Probing the gluonic matter in ultraperipheral collisions with the LHC experiments

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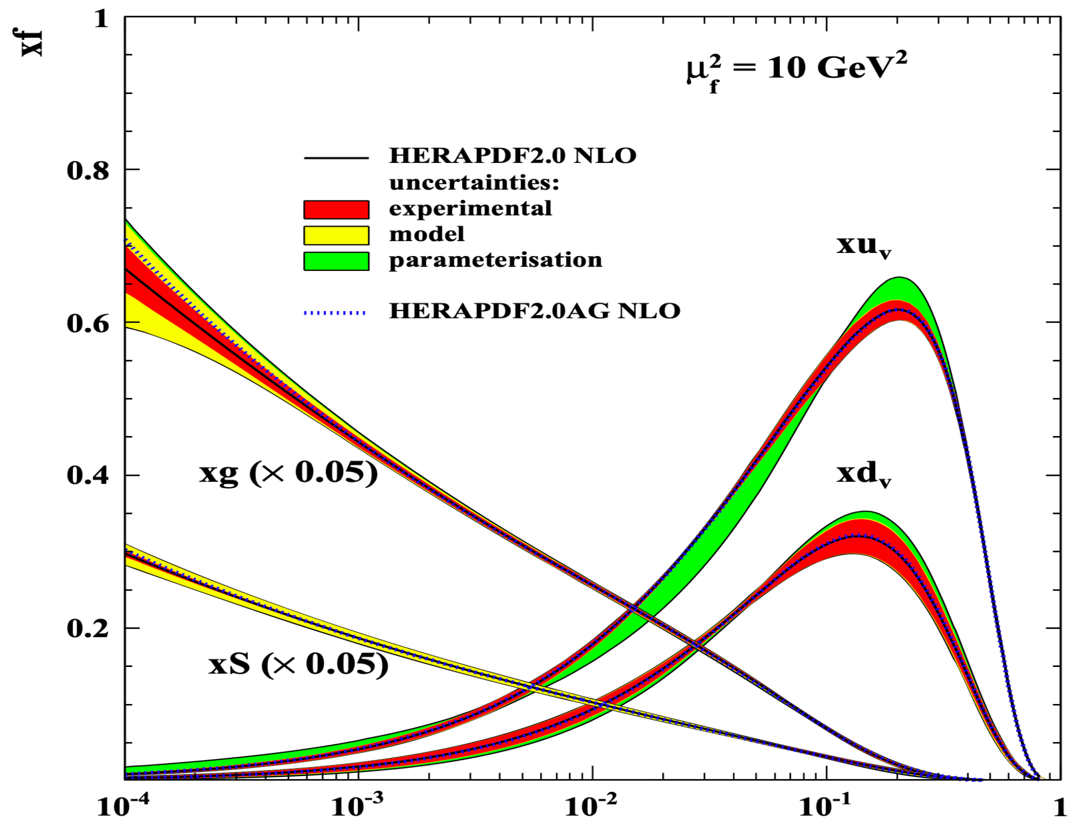
South China Normal University

Third EIC-Asia Workshop, Jan 29-31, 2024

Explore internal structure of matter

H1 and ZEUS, EPJC 75 (2015) 580



Small x ← Large x

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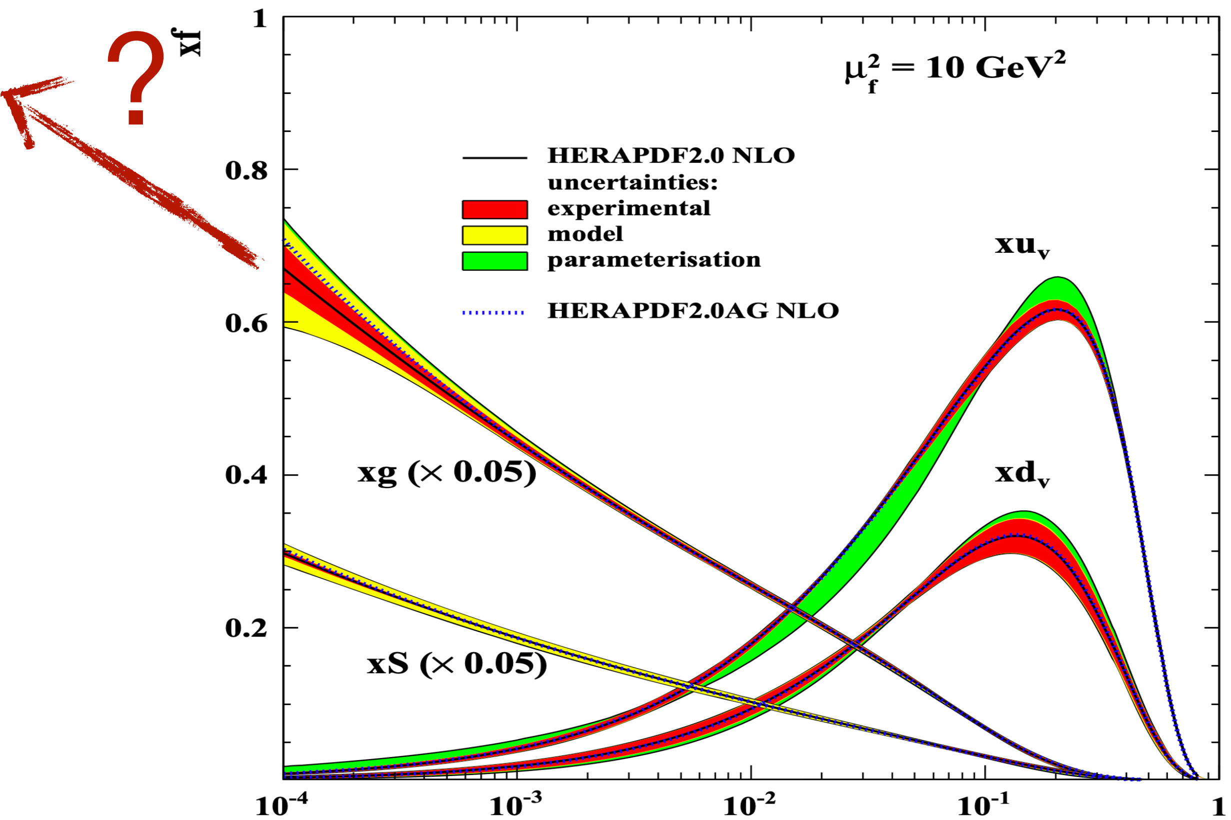

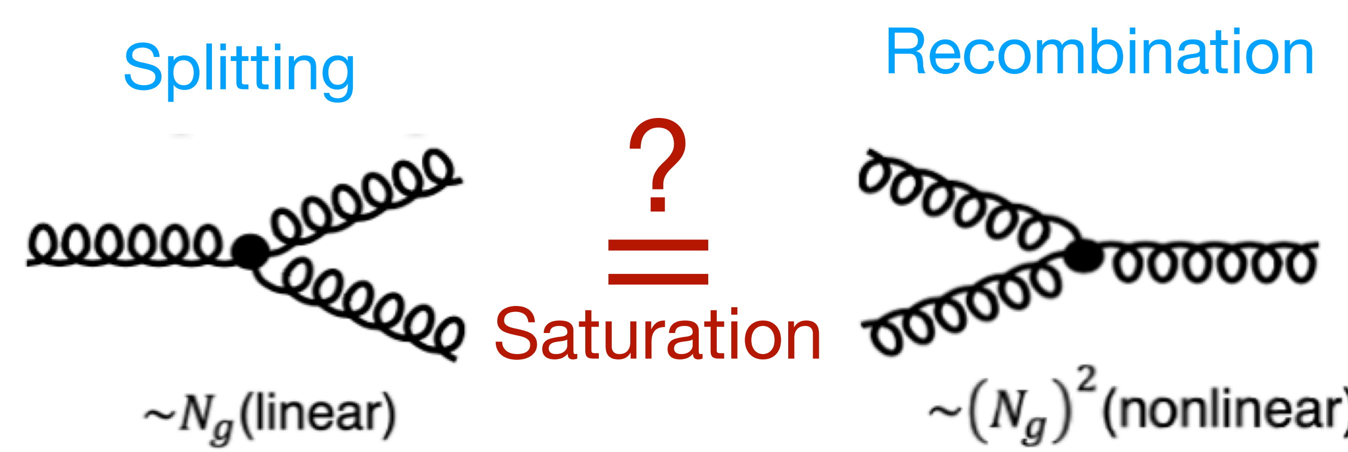

QCD unitarity: growth of gluon density can't continue indefinitely!

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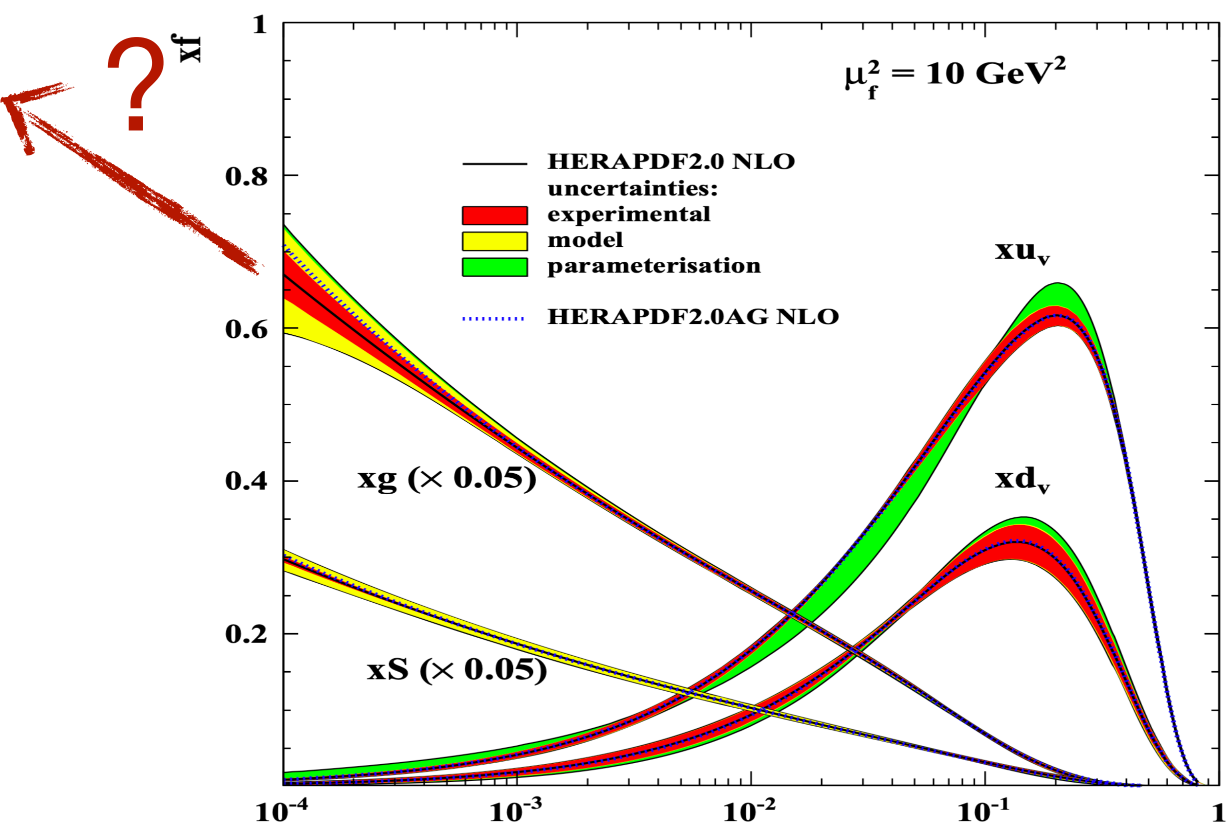

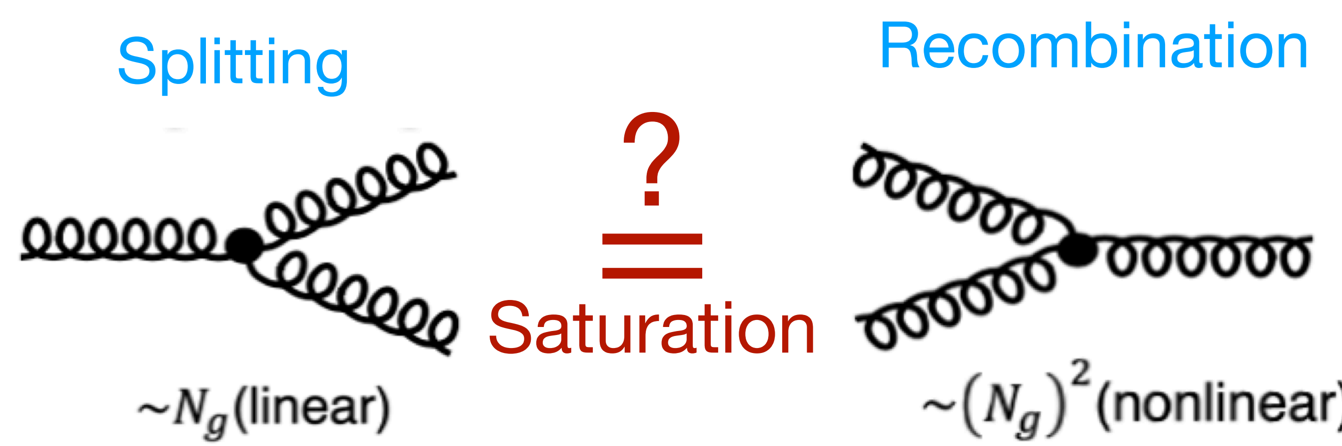

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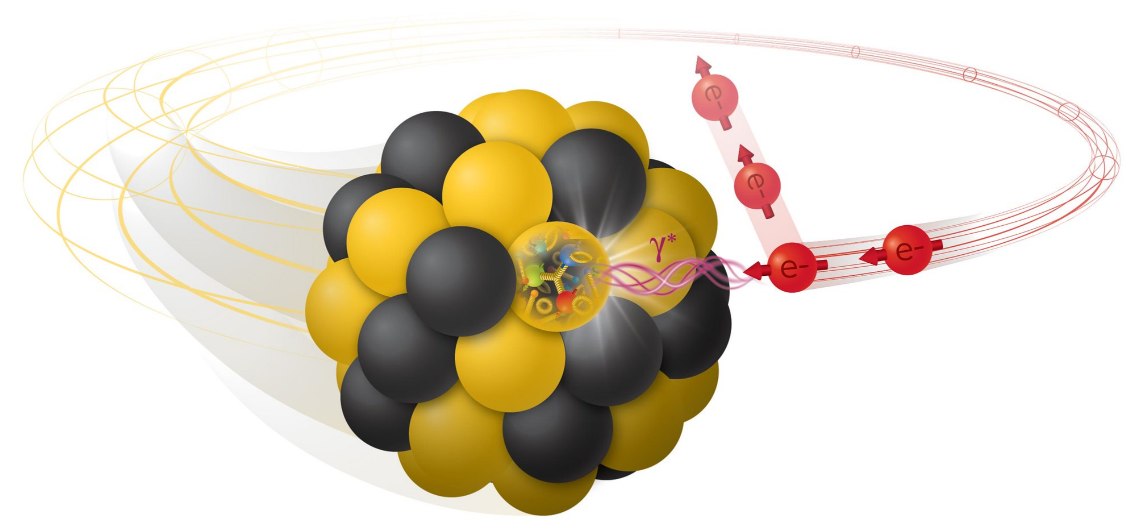

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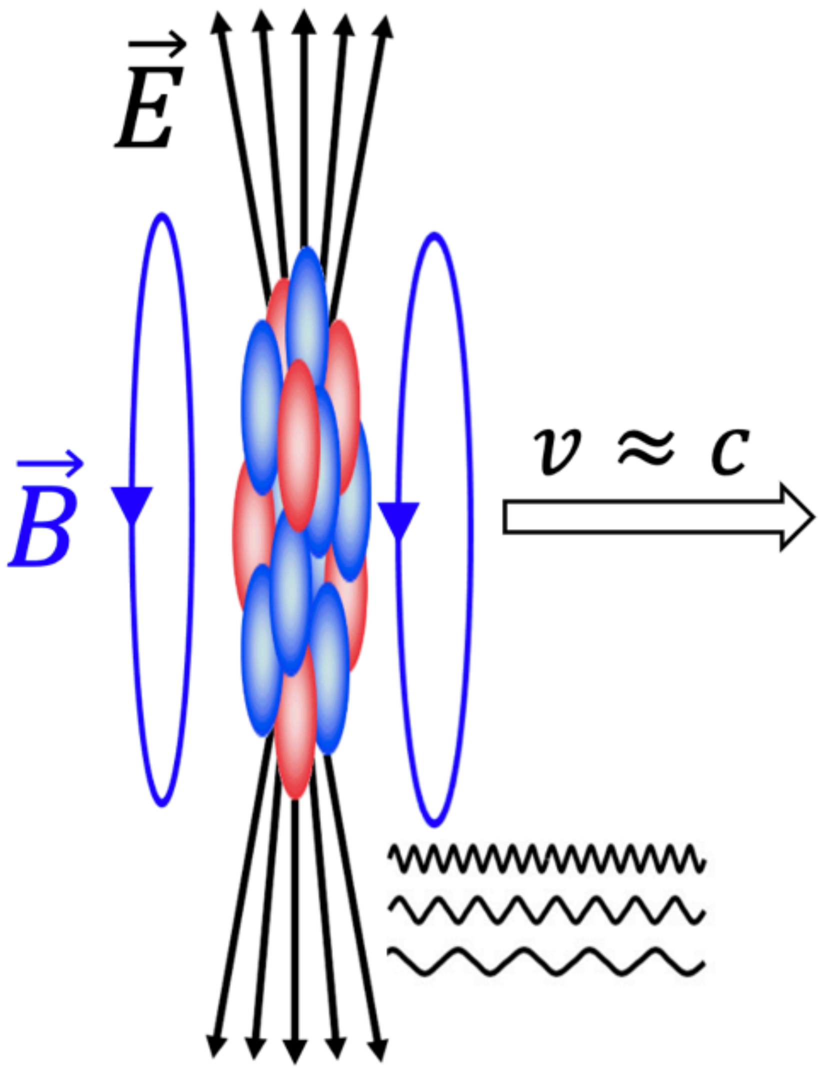
What can we do before EIC?



- **Equivalent Photon Approximation**
  - Proposed in 1924 by Fermi (1901-1954)
  - Extended EPA method to relativistic particles by Williams&Weiszsacker
  - Photon Flux $\propto Z^2$

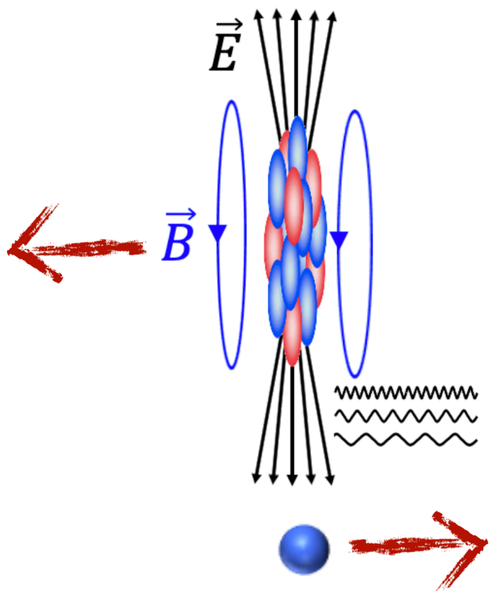
Fermi, Z. Phys. 29 (1924) 315
Williams, Phys. Rev. 45 (1934) 729
Weizsacker, Z. Phys. 88 (1934) 612

- **Photon kinematics**

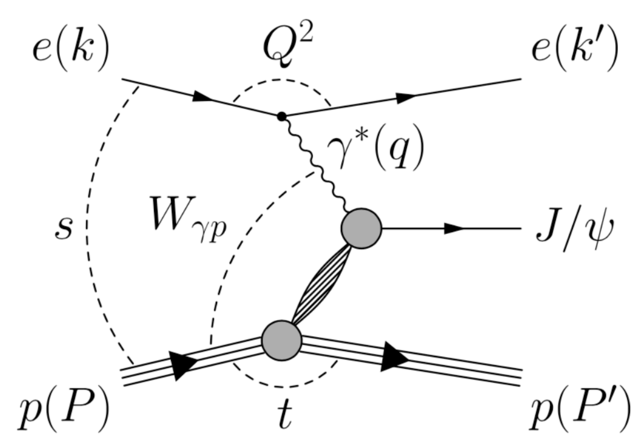
maximum energy $E_{\gamma,max} \sim \gamma(\hbar c/R)$	**80 GeV in Pb+Pb@LHC 3 GeV in Au+Au@RHIC**
typical p_T (& virtuality) $p_{Tmax} \sim \hbar c/R$	**O(30) MeV @ RHIC & LHC**
Coherent strengths (rates) scale as $\mathbf{Z^2}$: nuclei >> protons	Flux of photons on other nucleus ~ $\mathbf{Z^2}$, flux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

Photon-nuclear interactions

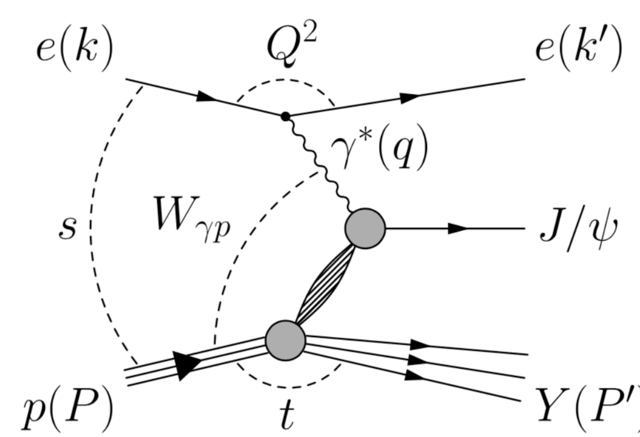
Little “HERA”



Elastic



Inelastic



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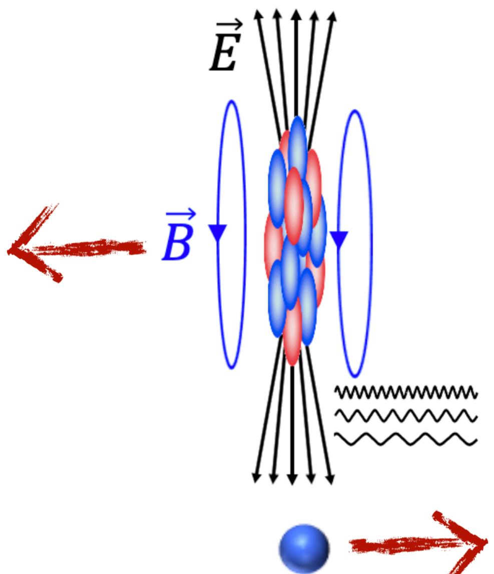

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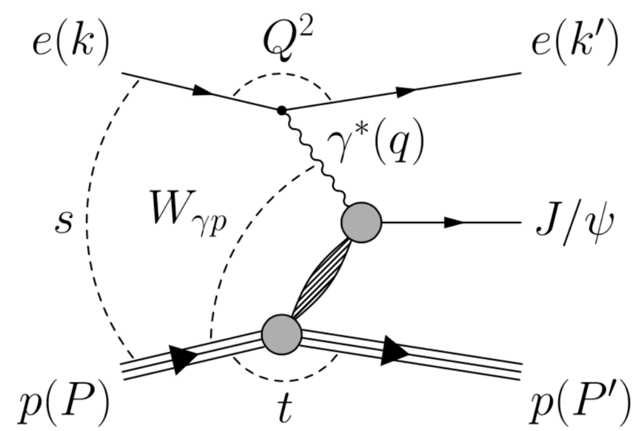

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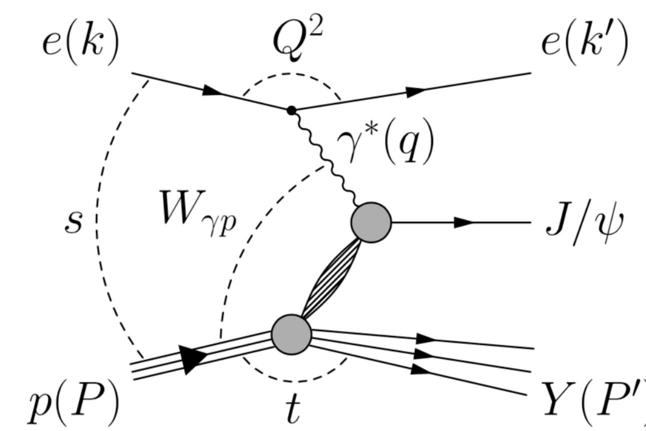
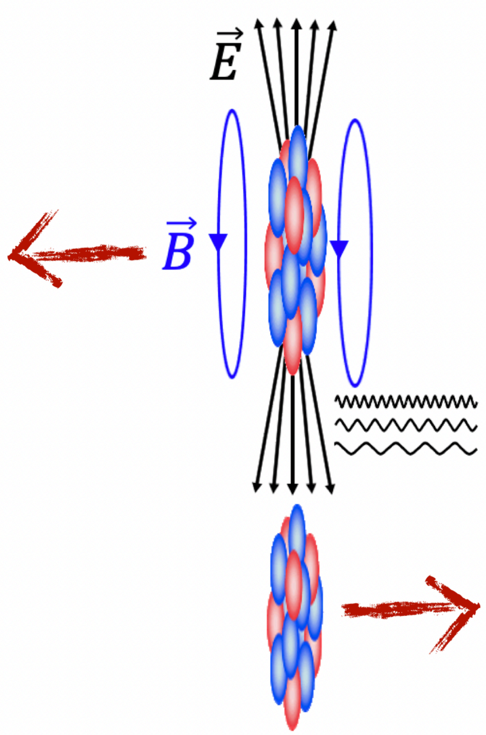
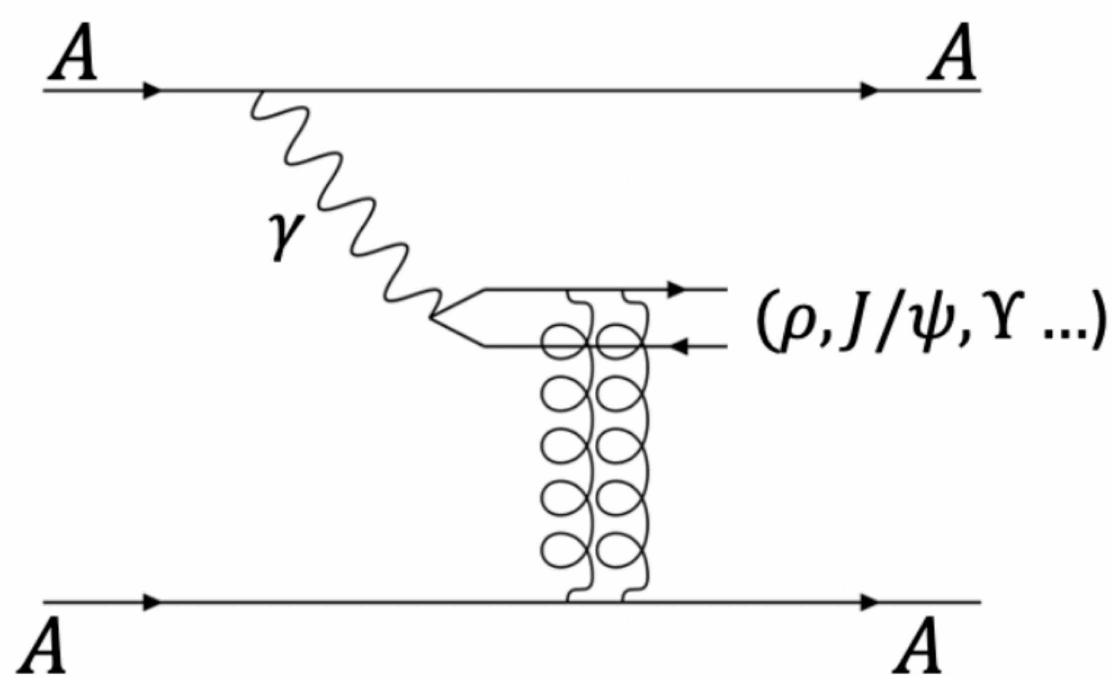


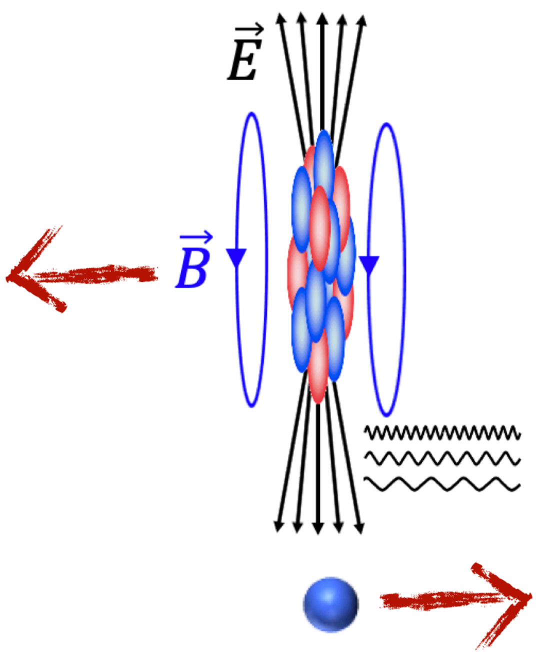
Little “EIC”

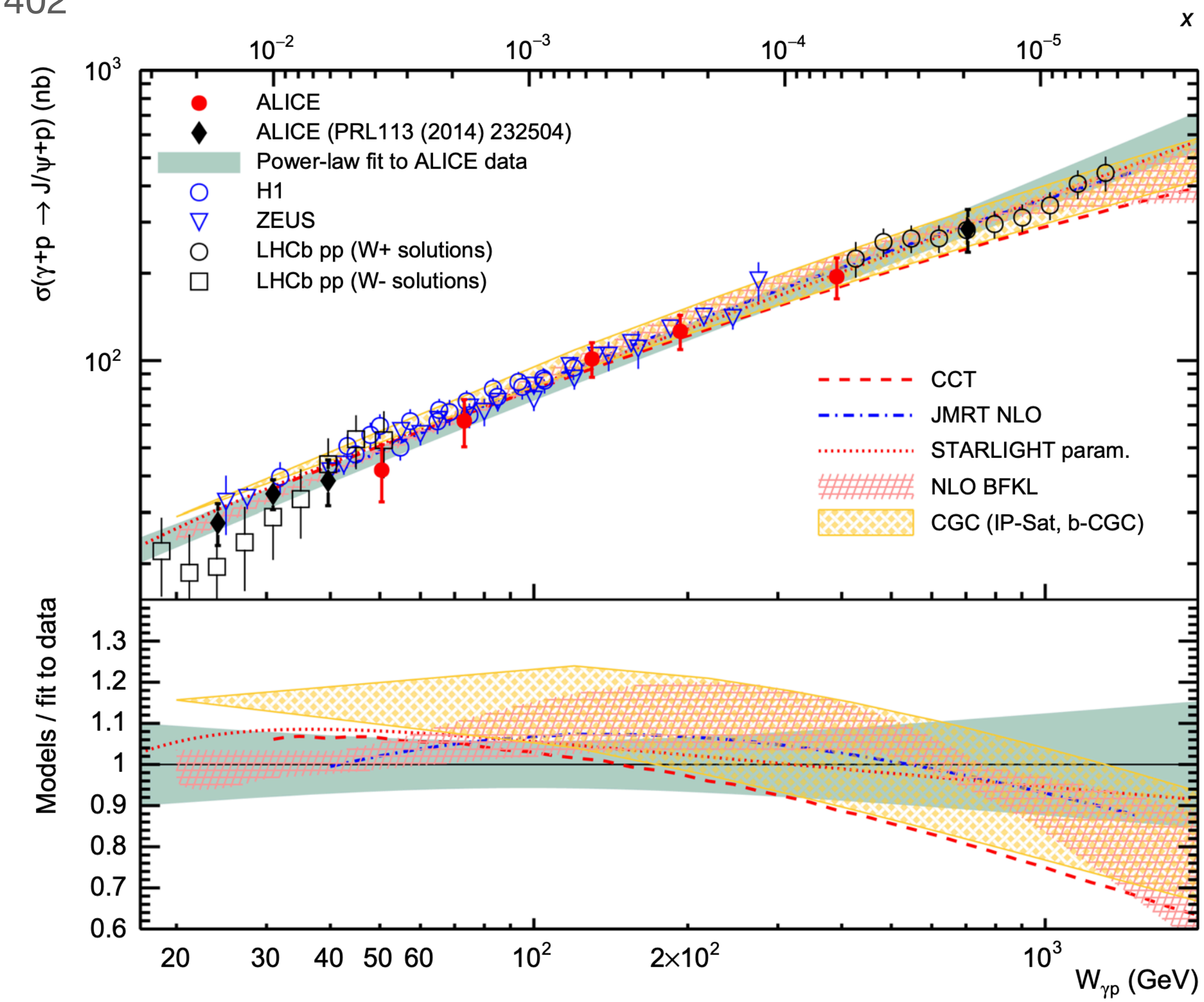




Imaging free nucleon

ALICE, EPJC 79 (2019) 402



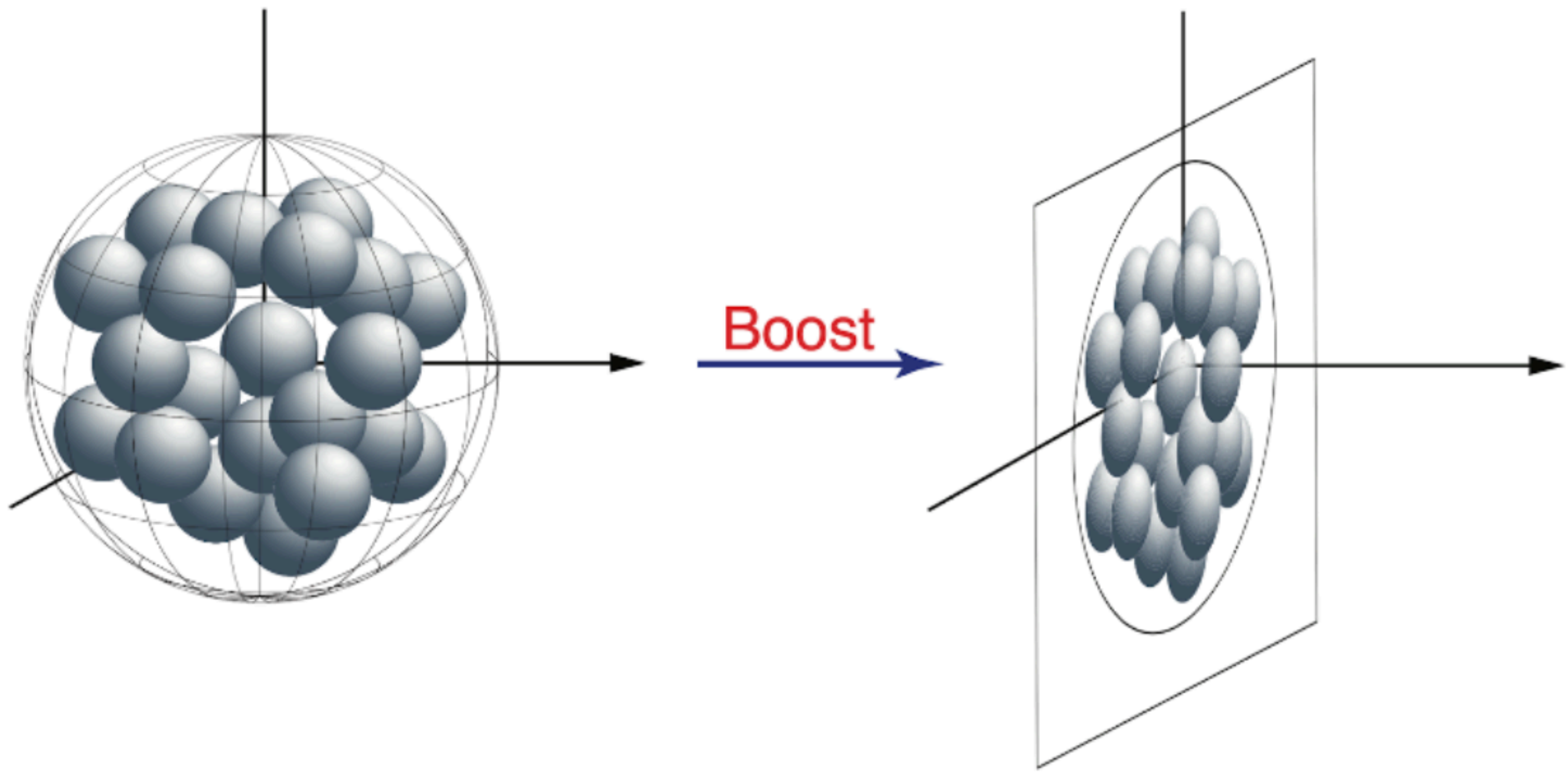


LO pQCD:

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

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

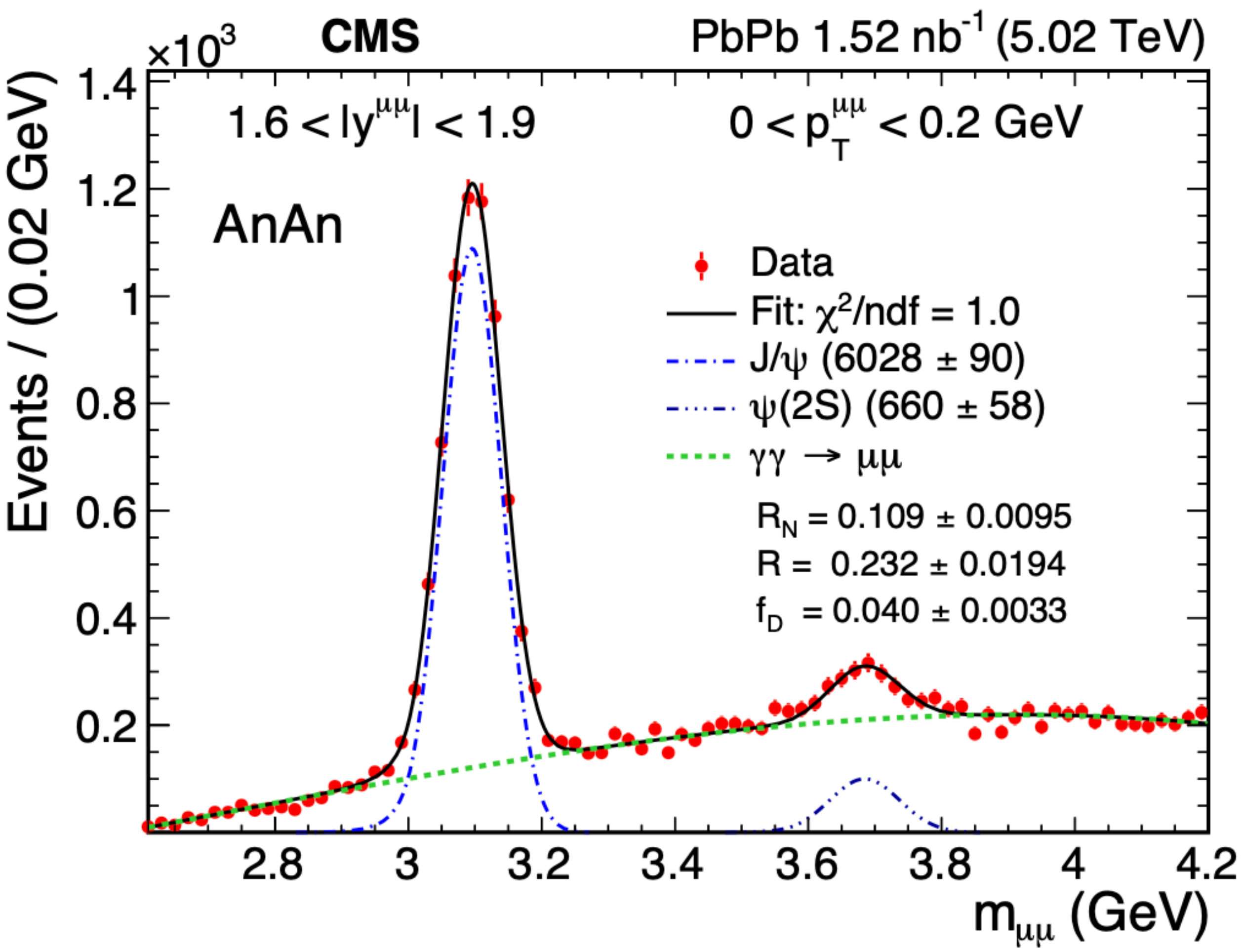
Ultra-dense gluonic matter

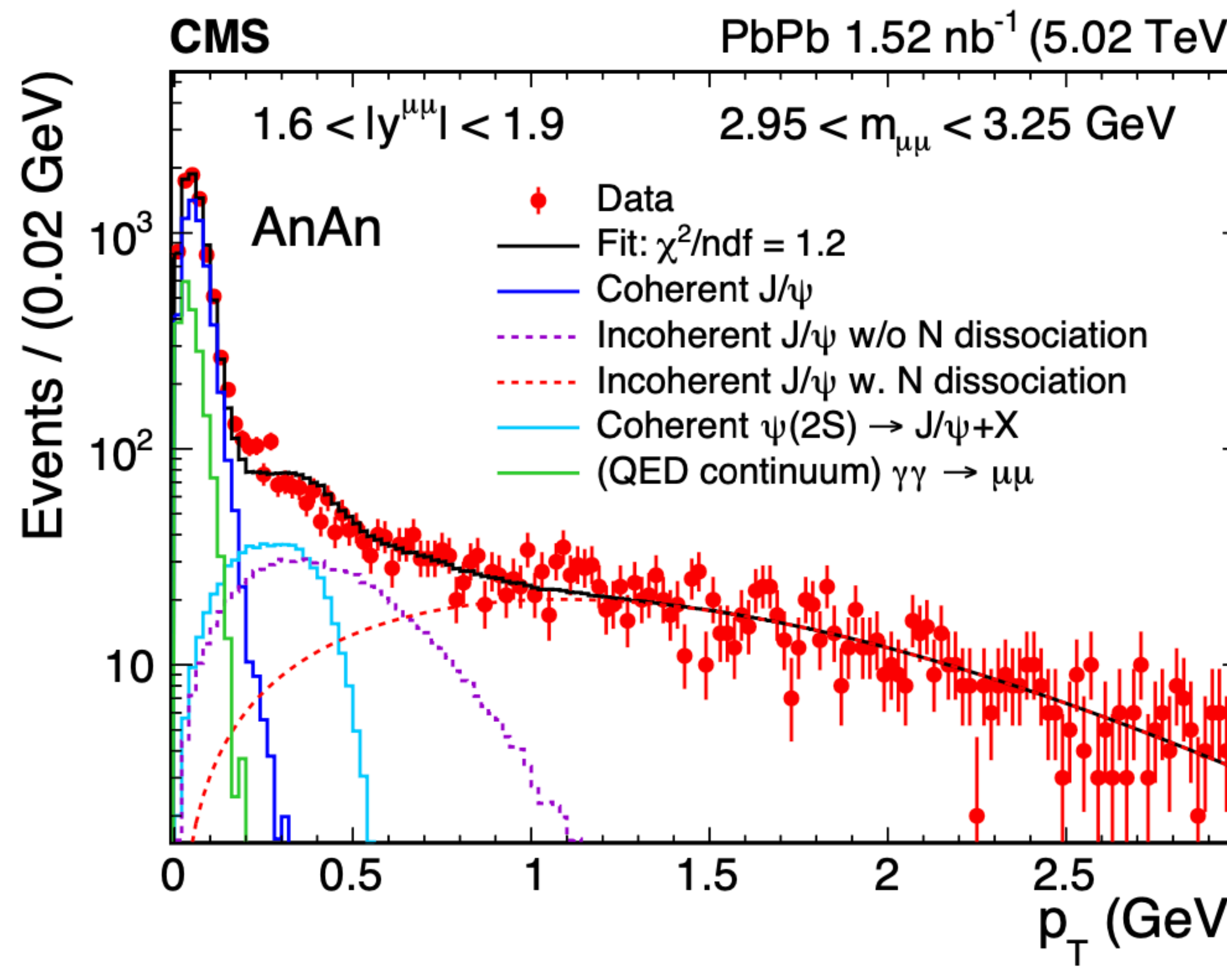


- Gluon saturation is expected to be easier to be achieved inside heavy nuclei

Signal extraction

CMS, PRL 131 (2023) 262301

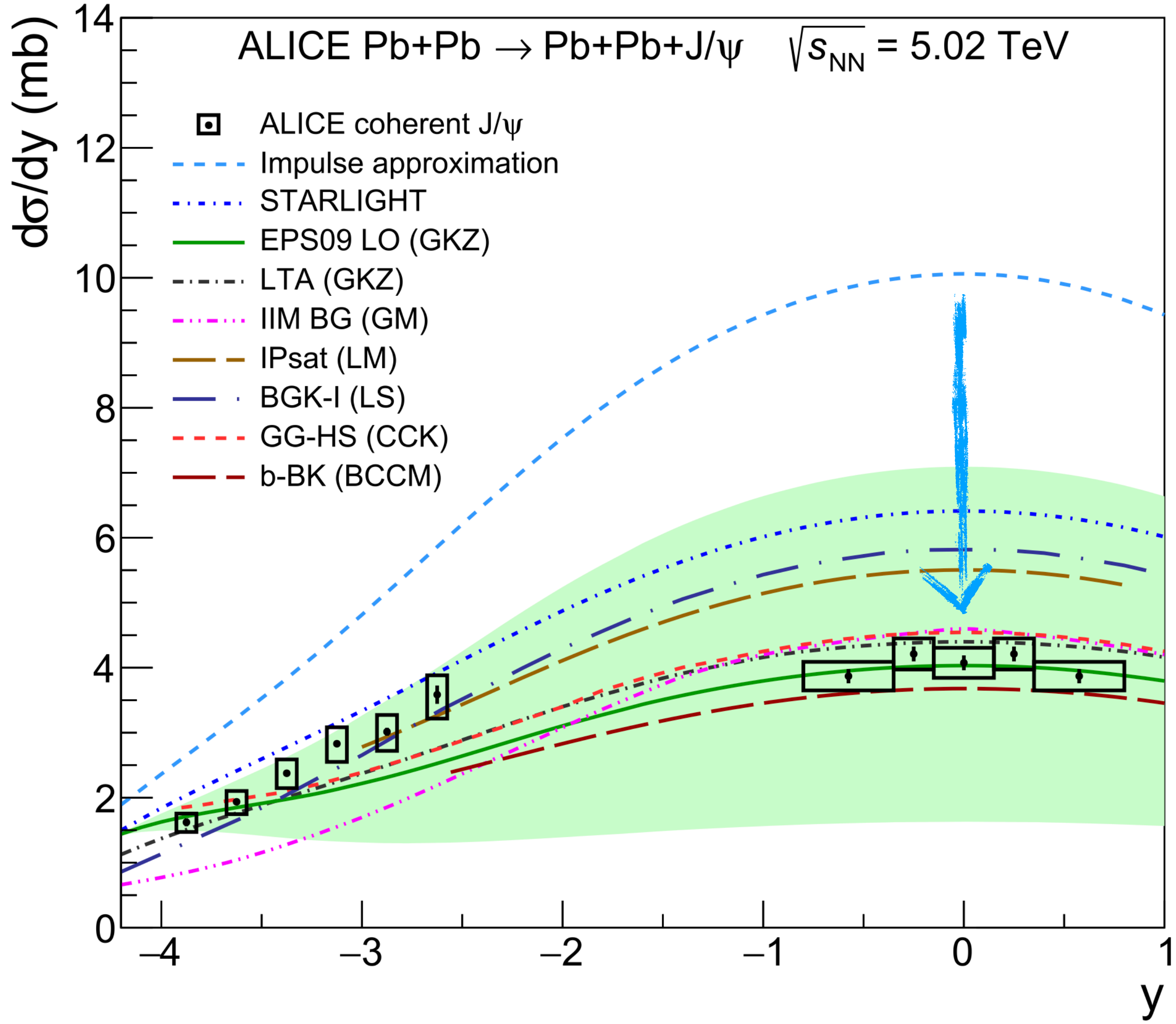




- Signals of coherent J/ψ are extracted by simultaneously fitting the mass and p_T spectra

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 $x \sim 10^{-3}$

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

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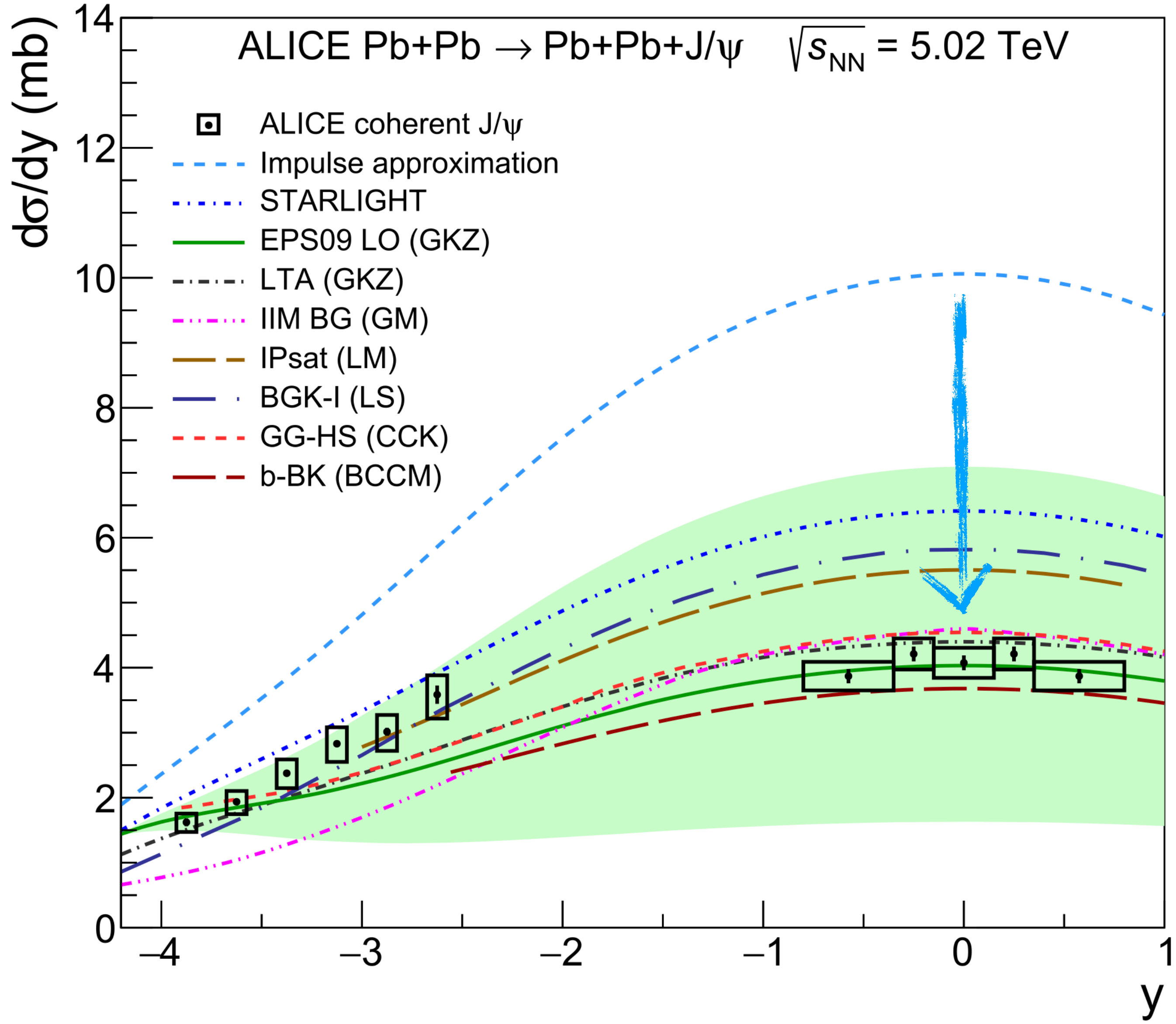

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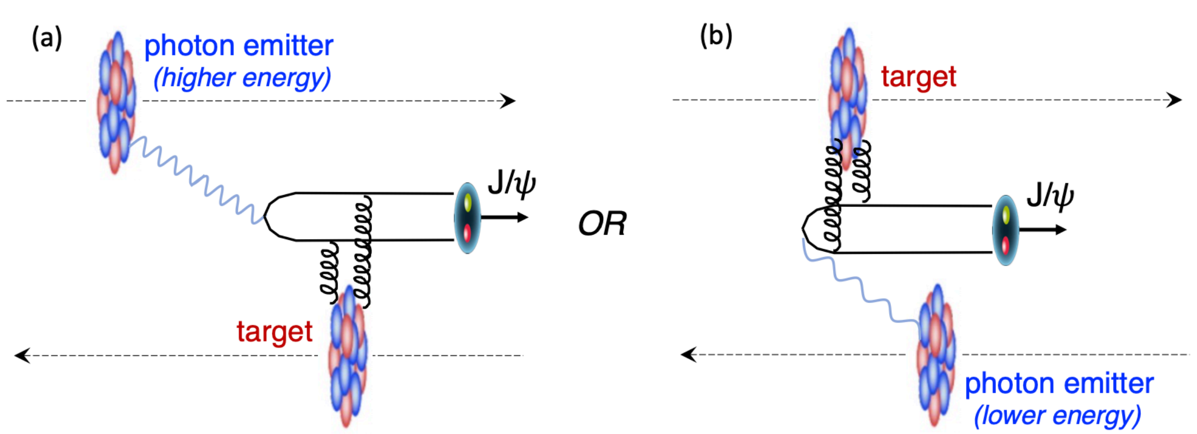
- Two-way ambiguity in A+A UPC



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

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

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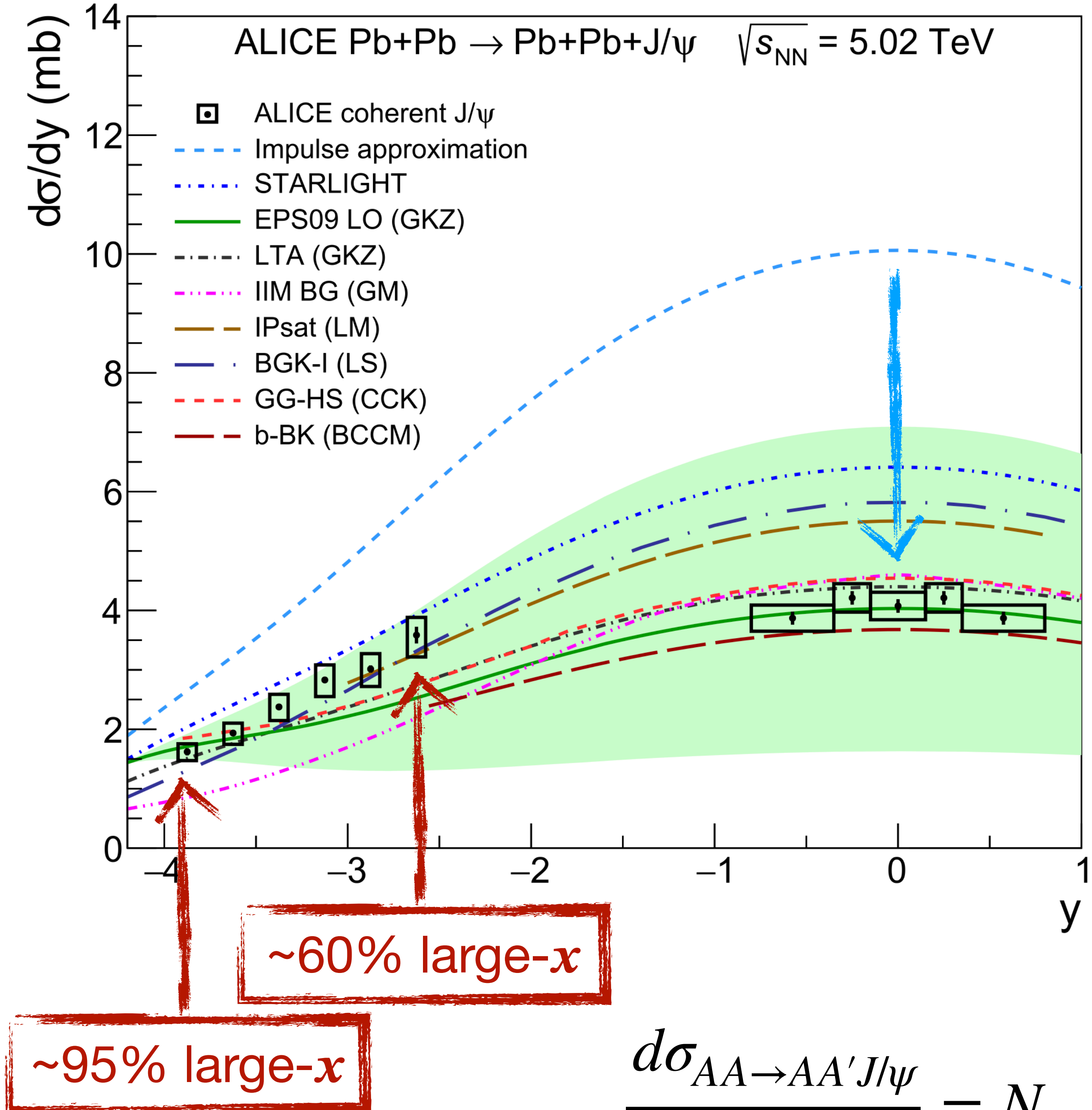

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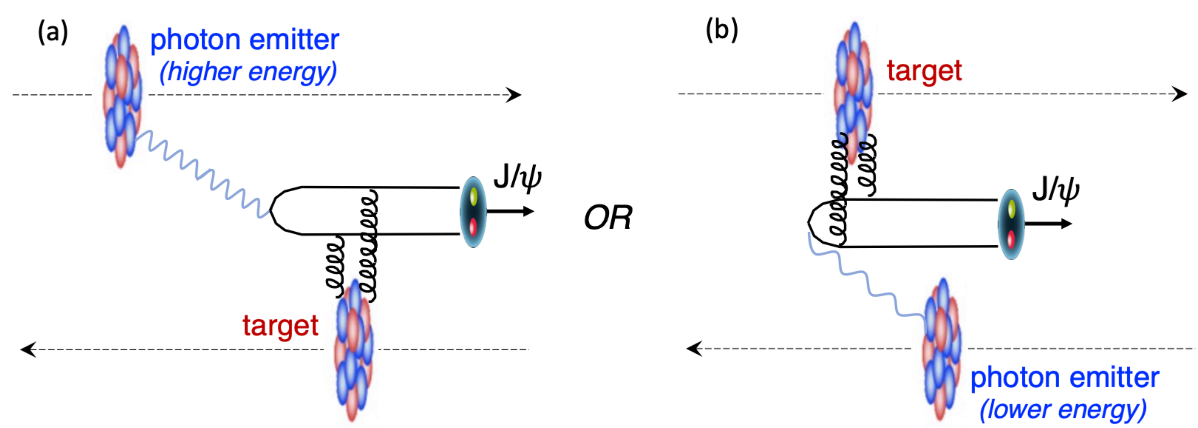

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CMS, PRL 131 (2023) 262301
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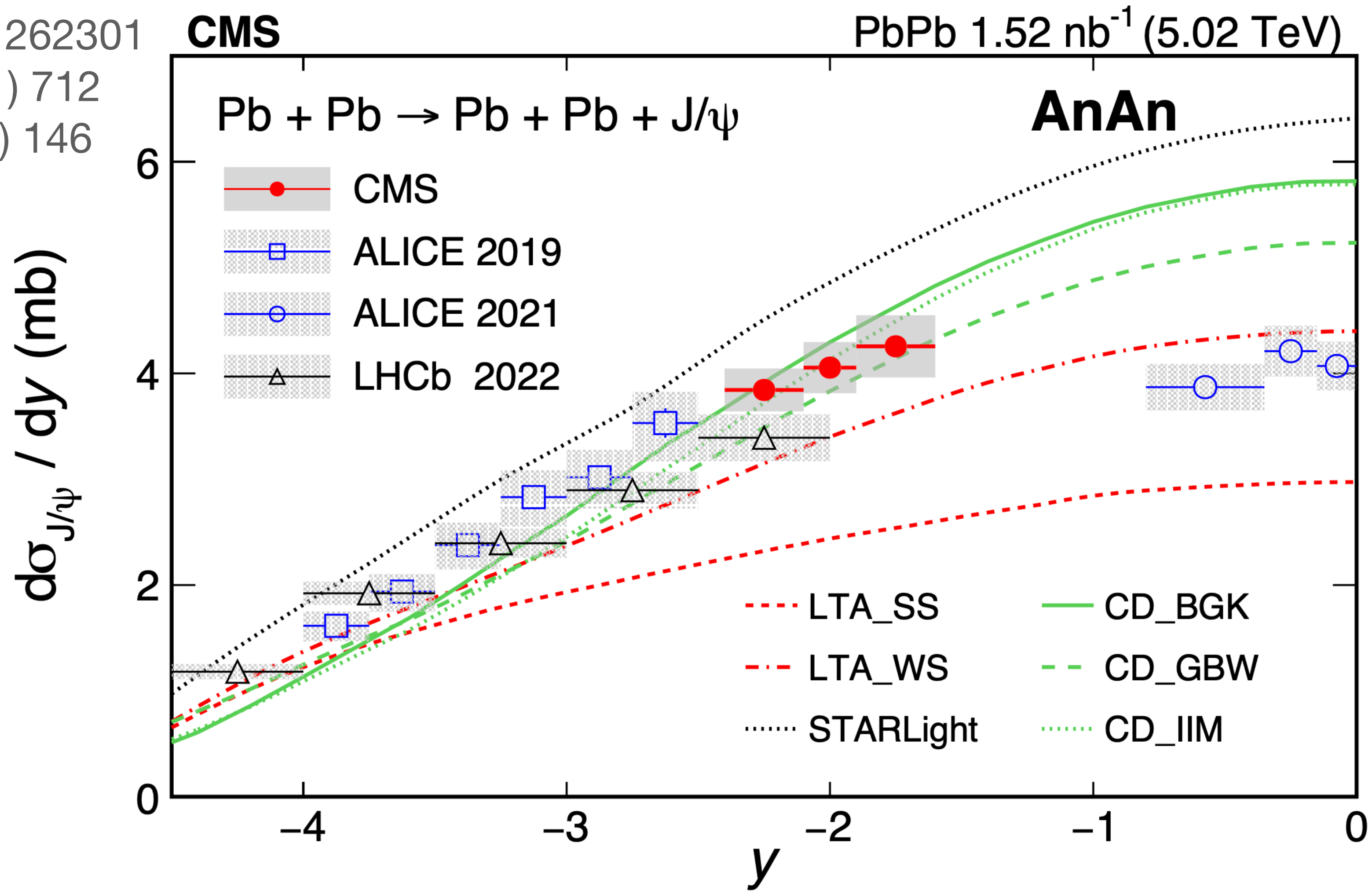
LHCb, JHEP 06 (2023) 146

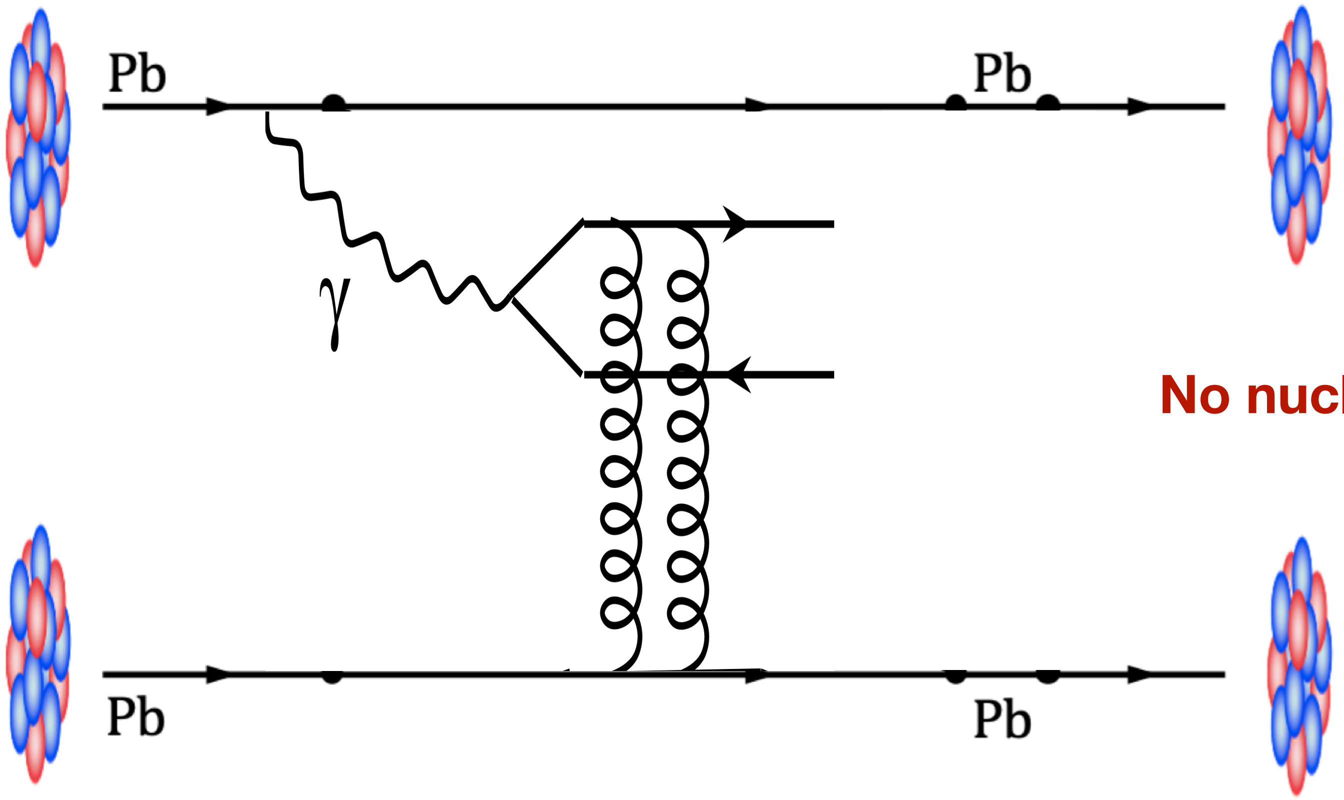


- LHC experiments complement each over a wide range of y region
  - No theory can describe data over full y region! What is missing?

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

A solution to the “two-way ambiguity”

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



No nucleus breakup

A solution to the “two-way ambiguity”

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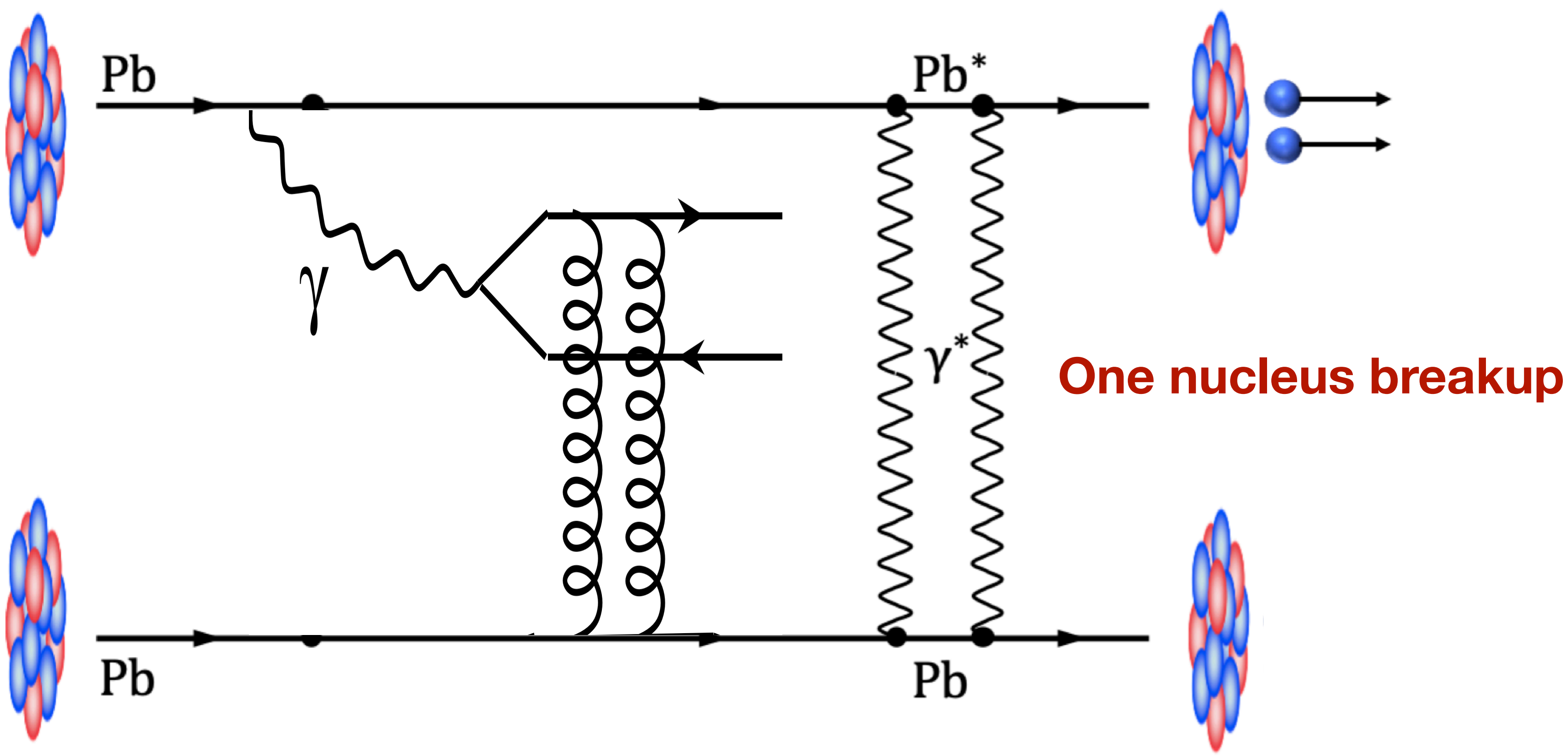

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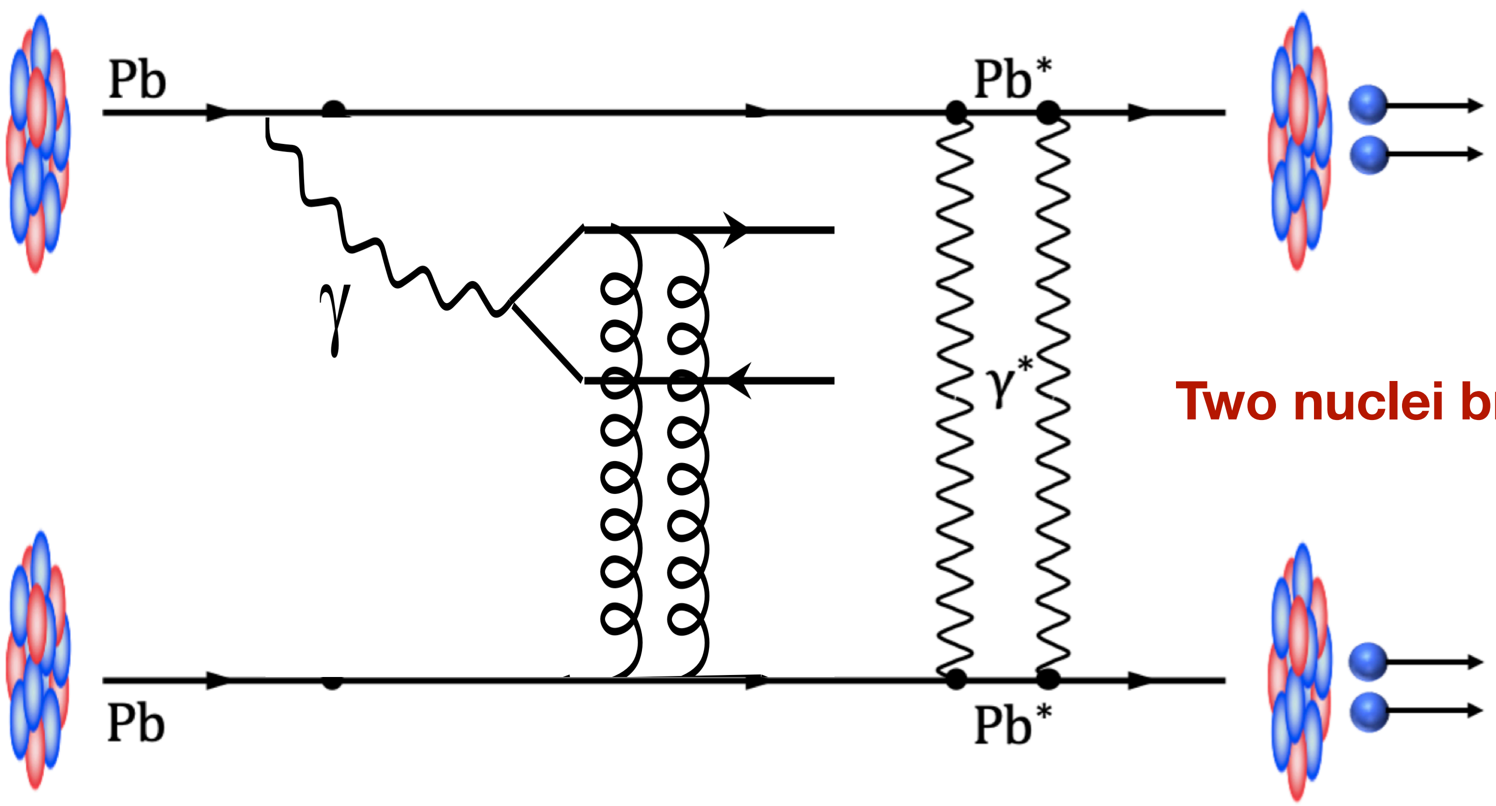

Two nuclei breakup

A solution to the “two-way ambiguity”

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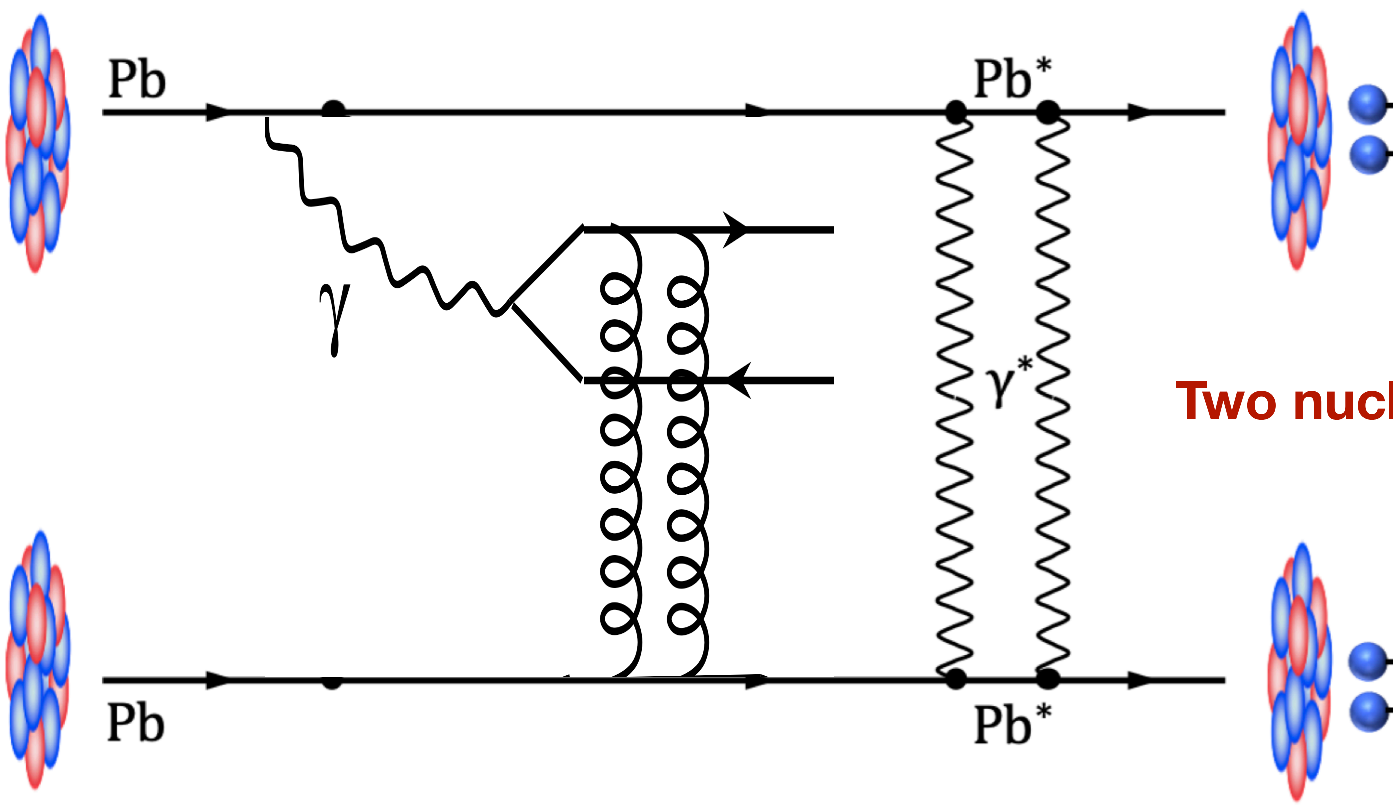
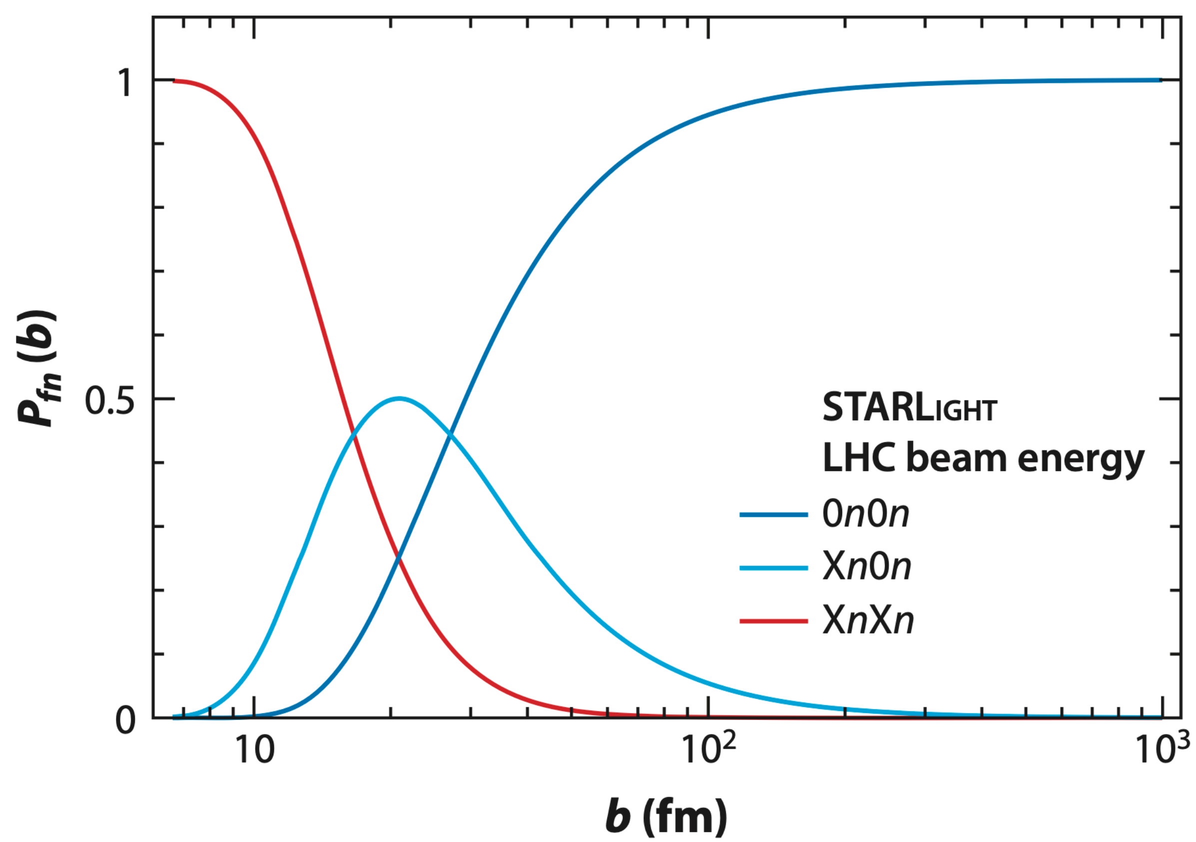




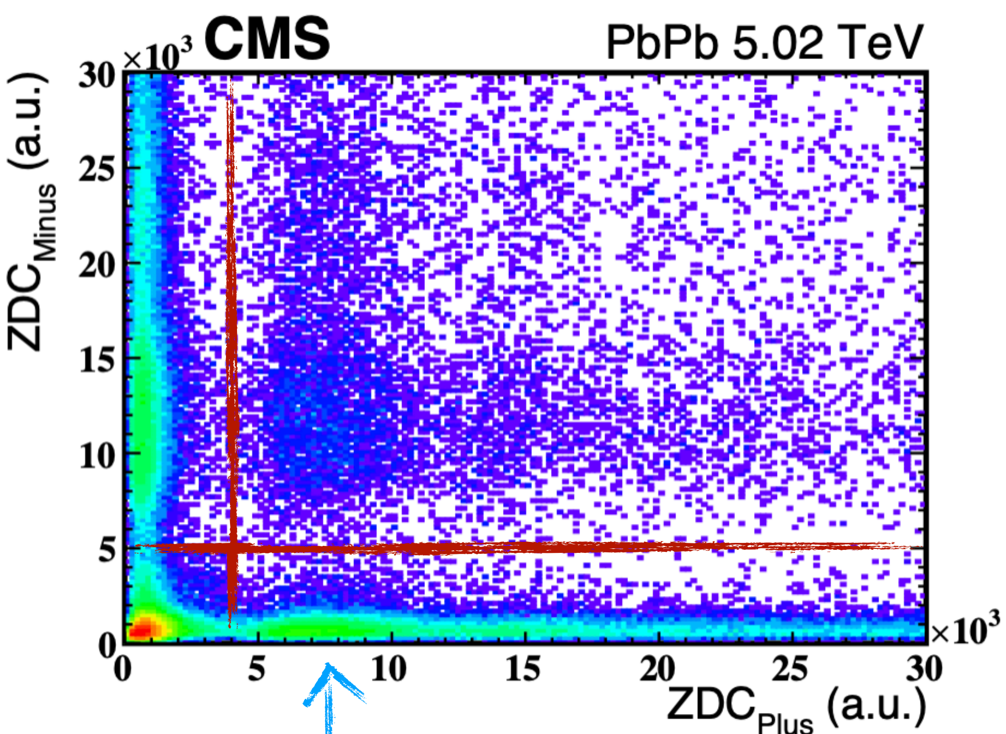
Klein and Steinberg, Ann. Rev. Nucl. Part. Sci. 70 (2020) 323

- Control the impact parameter of UPCs via forward neutron multiplicity
  - $b_{XnXn} < b_{0nXn} < b_{0n0n}$

A solution to the "two-way ambiguity"

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

CMS, PRL 127 (2021) 122001



Single neutron peak

Experimental measurements

Photon flux from theory

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

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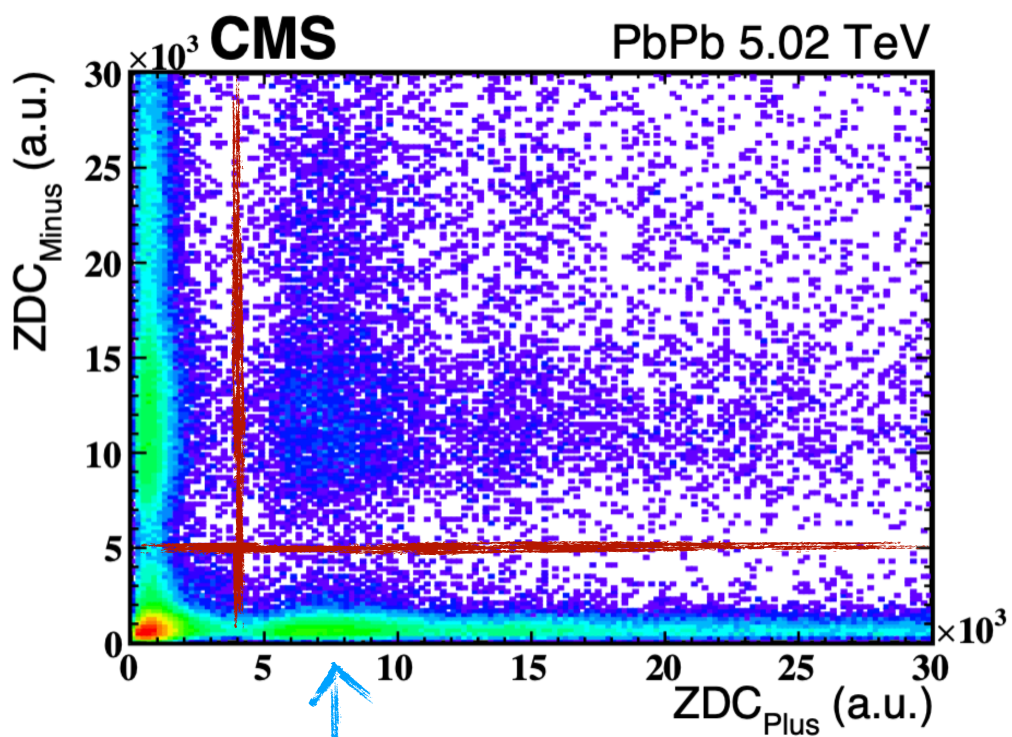

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What we need!

↓

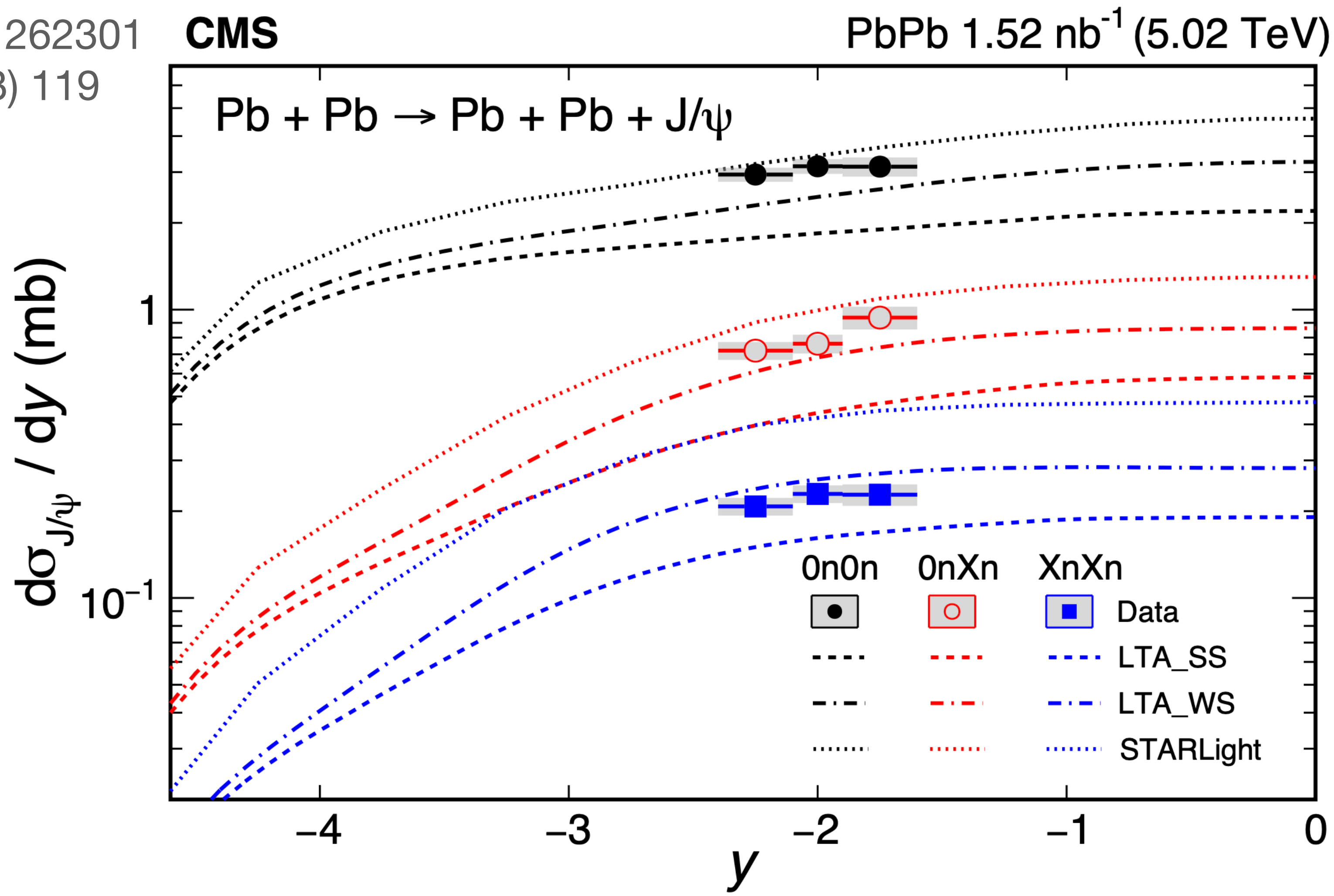
Solve the "two-way ambiguity"

↓

Probe gluons at x~10^{-5}-10^{-4} in heavy nucleus!

Coherent J/ψ production vs. XnYn

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



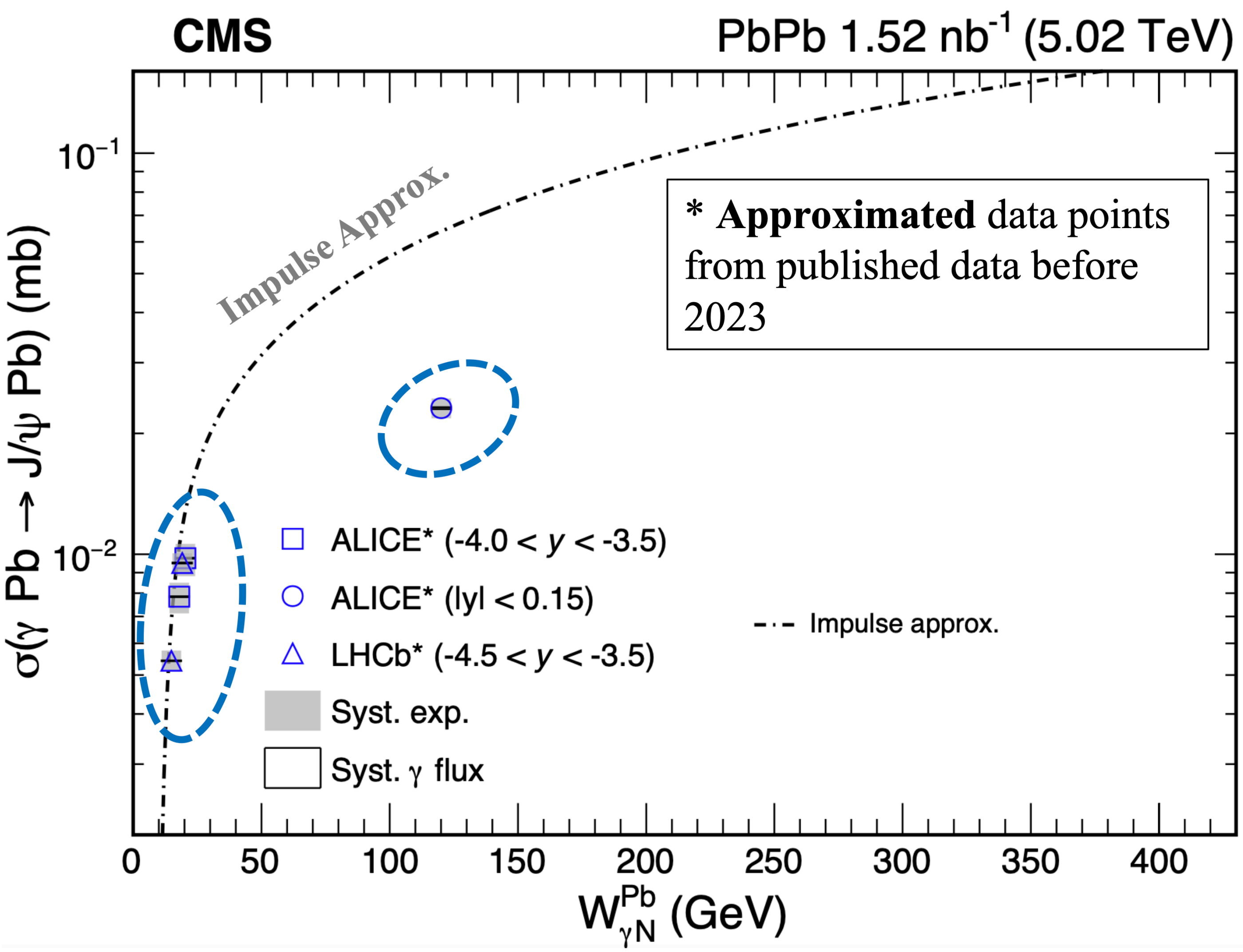
0n0n: ⟨b⟩ > 40 fm

0nXn: ⟨b⟩ ~ 20 fm

XnXn: ⟨b⟩ <15 fm

- First measurement of neutron multiplicity dependence of coherent J/ψ production
  - LTA and STARLight calculations cannot describe data
  - Enable to solve the “two-way ambiguity”

Coherent J/ψ 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
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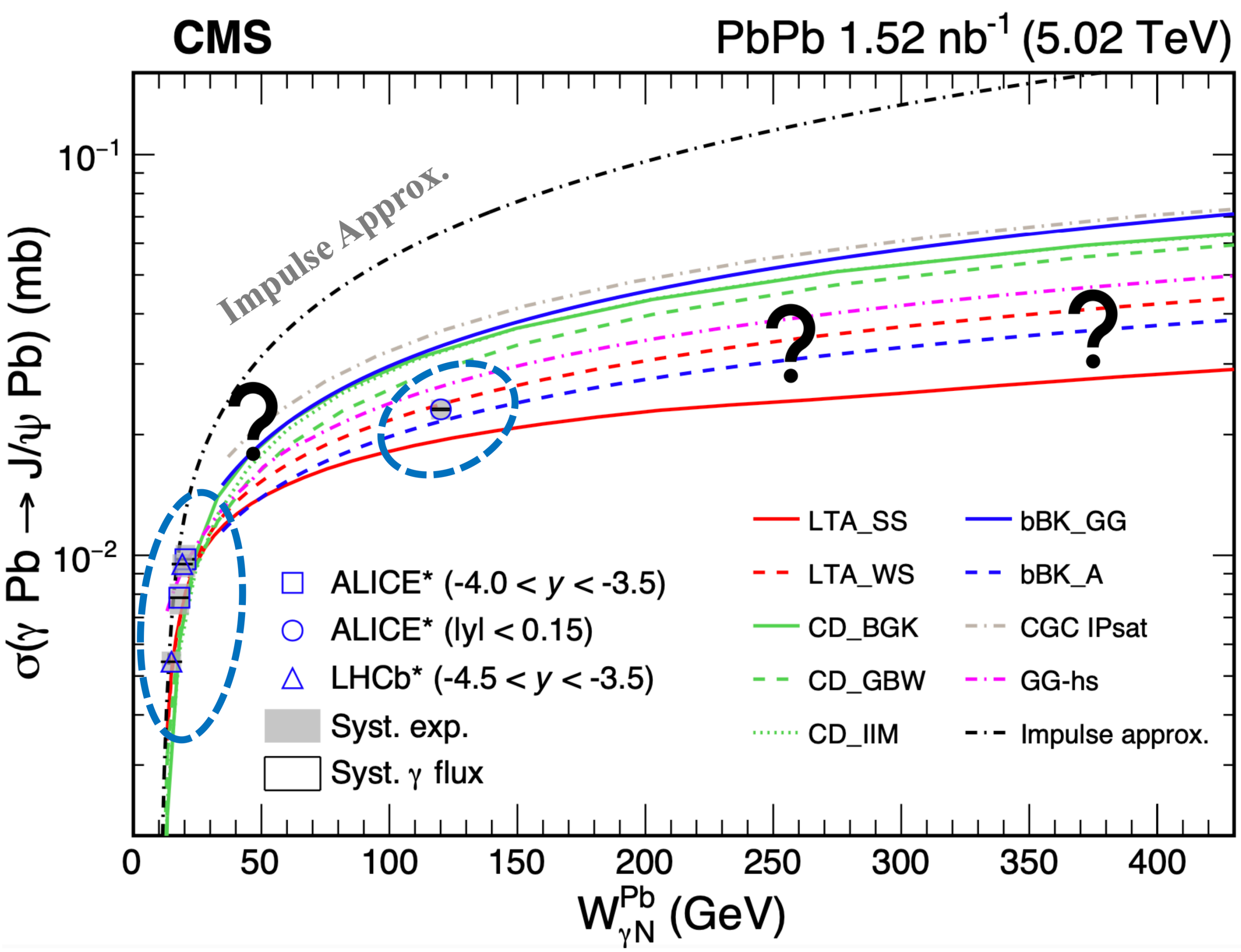

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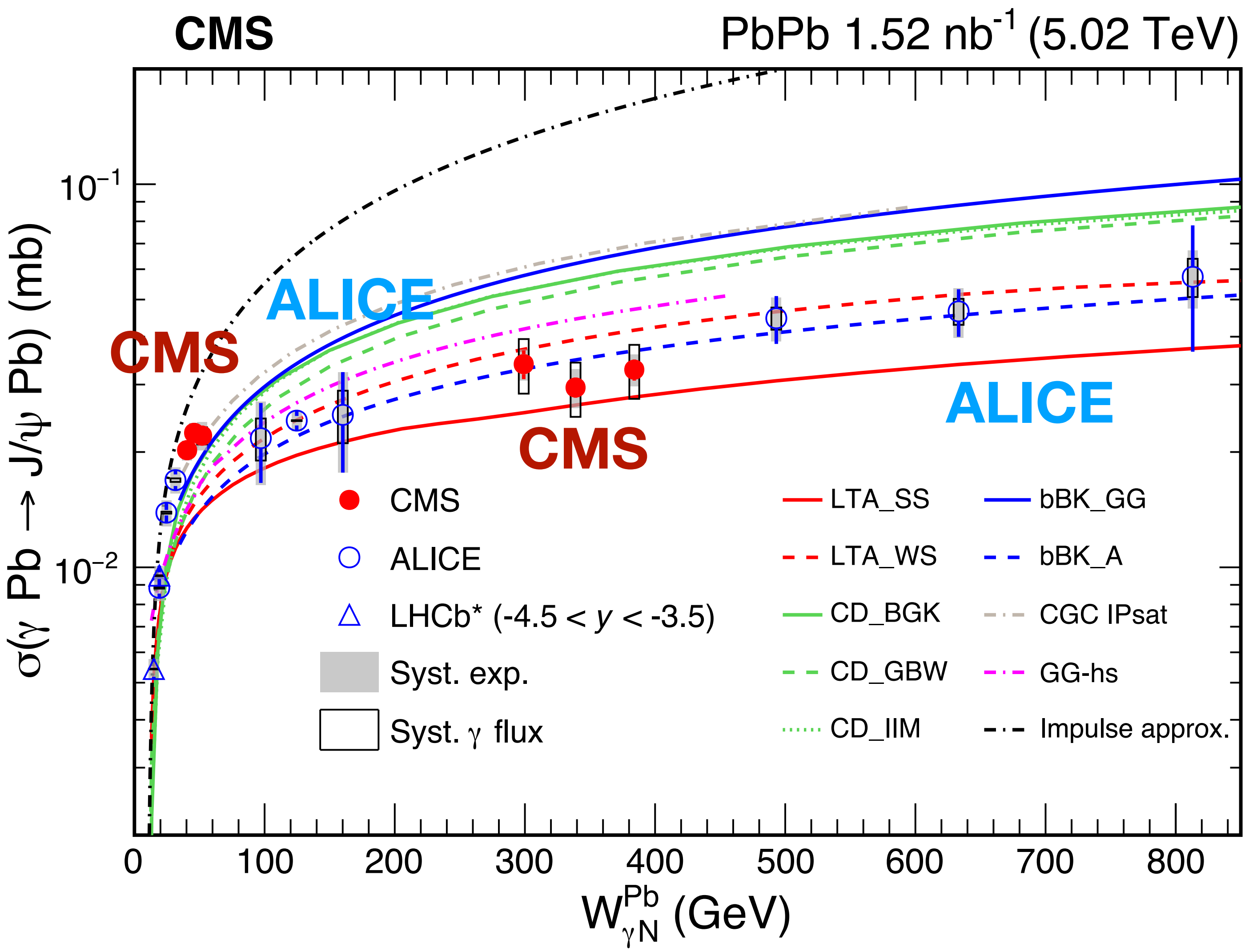

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- LHC measurement up to $W_{\gamma N}^{Pb} \approx 800$ GeV

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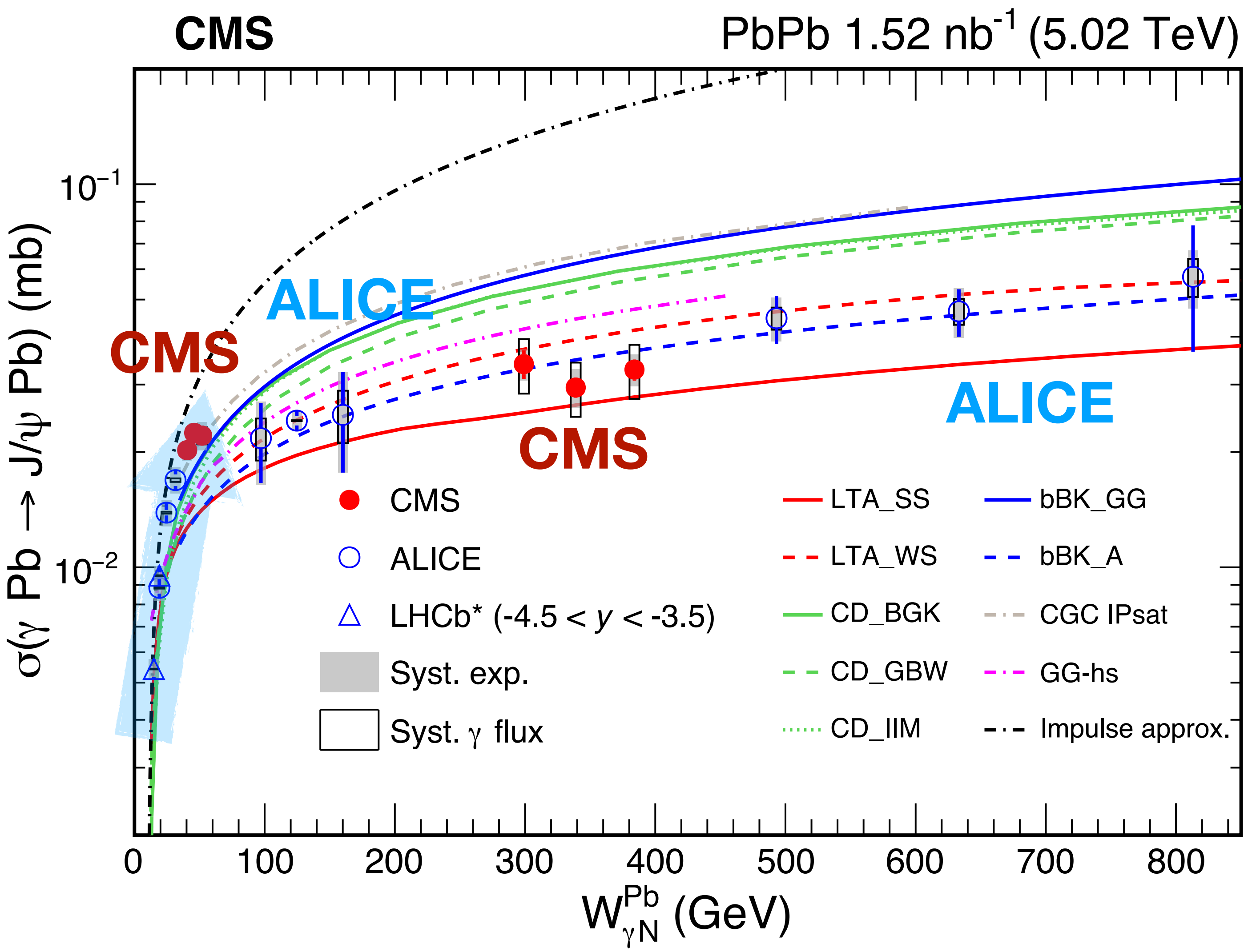

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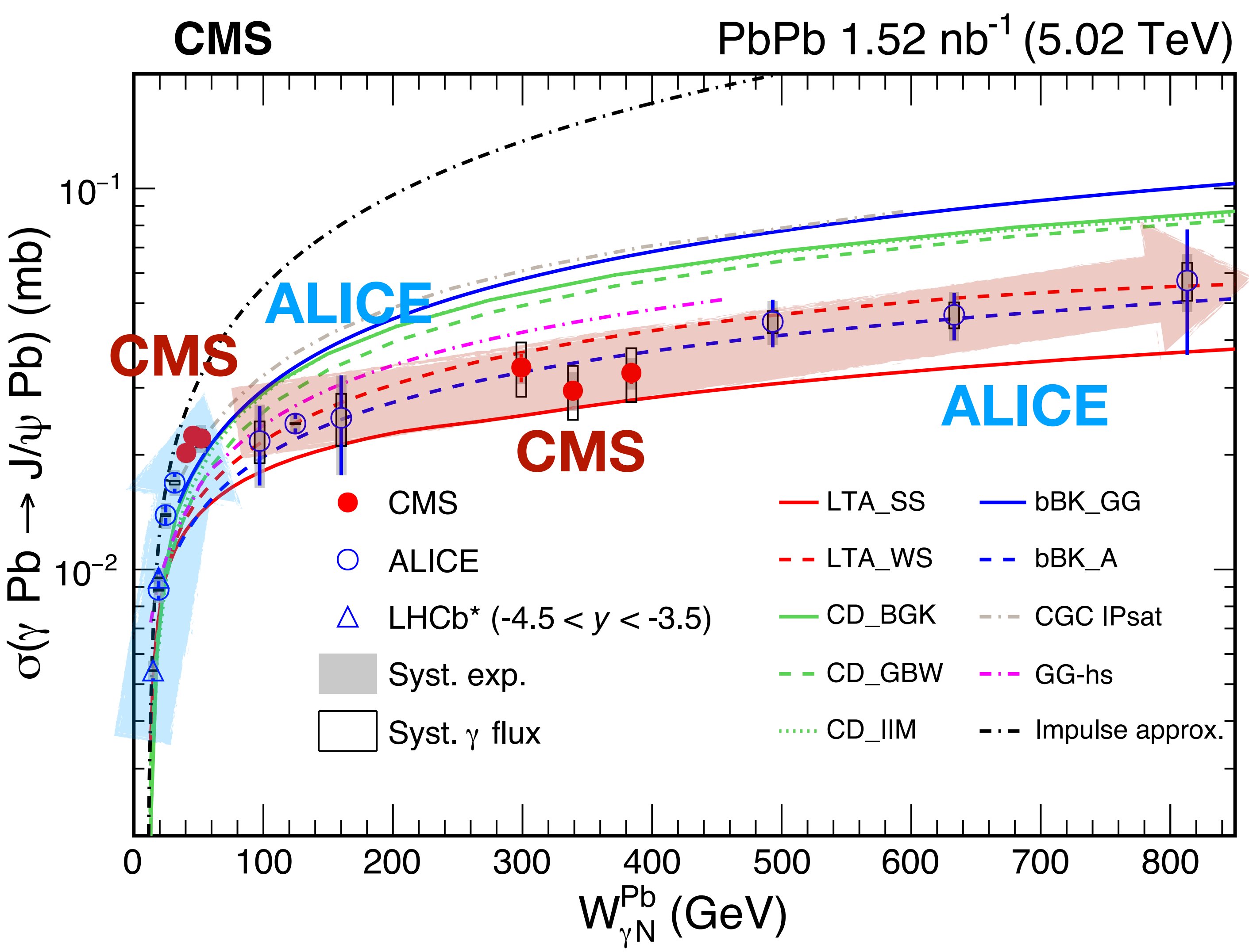
- LHC measurement up to $W_{\gamma N}^{Pb} \approx 800$ GeV
- $W_{\gamma N}^{Pb} < 40$ GeV: rapidly rising

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



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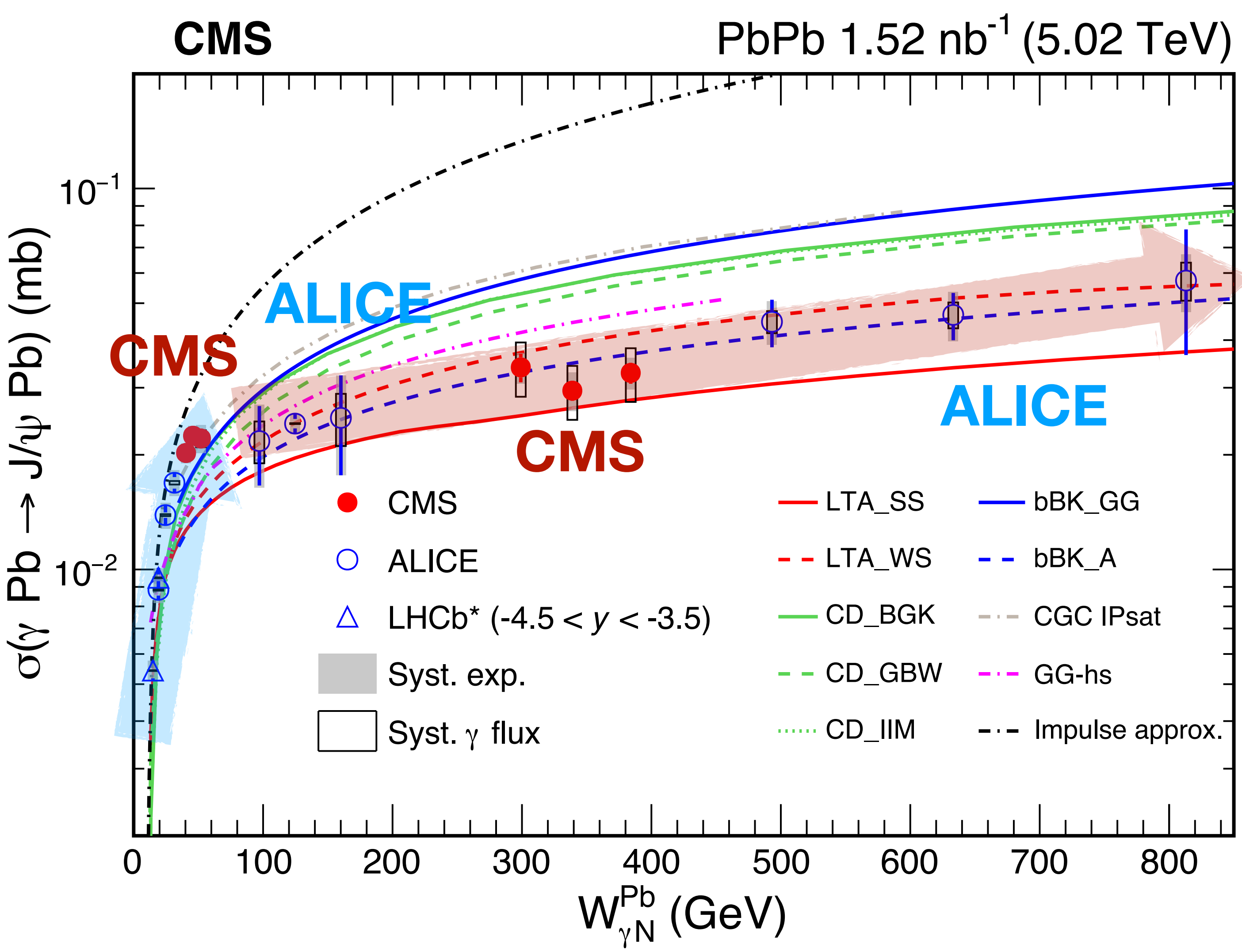
- LHC measurement up to $W_{\gamma N}^{Pb} \approx 800$ GeV
- $W_{\gamma N}^{Pb} < 40$ GeV: rapidly rising
- $40 < W_{\gamma N}^{Pb} < 800$ GeV: nearly flat with a much slower rising

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



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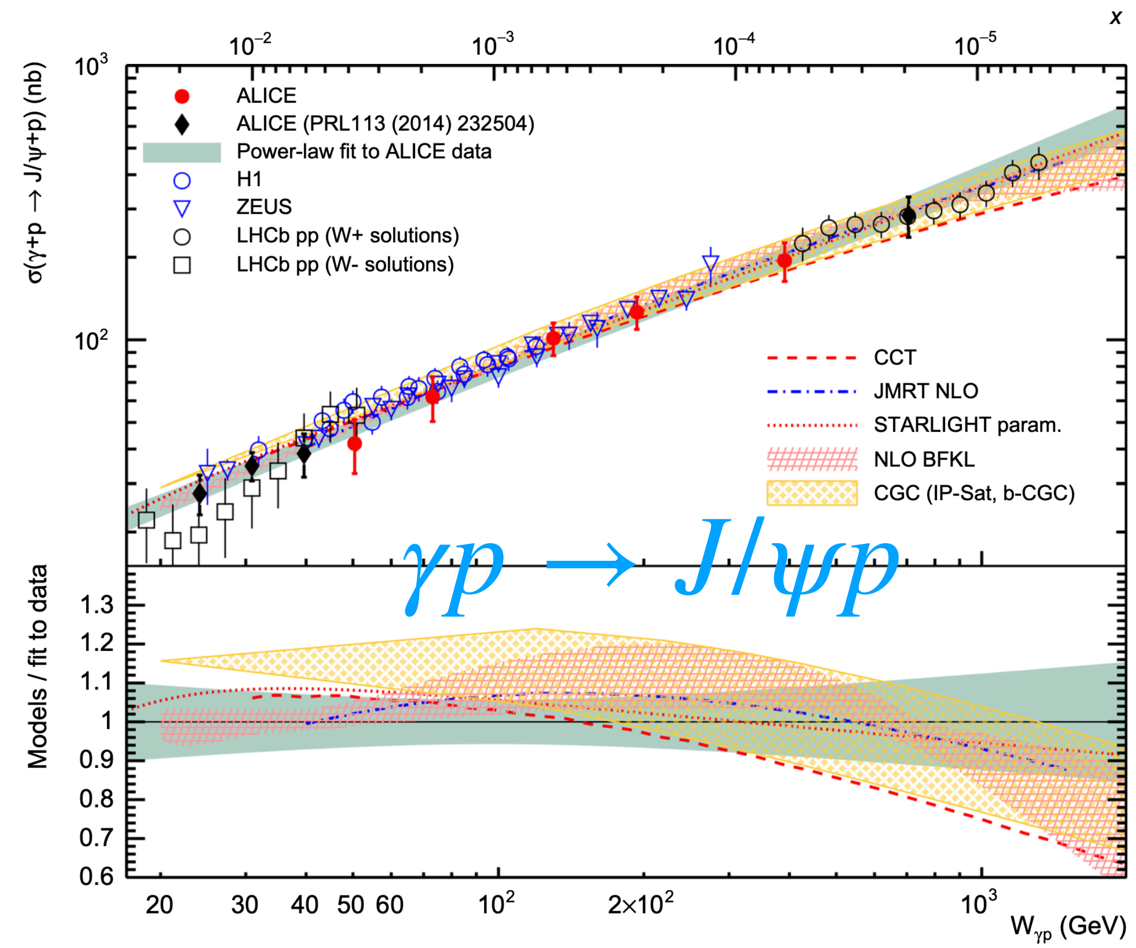

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What physics could be behind?

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

LO pQCD:
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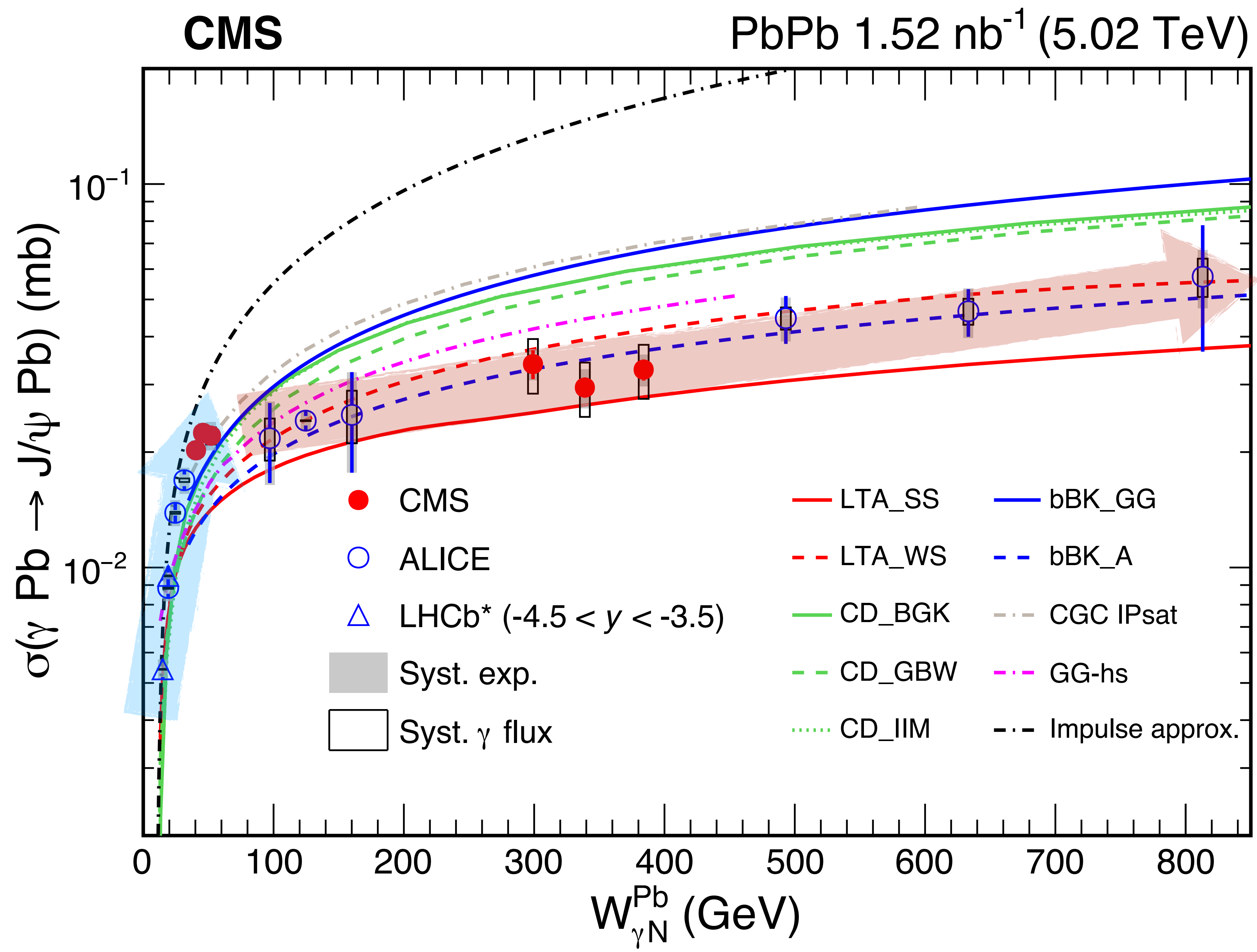
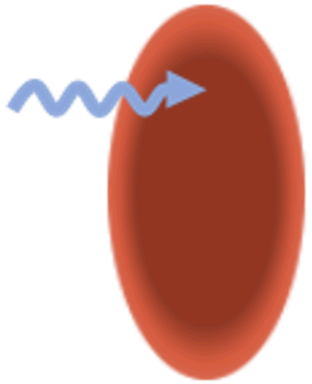


- Direct evidence of gluon saturation?

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

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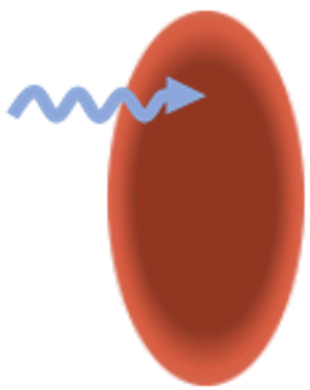

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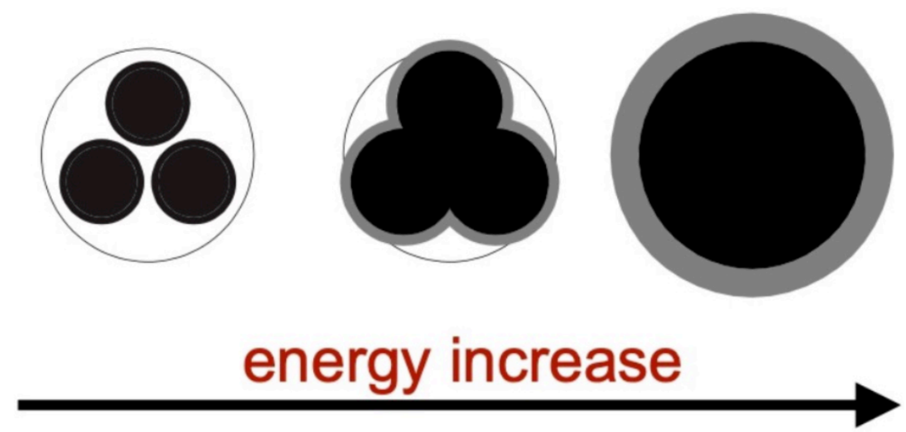
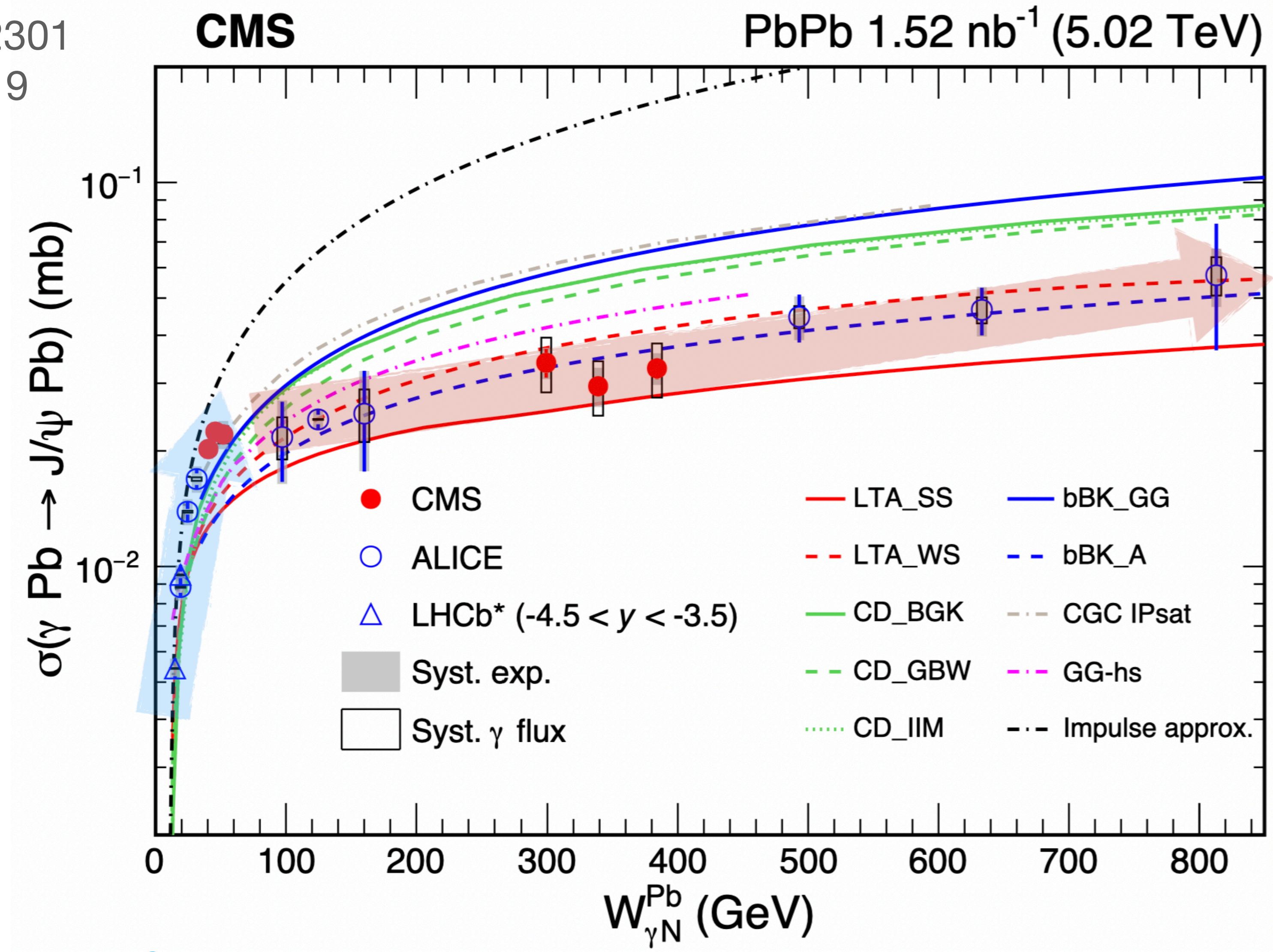
Frankfurt, PRL 87 (2001)192301
Frankfurt, PLB 537 (2002) 51



- 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

Another novel regime of QCD: BDL

CMS, PRL 131 (2023) 262301
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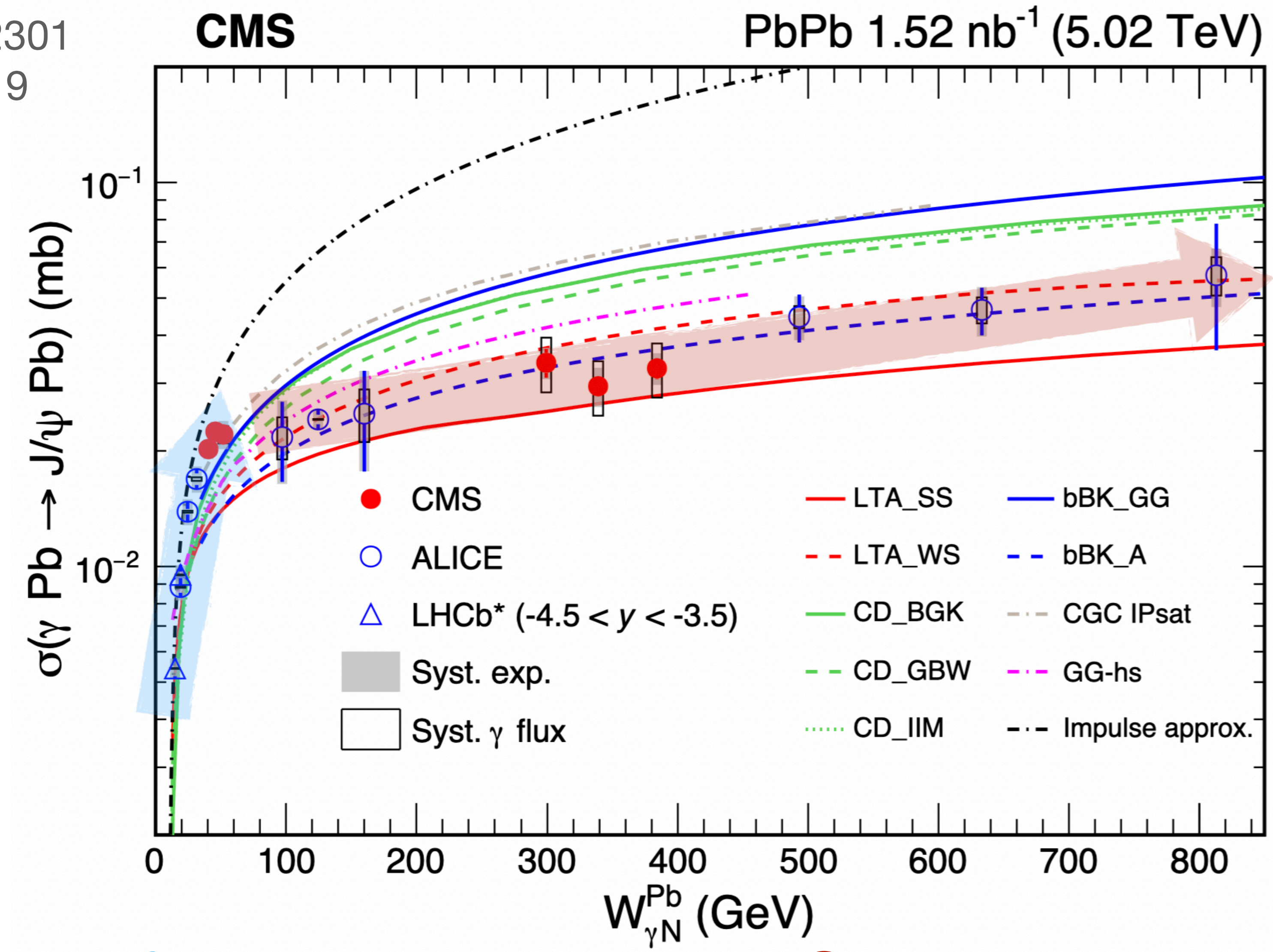
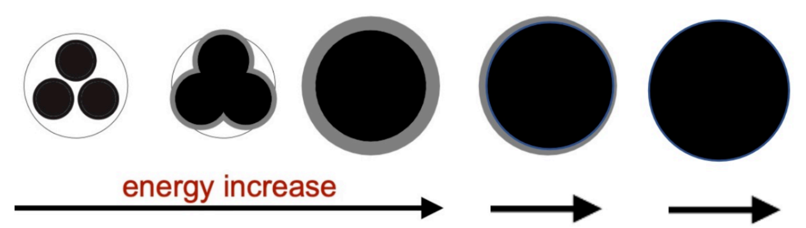
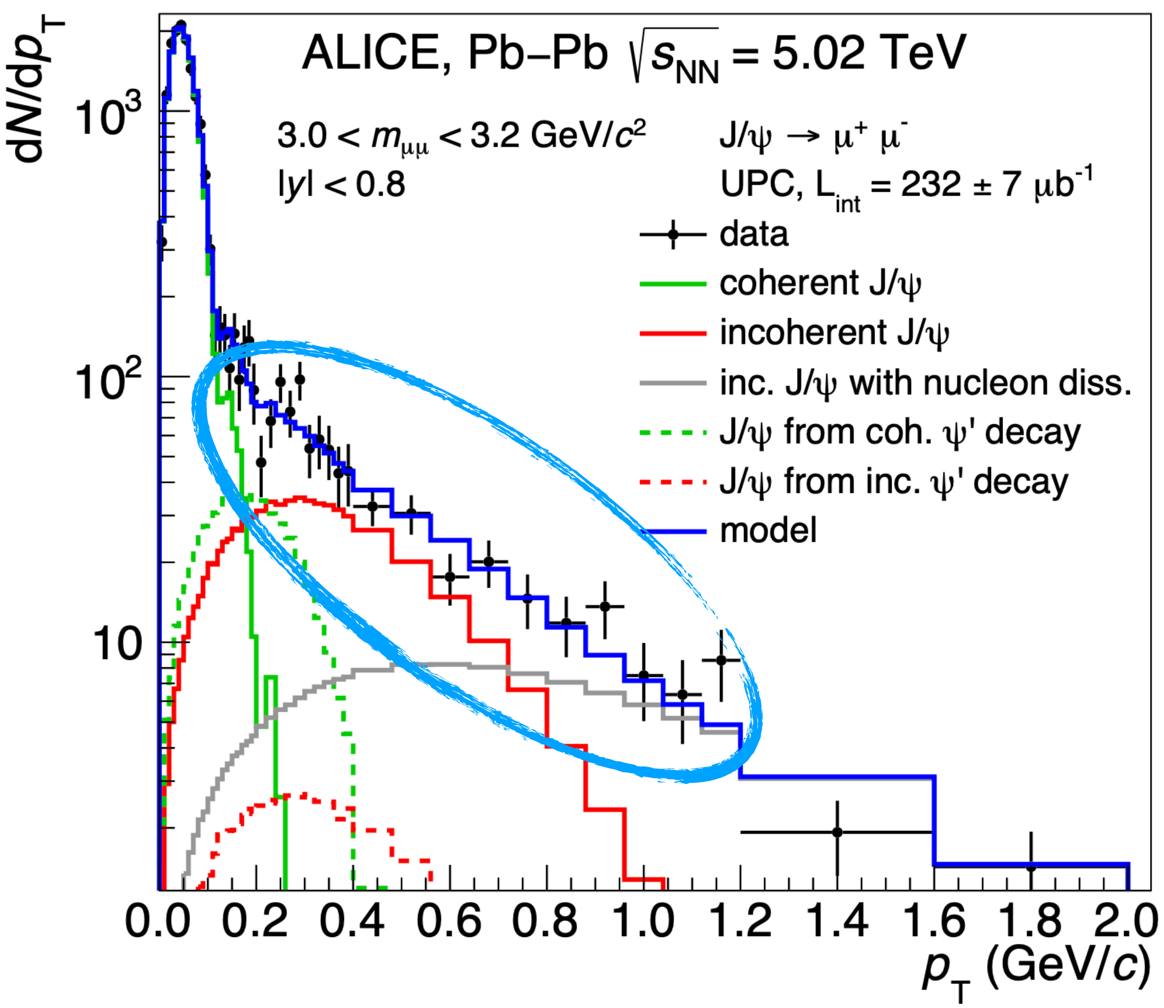


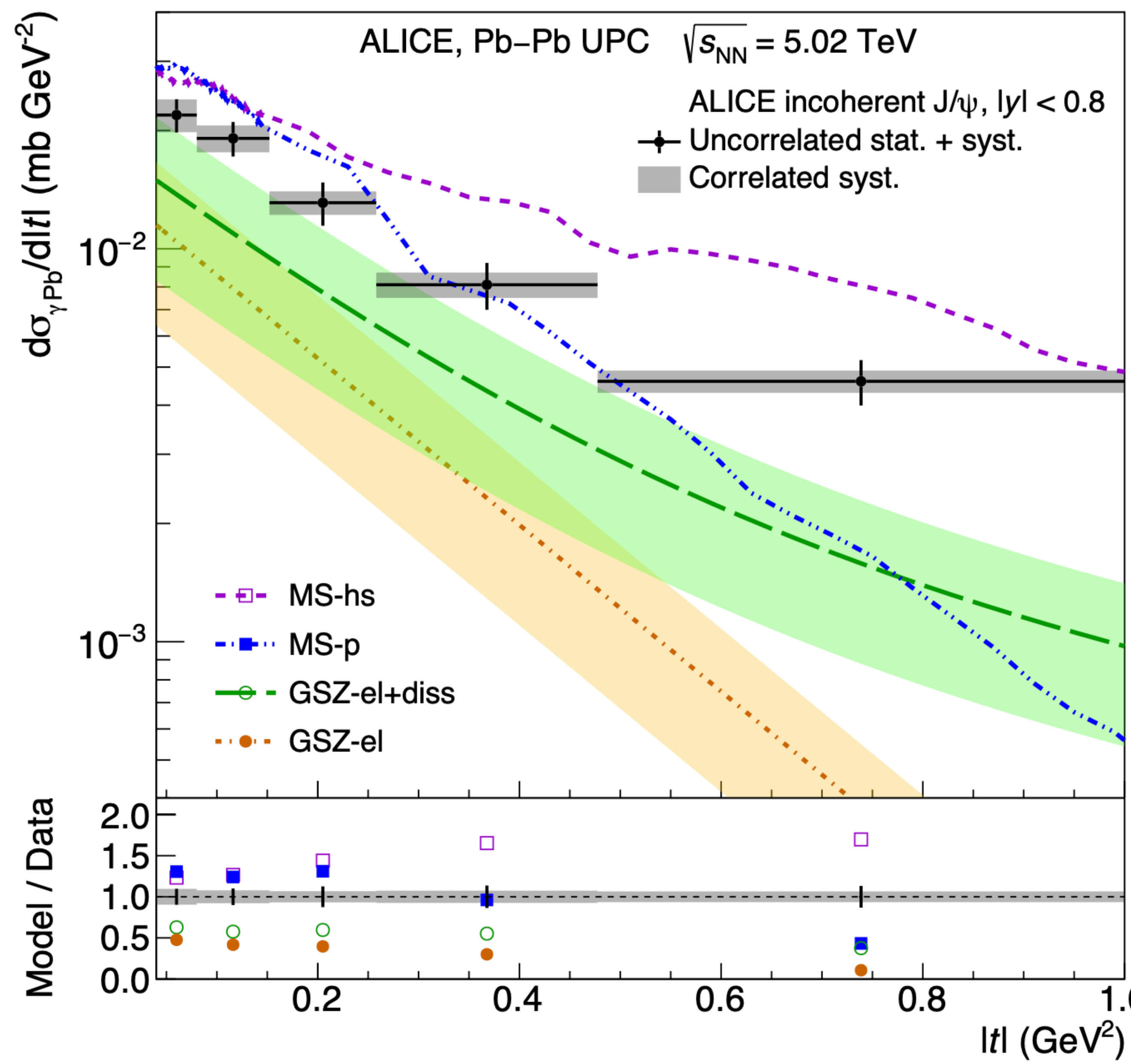
- Rapid grows reflect increased in gluon density
  - Amplitude of interaction is proportional to gluon density
- Slow grows may suggest the periphery of the nucleus has not become fully "black"



|t|-spectrum of incoherent J/ψ

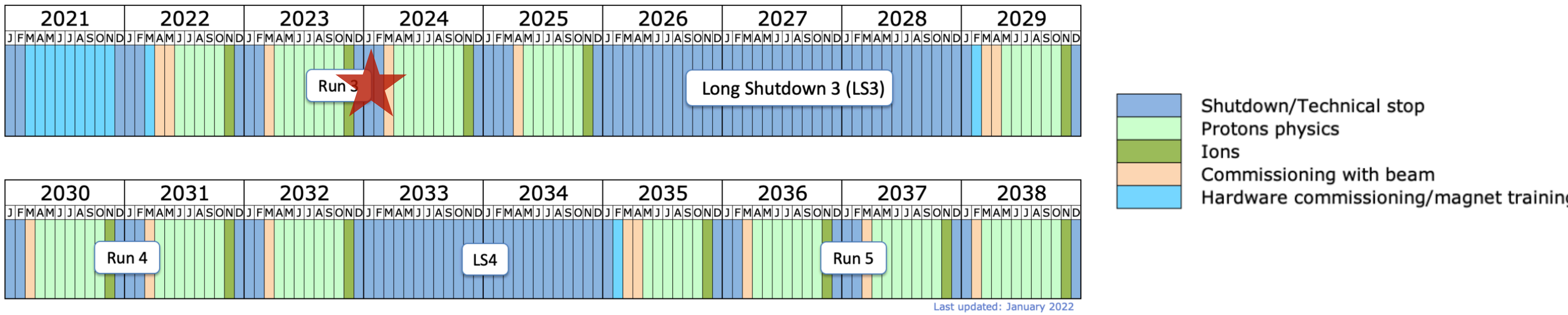
ALICE, arXiv:2305.06169 (accepted by PRL)



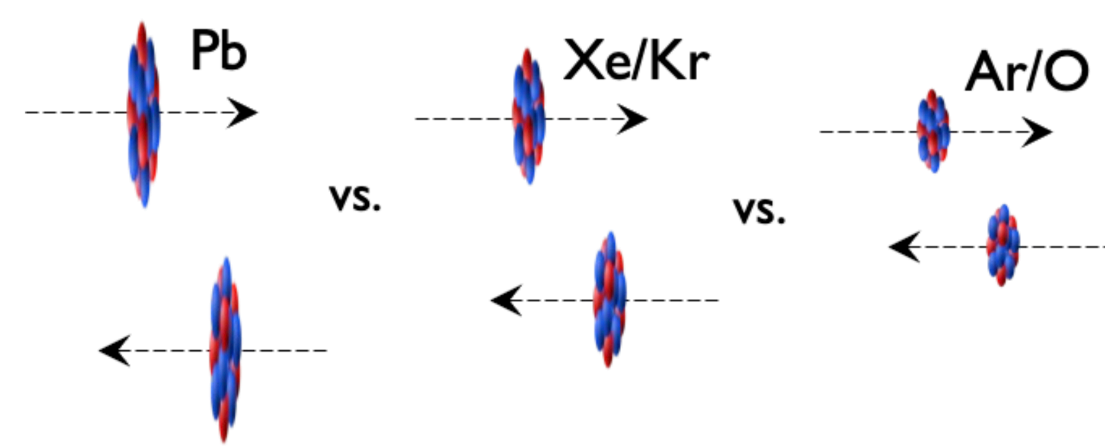


- First experimental step to use quantum fluctuations of the gluon field to search for saturation effects in heavy nuclei

Future opportunities at LHC



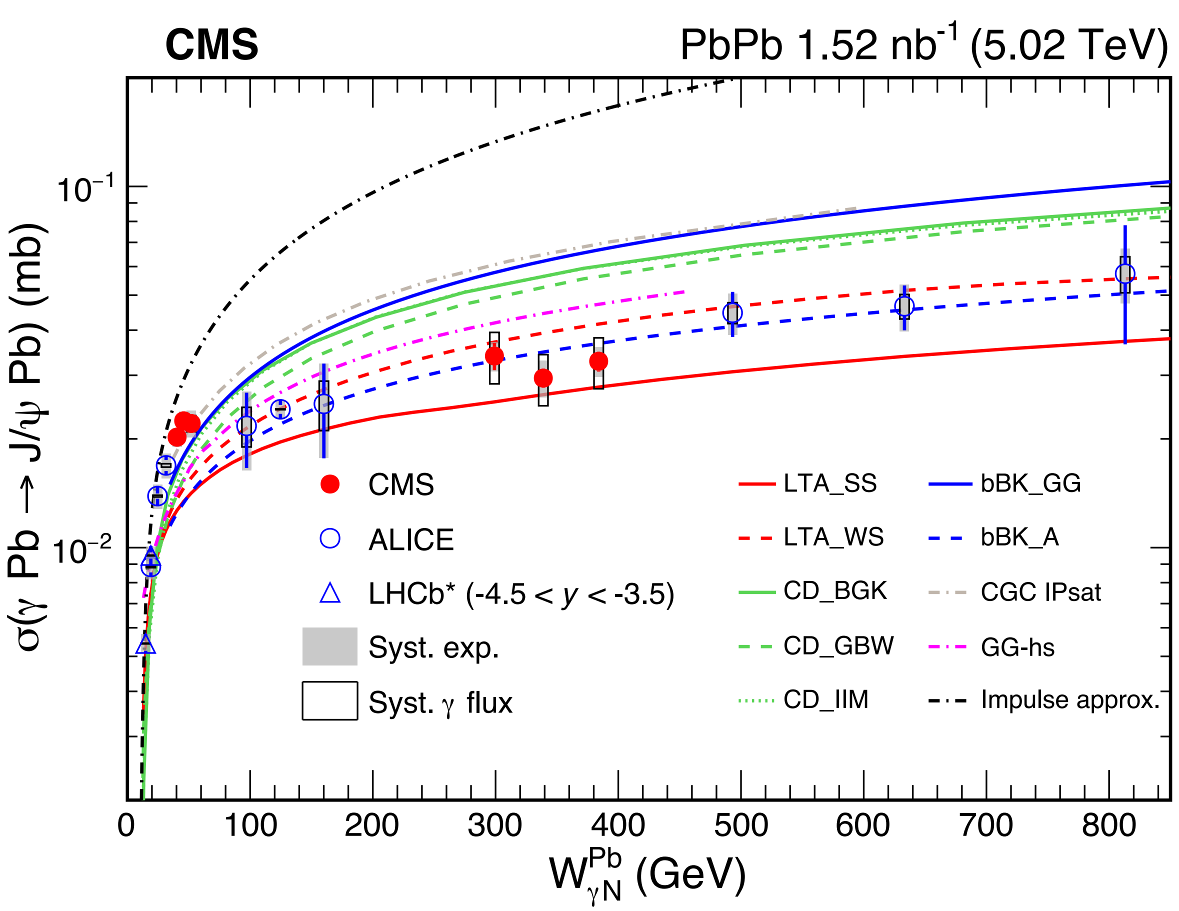
- Exciting opportunities ahead
  - Higher luminosities
  - Various ion species
  - Detector upgrade with new technologies



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

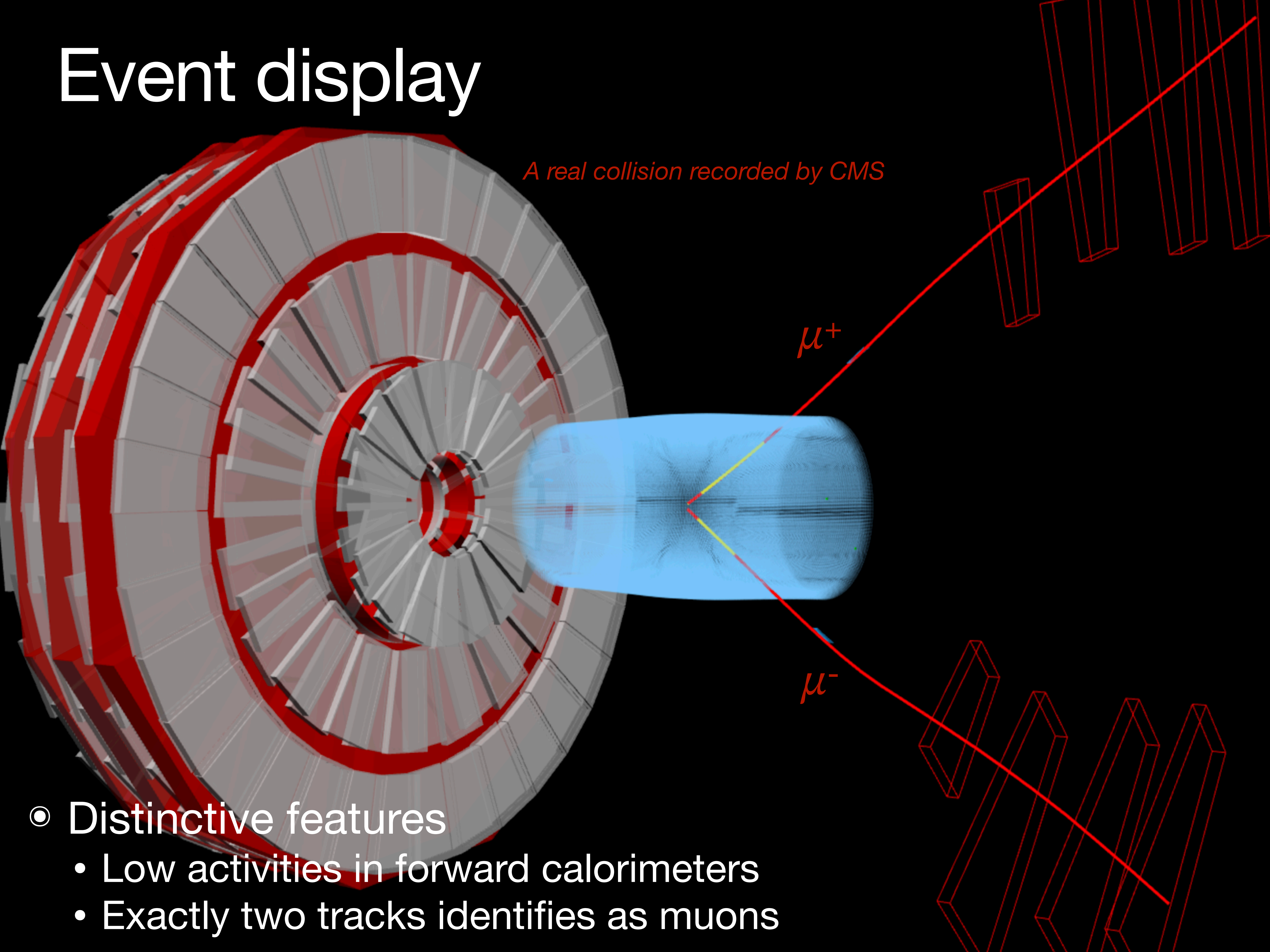
Summary

- For the first time, directly disentangled coherent $\sigma_{\gamma A \to J/\psi A}$ in ultra-peripheral A+A collisions
- Probed a new low-x gluon regime (10^{-5}) in Pb nucleus
  - Flattening of coherent $\sigma_{\gamma A \to J/\psi A}$ at high $W_{\gamma N}^{Pb}$ not predicted by theoretical models
- Search for saturation effects with incoherent J/ψ in heavy nuclei



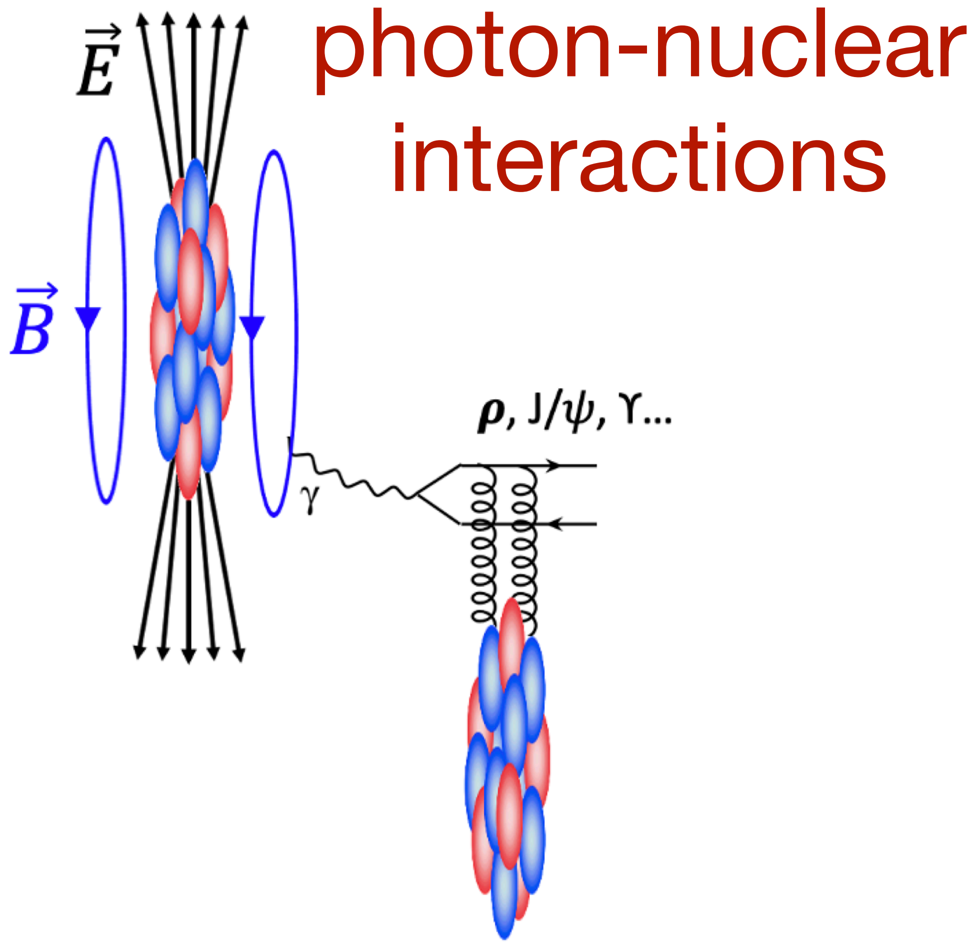
Thank you for your attention!

Event display



- Distinctive features
  - Low activities in forward calorimeters
  - Exactly two tracks identifies as muons

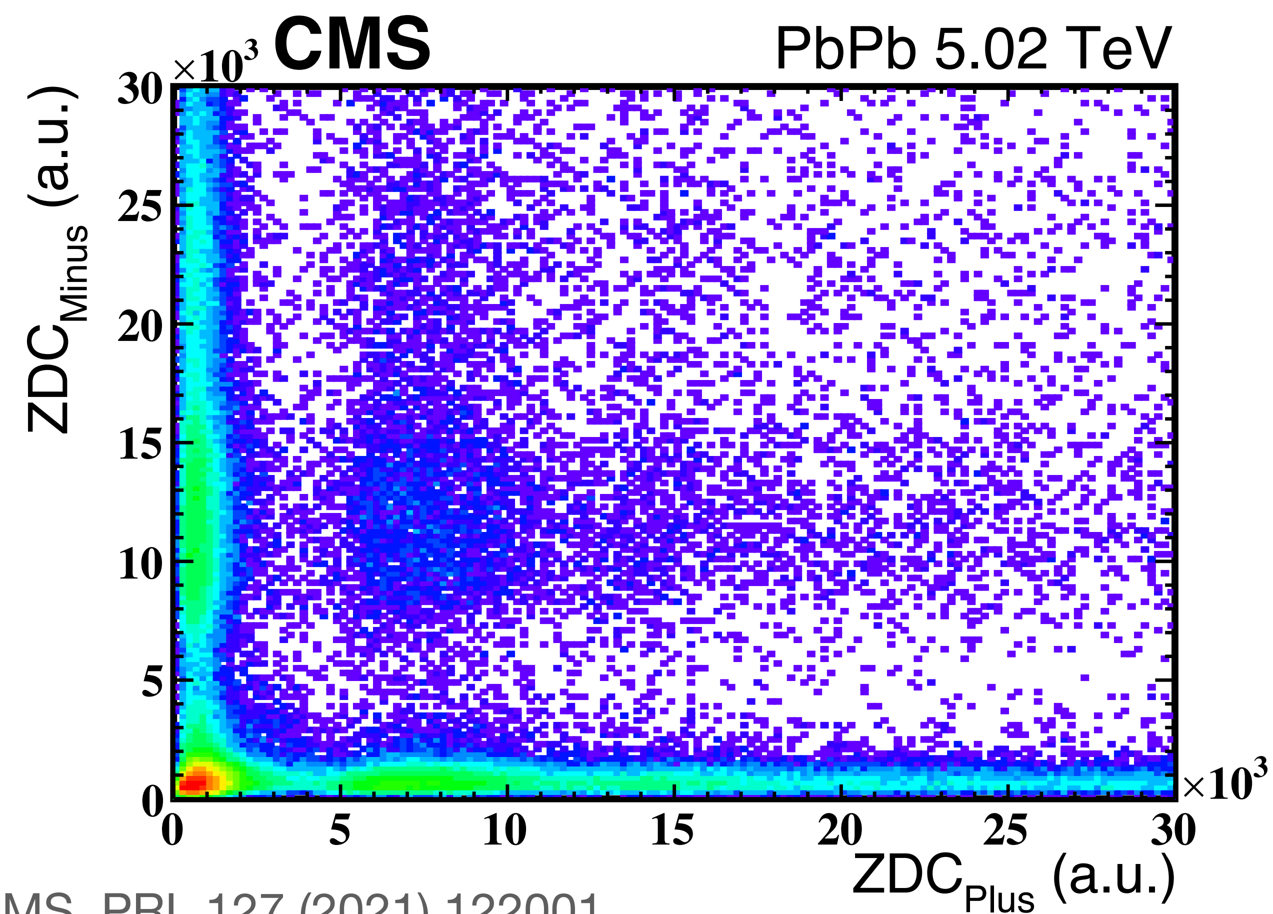
A clean probe of gluon structure

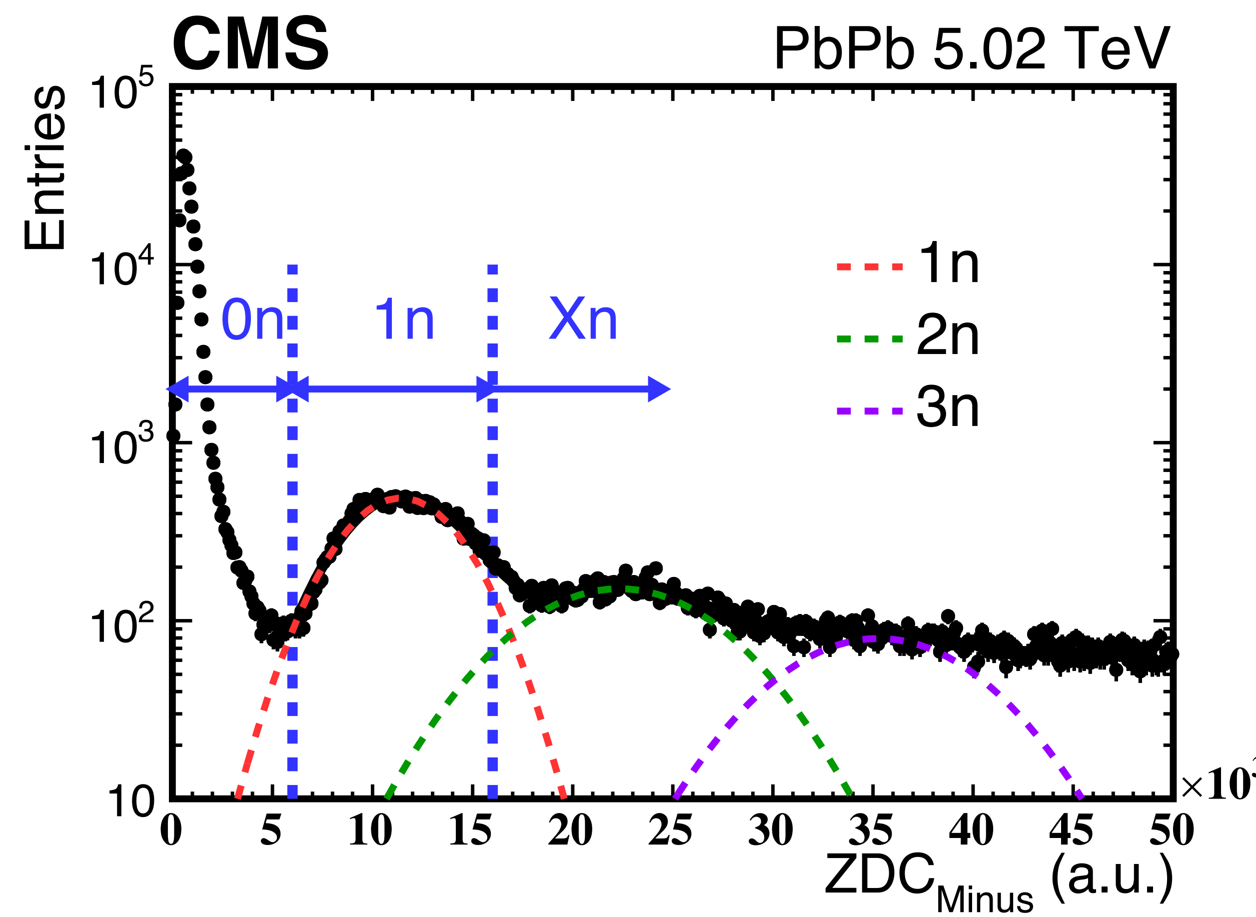


- LO pQCD: $\sigma^{VM} \propto$ flux $\otimes$ $[xG(x)]^2$
- Well defined kinematics
  - $\omega = \frac{M_{VM}}{2} e^{\pm y} \quad x = \frac{M_{VM}}{2E_{beam}} e^{\mp y}$
  - $W_{\gamma N}^2 = 2E_{beam} M_{VM} e^{\pm y}$
- Low $Q^2 \sim 0$, but heavy quark mass can provide a hard scale for pQCD

- Coherent: average gluon distribution
- Incoherent: event-by-event fluctuation

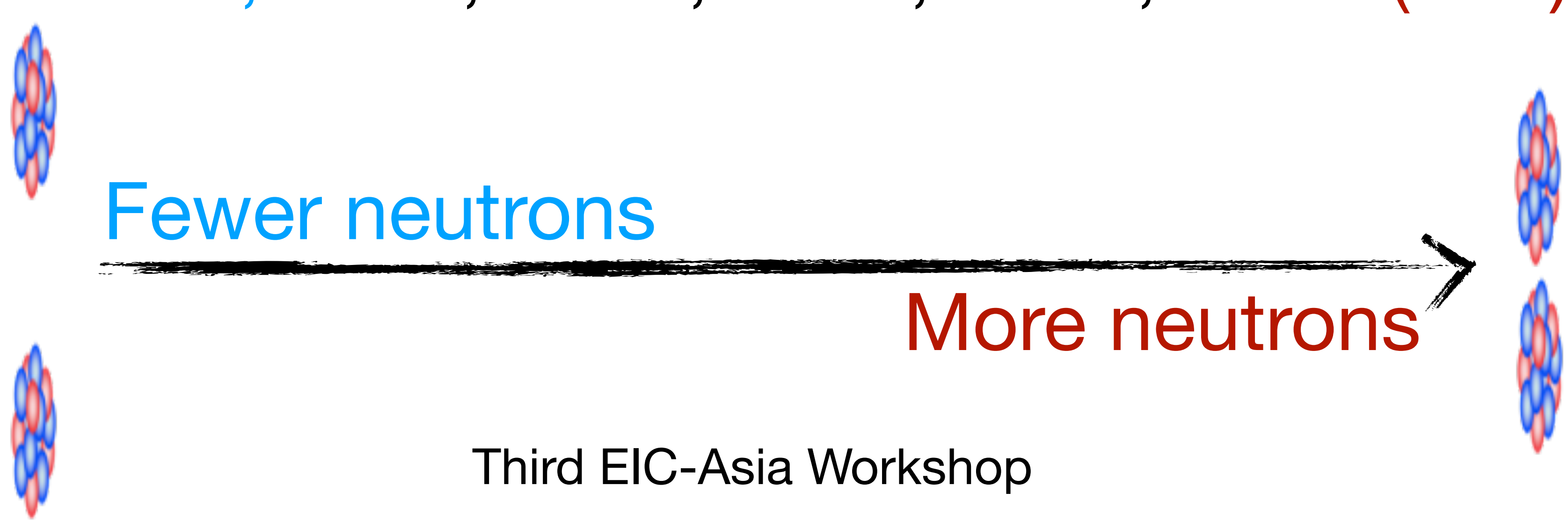
Determine neutron multiplicity





CMS, PRL 127 (2021) 122001

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



EM dissociation 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 zero-bias fraction

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

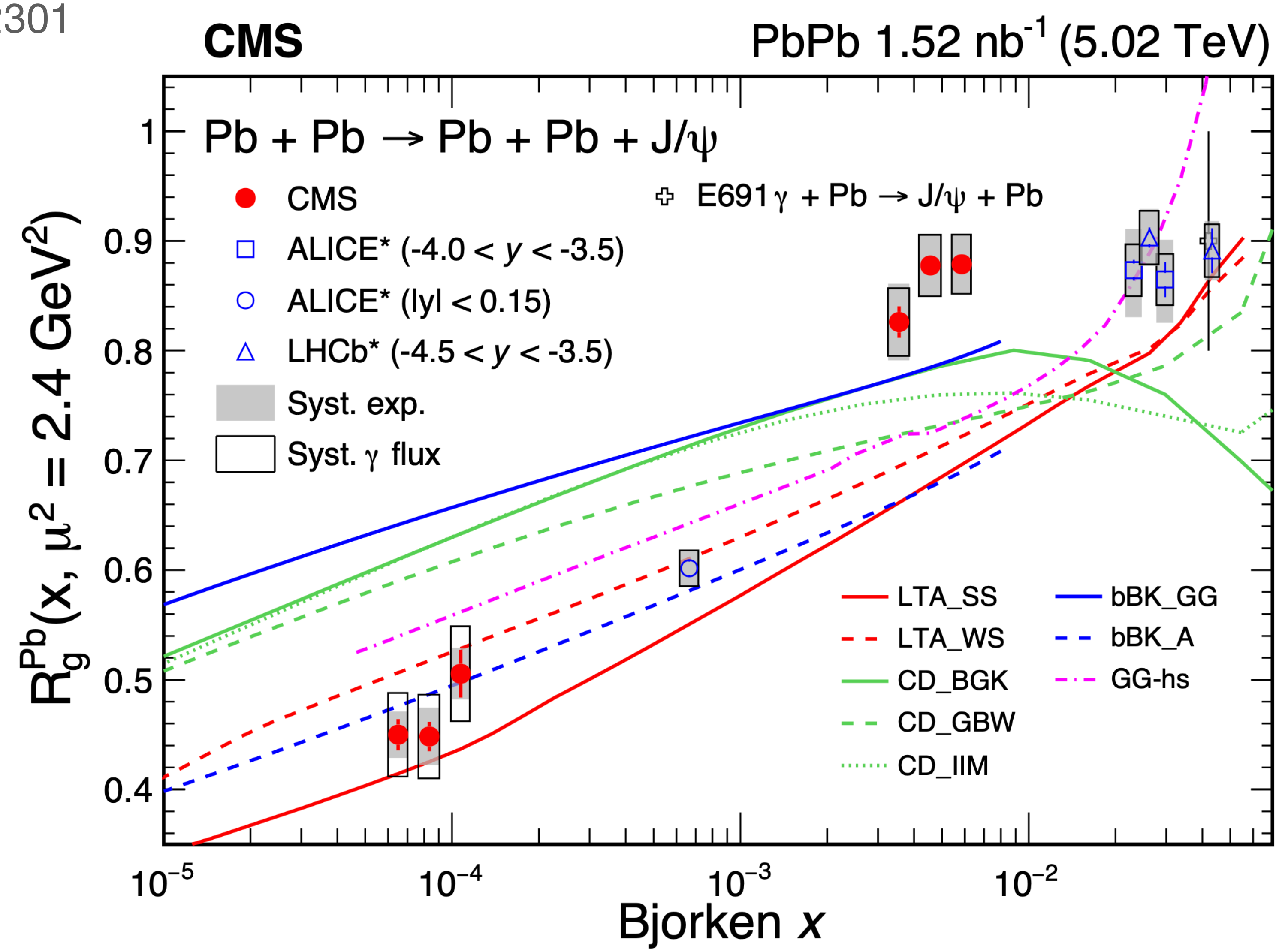
	f_{00}	f_{0X}	f_{X0}	f_{XX}
Fraction	0.889779	0.0530636	0.0508458	0.00631169

Nuclear gluon suppression factor

CMS, PRL 131 (2023) 262301

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

$$= \sqrt{\frac{\sigma^{exp}_{\gamma A\to J/\psi A}}{\sigma^{IA}_{\gamma A\to J/\psi A}}}$$



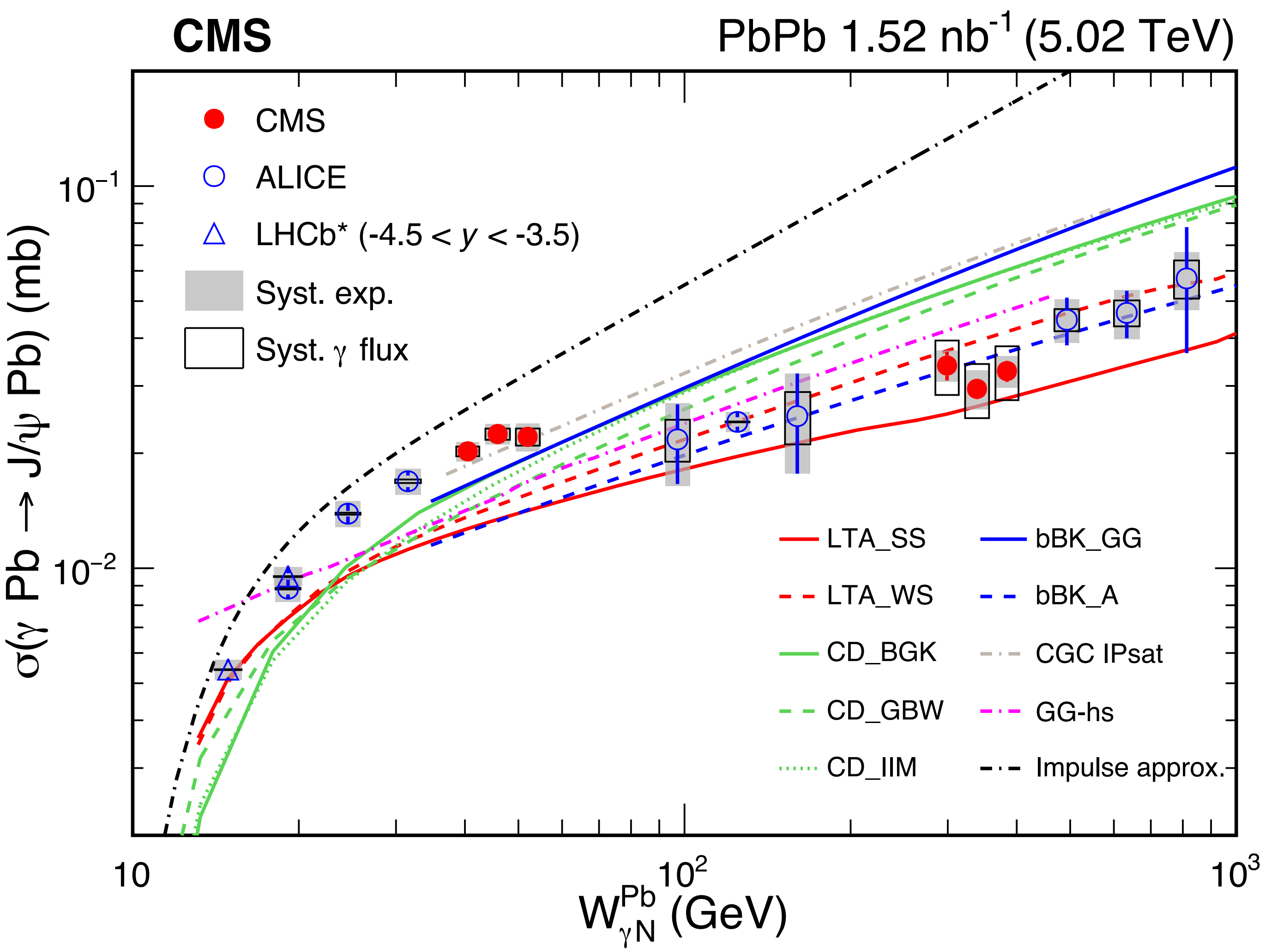
- R_g^A:nuclear suppression factor at LO approximation
  - A flat trend at high x (~3×10^{-3} - 5×10^{-2})
  - Rapidly decreasing towards very small x (~6×10^{-5})

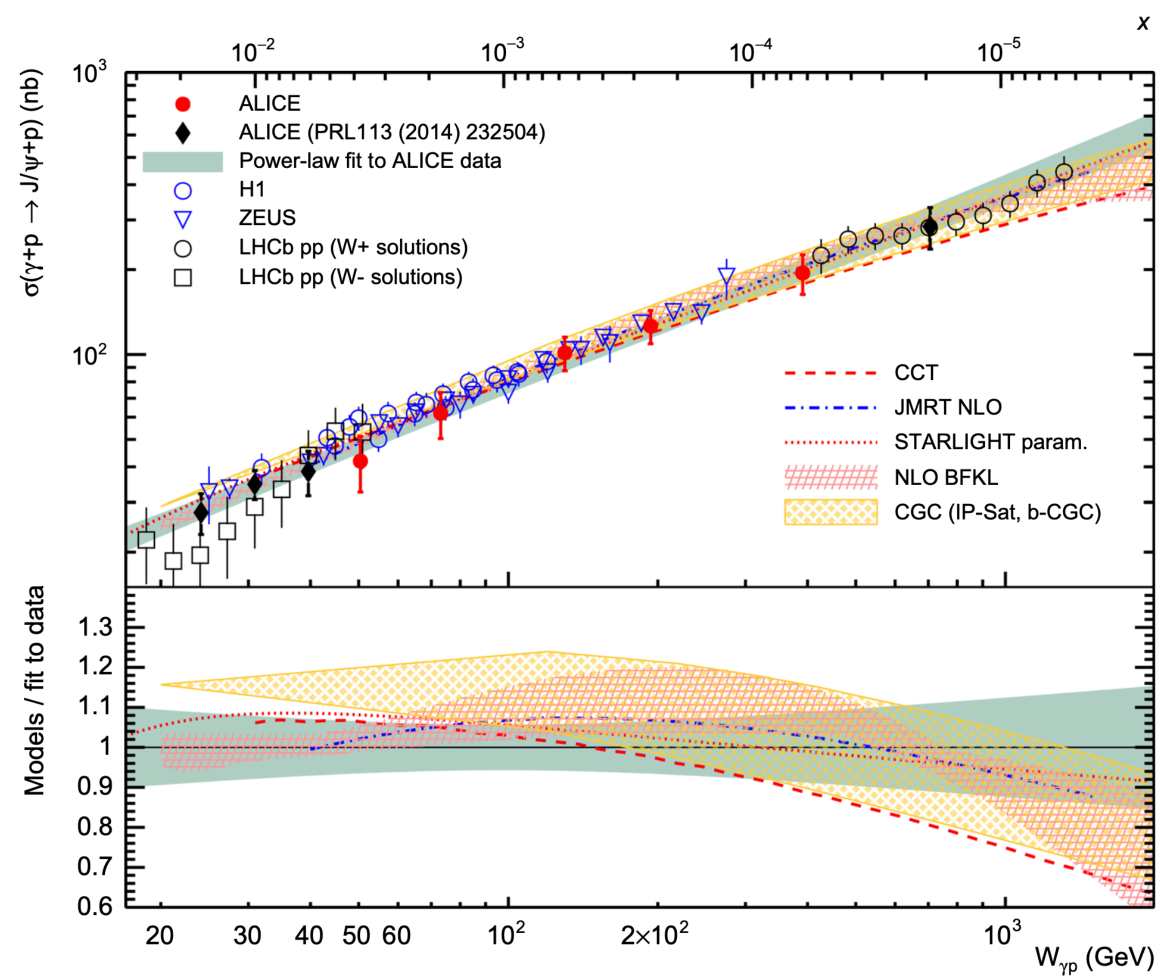
Coherent J/ψ production vs. $W_{\gamma N}^{Pb}$

ALICE, JHEP 10 (2023) 119
ALICE, EPJC 81 (2021) 712
ALICE, PLB 798 (2019) 134926

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

ALICE, EPJC 79 (2019) 402



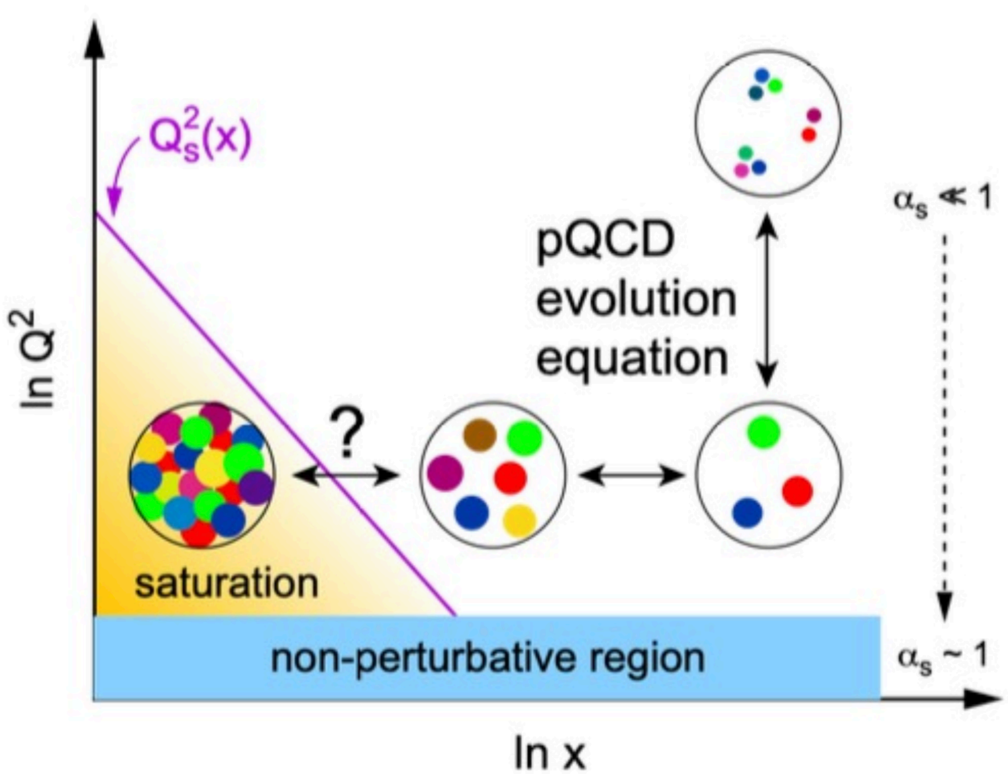


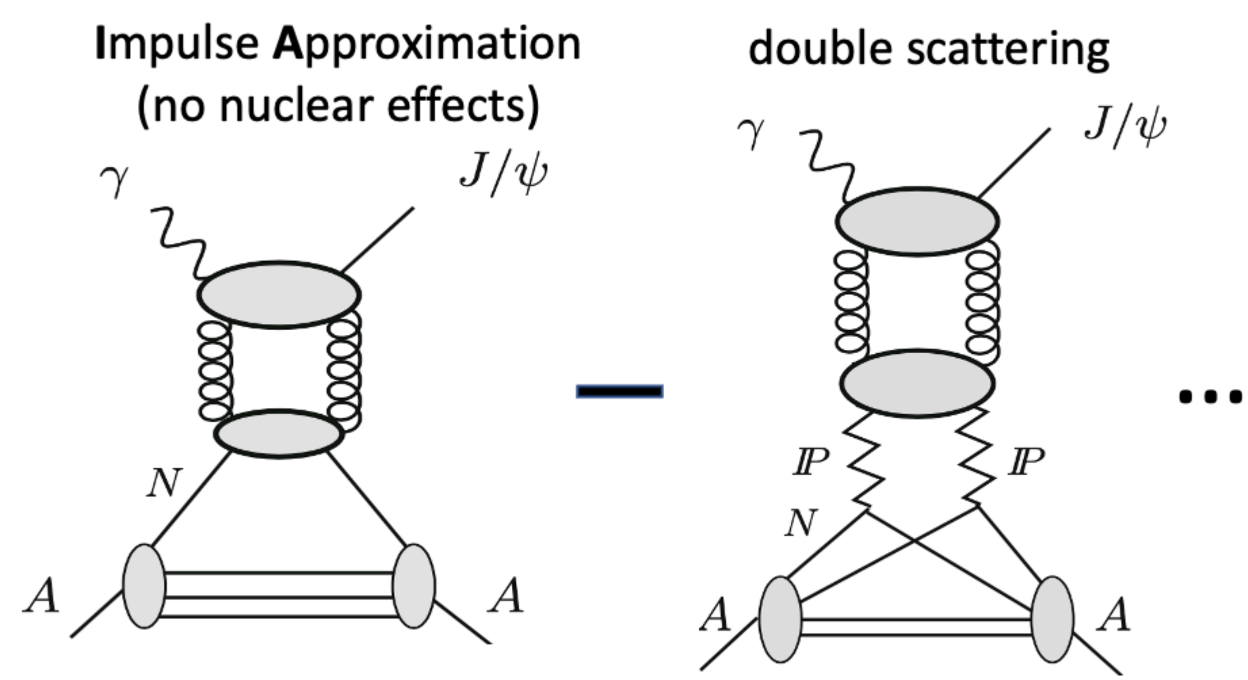
$\gamma A \to J/\psi A$

$\gamma p \to J/\psi p$

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