Probing initial dense gluonic states with ultra-peripheral collisions at the LHC

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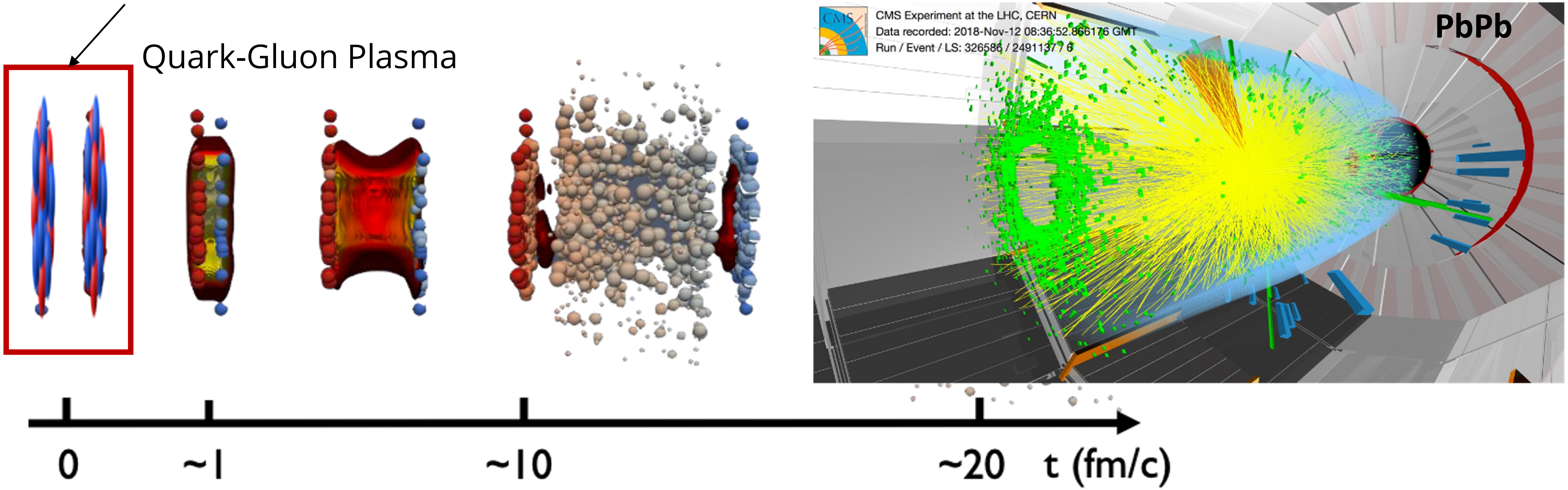
U.S. DEPARTMENT OF ENERGY
Office of Science

INT PROGRAM INT-23-1A
Intersection of nuclear structure and high-energy nuclear collisions
Jan. 23 - Feb 24, 2023

RICE

Understanding The Initial Stages of HIC

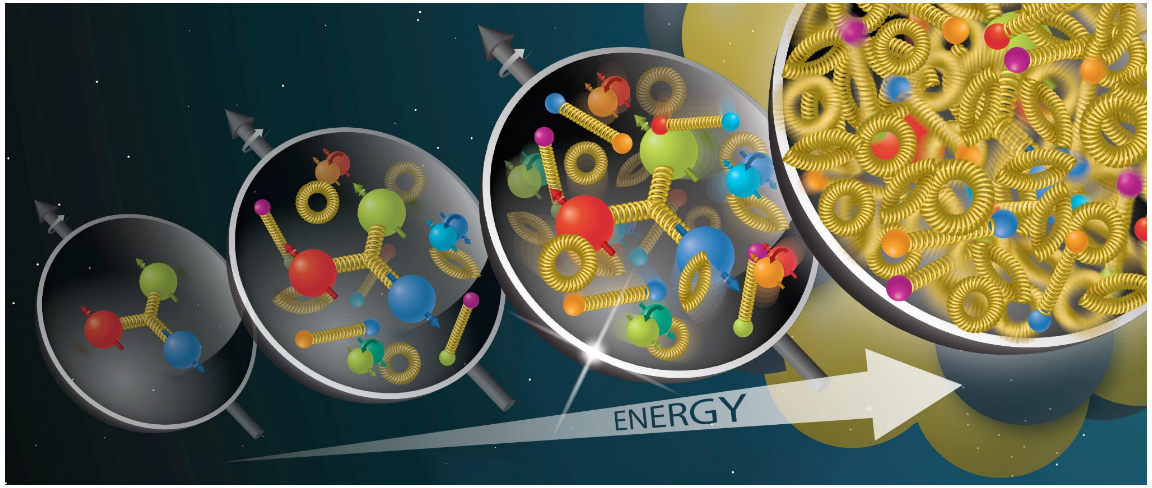
Main theme of this workshop



How are <u>IS at high energy</u> and <u>nuclear structure at low energy</u> connected?

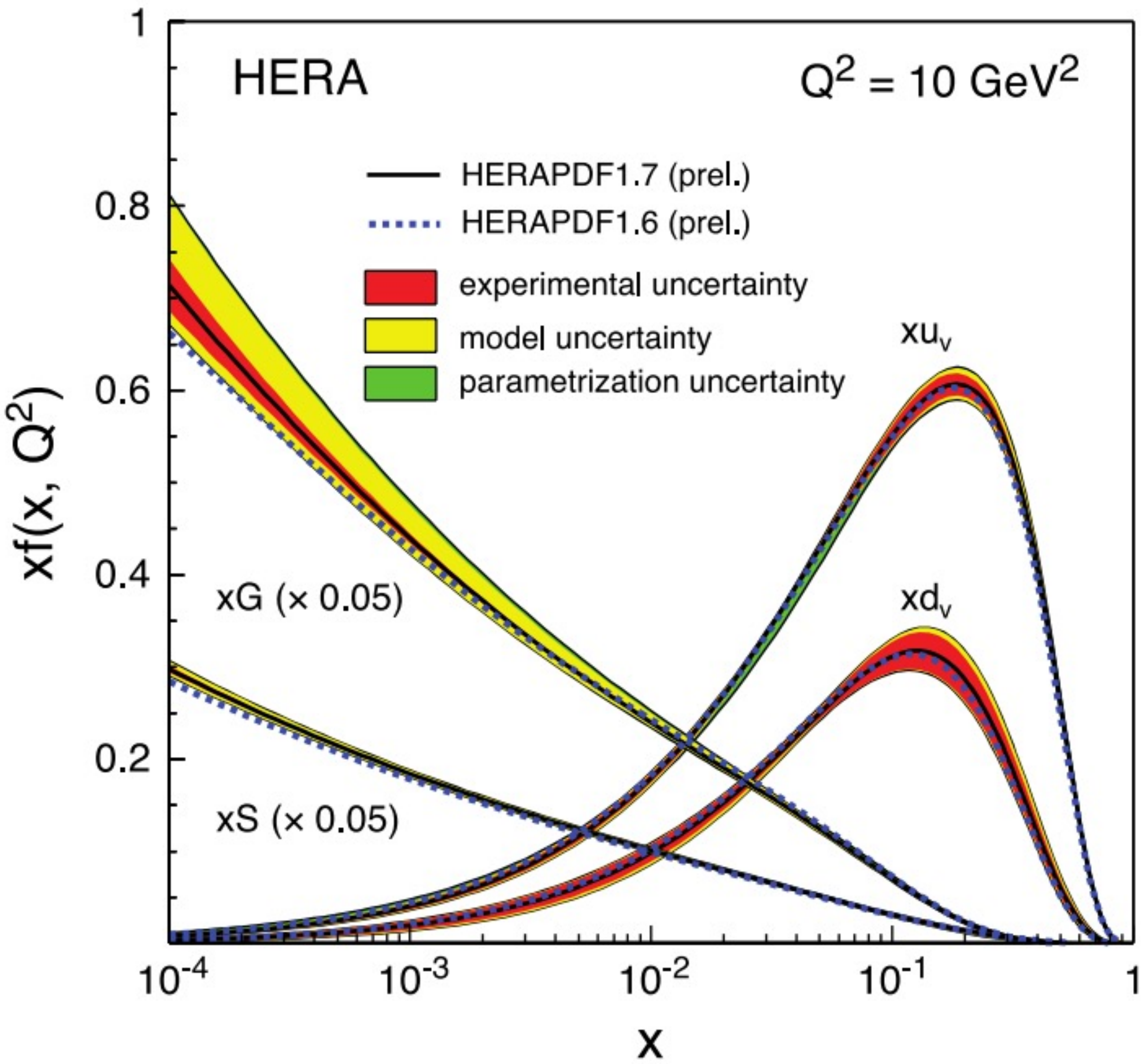
Relevant *d.o.f.* evolves with energy and gluons dominate at high energy (small *x*).

Glue that binds us all



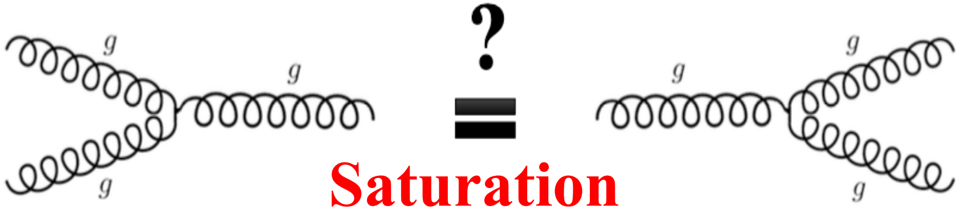
DIS results show a seemingly "**indefinite** rise" in gluon PDF

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



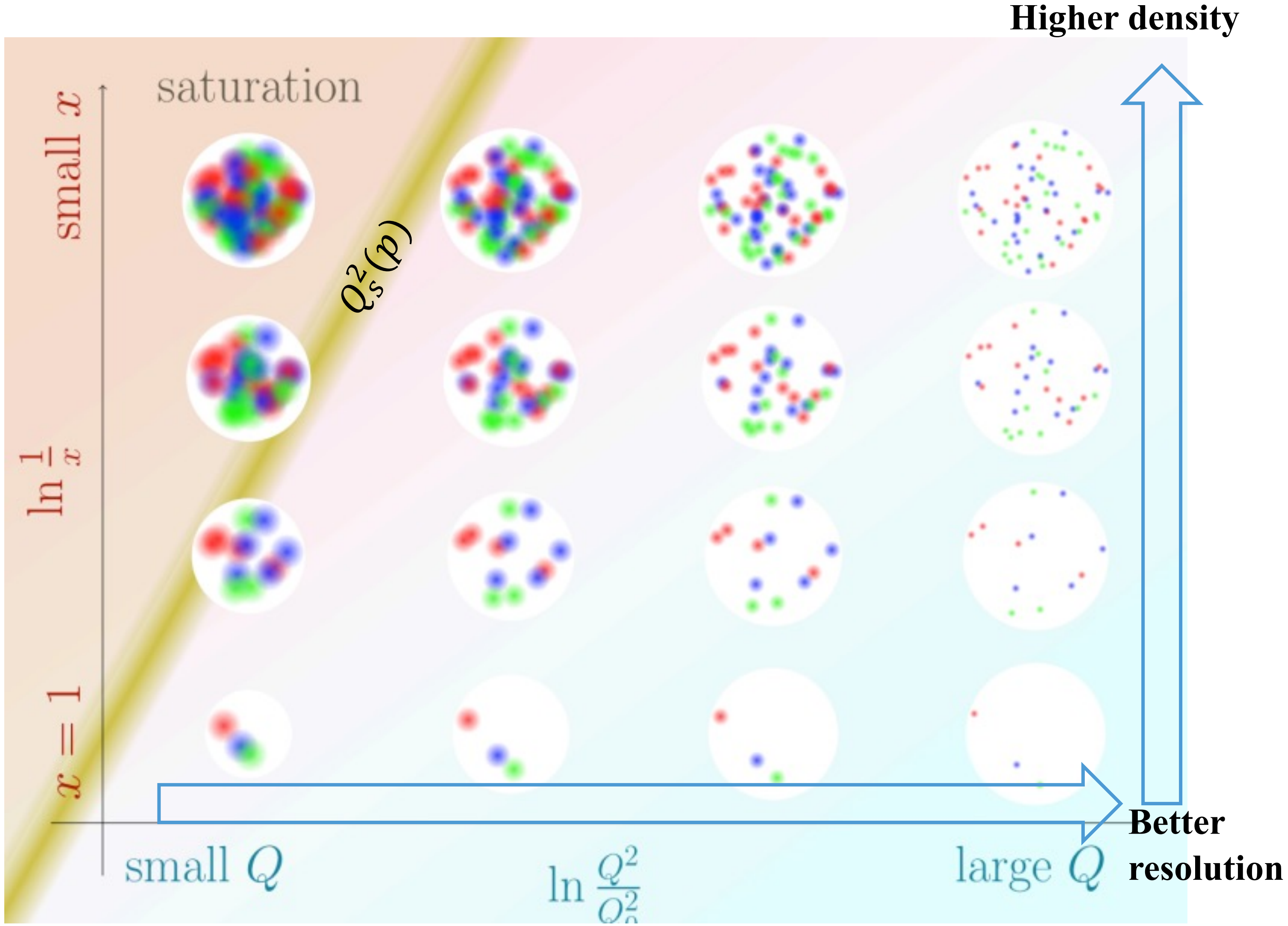
Glue that binds us all

QCD unitarity: Growth of gluon density can't continue indefinitely!



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

No conclusive evidence yet!



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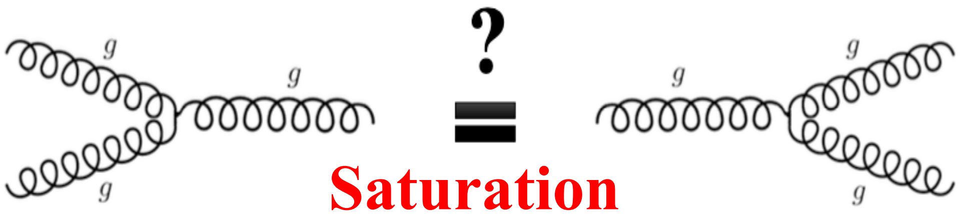

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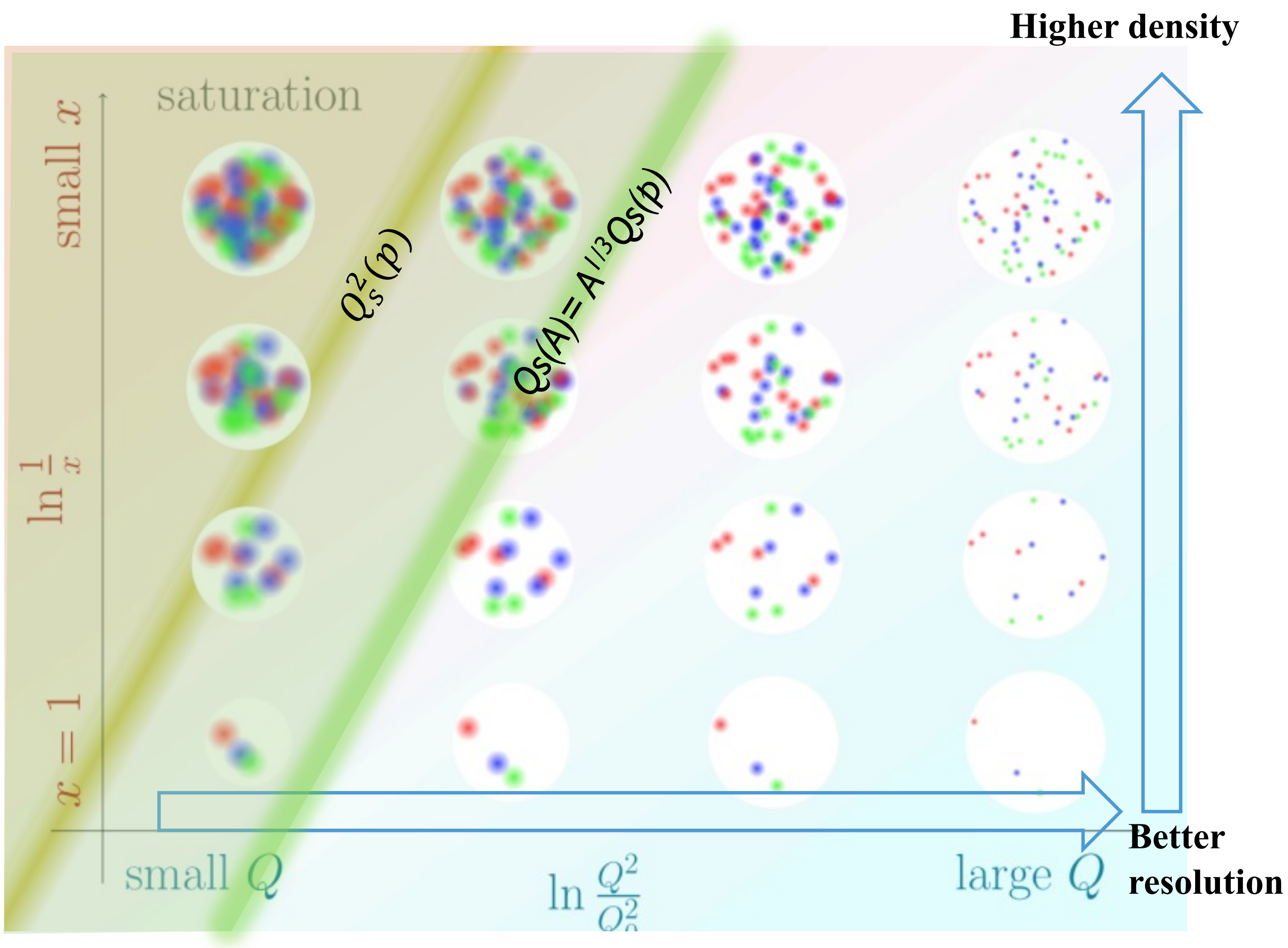
Better chance of observing the saturation in heavy nuclei!



Glue that binds us all

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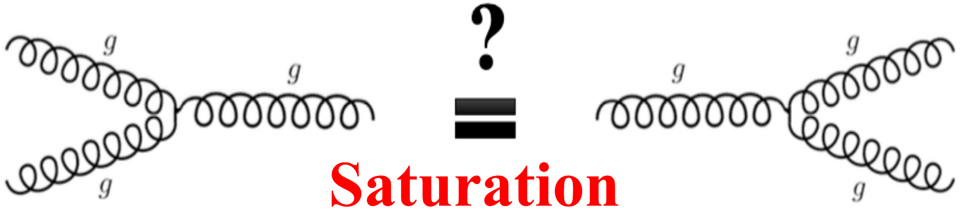

Saturation

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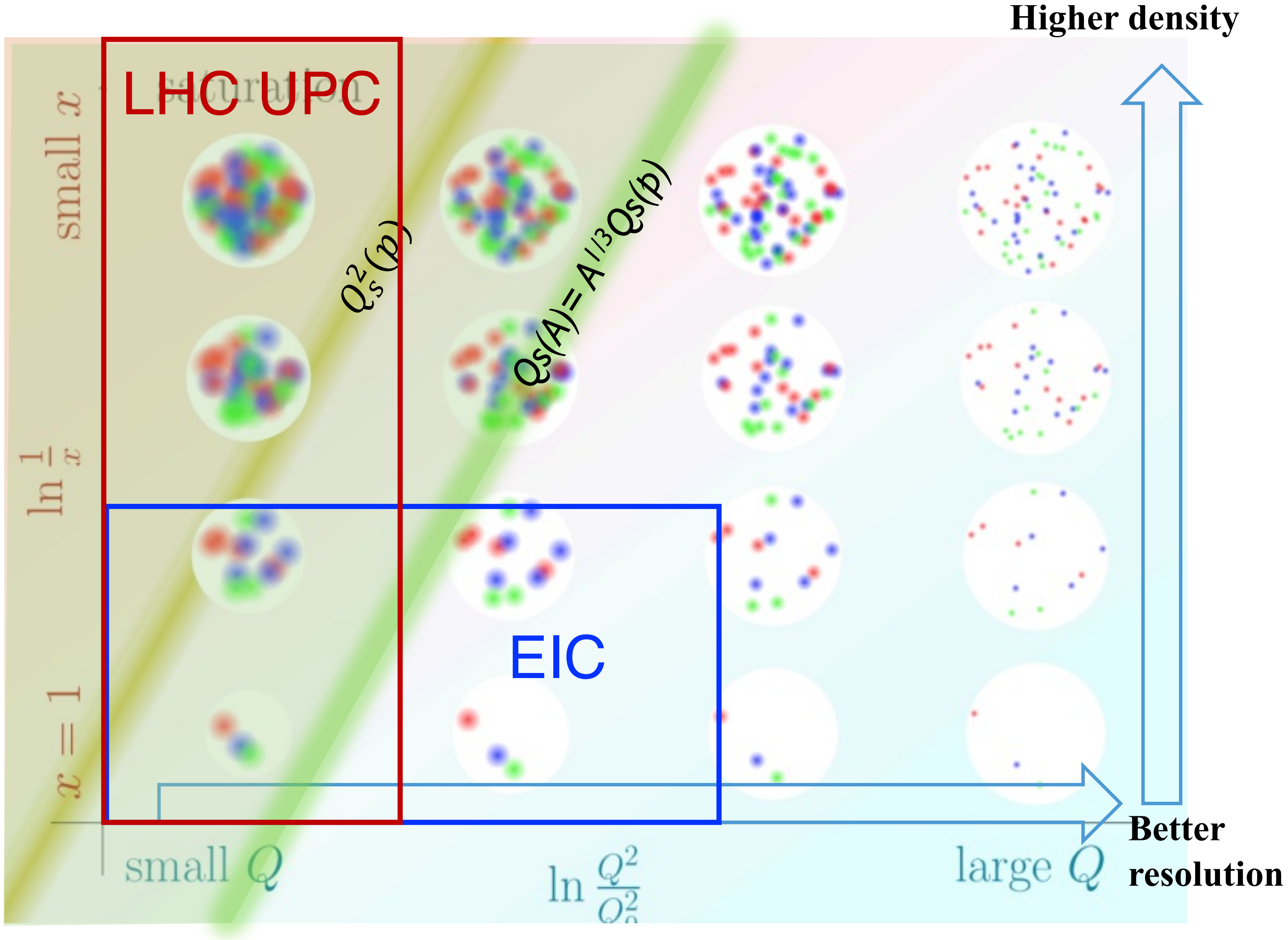
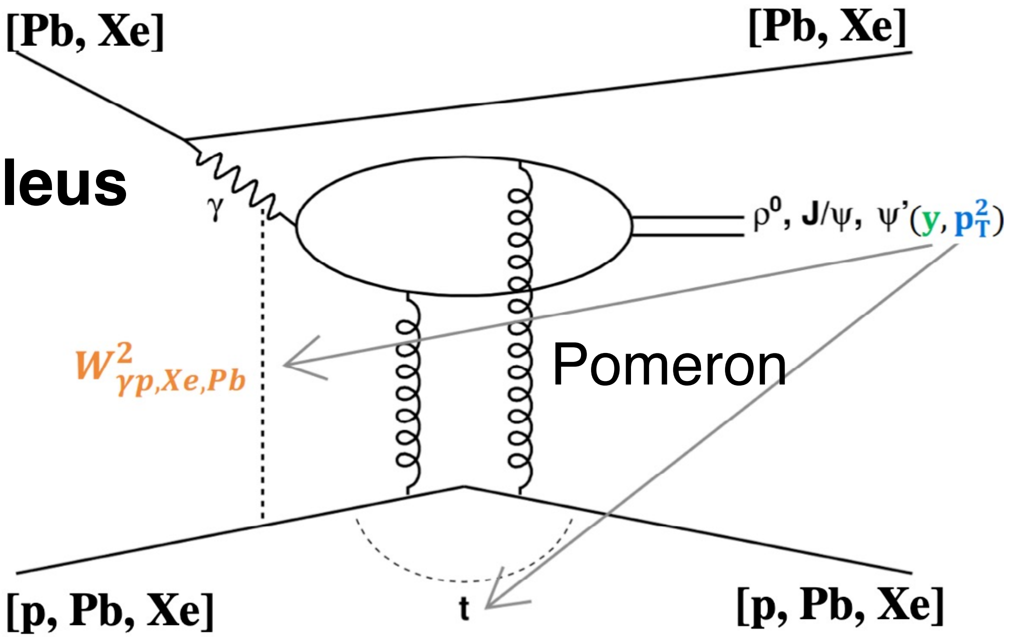


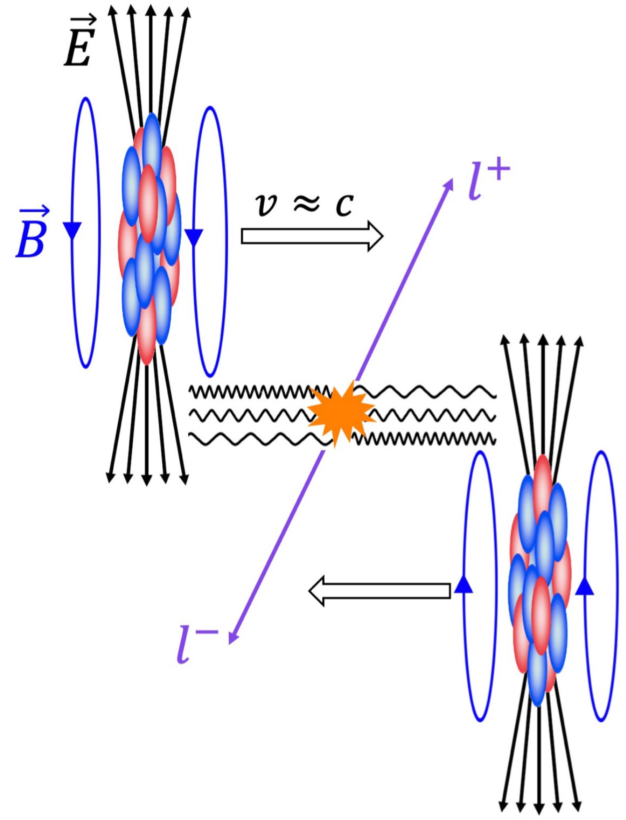
Nuclei "miss" each other (b > $R_A + R_B$)

- Boosted EM field of nuclei are source of photons
- Interactions via photon-photon (QED) or photon-nucleus (QCD)

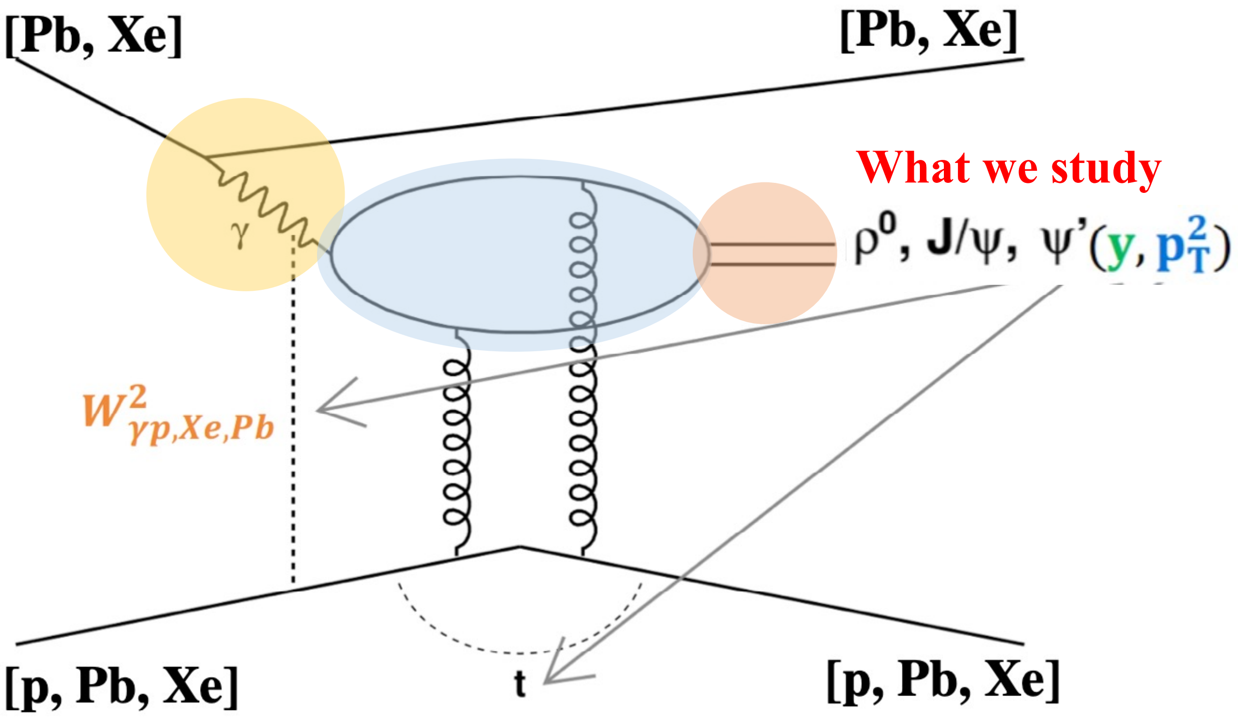
Photon-nucleus



Photon-photon



VM Photoproduction In UPCs



Well-defined kinematics:

$$(\mathrm{y},\ p_T^2) \rightarrow (W_{\gamma p}^2, \mathrm{t})$$

$$W^2 = M_{VM}\sqrt{s_{NN}} \cdot e^{\pm y}$$

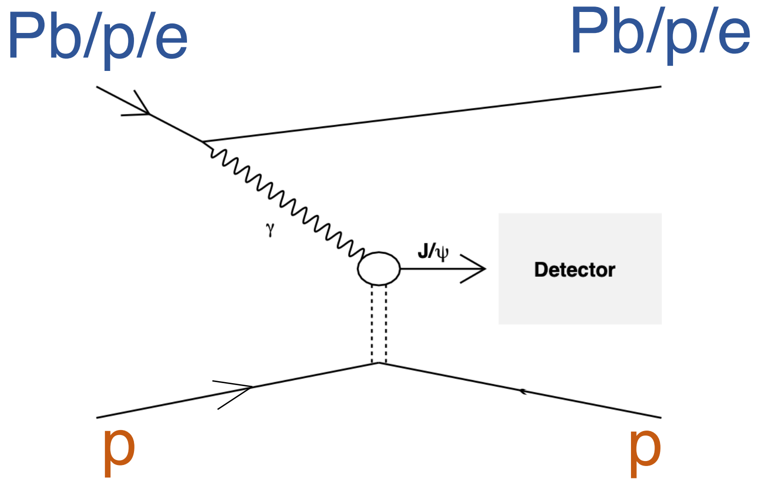
$$x = \frac{M_{VM}}{\sqrt{s_{\mathrm{NN}}}} e^{\mp y}$$

Cross section $\propto \left(xg(x, Q^2)\right)^2$ at LO QCD

- Coherent: average distribution
- Incoherent: event-by-event fluctuations

→ Excellent probe of gluonic IS

J/ψ photoproduction via γp

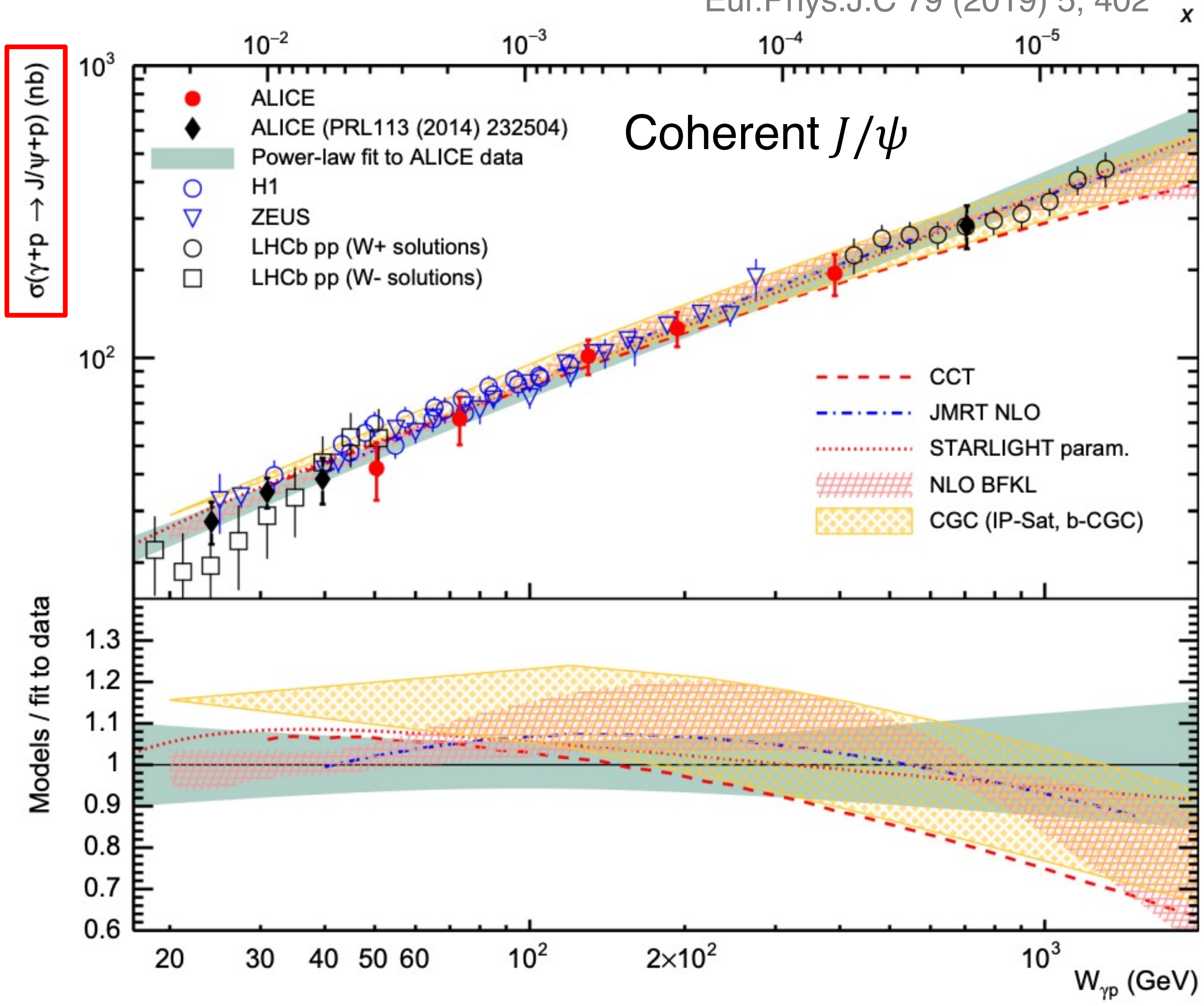


$\boldsymbol{\sigma}(W_{\gamma p})$ follows a universal power-law rise from HERA to the LHC.

Data described by theories with no/little saturation effects.

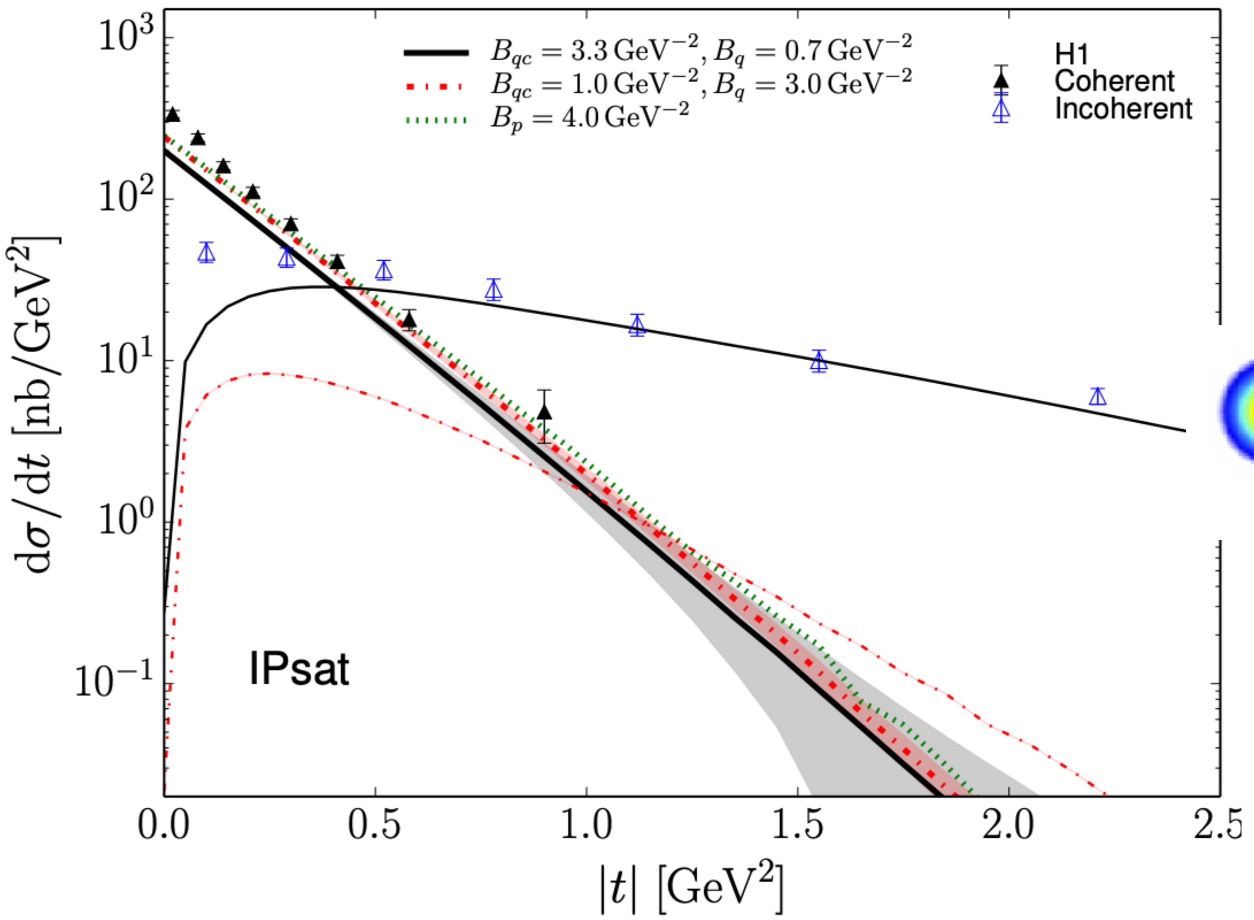
No clear signs of gluon saturation inside a proton to x ~ 10^{-5}!

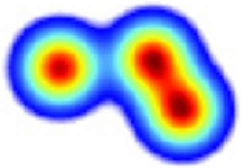
Eur.Phys.J.C 79 (2019) 5, 402

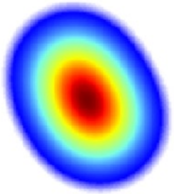


J/ψ photoproduction via γp

PRD 94, 034042 (2016)

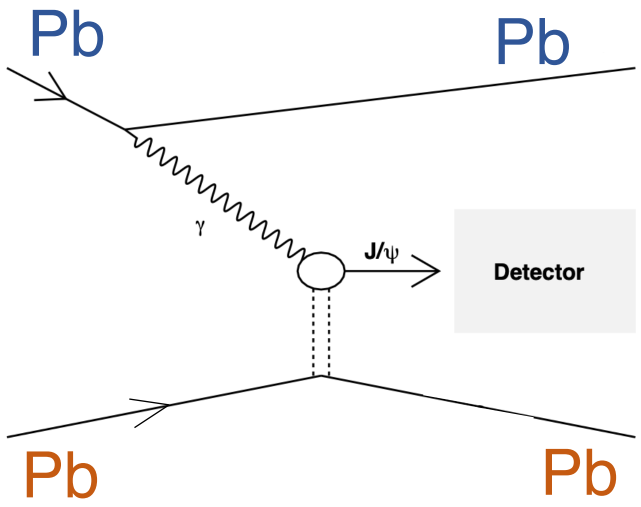




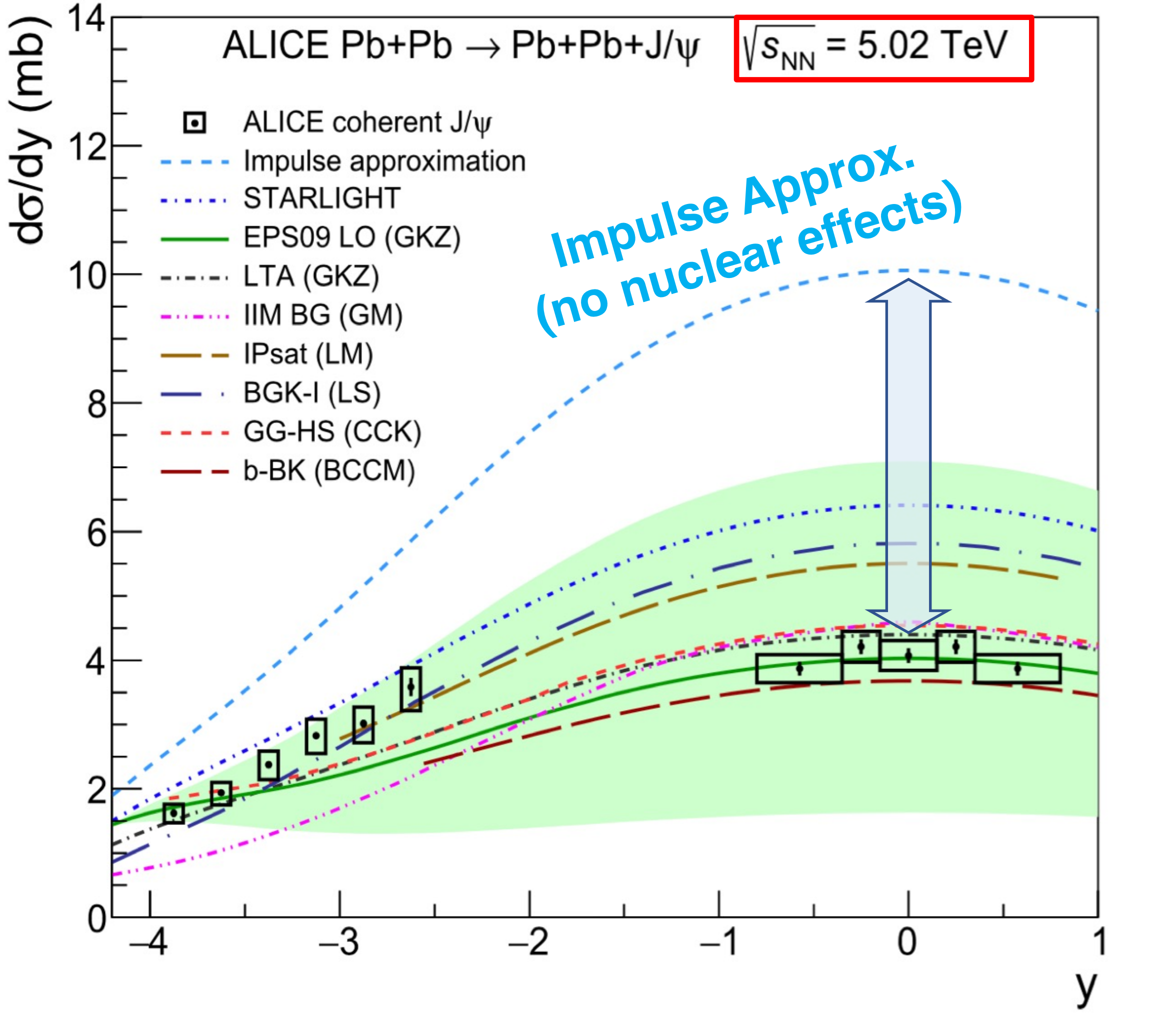


Incoherent production sensitive to **fluctuations of gluon distribution**

Coherent J/ψ Photoproduction in γPb



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



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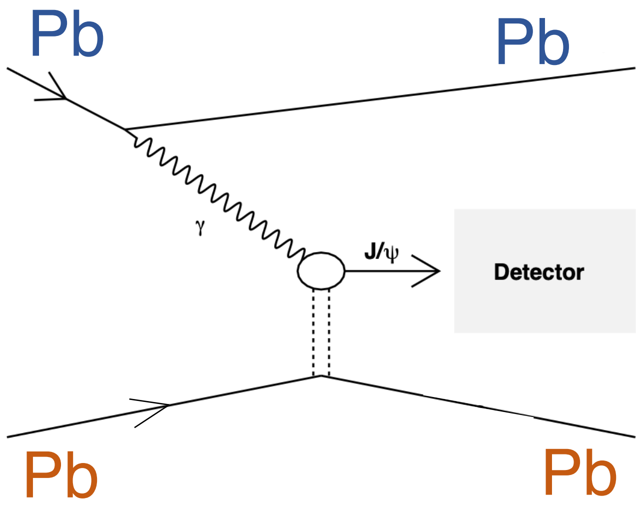

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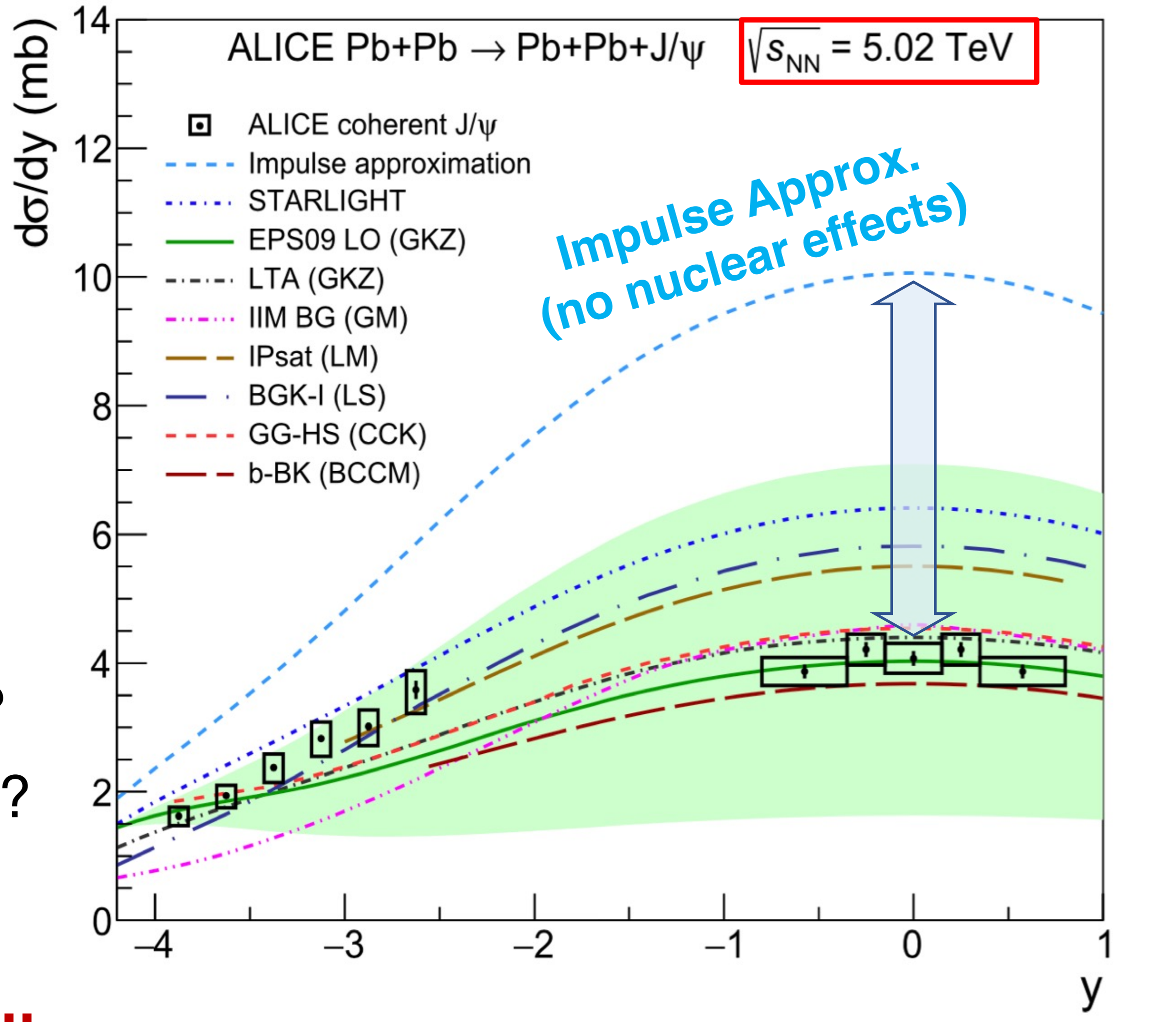


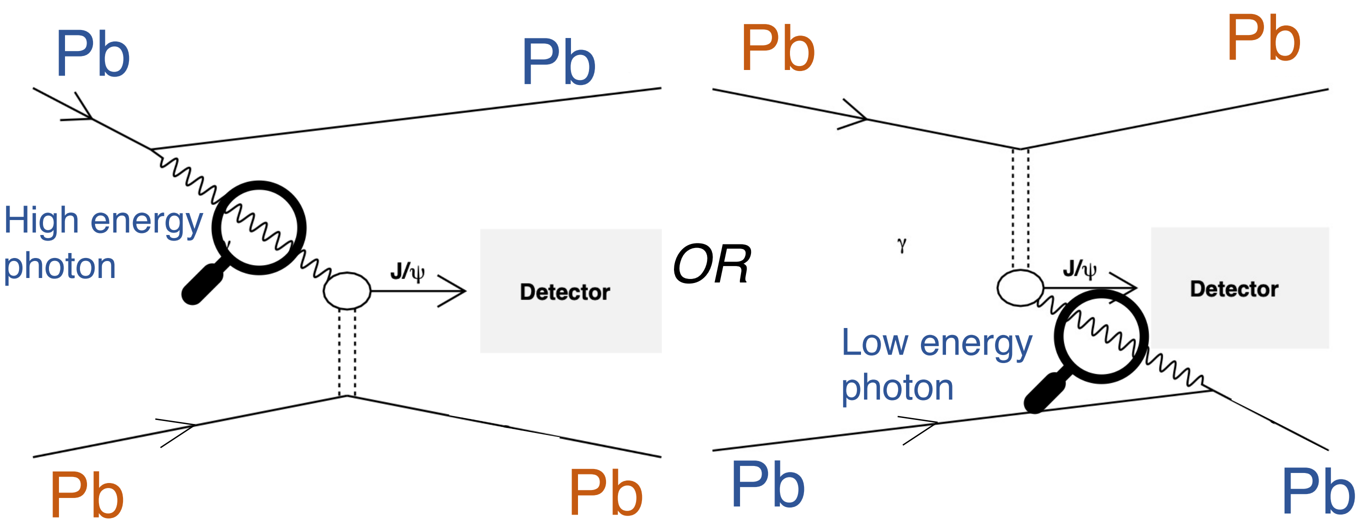
Strong suppression effects observed. But how?

- Nuclear shadowing (*Leading Twist Approx., LTA*)?
- Gluon saturation (e.g., *IPsat*)?

No theory can describe the data over the full y range

Coherent J/ψ Photoproduction in γPb

A "two-way ambiguity" in symmetric systems



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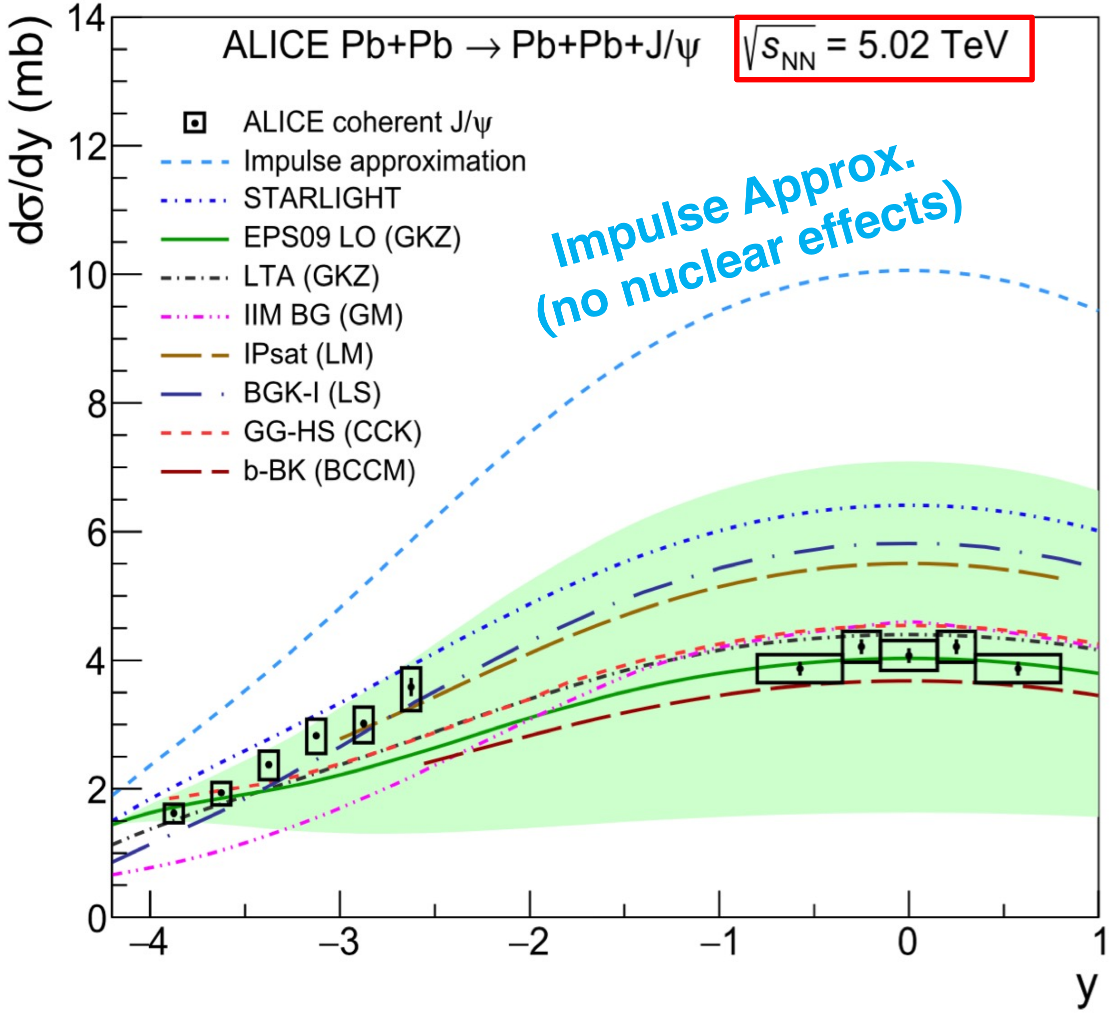

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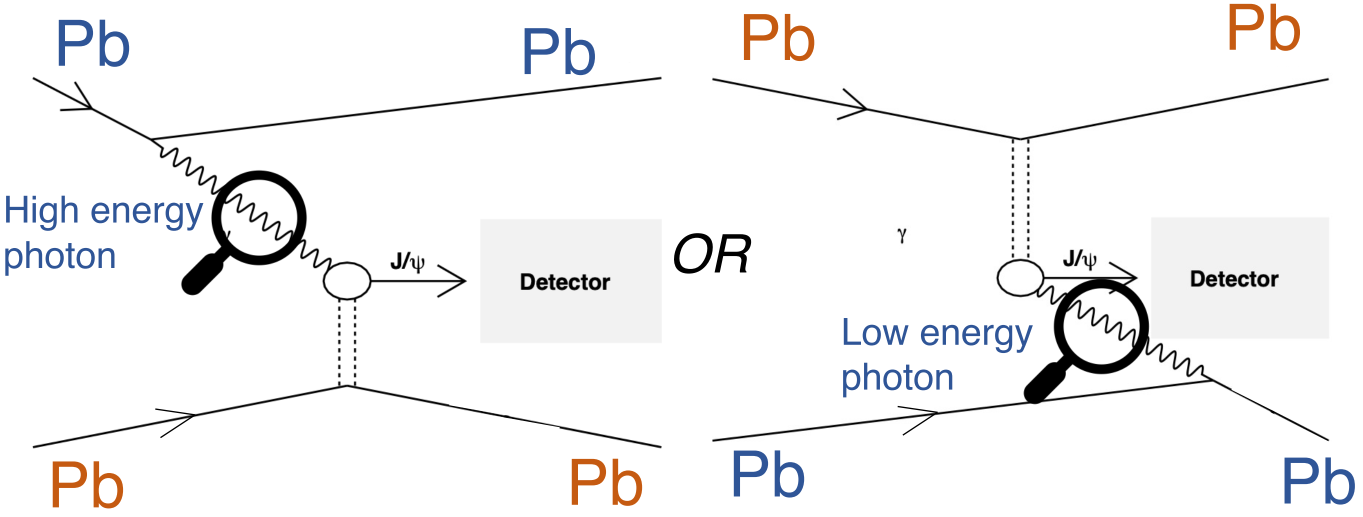

$$\frac{d\sigma_{AA\to AA'J/\psi}}{dy} = N_{\gamma/A}(\omega_1)\cdot\sigma_{\gamma A\to J/\psi A'}(\omega_1) + N_{\gamma/A}(\omega_2)\cdot\sigma_{\gamma A\to J/\psi A'}(\omega_2)$$

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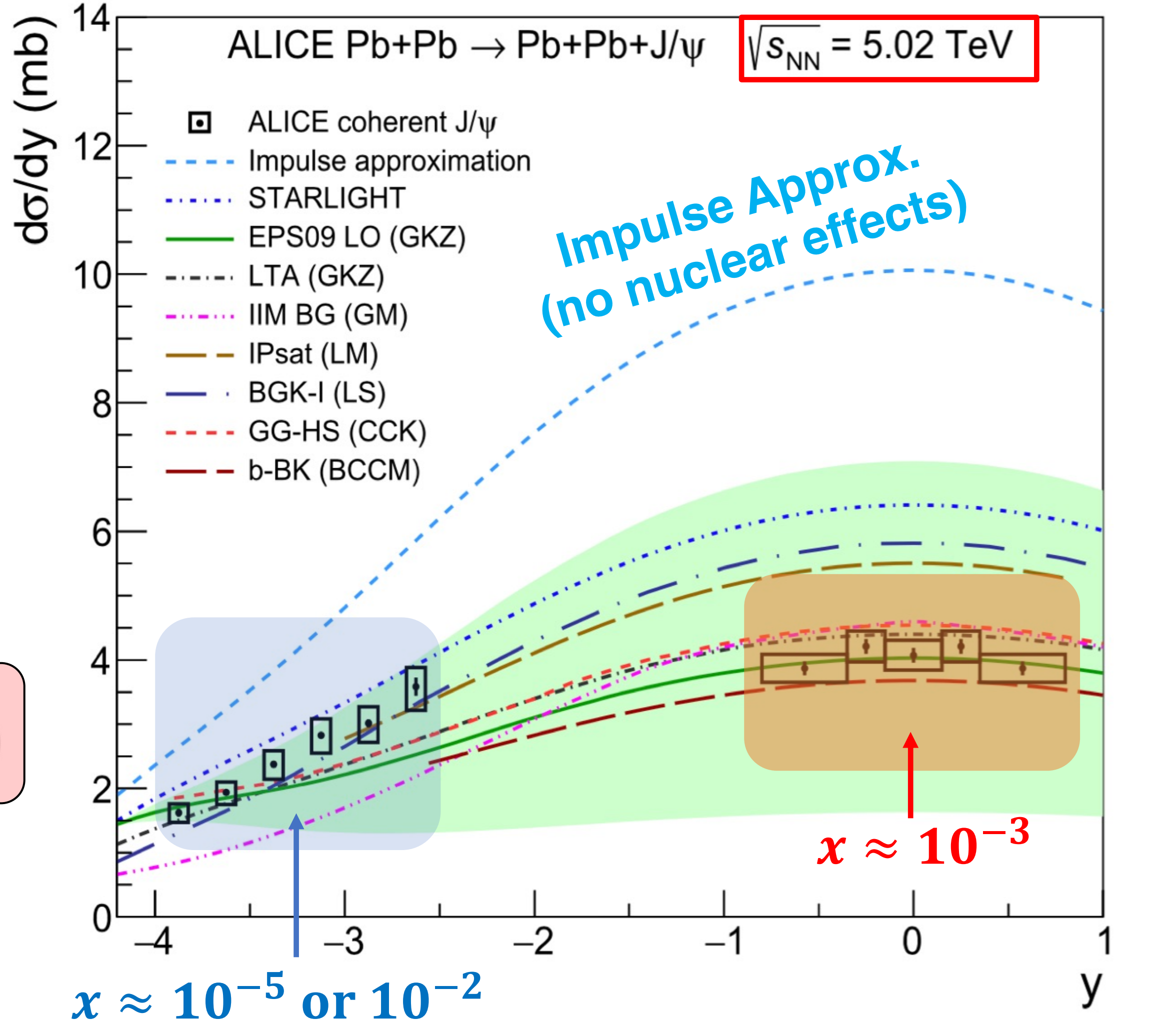

$x \approx 10^{-5}$ or 10^{-2}

(>95% high x!)

Coherent J/ψ Photoproduction in γPb

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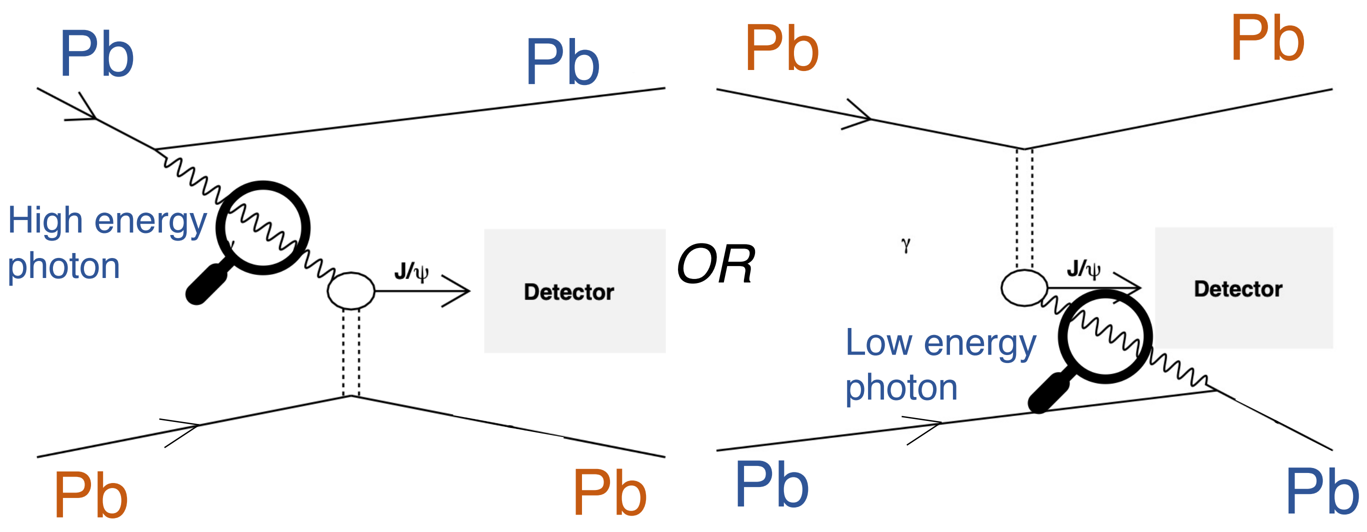

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No easy access to $\sigma\left(W_{\gamma N}^{\mathrm{Pb}}\right)$, and thus gluons inside a Pb nucleus at x ~ 10^{-5}!

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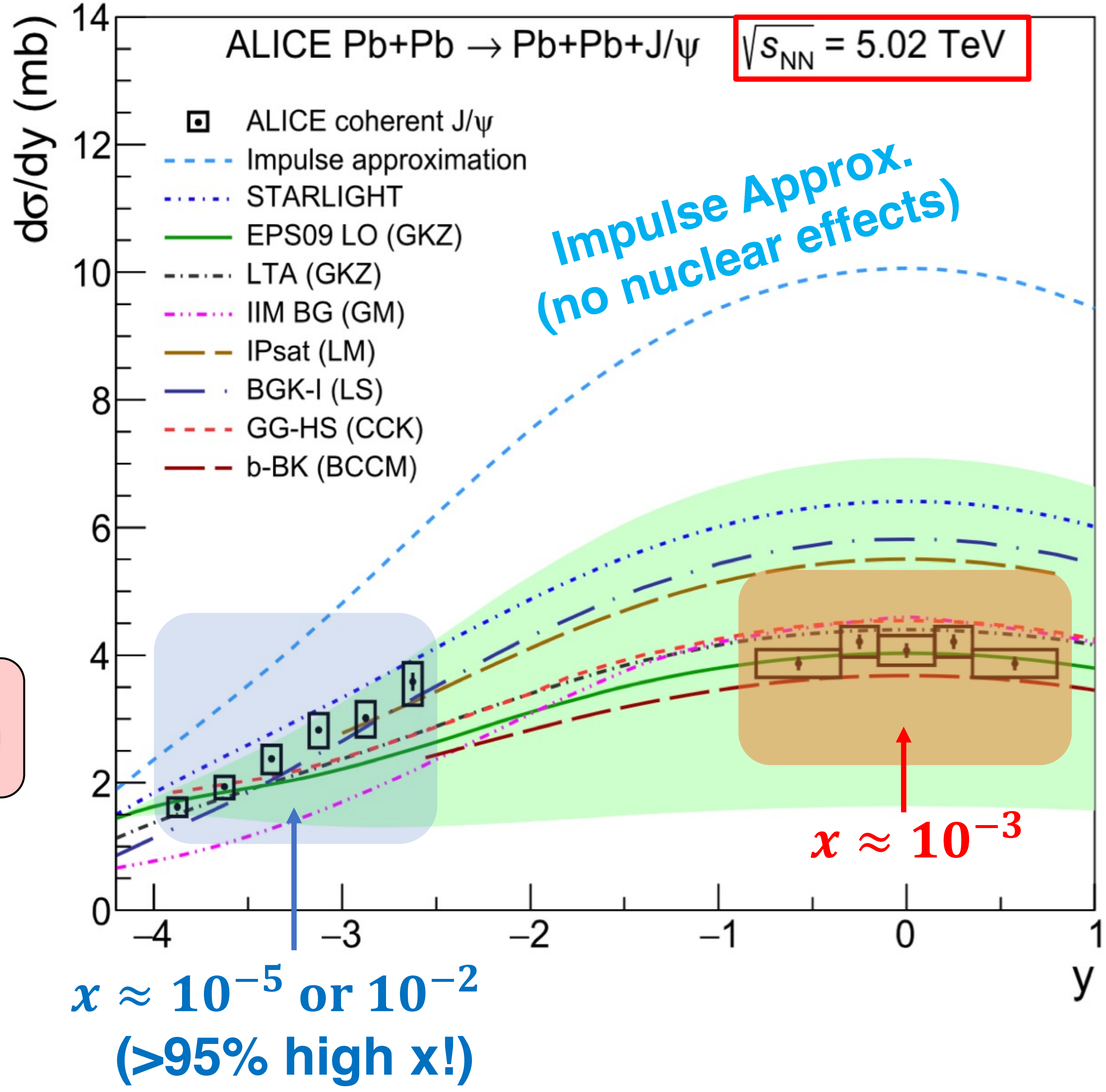
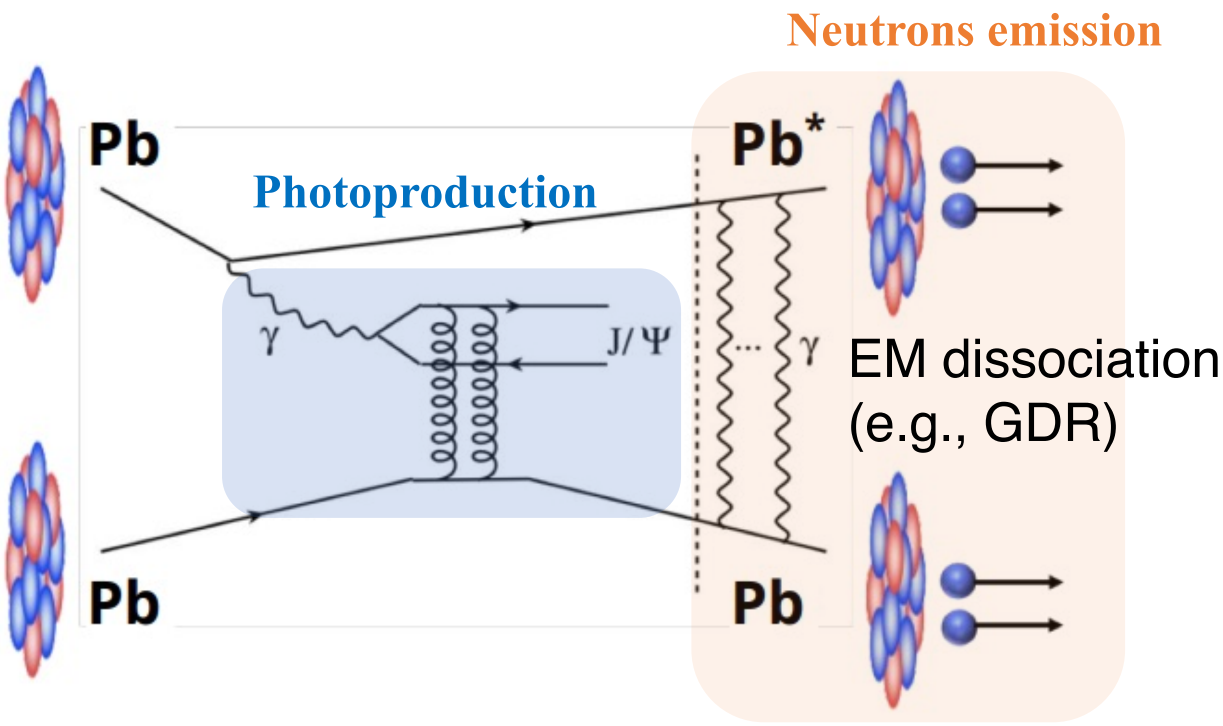


A Solution To The “Two-way Ambiguity”

Guzey et al., EPJC 74 (2014) 2942

Control the impact parameter or “centrality” of UPCs via forward neutron multiplicity



Nucleus excitation probability:

$$P_i(b) \propto 1/b^2$$

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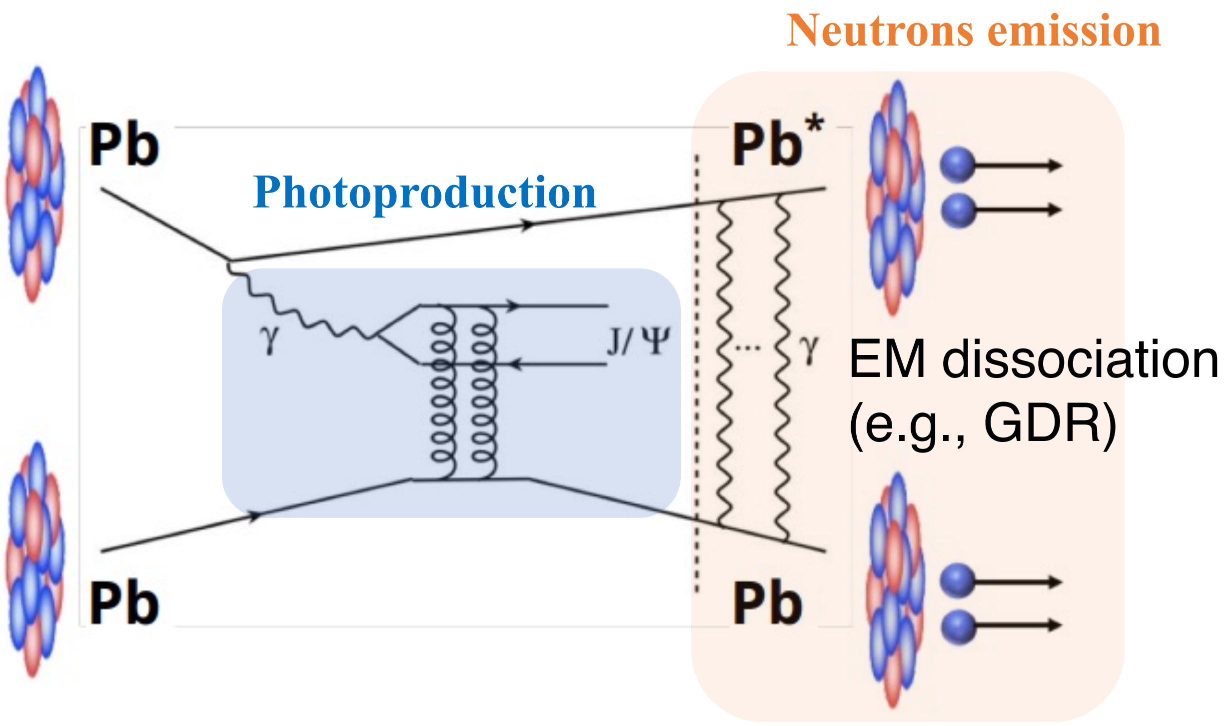

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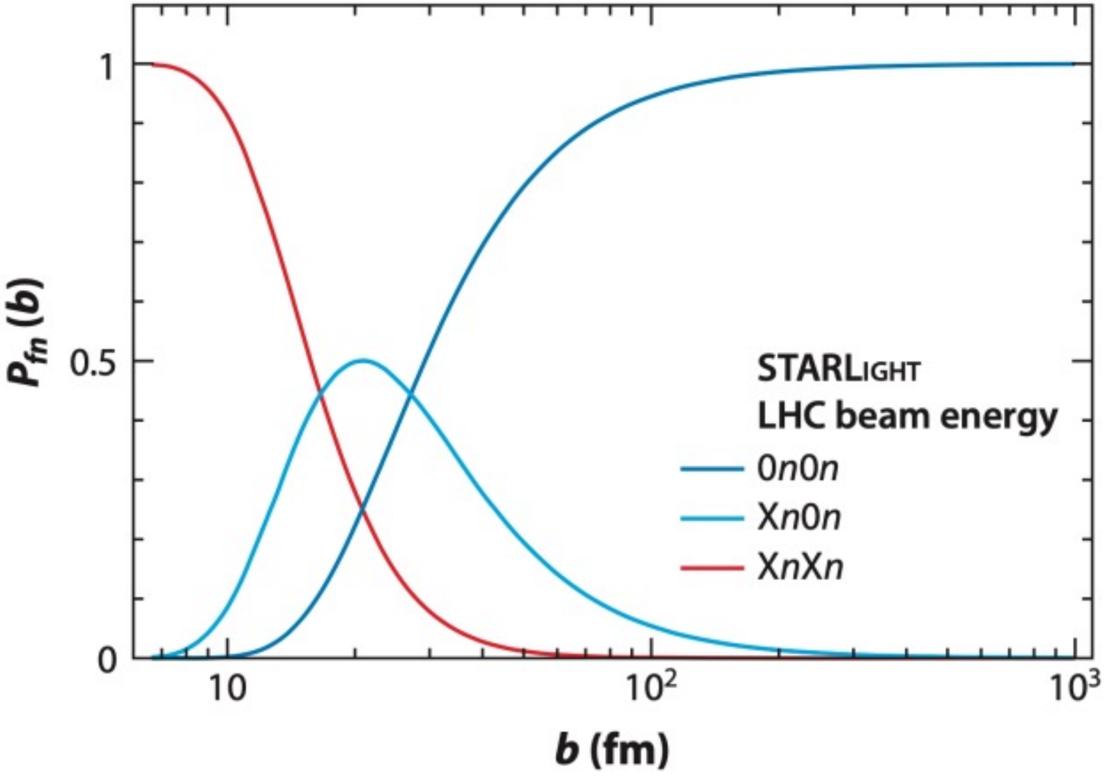

Spencer Klein & PAS, Ann Rev Nucl Part Sci Vol. 70:323-354

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

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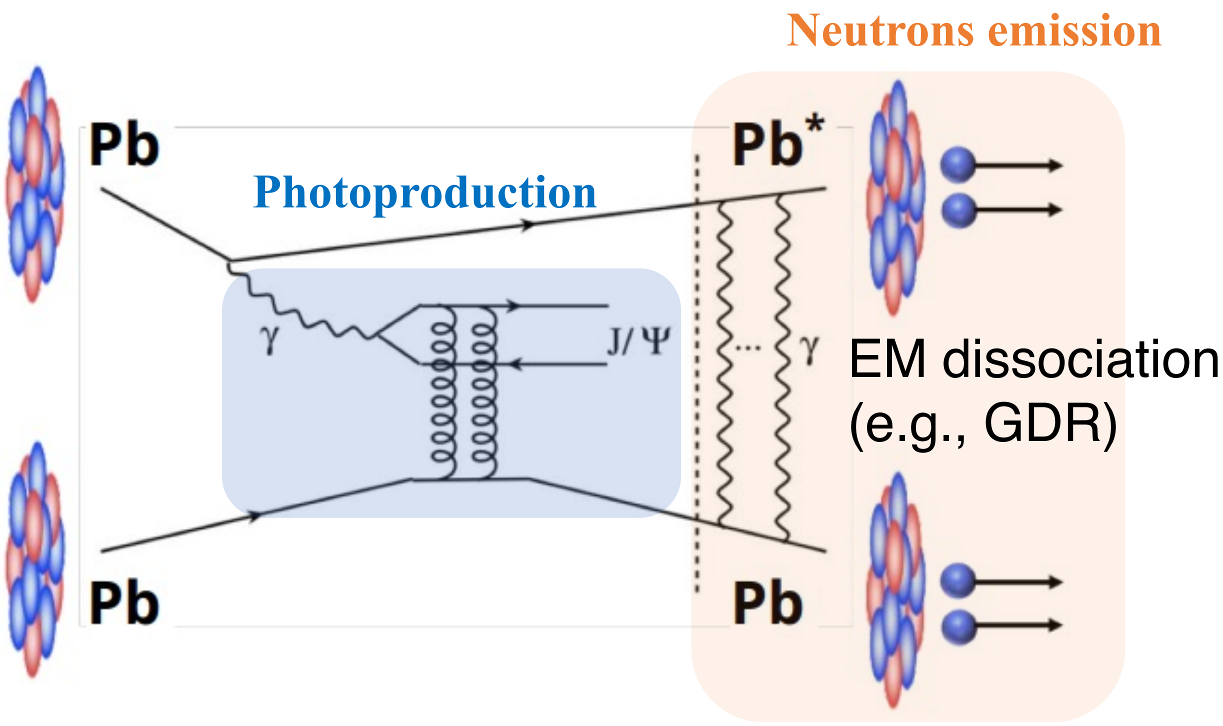

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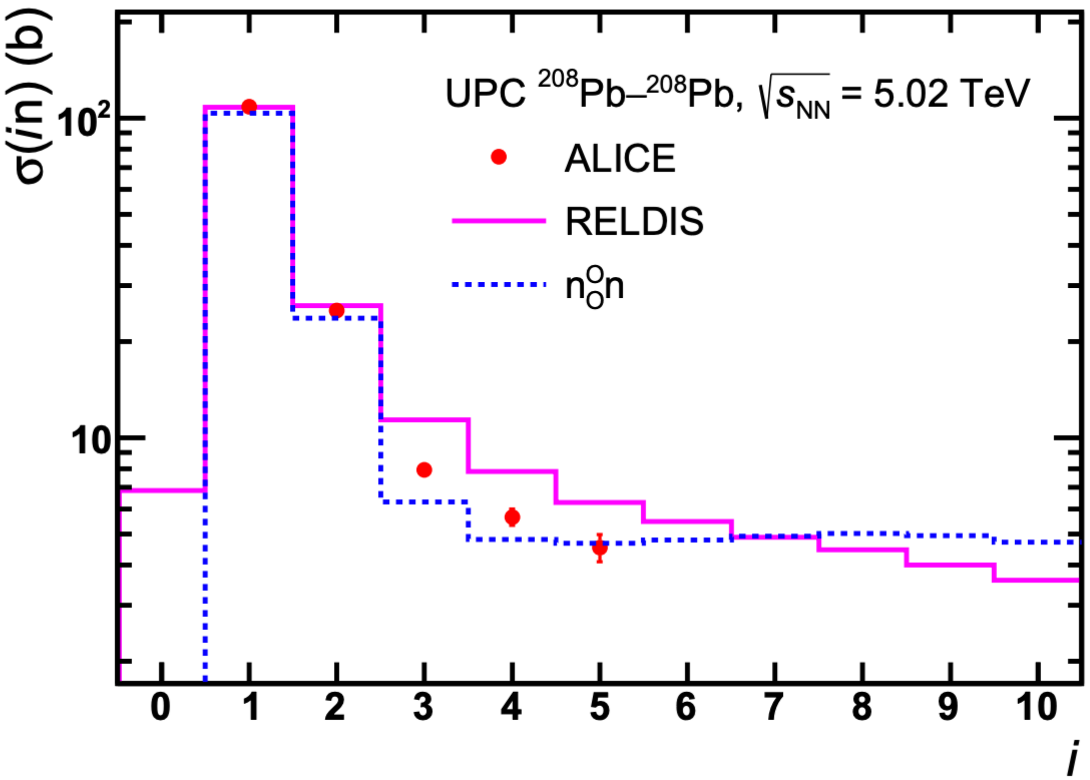
ALICE, arXiv:2209.04250



Neutrons from EMD reasonably understood

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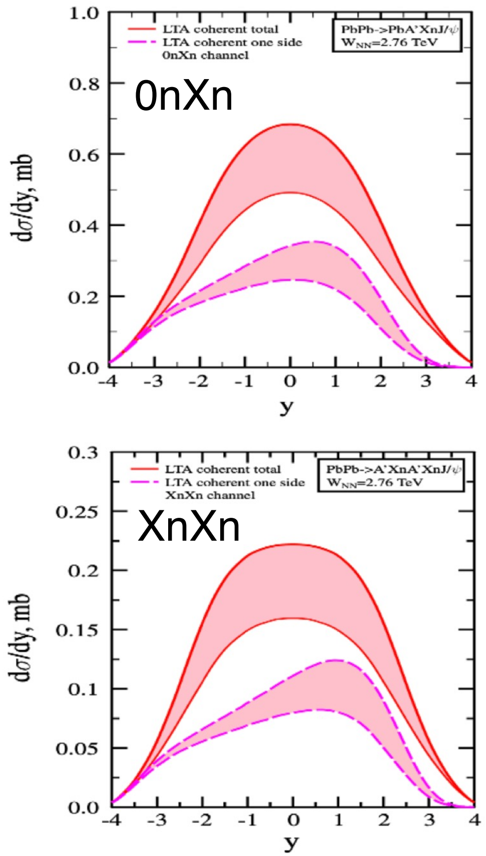

Guzey et al., EPJC 74 (2014) 2942

For each |y| bin,

$$\frac{d\sigma^{0n0n}_{AA\to AA'J/\psi}}{dy} = N^{0n0n}_{\gamma/A}(\omega_1)\cdot\sigma_{\gamma A\to J/\psi A'(\omega_1)} + N^{0n0n}_{\gamma/A}(w_2)\cdot\sigma_{\gamma A\to J/\psi A'(w_2)}$$

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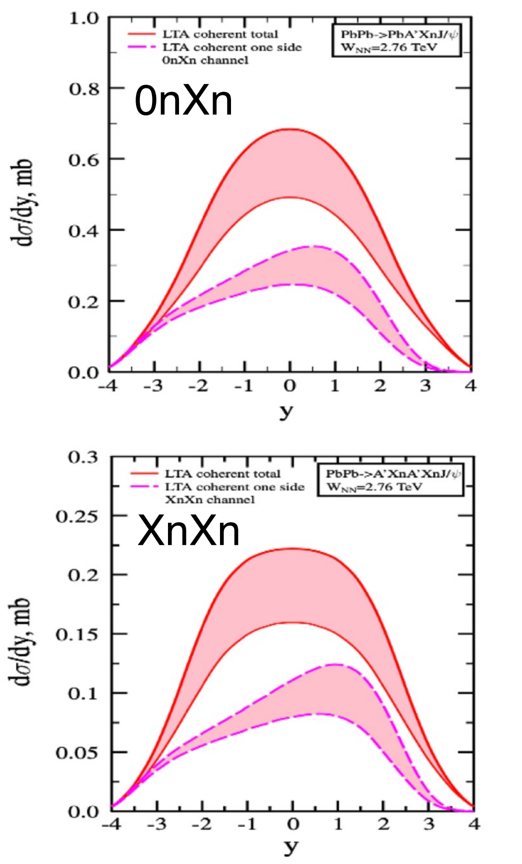

Guzey et al., EPJC 74 (2014) 2942

What is measured

Photon flux from theory

What we want

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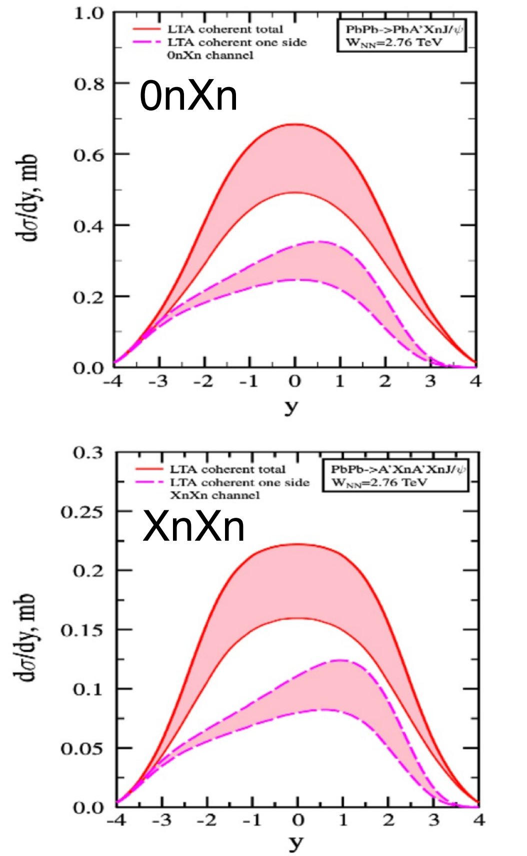

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Solve for $\sigma_{\gamma A\to J/\psi A'(w_1)}$ and $\sigma_{\gamma A\to J/\psi A'(w_2)}$

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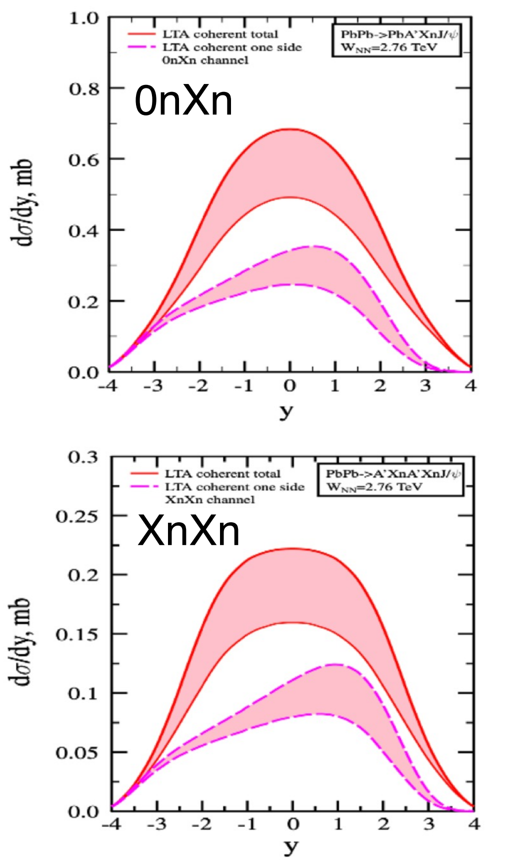

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For each |y| bin,

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

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⇩

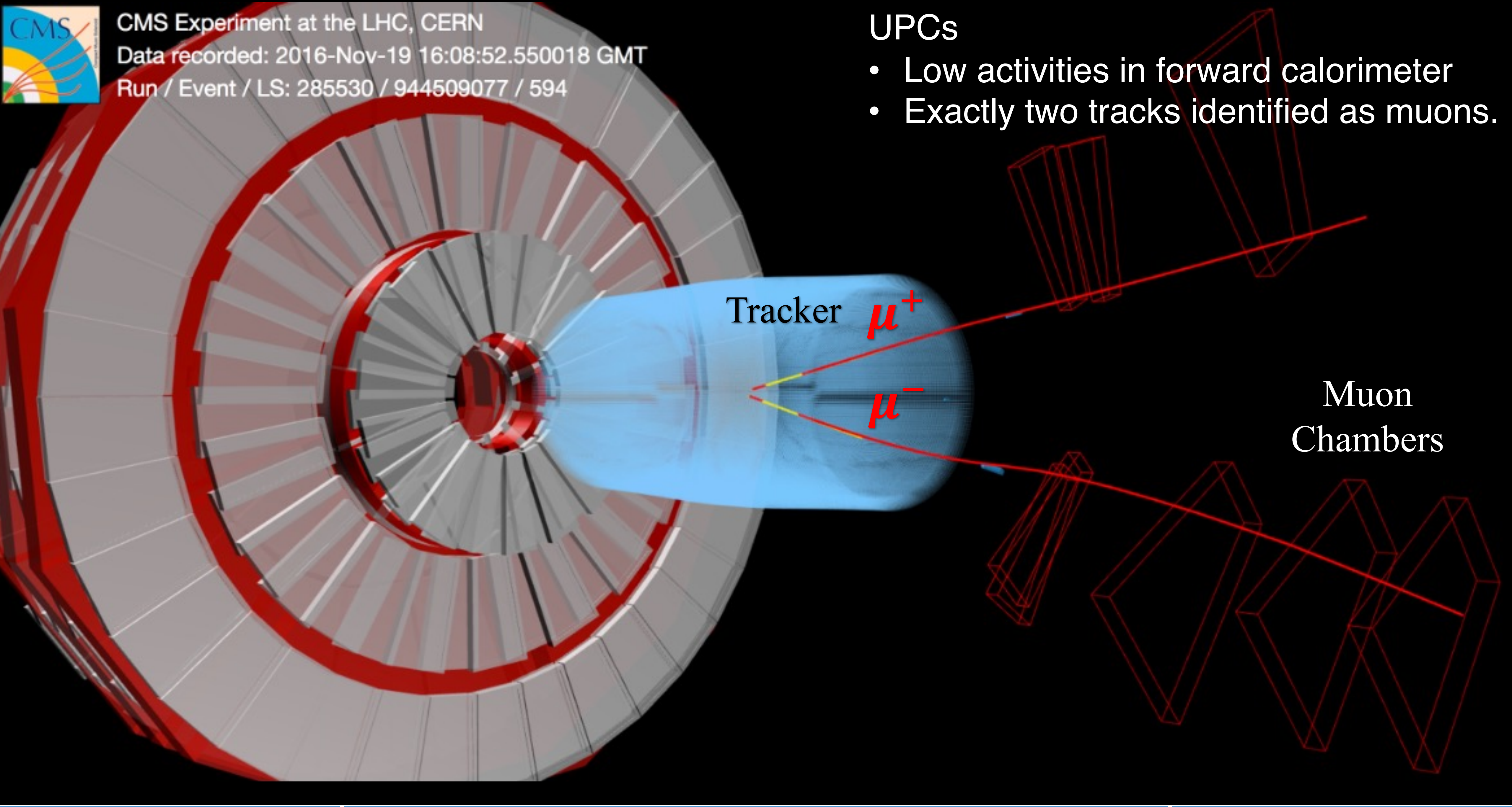
Solve for $\sigma_{\gamma A\to J/\psi A'(w_1)}$ and $\sigma_{\gamma A\to J/\psi A'(w_2)}$

⇩

$\sigma_{\gamma A\to J/\psi A'}\left(W^{Pb}_{\gamma N}\text{ or }x\right)$, probing $x \sim 10^{-4} - 10^{-5}$ gluons in nuclei!

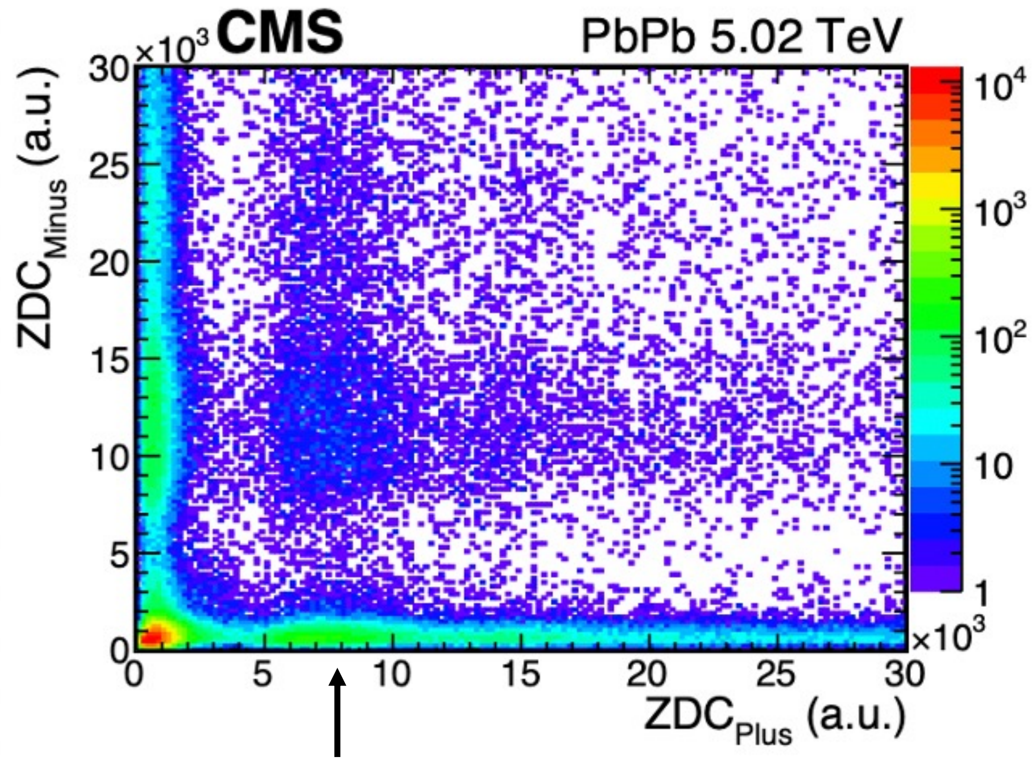
UPCs

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

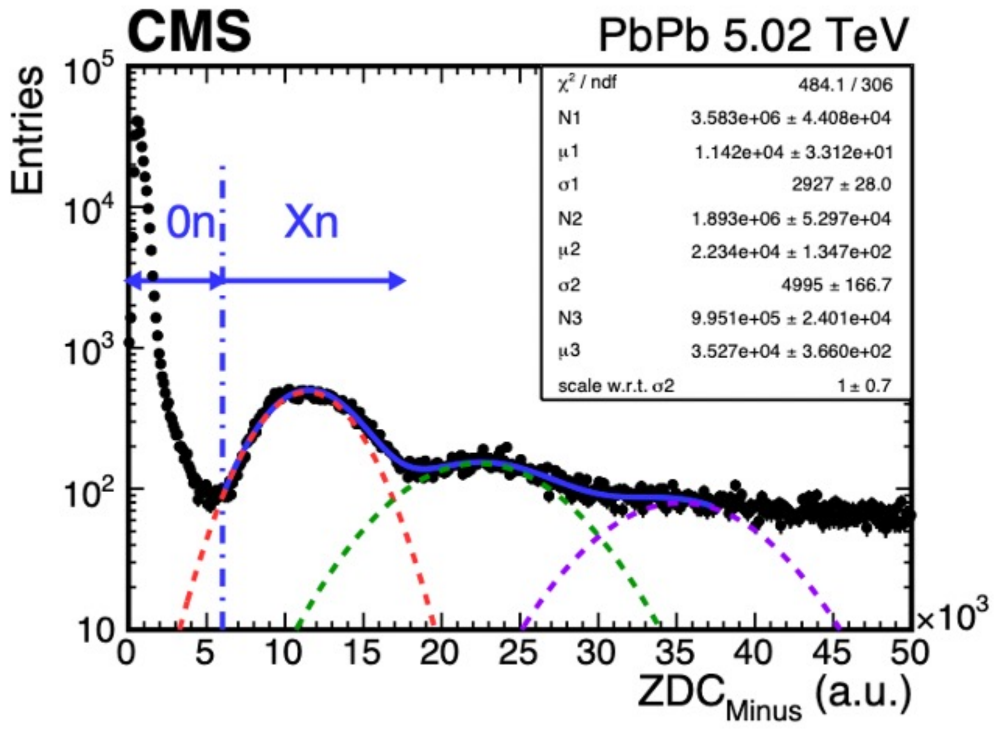


Determining the UPC centrality

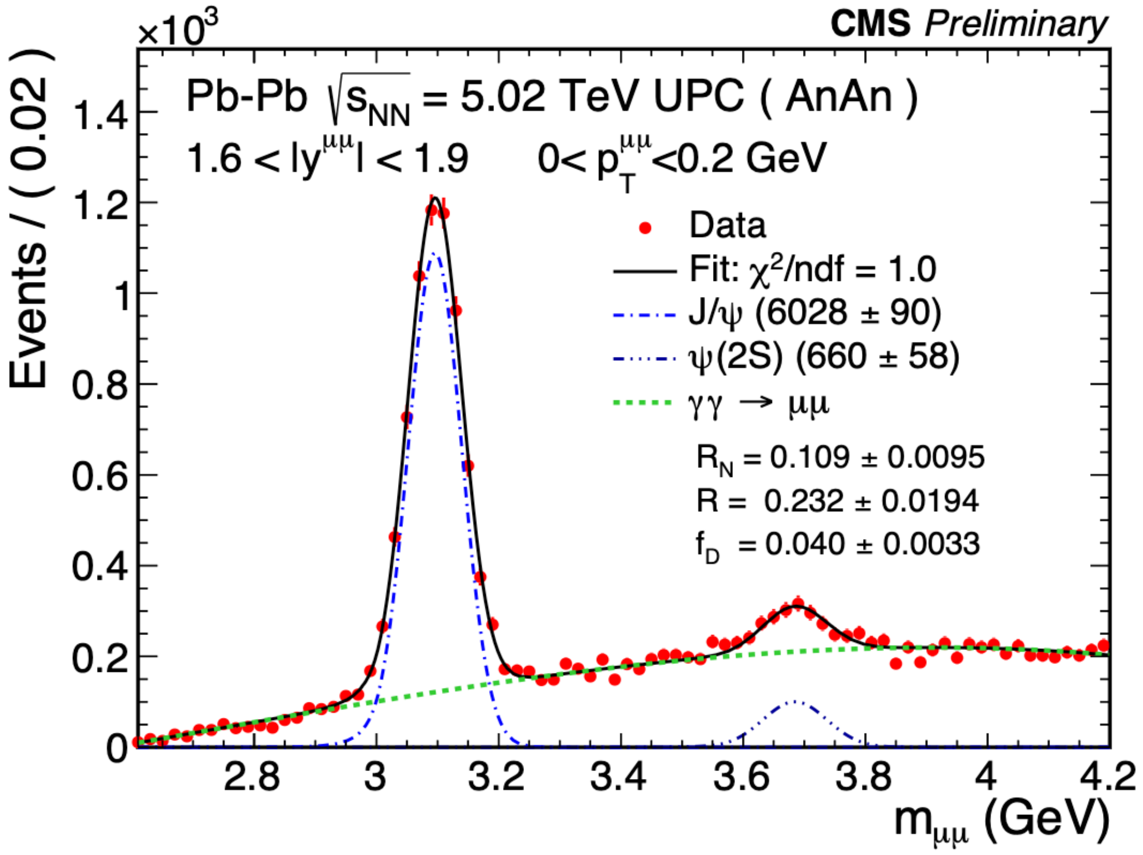
Neutron energy distribution in Zero Degree Calorimeters (ZDCs)

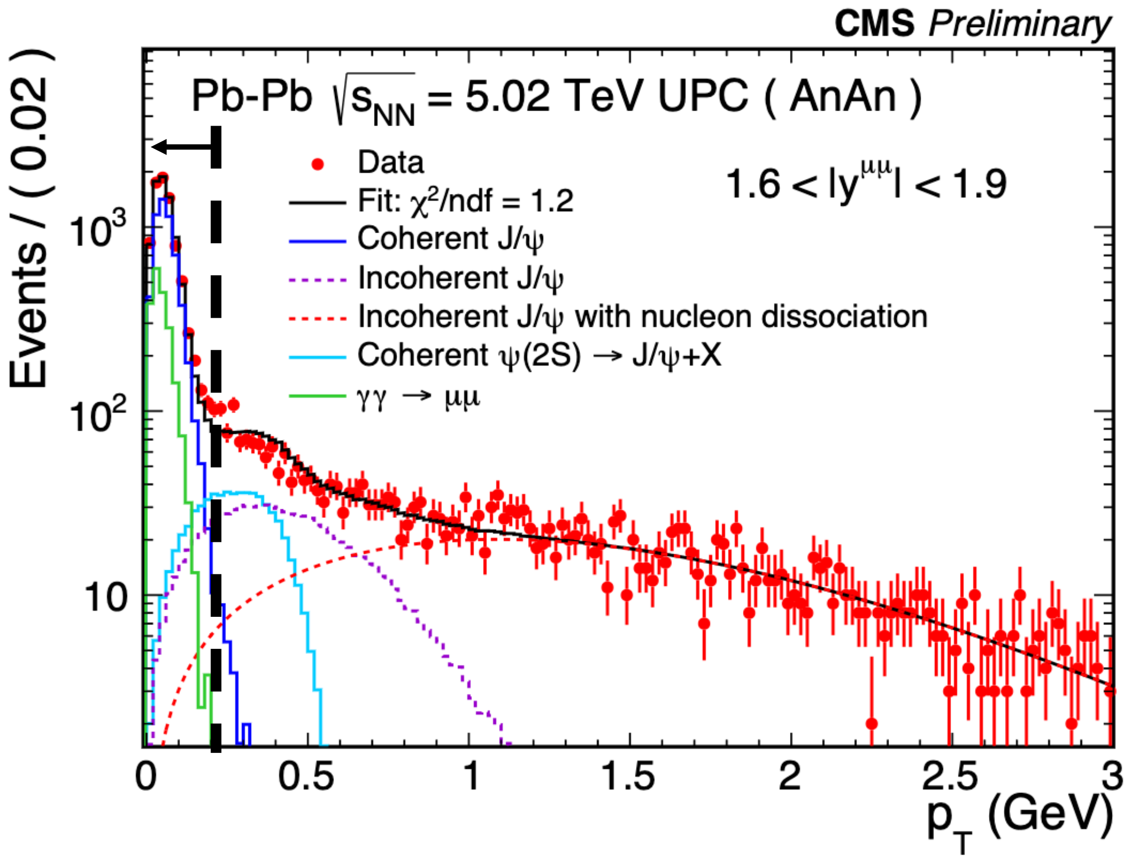


1 neutron peak



Coherent J/ψ signal extraction

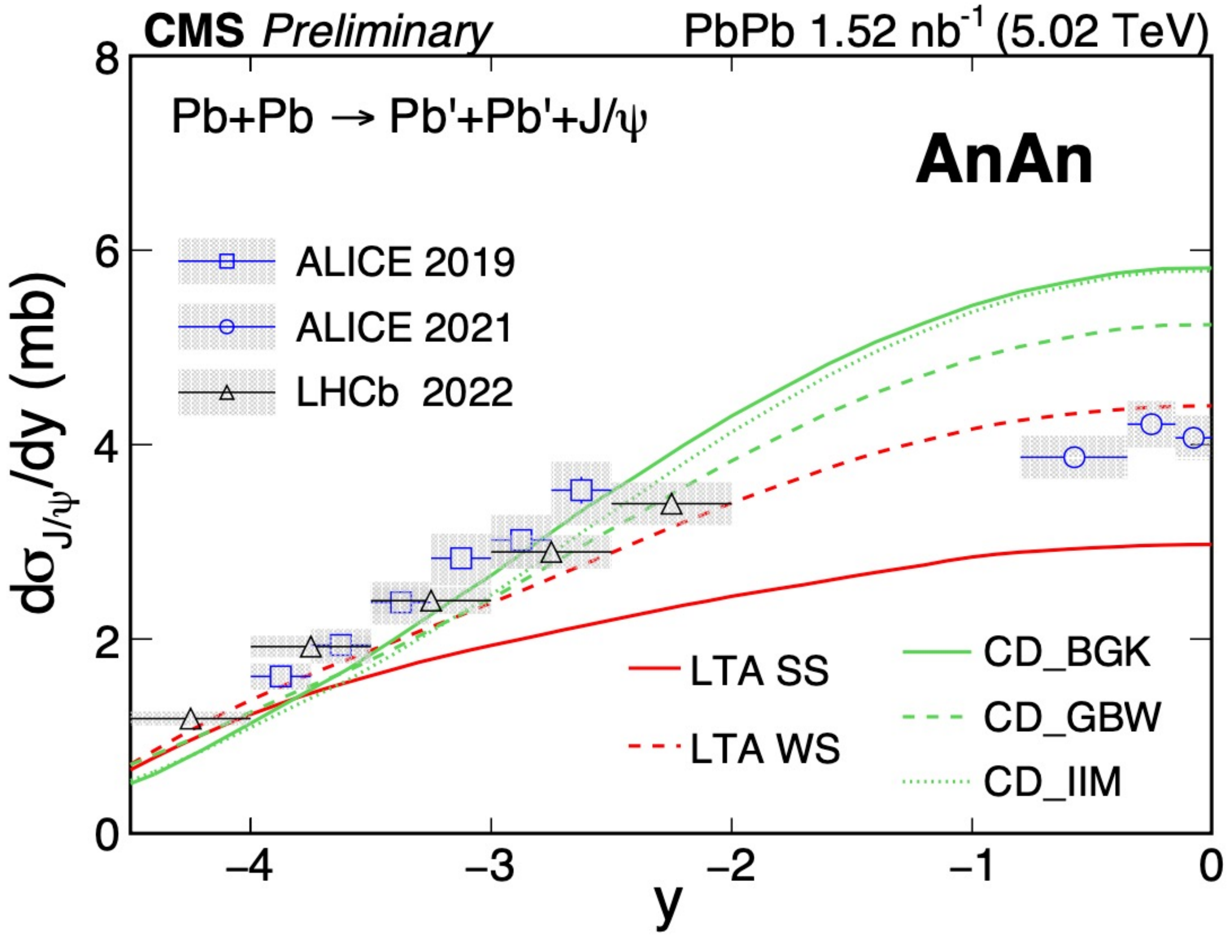




Signal yields are extracted by fitting the mass and transverse momentum spectra

AnAn: All possible neutron emissions

Neutron-Inclusive coherent J/ψ in UPC PbPb

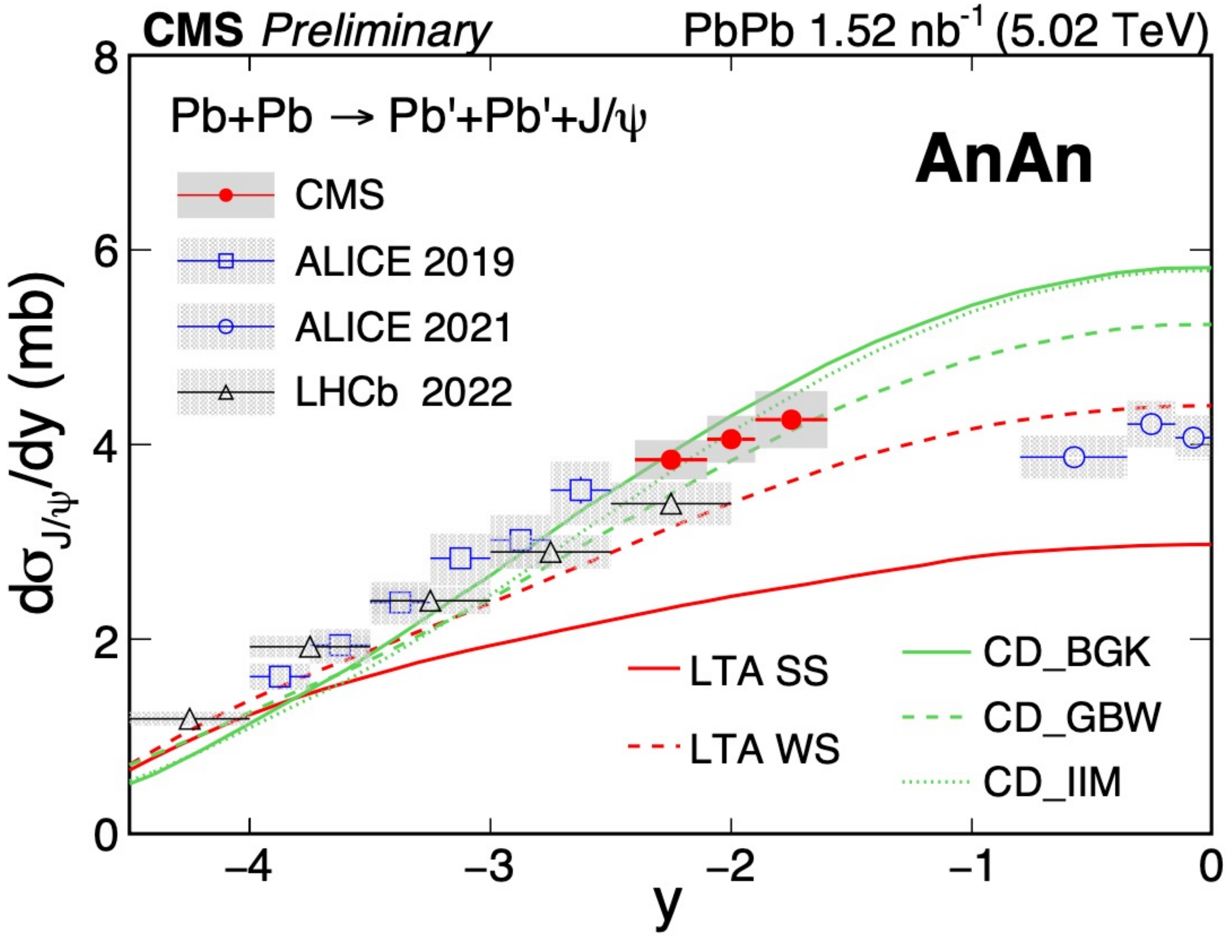


AnAn: All possible neutron emissions

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

- A tension between ALICE and LHCb forward data?
- *LTA Weak Suppression* connects ALICE mid-y and LHCb high-y

Inclusive coherent J/ψ in UPC PbPb



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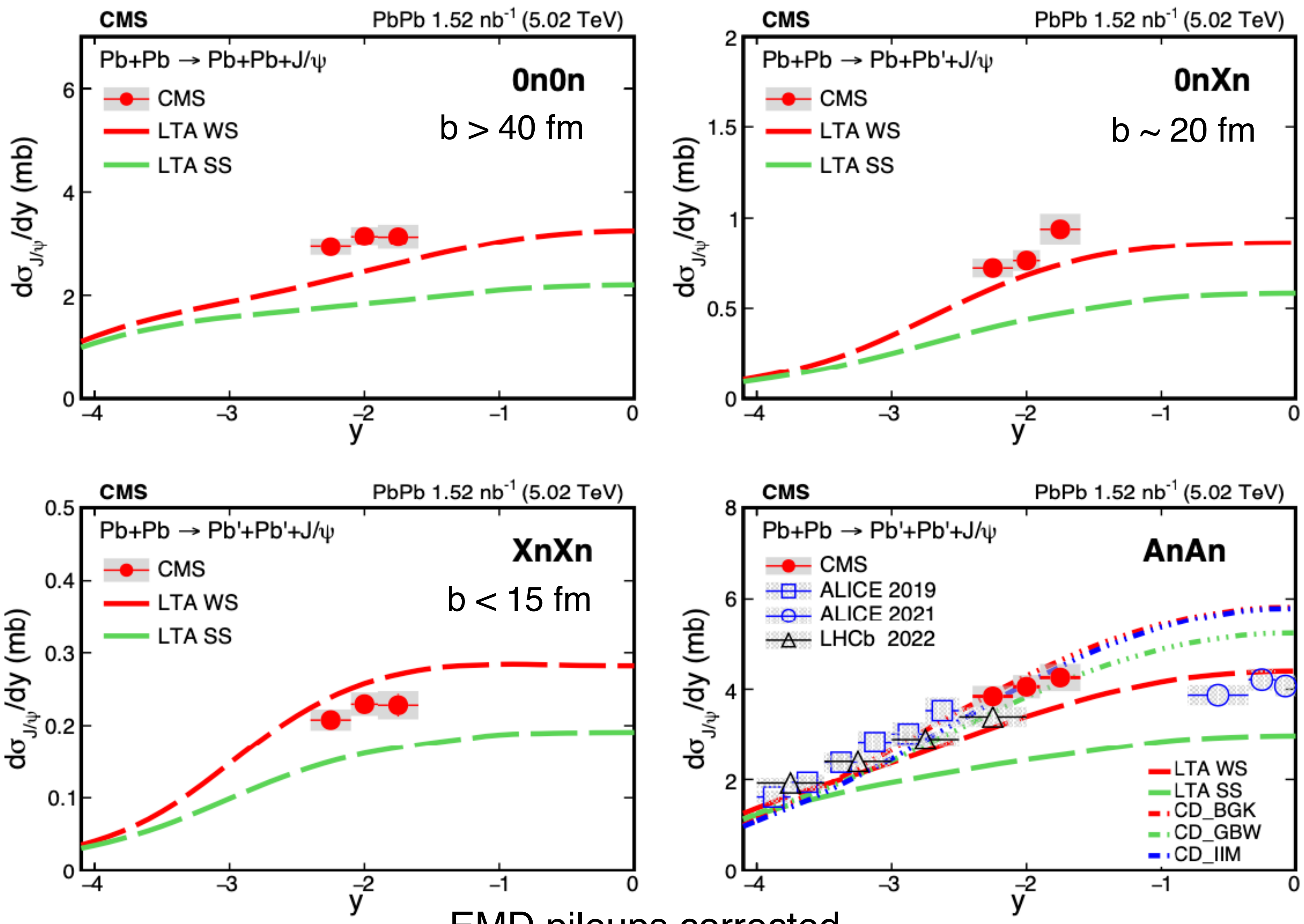
- A tension between ALICE and LHCb forward data?
- *LTA Weak Suppression* connects ALICE mid-y and LHCb high-y
- CMS data cover a unique new y region and tends to follow ALICE high-y trend

➢ will cover full |y|<2.4 in the near future

Coherent J/ψ in each “UPC centrality” class



EMD pileups corrected

- **First separation in different neutron classes!**
- LTA models cannot well describe data in different neutron classes

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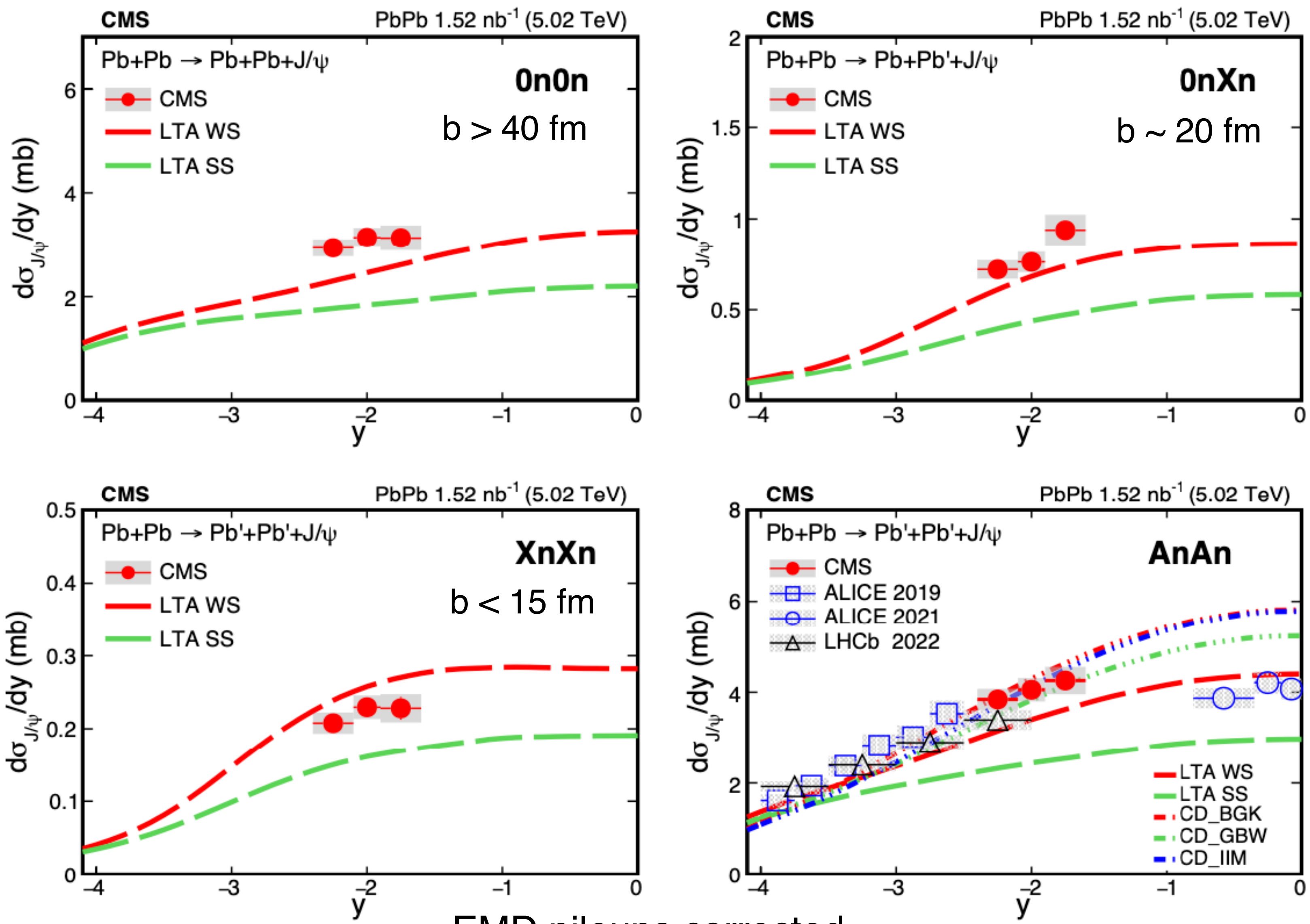

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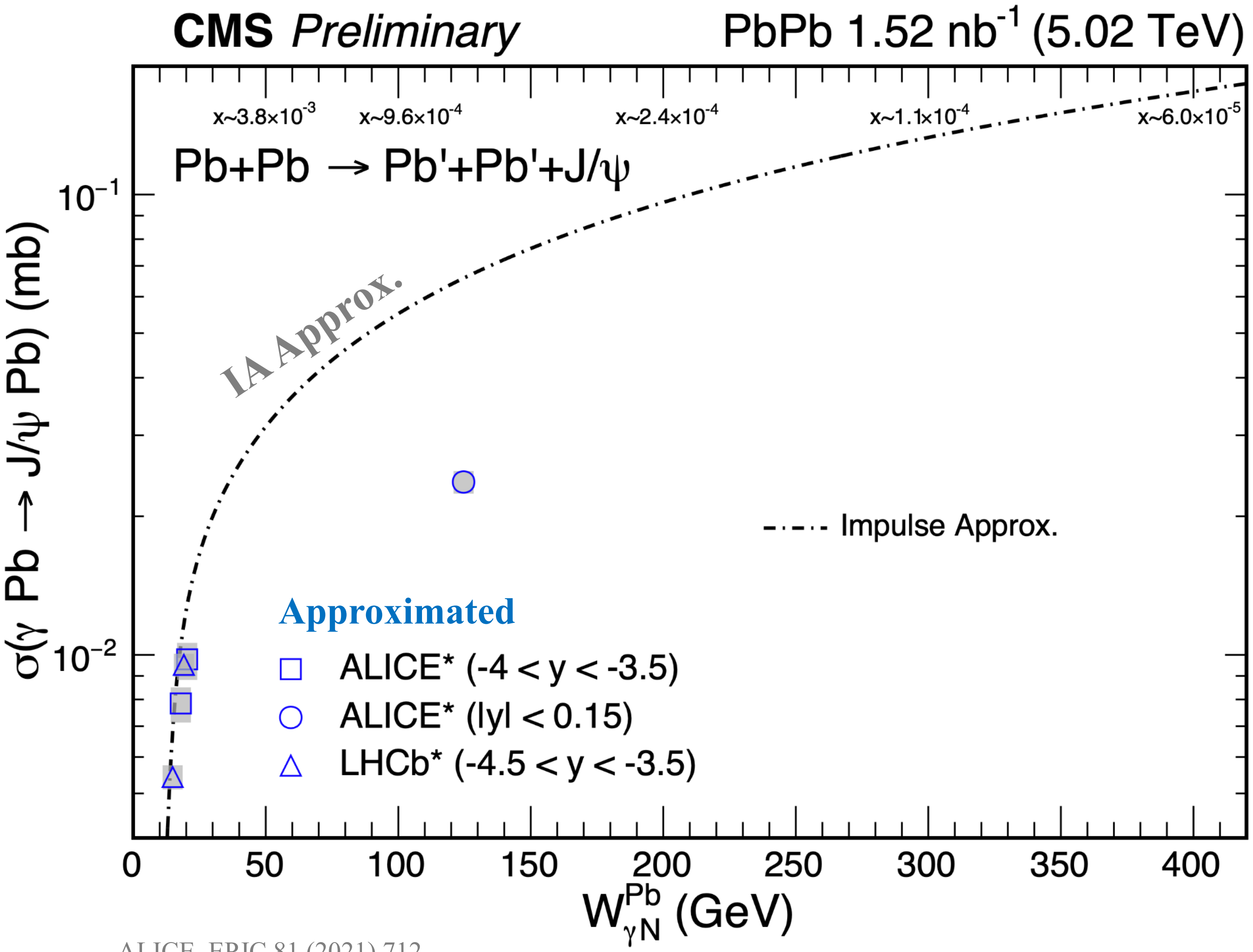
Disentangle the "two-way" ambiguity of high- and low-energy γPb contributions

$\sigma_{\gamma A \to J/\psi A'}\left(W_{\gamma N}^{Pb} \text{ or } x\right)$

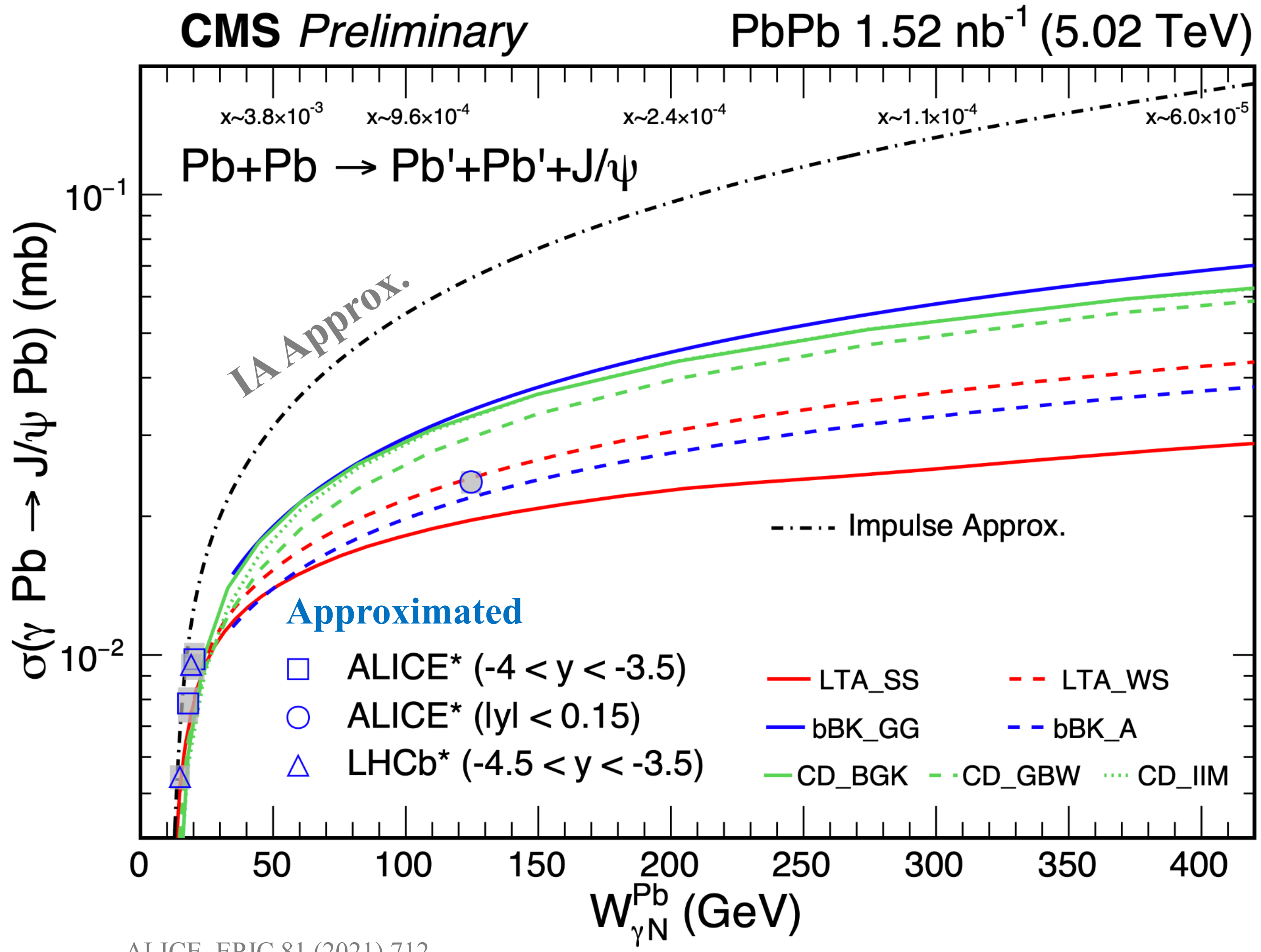
$\sigma_{\gamma A \to J/\psi A'}(W)$ results



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

Stronger suppression towards higher W from ALICE/LHCb data

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



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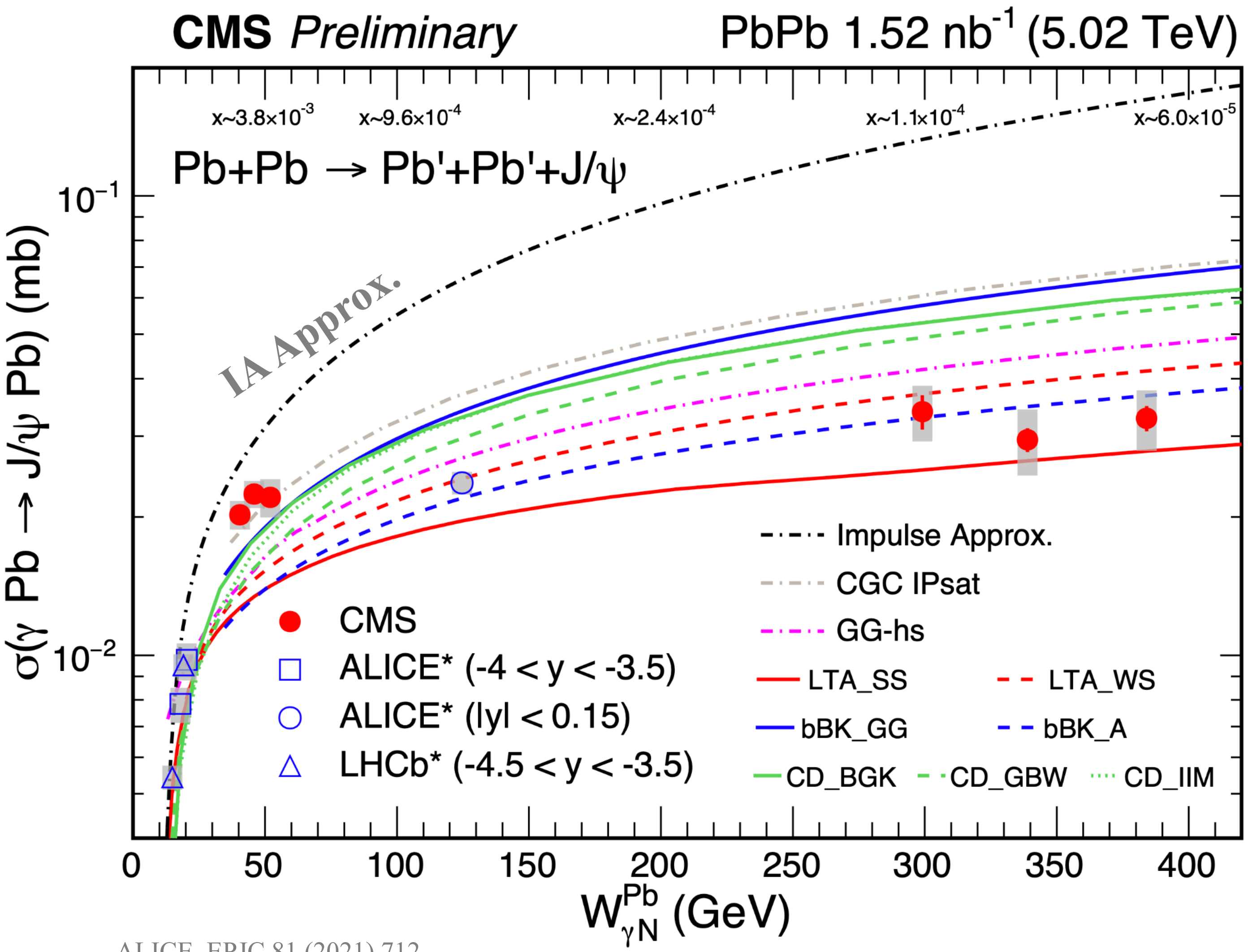
Stronger suppression towards higher W from ALICE/LHCb data

- some models capture the trend?

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



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

Stronger suppression towards higher W from ALICE/LHCb data

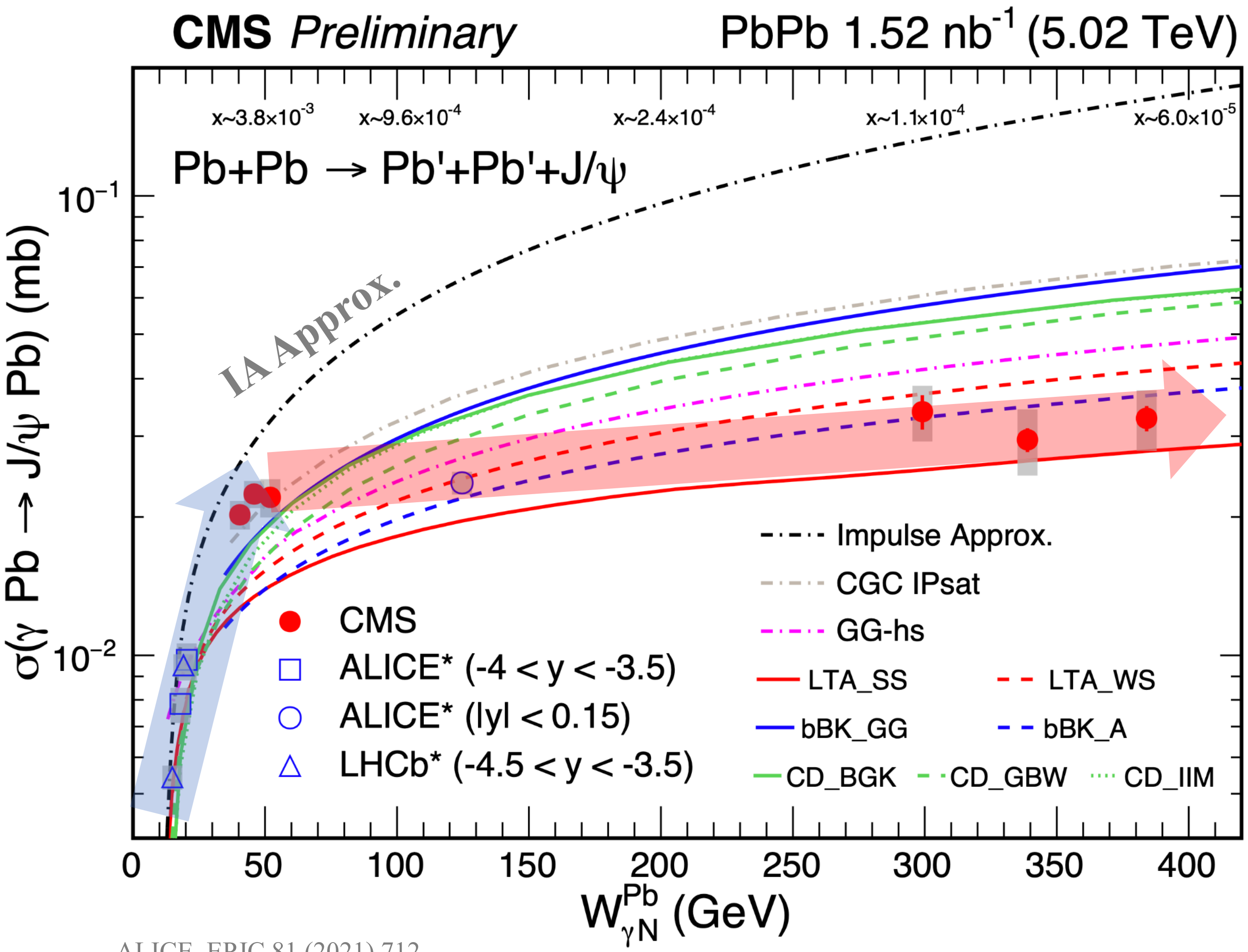
- ➢ some models capture the trend?

First direct measurement w/ **CMS**

- W < 40GeV: rapidly increasing
- 40 < W < 400GeV: nearly saturated

All models (shadowing, gluon saturation, etc.) fail to describe the surprising trend in data.

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



ALICE, EPJC 81 (2021) 712
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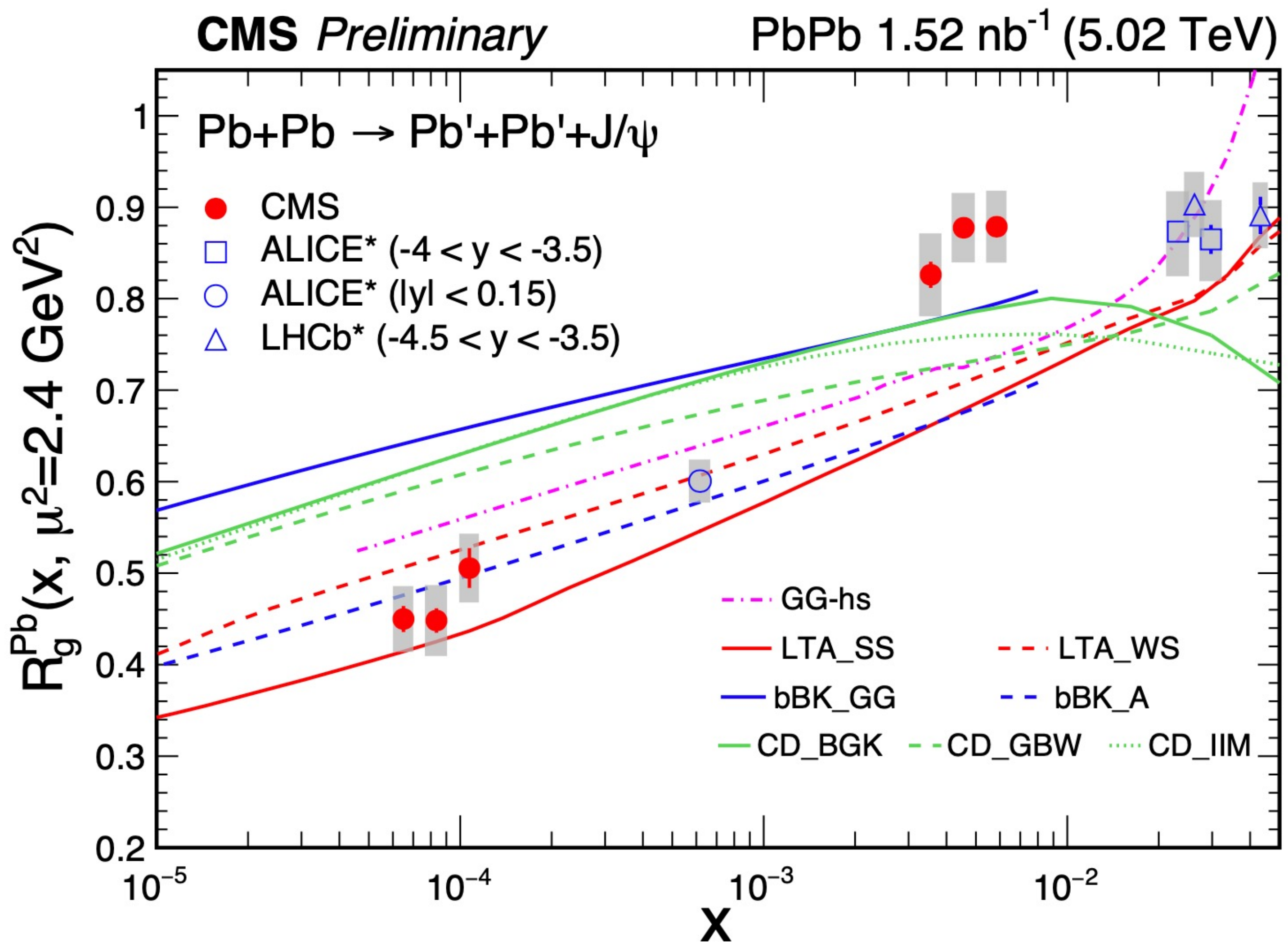
Nuclear Suppression Factor



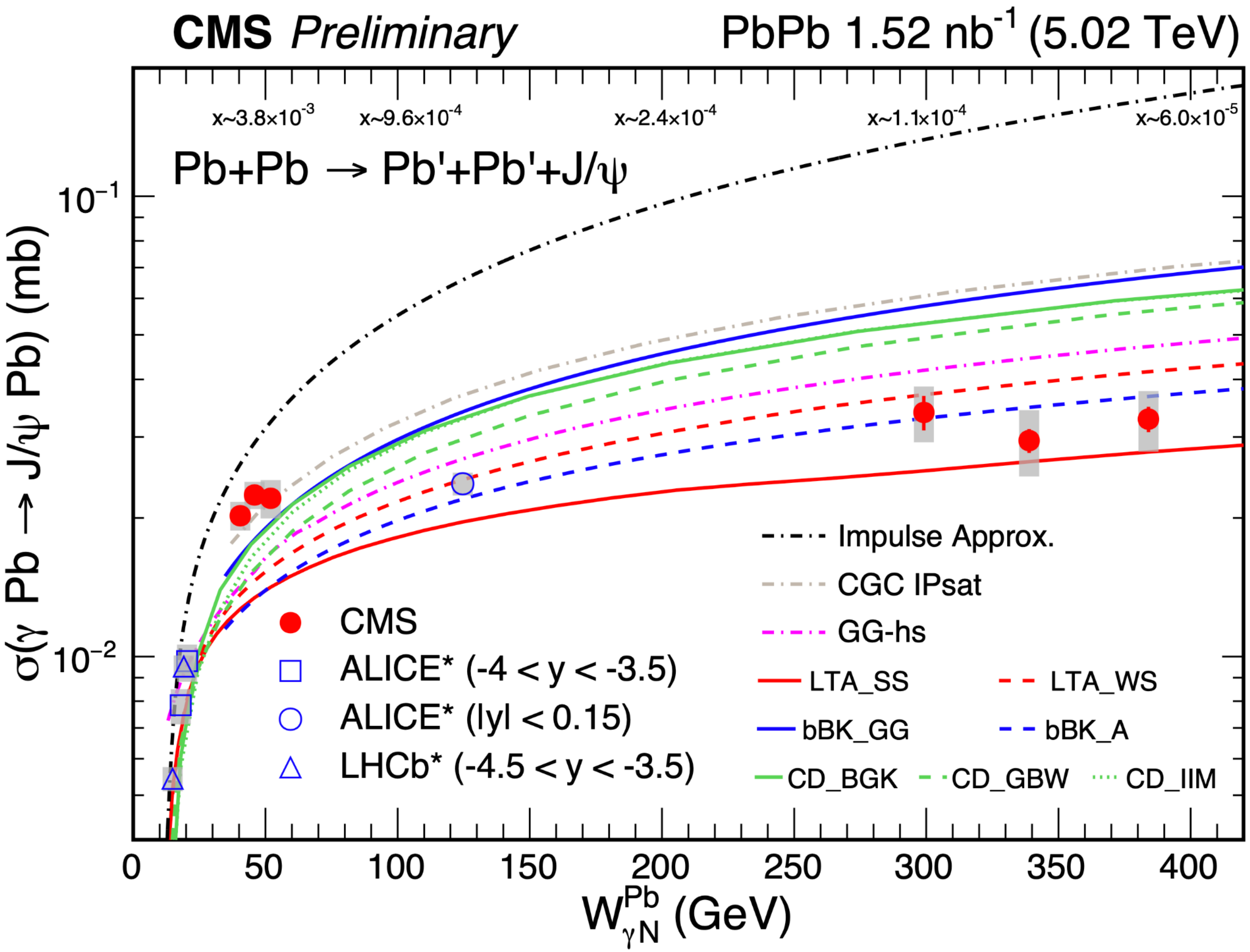
$$R_g^A = \frac{g_A(x,Q^2)}{A \cdot g_p(x,Q^2)} = \left(\frac{\sigma^{exp}_{\gamma A \to J/\psi A}}{\sigma^{IA}_{\gamma A \to J/\psi A}}\right)^{1/2}$$

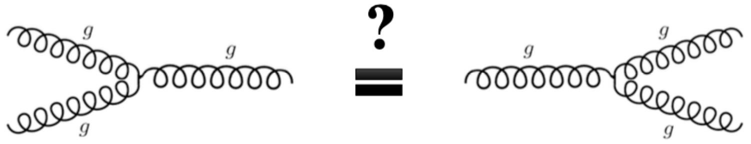
– nuclear gluon suppression factor at L.O. approx.

- A flat trend at x ~ $10^{-2} - 10^{-3}$
- Rapidly decrease towards very small x (~5x10^{-5}) region.

→ **Not described by any model**

What’s The Physics Behind?

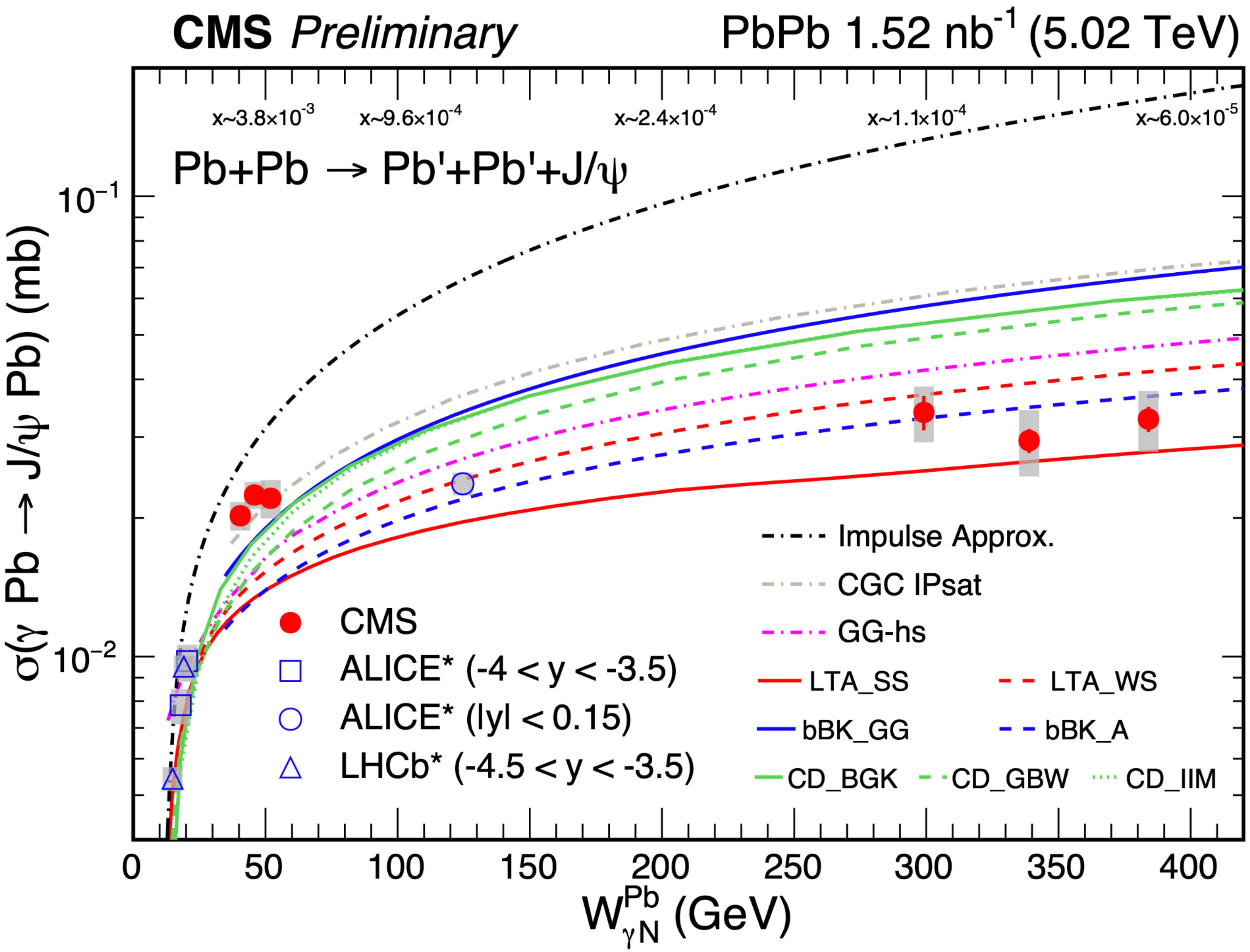


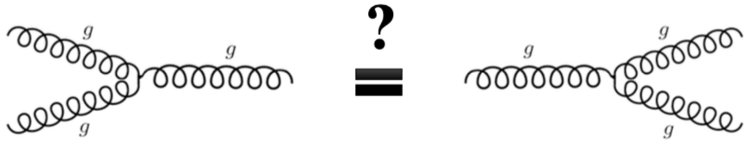


Gluon splitting vs. recombination becomes equal?

➢ **Direct evidence for gluon saturation!!?**

What's The Physics Behind?





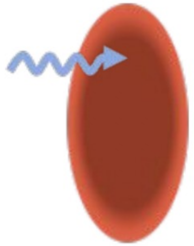
Gluon splitting vs. recombination becomes equal?

➤ **Direct evidence for gluon saturation!!?**

OR

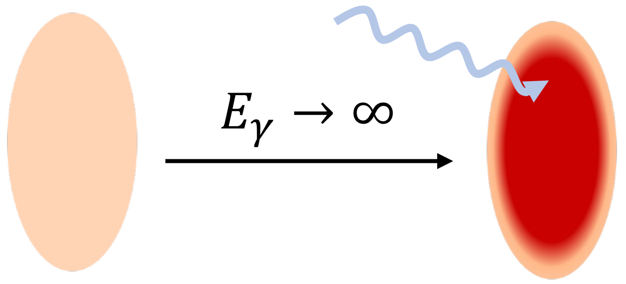
Cross section itself saturated instead of gluon density in the target

➤ **"Black Disk Limit"**



A Novel Regime Of QCD: Black Disk Limit

In strong absorption limits, the interaction probability may approach the unitarity.



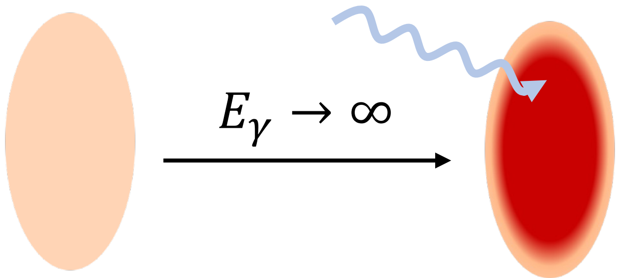
$$\hat{\sigma}^{\text{inel}}_{\text{PQCD}} \leq \hat{\sigma}_{\text{black}} = \pi R^2_{\text{target}}$$

– "Black Disk Limit (BDL)"

A Novel Regime Of QCD: Black Disk Limit

In strong absorption limits, the interaction probability may approach the unitarity.

totally absorptive



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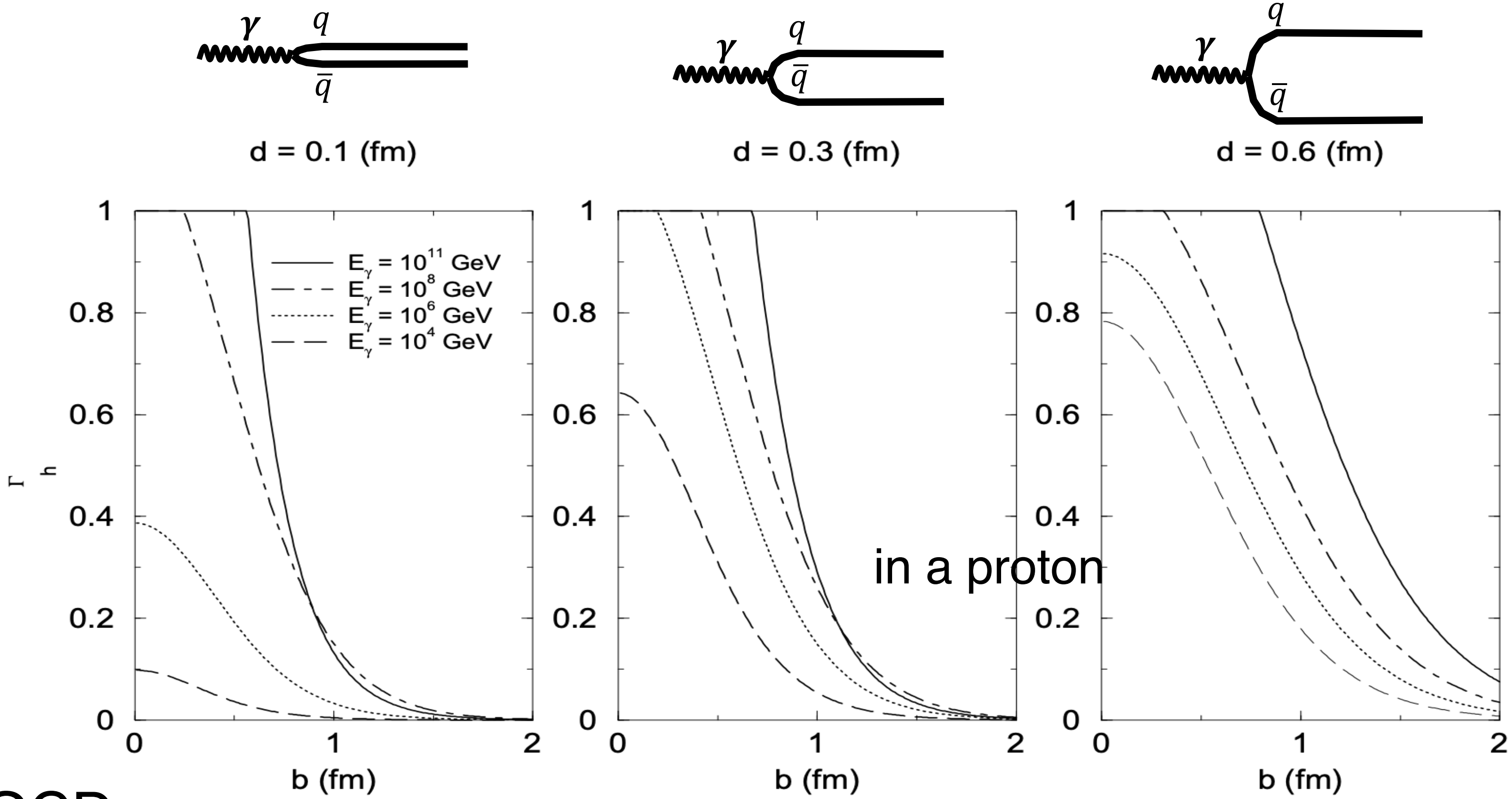
– **"Black Disk Limit (BDL)"**



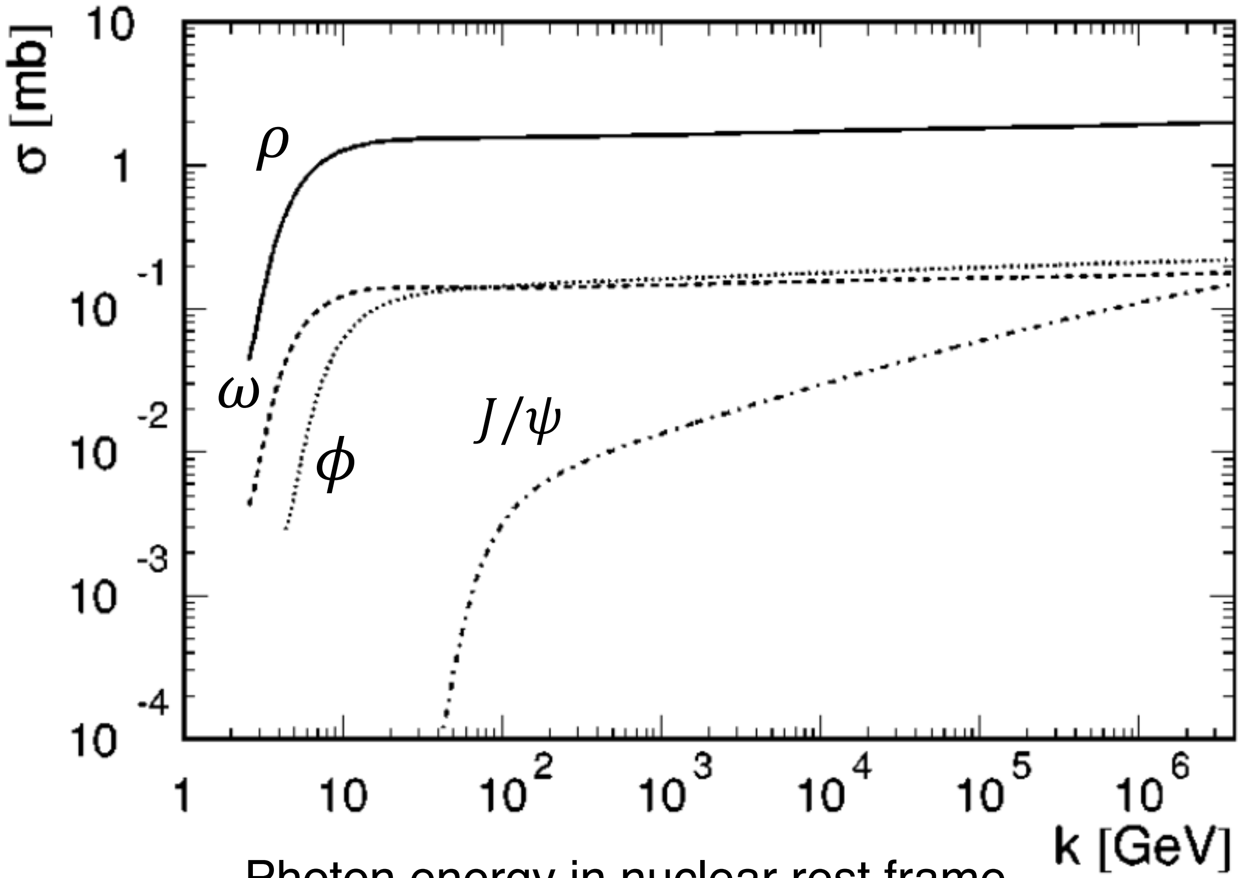
in a proton

"BDL": a novel regime of QCD
where new theoretical tools are needed

T.C. Rogers M.I. Strikman, arXiv:hep-ph/0512311
Physics Reports 512 (2012) 255

A Novel Regime Of QCD: Black Disk Limit

S. Klein and J. Nystrand , PRC 60, (1999) 014903



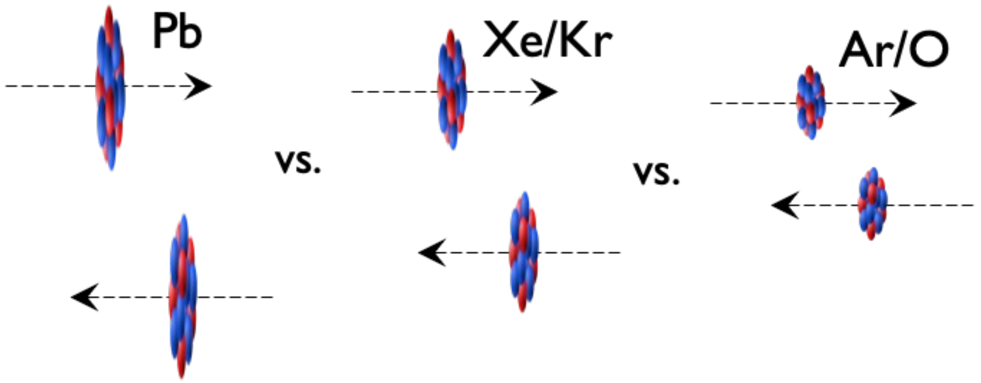
Photon energy in nuclear rest frame

Dipole size: $\boldsymbol{d \sim \frac{1}{m_{\mathrm{VM}}}}$ **(?)**

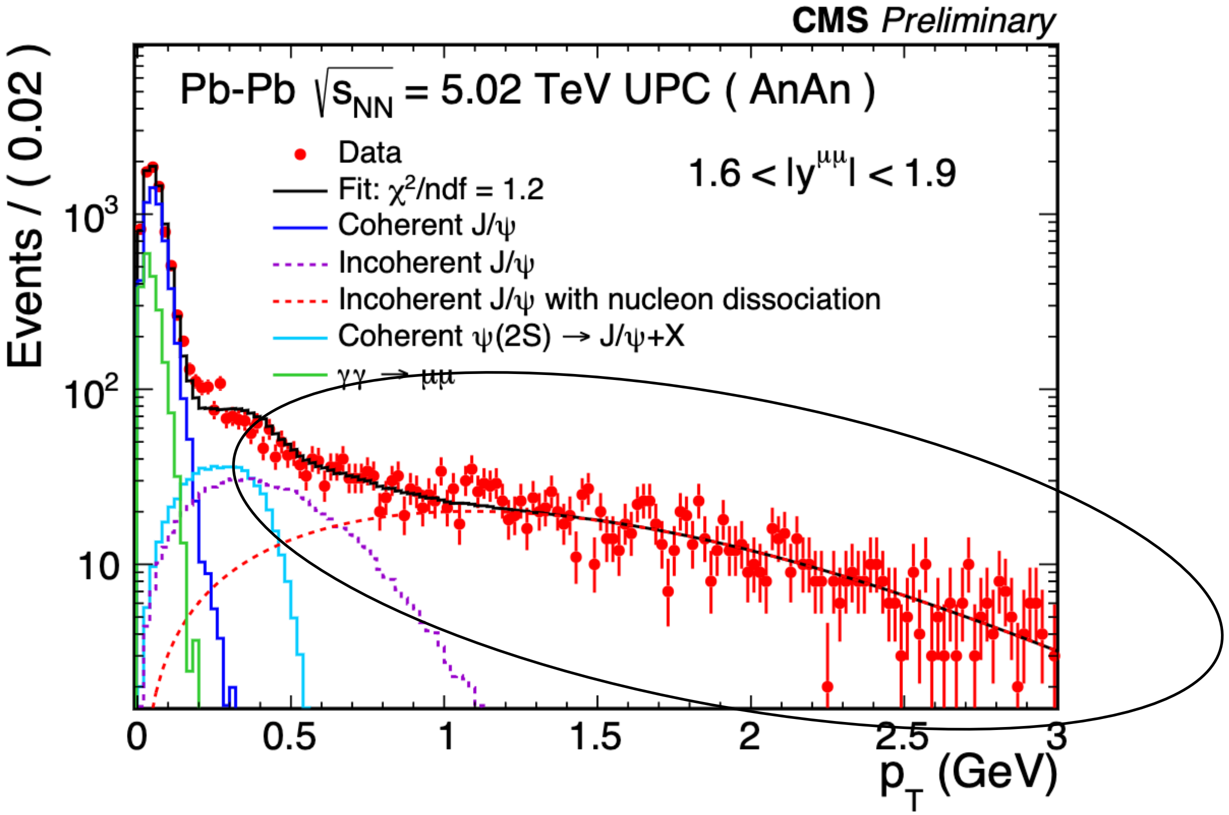
Various VM species in γPb as a function of *W* with neutron tagging will provide a complete picture

A Novel Regime Of QCD: Black Disk Limit

Coherent cross section should scale with $A^{2/3}$



Incoherent cross section strongly suppressed as internal substructure becomes invisible

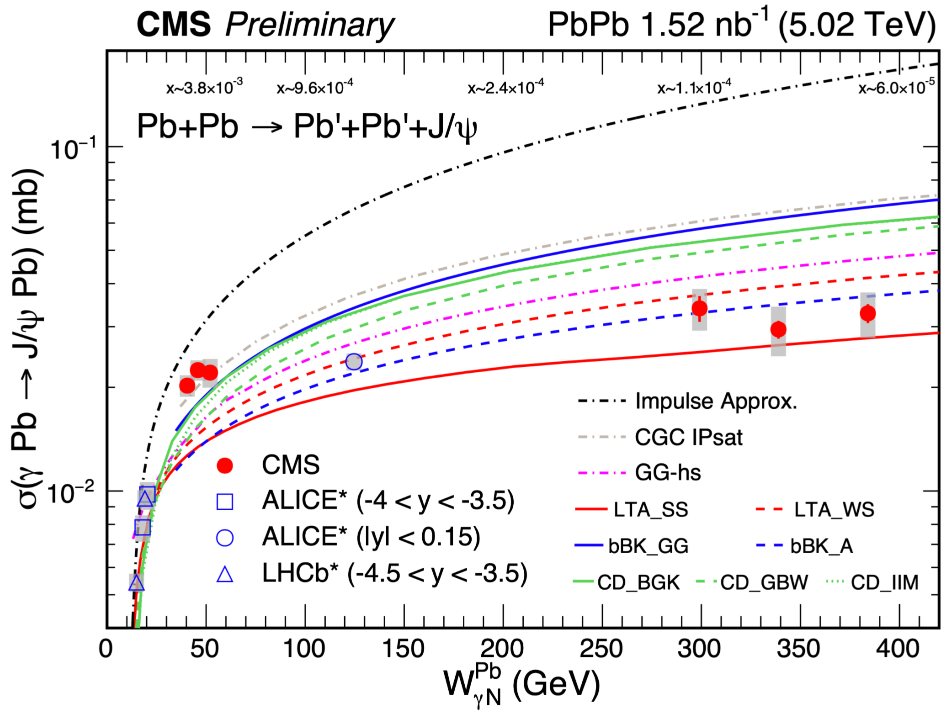


Exciting future LHC program with upgraded detectors and more ion species

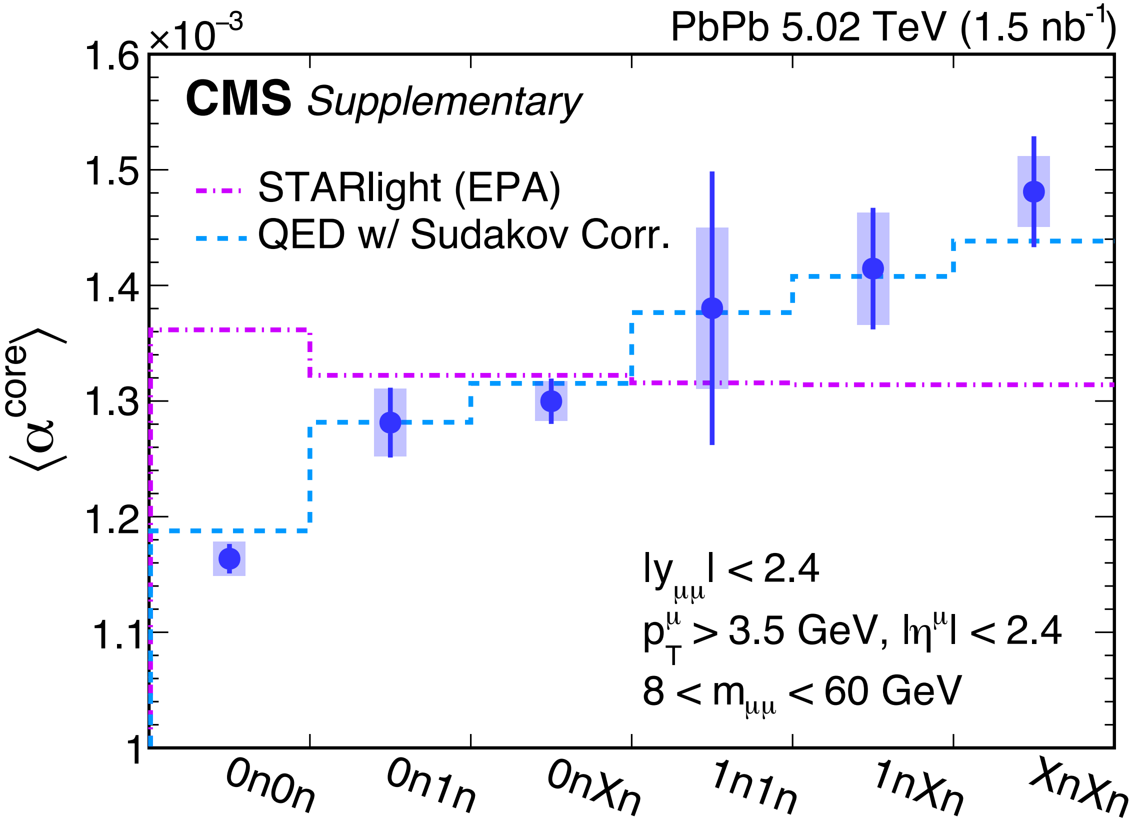
Summary

- 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
  - **Direct evidence for gluon saturation**? or **black disk limit**? Or sth. else?

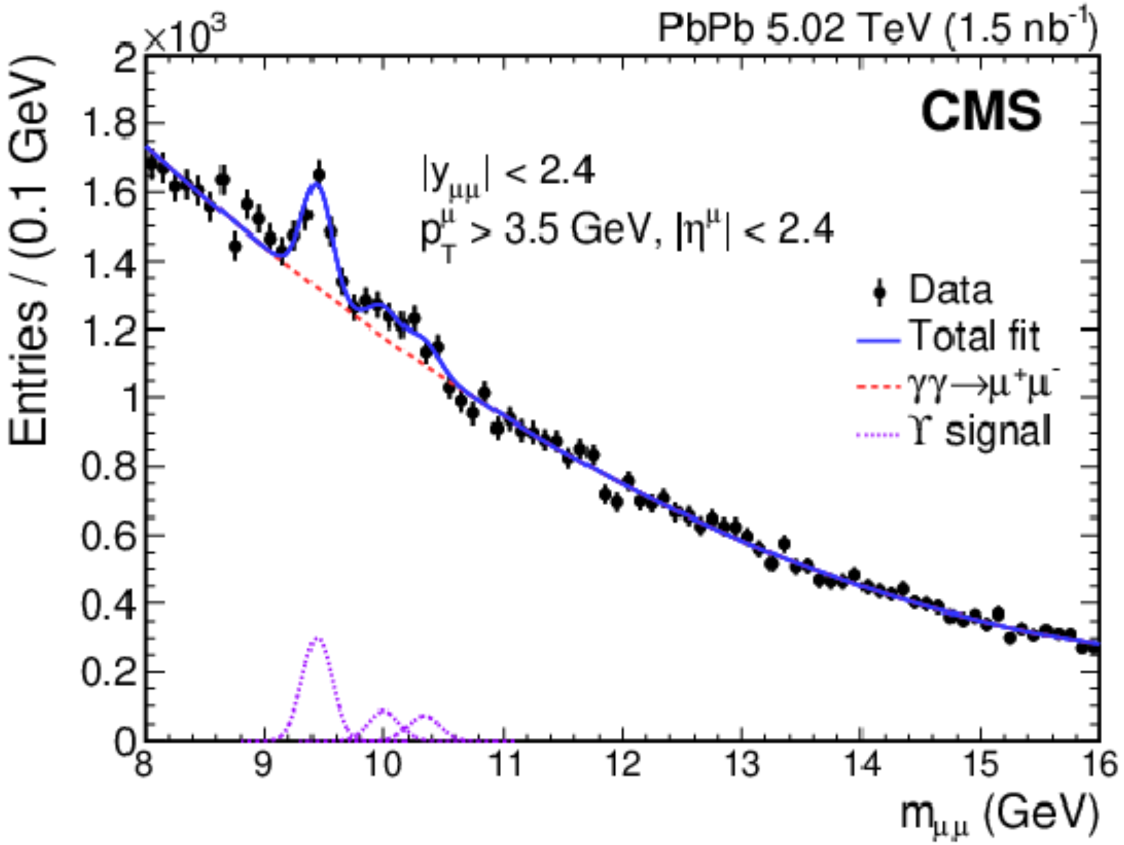
New insights to ultra-dense gluonic initial states!



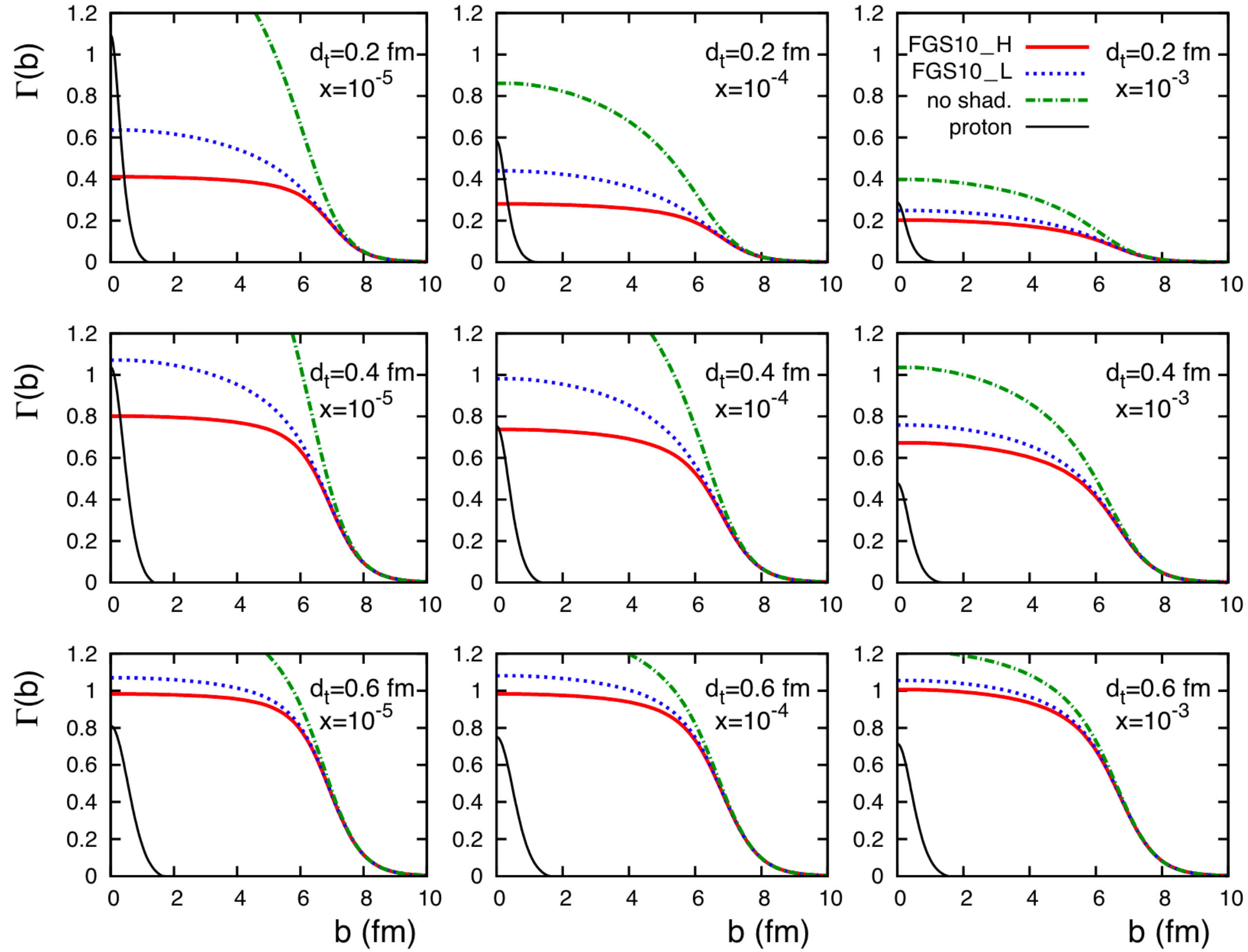
EXTRA



PbPb 5.02 TeV (1.5 nb-1)
CMS Supplementary
STARlight (EPA)
QED w/ Sudakov Corr.
⟨α core⟩
|yμμ| < 2.4
pTμ > 3.5 GeV, |ημ| < 2.4
8 < mμμ < 60 GeV
0n0n
0n1n
0nXn
1n1n
1nXn
XnXn



PbPb 5.02 TeV (1.5 nb-1)
CMS
|yμμ| < 2.4
pTμ > 3.5 GeV, |ημ| < 2.4
Data
Total fit
γγ→μ+μ-
ϒ signal
Entries / (0.1 GeV)
mμμ (GeV)



Physics Reports 512 (2012) 255

Fig. 99. The impact factor $\Gamma_A(x, b, d_\perp)$ for ^{208}Pb at $Q^2 = 4$ GeV^2 as a function of the impact parameter b for different values of x and dipole sizes $d_\perp$. The solid (red) curves correspond to model FGS10_H; the dotted curves correspond to FGS10_L. For comparison, we also give the impulse approximation predictions for $\Gamma_A(x, b, d_\perp)$ by the dot-dashed curves and the free proton $\Gamma(x, b, d_\perp)$ by the thin solid (black) curves.

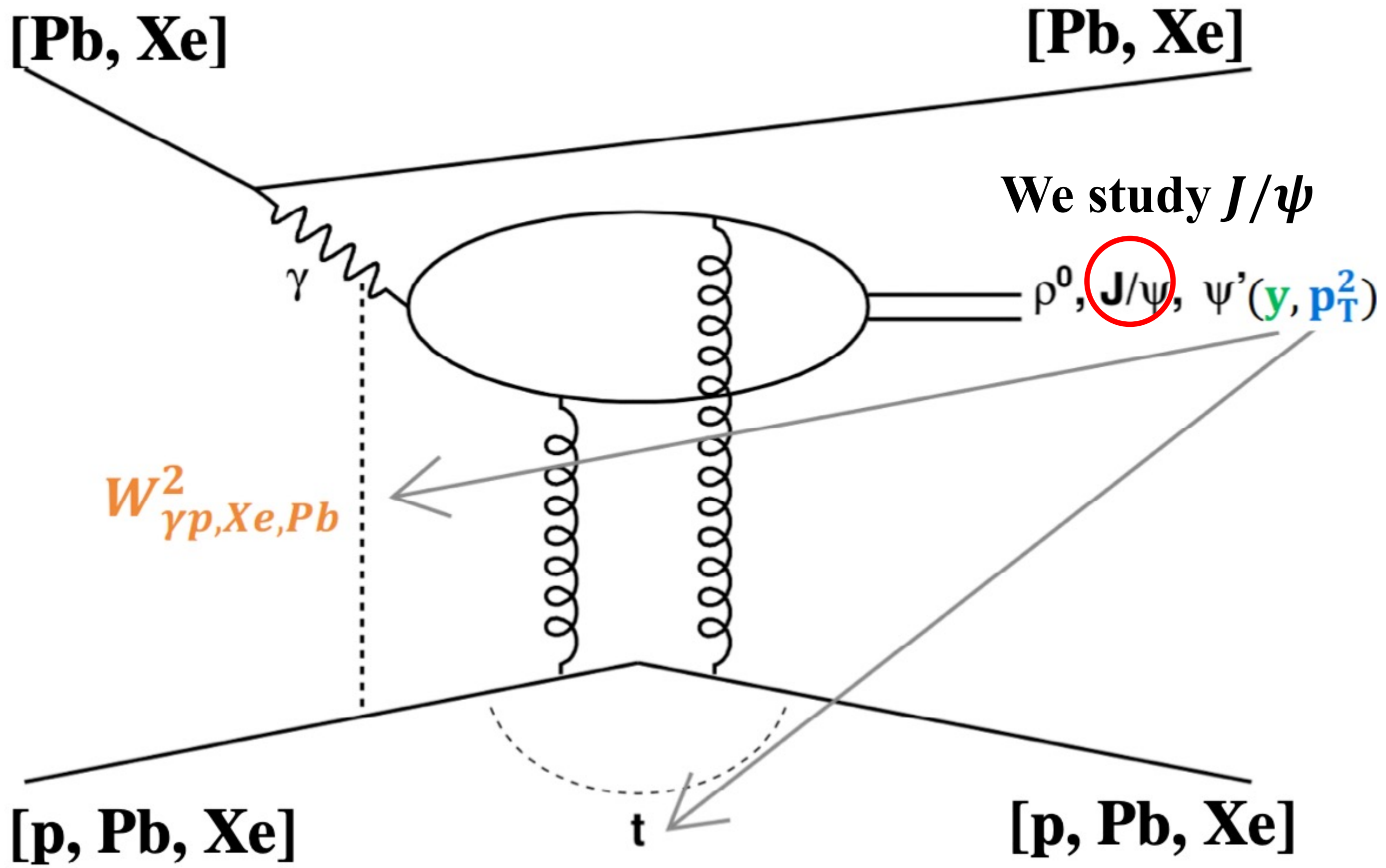
$$N(k) = \int d^2b N(k, b) P_{0\mathrm{had}}(b),$$

$$N(k) = \int d^2b N(k, b) P_{0\mathrm{had}}(b) P_1(b) P_2(b),$$

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

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

Coherent J/ψ yields

- Raw yields within the mass window

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

Feed down ratio

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

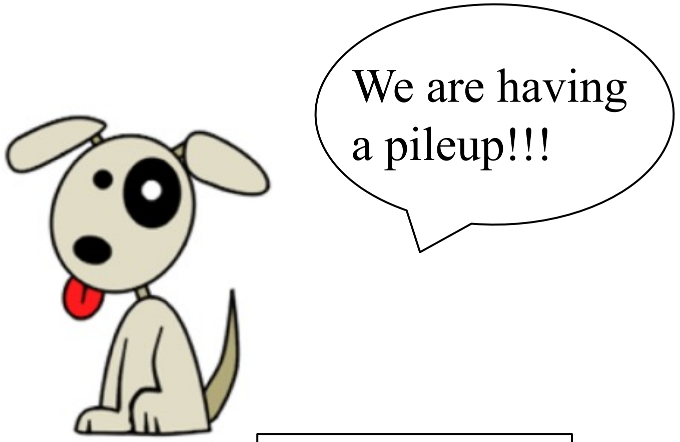
Incoherent fraction

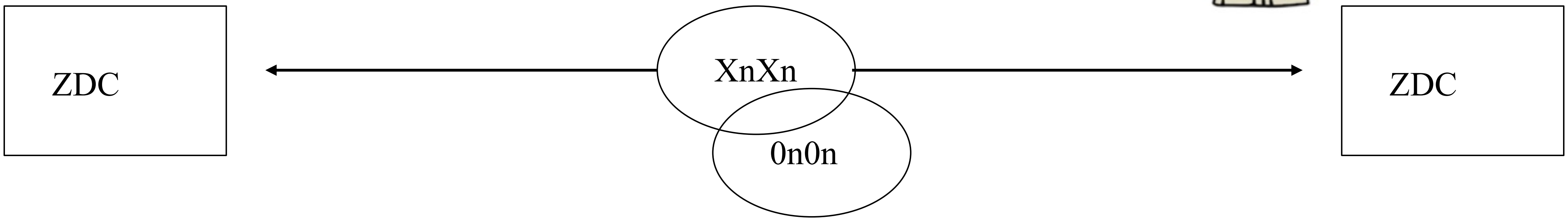
- $f_I = \frac{N(InCoh\ J/\psi)}{N(Coh\ J/\psi)}$

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

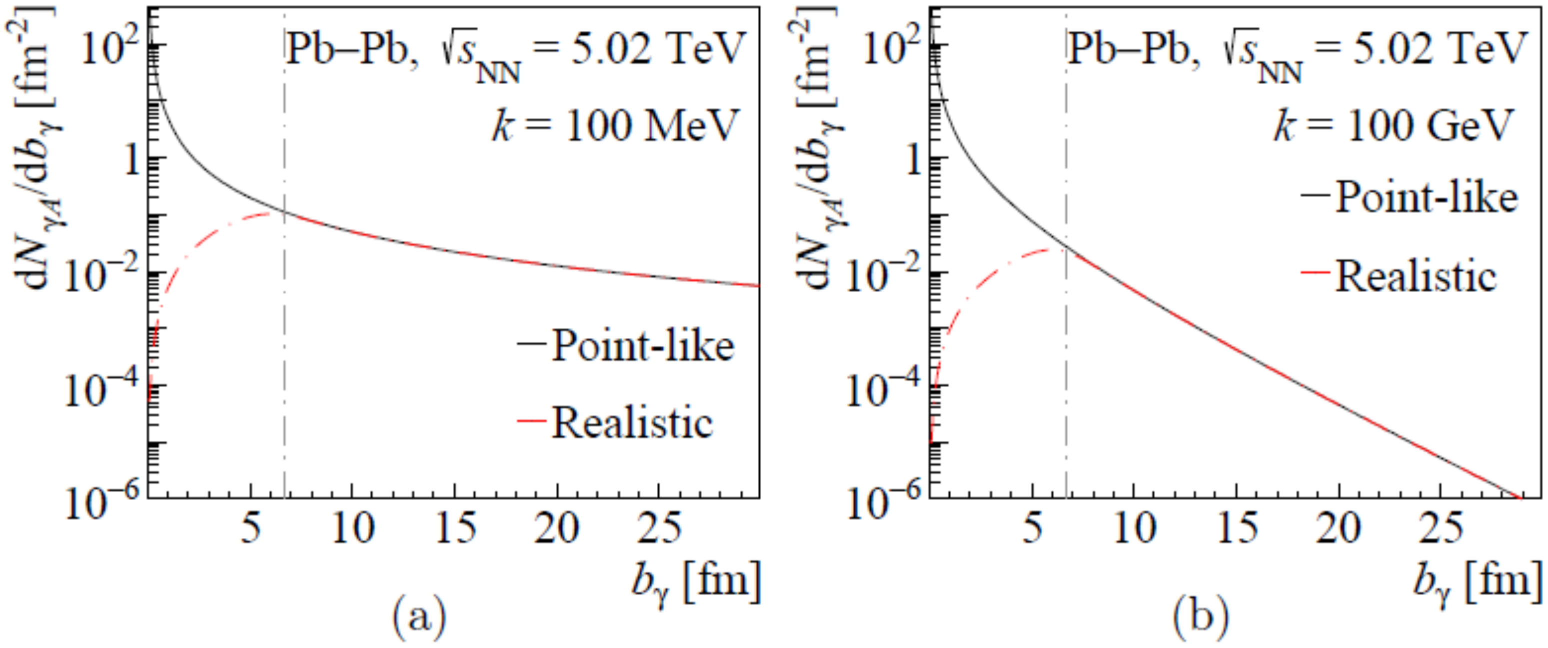
$$\begin{pmatrix} N^{00} \\ N^{0X} \\ N^{X0} \\ N^{XX} \end{pmatrix}^{\text{Obs}} = \begin{pmatrix} P^{00}_{00} & 0 & 0 & 0 \\ P^{0X}_{00} & P^{0X}_{0X} & 0 & 0 \\ P^{X0}_{00} & 0 & P^{X0}_{X0} & 0 \\ P^{XX}_{00} & P^{XX}_{0X} & P^{XX}_{X0} & P^{XX}_{XX} \end{pmatrix} \begin{pmatrix} N_{00} \\ N_{0X}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

- The matrix element can be obtained from ZB fraction
  - $P^{00}_{00} = f_{00}$
  - $P^{0X}_{00} = f_{0X}, P^{0X}_{0X} = f_{00} + f_{0X}$
  - $P^{X0}_{00} = f_{X0}, P^{X0}_{X0} = f_{00} + f_{X0}$
  - $P^{XX}_{00} = f_{XX}, P^{XX}_{0X} = f_{X0} + f_{XX}, P^{XX}_{X0} = f_{0X} + f_{XX}, P^{XX}_{XX} = f_{00} + f_{0X} + f_{X0} + f_{XX} = 1$

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.

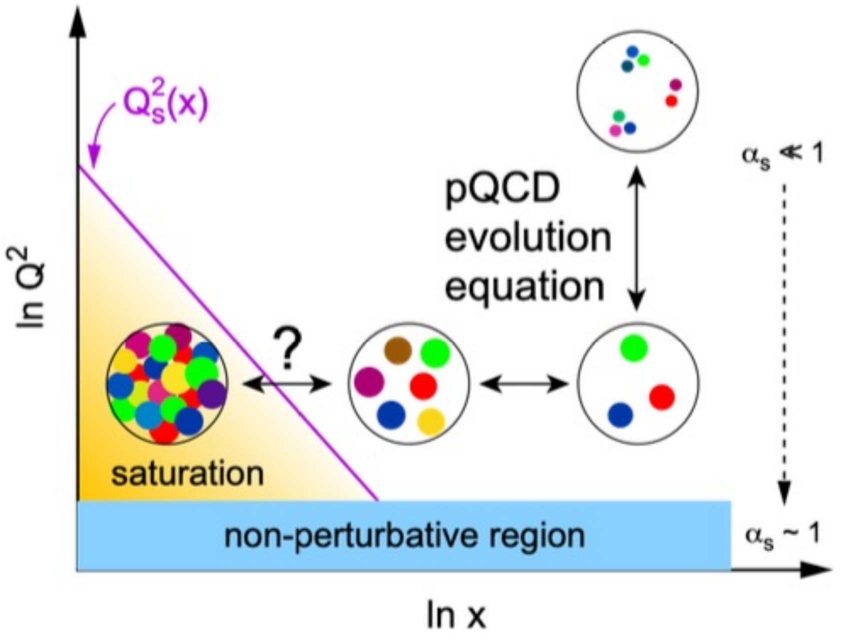
arXiv:2111.11383



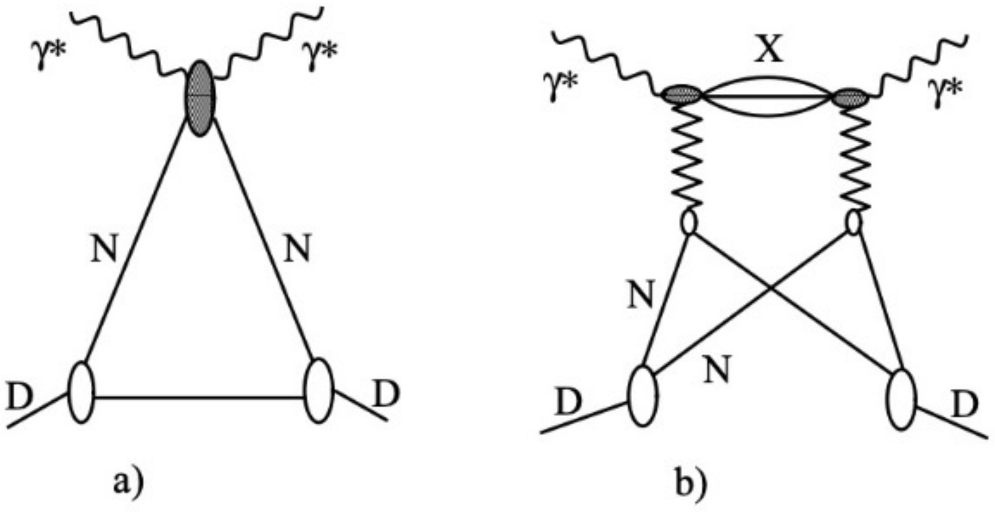
(Color online) Photon fluxes coming from a nucleus in the point-like source approximation and the realistic description as functions of impact parameter b calculated at different photon energies: 100 MeV (a), 100 GeV (b)

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

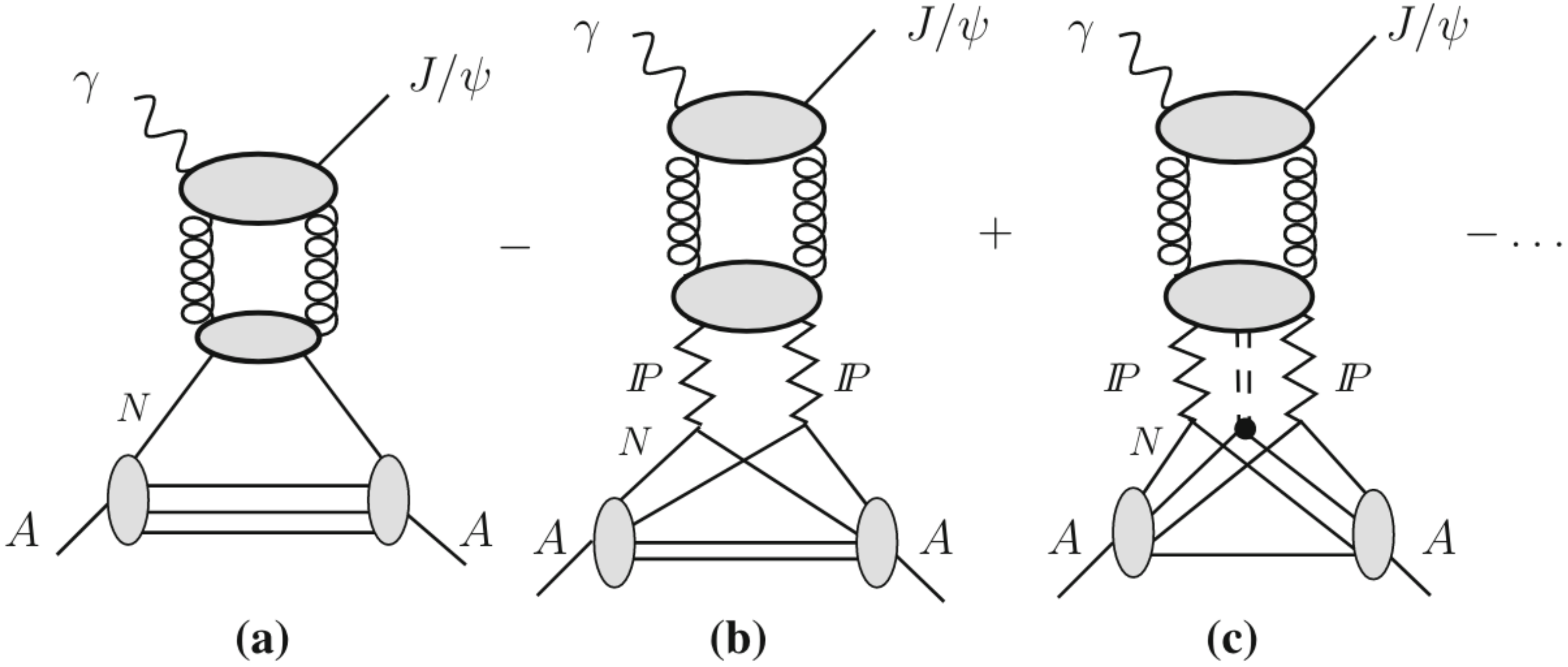


Gluon saturation



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

Nuclear shadowing

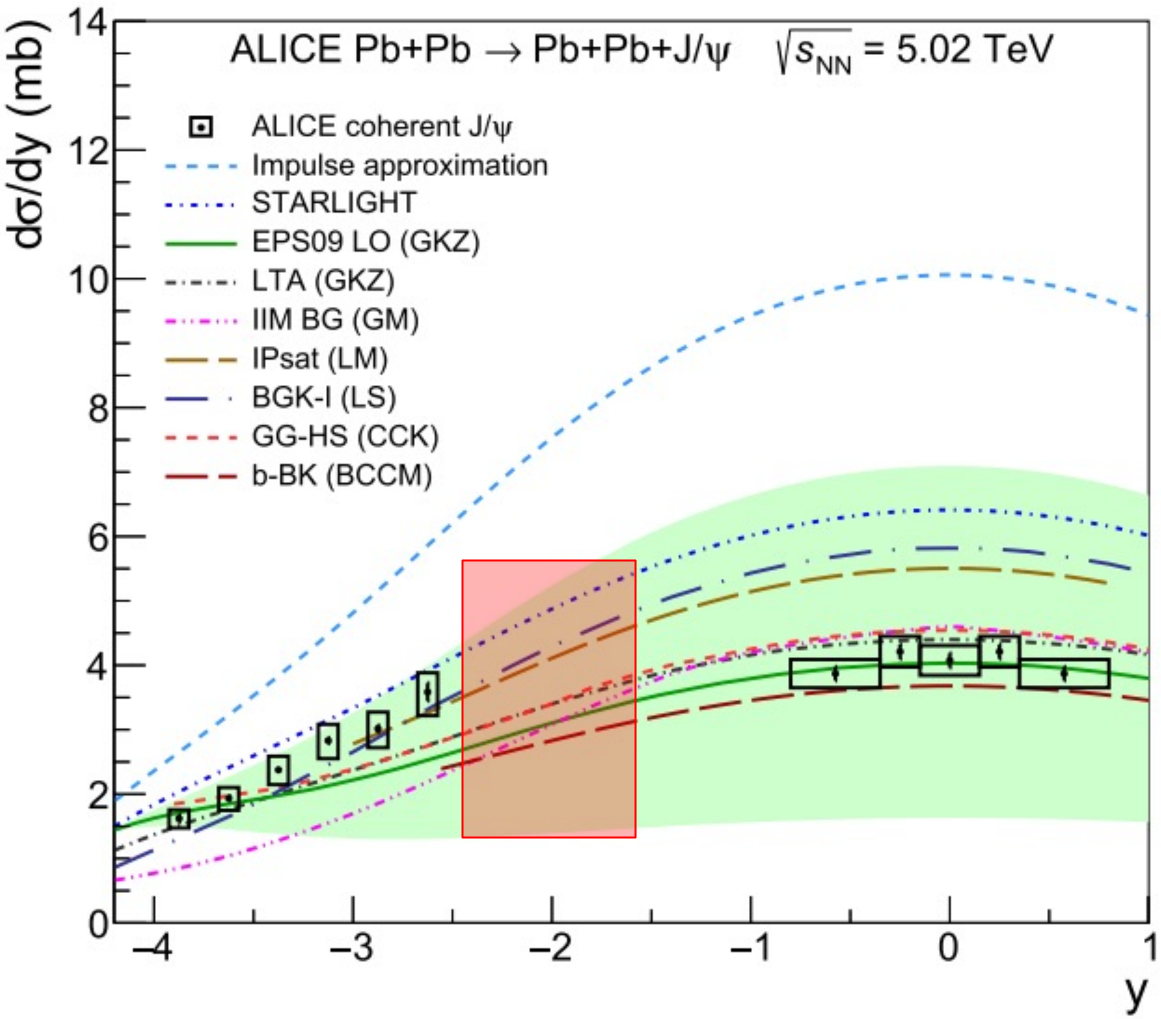

γ
J/ψ
N
A
A
−
ℙ
ℙ
+
− . . .
(a)
(b)
(c)

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
- STARLIGHT: Parameterization of HERA and fixed target data

$\frac{d\sigma_{PbPb \to PbPb' J/\psi}}{dy}$ models explained

- Impulse approximation: Exclusive photoproduction data off protons, neglecting all nuclear effects except coherence.
- STARlight: Vector Meson Dominance model with Glauber-like formalism to calculate cross section in Pb-Pb
- EPS09 LO parametrization of the nuclear shadowing data
- Leading twist approximation (LTA) of nuclear shadowing
- CCK: Color dipole model with the structure of the nucleon described by the hot spots
- BCCM: Color dipole approach coupled to the solutions of the Balitsky-Kovchegov equation
- GM, LM, LS: Color dipole approach coupled to the Color Glass Condensate formalism with different assumptions on the dipole-proton scattering amplitude



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