Small-x Physics at LHC

(Status and Upgrades)

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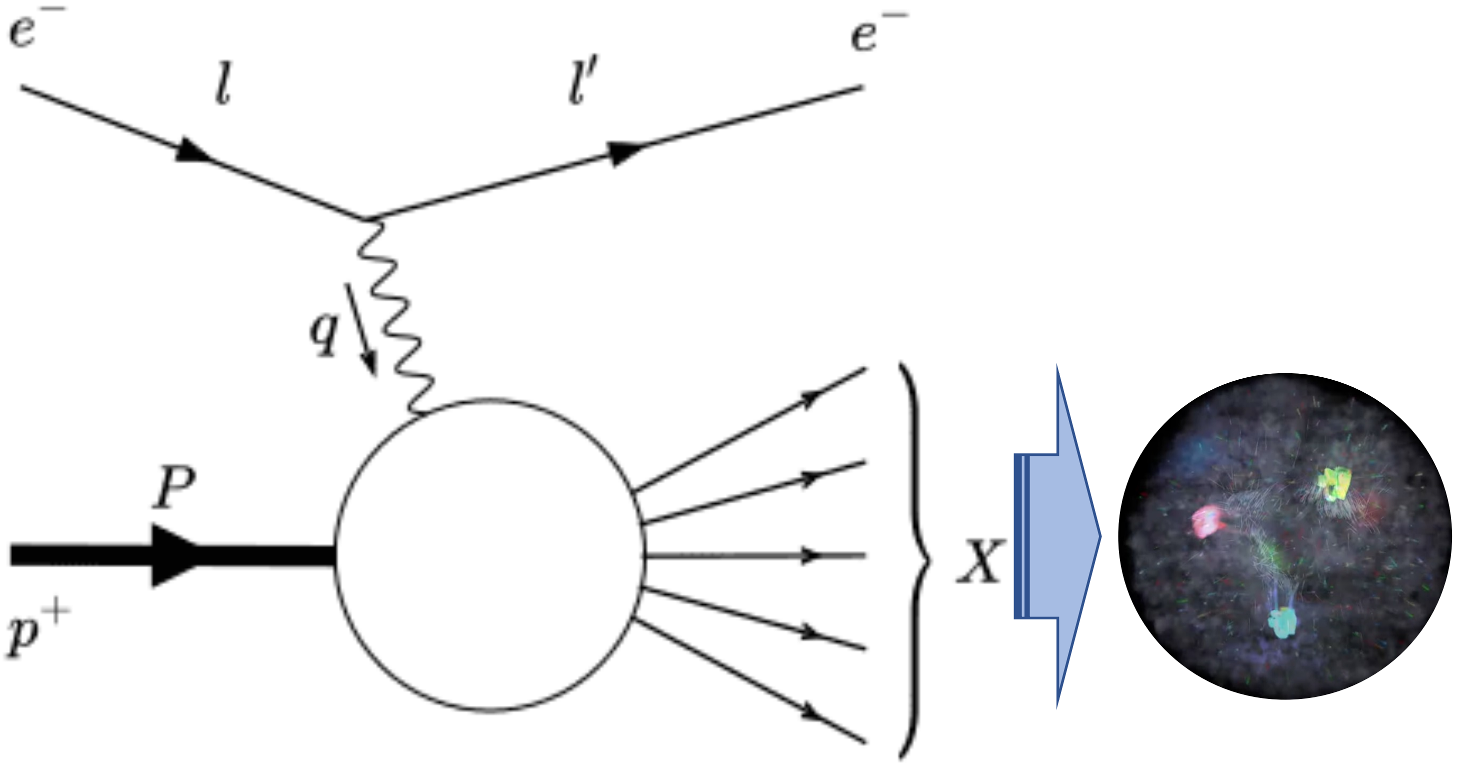
Why Small-x Physics are Important?

Explore the nucleon/nucleus structure via high energy probes



Deep Inelastic Scattering

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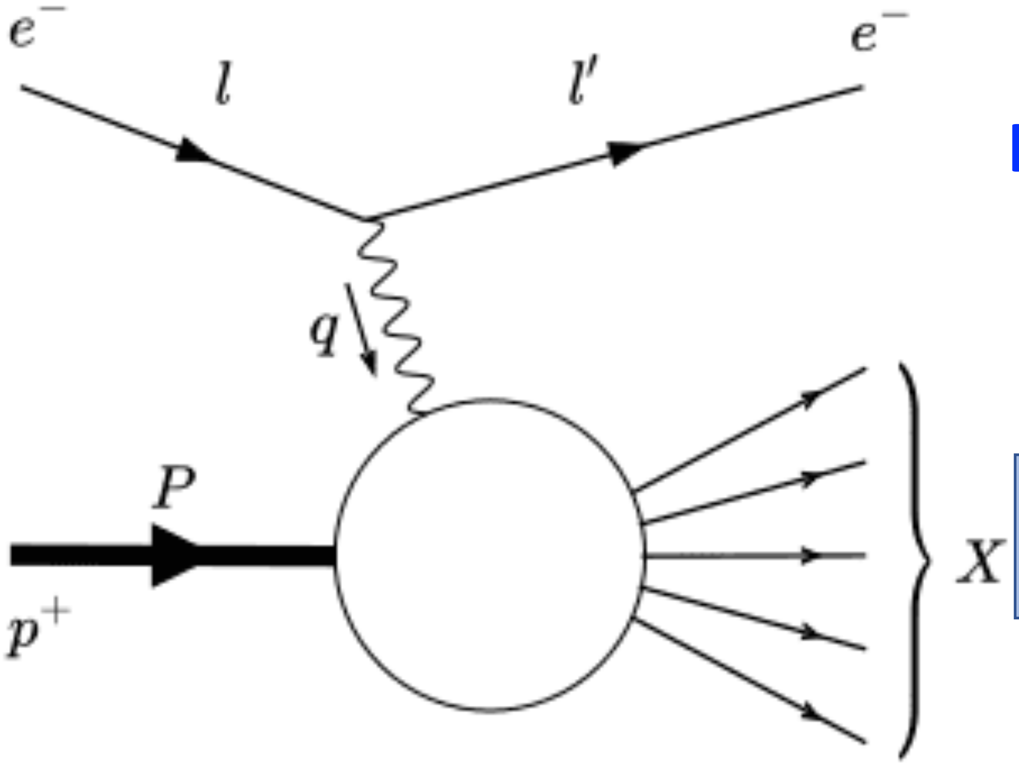
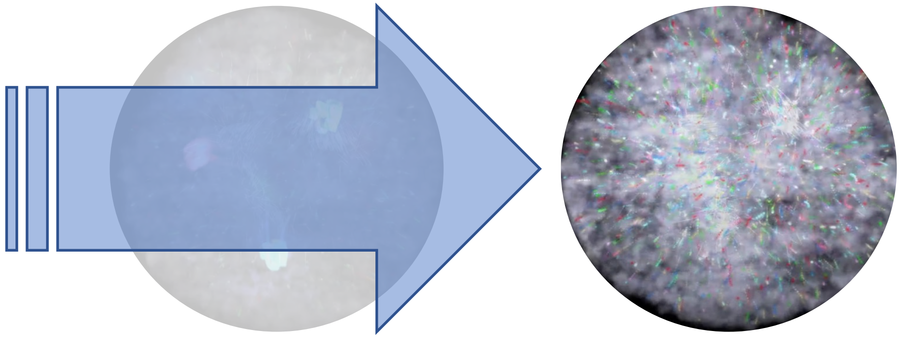


Deep Inelastic Scattering

Higher energy, probing lower-x partons



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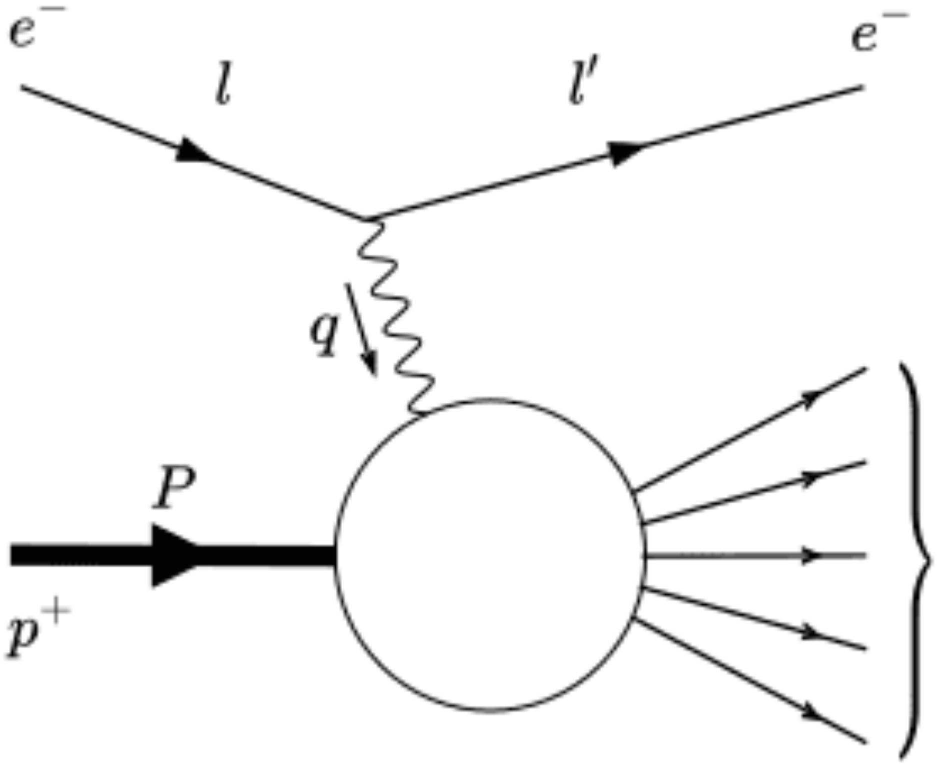

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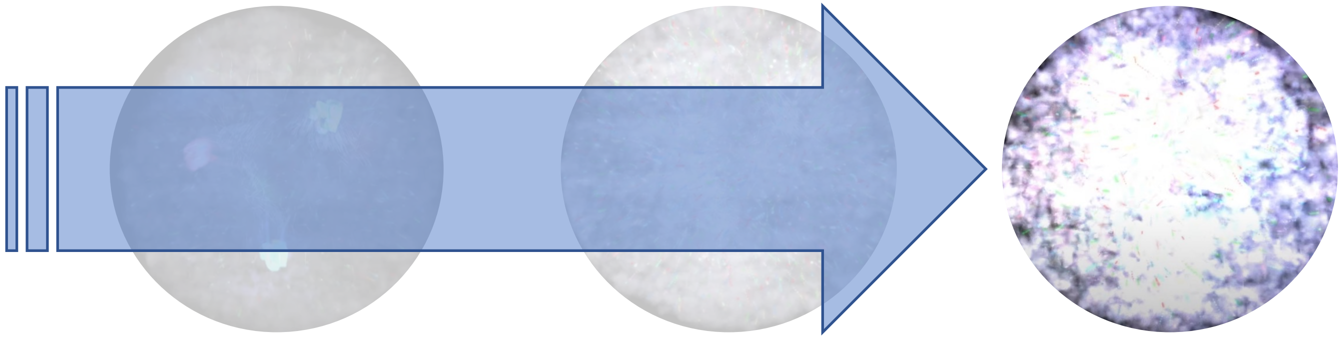

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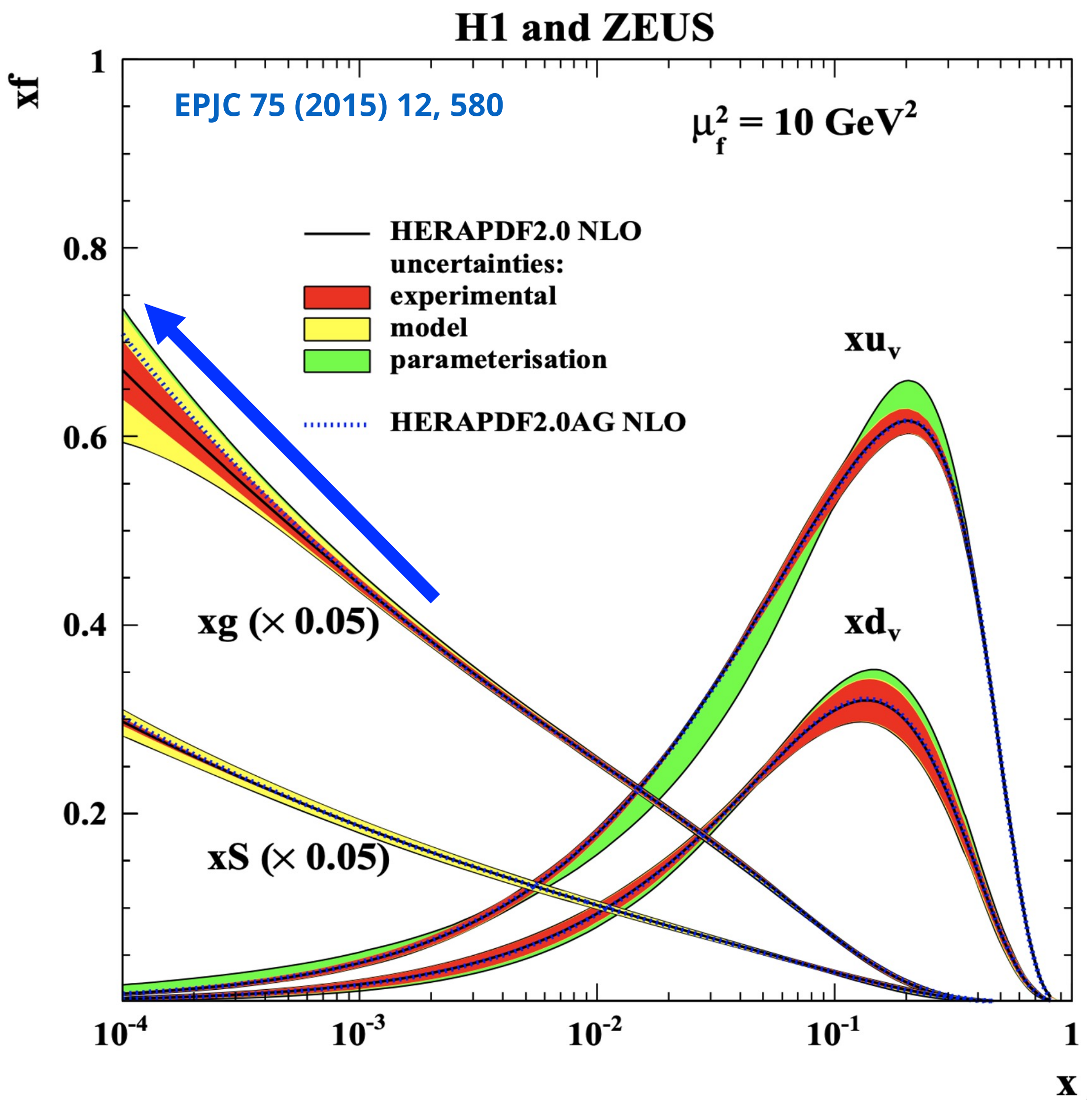
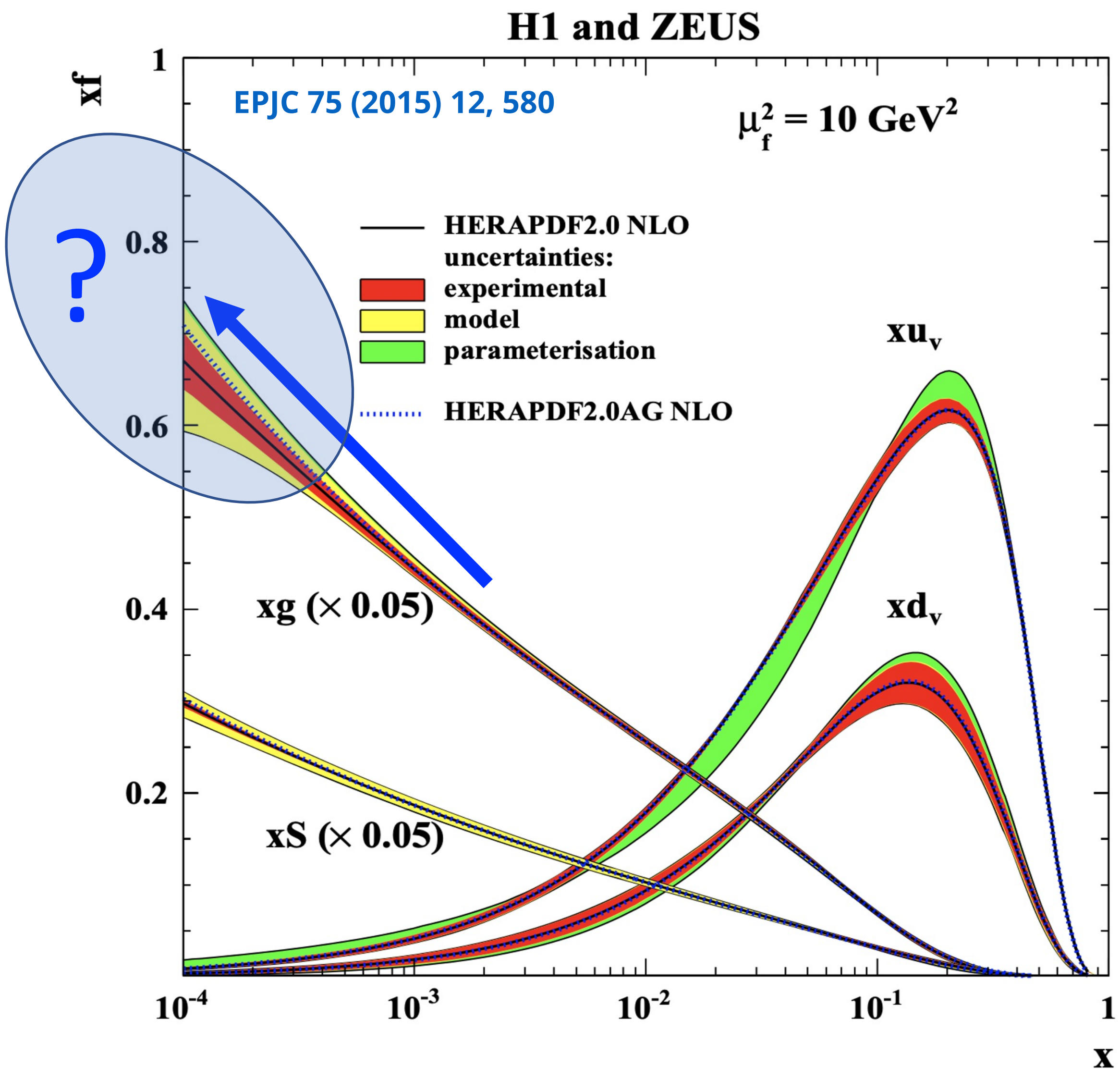


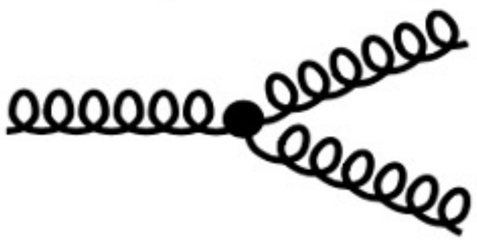
Why Small-x Physics are Important?

What is the fate of gluons at extreme densities?



Why Small-x Physics are Important?

Splitting

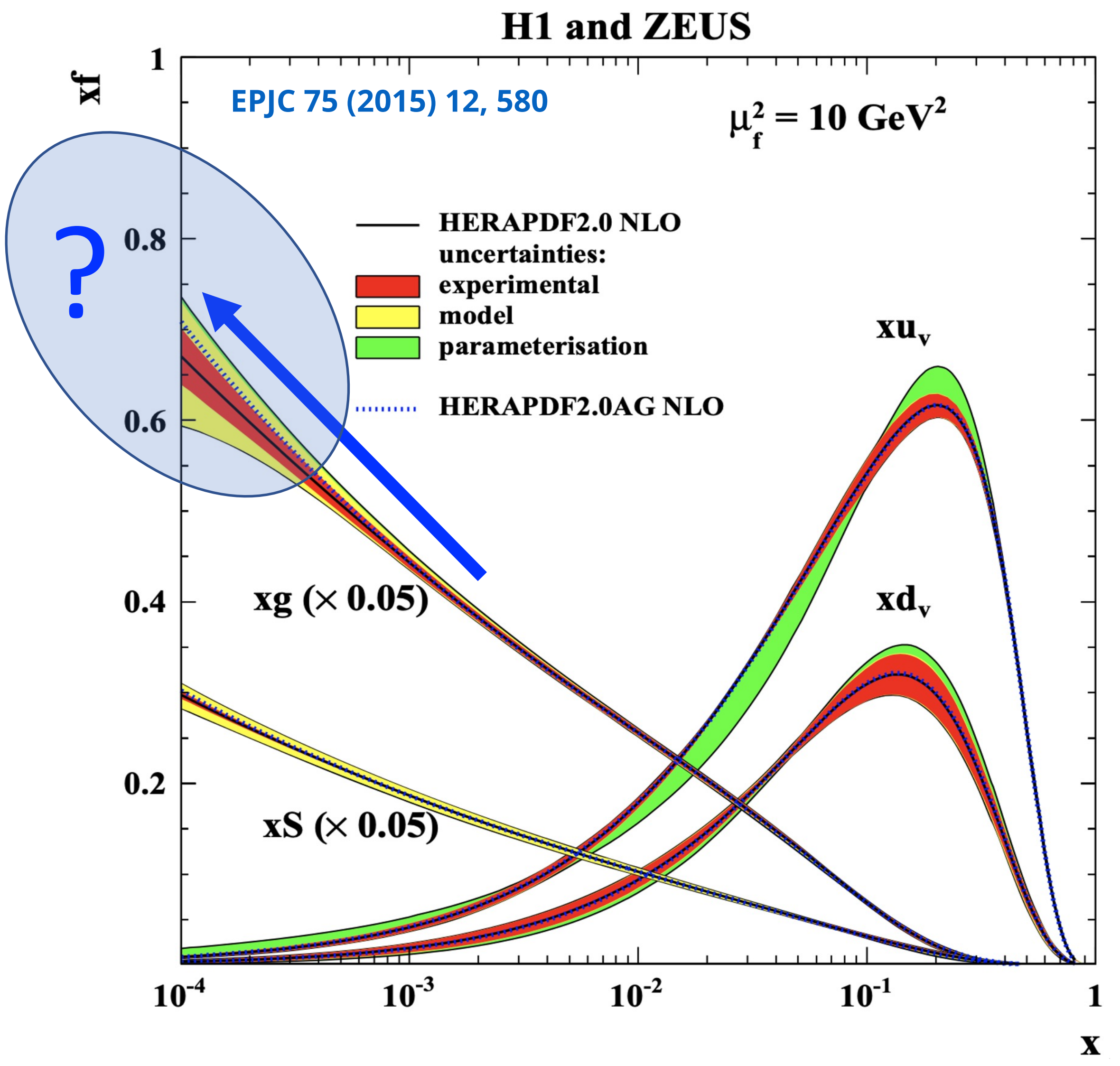


$\sim N_g$ (linear)

Gluon Saturation?

Recombination

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



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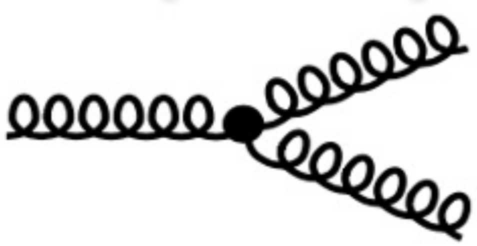


$\sim N_g$ (linear)

Gluon Saturation?

Recombination

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

➢ Why "Gluon Saturation" matters?

- ❑ **A new regime of QCD:**

  Reveals transition from Linear to **nonlinear** QCD dynamics

- ❑ **A natural limit to gluon growth:**

  Prevents the unlimited growth of gluon density and preserves unitarity

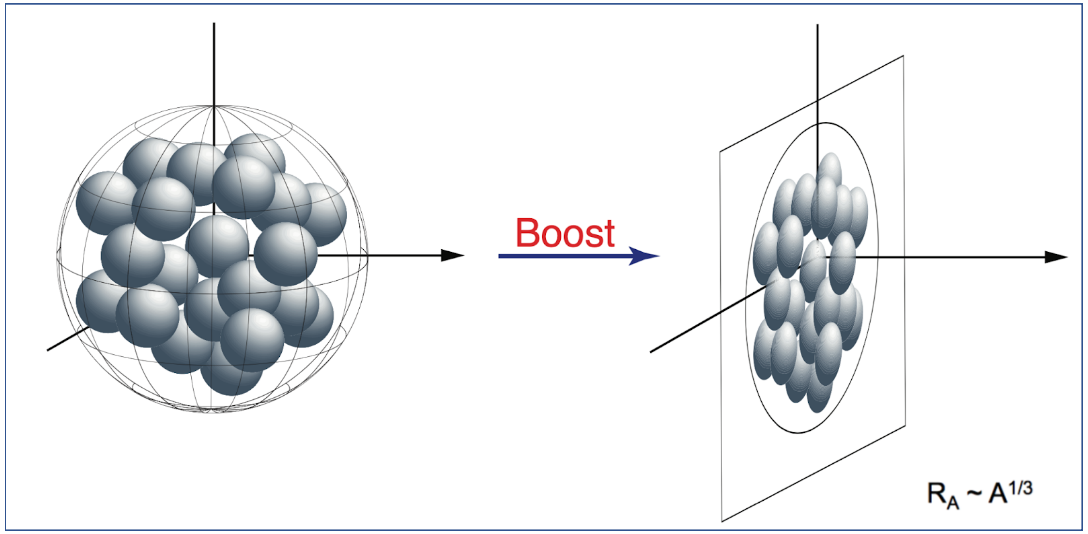
- ❑ **A fundamental aspect of hadron/nuclear structure:**

  Determines gluonic structure at high-energy (small-x) limit

- ❑ **A key ingredient for understanding HI collisions:**

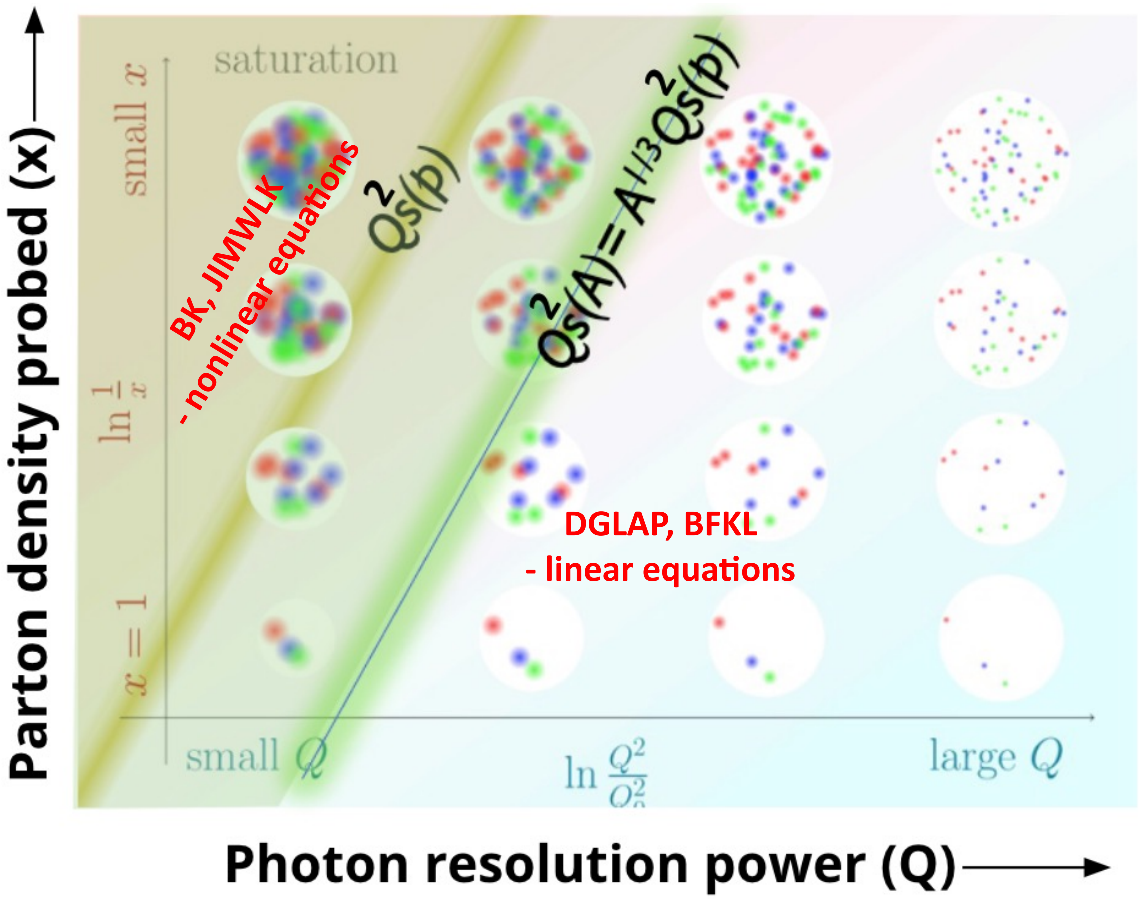
  Set the initial conditions, shaping particle production and early dynamics of QGP

Advantages of Gluon Saturation Search in Nucleus



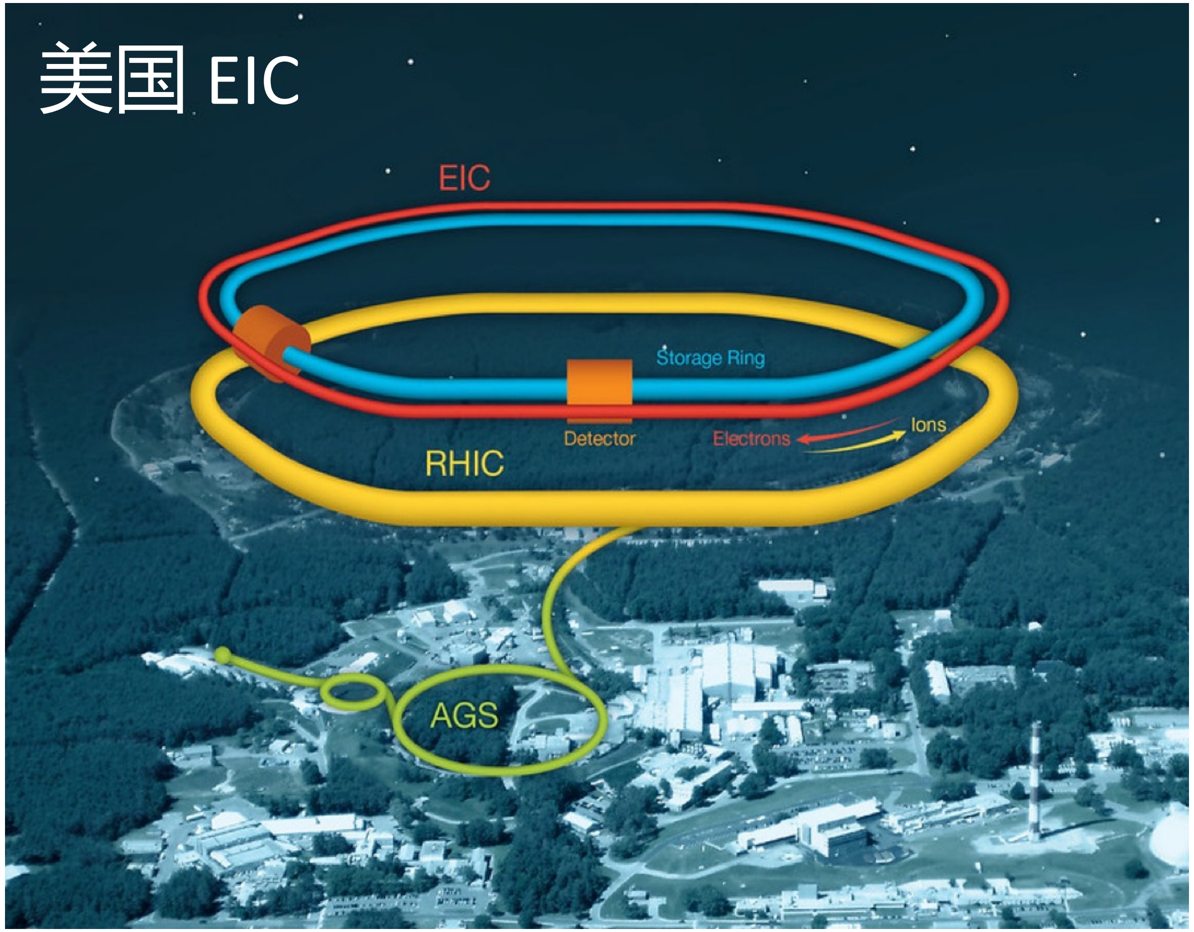
Gluons is **enhanced** by a factor of $A^{1/3}$ in **nucleus** compared to what in free nucleon

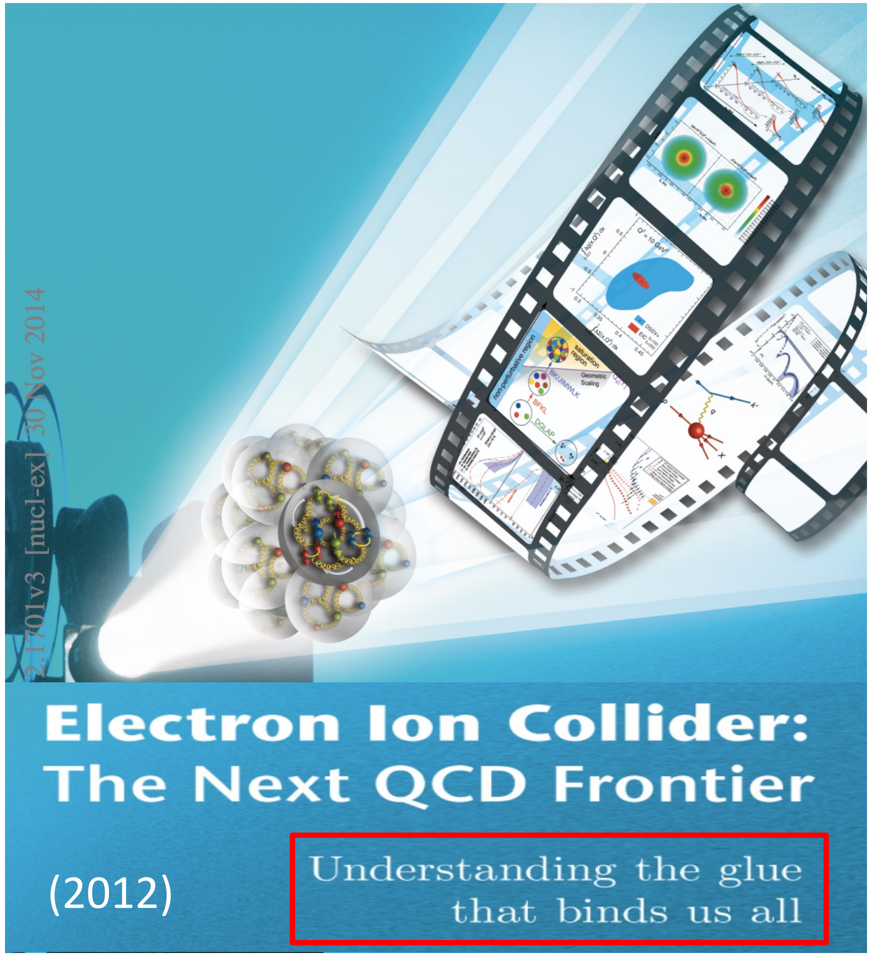
Saturation scale: $Q_s^2 \sim A^{1/3} \left(\frac{1}{x}\right)^{\lambda}$



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

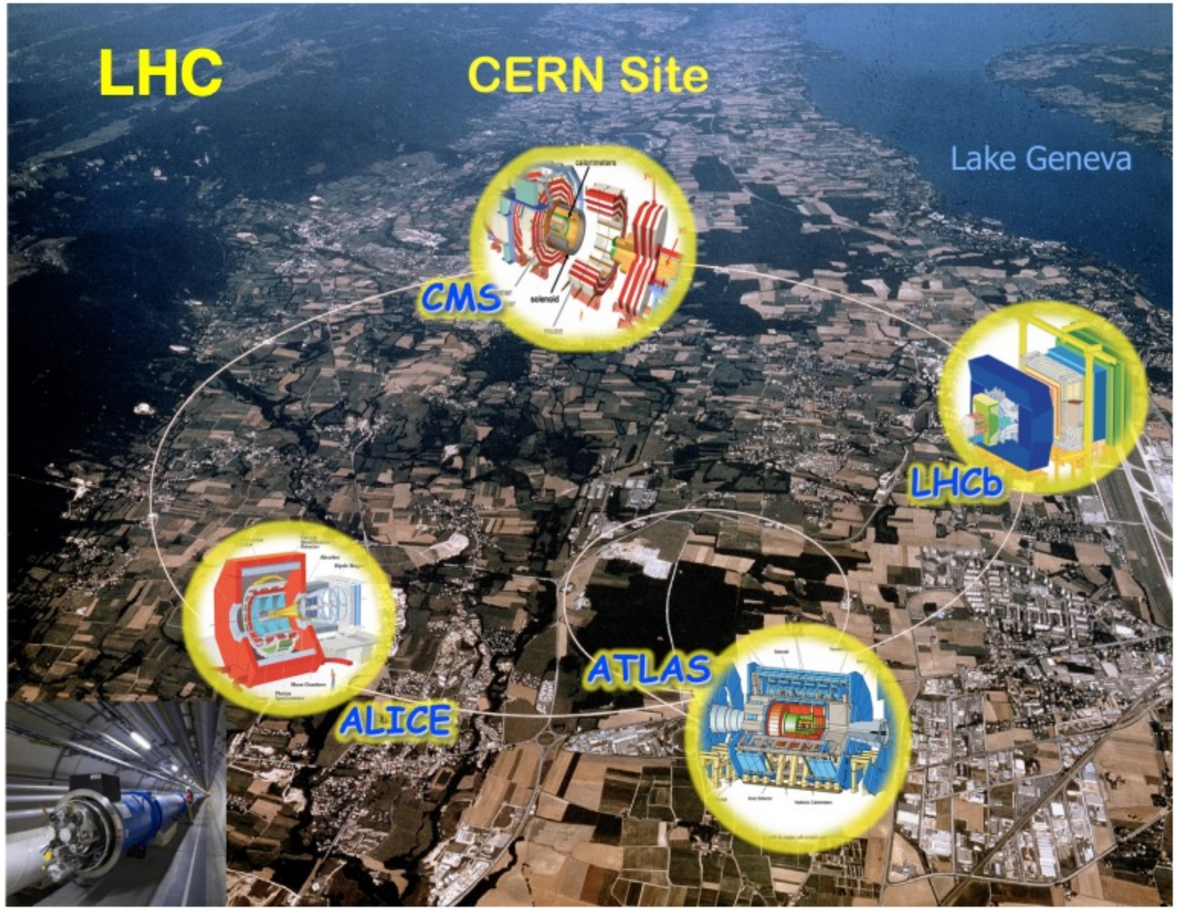
Key Goal of Future Electron Ion Collider





- ➢ Exploring small-x gluon dynamics is one of the key goals of EIC.
- ➢ But: EIC operation is still $\sim$10 (+?) years away.

Advantages of Studying Small-x Physics at LHC



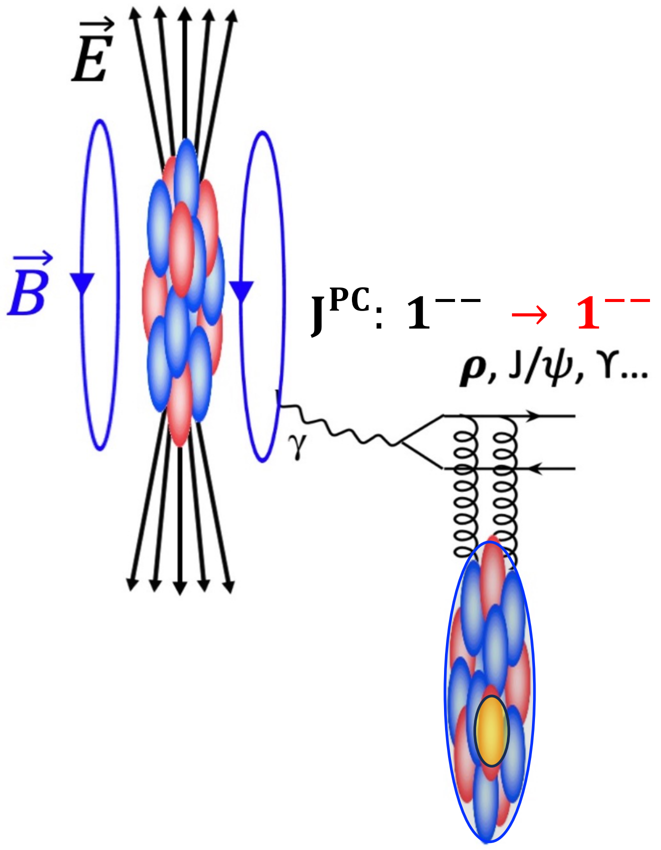
- The LHC provides a unique opportunity to explore high-density QCD at **unprecedented energies**, reaching the **smallest-x** regime ever accessible.

Wide range of collision systems and energies:

- pp, pPb, **PbPb**, XeXe, OO, NeNe, p-O
- PbPb @ 2.76, 5.02, 5.36 TeV

Probe Nuclear Gluonic Structure via VMs in UPCs

Vector Meson photoproduction is sensitive to the gluonic structure of target nucleus



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

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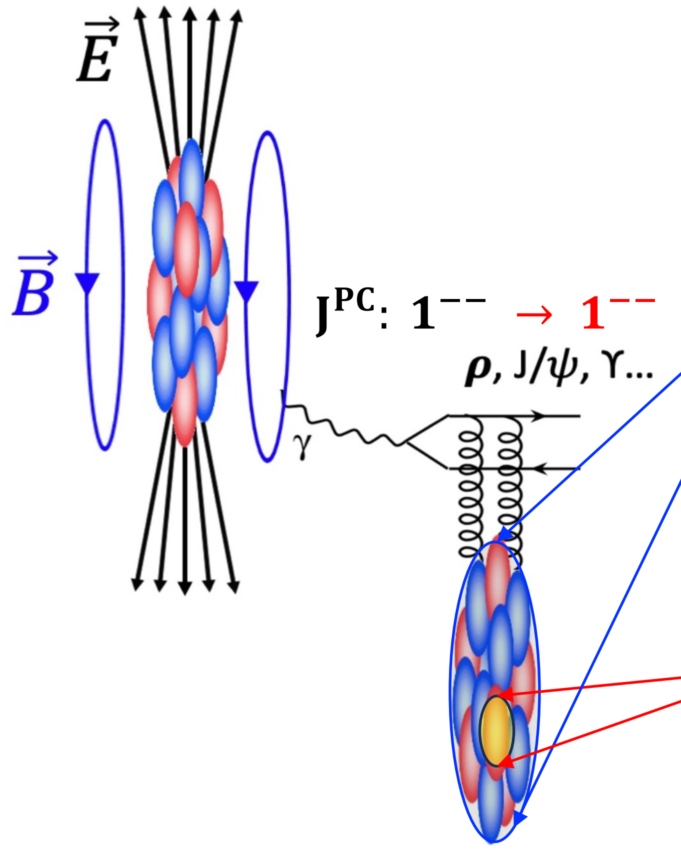


$\sigma \propto [xG(x,Q^2)]^2$

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**

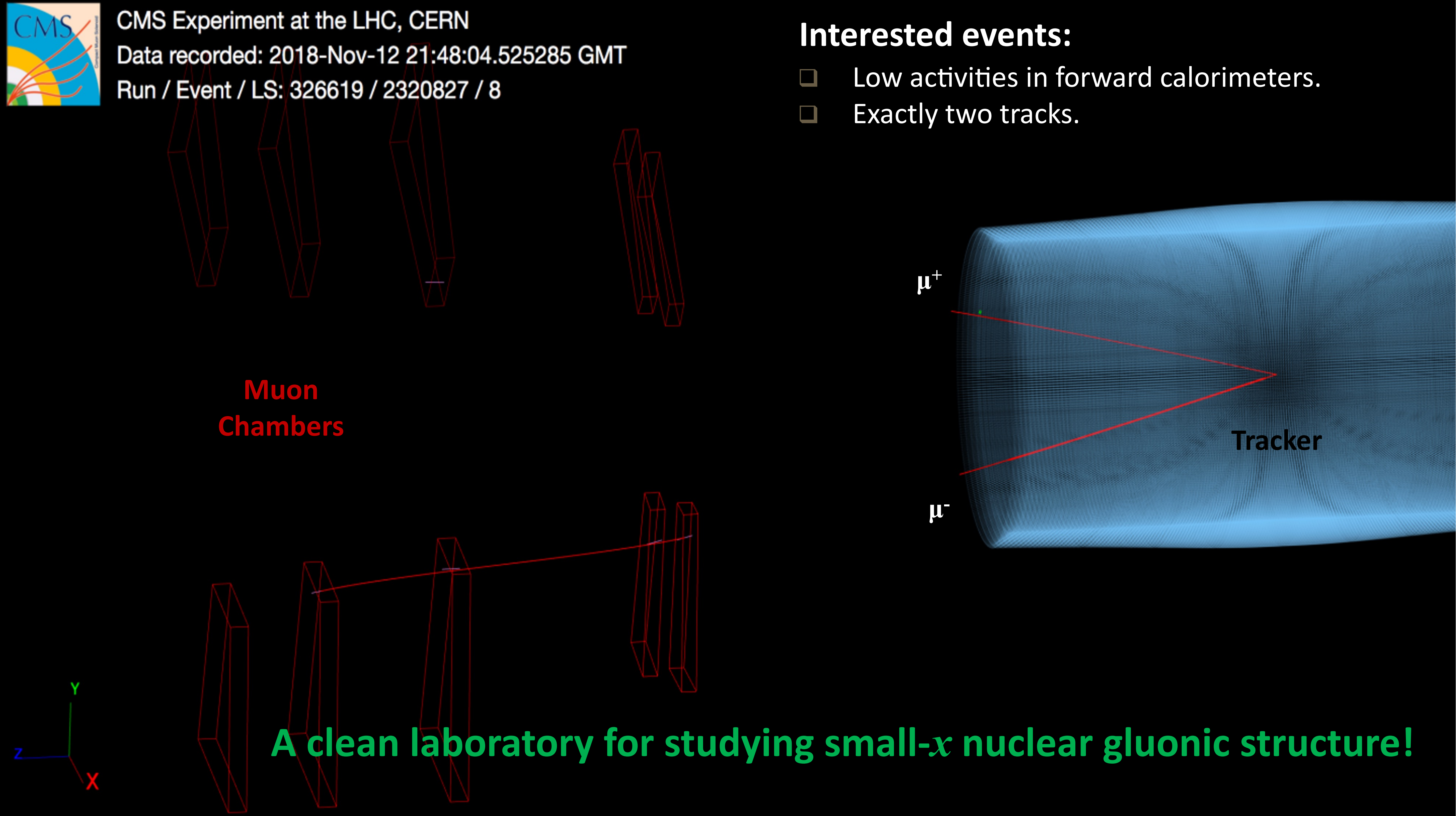
Incoherent production:

- 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**

Excellent probe for the gluon saturation search!

Interested events:

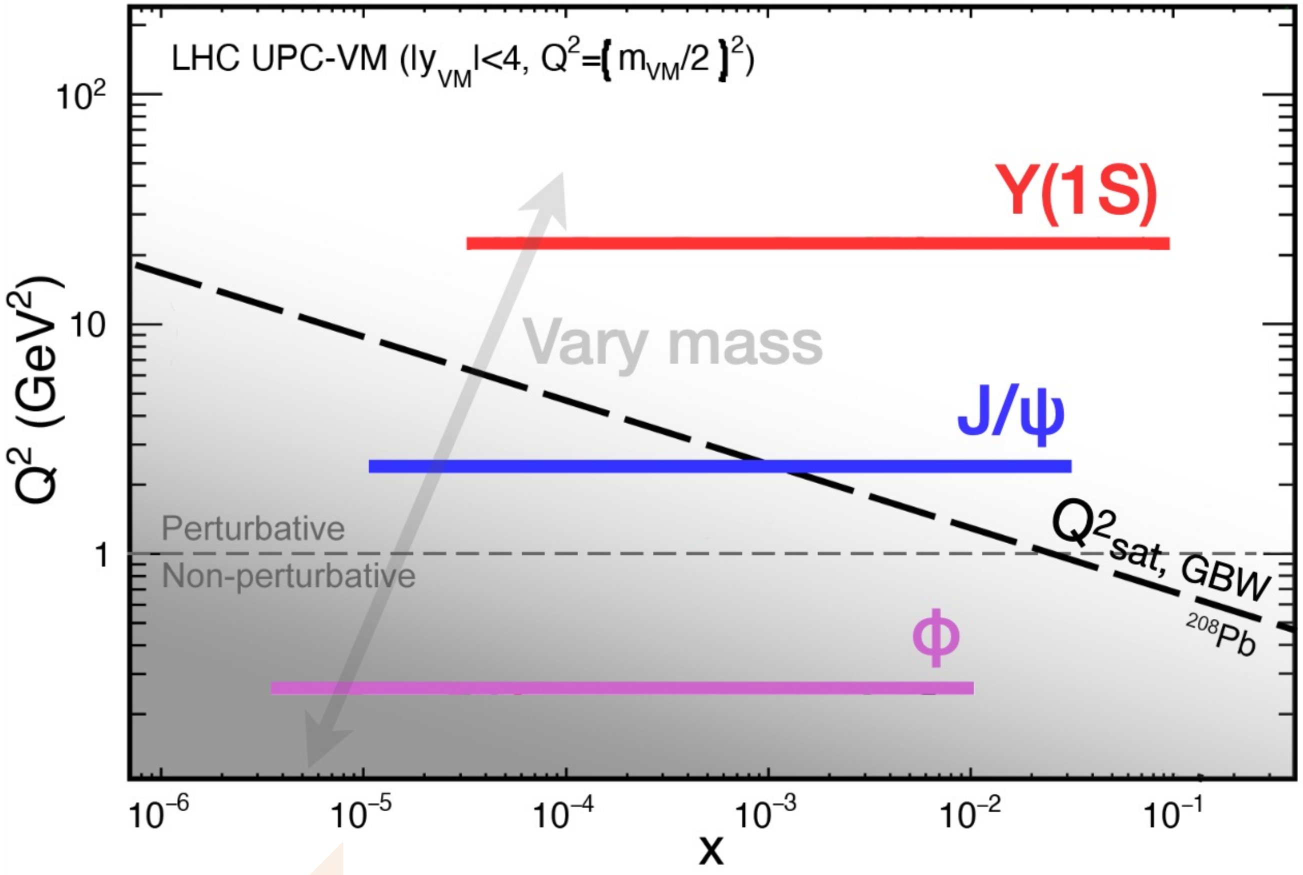
- Low activities in forward calorimeters.
- Exactly two tracks.



A clean laboratory for studying small-x nuclear gluonic structure!

Probe Nuclear Gluonic Structure via VMs in UPCs

Explore in 2 dimensions: Q^2 vs. x



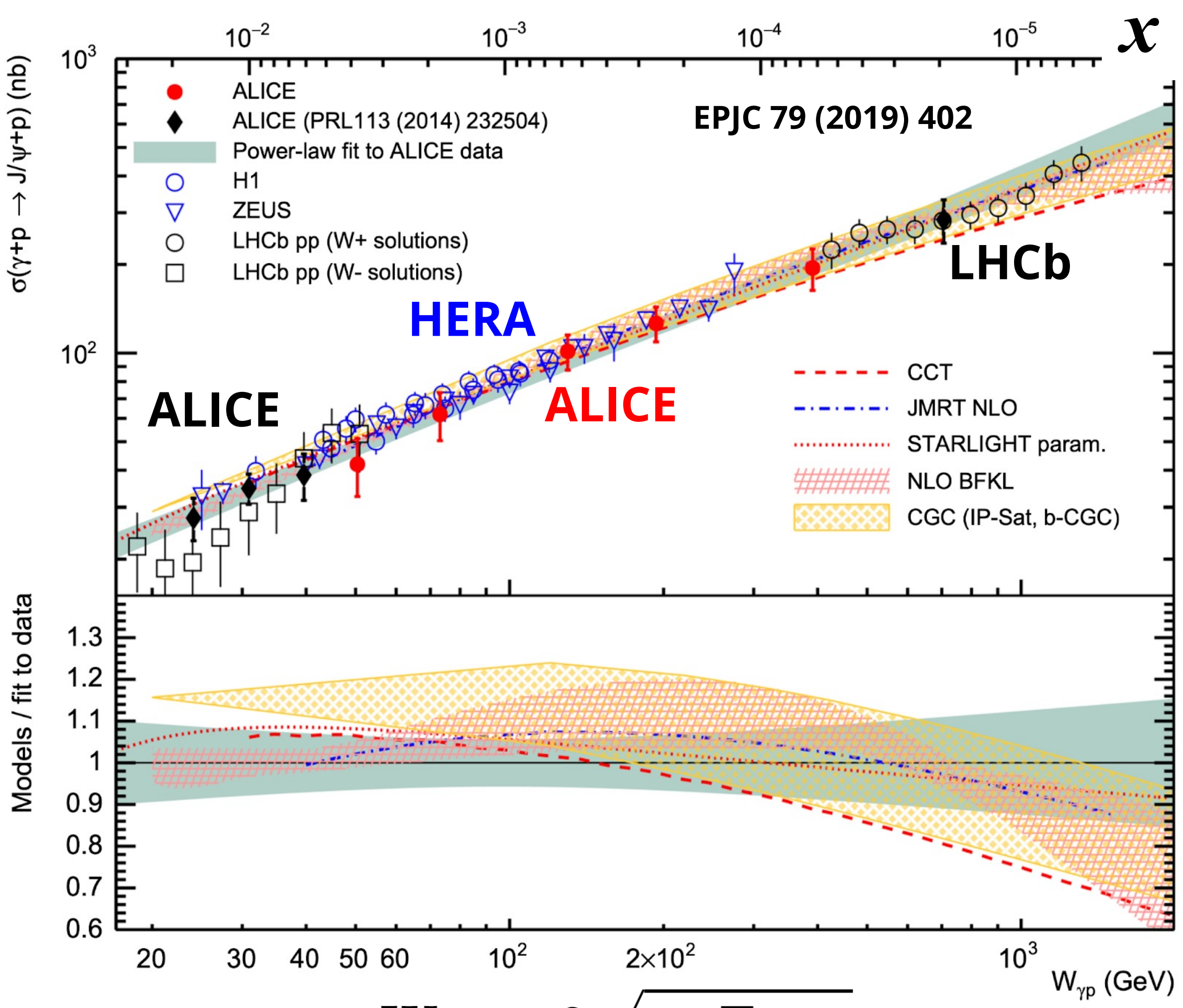
Lighter VM

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

Higher energy

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

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



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

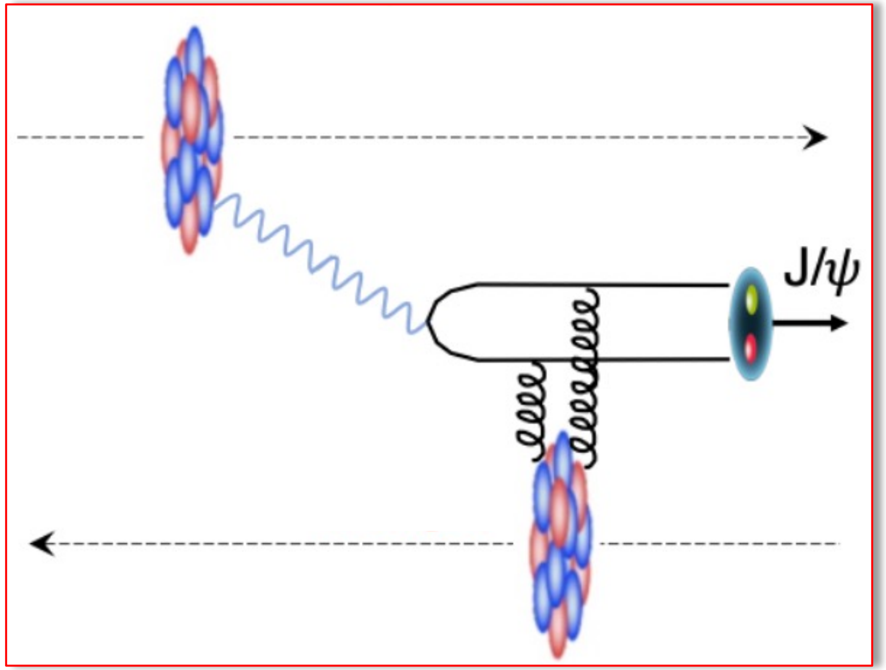
$$\gamma + p \rightarrow J/\psi + p$$

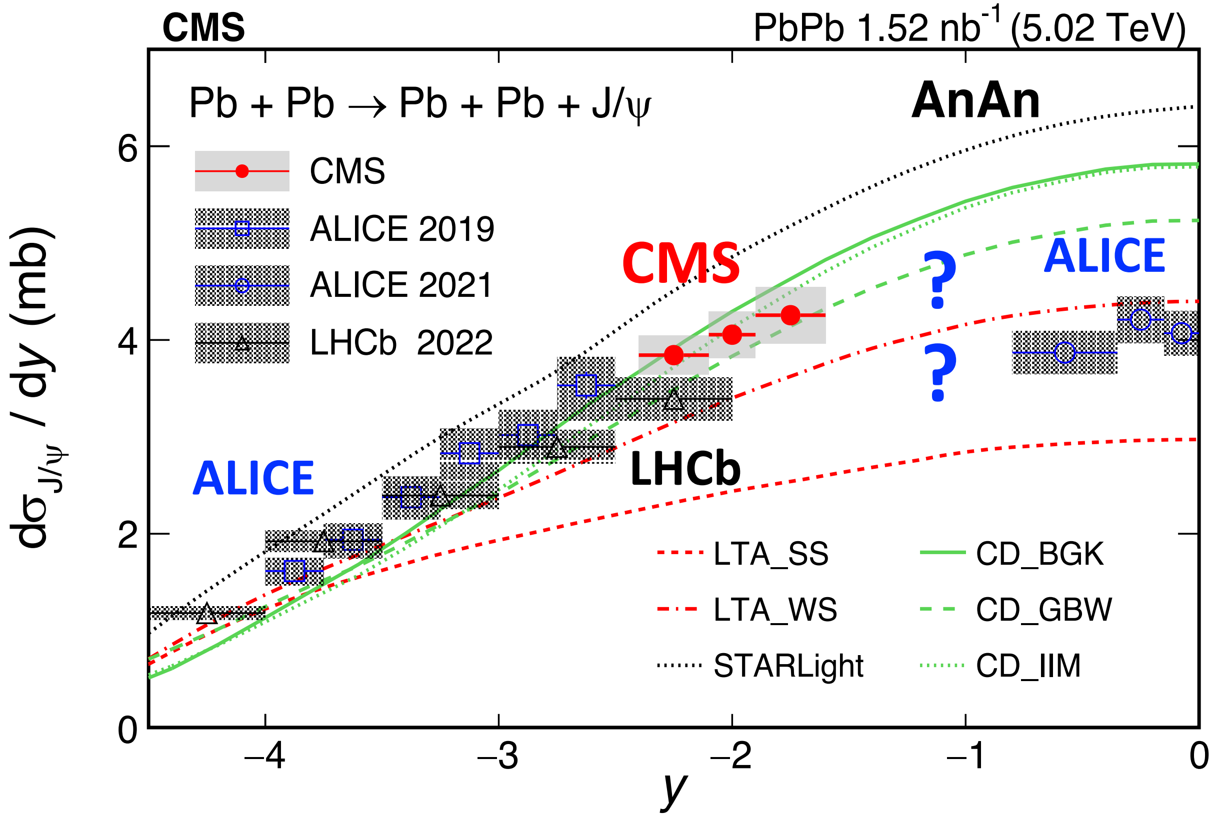
- Data from **LHC** and **HERA** follow a **common** power-law trend, consistent with the expectation from the rapidly increasing gluon density in a proton

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

Coherent J/Ψ Photoproduction in Pb-Pb UPCs

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



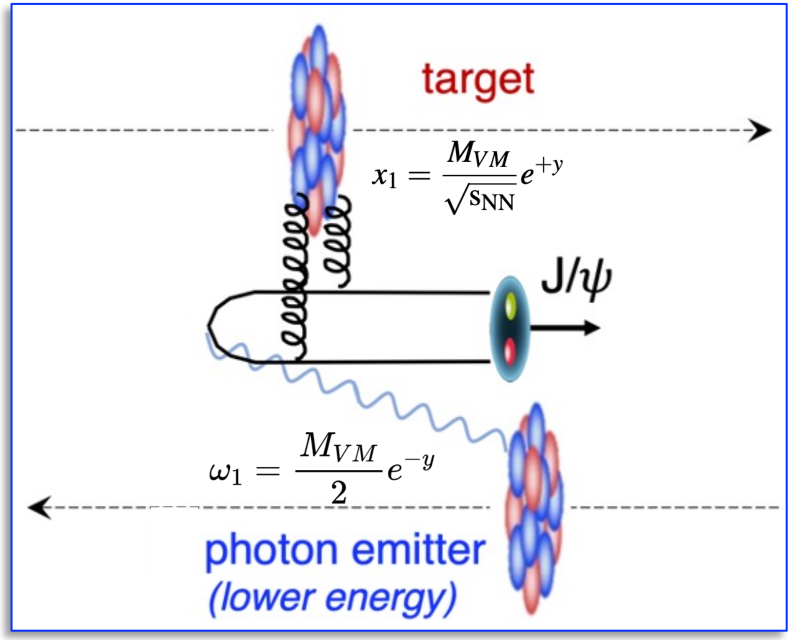


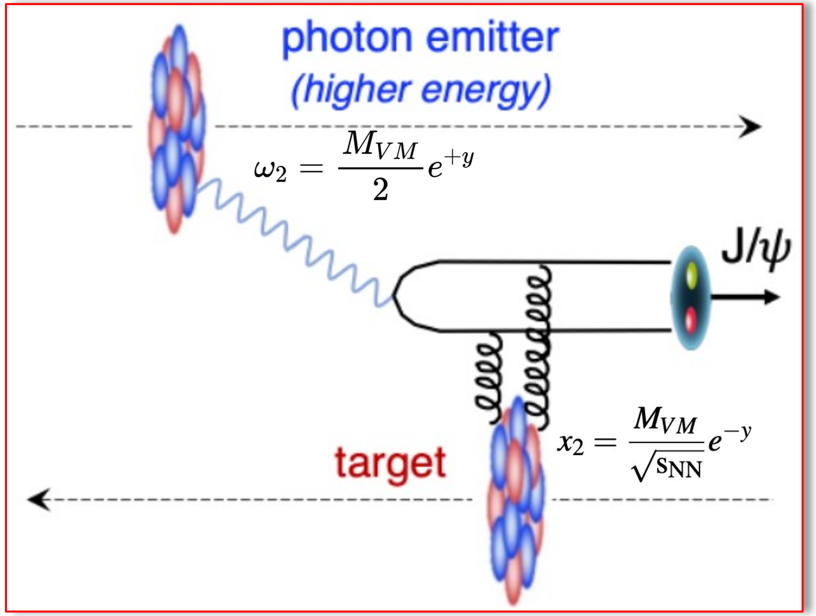
CMS: PRL 131, 262301 (2023)
LHCb: JHEP 06 146 (2023)

- **However,** the rapidity distribution was **a puzzle**

Two-Way Ambiguity in A-A UPC

For a given |y| window





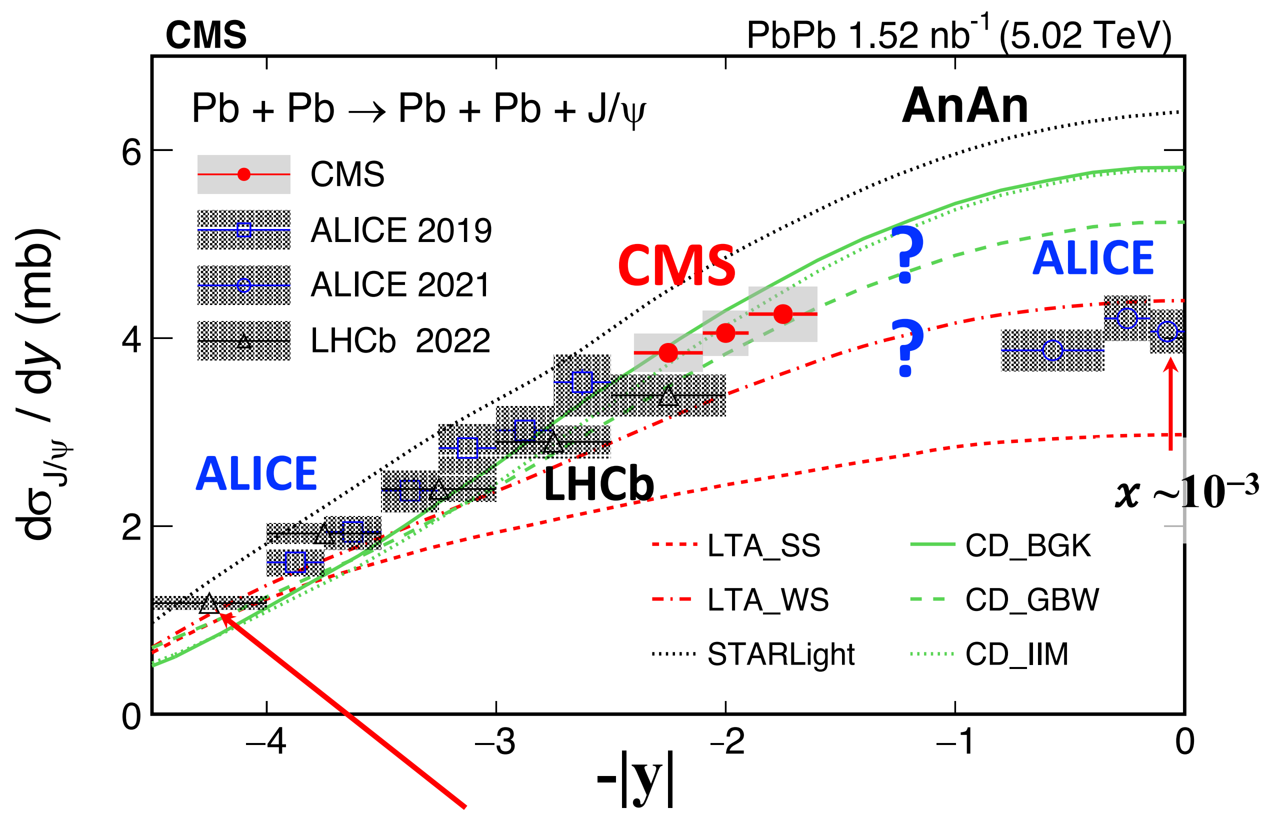
what we measure

Smaller-*x*

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

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

Two-Way Ambiguity in A-A UPC



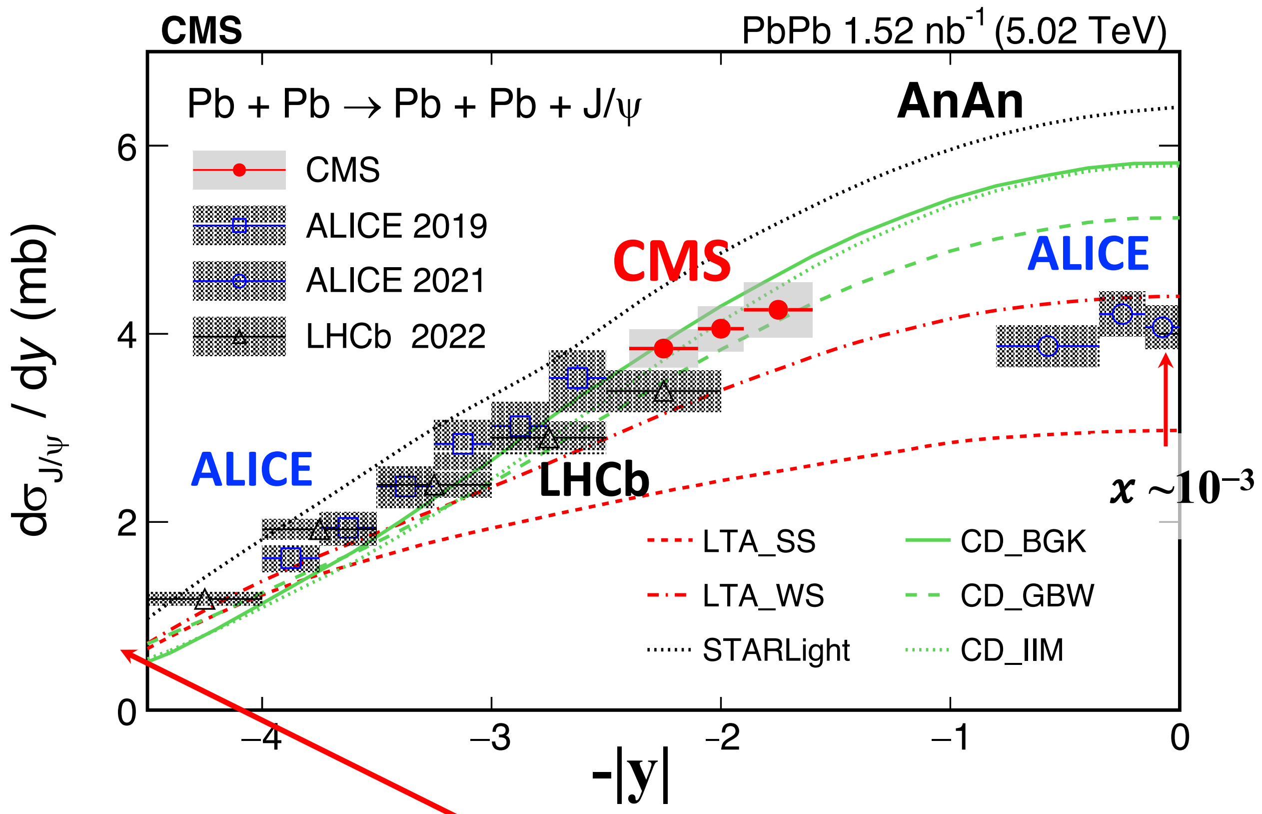
$$x = \frac{M_{VM}}{\sqrt{s_{\rm NN}}} e^{\mp y}$$

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

low-energy photons dominant

(large-x gluons dominant)

Two-Way Ambiguity in A-A UPC



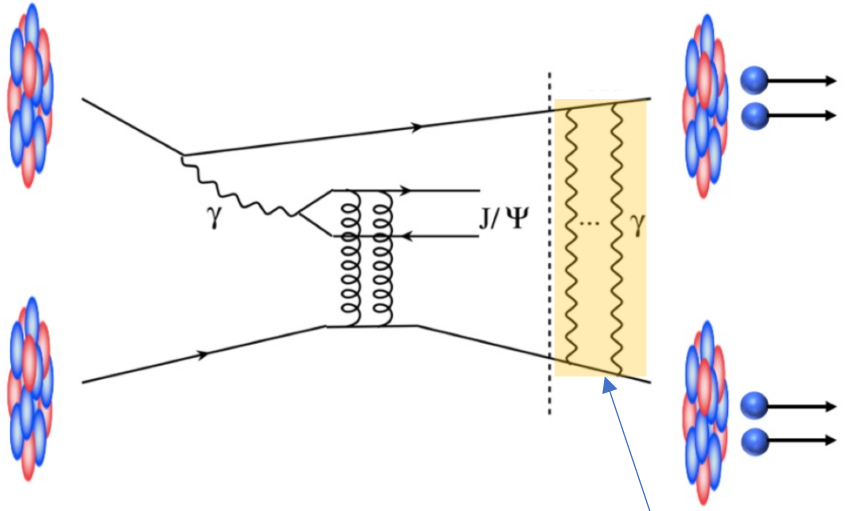
$$x = \frac{M_{VM}}{\sqrt{s_{\mathrm{NN}}}} e^{\mp y}$$

Accessing **smaller** x requires moving to **more forward** regions, where **larger** x contributes **higher** fractions!

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**



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

from theoretical calculation

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

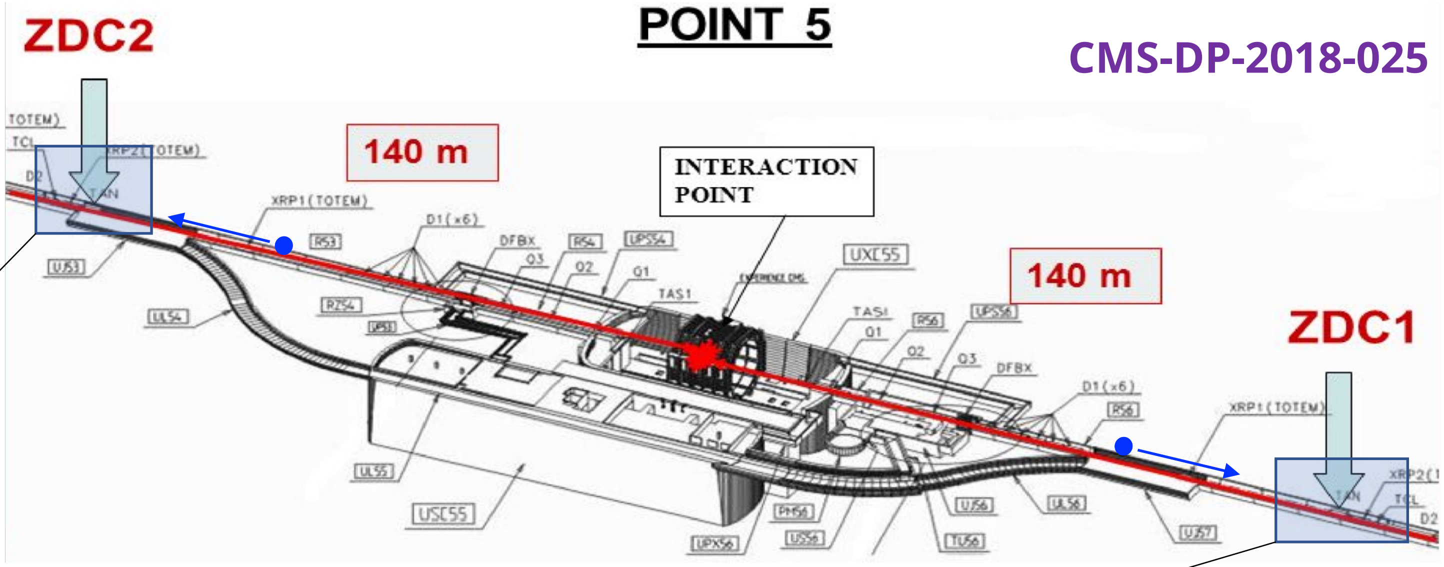
$\sigma_{\gamma A\to J/\psi A'(\omega_1)}$ **Larger-x**

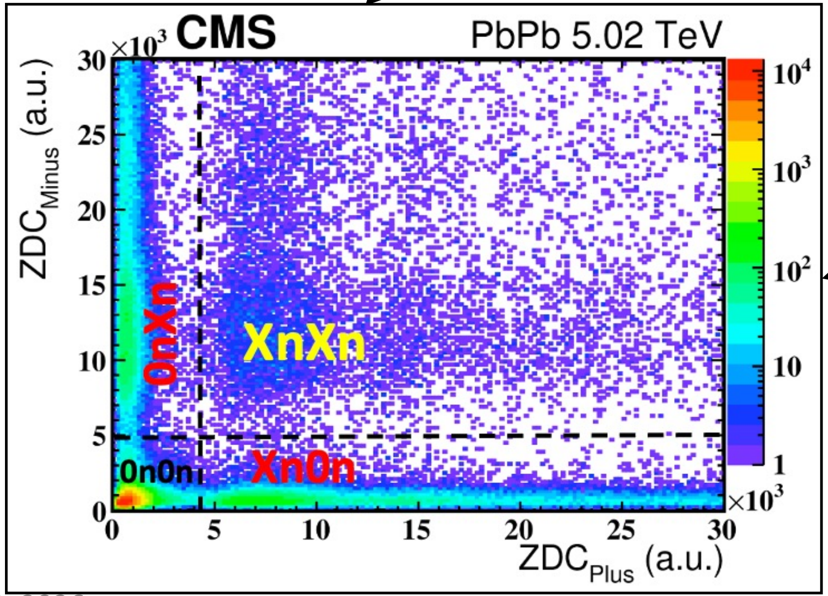
$\sigma_{\gamma A\to J/\psi A'(w_2)}$ **Smaller-x**

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

Neutron Tag with Forward Zero Degree Calorimeter

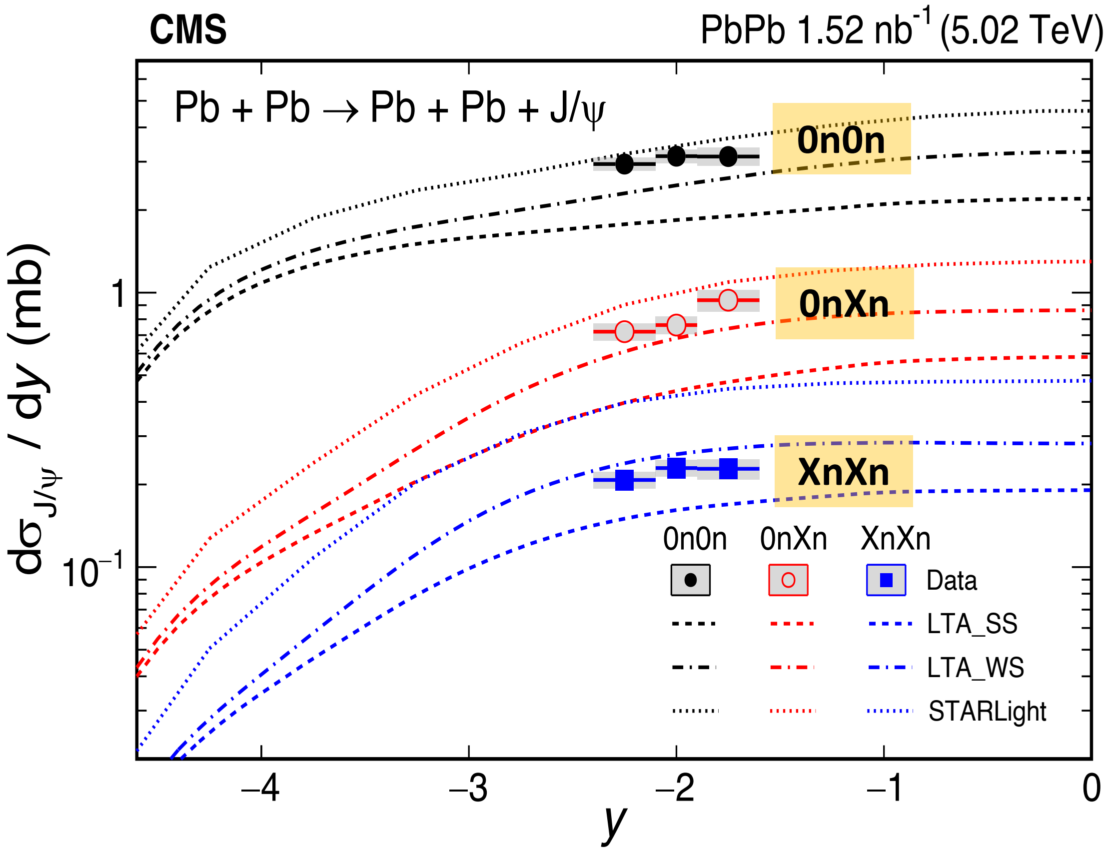




Tag events with **neutrons**:

- 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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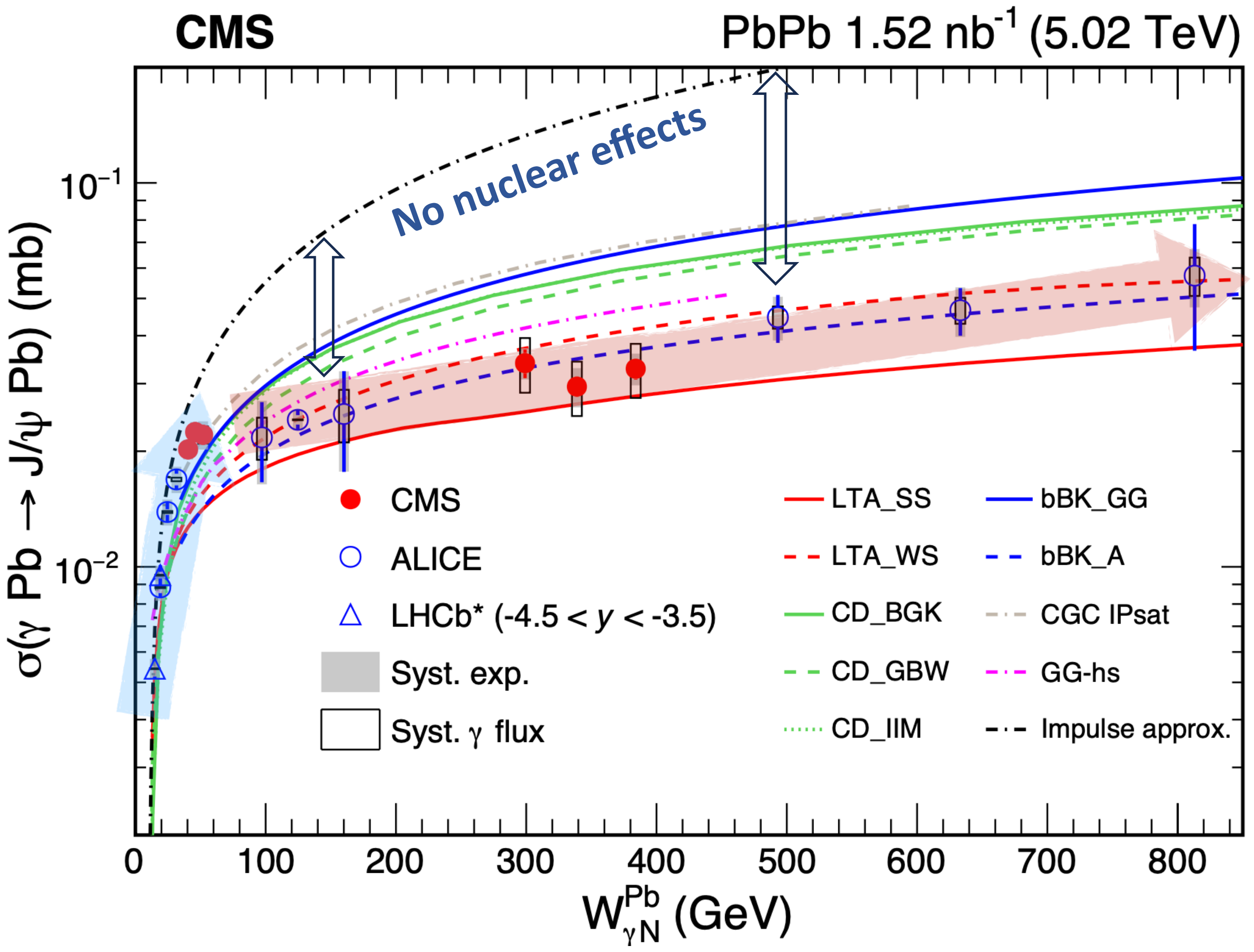
$\sigma_{\gamma A\to J/\psi A'}(\omega_1)$ $\sigma_{\gamma A\to J/\psi A'}(w_2)$

Larger-x **Smaller-x**

➢ **Separate small and large x contributions by solving equations**

Coherent J/Ψ Cross Section of Per γ+Pb

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



***σ* vs. W** (γ-N center-of-mass energy)

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

Strongly saturated cross sections

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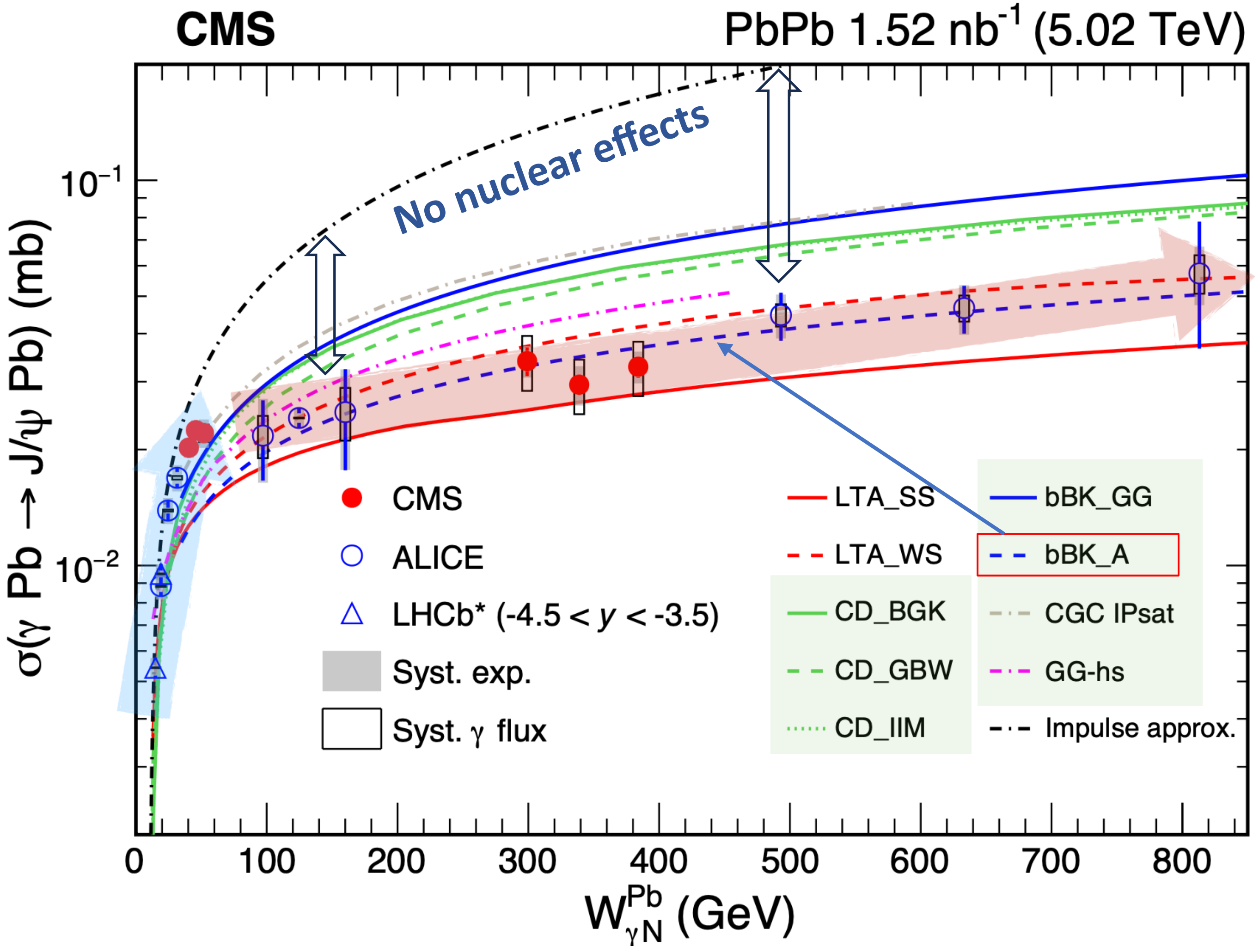

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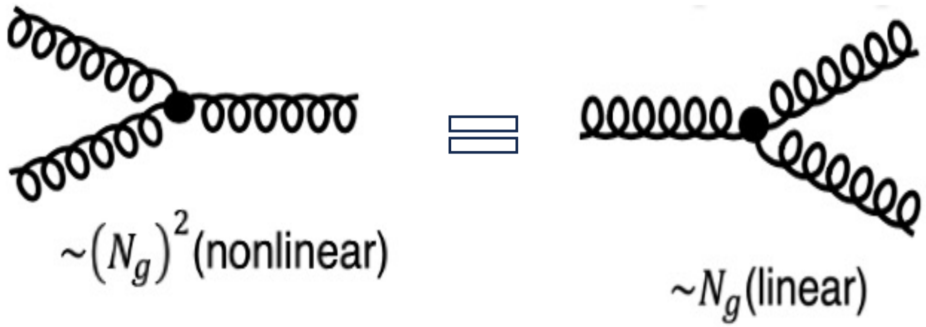
Gluon Saturation?



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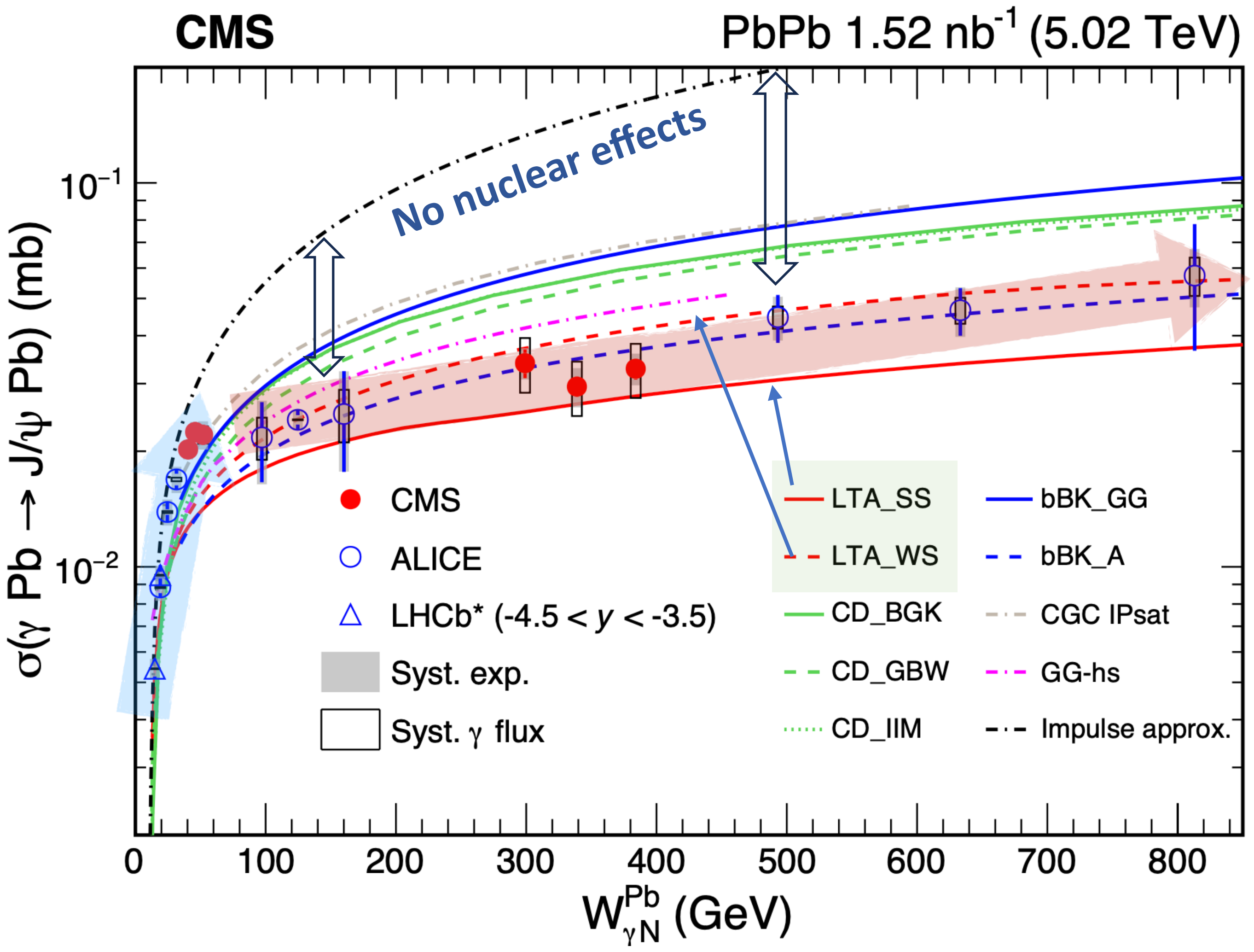

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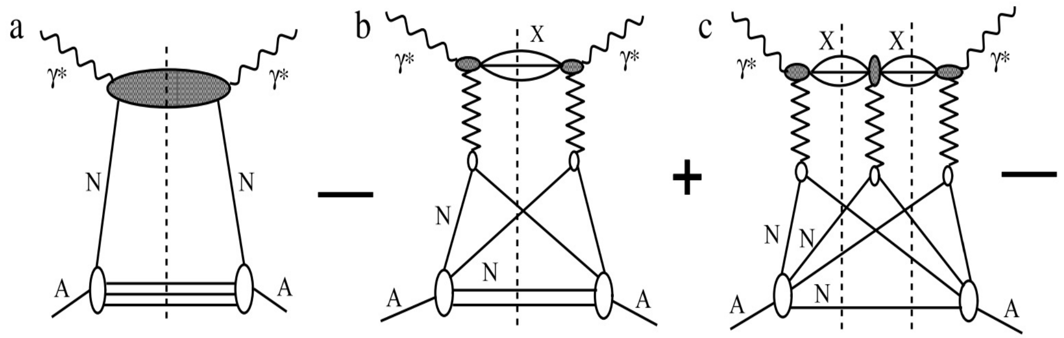
Nuclear shadowing?



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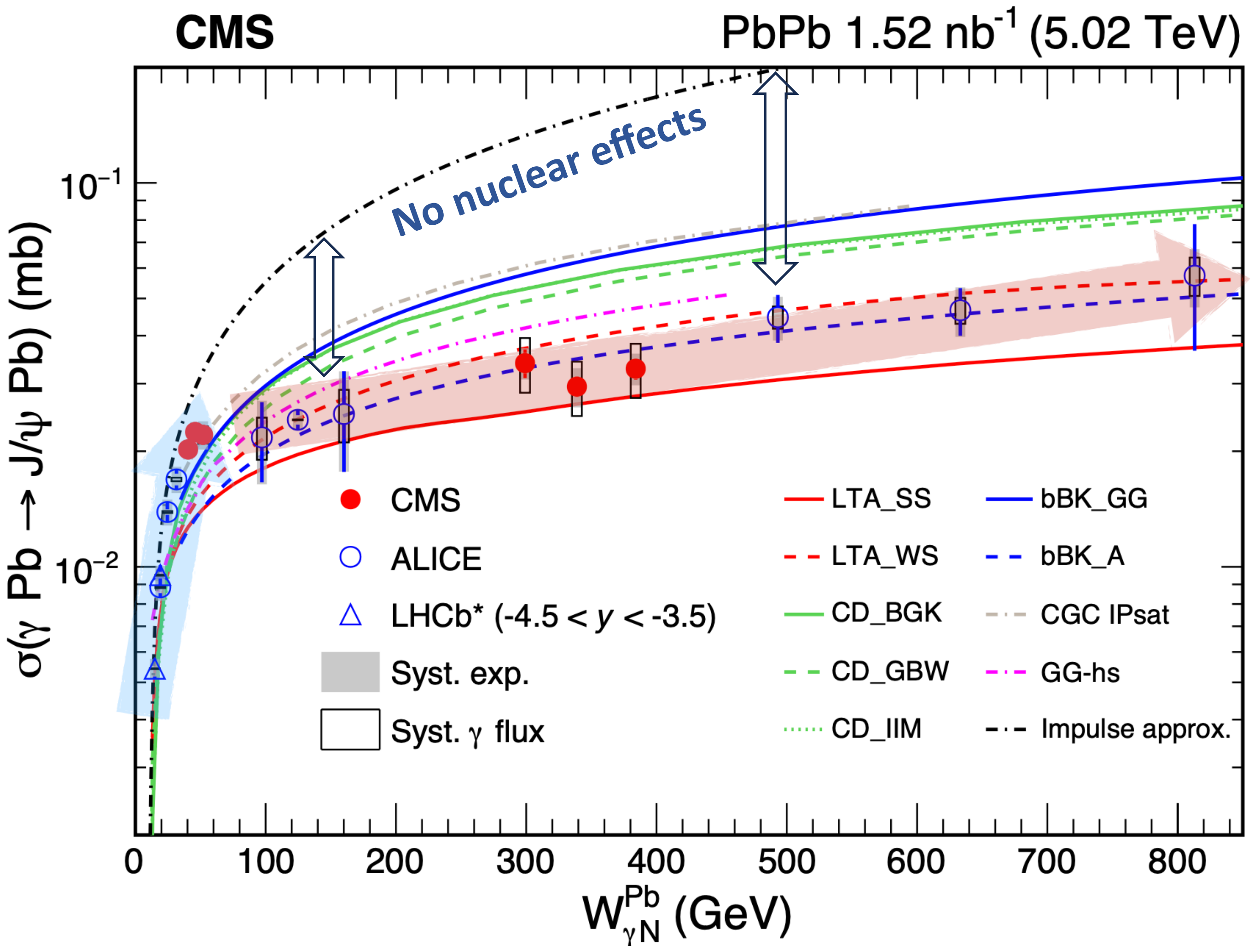
CMS: PRL 131, 262301 (2023)
ALICE: JHEP 10 119 (2023)



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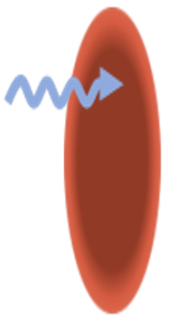
Black Disk Limit?

(not in the figure)

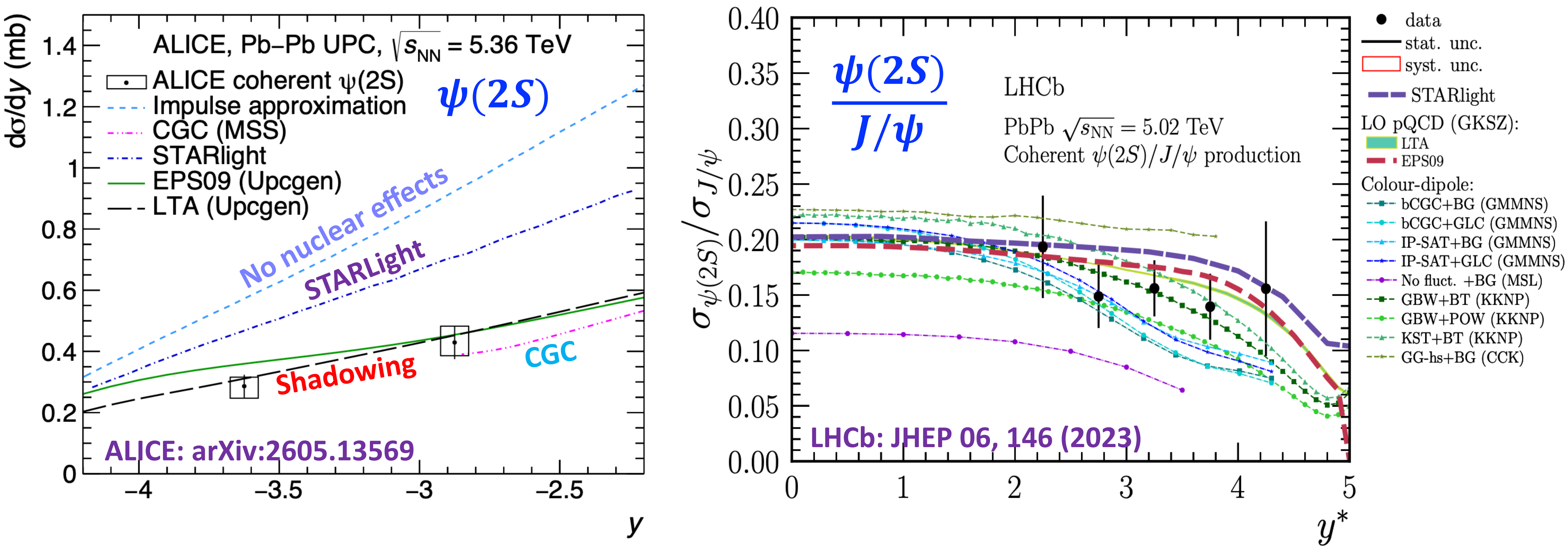


$$\hat{\sigma}^{\rm inel}_{\rm PQCD} \leq \hat{\sigma}_{\rm black} = \pi R^2_{\rm target}$$

L. Frankfurt, et al.,
PRL 87 (2001) 192301, PLB 537 (2002) 51

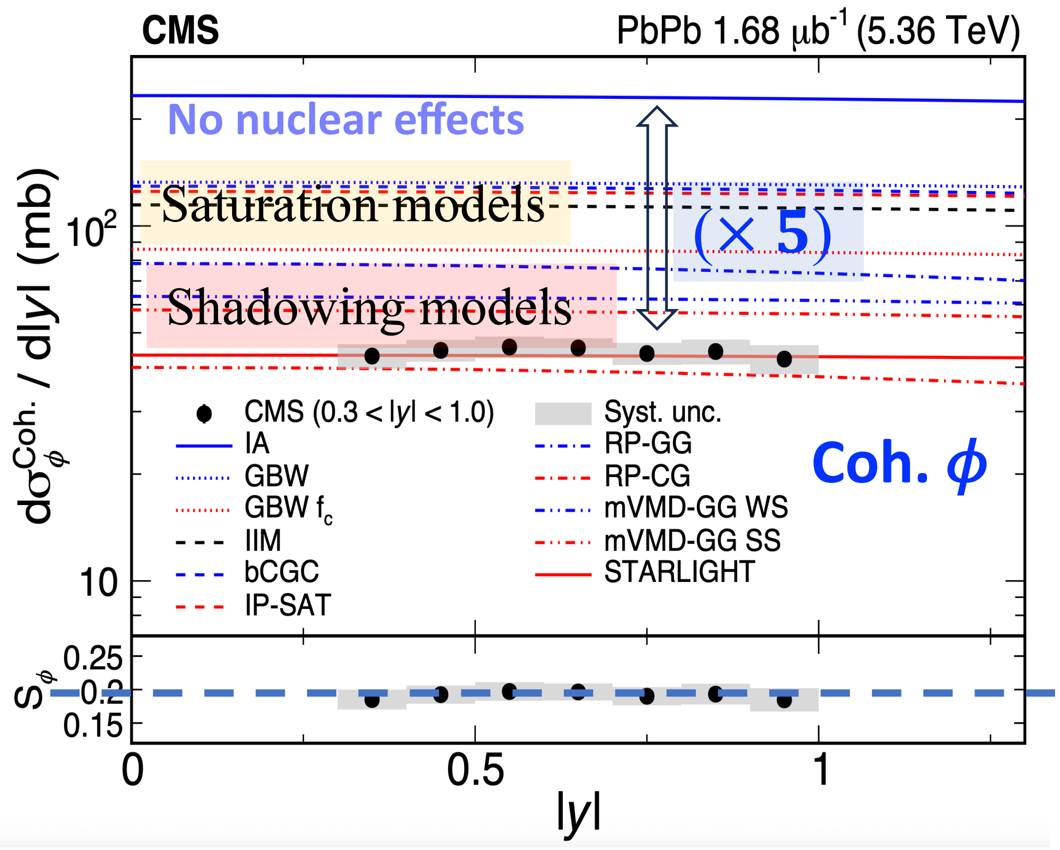
Exact underlying physics is still unclear!

Coh. Ψ(2S) Photoproduction in UPCs

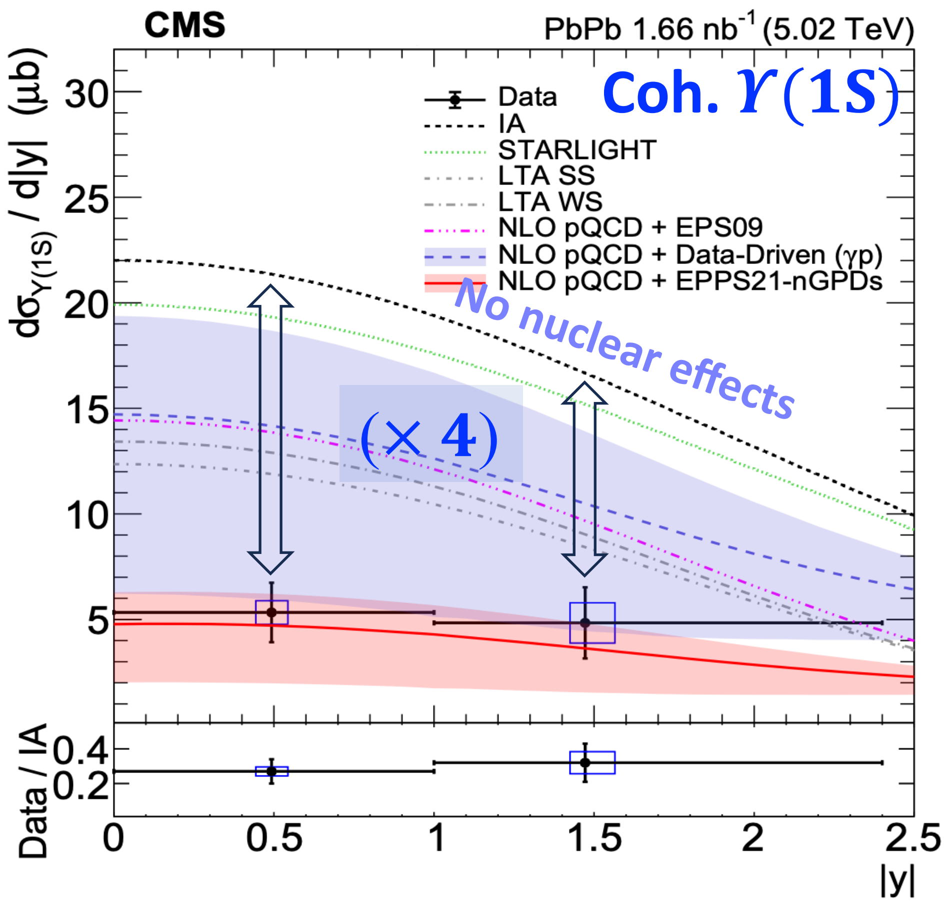


➢ **Both shadowing model and gluon saturation model describes the data**

First Coh. ϕ and $\Upsilon(1S)$ Photoproduction in UPCs



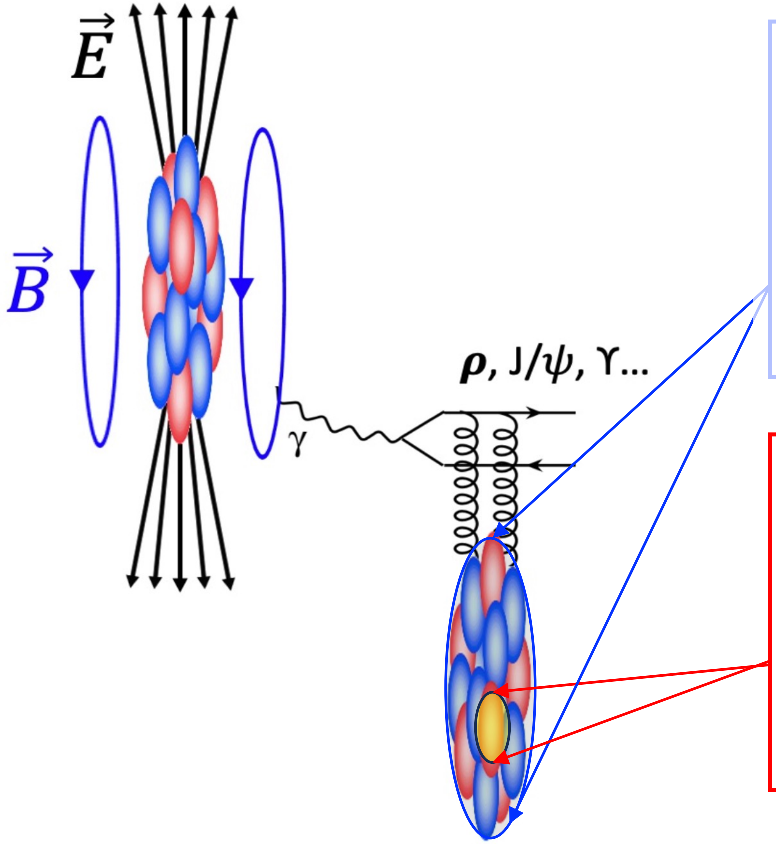
CMS, PRL 135, 262301 (2025)



CMS, arXiv:2604.05814 , submitted to PRL

- ➢ **Their cross sections are strongly suppressed, exceeding gluon saturation predictions**
- ➢ **Shadowing models generally better describe the data**

How About Incoherent J/Ψ Photoproduction?



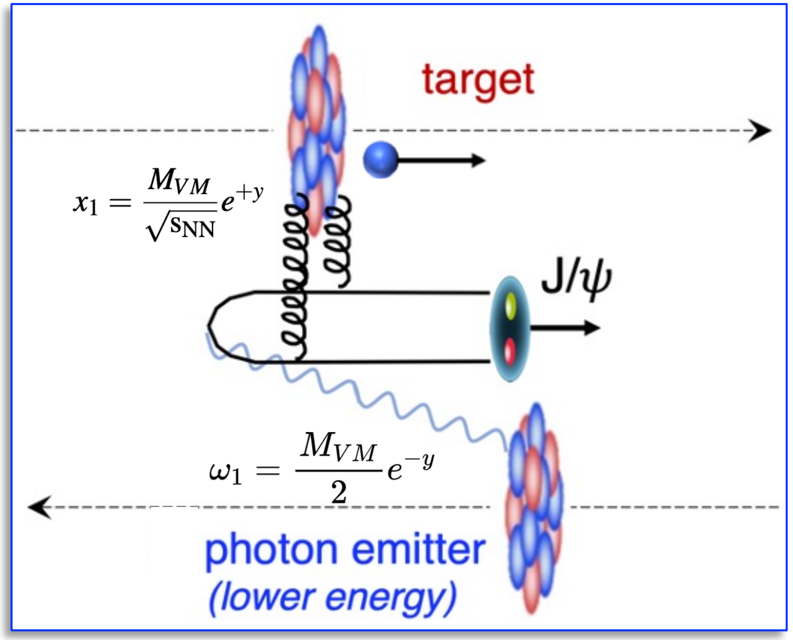
Coherent production:

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

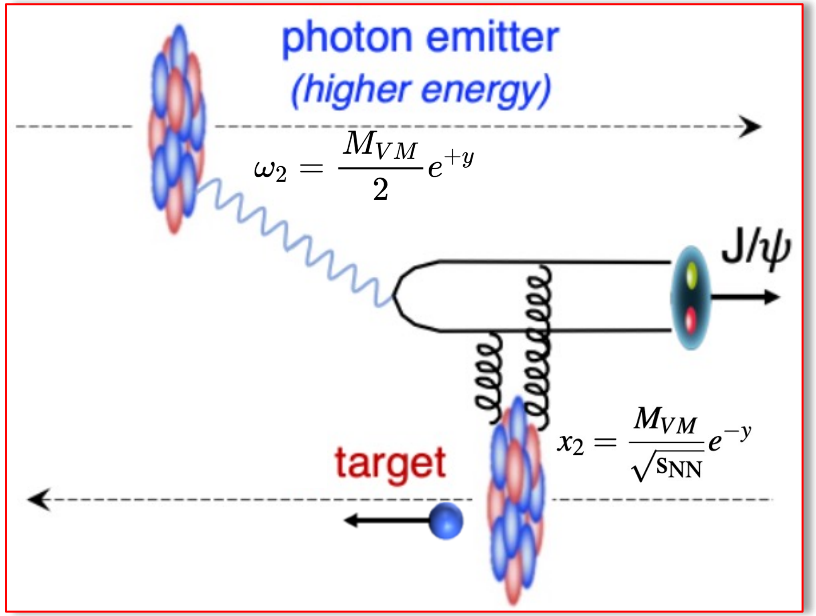
Incoherent production:

- Photon fluctuated dipole couples to **local gluonic hotspots Target** nucleus usually **breaks**
- VM $<p_T>$ ~ **10^2-10^3 MeV**
- Probing the **local gluon density** and **fluctuations**

Solve “Two-Way Ambiguity” via Forward Neutrons



J/Ψ-Xn (Same Direction)

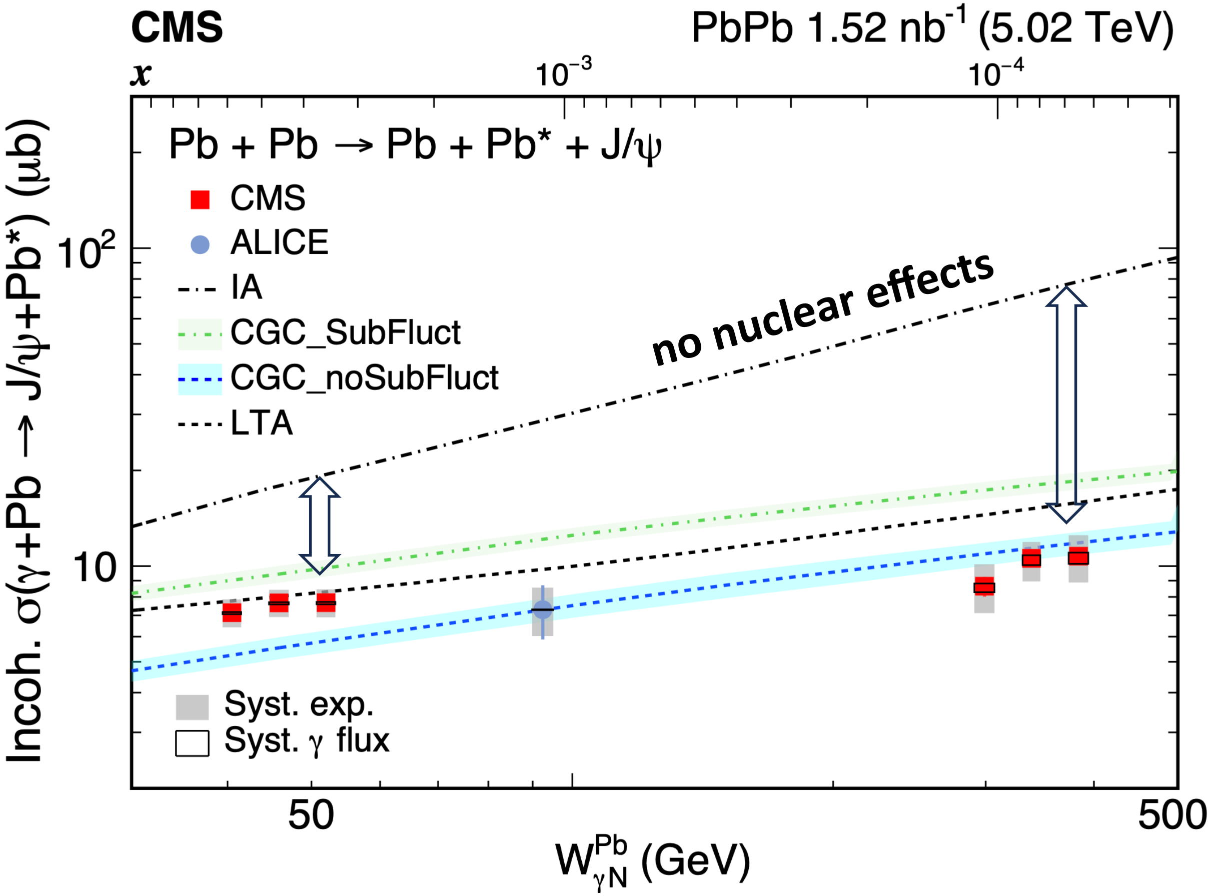


J/Ψ-Xn (Opposite Direction)

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”

Incoh. J/Ψ Cross Section Per γ+Pb



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

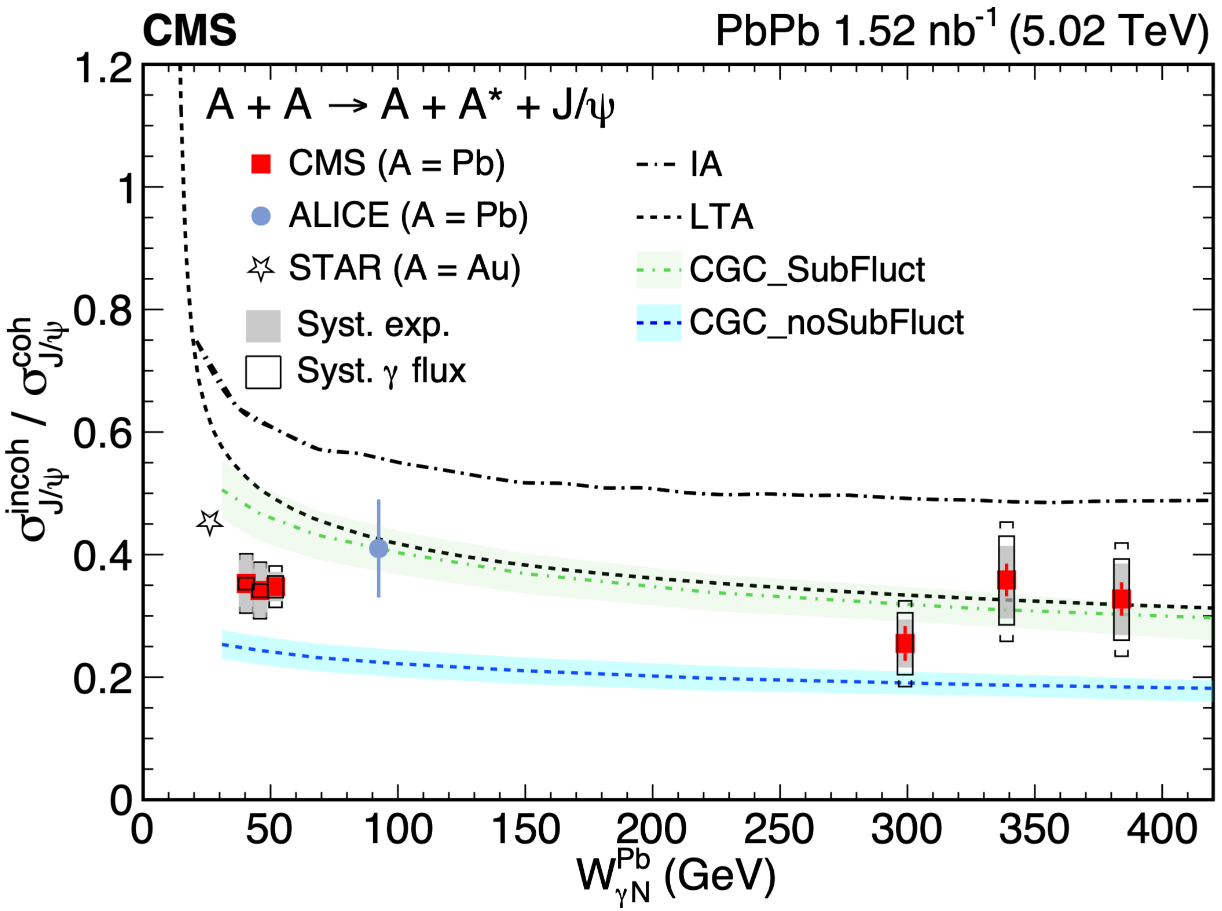
$$\sigma_{\rm inc} \propto \langle |A|^2\rangle - |\langle A\rangle|^2$$

Measuring the variance of gluonic configurations

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

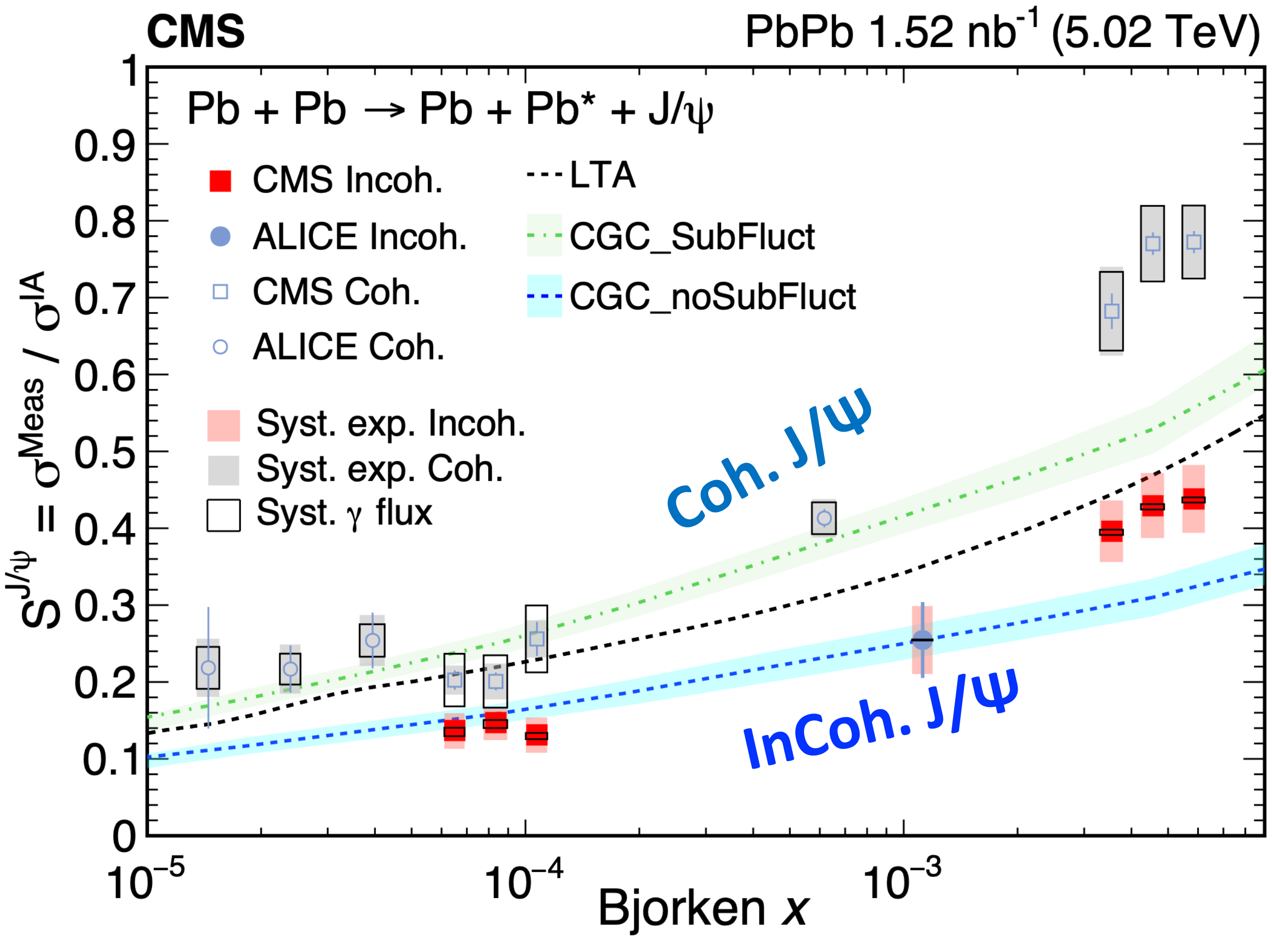


CMS, PRL 135, 112301 (2025), Editors' Suggestion

- **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

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

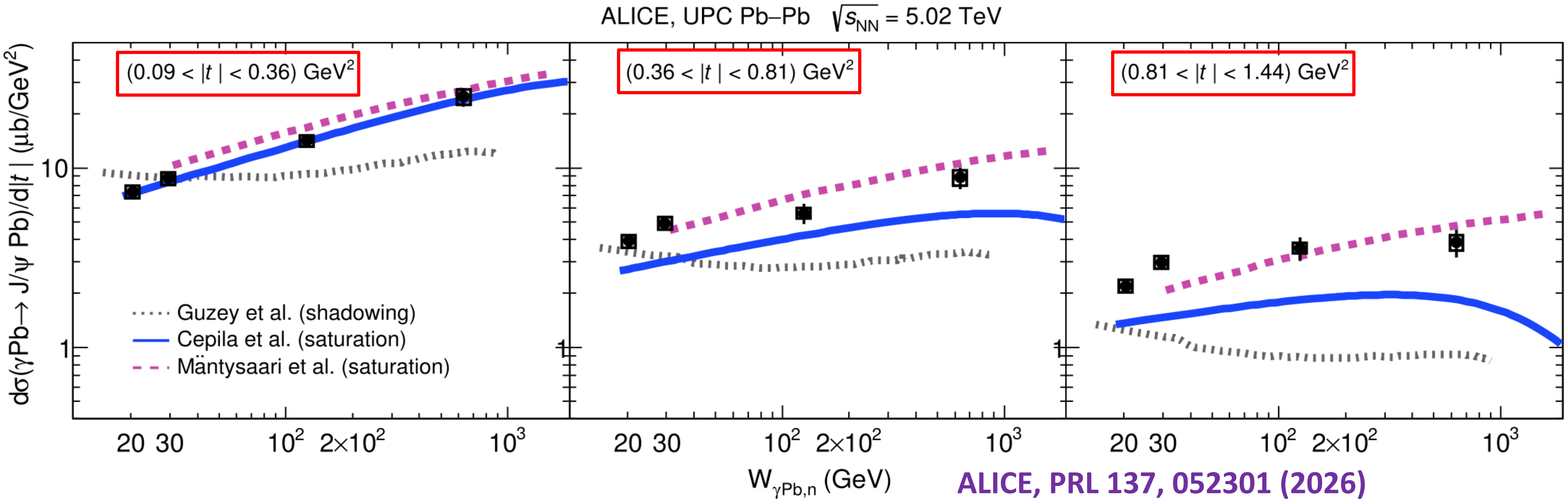
$$S^{J/\psi} = \frac{\sigma^{exp}_{\gamma Pb\to J/\psi Pb'}}{\boxed{\sigma^{IA}_{\gamma Pb\to J/\psi Pb'}}}$$

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 Energy (x)-Dependent Incoh. J/Ψ in Various t Intervals

Incoherent production is sensitive to event-by-event gluonic fluctuations.



ALICE, PRL 137, 052301 (2026)

- t-dependent measurements probe gluon fluctuations at **different transverse spatial scales**.
- At **large t,** data exhibits **a slower growth** compared with the **low-t** region, **favor the gluon saturation models** over nuclear shadowing model.
- **Saturation suppresses gluon fluctuations**, reduce the increase of incoherent cross section.

What We Learnt So far?

- **First energy-dependent Coh. and Incoh. J/Ψ are measured**
  - 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
  - t slope of Incoh J/Ψ support the subnucleonic fluctuations
  - Incoh J/Ψ show slower growth with energy at larger t region
- **First Coh. ϕ and $\Upsilon(1S)$ photoproduction off heavy nuclei is observed:**
  - Nuclear suppression factor $\sim\mathbf{5}$ **and** $\sim\mathbf{4}$

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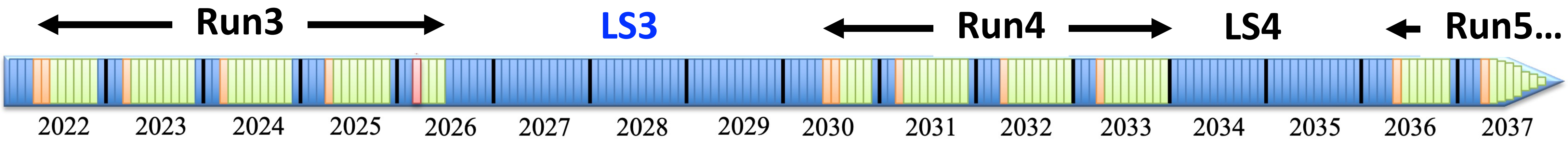
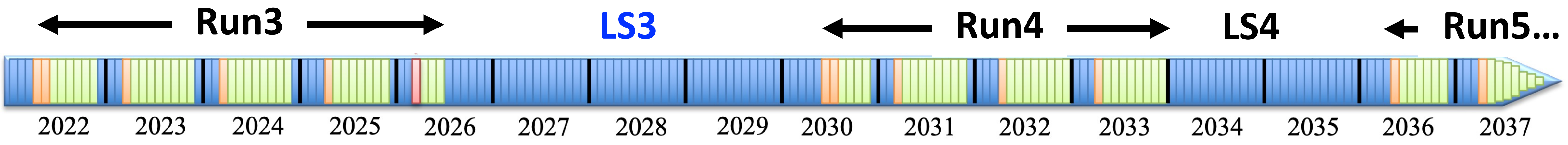
- **First Coh. ϕ and $\Upsilon(1S)$ photoproduction off heavy nuclei is observed:**
  - Nuclear suppression factor ~ 5 and ~ 4

- **Current models based on gluon saturation or nuclear shadowing provide valuable insights but cannot consistently reproduce the full set of measurements.**
- **A complete understanding of the small-x dynamics and the onset of high-density gluonic matter remains an open question.**

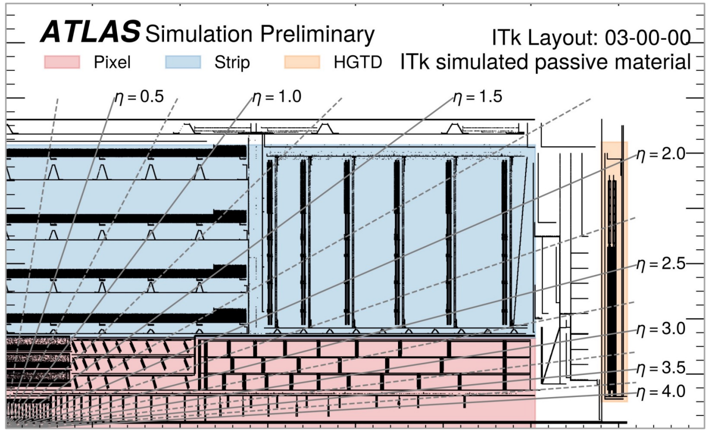
Looking **Forward** Upgrades at LHC



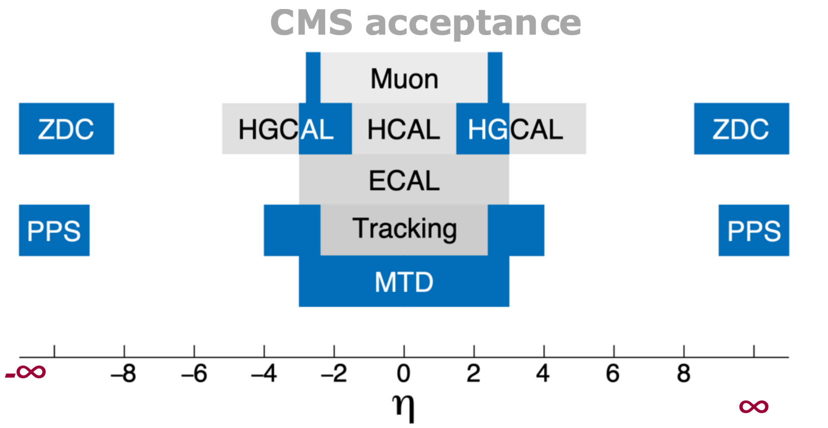
Looking **Forward** Upgrades at LHC



Improved Trigger and DAQ



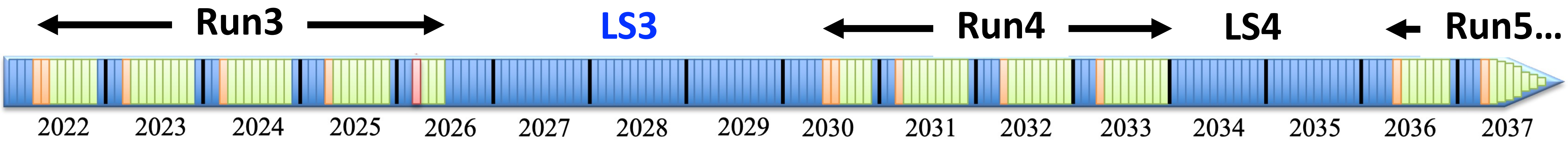
CERN-LHCC-2012-022



ATLAS, CMS phase II

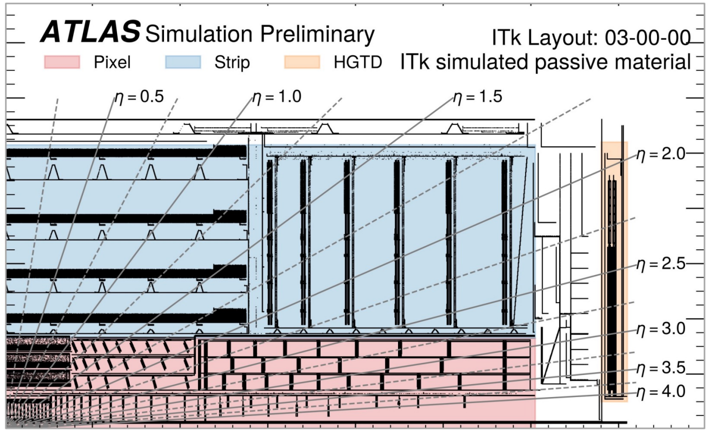
- HL-ZDC (CMS-ATLAS joint)
- Extend tracking to |**η**| = **4.0**
- Extend muon |**η**| (2.4→**2.8**) by CMS
- MTD (time resolution ~30ps) by CMS

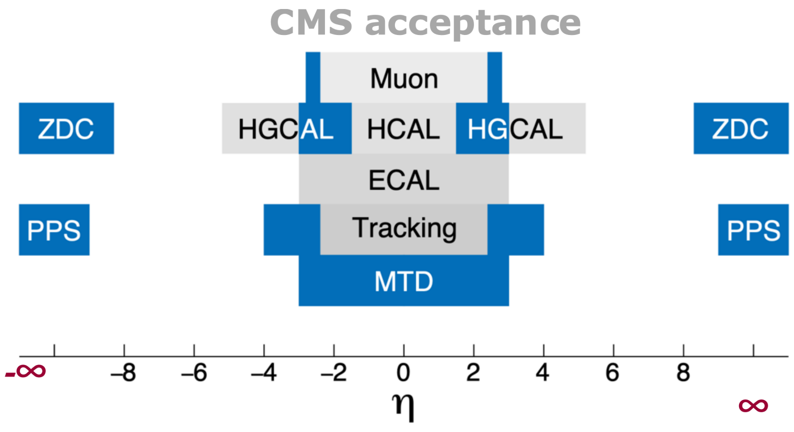
Looking **Forward** Upgrades at LHC



Improved Trigger and DAQ

CERN-LHCC-2012-022





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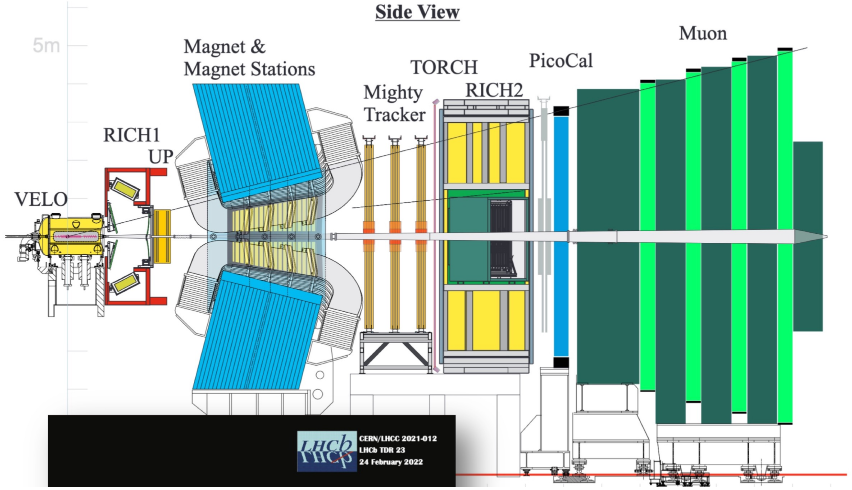


LHCb upgrade II

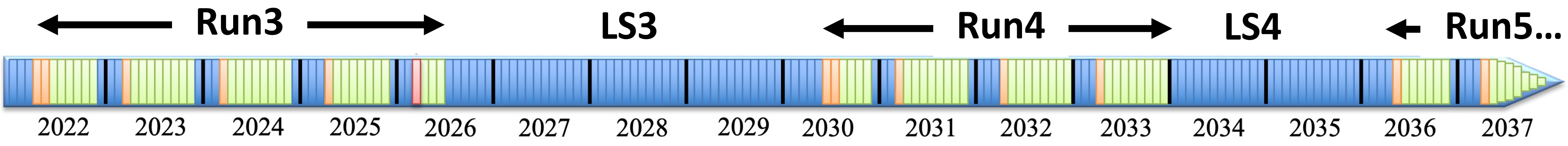
Tracking upgrade

- New Upstream Tracker (timing)
- Mighty tracker (SciFi+silicon)
- VErtex LOcator upgrade

TORCH, RICH, ECAL and Muon upgrades

- Timing across multiple detectors

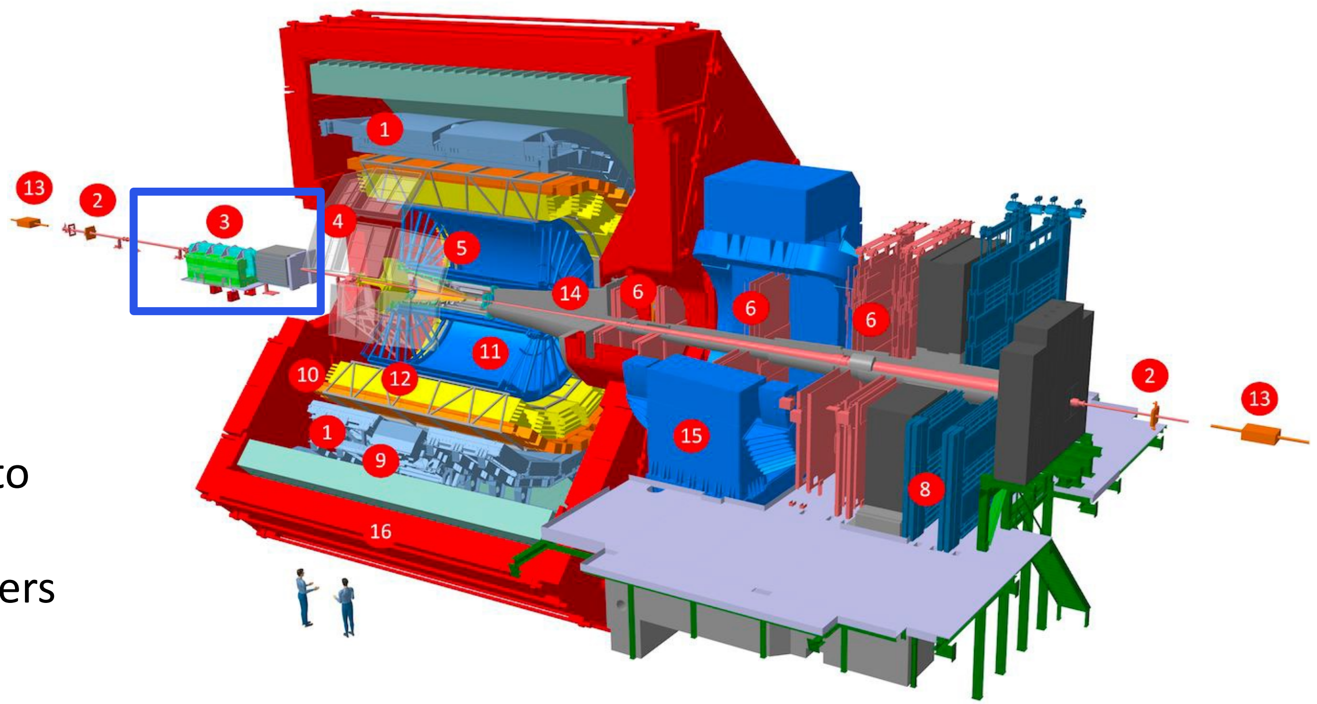
Looking **Forward** Upgrades at LHC



ALICE FoCal: most important upgrades for small-x physics

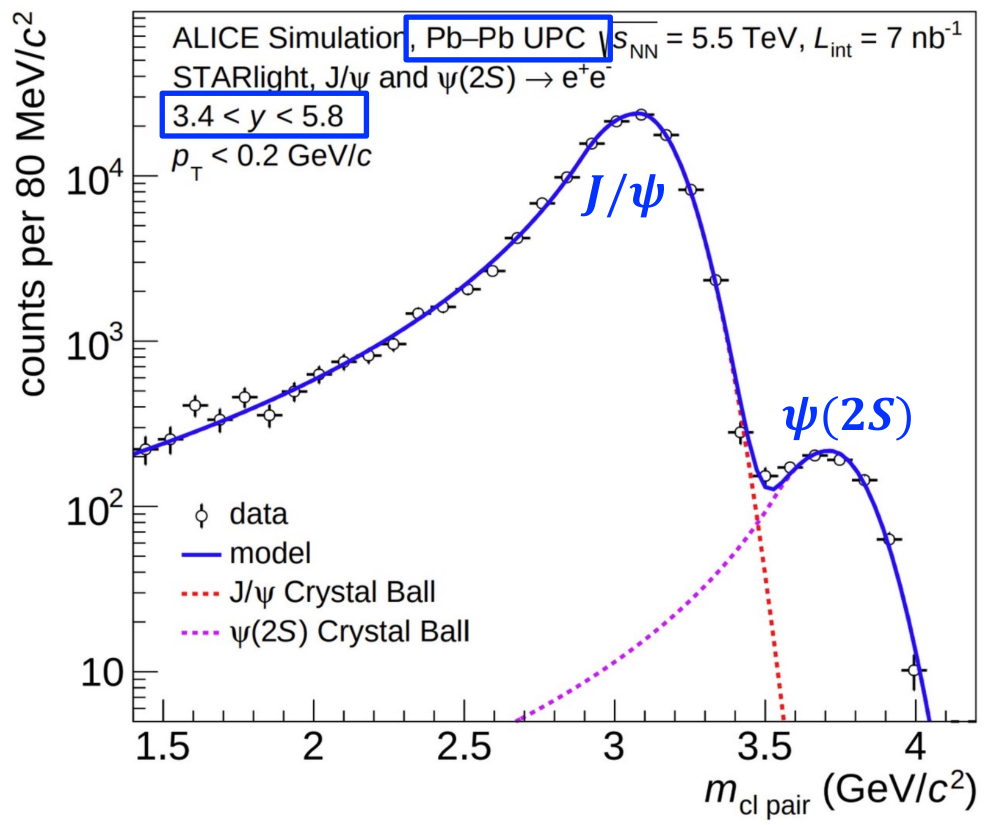
Forward **Cal**orimeter

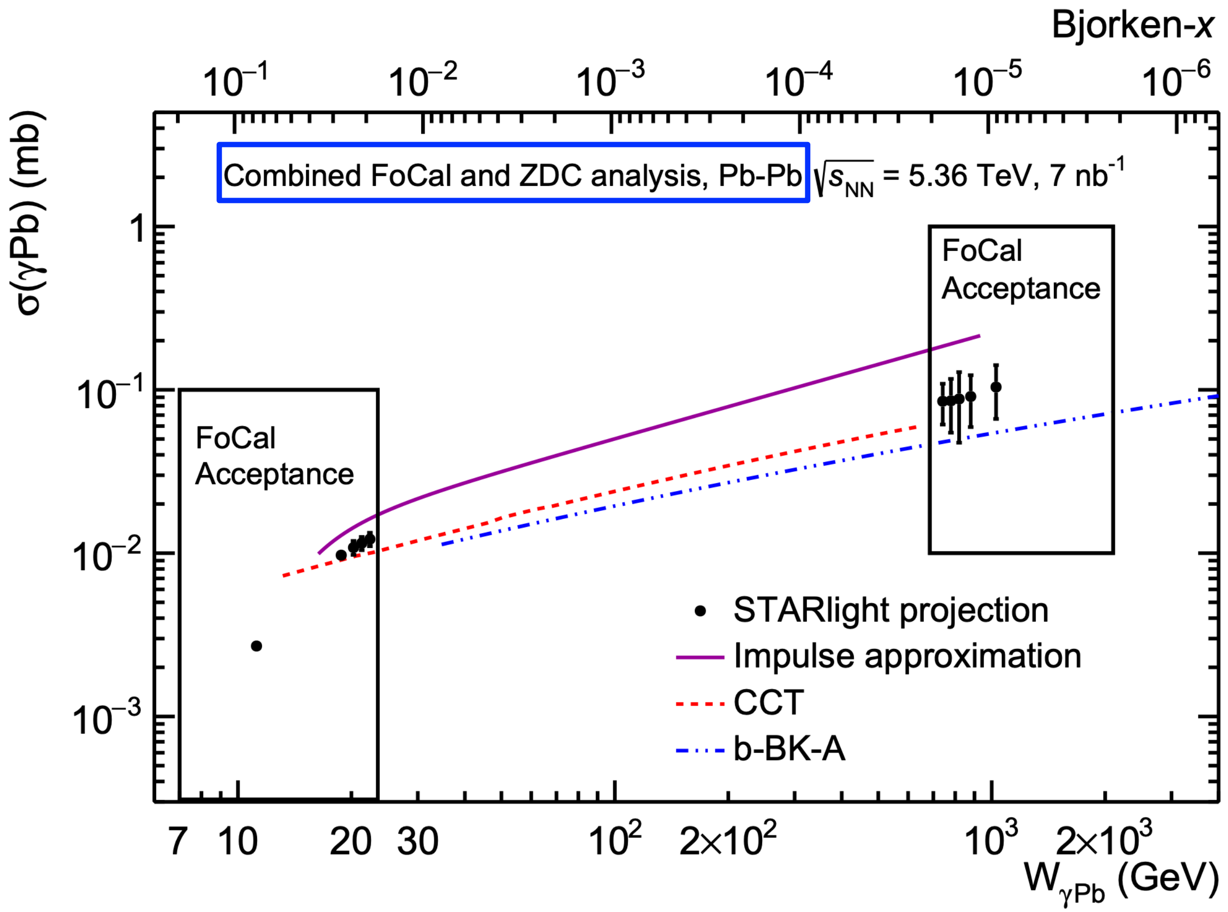
- Electromagnetic: **FoCal-E**
- Hadronic: **FoCal-H**
- Positioned 7m from IP
- **Covering 3.4 < η < 5.8**
- **Forward** particles:
  - Photons
  - Electrons
  - Neutron particles decay into di-photons or di-electrons
  - Hadronic /Jet energy showers



1. **EMCAL** | Electromagnetic Calorimeter
2. **FIT** | Fast Interaction Trigger
3. **FoCal** | Forward Calorimeter
4. **HMPID** | High Momentum Particle Identification Detector
5. **ITS** | Inner Tracking System
6. **MCH** | Muon Tracking Chambers
7. **MFT** | Muon Forward Tracker
8. **MID** | Muon Identifier
9. **PHOS/CPV** | Photon Spectrometer
10. **TOF** | Time Of Flight
11. **TPC** | Time Projection Chamber
12. **TRD** | Transition Radiation Detector
13. **ZDC** | Zero Degree Calorimeter
14. **Absorber**
15. **Dipole Magnet**
16. **L3 Magnet**

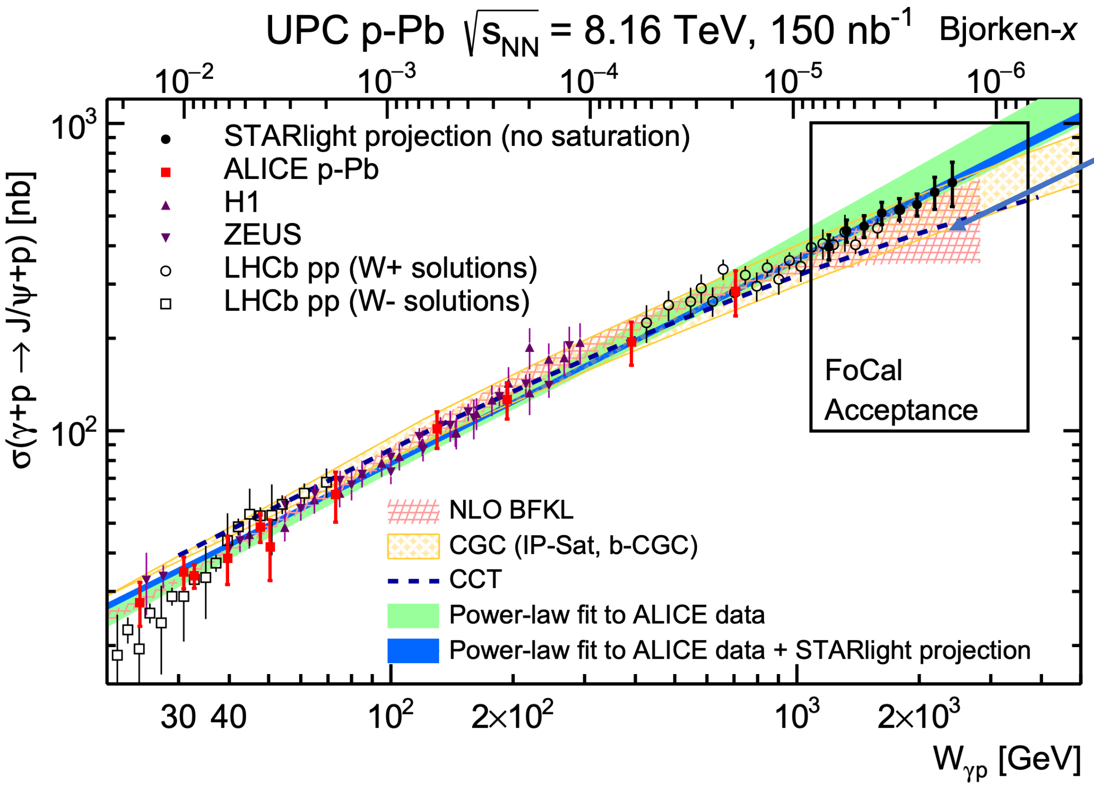
Vector Meson in UPCs with ALICE FoCal





- Extending coverage in W up to **2 TeV**, probing gluon x **down to 10^{-6}**.

Vector Meson in UPCs with ALICE FoCal



- Look for **a slower growth trend** due to **gluon saturation** in **γ + p** interaction, where **nuclear shadowing is turned off**

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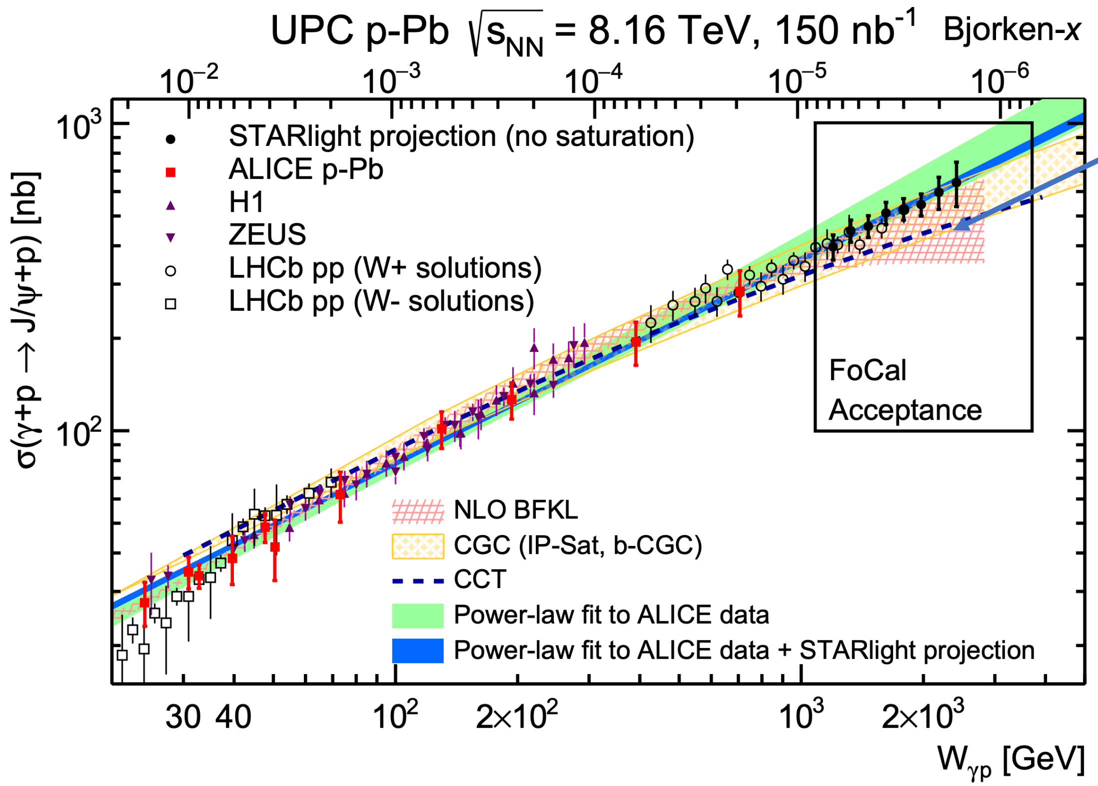

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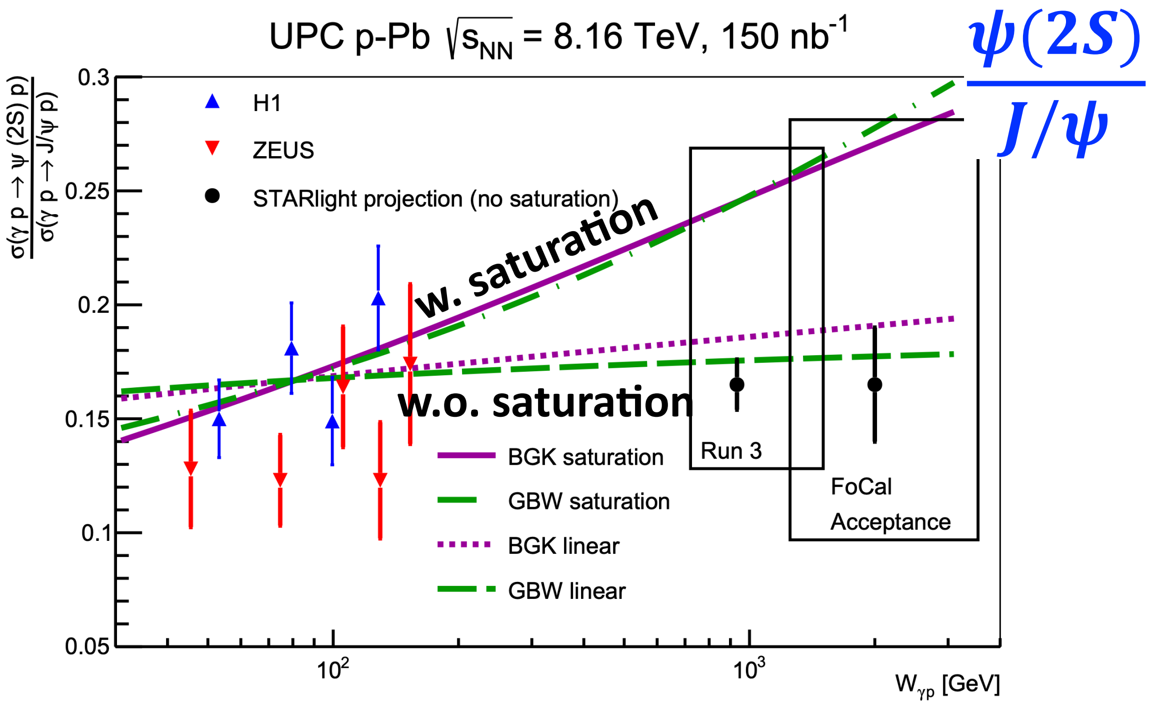
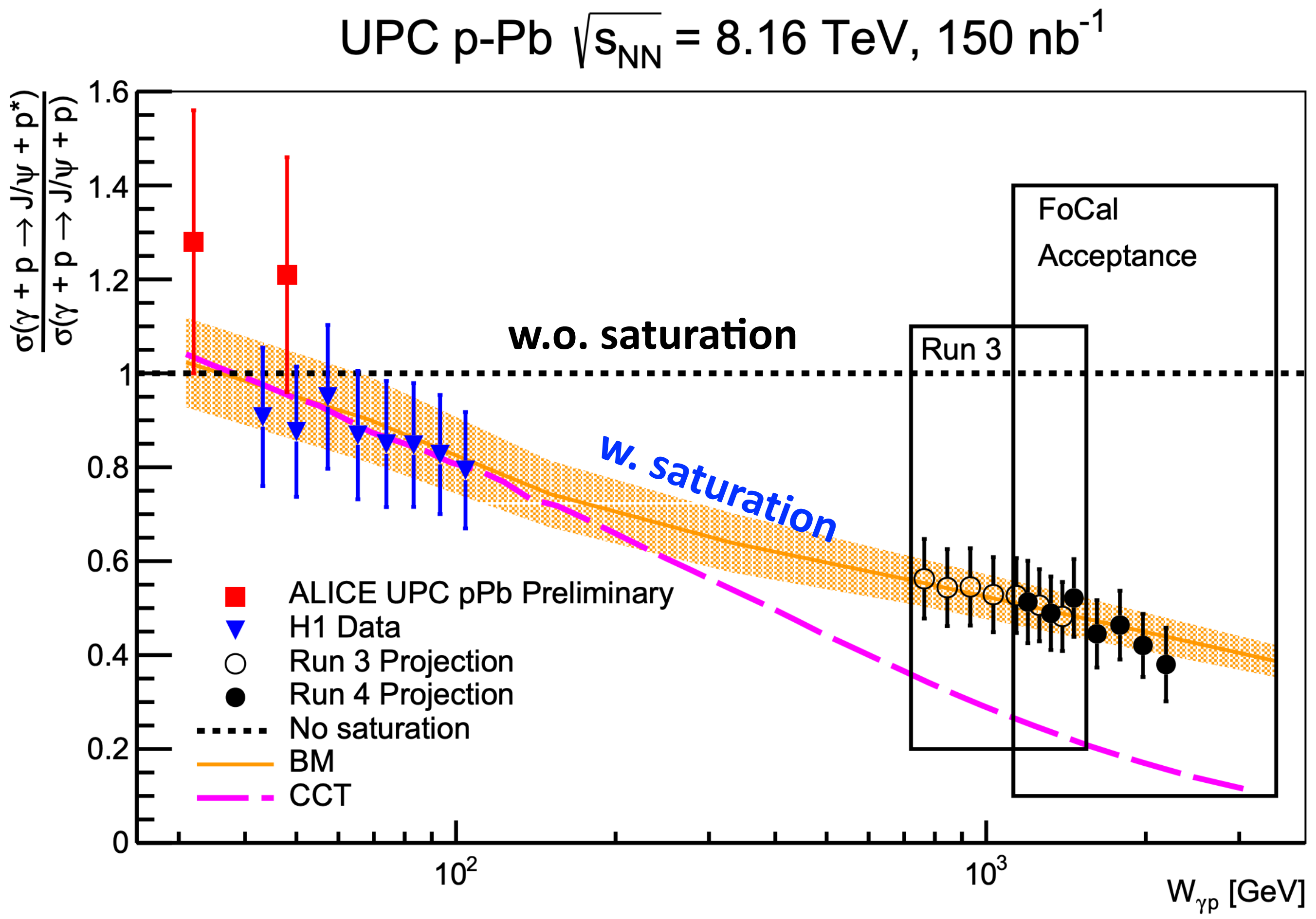


- Extending coverage in W up to **2 TeV**, probing gluon x **down to 10^{-6}**.
- Look for **a significant rising trend in ratio of $\psi(2S)$ / J/ψ** due to **gluon saturation**

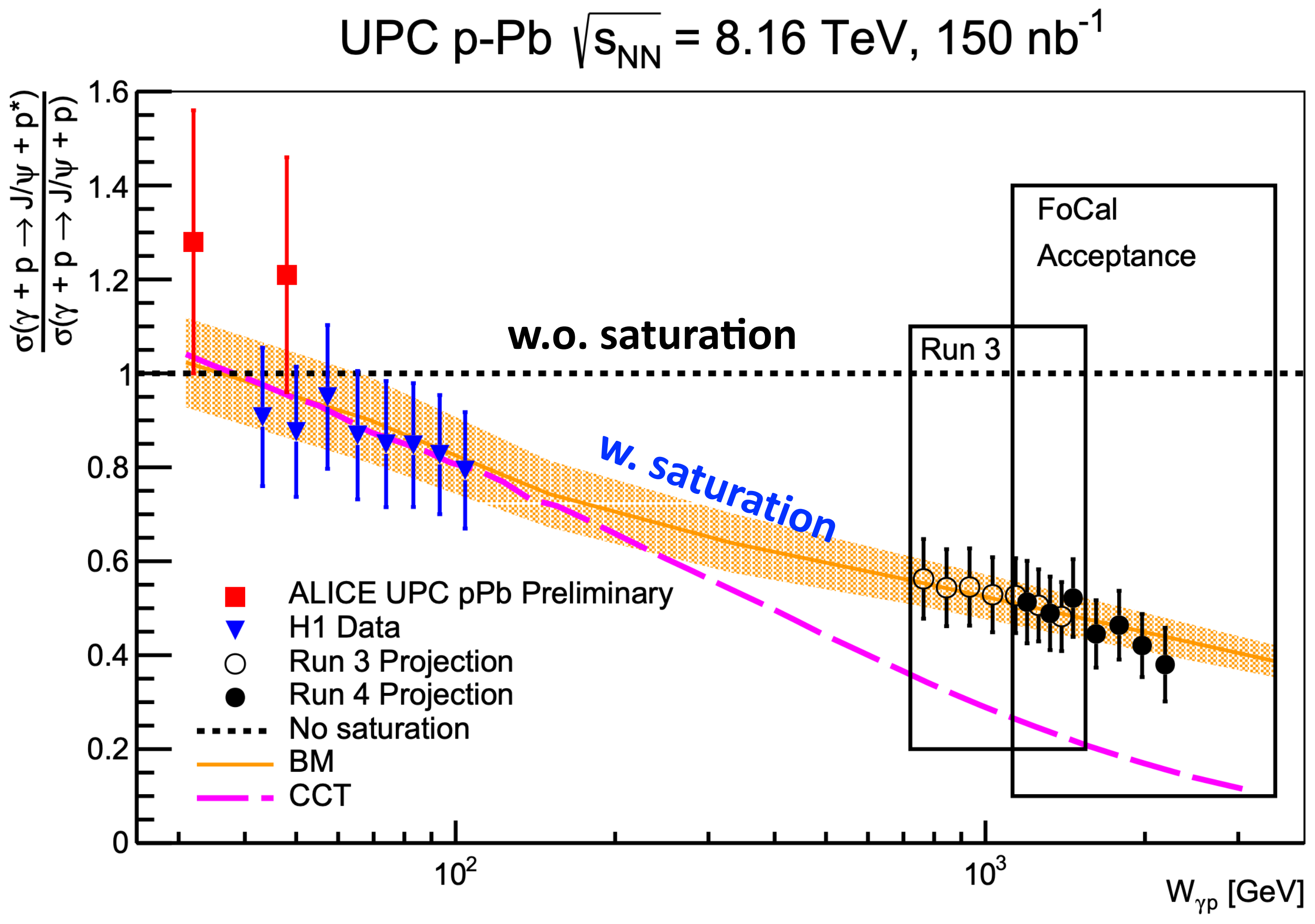
Vector Meson in UPCs with ALICE FoCal



- Look for **decreasing trend in the ratio between dissociative and elastic $\gamma + p$ interactions** due to **gluon saturation**

- As the energy grows → variance grows → cross section grows → until **saturation is reached** and **variance starts to decrease** → cross section starts to **decrease**!

Vector Meson in UPCs with ALICE FoCal



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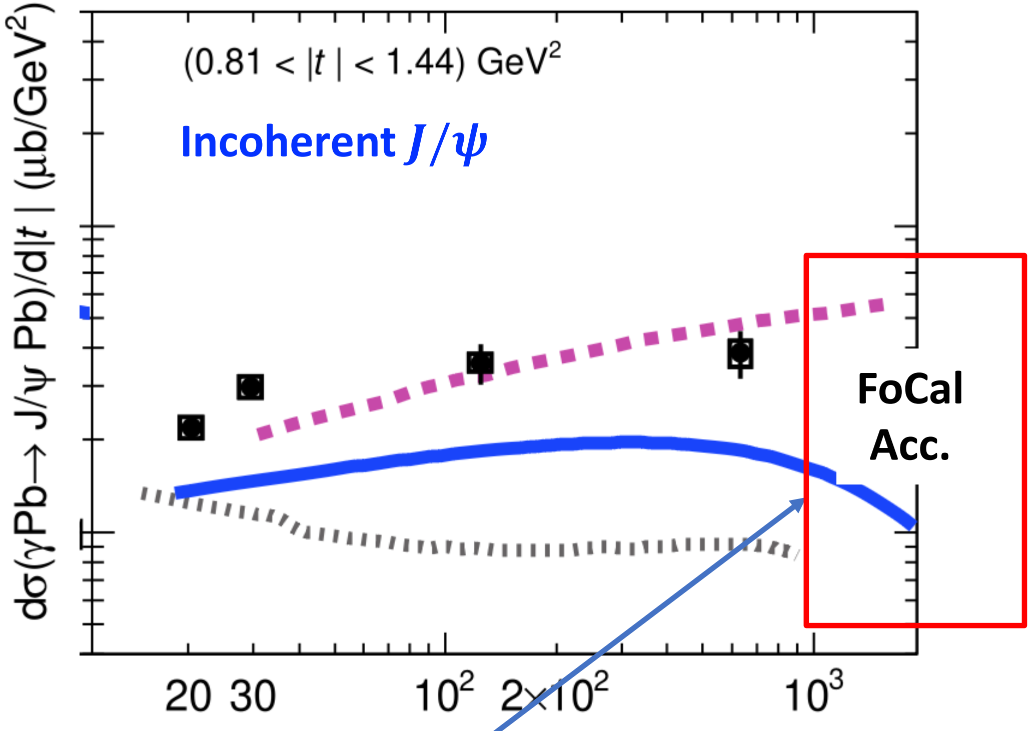
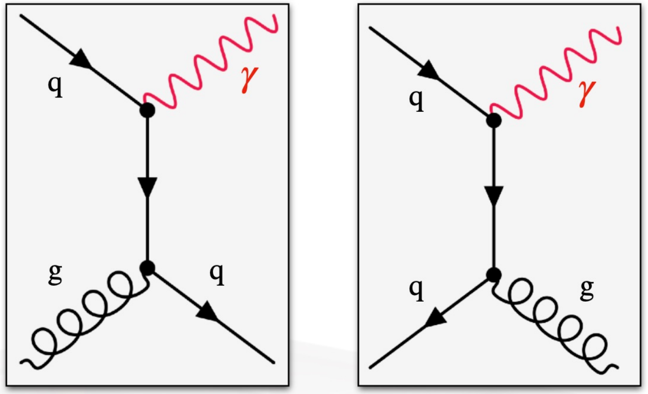


- As the energy grows → variance grows → cross section grows → until **saturation is reached** and **variance starts to decrease** → cross section starts to **decrease**!

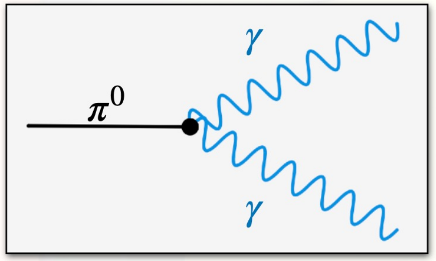
- Look for **a turn over trend in incoh. J/ψ** due to **gluon saturation**

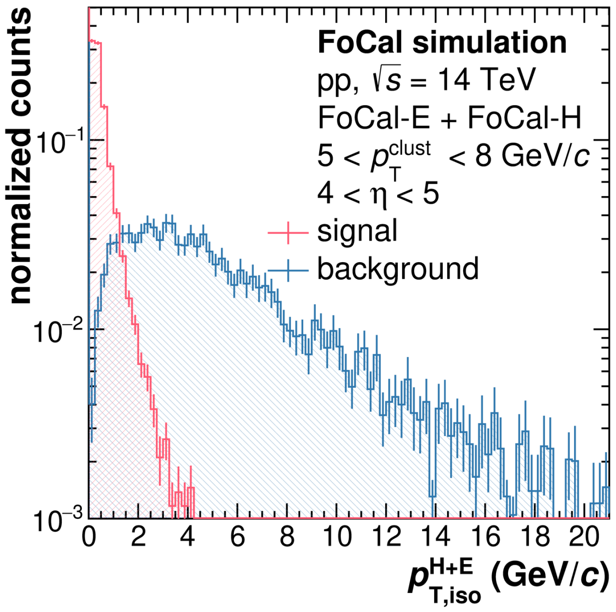
Prompt Photons with ALICE FoCal

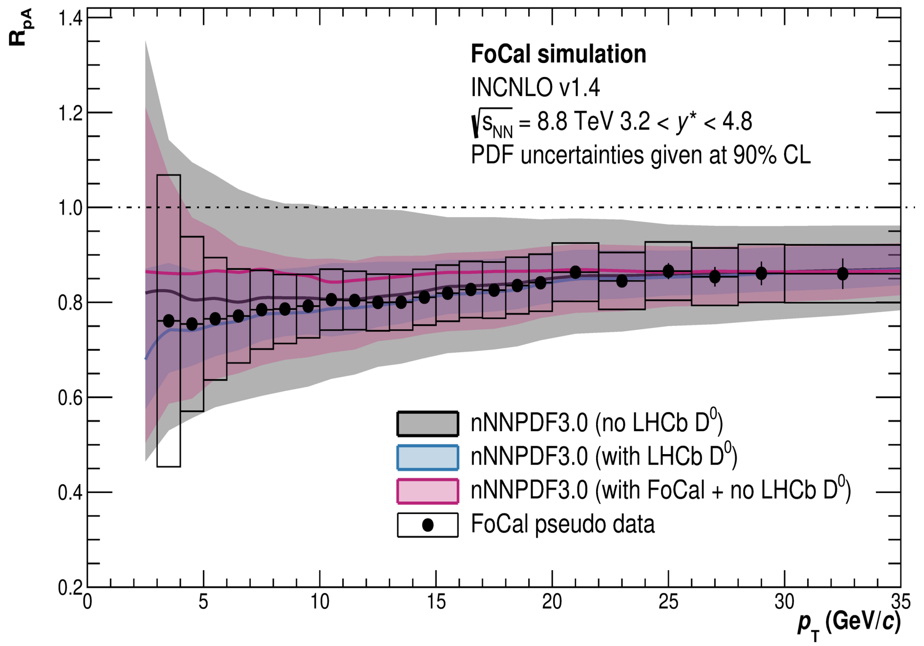
- **At LO**, prompt photons dominantly produced from **q-g Compton scattering (gq → γq)** and quark fragmentation (**q $\bar{\mathbf{q}}$ → γg**)
- Photon **isolation** suppresses fragmentation and decay photon background allowed by **FoCal**



Pi0 decays are the main background



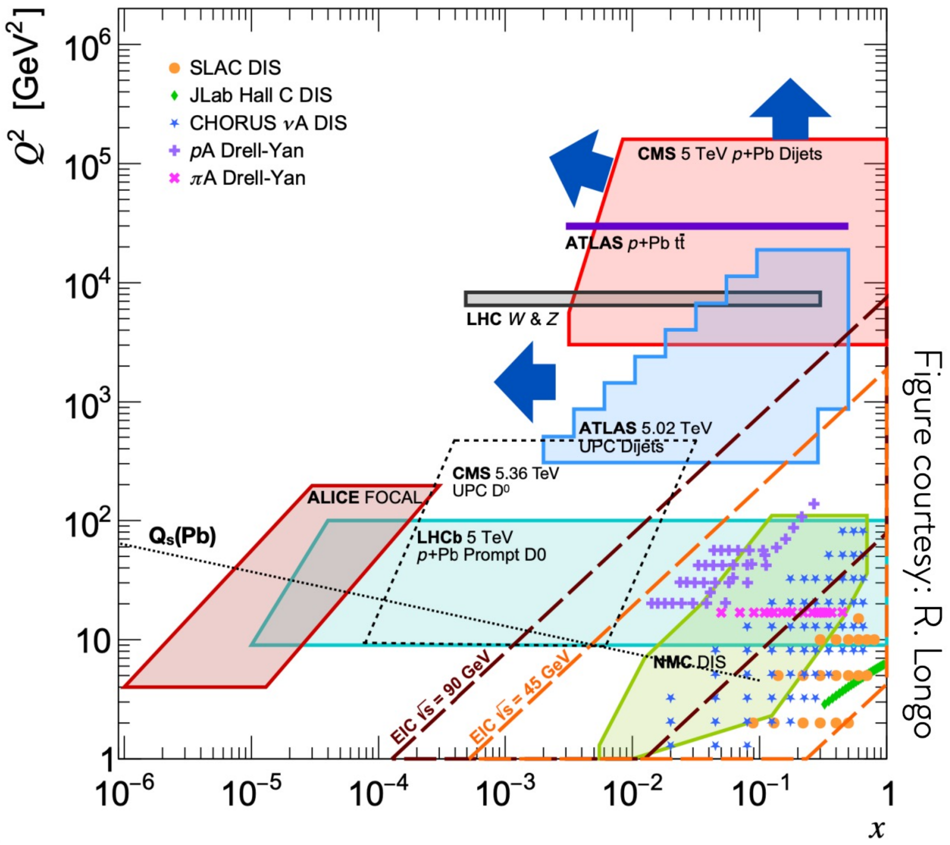




➢ Prompt photons are not affected by final-state effects:
  - ideal for constraining small-x nucleus/nucleon structure

Summary

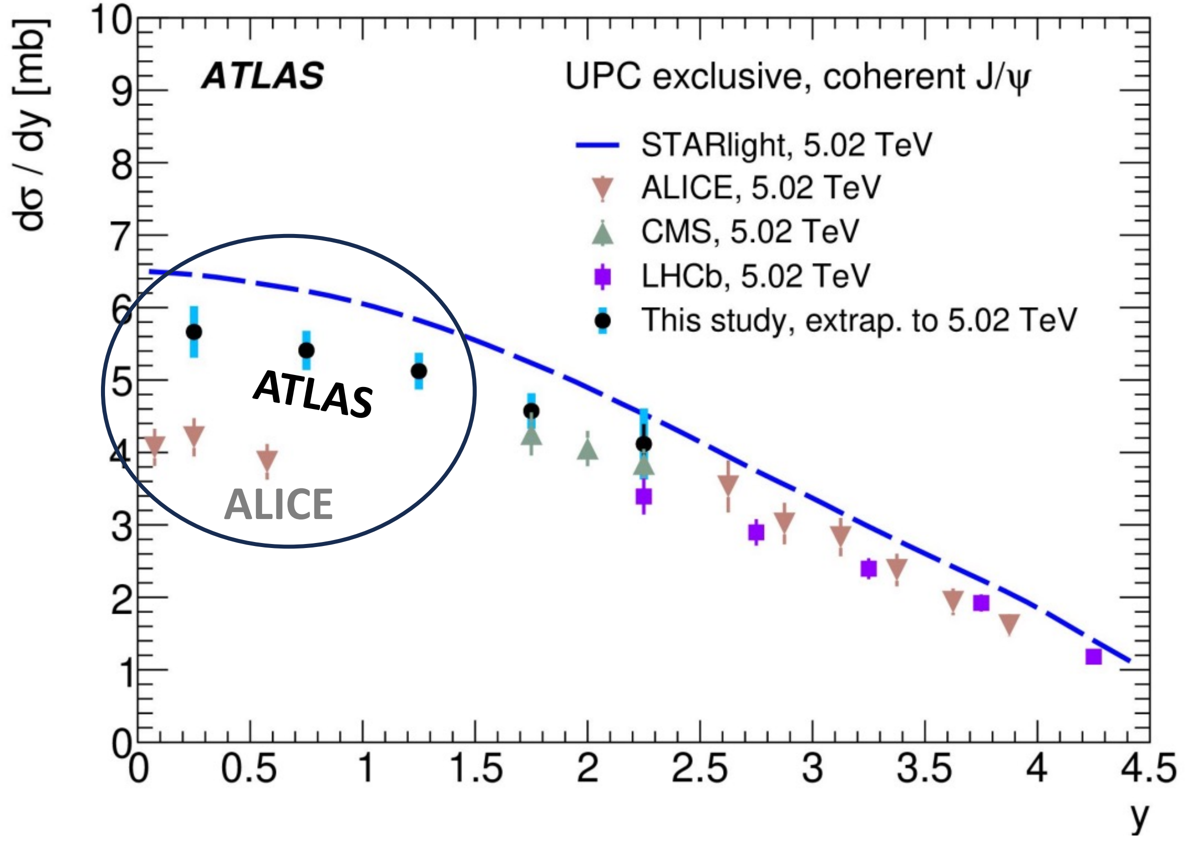
- **Recent LHC measurements reveal significant nuclear modifications**
- **A complete understanding of the small-x regime remains an open question**
- **Future LHC upgrades will open new opportunities to explore gluon saturation and the high-density QCD**

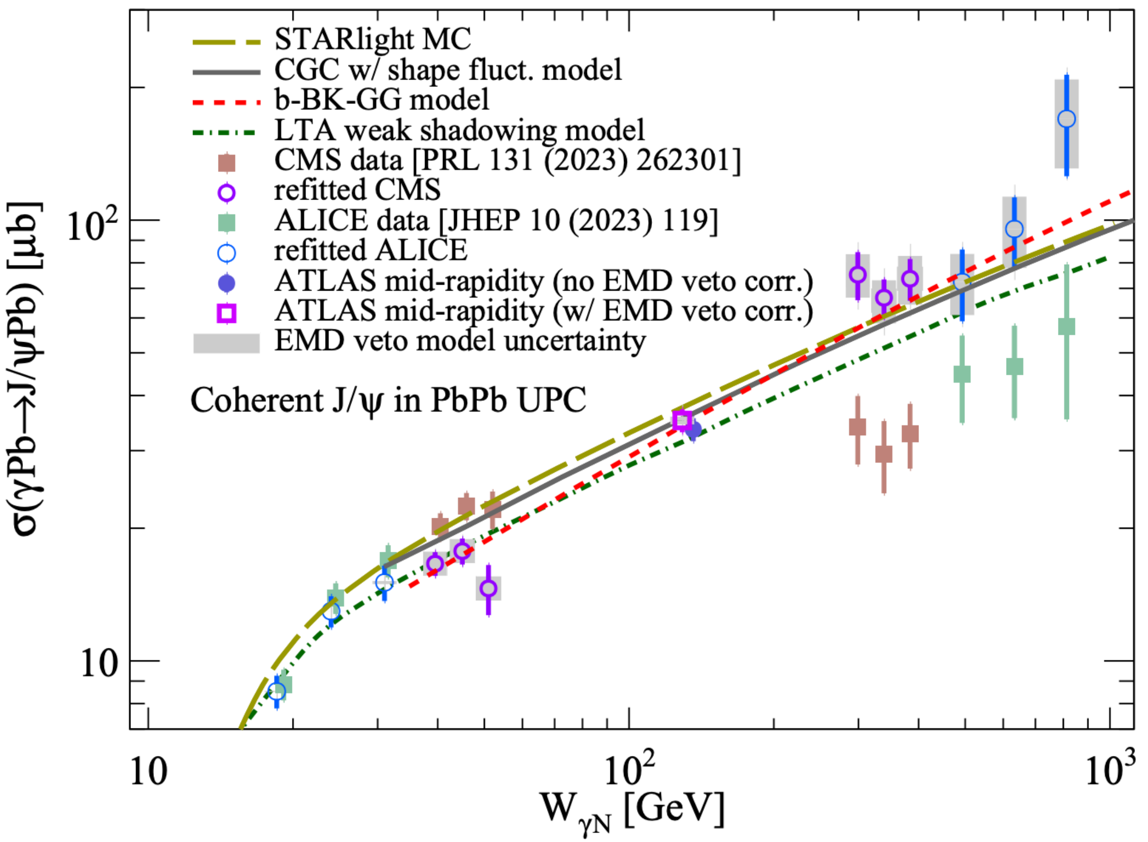


Thanks!

Backup Slides

Homework For Experiment and Theory





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

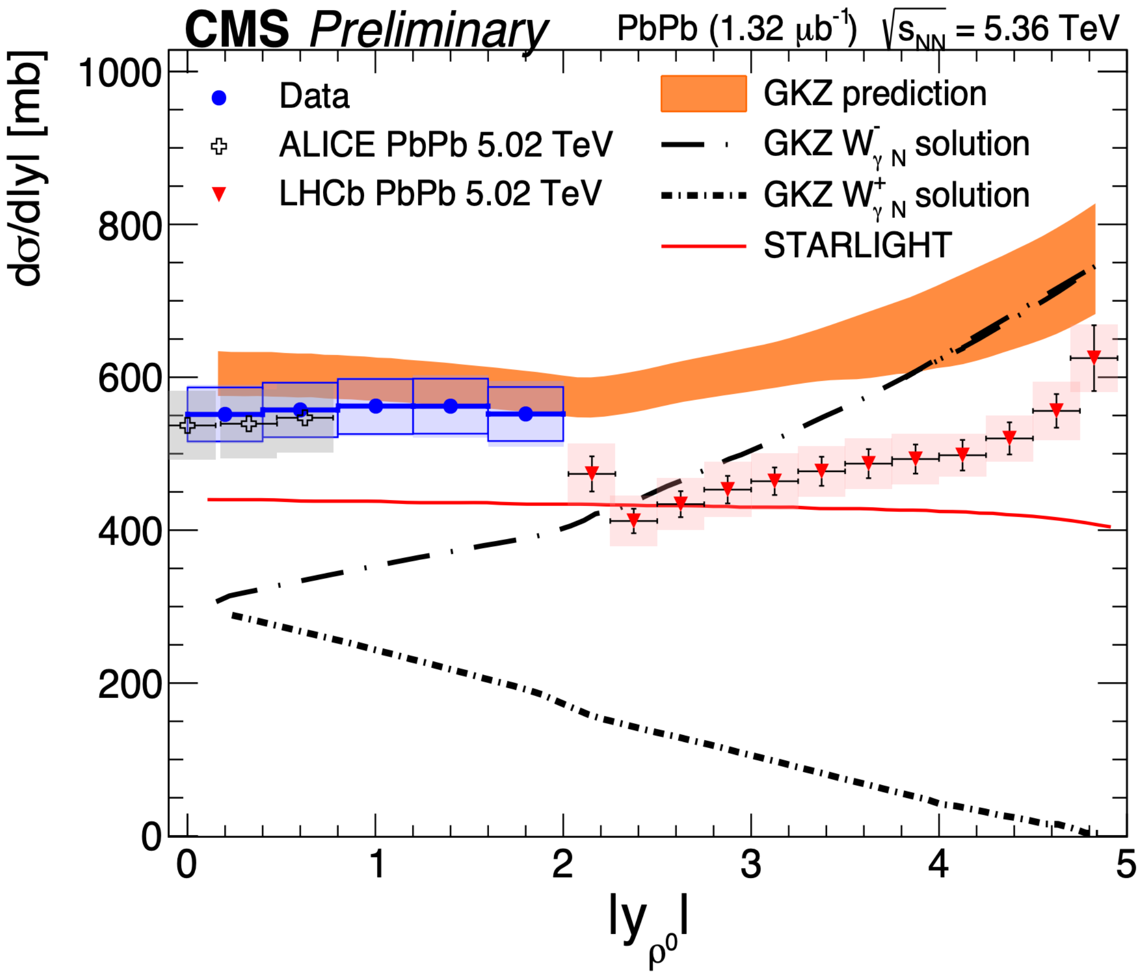
A First Account of the Impact of Ion Electromagnetic Dissociation on Event Exclusivity in Ultraperipheral LHC Collisions

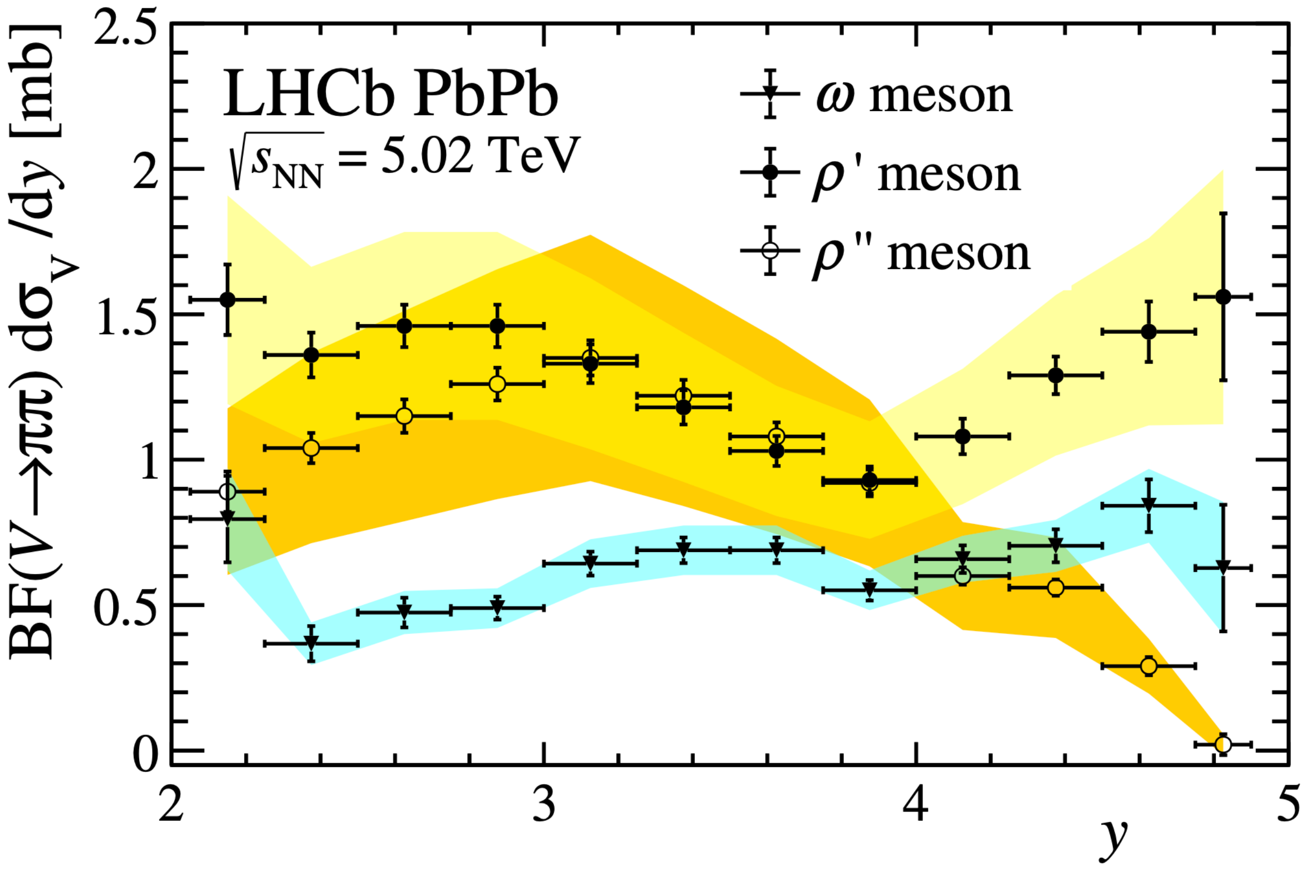
M. Dyndal*
AGH University of Krakow, Faculty of Physics and Applied Computer Science, al. Mickiewicza 30, 30-059 Krakow, PL

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

(Dated: April 30, 2026)

Coh. Light VM Photoproduction in UPCs

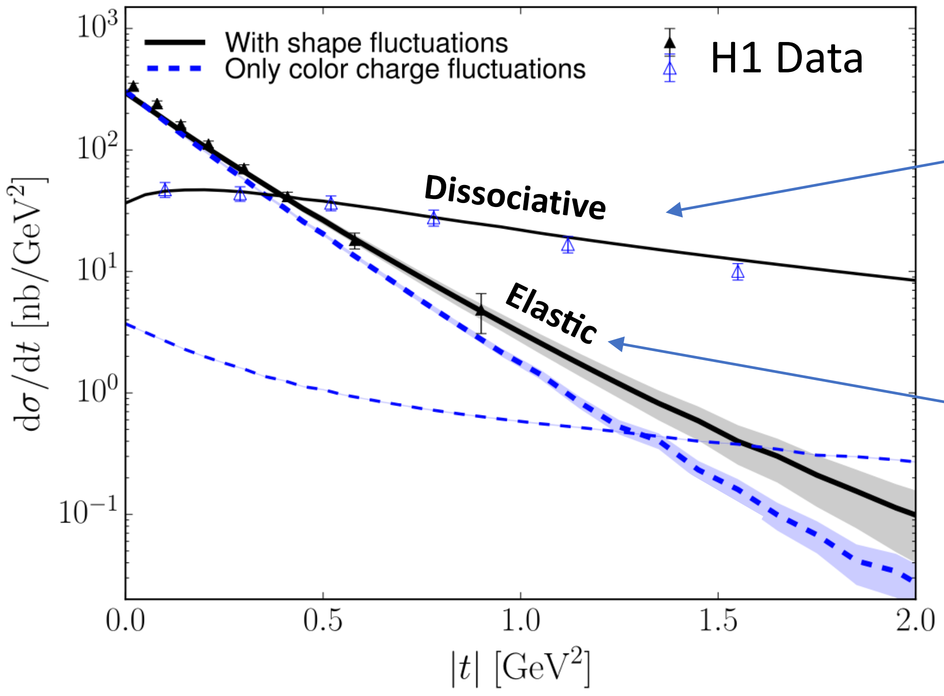


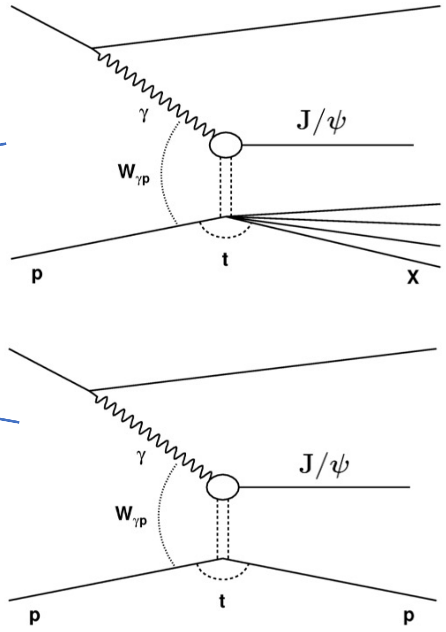


Fluctuating Gluons inside Nucleon

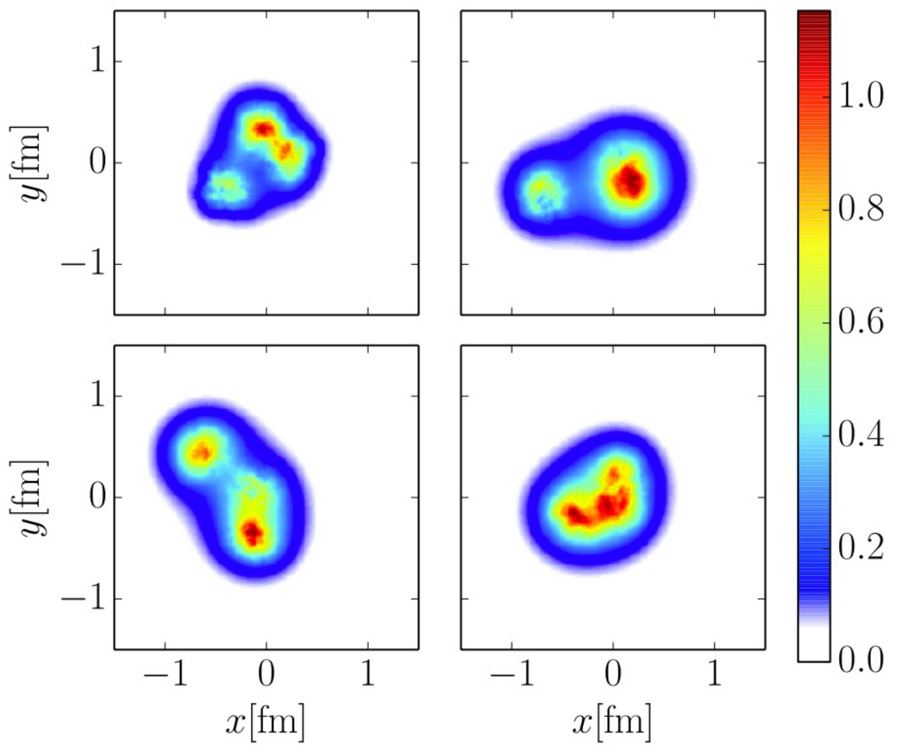
CGC IPsat considering the **fluctuations** of **geometry** (shape and size), **energy density**, **local saturation scale** and **color charge**, successfully describe the HERA data

J/Ψ Photoproduction at HERA





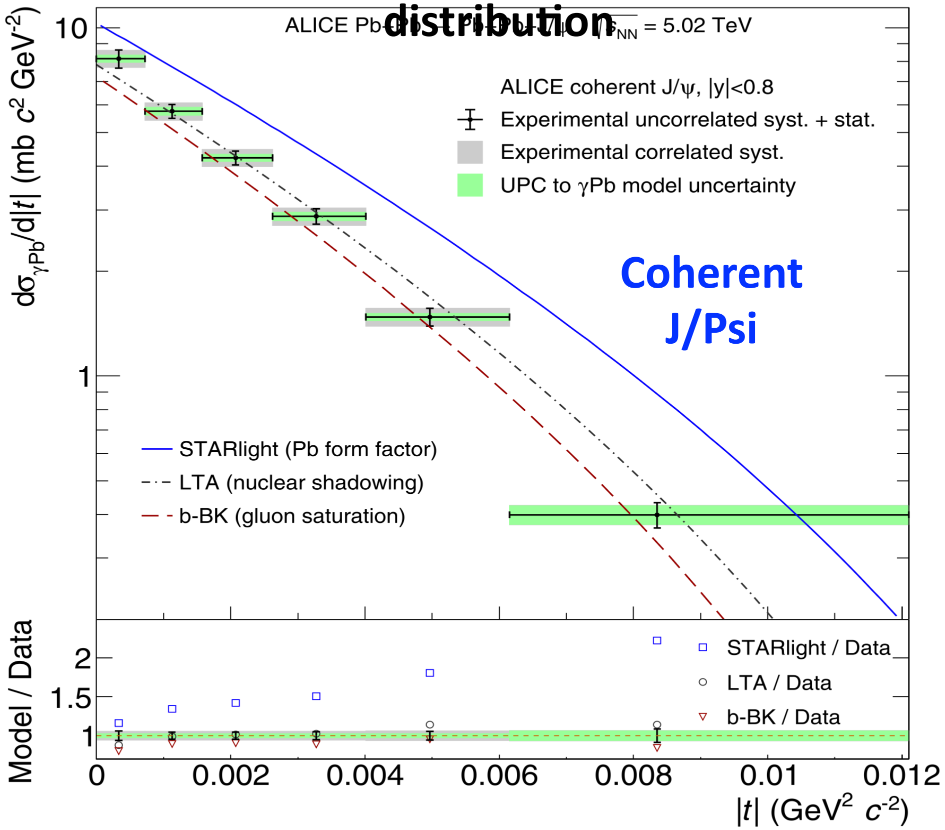
Rep. Prog. Phys. **83** (2020) 082201



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

Reveal Average Distribution and Fluctuations of Nuclear Gluonic Structure via t spectra

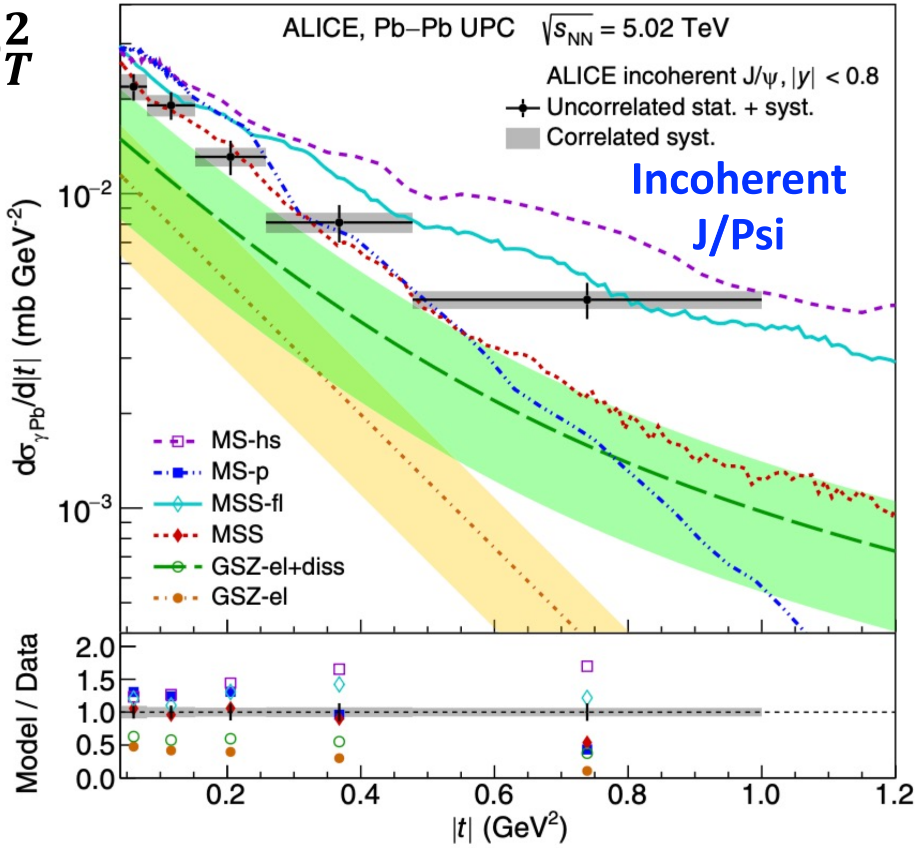
Probe average transverse distribution



ALICE, PLB 817, 136280 (2021)

$$|t| \approx p_T^2$$

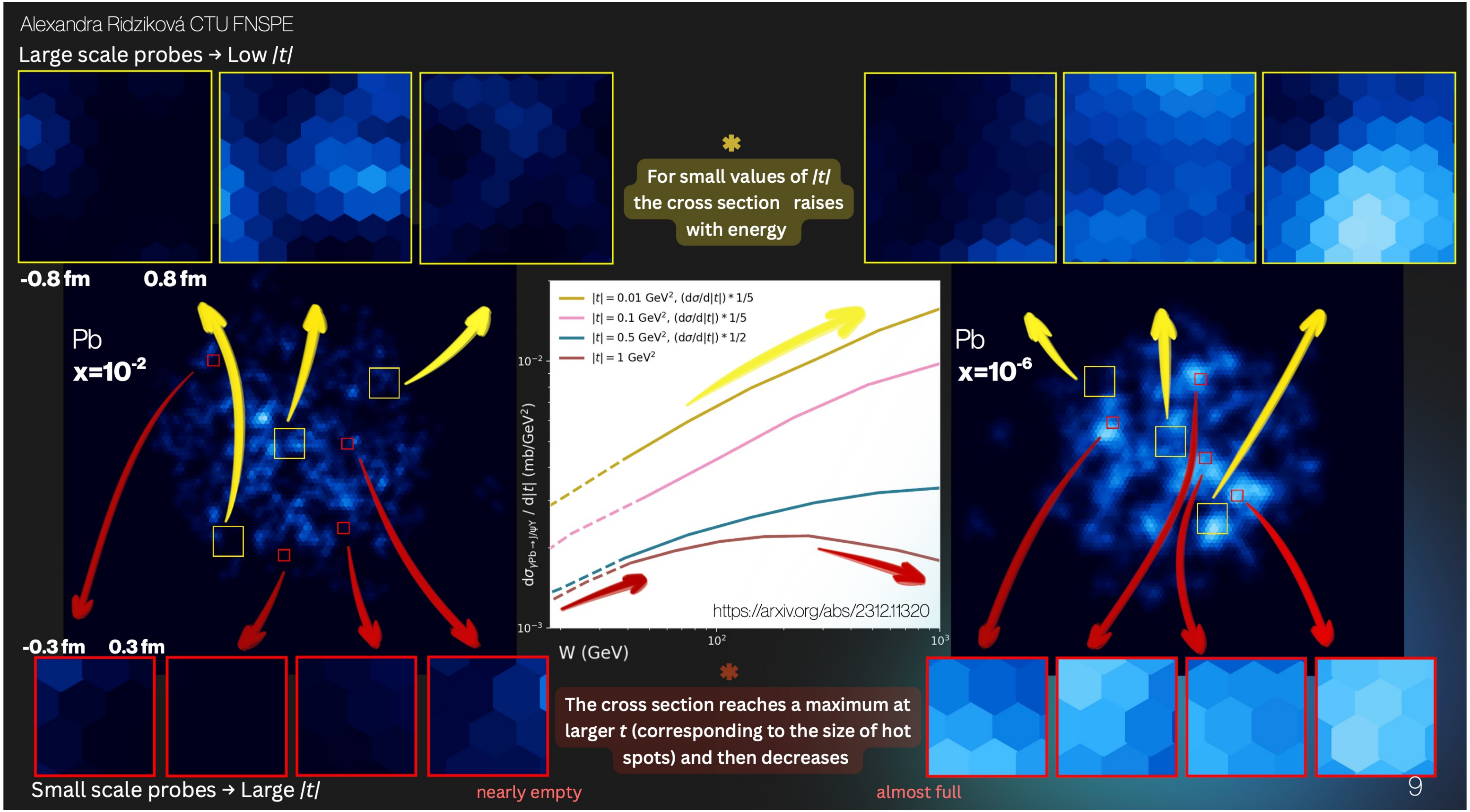
Probe local gluonic fluctuations



ALICE, PRL 132, 162302 (2024)

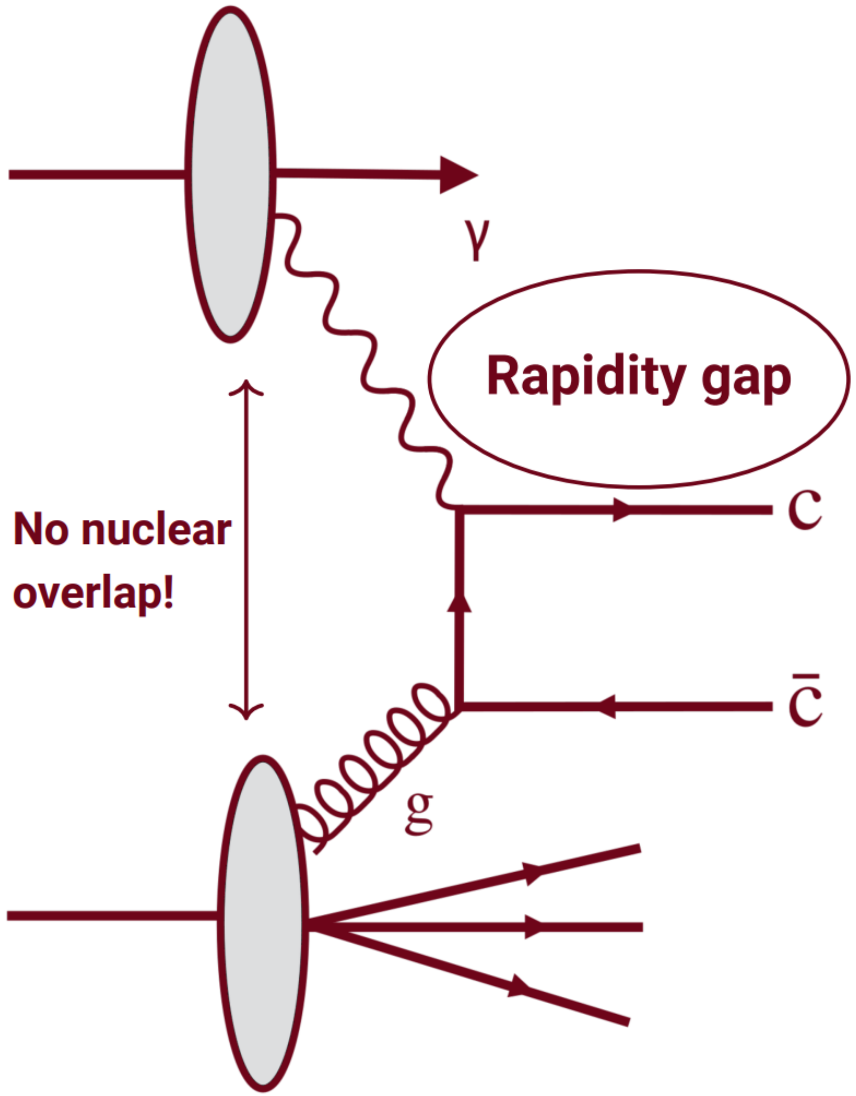
- **Both gluon saturation and shadowing models describes the coherent $|t|$ spectra**
- **No models describes both magnitude and slope of incoherent $|t|$ spectra**

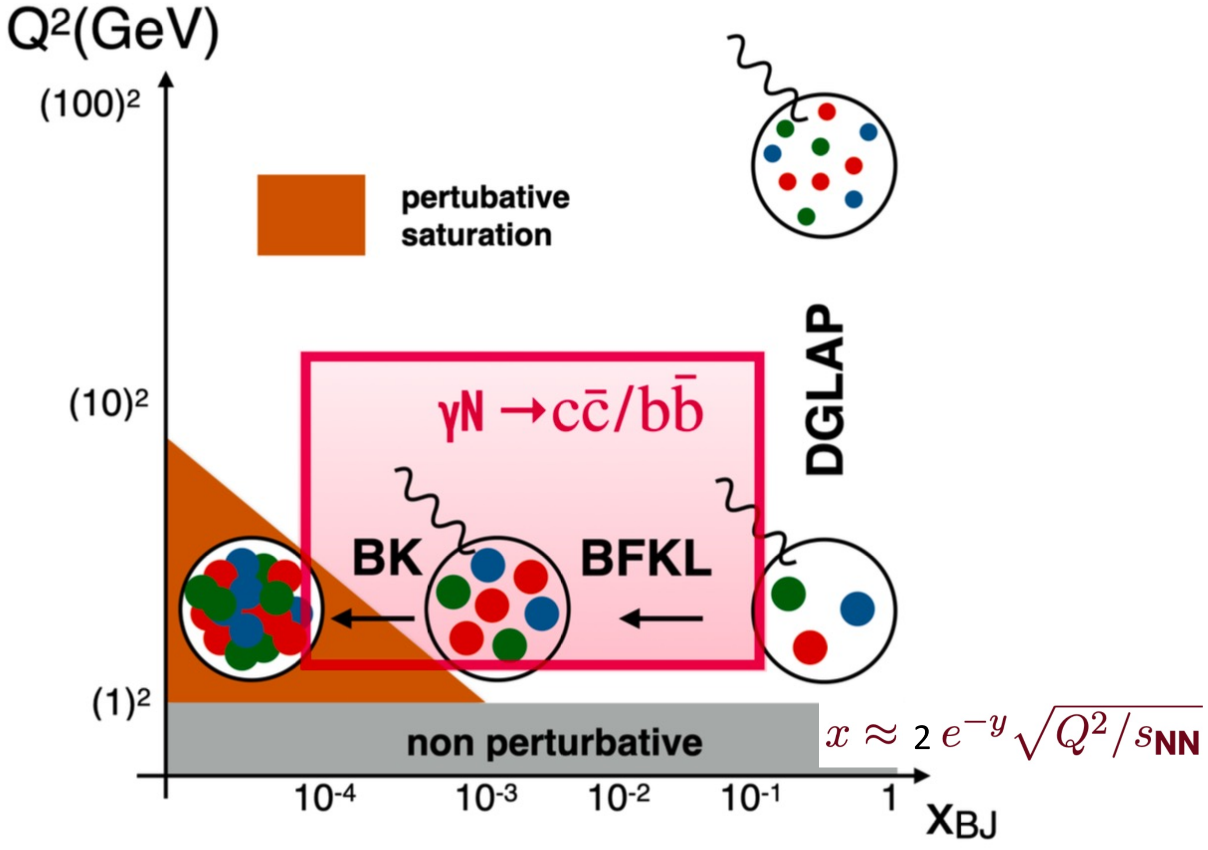
Energy (x)-Dependent Incoh. J/Ψ t Spectra



See more details at Alexandra's talk at UPC 2025

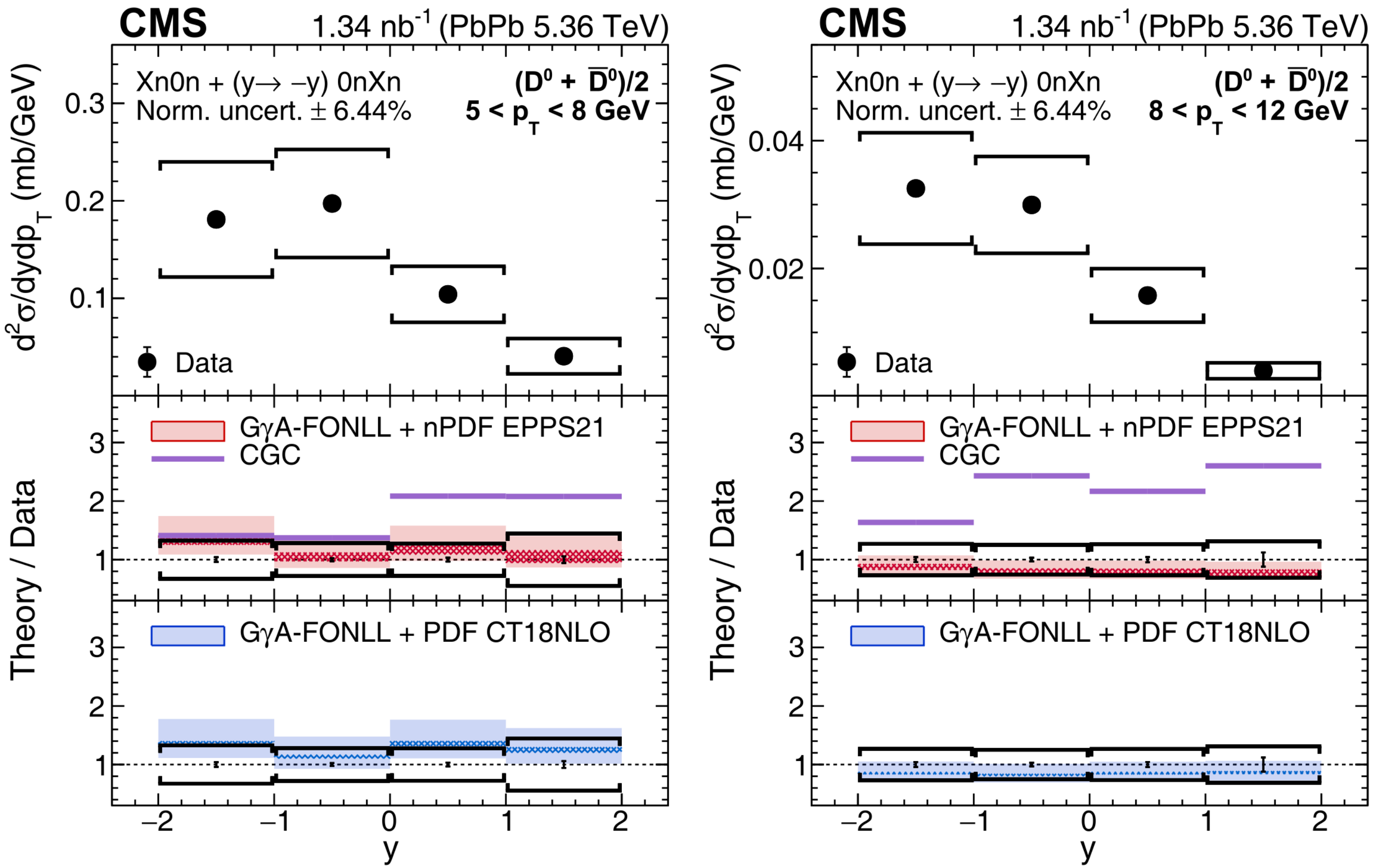
First **Open Charm** Photoproduction in UPCs



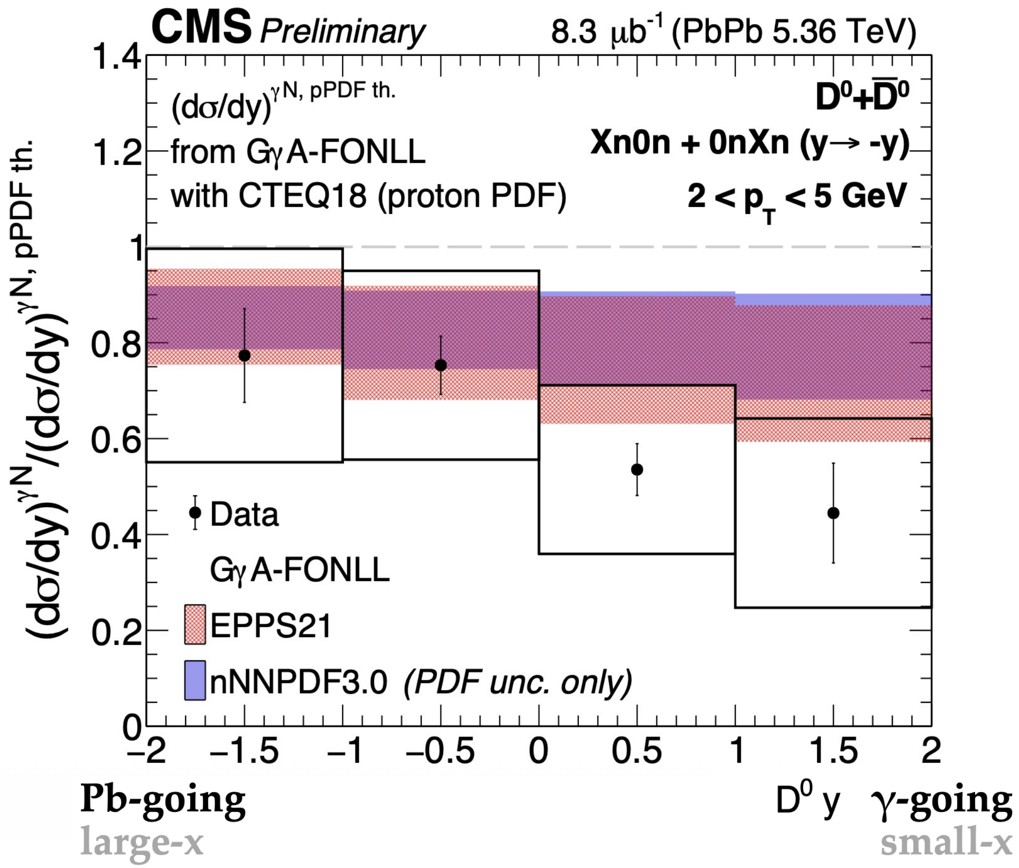


- **Mass of charm $\rightarrow$ pQCD control at p_{T} =0!**
- **Probes Q^2 $\sim$ (charm/bottom mass)^2**
- **Complements higher Q^2 of dijets down to Q^2 J/ψ**

First Open Charm Photoproduction in UPCs



CMS, PRL 136, 122303 (2026)



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