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

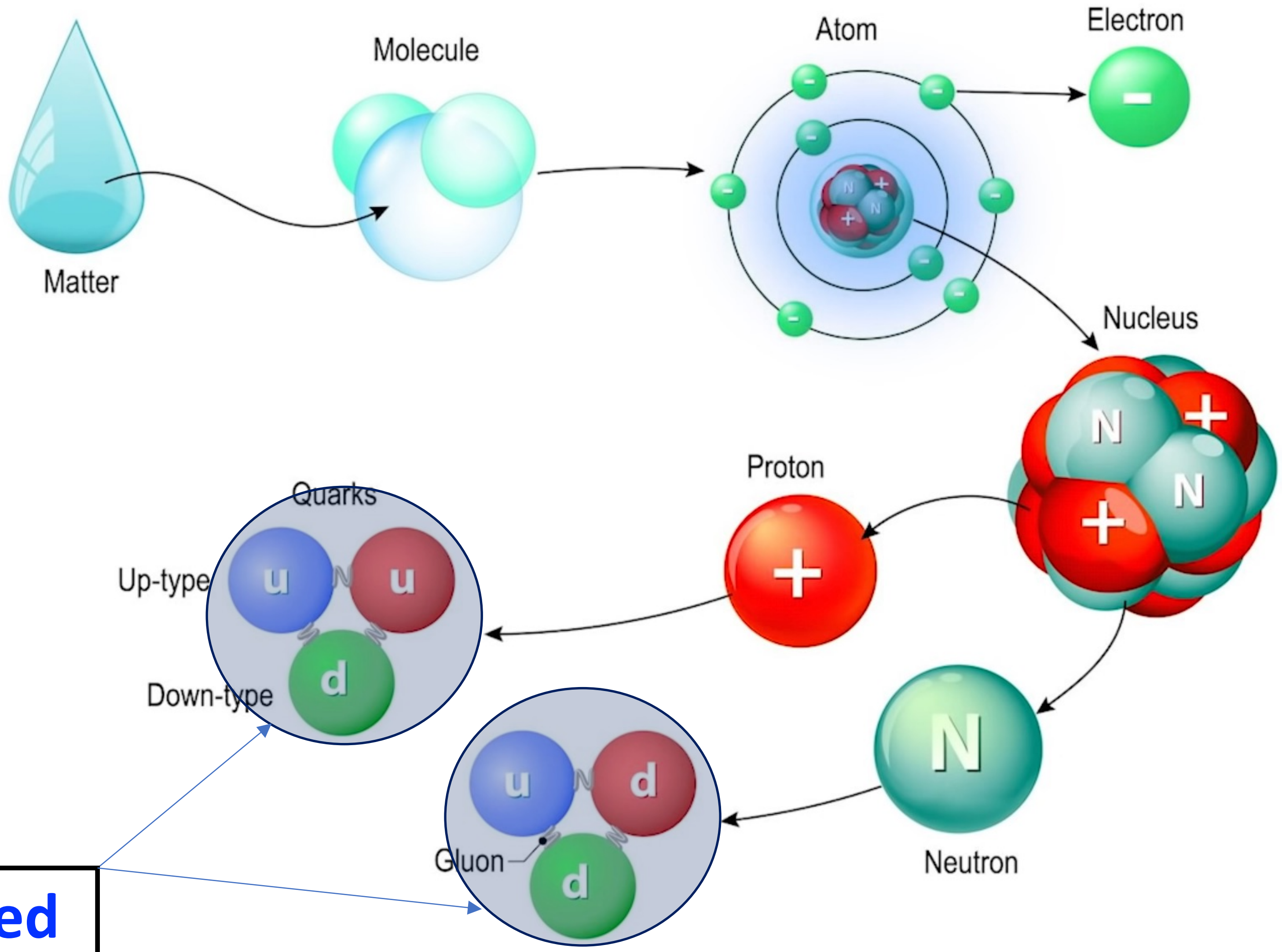
叶早晨 (华南师范大学)

中国科学院大学 2025年4月30日

- CMS, PRL 131, 262301 (2023)
- CMS, arXiv:2503.08903 (submitted to PRL)
- CMS, arXiv:2504.05193 (submitted to PRL)

In collaboration with X. Huang, J. Lin, S. Yang and W. Li

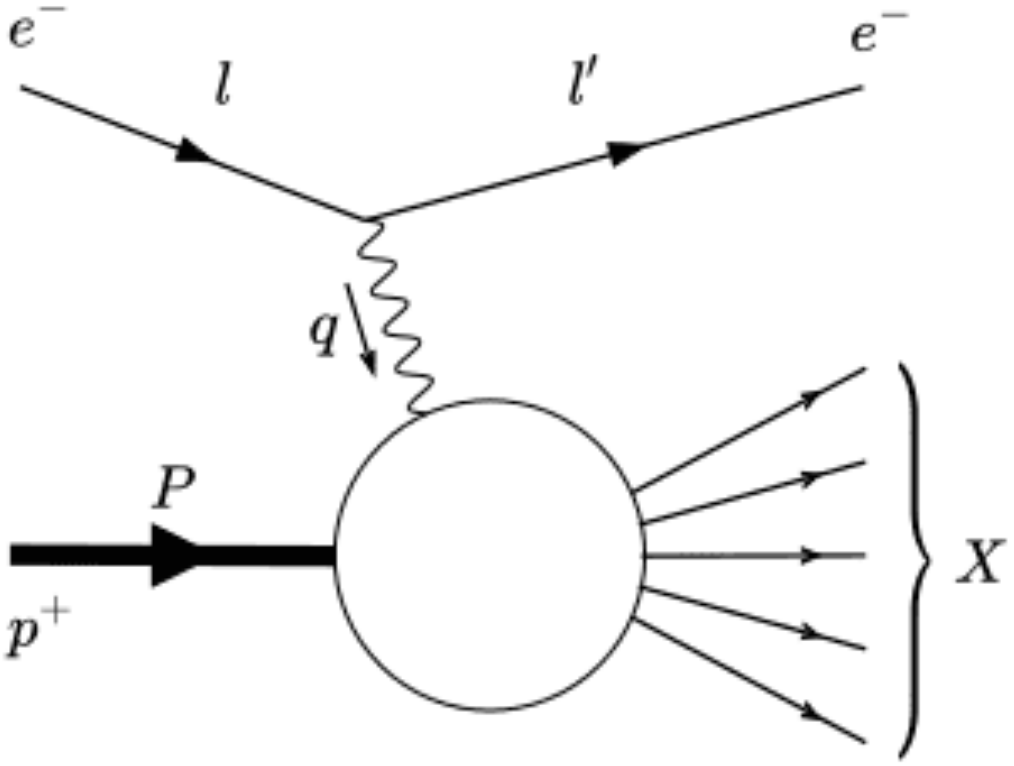
Understand Fundamental Structure of Matter



Confined

Understand Nucleon Structure via DIS

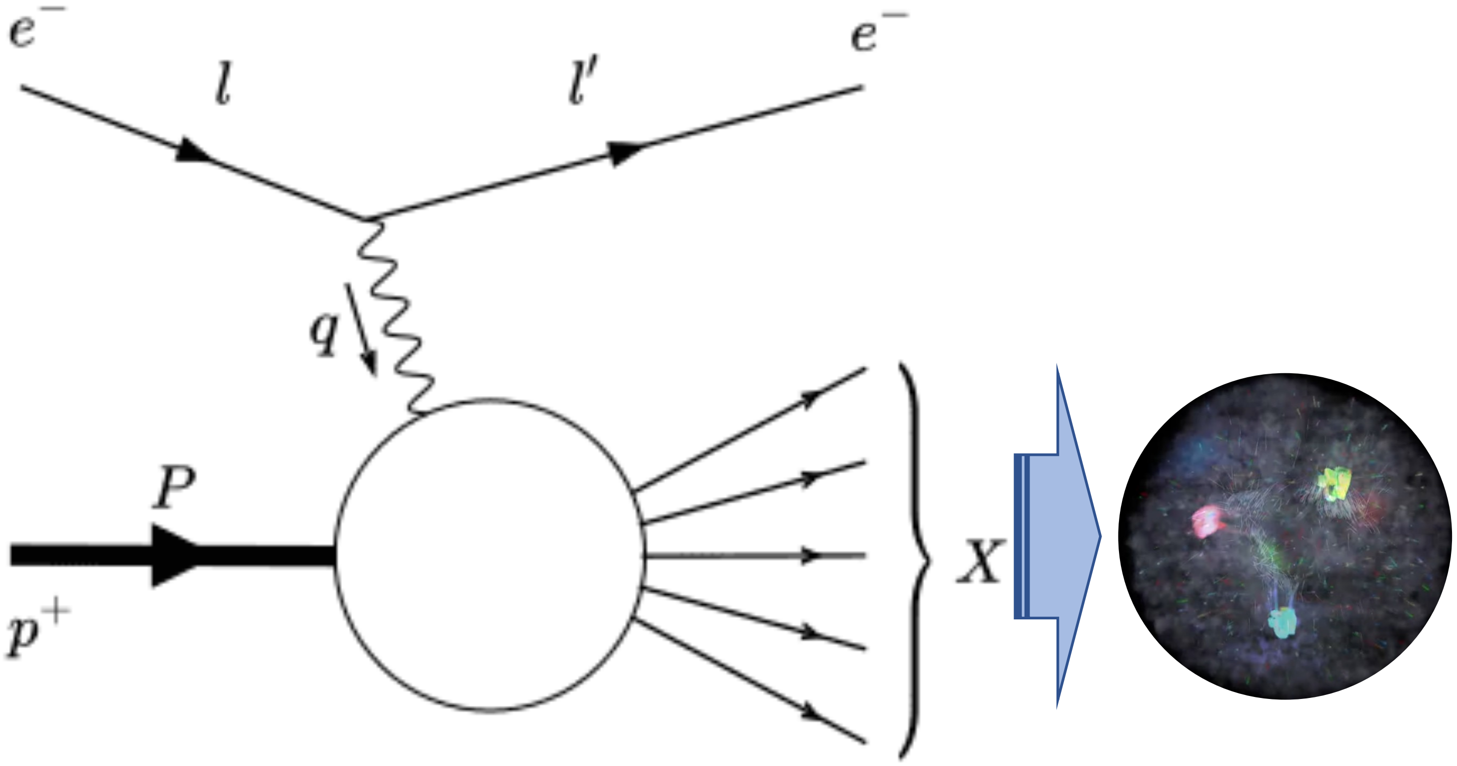
Smash them!!!



Deep Inelastic Scattering

Understand Nucleon Structure via DIS

Smash them!!!



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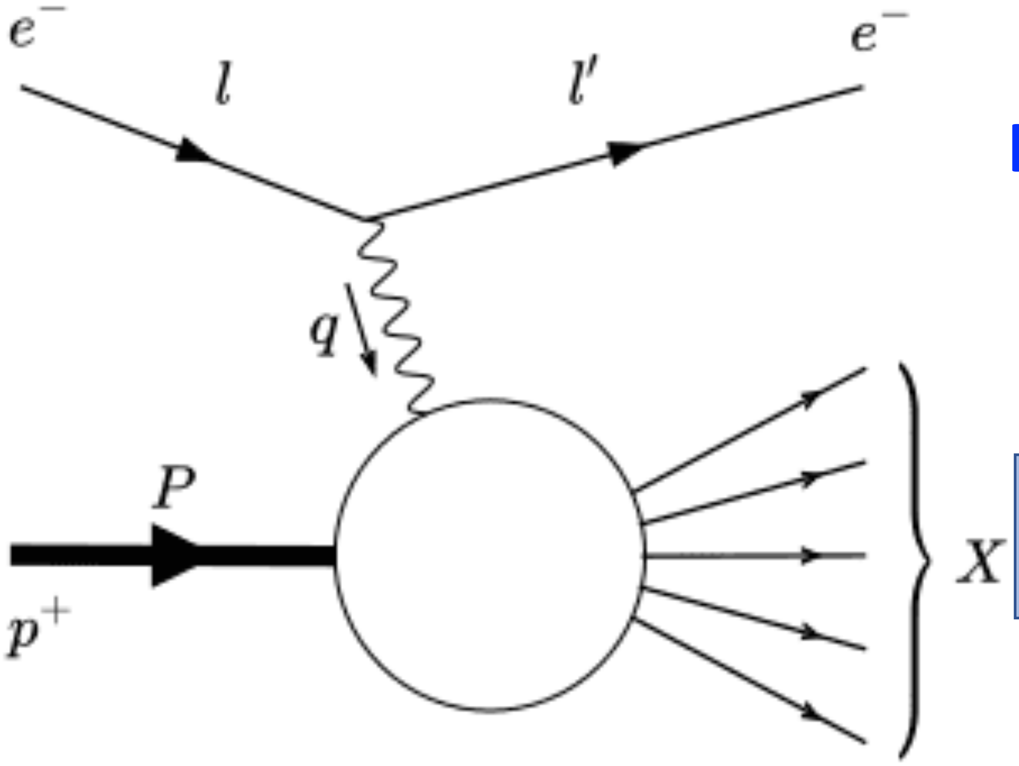
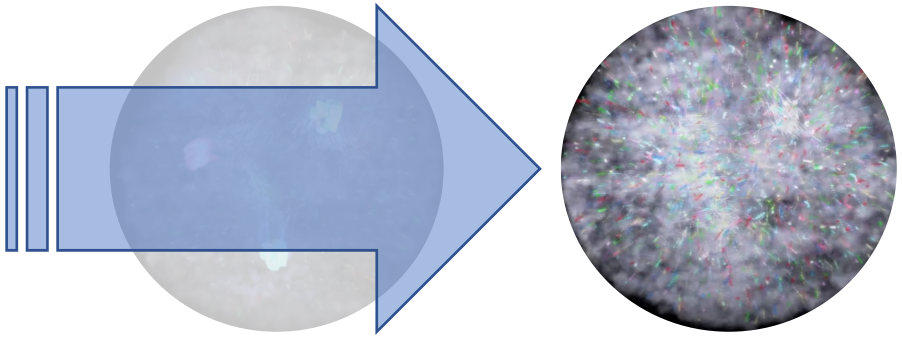


Higher energy, probing lower-x partons



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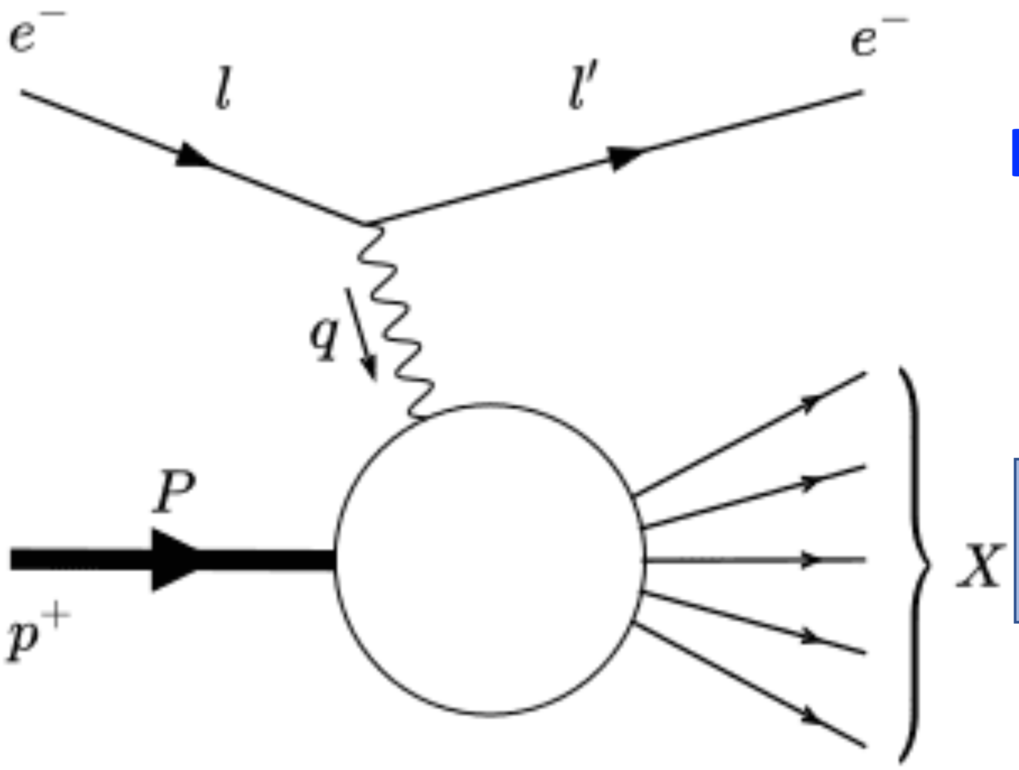

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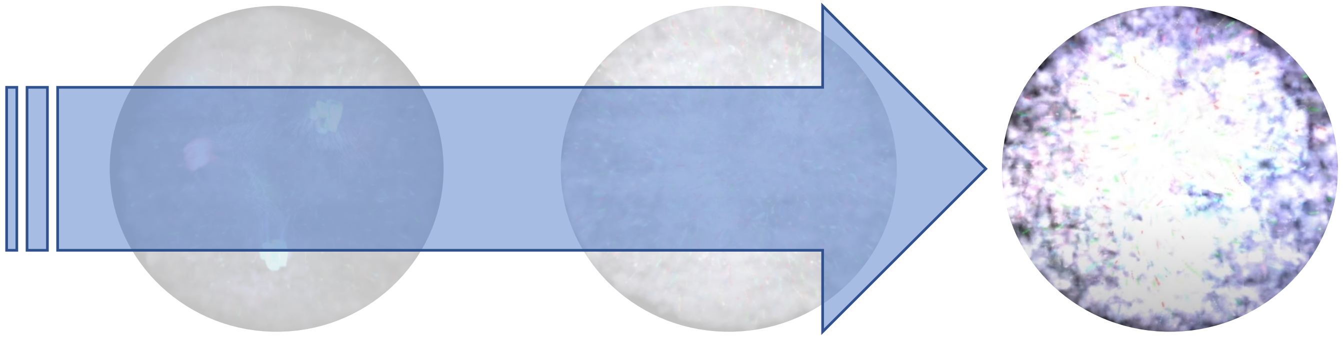
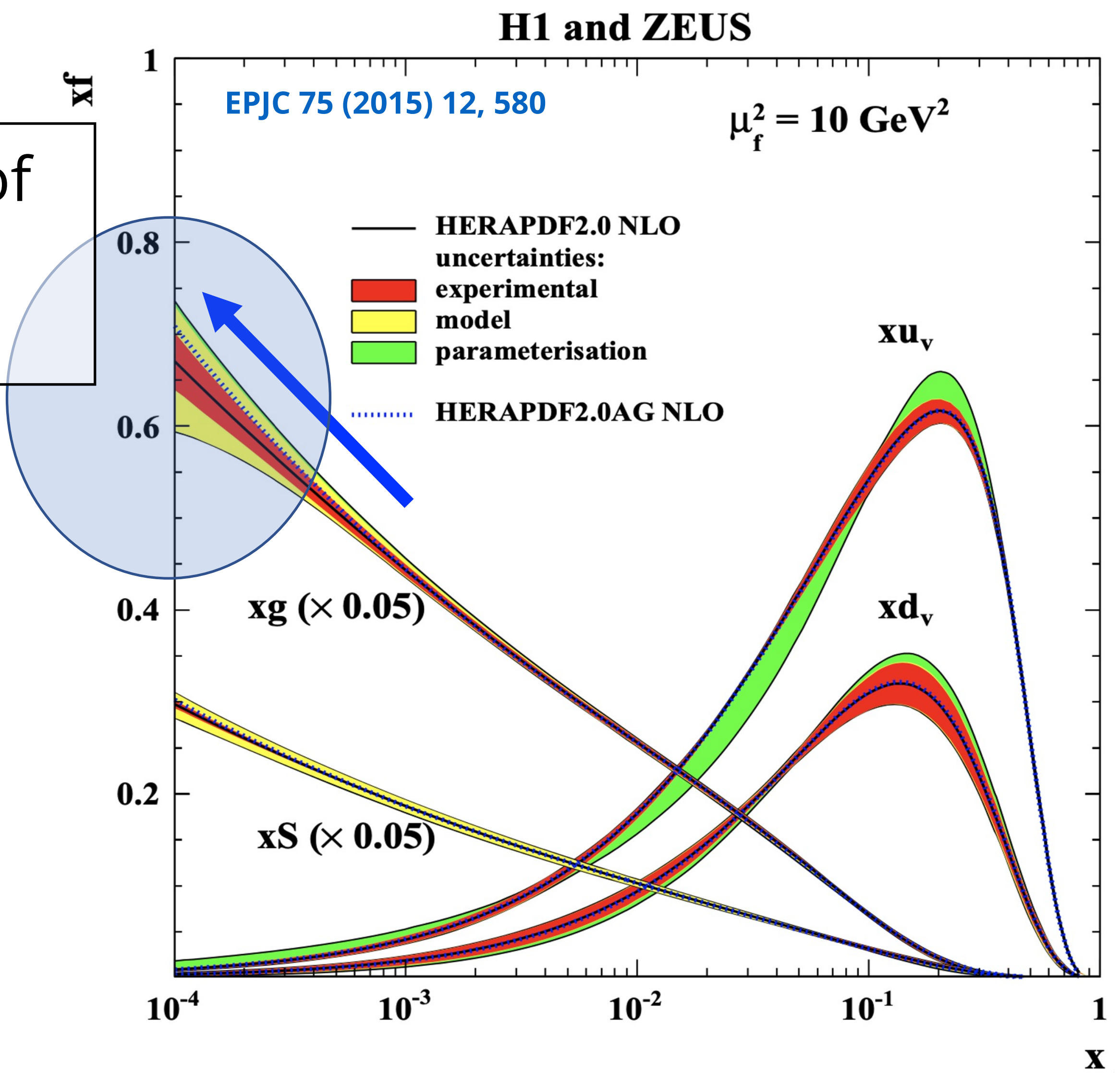


Deep Inelastic Scattering

Understand Nucleon Structure

e-p collider

Rapid increase of gluon density towards small x.



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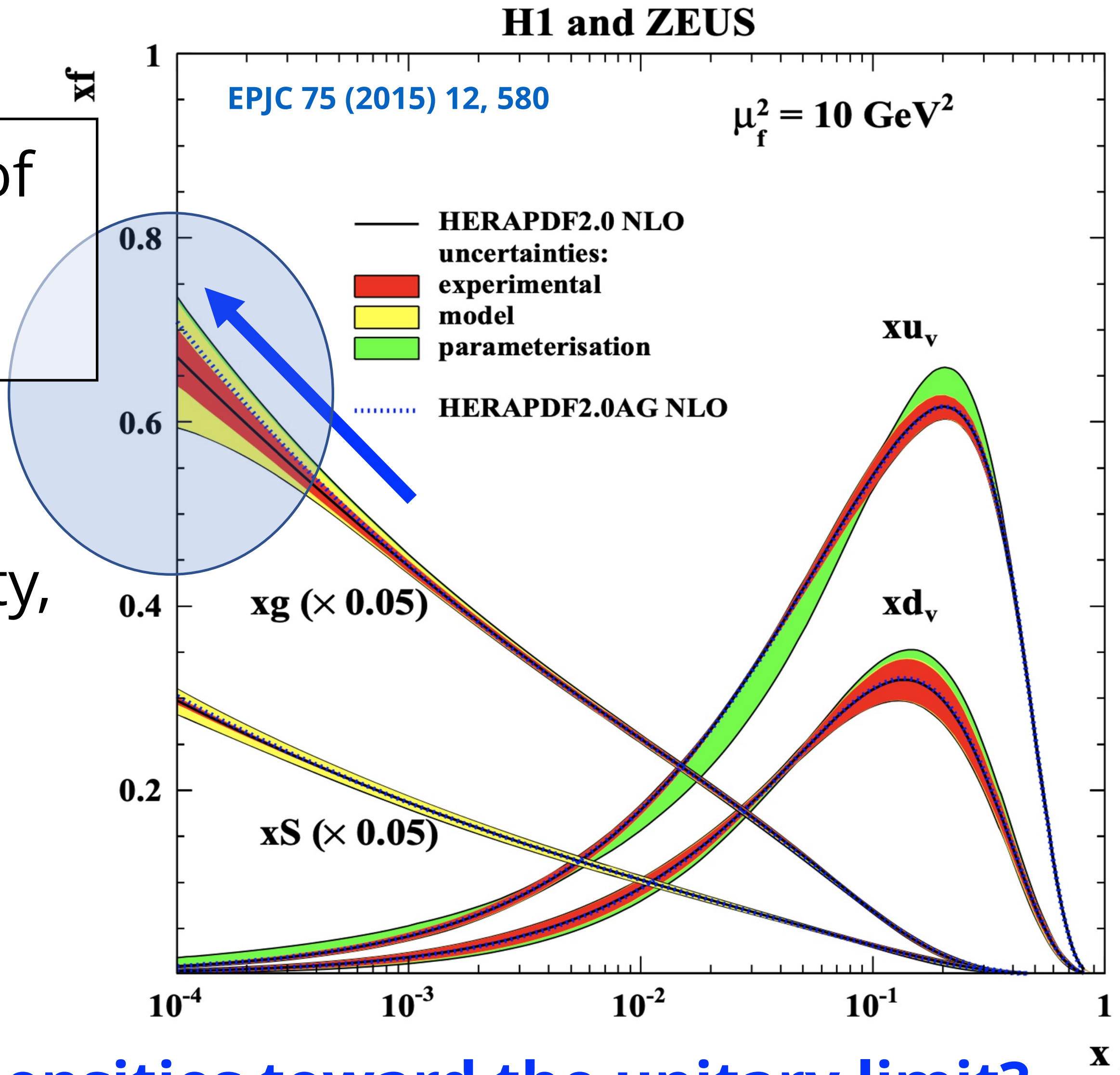
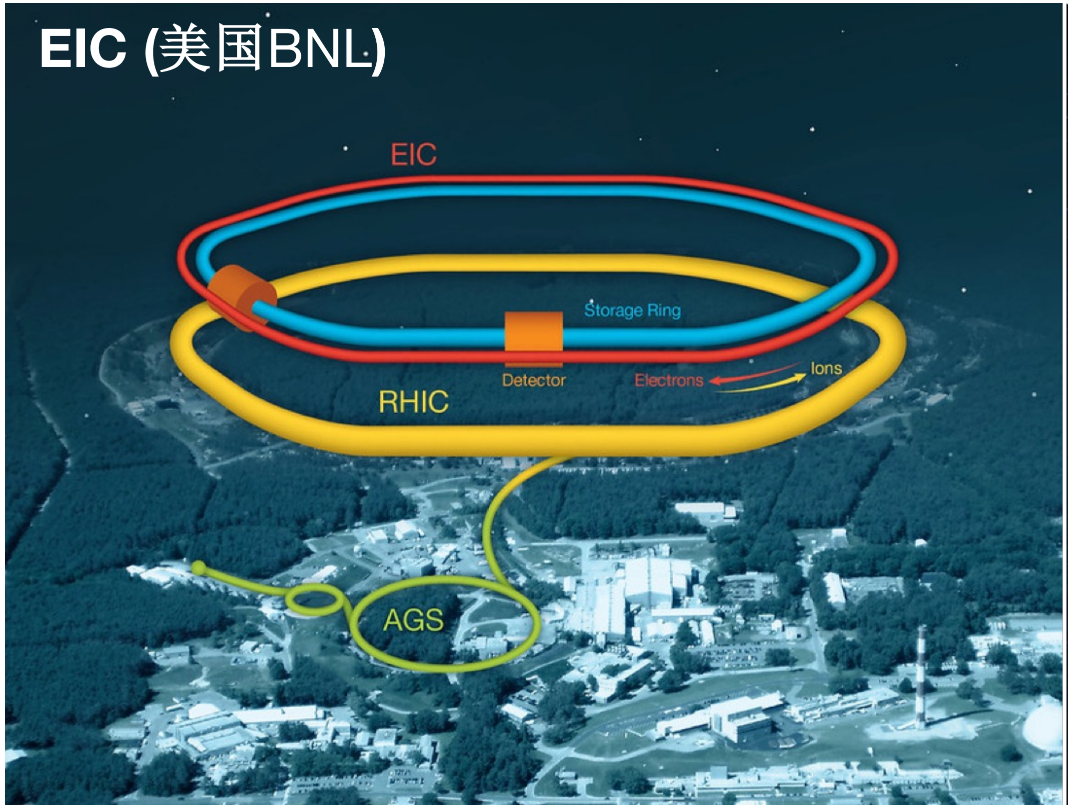


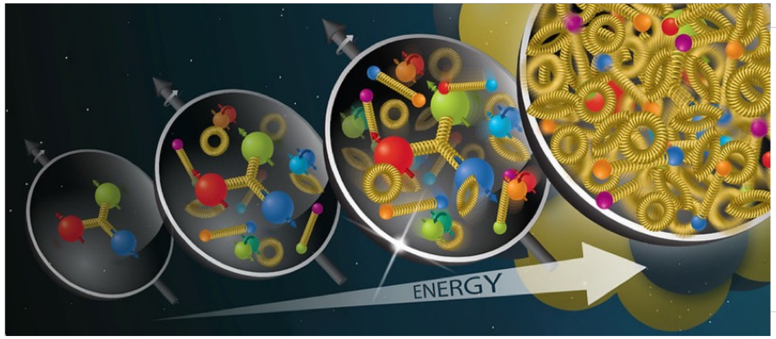
Indefinite growth at small-x violates unitarity, new mechanism is expected.

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

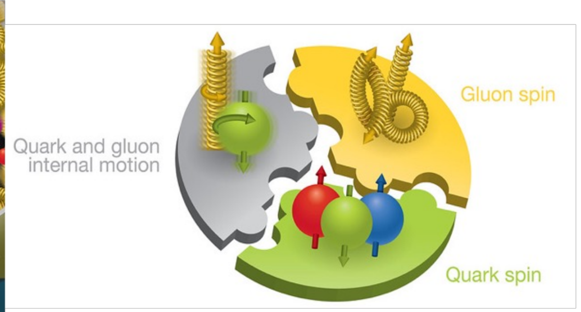
Next Generation Facility



Confinement & Gluon Saturation

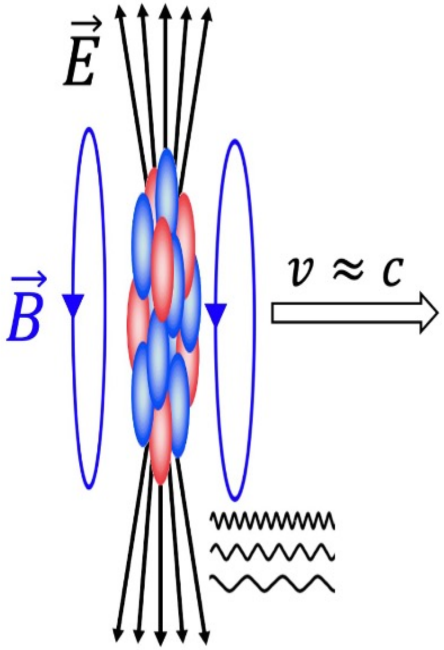


Spin Crisis



Mass Origin

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**

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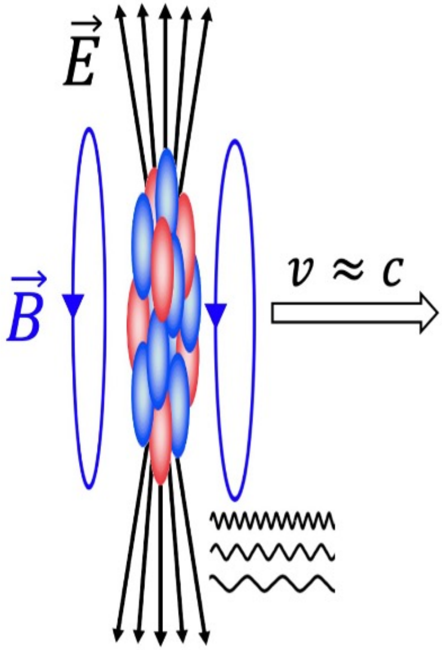

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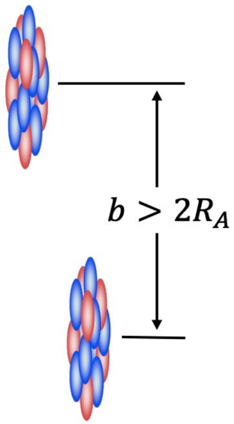
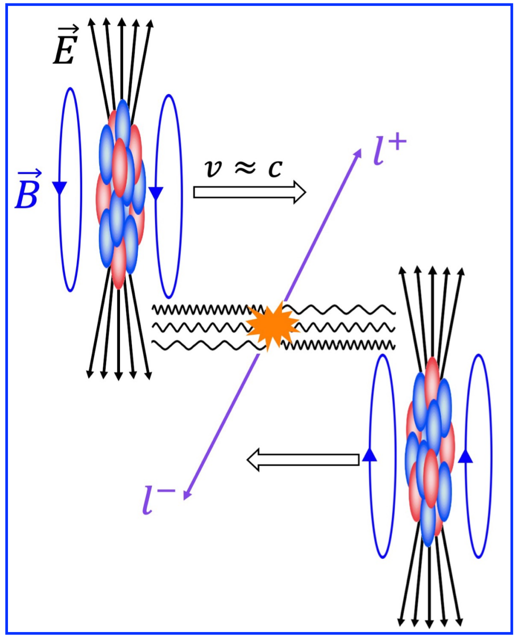
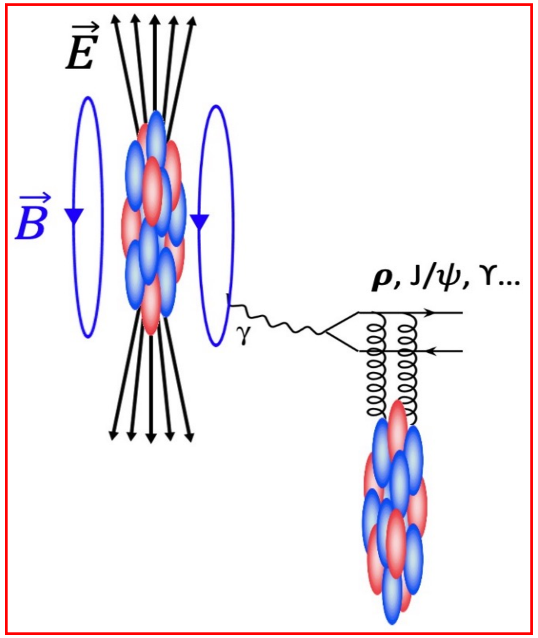
Heavy ion collider is also a Photon-Photon and Photon-Ion collider !!!

UPC:







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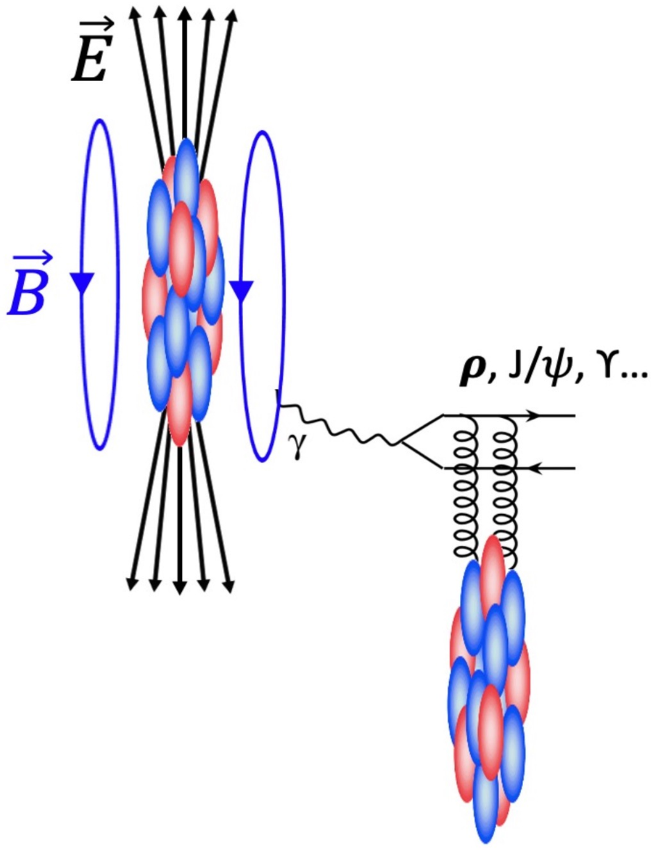
Vector Meson Photoproduction in UPC

Vector meson photoproduction directly probes gluonic structure of nucleus/nucleon

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



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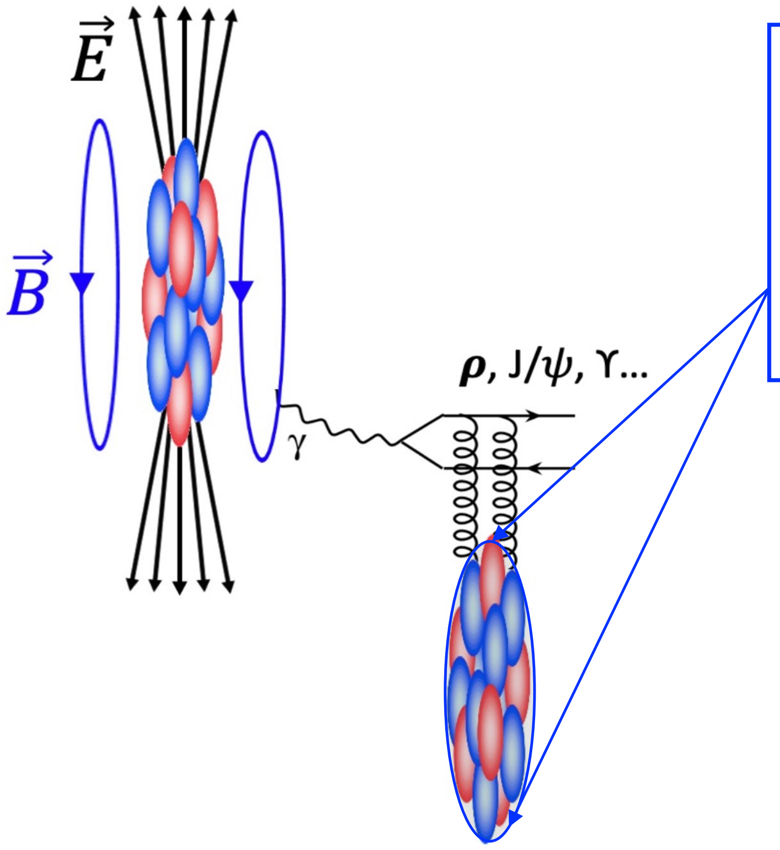

Coherent production:

- 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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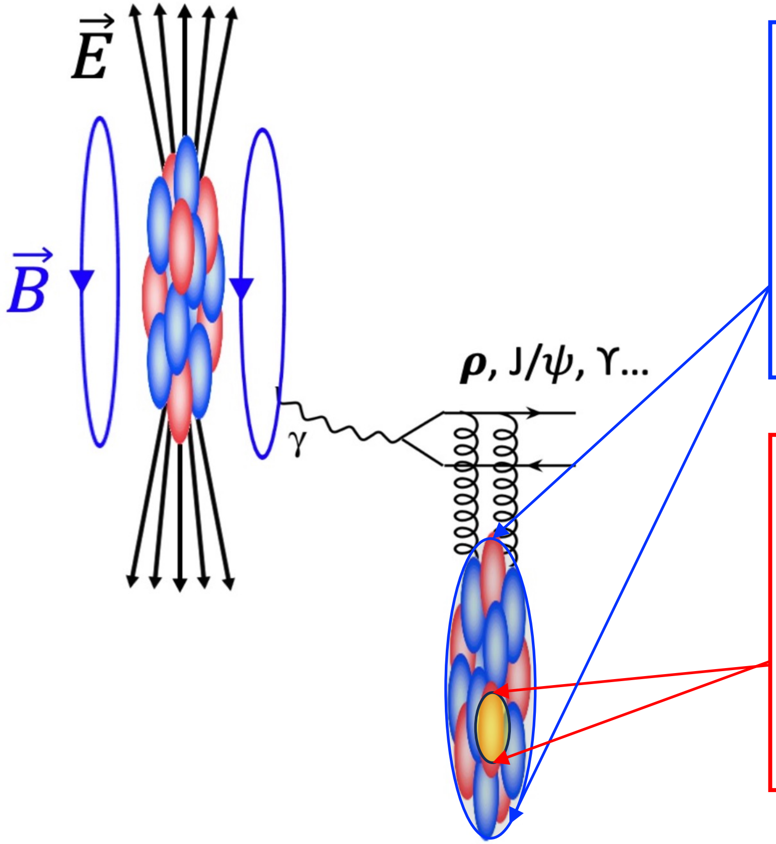

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Incoherent production:

- Photon fluctuated dipole couples to **individual nucleon or sub-nucleon**
- **Target** nucleus usually **breaks**
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- Probing the **local gluon density** and **fluctuations**

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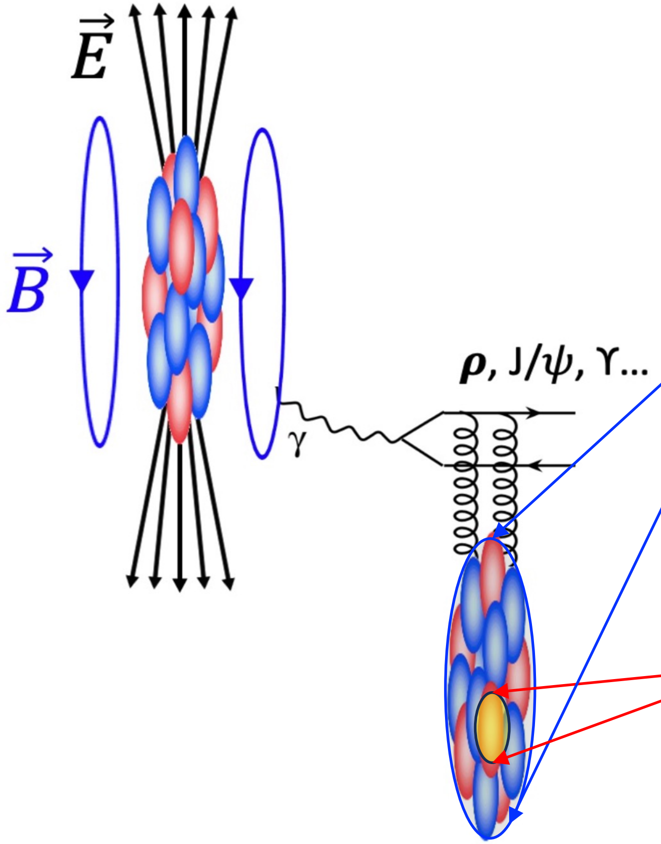

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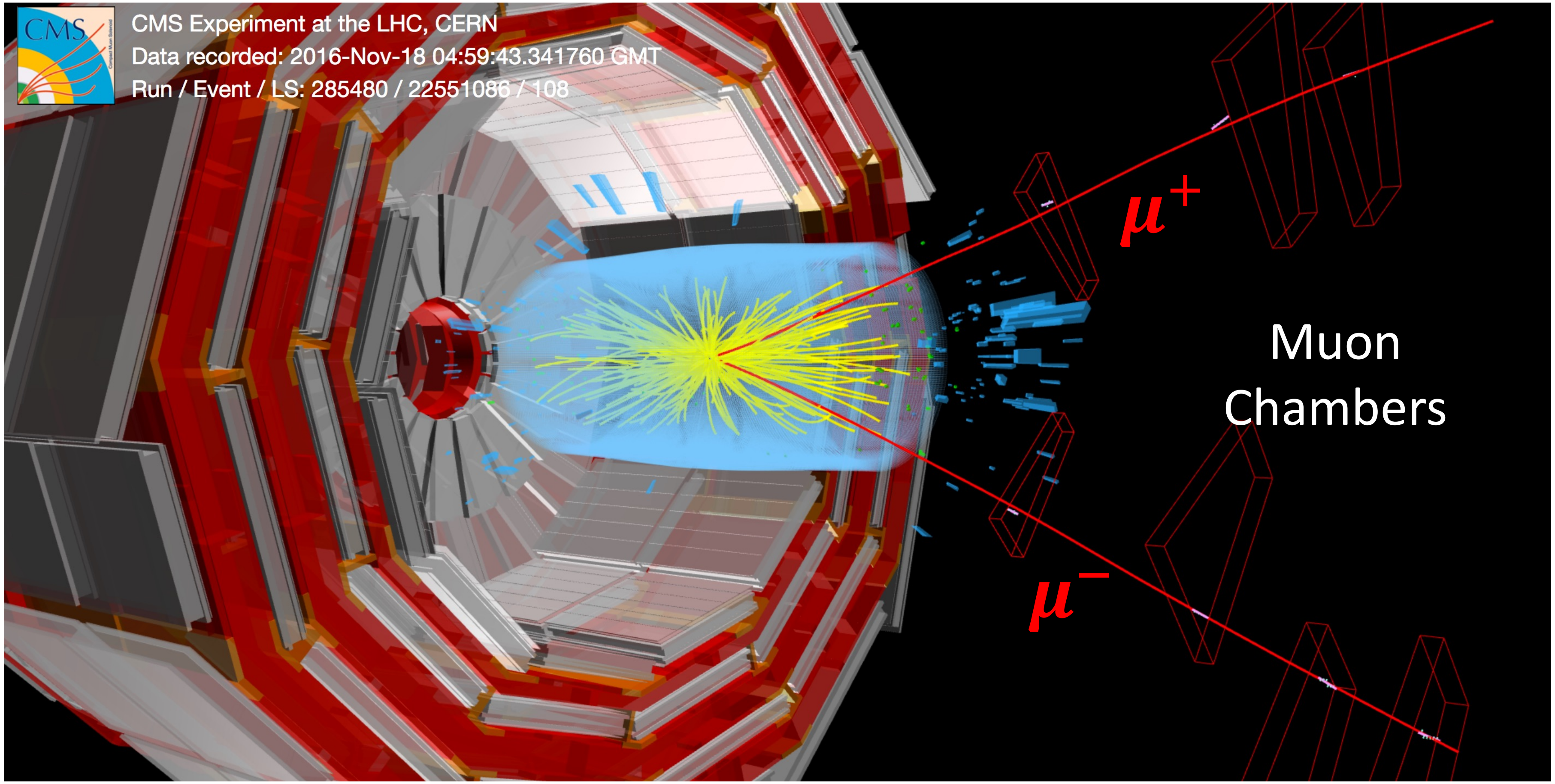
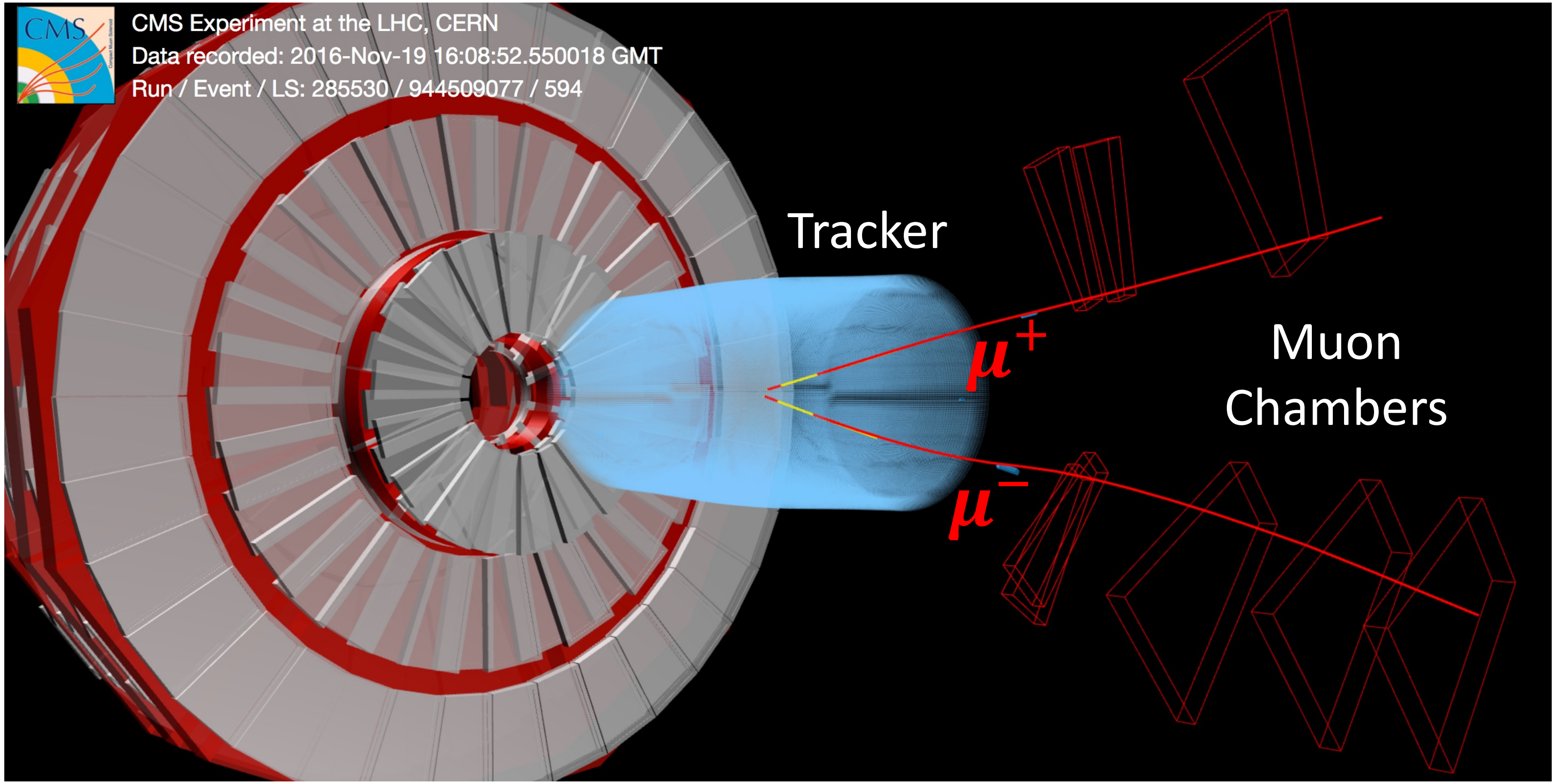
$$\omega = \frac{M_{VM}}{2} e^{\pm y} \qquad x = \frac{M_{VM}}{\sqrt{s_{NN}}} e^{\mp y} \qquad W_{\gamma p} = 2\sqrt{\omega \cdot E_{beam}}$$

Event Example in Heavy-Ion Collisions

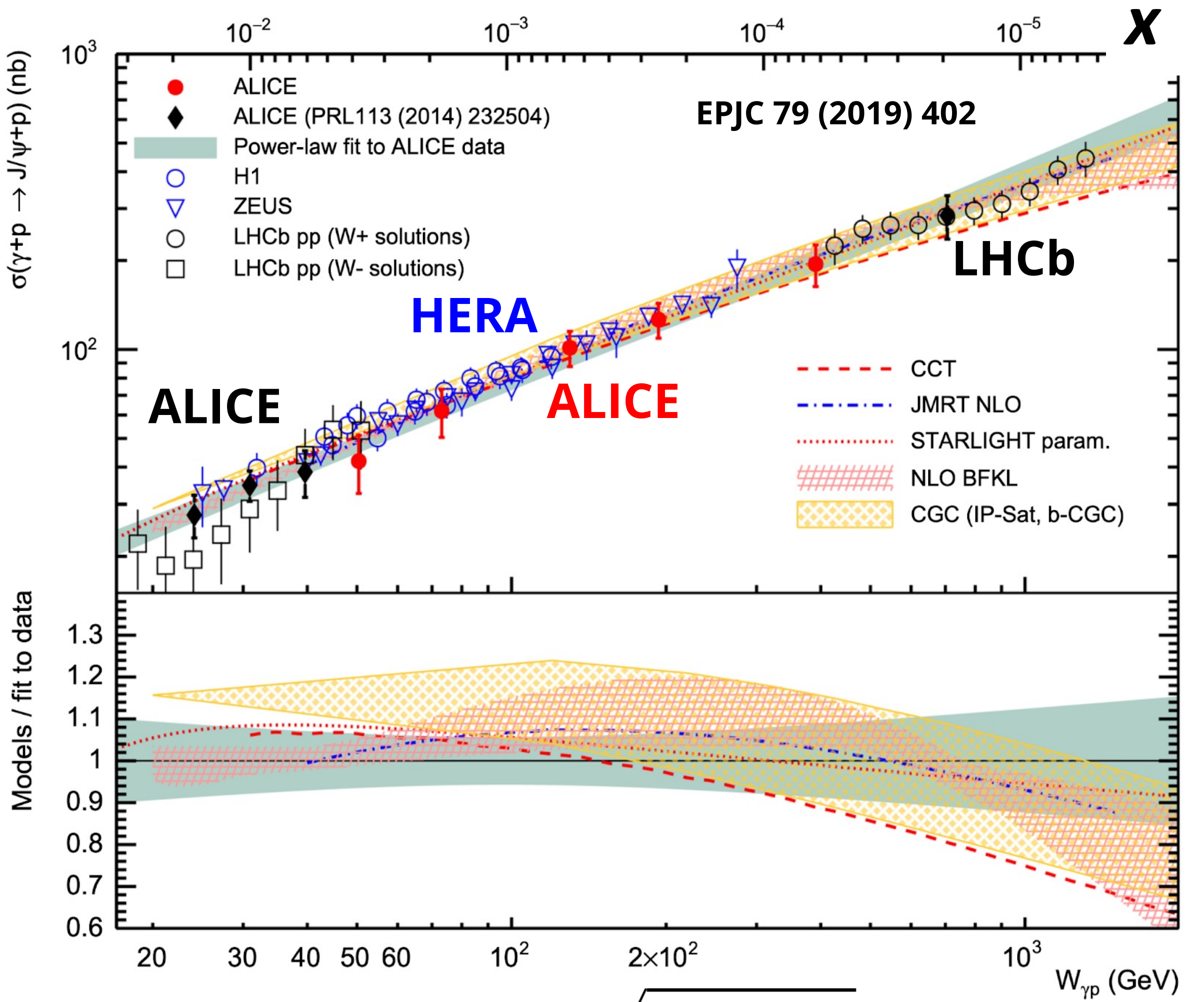


Event Example in UPCs



Vector meson photoproductions in UPCs are very clean events

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



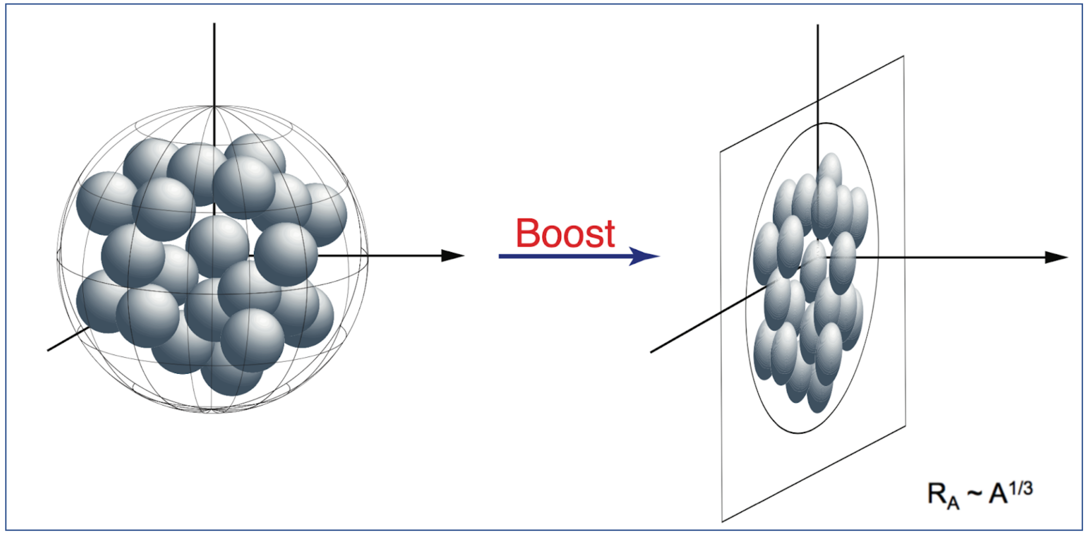
$$W_{\gamma p} = 2\sqrt{\omega \cdot E_{beam}}$$

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

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

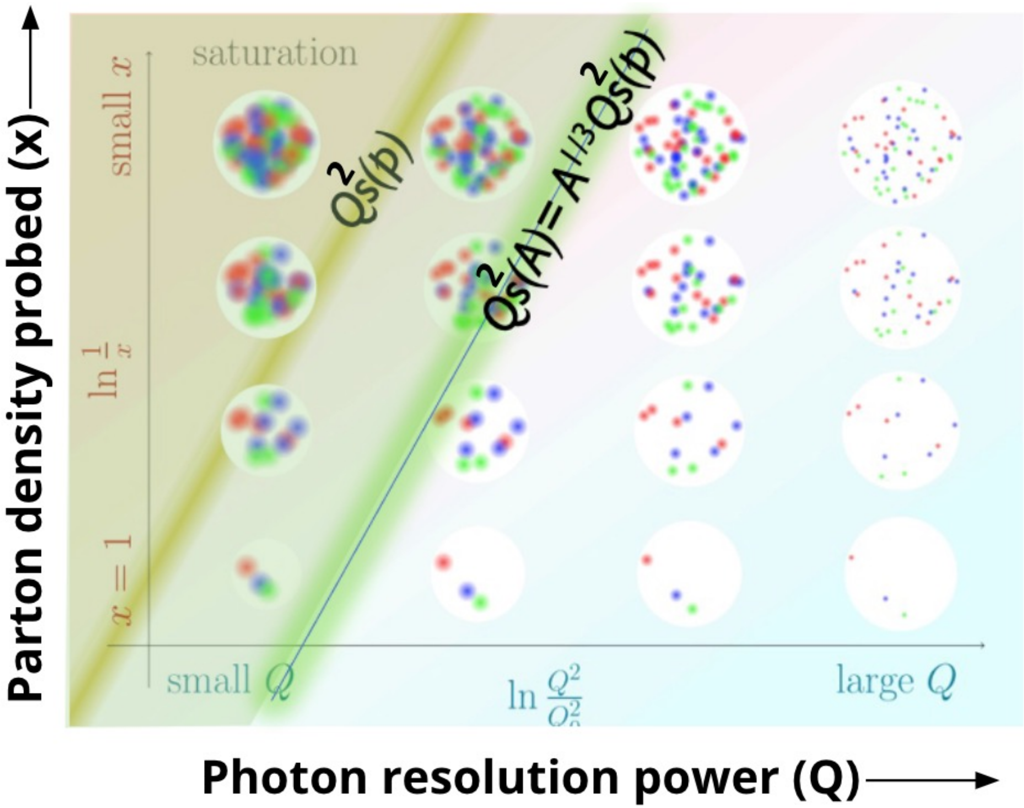
No clear indication of gluon saturation, even down to x~10^{-5} in a free nucleon!

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

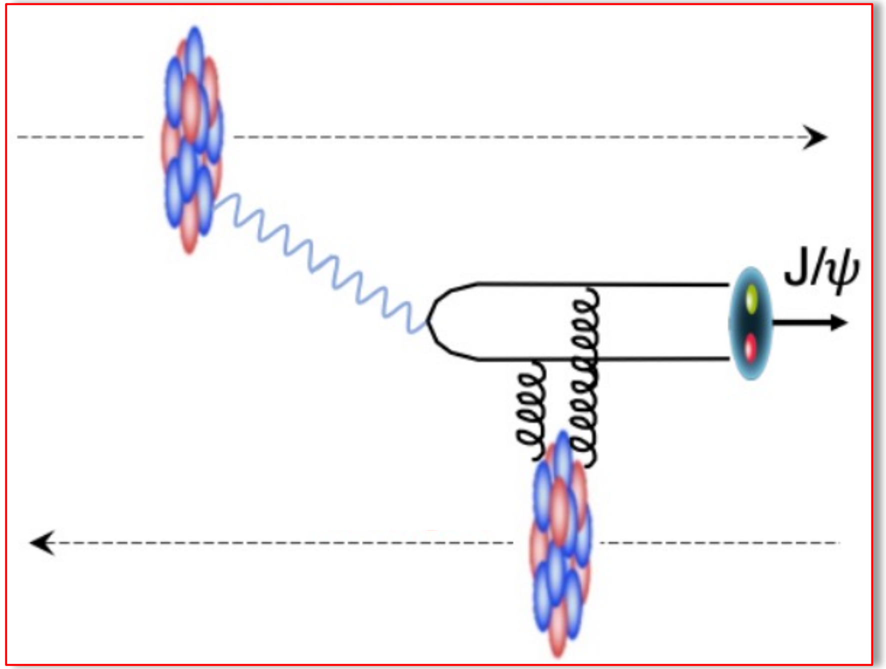
$$Q_s^2 \sim A^{1/3} \left(\frac{1}{x}\right)^{\lambda}$$



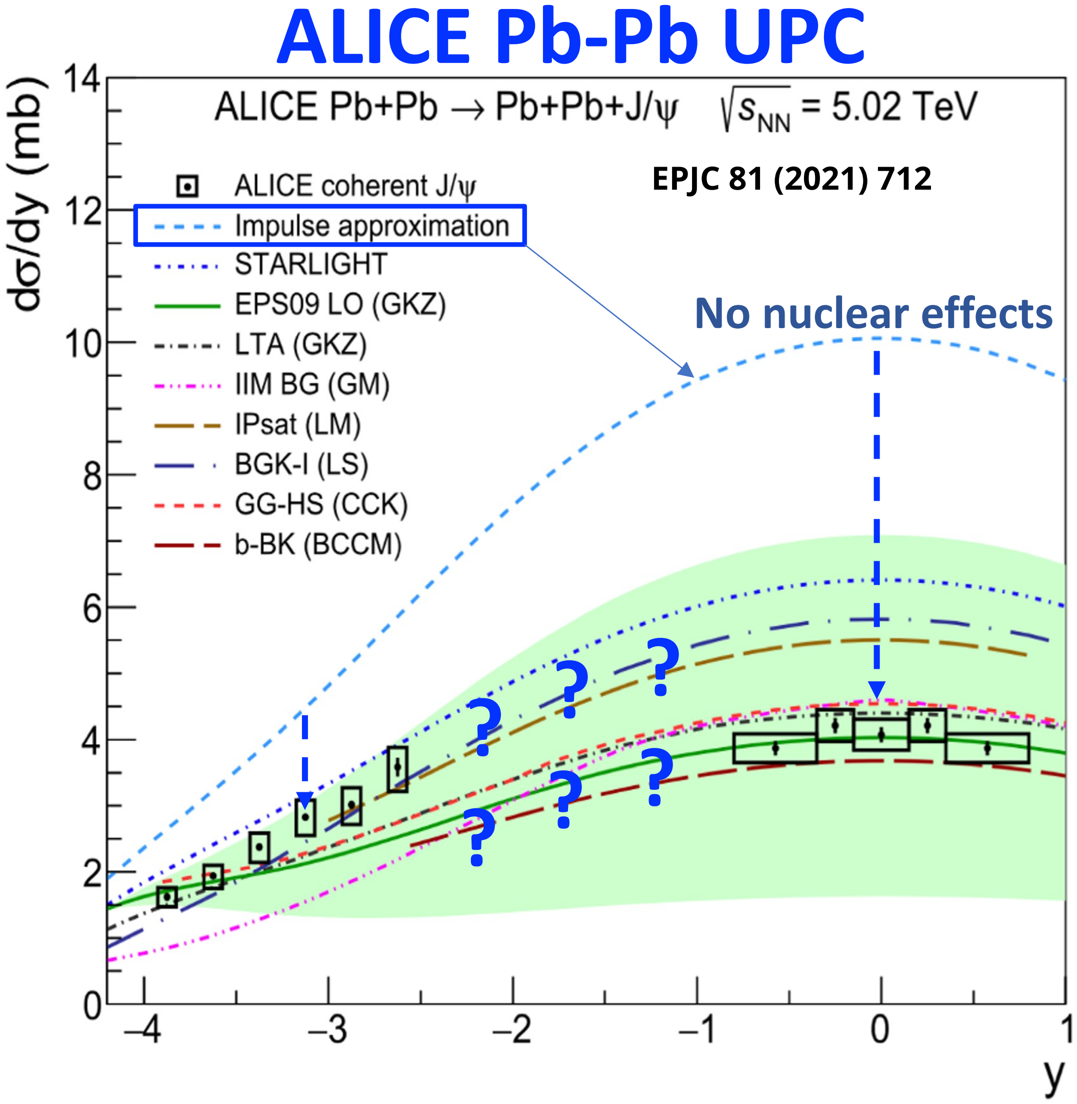
- **Gluon saturation can be more easily reached in heavy nuclei**

Coherent J/Ψ Photoproduction in A-A UPCs

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



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



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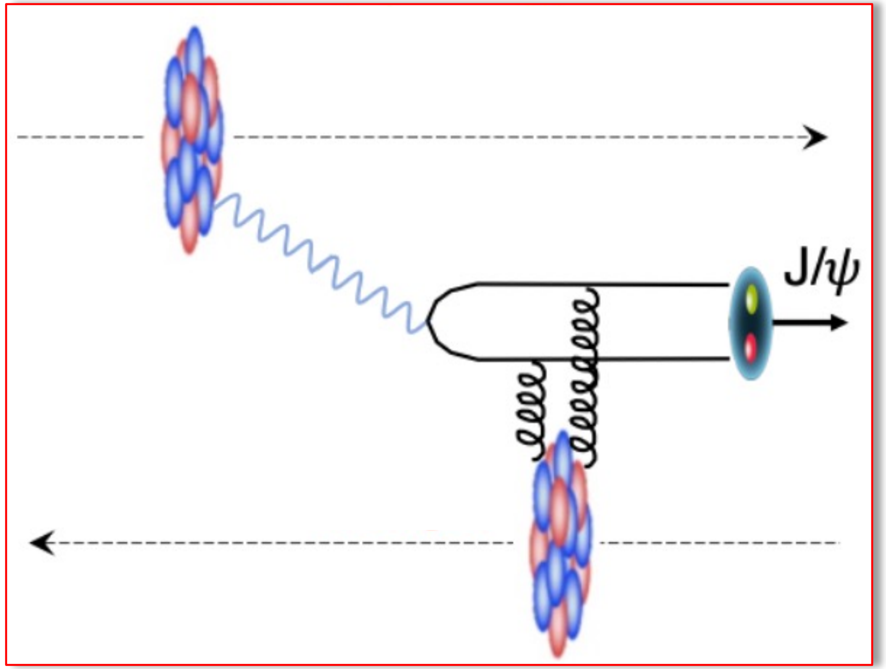

CMS: PRL 131, 262301 (2023)
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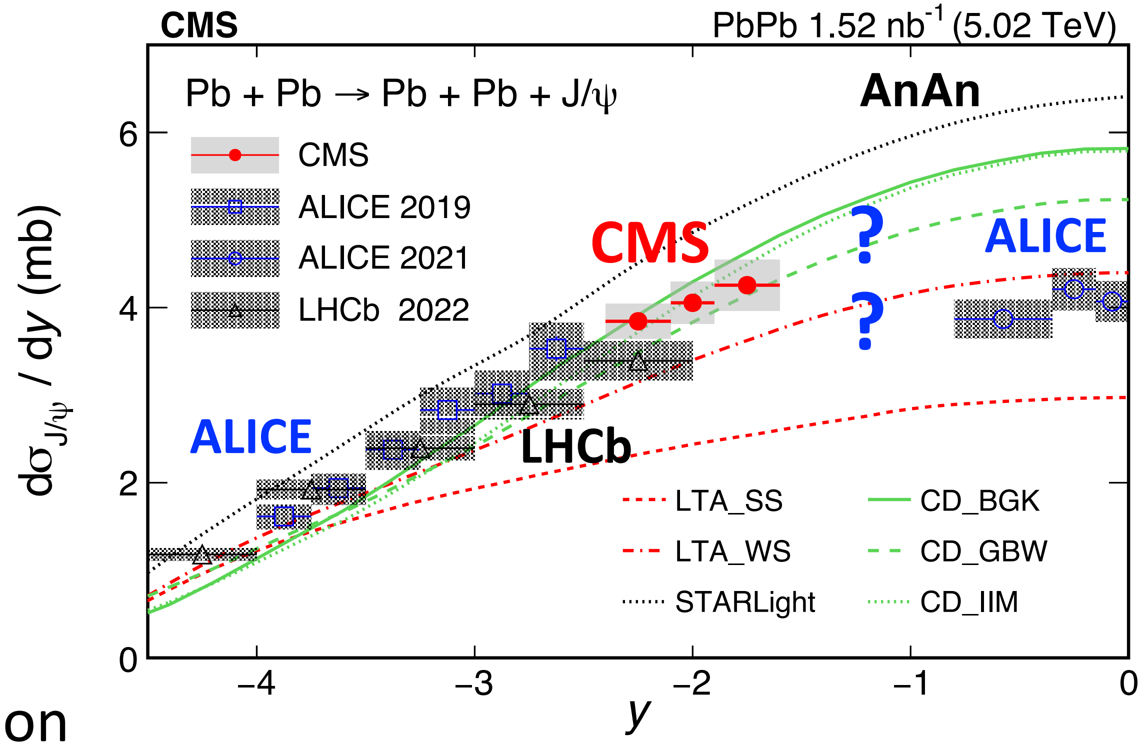

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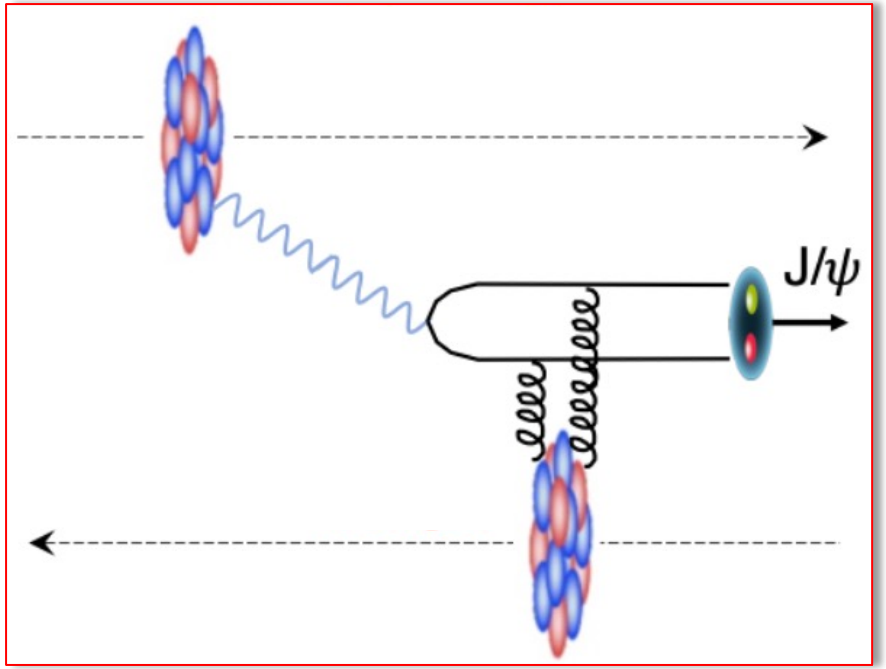

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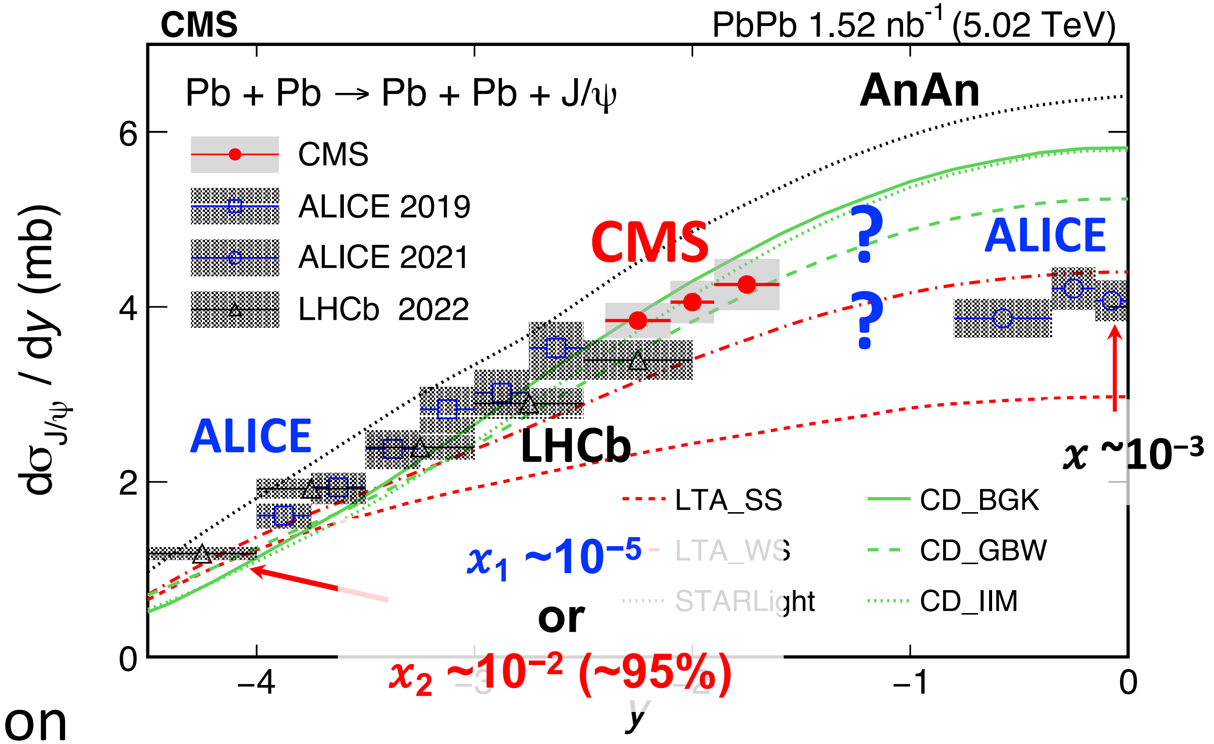

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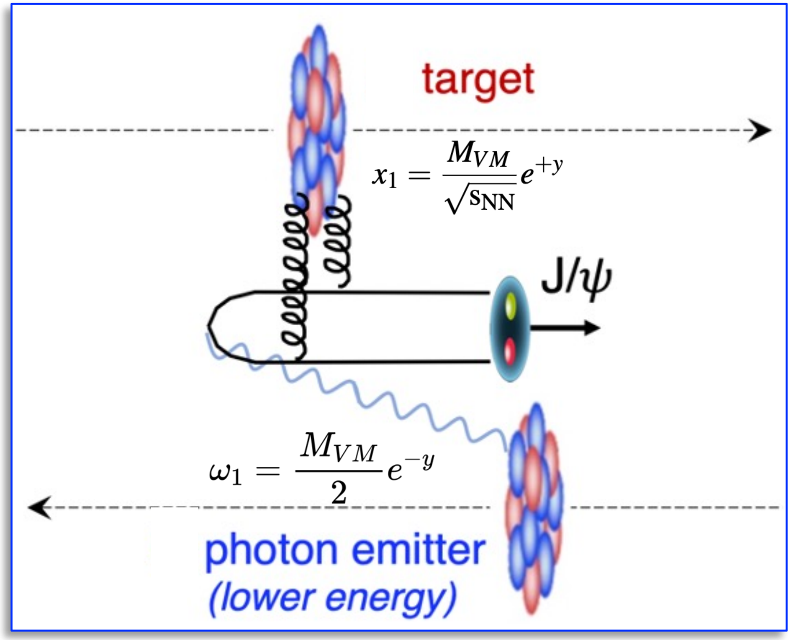
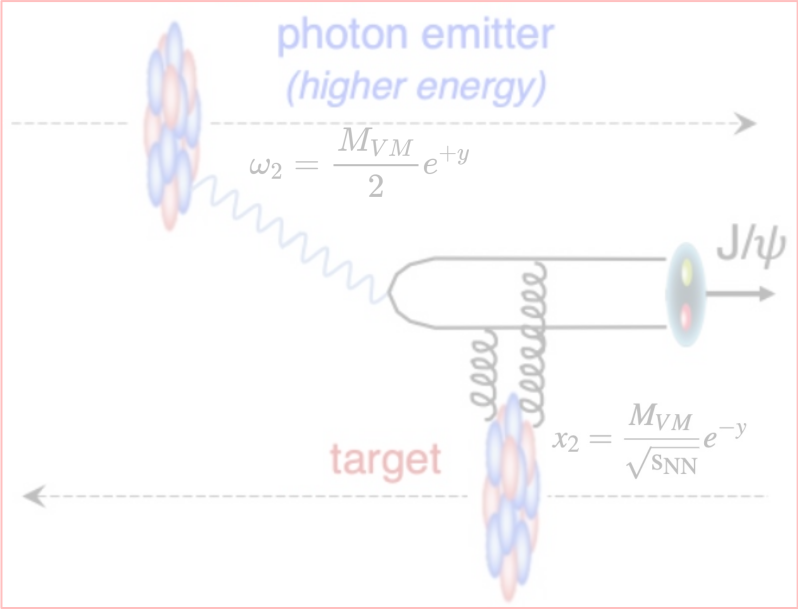
$$x = \frac{M_{VM}}{\sqrt{s_{NN}}} e^{\mp y}$$

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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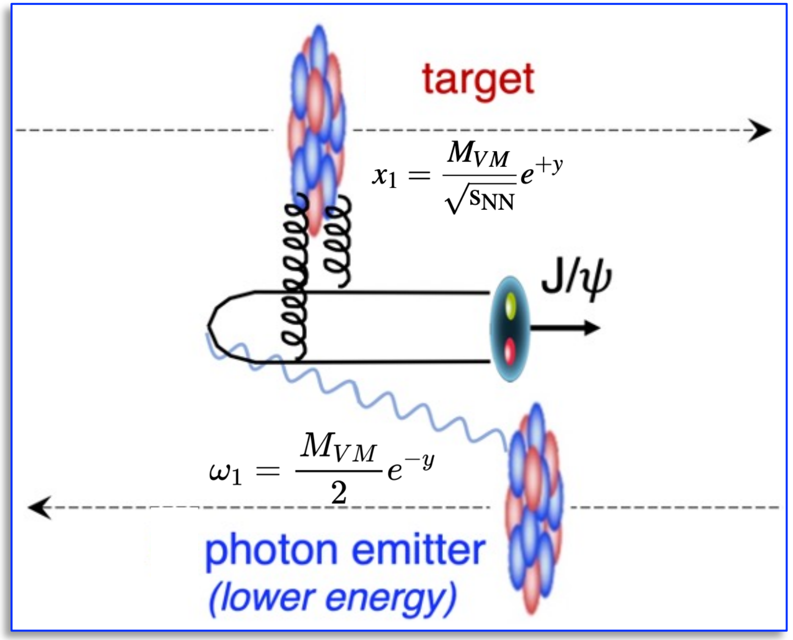

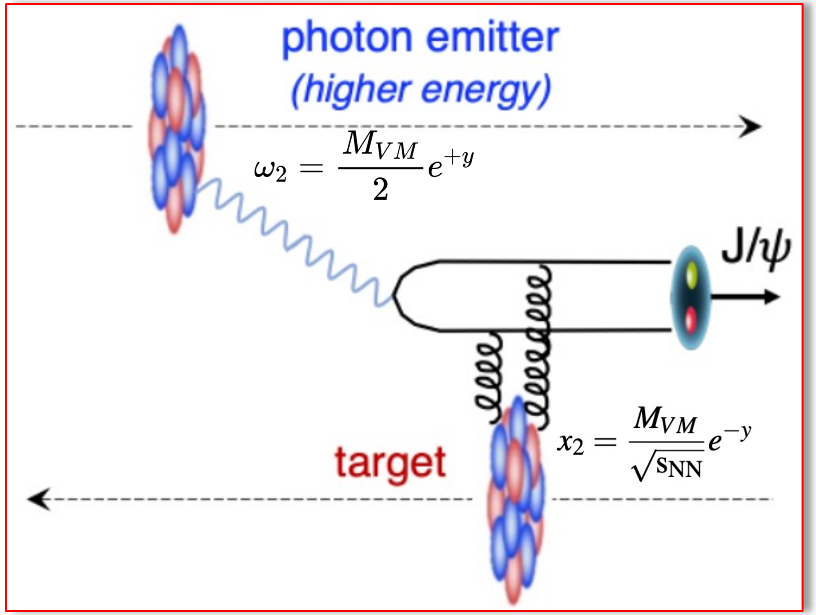

Smaller-*x*

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

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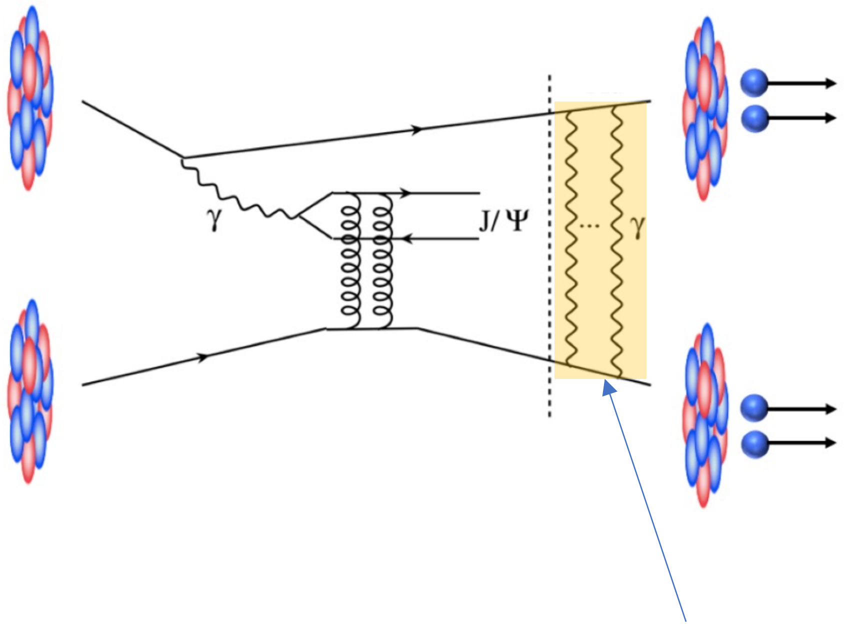
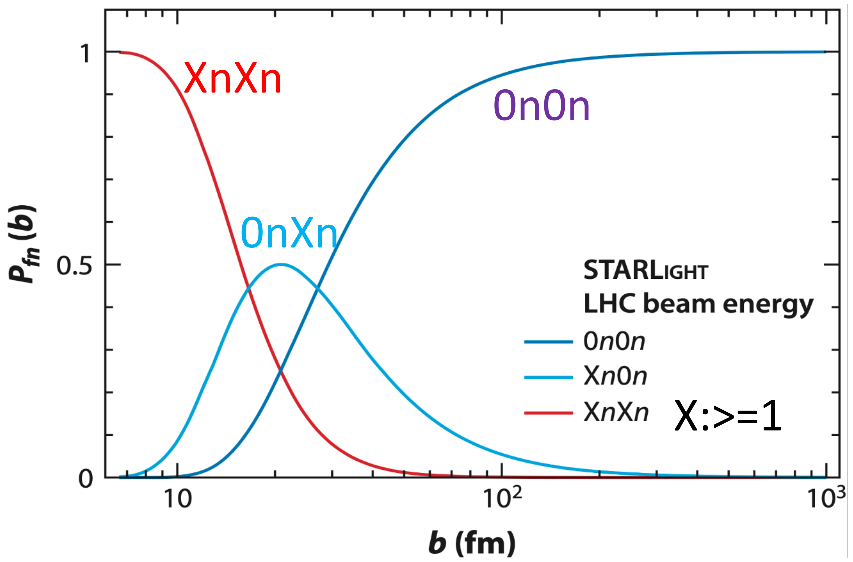
Method to Solve Two-Way Ambiguity in A-A UPC

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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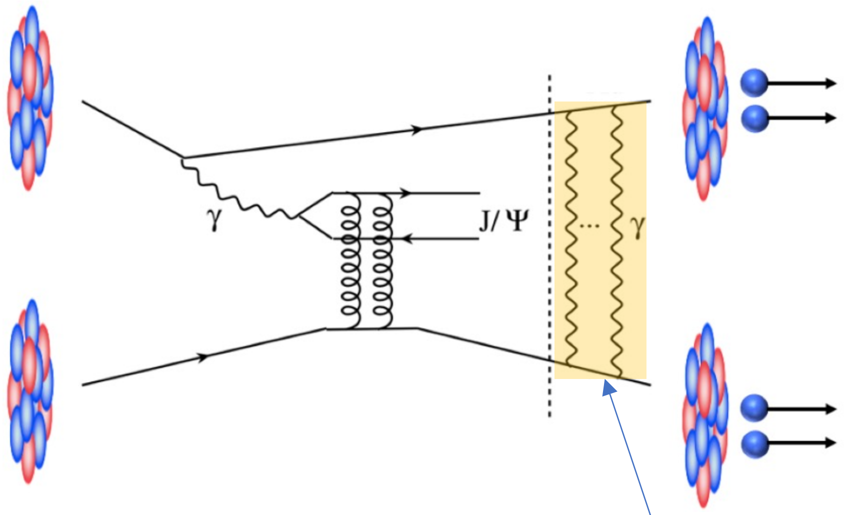

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from theoretical calculation

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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**

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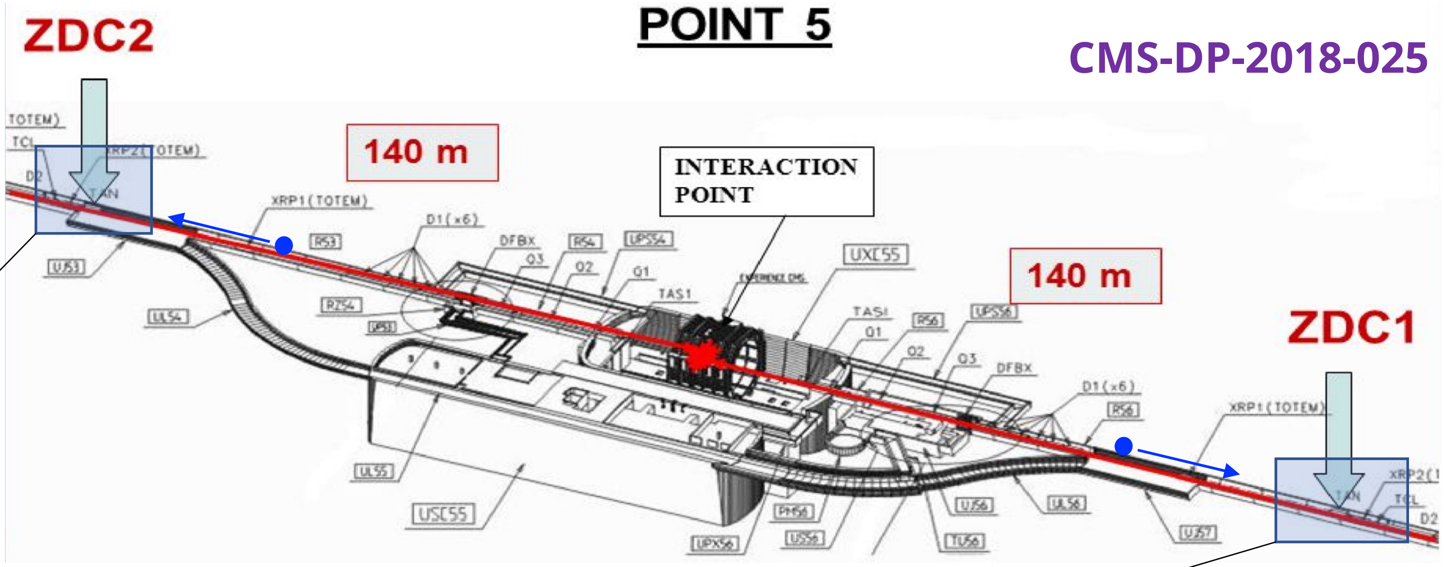
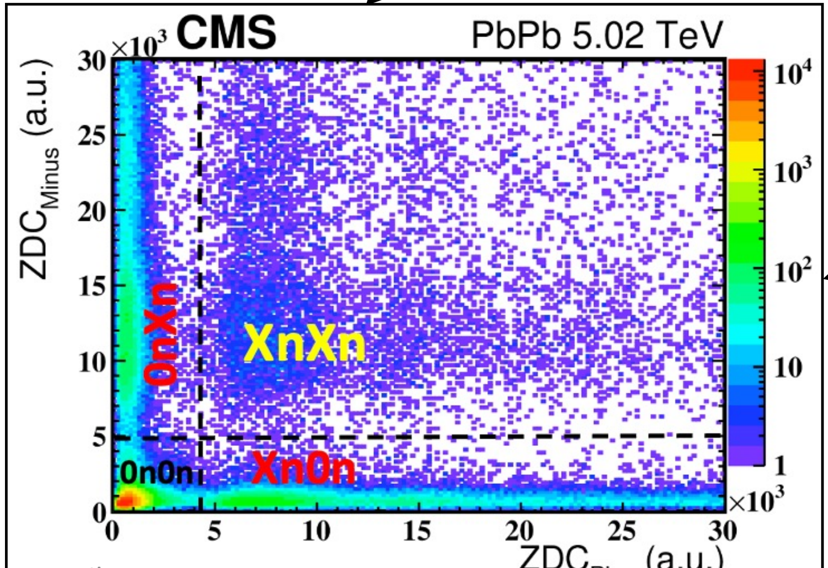
Neutron Tag with Zero Degree Calorimeter



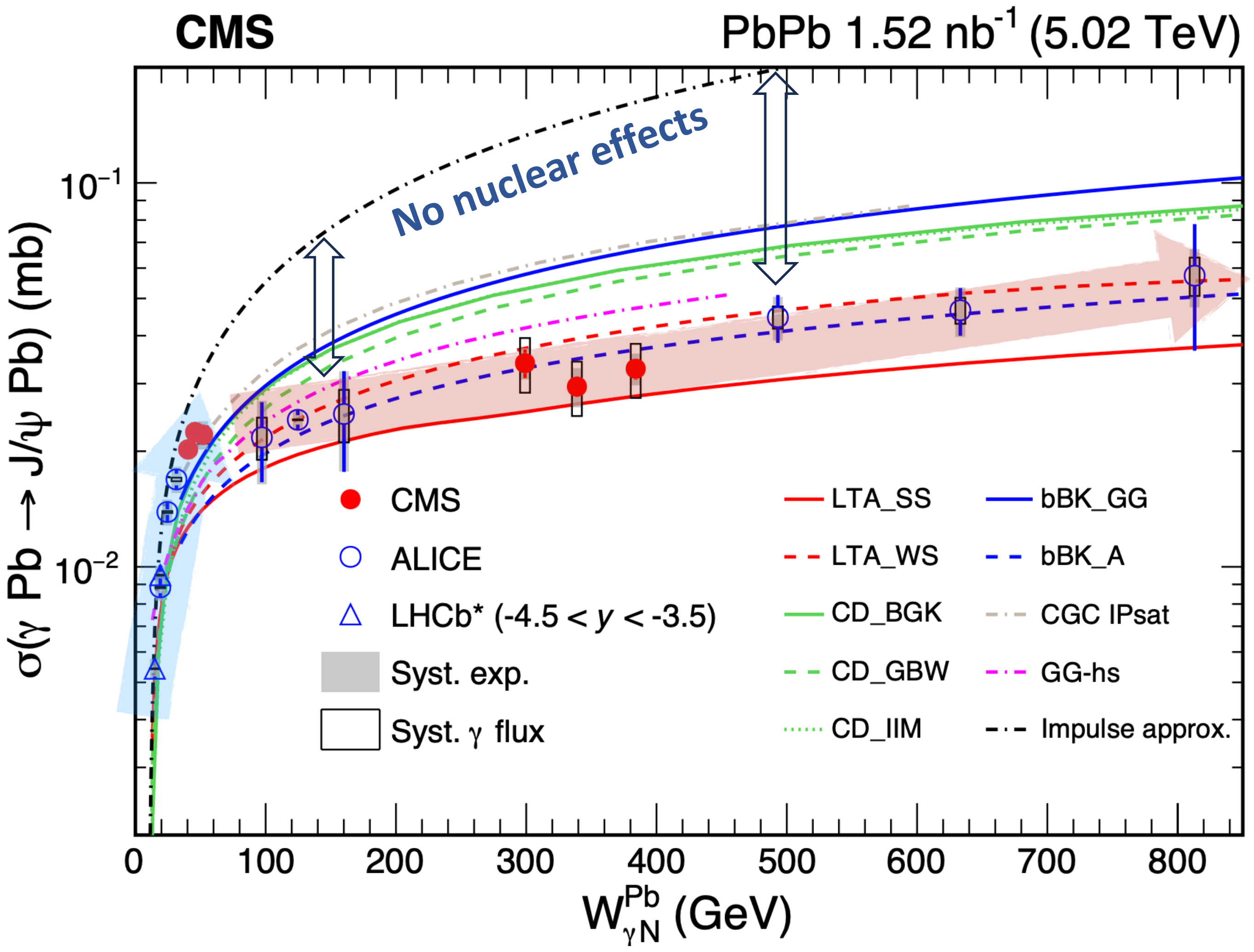


Tag events with **neutrons**:

- 0n0n, 0nXn, XnXn (X: ≥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

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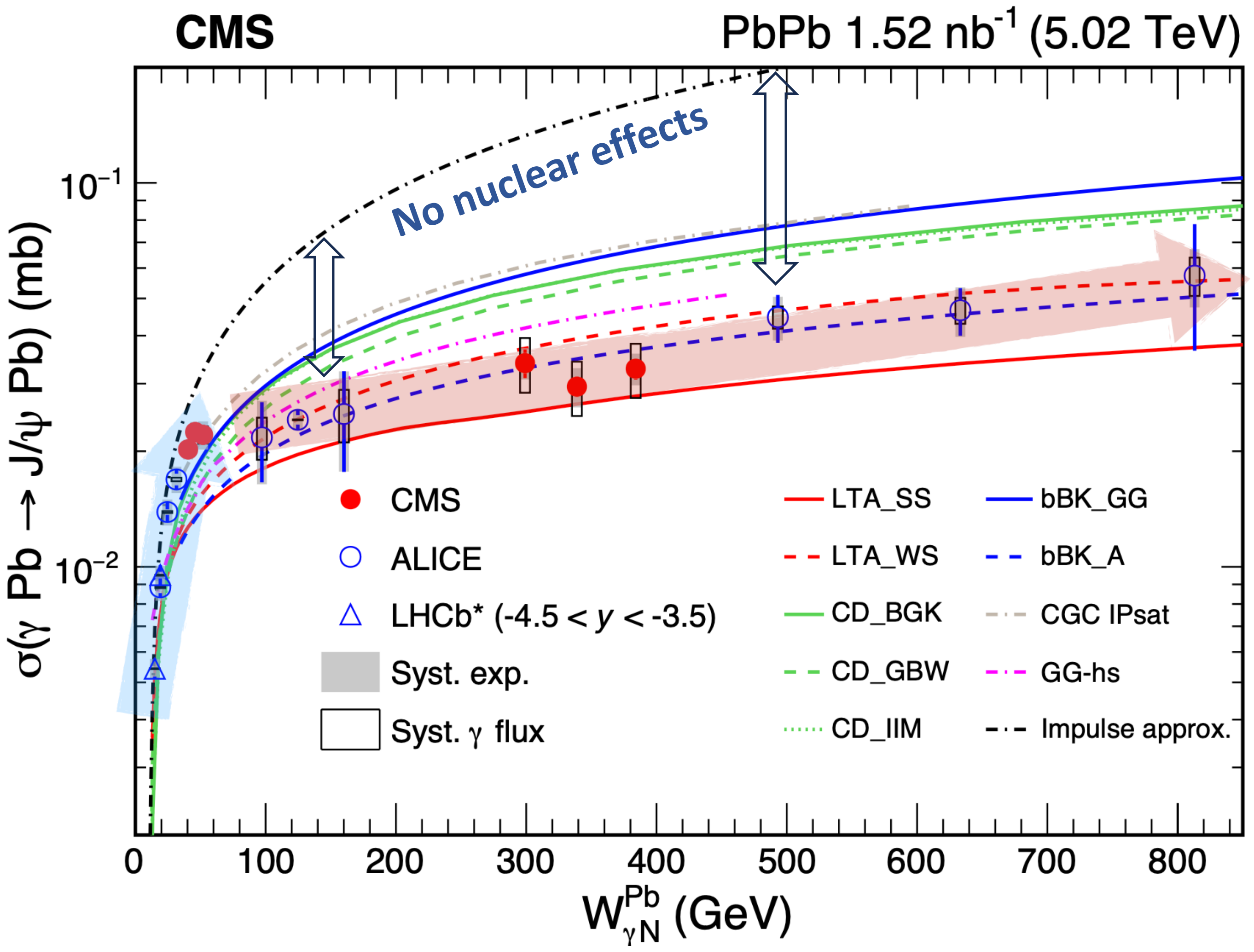

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See Jani Penttala's talk

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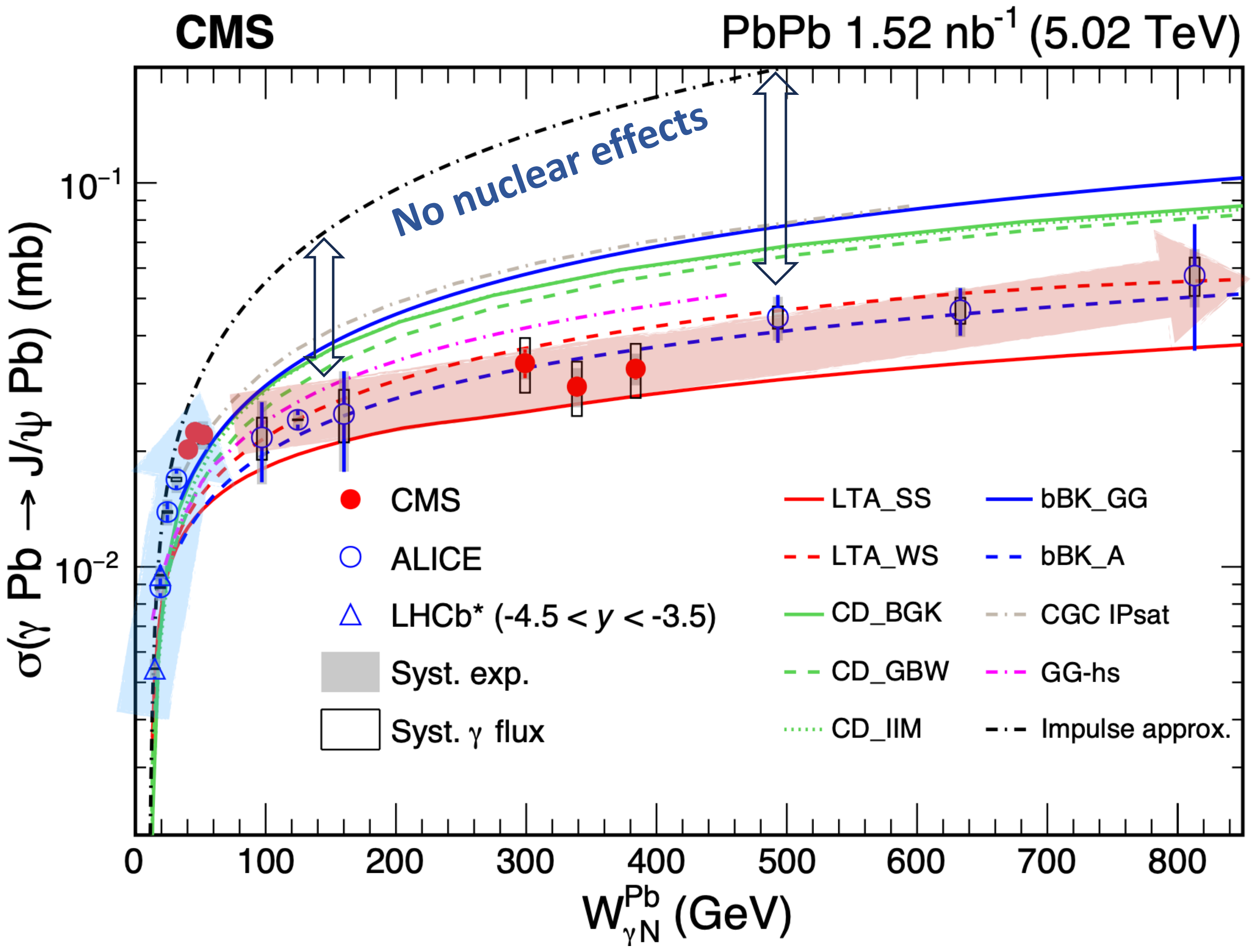

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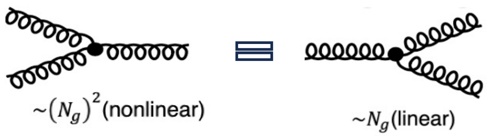
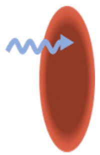
Gluon Saturation?

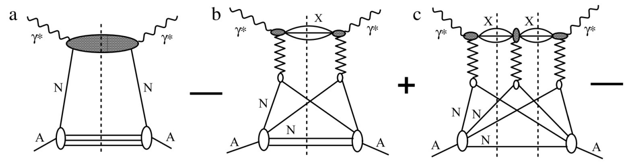


Black Disk Limit?



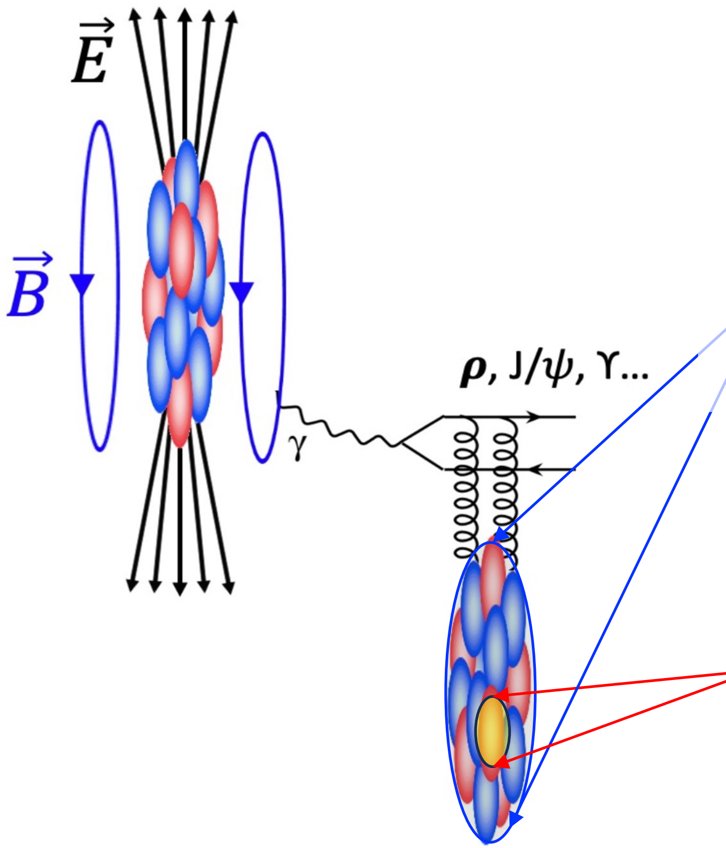
$$\hat{\sigma}_{\rm PQCD}^{\rm inel} \leq \hat{\sigma}_{\rm black} = \pi R_{\rm target}^2$$

Nuclear shadowing?



What's the underlying physics?

How About Incoherent J/Ψ Photoproduction?



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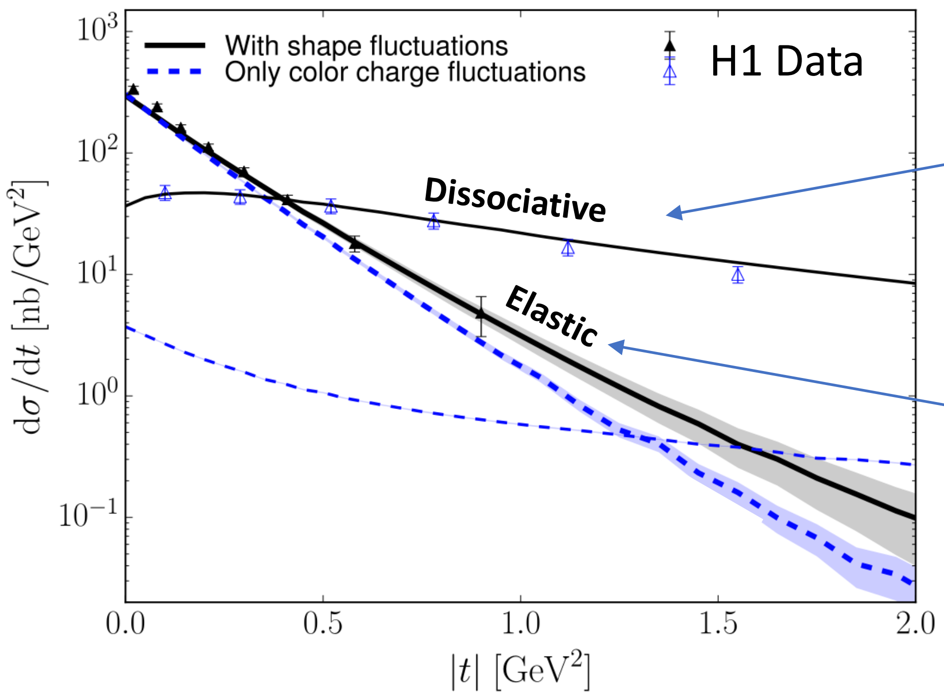
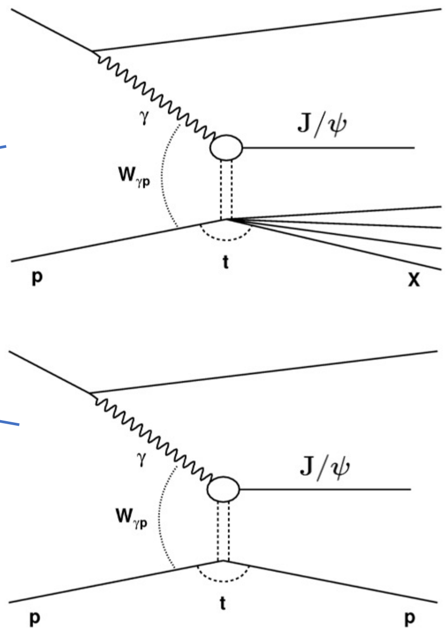
Fluctuating Gluons Probed via γ+p

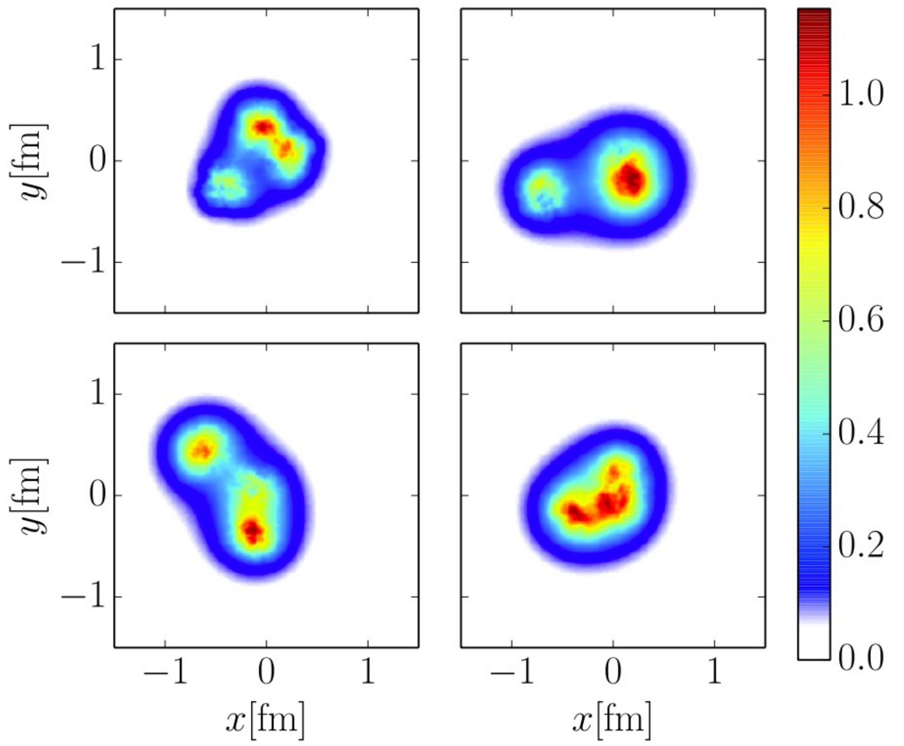
CGC IPsat considering the **fluctuations** of **geometry** (shape and size), **energy density**, **local saturation scale** and **color charge**, successfully describe the HERA data

J/Ψ Photoproduction at HERA



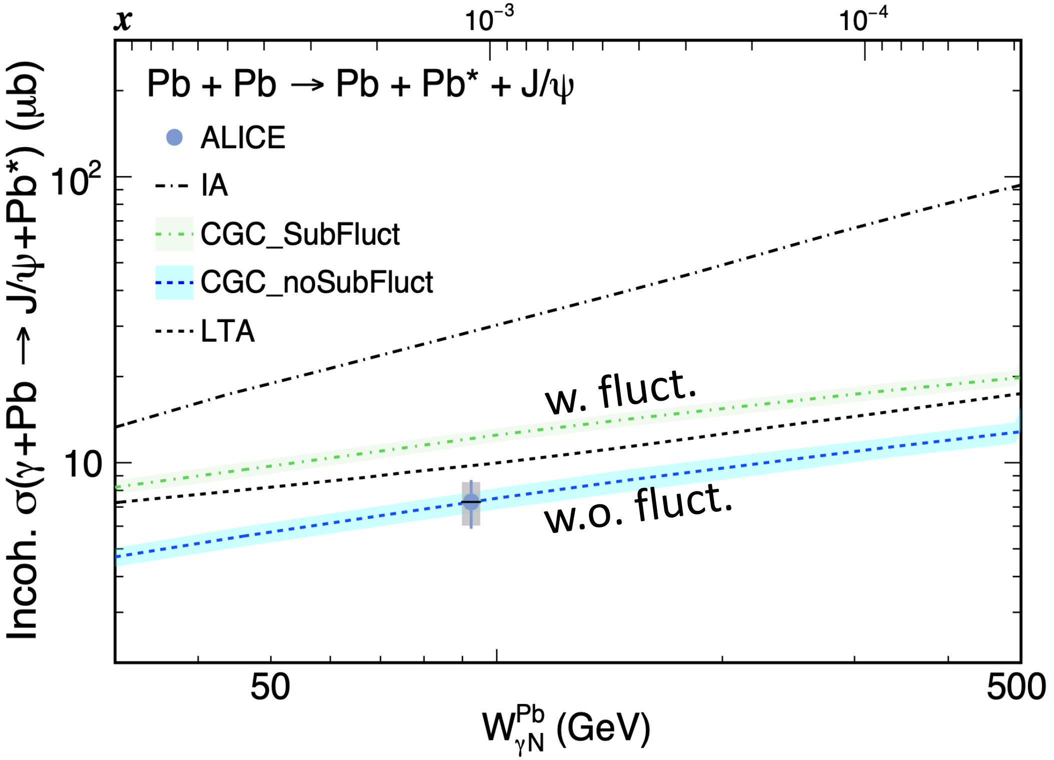


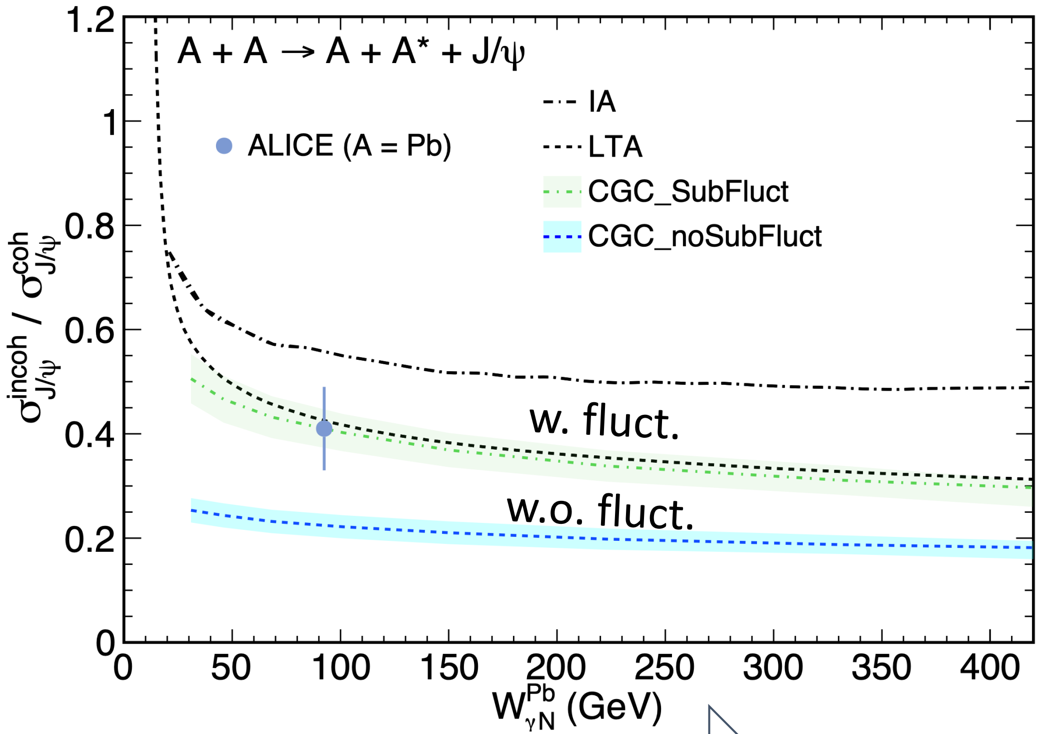
Rep. Prog. Phys. **83** (2020) 082201



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

Fluctuating Gluons and Energy Dependence

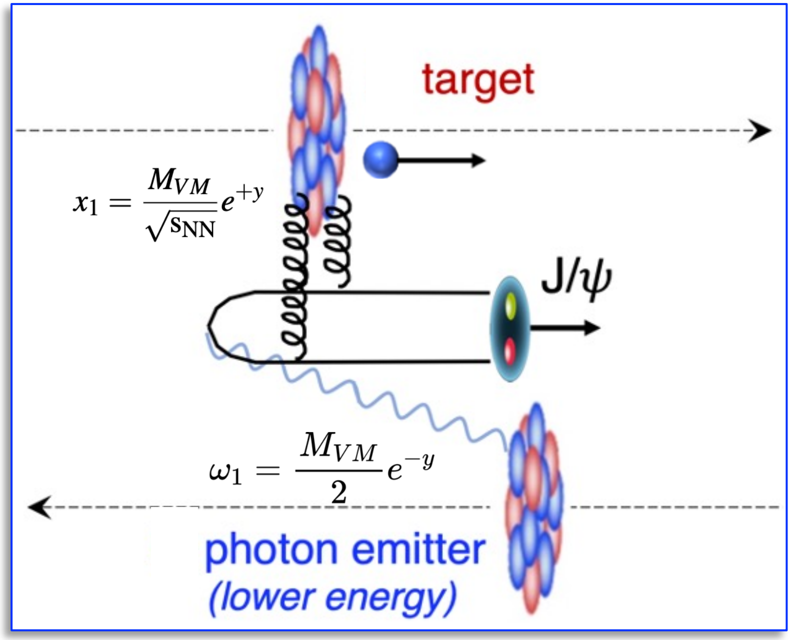




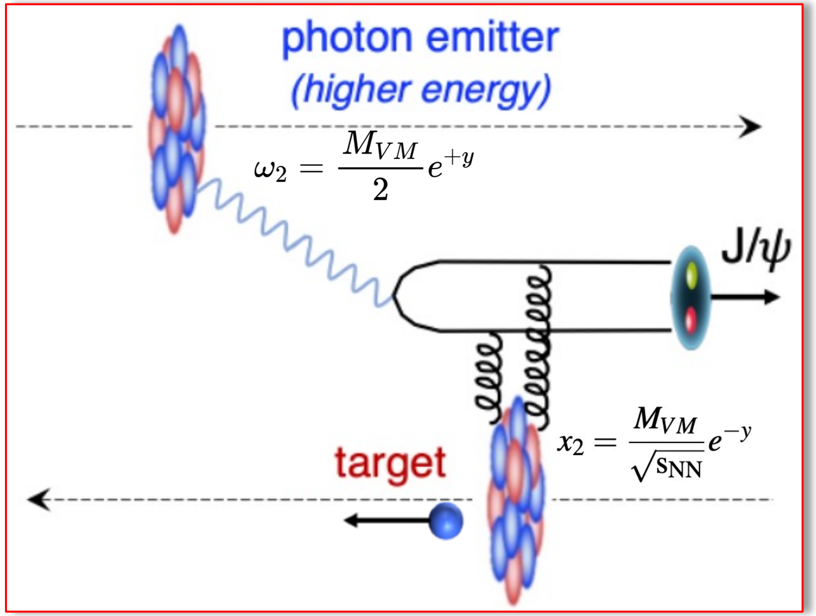
How the fluctuating gluons evolute, especially towards small-x limit?

- 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

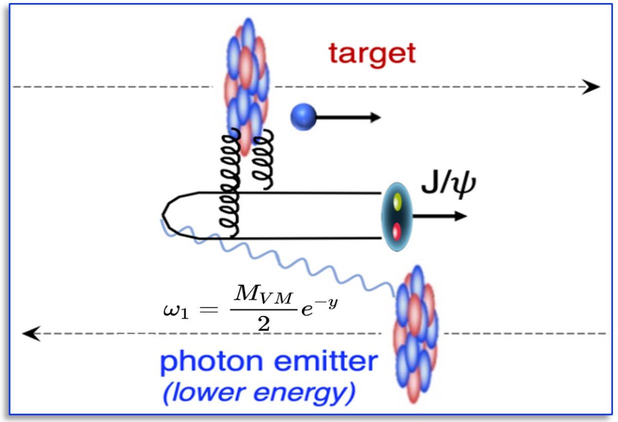
- **Incoh. J/Ψ photoproduction itself has ~85% chance to induce the forward neutrons**
  → Detecting these neutrons will identify target nucleus
  → Help to solve the "Two-Way Ambiguity"

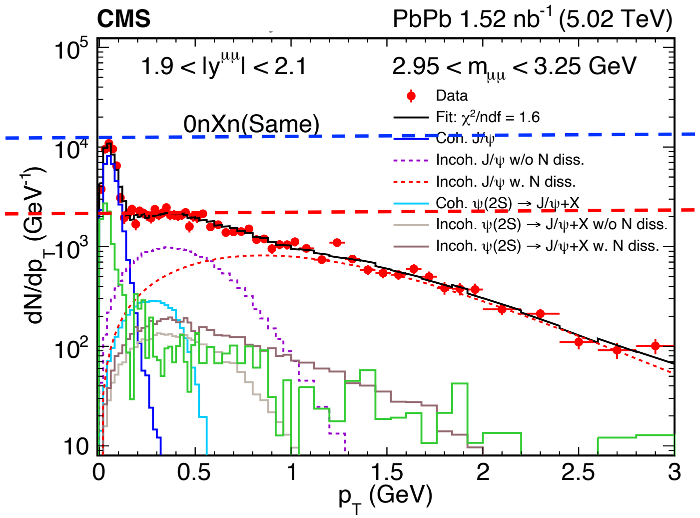
Example Signals (J/Ψ-Xn Correlations)

Low-W

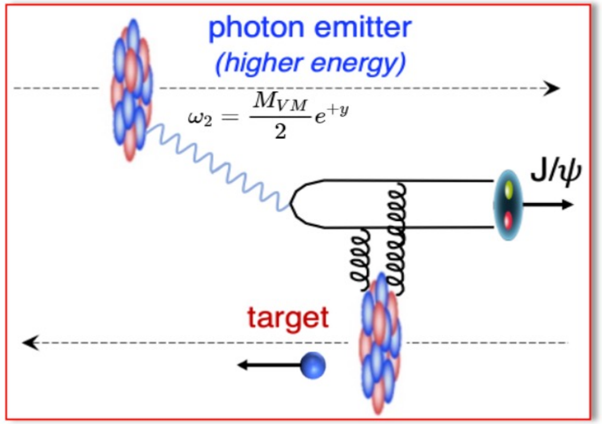
-y

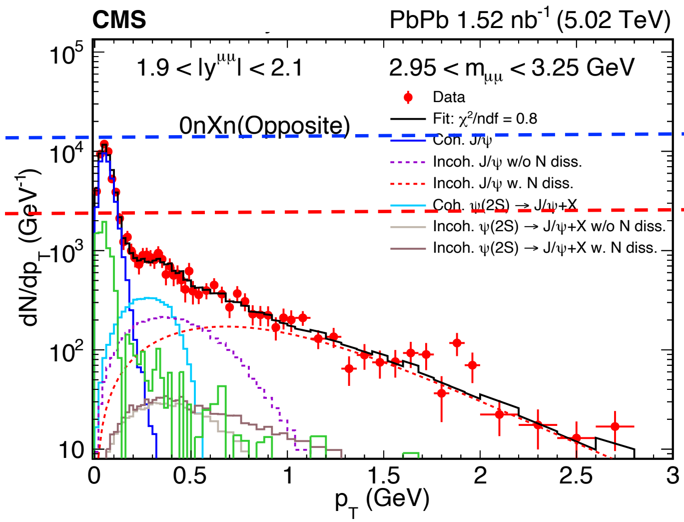
J/Ψ-Xn (Same Direction)





J/Ψ-Xn (Opposite Direction)



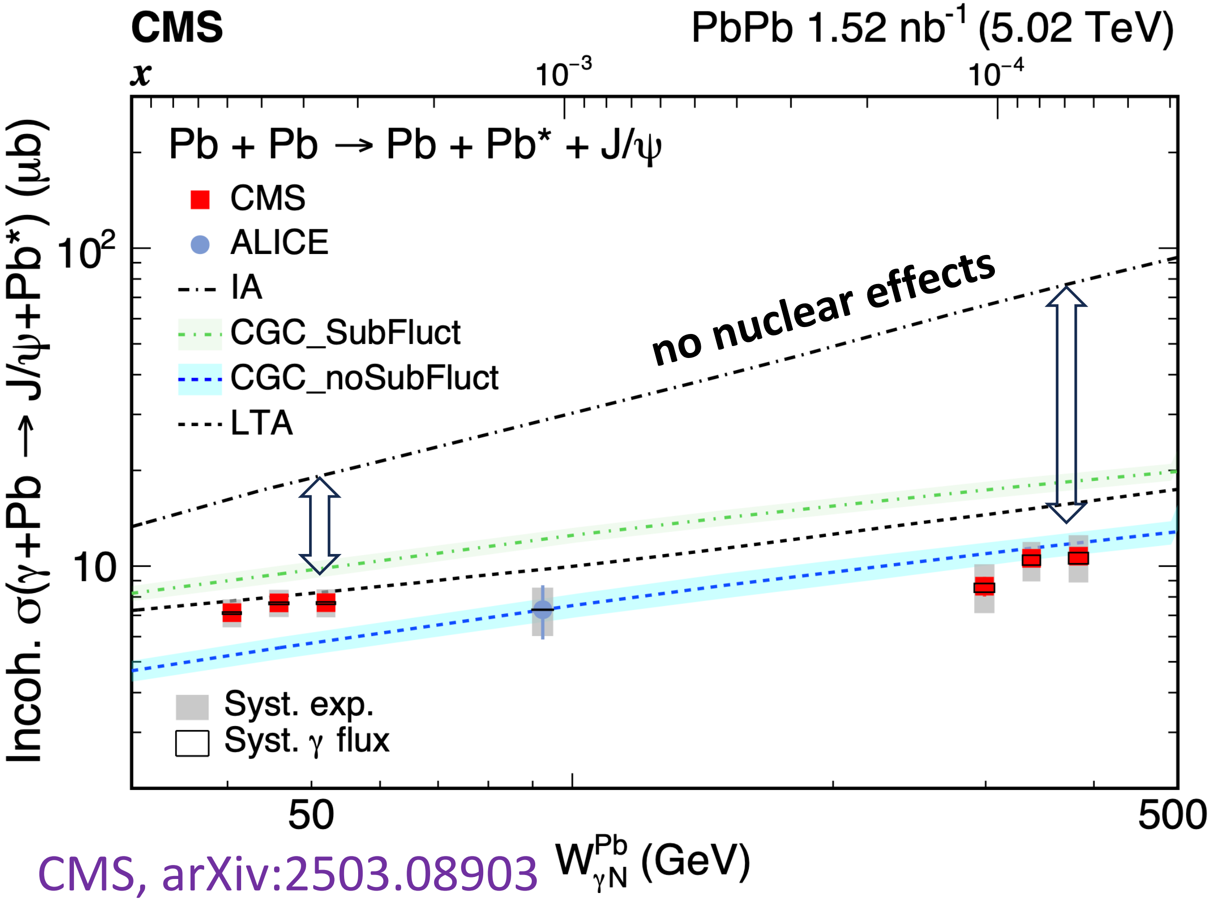


High-W

+y

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

Incoh. J/Ψ Cross Section Per γ+Pb

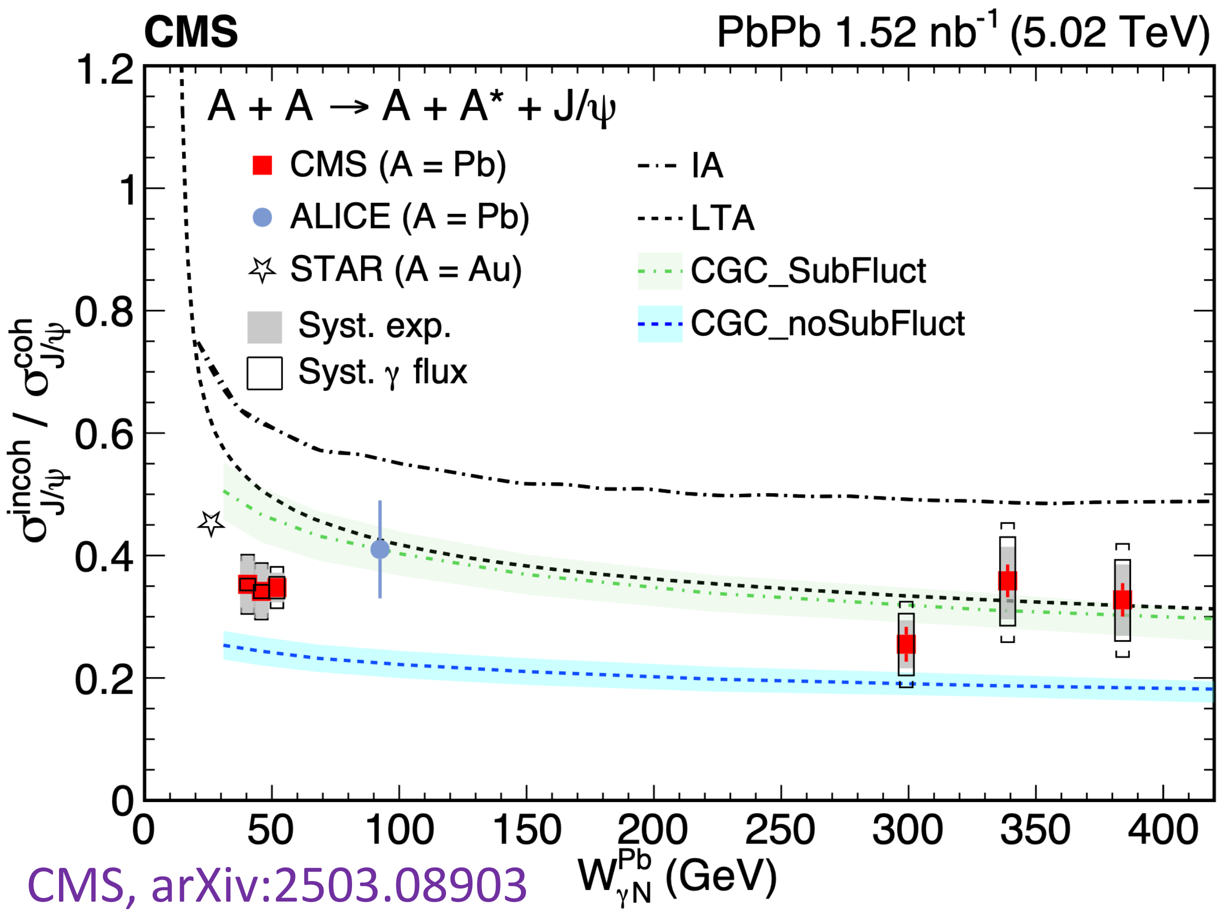


CMS, arXiv:2503.08903

- **First energy-dependent** measurement of incoh. 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



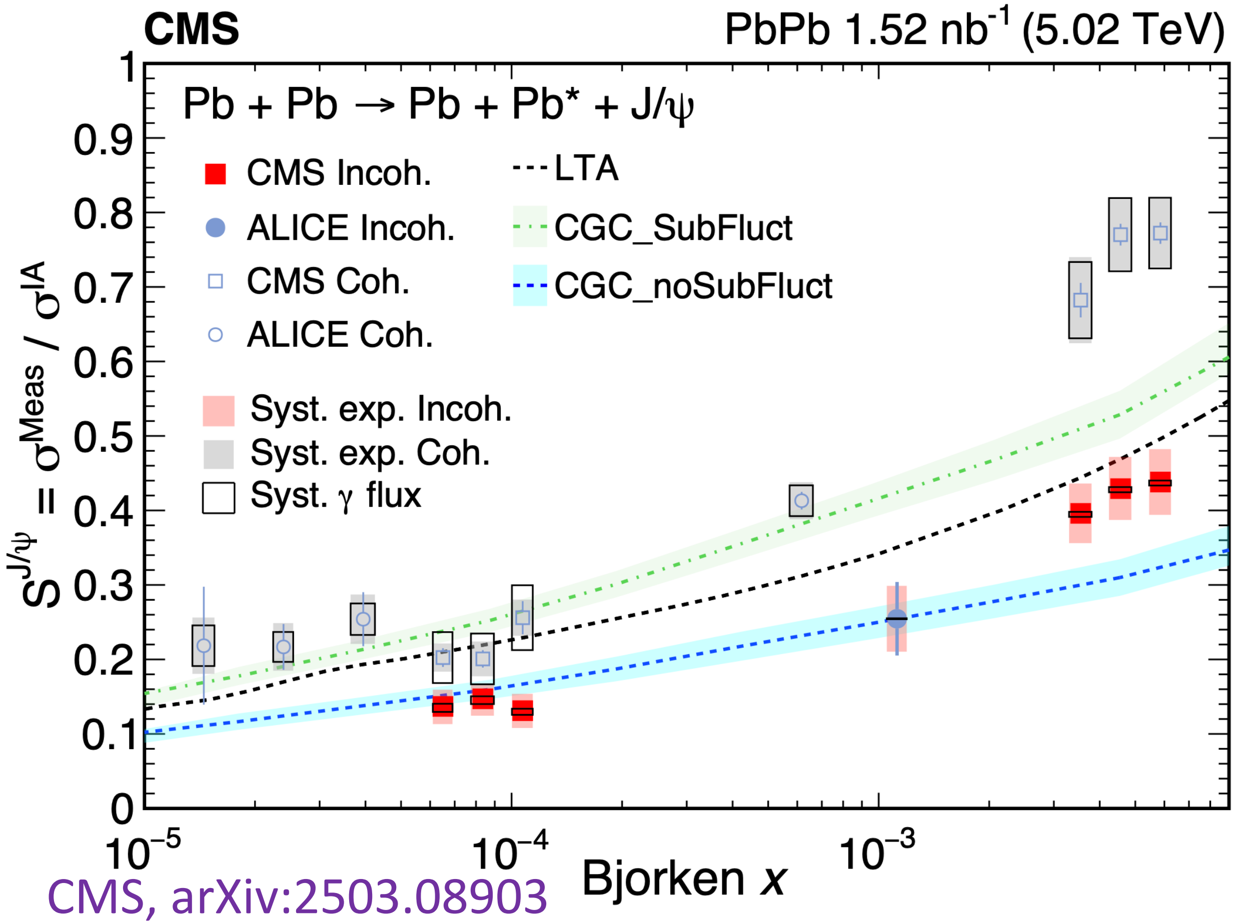
CMS, arXiv:2503.08903

- **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, arXiv:2503.08903

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

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

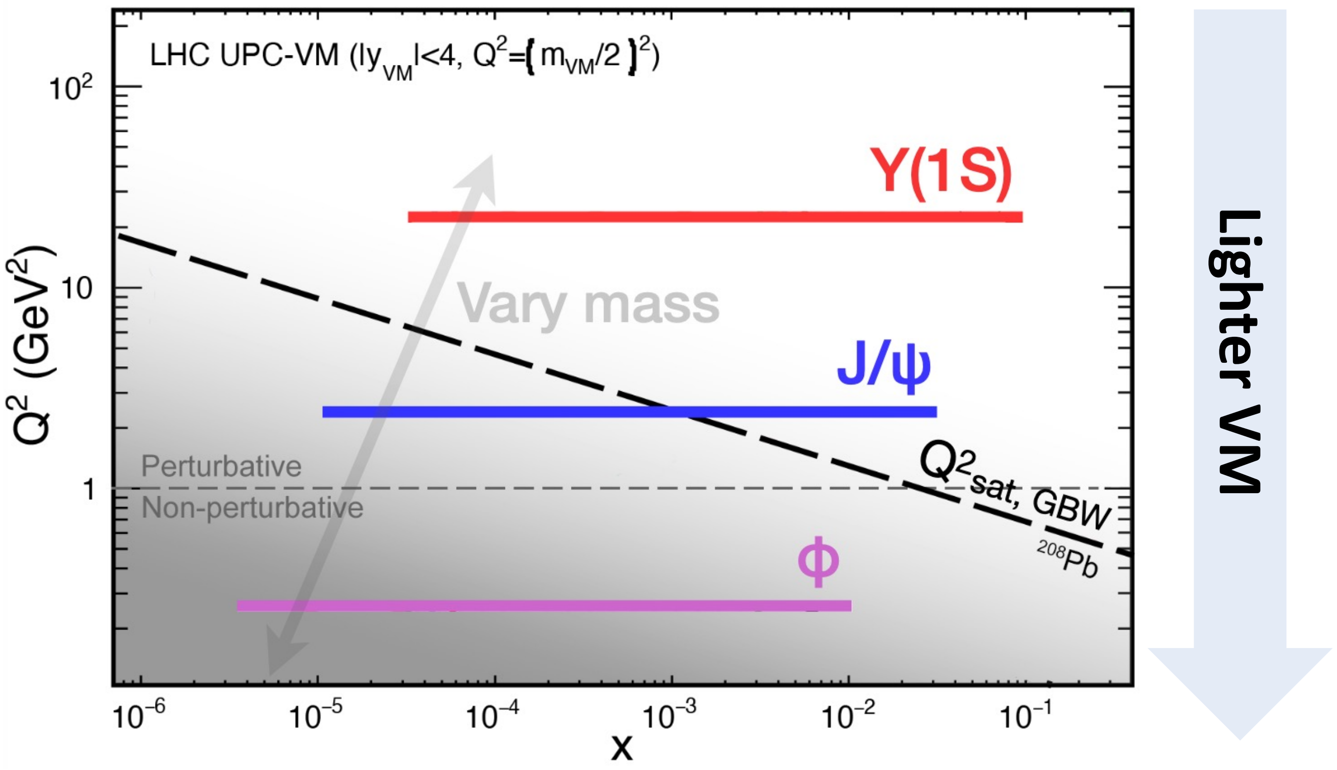
$$S^{J/\psi} = \frac{\sigma^{exp}_{\gamma Pb \to J/\psi Pb'}}{\sigma^{IA}_{\gamma Pb \to J/\psi Pb'}}$$

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

Enter **Lower Q^2** Region with **Lighter** VM

Results from J/ψ highlights unresolved aspects of the underlying physics



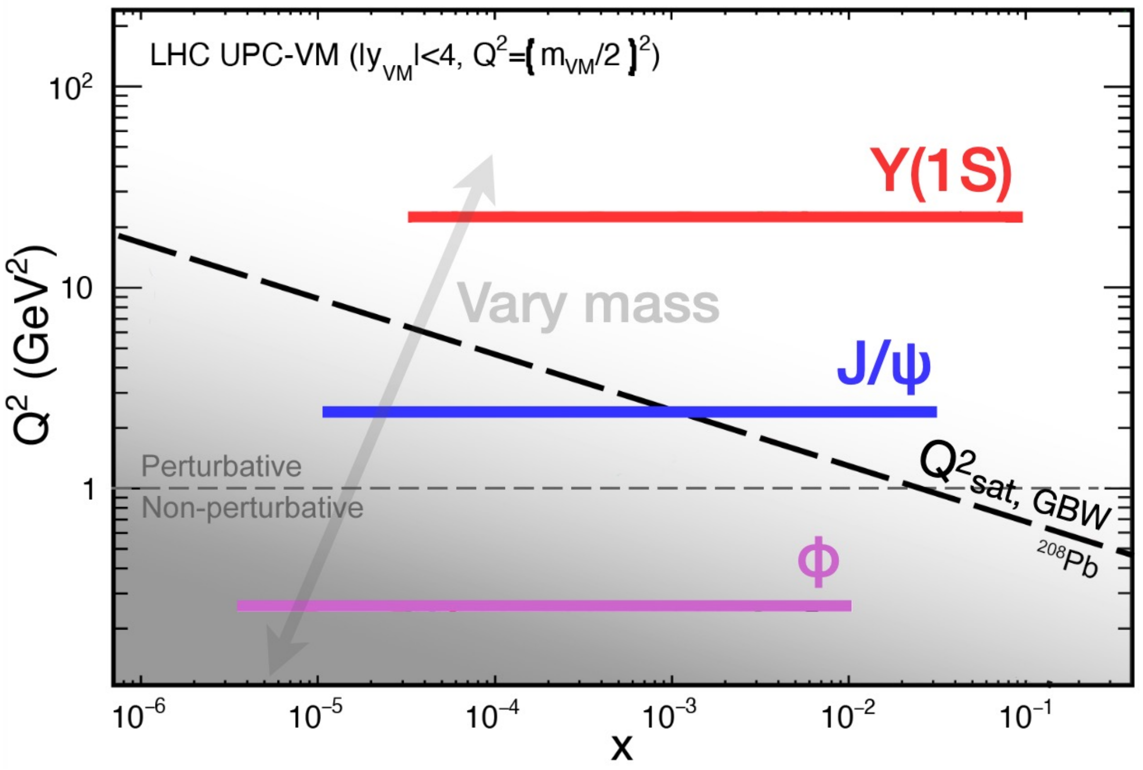
$$r^2 \sim \frac{1}{Q^2} \sim \frac{1}{M_{VM}^2}$$

Amplify the nonlinear QCD effects by lowering Q^2

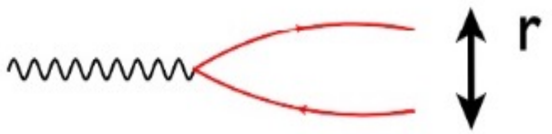
Measure Coh. ϕ

Enter Lower Q^2 Region with Lighter VM

Results from J/ψ highlights unresolved aspects of the underlying physics



Lighter VM



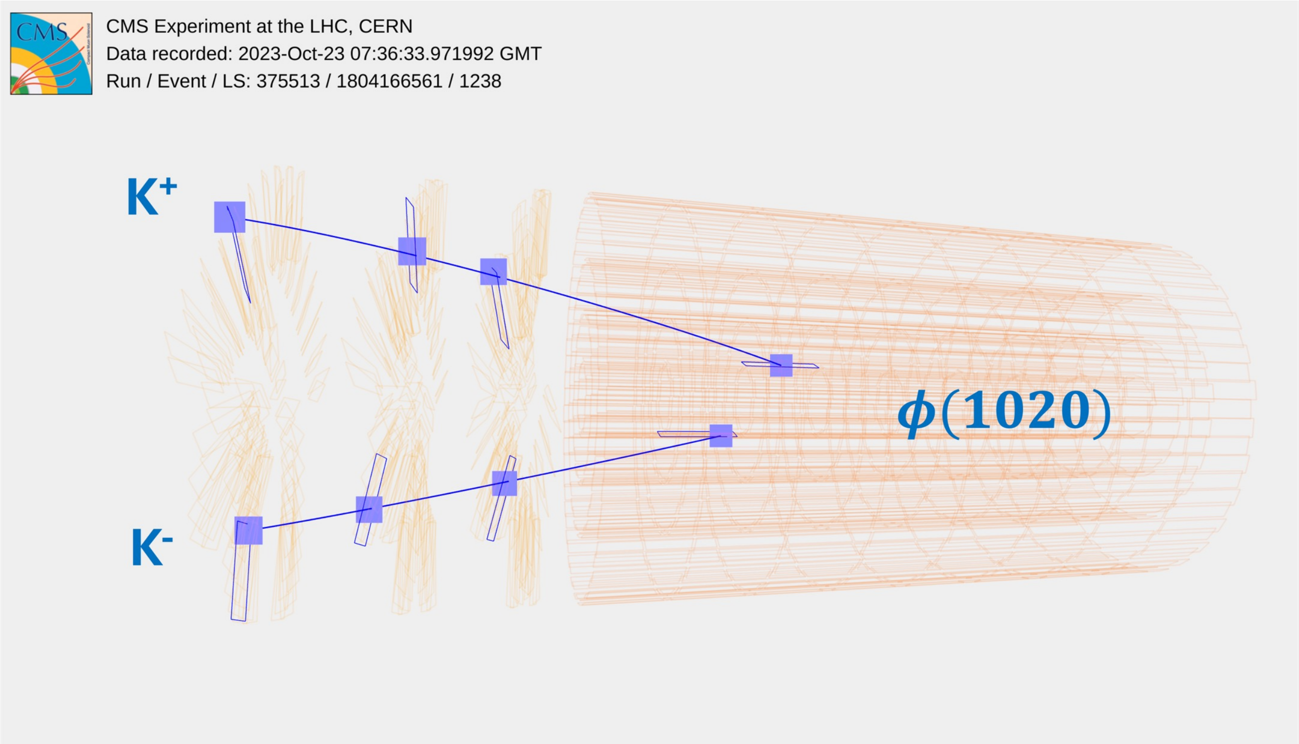
$$r^2 \sim \frac{1}{Q^2} \sim \frac{1}{M_{VM}^2}$$

Amplify the nonlinear QCD effects by lowering Q^2

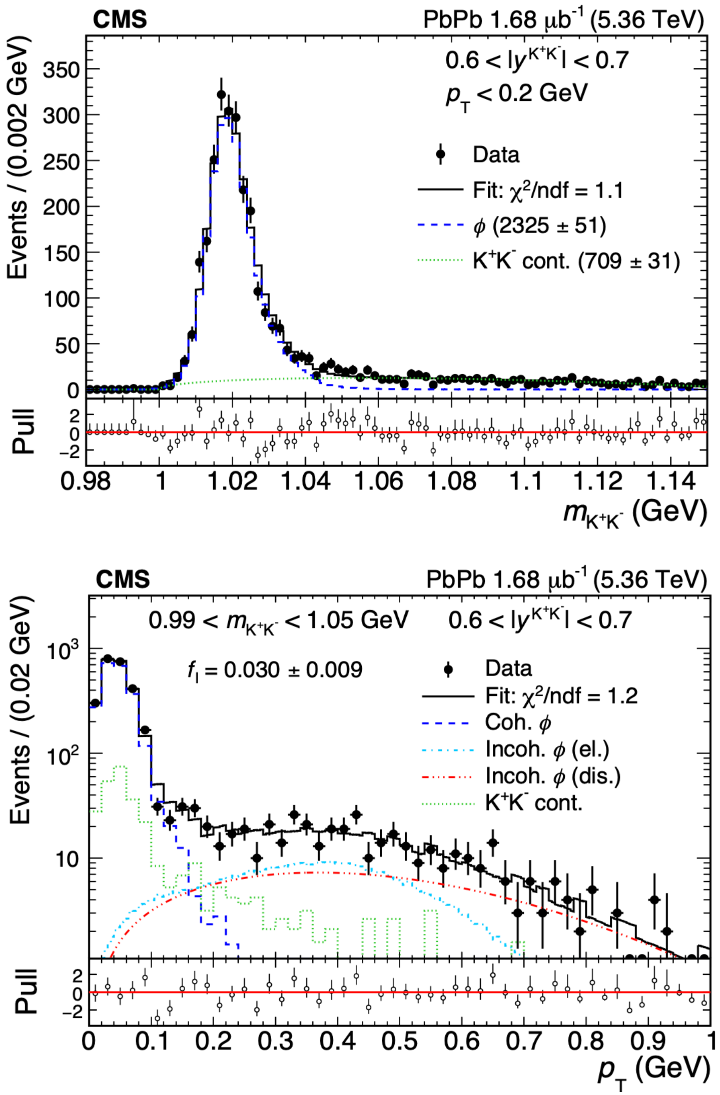
Measure Coh. ϕ

Experimental challenging: $M_\phi \sim 2 \cdot M_K$ → very low p_T Kaons

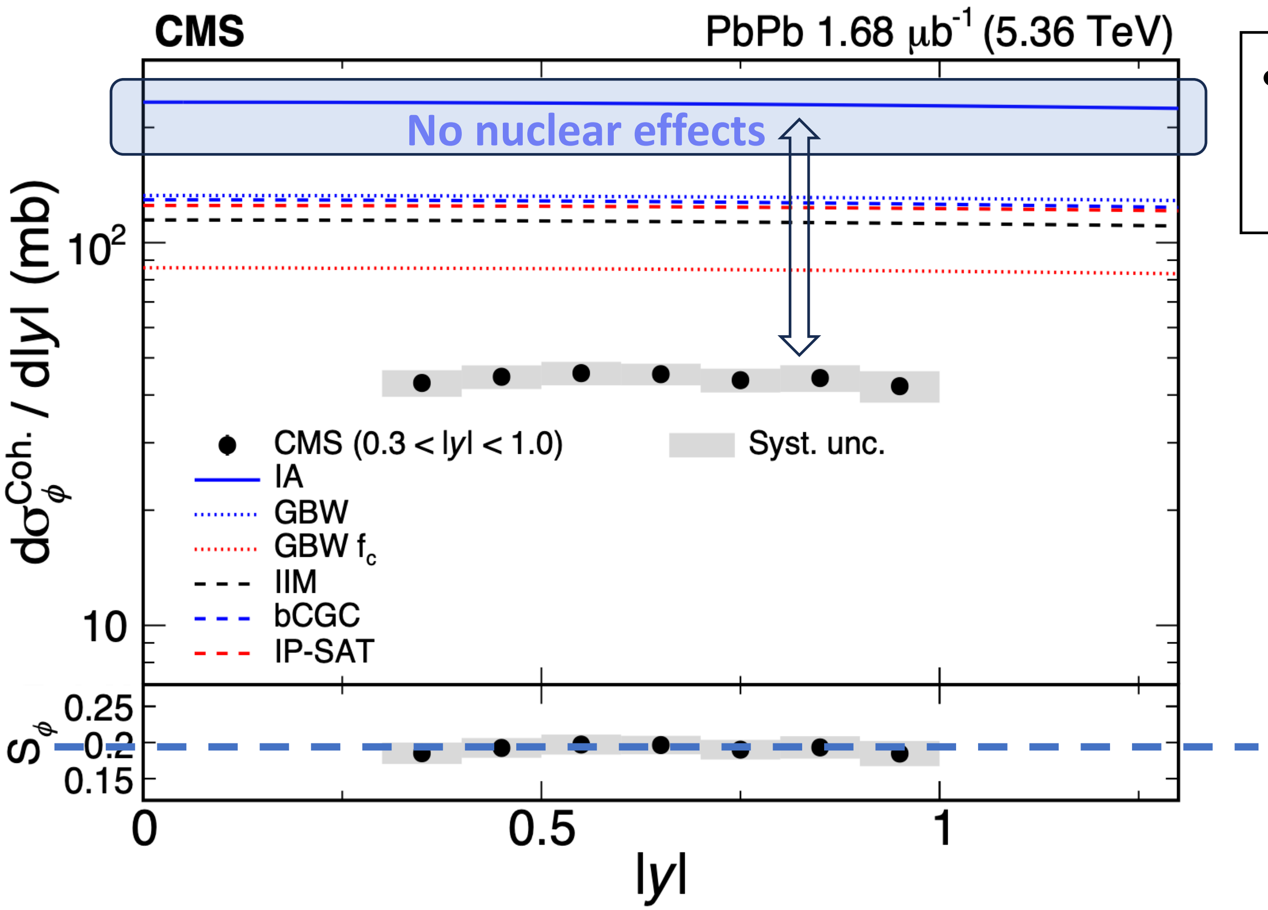
First Observation of ϕ Photoproduction in UPCs



CMS, arXiv:2504.05193



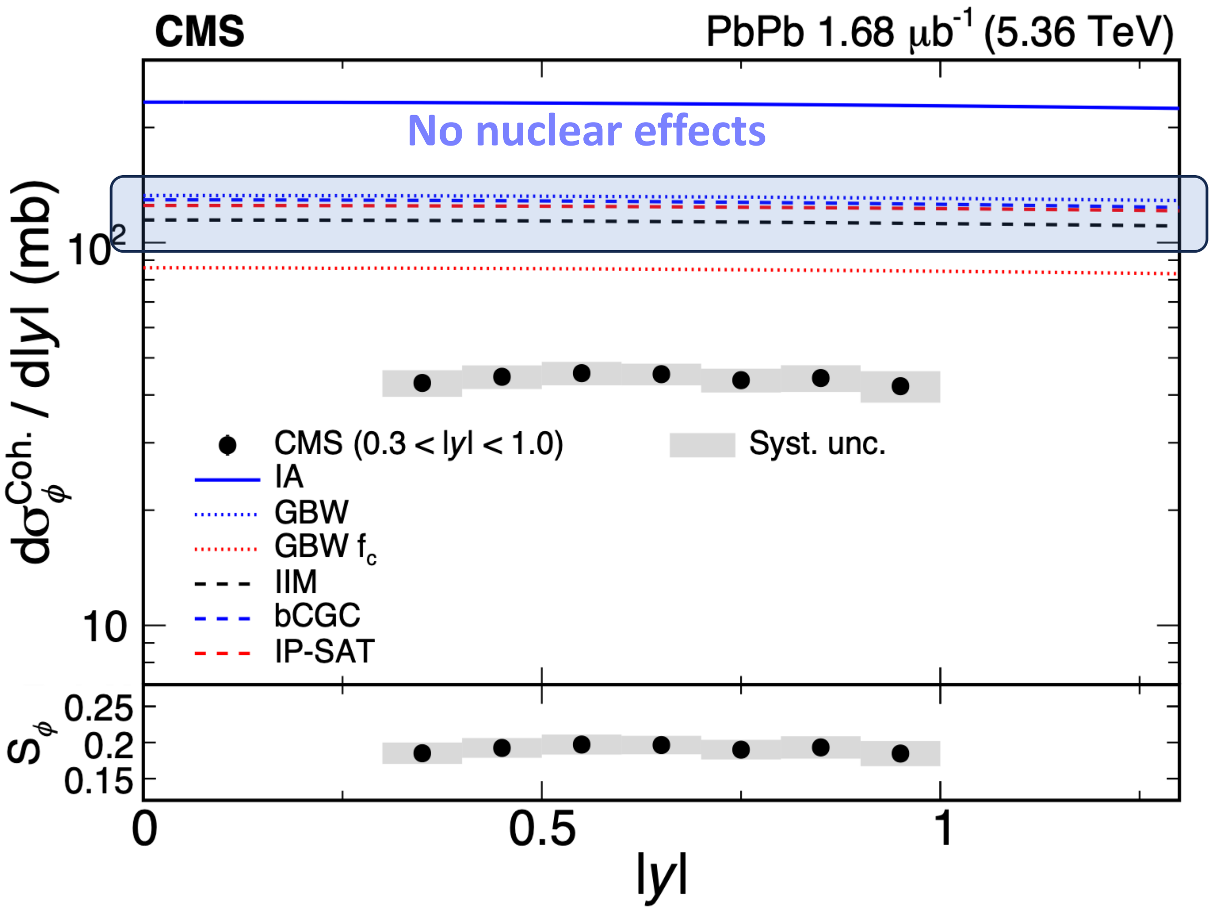
First Observation of ϕ Photoproduction in UPCs



- **Strong suppression of Coh. ϕ is observed (a factor of 5)**

CMS, arXiv:2504.05193

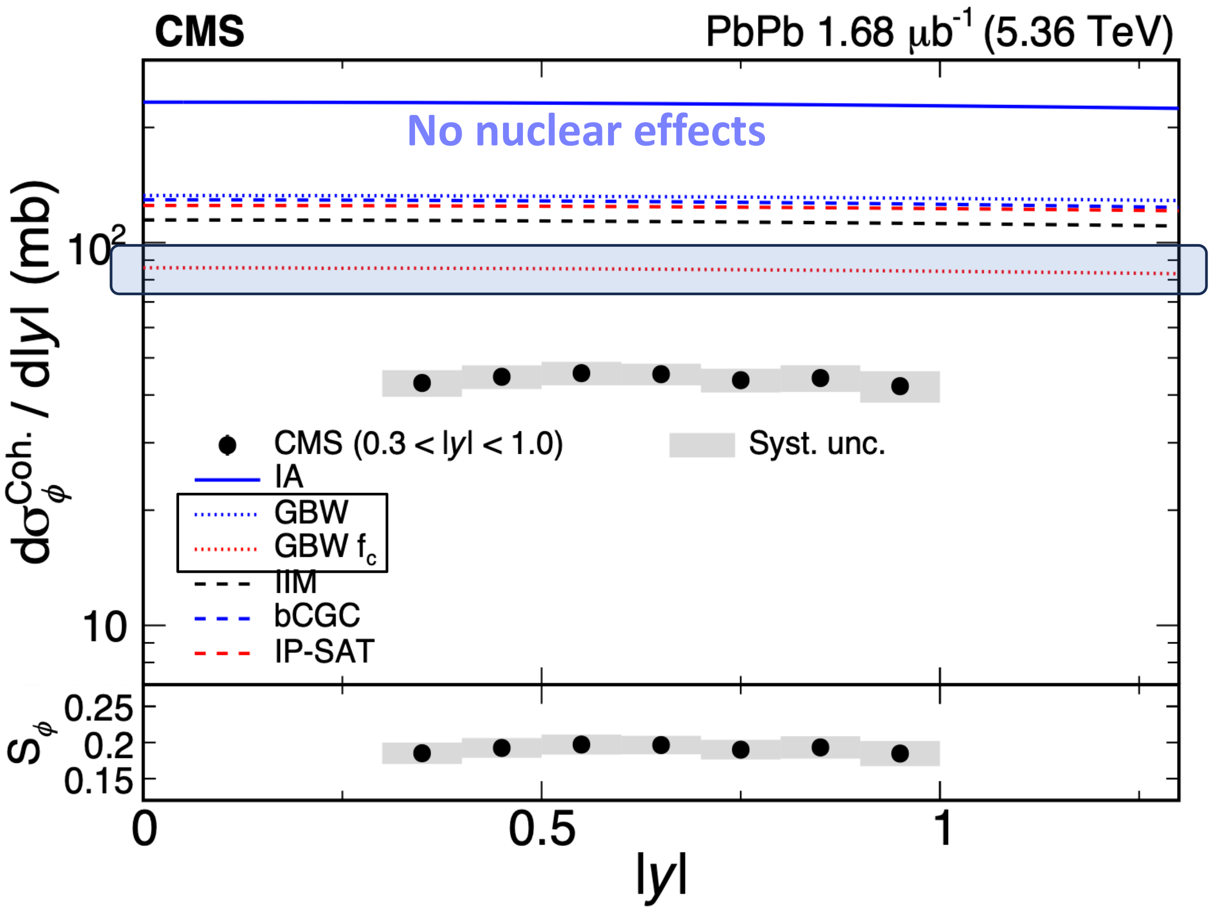
First Observation of ϕ Photoproduction in UPCs



CMS, arXiv:2504.05193

- **Strong suppression of Coh. ϕ is observed (a factor of 5)**
- Gluon saturation models:
  - Overpredicted data by a factor of 2.6-3

First Observation of ϕ Photoproduction in UPCs



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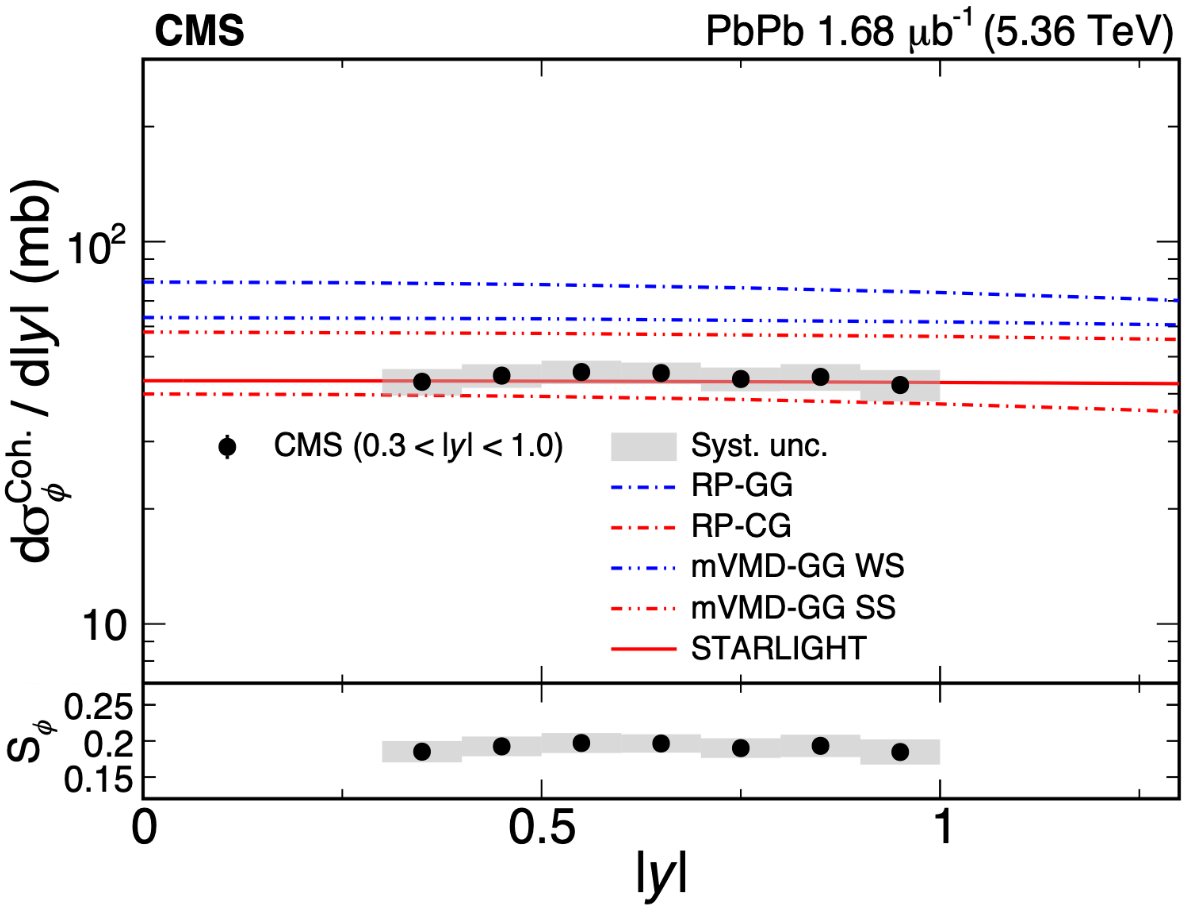
  - Non-pQCD correction reduce ~40%, but still a factor of 2 higher

CMS, arXiv:2504.05193

First Observation of ϕ Photoproduction in UPCs



CMS, arXiv:2504.05193

- **Strong suppression of Coh. ϕ is observed (a factor of 5)**
- Gluon saturation models:
  - Overpredicted data by a factor of 2.6-3
  - Non-pQCD correction reduce ~40%, but still a factor of 2 higher
- Nuclear shadowing models:
  - Generally better agree with data
  - VMD + Gribov Glauber (GG) over predict data
  - VMD + Classical Glauber (CG) best describe data
    - STARLIGHT and RP-CG

Summary

- **First energy-dependent Coh. and Incoh. J/Ψ are measured by CMS**
  - 40 < W < 400 GeV, probing broad x interval: **10^{-2} - 10^{-5}**
- **Both Coh. and Incoh. J/Ψ cross sections are strongly saturated at high energy**
- **Ratio of Incoh/Coh J/Ψ stay constant ~0.3-0.5 for 40 < W < 400 GeV**
  - Sub-nucleonic fluctuations are needed; Not support that BDL is reached
- **Nuclear suppression factor** of J/Ψ photoproduction in γ+Pb interaction:
  - **Stronger towards lower x, eventually flattens out**
  - Incoh. J/Ψ is **more suppressed** than Coh. J/Ψ
- **Coh. ϕ photoproduction off heavy nuclei is observed by CMS:**
  - Nuclear suppression factor ~5
  - Gluon saturation models overpredict data by a factor of 2-3
  - Nuclear shadowing models (VMD+CG) best agree with data
- **Significant theoretical improvements are needed towards uncovering the underlying physics mechanisms at small x**

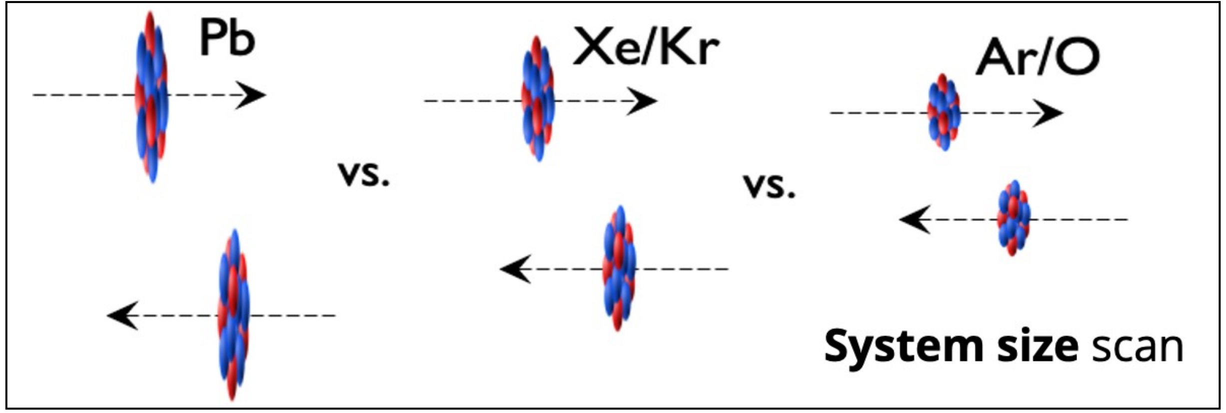
Future Opportunities

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

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

$$x\ vs.\ Q^2\ vs.\ Q_S^2$$

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

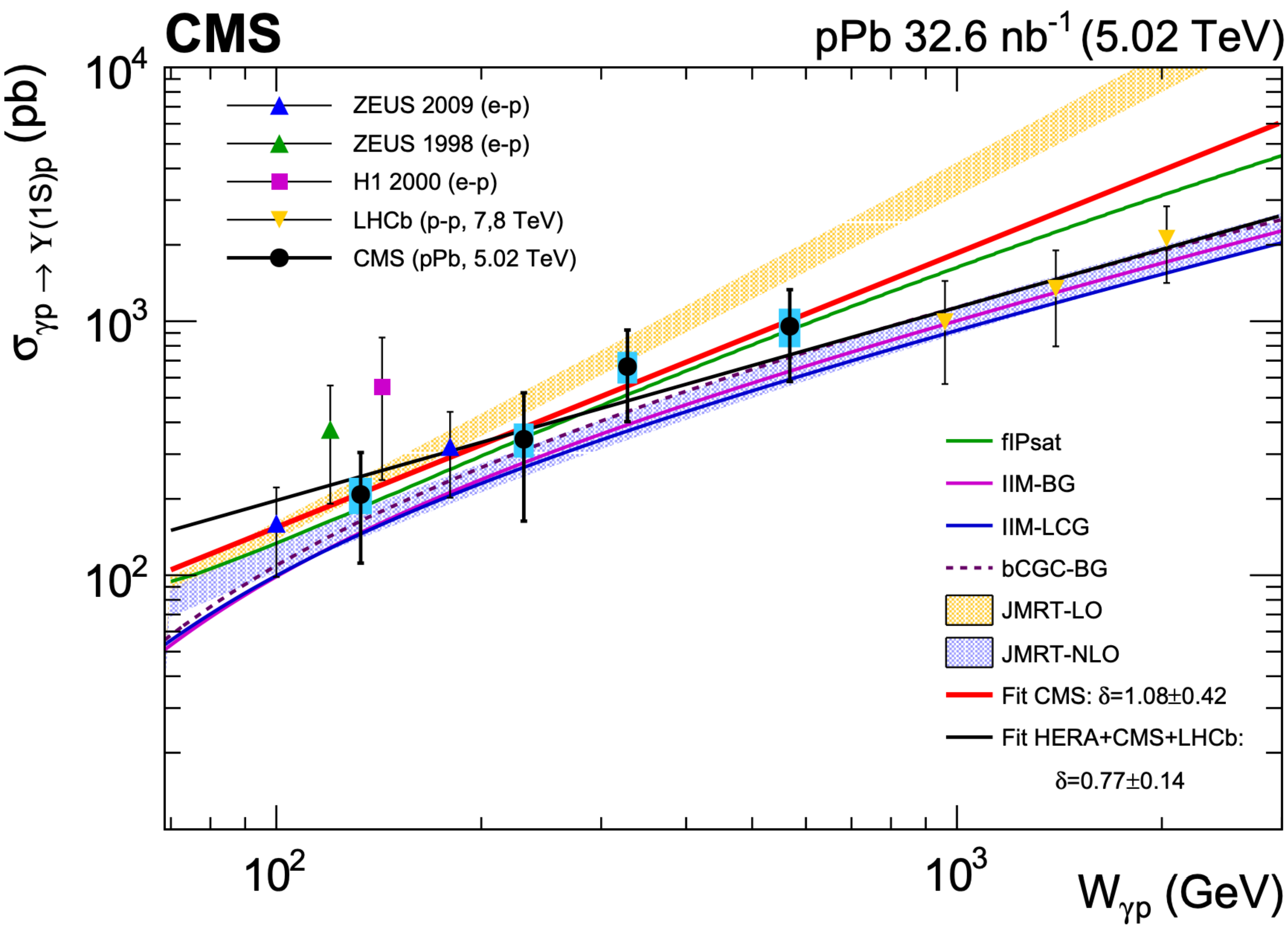


CERN Yellow Report, arXiv:1812.06772

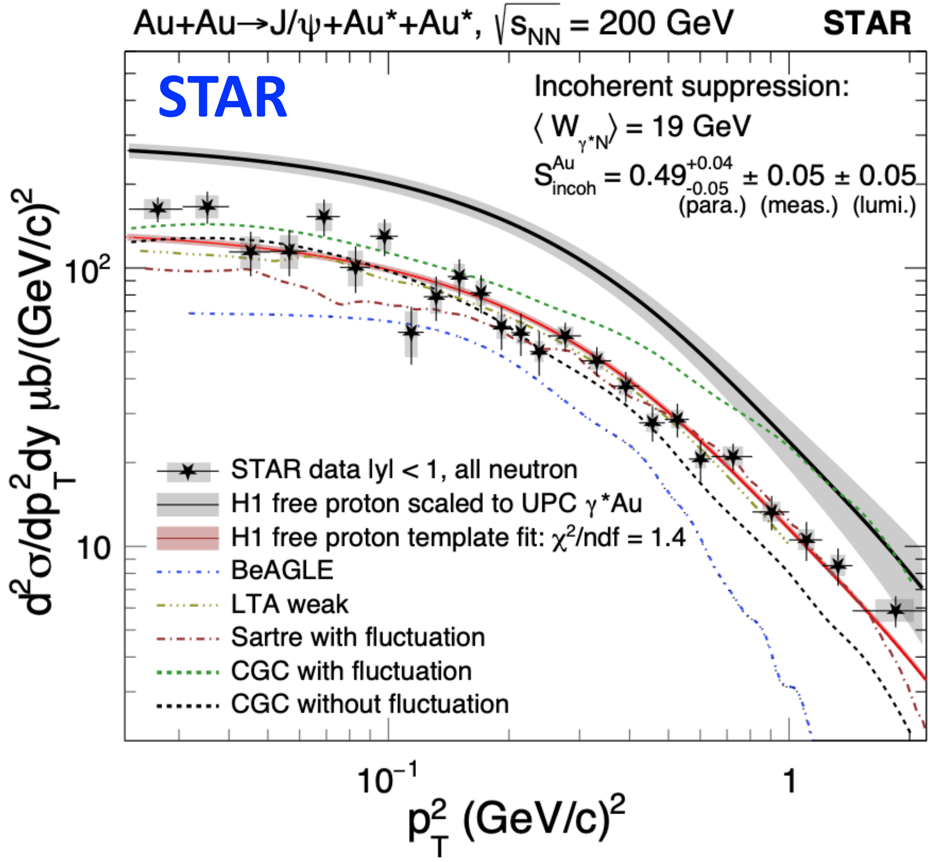
Thanks You!

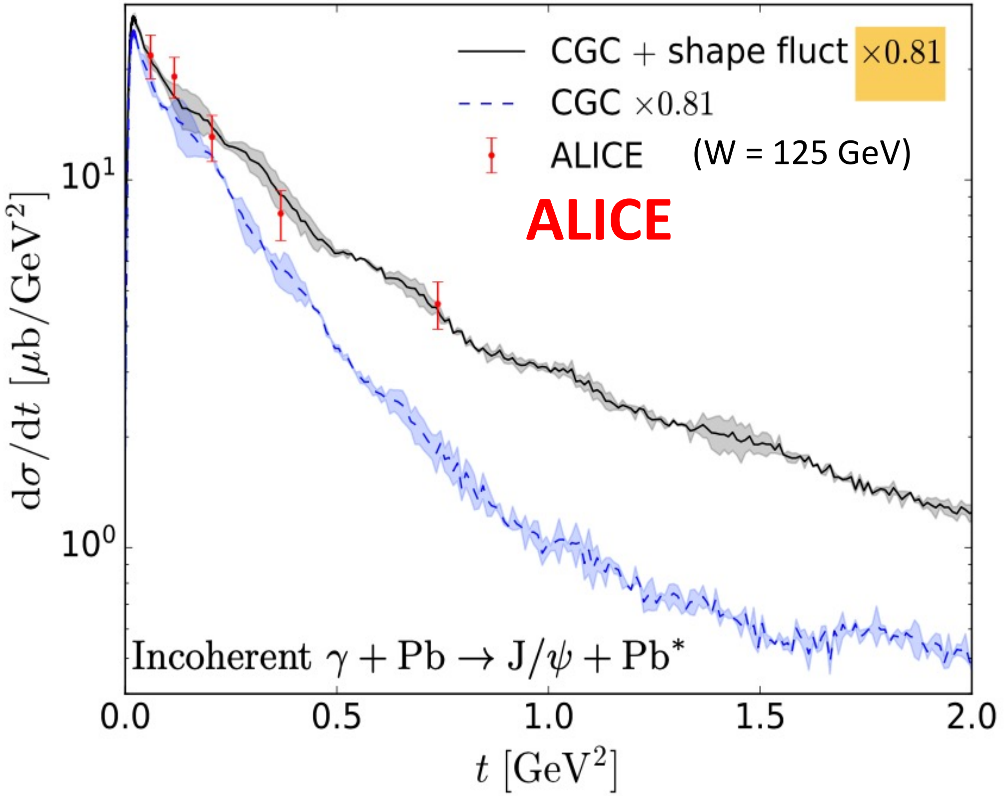
Backup Slides

Exlusive Upsilon(1S) via γ+p Interactions



Fluctuating Gluons Probed via Incoherent γ+Au/Pb





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

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

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

CPC 277 (2022) 108388

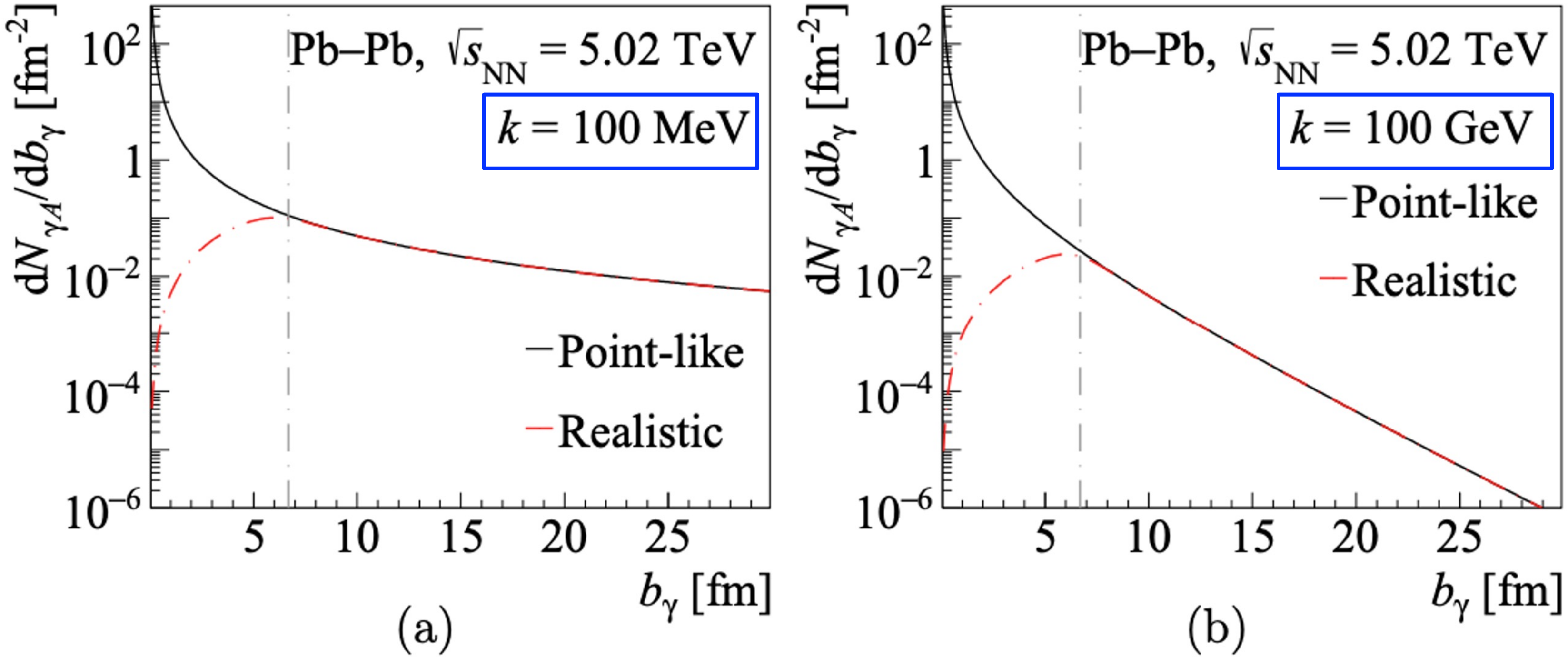
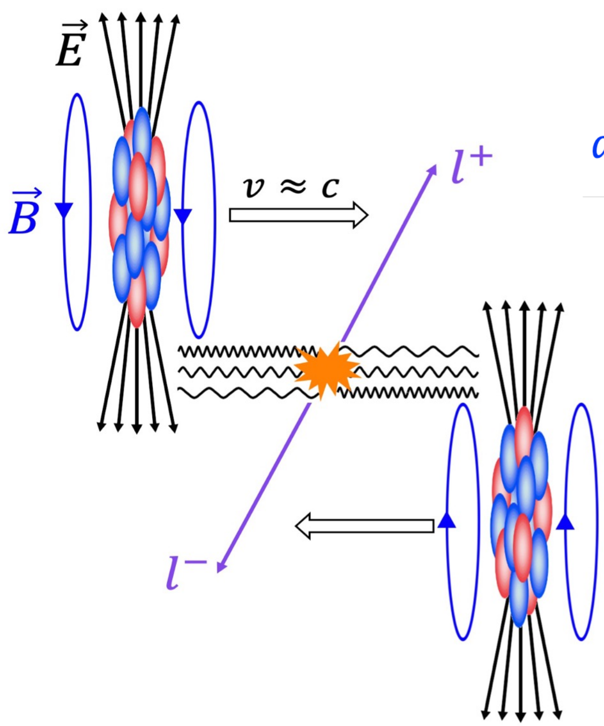


Figure 4: (Color online) Photon fluxes coming from a nucleus $N_{\gamma A}$ in the point-like source approximation and the realistic description as functions of impact parameter b_γ calculated at different photon energies: 100 MeV (a), 100 GeV (b).

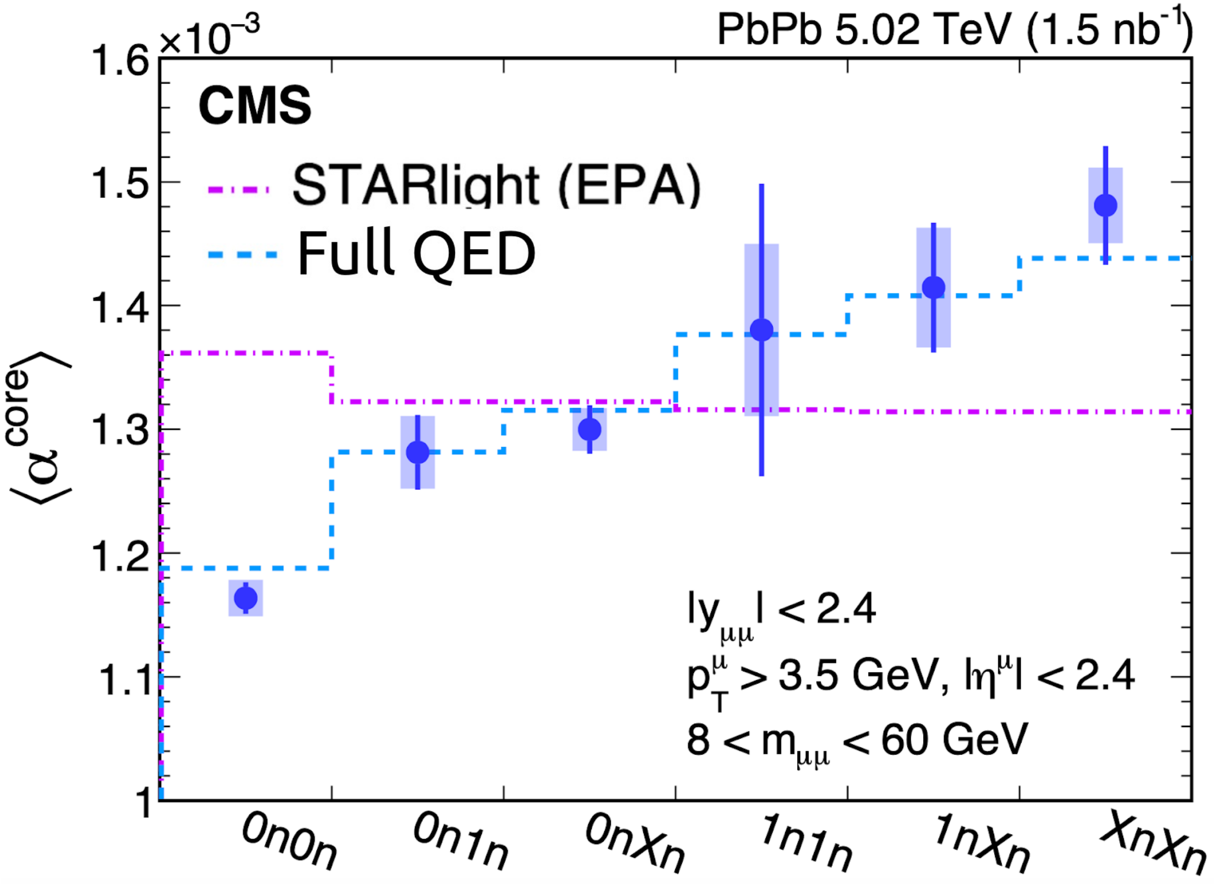
QED Dimuon with Neutron Tagging at CMS

PRL 127 (2021) 122001

$$\gamma\gamma \to \mu^+\mu^-$$



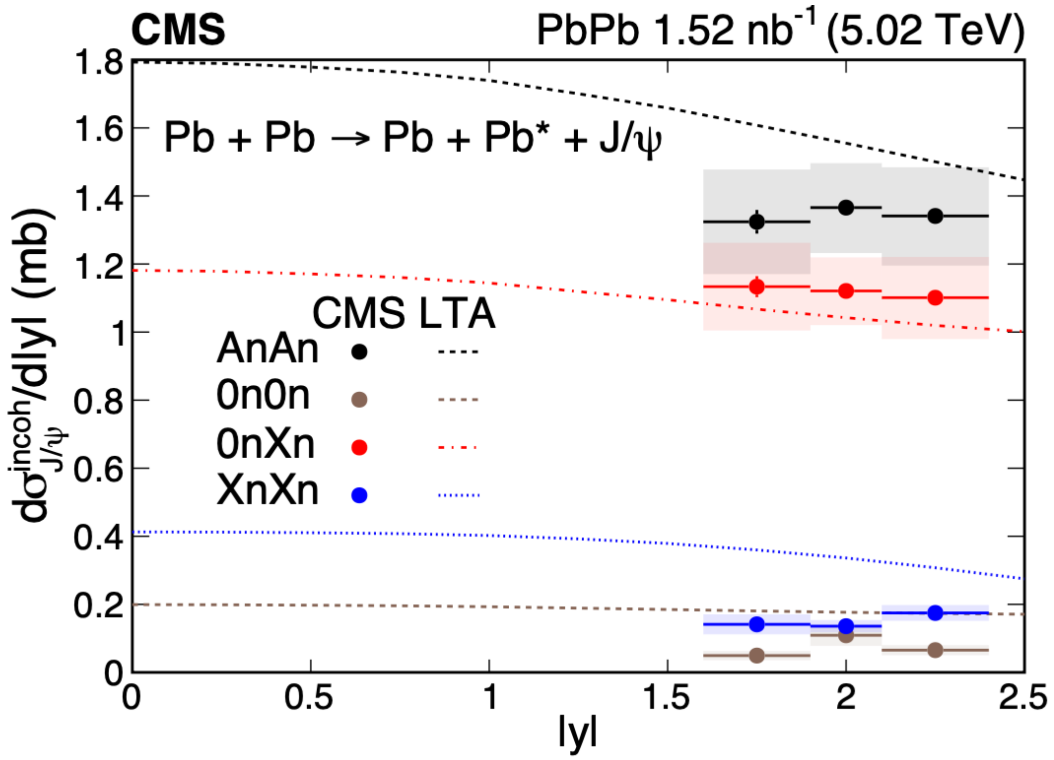
$$\alpha = 1 - \frac{|\phi^+ - \phi^-|}{\pi}, \alpha \propto p_T^{l^+l^-}$$

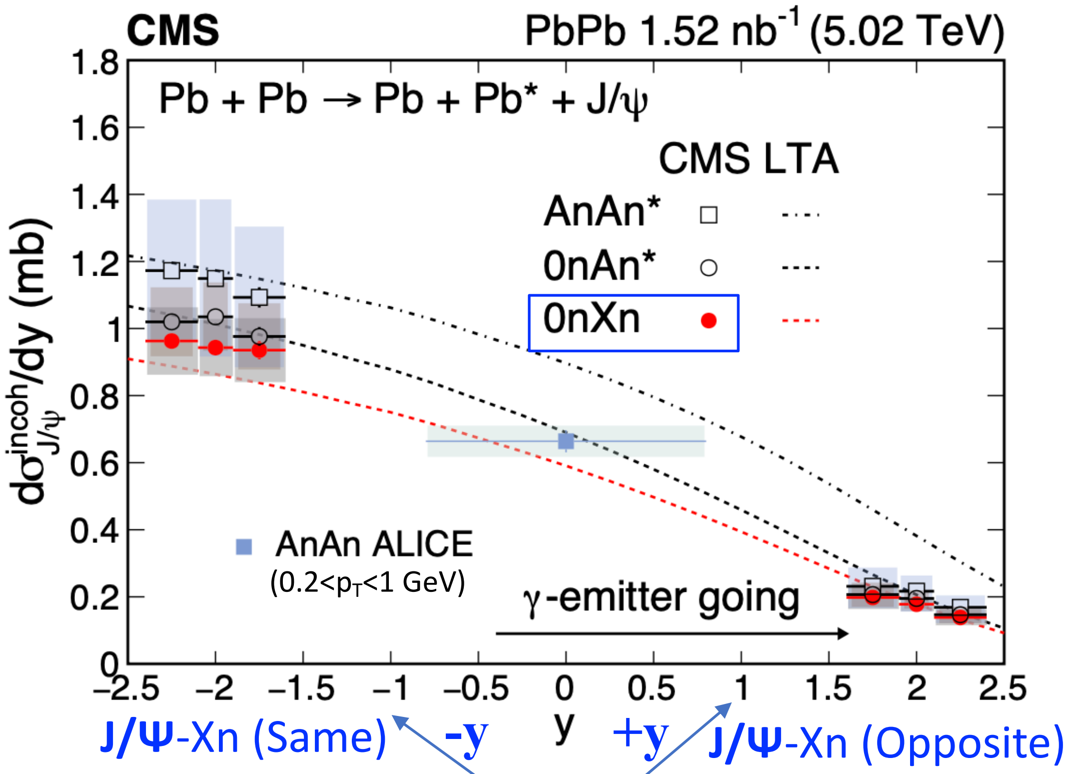


(X: ≥2)

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

Total InCoh. J/Ψ Photoproduction Cross Section





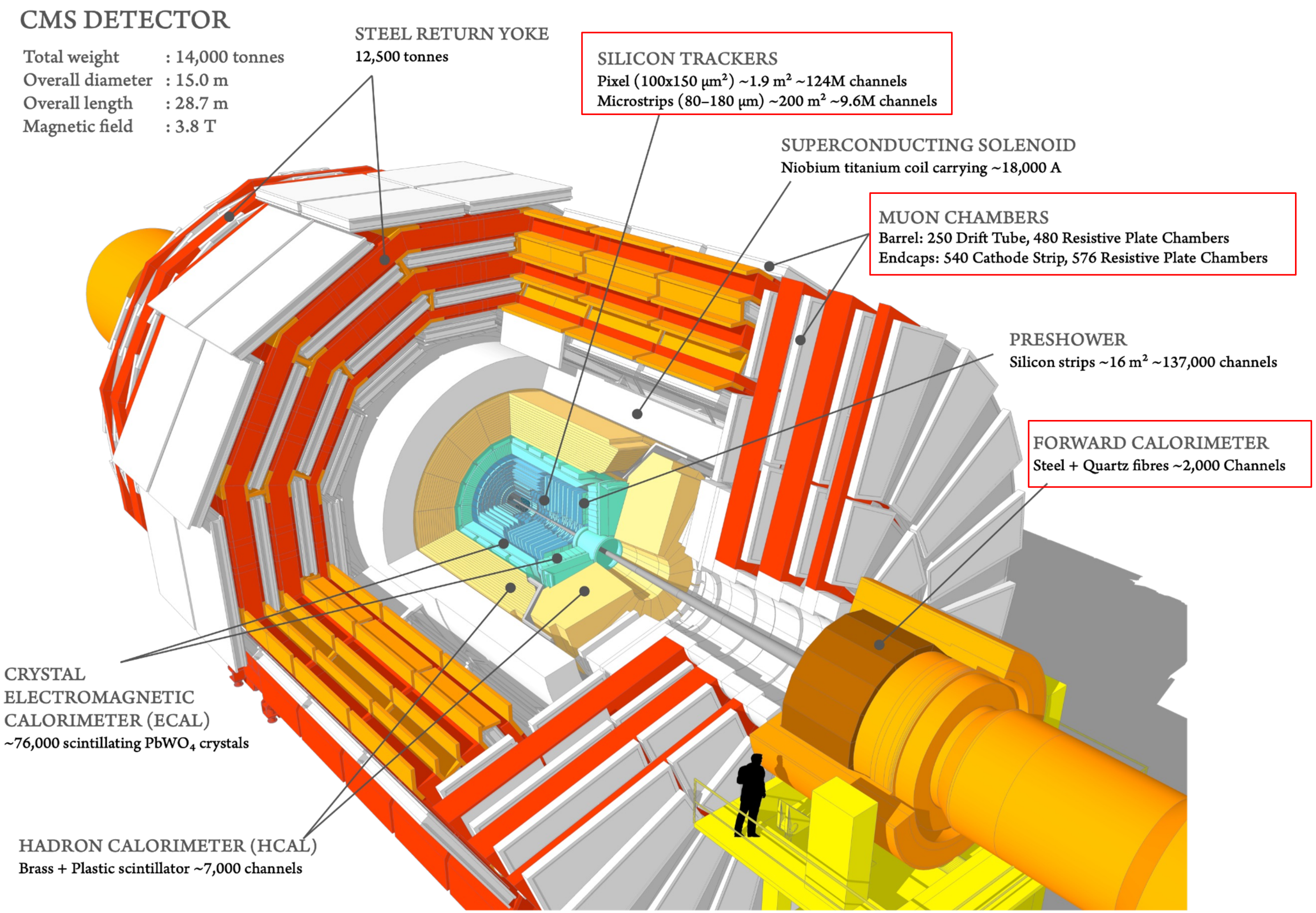
LTA: V. Guzey et al. PRC 108 (2023) 024904, PRC 99 (2019) 015201
ALICE: PRL 132, 162302 (2024)

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

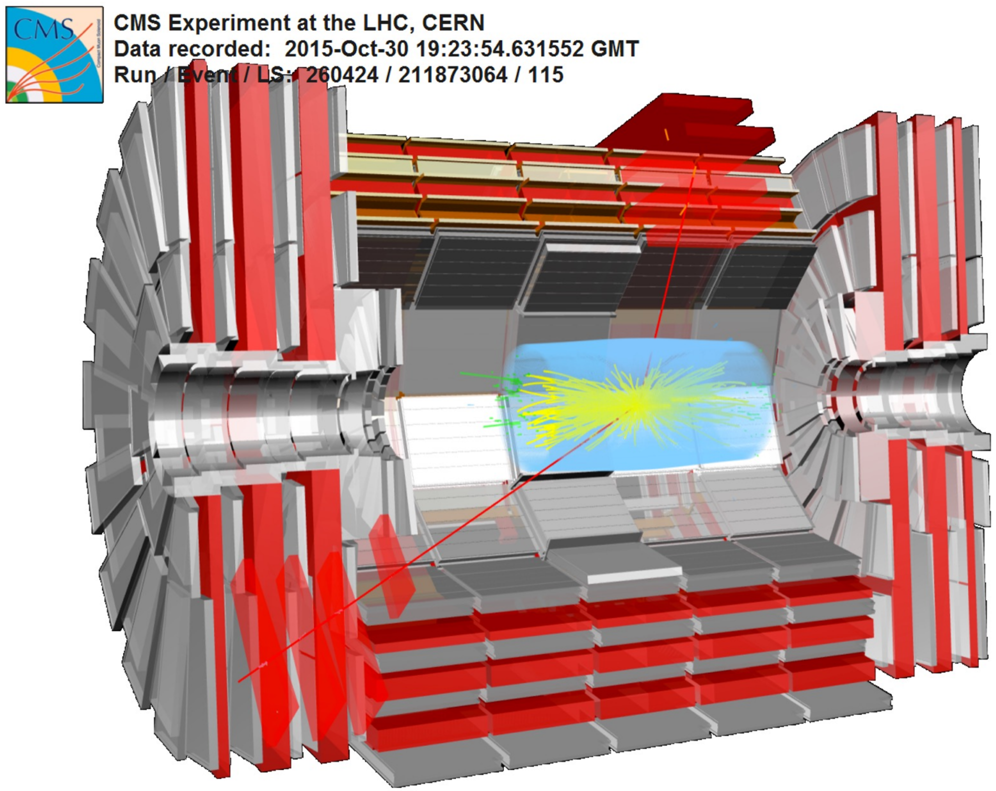
- 0nXn events: Data at (-y) are **5-6 times** of data at (+y) ➔ **Strong incoh. J/Ψ – Xn correlation**

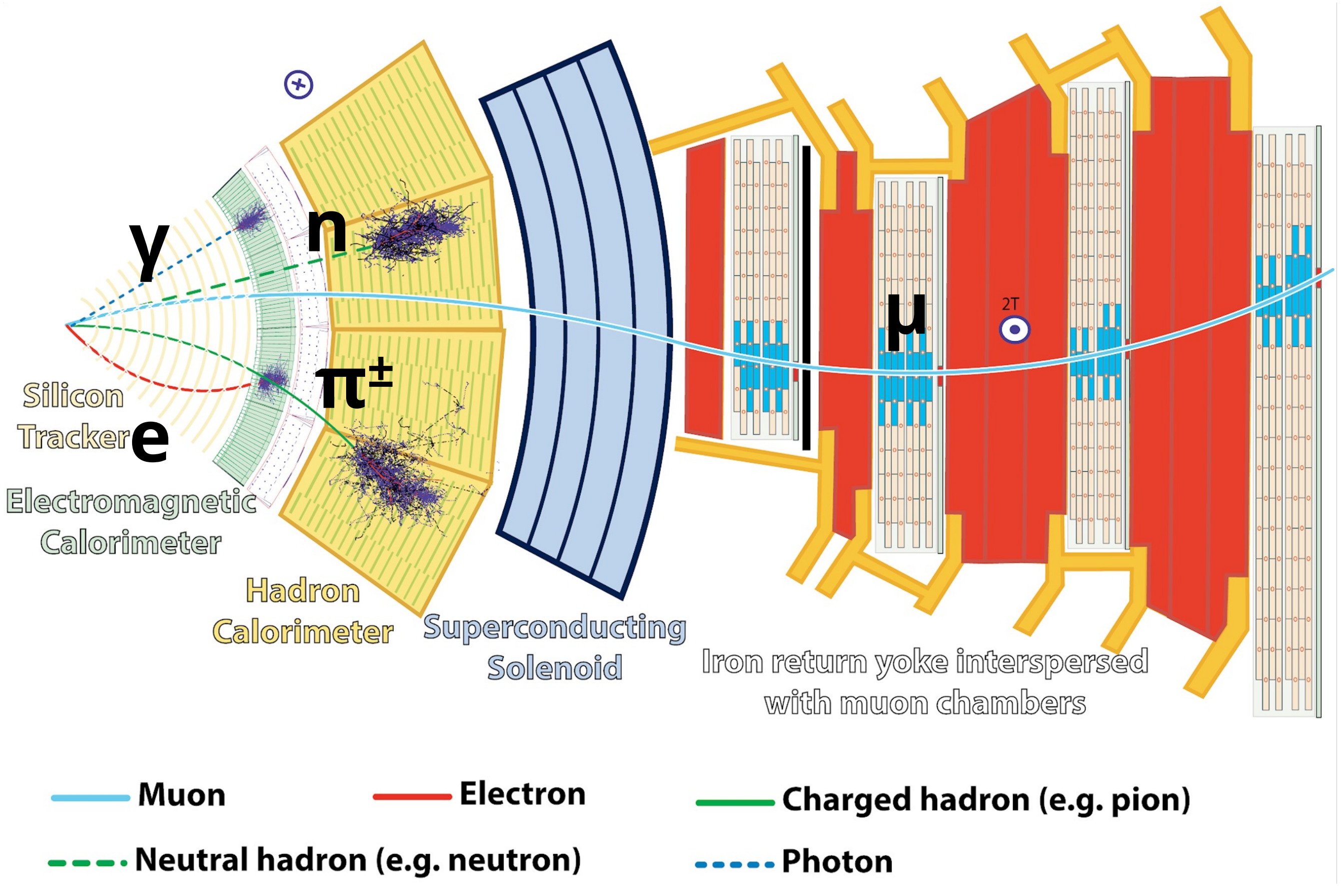
Relative fractions at (+y) and (-y) in 0n0n are asummed to be same as what measured in 0nXn events

Compact Muon Solenoid Detector



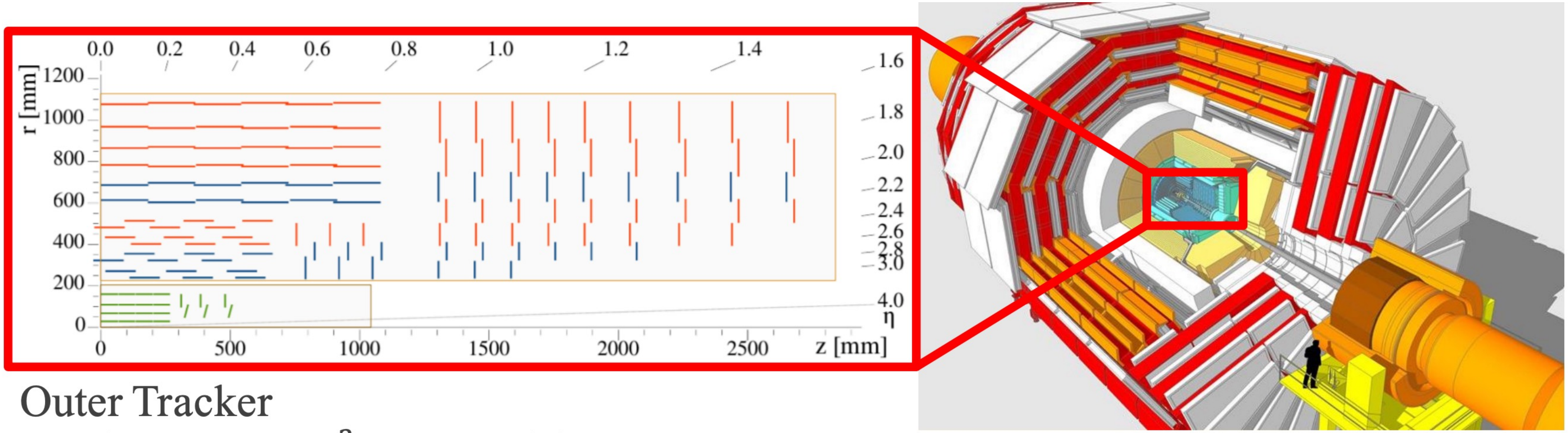
Muon Reconstruction





- Tracker and muon detectors used to reconstruct/identify muons.

CMS Tracker Run2-Run3

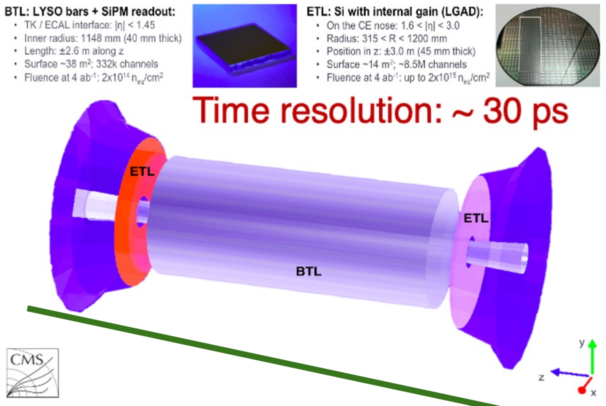


Outer Tracker

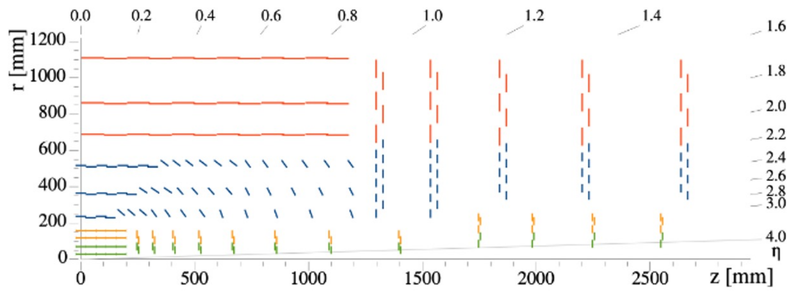
- Active area: 200 m^2,15148 modules
- 10 layers in barrel region
- 9 + 3 disks in inner disks and endcaps
- Orange: single sided module
- Blue: double sided module
- Analog readout

Future Opportunities

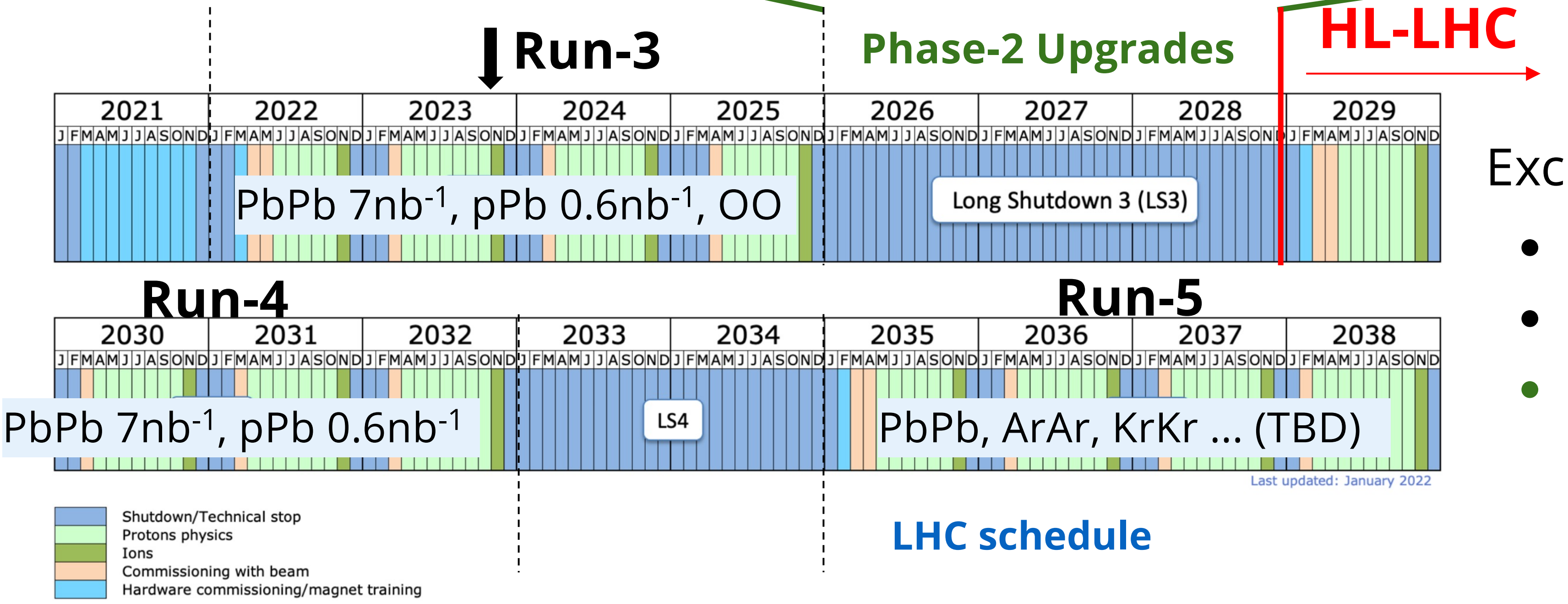
MIP Timing Detector for PID



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!