Probing A New Regime Of Ultra-dense Gluonic Matter Using High-energy Photons With The CMS Experiment

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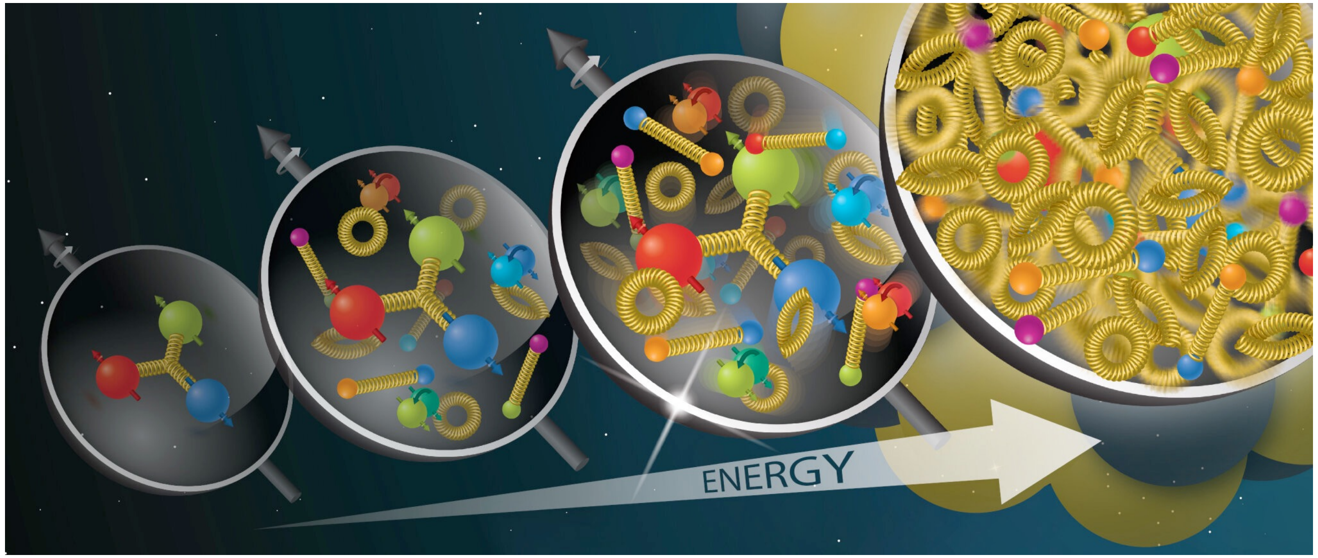
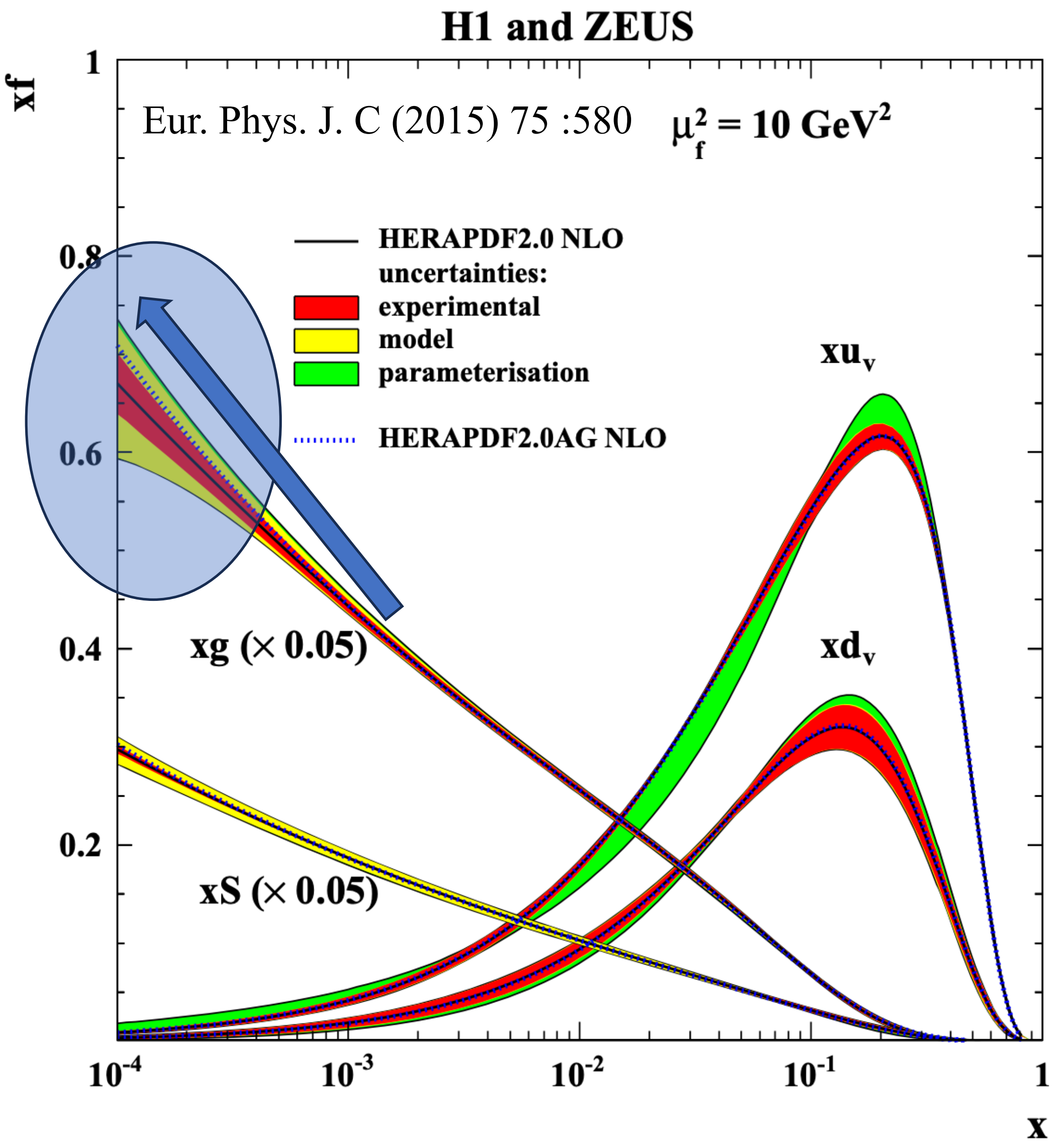
Rice University

Supported by

U.S. DEPARTMENT OF ENERGY | Office of Science

Understand The Gluon That Binds Us All





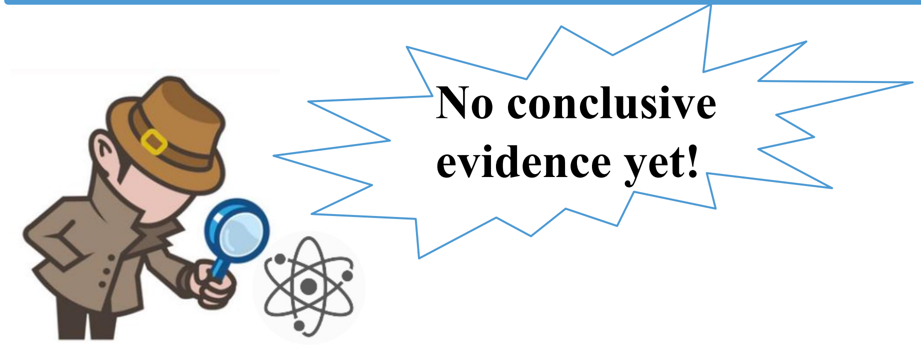
- DIS results show a seemingly "**indefinite** rise" in gluon PDF with linear evolution (gluon splitting)

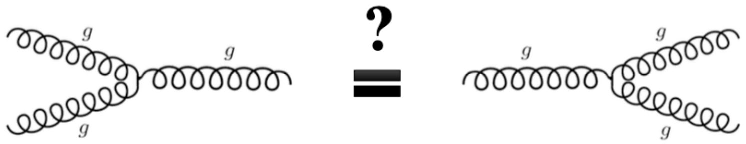
- **What is the fate of gluons at extreme densities (small x)?**

Ultra-dense Gluonic Matter

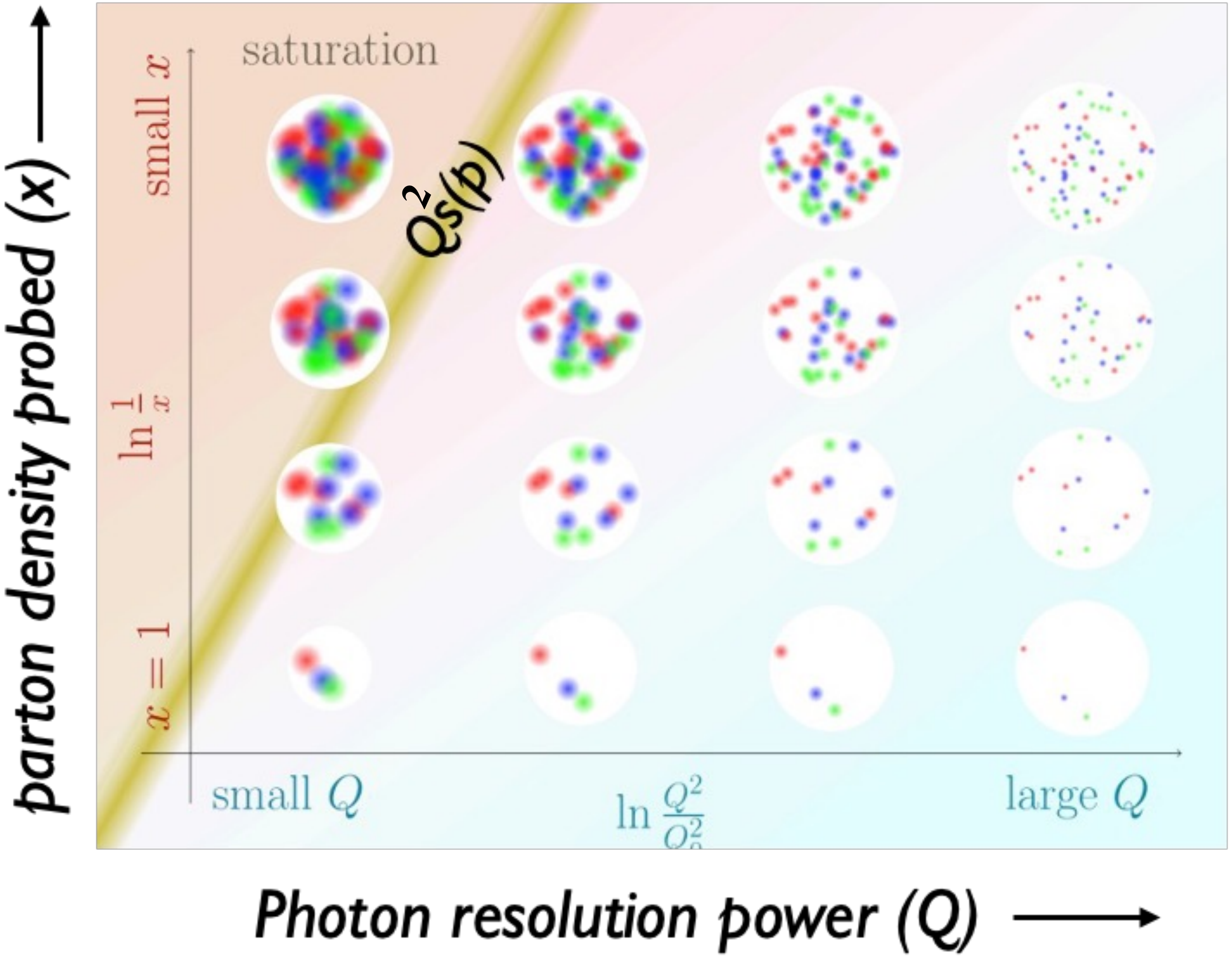
- QCD unitarity: Growth of gluon density cannot continue indefinitely!

- Gluons start to overlap and eventually recombine





Saturation?



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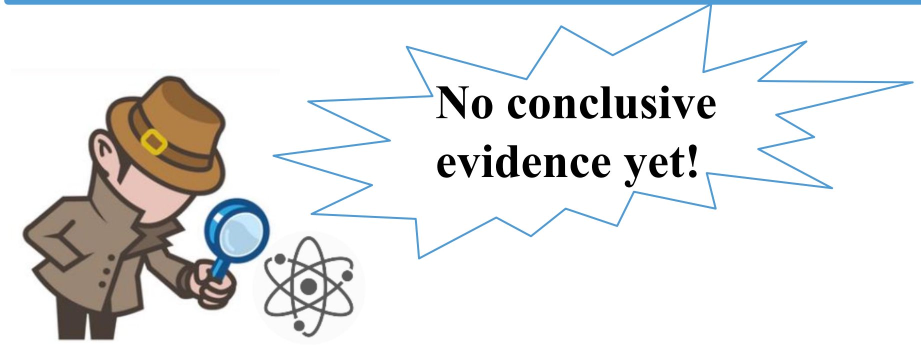

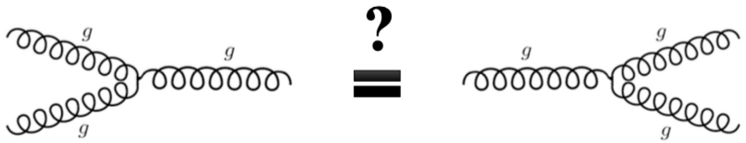

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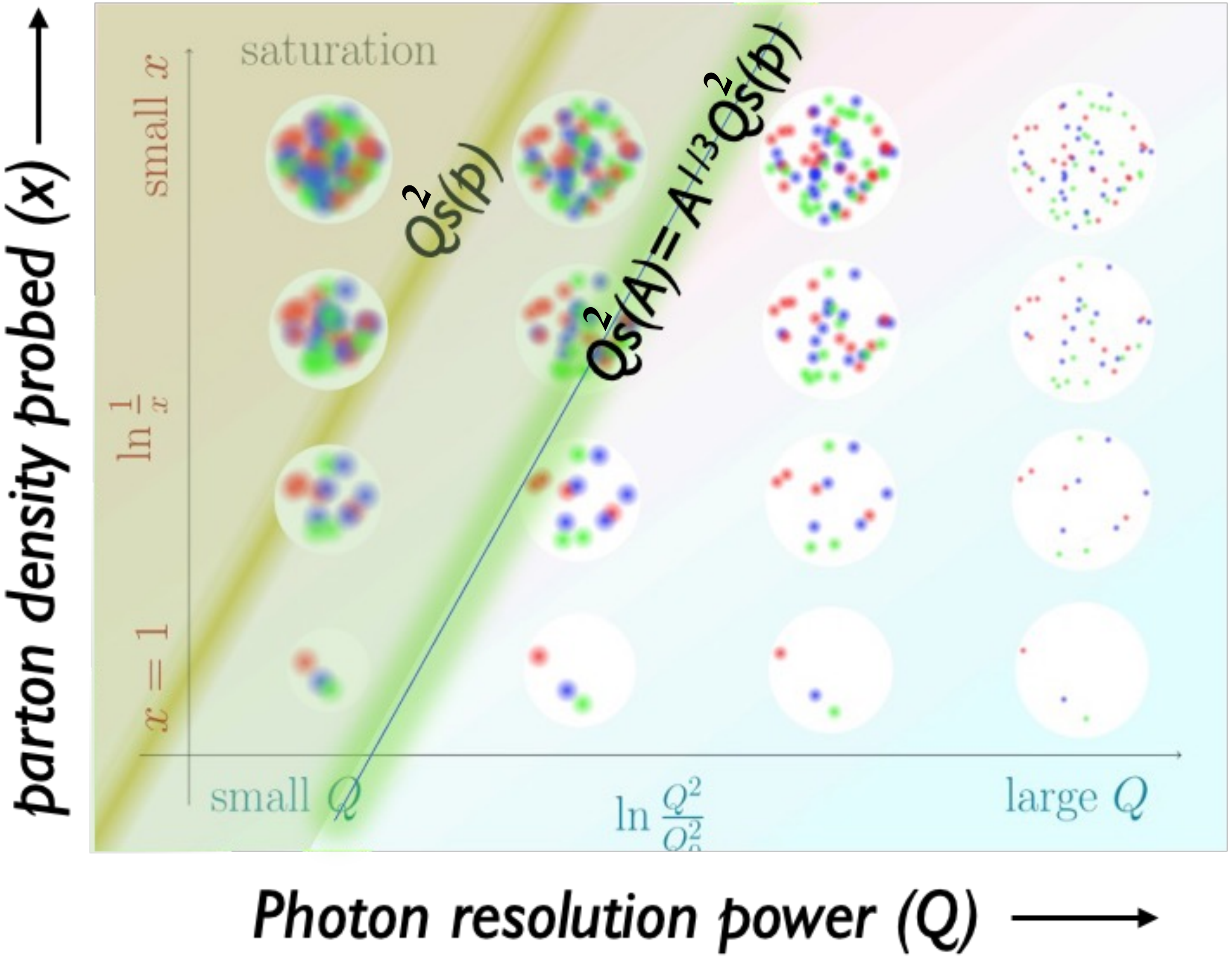
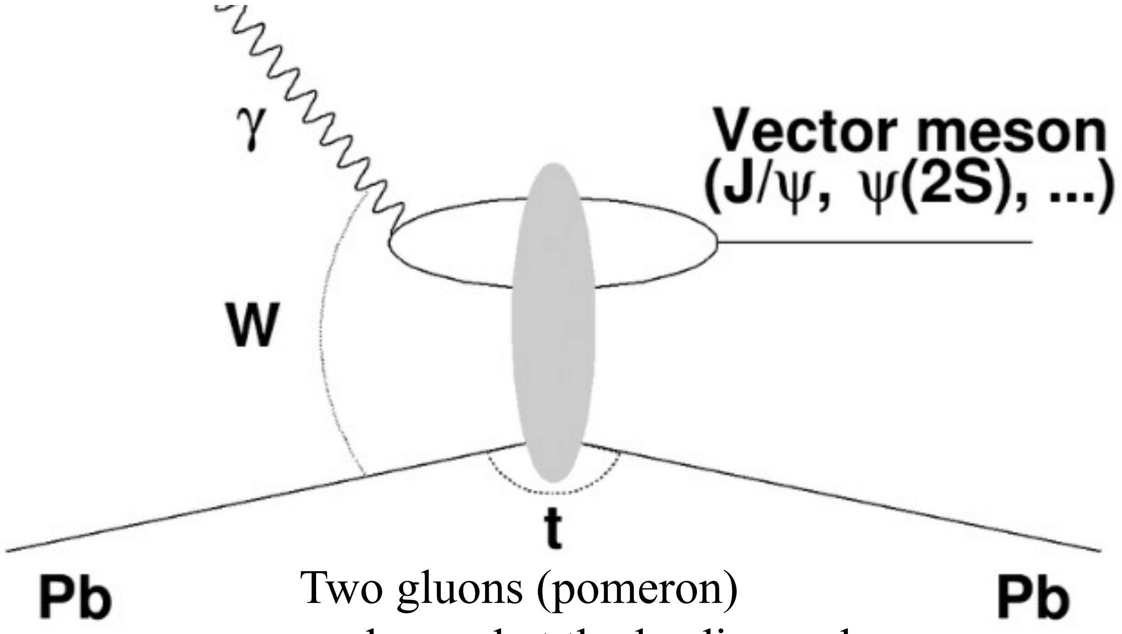


Using Photon As The Probe

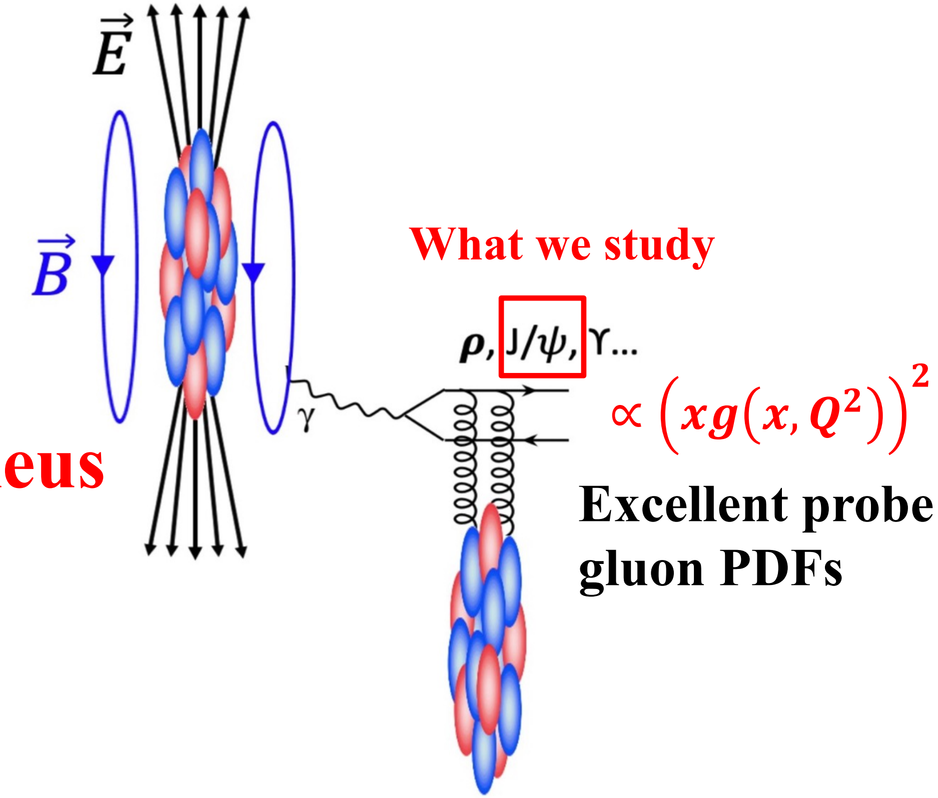
- Photoproduced VM cross section at small x can test on the gluon density scaling behavior
- **VM Photoproduction** $\propto \left(xg(x, Q^2)\right)^2$ **at the LO in pQCD**



Two gluons (pomeron) exchanged at the leading order

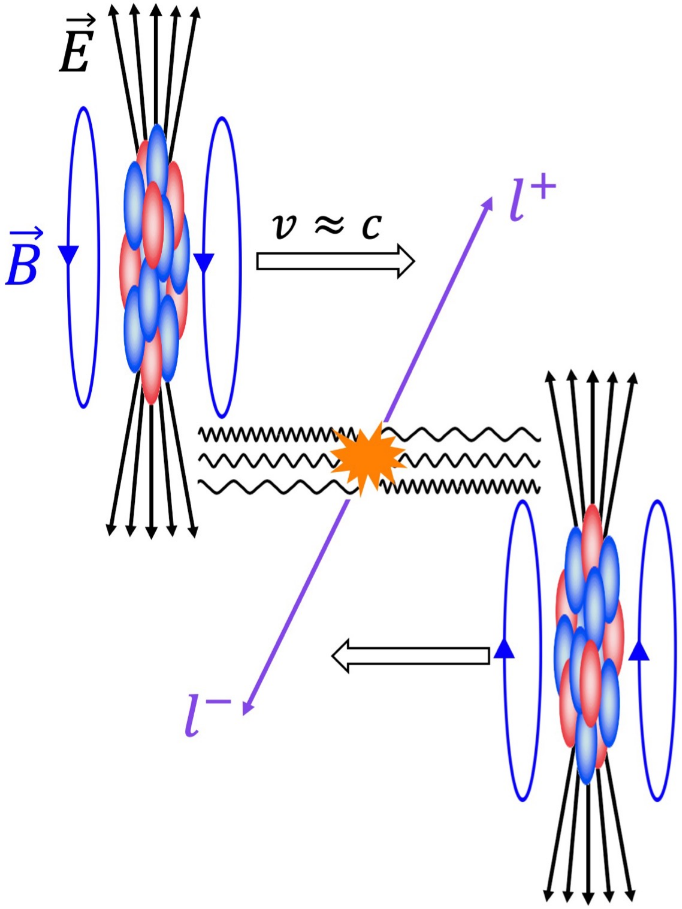
Ultra-Peripheral Collision (UPC)

- Nuclei "miss" each other (b > $R_A + R_B$)
- Boosted EM field of nuclei are source of photons
- Interactions via photon-photon or photon-nucleus



Photon-Nucleus

Excellent probe of gluon PDFs



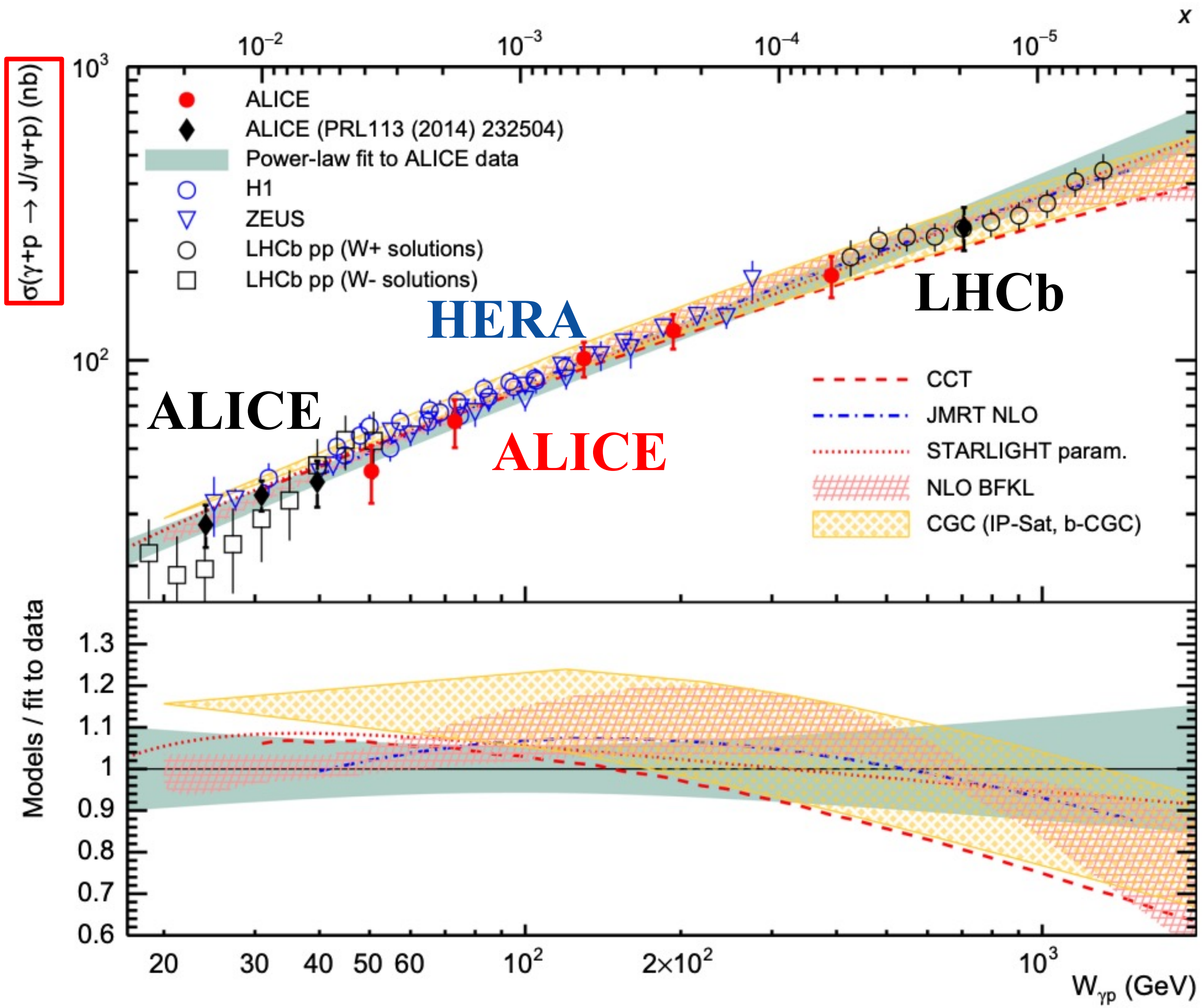
Photon-Photon

J/ψ Photoproduction In $\gamma + p$

Eur.Phys.J.C 79 (2019) 5, 402

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

- Gluons inside a proton:
  - Investigated via γp interactions by HERA and LHC
  - Consistent results between HERA and LHC: power law
- **No clear signs of gluon saturation inside proton**

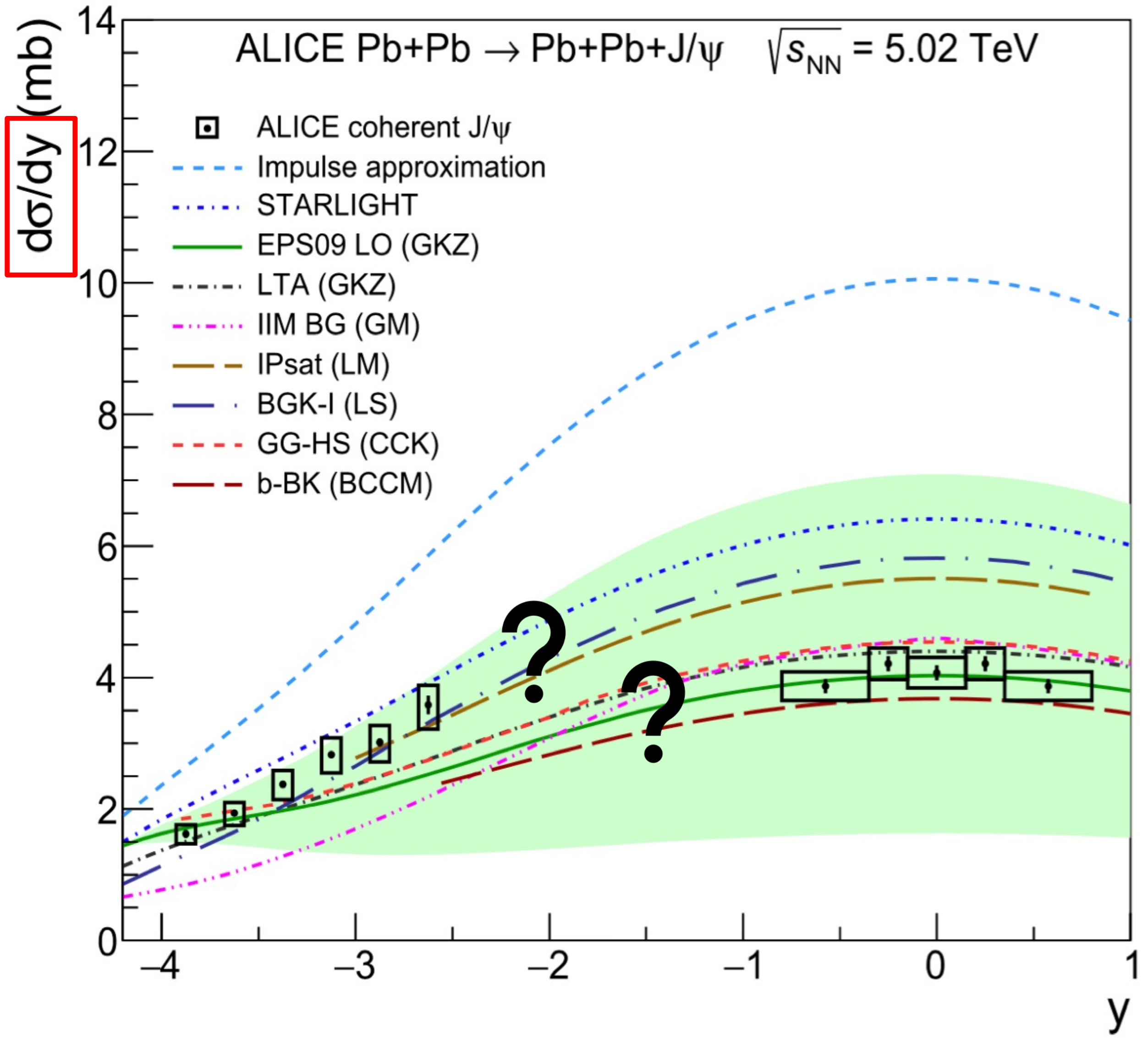


J/ψ Photoproduction In $\gamma + Pb$

Eur. Phys. J. C (2021) 81:712

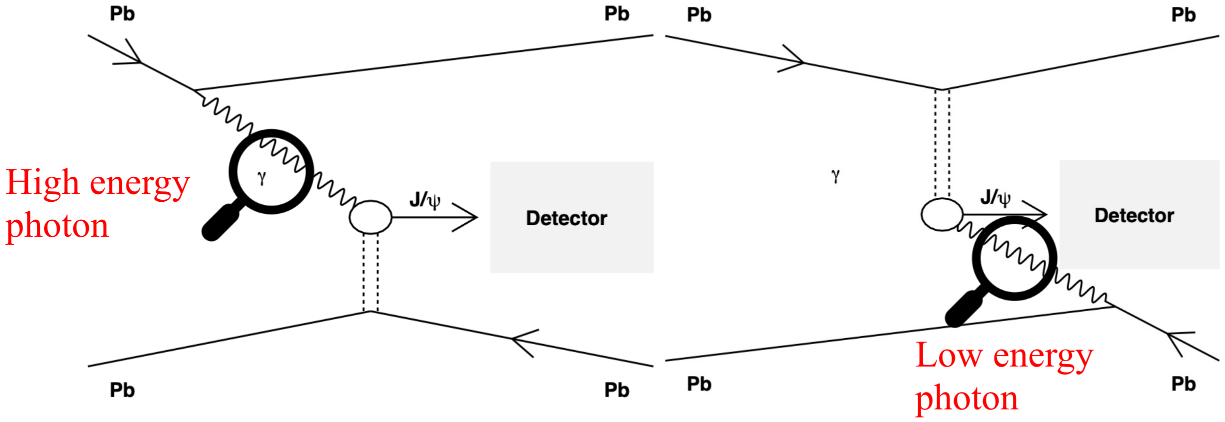
$$\gamma + Pb \rightarrow J/\psi + Pb$$

- Measurements from ALICE
- The data trend **challenge** all existing theoretical models
  - Shadowing models
  - Saturation models
- Natural questions:
  - Data in the gap region?
  - If data are correct, what's the underlying physics?



J/ψ Photoproduction In $\gamma + Pb$

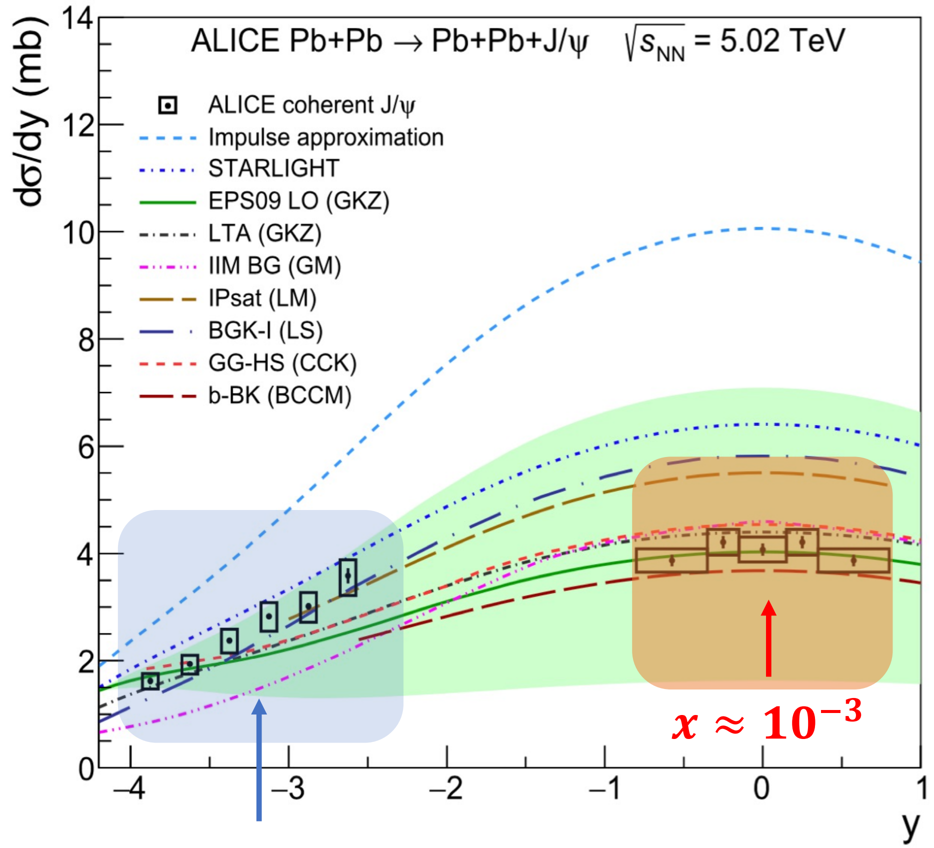
- Symmetric: both can serve as the photon source and the target
- Each data point: low energy photon + high energy photon contribution



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

No easy access to x ~ 10^{-5} in Pb

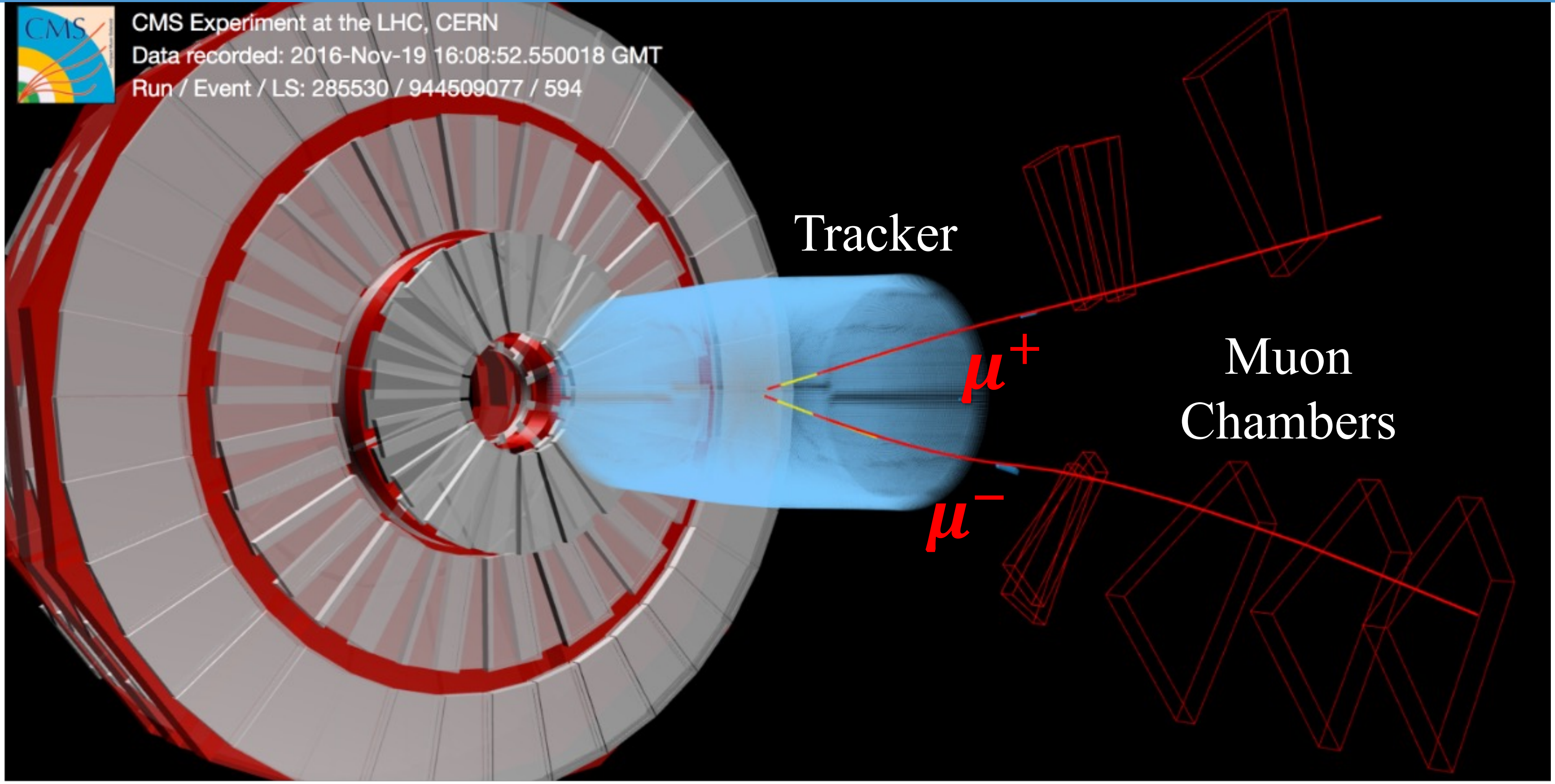
Eur. Phys. J. C (2021) 81:712



$x \approx 10^{-5}$ *or* 10^{-2}
(~95% high x)

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

UPC J/ψ Photoproduction Event

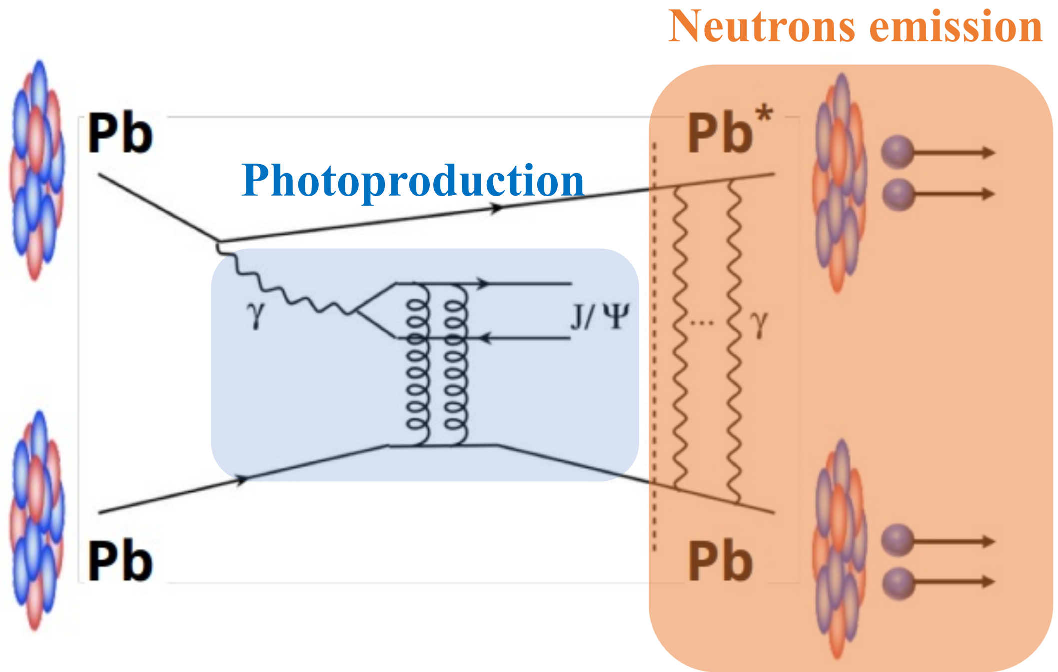


- **UPCs produce few particles:**
  - **Require low energy measured in the forward calorimeters to suppress hadronic collisions.**
  - **Select events with exactly two reconstructed tracks identified as muons.**

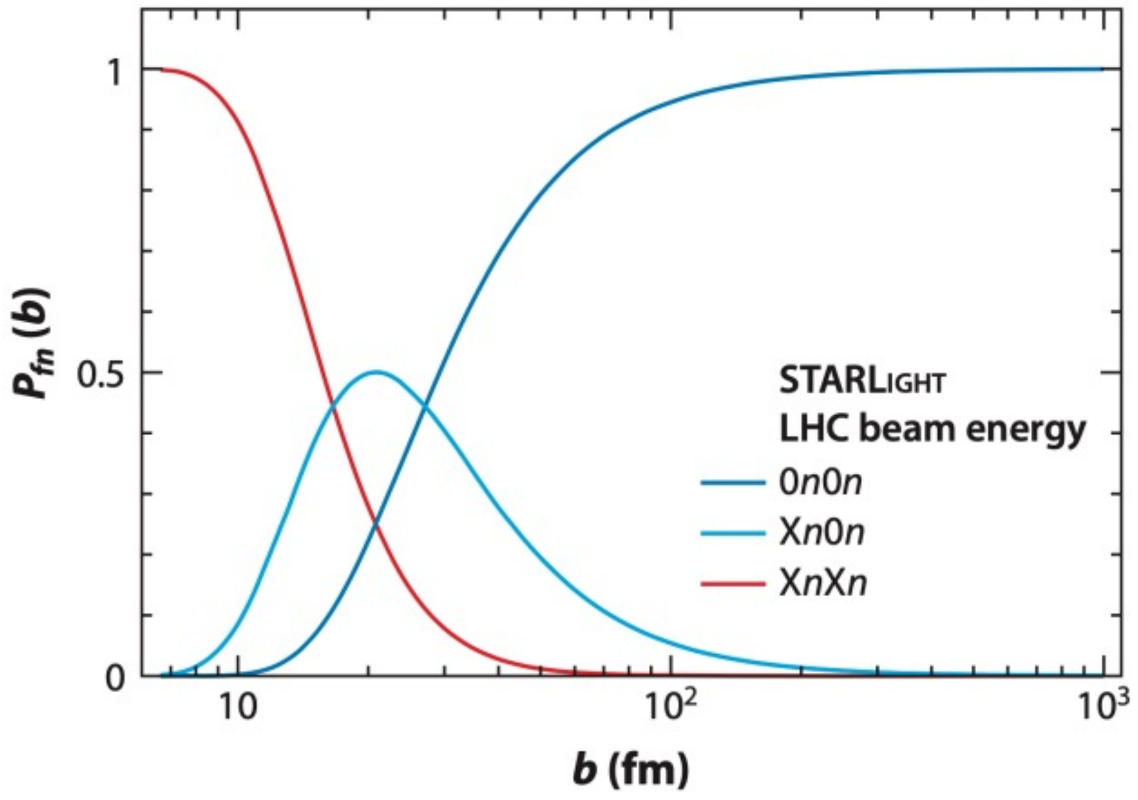
A Solution To The Two-way Ambiguity Puzzle

Guzey et al., EPJC 74 (2014) 2942

Control the impact parameter of UPCs via forward emitted neutrons $P_i(b) \propto 1/b^2$



- Additional photon exchange
- Soft photons (energy ~10 MeV)
- Independent of interested physical process
- Large cross section ~200 b (single EMD)

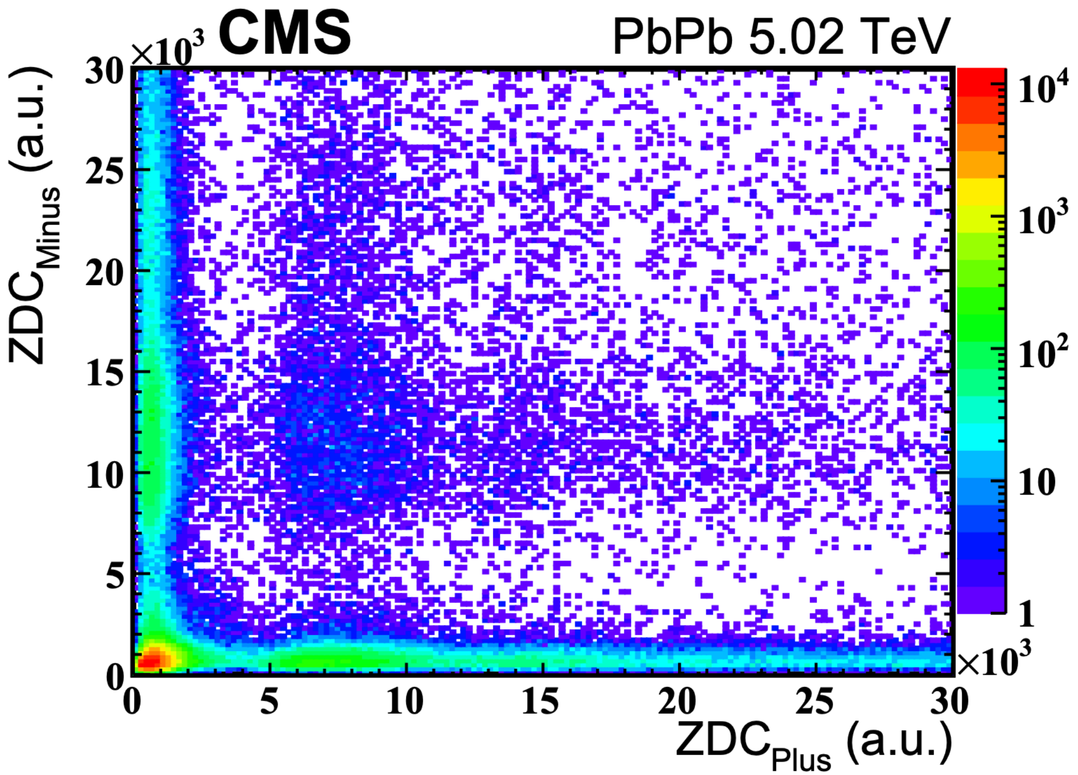


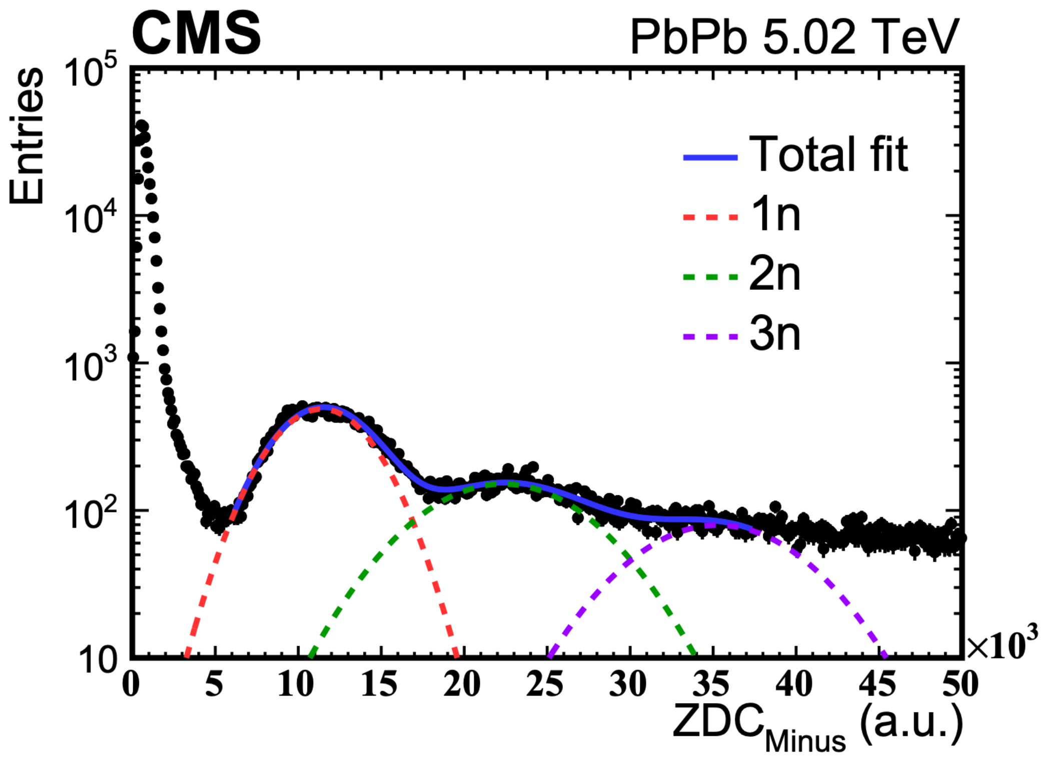
Spencer Klein & PAS, Ann Rev Nucl Part Sci Vol. 70:323-354

•Analogous to centrality:
- $b_{XnXn} < b_{0nXn} < b_{0n0n}$

Determining Neutron Multiplicity

Phys. Rev. Lett. 127, 122001 (2021)





Neutron Classes → Different impact parameter b

- XnXn → Smaller b
- 0n0n → Larger b

Entering A New Regime Of Small x Gluonic Matter

Dominant b ranges of different neutron classes:

- 0n0n: b > 40 fm
- 0nXn: b ~ 20 fm
- XnXn: b < 15 fm

What is measured | Photon flux from theory | What we want

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

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

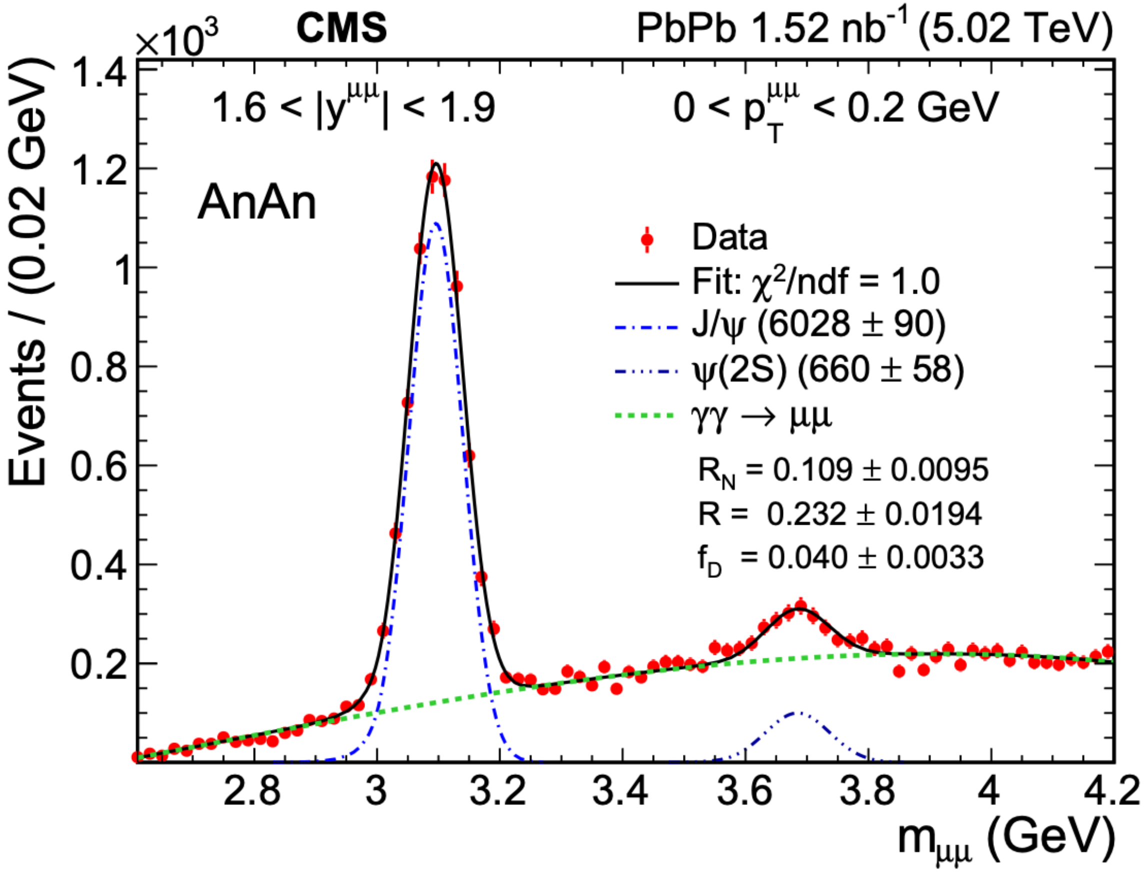
$$\frac{d\sigma^{XnXn}_{AA\to A'A'J/\psi}}{dy} = N^{XnXn}_{\gamma/A}(y)\cdot\sigma_{\gamma A\to J/\psi A'}(y) + N^{XnXn}_{\gamma/A}(-y)\cdot\sigma_{\gamma A\to J/\psi A'}(-y)$$

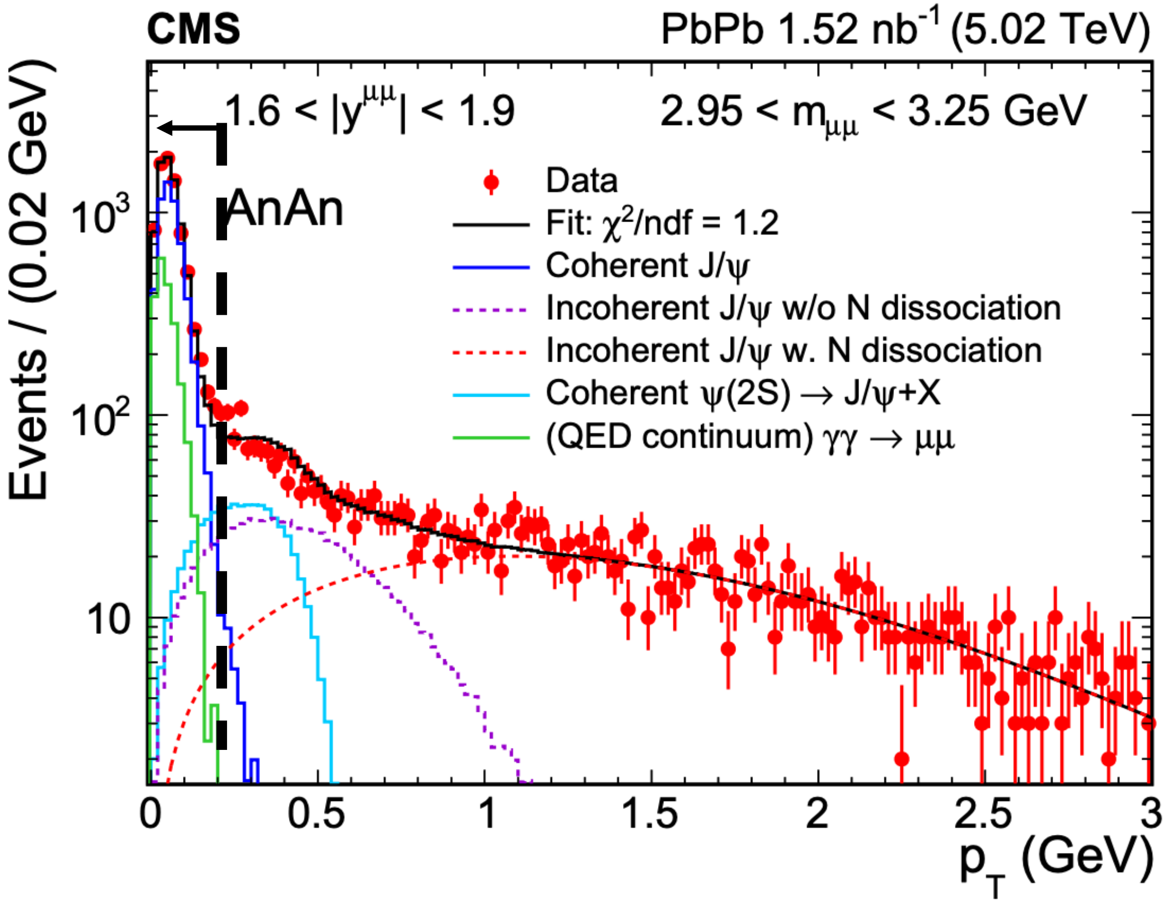
→ Solve for $\sigma_{\gamma A\to J/\psi A'}(y)$ and $\sigma_{\gamma A\to J/\psi A'}(-y)$, and $x = \left(\frac{M_{VM}}{\sqrt{s_{NN}}}\right)e^{\mp y}$

Entering a new regime of small x ~ $10^{-4} - 10^{-5}$ in nuclei!

Signal Extraction

arXiv:2303.16984





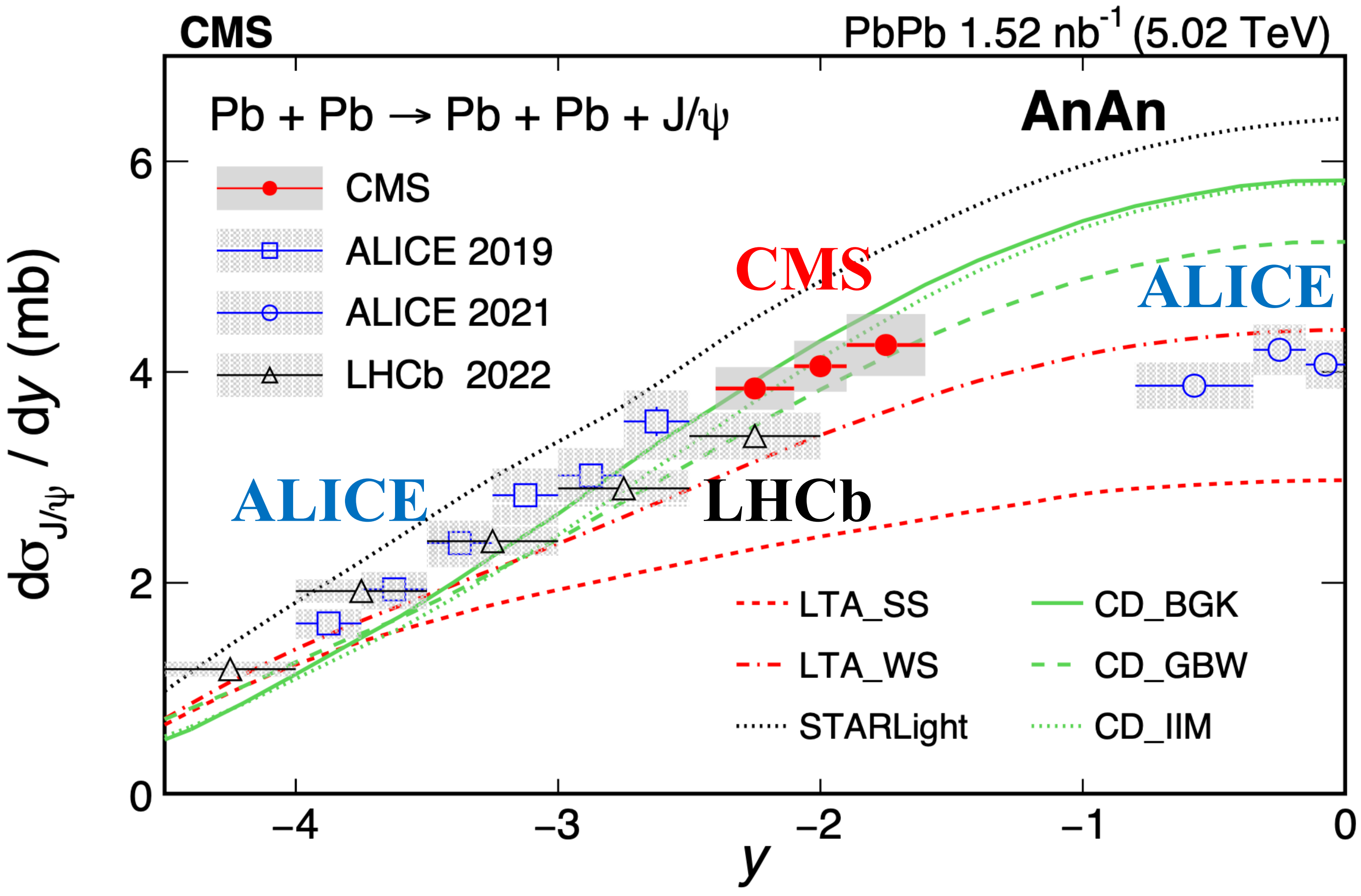
Signal yields are extracted by fitting the mass and transverse momentum spectra

AnAn: All possible neutron emissions

arXiv:2303.16984

ALICE, EPJC 81 (2021) 712
LHCb, arXiv:2206.08221

$$\frac{d\sigma^{coh}_{J/\psi}}{dy} = \frac{N(J/\psi)}{(1+f_I+f_D)\cdot\epsilon(J/\psi)\cdot Acc(J/\psi)\cdot BR(J/\psi\to\mu\mu)\cdot L_{int}\cdot\Delta y}$$



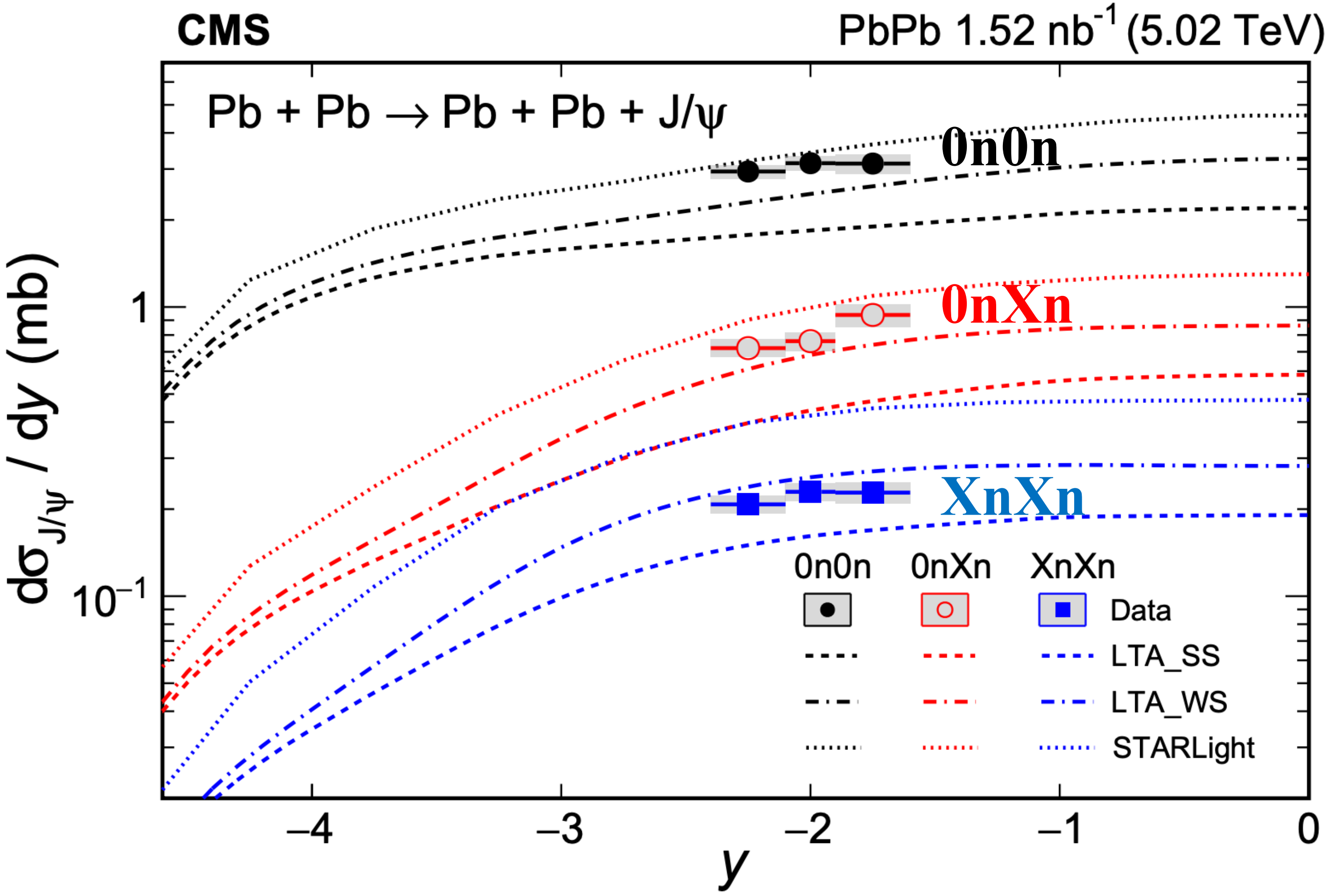
AnAn: All possible neutron emissions

- LHC experiments complement each others over a wide range of rapidity region

- **CMS data covers a unique rapidity region and follows ALICE forward rapidity trend**

Coh. J/ψ In Neutron Configurations

arXiv:2303.16984



- **First separation in different neutron classes**

- LTA models cannot well describe data in different neutron classes

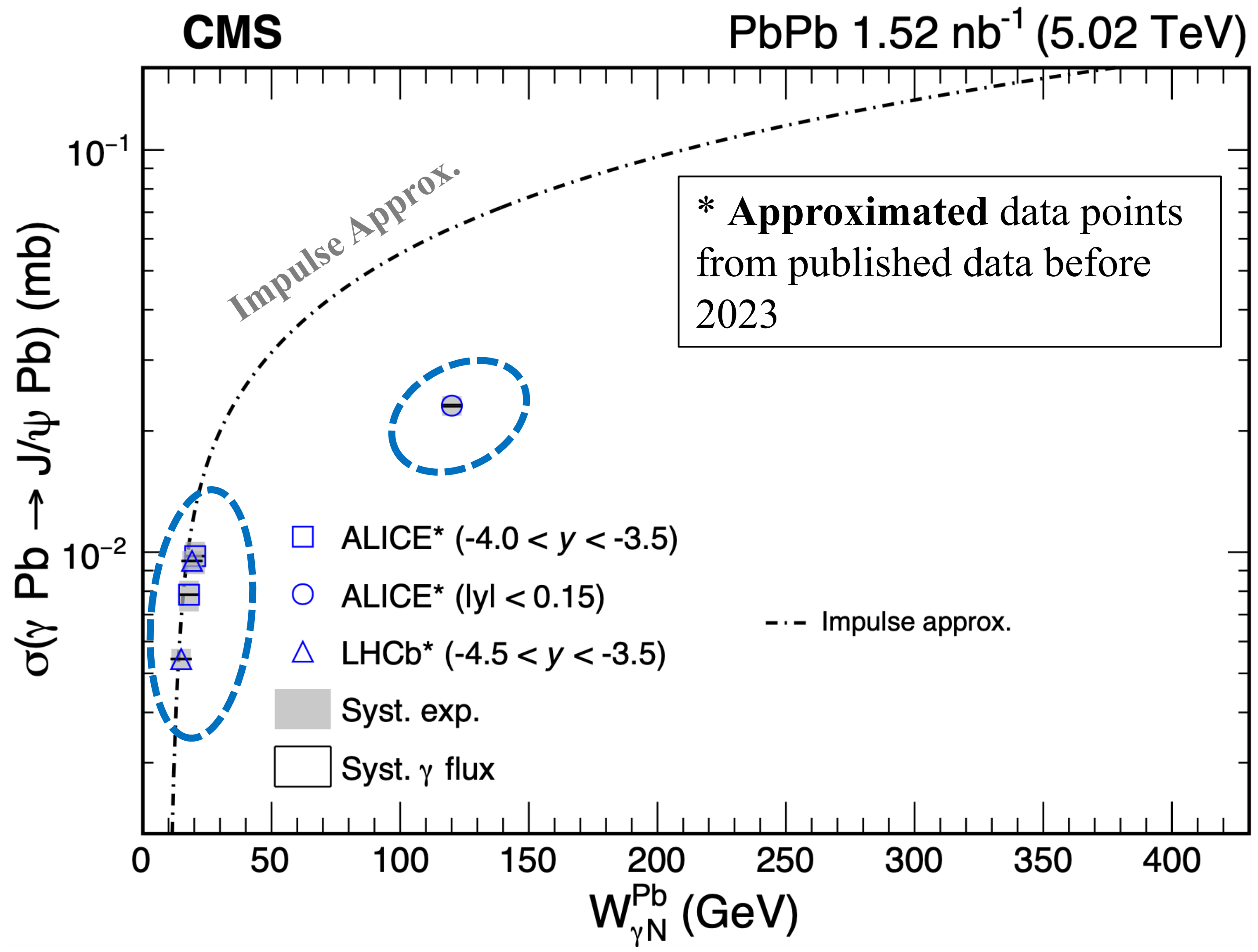
→A deeper look at J/Ψ production from γ+Pb at a given W without the "two-way ambiguity" may tell more.

High x Low x

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

Result: $\sigma_{\gamma A \to J/\psi A'}(W)$

arXiv:2303.16984



- ALICE, LHCb vs. IA:
  - Impulse Approx. (IA): neglects all nuclear effects
  - Data is close to IA at low W.
  - Data is significantly lower than IA at W~125 GeV.
- Larger suppression towards higher W.

Result: $\sigma_{\gamma A \to J/\psi A'}(W)$

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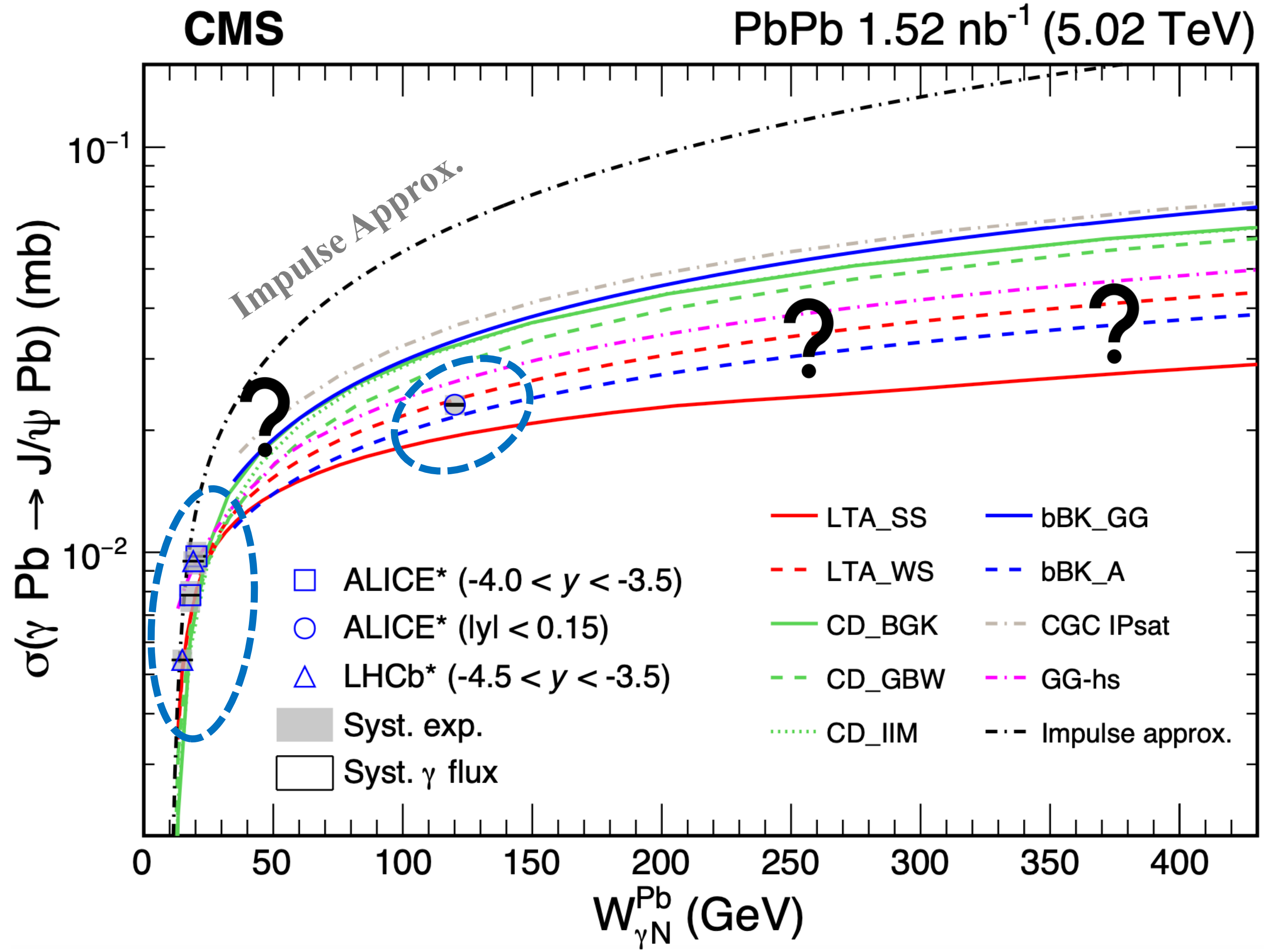

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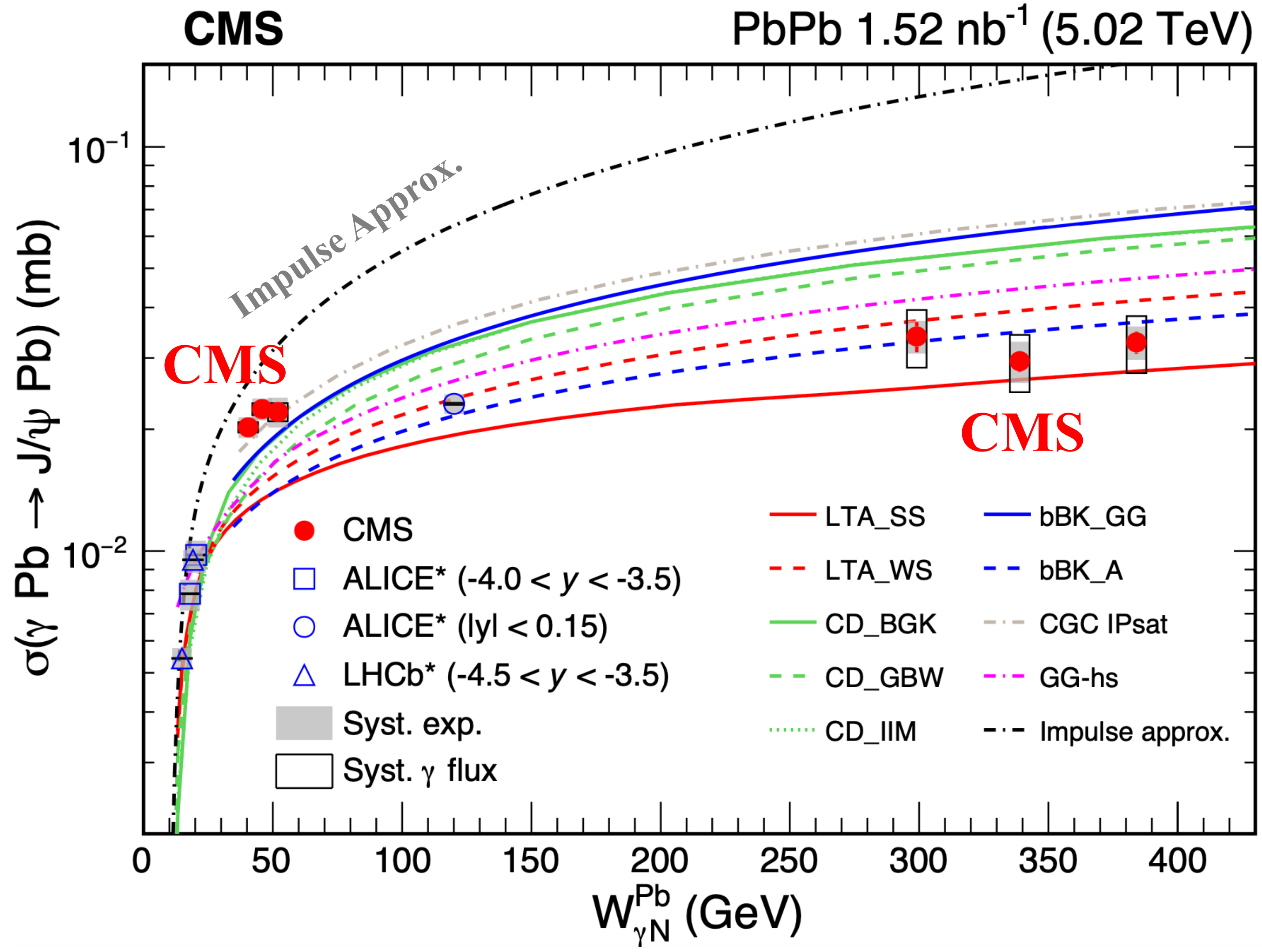

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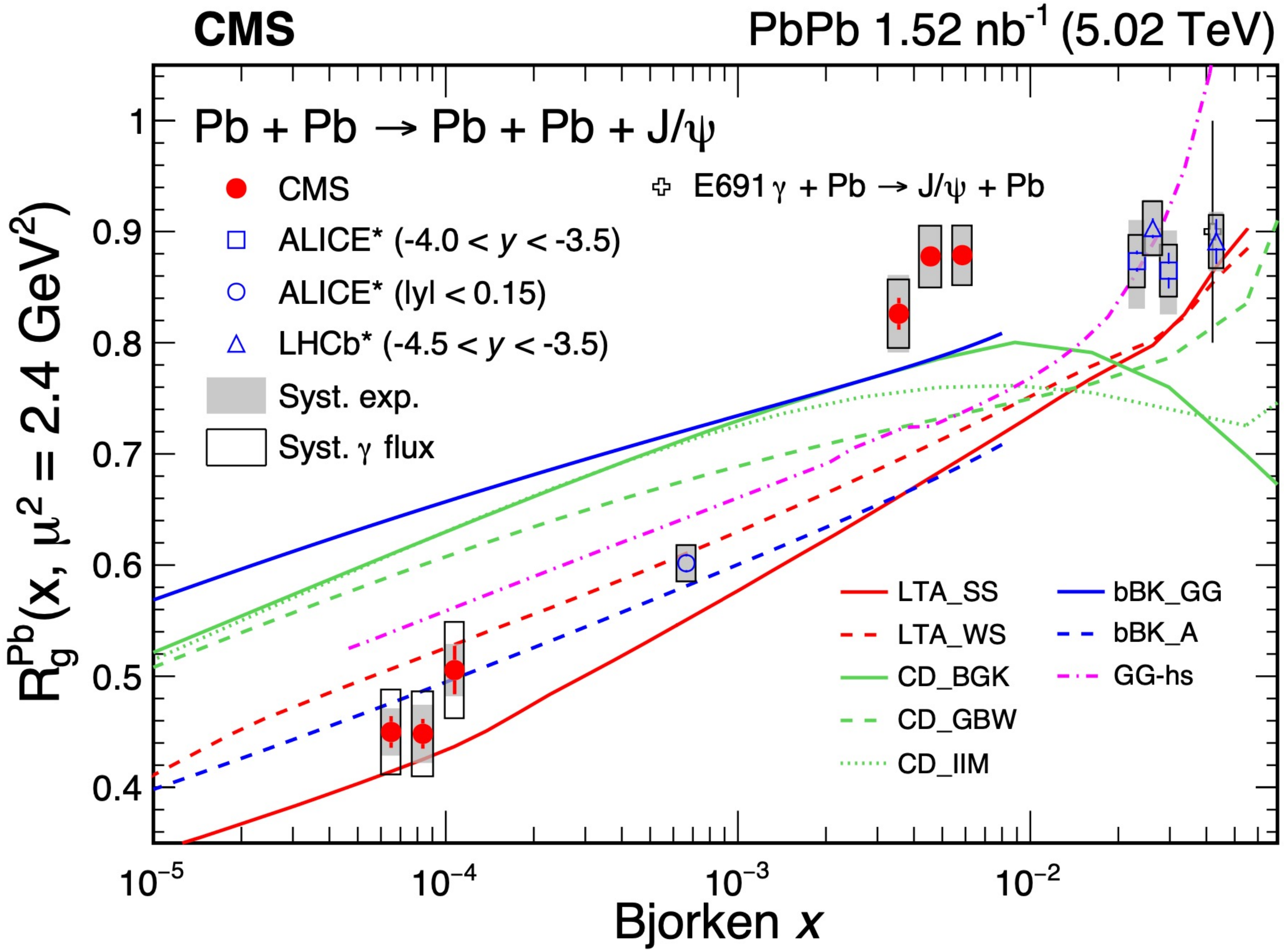
- **First measurement** with CMS
  - W < 40 GeV: rapidly increasing
  - 40 < W < 400 GeV: slowly raising -- **Physics process changed**

→Models considering shadowing effects or gluon saturation effects all fail to describe data trend

Nuclear Suppression Factor

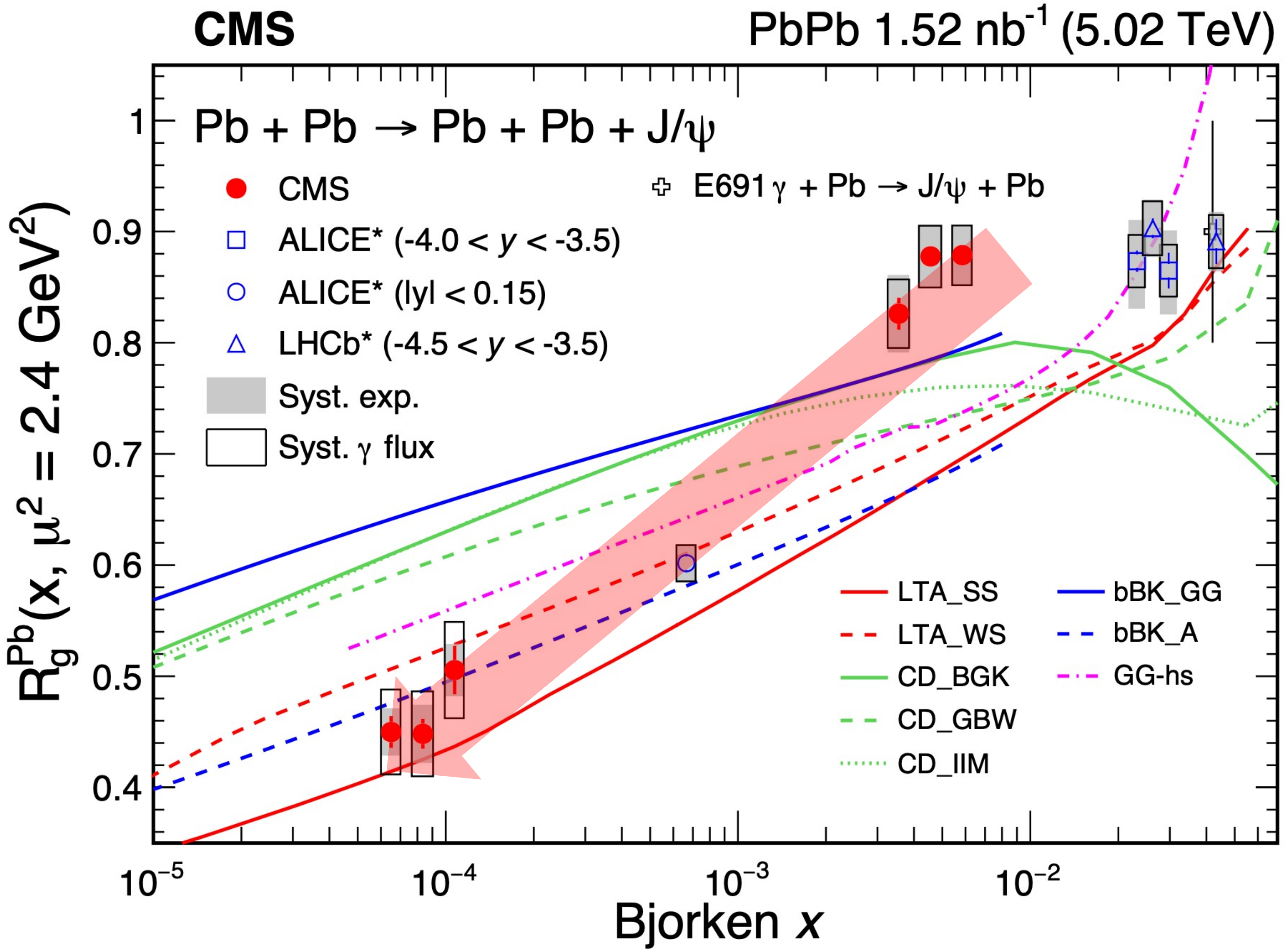
arXiv:2303.16984



- $R_g^A = \frac{g_A(x,Q^2)}{A\cdot g_p(x,Q^2)} = \left(\frac{\sigma^{exp}_{\gamma A\to J/\psi A}}{\sigma^{IA}_{\gamma A\to J/\psi A}}\right)^{1/2}$
  - represents nuclear gluon suppression factor at LO.

Nuclear Suppression Factor

arXiv:2303.16984



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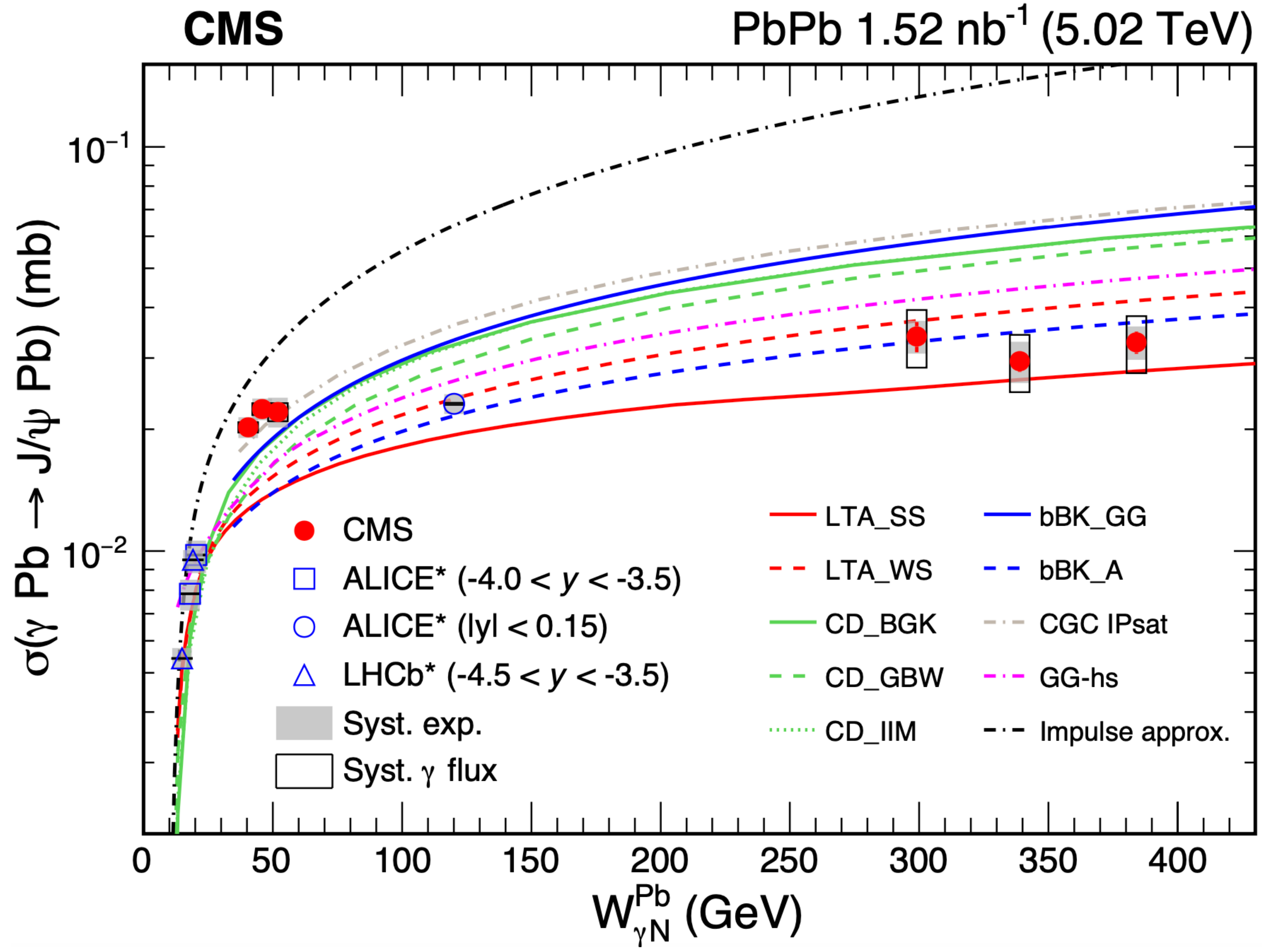
  - represents nuclear gluon suppression factor at LO.

- x ~ $10^{-2} - 10^{-3}$: Flat trend
- Quickly decrease towards lower x region

→Beyond model's expectation

What's The Physics Behind?

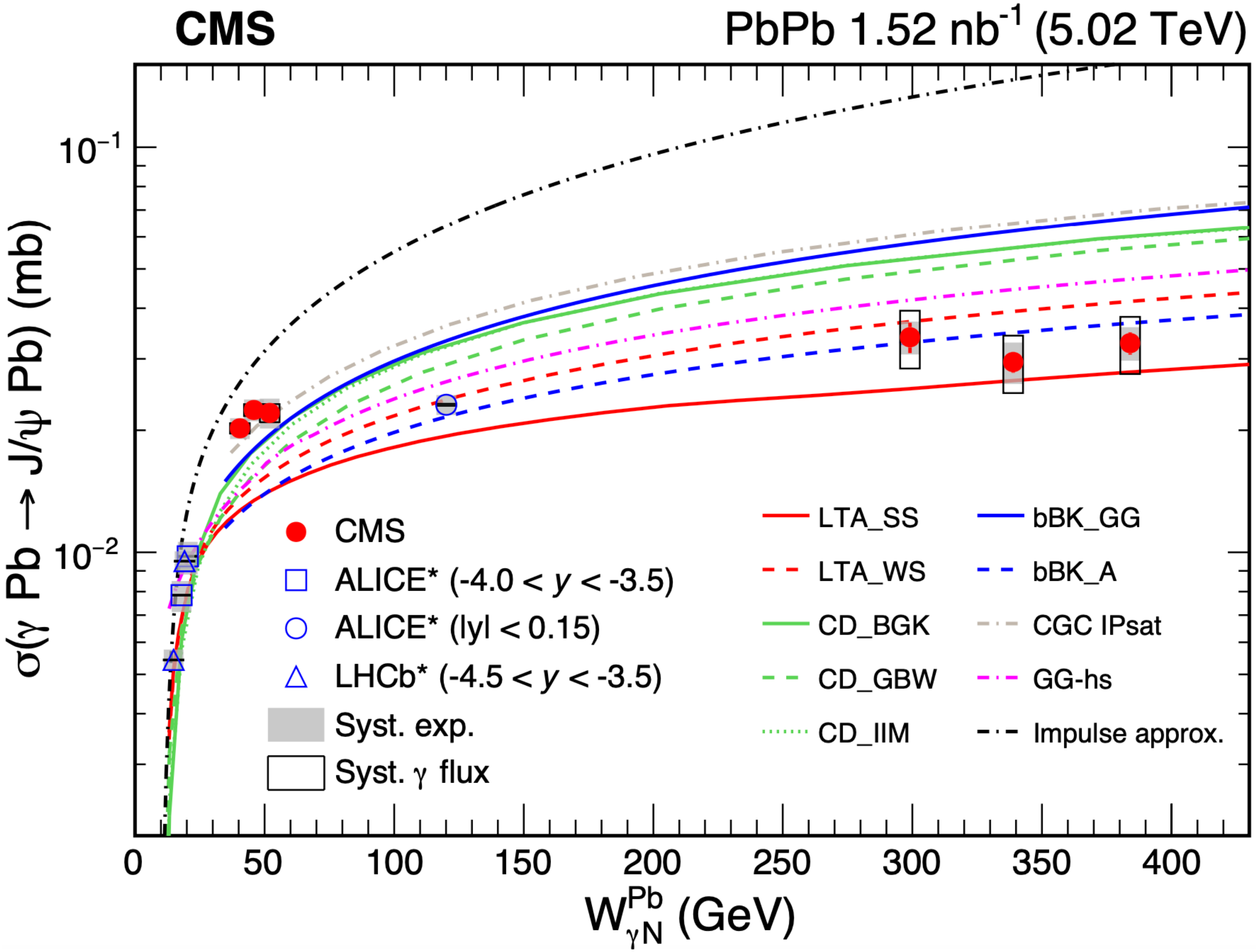
arXiv:2303.16984



- σ stops rapid rising trend → splitting and recombination of gluons become equal
- **Direct evidence for gluon saturation!!?**

What's The Physics Behind?

arXiv:2303.16984



- σ stops rapid rising trend → splitting and recombination of gluons become equal
- **Direct evidence for gluon saturation!!?**

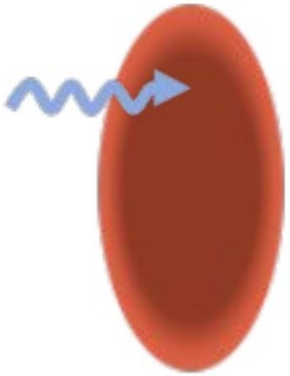
- Nucleus target becomes totally absorptive to incoming photons
- **Black Disk Limit, internal structure invisible!!?**

Another Novel Regime Of QCD: Black Disk Limit

Physics Letters B 537 (2002) 51–61
Phys. Rev. Lett. 87 192301, 2001

In the strong absorption scenario, the interaction probability may reach the unitarity limit. The nucleus target becomes totally absorptive to incoming photons.

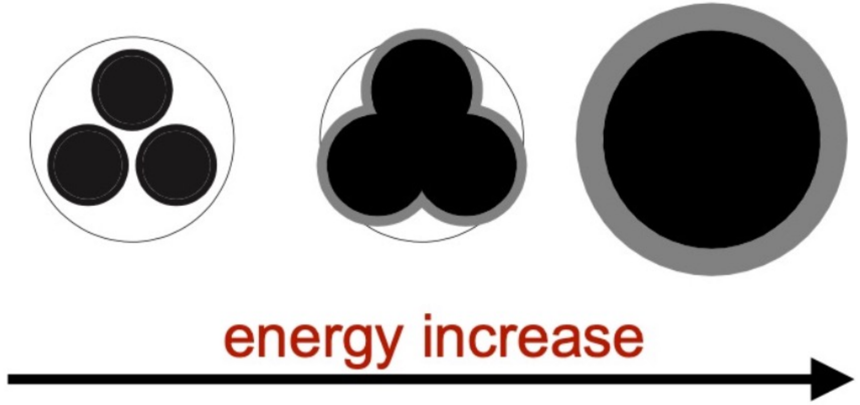
- Total cross section of dipole-nucleus interaction → $2\pi R_A^2$



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

“Black Disk Limit (BDL)”

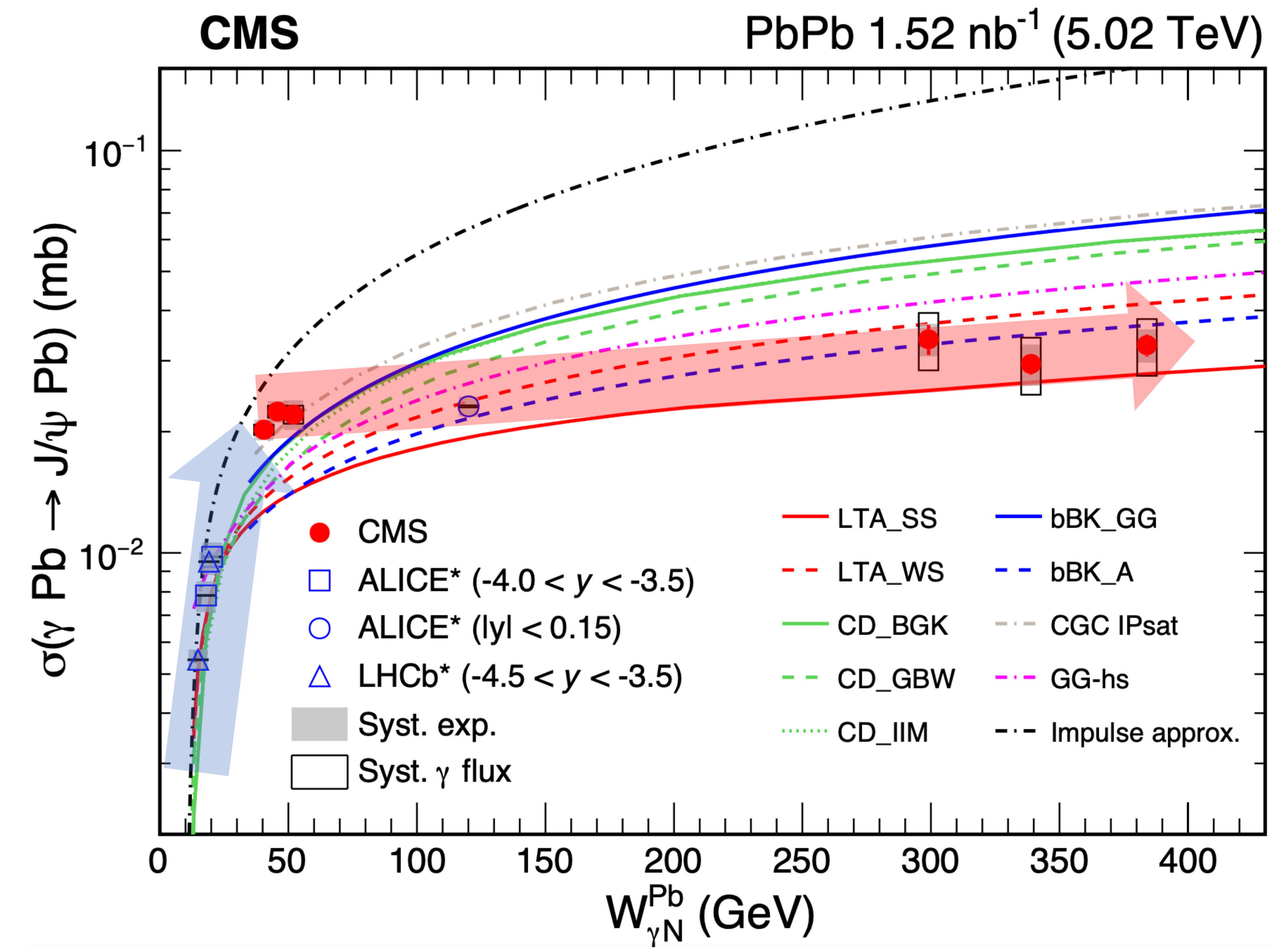
- opposite to the “color transparency”



The BDL represents a novel regime at small x when the LO QCD and the notion of the parton distributions becomes inapplicable for describing hard processes.

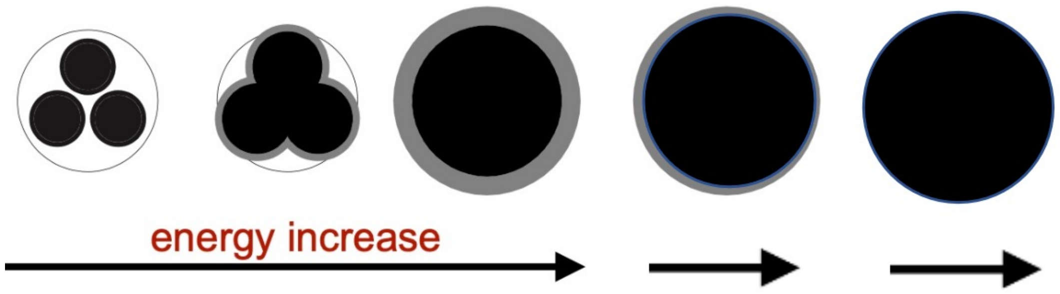
- New theoretical tools are needed in this regime!

Another Novel Regime Of QCD: Black Disk Limit



- Rapid grows reflect increased in gluon density
    - Amplitude of interaction is proportional to gluon density

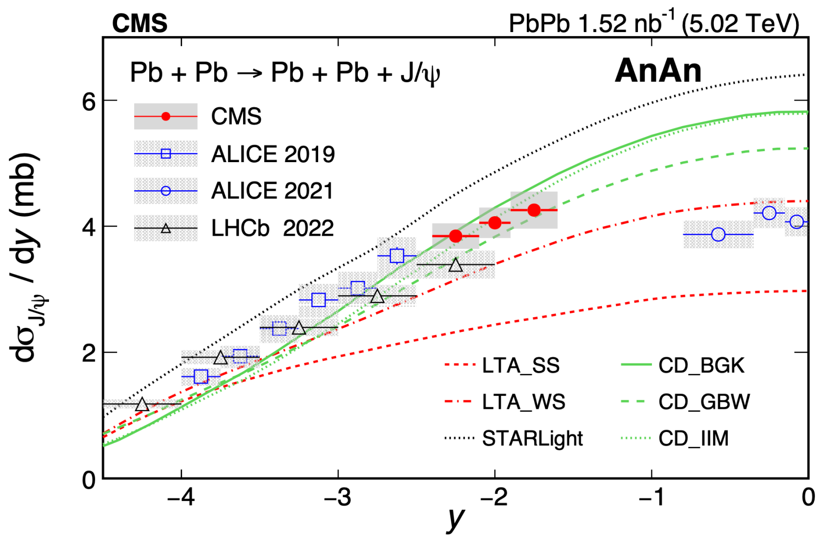
- Slow growth may suggest the periphery of the nucleus has not become fully “black”

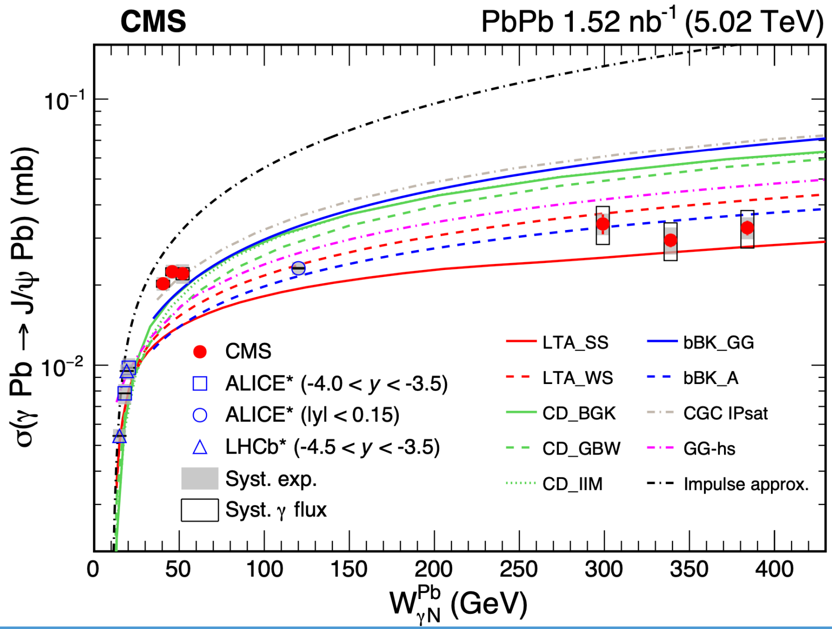


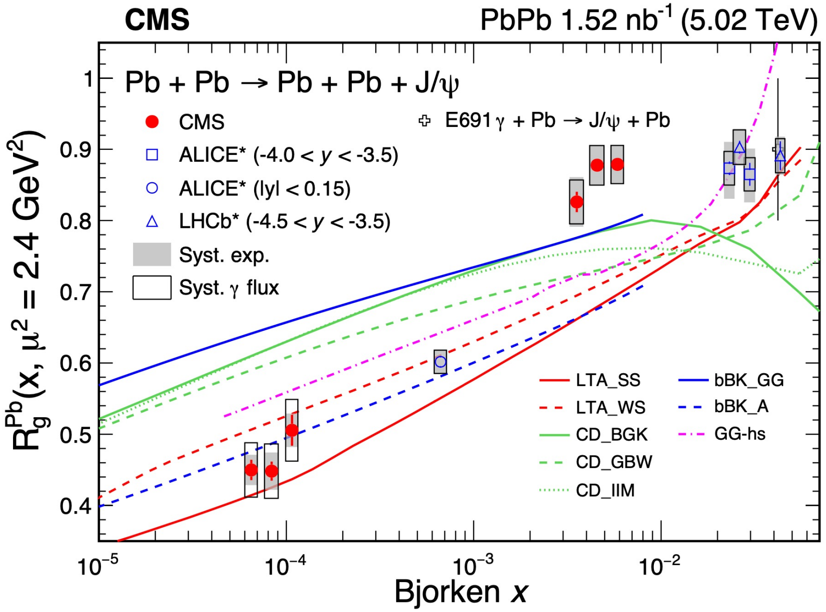
Summary

- For the first time, **directly disentangled coh. $\boldsymbol{\sigma_{\gamma A \to J/\psi A'}(W)}$** in UPC AA
- CMS measured coh. $\sigma_{\gamma A \to J/\psi A'}(W)$ to a **new unprecedentedly low-x gluon regime ($\mathbf{10^{-4} - 10^{-5}}$).**
- Flattening of coh. $\sigma_{\gamma A \to J/\psi A'}(W)$ not predicted by state-of-the-art models
  - **Gluon saturation**? **black disk limit**? or other physic effects?

Submitted to PRL: arXiv:2303.16984



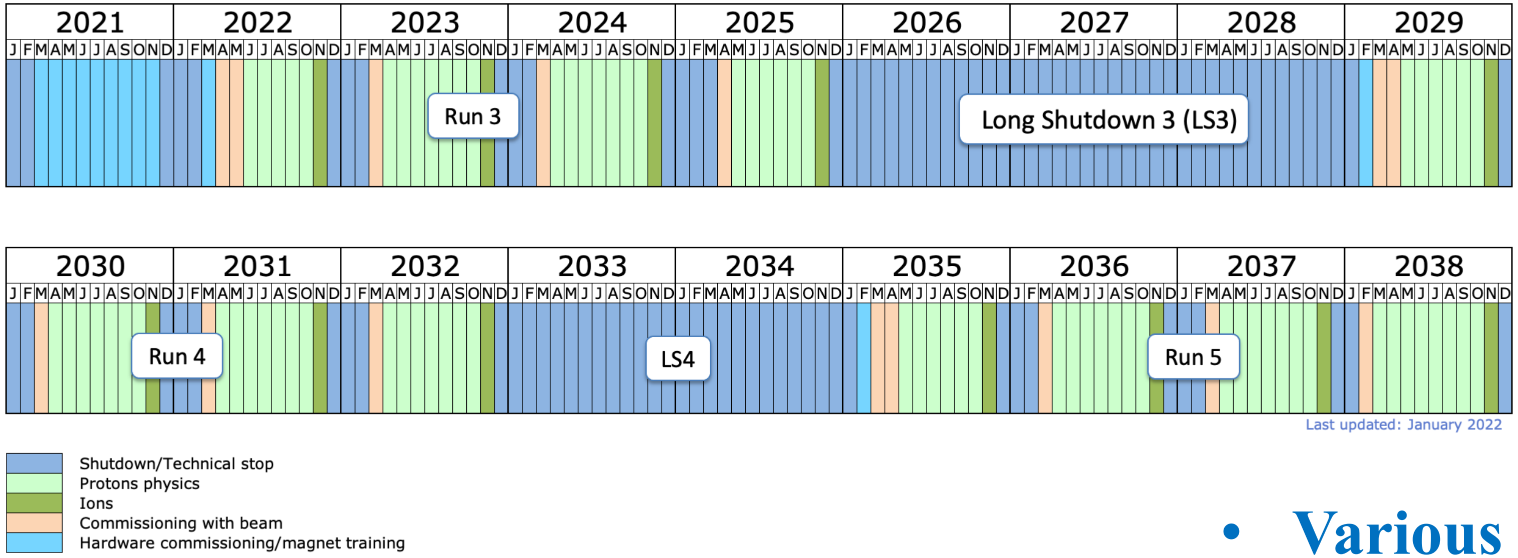




Thank You!

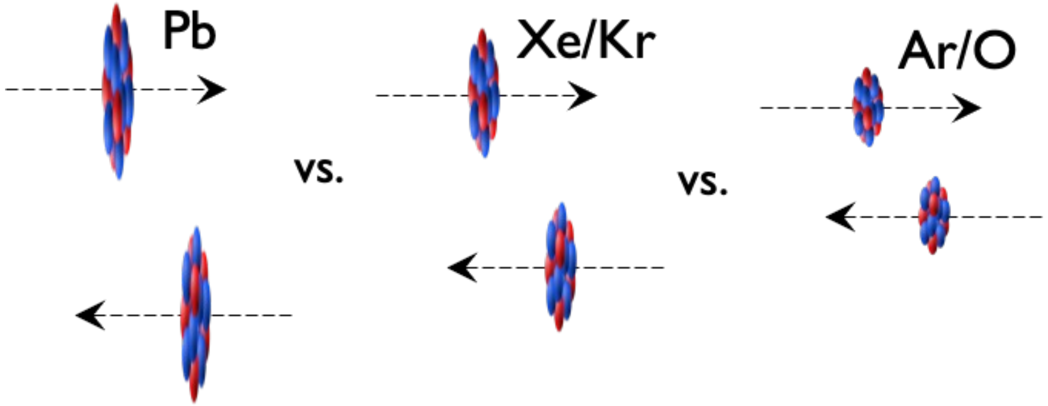
EXTRA

The Future



Exciting opportunities ahead

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



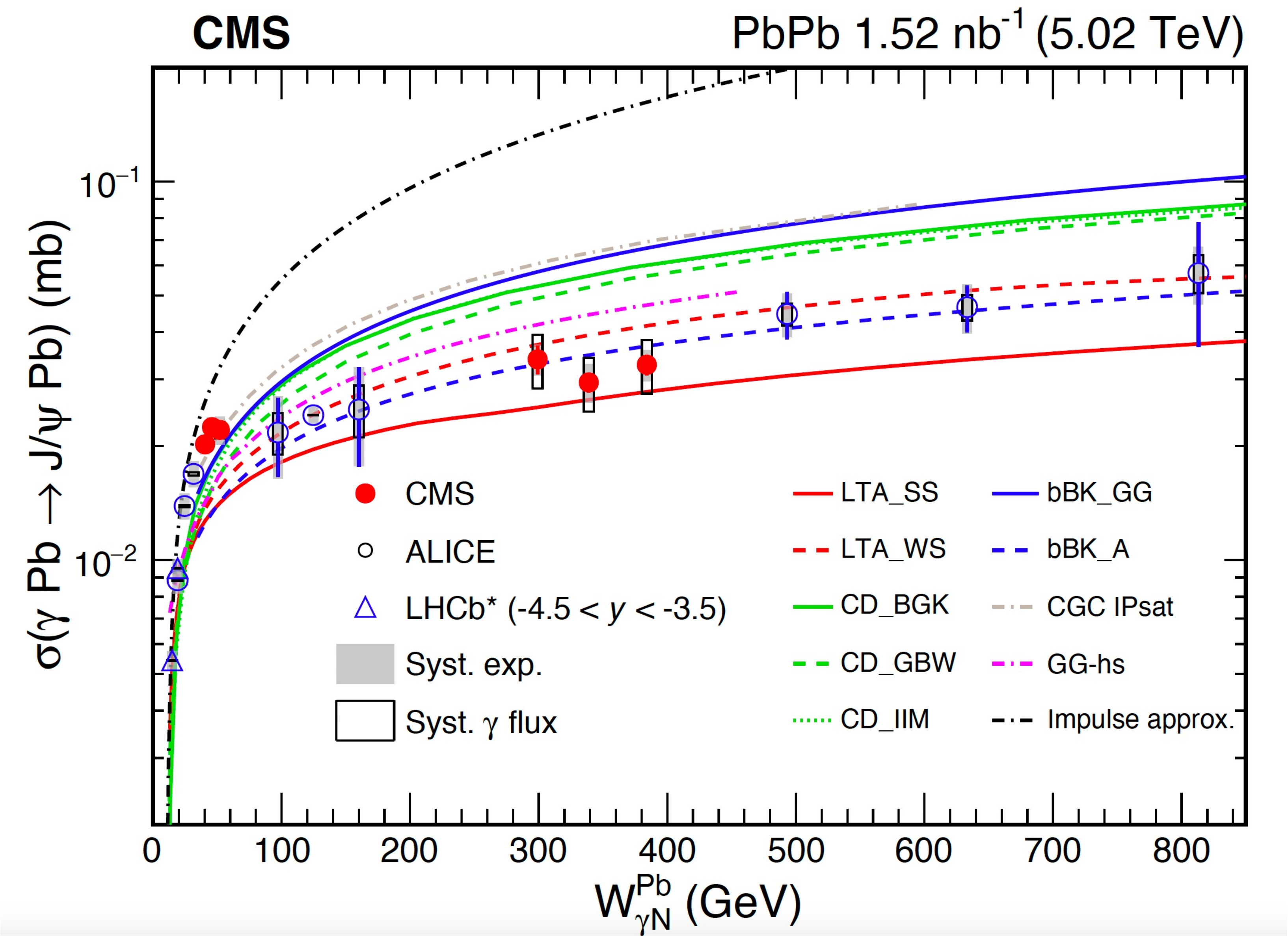
- **Various VM species in γPb with neutron tagging**
- **System size scan with different ion species**

When approaching the BDL

- Coh. cross section scales with $A^{2/3}$
- Incoh. cross section strongly suppressed; internal substructure becomes invisible

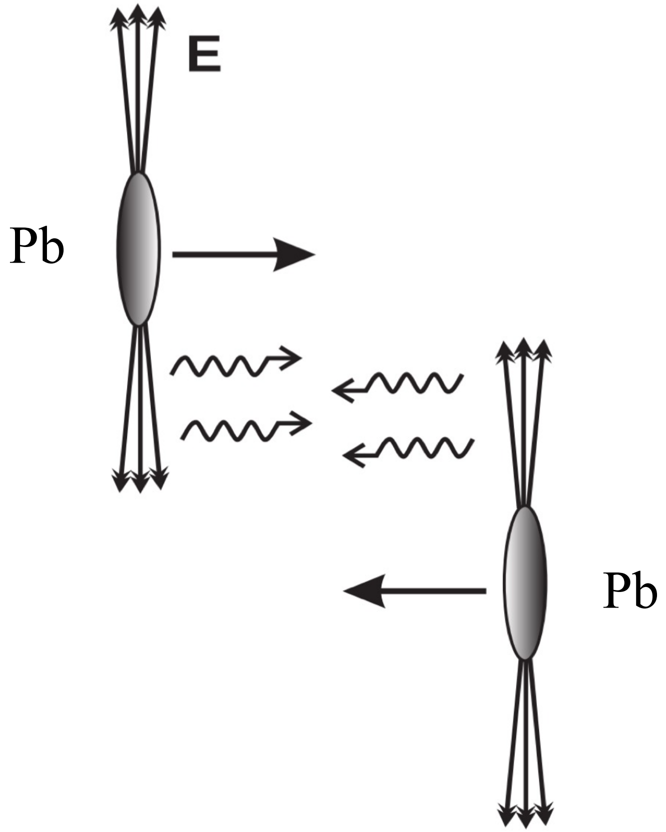
Comparison With ALICE

arXiv:2305.19060



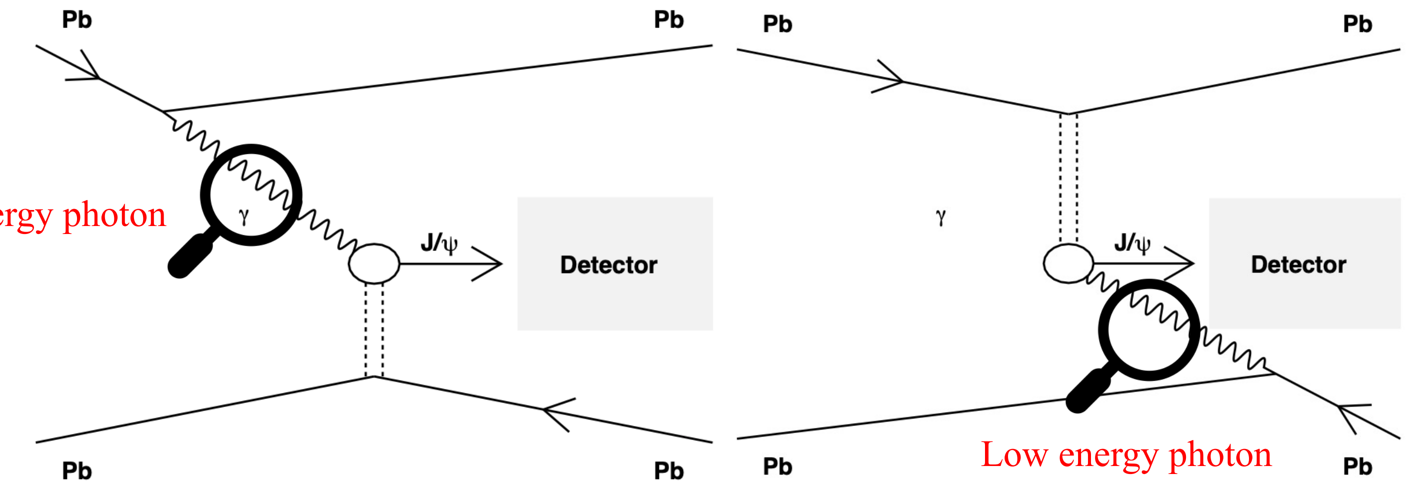
Advantages of J/ψ in UPC γPb

- Higher density, easer to reach the saturation
  - Gluons is enhanced by a factor of A^1/3 in nucleus compared to what in free nucleon.
- Nuclei as target, more nucleons, can lead to nuclear shadowing effects
- Photon flux $\propto Z^2$
- Possibility of multiphoton exchange: Neutron tagging



Problem of Mixing Contributions

A two-way ambiguity! →



Measured J/ψ at y

Two unknows but **one** equation!

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

What we measured

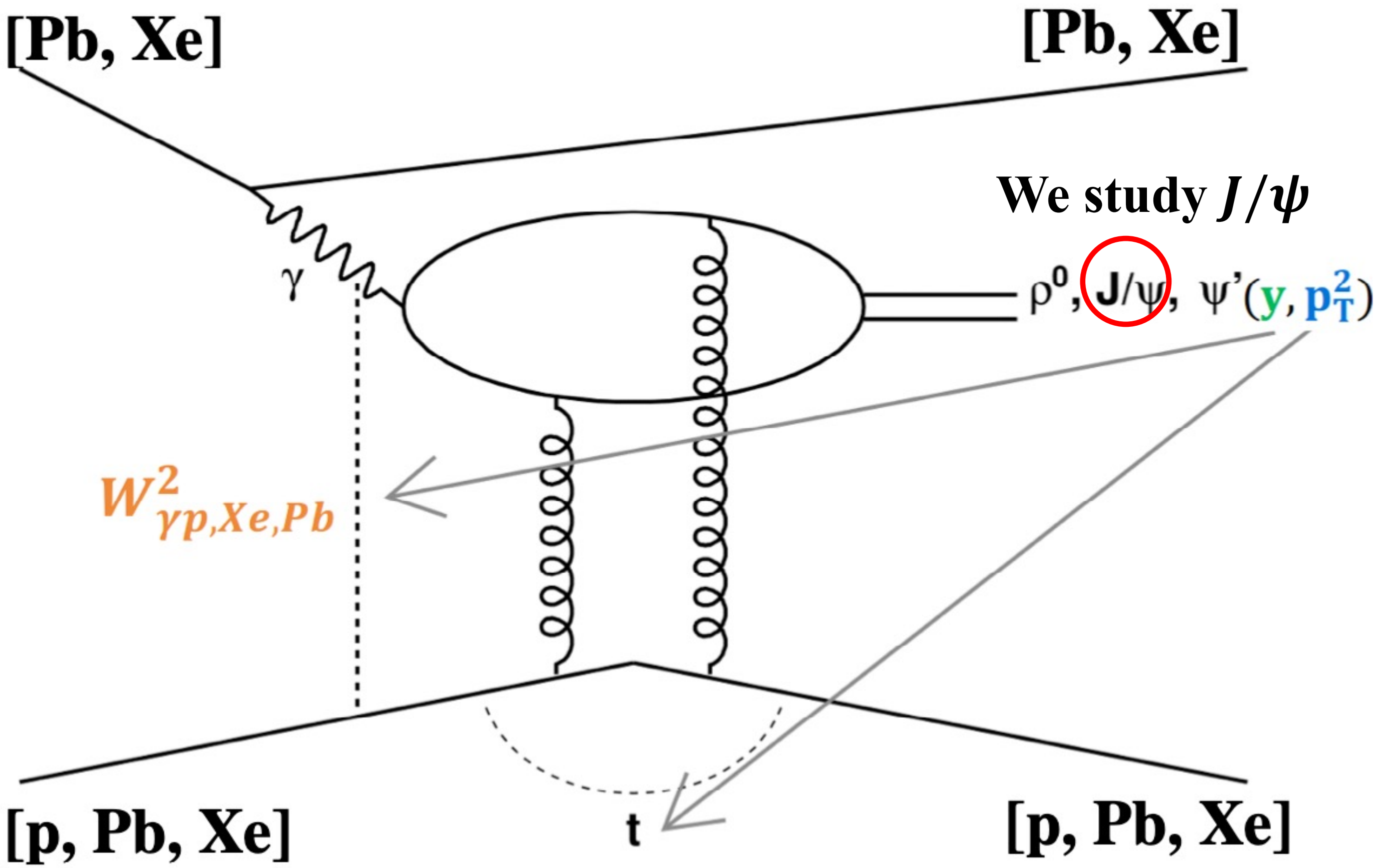
Photon flux from theory

What we want: VM cross section of one single γ+Pb at each y

VM Photoproduction in UPC

- A given y → Fixes ω, x, W

- $\omega = \frac{M_{VM}}{2} e^{\pm y}$
  - y: Rapidity of the VM
  - ω: Photon energy
  - M_{VM}: Mass of the VM
- $x = \left(\frac{M_{VM}}{\sqrt{s_{NN}}}\right) e^{\mp y}$
- $W^2 = M_{VM}\sqrt{s_{NN}} \cdot e^{\pm y}$
  - W: Centre-of-mass energy of the photon–target system



Differential Cross Section Calculation

- $$\frac{d\sigma^{coh}_{J/\psi}}{dy} = \frac{N(J/\psi)}{(1+f_I+f_D)\cdot\epsilon(J/\psi)\cdot Acc(J/\psi)\cdot BR(J/\psi\rightarrow\mu\mu)\cdot L_{int}\cdot\Delta y}$$

Coherent J/ψ yields

- Raw yields within the mass window

Calculated from **mass fit** within pt < 0.2 GeV

Feed down ratio

- $$f_D = \frac{N(feed\text{−}down\ J/\psi)}{N(primary\ J/\psi)}$$

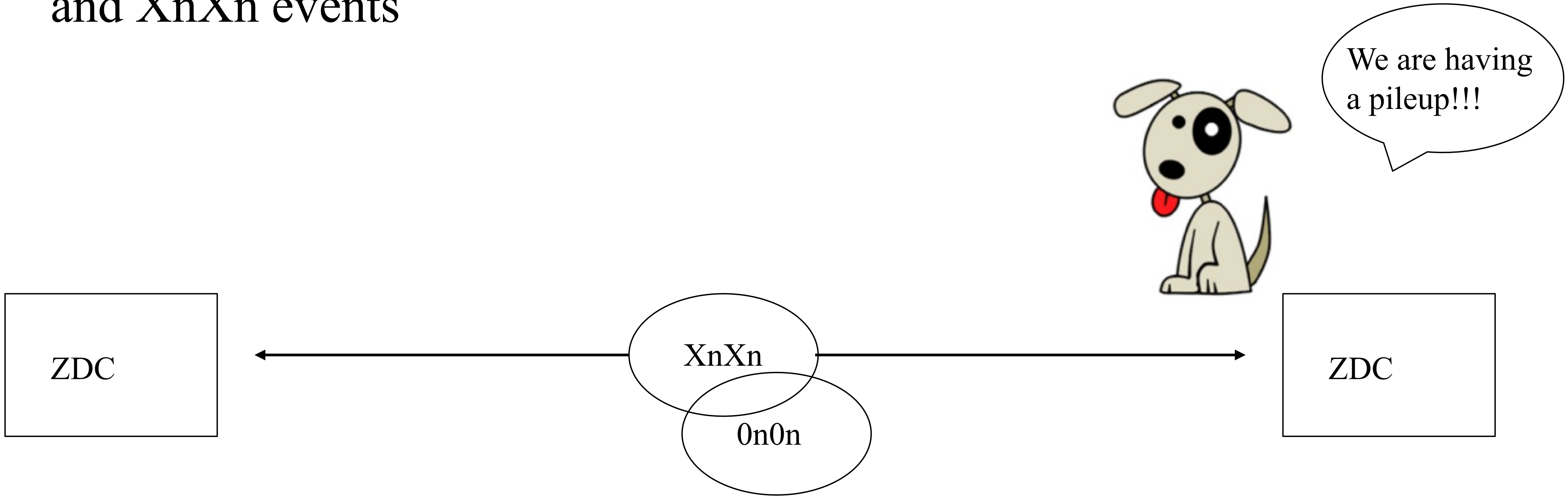
Incoherent fraction

- $$f_I = \frac{N(InCoh\ J/\psi)}{N(Coh\ J/\psi)}$$

Calculated from **pt fit**

EM Diss. Correction

- Pileup in EM dissociation (EMD): Multiple EMD within the same bunch crossing
- Leads to a decrease in 0n0n Events increase in 0nXn and XnXn events



EM Diss. Correction

- The correction can be obtained by inverting migration matrix

$$\begin{pmatrix} N^{00} \\ N^{0X} \\ N^{X0} \\ N^{XX} \end{pmatrix}^{\text{Obs}} = \begin{pmatrix} P_{00}^{00} & 0 & 0 & 0 \\ P_{00}^{0X} & P_{0X}^{0X} & 0 & 0 \\ P_{00}^{X0} & 0 & P_{X0}^{X0} & 0 \\ P_{00}^{XX} & P_{0X}^{XX} & P_{X0}^{XX} & P_{XX}^{XX} \end{pmatrix} \begin{pmatrix} N_{00} \\ N_{0X} \\ N_{X0} \\ N_{XX} \end{pmatrix}^{\text{True}}$$

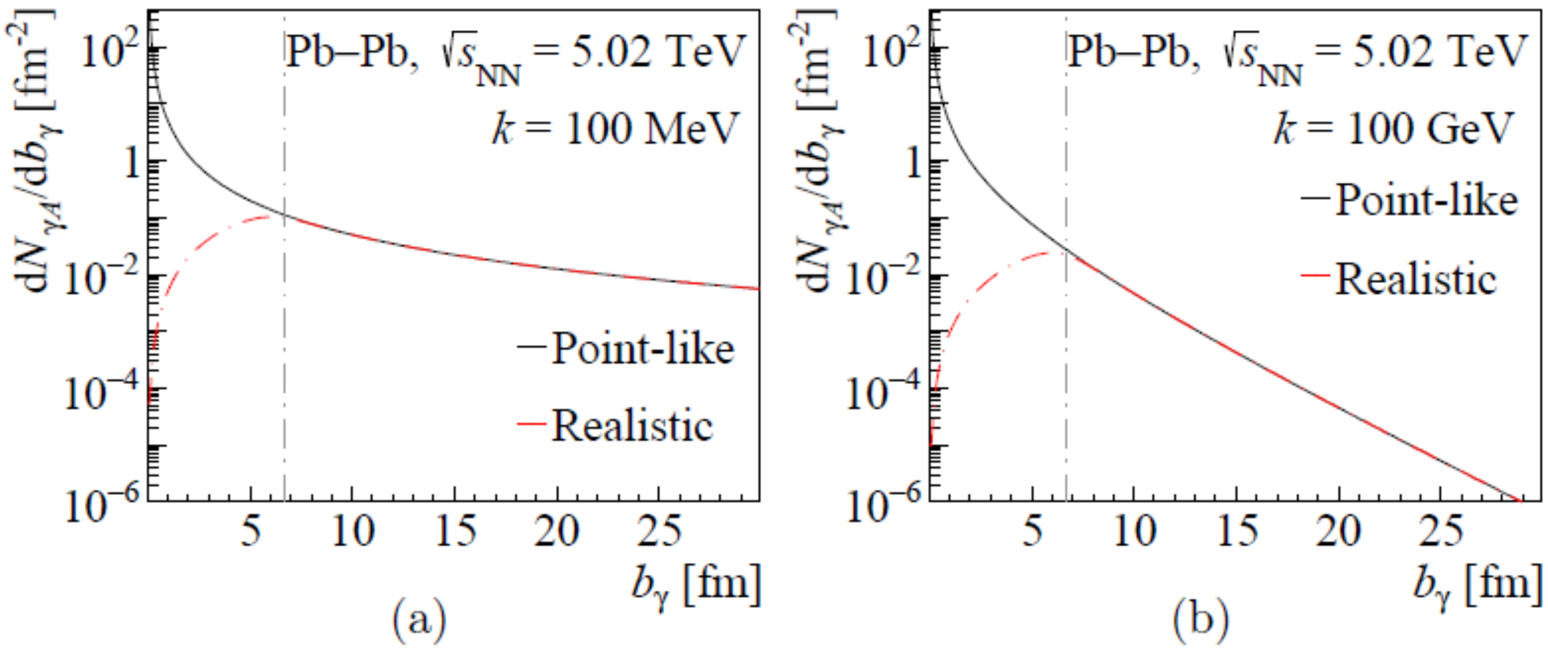
- The matrix element can be obtained from ZB fraction

  - $P_{00}^{00} = f_{00}$
  - $P_{00}^{0X} = f_{0X}, P_{0X}^{0X} = f_{00} + f_{0X}$
  - $P_{00}^{X0} = f_{X0}, P_{X0}^{X0} = f_{00} + f_{X0}$
  - $P_{00}^{XX} = f_{XX}, P_{0X}^{XX} = f_{X0} + f_{XX}, P_{X0}^{XX} = f_{0X} + f_{XX}, P_{XX}^{XX} = f_{00} + f_{0X} + f_{X0} + f_{XX} = 1$

Flux From StarLight

- The flux of a point-like source with additional cut-off at RA is widely used in phenomenological calculations for UPC processes, such as STARlight.
- This approach is well motivated in photon-nucleus interactions since the flux at impact parameters smaller than the nuclear radius is effectively suppressed by the requirement of no strong interactions between nuclei.

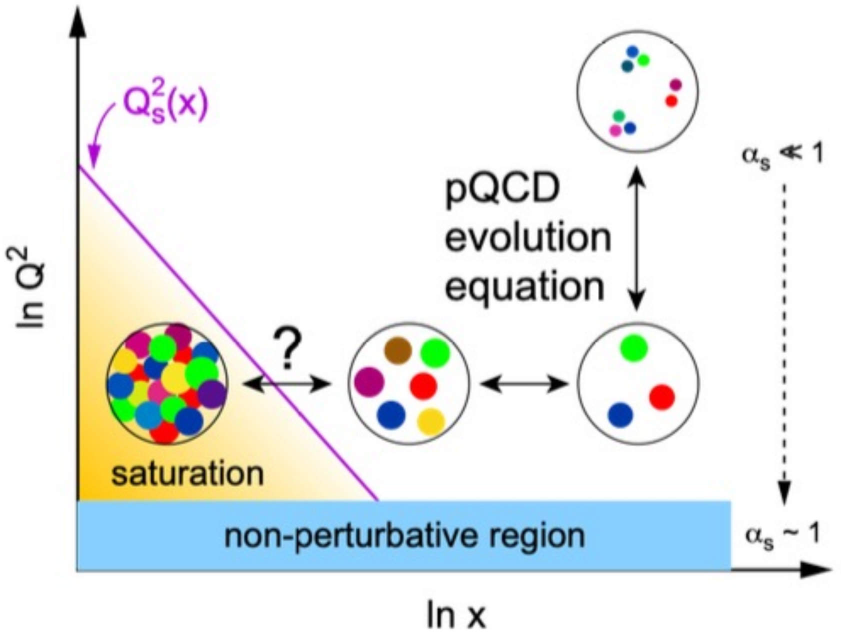
arXiv:2111.11383



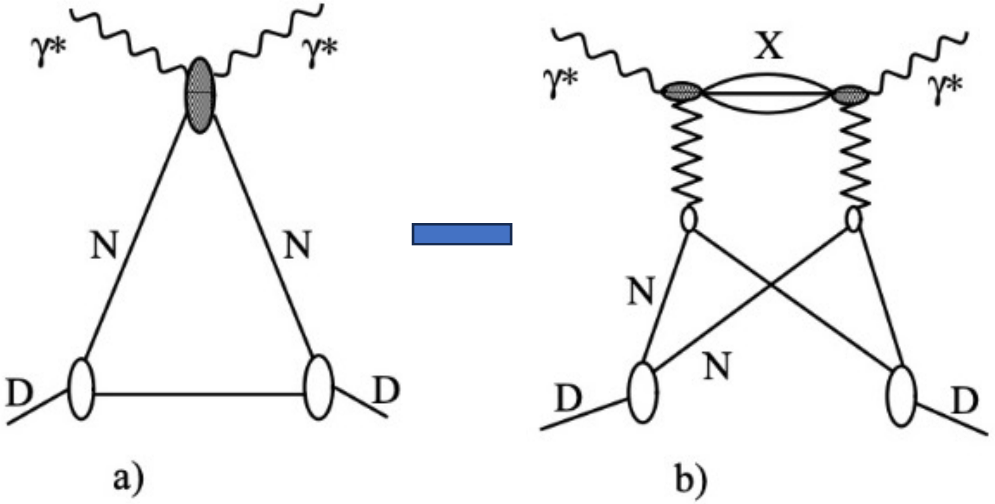
(Color online) Photon fluxes coming from a nucleus in the point-like source approximation and the realistic description as functions of impact parameter b calculated at different photon energies: 100 MeV (a), 100 GeV (b)

Saturation vs Shadowing

- Both relate to the same concept: density of gluons in nPDF at small-x is reduced wrt the simple addition of the gluon PDF
- Saturation: Dynamical description via gluon self-interactions that tame the growth of gluon → CGC
- Nuclear shadowing: Gribov-Glauber model of multiple scatterings → LTA



Gluon saturation



L. Frankfrut,, V. Guzey, M. Strikman (Physics Reports 512 (2012) 255-393)

Nuclear shadowing

Theory Description

- Impulse approximation (IA): Photoproduction data from protons, does not include nuclear effects except coherence
- STARlight: Photoproduction data from protons + Vector Meson Dominance model, includes multiple scattering but no gluon shadowing
- EPS09 LO: parametrization of nuclear shadowing data
- LTA: Leading Twist Approximation of nuclear shadowing
- IIM BG, IPsat, BGK-I: Color dipole approach coupled to the Color Glass Condensate formalism with different assumptions on the dipole-proton scattering amplitude
- GG-HS: Color dipole model with hot spots nucleon structure
- b-BK: Color dipole approach coupled with impact-parameter dependent Balitsky-Kovchegov equation
- JMRT NLO: DGLAP formalism with main NLO contributions included
- CCT: Saturation in an energy dependent hot spot model
- CGC: Color dipole model
- NLO BFKL: BFKL evolution of HERA values