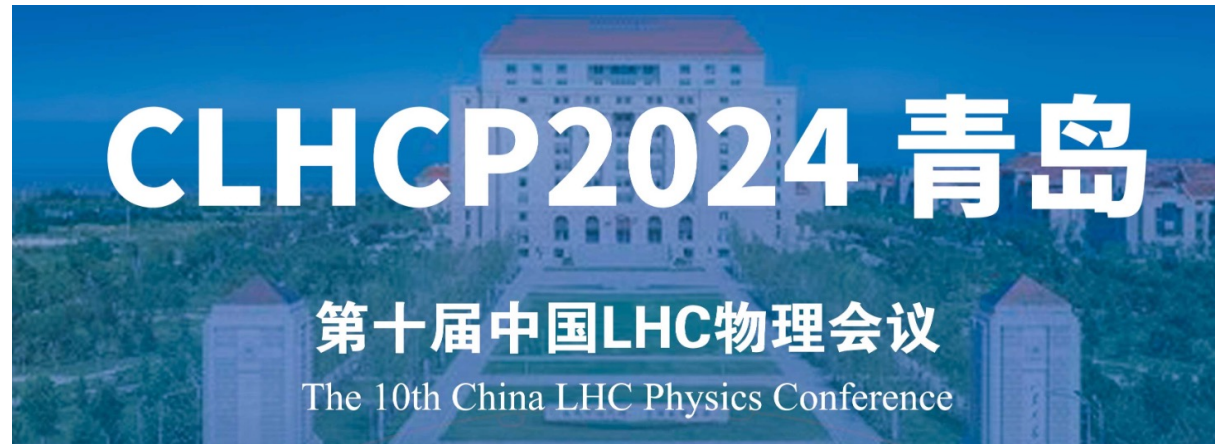
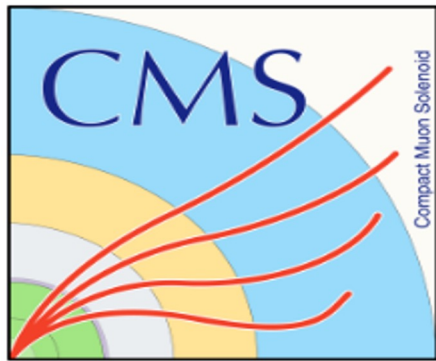


# Detecting fluctuating gluonic structure via energy-dependent incoherent $J/\psi$ photoproduction in Pb-Pb UPCs at 5.02 TeV with the CMS experiment

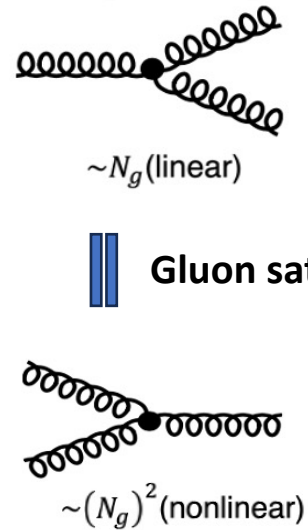
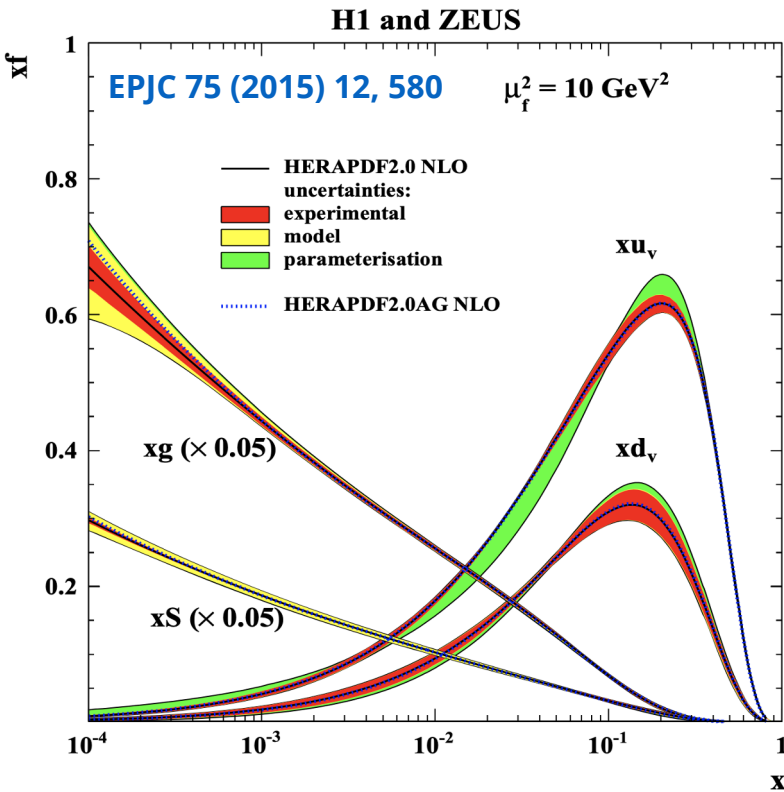
Zaochen Ye (叶早晨)

For the CMS Collaboration

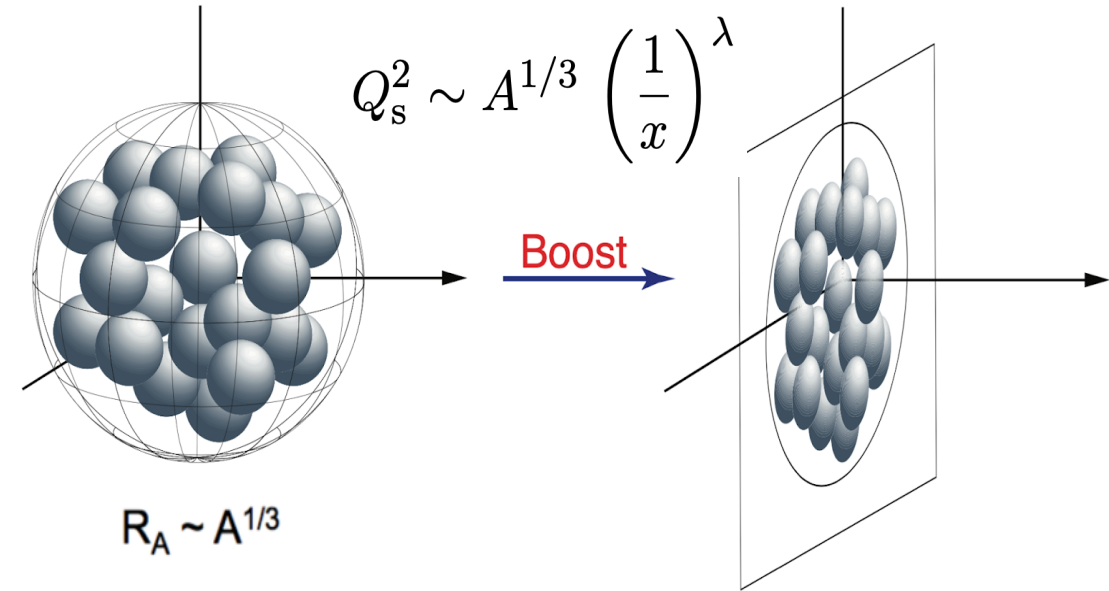
CMS-PAS-HIN-23-009



# Advantages of Gluon Saturation Search in Nucleus



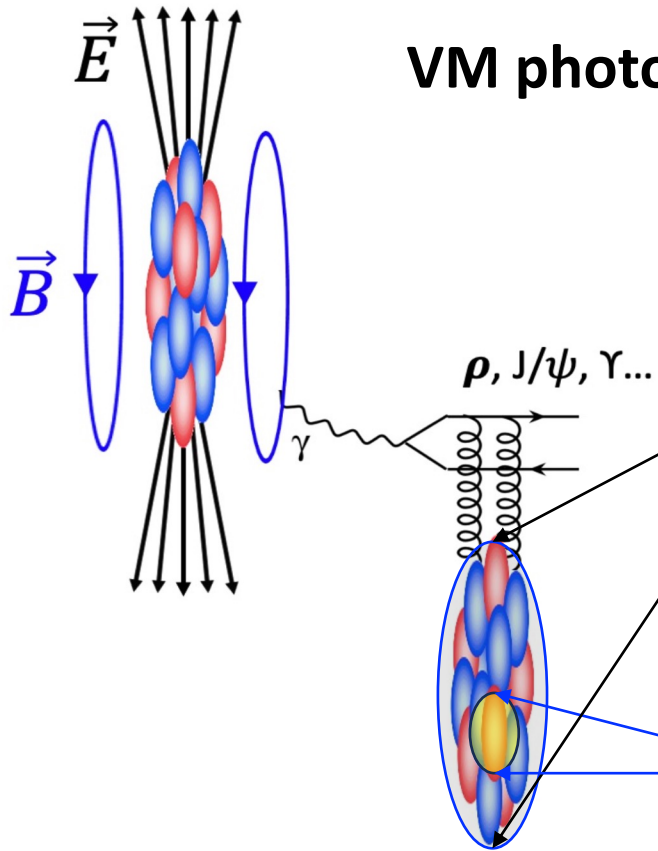
Gluon density is enhanced in nucleus



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

# Vector Meson Photoproduction in UPCs

VM photoproduction is sensitive to the gluonic structure of target nucleus



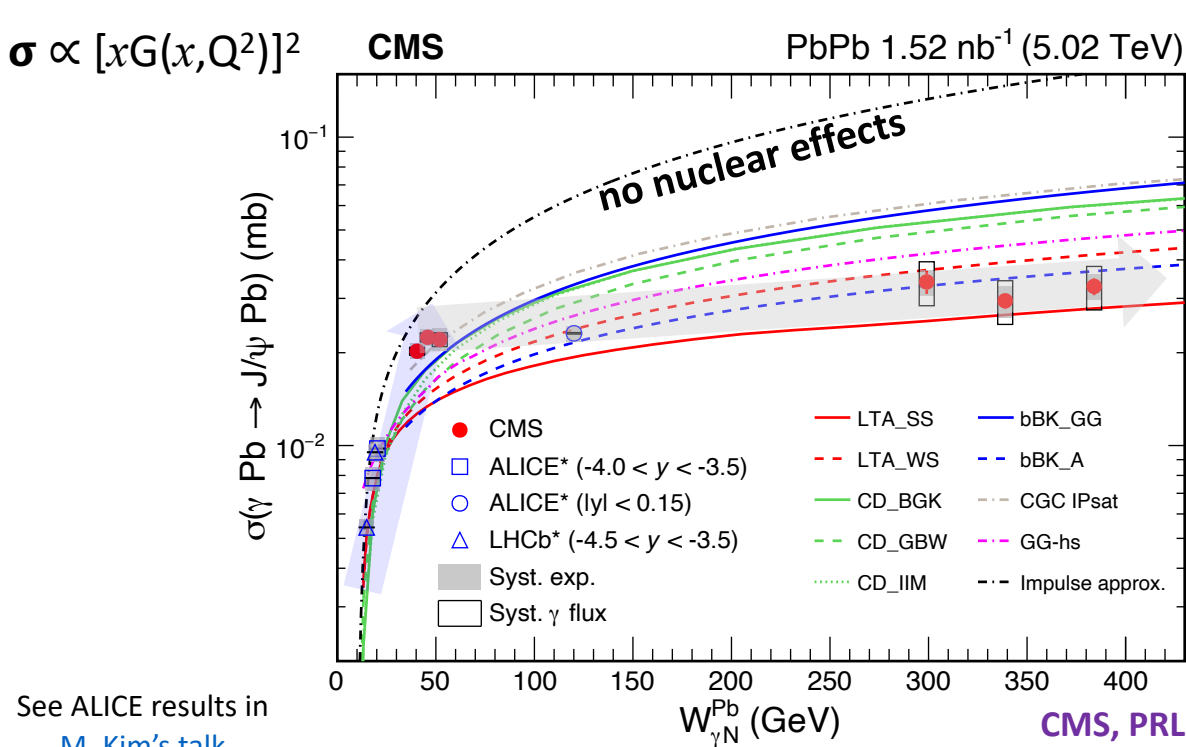
## Coherent photoproduction:

- Photon interact with entire nucleus
- **Target** nucleus remains intact
- VM  $\langle p_T \rangle \sim 50 \text{ MeV}$
- Probing the averaged gluon density

## Incoherent photoproduction:

- Photon interact with individual nucleon or sub-nucleon
- **Target** nucleus usually breaks
- VM  $\langle p_T \rangle \sim 500 \text{ MeV}$
- Probing the local gluon density and fluctuations

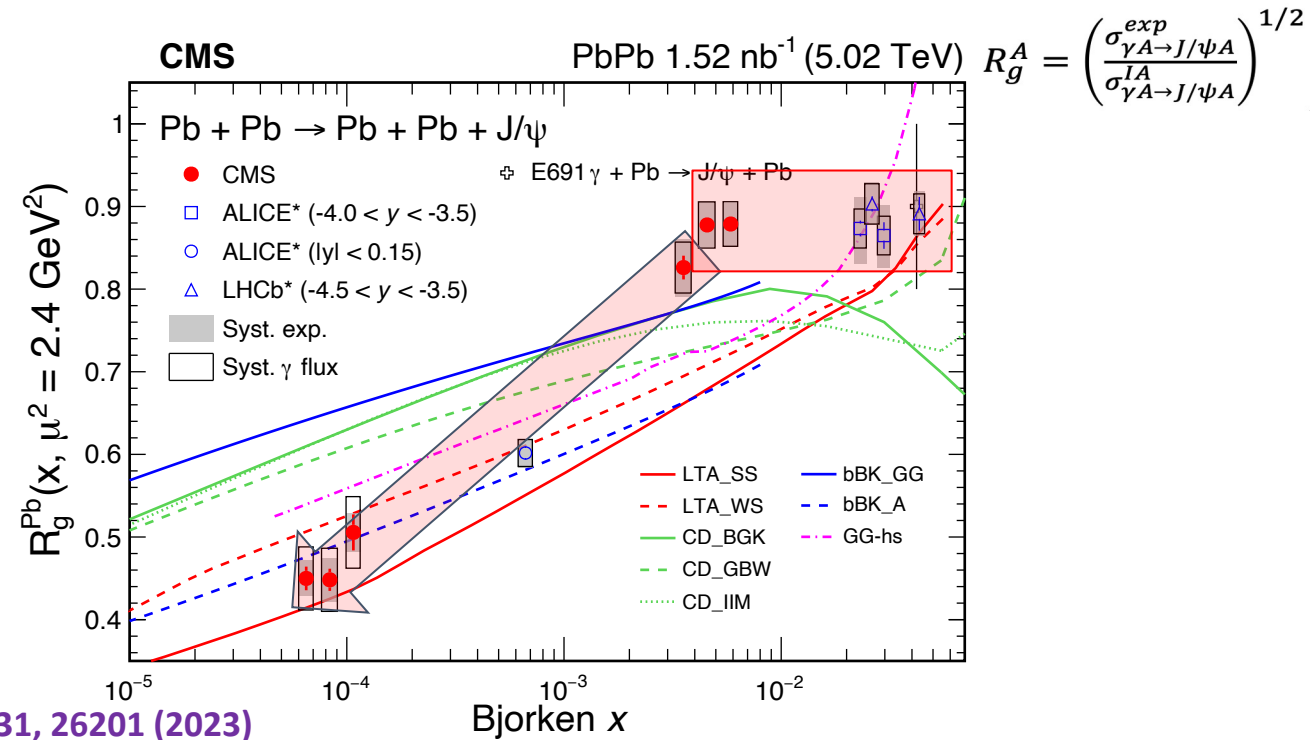
# Recent Coh. J/ψ Photoproduction off Pb Nucleus



See ALICE results in [M. Kim's talk](#)

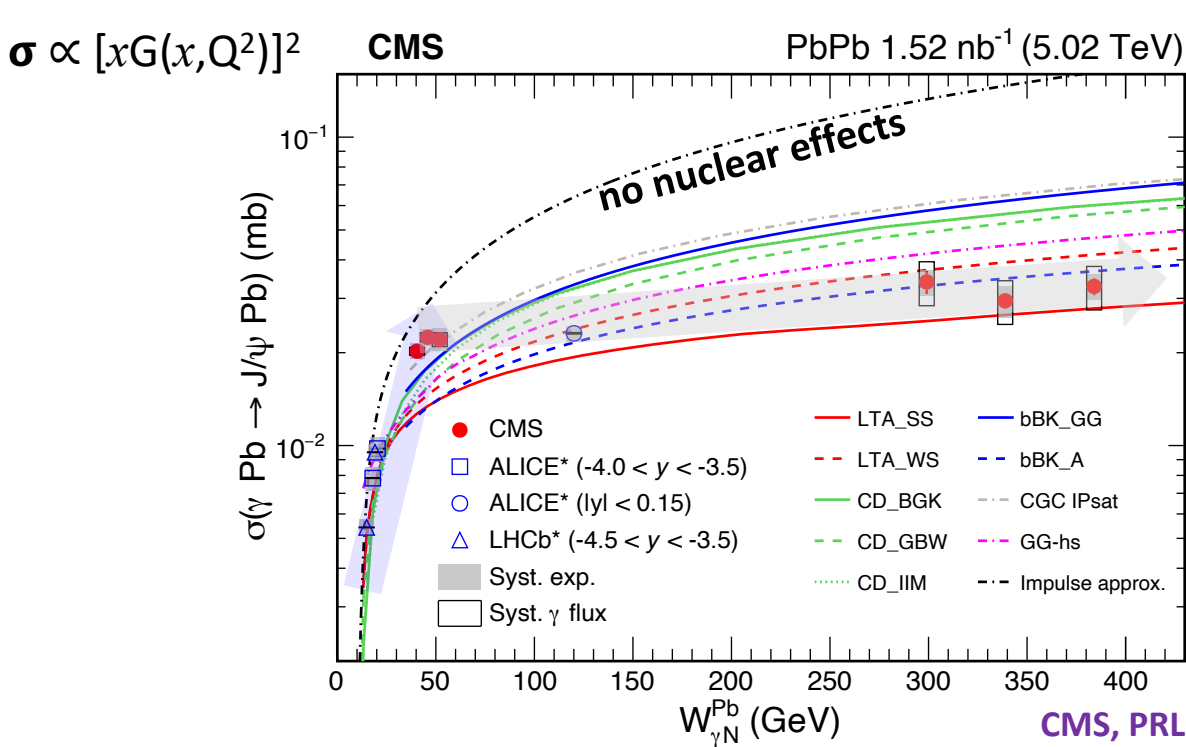
**Strongly saturated cross section**

CMS, PRL 131, 26201 (2023)

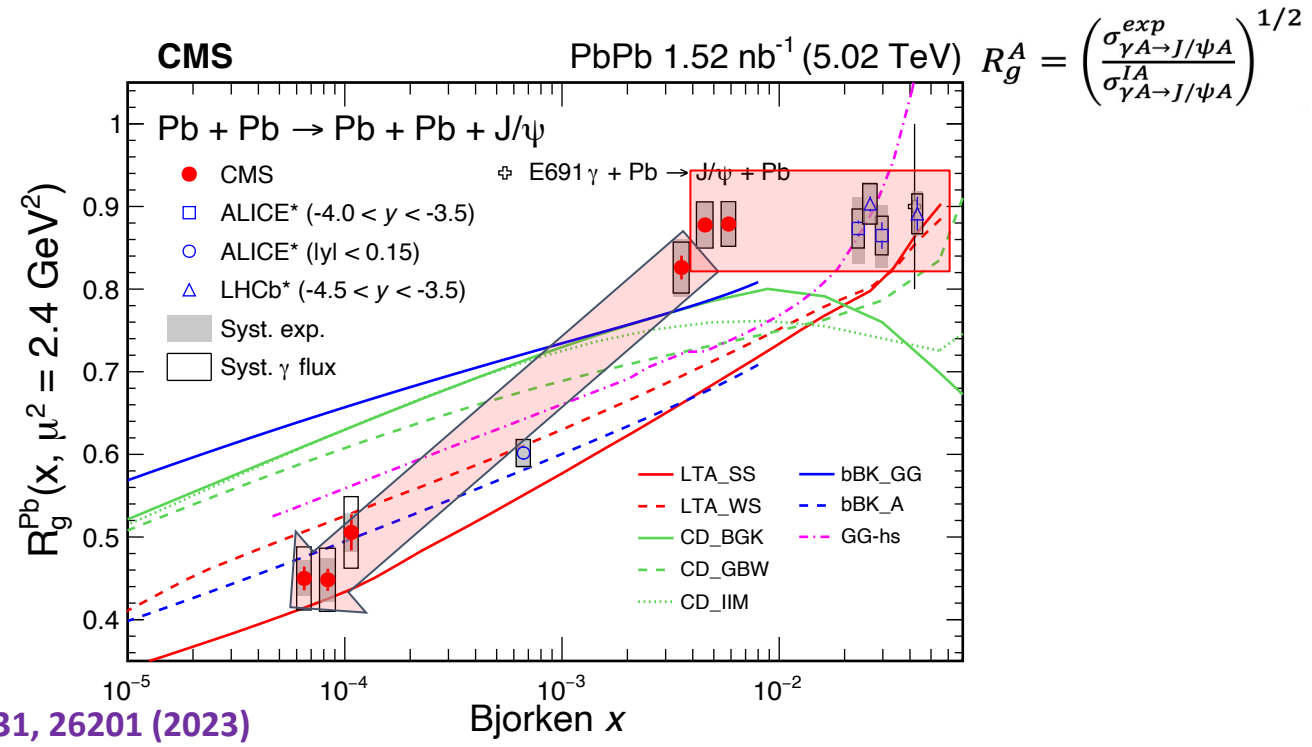


**Strongly suppressed gluon density**

# Recent Coh. J/ψ Photoproduction off Pb Nucleus

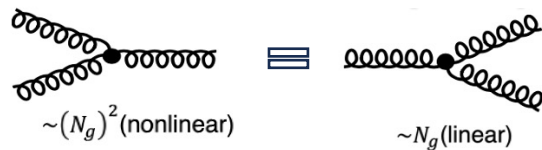


**Strongly saturated cross section**



**Strongly suppressed gluon density**

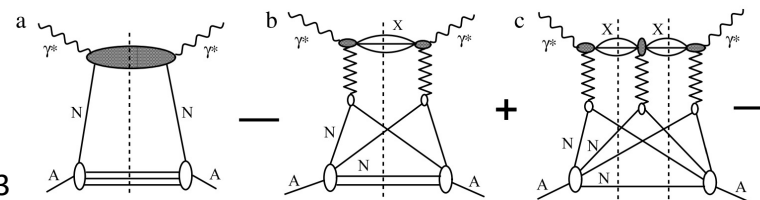
## Glue Saturation?



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

November 16, 2024

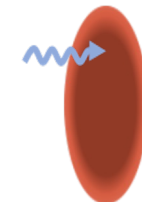
## Nuclear shadowing?



V. Guzey et al. EPJ C 74 (2014) 2942

## Black Disk Limit?

...?



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

L. Frankfurt et al. PRL 87 (2001) 192301

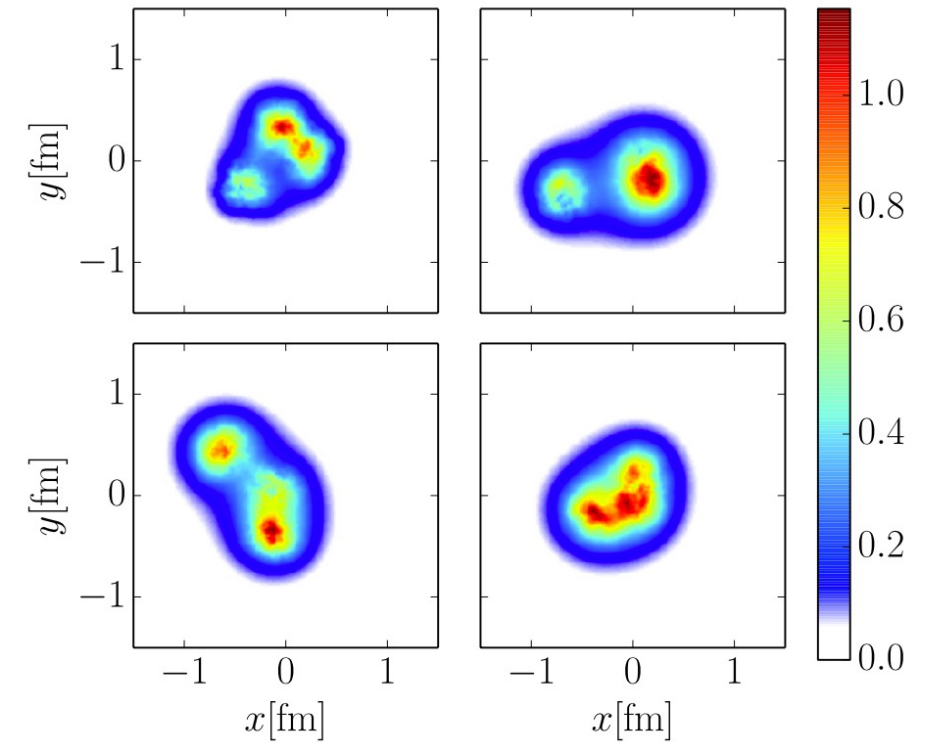
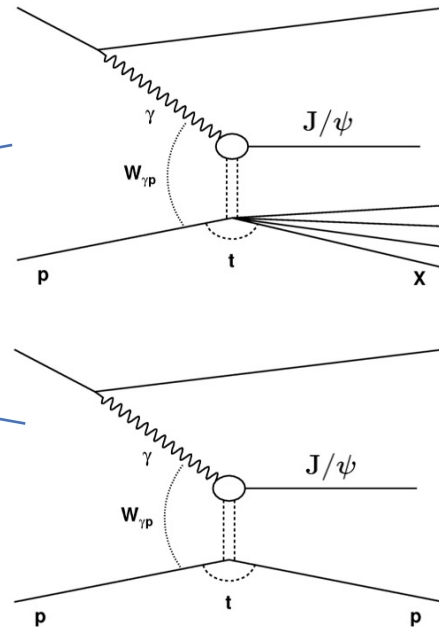
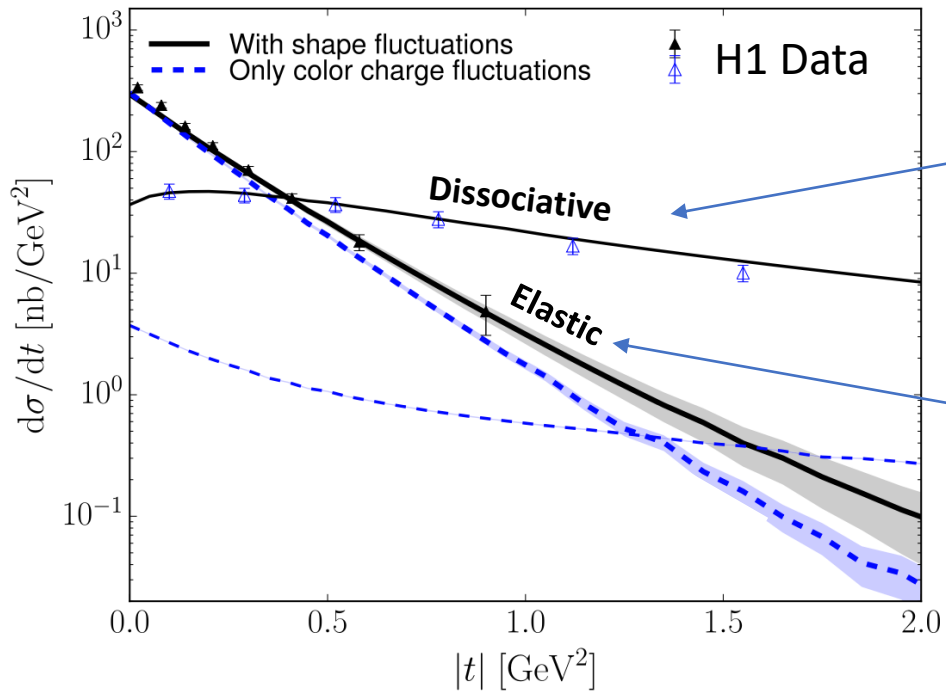
L. Frankfurt et al. PLB 537 (2002) 51

# Probing Fluctuating Gluonic Structure 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

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

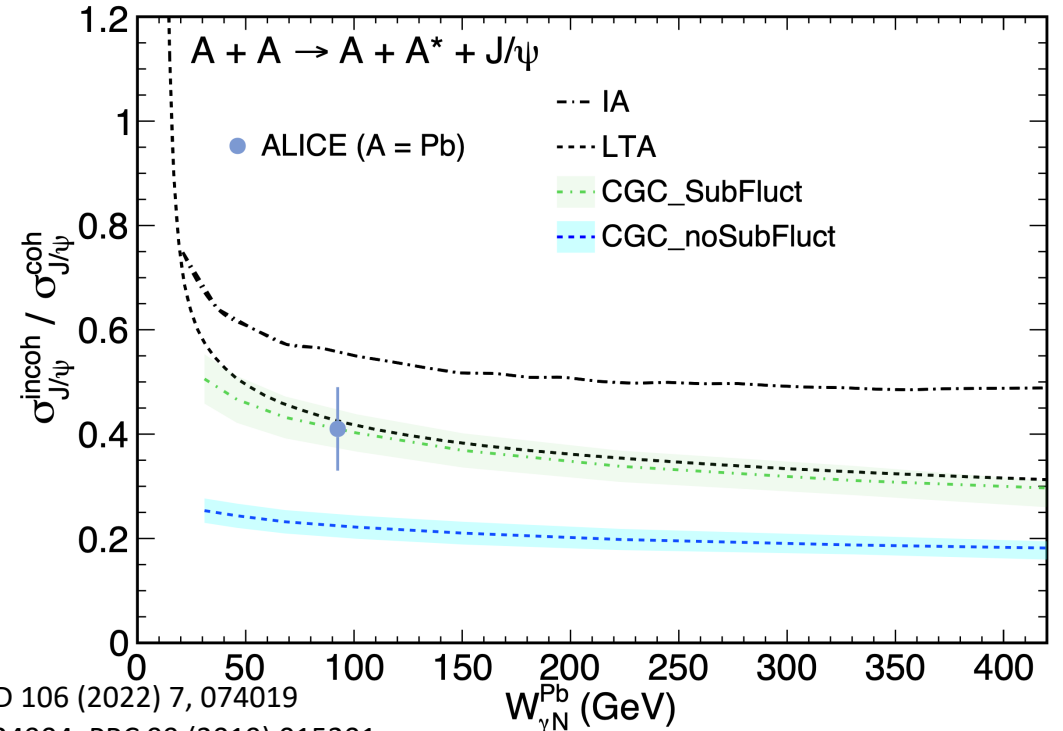
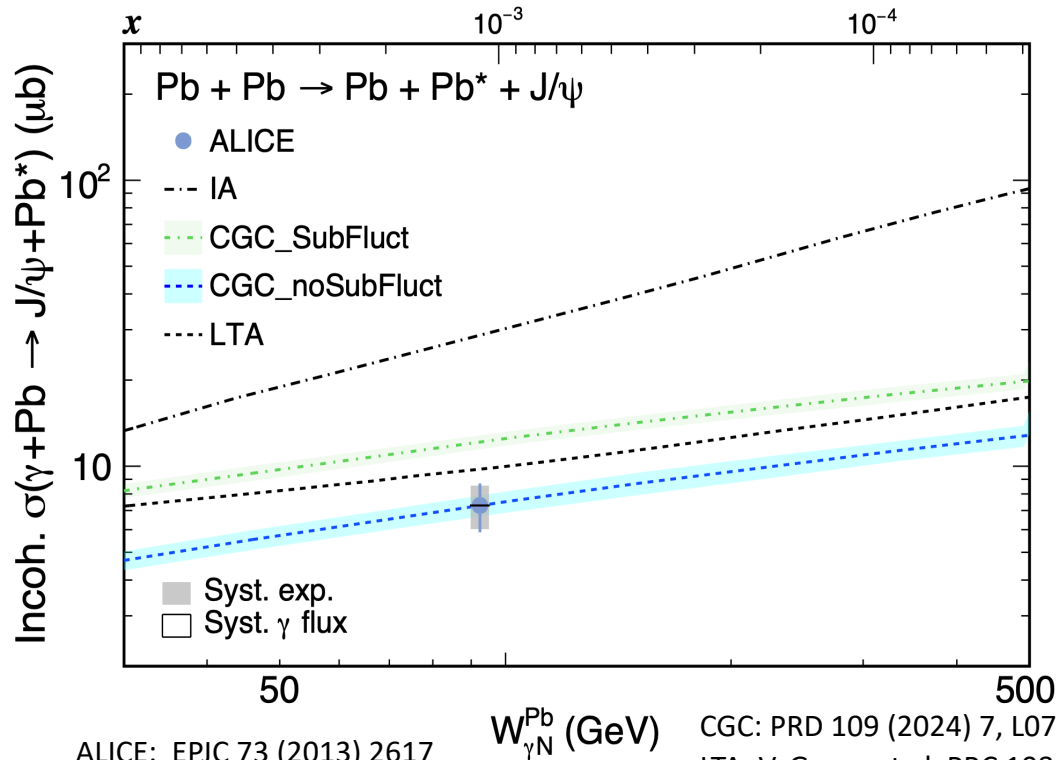
## J/ $\psi$ Photoproduction off proton at HERA



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

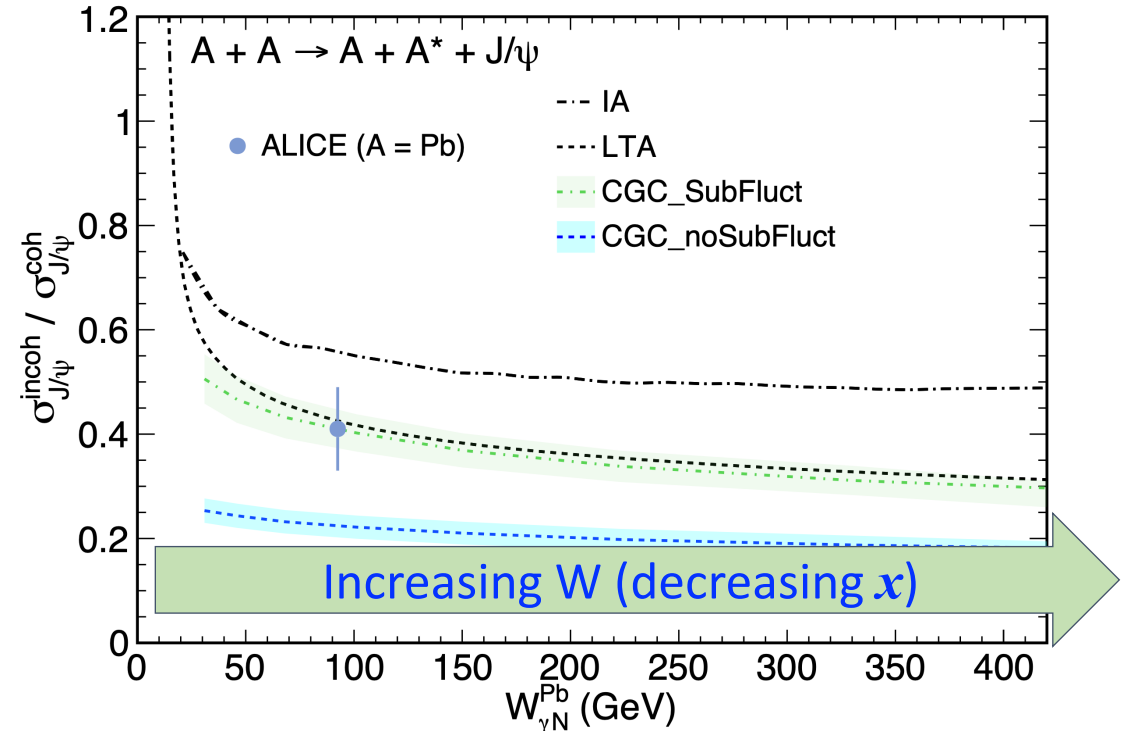
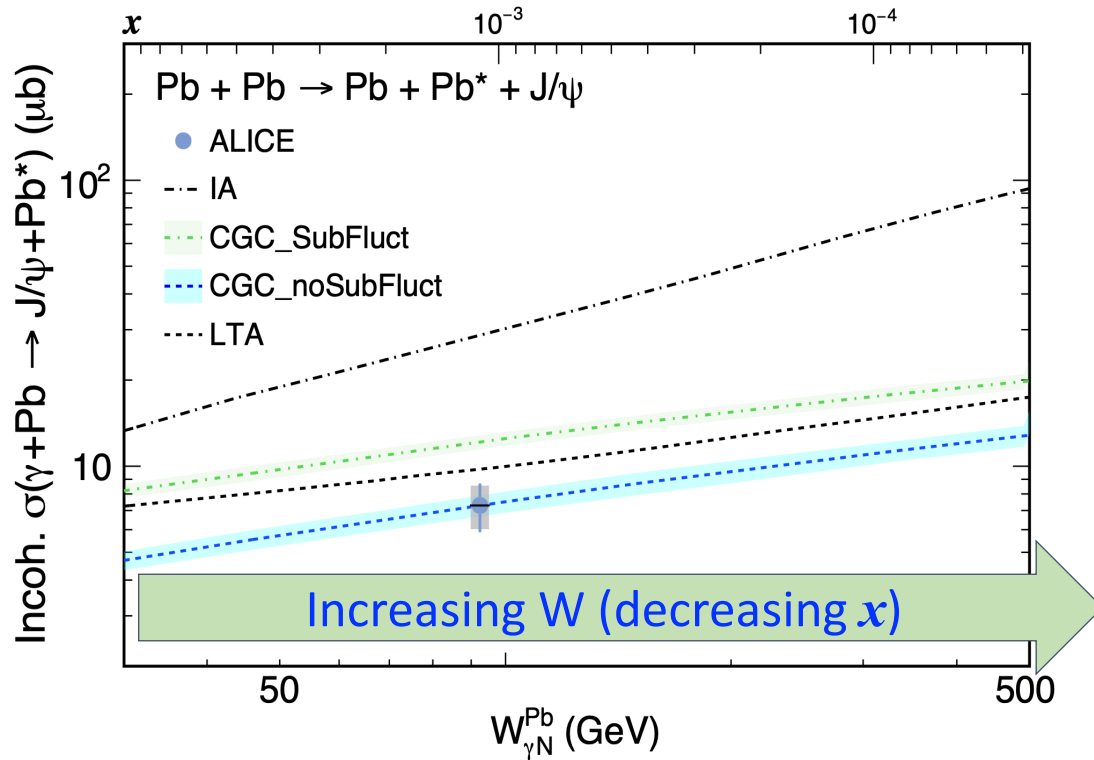


# Probing Fluctuating Gluonic Structure via Incoh. $\gamma$ +Pb



- CGC IPsat (w or w/o) sub-nucleonic fluctuations cannot describe the data
- LTA (leading twist approximation, nuclear shadowing model) seems to be better?

# Probing Fluctuating Gluonic Structure via Incoh. $\gamma$ +Pb



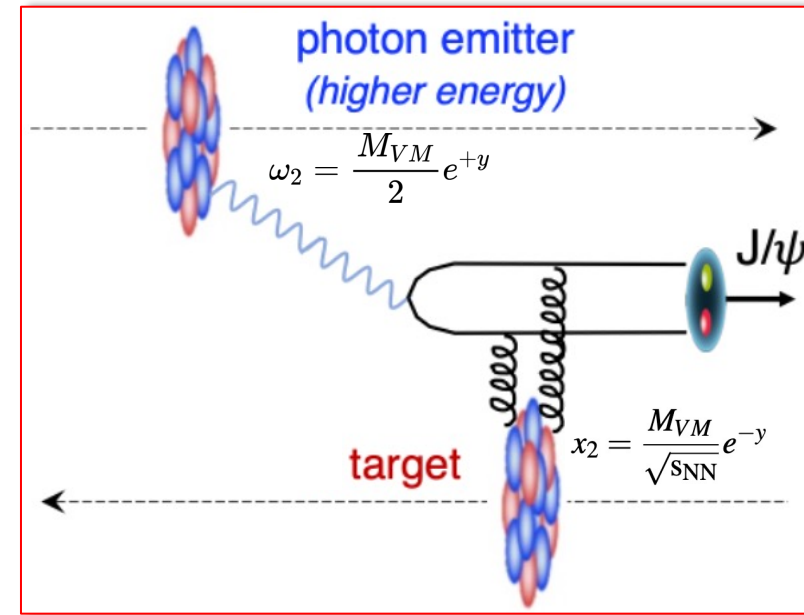
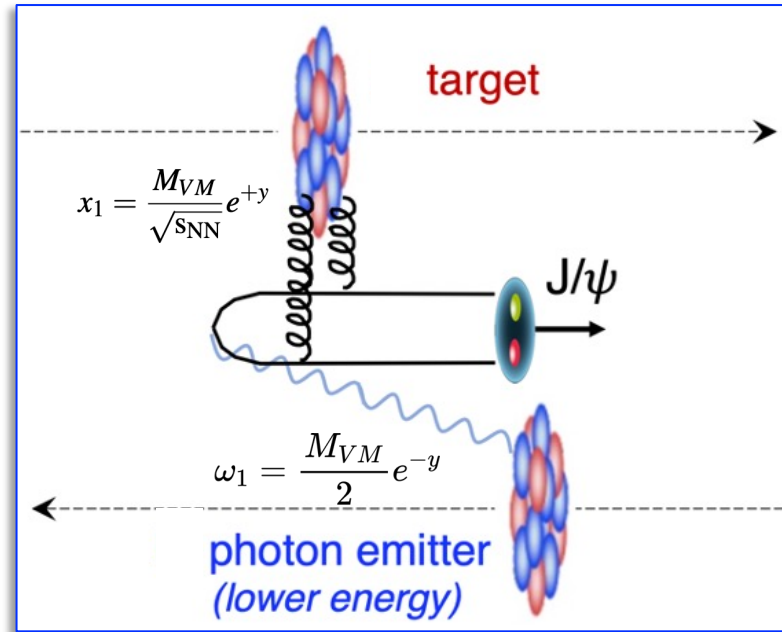
- CGC IPsat (w or w/o) sub-nucleonic fluctuations cannot describe the data
- LTA (leading twist approximation, nuclear shadowing model) seems to be better?

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

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



# “Two-way Ambiguity” in A-A UPCs

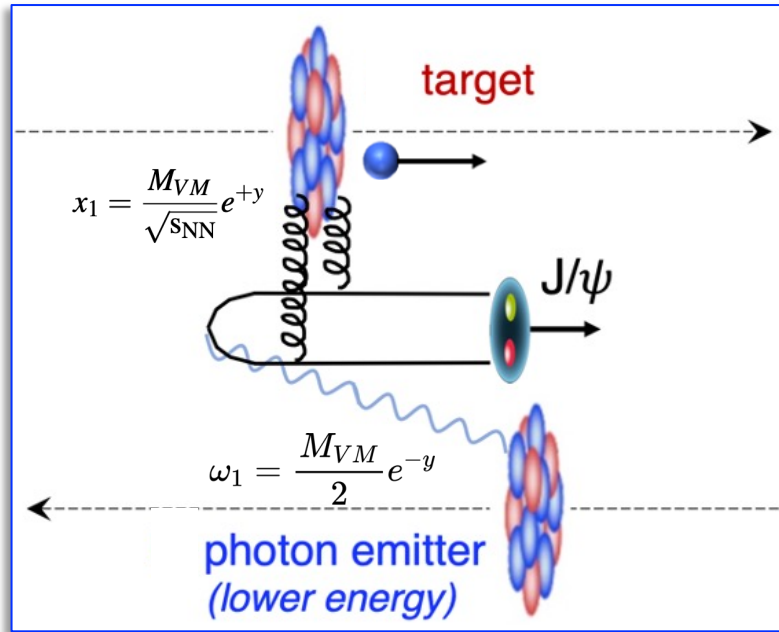


$$\frac{d\sigma_{AA \rightarrow AA' J/\psi}}{dy} = N_{\gamma/A}(\omega_1) \cdot \sigma_{\gamma A \rightarrow J/\psi A'}(\omega_1) + N_{\gamma/A}(\omega_2) \cdot \sigma_{\gamma A \rightarrow J/\psi A'}(\omega_2)$$

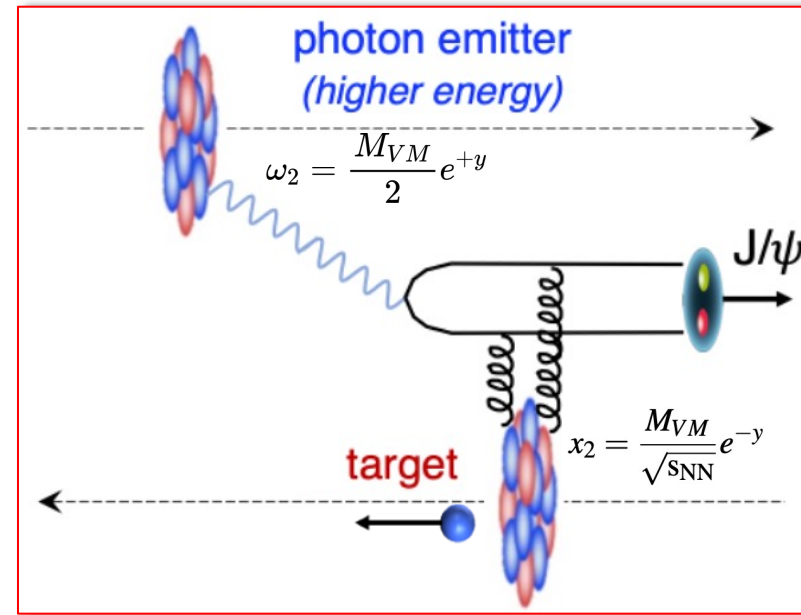
what we measure

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

# Solve “Two-Way Ambiguity” via Forward Neutrons



$J/\psi$ -Xn (Same Direction)



$J/\psi$ -Xn (Opposite Direction)

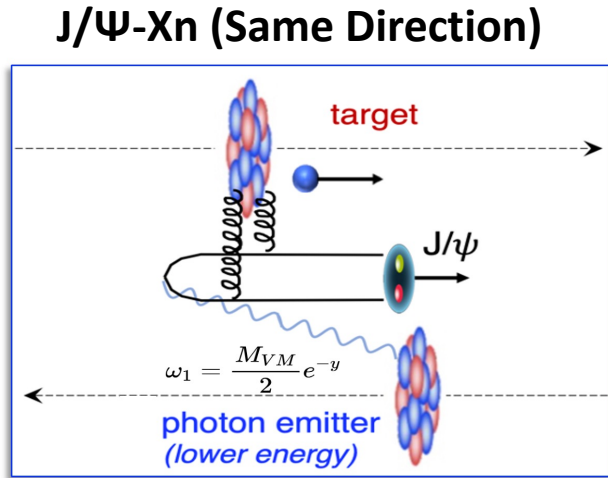
V. Guzey, M. Strikman, M. Zhalov, EPJC (2014) 72 2942

- **Incoh.  $J/\psi$  photoproduction** itself has  $\sim 85\%$  chance to induce the forward neutrons
  - Detecting these neutrons will identify target nucleus
  - Help to solve the “two-way Ambiguity”

# Example of Signal Extraction (0nXn)

Low-W

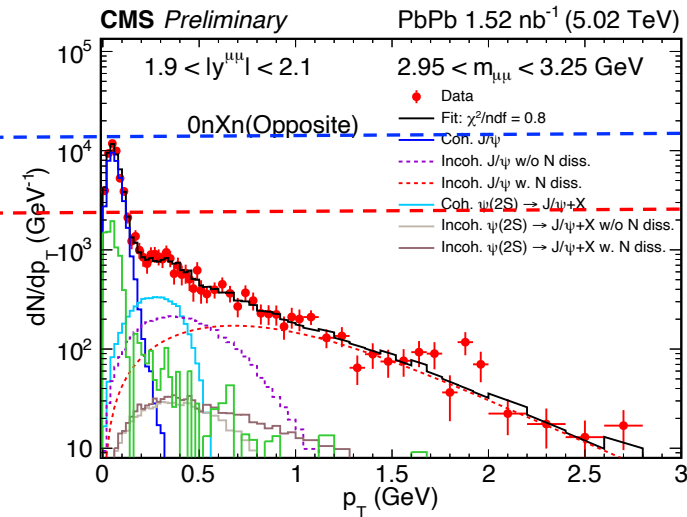
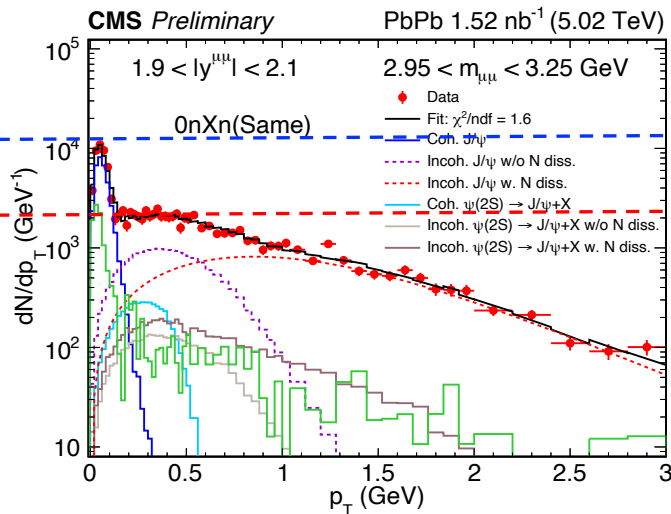
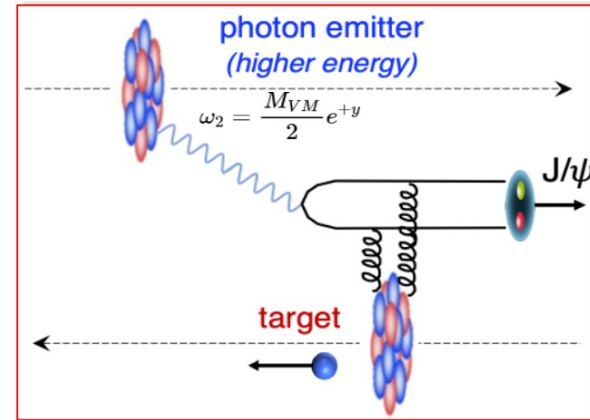
$-y$



**J/ψ-Xn (Opposite Direction)**

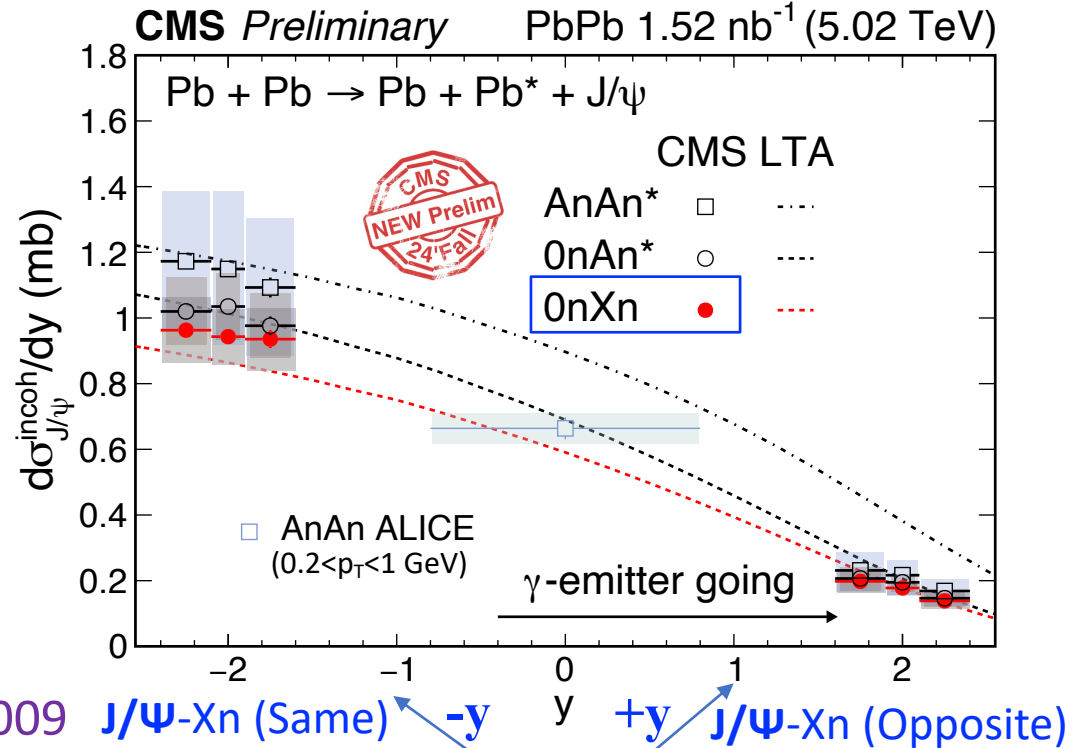
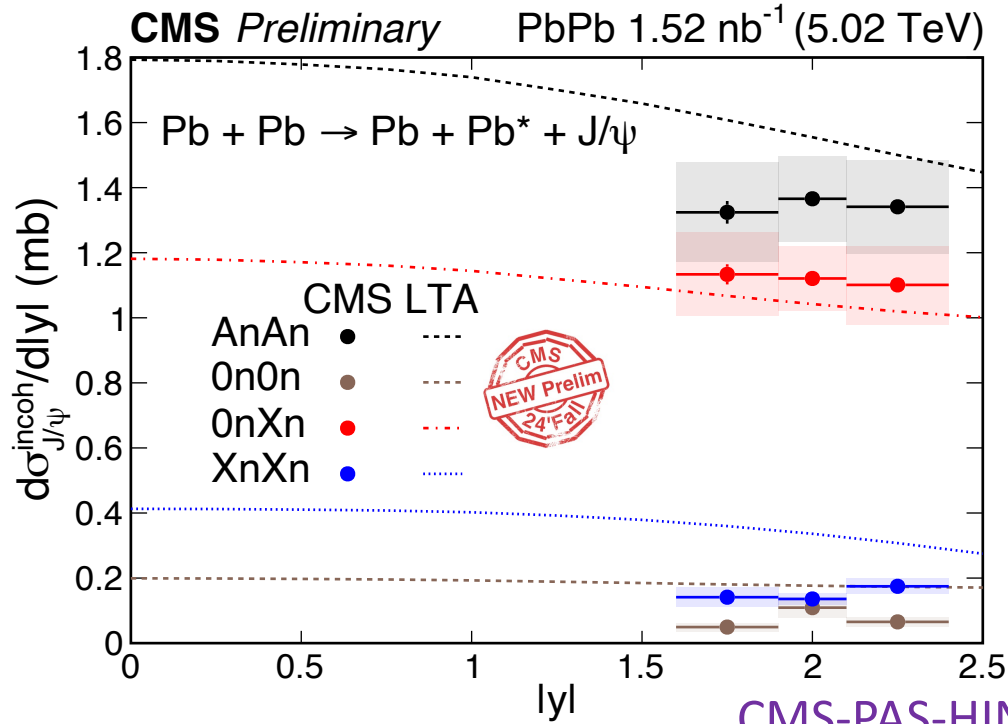
High-W

$+y$



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

# Total InCoh. J/ψ Photoproduction Cross Section



LTA: V. Guzey et al. PRC 108 (2023) 024904, PRC 99 (2019) 015201  
 ALICE: PRL 132, 162302 (2024)

$$\frac{d\sigma_{\text{PbPb} \rightarrow \text{PbPb}' J/\psi}^{0nAn^*}(y)}{dy} = \frac{d\sigma_{\text{PbPb} \rightarrow \text{PbPb}' J/\psi}^{0nXn}(y)}{dy} + \frac{d\sigma_{\text{PbPb} \rightarrow \text{PbPb}' J/\psi}^{0n0n}(y)}{dy}$$

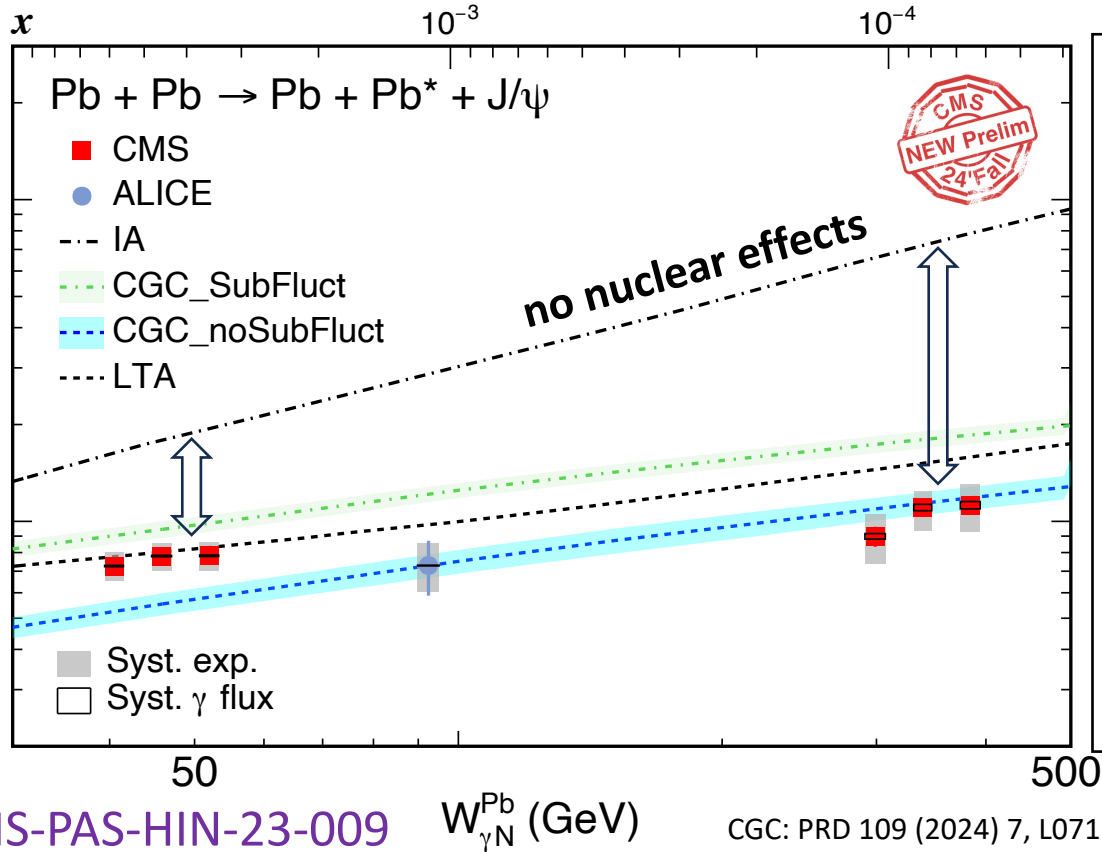
- OnXn events: Data at (-y) are 5-6 times of data at (+y) → **Strong incoh. J/ψ – Xn correlation**

Relative fractions at (+y) and (-y) in OnOn are assumed to be same as what measured in OnXn events

# Incoh. J/ψ Cross Section per γ+Pb

CMS Preliminary

PbPb 1.52 nb<sup>-1</sup> (5.02 TeV)



- Strong suppression compared to Impulse Approximation (IA)
- Increasing slope is much smaller than IA: stronger suppression towards higher W
- LTA (nuclear shadowing model) describe the data at W<60 GeV
- CGC **without** Sub-N fluctuations better describe data at W>90 GeV

CMS-PAS-HIN-23-009

$W_{\gamma N}^{Pb}$  (GeV)

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

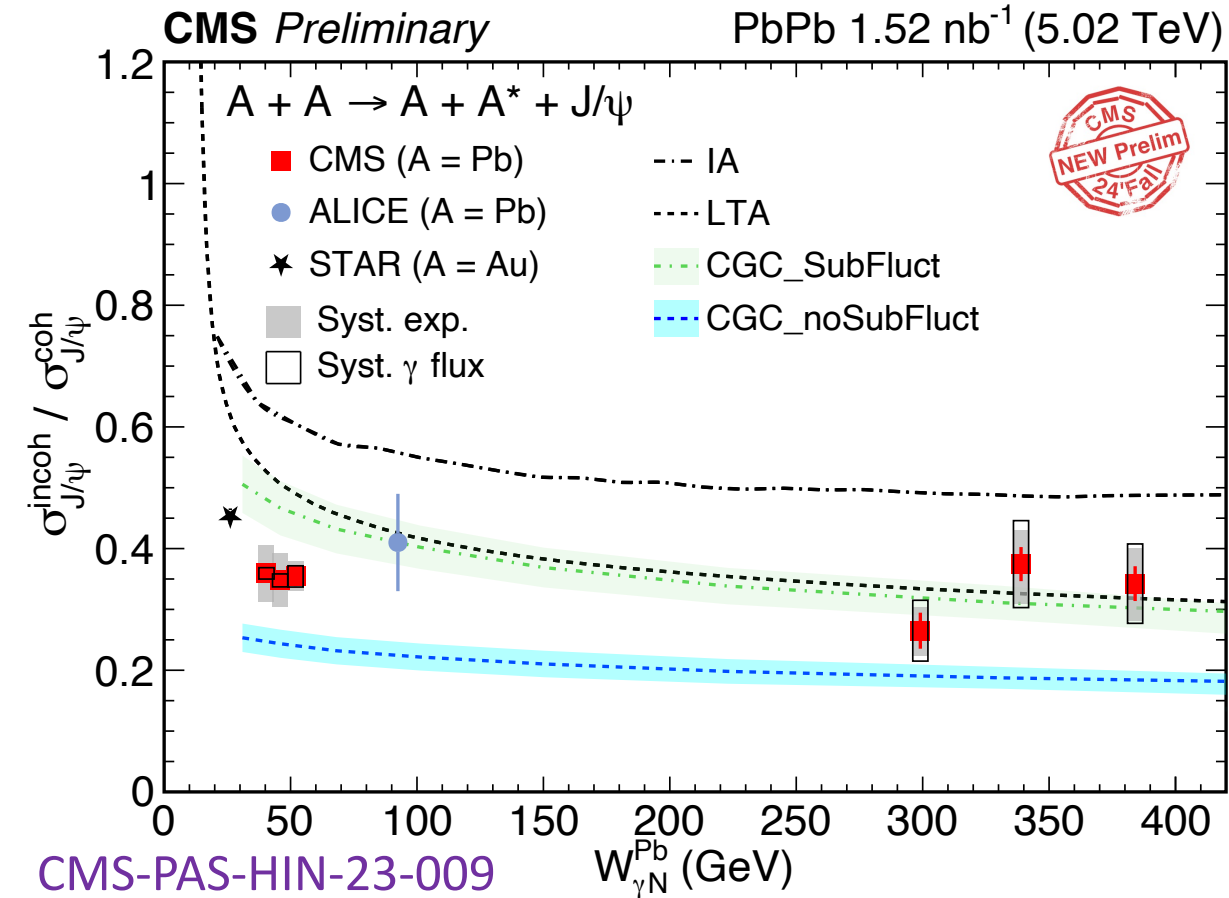
LTA: V. Guzey et al. PRC 108 (2023) 024904, PRC 99 (2019) 015201

ALICE: EPJC 73 (2013) 2617

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

$$\sigma_{\gamma Pb \rightarrow J/\psi Pb'}(\omega) = \frac{d\sigma_{PbPb \rightarrow PbPb' J/\psi}(y)}{dy} / n_{\gamma/Pb}^{0nAn^*}(\omega)$$

# Cross Section Ratio of Incoh/Coh

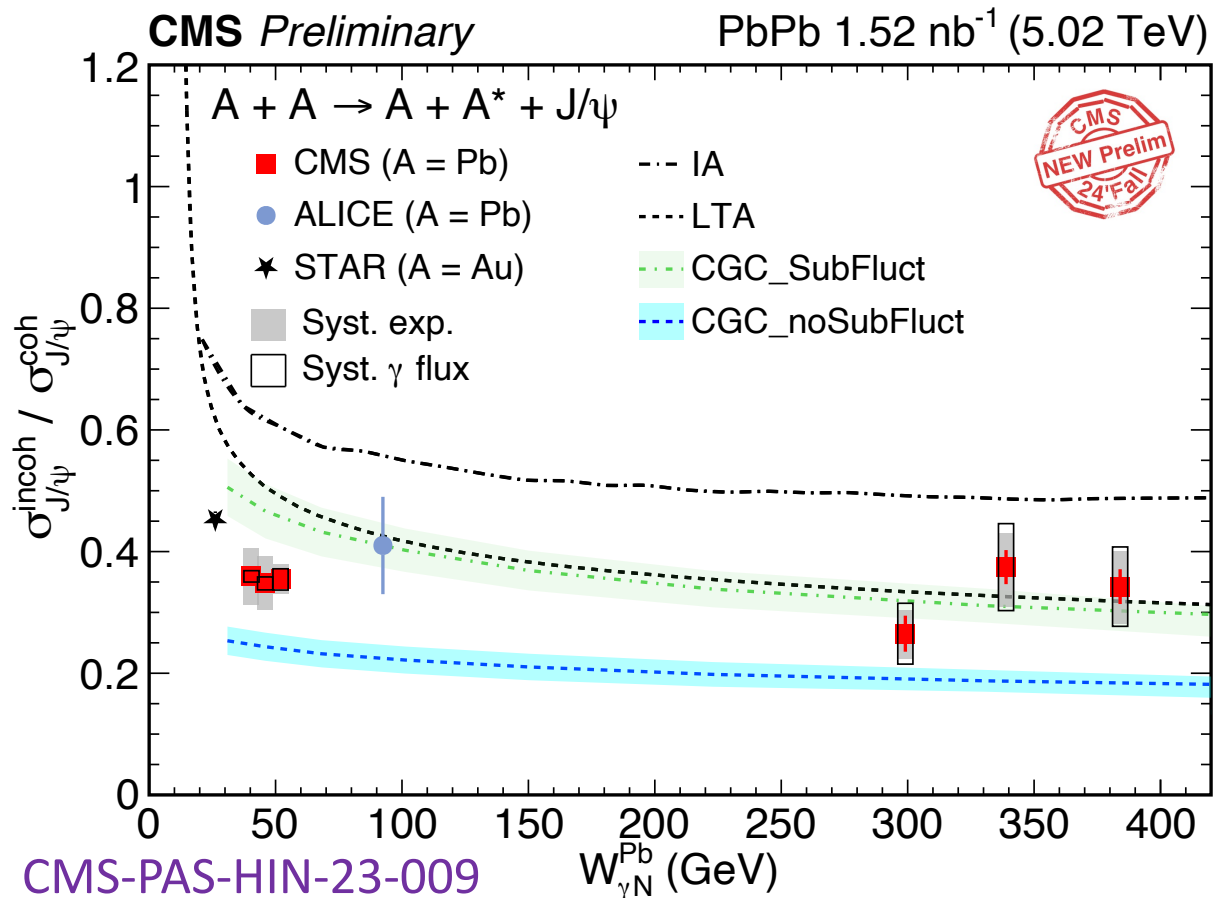


Theoretical uncertainties from **VM wave function, nuclear density, nuclear form factor, free nucleon PDFs, photon flux, and J/ $\psi$  formation probability** are largely canceled.

**Cleanest test** for examining theoretical assumptions on nuclear effects: saturation or nuclear shadowing...



# Cross Section Ratio of Incoh/Coh



- No clear  $W$  dependent ( $40 < W < 400$  GeV)
  - Not support BDL is reached
- ALICE data agrees with CMS data, while STAR data slightly rises towards lower  $W$
- Data is lower than IA  $\rightarrow$  Incoh.  $J/\psi$  is more suppressed than Coh.  $J/\psi$
- LTA and CGC with Sub-N fluctuation qualitatively describe data trend
  - Still overpredict data for  $W < 60$  GeV

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

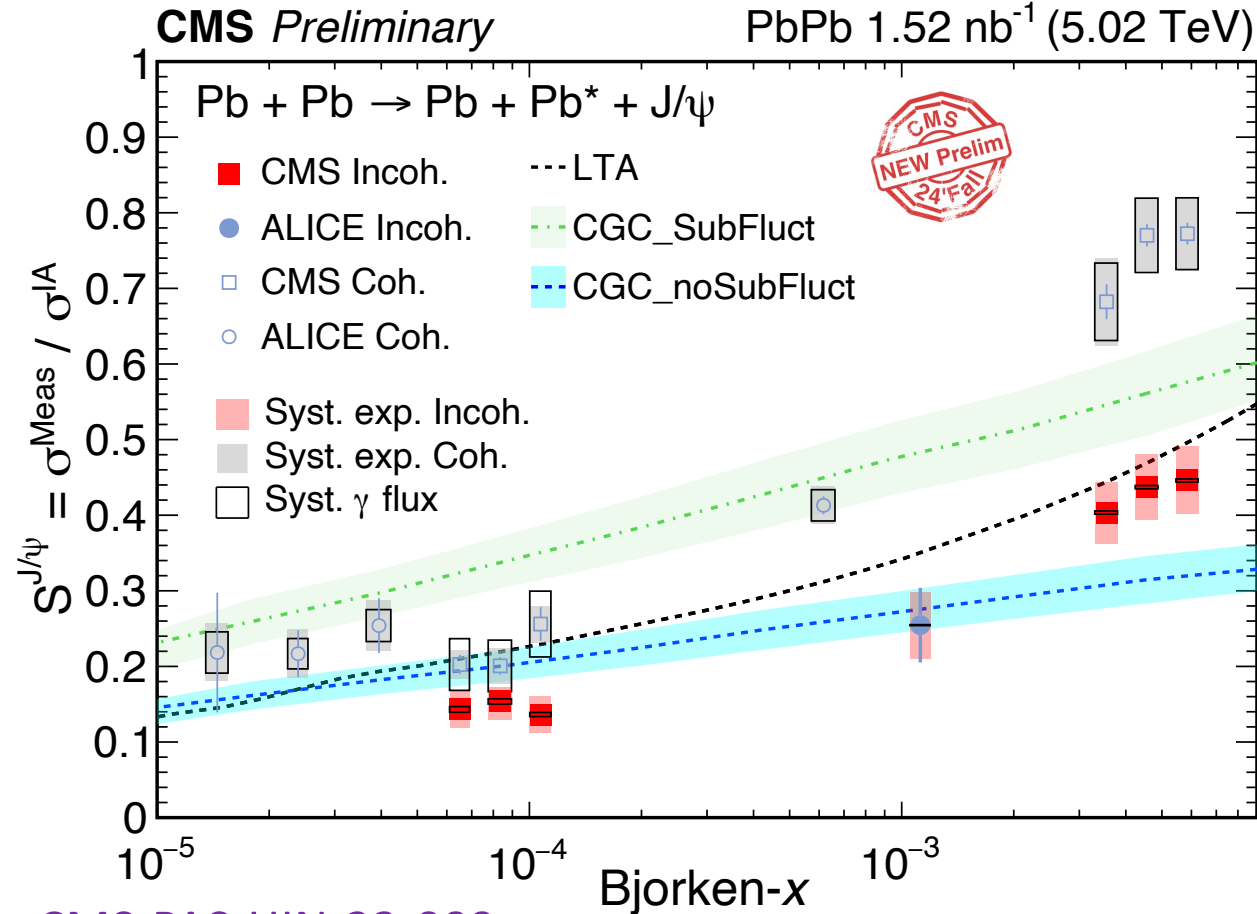


**Cleanest test** for examining theoretical assumptions on nuclear effects: saturation or nuclear shadowing...

# Nuclear Suppression

$$S^{J/\psi} = \frac{\sigma_{\gamma Pb \rightarrow J/\psi Pb'}^{exp}}{\sigma_{\gamma Pb \rightarrow J/\psi Pb'}^{IA}}$$

No nuclear effects



- Stronger suppression towards lower  $x$ , and eventually flattens out
- ALICE data follows CMS data trend
- Incoh. J/ψ is more suppressed than Coh. J/ψ
- Incoh. J/ψ gets closer to Coh J/ψ for  $x < 10^{-4}$
- No models can describe the data

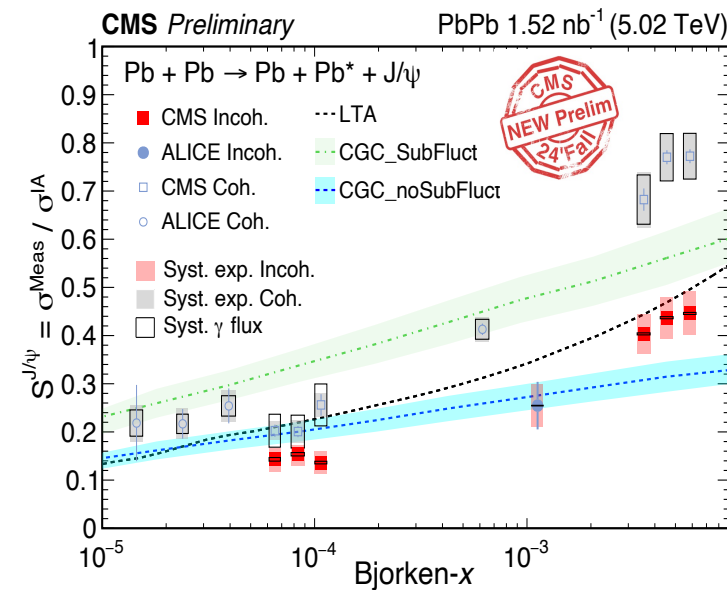
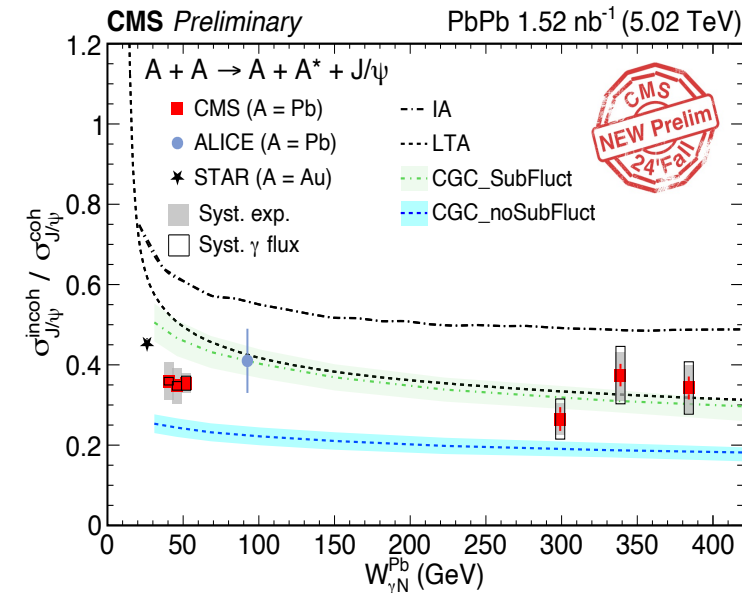
CMS-PAS-HIN-23-009 Coh: CMS, PRL 131, 26201 (2023); ALICE, JHEP 10, (2023) 119

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

# Summary

- **First energy-dependent** measurement of incoh.  $J/\psi$  photoproduction off nucleus
- Probing fluctuating gluon fields over broad  $x$  interval:  $5.8 \times 10^{-3} - 6.5 \times 10^{-5}$
- Ratio of Incoh./Coh is  **$\sim 0.3-0.5$**  for  $40 < W < 400$  GeV
  - Sub nucleonic fluctuations are need to describe data
  - Not support that black disk limit is reached
- Nuclear suppression of Incoh.  $J/\psi$  photoproduction:
  - **Stronger towards lower  $x$ , eventually flattens out**
  - **Stronger** than Coh.  $J/\psi$  photoproduction
- Theoretical models (saturation or shadowing) **only occasionally describe partial** measured observables
  - Strong constrains on model assumptions

CMS-PAS-HIN-23-009



# THANKS

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

CGC: H. Mantysaari, F. Salazar and B. Schenke

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

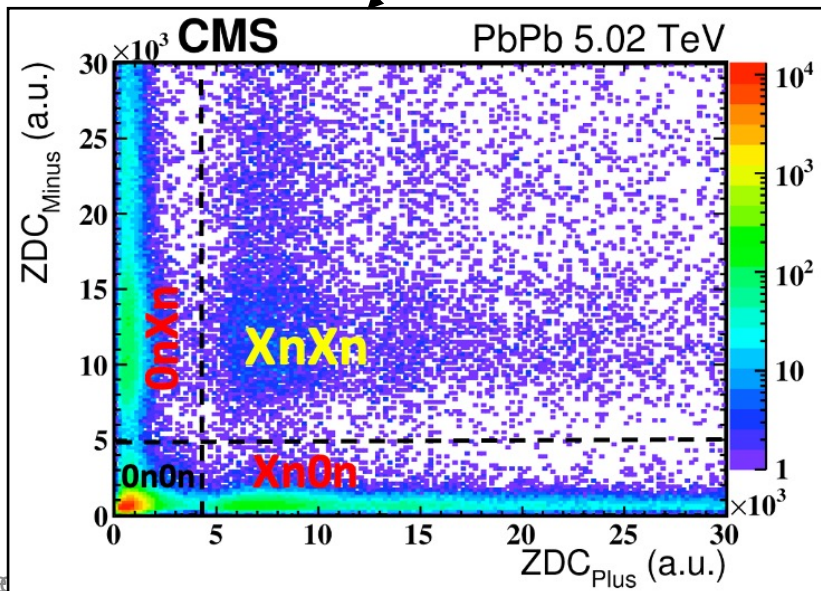
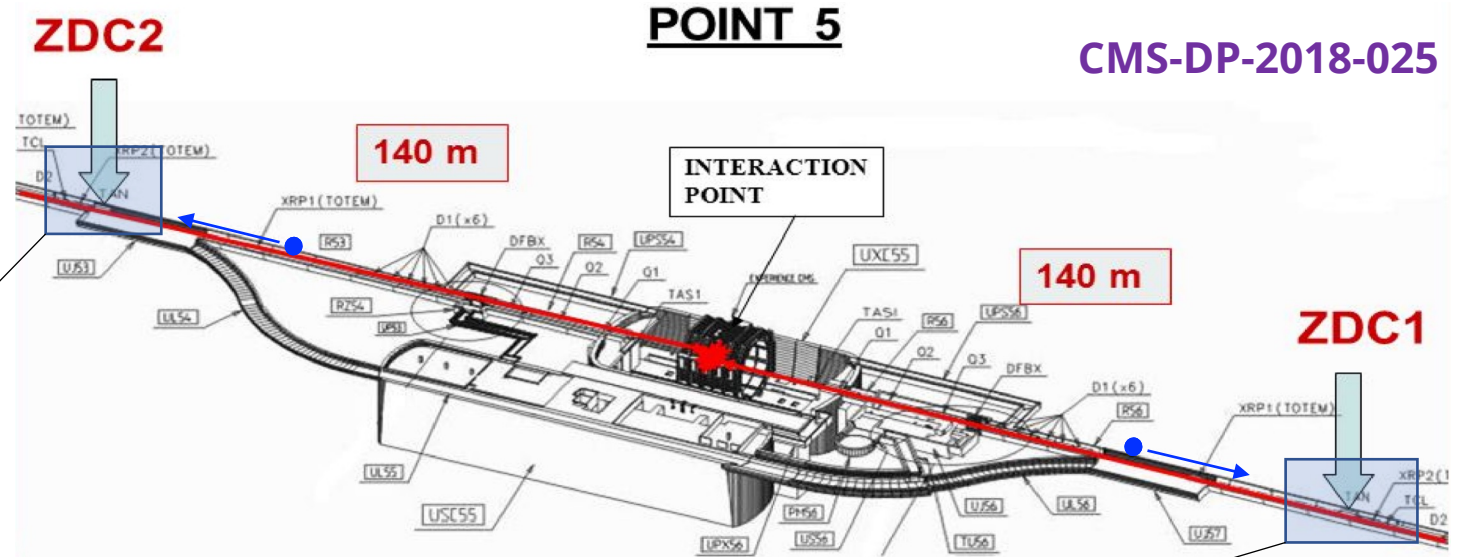
# Backup

# Neutron Tag with Zero Degree Calorimeter

CMS-DP-2018-025

Tag events with neutrons:

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

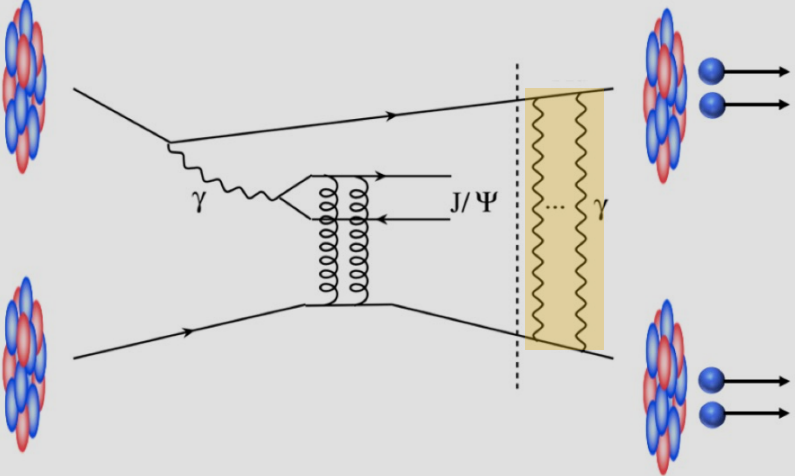


EMD pileup corrections are needed



# Solution Based on Forward Neutrons

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

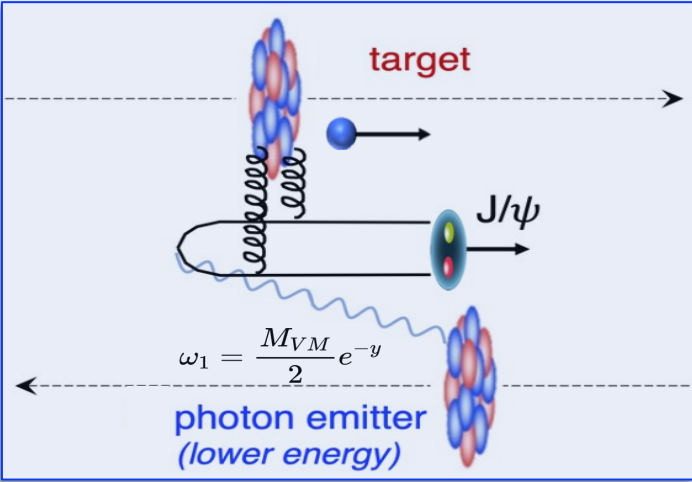


$$\frac{d\sigma_{AA \rightarrow AA' J/\psi}^{0nXn}}{dy} = N_{\gamma/A}^{0nXn}(\omega_1) \cdot \sigma_{\gamma A \rightarrow J/\psi A'}(\omega_1) + N_{\gamma/A}^{0nXn}(\omega_2) \cdot \sigma_{\gamma A \rightarrow J/\psi A'}(\omega_2)$$

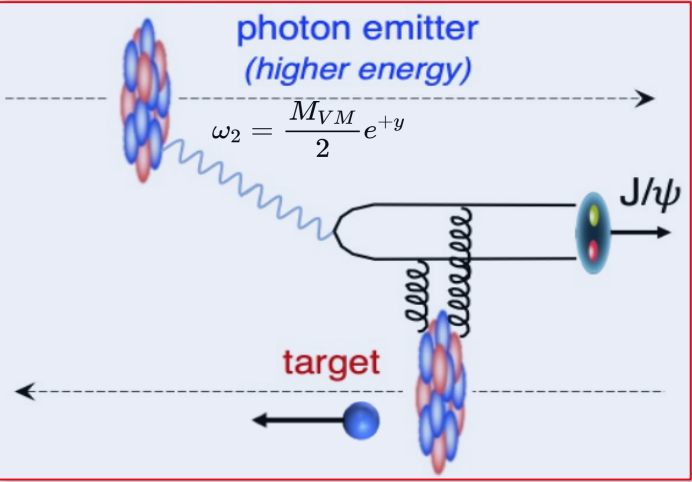
from theoretical calculation

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

**Coh. Jpsi Xsec at w1 and w2 are solved by making use of neutrons induced by EMD process**



**J/Psi-Xn (Same Direction)**



**J/Psi-Xn (Opposite Direction)**

**Incoh. J/Psi production itself has ~85% chance to induce the forward neutrons →**

Detecting these neutrons will identify the target nucleus and solve the two-way ambiguity

# Solve “Two-Way Ambiguity” via Forward Neutrons

Both incoherent and EMD processes can induce neutron emissions, their configurations need careful considerations for the photon flux calculations.

1. 0n0n events, no neutrons are from either process
2. 0nXn events, mainly two cases:
  - a) **neutrons solely from incoherent process (dominant)**
  - b) neutrons from both processes, aligning each other with 50% chance
3. XnXn events:
  - a) Single-side neutrons from both processes, opposing each other
  - b) EMD-induce neutrons in both directions, regardless of incoherent process

**Direct disentanglement**

J/Ψ-Xn (Same)  
J/Ψ-Xn (Opposite)

The photon flux calculation are only available for EMD process, so the measurements from 0n0n and 0nXn are combined as 0nAn\* for a practical photon flux determination and corrections.

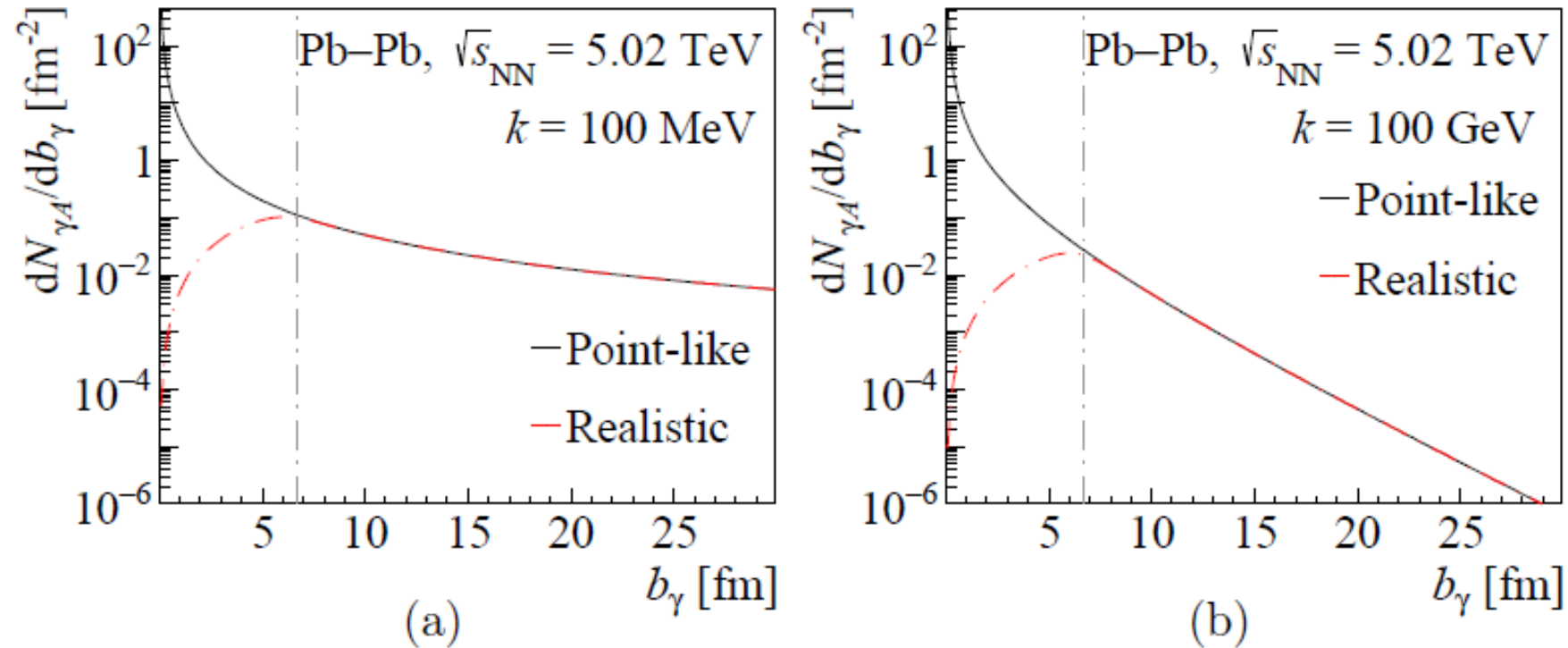
$$\frac{d\sigma_{\text{PbPb} \rightarrow \text{PbPb}' J/\psi}^{0nAn^*}}{dy} = \frac{d\sigma_{\text{PbPb} \rightarrow \text{PbPb}' J/\psi}^{0nXn}}{dy} + \frac{d\sigma_{\text{PbPb} \rightarrow \text{PbPb}' J/\psi}^{0n0n}}{dy} \quad n_{\gamma/\text{Pb}}^{0nAn^*}(\omega) = n_{\gamma/\text{Pb}}^{0n0n(\text{EMD})}(\omega) + \frac{1}{2}n_{\gamma/\text{Pb}}^{0nXn(\text{EMD})}(\omega)$$

$$\sigma_{\gamma\text{Pb} \rightarrow J/\psi\text{Pb}'}(\omega) = \frac{d\sigma_{\text{PbPb} \rightarrow \text{PbPb}' J/\psi}^{0nAn^*}}{dy} / n_{\gamma/\text{Pb}}^{0nAn^*}(\omega)$$

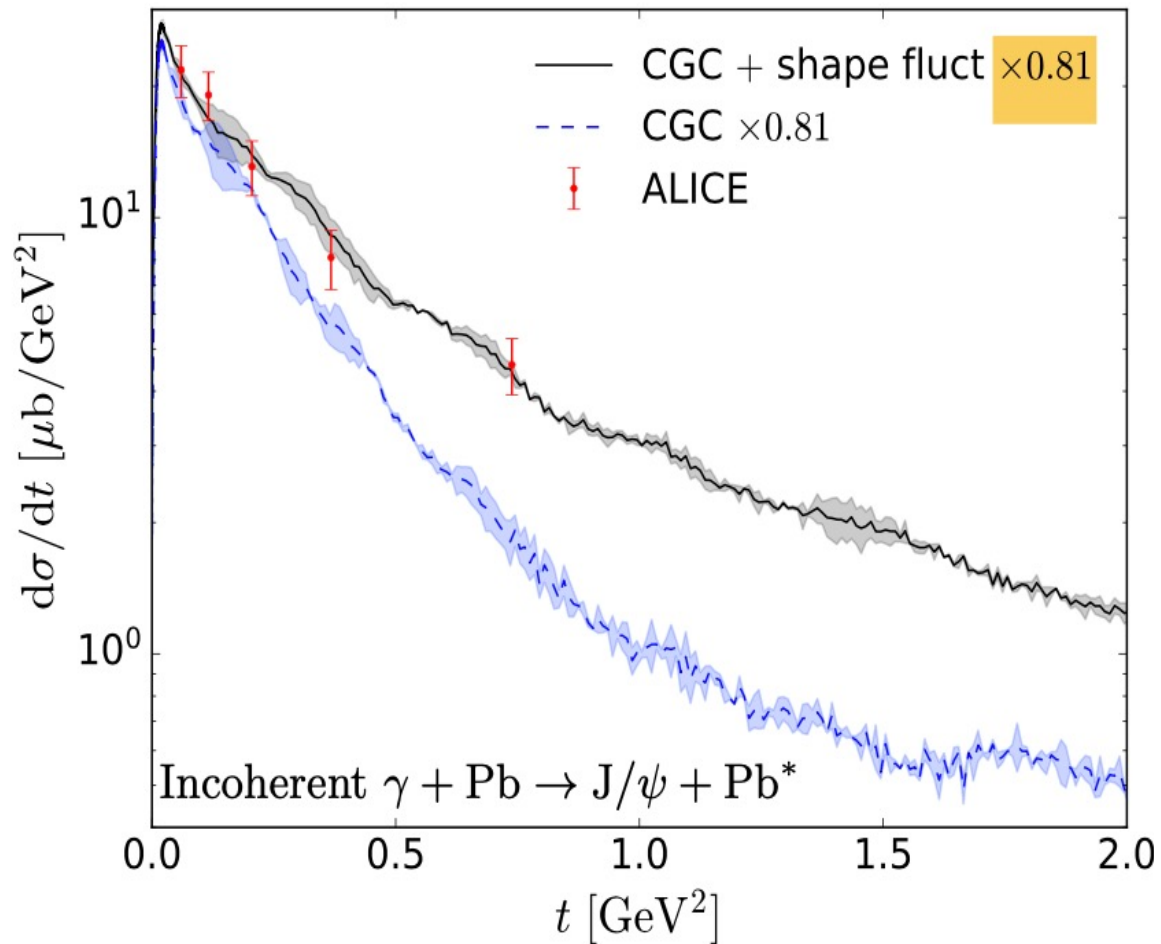
No neutrons to tag the target nucleus, assume the same relative fractions at (+y) and (-y) as in 0nXn

# Photon Flux: Realistic Nucleus vs. Point Charge

[J. CPC. \(2022\) 108388](#)

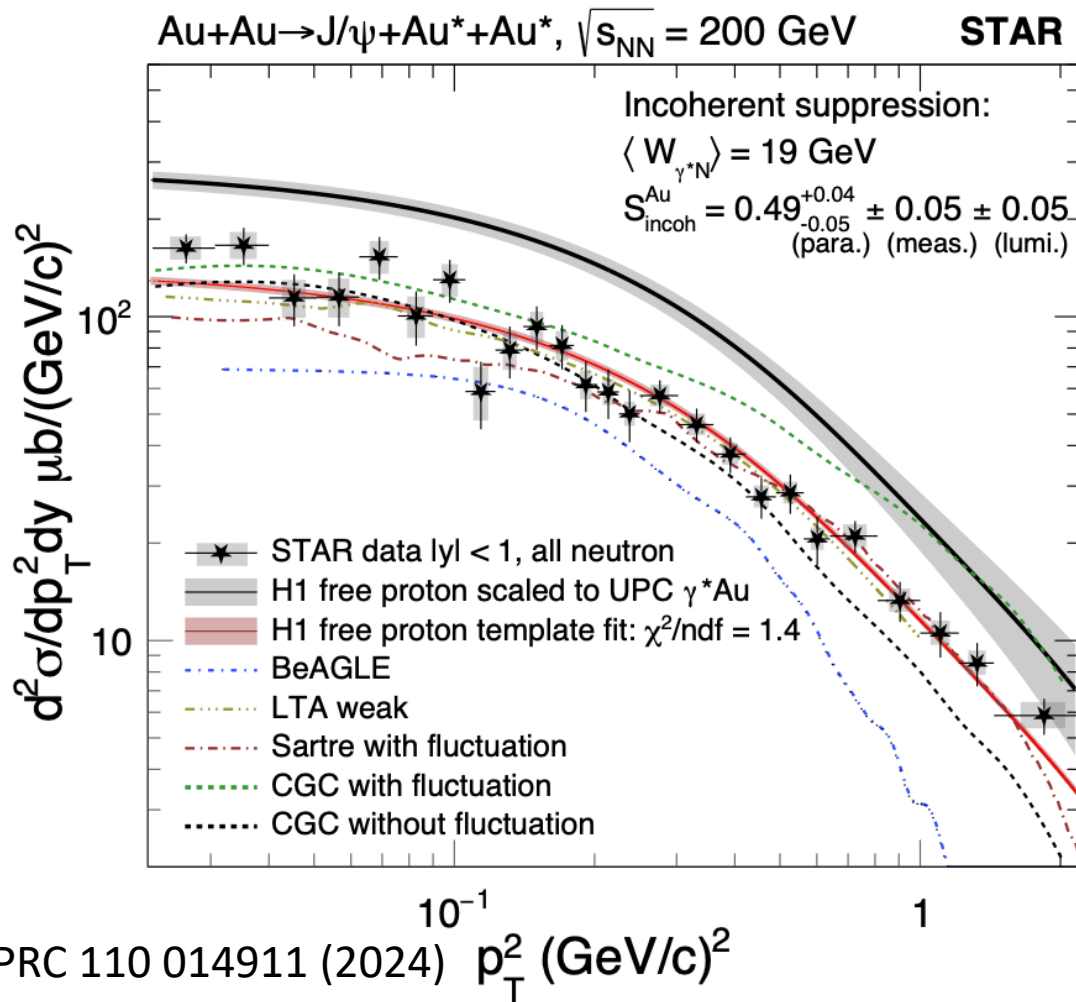


Photon fluxes coming from a nucleus in the point-like source approximation and the realistic description as functions of impact parameter  $b$  calculated at different photon energies: 100 MeV (a), 100 GeV (b)



CGC: PRD 109 (2024) 7, L071504

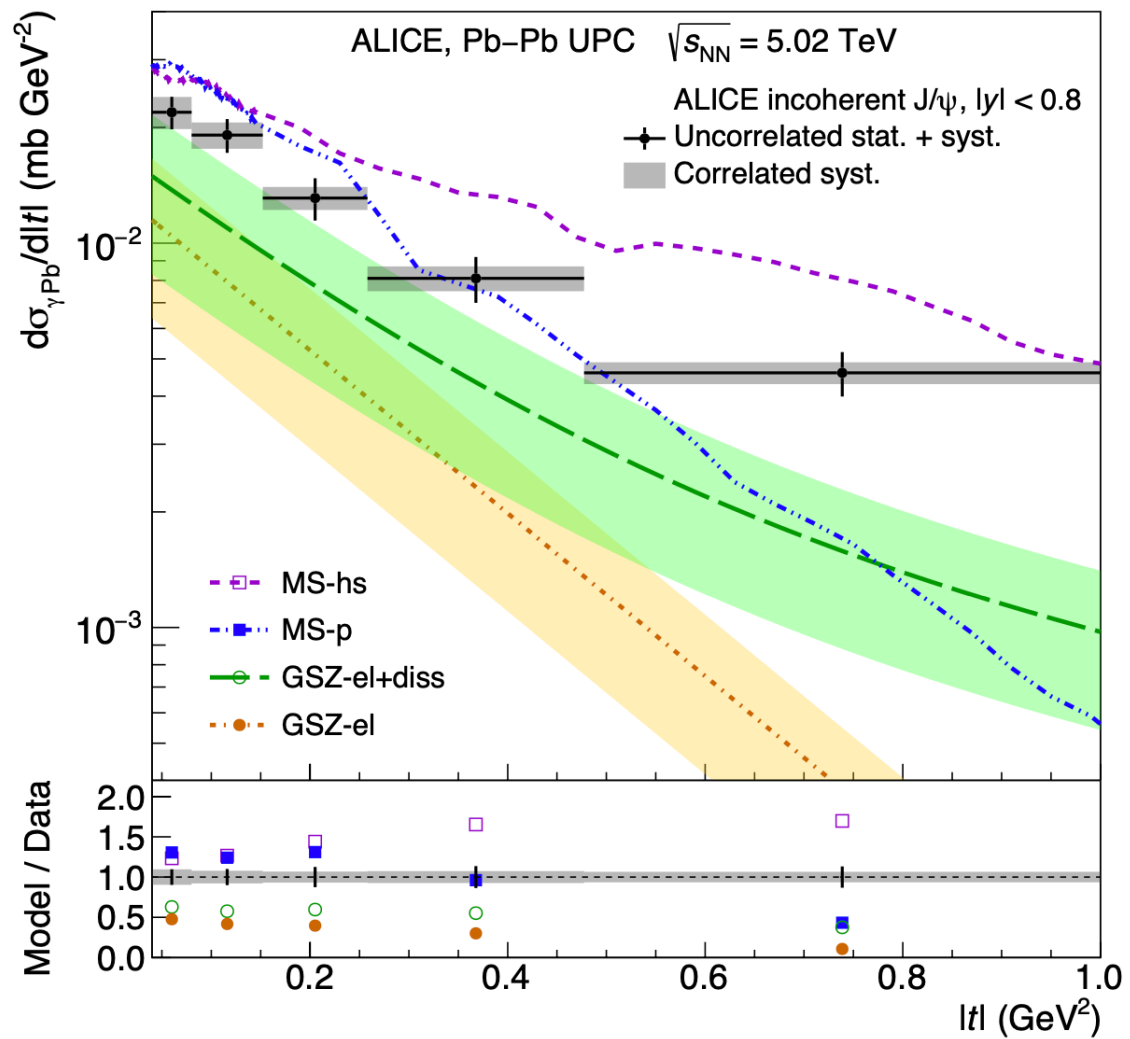
$d\text{Sigma}/dt \sim \exp(-B*t)$



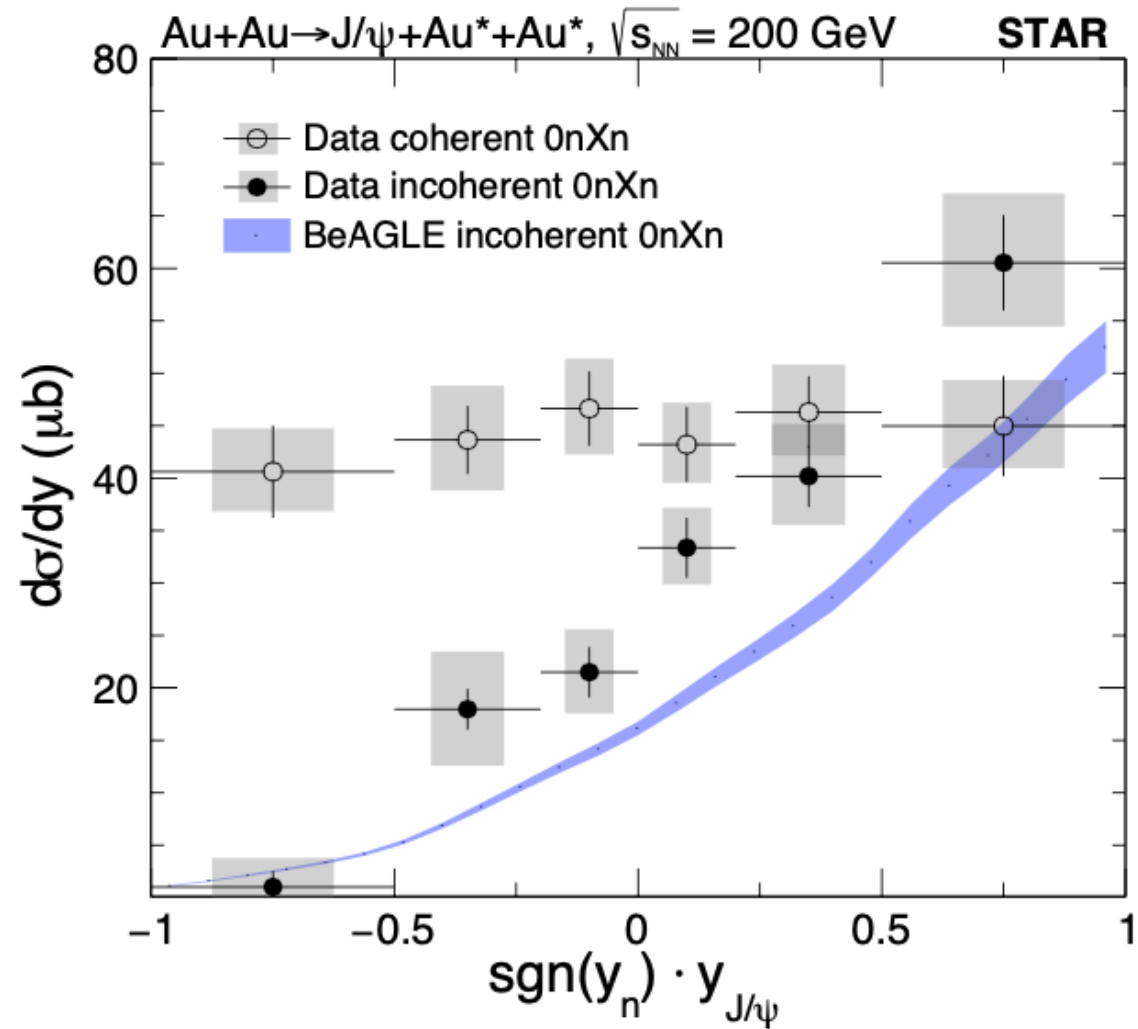
STAR: PRC 110 014911 (2024)  $p_T^2$  ( $\text{GeV}/c$ )<sup>2</sup>

**B** represents the size of fluctuating target objects

The elastic/exclusive production dominant  $p_T$  region, the  $t$  slopes agree with the theoretical calculations parameterized to H1 data



ALICE: PRL 132, 162302 (2024)



STAR: PRC 110 014911 (2024)