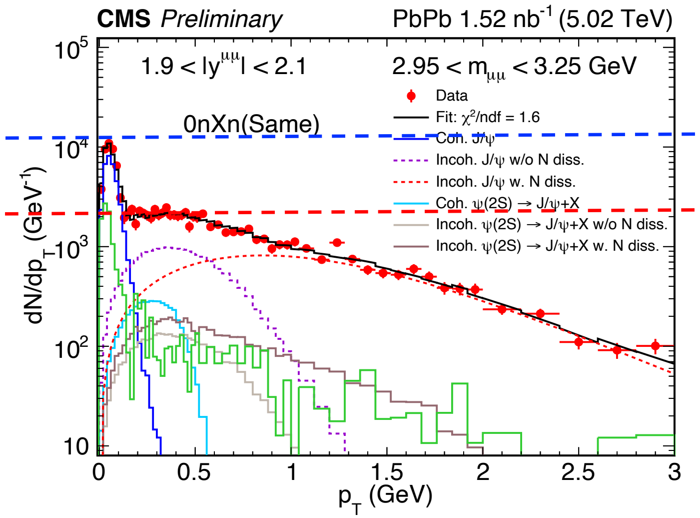
Example of Signal Extraction (0nXn)

Low-W

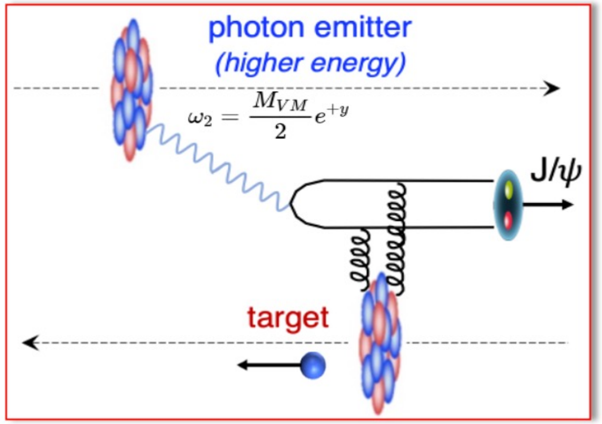
-y

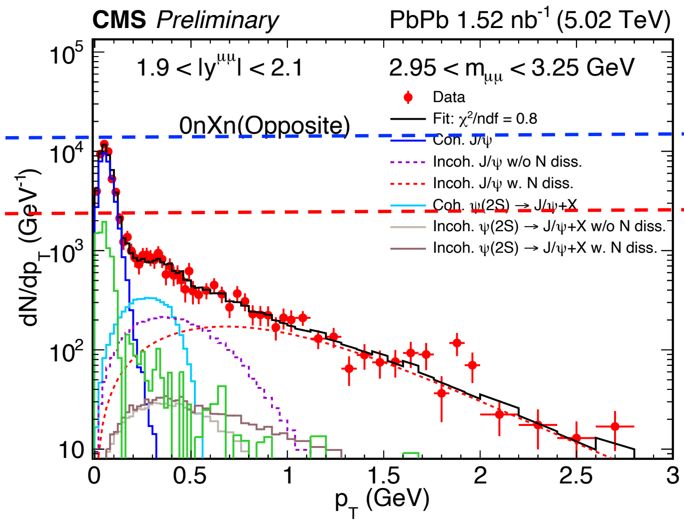
J/Ψ-Xn (Same Direction)





J/Ψ-Xn (Opposite Direction)



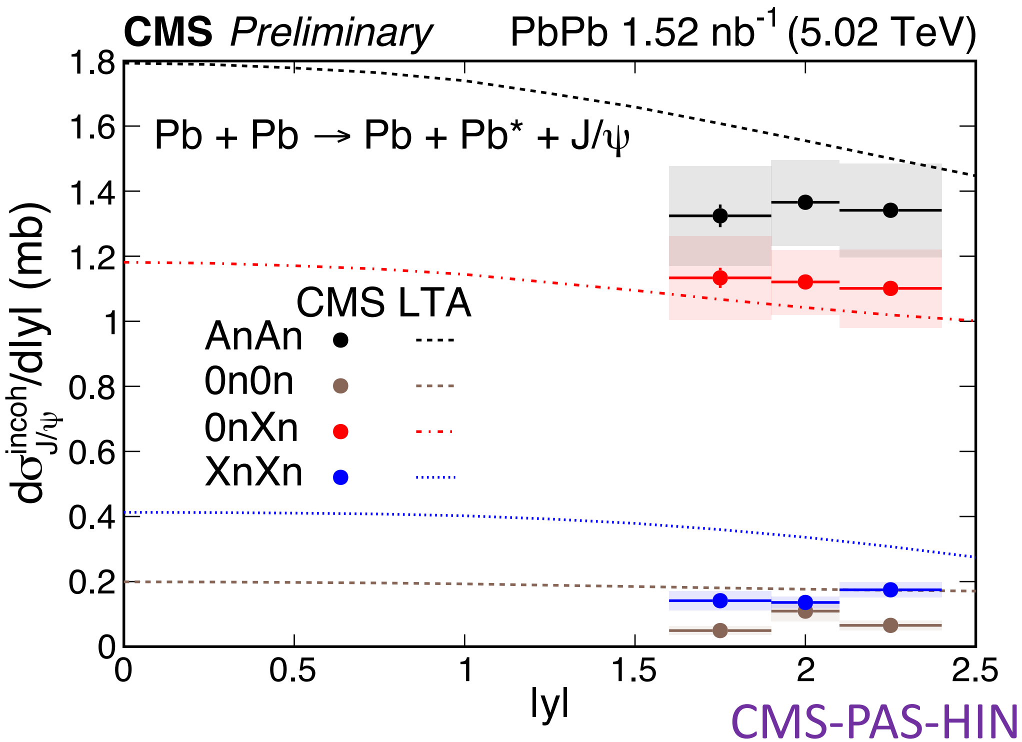


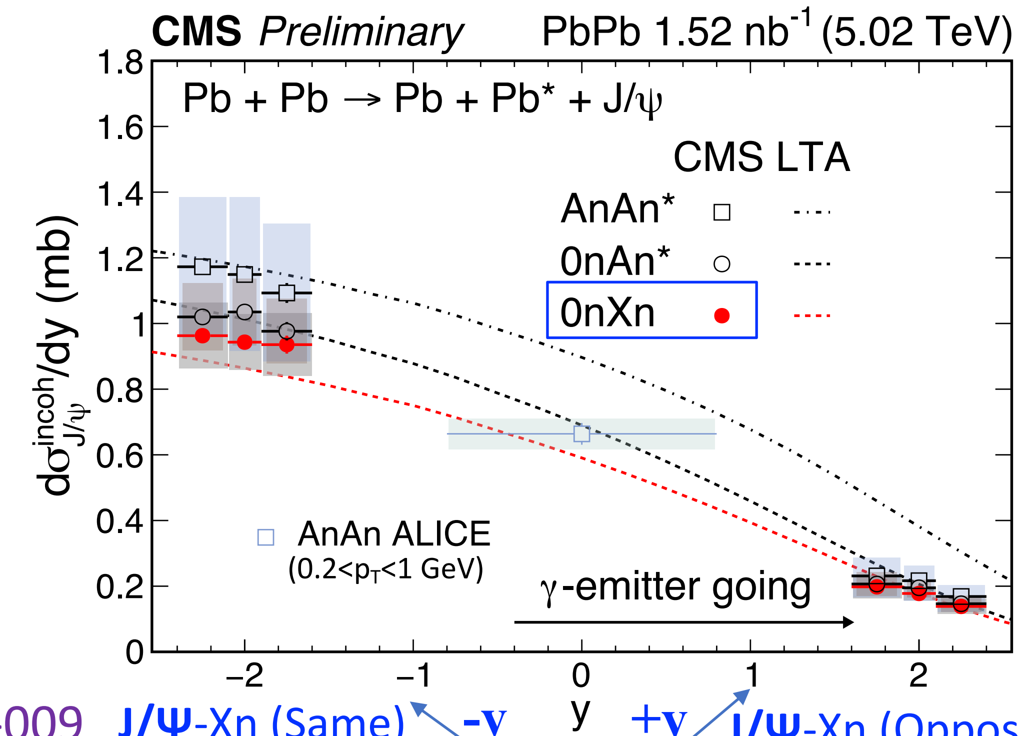
High-W

+y

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

Total InCoh. J/Ψ Photoproduction Cross Section





CMS-PAS-HIN-23-009

J/Ψ-Xn (Same) **-y** **+y** J/Ψ-Xn (Opposite)

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

ALICE: PRL 132, 162302 (2024)

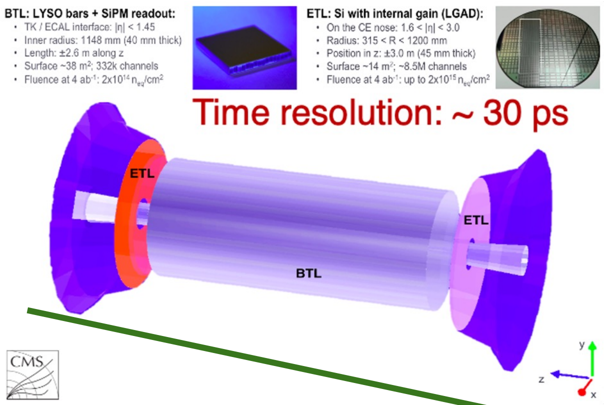
$$\frac{d\sigma^{0nAn^*}_{PbPb\to PbPb'\,J/\psi}(y)}{dy} = \frac{d\sigma^{0nXn}_{PbPb\to PbPb'\,J/\psi}(y)}{dy} + \frac{d\sigma^{0n0n}_{PbPb\to PbPb'\,J/\psi}(y)}{dy}$$

- 0nXn events: Data at (-y) are **5-6 times** of data at (+y) ➔ **Strong incoh. J/Ψ – Xn correlation**

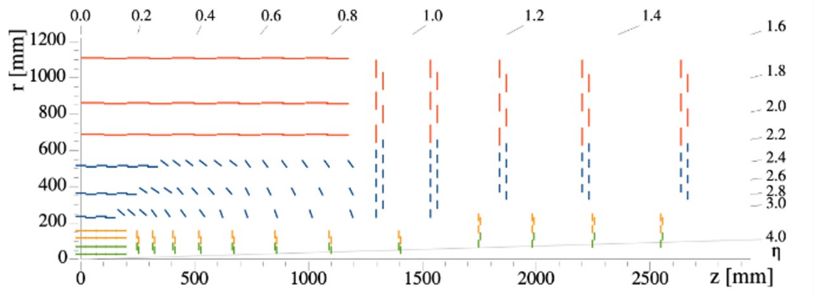
Relative fractions at (+y) and (-y) in 0n0n are asummed to be same as what measured in 0nXn events

Future Opportunities

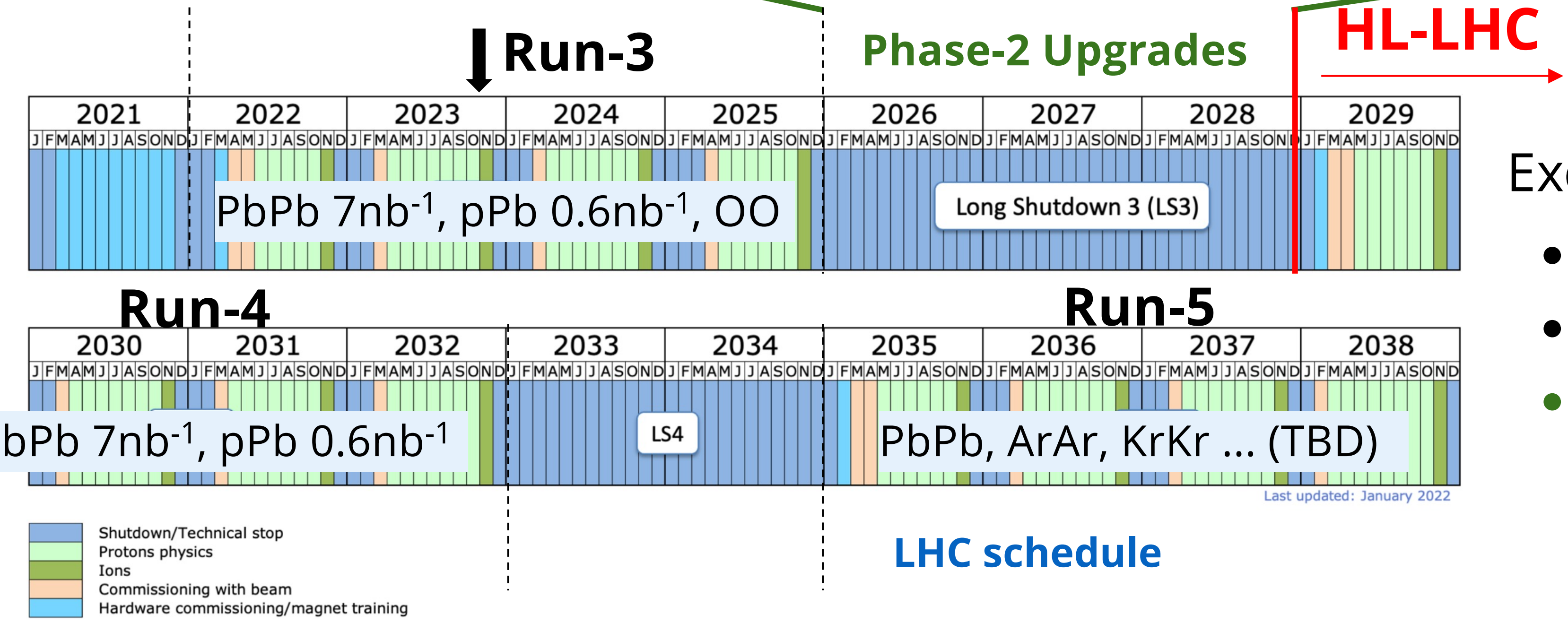
MIP Timing Detector for PID



Tracker with |η|<4 and better resolution, lighter materials



- Muon systems with |η|<**2.8**
- Trigger and DAQ rate: ~**10x**



LHC schedule

Exciting opportunities ahead by:

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