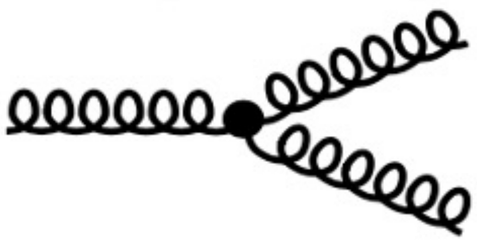
Recent Small-*x* Physics Results from CMS

Zaochen Ye (SCNU)

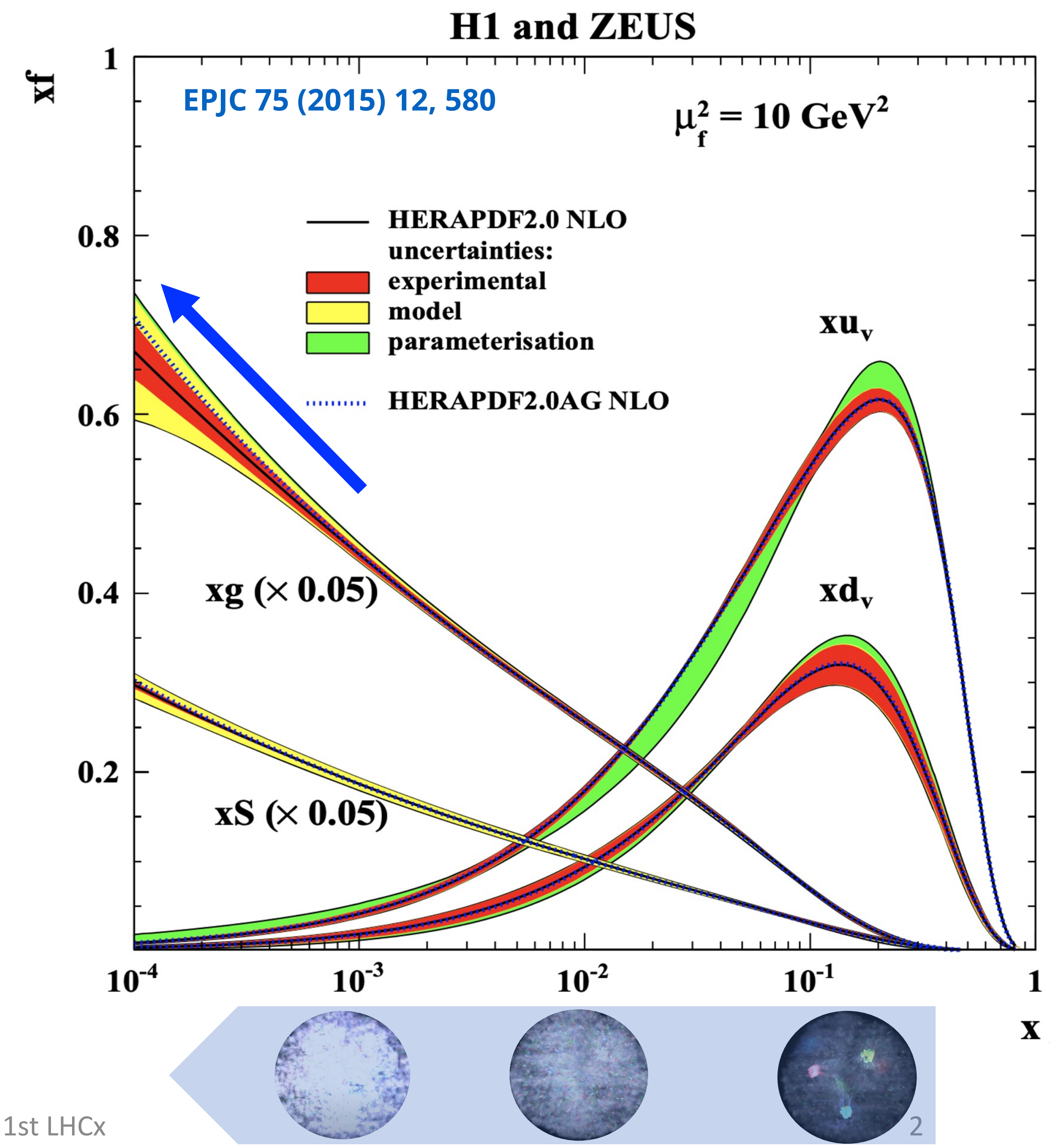
July 07, 2026

Understand Nucleon Structure

Splitting



$\sim N_g$ (linear)



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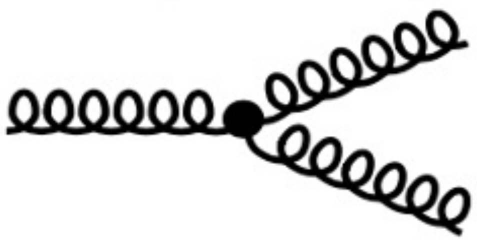

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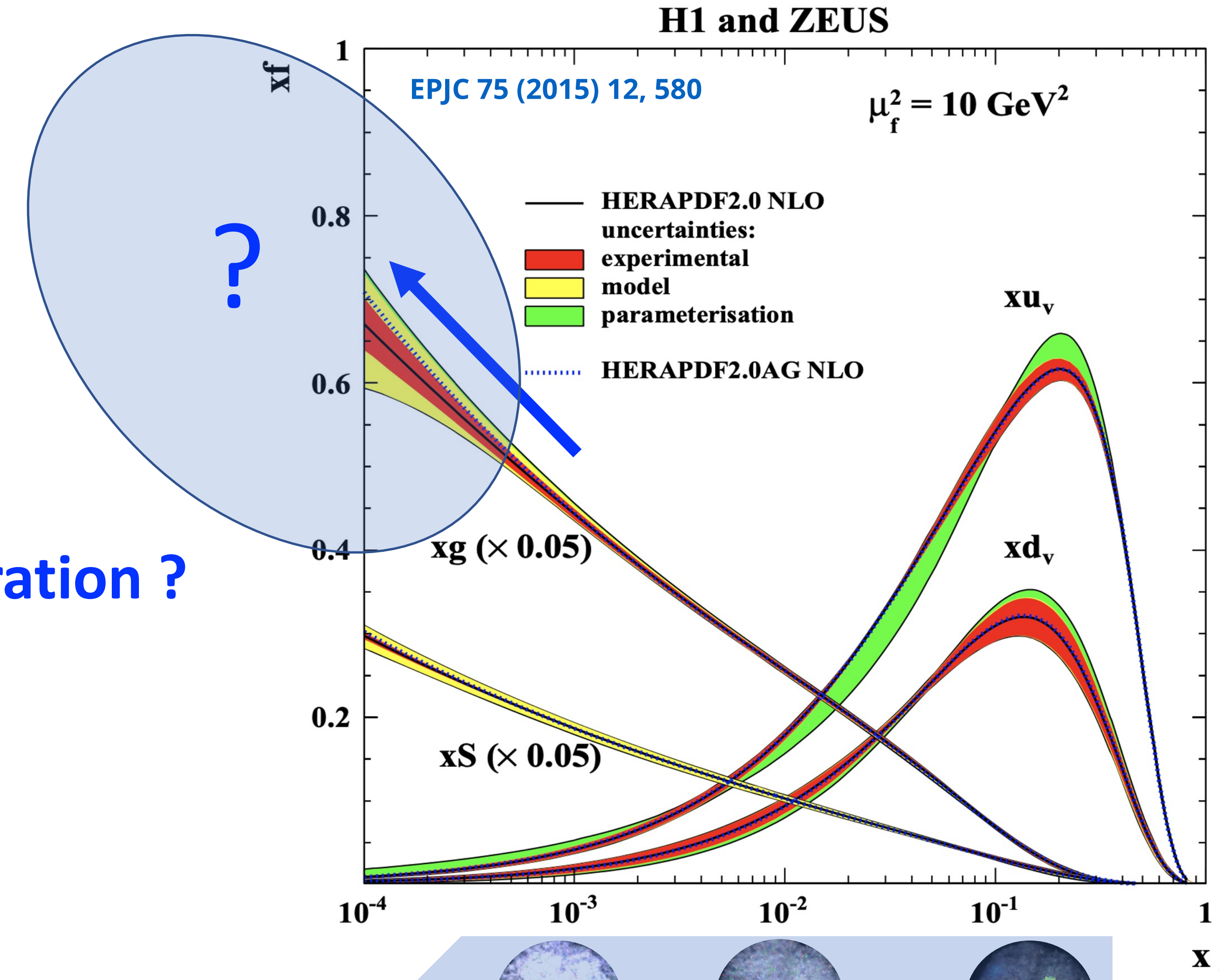
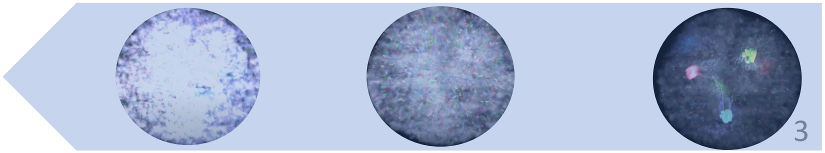


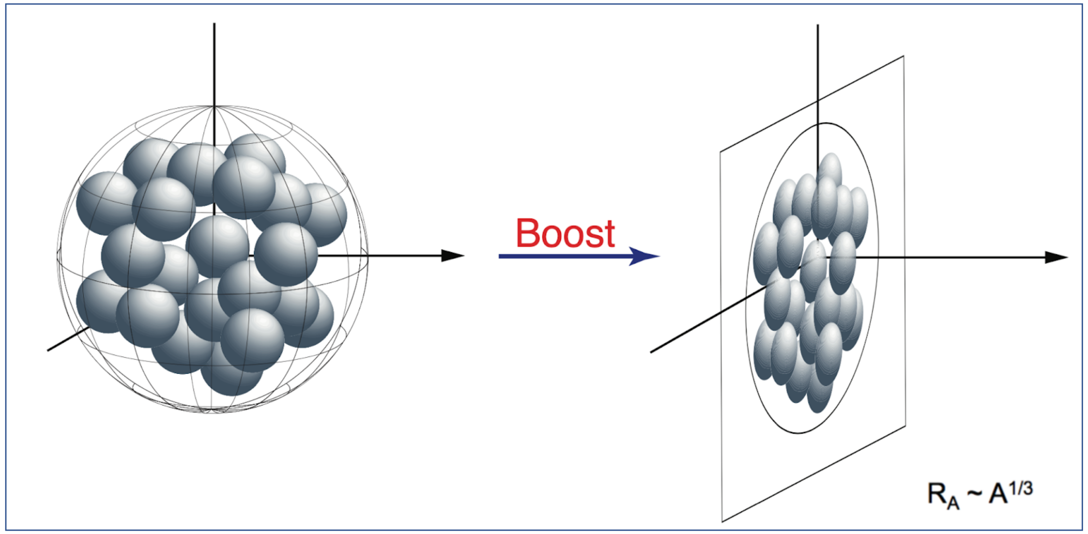


Gluon Saturation ?

Recombination

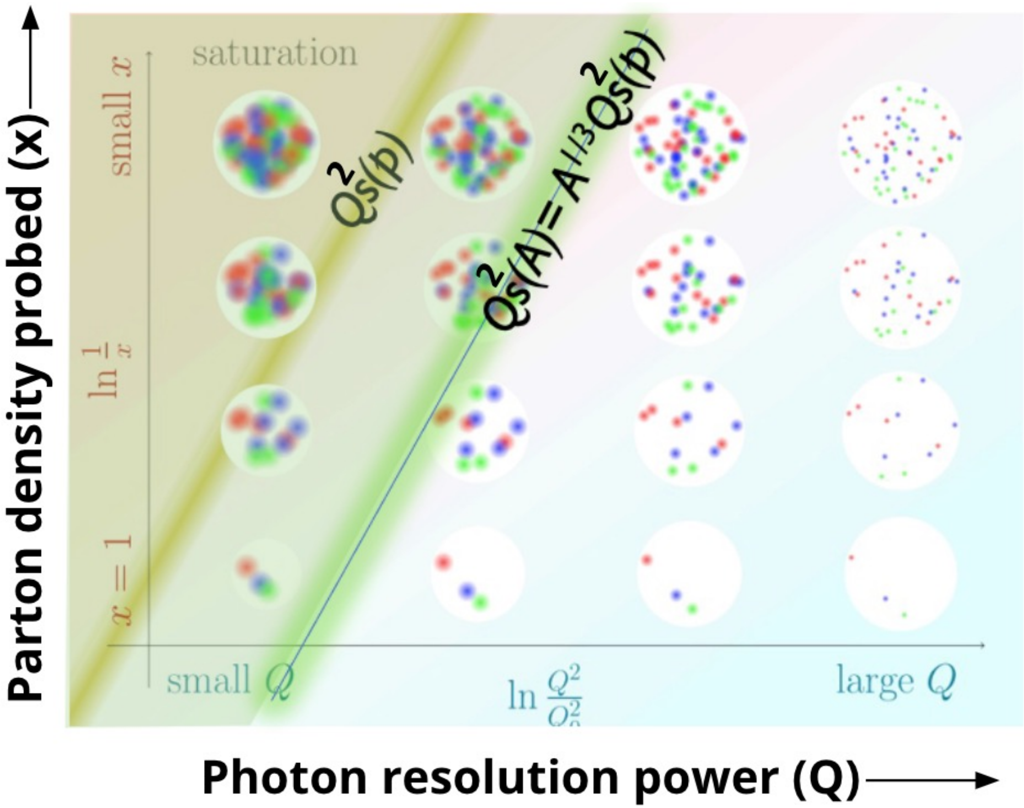
$\sim (N_g)^2$(nonlinear)

Advantages of Gluon Saturation Search in Nucleus



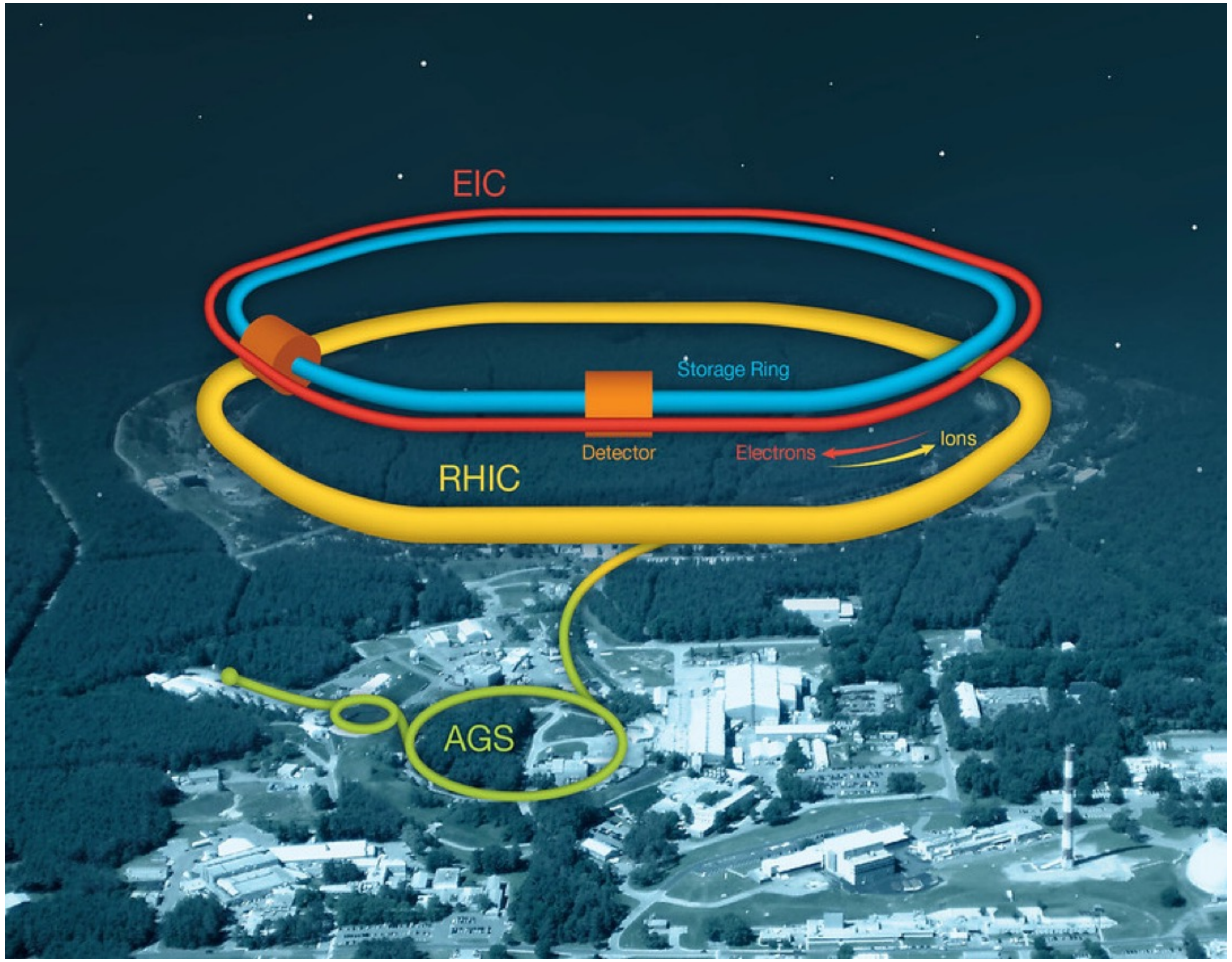
Gluons is **enhanced** by a factor of $A^{1/3}$ in **nucleus** compared to what in free nucleon

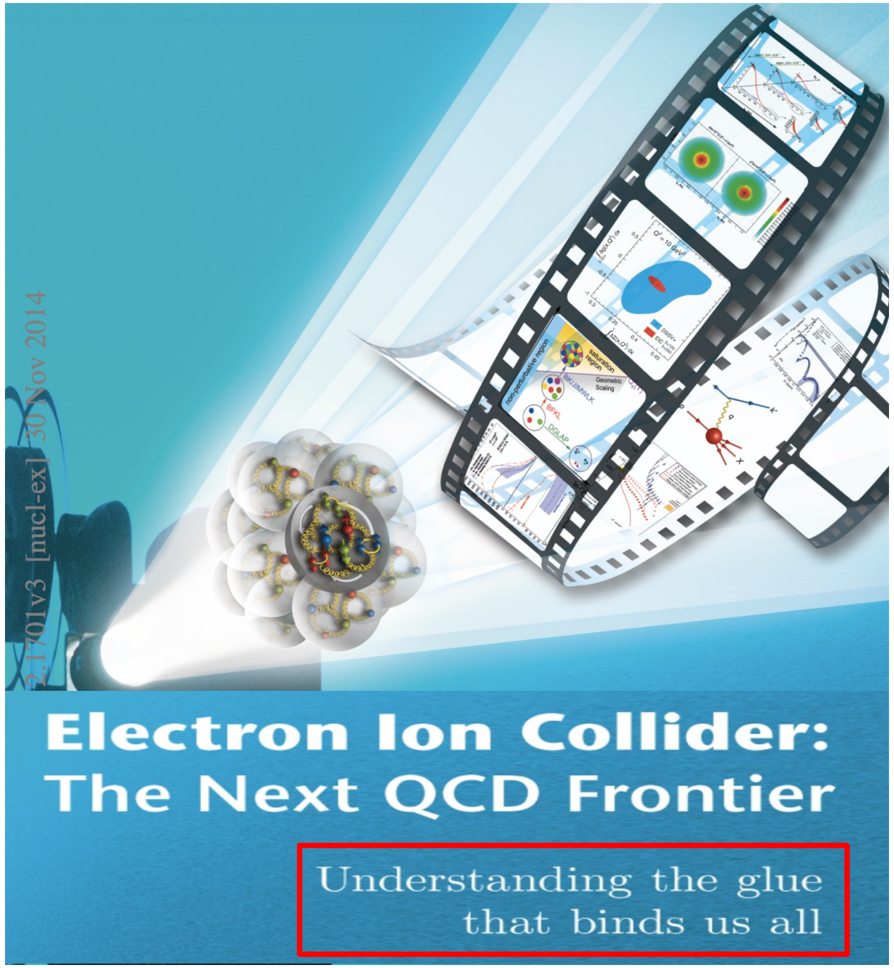
$$Q_s^2 \sim A^{1/3} \left(\frac{1}{x}\right)^{\lambda}$$



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

Key Goal of Future Electron Ion Collider

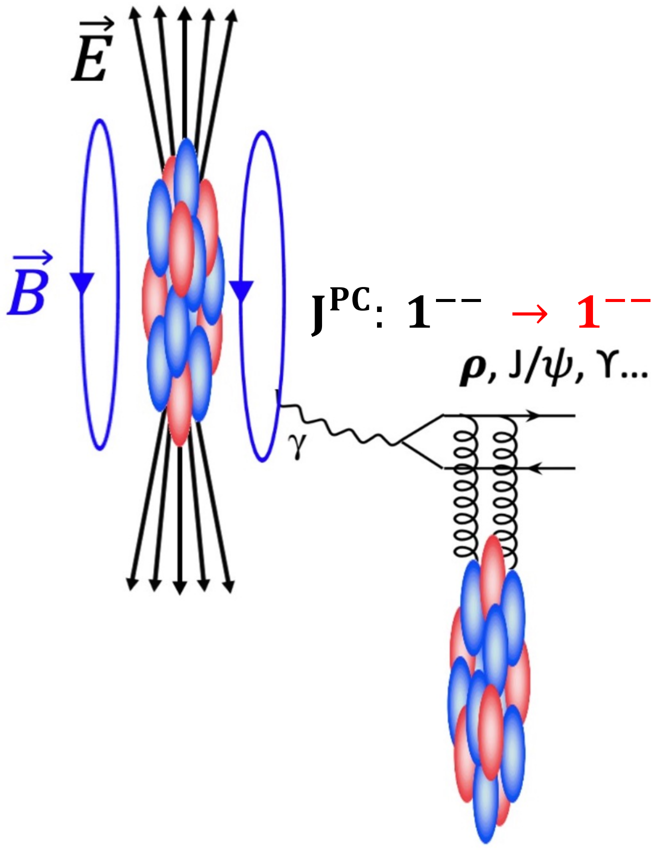




Probe Nuclear Gluonic Structure via VMs in UPCs

Vector meson photoproduction directly probes gluonic structure of nucleus/nucleon

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



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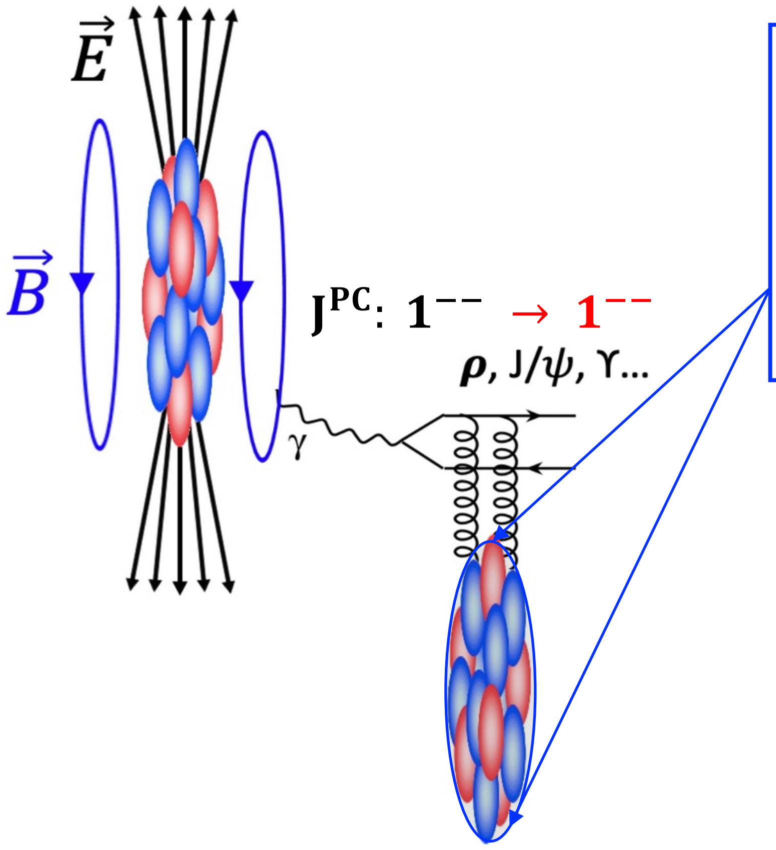

Coherent production:

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

Probe Nuclear Gluonic Structure via VMs in UPCs

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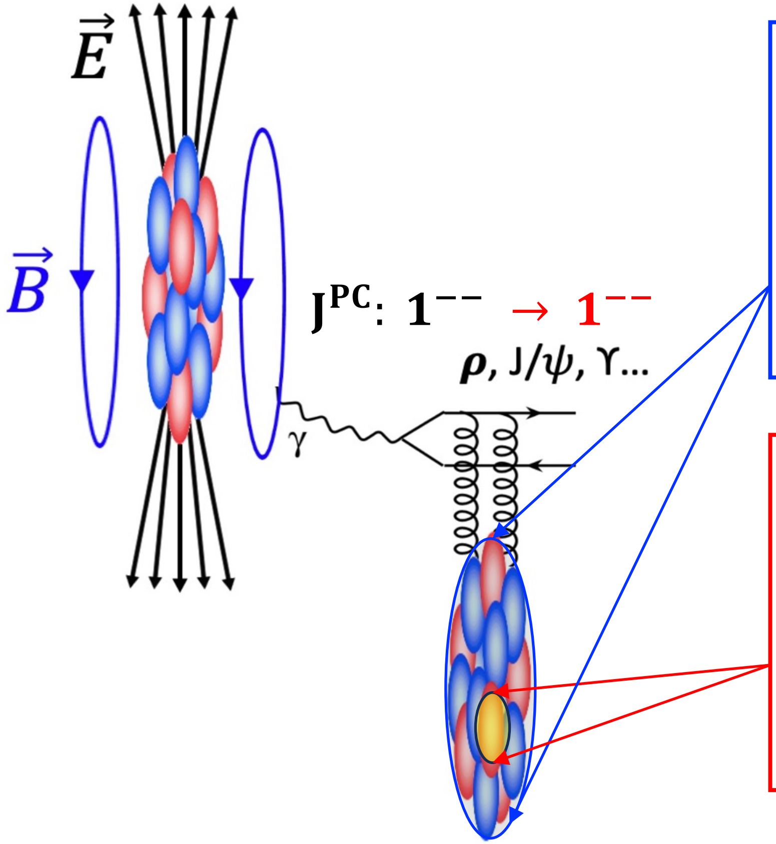


Coherent production:

- Photon fluctuated dipole couples **coherently to entire nucleus**
- **Target** nucleus remains **intact** at ground state
- VM <p_T> ~ **10^1 MeV**
- Probing the **average gluon density**

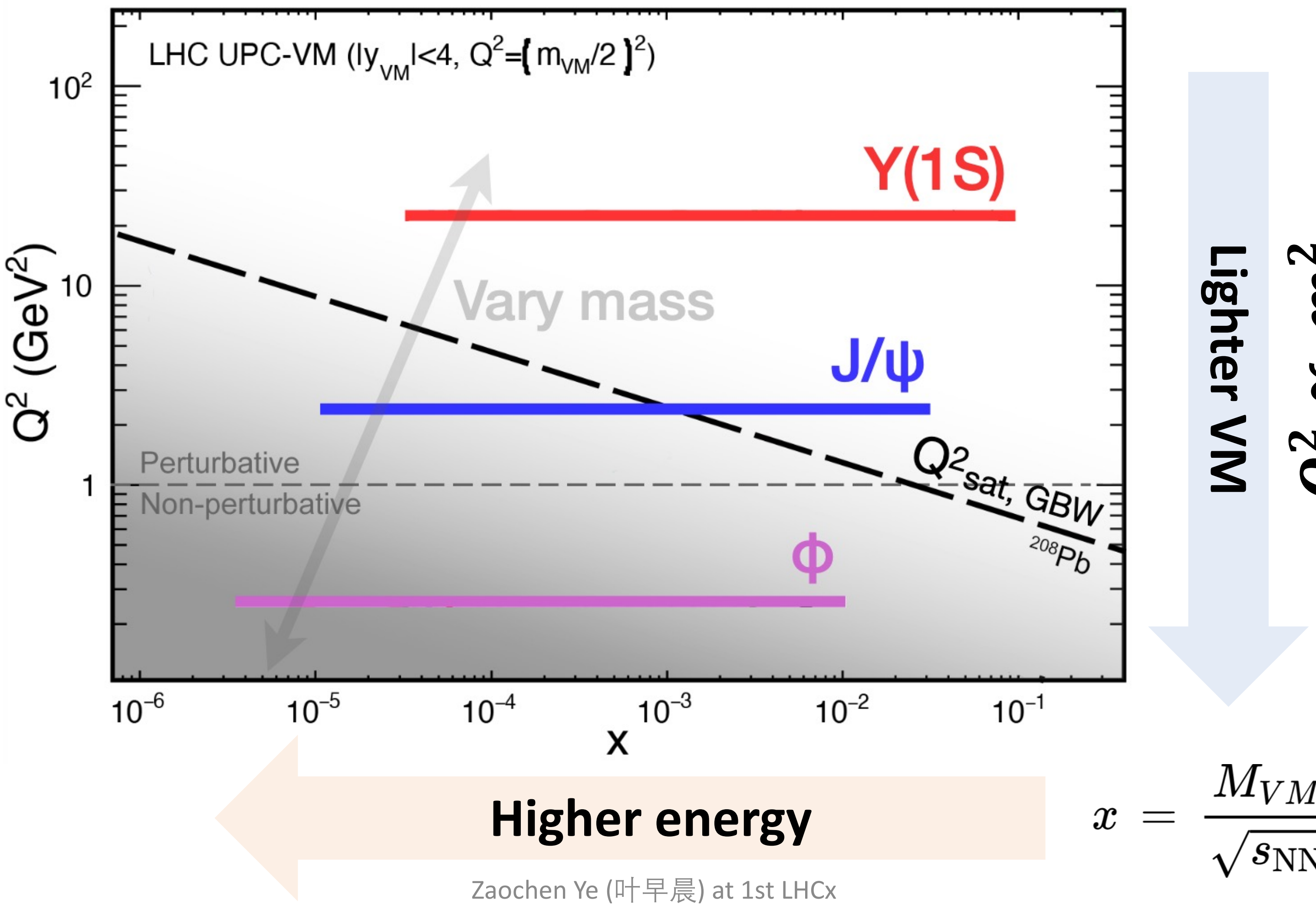
Incoherent production:

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

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

Probe Nuclear Gluonic Structure via VMs in UPCs

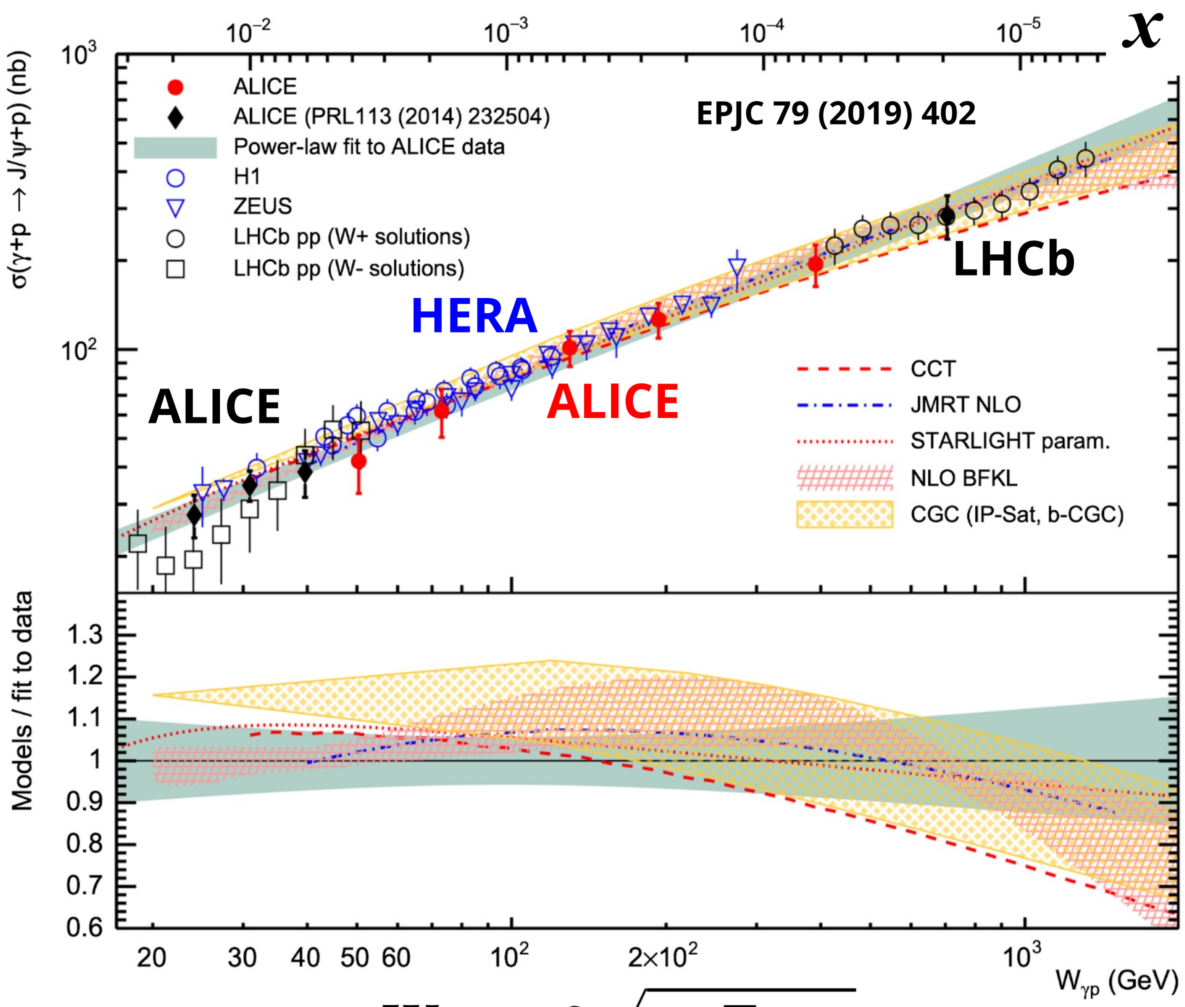
Explore in 2 dimensions: Q^2 vs. x



$Q^2 \propto m_{VM}^2$

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

Coherent J/Ψ Photoproduction via $\boldsymbol{\gamma + p}$ (Free Nucleon)



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

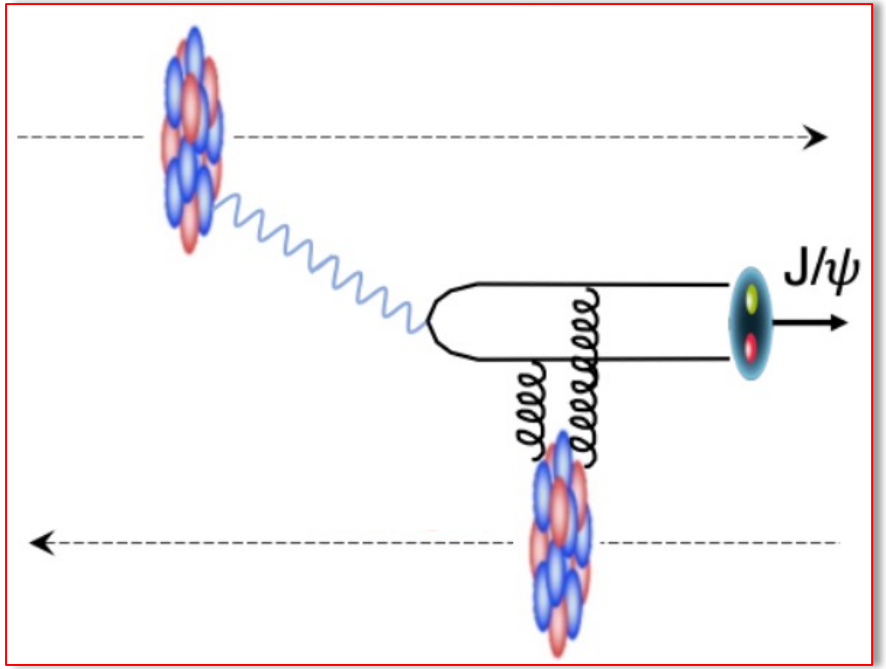
$$\gamma + p \rightarrow J/\psi + p$$

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

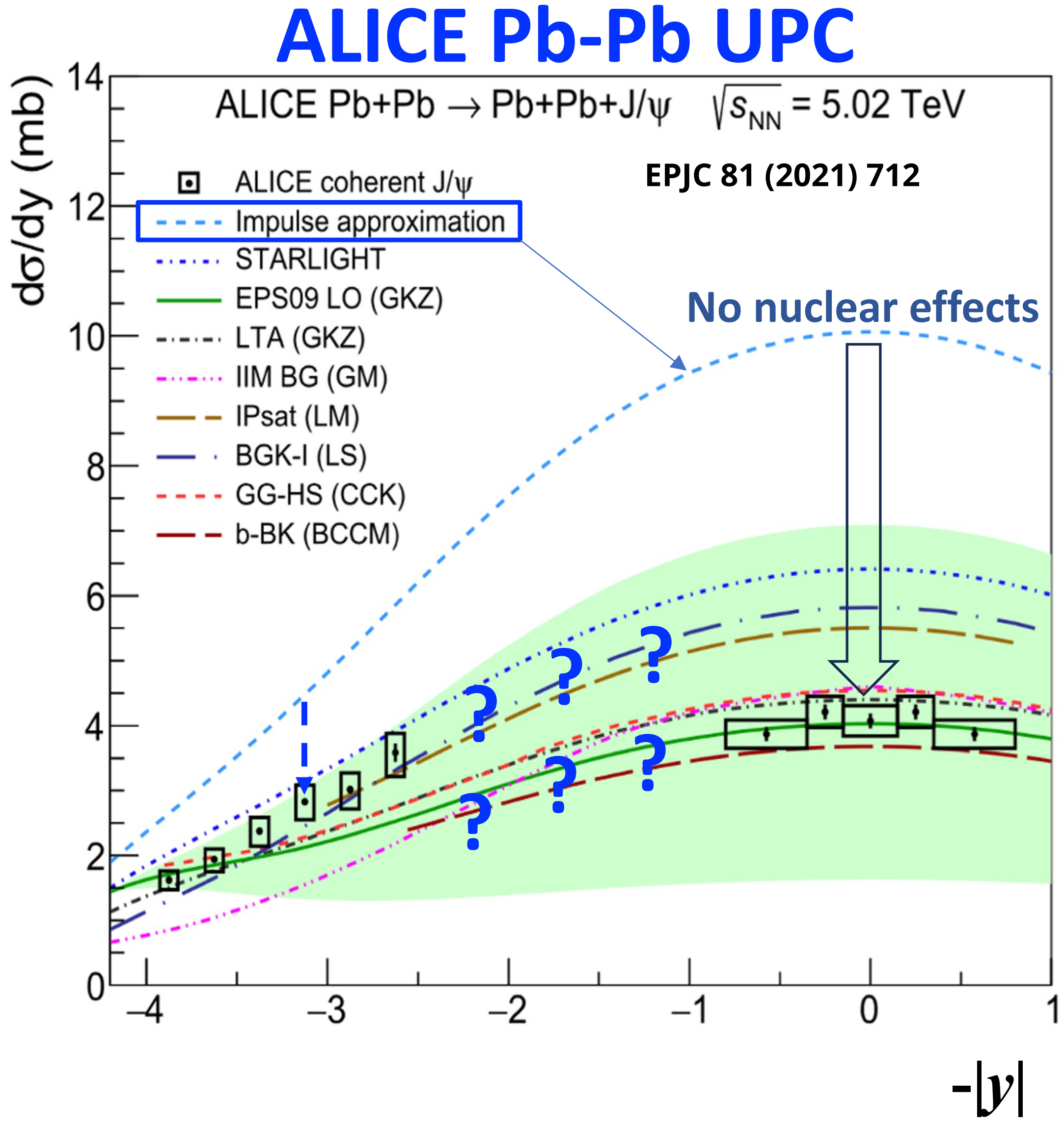
No clear indication of gluon saturation, even down to x~10^{-5} in a free nucleon!

Coherent J/Ψ Photoproduction in A-A UPCs

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

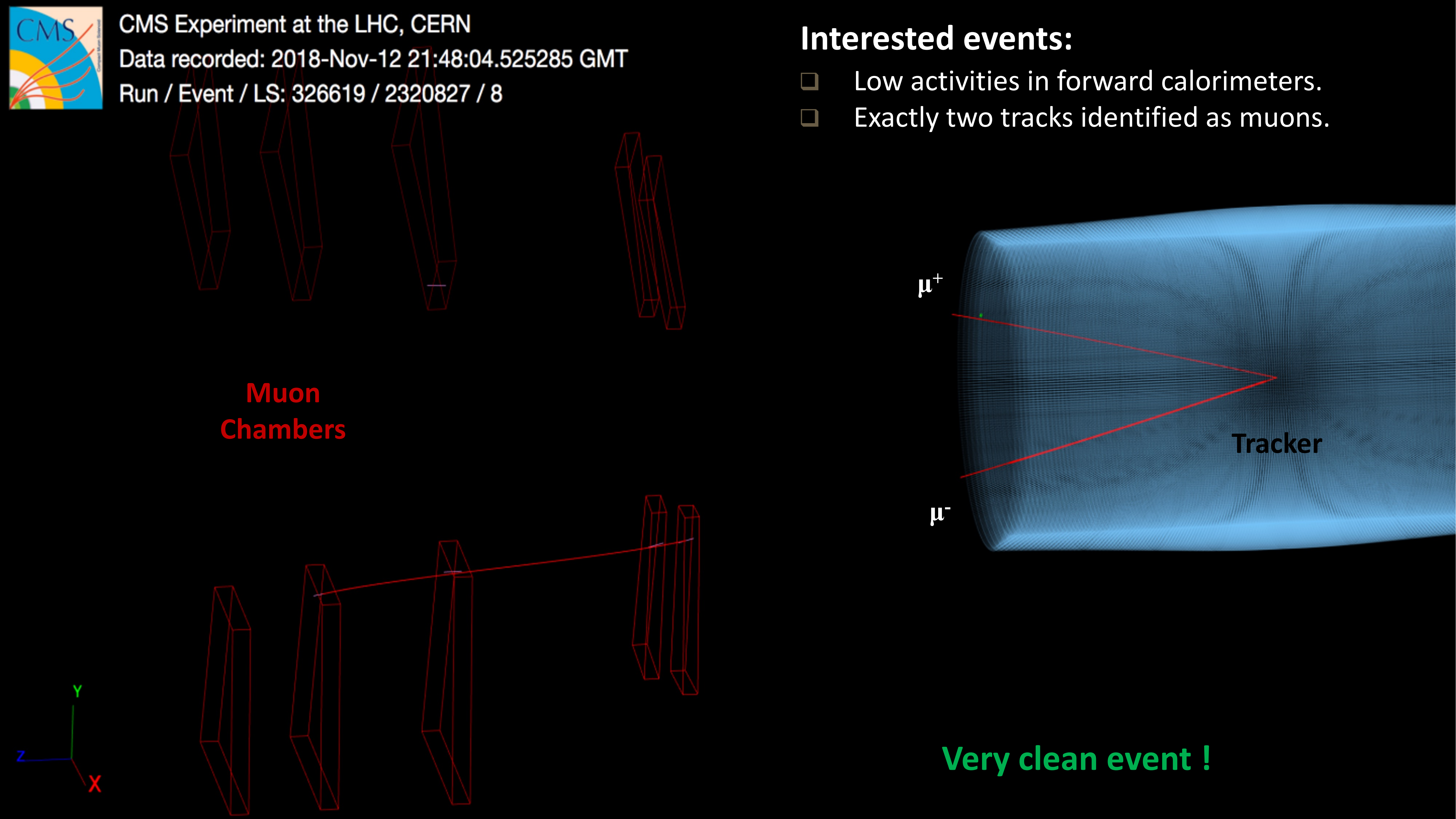


- **Strong suppression**, but the rapidity distribution was **a puzzle**



Interested events:

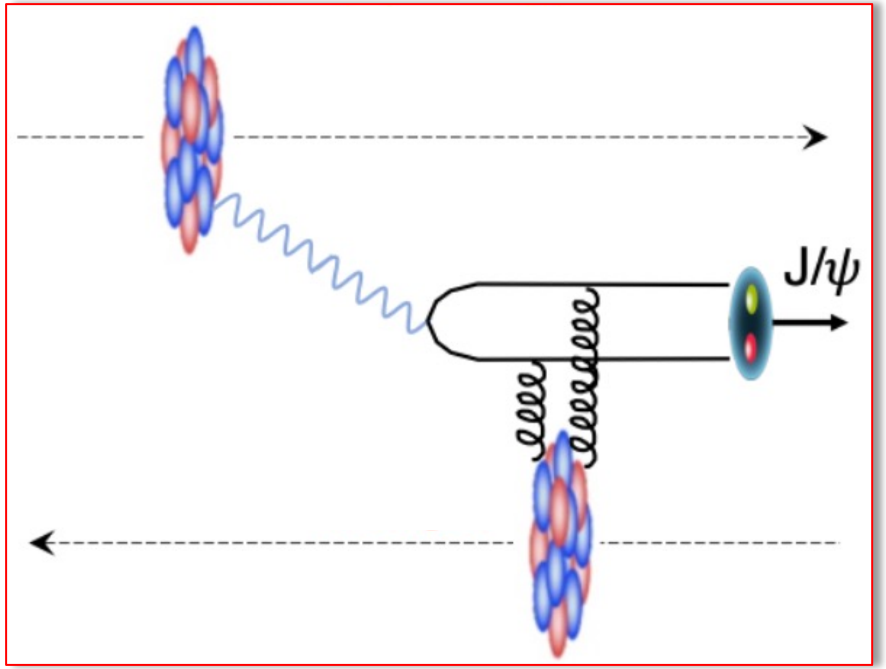
- ❑ Low activities in forward calorimeters.
- ❑ Exactly two tracks identified as muons.



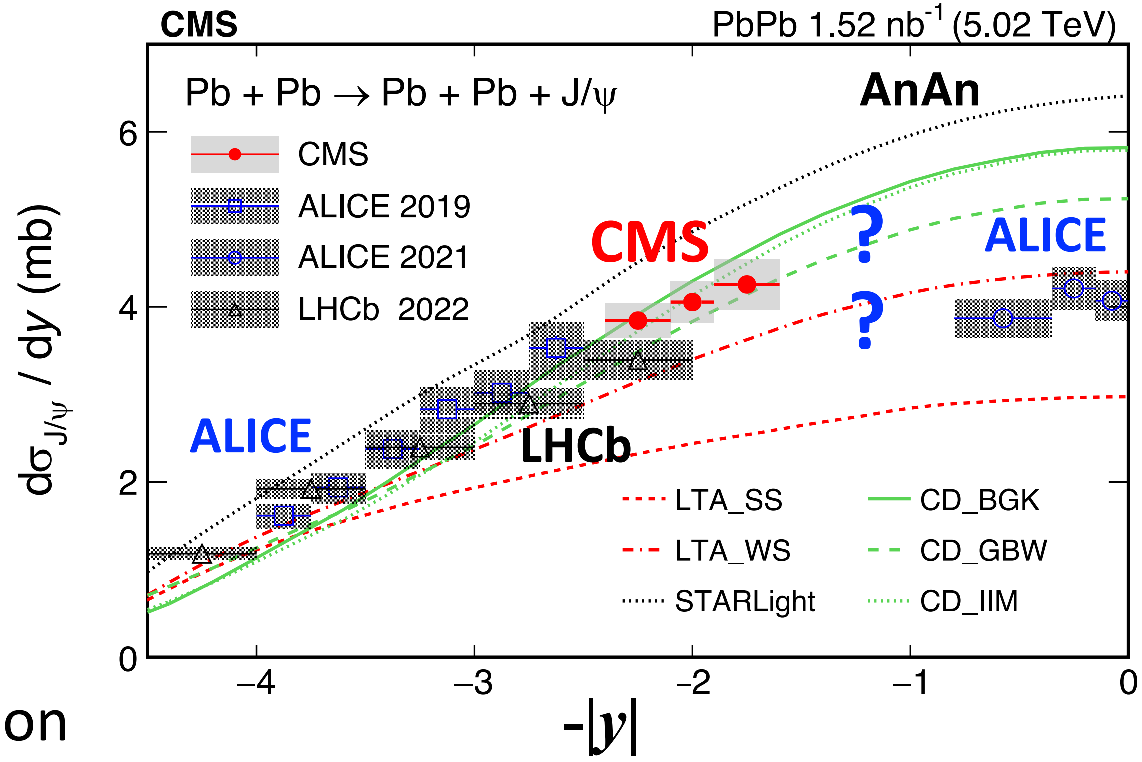
Very clean event !

Coherent J/Ψ Photoproduction in A-A UPCs

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



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



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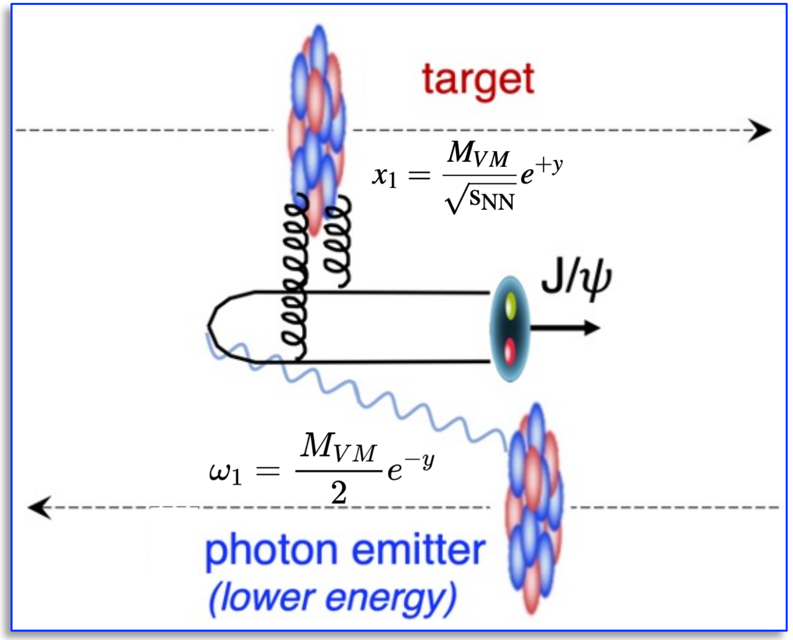
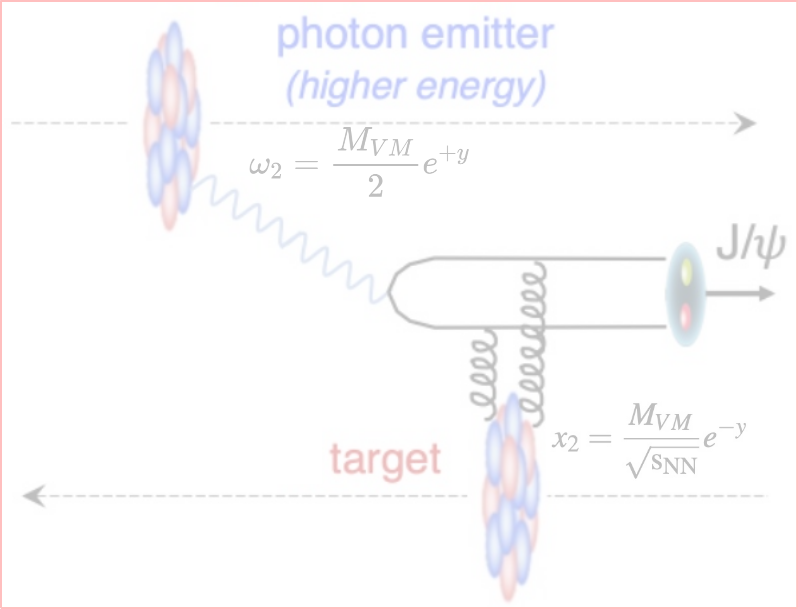
Two-Way Ambiguity in A-A UPC



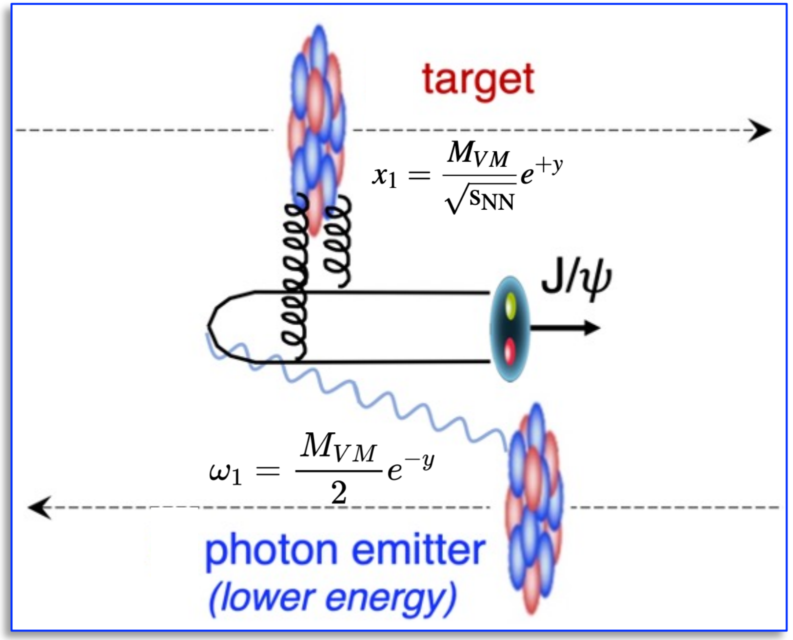


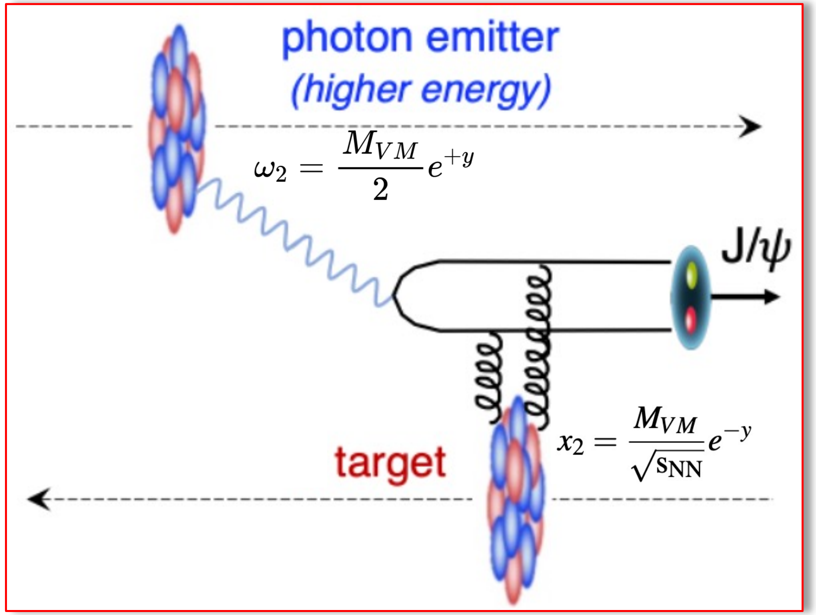
what we measure

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

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

Two-Way Ambiguity in A-A UPC





what we measure

Smaller-x

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

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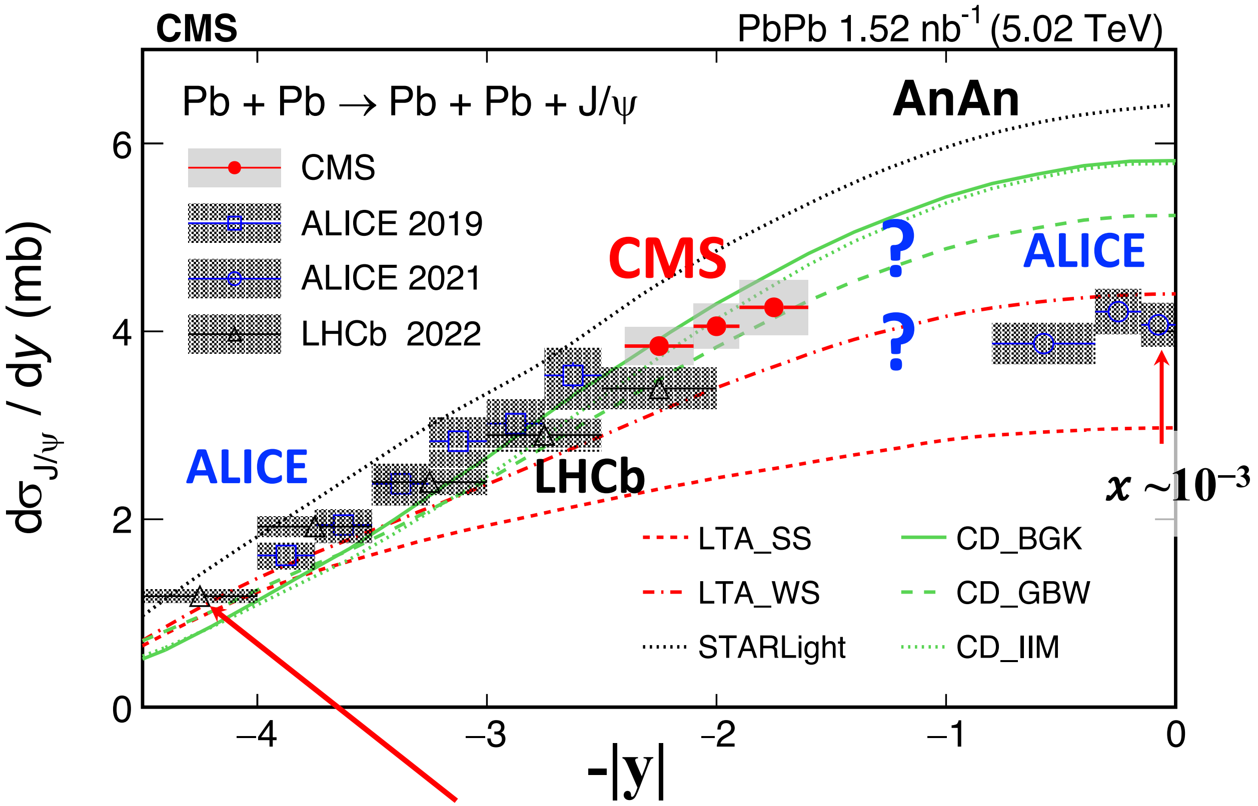
Two-Way Ambiguity in A-A UPC



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

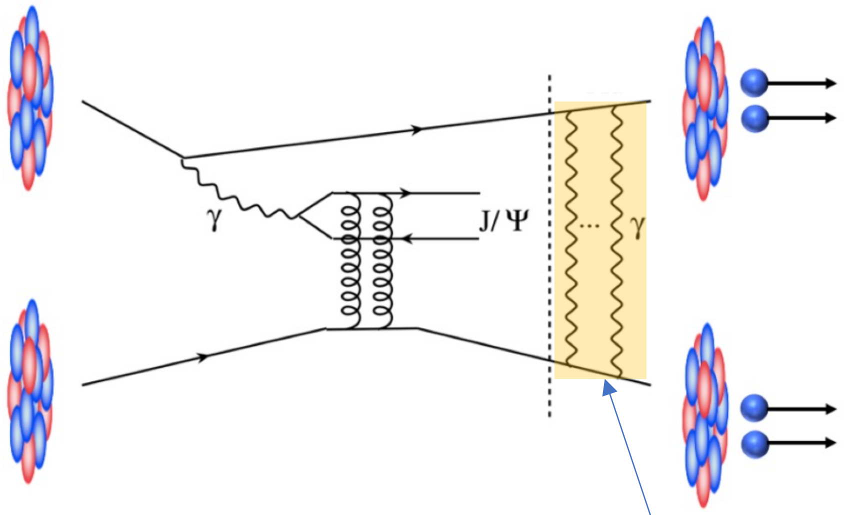
x_1 ~10^{-5} or x_2 ~10^{-2} (~95%)

low-energy photons dominant

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

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

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



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

Neutron emission via EMD with additional photon exchange:

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

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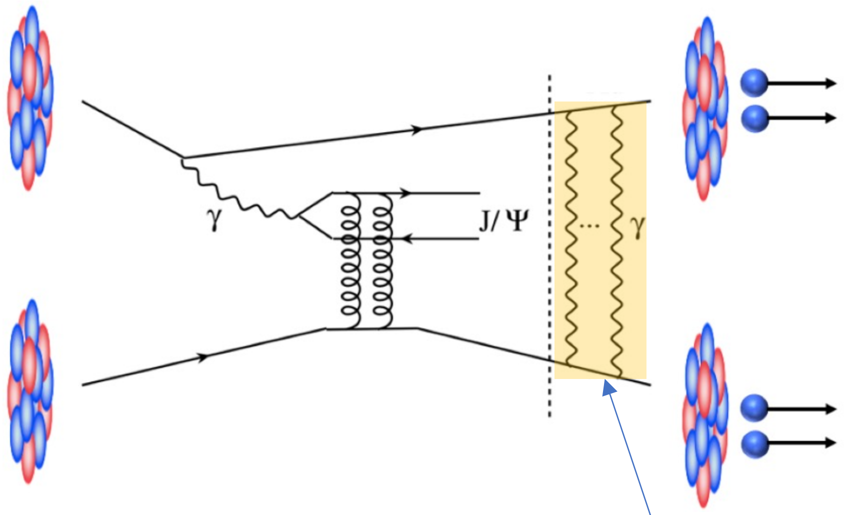

$$\frac{d\sigma^{0nXn}_{AA\to AA'J/\psi}}{dy} = \boxed{N^{0nXn}_{\gamma/A}(\omega_1)} \cdot \sigma_{\gamma A\to J/\psi A'(\omega_1)} + \boxed{N^{0nXn}_{\gamma/A}(w_2)} \cdot \sigma_{\gamma A\to J/\psi A'(w_2)}$$

from theoretical calculation

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

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

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

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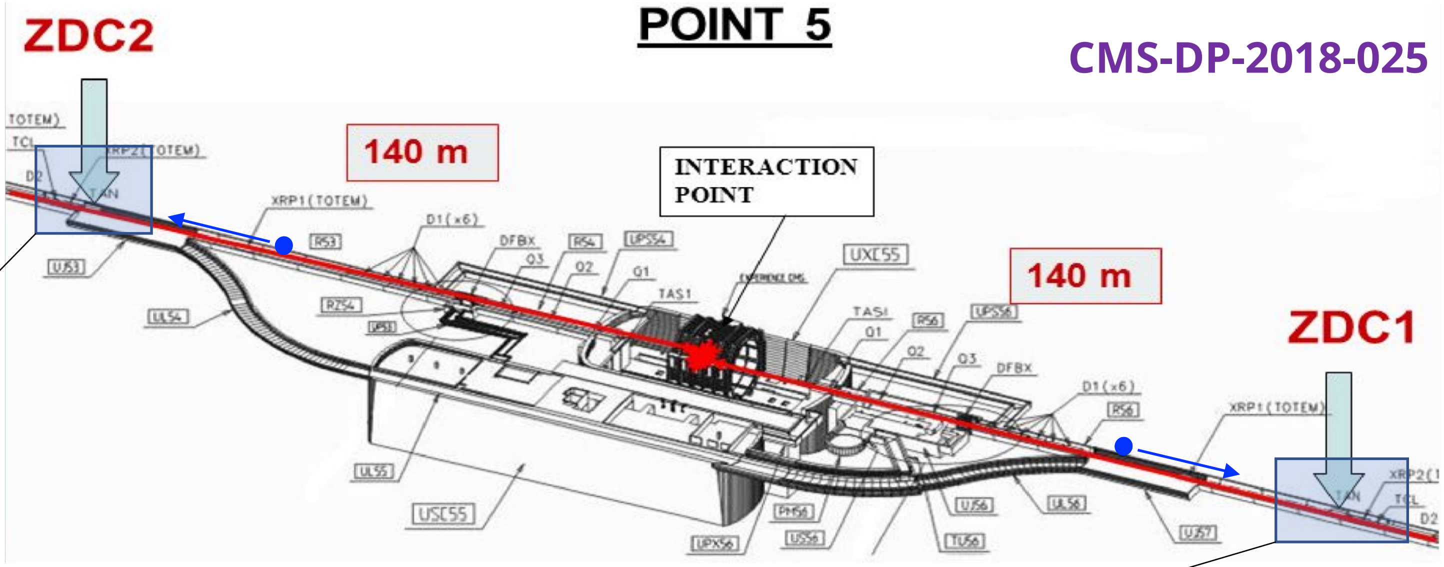
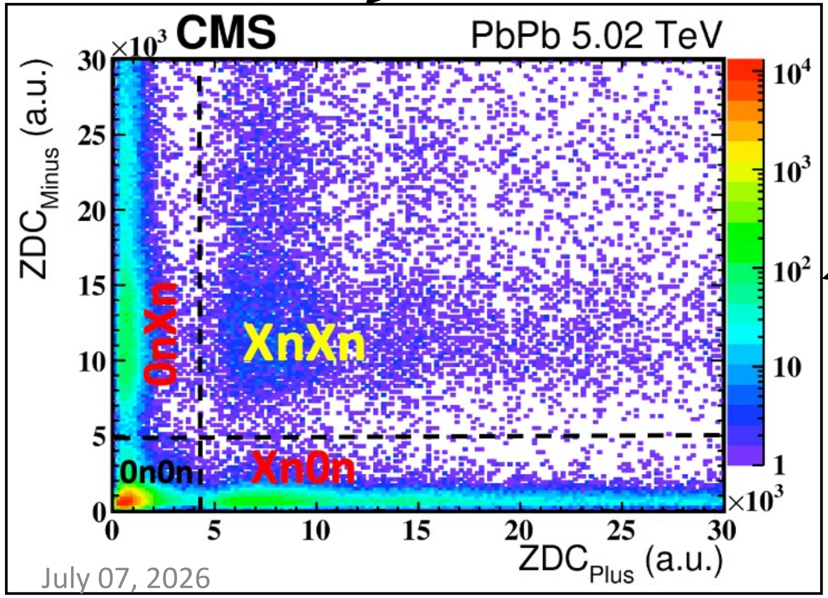
Neutron Tag with Zero Degree Calorimeter

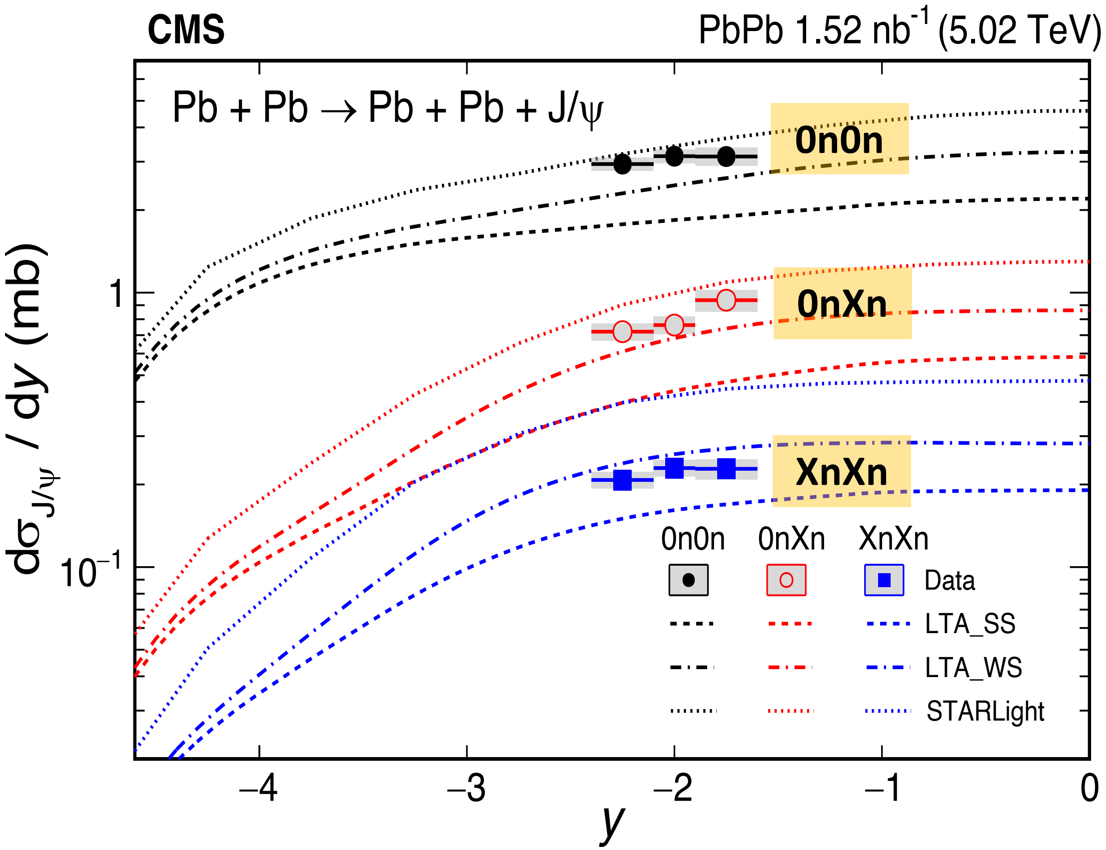




Tag events with **neutrons**:

- 0n0n, 0nXn, XnXn (X: ≥1)

Total Coh. J/Ψ Cross Section in Different Neutron Classes



CMS: PRL 131, 262301 (2023)

$$\frac{d\sigma^{0n0n}_{AA\to AAJ/\psi}}{dy} = N^{0n0n}_{\gamma/A}(y)\cdot\sigma_{\gamma A\to J/\psi A'}(y) + N^{0n0n}_{\gamma/A}(-y)\cdot\sigma_{\gamma A\to J/\psi A'}(-y)$$

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

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

Larger-x

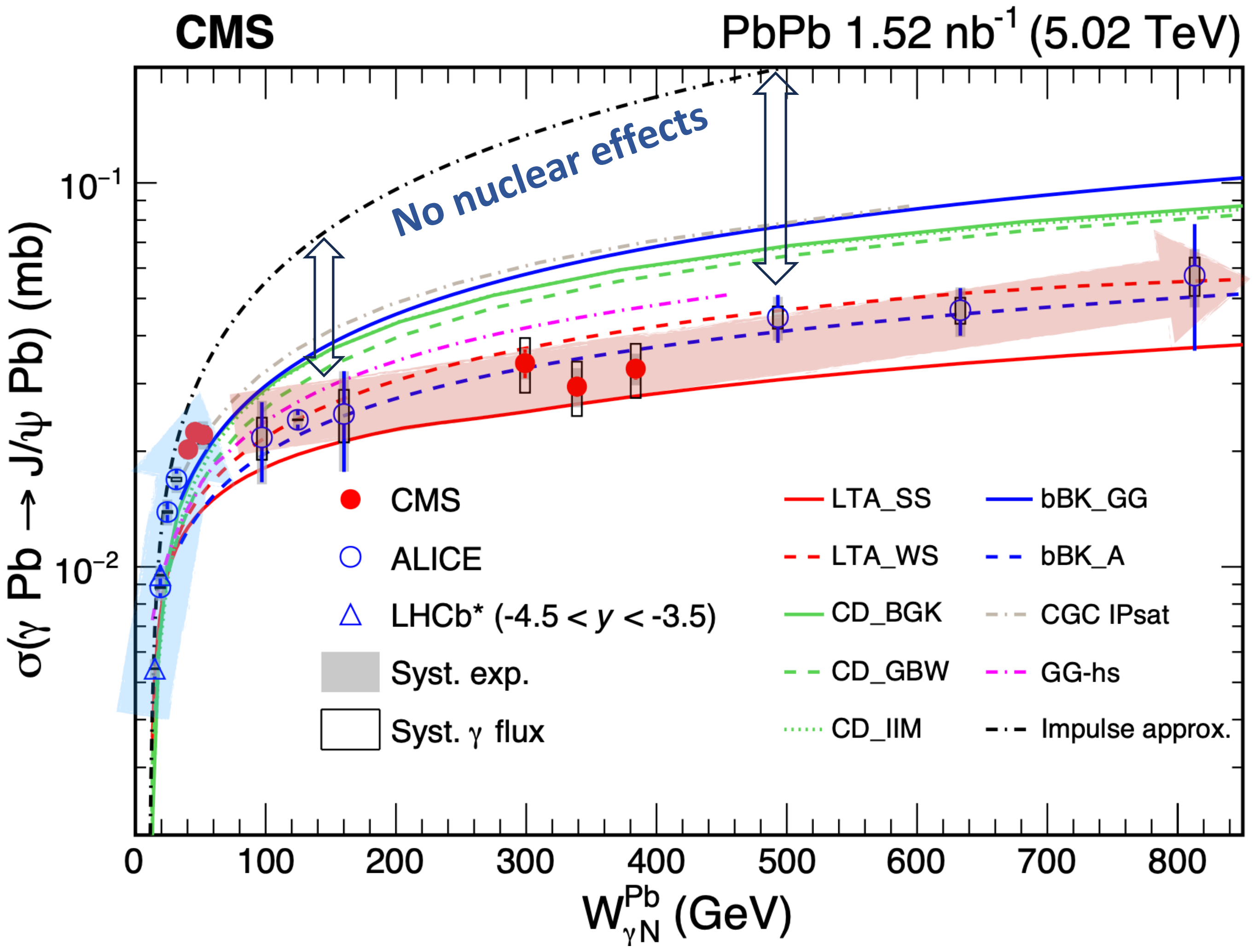
$\sigma_{\gamma A\to J/\psi A'}(w_2)$

Smaller-x

Coherent J/Ψ Cross Section of Per γ+Pb

CMS: PRL 131, 262301 (2023)

ALICE: JHEP 10 119 (2023)



Data show:

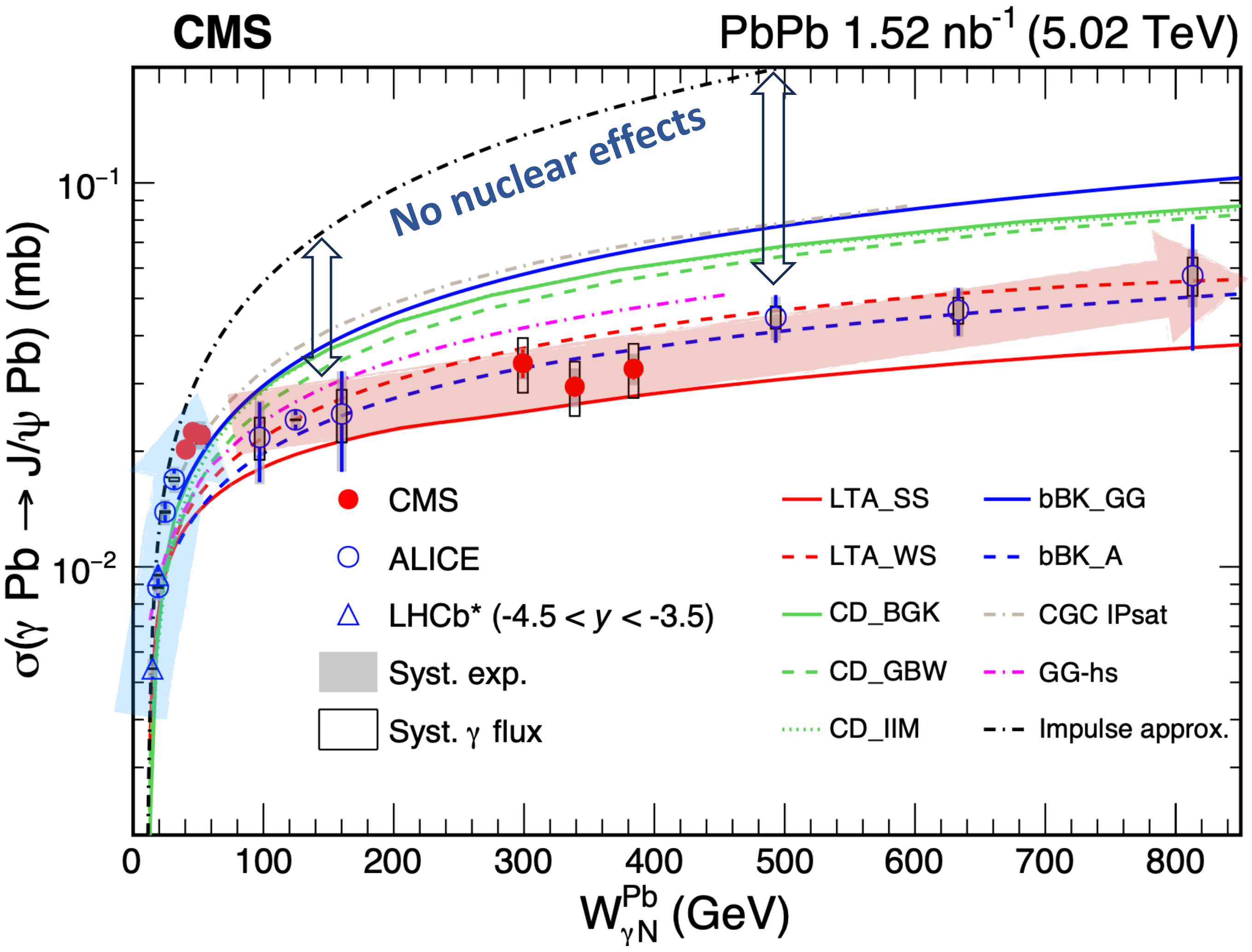
- **Rapid increase** at W < 40 GeV
- Turn into a **nearly flat** (**slower rising**) trend for W > 40 GeV

Strongly saturated cross sections

Coherent J/Ψ Cross Section of Per γ+Pb

CMS: PRL 131, 262301 (2023)

ALICE: JHEP 10 119 (2023)



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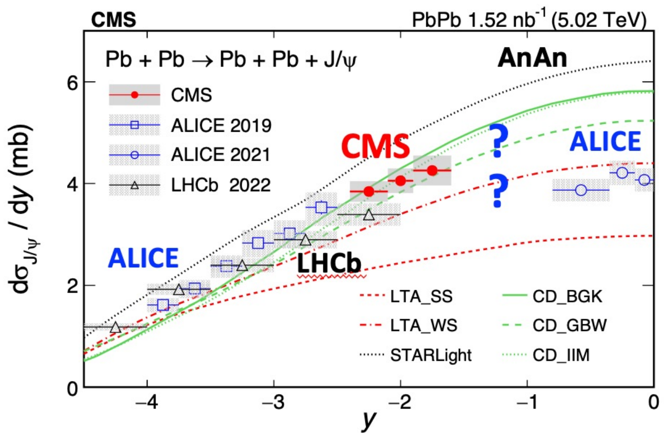
- **y distribution puzzle is solved by studying the W dependence**
- **Strong suppression**

Strongly saturated cross sections



Coherent J/Ψ Cross Section of Per γ+Pb

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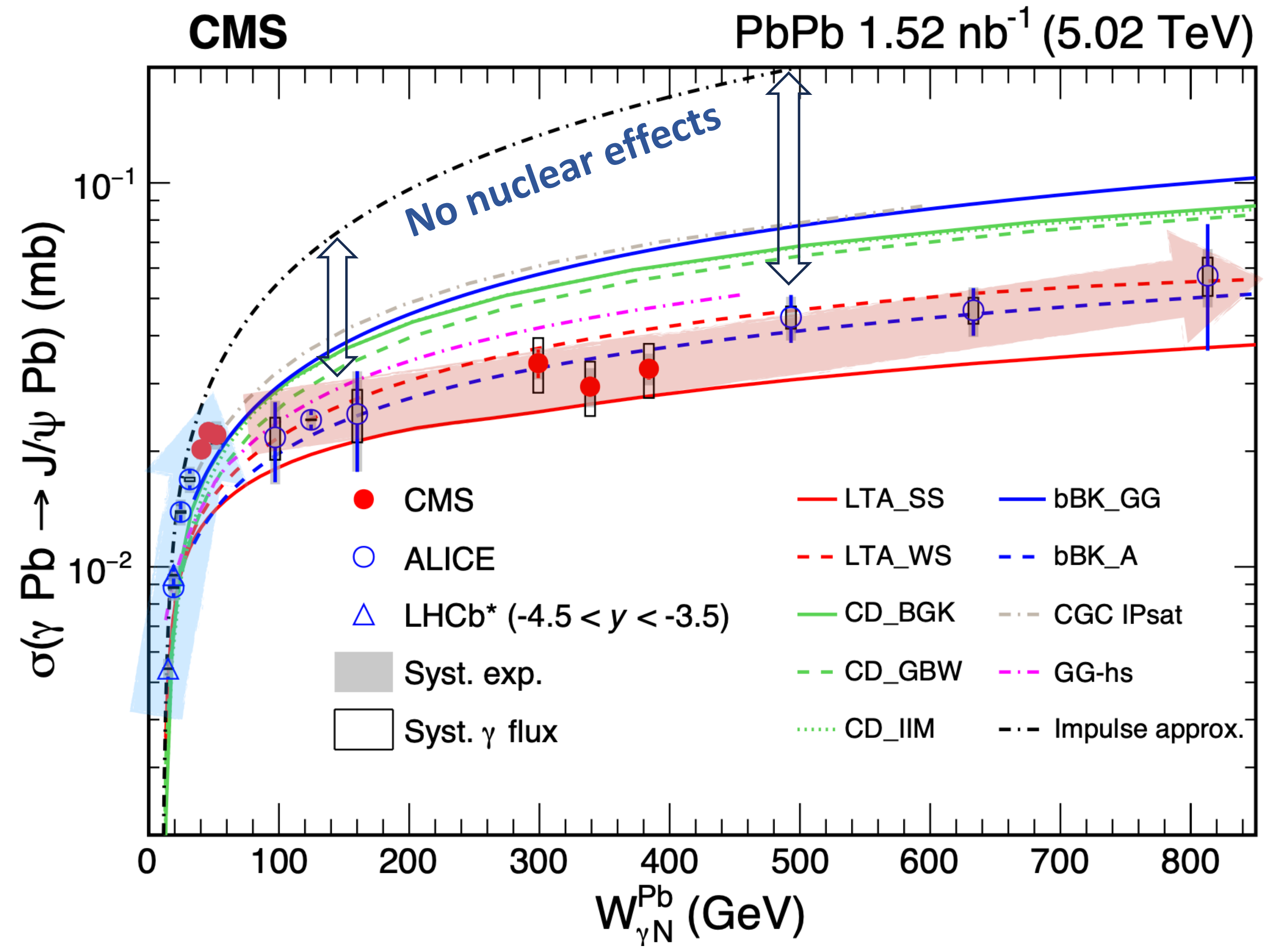

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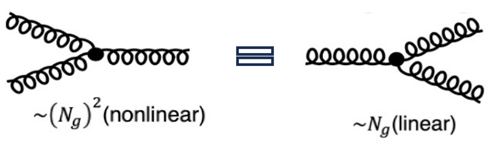
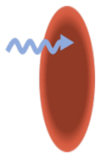
Strongly saturated cross sections

Gluon Saturation?

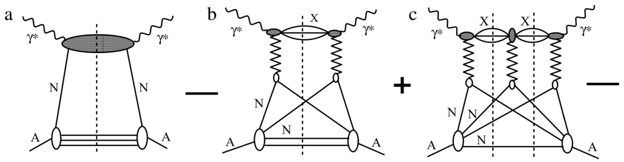


Black Disk Limit?



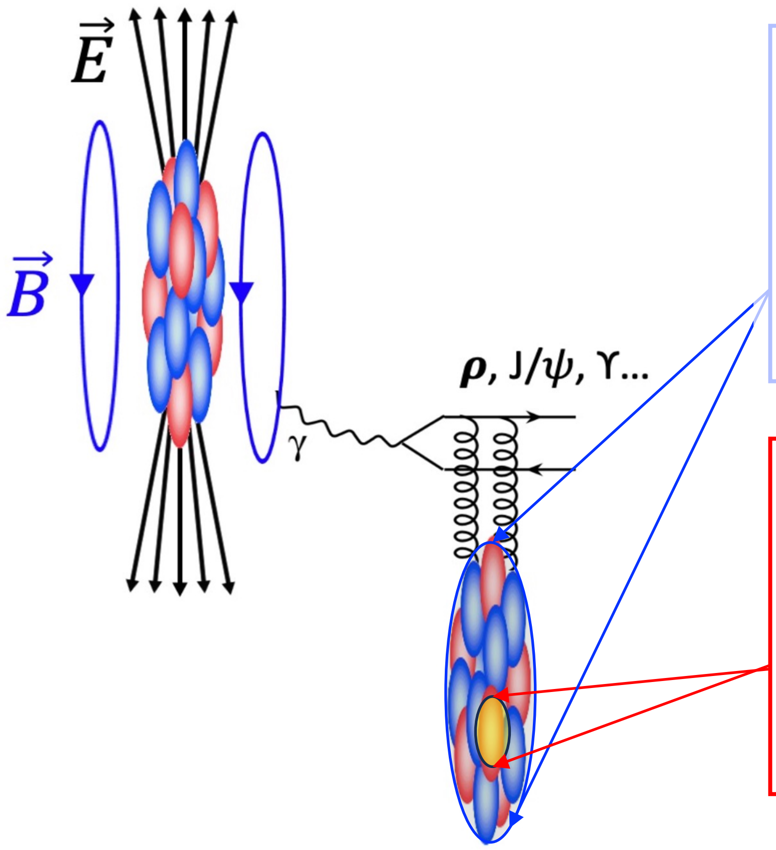
$\hat{\sigma}^{\text{inel}}_{\text{PQCD}} \leq \hat{\sigma}_{\text{black}} = \pi R^2_{\text{target}}$

Nuclear shadowing?



What's the underlying physics?

How About Incoherent J/Ψ Photoproduction?



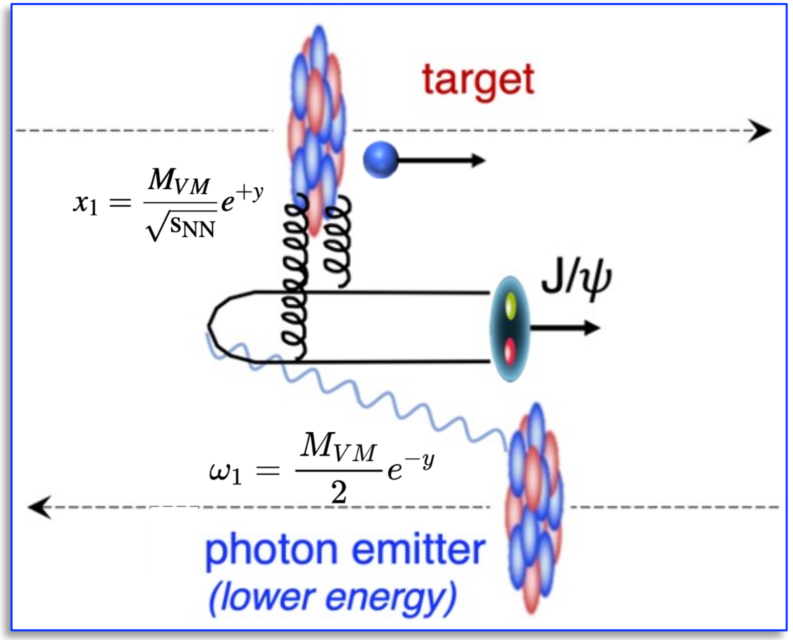
Coherent production:

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

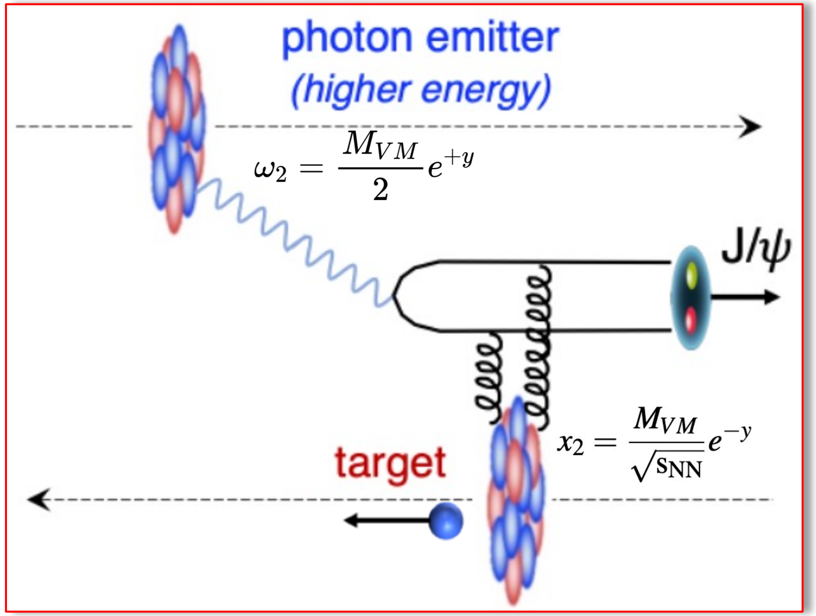
Incoherent production:

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

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

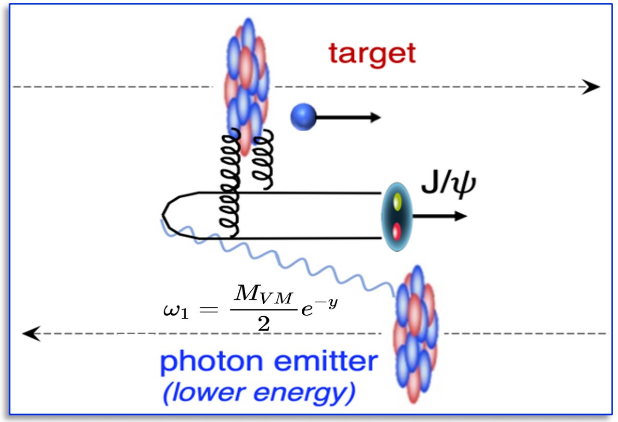
- **Incoh. J/Ψ photoproduction itself has ~85% chance to induce the forward neutrons**
  → Detecting these neutrons will identify target nucleus
  → Help to solve the "Two-Way Ambiguity"

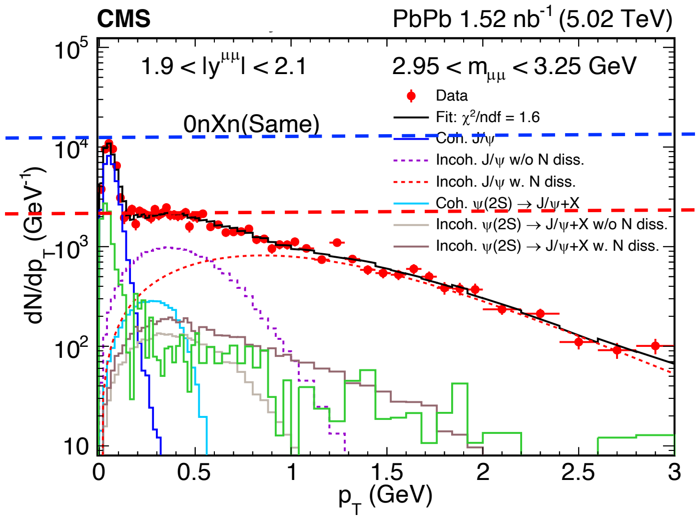
Example Signals (J/Ψ-Xn Correlations)

Low-W

-y

J/Ψ-Xn (Same Direction)

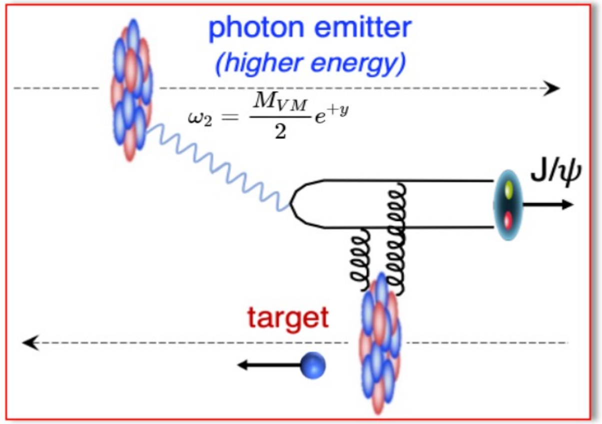


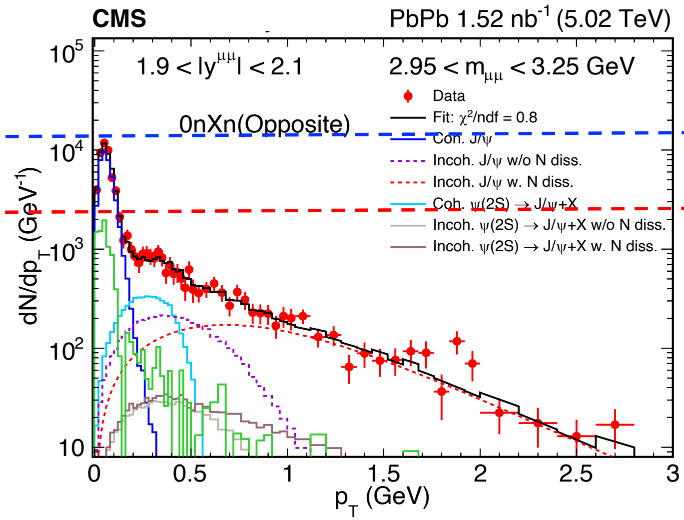


J/Ψ-Xn (Opposite Direction)

High-W

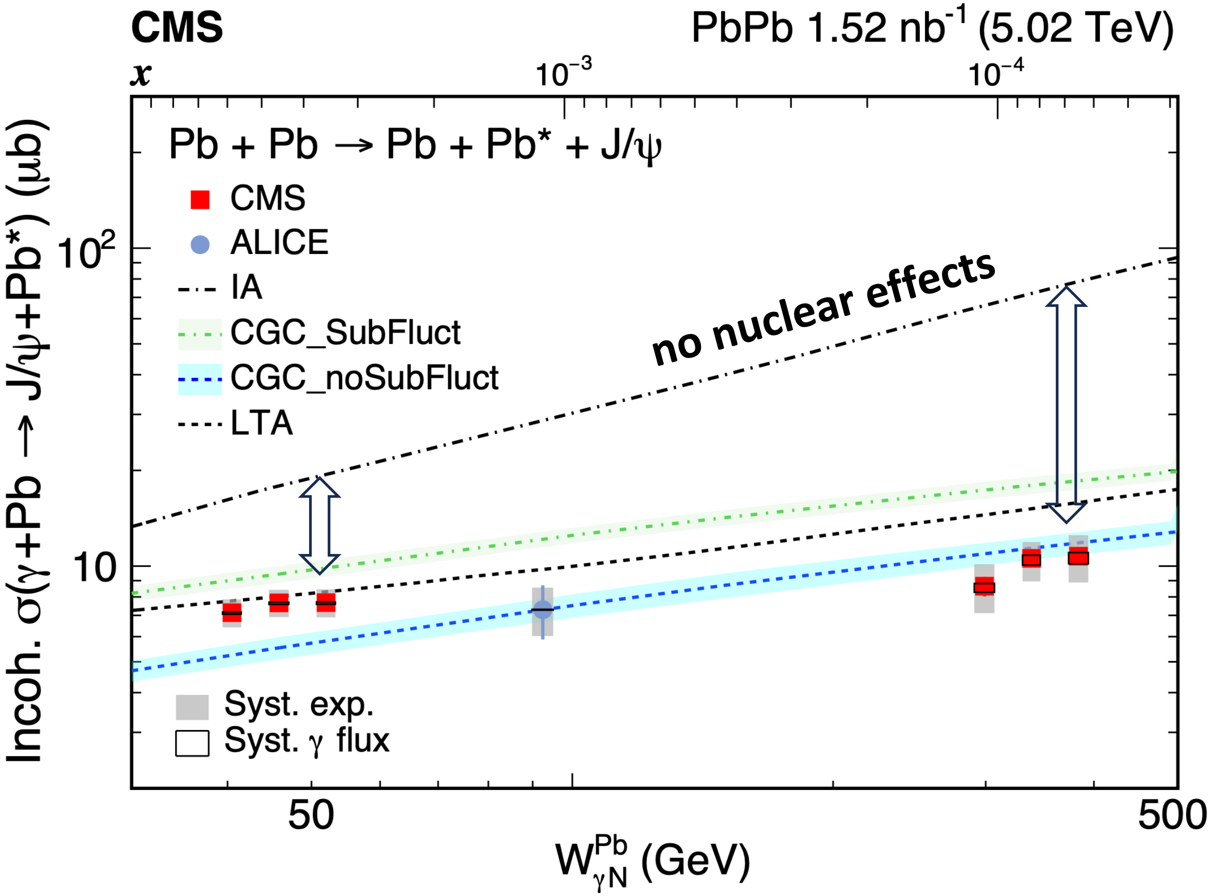
+y





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

Incoh. J/Ψ Cross Section Per γ+Pb

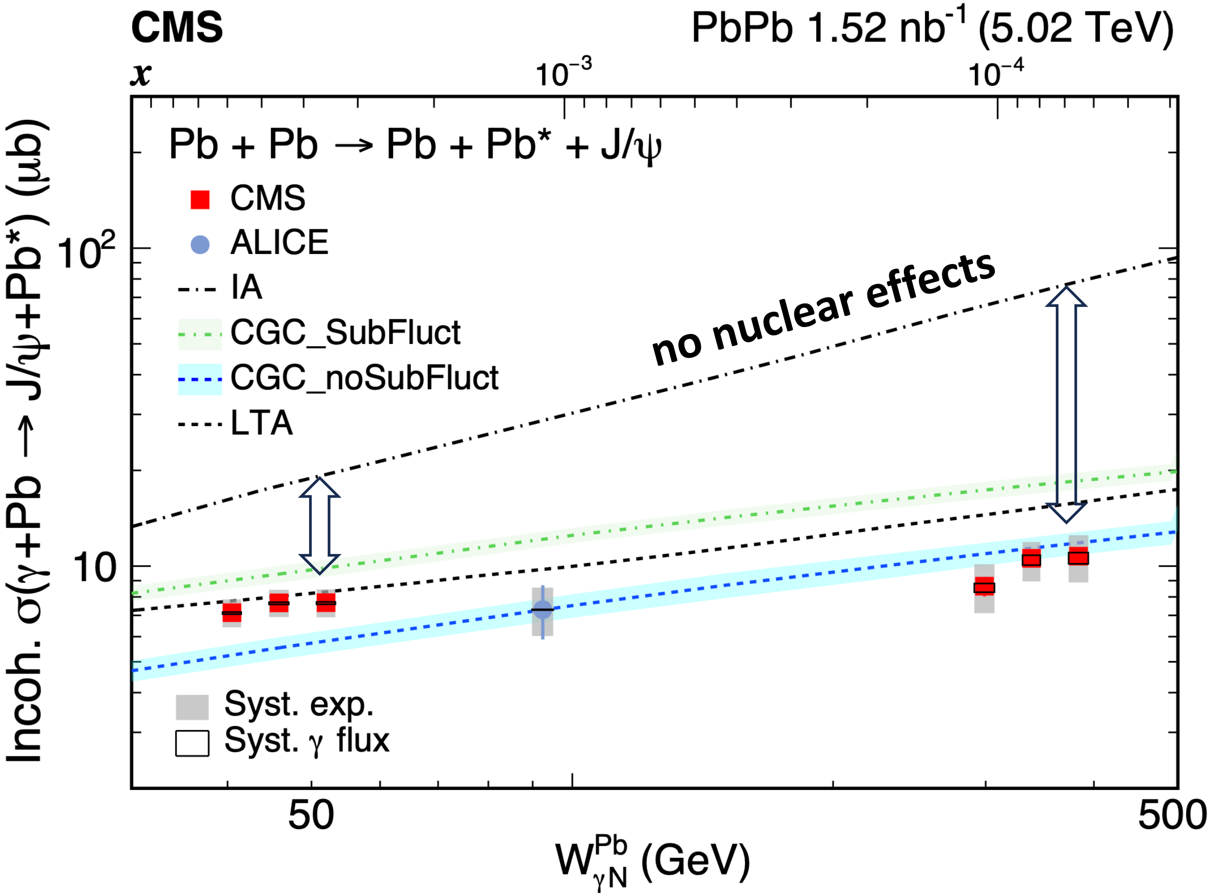


CMS, PRL 135, 112301 (2025), Editors' Suggestion

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

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

Incoh. J/Ψ Cross Section Per γ+Pb



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

- **First energy-dependent** measurement of incoh. J/Ψ photoproduction
  - **Strongly saturated trend again**
- **Strong suppression** compared to Impulse Approximation (IA)
- **LTA** describe data at **W < 60 GeV**
- **CGC without** sub-nucleonic fluctuations better describe data at **W > 90 GeV**

CGC: PRD 109 (2024) 7, L071504, PRD 106 (2022) 7, 074019
LTA: V. Guzey et al. PRC 108 (2023) 024904, PRC 99 (2019) 015201
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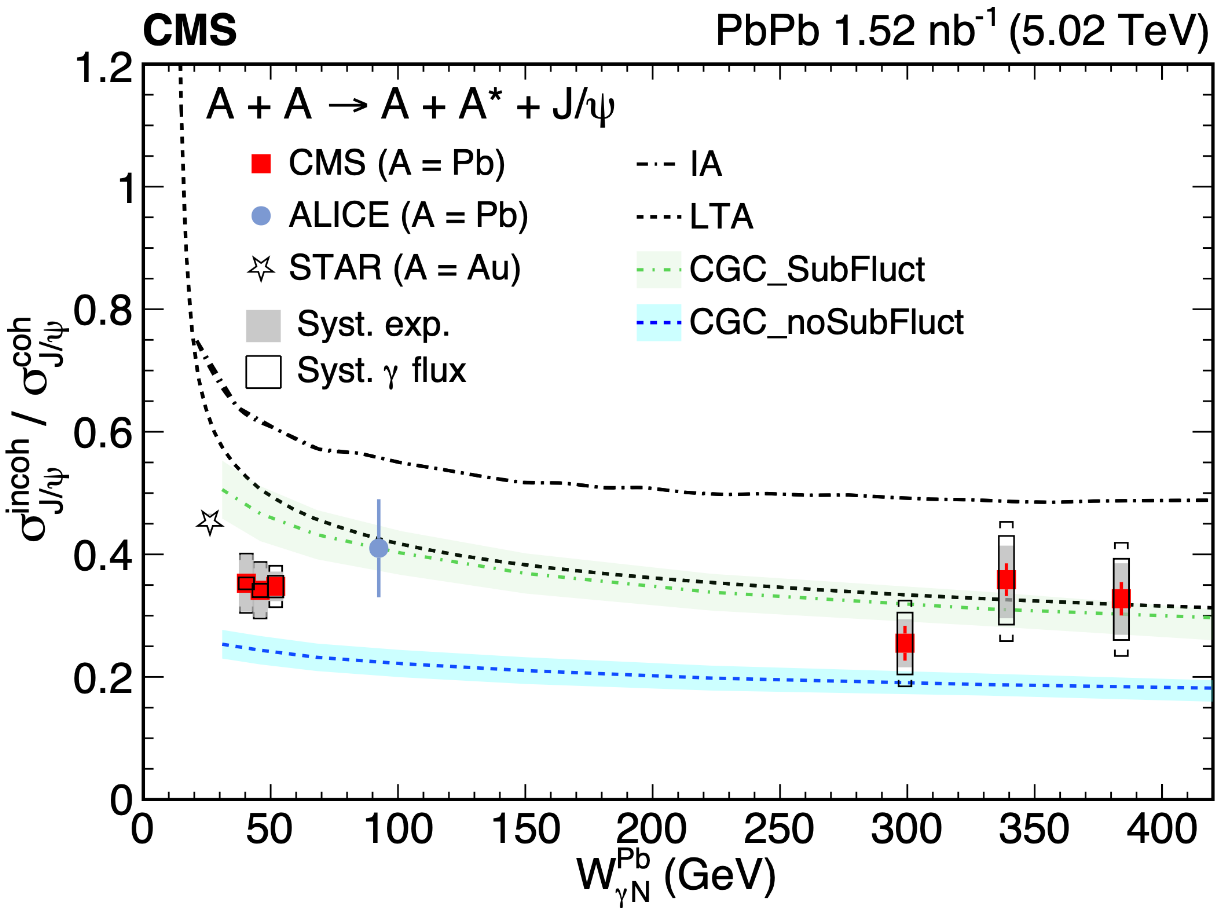
Cross Section Ratio of Incoh./Coh. J/Ψ

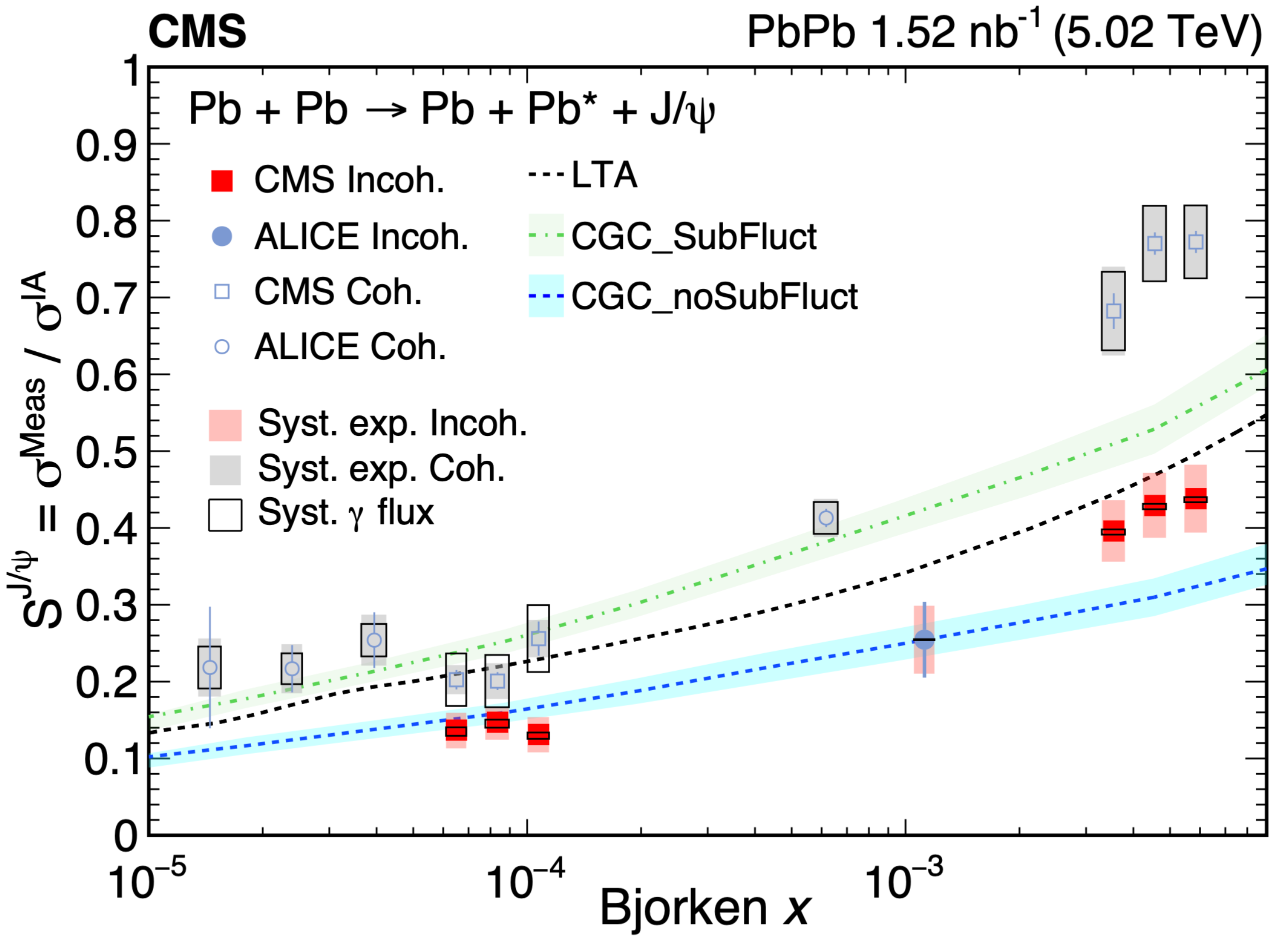


CMS, PRL 135, 112301 (2025), Editors' Suggestion

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

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

Nuclear Suppression Factor



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

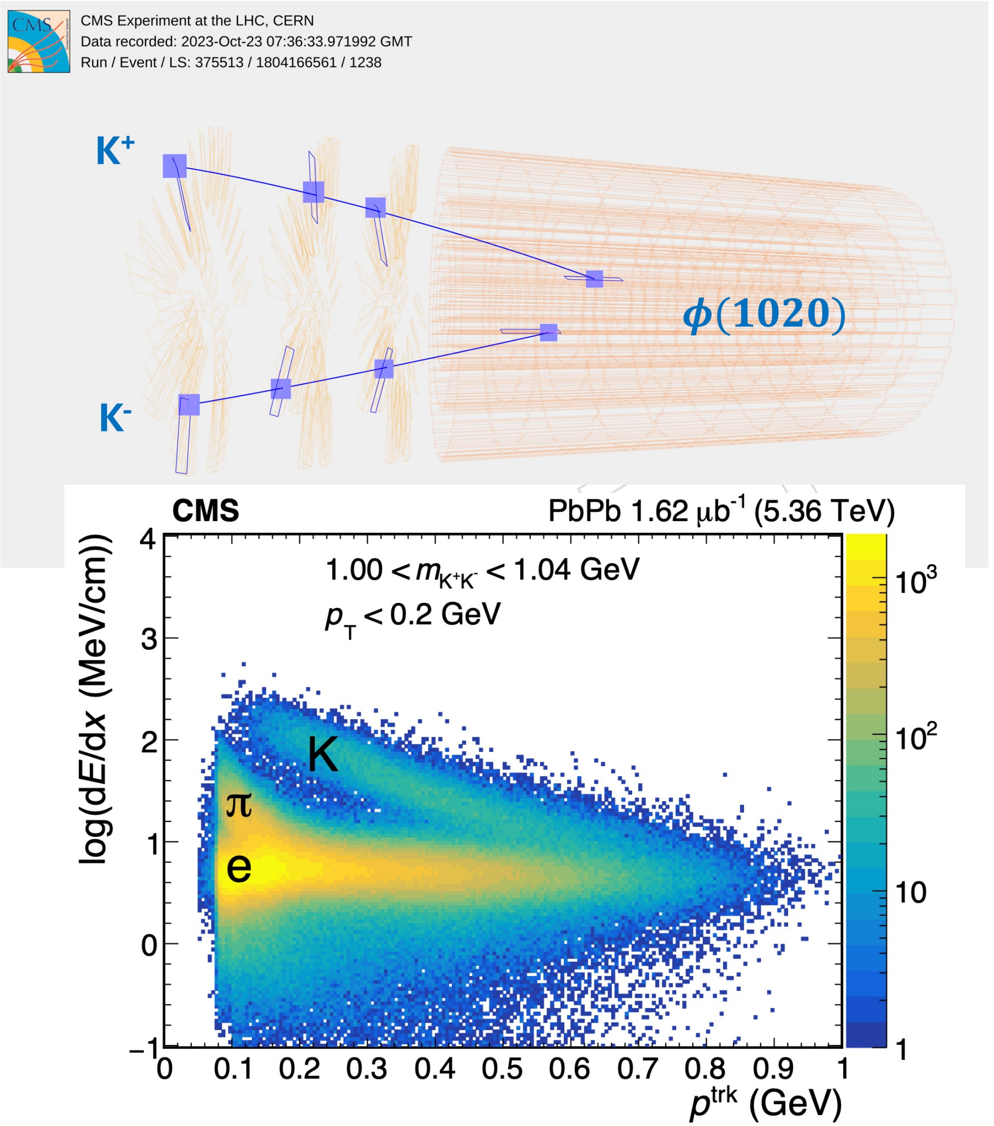
$$S^{J/\psi}_{\text{coh}}(x,\mu^2) = (R_g)^2$$

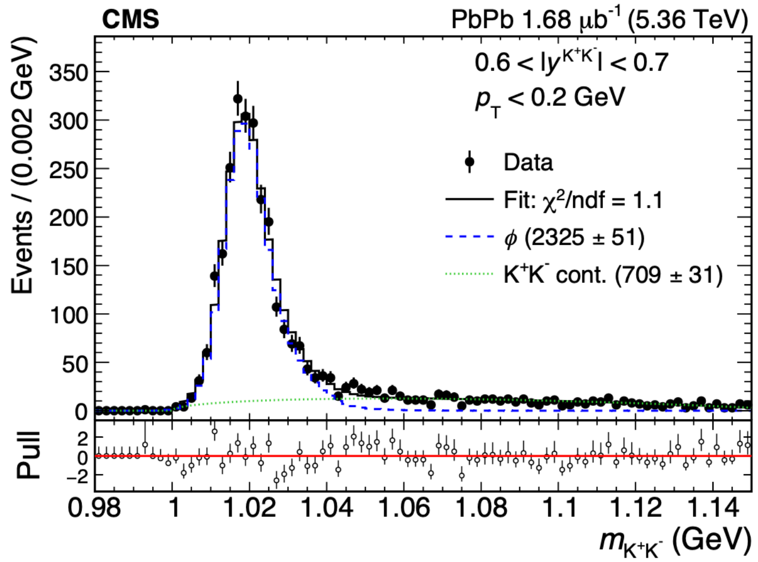
$$S^{J/\psi} = \frac{\sigma^{exp}_{\gamma Pb \to J/\psi Pb'}}{\boxed{\sigma^{IA}_{\gamma Pb \to J/\psi Pb'}}}$$

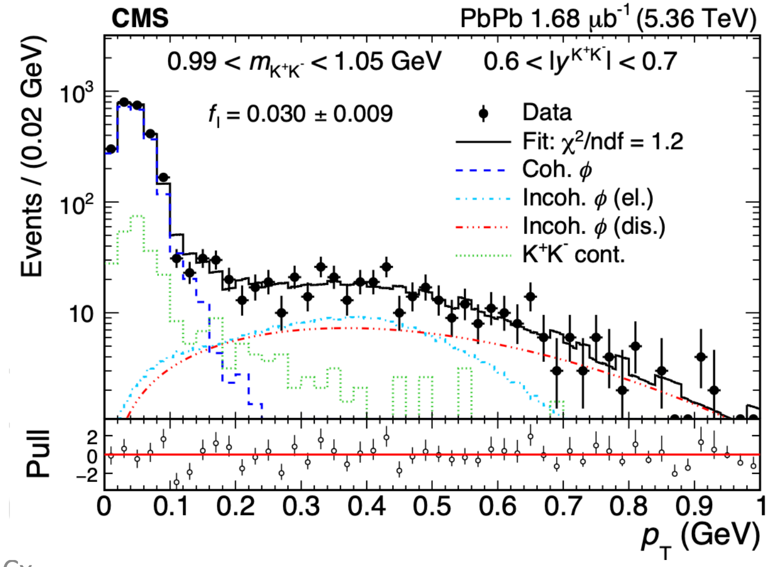
No nuclear effects

- 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 $x < 10^{-4}$

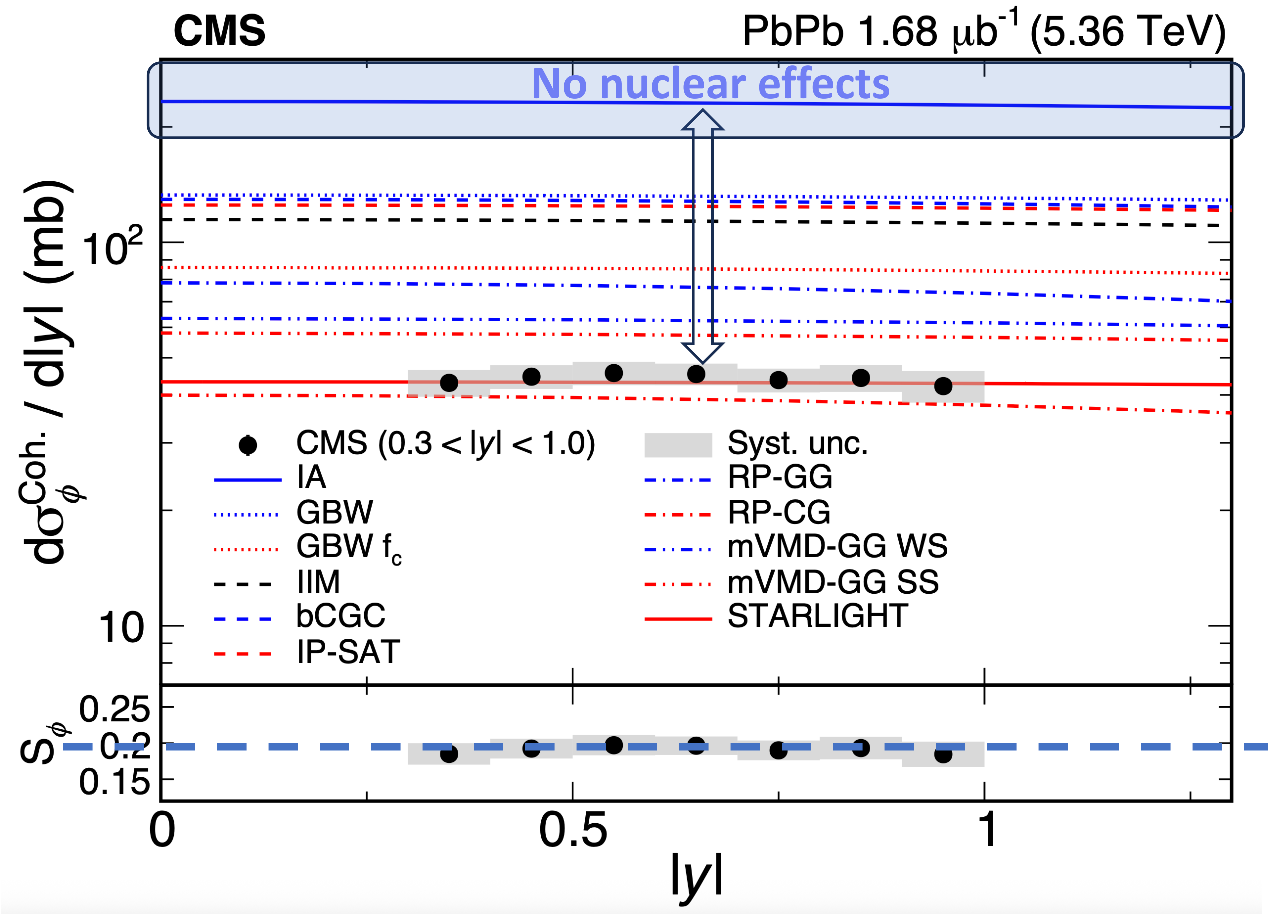
First Observation of ϕ Photoproduction in UPCs







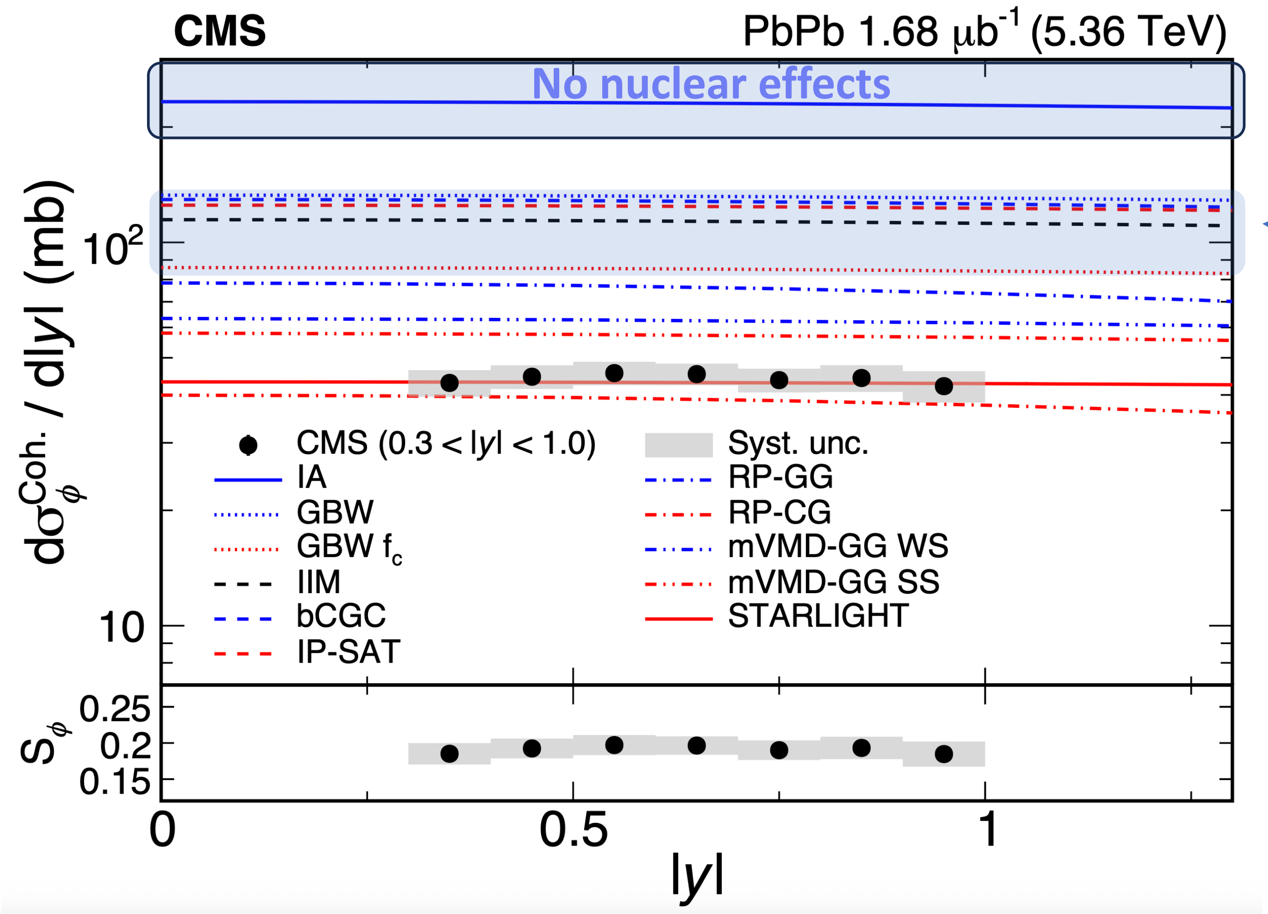
First Observation of ϕ Photoproduction in UPCs



- **Strong (~5x) suppression is observed**

CMS, PRL 135, 262301 (2025)

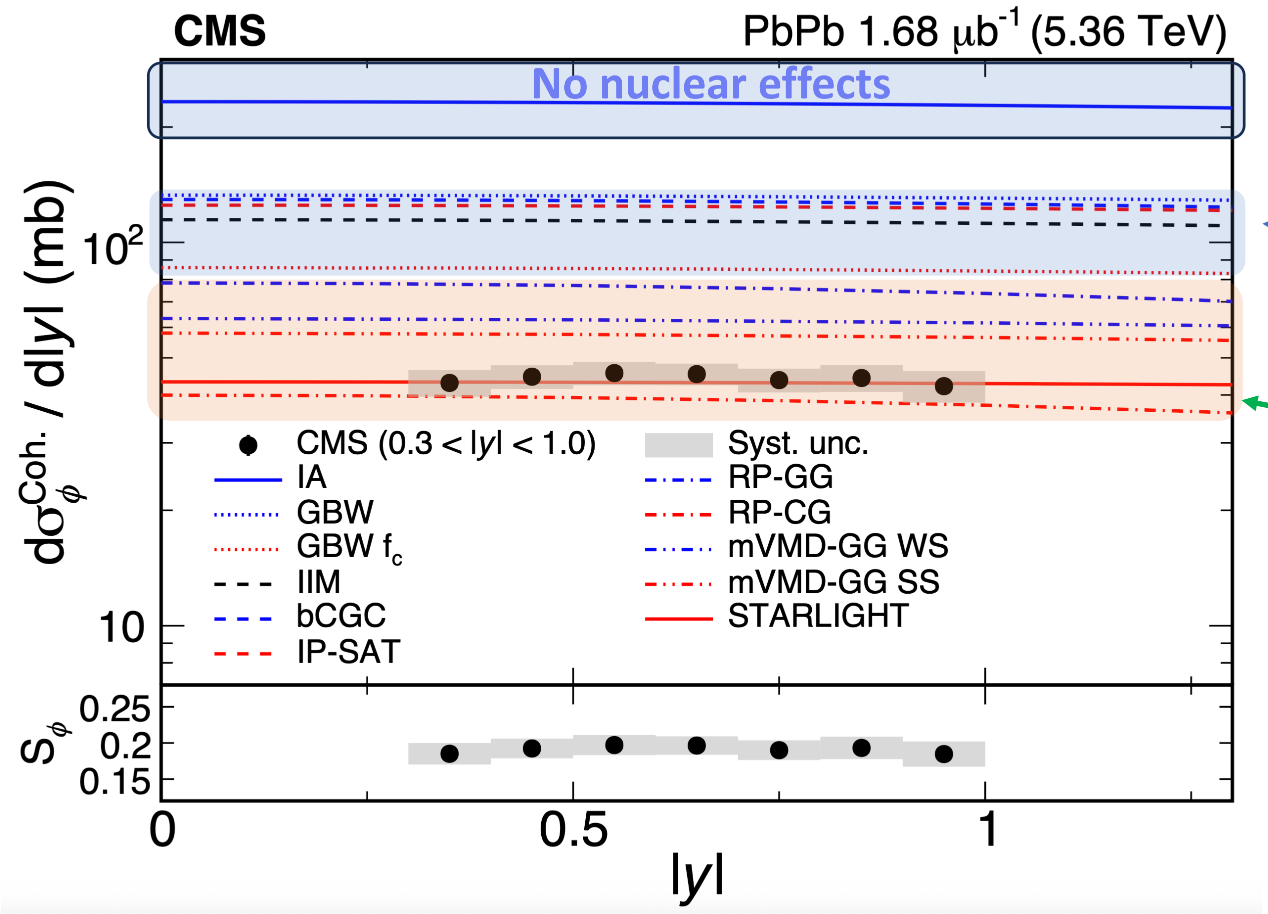
First Observation of ϕ Photoproduction in UPCs



- **Strong (~5x) suppression is observed**
- **Gluon saturation models:**
  - Overpredicted data by a factor of **2-3**

CMS, PRL 135, 262301 (2025)

First Observation of ϕ Photoproduction in UPCs

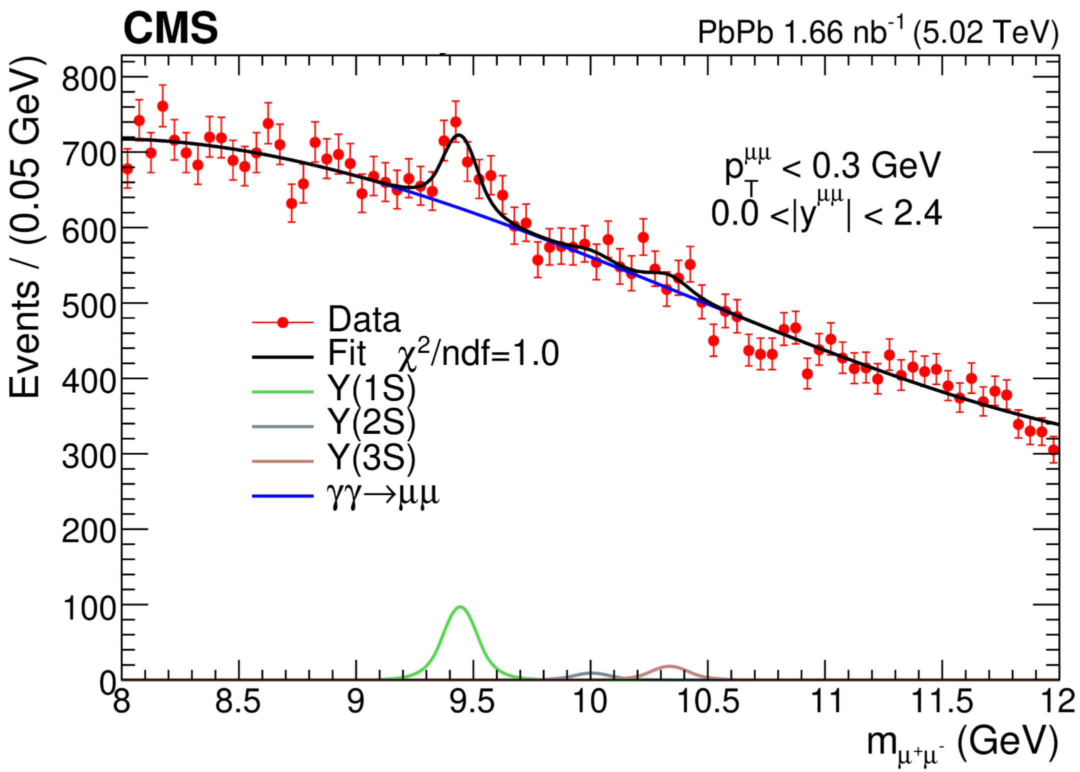


CMS, PRL 135, 262301 (2025)

- **Strong (~5x) suppression is observed**
- **Gluon saturation models:**
  - Overpredicted data by a factor of **2-3**
- **Nuclear shadowing models:**
  - Generally better describe data
  - VMD + Gribov Glauber (GG) over predict data
  - VMD + Classical Glauber (CG) best describe data
    - STARLIGHT and RP-CG
      - But not describe J/Ψ and ρ results

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

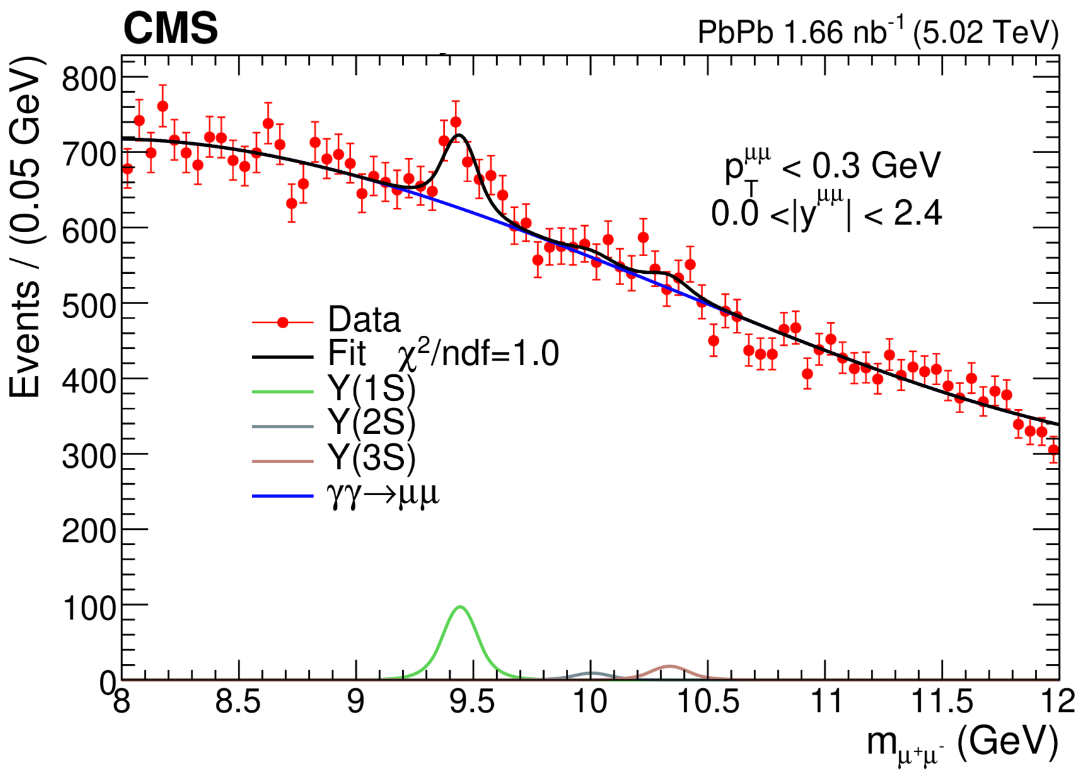
Υ is expected to be less sensitive to the non-linear QCD effects



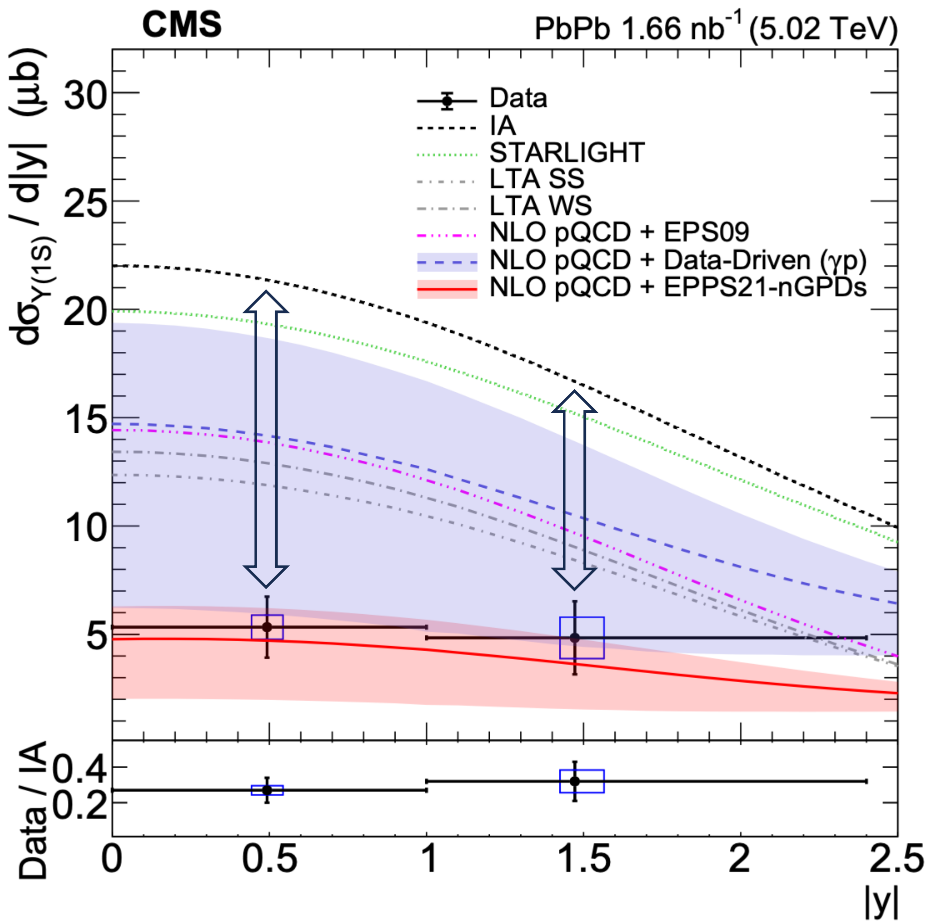
CMS: arXiv:2604.05814 , submitted to PRL

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

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



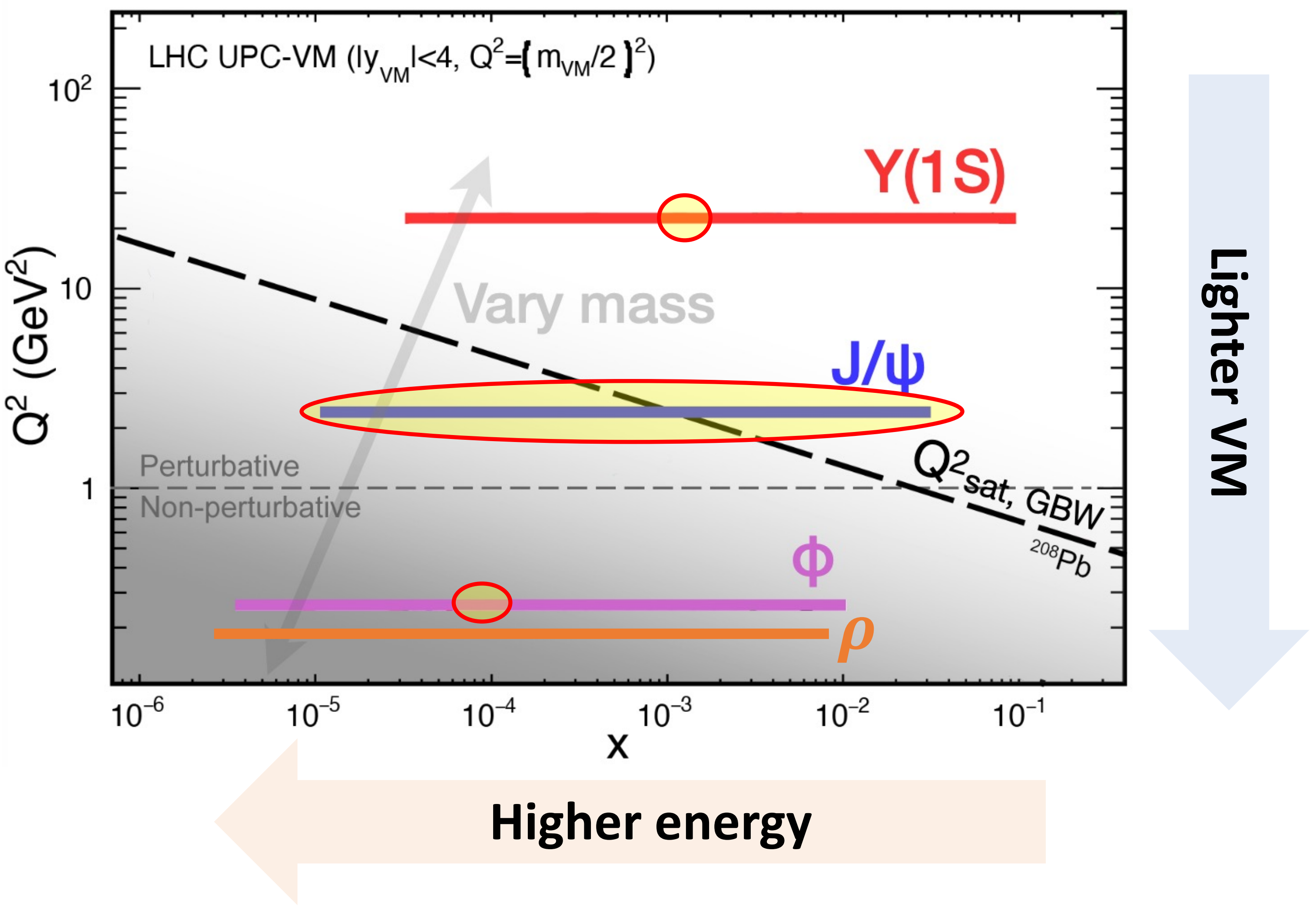
CMS: arXiv:2604.05814 , submitted to PRL



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

What's Next for VM Photoproduction at CMS

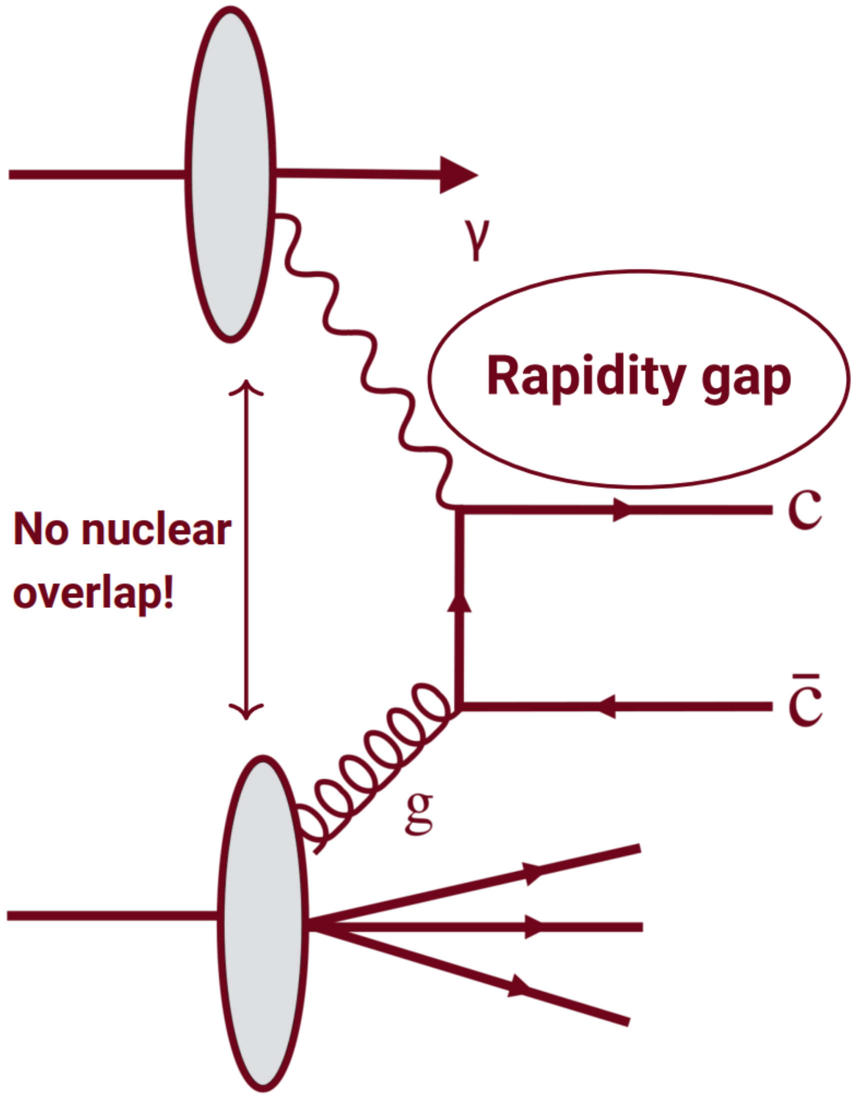
Explore nuclear gluonic structure in : $\boldsymbol{x}\ \boldsymbol{vs.}\ \boldsymbol{Q^2}\ \boldsymbol{vs.}\ \boldsymbol{Q_S^2}$



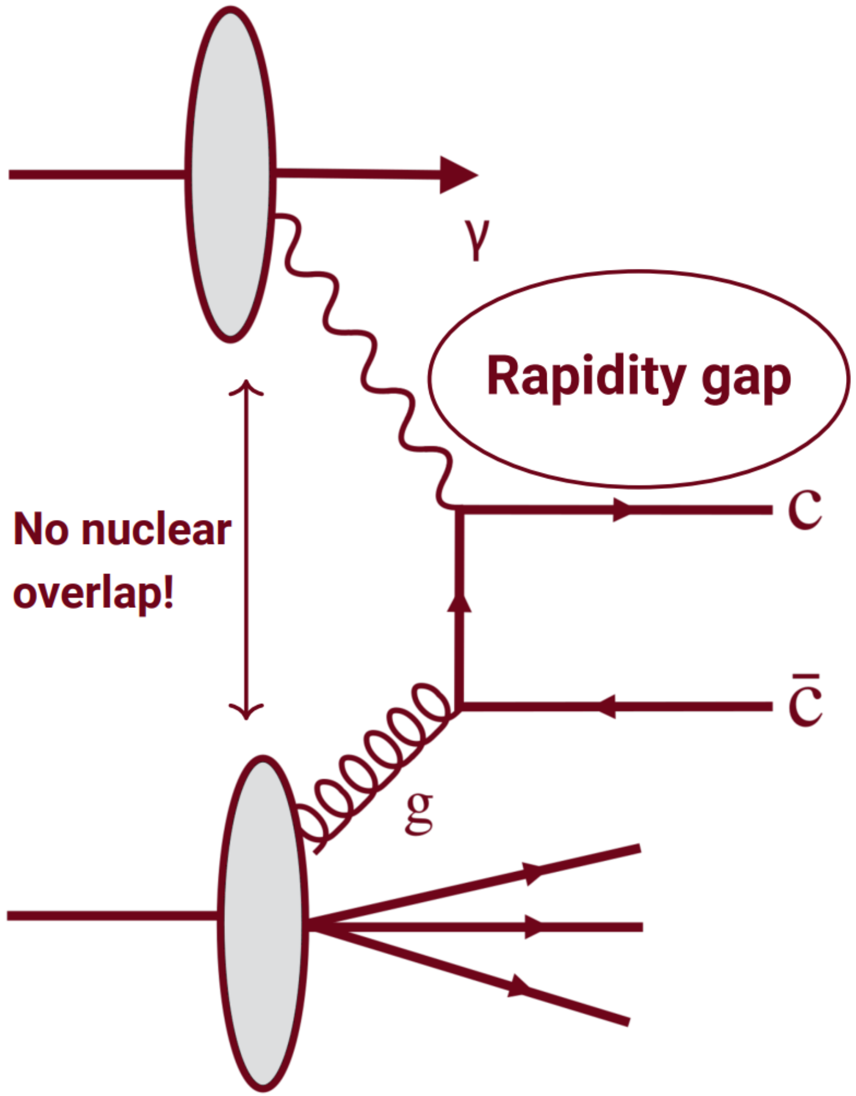
Various VMs in different nucleus-nucleus UPCs:

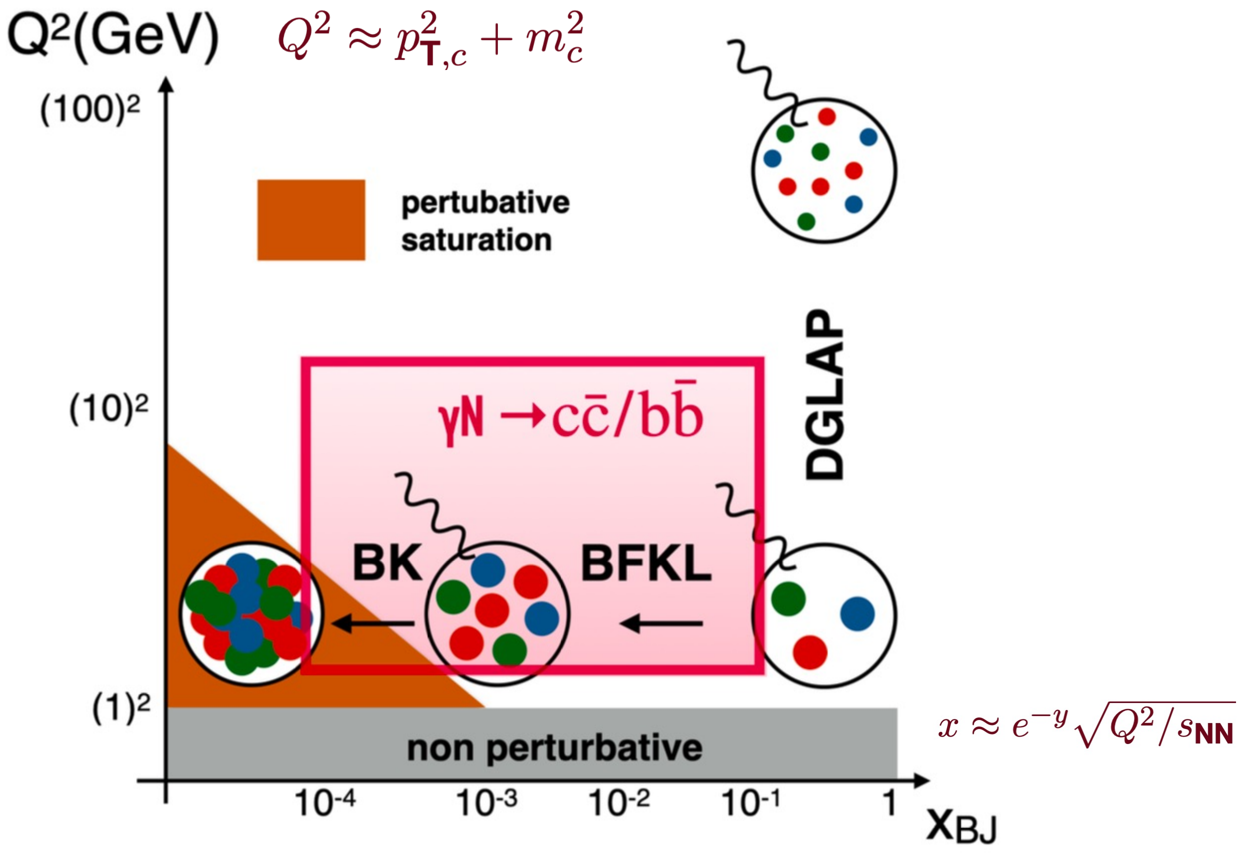
- **Coherent** and **Incoherent**
- **Dipole sizes** and **hard scales**
- **Energy** (x) **dependence**
- **A (saturation scale) dependences**
  - **OO, NeNe, PbPb…**

First **Open Charm** Photoproduction in UPCs



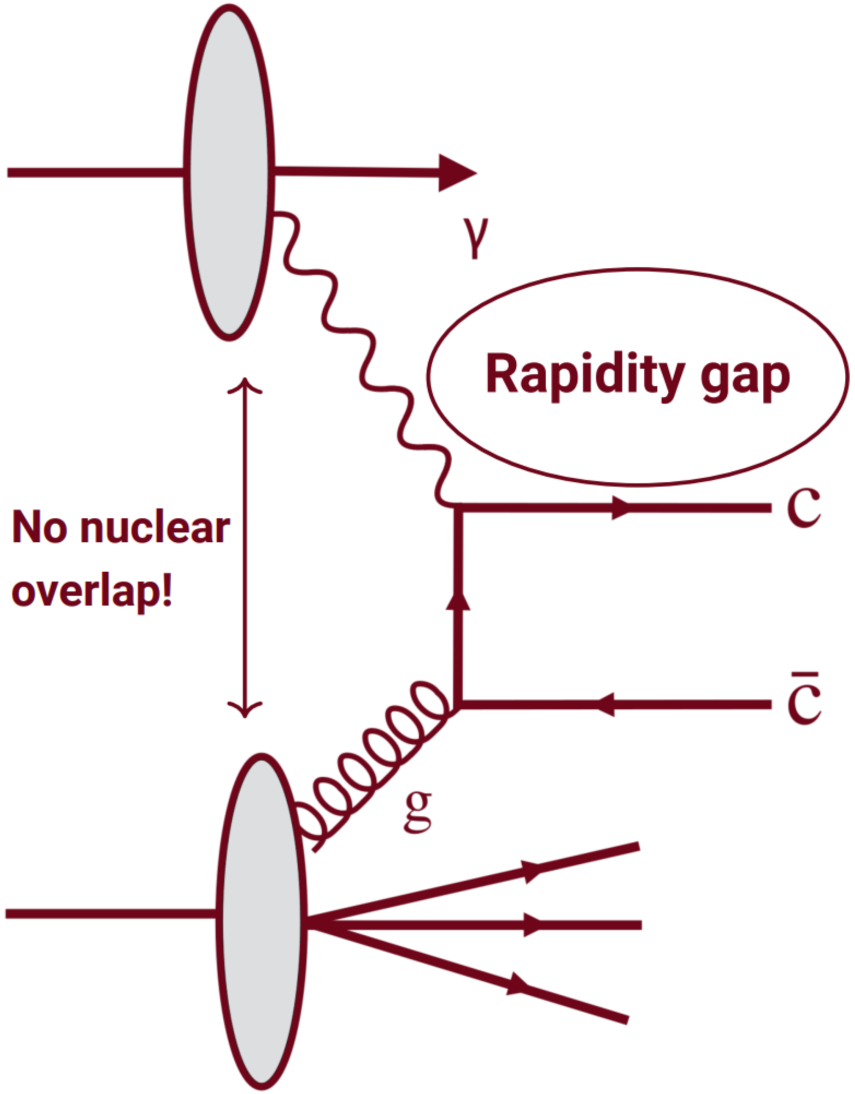
First **Open Charm** Photoproduction in UPCs

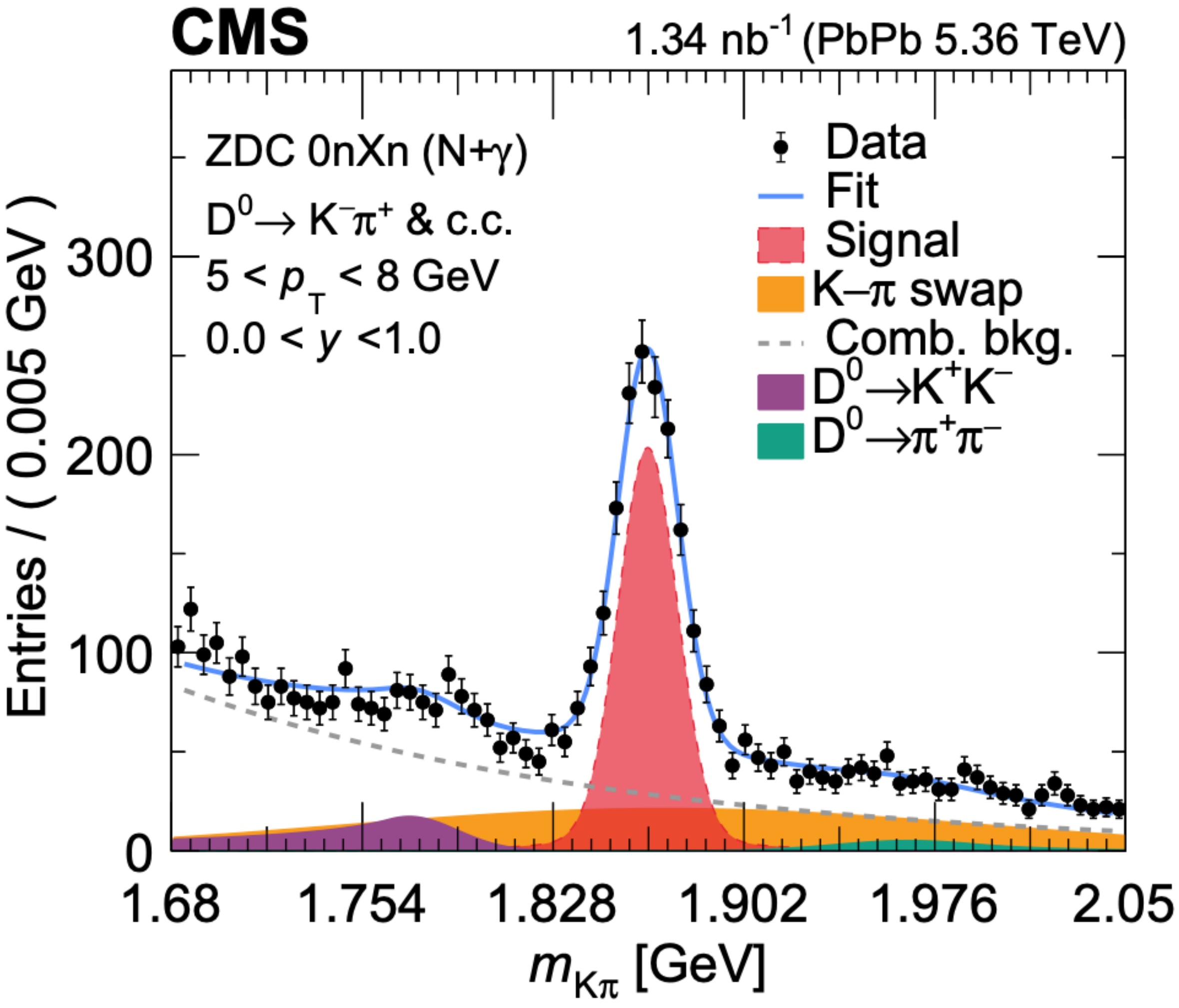




- **Mass of charm $\rightarrow$ pQCD control at p_{T} =0!**
- **Probes $\mathrm{Q}^2 \sim$ (charm/bottom mass)^2**
- **Complements higher Q^2 of dijets down to Q^2 J/ψ**

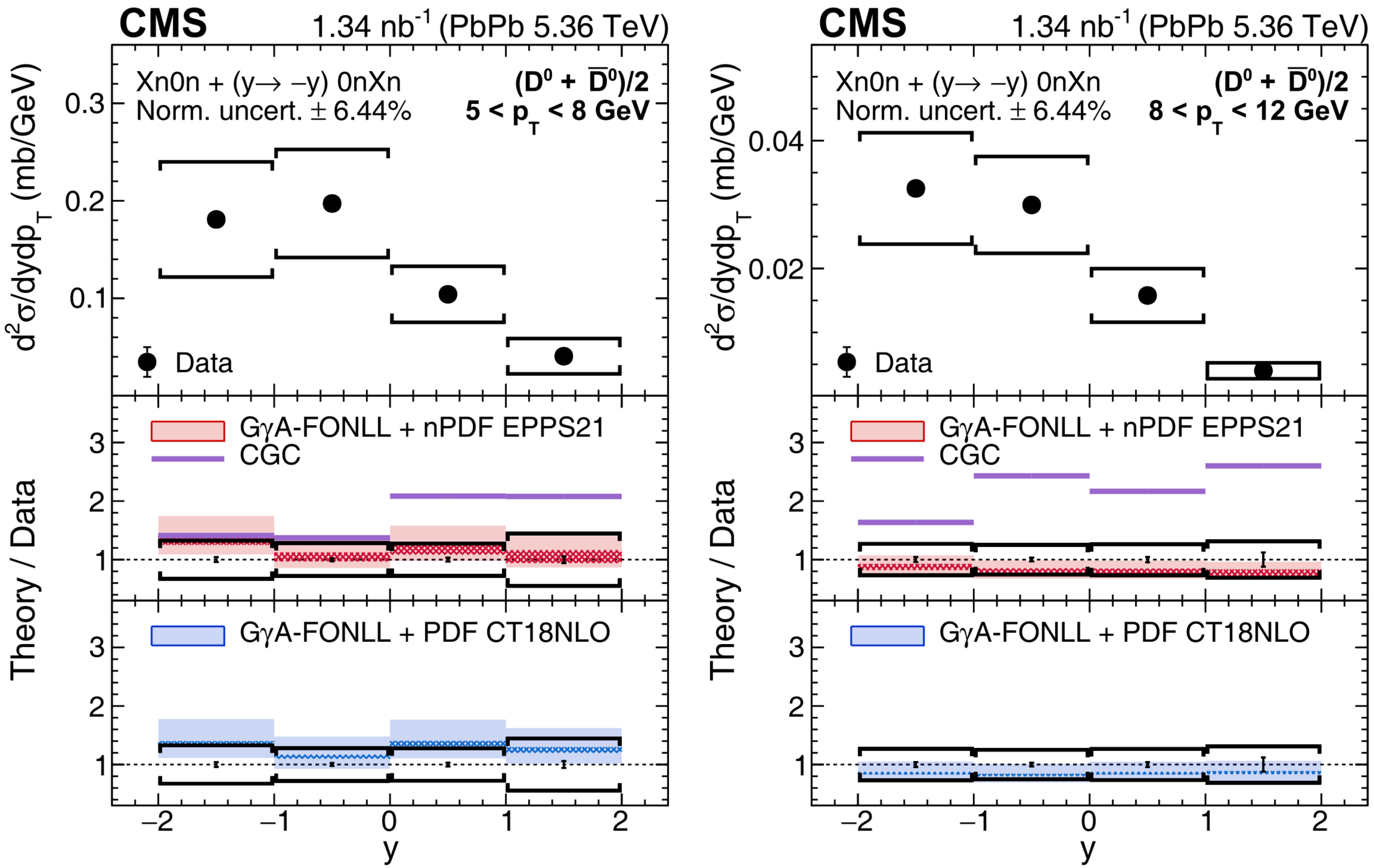
First **Open Charm** Photoproduction in UPCs





CMS, PRL 136, 122303 (2026)

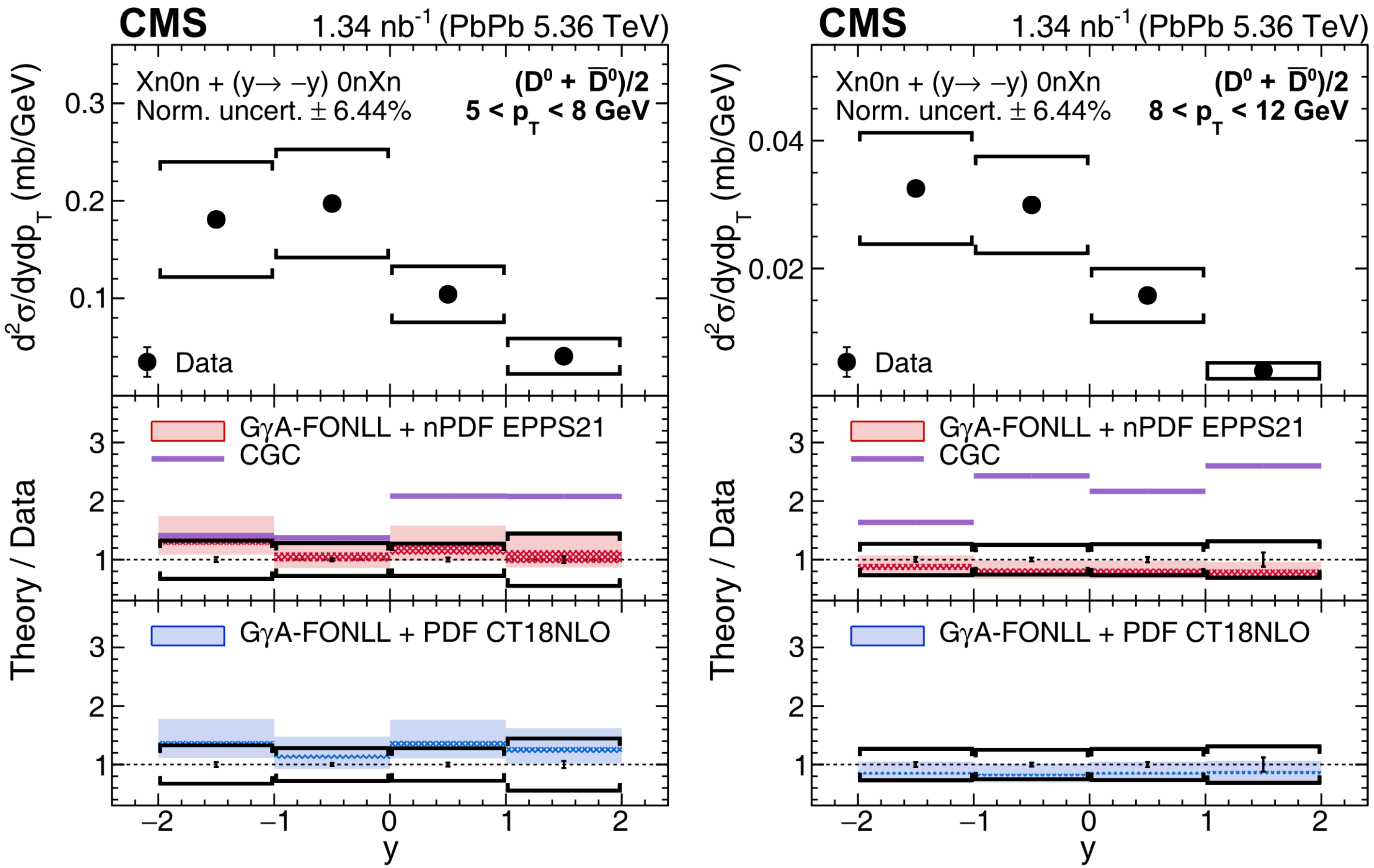
First **Open Charm** Photoproduction in UPCs



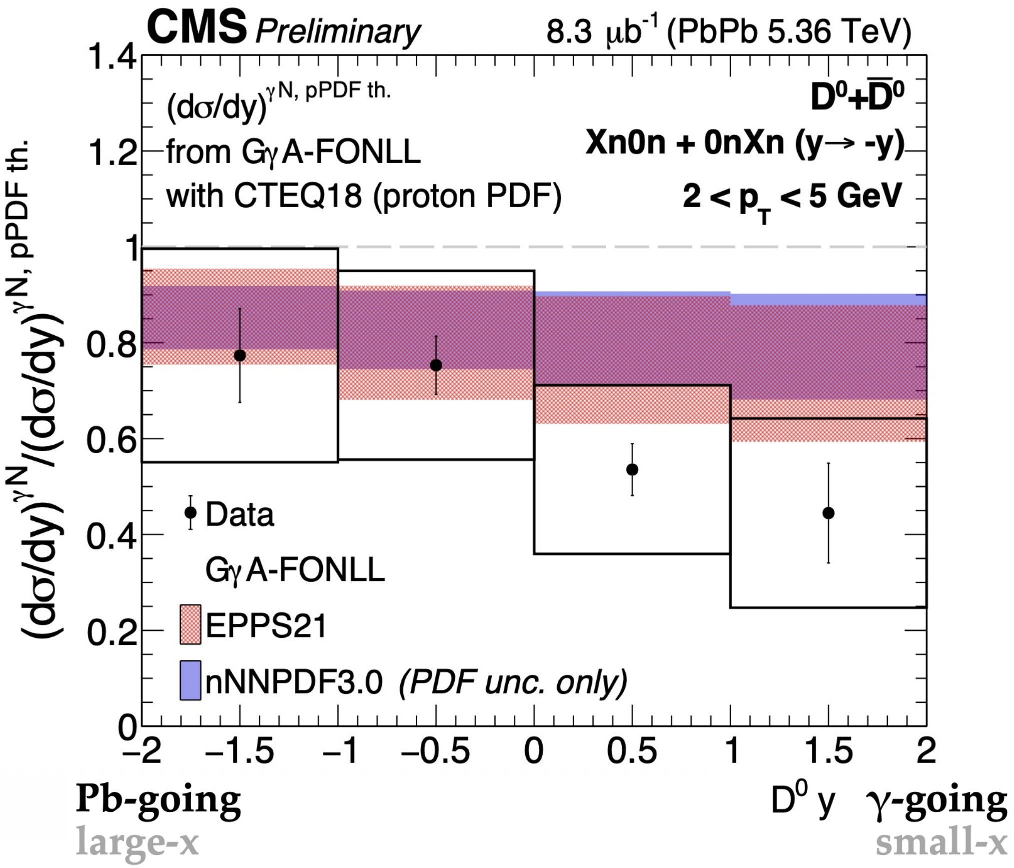
CMS, PRL 136, 122303 (2026)

- Data agree with pQCD FONLL w/ PDF, nPDF
- Hint of data-CGC deviation at p_T region

First **Open Charm** Photoproduction in UPCs



CMS, PRL 136, 122303 (2026)



CMS-PAS-HIN-25-002

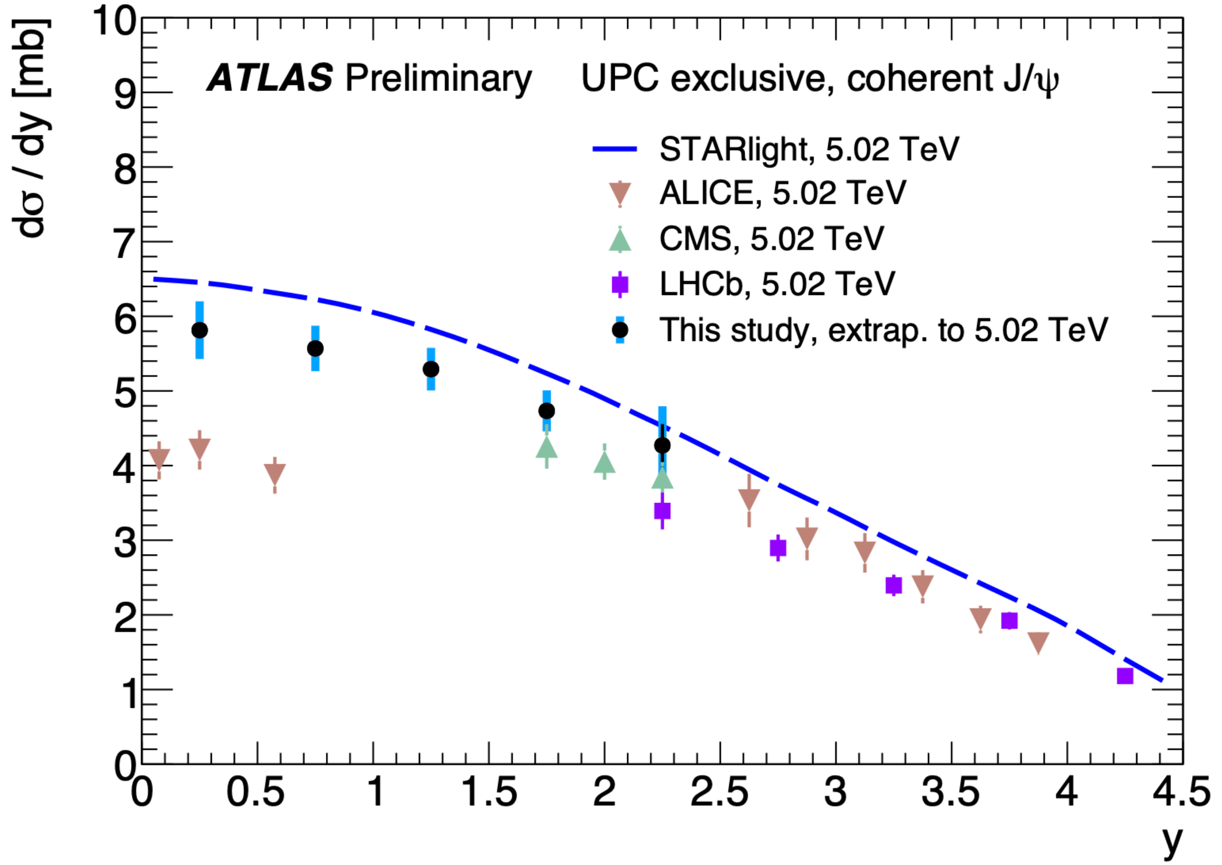
- Data agree with pQCD FONLL w/ PDF, nPDF
- Hint of data-CGC deviation at p_T region

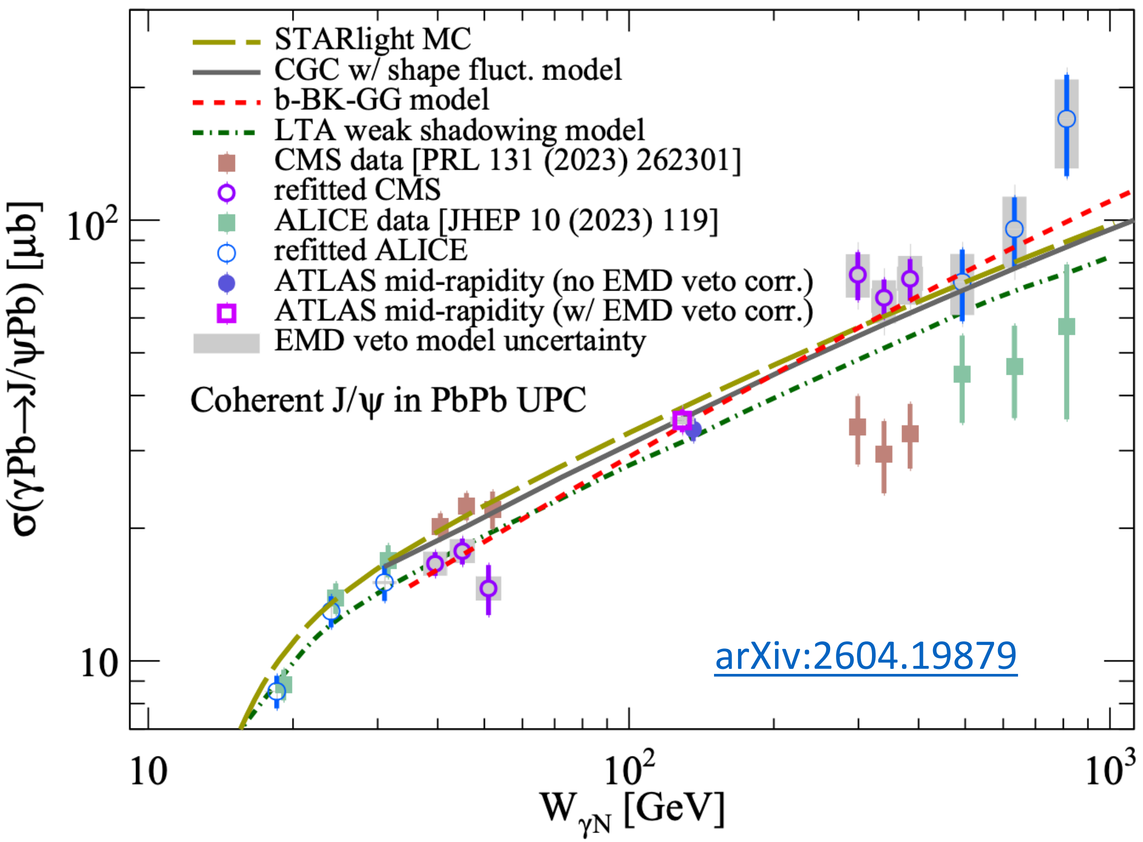
- Suppressed w.r.t. calculation without nuclear effect

Summary

- **First energy-dependent Coh. and Incoh. J/Ψ are measured by CMS**
  - Both are strongly saturated at high energy or small x
  - Ratio of Incoh/Coh J/Ψ stay at a constant
  - Stronger suppression towards lower x, eventually flattens out
  - Incoh. J/Ψ is more suppressed than Coh. J/Ψ
- **First Coh. ϕ photoproduction off heavy nuclei is observed by CMS:**
  - Nuclear suppression factor $\sim\mathbf{5}$
- **First Coh. $\Upsilon(1S)$ photoproduction off heavy nuclei is observed by CMS:**
  - Nuclear suppression factor $\sim\mathbf{4}$
- **First D_0 photoproduction via photonuclear interaction is observed by CMS**
- **The fundamental physics mechanisms governing the small-x regime remain to be fully understood.**

Discussions





Further investigations across multiple experiments, theoretical studies, are needed for a final conclusion.

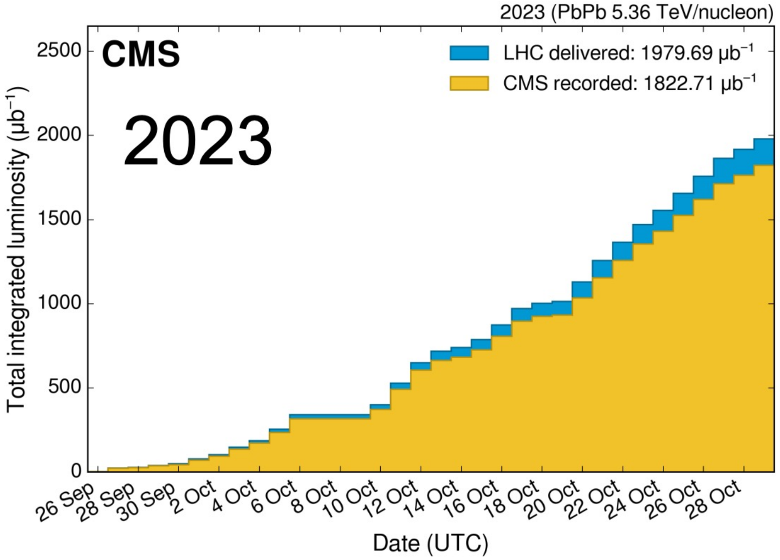
A First Account of the Impact of Ion Electromagnetic Dissociation on Event Exclusivity in Ultraperipheral LHC Collisions

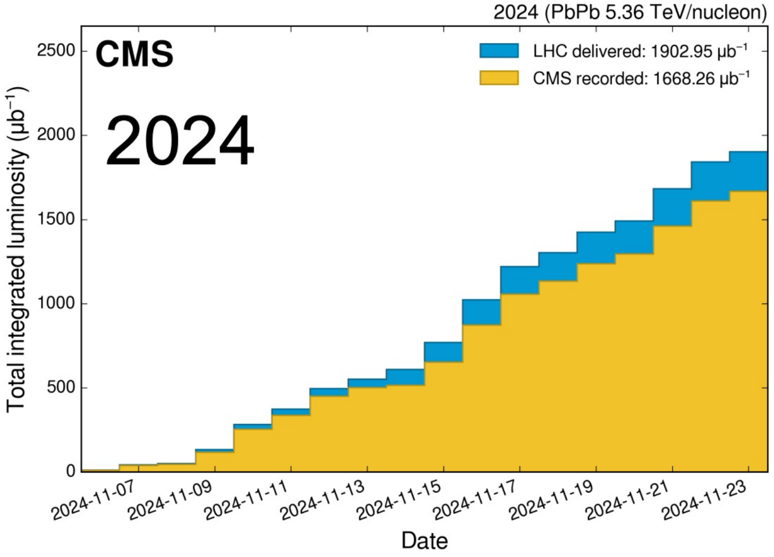
M. Dyndal*
AGH University of Krakow, Faculty of Physics and Applied Computer Science, al. Mickiewicza 30, 30-059 Krakow, PL

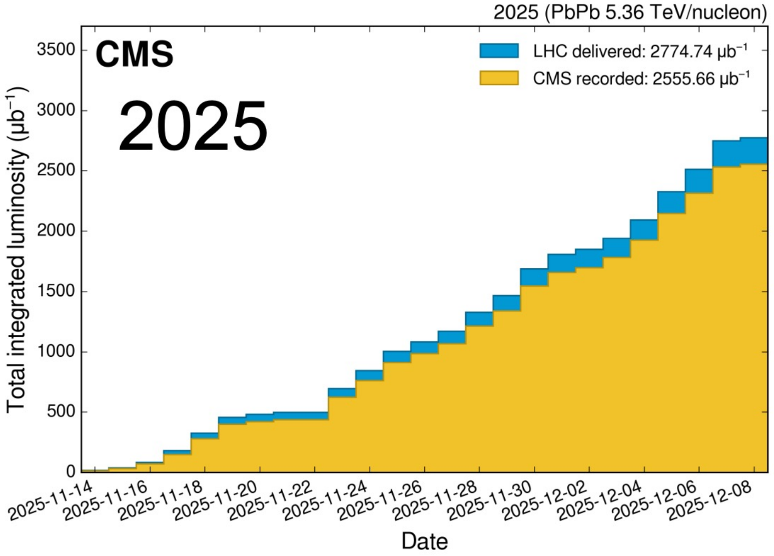
L. A. Harland-Lang†
Department of Physics and Astronomy, University College London, London, WC1E 6BT, UK

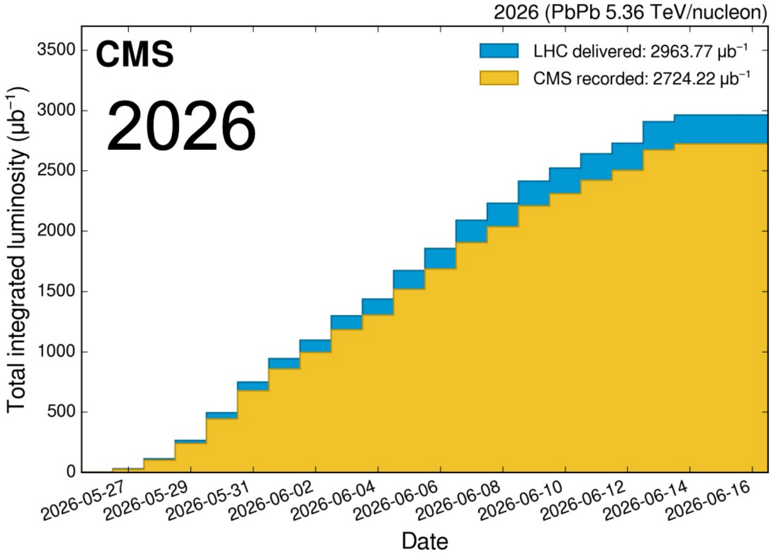
(Dated: April 30, 2026)

Outlook





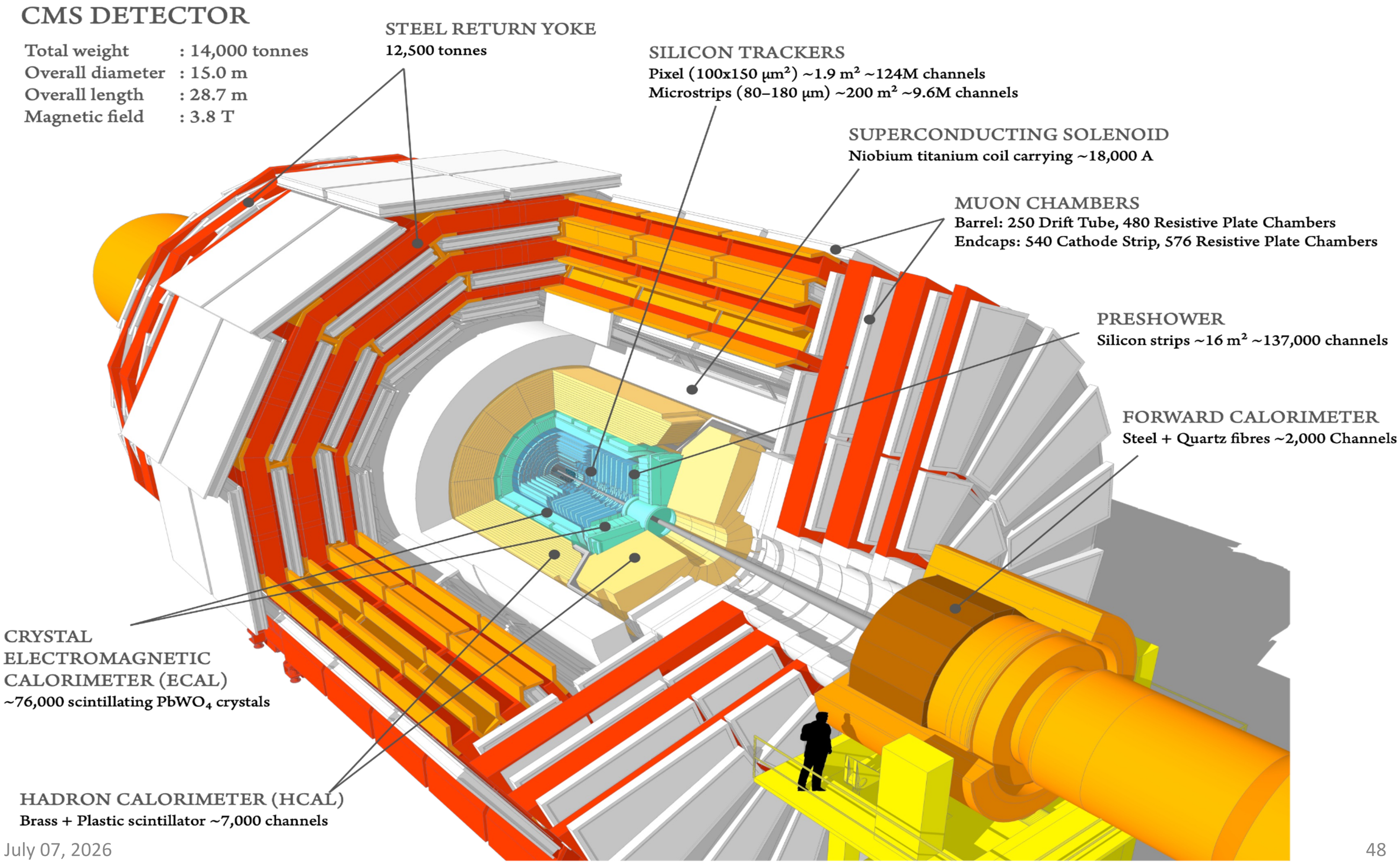




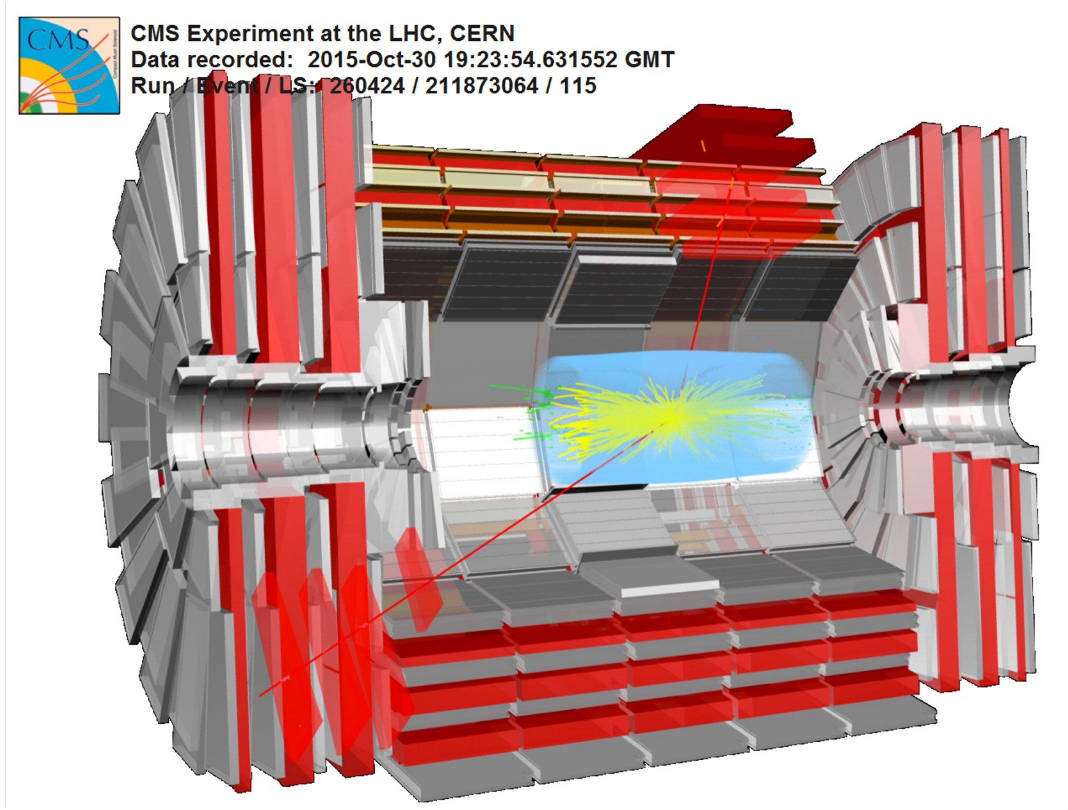
Successful data taking during LHC Run 3 promises a rich program of small-x physics at CMS!

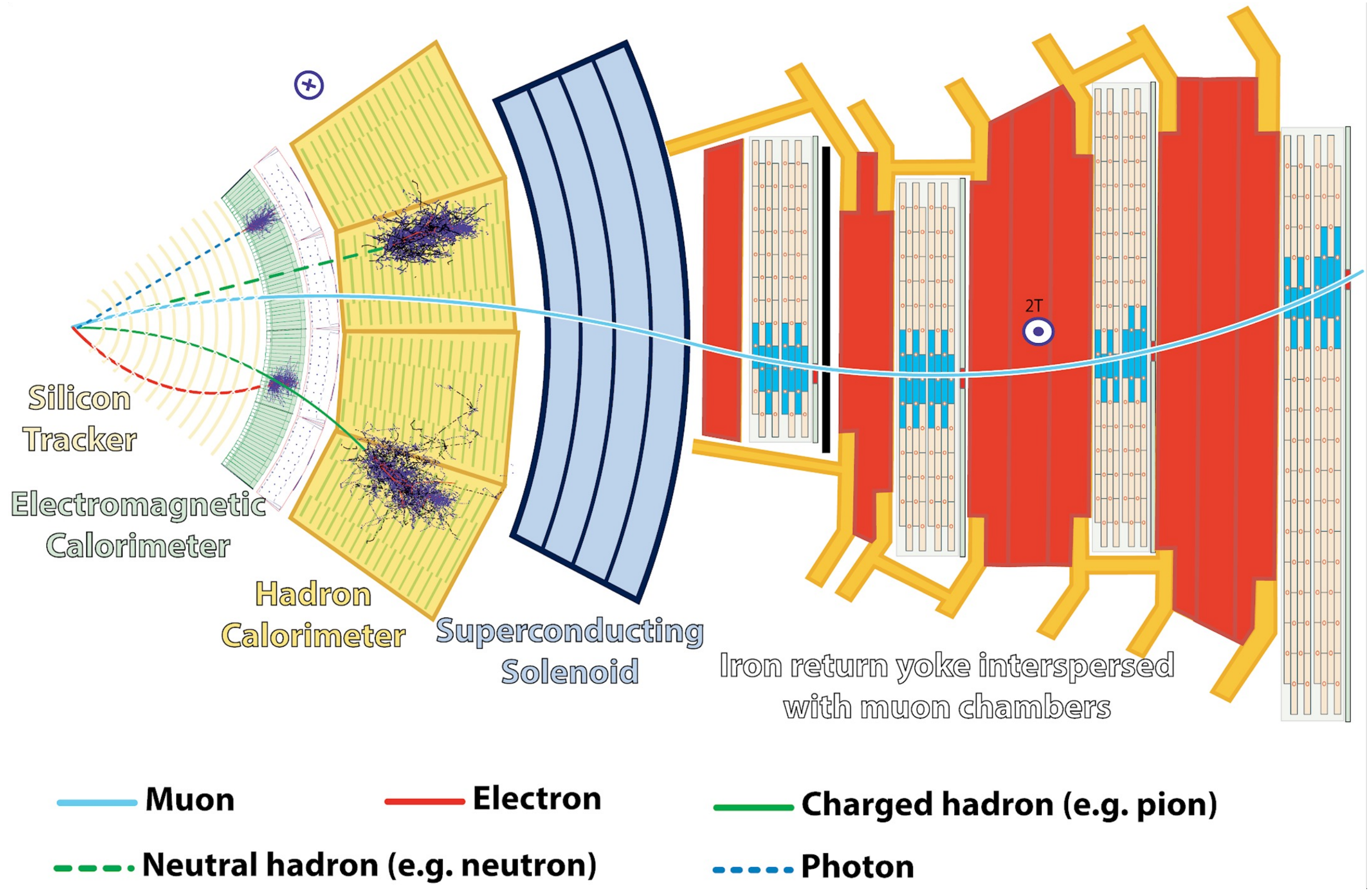
Thanks!

Backup Slides


CMS DETECTOR
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T
STEEL RETURN YOKE
12,500 tonnes
SILICON TRACKERS
Pixel (100x150 μm²) ~1.9 m² ~124M channels
Microstrips (80–180 μm) ~200 m² ~9.6M channels
SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000 A
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 540 Cathode Strip, 576 Resistive Plate Chambers
PRESHOWER
Silicon strips ~16 m² ~137,000 channels
FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels
CRYSTAL
ELECTROMAGNETIC
CALORIMETER (ECAL)
~76,000 scintillating PbWO4 crystals
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

Muon Reconstruction at CMS

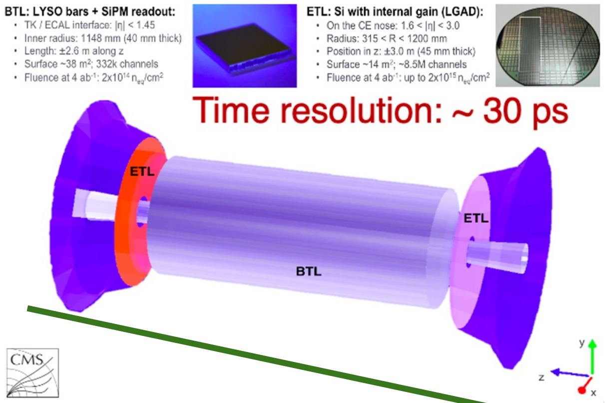




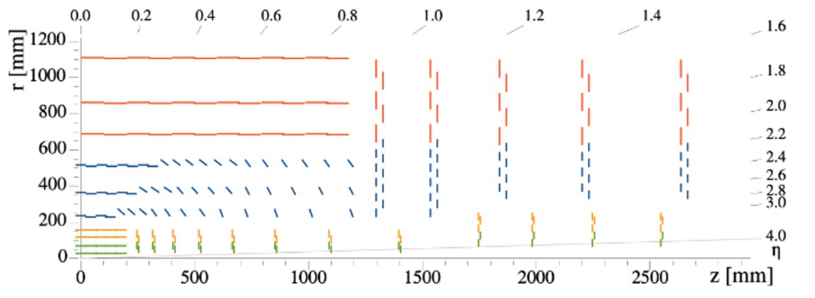
- Tracker and muon detectors used to reconstruct/identify muons.

Future Opportunities

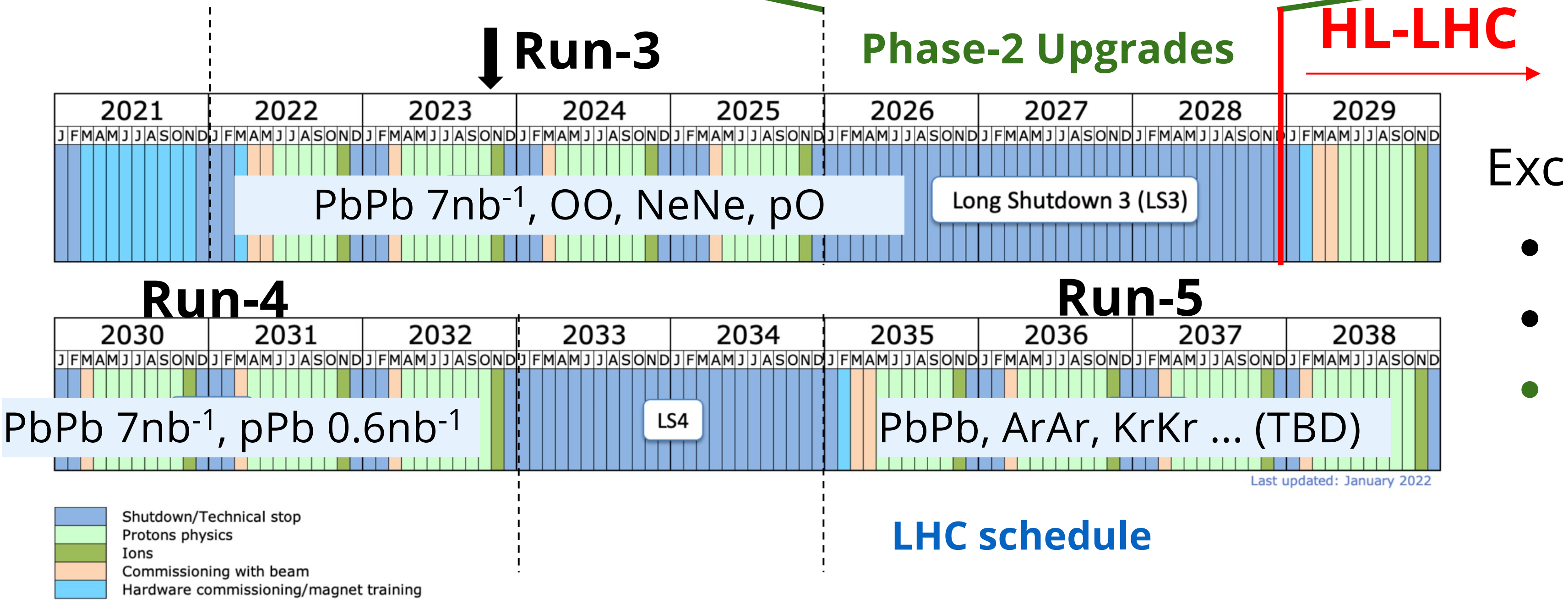
MIP Timing Detector for PID



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



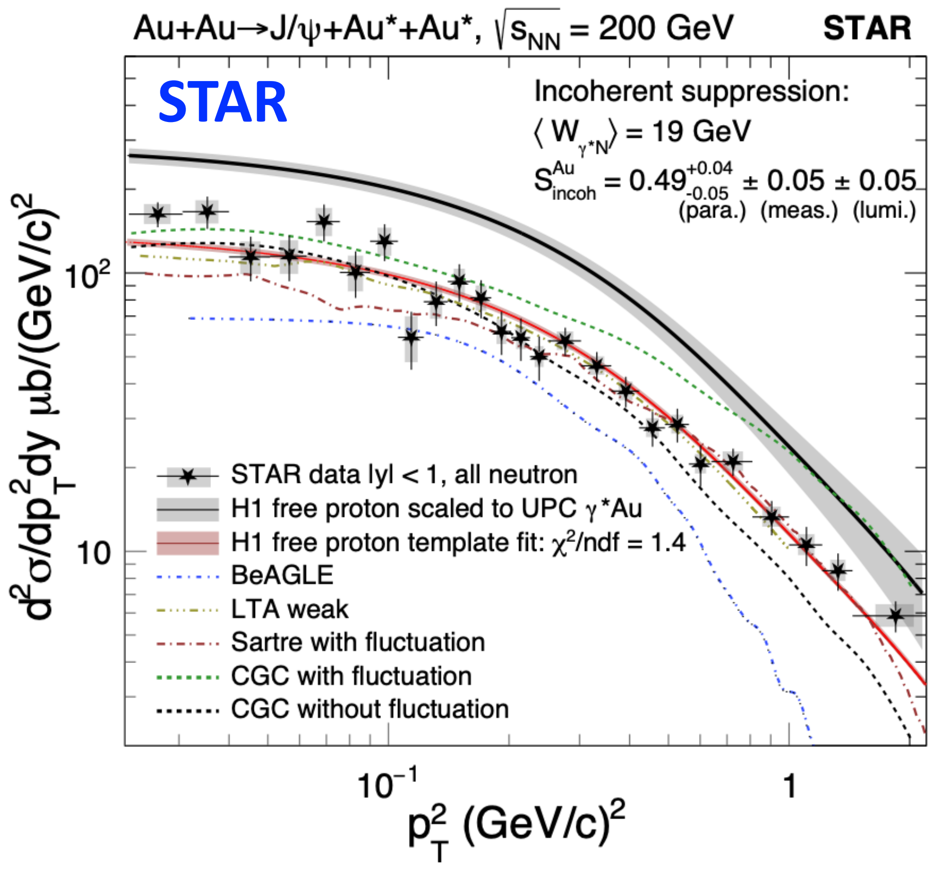
- Muon systems with |η|<**2.8**
- Trigger and DAQ rate: ~**10x**

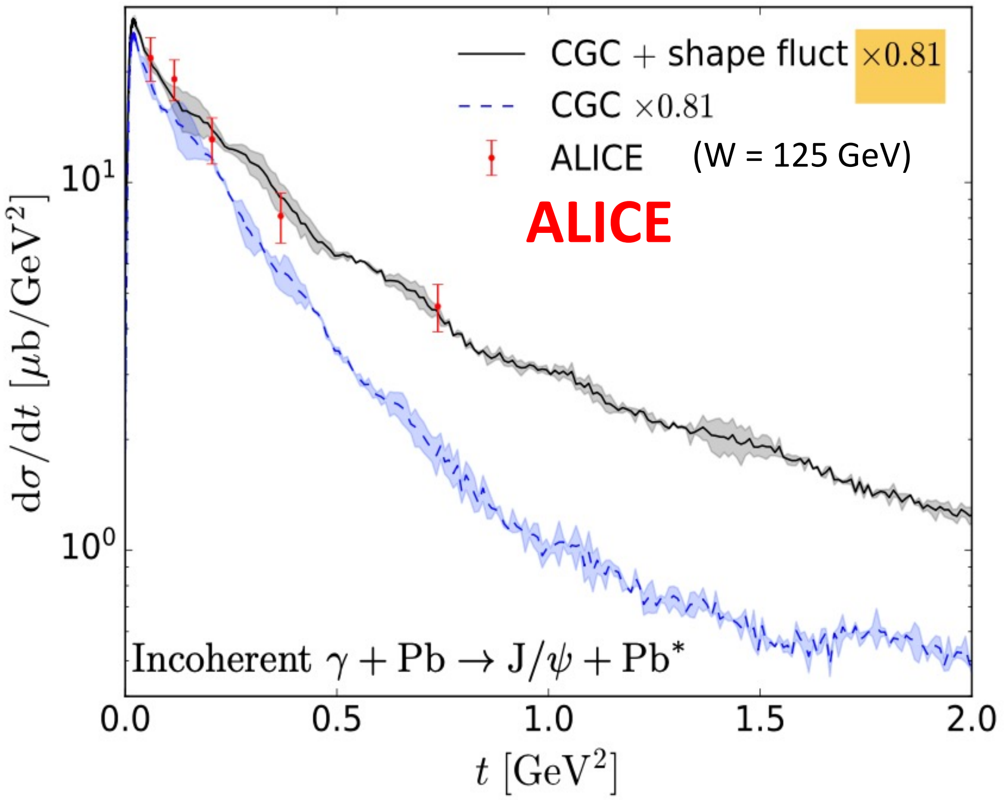


Exciting opportunities ahead by:

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

Fluctuating Gluons Probed via Incoherent γ+Au/Pb





t distribution from STAR: well described by LTA, but in between two scenarios of CGC with and without sub-nucleonic fluctuations

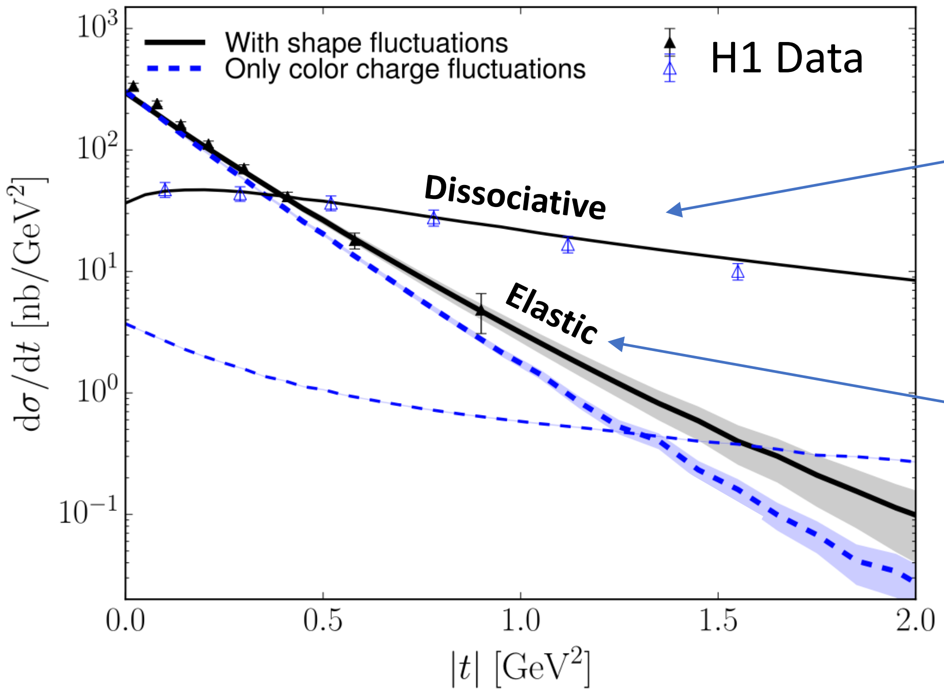
t distribution from ALCIE: slope is well describe by CGC with sub-nucleonic fluctuations however, missed by a common scaling factor

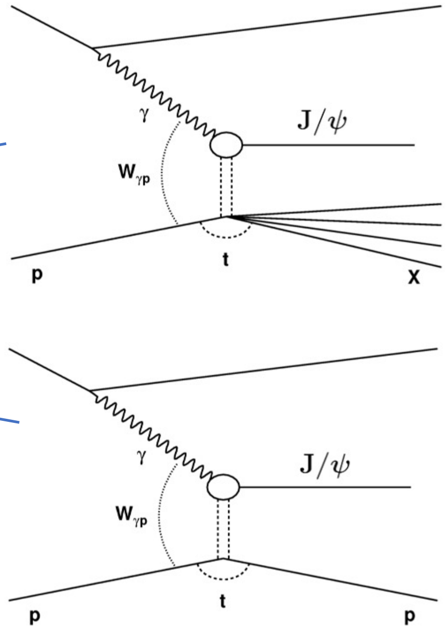
CGC: PRD 109 (2024) 7, L071504
ALICE: PRL 132, 162302 (2024)
STAR: PRC 110 014911 (2024)

Fluctuating Gluons Probed via γ+p

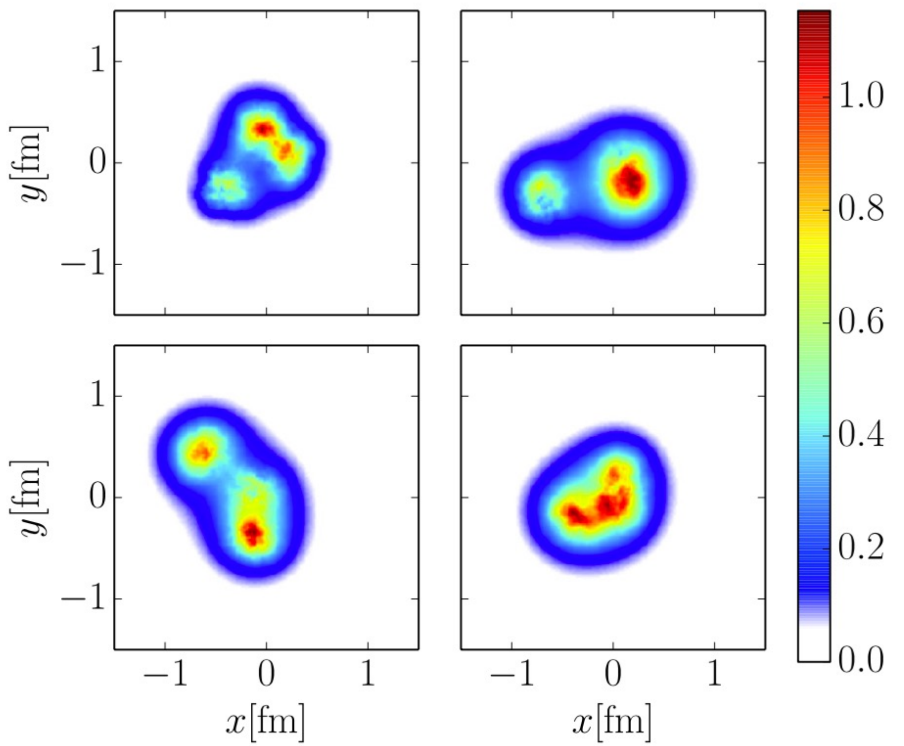
CGC IPsat considering the **fluctuations** of **geometry** (shape and size), **energy density**, **local saturation scale** and **color charge**, successfully describe the HERA data

J/Ψ Photoproduction at HERA



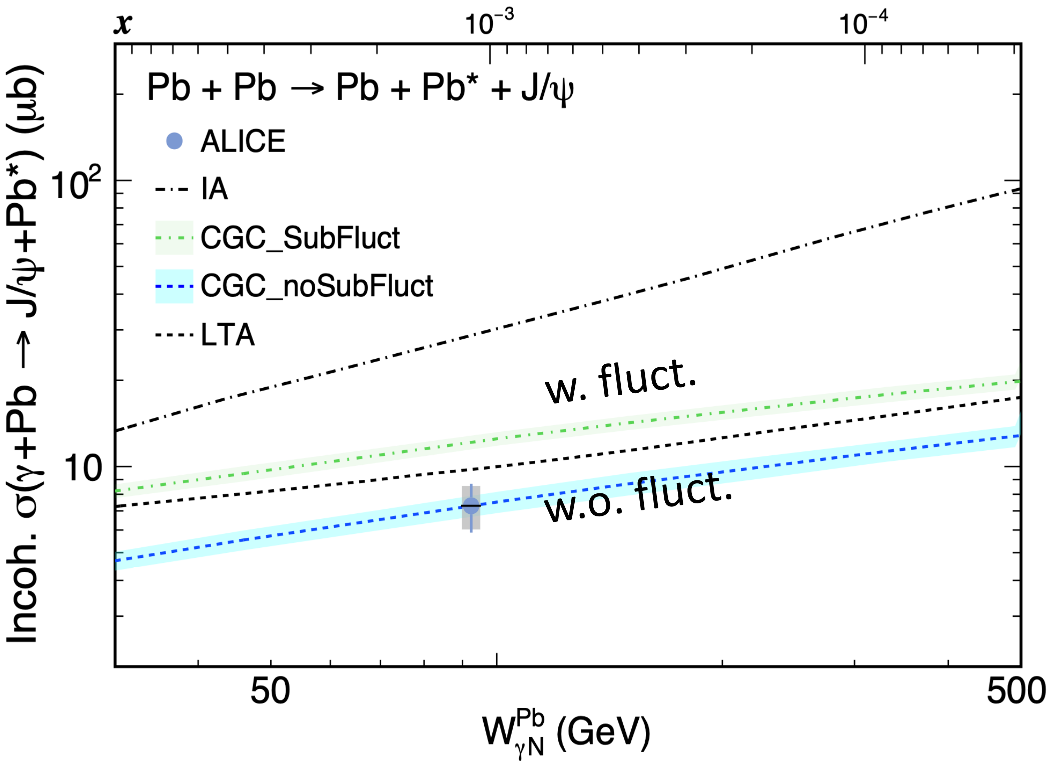


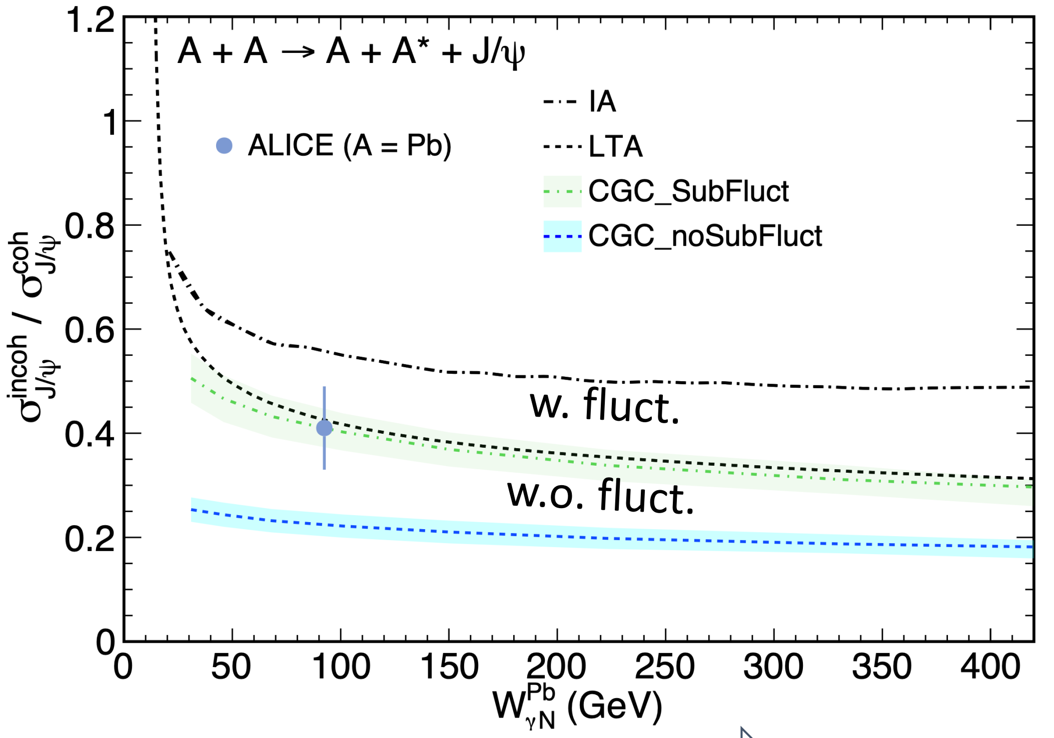
Rep. Prog. Phys. **83** (2020) 082201



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

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**

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

CPC 277 (2022) 108388

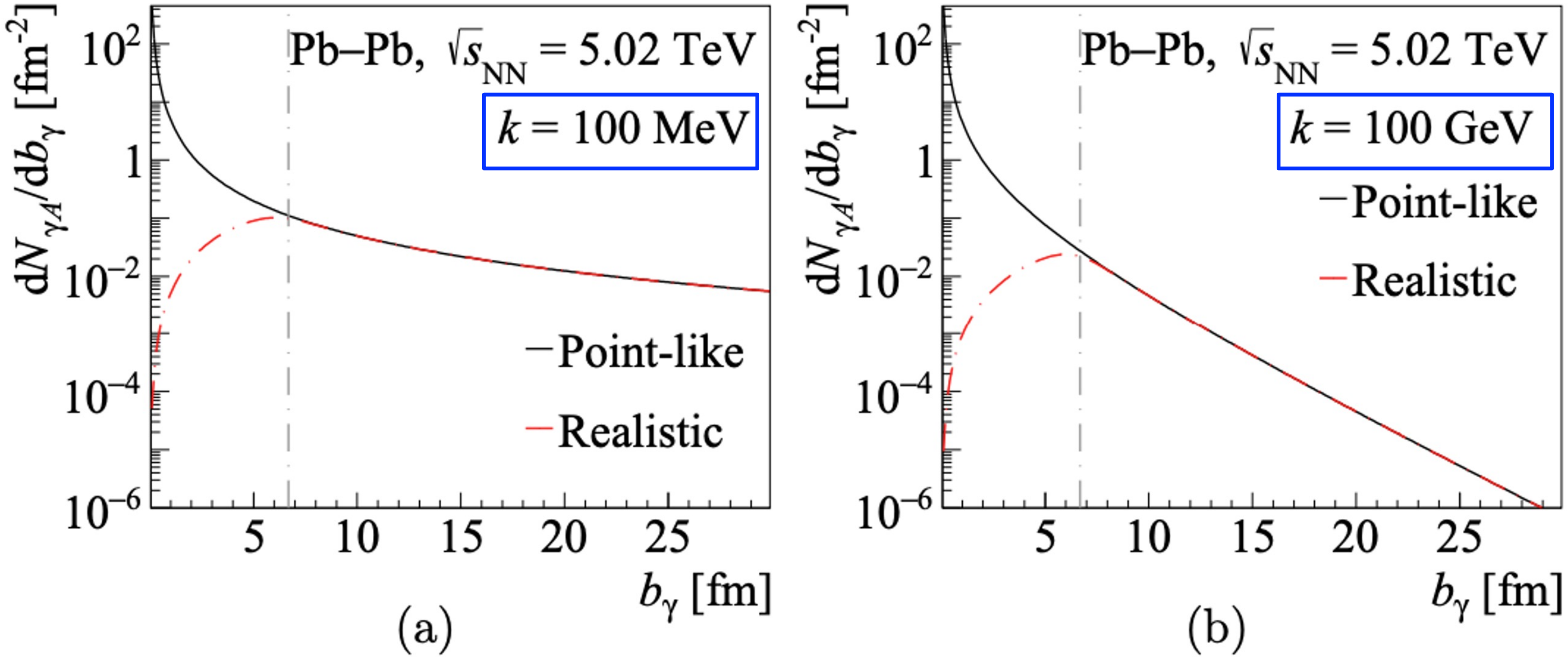
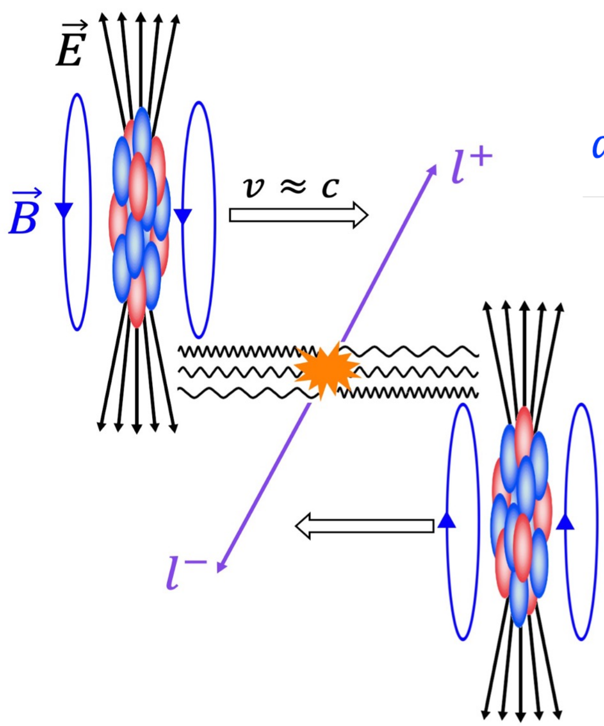


Figure 4: (Color online) Photon fluxes coming from a nucleus $N_{\gamma A}$ in the point-like source approximation and the realistic description as functions of impact parameter b_γ calculated at different photon energies: 100 MeV (a), 100 GeV (b).

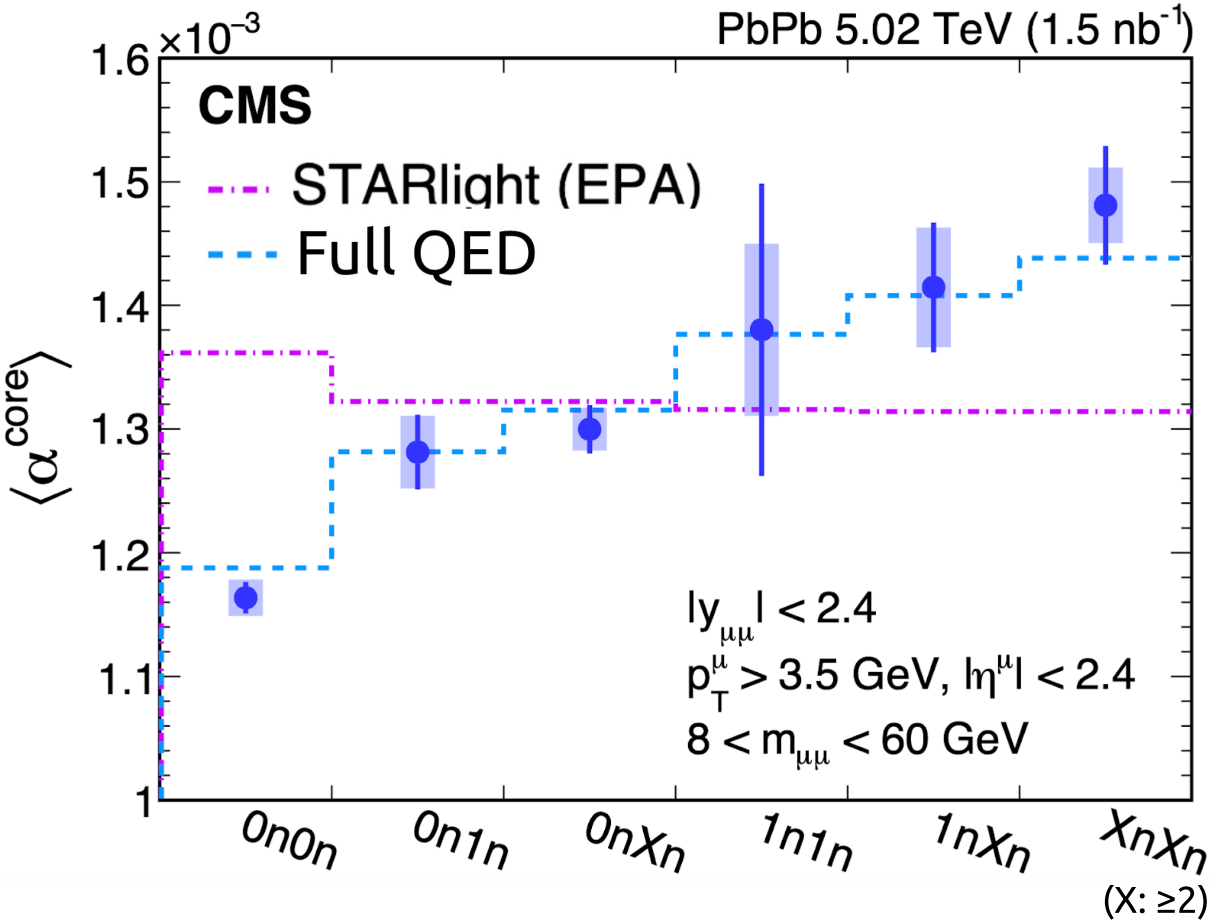
QED Dimuon with Neutron Tagging at CMS

PRL 127 (2021) 122001

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



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



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