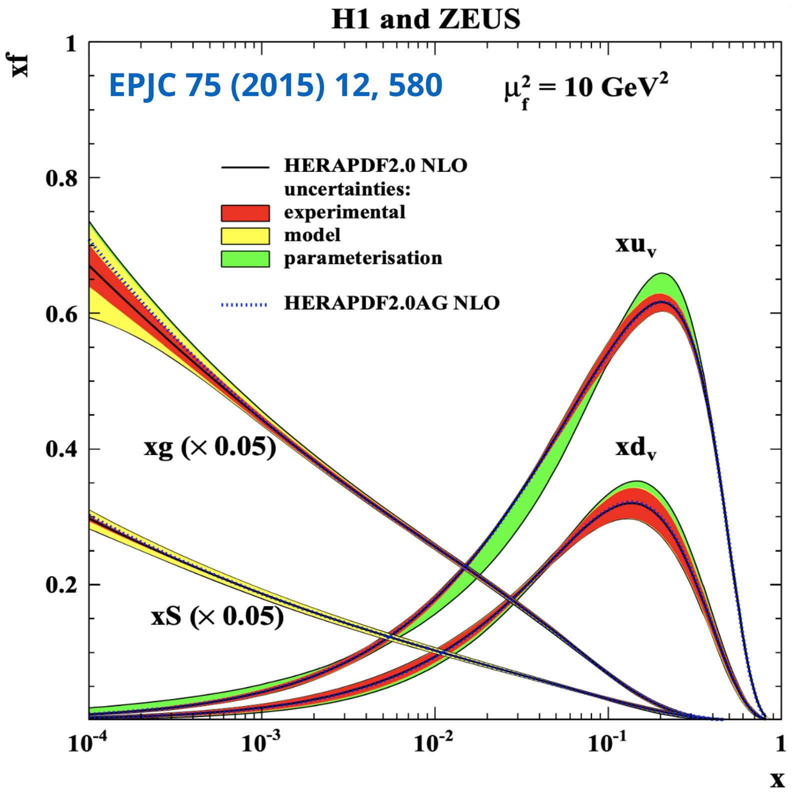
Detecting fluctuating gluonic structure via energy-dependent incoherent J/Ψ photoproduction in Pb-Pb UPCs at 5.02 TeV with the CMS experiment

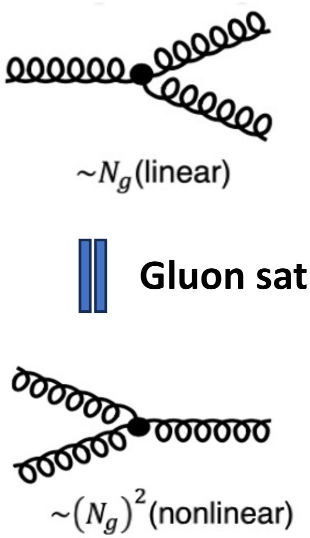
Zaochen Ye (SCNU)

For the CMS Collaboration

CMS-PAS-HIN-23-009

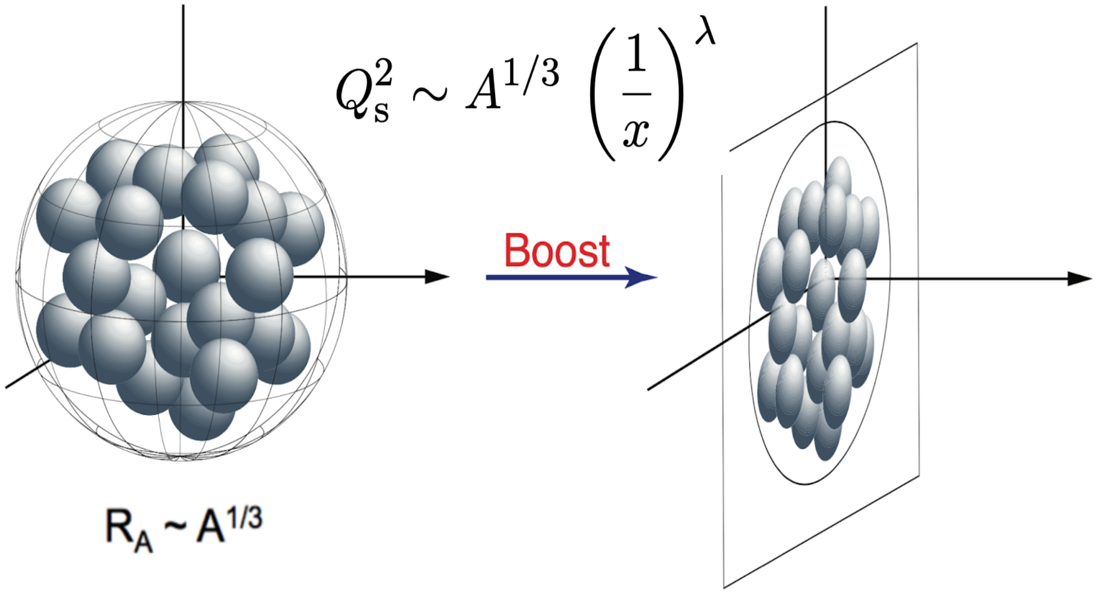
Advantages of Gluon Saturation Search in Nucleus


EPJC 75 (2015) 12, 580



‖ **Gluon saturation?**

Gluon density is **enhanced** in **nucleus**

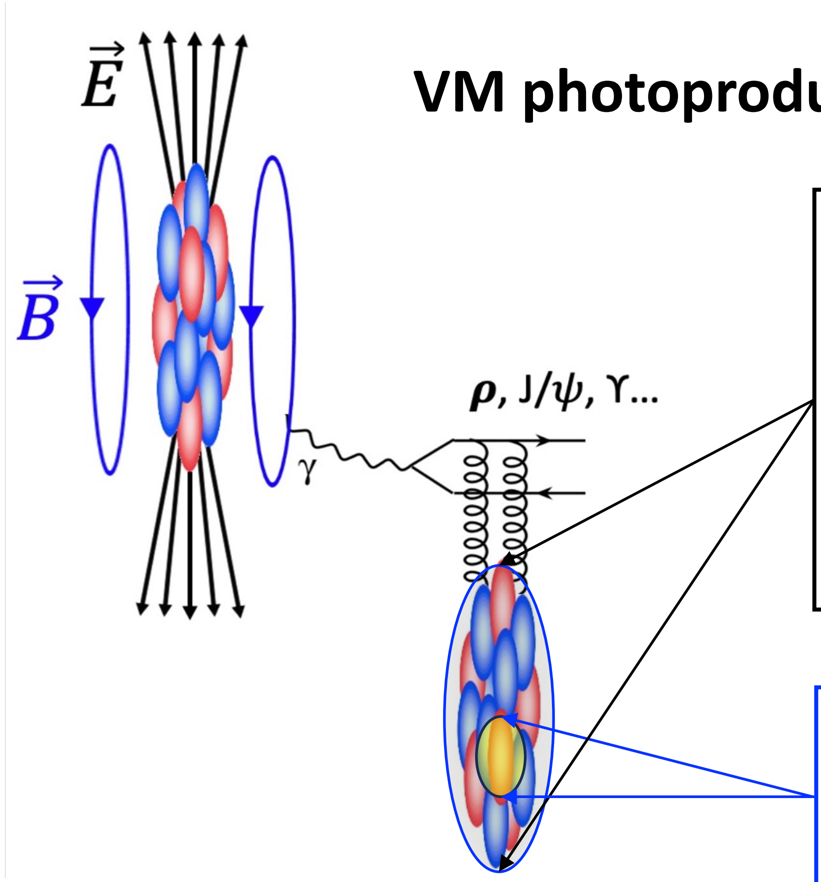


$$Q_s^2 \sim A^{1/3} \left(\frac{1}{x}\right)^{\lambda}$$

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

Vector Meson Photoproduction in UPCs

VM photoproduction is sensitive to the gluonic structure of target nucleus



Coherent photoproduction:

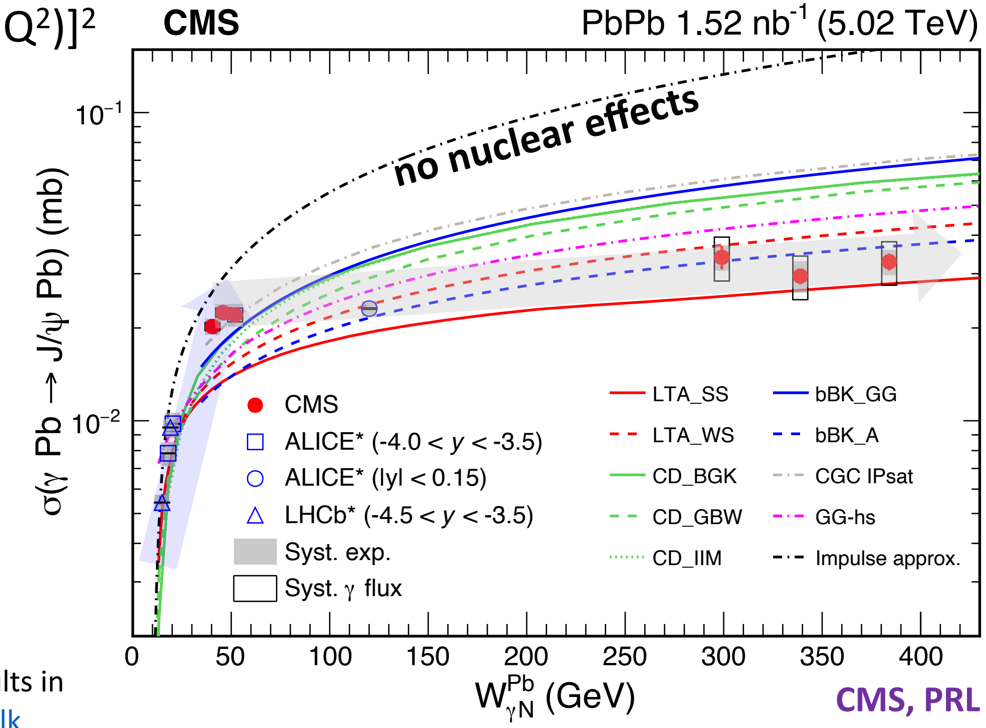
- Photon **interact with entire nucleus**
- **Target** nucleus remains **intact**
- VM $\langle p_T \rangle$ ~ **50 MeV**
- Probing the **averaged gluon density**

Incoherent photoproduction:

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

Recent Coh. J/Ψ Photoproduction off Pb Nucleus

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

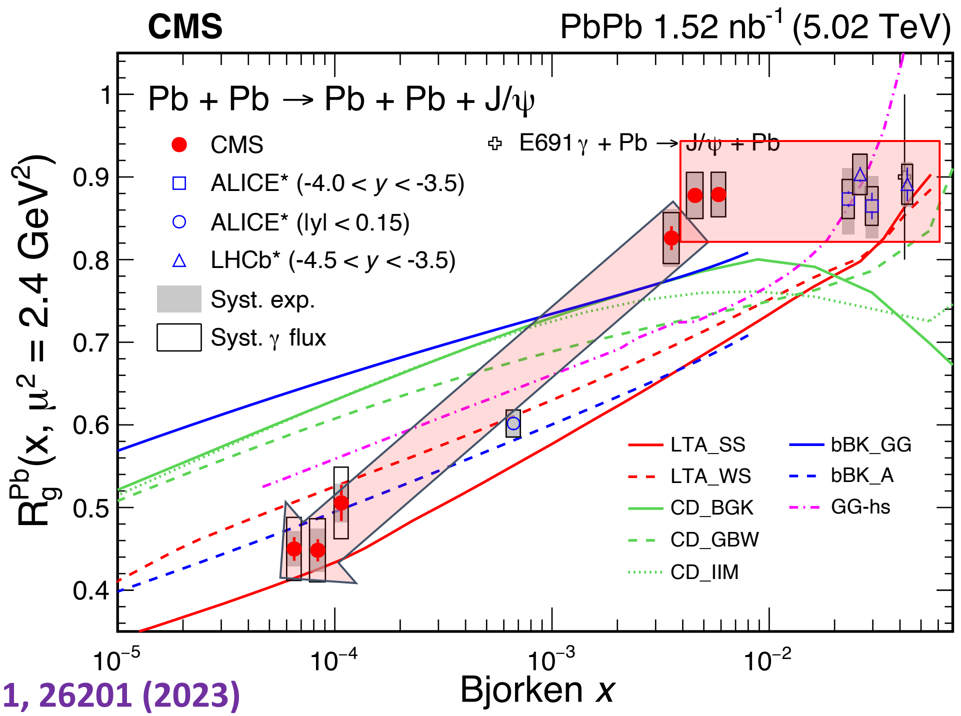


Strongly saturated cross section

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

CMS, PRL 131, 26201 (2023)

$$R_g^A = \left(\frac{\sigma^{exp}_{\gamma A \to J/\psi A}}{\sigma^{IA}_{\gamma A \to J/\psi A}}\right)^{1/2}$$



Strongly suppressed gluon density

Recent Coh. J/Ψ Photoproduction off Pb Nucleus

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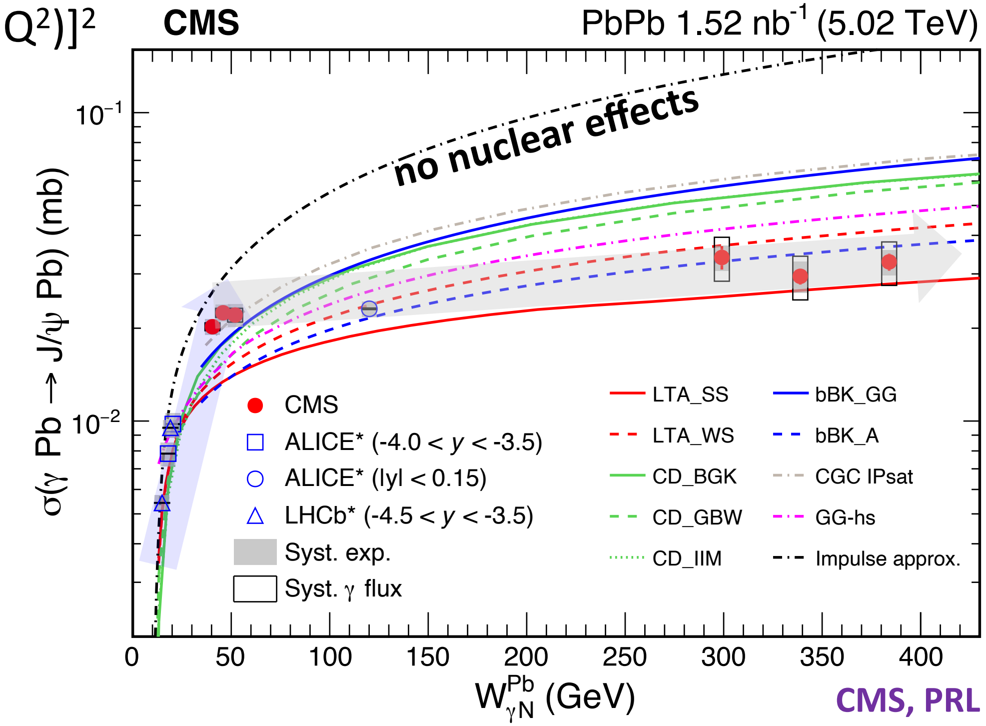

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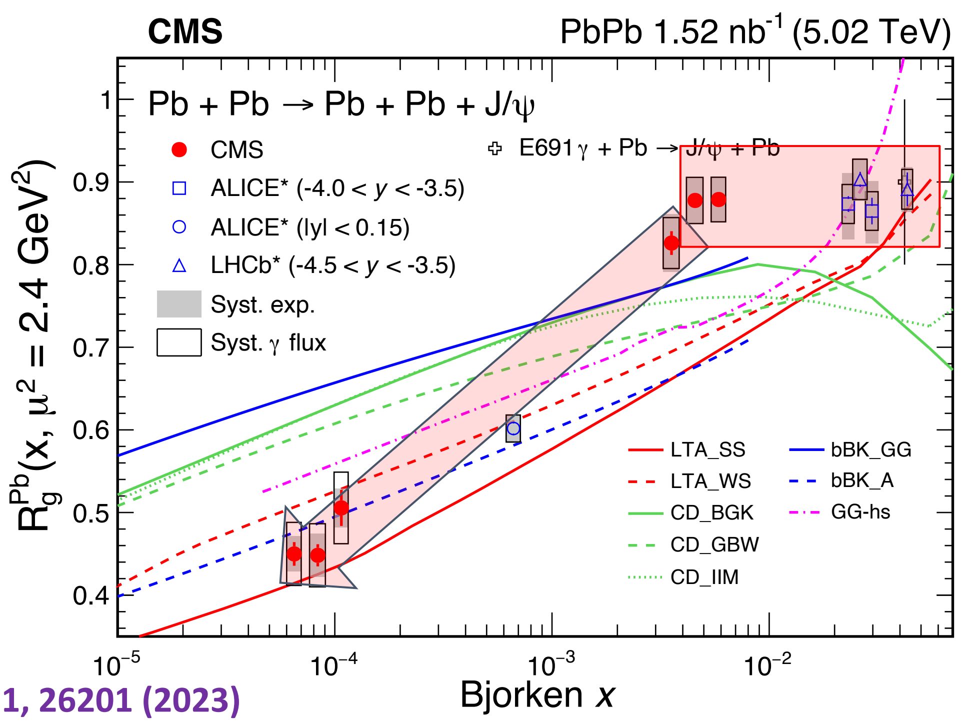


CMS, PRL 131, 26201 (2023)

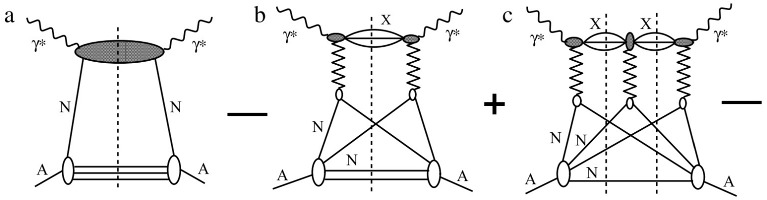
Strongly saturated cross section

Strongly suppressed gluon density

Gluon Saturation?

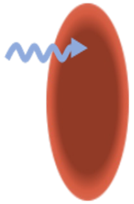
F. Gelis et al. Annu. Rev. Nucl. Part. Sci. 60 (2010) 463

Nuclear shadowing?



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

Black Disk Limit?



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

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

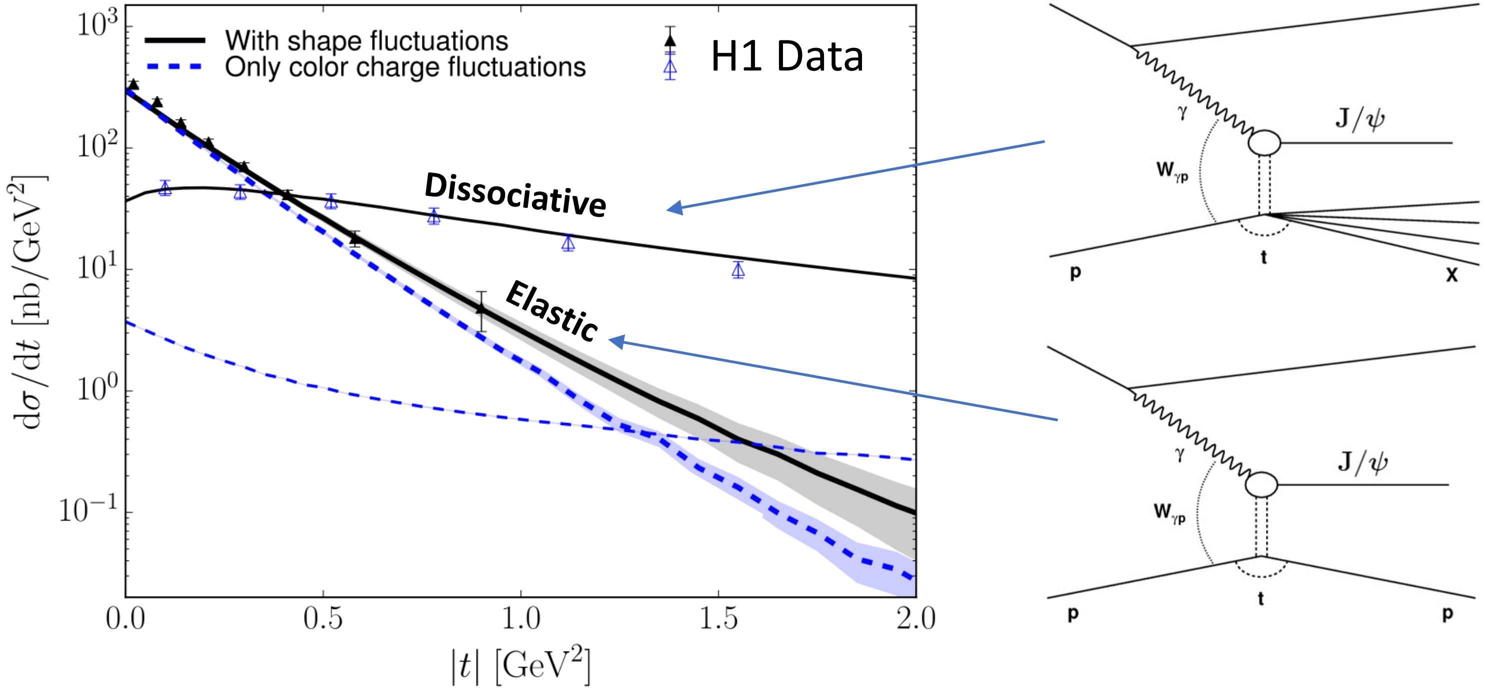
L. Frankfurt et al. PLB 537 (2002) 51

…?

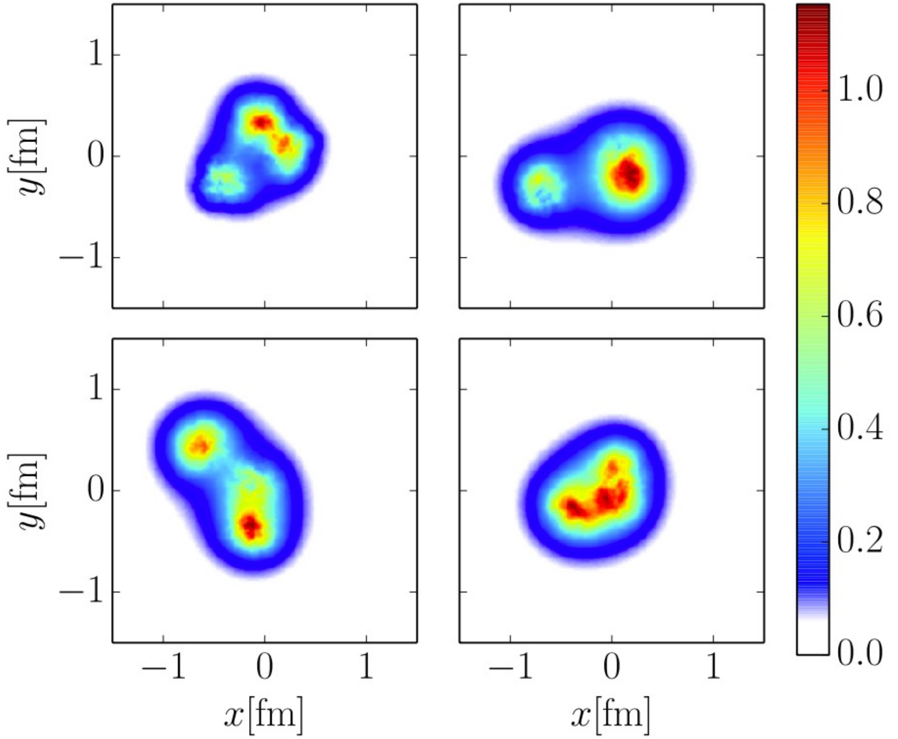
Probing Fluctuating Gluonic Structure via γ+p

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 off proton at HERA

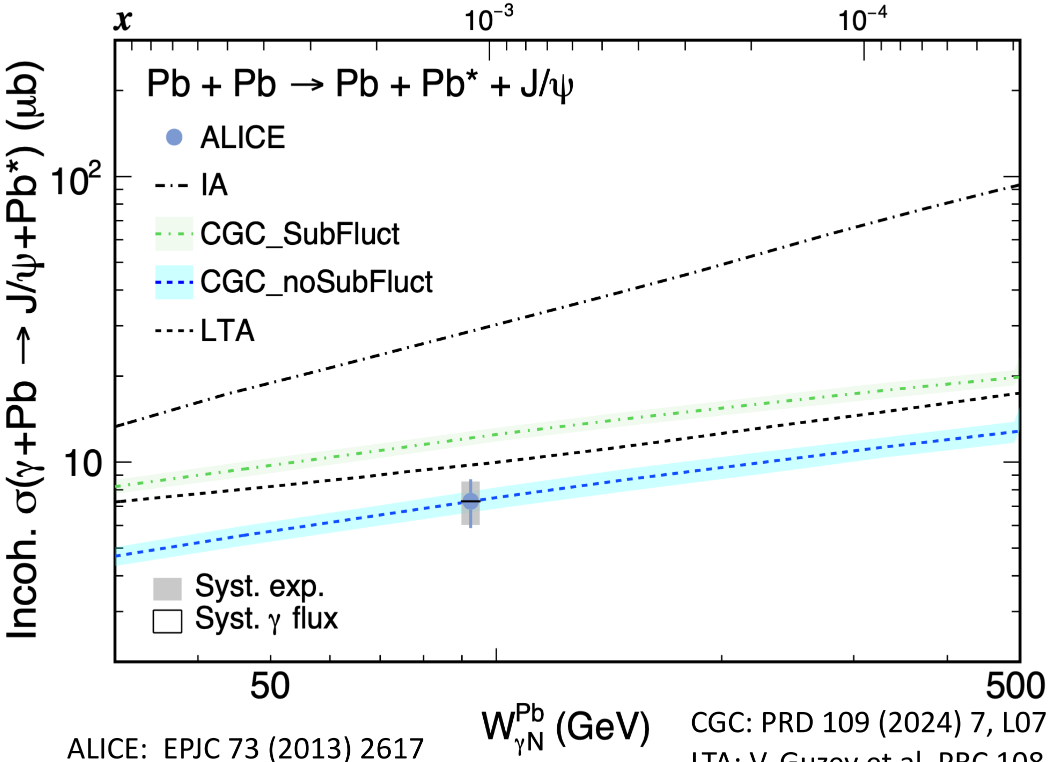


Rep. Prog. Phys. **83** (2020) 082201

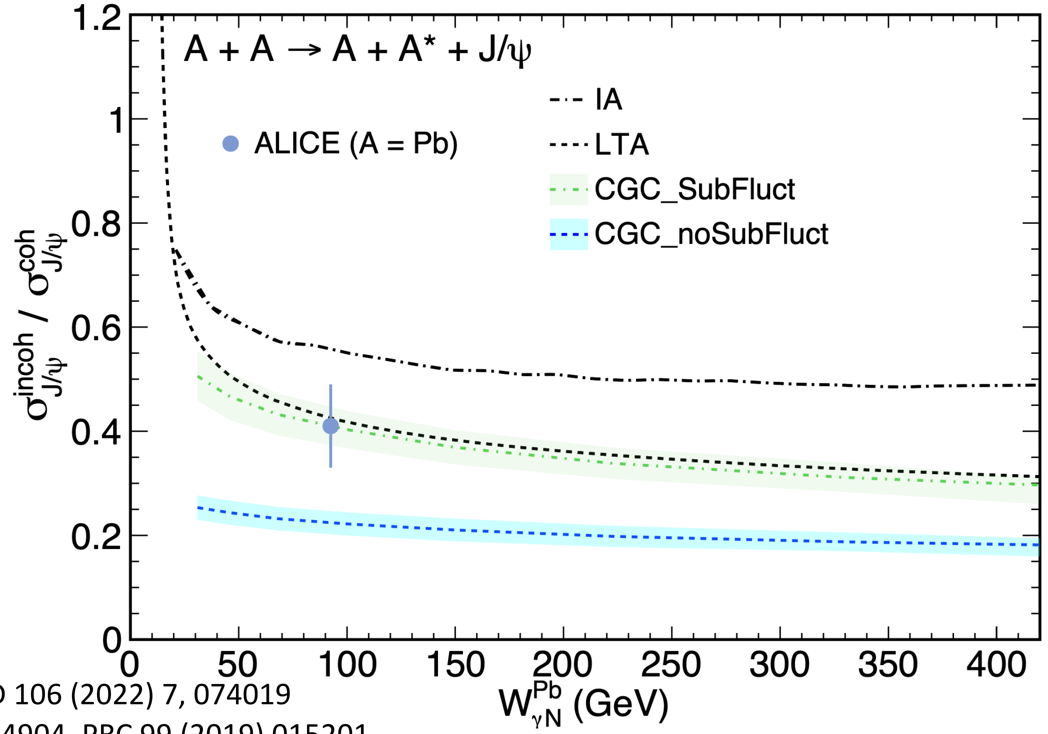


CGC Ipsat is impact parameter dependent saturation model under the Color-Glass Condensate framework.

Probing Fluctuating Gluonic Structure via Incoh. γ+Pb



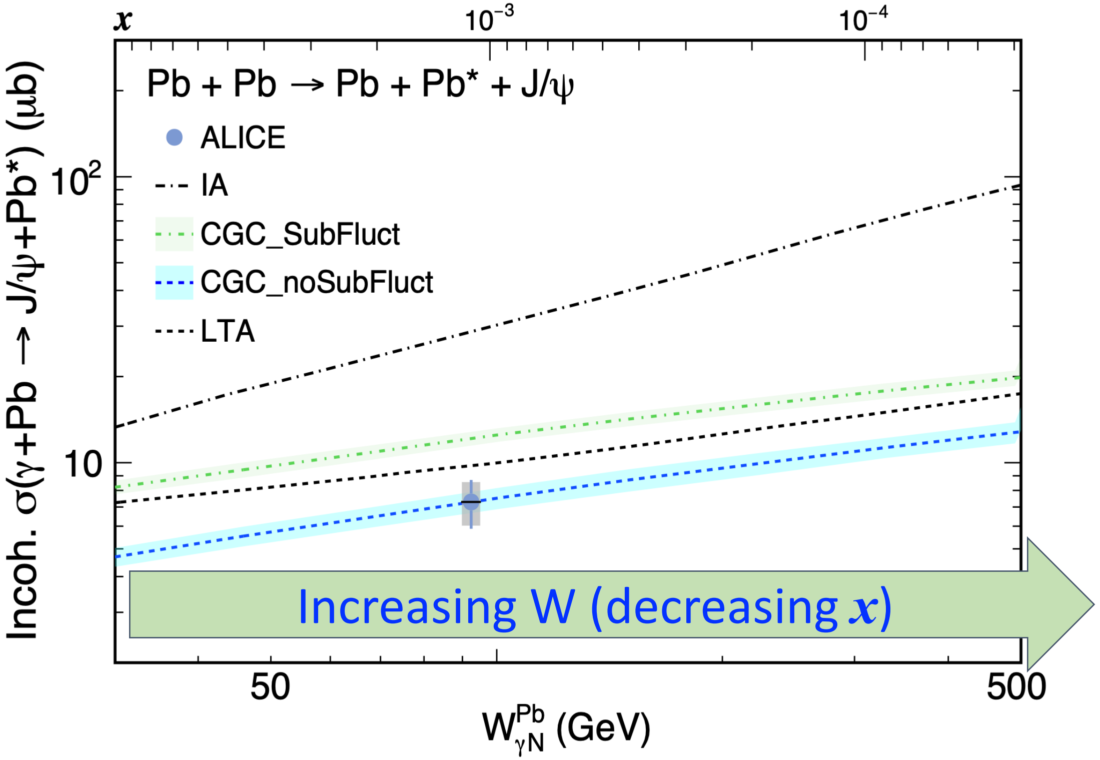
ALICE: EPJC 73 (2013) 2617



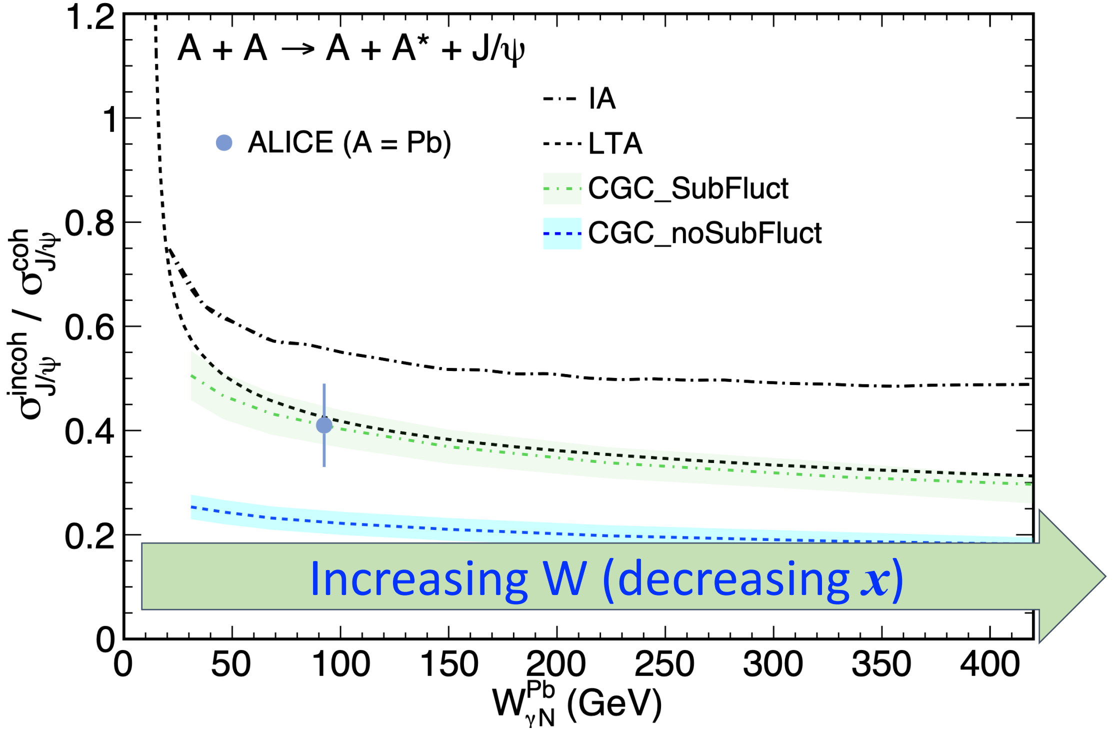
CGC: PRD 109 (2024) 7, L071504, PRD 106 (2022) 7, 074019
LTA: V. Guzey et al. PRC 108 (2023) 024904, PRC 99 (2019) 015201

- 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. γ+Pb



Increasing W (decreasing *x*)



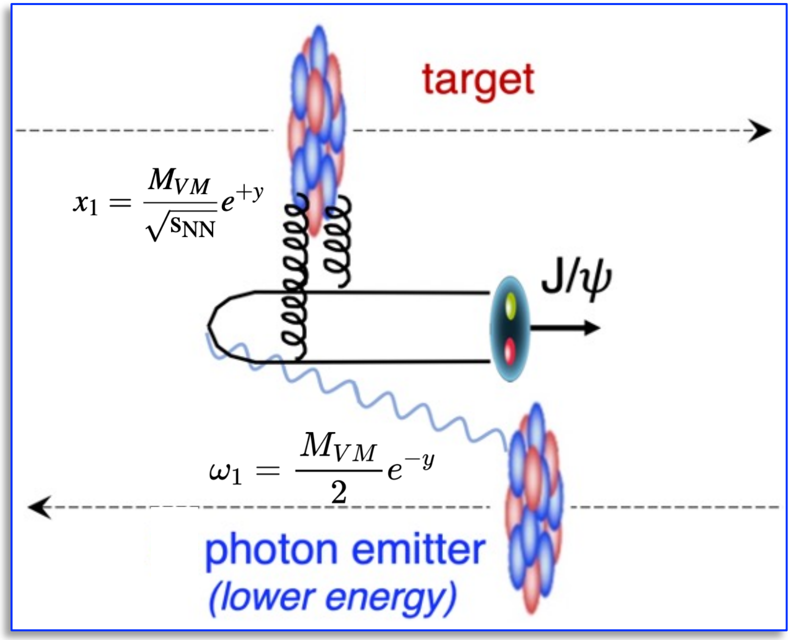
Increasing W (decreasing *x*)

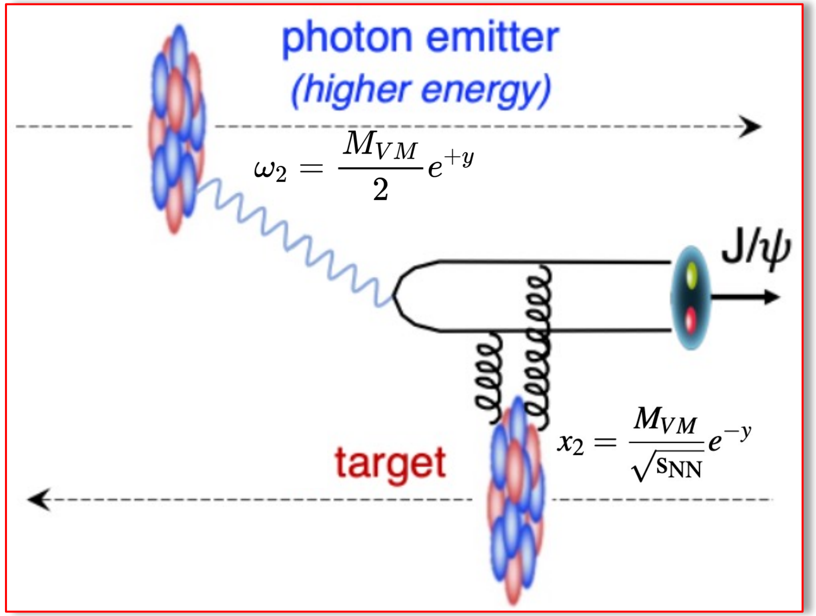
- CGC IPsat (w or w/o) sub-nucleonic fluctuations cannot describe the data
- LTA (leading twist approximation, nuclear shadowing model) seems to be better?

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

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

“Two-way Ambiguity” in A-A UPCs



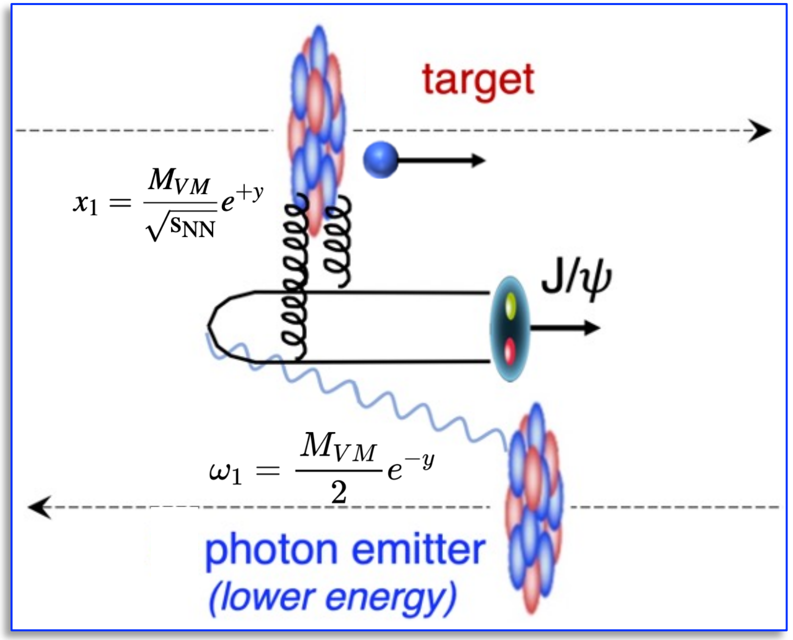


$$\frac{d\sigma_{AA\to AA'J/\psi}}{dy} = N_{\gamma/A}(\omega_1)\cdot \boxed{\sigma_{\gamma A\to J/\psi A'}(\omega_1)} + N_{\gamma/A}(w_2)\cdot \boxed{\sigma_{\gamma A\to J/\psi A'}(w_2)}$$

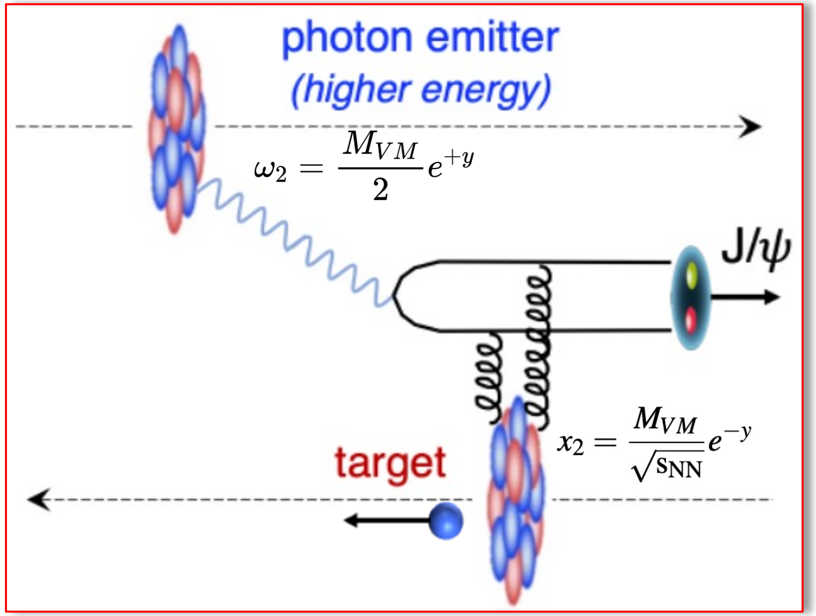
what we measure

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

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

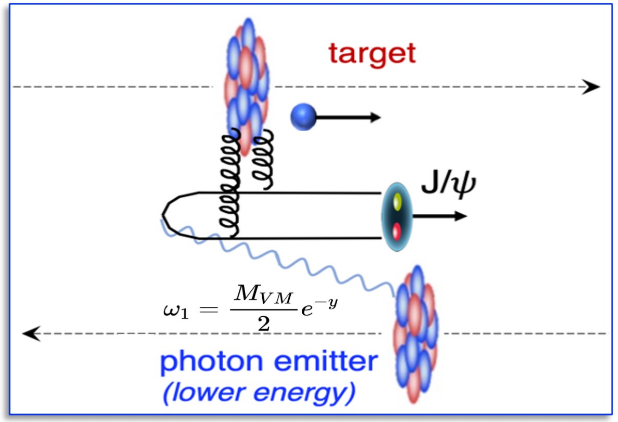
- **Incoh. J/Ψ photoproduction** itself has ~85% chance to induce the forward neutrons
  → Detecting these neutrons will identify target nucleus
  → Help to solve the “two-way Ambiguity”

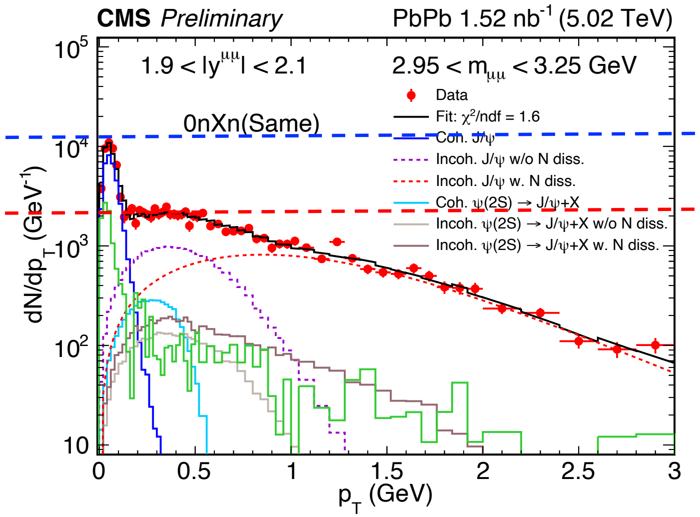
Example of Signal Extraction (**0nXn**)

Low-W

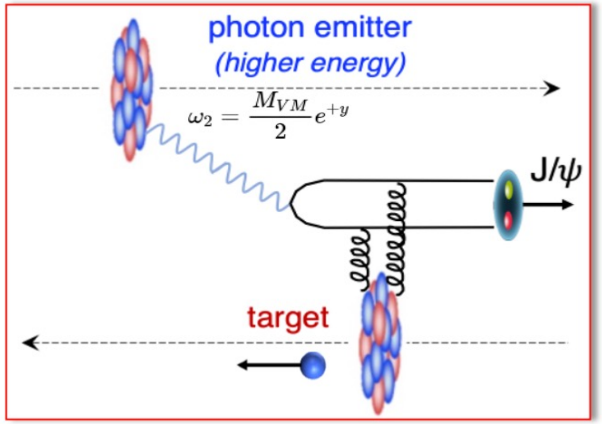
-y

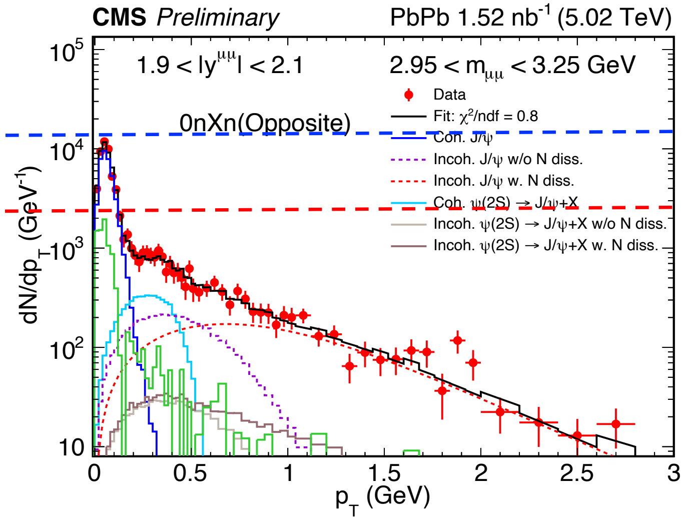
J/Ψ-Xn (Same Direction)





J/Ψ-Xn (Opposite Direction)



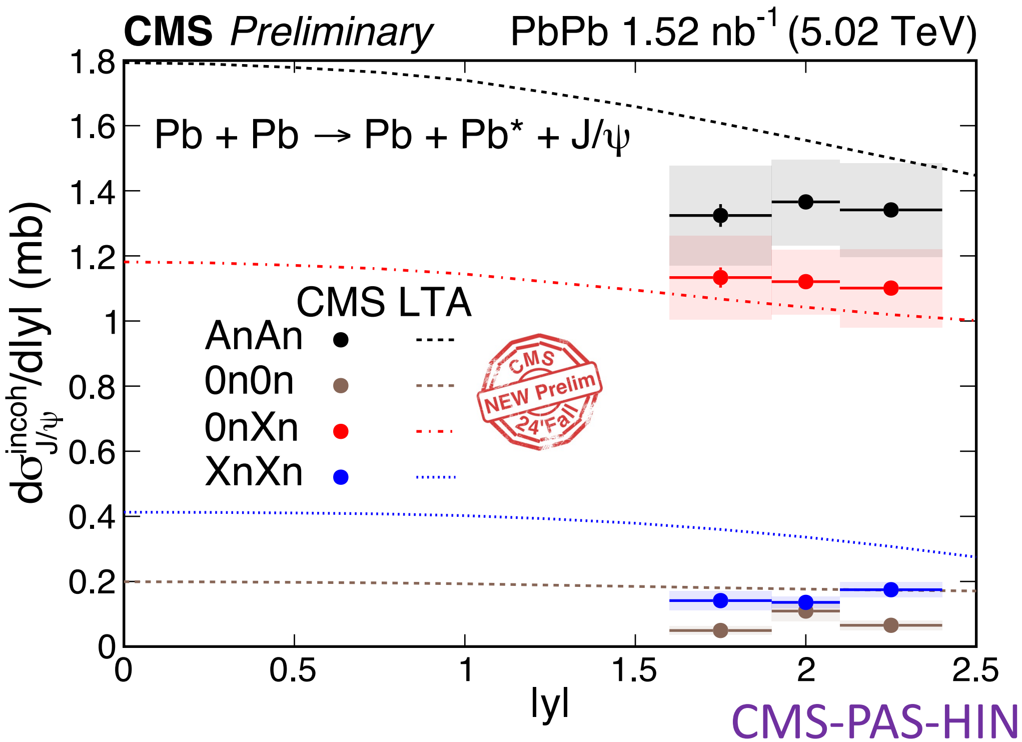


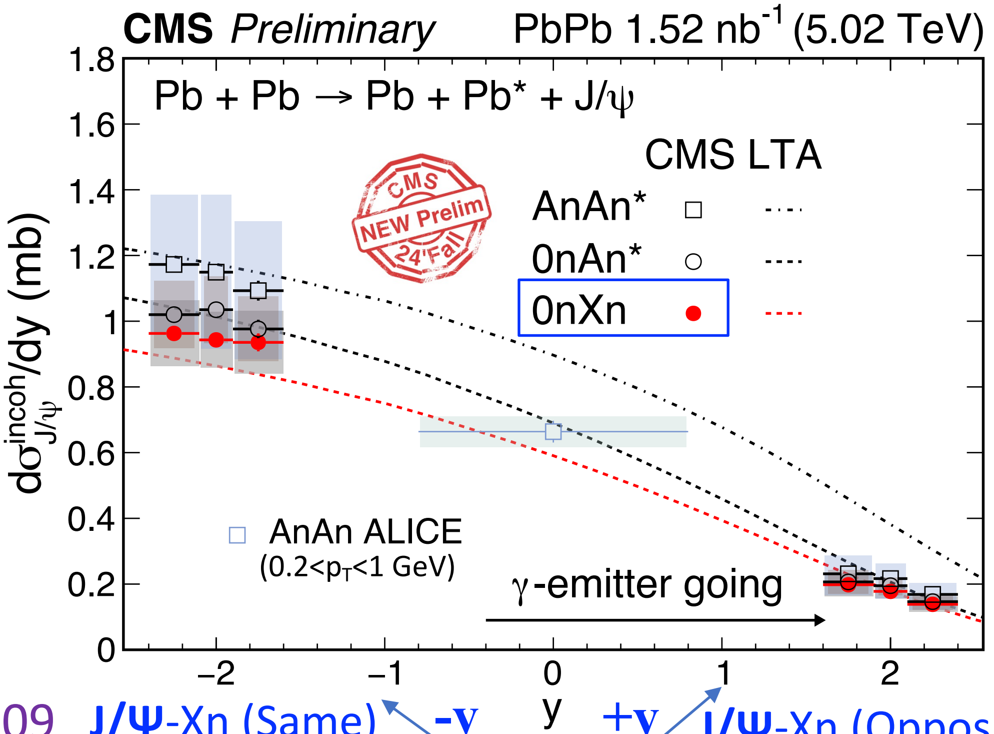
High-W

+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)**

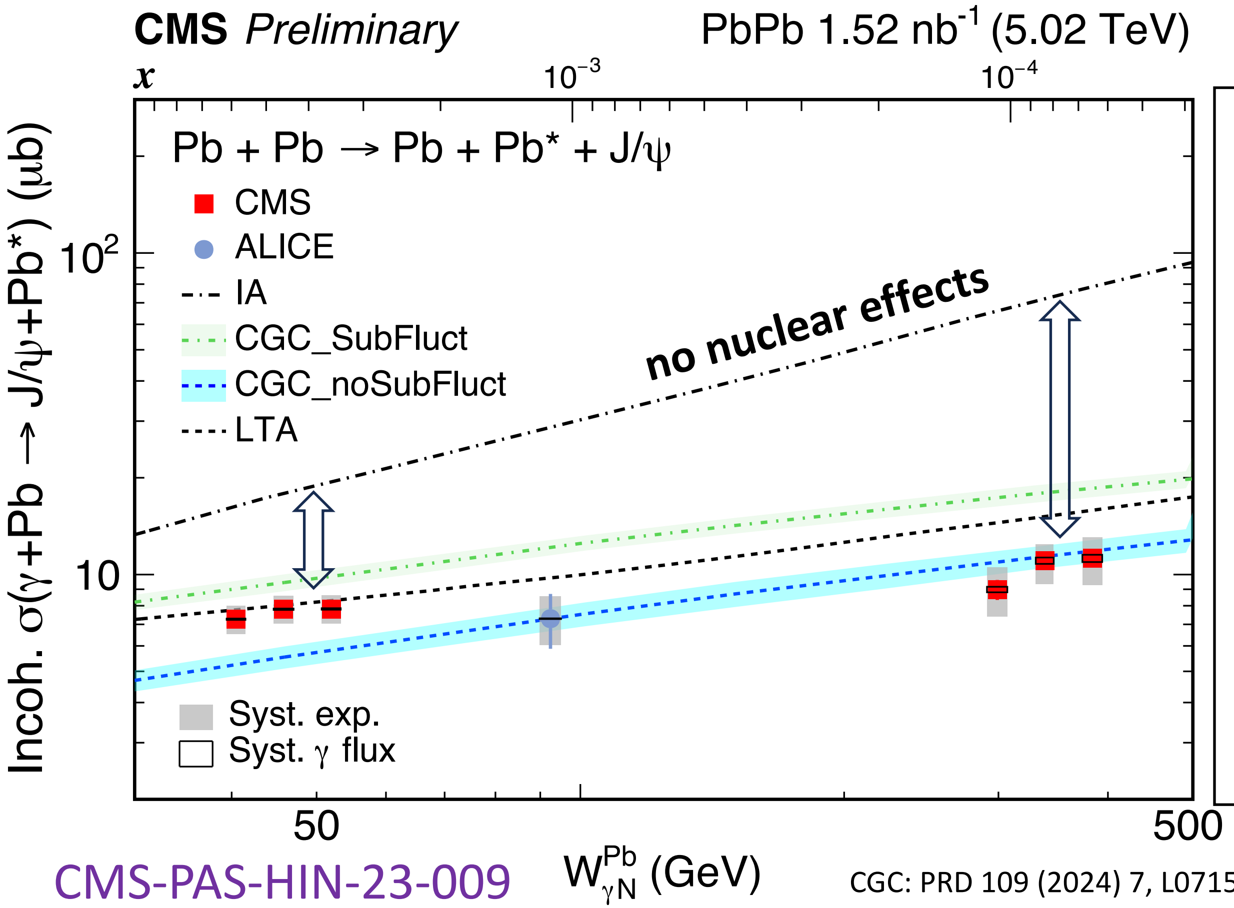
LTA: V. Guzey et al. PRC 108 (2023) 024904, PRC 99 (2019) 015201
ALICE: PRL 132, 162302 (2024)

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

- 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

Incoh. J/Ψ Cross Section per γ+Pb



- 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<50 GeV
- CGC **without** Sub-N fluctuations better describe data at W>90 GeV

CMS-PAS-HIN-23-009

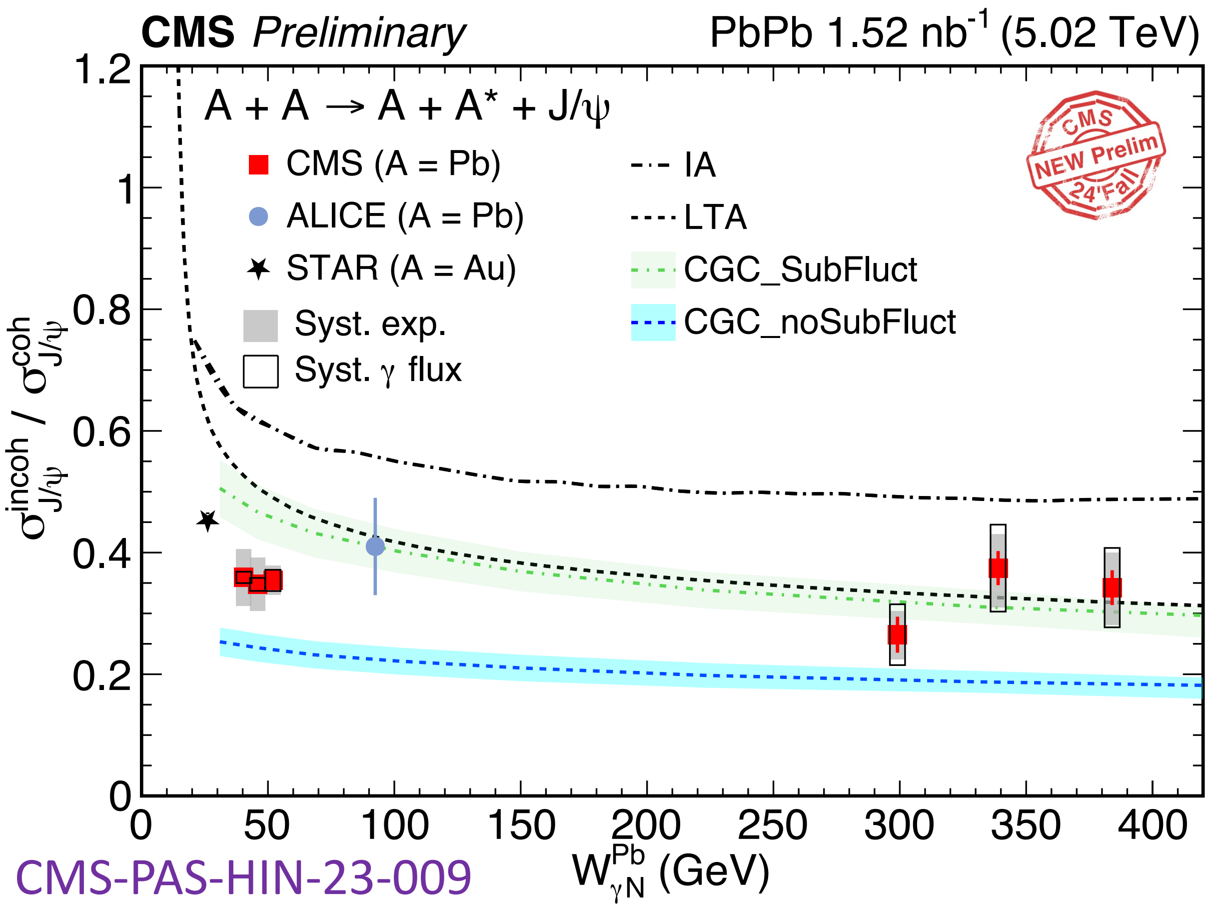
CGC: PRD 109 (2024) 7, L071504, PRD 106 (2022) 7, 074019
LTA: V. Guzey et al. PRC 108 (2023) 024904, PRC 99 (2019) 015201

ALICE: EPJC 73 (2013) 2617

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

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

Cross Section Ratio of Incoh/Coh



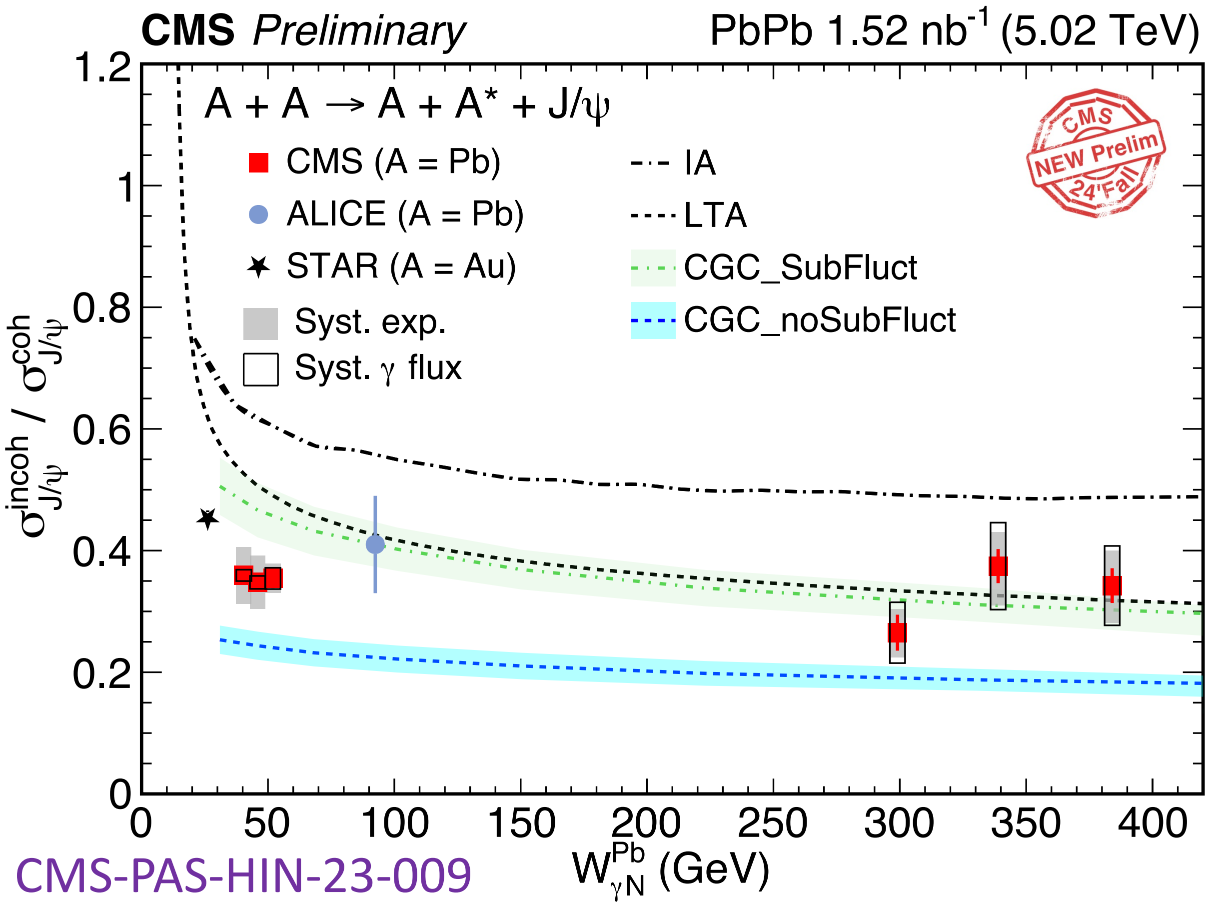
CMS-PAS-HIN-23-009

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 examining theoretical assumptions on nuclear effects: saturation or nuclear shadowing...

Cross Section Ratio of Incoh/Coh



CMS-PAS-HIN-23-009

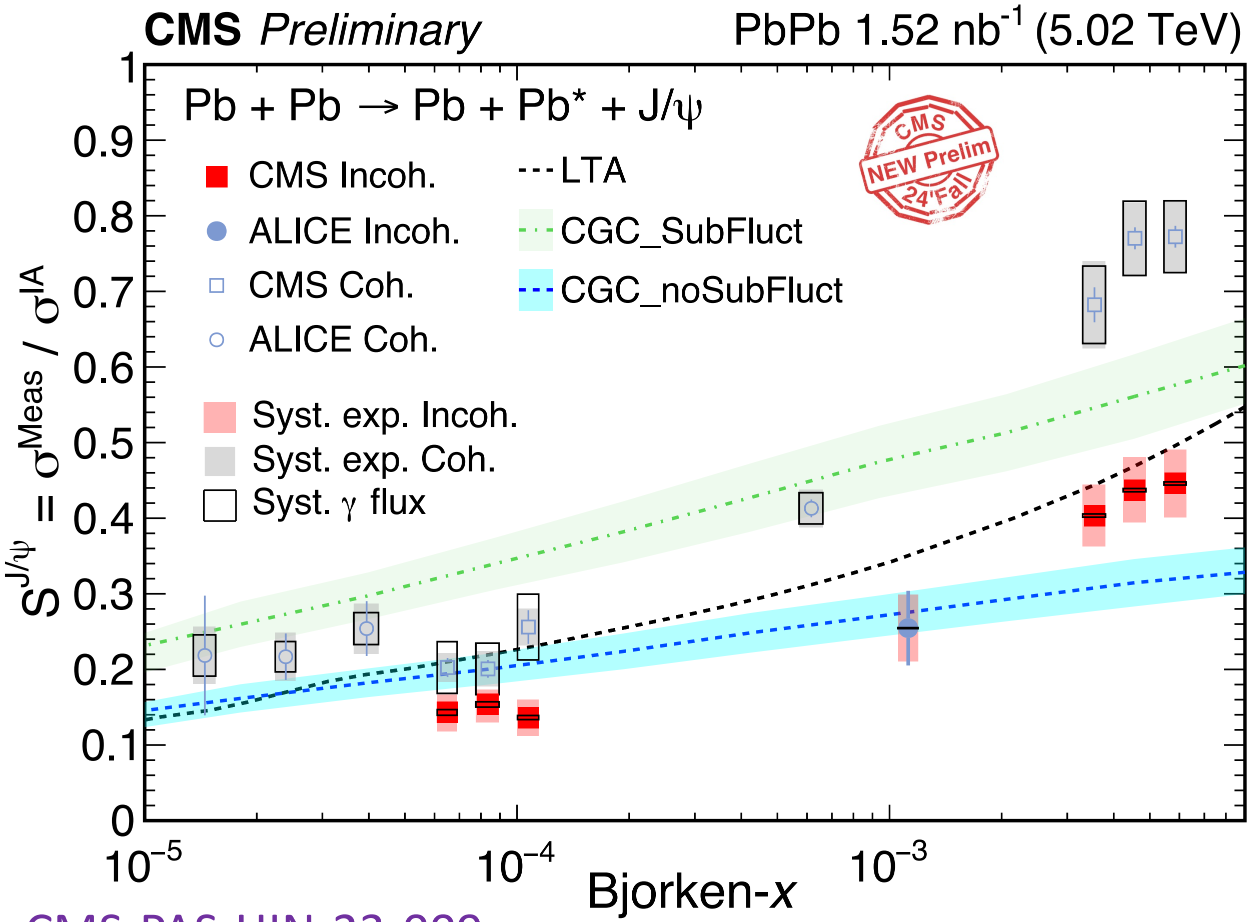
- No clear W dependent (40<W<400 GeV)
  - No support BDL is reached
- ALICE data agrees with CMS data, while STAR data slightly rises towards lower W
- Data is lower than IA → Incoh. J/Ψ is more suppressed than Coh. J/Ψ
- LTA and CGC with Sub-N fluctuation qualitatively describe data trend
  - Still overpredict data for W<60 GeV

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

→

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

Nuclear Suppression



CMS-PAS-HIN-23-009

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

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

No nuclear effects

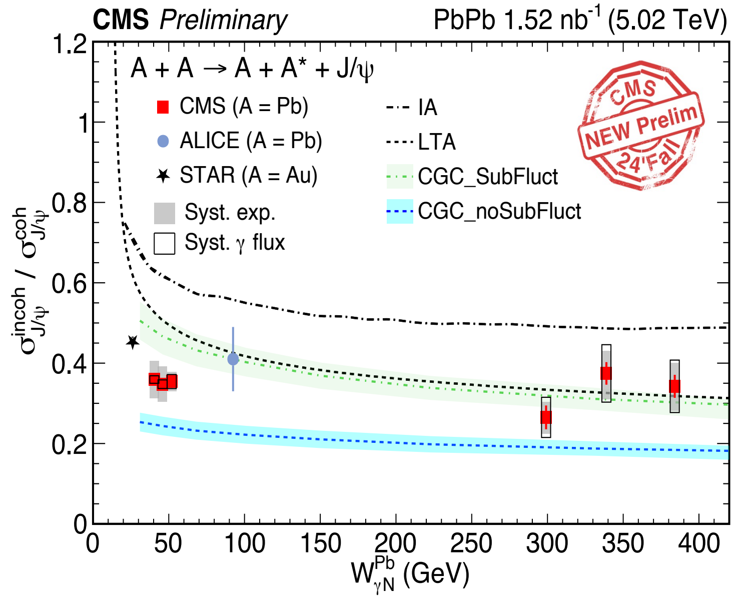
- Stronger suppression towards lower x, and eventually flattens out
- ALICE data follows CMS data trend
- Incoh. J/Ψ is more suppressed than Coh. J/Ψ
- Incoh. J/Ψ gets closer to Coh J/Ψ for $x<10^{-4}$
- No models can describe the data

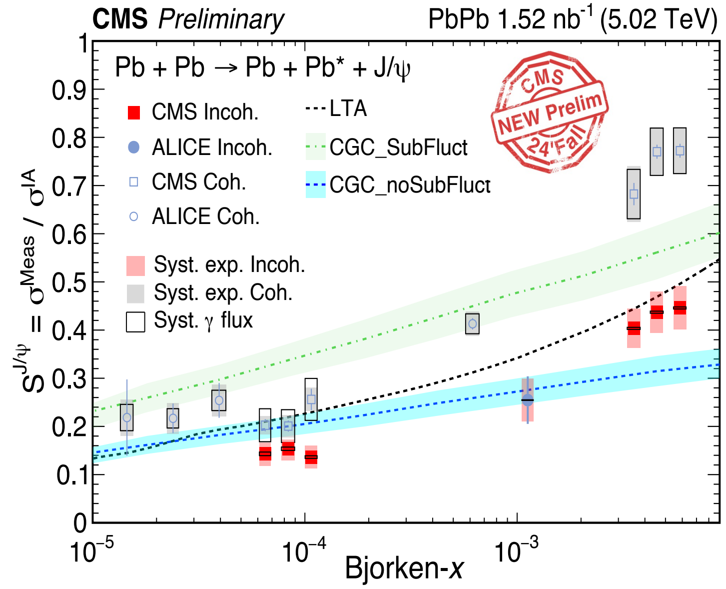
$$S^{J/\psi}_{coh}(x, \mu^2) = (R_g)^2$$

Summary

- **First energy-dependent** measurement of incoh. J/Ψ photoproduction off nucleus
- Probing fluctuating gluon fields over broad x interval: 5.8x$\mathbf{10^{-3}}$ - 6.5x$\mathbf{10^{-5}}$
- Ratio of Incoh/Coh is **~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/Ψ photoproduction:
    - ○ **Stronger towards lower x, eventually flattens out**
    - ○ **Stronger** than Coh. J/Ψ 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

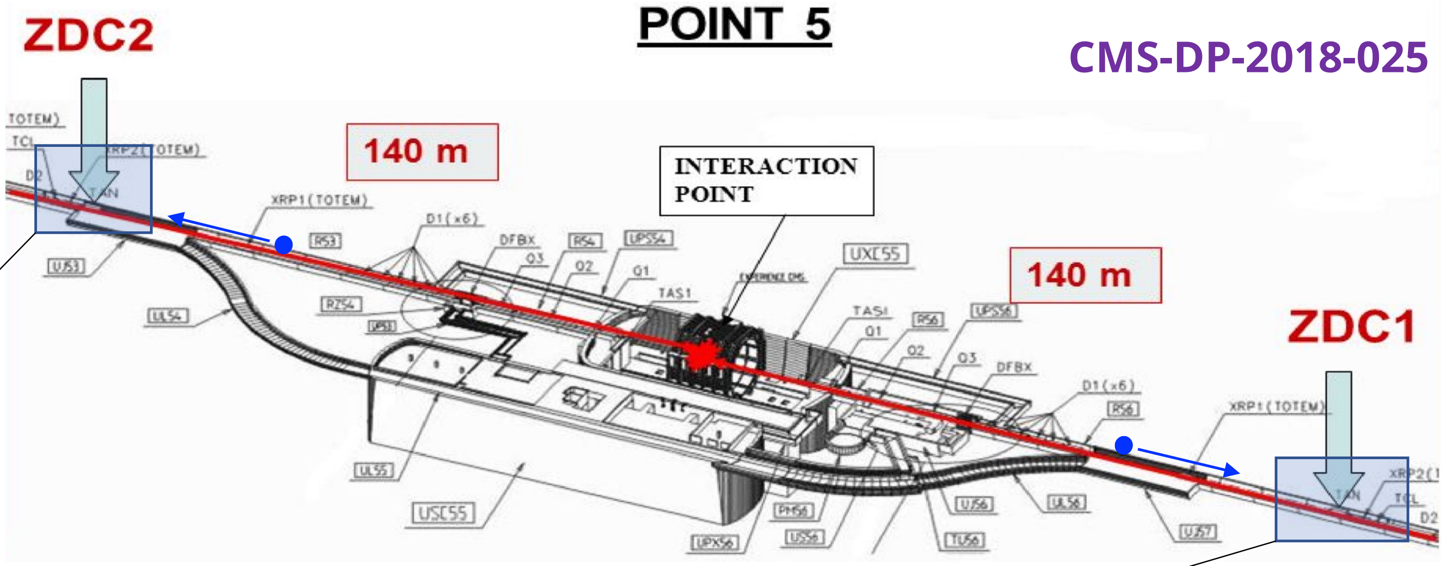
LTA: V. Guzey, M. Strikman, M. Zhalov and E. Kryshen

Backup

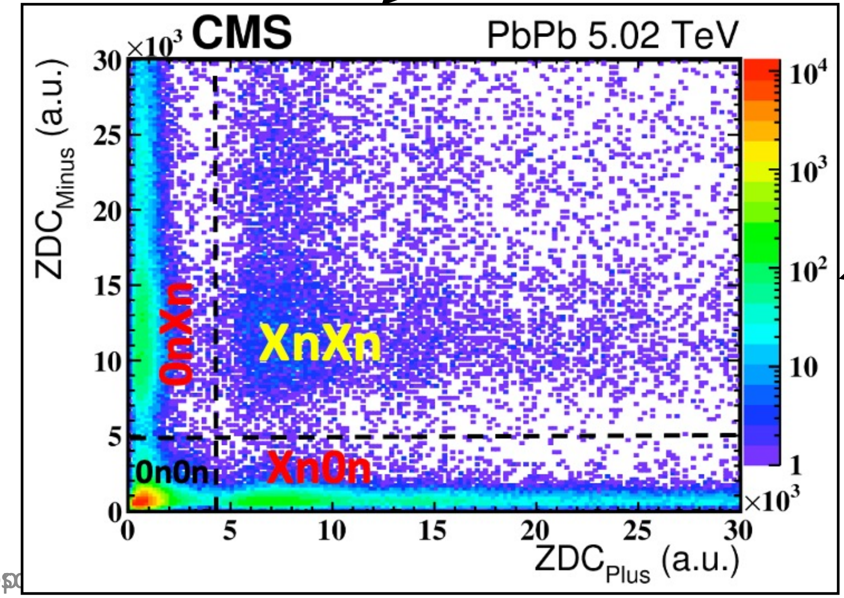
Neutron Tag with Zero Degree Calorimeter

Tag events with **neutrons**:

- **0n0n, 0nXn, XnXn** (X: ≥1)



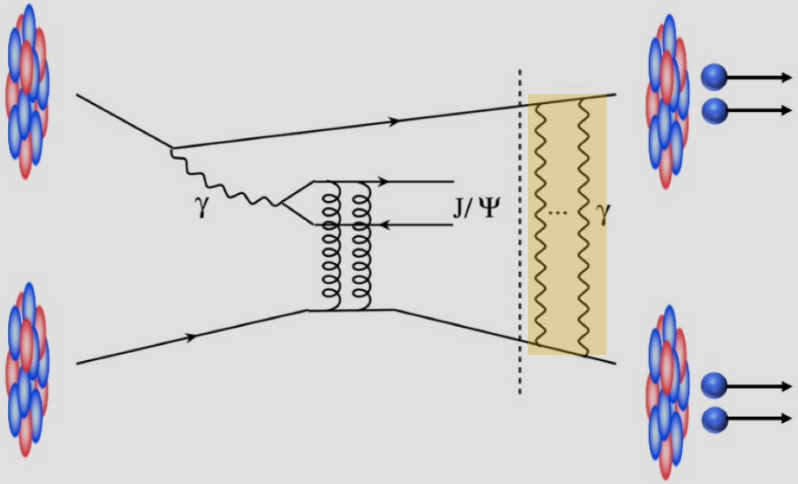
CMS-DP-2018-025



EMD pileup corrections are needed

Solution Based on Forward Neutrons

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

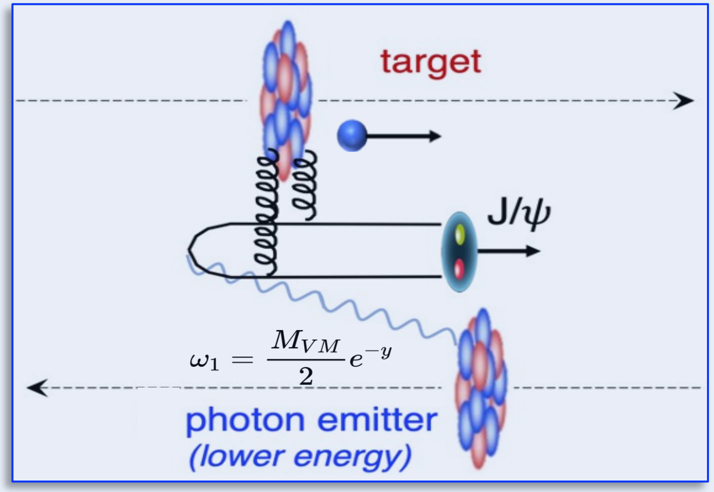


$$\frac{d\sigma^{0nXn}_{AA\to AA'J/\psi}}{dy} = \boxed{N^{0nXn}_{\gamma/A}(\omega_1)}\cdot \sigma_{\gamma A\to J/\psi A'(\omega_1)} + \boxed{N^{0nXn}_{\gamma/A}(w_2)}\cdot \sigma_{\gamma A\to J/\psi A'(w_2)}$$

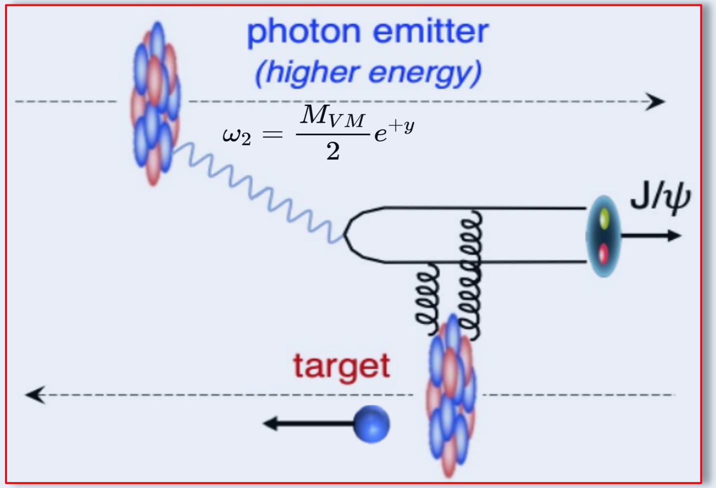
from theoretical calculation

$$\frac{d\sigma^{XnXn}_{AA\to AA'J/\psi}}{dy} = \boxed{N^{XnXn}_{\gamma/A}(\omega_1)}\cdot \sigma_{\gamma A\to J/\psi A'(\omega_1)} + \boxed{N^{XnXn}_{\gamma/A}(w_2)}\cdot \sigma_{\gamma A\to J/\psi A'(w_2)}$$

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.

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

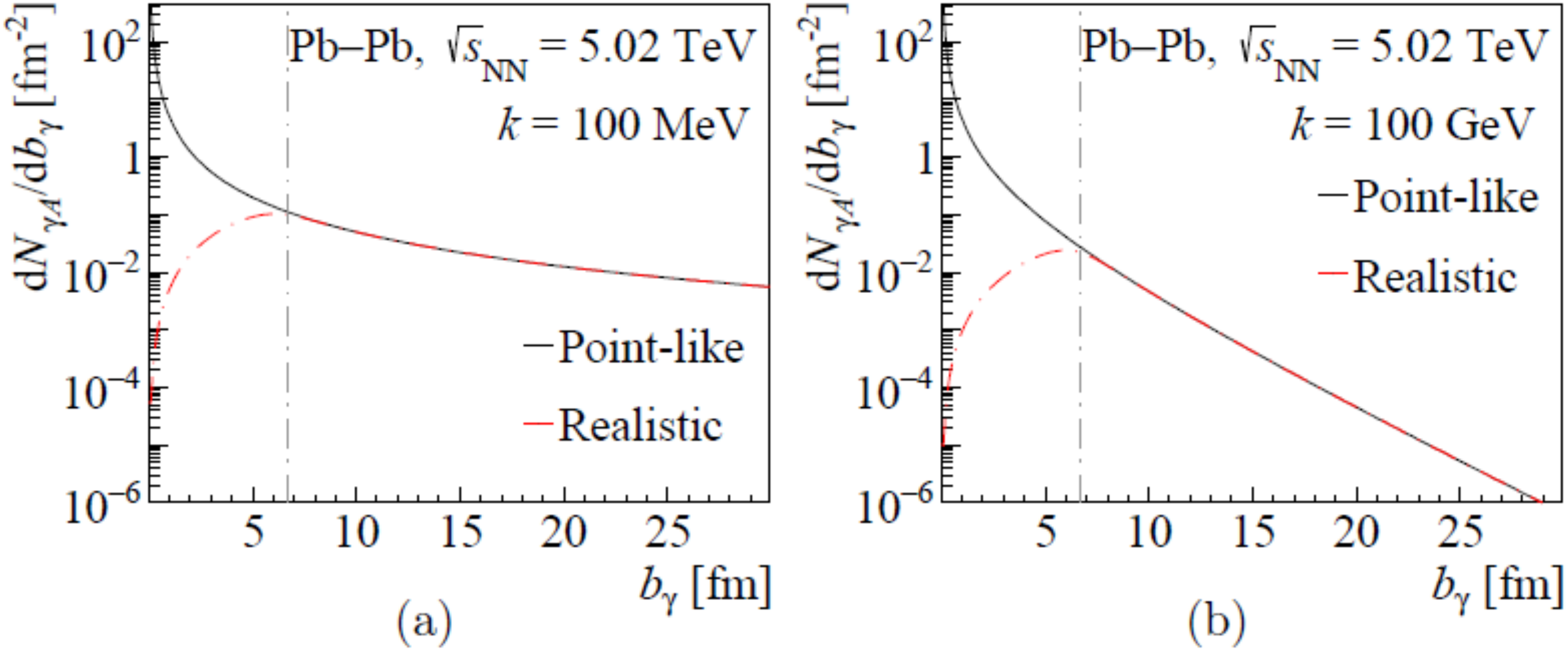
$$n^{\mathrm{0nAn^*}}_{\gamma/\mathrm{Pb}}(\omega) = n^{\mathrm{0n0n(EMD)}}_{\gamma/\mathrm{Pb}}(\omega) + \frac{1}{2} n^{\mathrm{0nXn(EMD)}}_{\gamma/\mathrm{Pb}}(\omega)$$

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

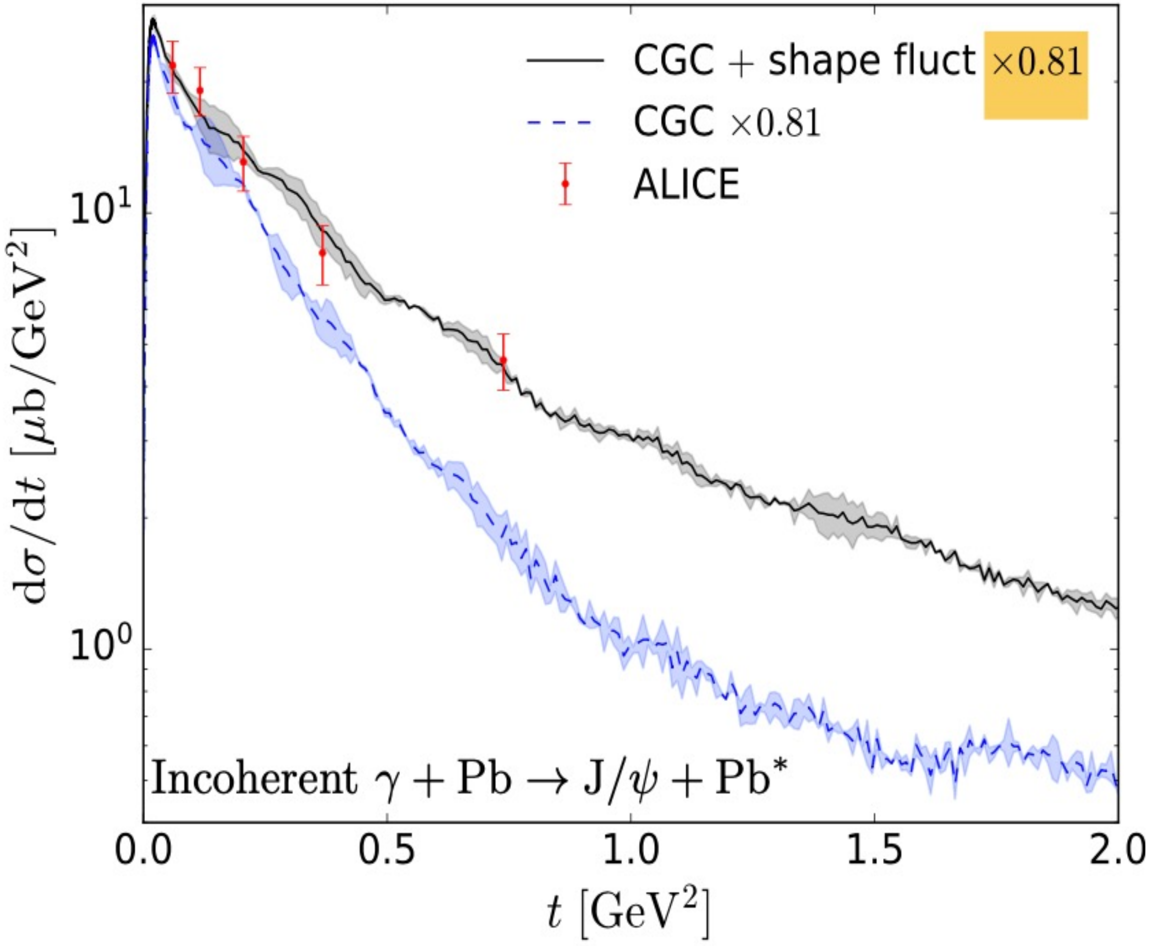
No neutrons to tag the target nucleus, assume the same relative fractions at (+y) and (-y) as in 0nXn

Photon Flux: Realistic Nucleus vs. Point Charge

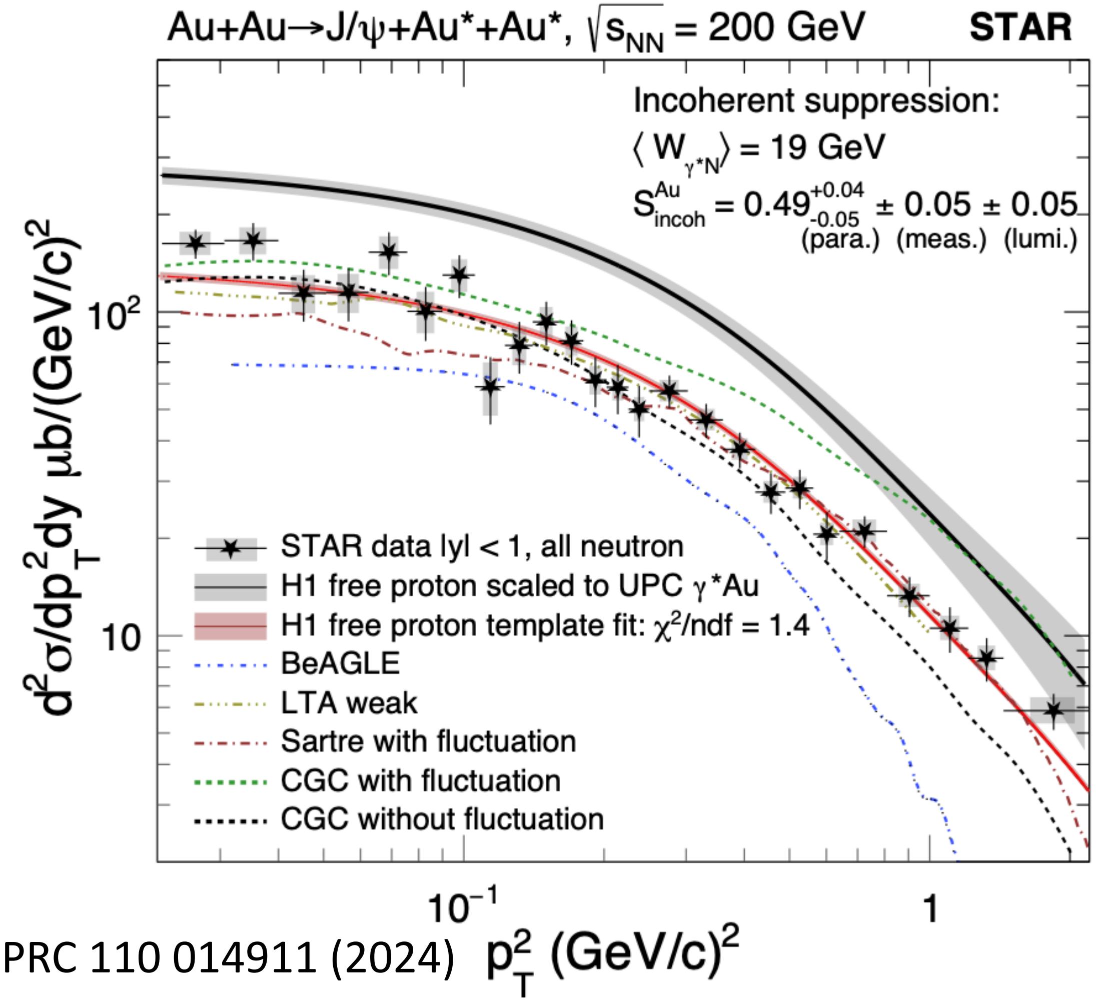
J. CPC. (2022) 108388



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)



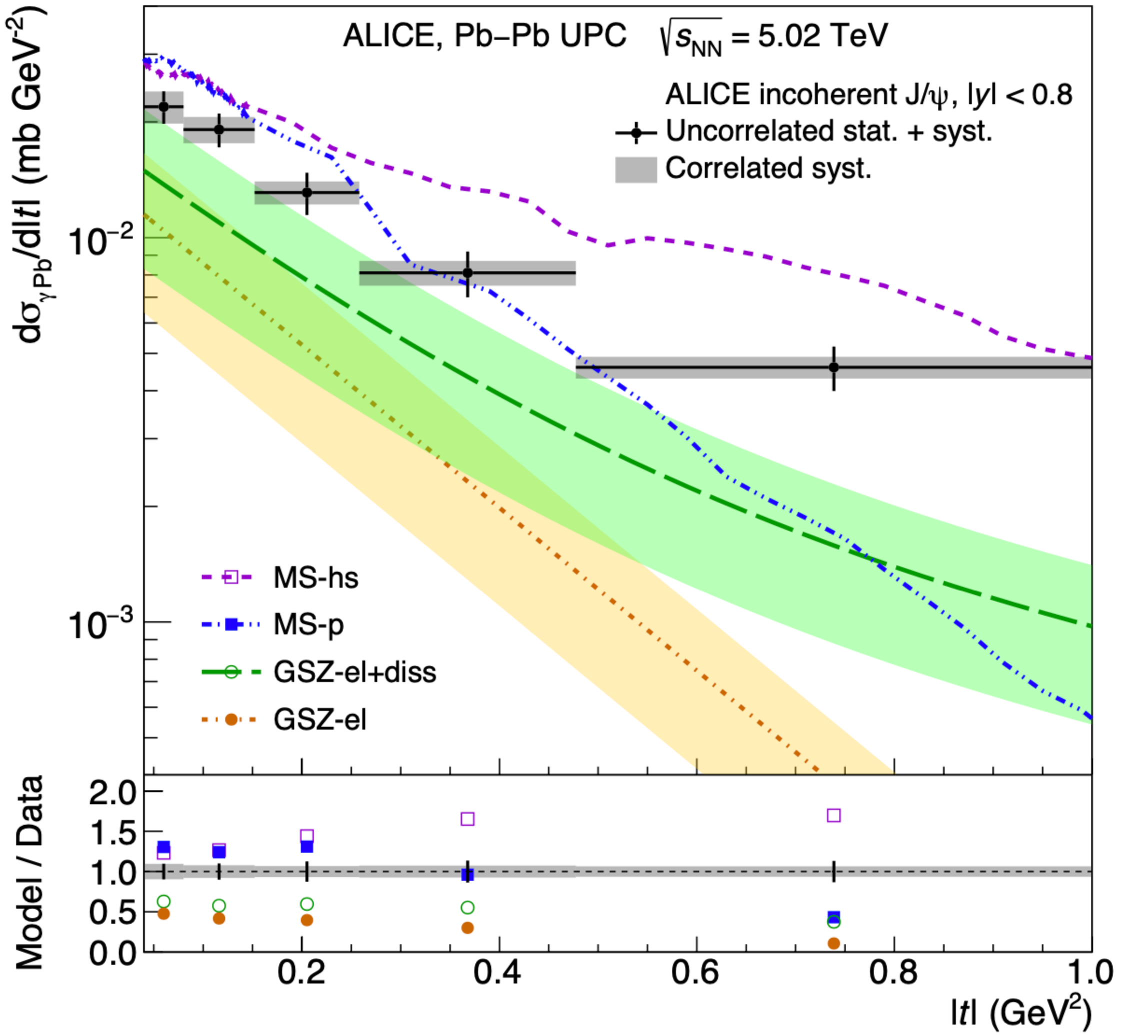
CGC: PRD 109 (2024) 7, L071504



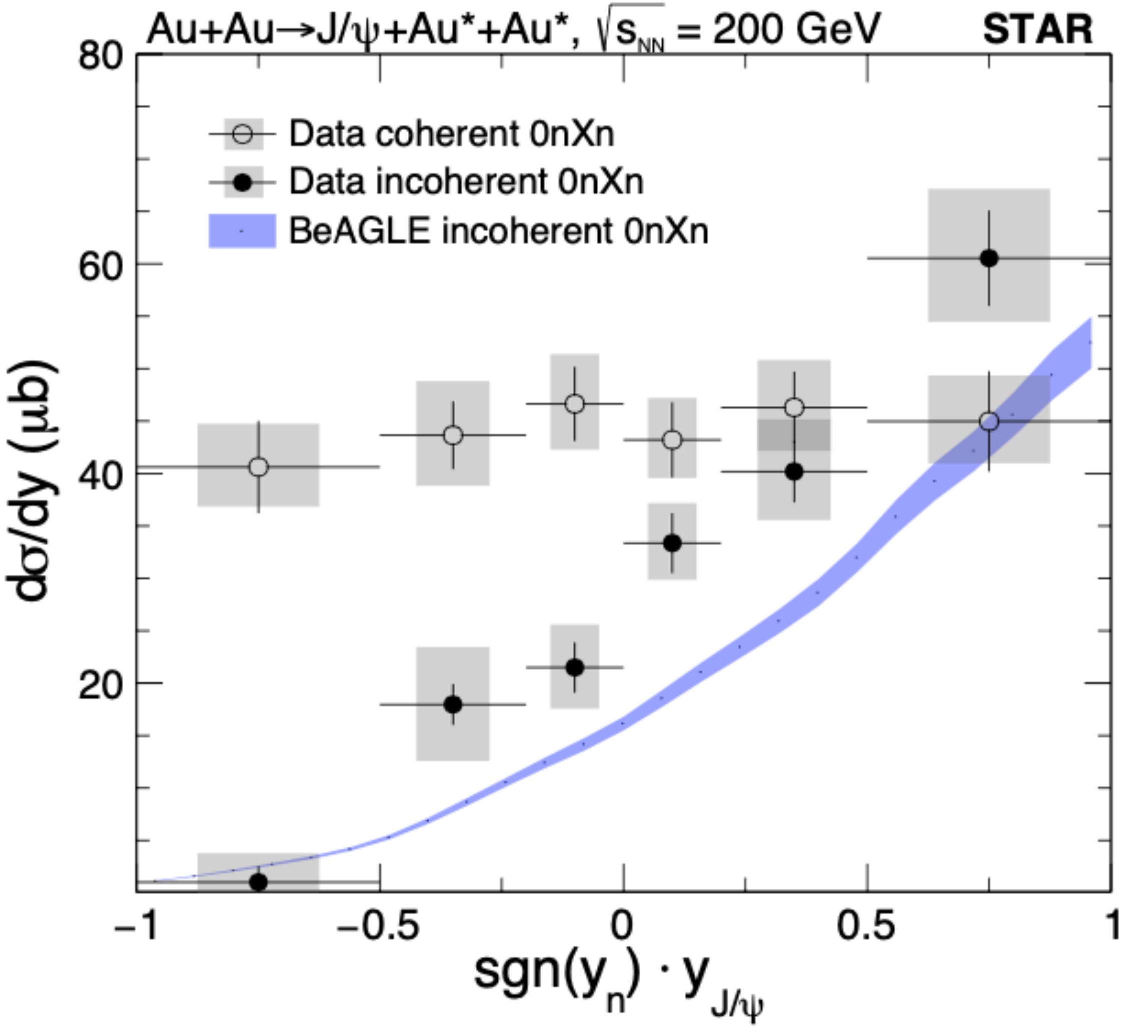
STAR: PRC 110 014911 (2024)

dSigma/dt ~ exp(-B*t) **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)