# Probing nuclear structure with ultraperipheral collisions

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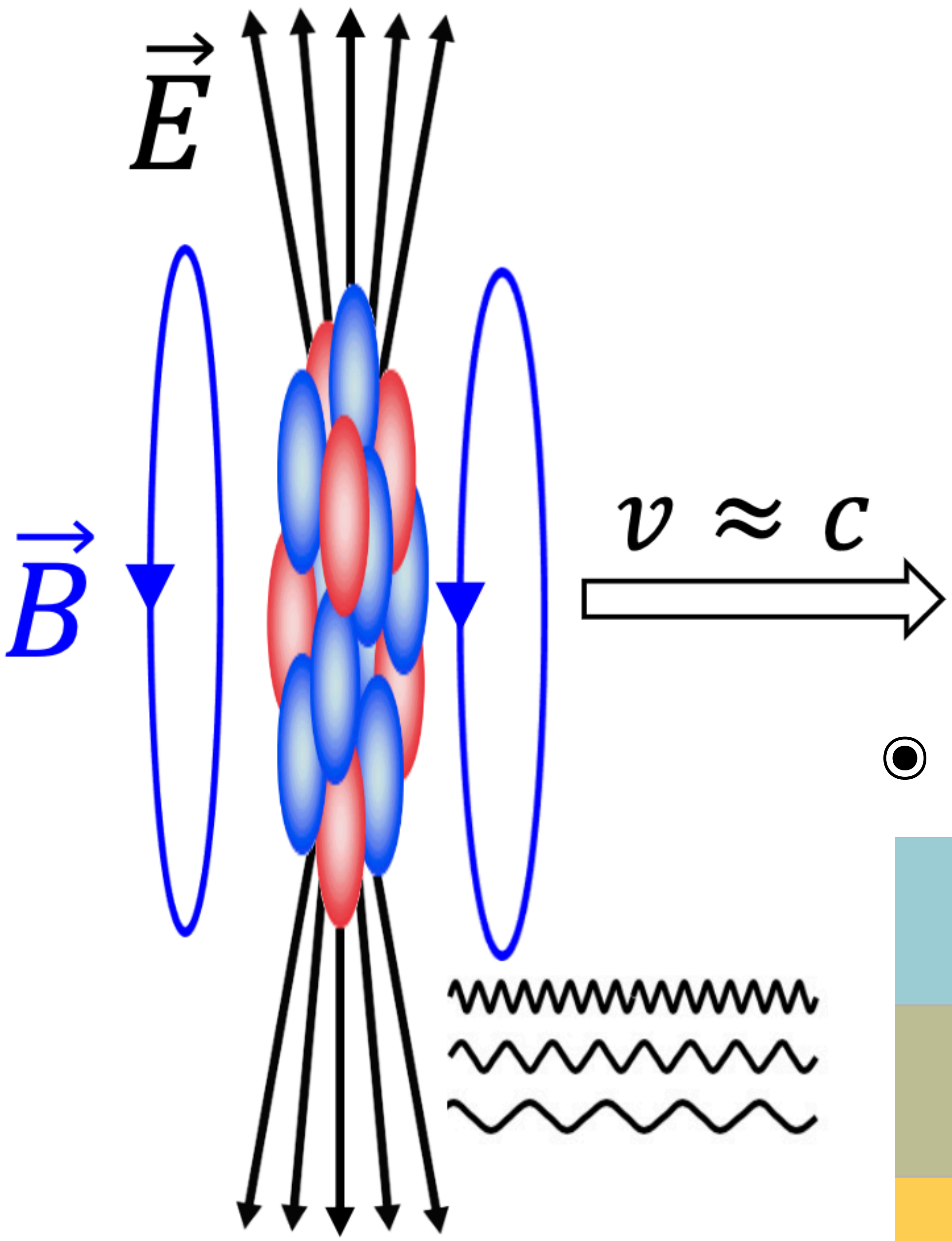
South China Normal University

Exploring nuclear physics across energy scales, Apr 20-24, 2024

# Equivalent photon



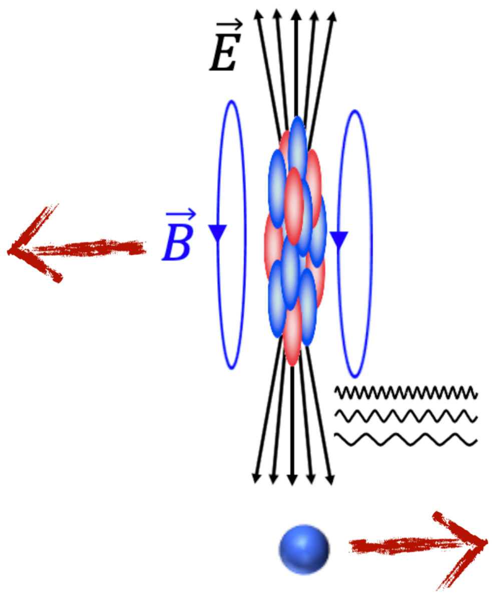

- **E**quivalent **P**hoton **A**pproximation
  - Photon Flux ∝ $Z^2$
  - $p_T$ < ~30 MeV ($Q^2$~0)

- Photon kinematics

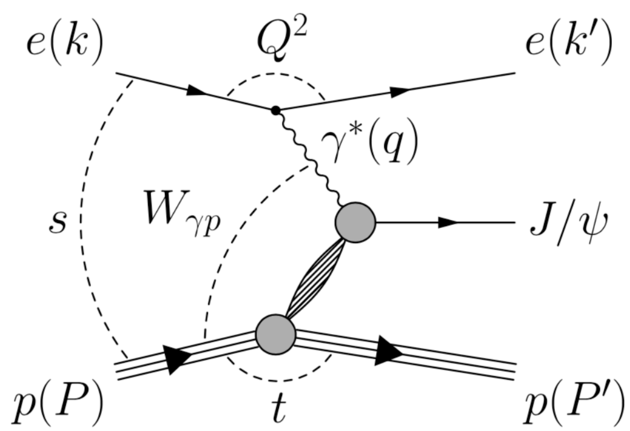
| | |
|---|---|
| maximum energy<br>**$E_{\gamma,max}$~γ(ℏc/R)** | **80 GeV in Pb+Pb@LHC<br>3 GeV in Au+Au@RHIC** |
| typical $p_T$ (& virtuality)<br>**$p_{Tmax}$ ~ ℏc/R** | **O(30) MeV @ RHIC & LHC** |
| Coherent strengths (rates) scale as **$Z^2$**: nuclei >> protons | Flux of photons on other nucleus ~ **$Z^2$**, flux of photons on photons ~ **$Z^4$ (45M!)** |

# Photon-nulcear interactions

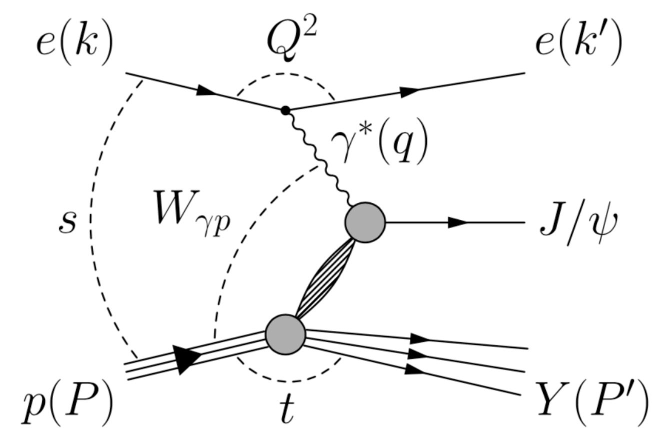
Little “HERA”




Elastic

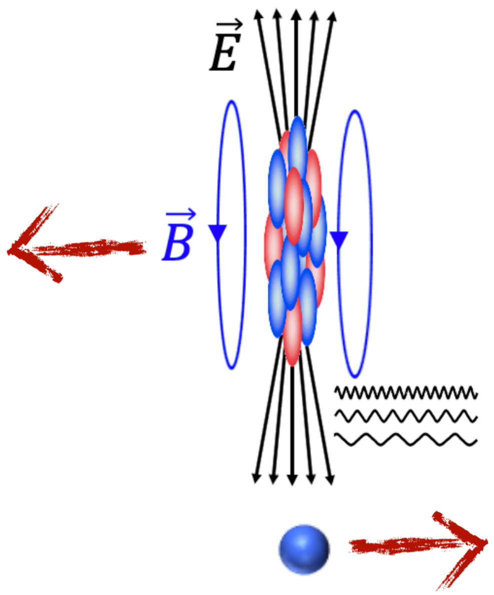


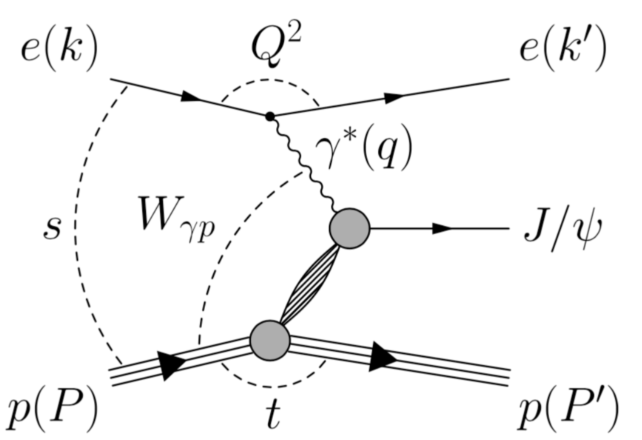

Inelastic

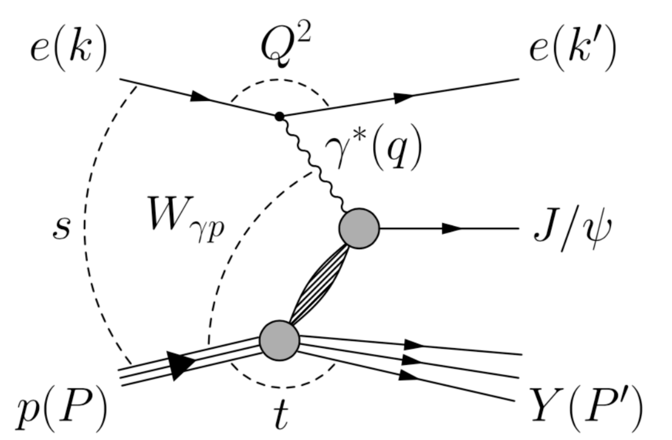


# Photon-nulcear interactions

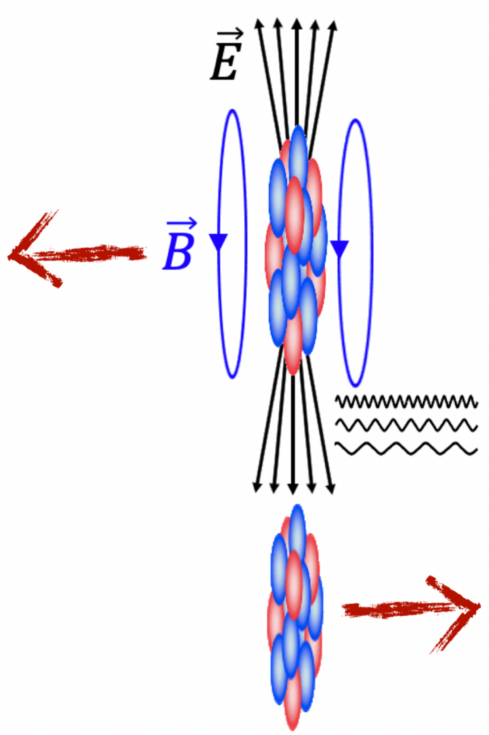
## Little "HERA"

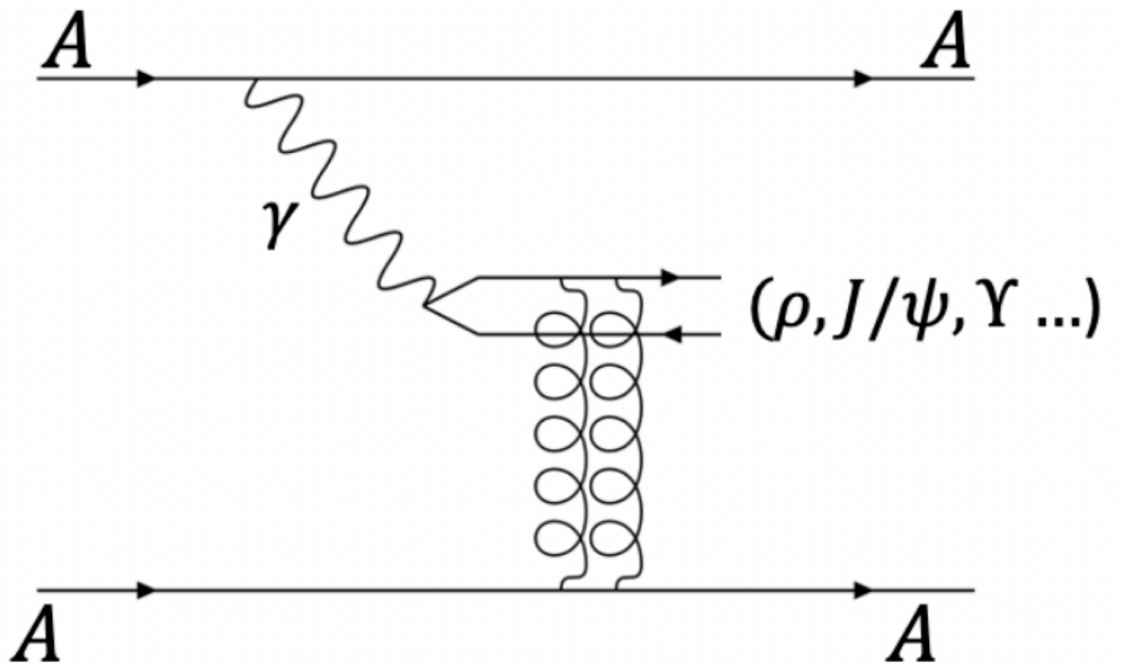


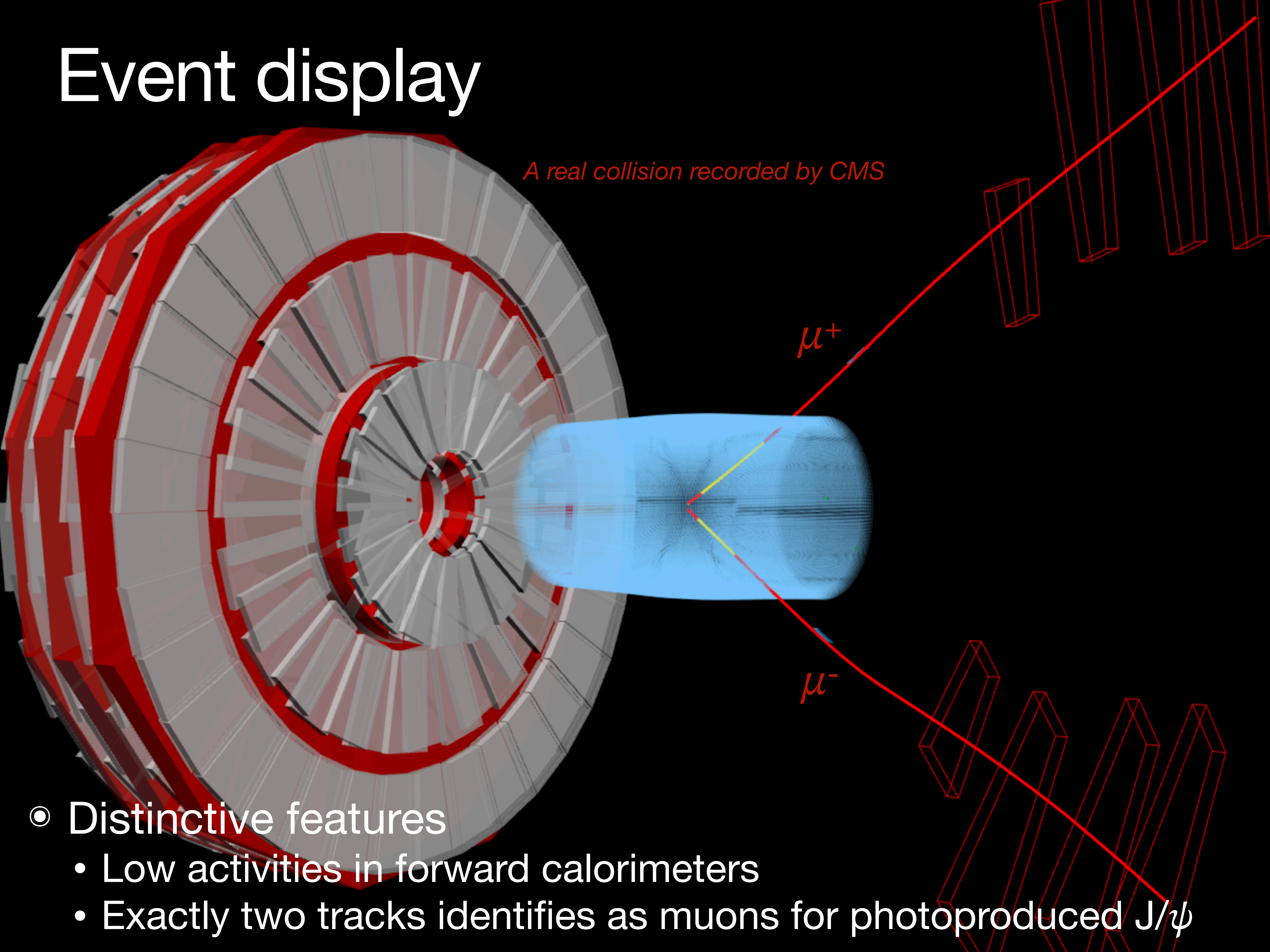




## Little "EIC"



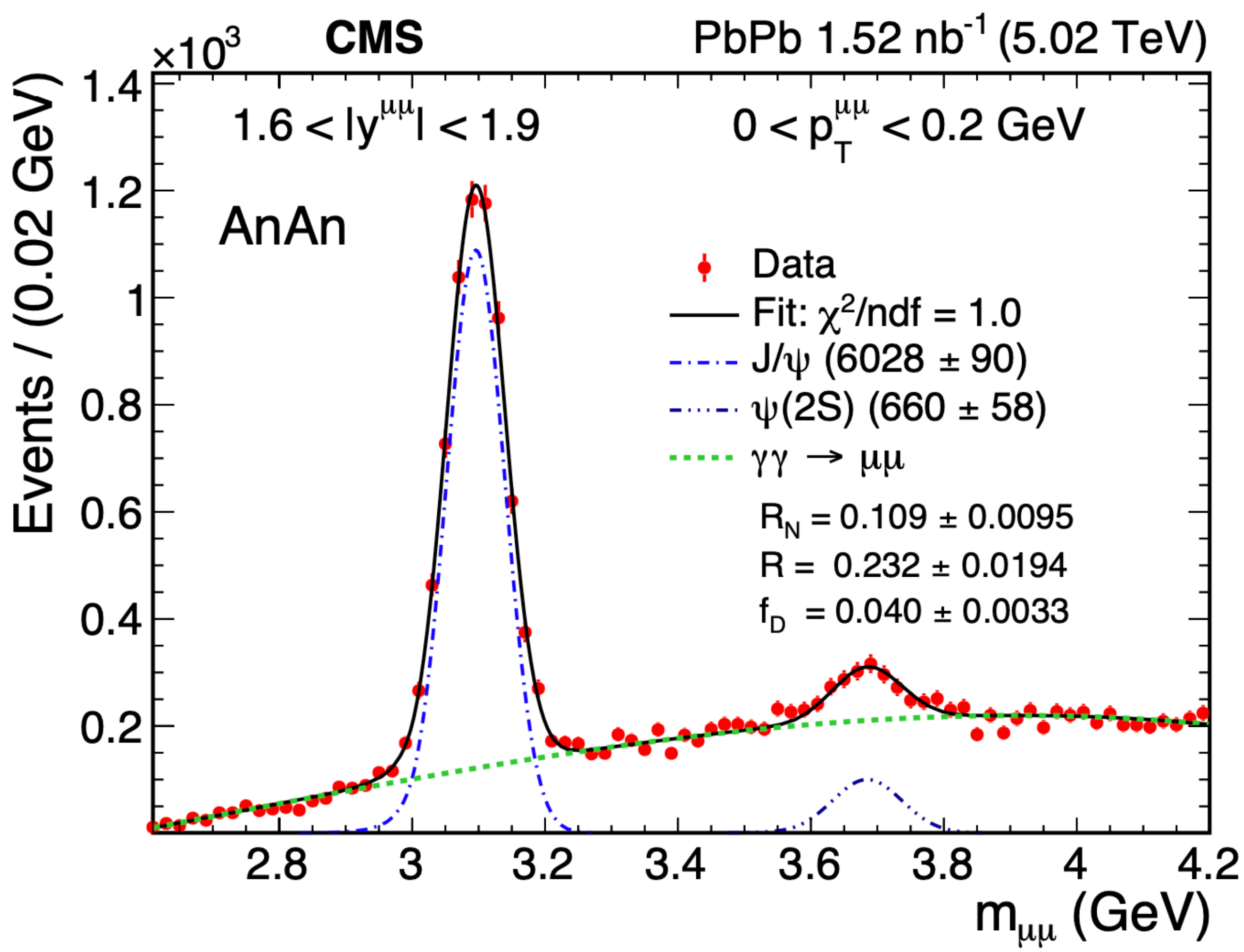
# Event display

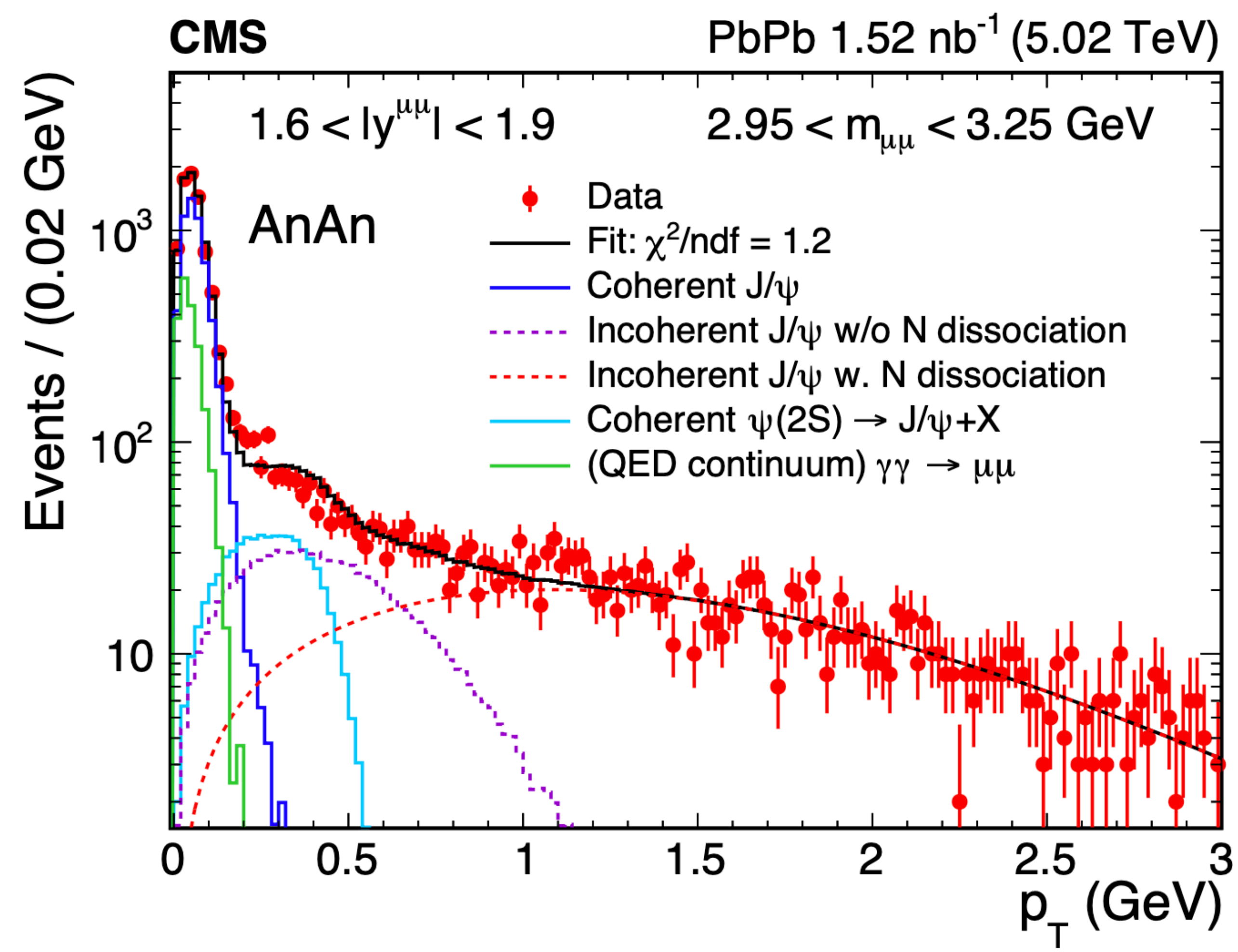



- Distinctive features
  - Low activities in forward calorimeters
  - Exactly two tracks identifies as muons for photoproduced J/$\psi$

# Event display

*A real collision recorded by CMS*

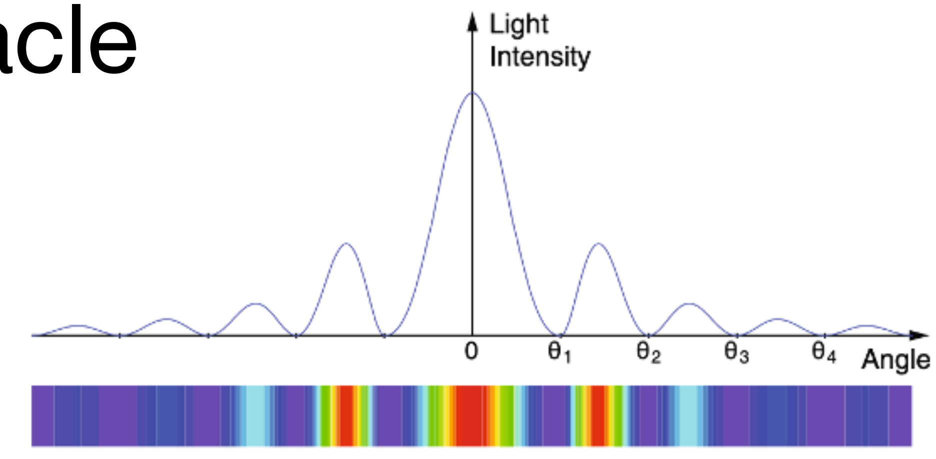


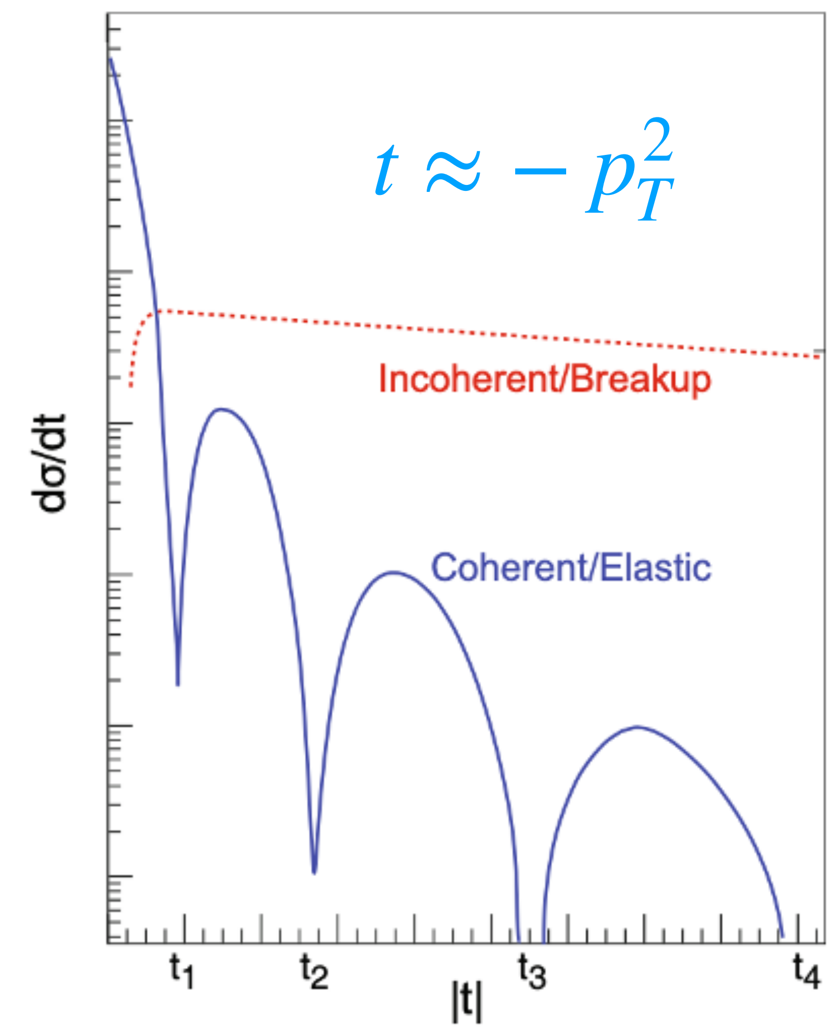

- Distinctive features
  - Low activities in forward calorimeters
  - Exactly two tracks identifies as muons for photoproduced J/$\psi$

# Imaging nucleus in spatial space

- Light diffractive on a circular obstacle
  - Small deflection angle $\theta_i$ ~ $1/(\boldsymbol{k}R)$



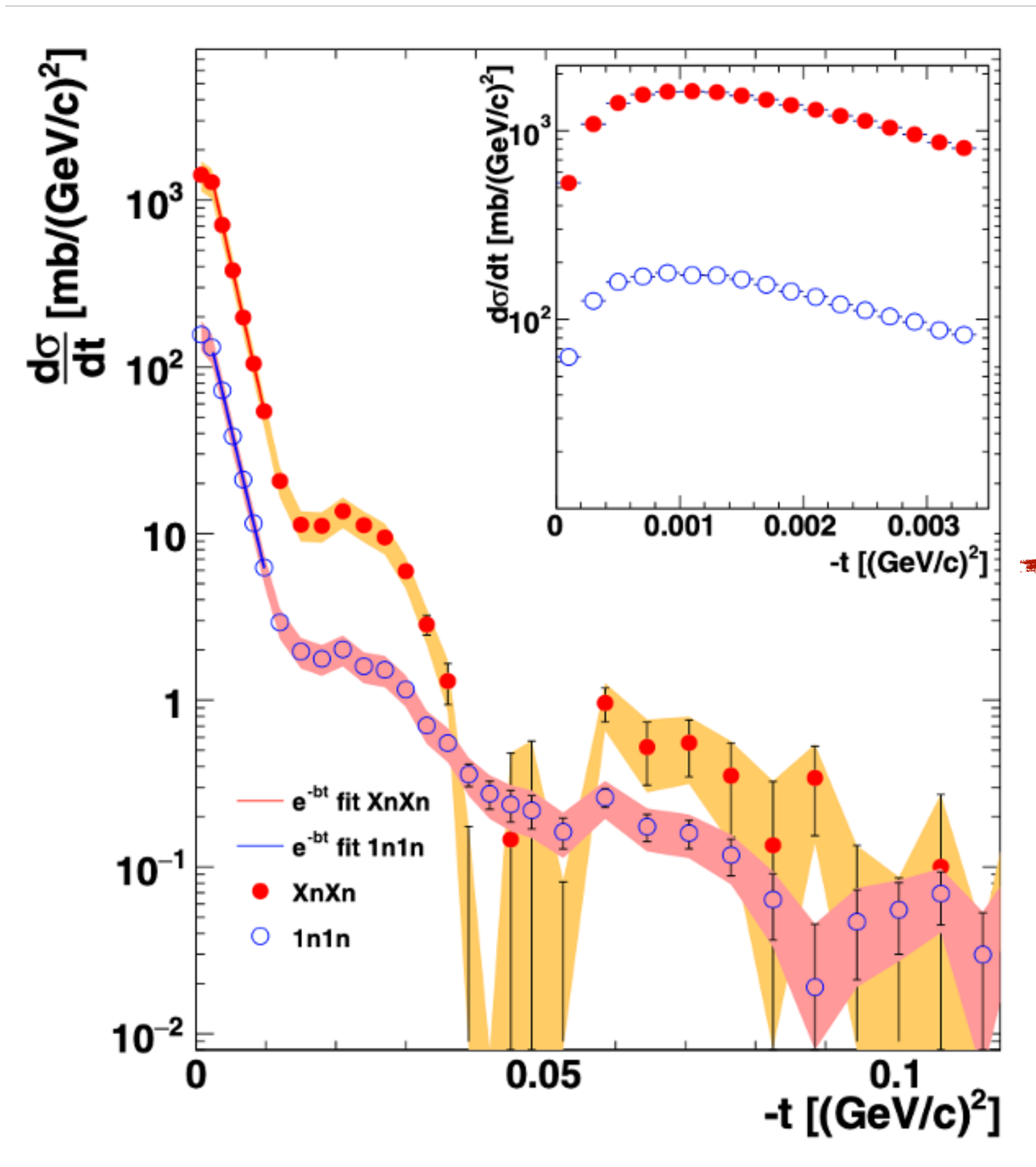

- The $t$ spectrum of coherent photo-produced vector meson
  - The diffractive minima are related to the size of nucleus
  - $|\boldsymbol{t}_i|$ ~ $1/R^2$




A. Accardi *et al.*, EPJA 52 (2016) 268

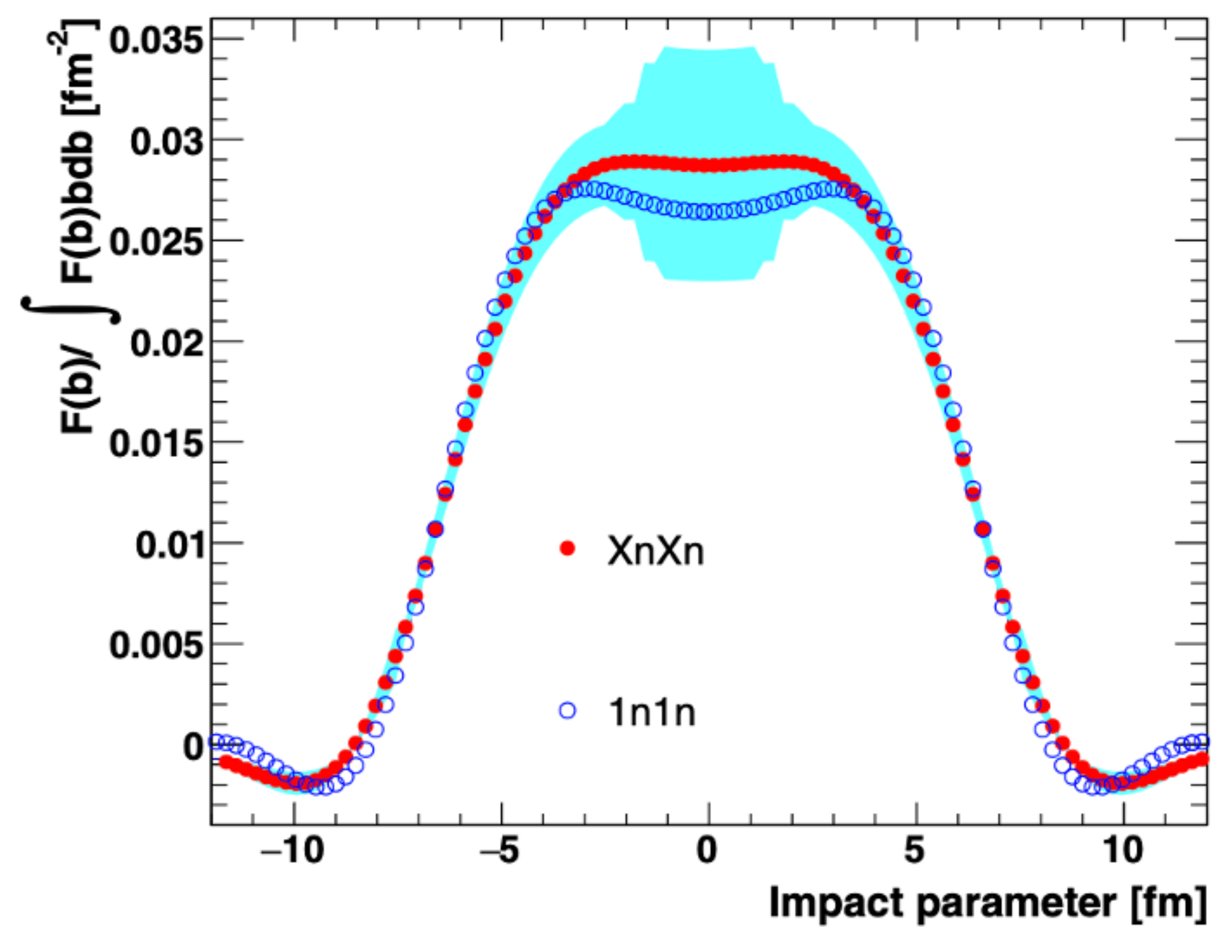
# Imaging nucleus in spatial space

- The $t$ spectrum of coherent photoproduced $\rho$ in ultra-peripheral Au+Au collisions at 200 GeV




STAR, PRC 96 (2017) 054904

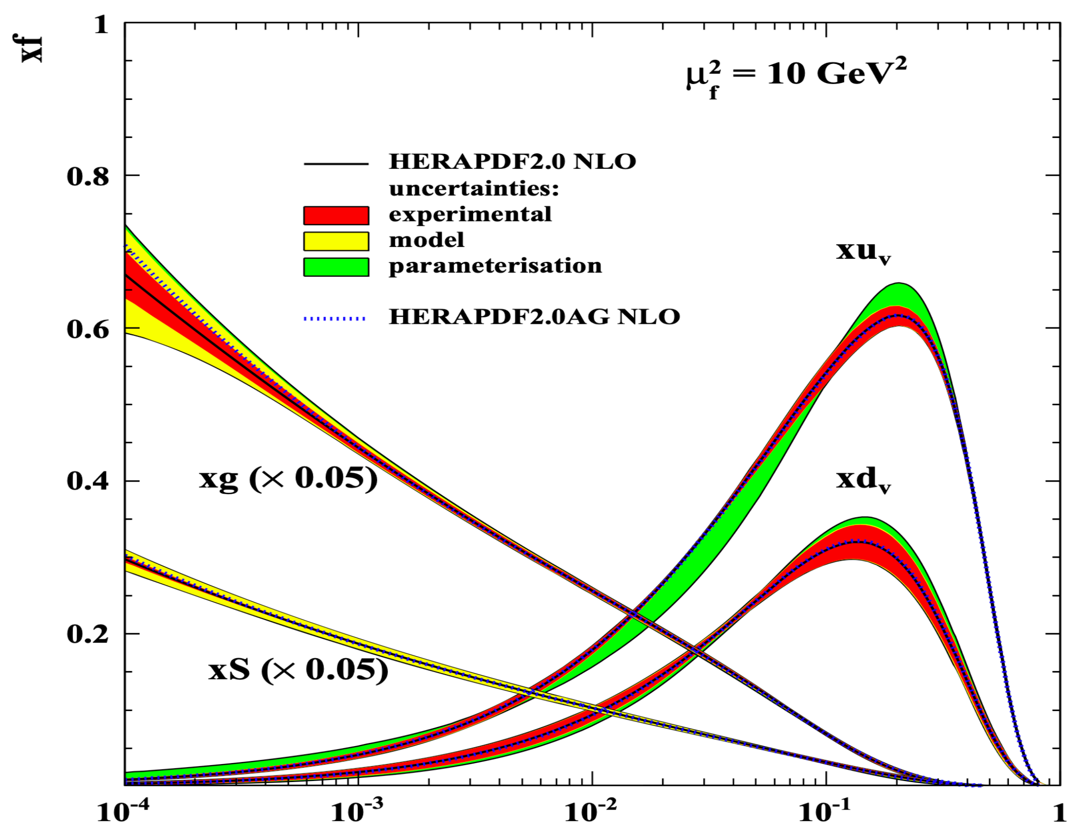
$$F(b) \propto \frac{1}{2\pi}\int_0^\infty dp_T\, p_T\, J_0(bp_T)\sqrt{\frac{d\sigma}{dt}}.$$




See detailed discussion in Zhangbu's seminar on April 25th

# Imaging nucleus in momentum space

H1 and ZEUS, EPJC 75 (2015) 580




Small $x$ ← Large $x$

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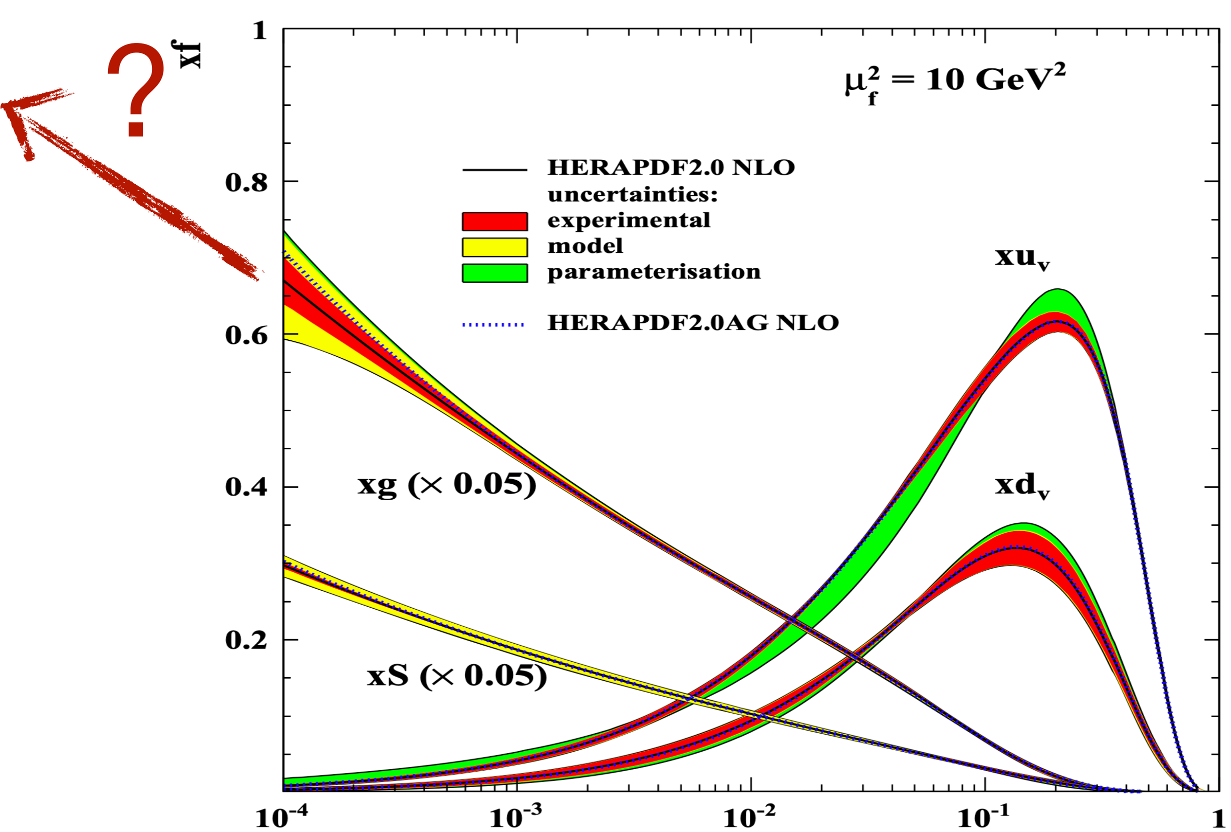
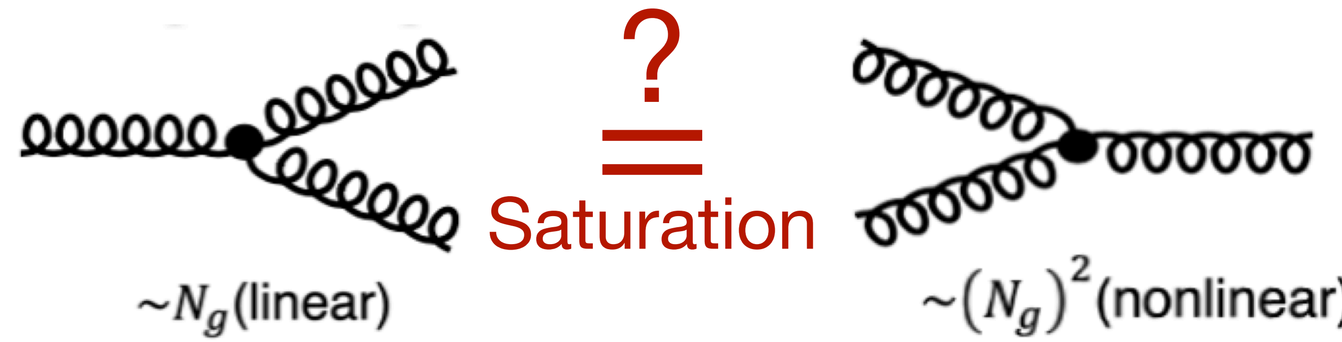
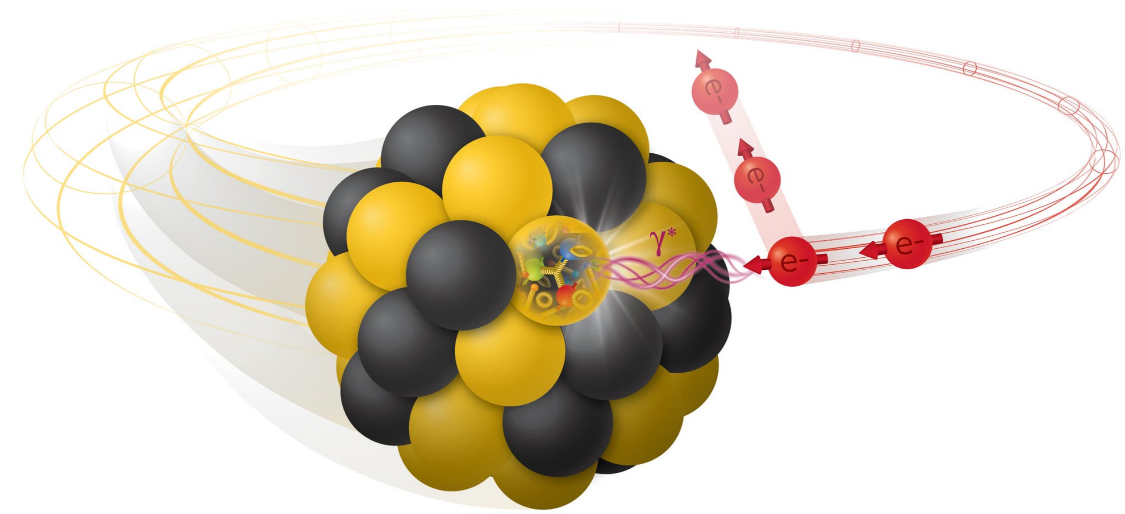
H1 and ZEUS, EPJC 75 (2015) 580



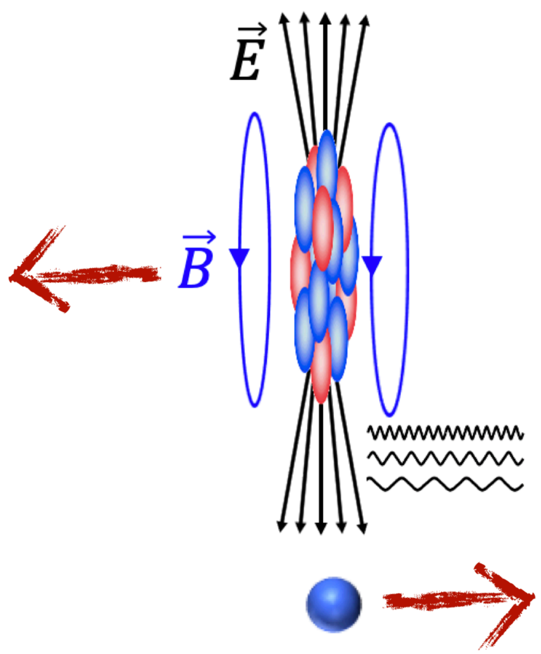

QCD unitarity: growth of gluon density can't continue indefinitely!

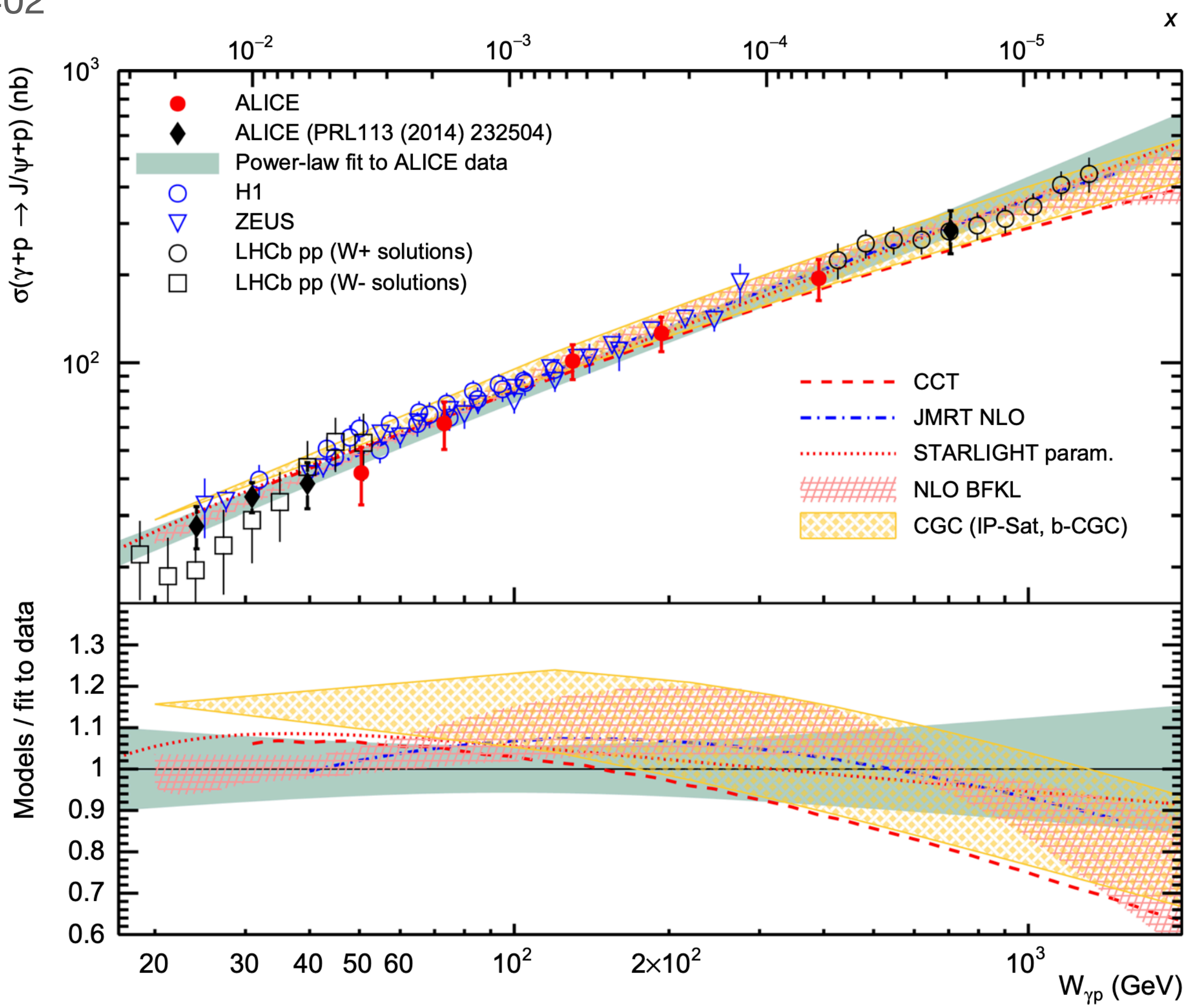



Small $x$ ← Large $x$

# Imaging free nucleon

ALICE, EPJC 79 (2019) 402

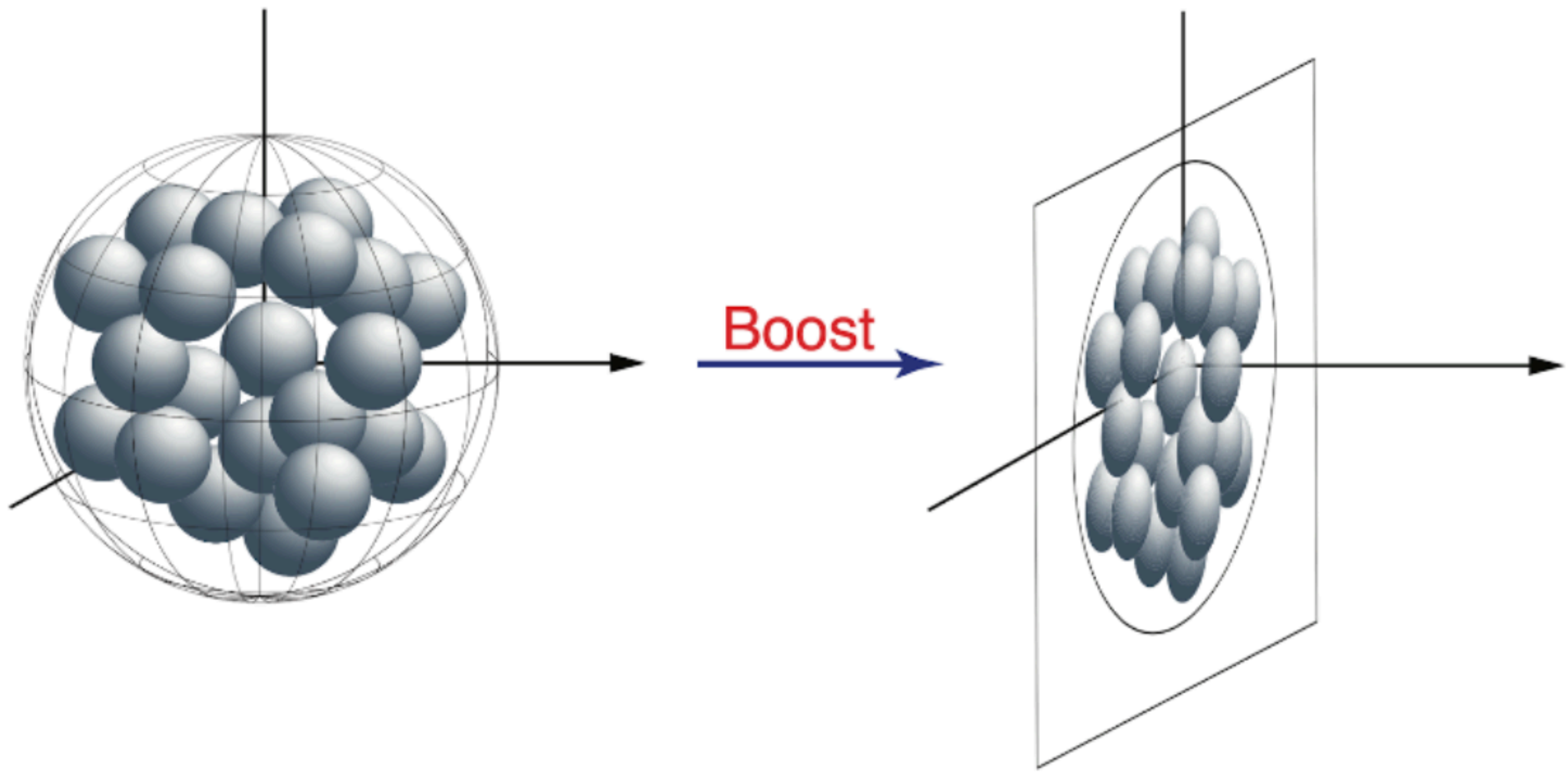



LO pQCD:
$\sigma^{VM} \propto [xG(x)]^2$

- $\sigma(W_{\gamma p})$ follows a universal power-law rise from HERA to LHC
- No clear sign of gluon saturation in proton down to $x$~$10^{-5}$

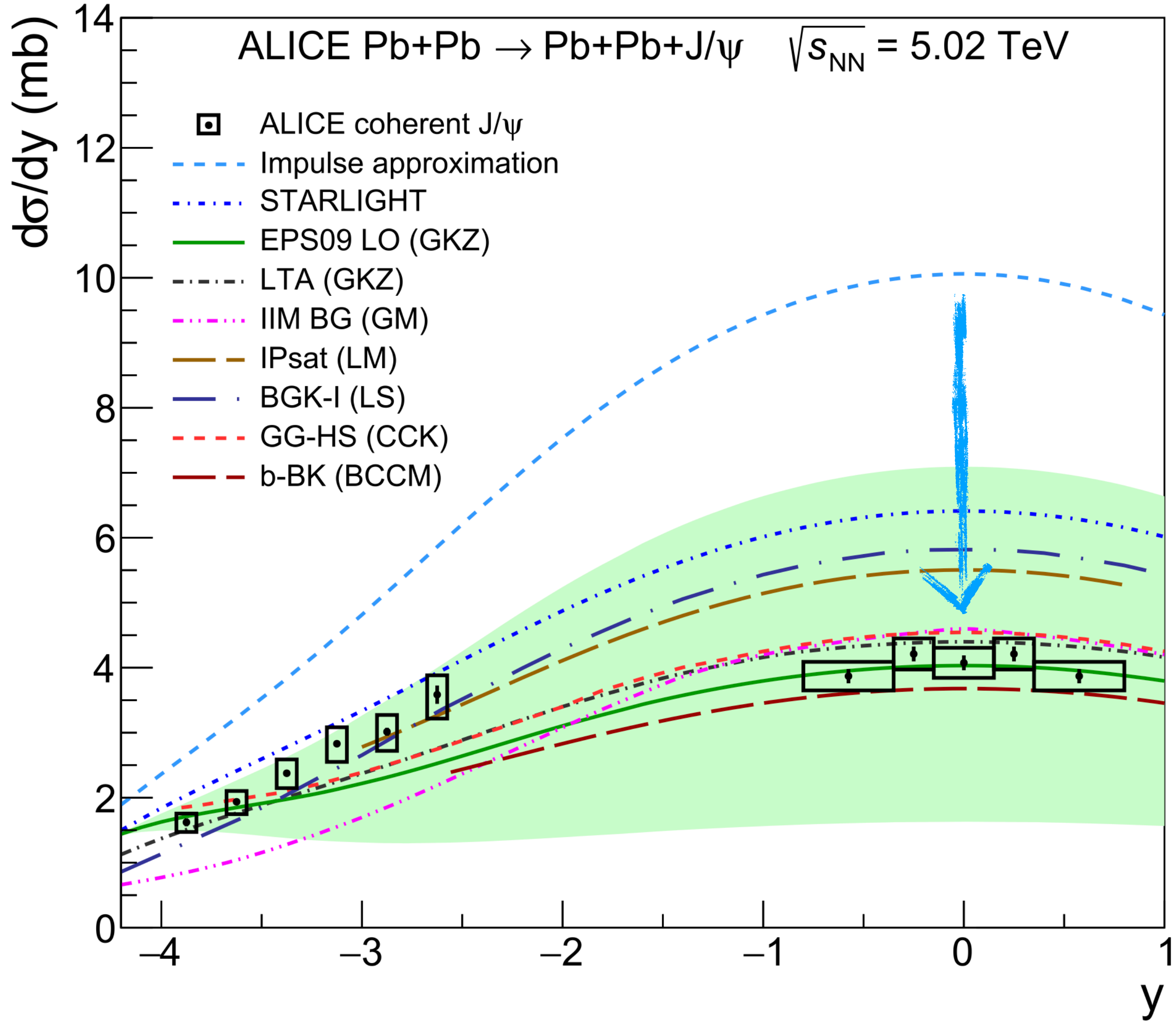
# Ultra-dense gluonic matter




- Gluon saturation is expected to be easier to be achieved inside heavy nuclei

# Imaging heavy nucleus

*ALICE, PLB 798 (2019) 134926*
*ALICE, EPJC 81 (2021) 712*

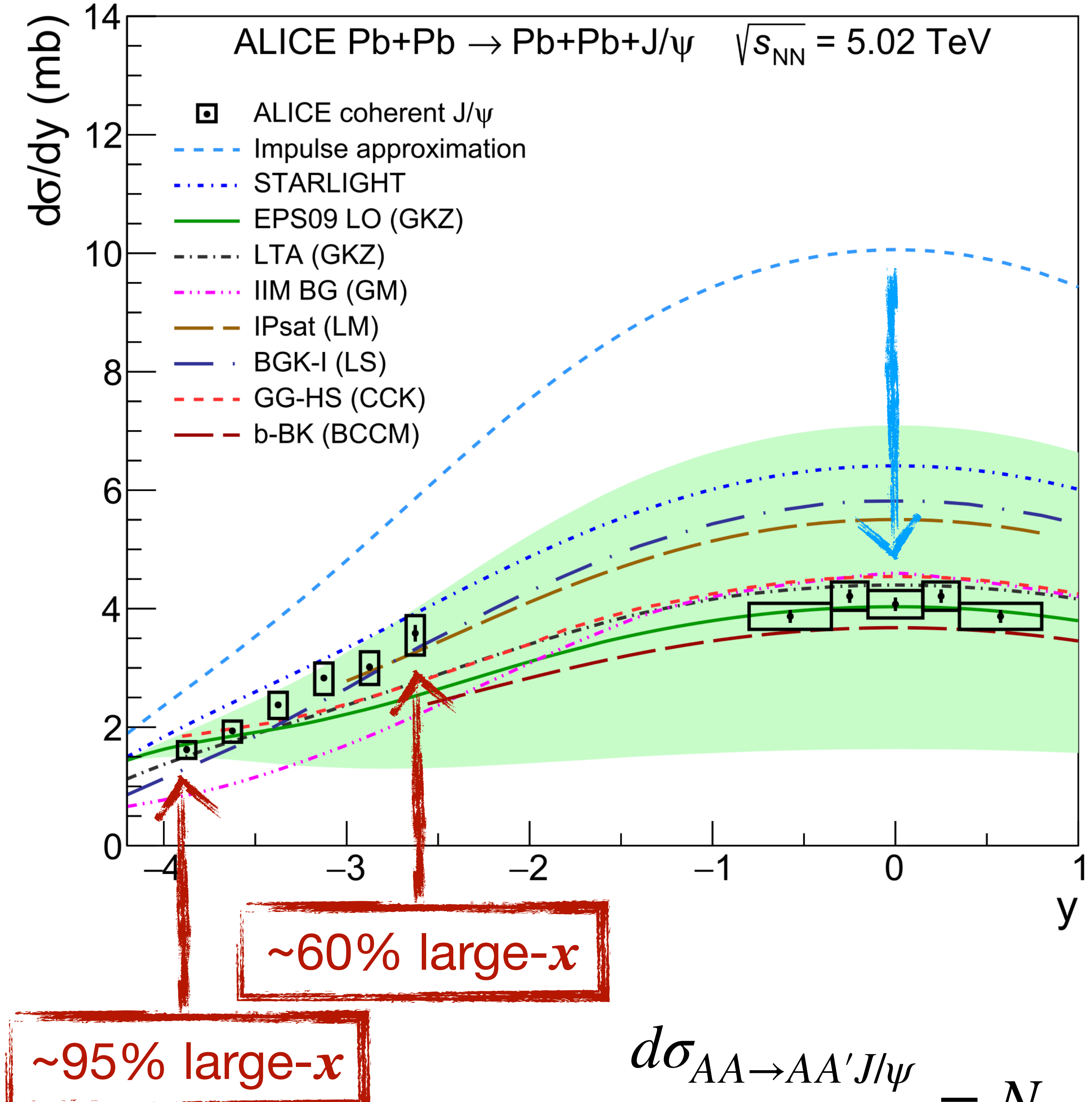



- Nuclear gluon suppression factor $R_g^{Pb} = 0.64 \pm 0.04$ at $x \sim 10^{-3}$

$$R_g^A = \frac{g_A(x, Q^2)}{A \cdot g_p(x, Q^2)}$$

# Imaging heavy nucleus

*ALICE, PLB 798 (2019) 134926*
*ALICE, EPJC 81 (2021) 712*

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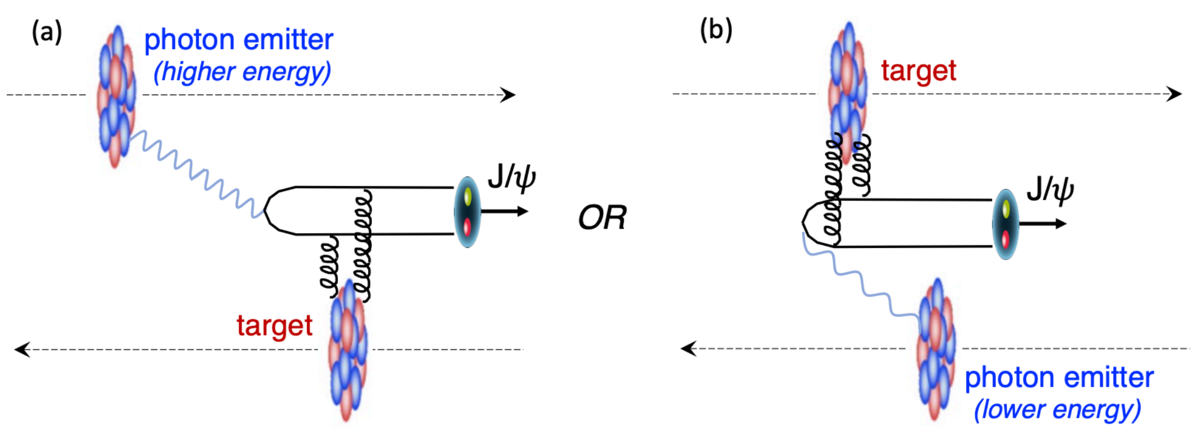
- Two-component ambiguity in A+A UPC

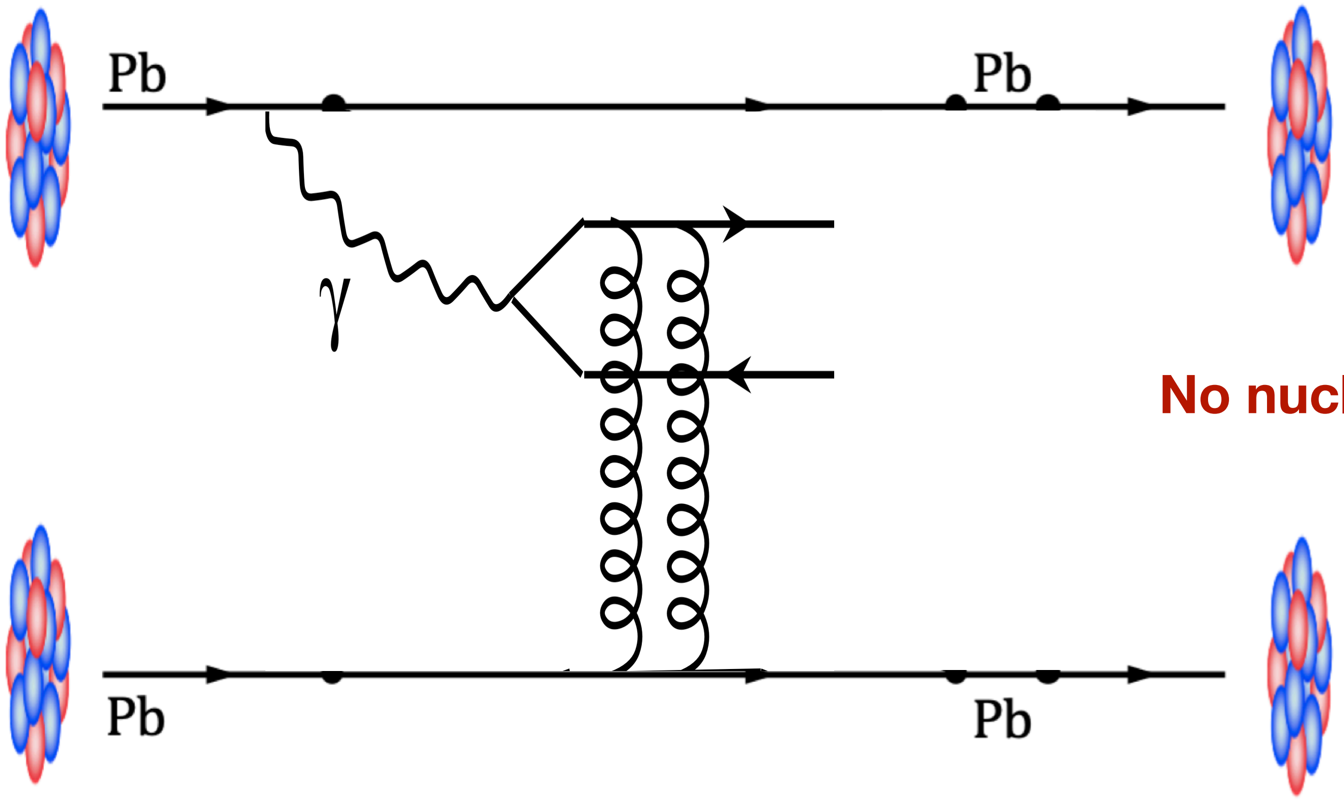



$$x = \frac{M_{J/\psi}}{2E_{beam}} e^{-y} \qquad x = \frac{M_{J/\psi}}{2E_{beam}} e^{+y}$$

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

# “Two-component ambiguity” solution

Nuclei **may** exchange soft photon(s) $\Longrightarrow$ nuclear dissociation




**No nucleus breakup**

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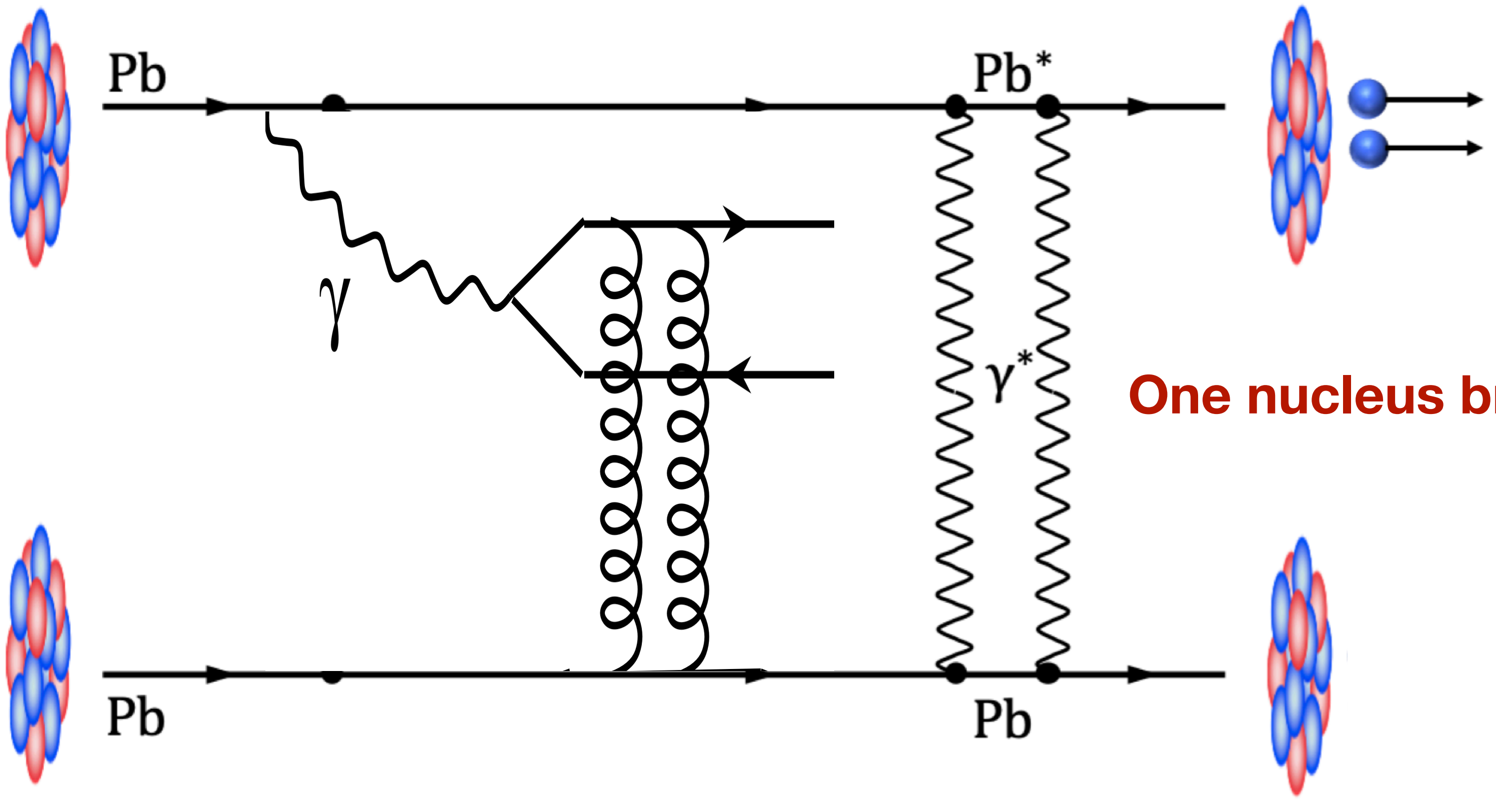


**One nucleus breakup**

# “Two-component ambiguity” solution

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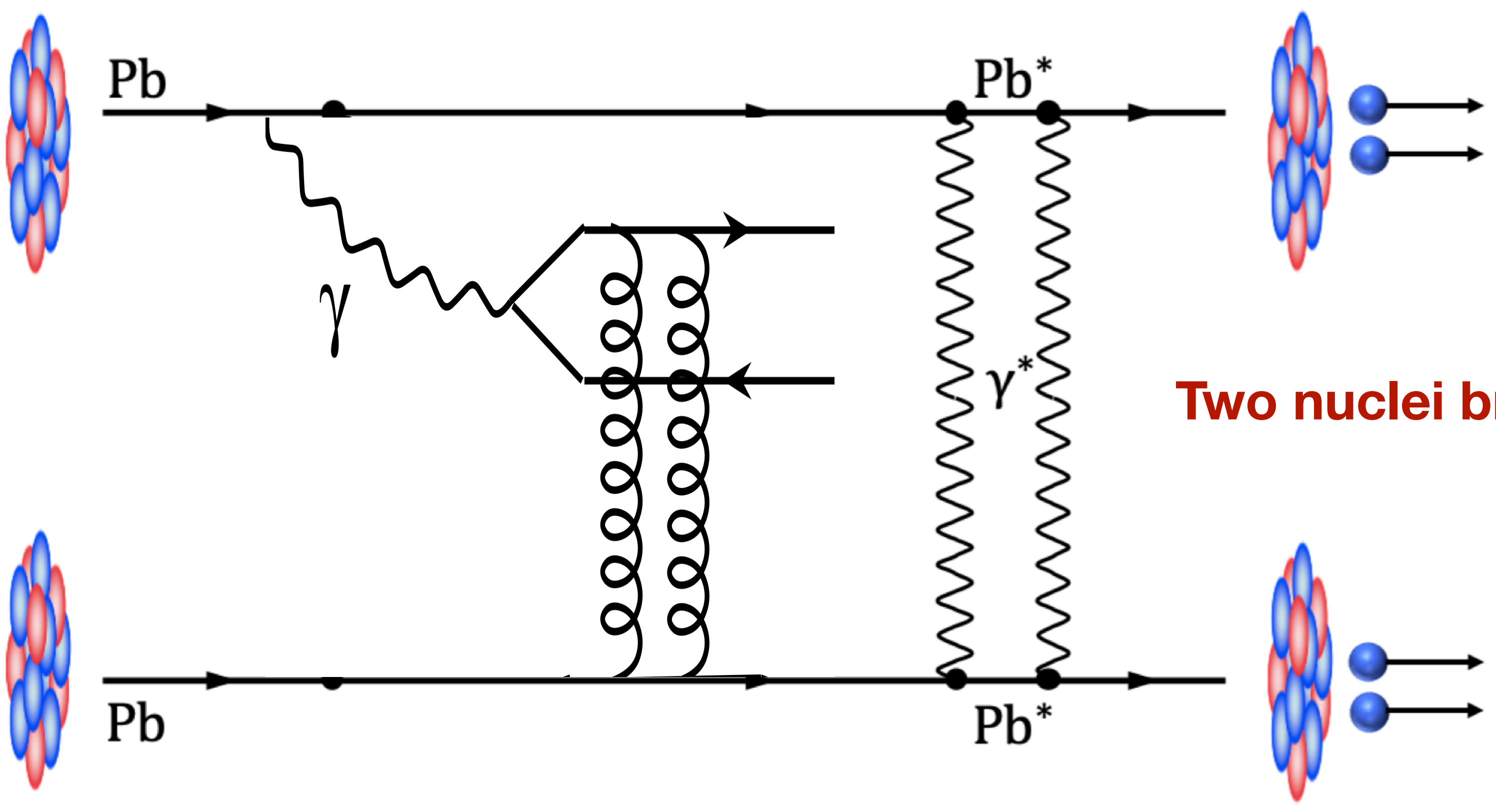


**Two nuclei breakup**

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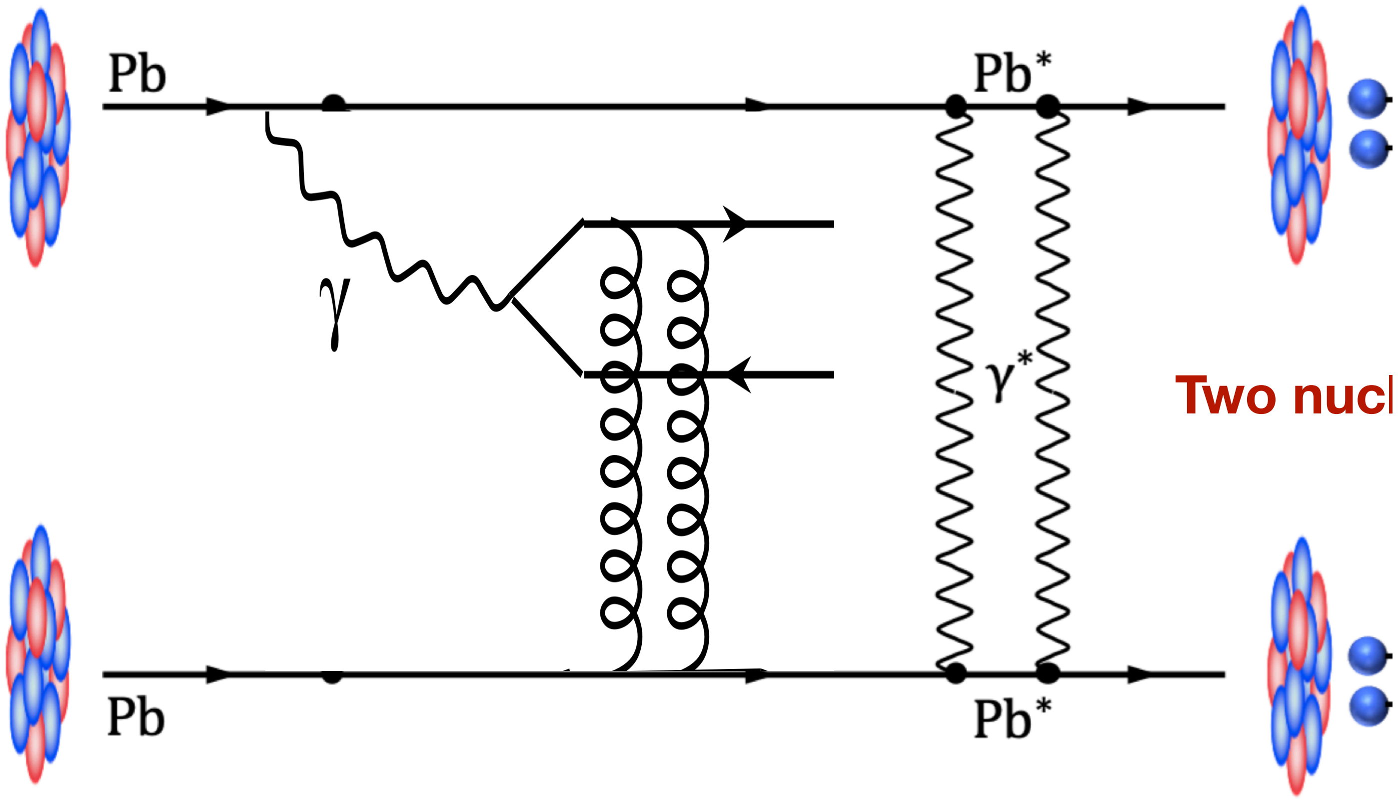
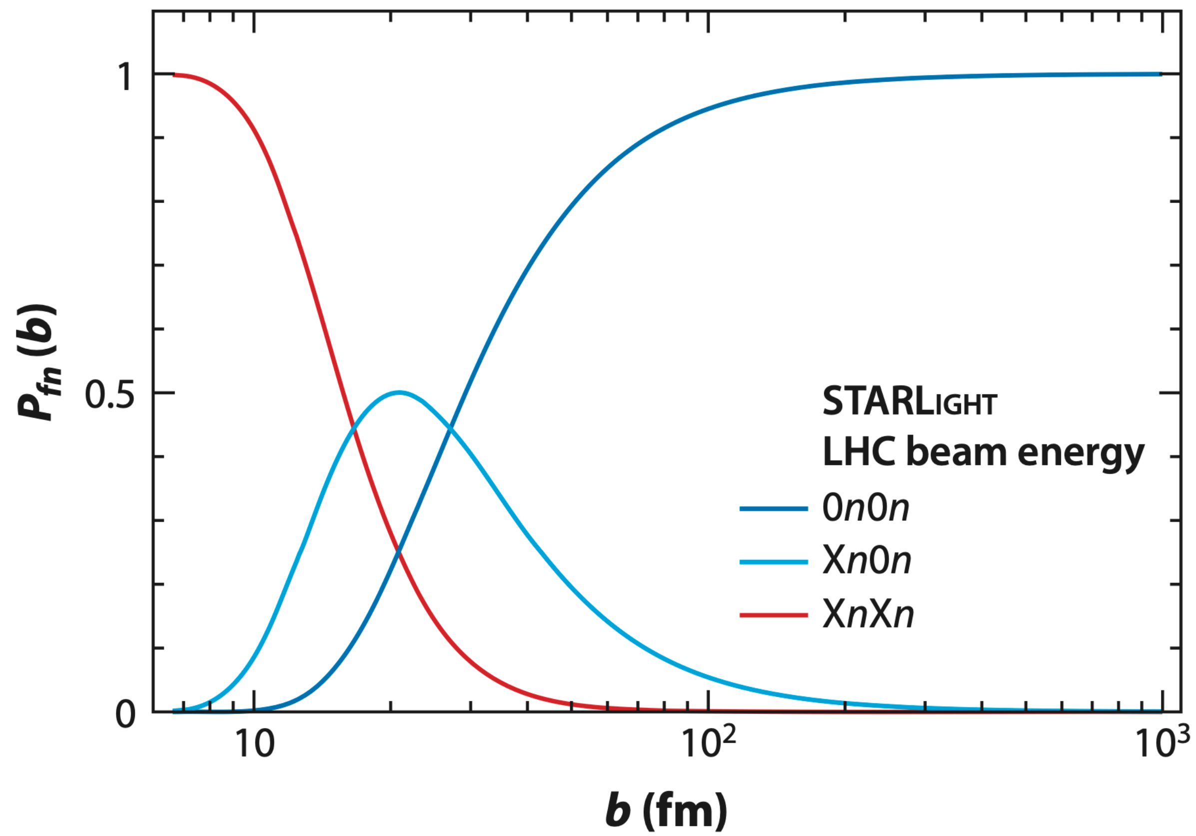


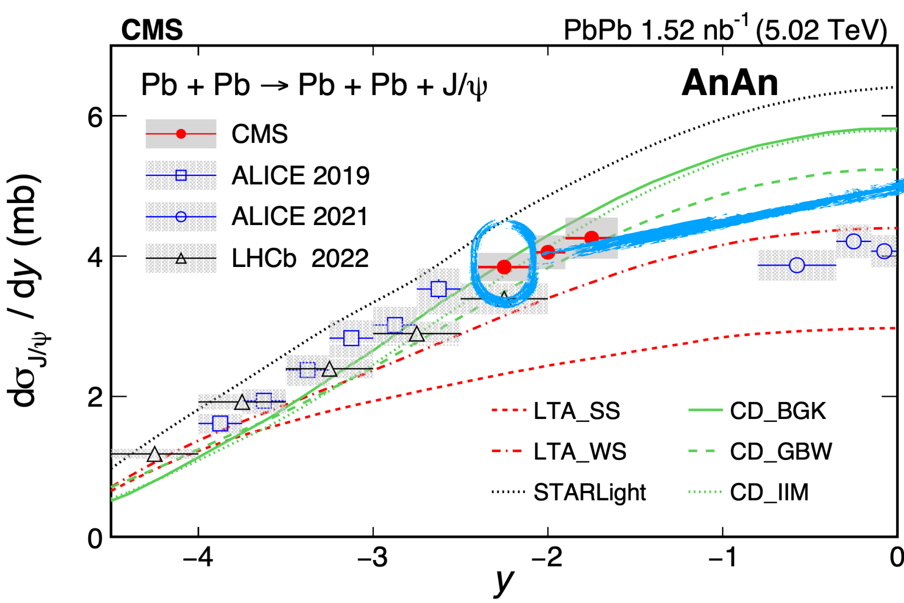



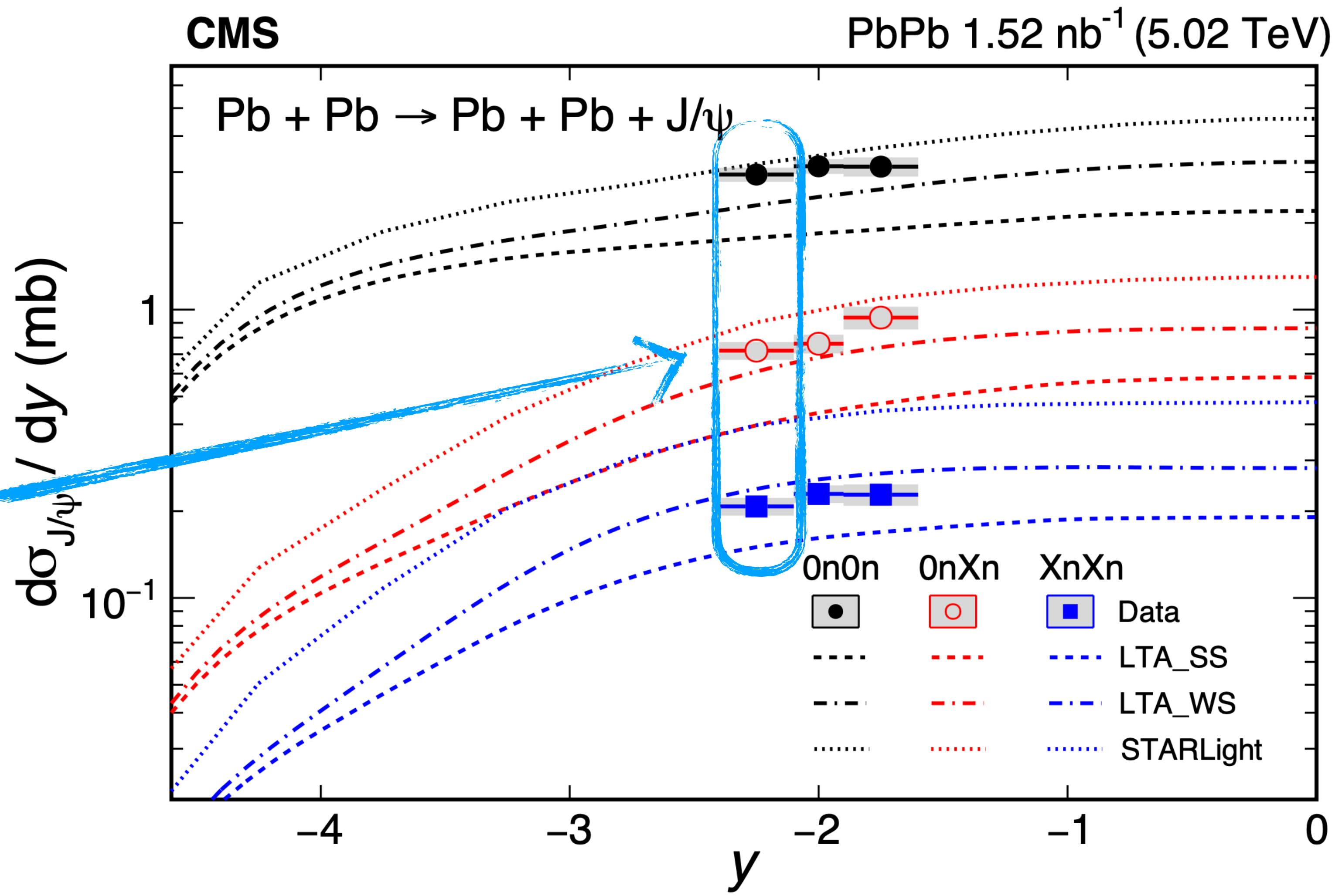

Klein and Steinberg, Ann. Rev. Nucl. Part. Sci. 70 (2020) 323

- Control the impact parameter of UPCs via forward neutron multiplicity
  - $\langle b \rangle_{\mathrm{XnXn}} < \langle b \rangle_{\mathrm{0nXn}} < \langle b \rangle_{\mathrm{0n0n}}$

# “Two-component ambiguity” solution

CMS, PRL 131 (2023) 262301
ALICE, EPJC 81 (2021) 712
LHCb, JHEP 06 (2023) 146




- First measurement of neutron multiplicity dependence of coherent $J/\psi$ production
  - Enable to solve the “two-component ambiguity”

# “Two-component ambiguity” solution

Experimental measurements

Guzey *et al.*, EPJC 74 (2014) 2942

$$\frac{d\sigma^{0n0n}_{AA\to AA'J/\psi}}{dy} = N^{0n0n}_{\gamma/A}(\omega_1)\cdot\sigma_{\gamma A\to J/\psi A'(\omega_1)} + N^{0n0n}_{\gamma/A}(\omega_2)\cdot\sigma_{\gamma A\to J/\psi A'(\omega_2)}$$

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What we need!

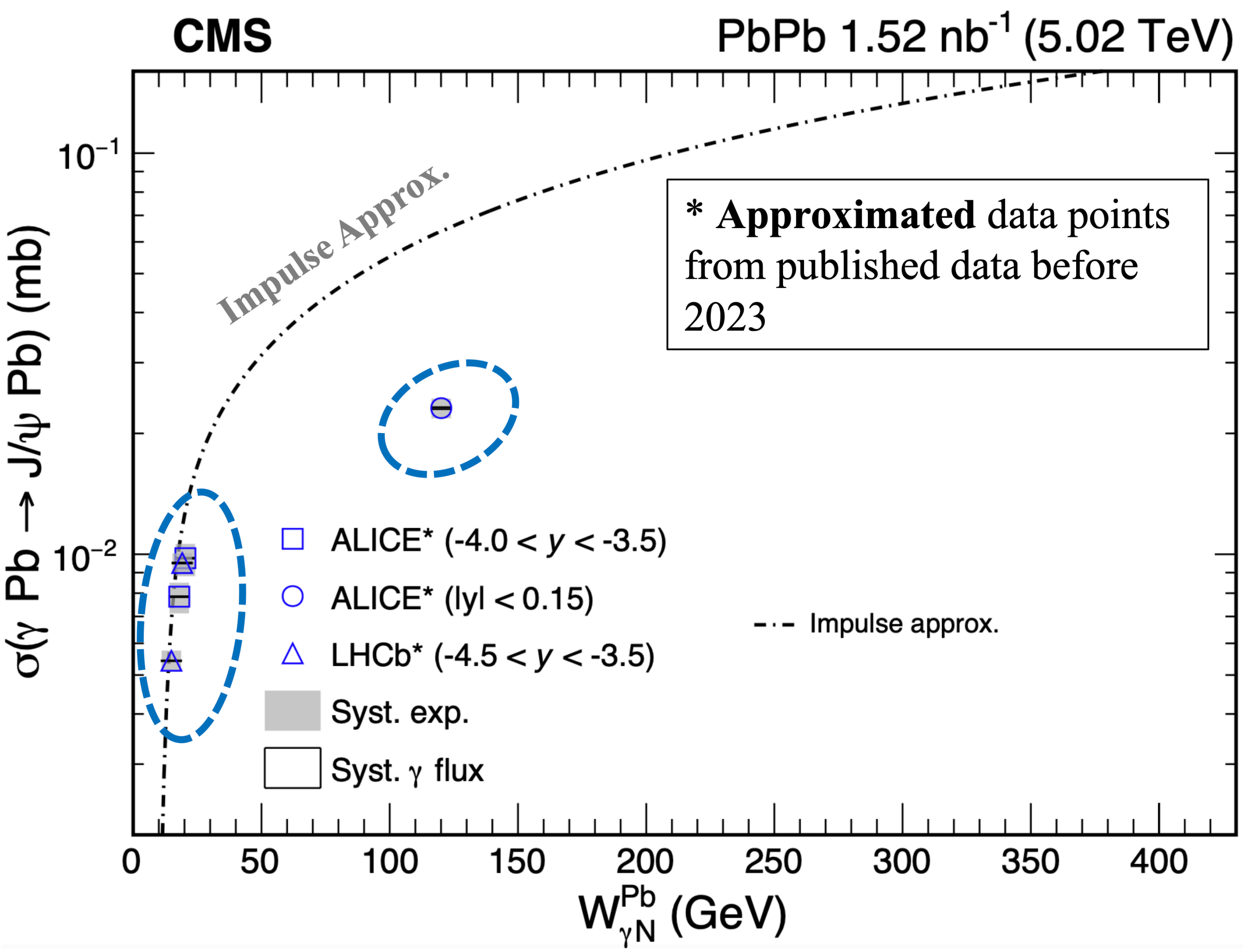
↓

Solve the "two-component ambiguity"

↓

Probe gluons at $x$~10$^{-5}$ in heavy nucleus!

# Coherent J/$\psi$ production vs. $W_{\gamma N}^{Pb}$

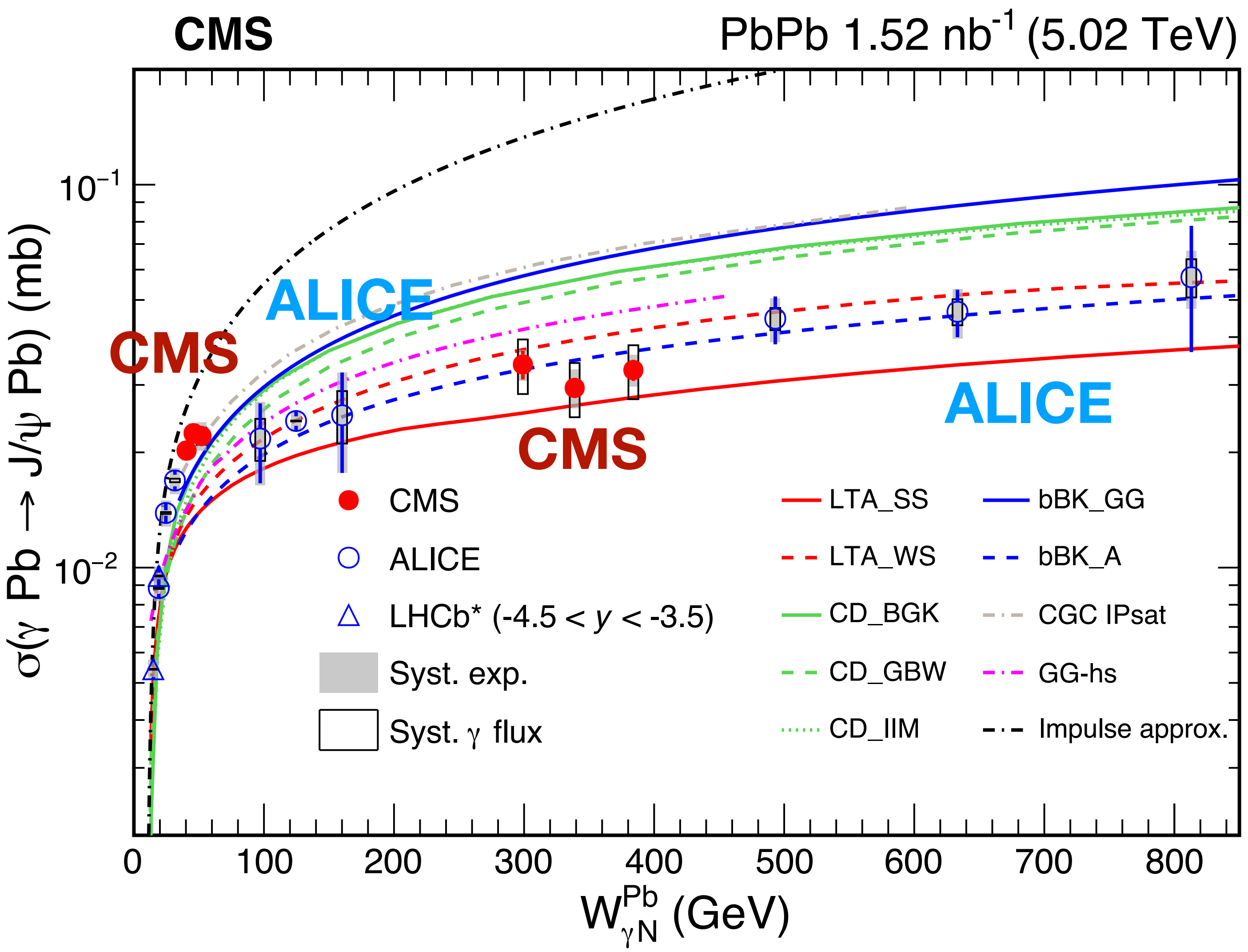



- ALICE, LHCb vs. IA
  - IA: neglects all nuclear effects
  - Data close to IA at low W
  - Data significant lower than IA at W~125 GeV ($x \sim 10^{-3}$)

ALICE, PLB 798 (2019) 134926
ALICE, EPJC 81 (2021) 712
LHCb, JHEP 06 (2023) 146

# Coherent J/$\psi$ production vs. $W_{\gamma N}^{Pb}$

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

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LHCb, JHEP 06 (2023) 146

- LHC measurements up to $W_{\gamma N}^{Pb} \approx 800$ GeV

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CMS, PRL 131 (2023) 262301
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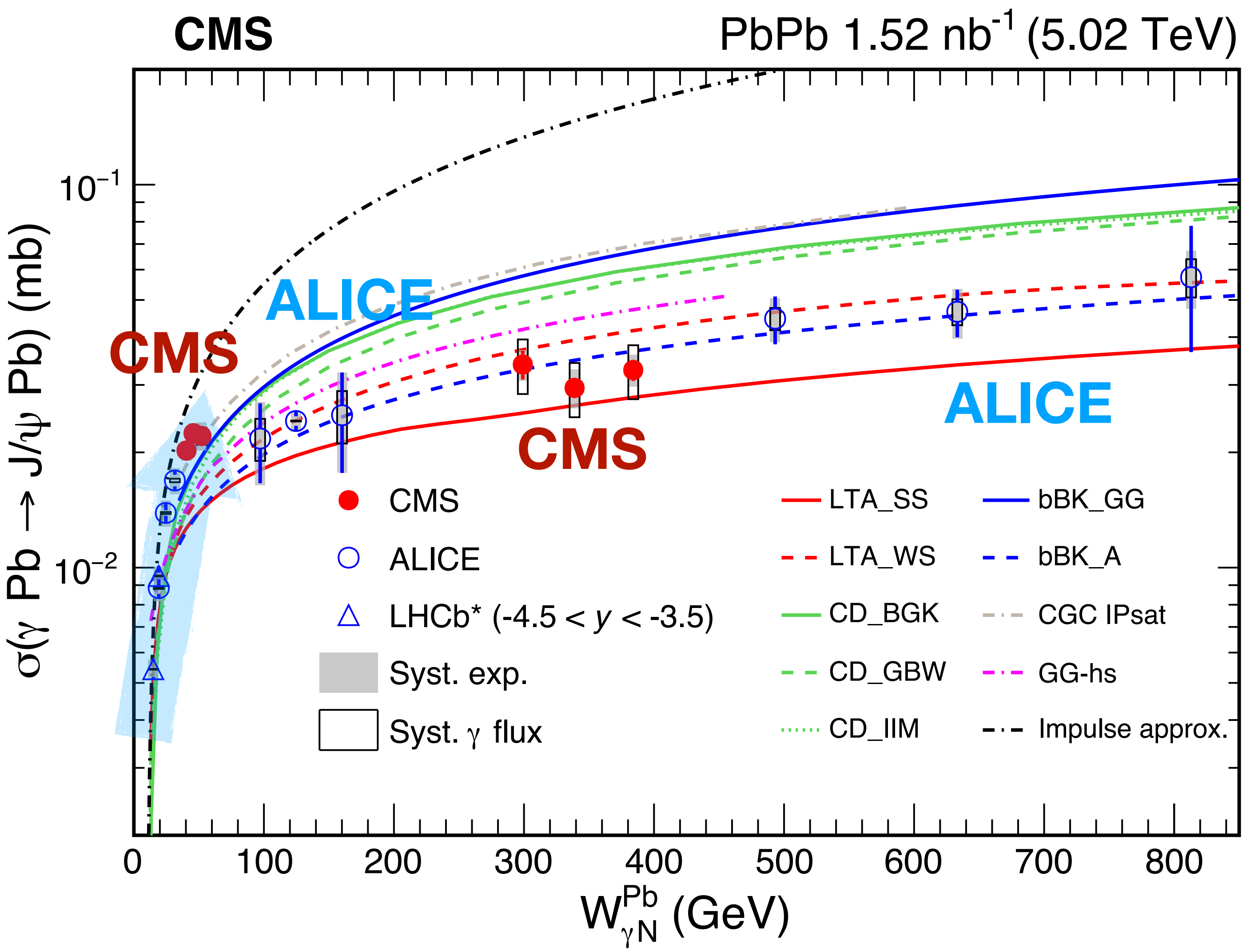


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LHCb, JHEP 06 (2023) 146

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- $W_{\gamma N}^{Pb} < 40$ GeV: rapidly rising

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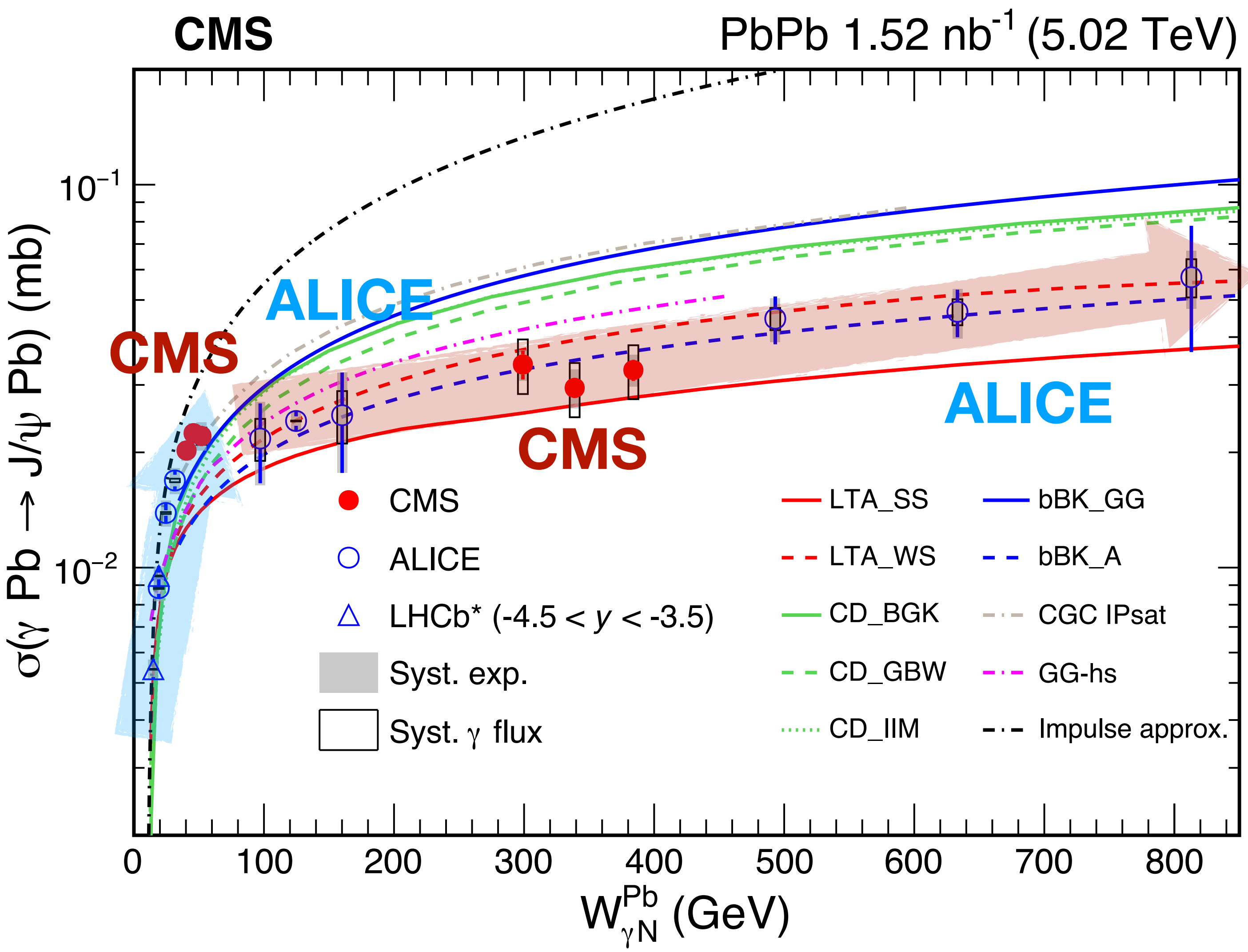


CMS, PRL 131 (2023) 262301
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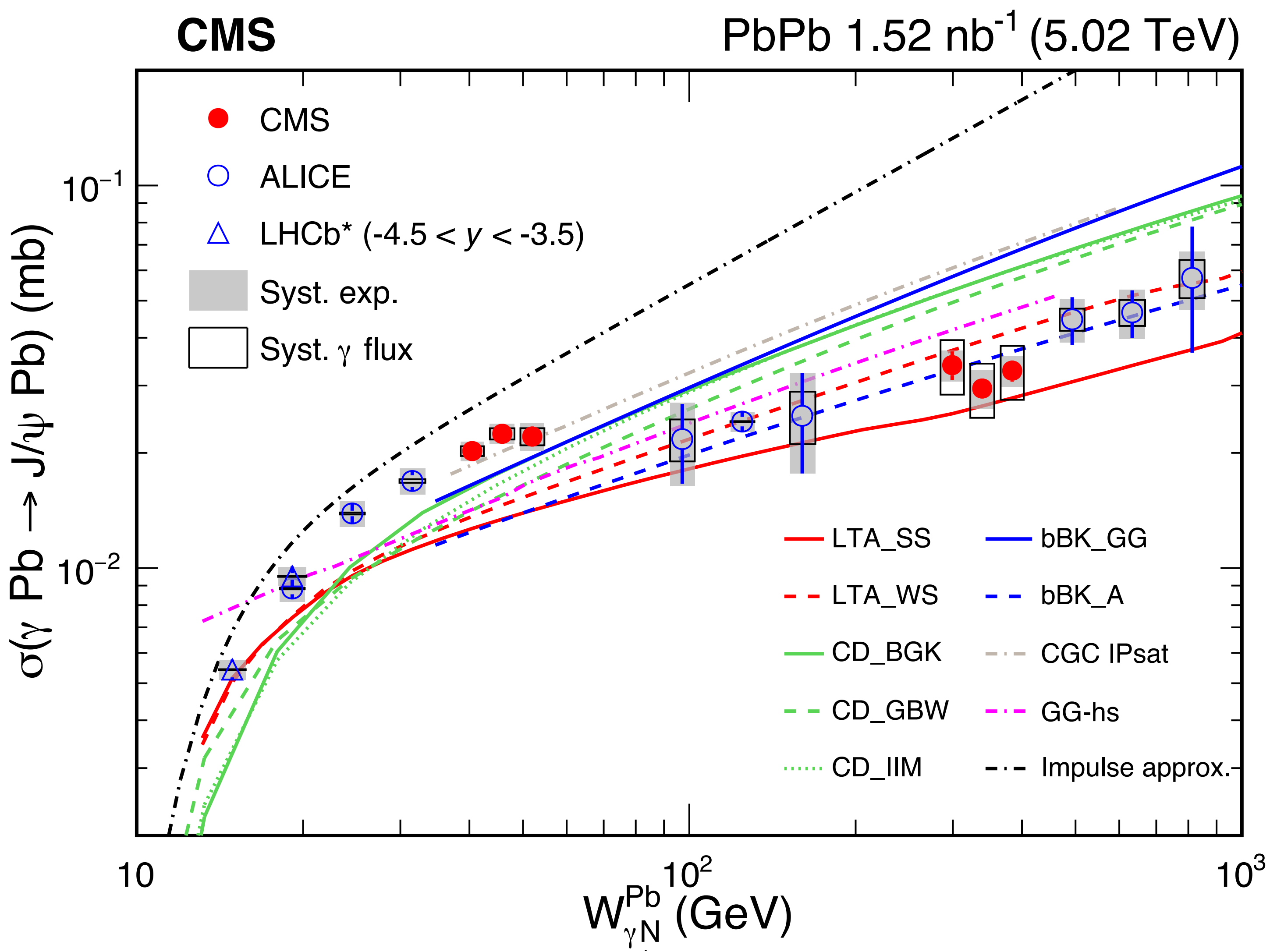
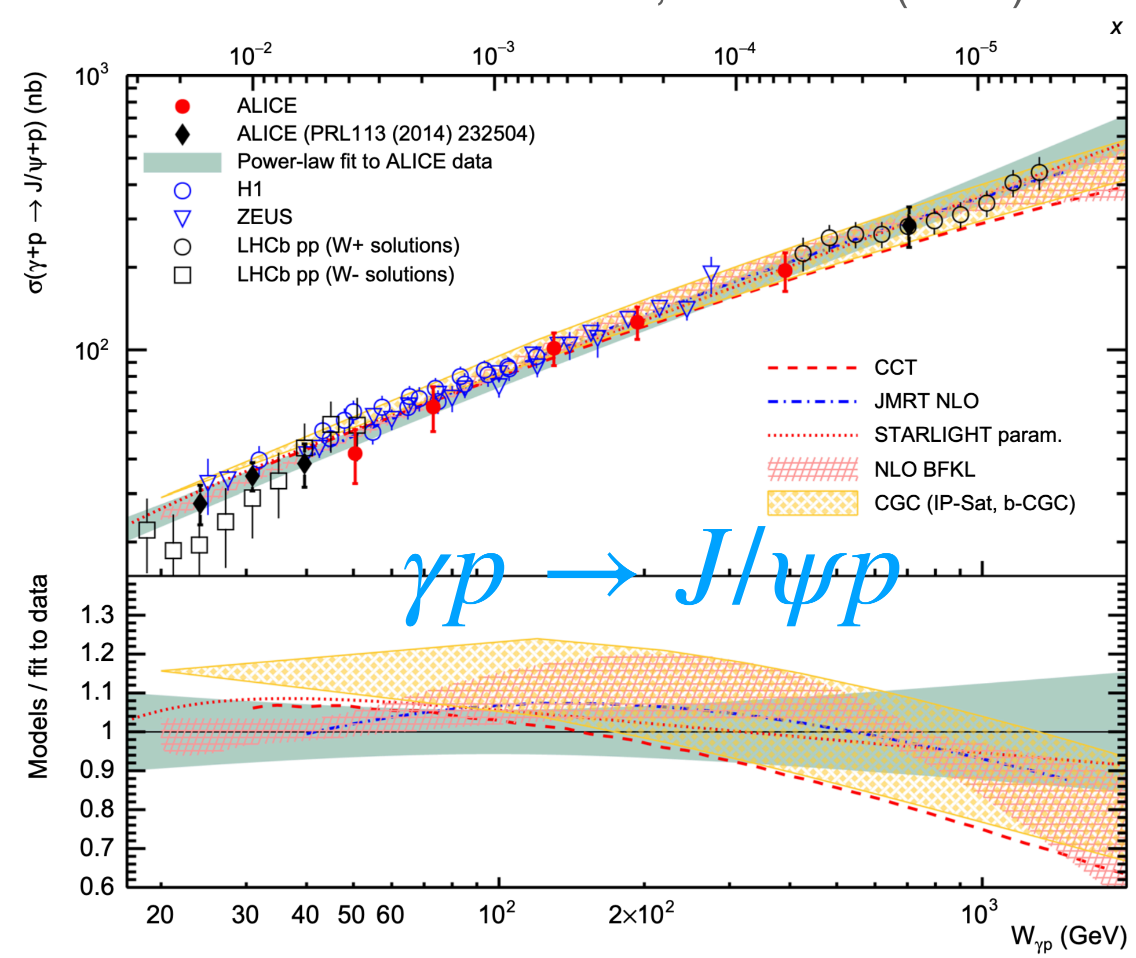
ALICE, PLB 798 (2019) 134926
ALICE, EPJC 81 (2021) 712
LHCb, JHEP 06 (2023) 146

- LHC measurements up to $W_{\gamma N}^{Pb} \approx 800$ GeV
- $W_{\gamma N}^{Pb} < 40$ GeV: rapidly rising
- $40 < W_{\gamma N}^{Pb} < 800$ GeV: nearly flat with a much slower rising

# Coherent J/$\psi$ production vs. $W_{\gamma N}^{Pb}$




CMS, PRL 131 (2023) 262301
ALICE, JHEP 10 (2023) 119
ALICE, EPJC 79 (2019) 402

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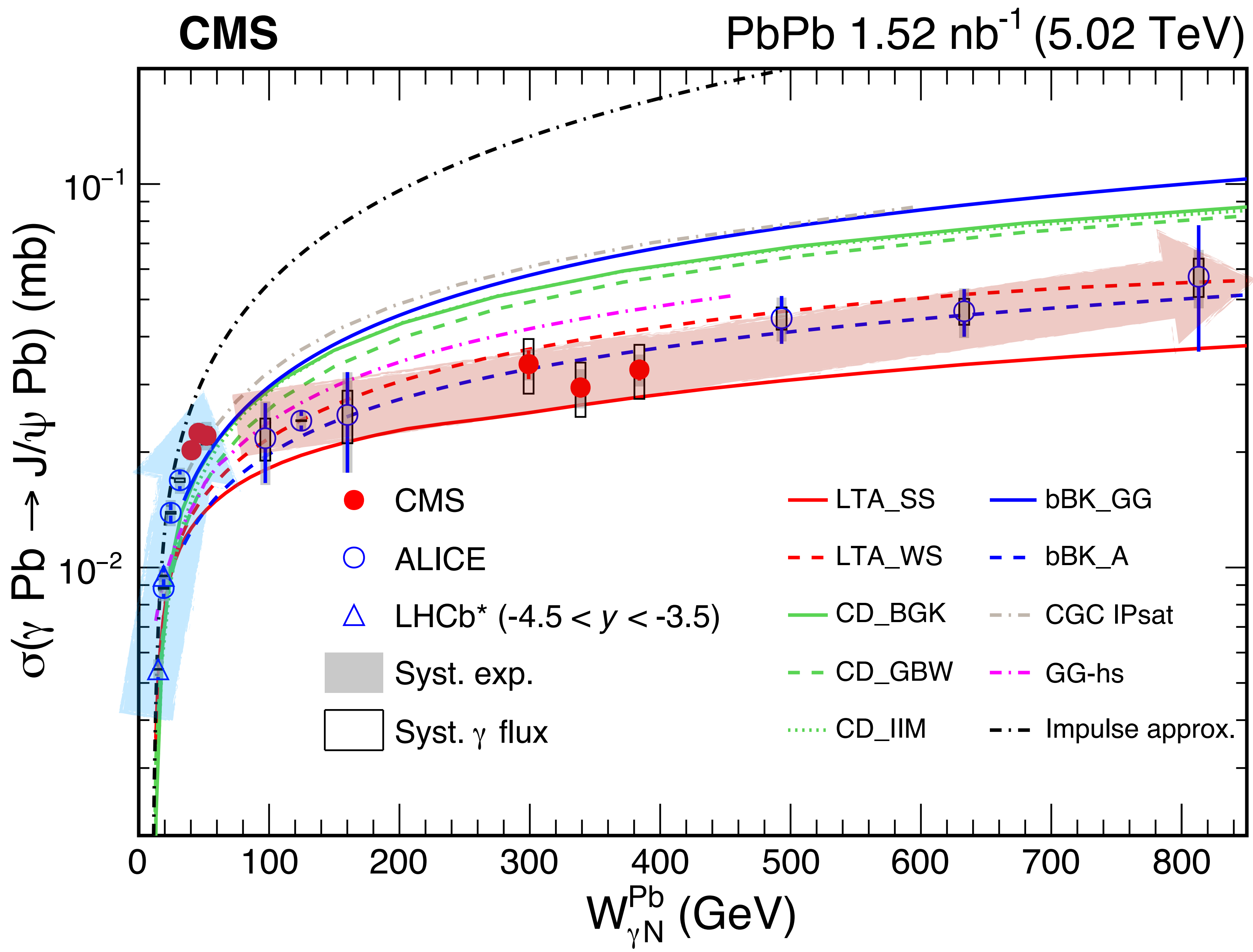
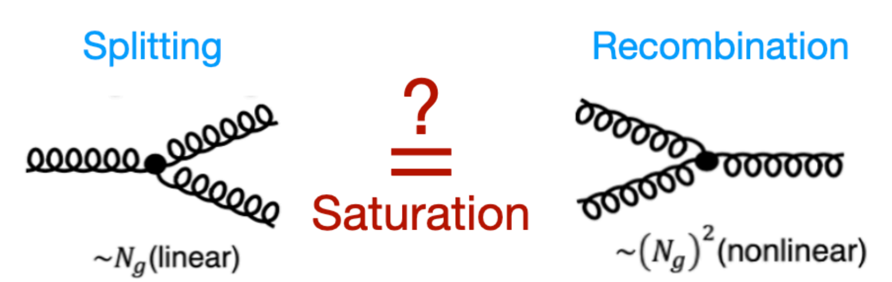
# What physics could be behind?

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

LO pQCD:
$\sigma^{VM} \propto [xG(x)]^2$

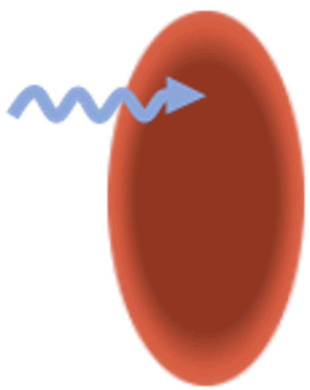



- Direct evidence of gluon saturation?



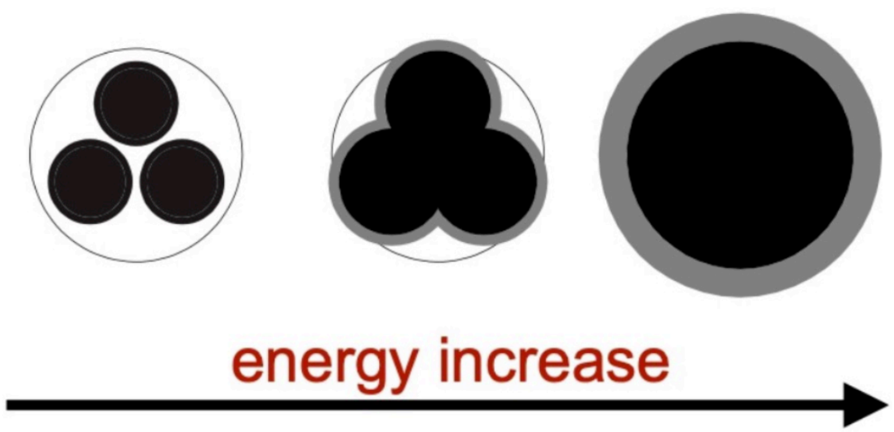
# Another novel regime of QCD: BDL

- Total cross section dipole-nuclear interaction $\rightarrow \pi R_A^2$
  - Black disk limit (BDL): the nuclear target becomes totally absorptive to incoming photons



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

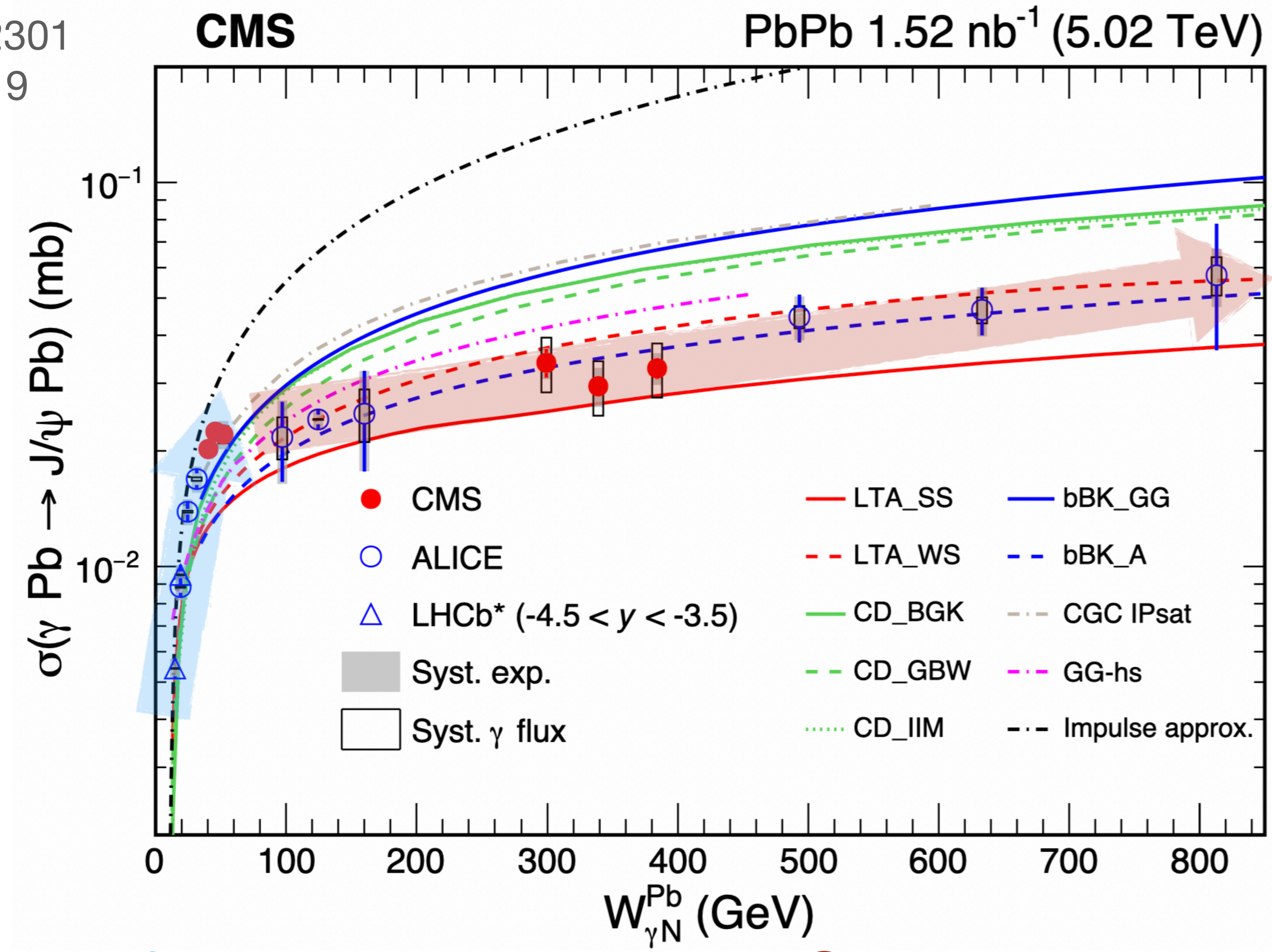
Frankfurt, PRL 87 (2001)192301
Frankfurt, PLB 537 (2002) 51



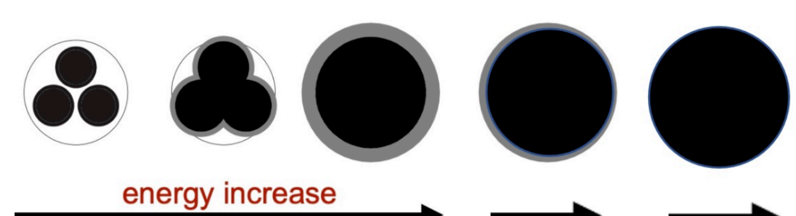

- Early onset is possible before gluon saturation if the dipole size is large
  - Depends on the weakly vs. strongly coupled regime and is not mutually exclusive with gluon saturation

# Another novel regime of QCD: BDL

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



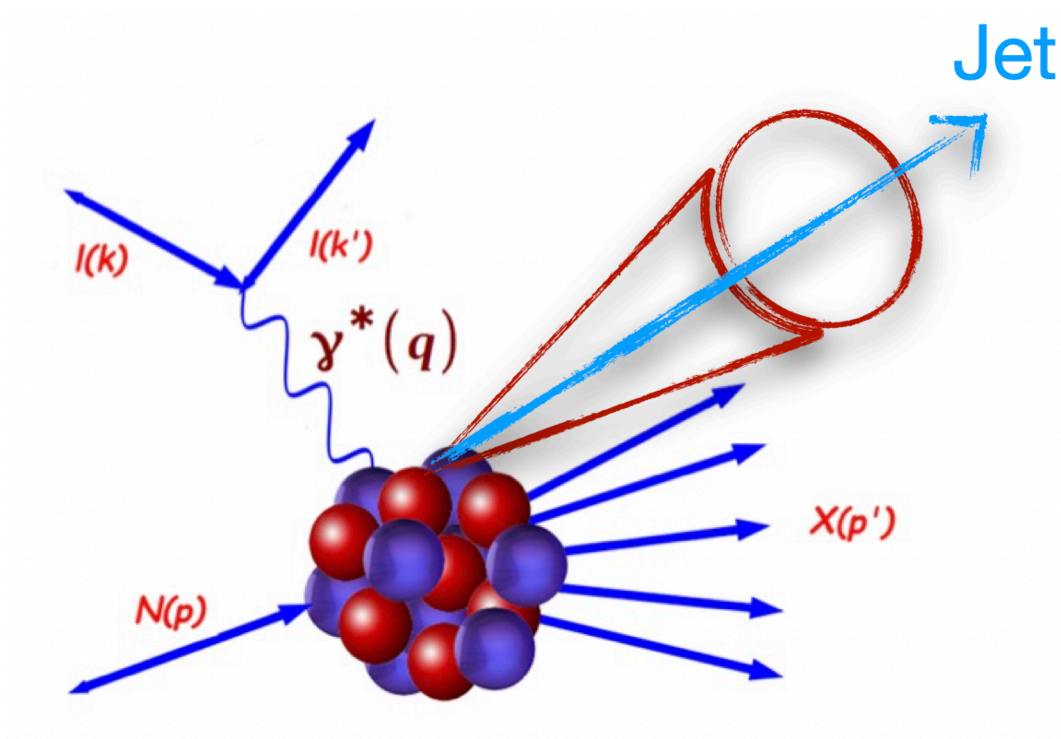

- Rapid grows reflect increased in gluon density
  - Amplitude of interaction is proportional to gluon density
- Slow grows may suggest the periphery of the nucleus has not become fully “black”

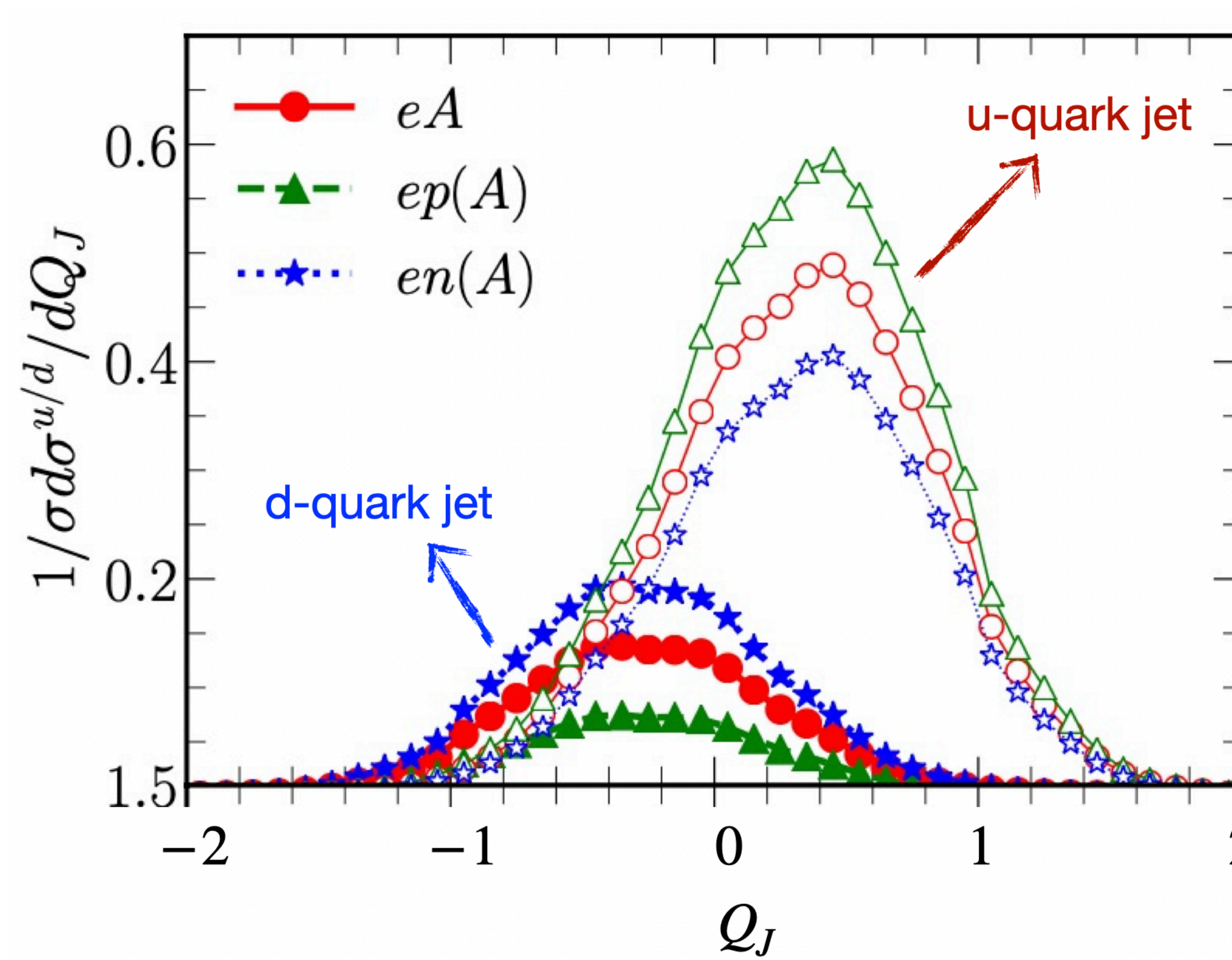


# Jet probe of neutron skin at EIC

Shan-Liang Zhang, Xin-Nian Wang, Hongxi Xing, appear soon

$$Q_J = \sum_i \left(\frac{p_{i,T}}{p_J}\right)^{\kappa} Q_i$$




- Jet charge distribution in ePb collisions.

# Jet probe of neutron skin at EIC

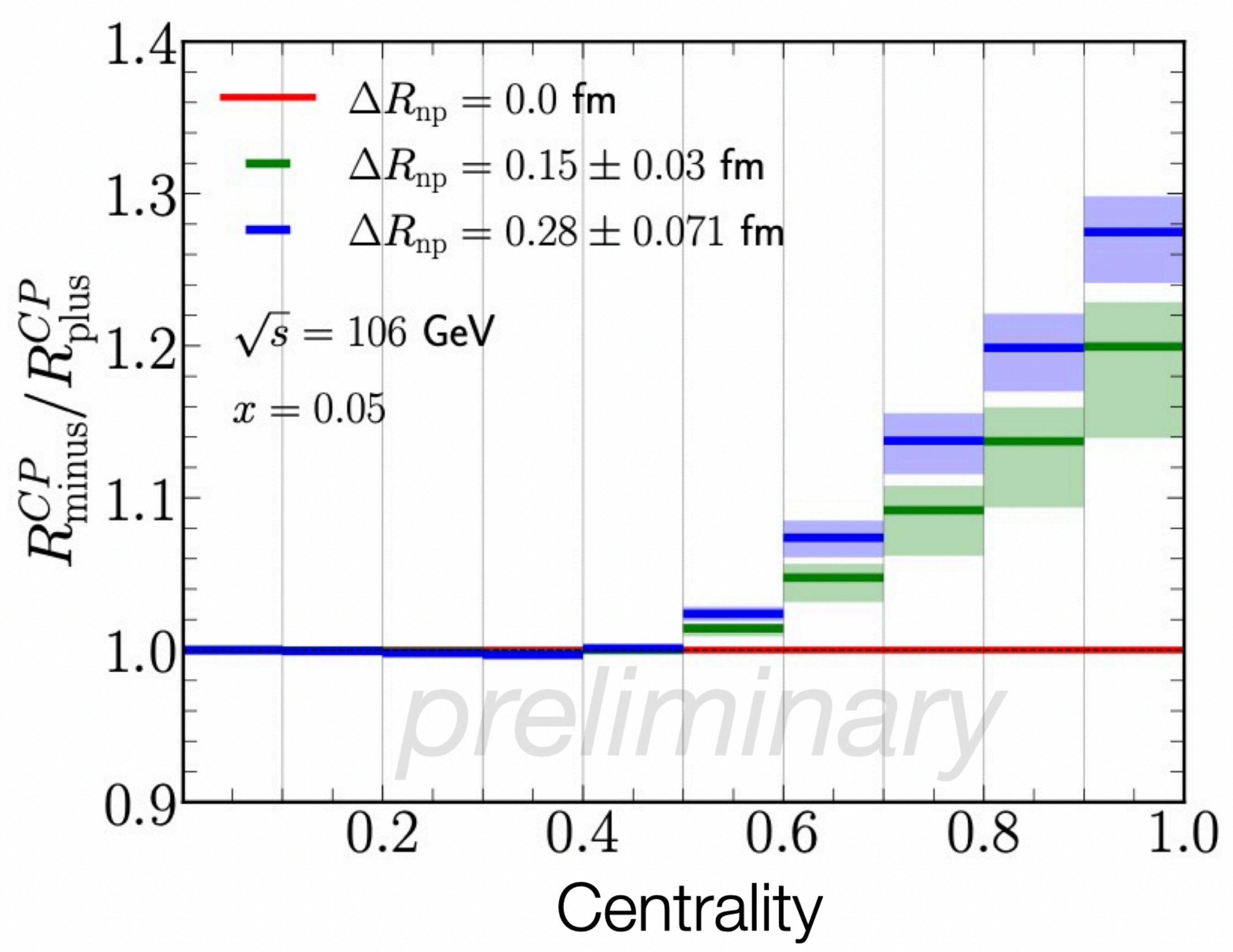
- Nucleon density distribution

Shan-Liang Zhang, Xin-Nian Wang, Hongxi Xing, appear soon

$$\rho_{n,p}(r) \propto \frac{1}{1 + \exp\left(\frac{r - R_{n,p}}{a_{n,p}}\right)}$$

- Peripheral-to-MinimumBias ratio ("$R^{CP}$")

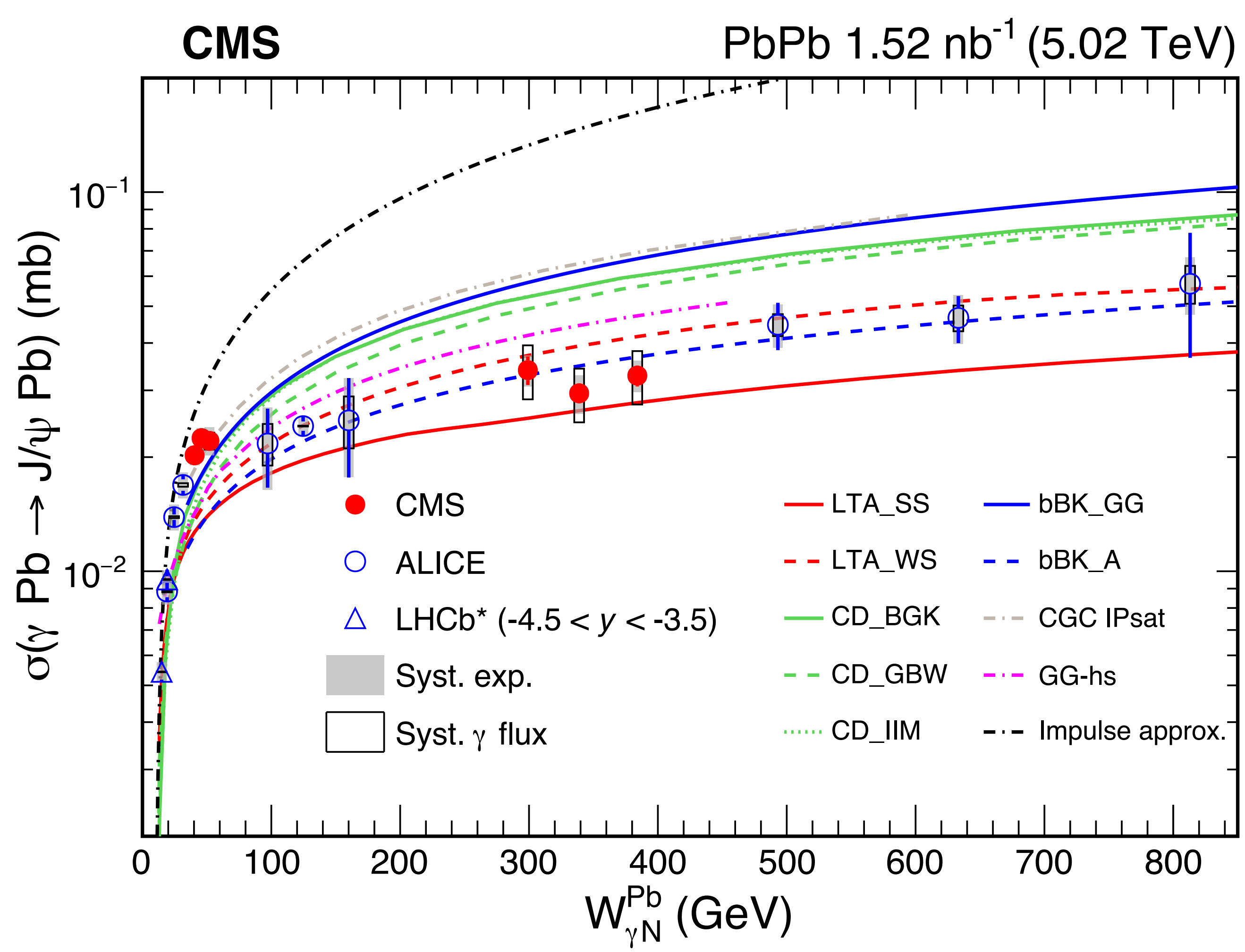
$$R^{CP} = \frac{d\sigma^{eA}_{perp}/dx}{d\sigma^{eA}_{mb}/dx}$$




- The centrality dependence of jet charge distribution is sensitive to the neutron skin

# Summary

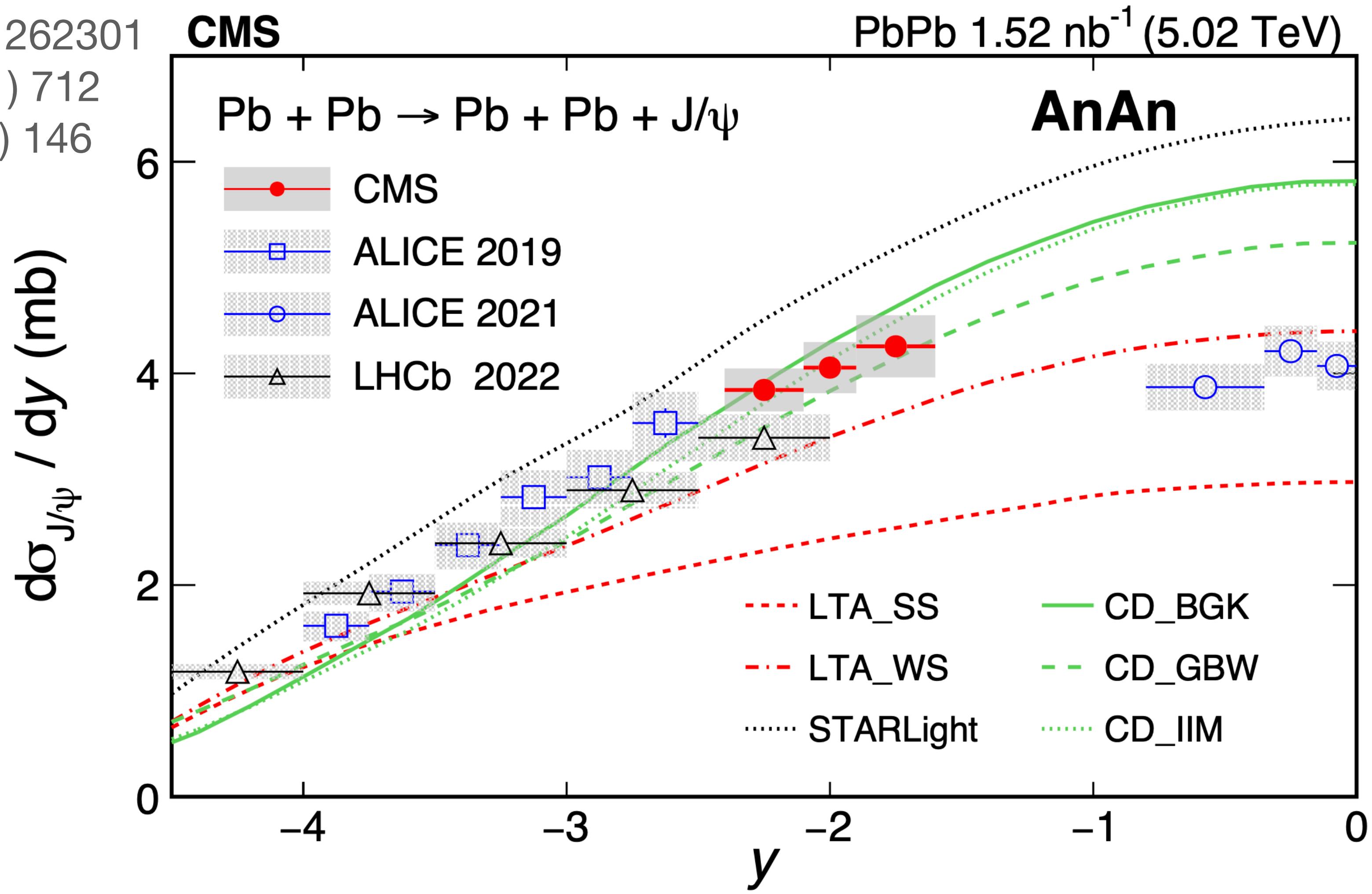
- Imaging nucleus structure in spatial space
  - Strong interaction radius ⟹ connect neutron skin
- Imaging nucleus structure in momentum space
  - New low-x gluon regime in Pb nucleus ⟹ Gluon saturation?
- Exploring a new idea to measure neutron skin



Thank you for your attention!

# Imaging heavy nucleus

CMS, PRL 131 (2023) 262301
ALICE, EPJC 81 (2021) 712
LHCb, JHEP 06 (2023) 146



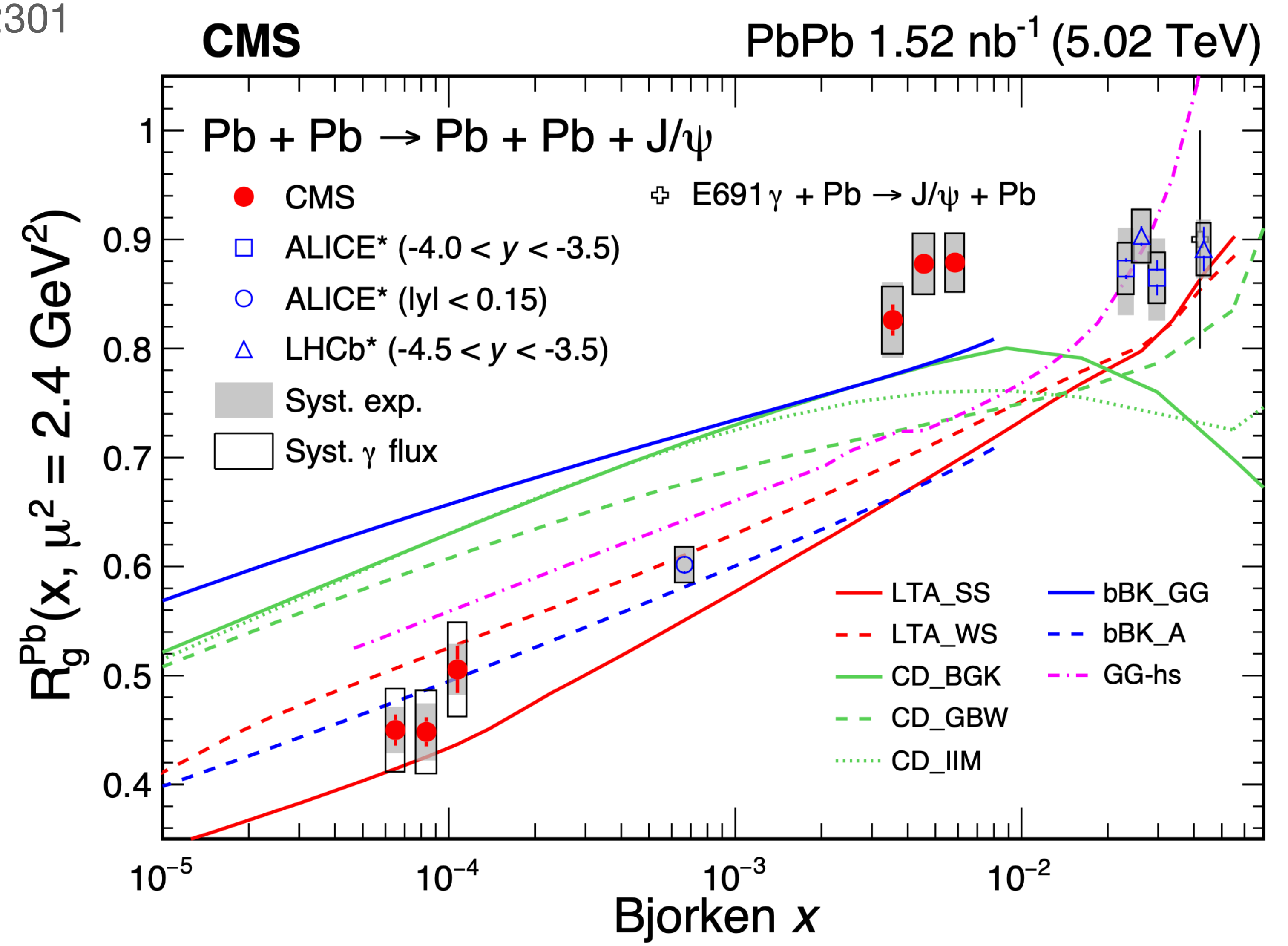

- LHC experiments complement each over a wide range of y region
  - No theory can describe data over full y region! What is missing?

Solving the “two-component ambiguity” is the key!

# Nuclear gluon suppression factor

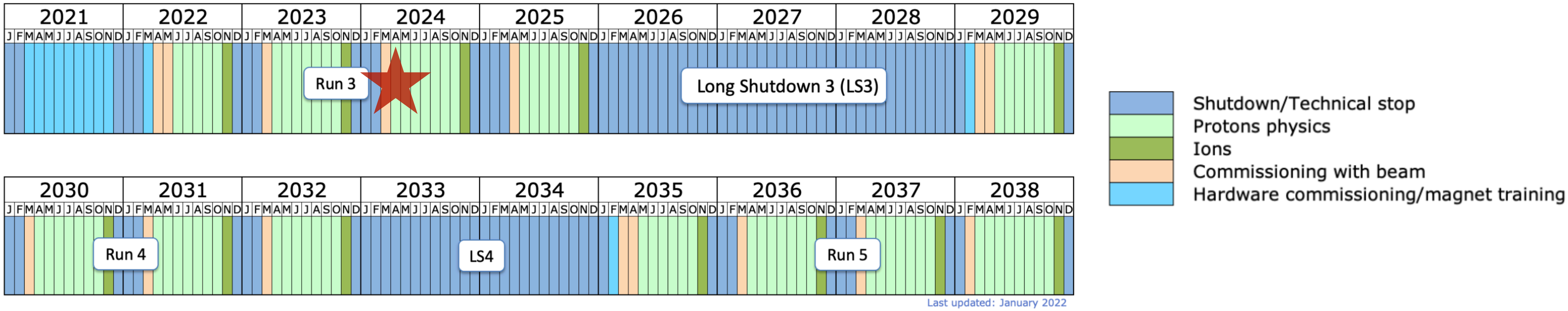
CMS, PRL 131 (2023) 262301

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

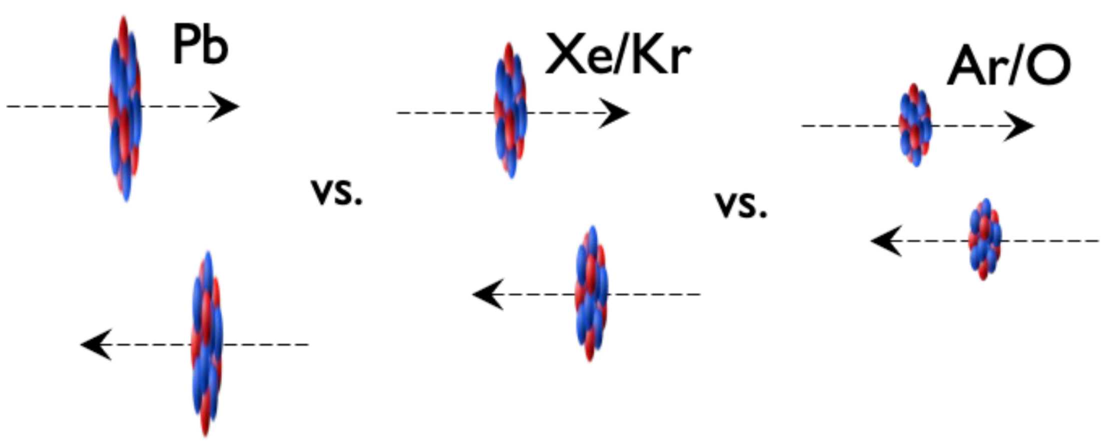



- $R_g^A$:nuclear suppression factor at LO approximation
  - A flat trend at high $x$ (~3×10$^{-3}$ - 5×10$^{-2}$)
  - Rapidly decreasing towards very small $x$ (~6×10$^{-5}$)

# Future opportunities at LHC



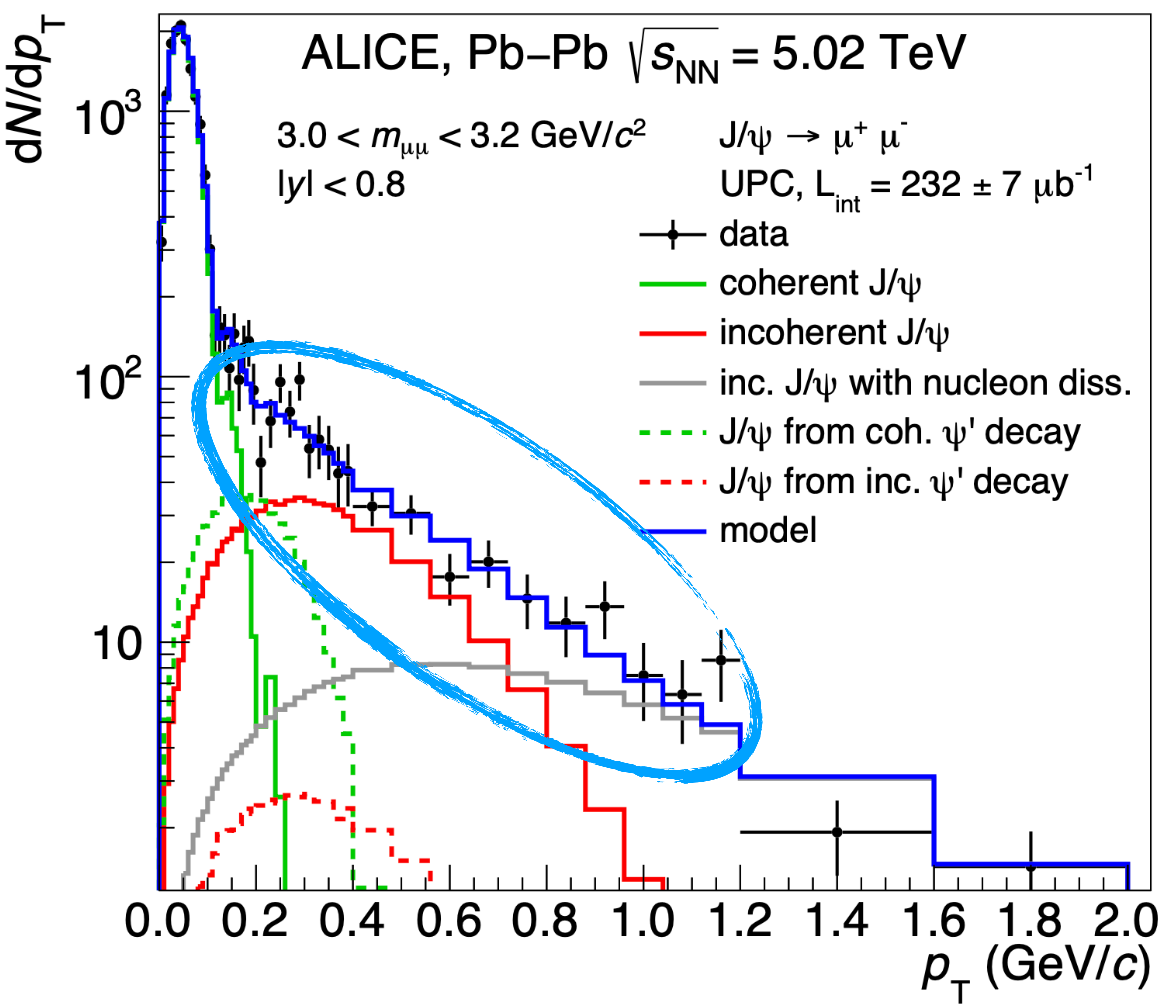

- Exciting opportunities ahead
  - Higher luminosities
  - Various ion species
  - Detector upgrade with new technologies

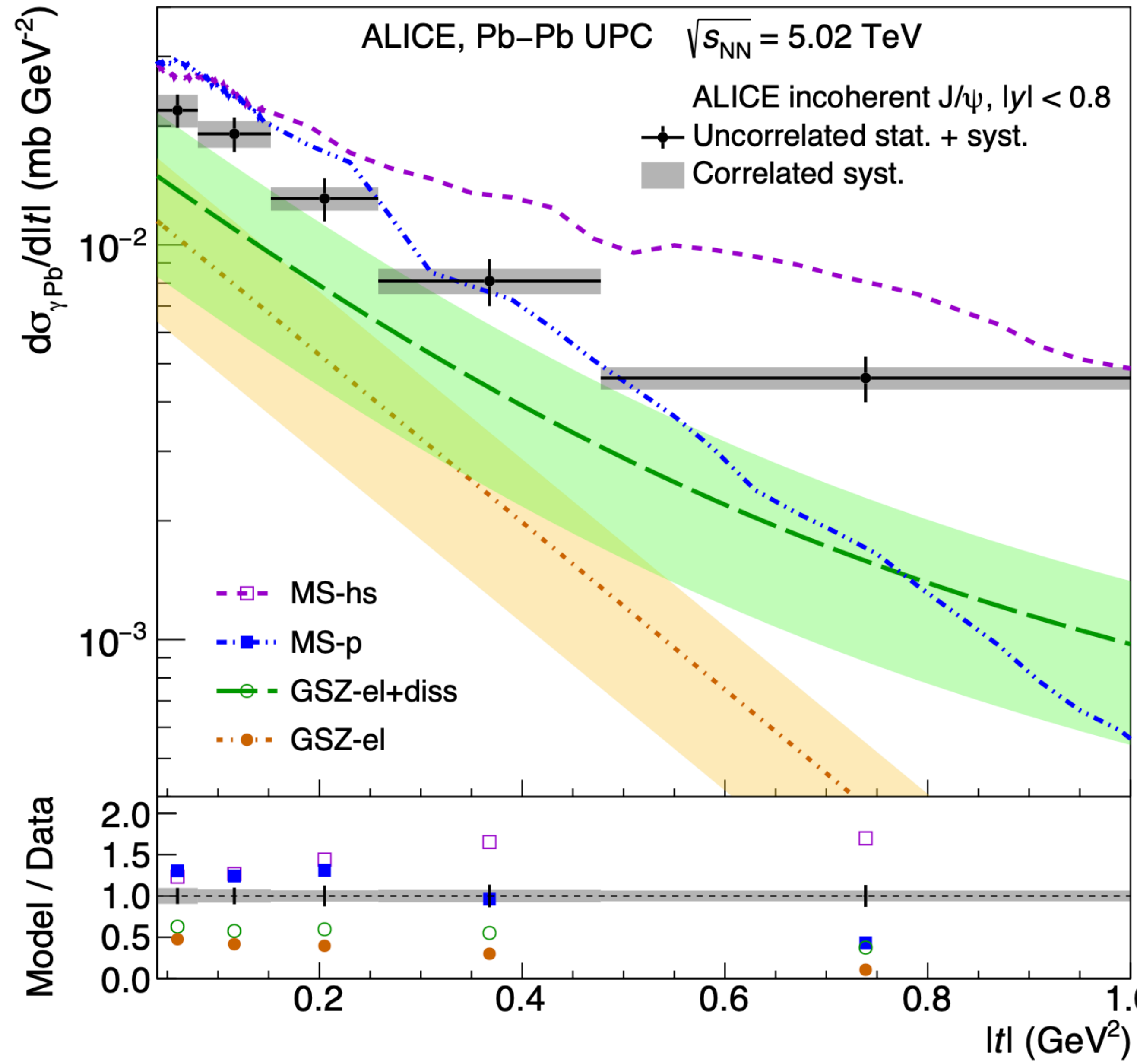



- UPC programs
  - Various vector meson productions in $\gamma$Pb with neutron tagging
  - System size scan with different ion species
  - Incoherent vector meson productions
  - Photoproduced (di-)jet measurements

# |t|-spectrum of incoherent J/ψ

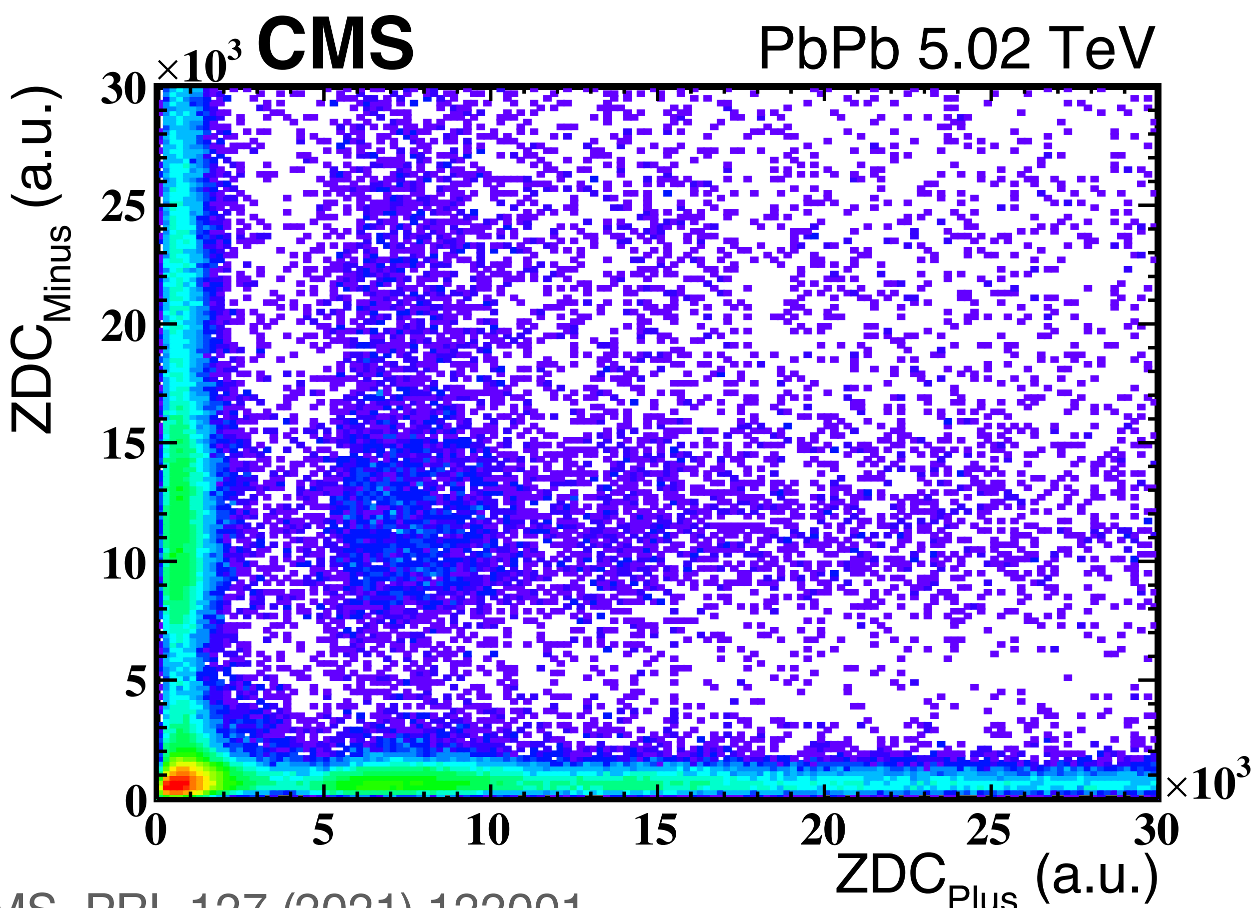
ALICE, PRL 132 (2024) 162302

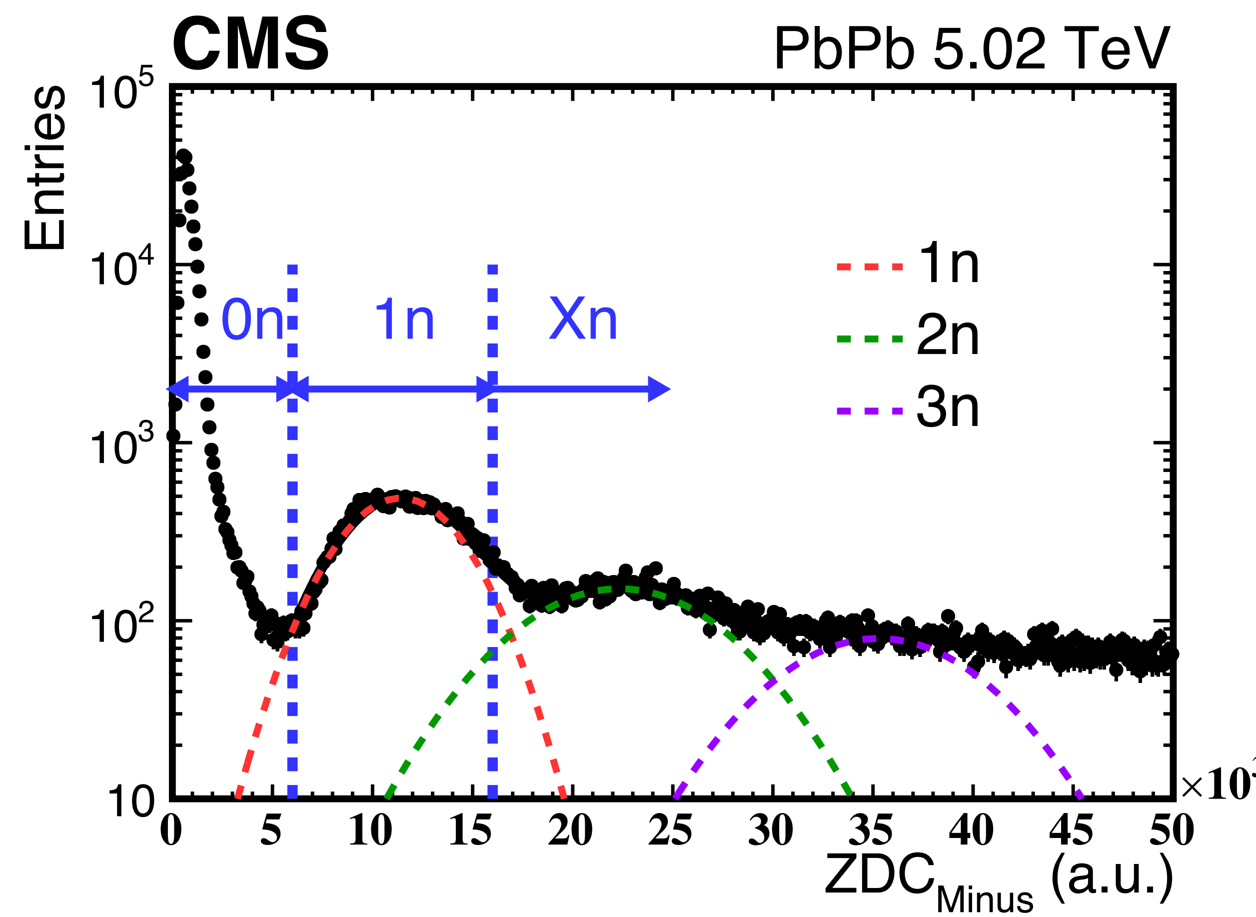



- First experimental step to use quantum fluctuations of the gluon field to search for saturation effects in heavy nuclei

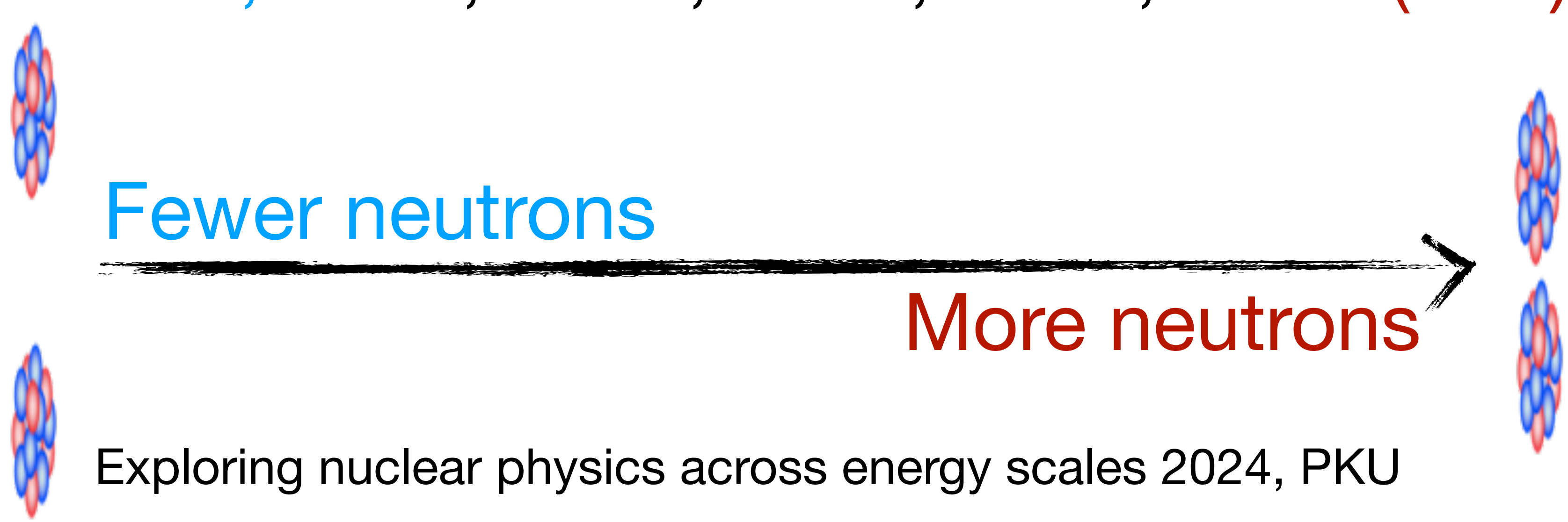
# Determine neutron multiplicity



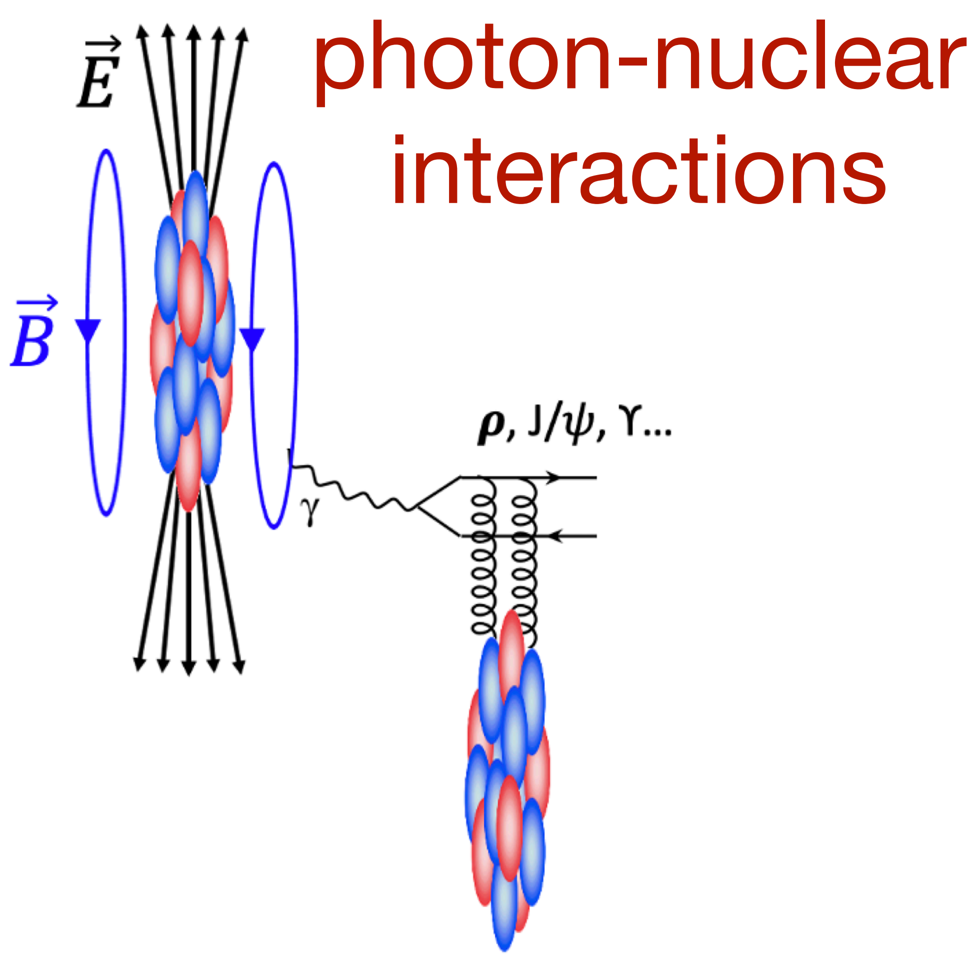




CMS, PRL 127 (2021) 122001

- Straight cuts to disentangle neutrons
  - 0n0n, 0n1n, 0nXn, 1n1n, 1nXn, XnXn (X≥2)



# A clean probe of gluon structure




- LO pQCD: $\sigma^{VM} \propto$ flux $\otimes$ $[xG(x)]^2$

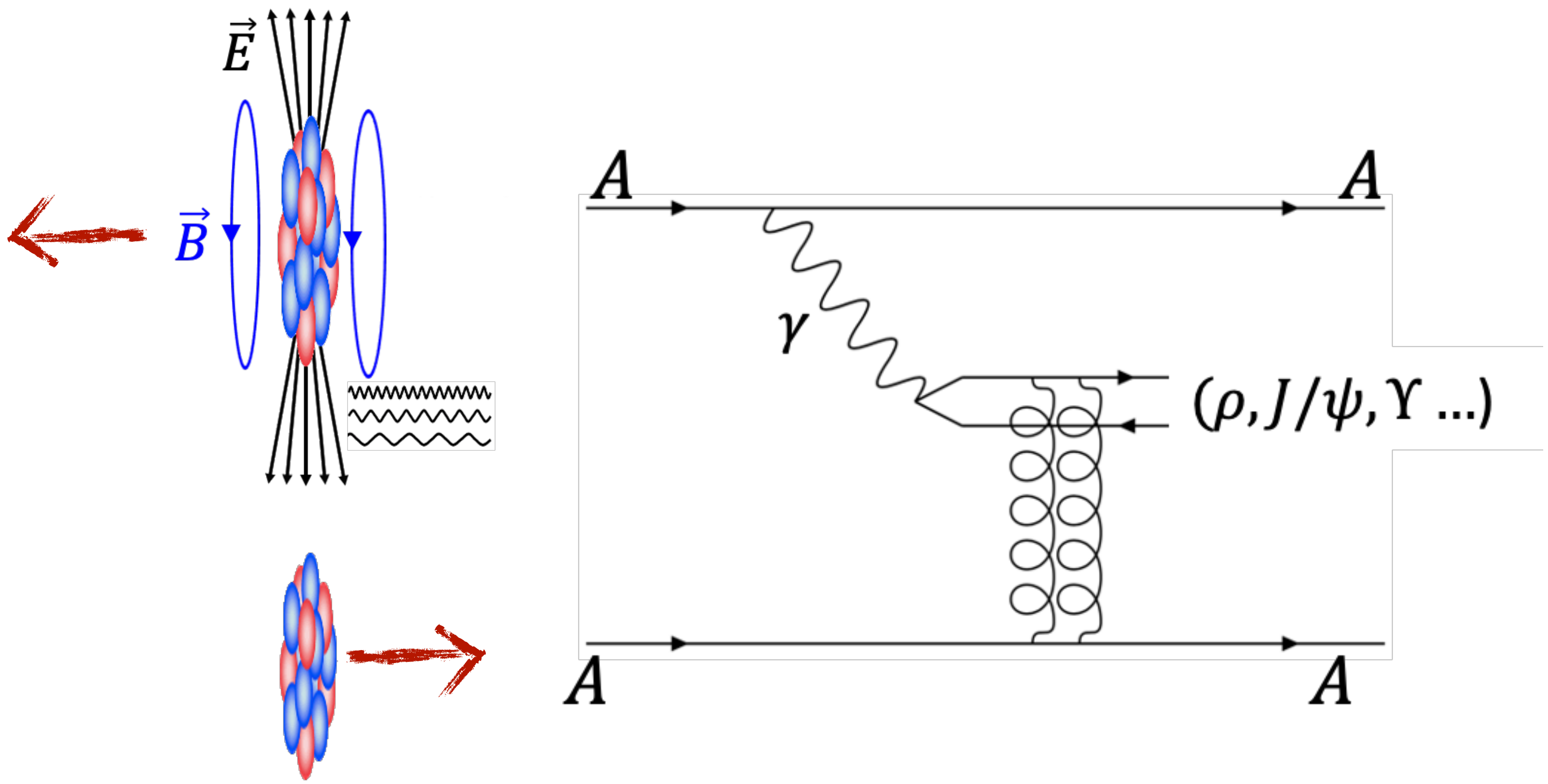
- Well defined kinematics
  - $\omega = \frac{M_{VM}}{2} e^{\pm y} \quad x = \frac{M_{VM}}{2E_{beam}} e^{\mp y}$
  - $W_{\gamma N}^2 = 2E_{beam} M_{VM} e^{\pm y}$

- Low $Q^2 \sim 0$, but heavy quark mass can provide a hard scale for pQCD

- Coherent: average gluon distribution

- Incoherent: event-by-event fluctuation

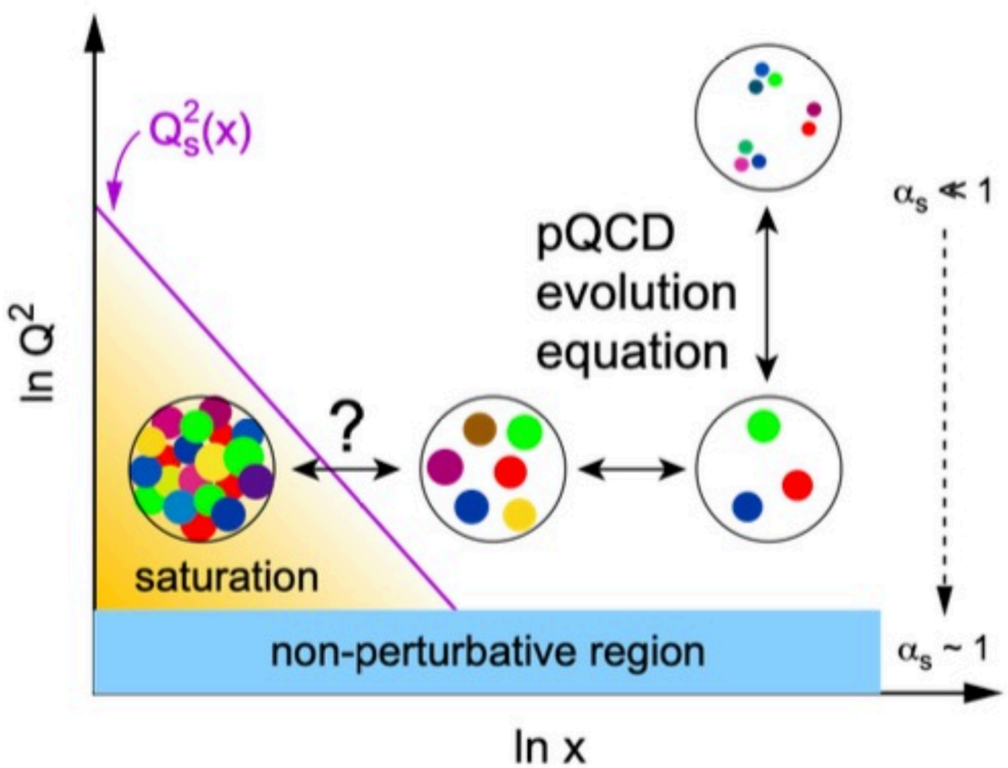
# Concepts in large A+A systems

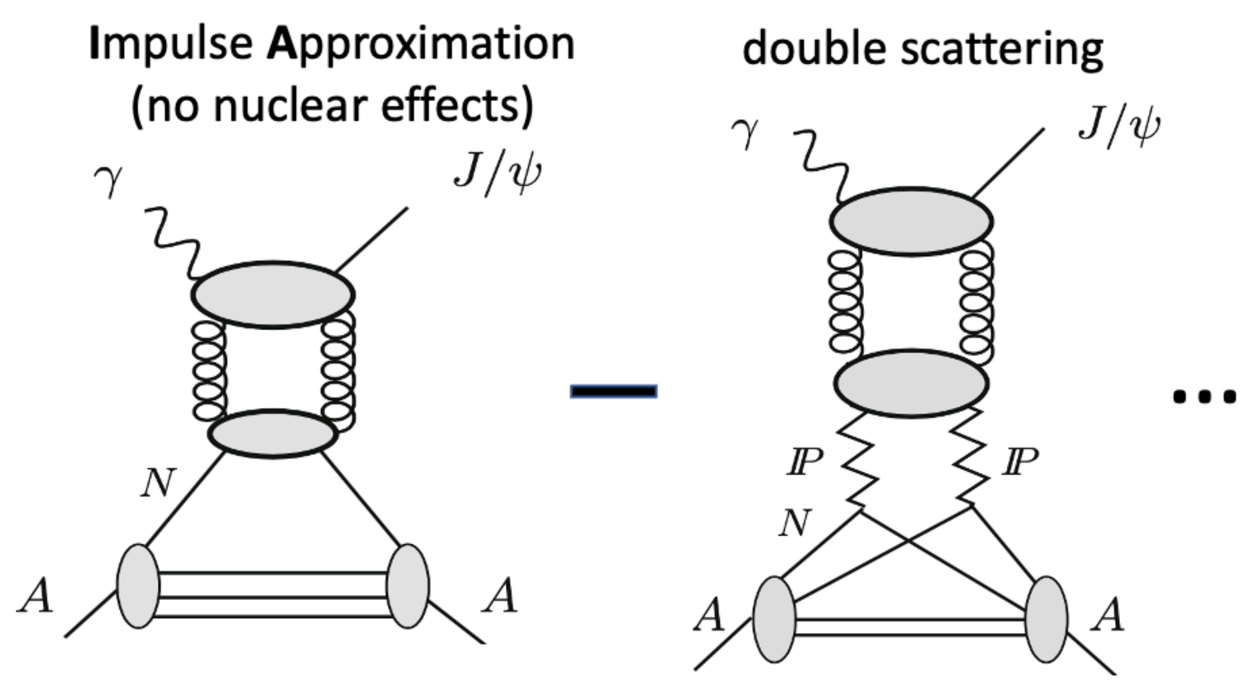



- **Coherent** photoproduction ⟹ scattering off nucleus
- **Incoherent** photoproduction ⟹ scattering off nucleon
  - **Elastic** incoherent process → nucleon keeps intact
  - **Dissociative** incoherent process → nucleon breaks up

# Saturation vs. shadowing

- Both relate to the same concept: density of gluons in nPDF at small-x is reduced w.r.t. the simple addition of the gluon PDF
- Saturation: Dynamical description via gluon self-interactions that tame the growth of gluon
- Nuclear shadowing: Gribov-Glauber model of multiple scattering



# 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

# Theory description

*ALICE, EPJC 81 (2021) 712*

- 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