Probing the gluonic matter in ultraperipheral collisions with the LHC experiments

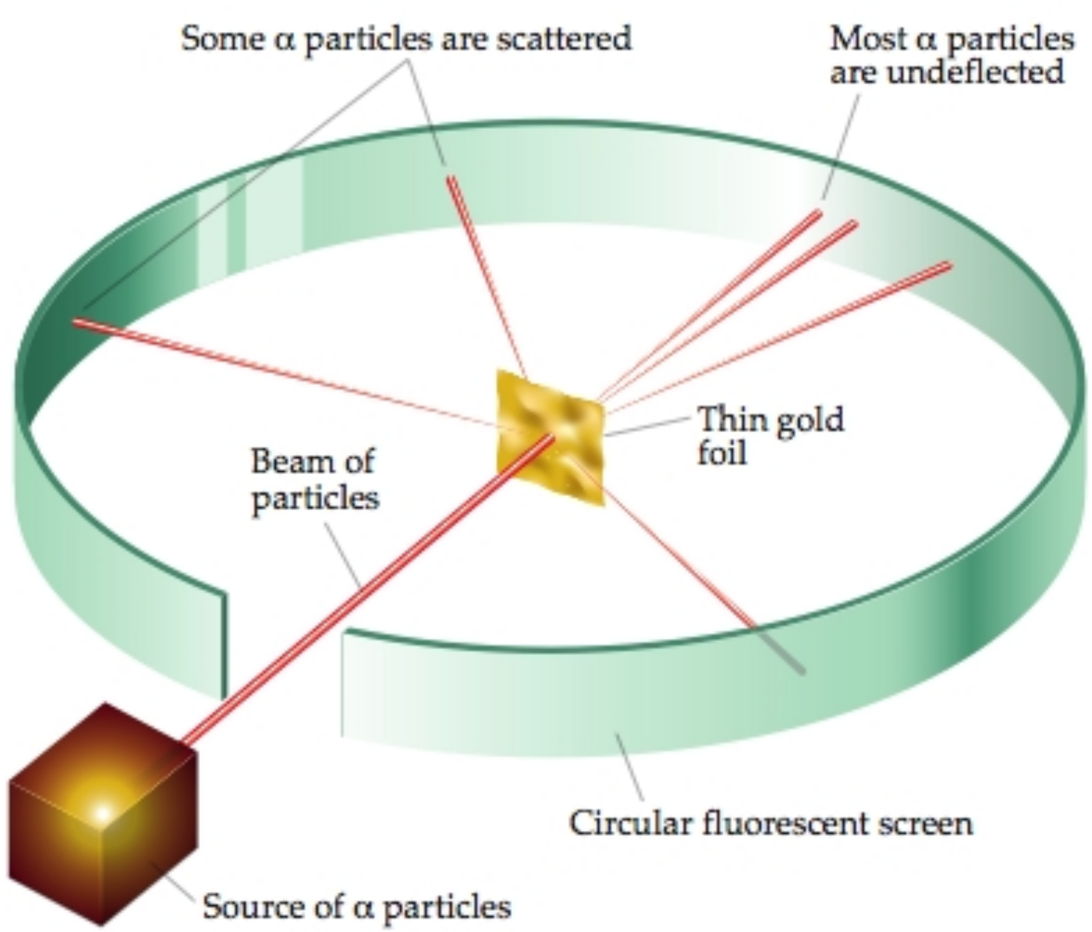
杨帅

华南师范大学

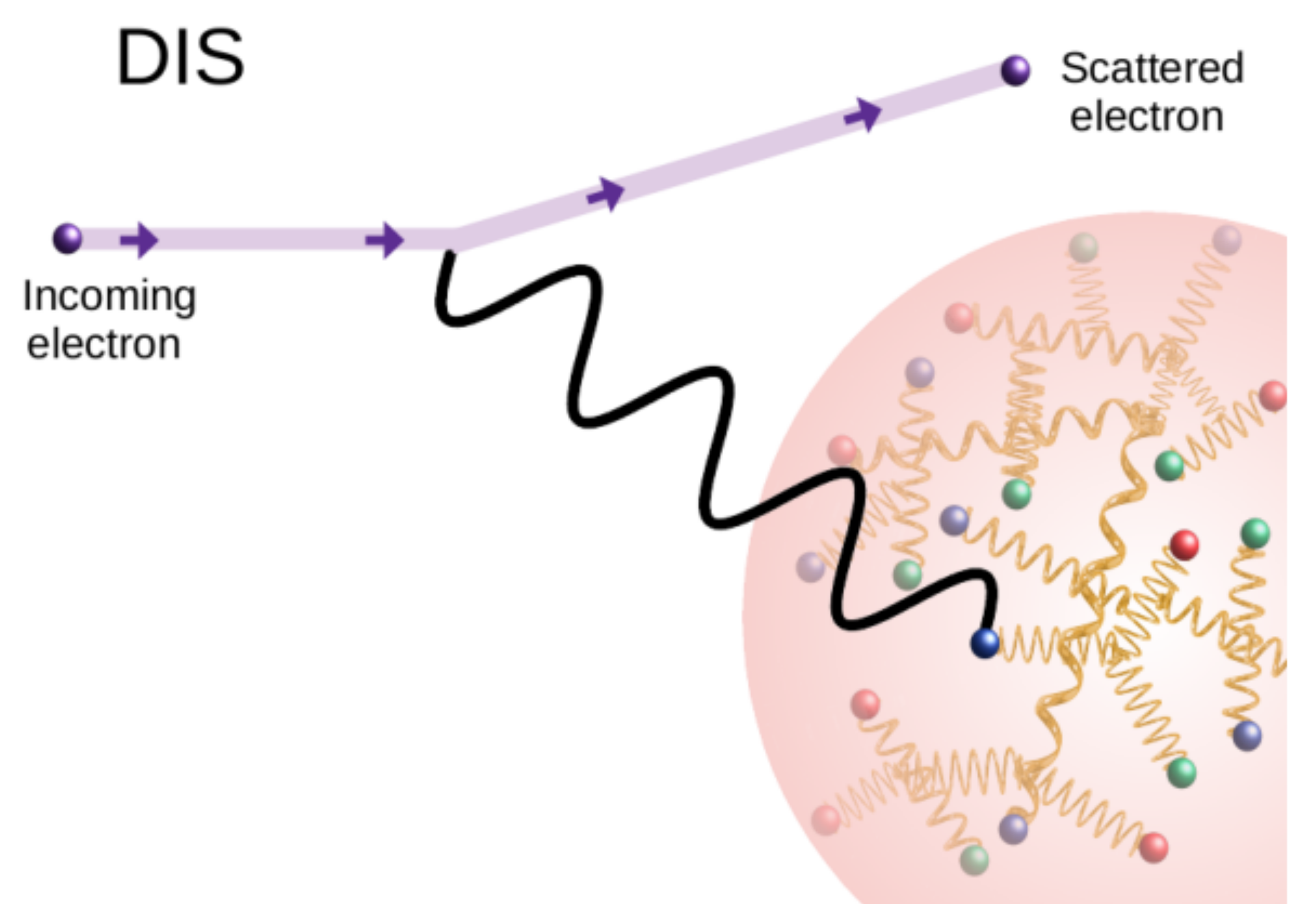
Spicy Gluon (胶麻) 2024, May 15th - 19th, 2024, Hefei

Explore internal structure of matter

1909 - 1914, RBS

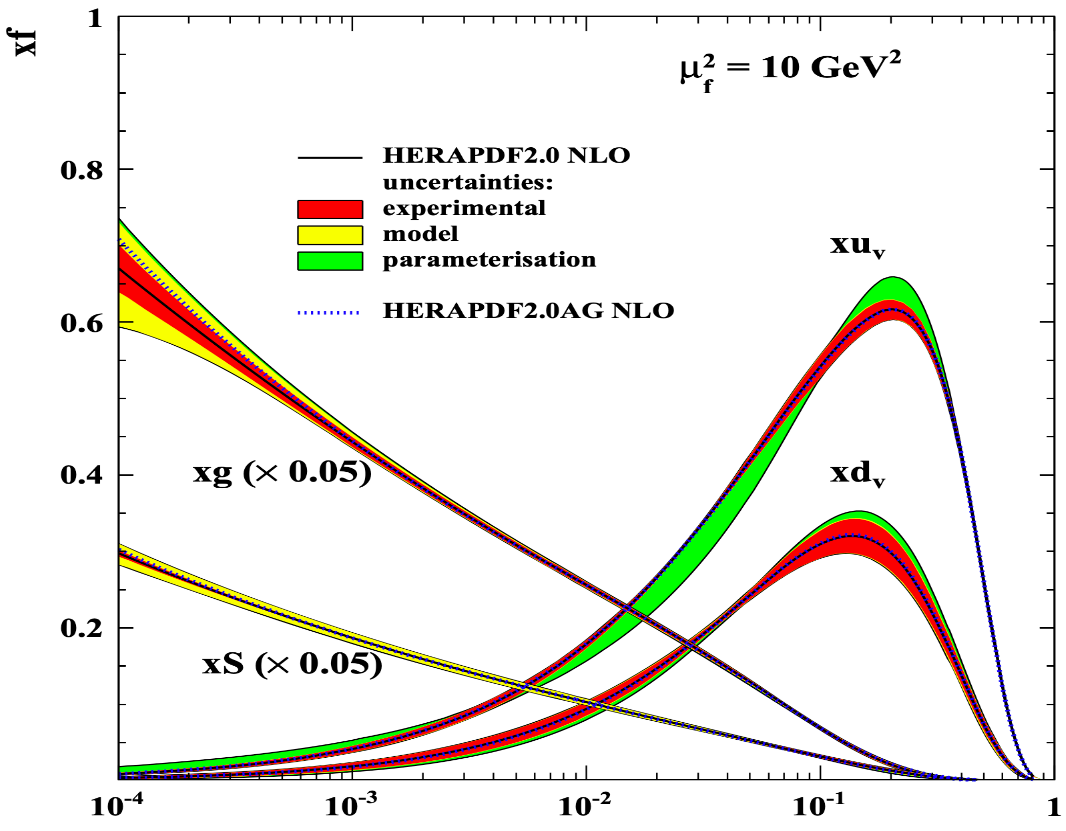


1960s - 1970s, SLAC
1992 - 2007, HERA



Explore internal structure of matter

H1 and ZEUS, EPJC 75 (2015) 580



Small x ← Large x

Explore internal structure of matter

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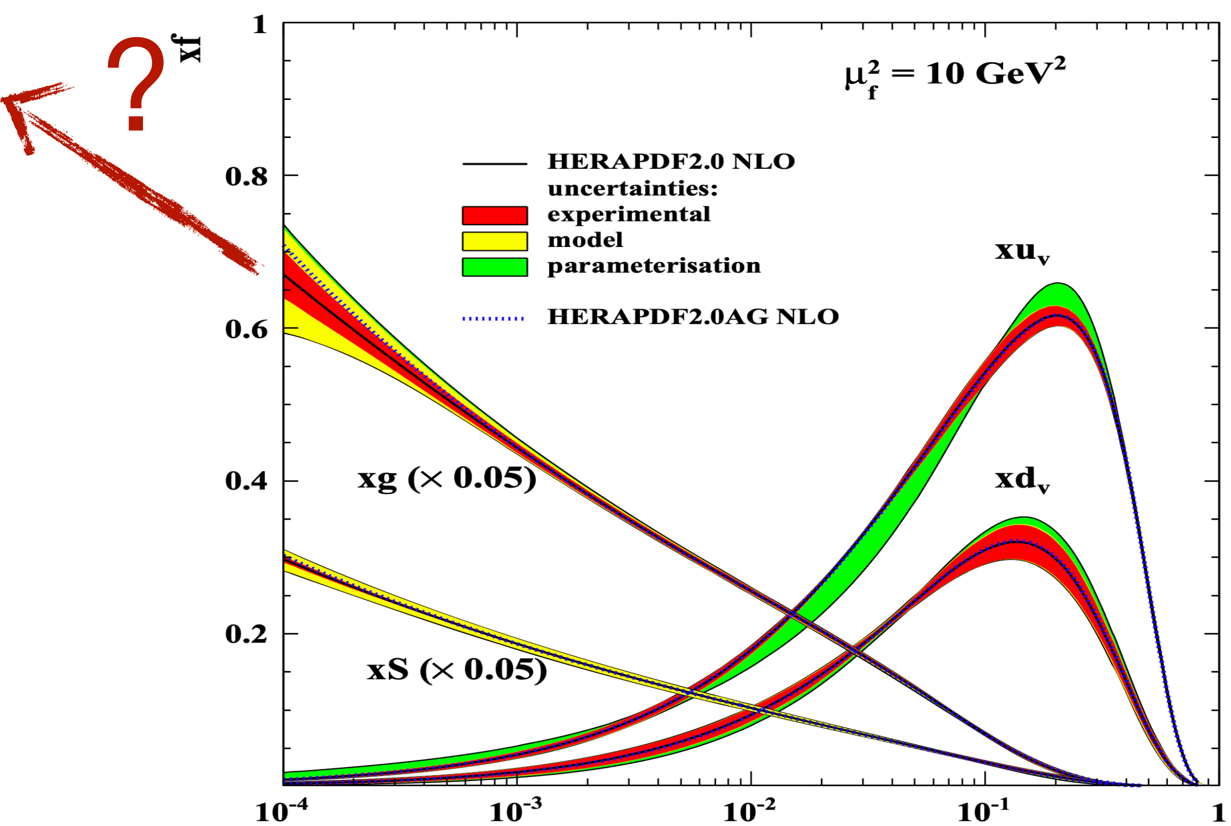

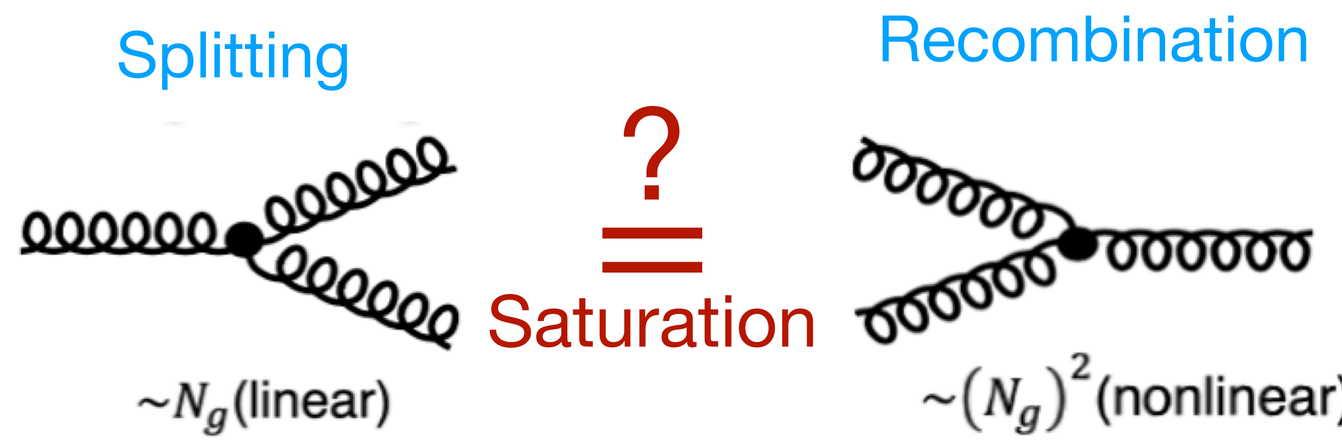

QCD unitarity: growth of gluon density can't continue indefinitely!

Small x ← Large x

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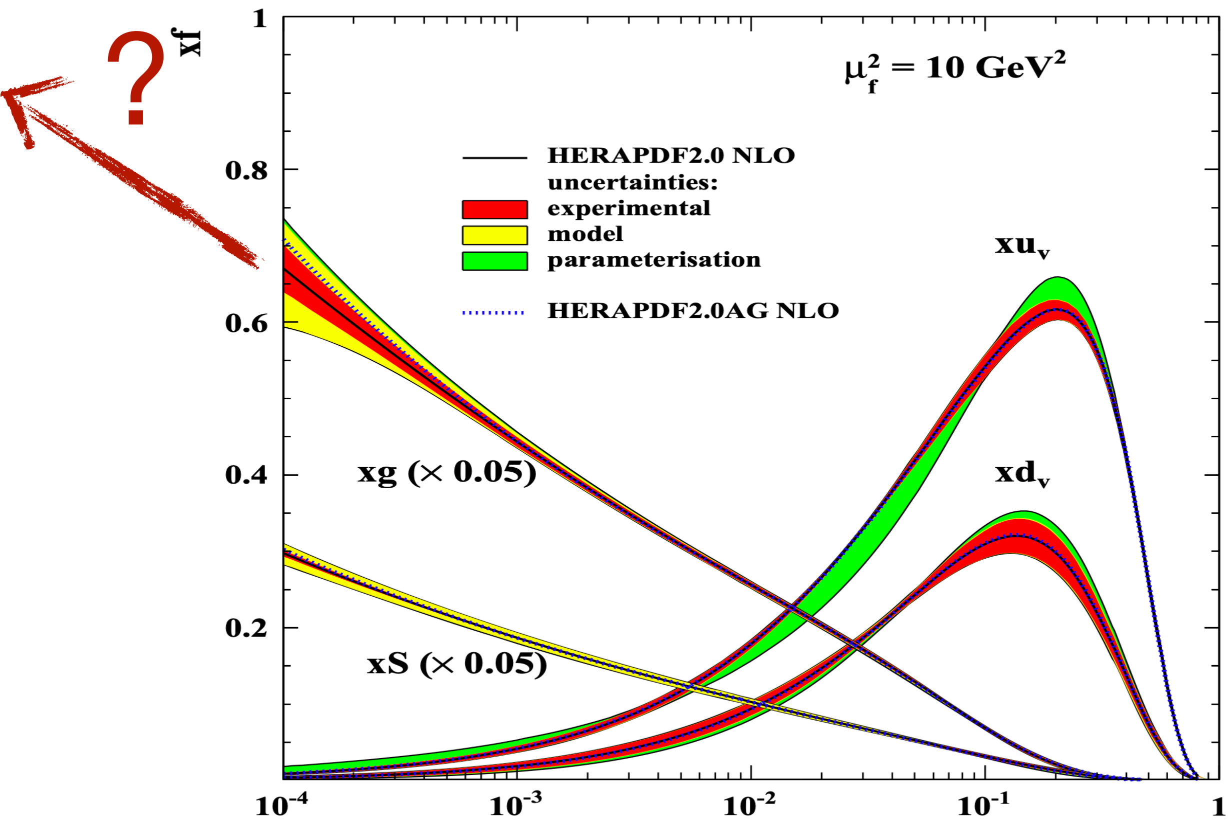
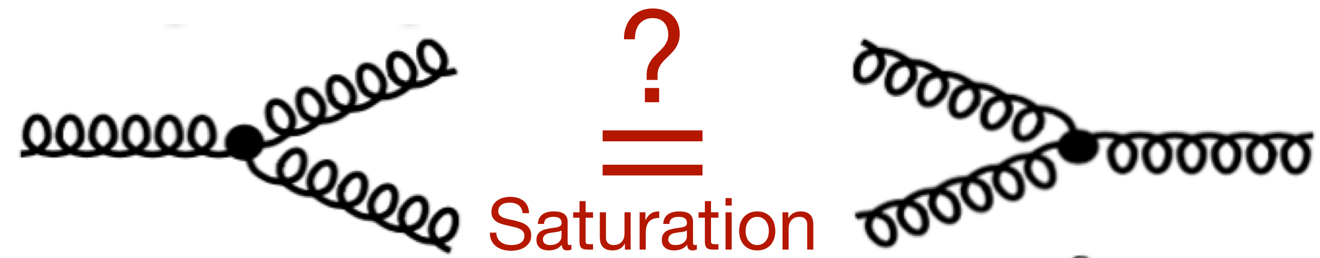


Splitting

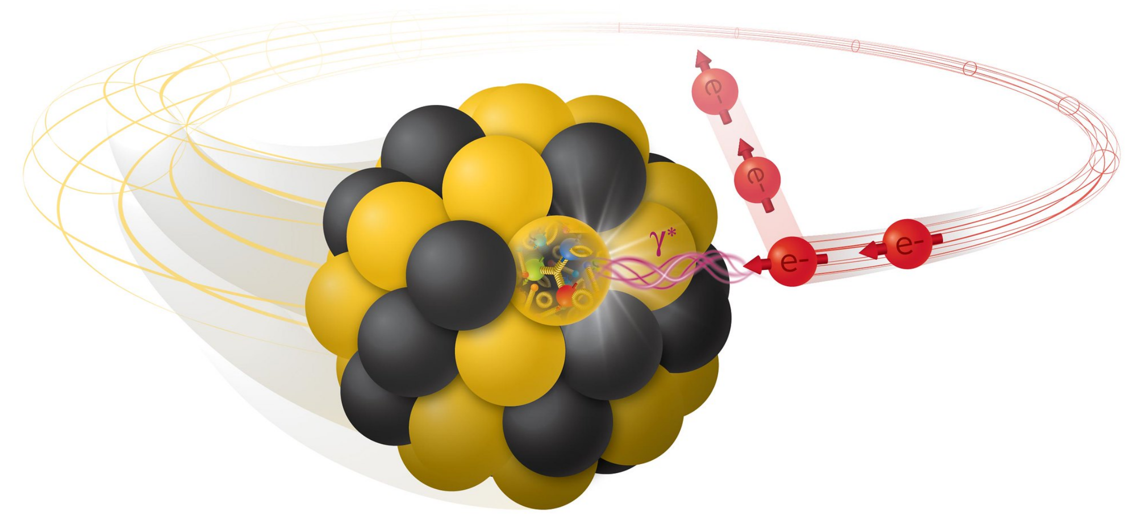
Recombination



$\sim N_g$(linear)

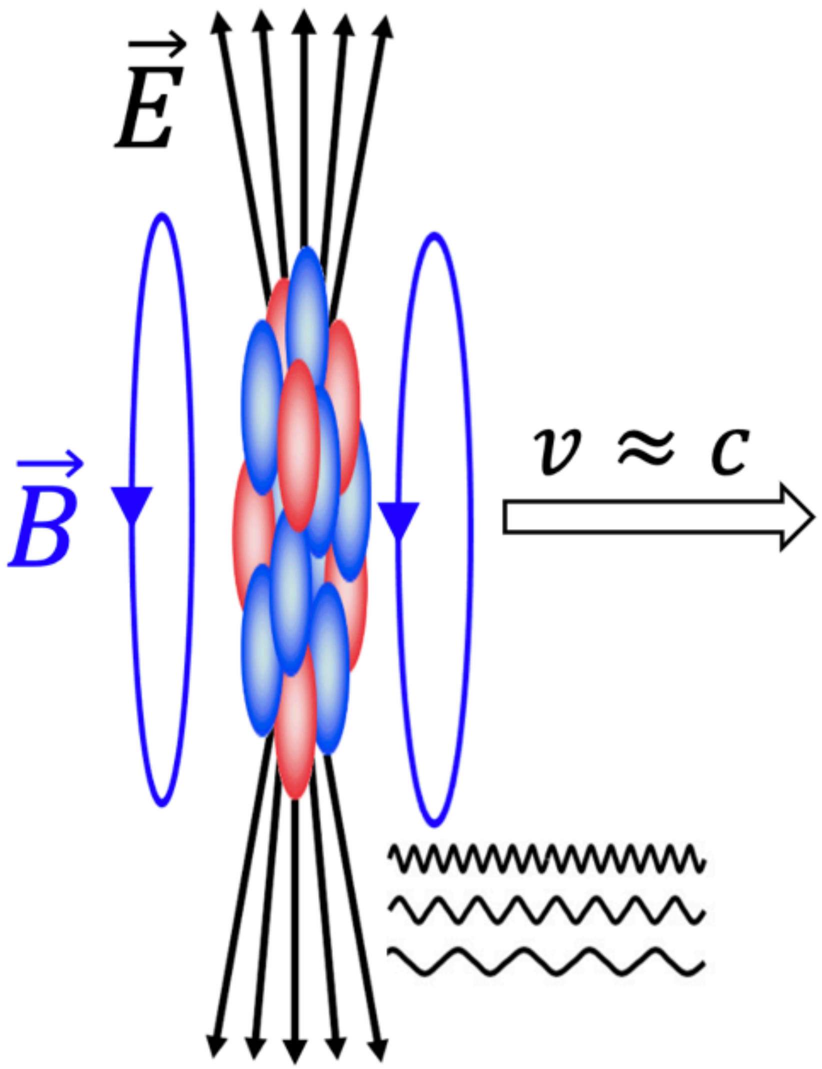
$\sim (N_g)^2$(nonlinear)

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



Small x ← Large x

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 ∝ Z^2

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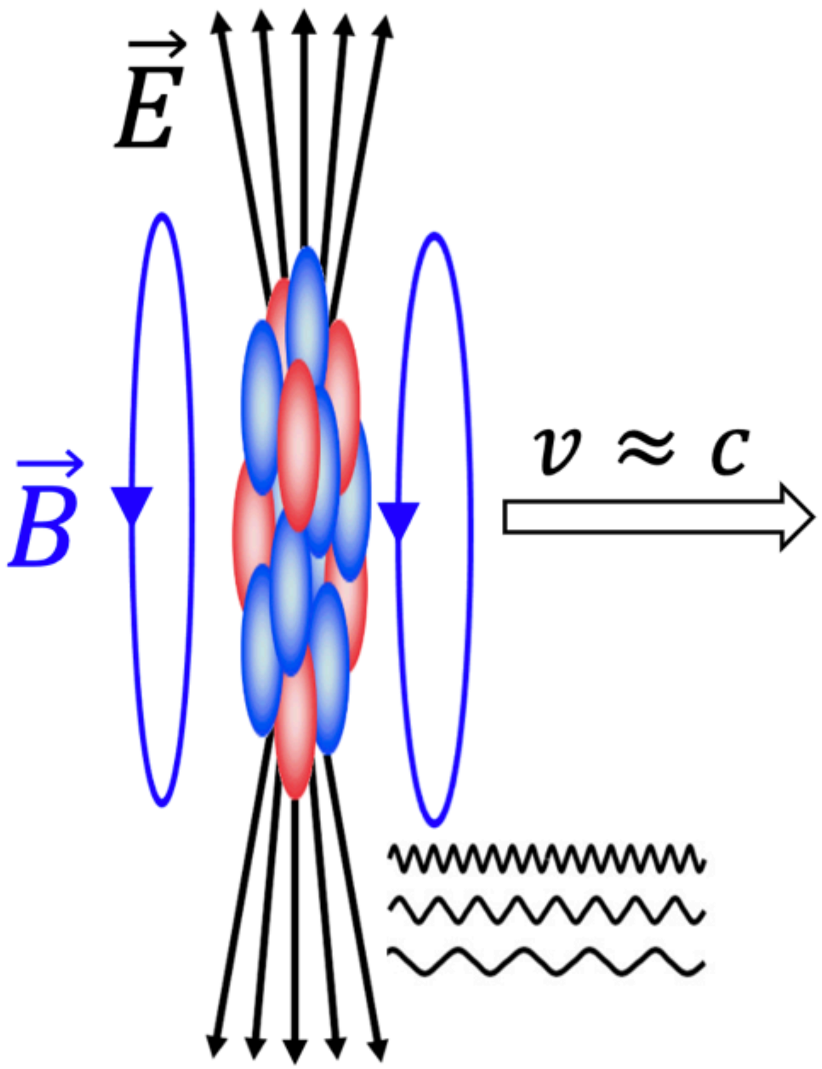

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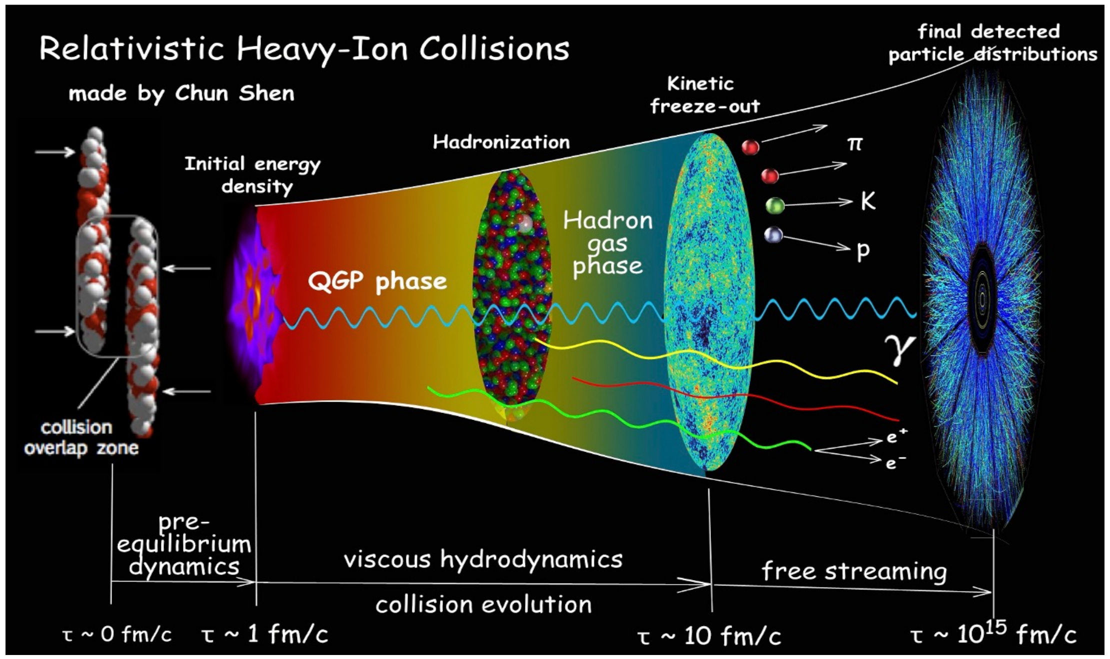
Photon kinematics

maximum energy $E_{\gamma,max}$~γ(ℏc/R)	**80 GeV in Pb+Pb@LHC** **3 GeV in Au+Au@RHIC**
typical p_T (& virtuality) 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!)**

What can we do before EIC?



Hadron Collider

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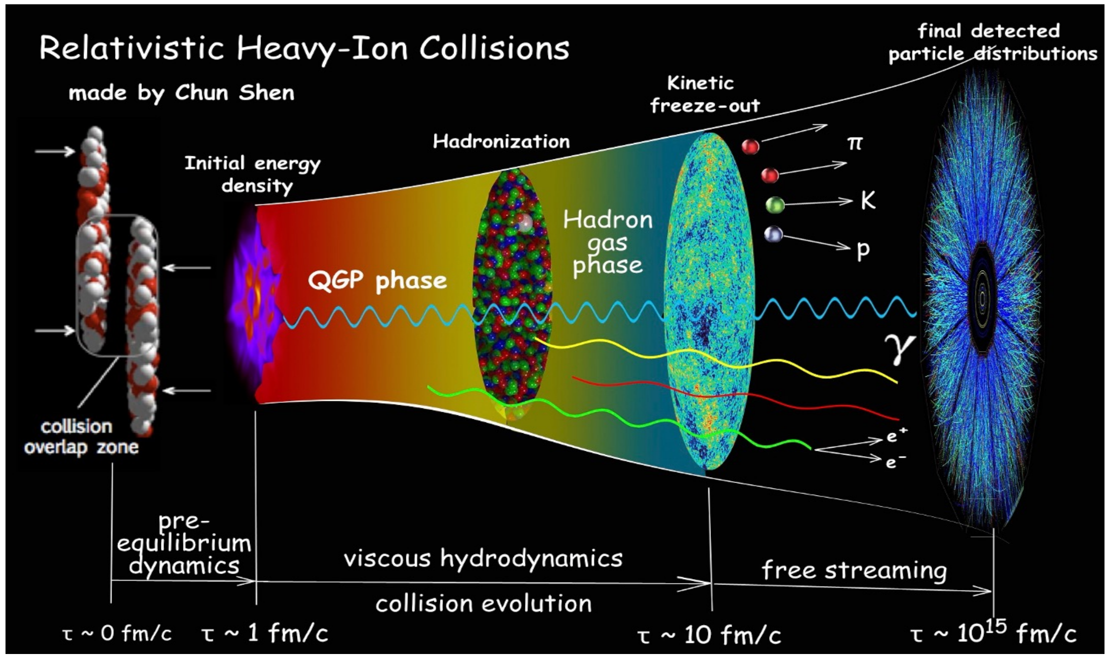
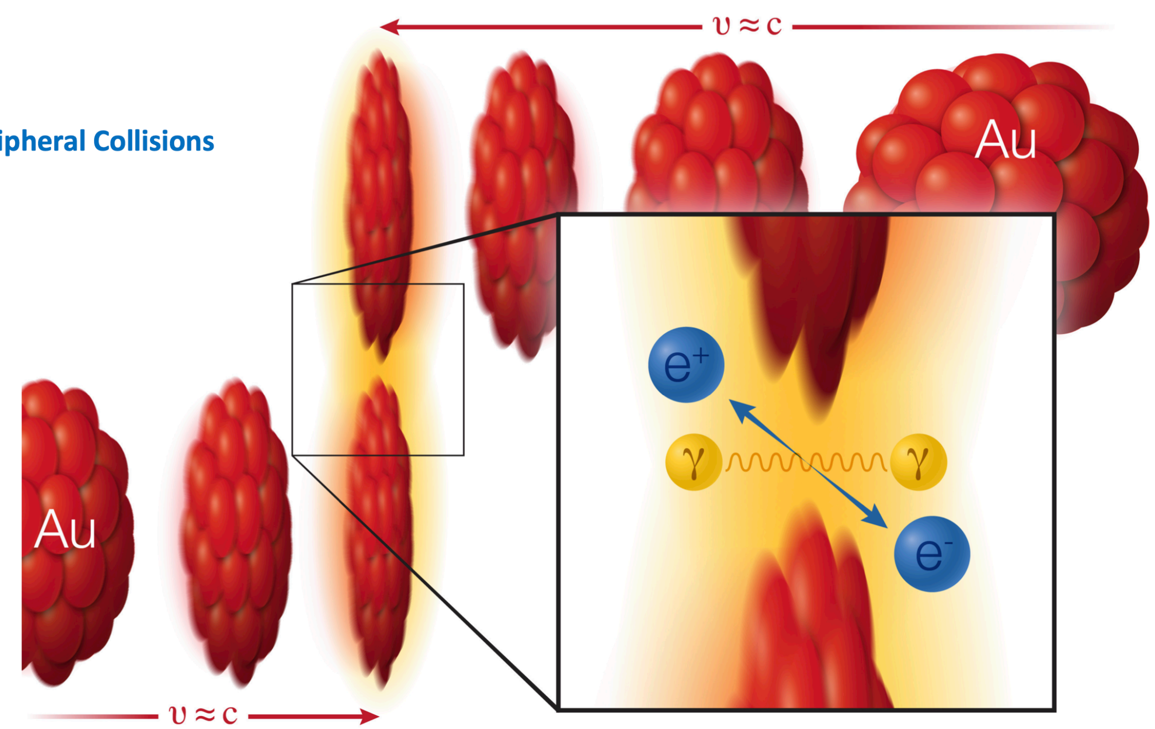
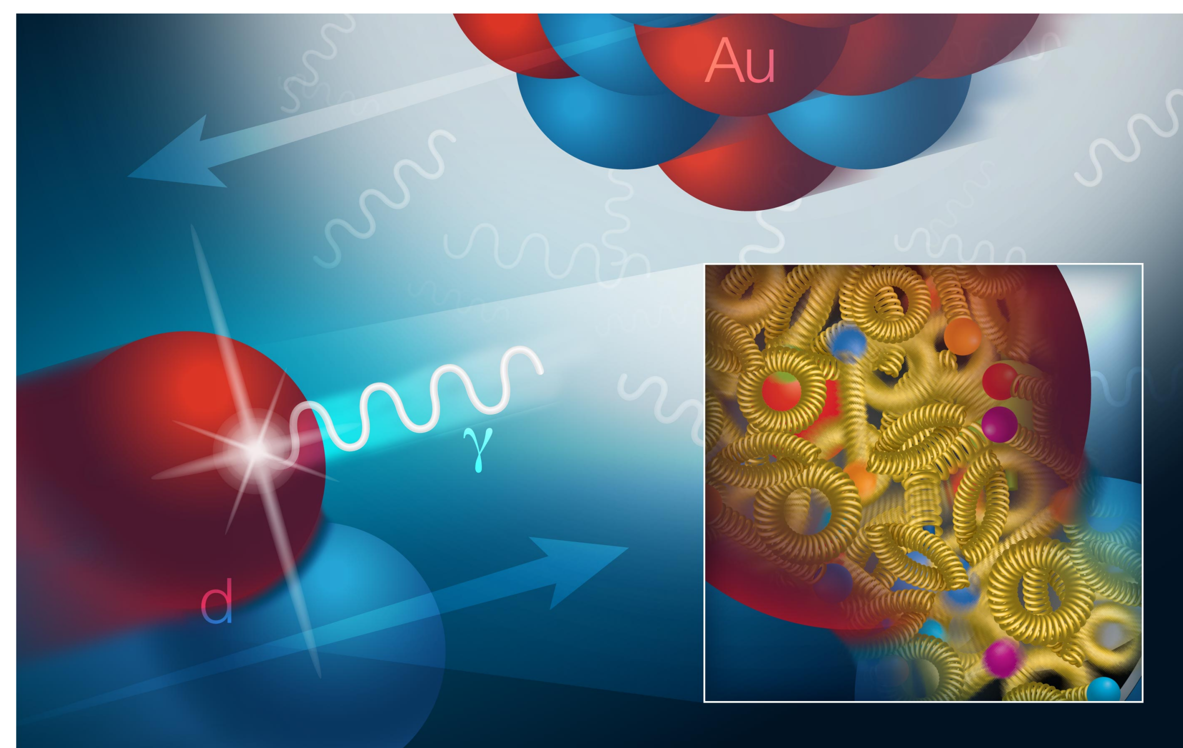


Hadron Collider

Photon Collider

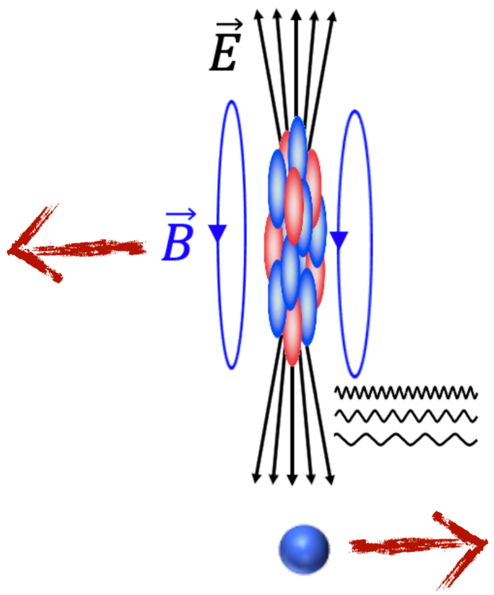
Ultra-Peripheral Collisions



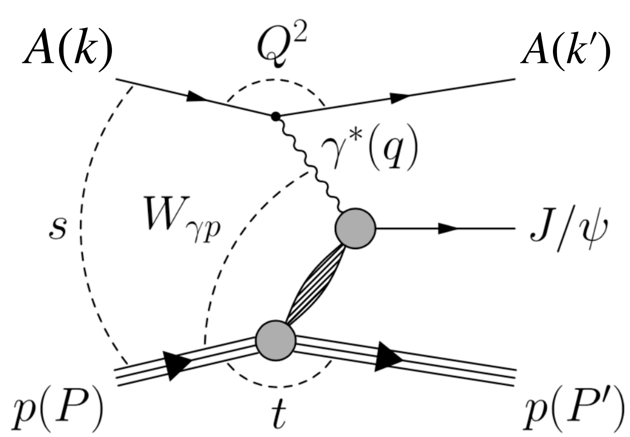


Photon-nuclear interactions

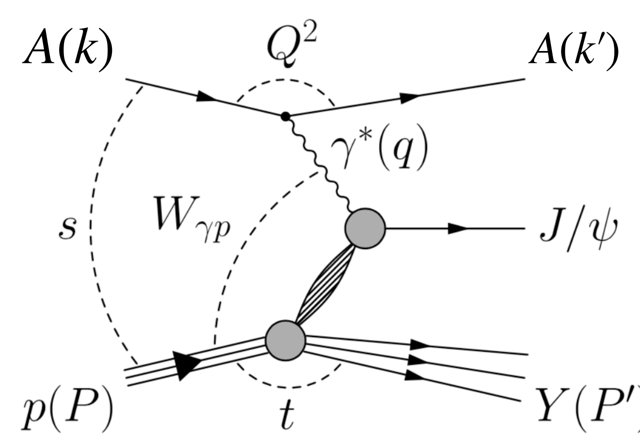
Little "HERA"



Elastic



Inelastic



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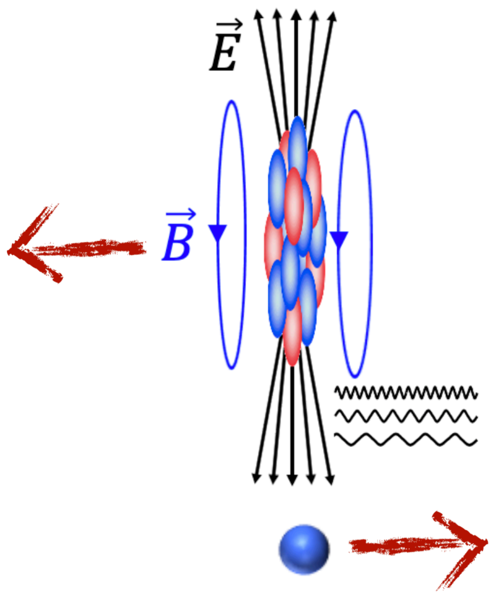

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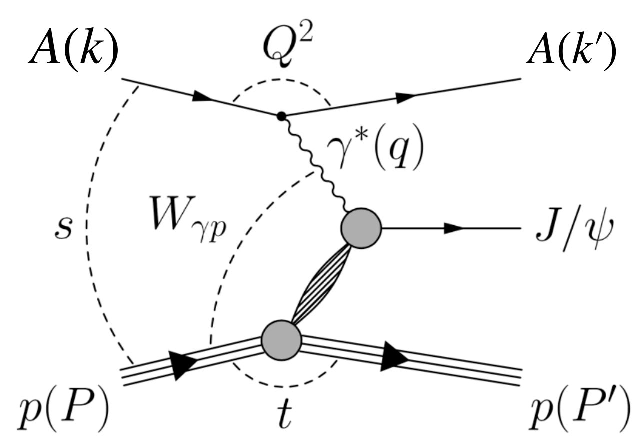

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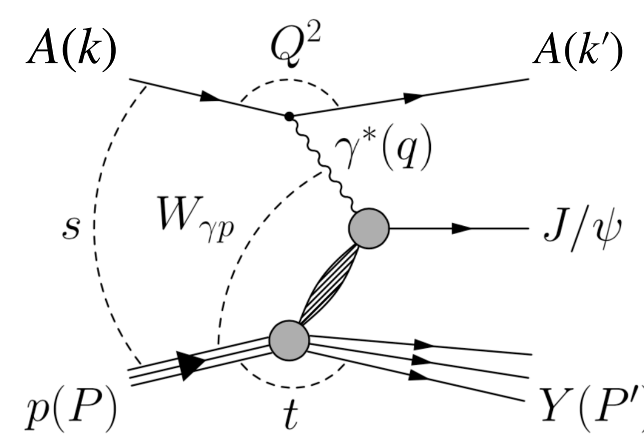

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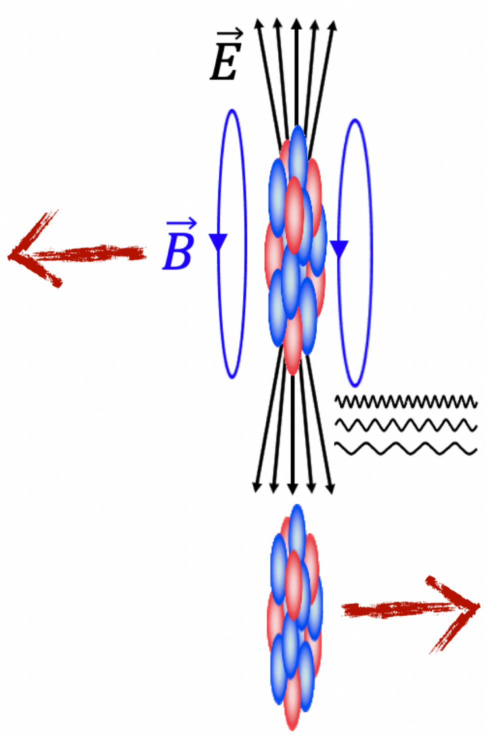
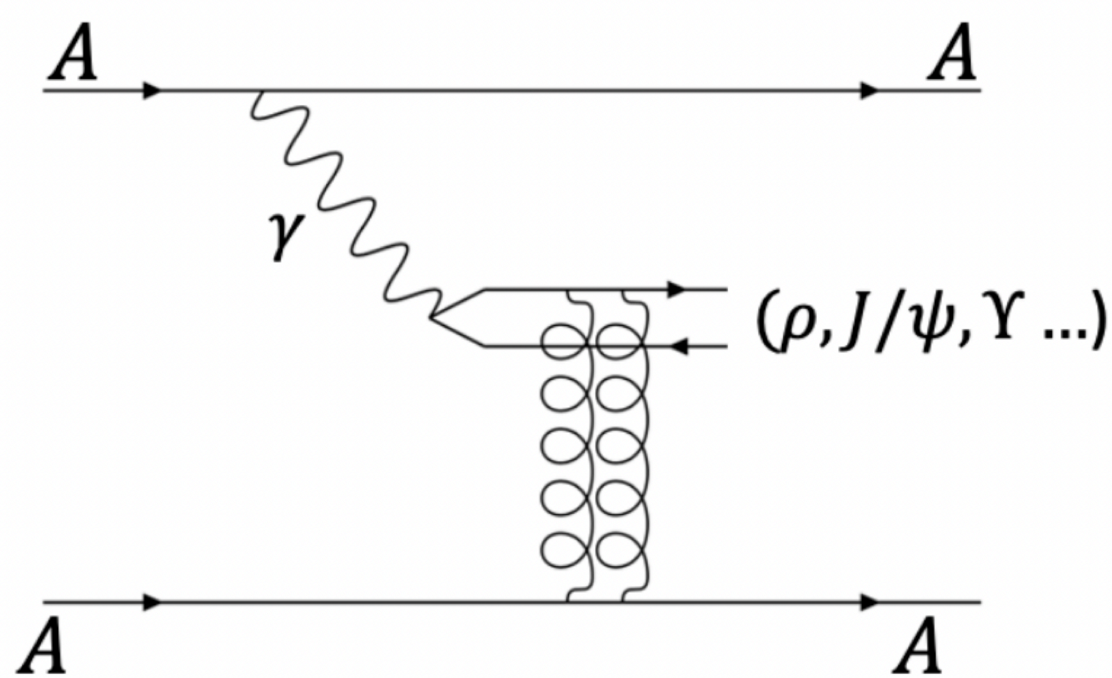
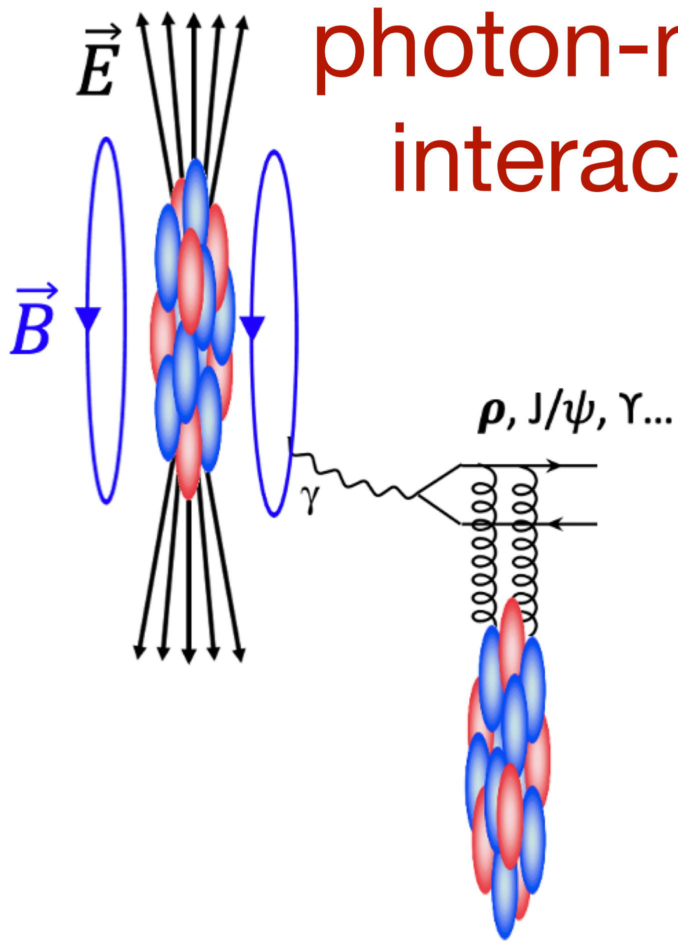




A clean probe of gluon structure



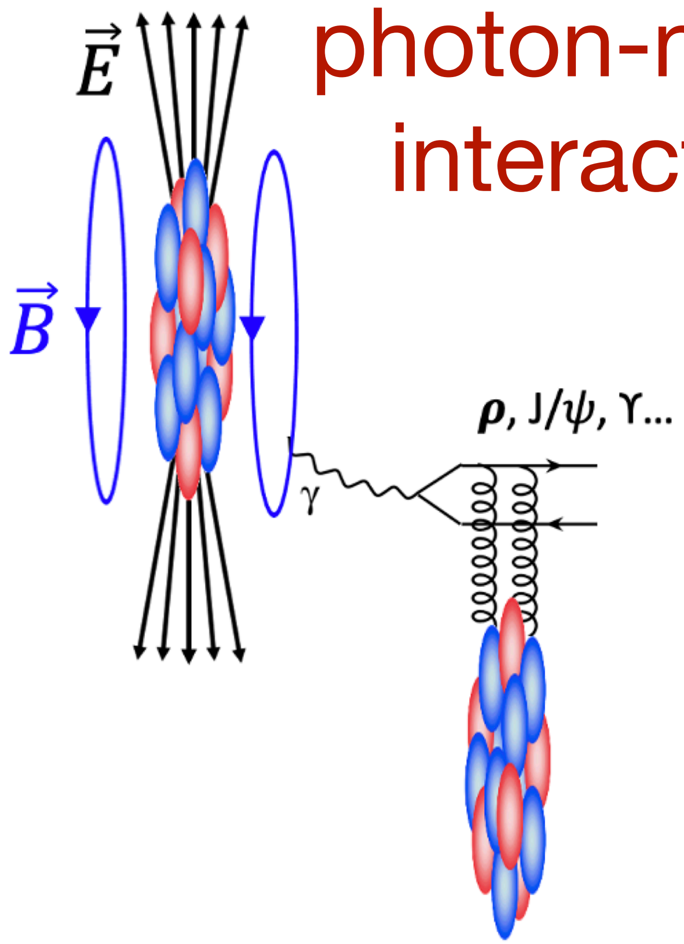
photon-nuclear interactions

- 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^2~0, but heavy quark mass can provide a hard scale for pQCD

- Coherent: average gluon distribution

- Incoherent: event-by-event fluctuation

A clean probe of gluon structure



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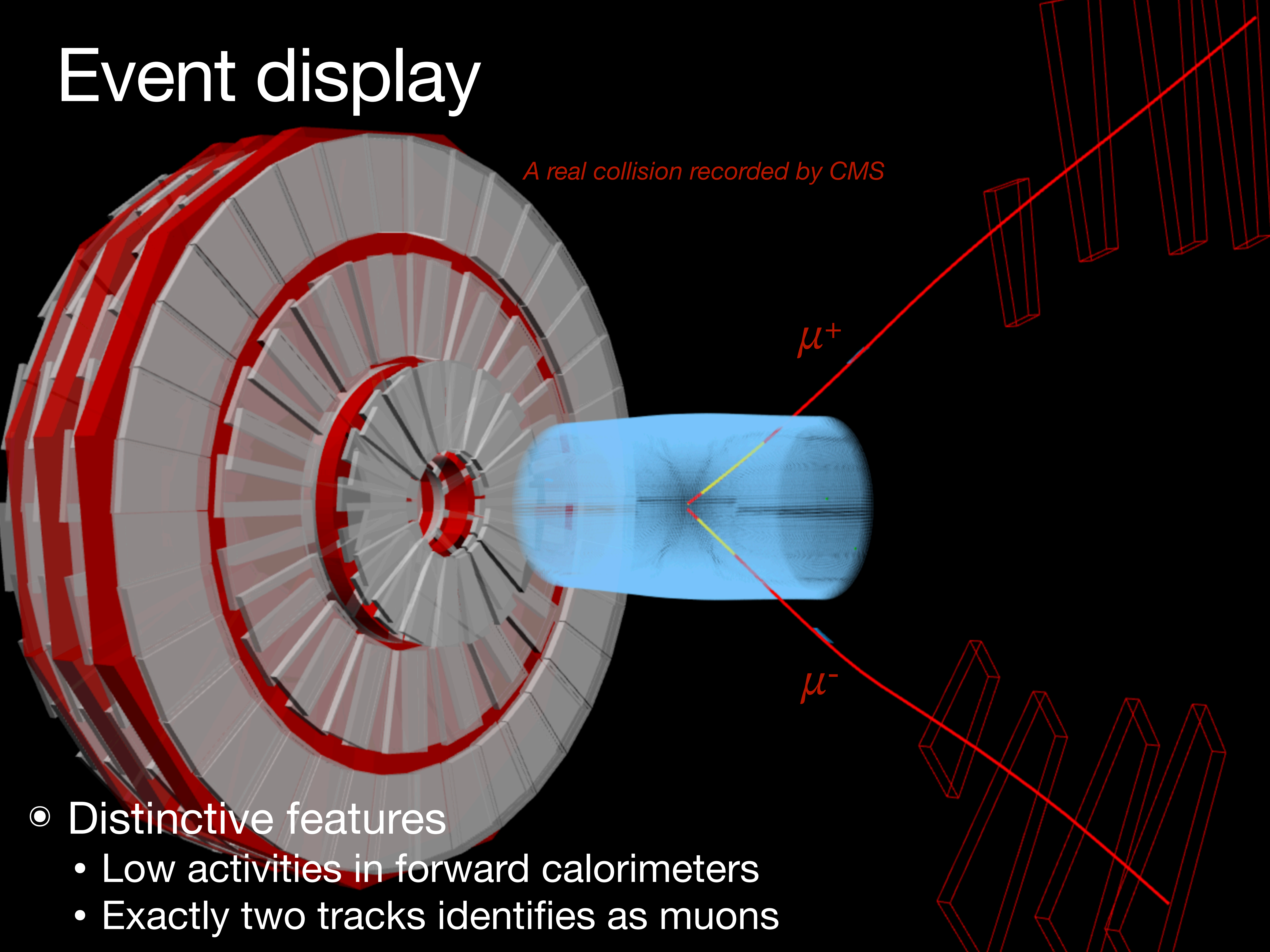
Focus by this talk

- Incoherent: event-by-event fluctuation

Large Hadron Collider

- Energies: 0.9 - 14 TeV
- Species: p+p, pPb, PbPb, XeXe, OO, ArAr, and KrKr

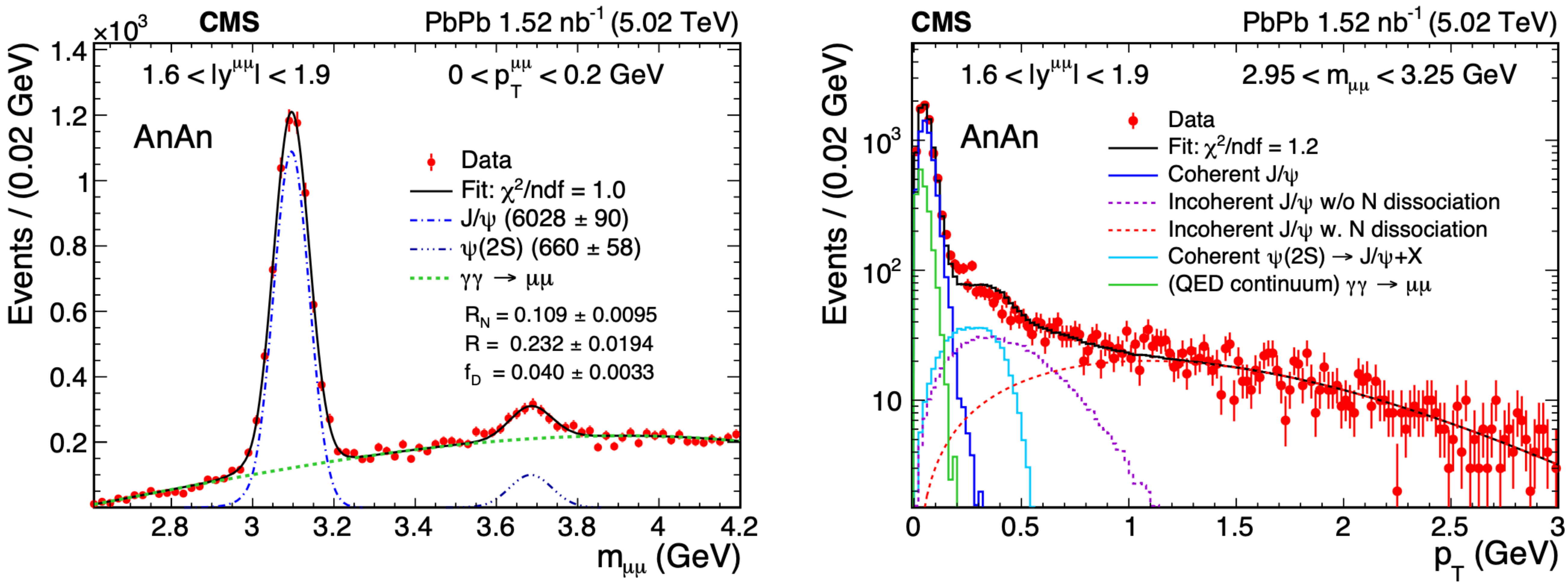
Event display



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

Signal extraction

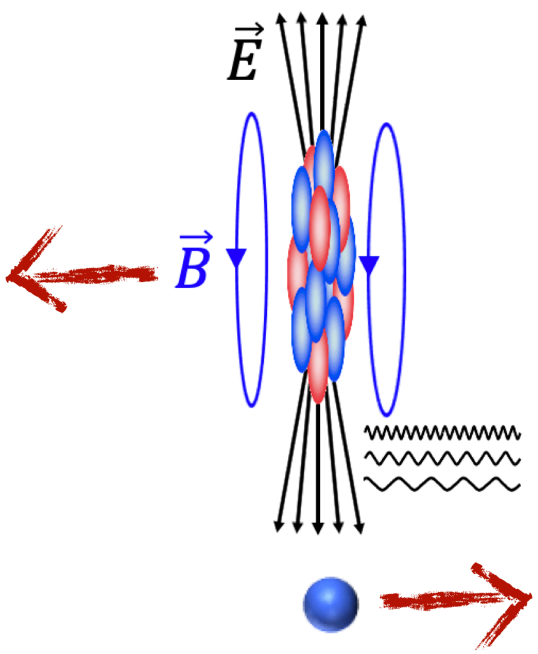
CMS, PRL 131 (2023) 262301

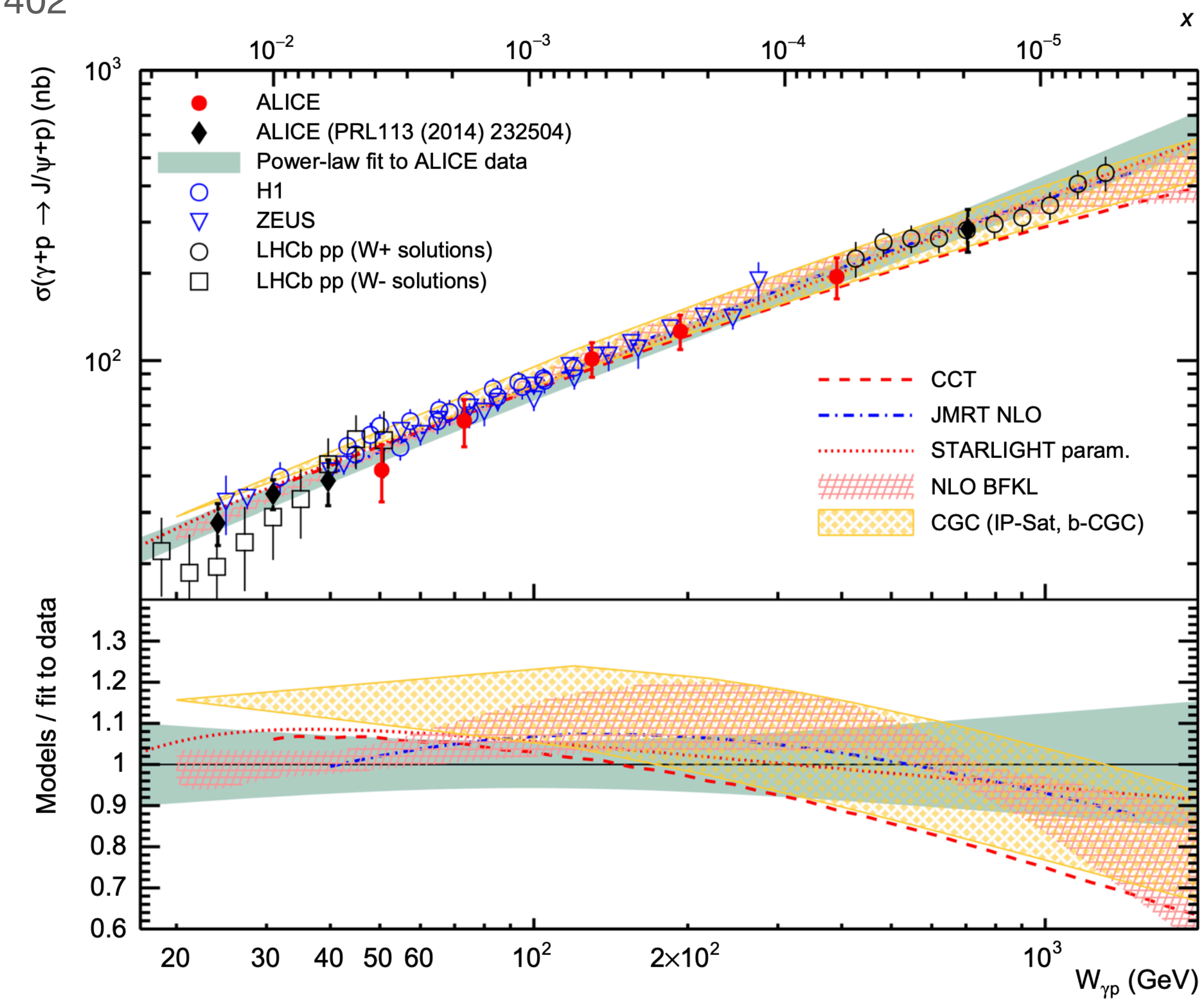


- Signals of coherent J/ψ are extracted by simultaneously fitting the mass and p_T spectra

Imaging free nucleon

ALICE, EPJC 79 (2019) 402

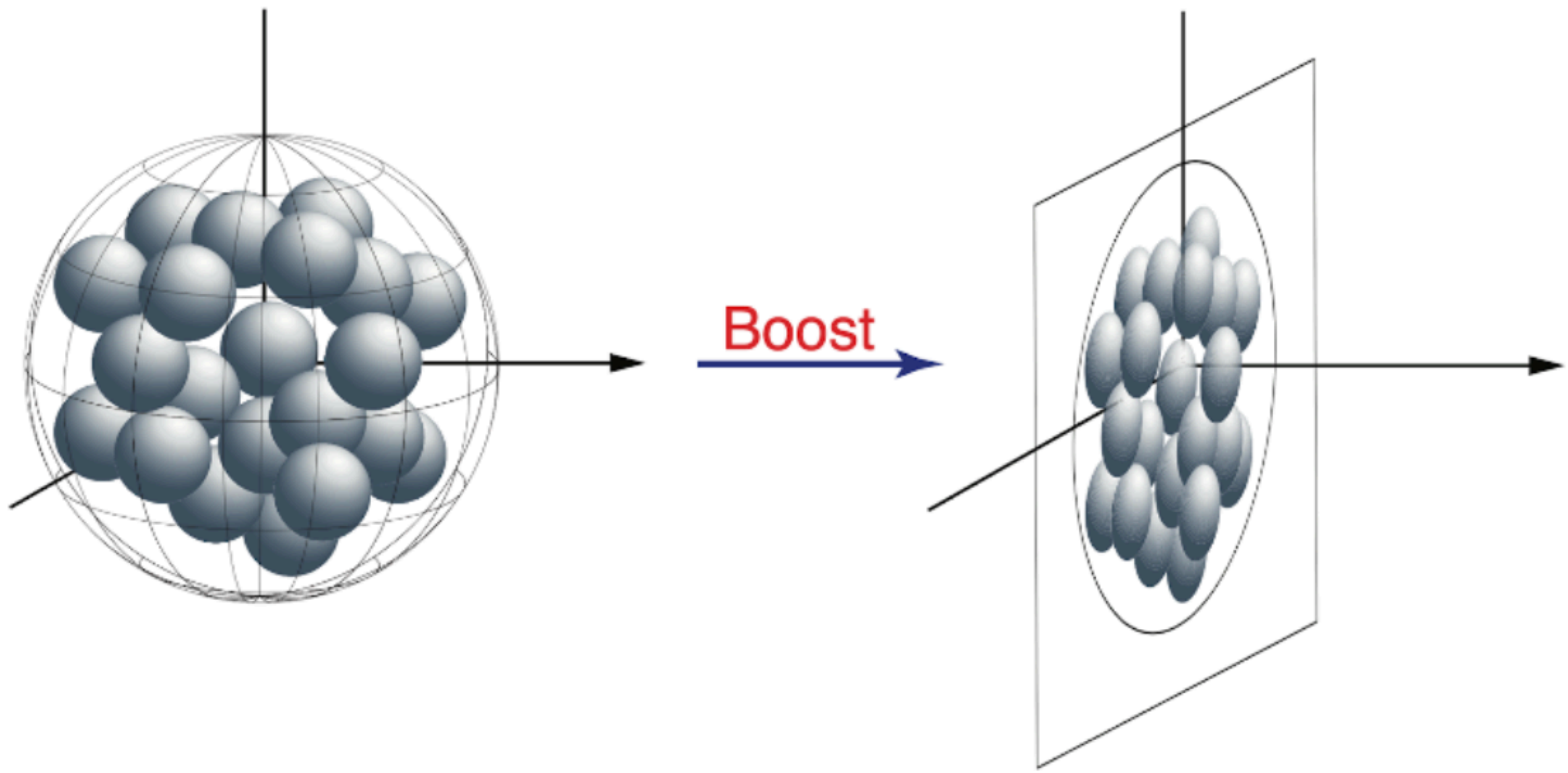




LO pQCD:
$\sigma^{VM} \propto [xG(x)]^2$

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

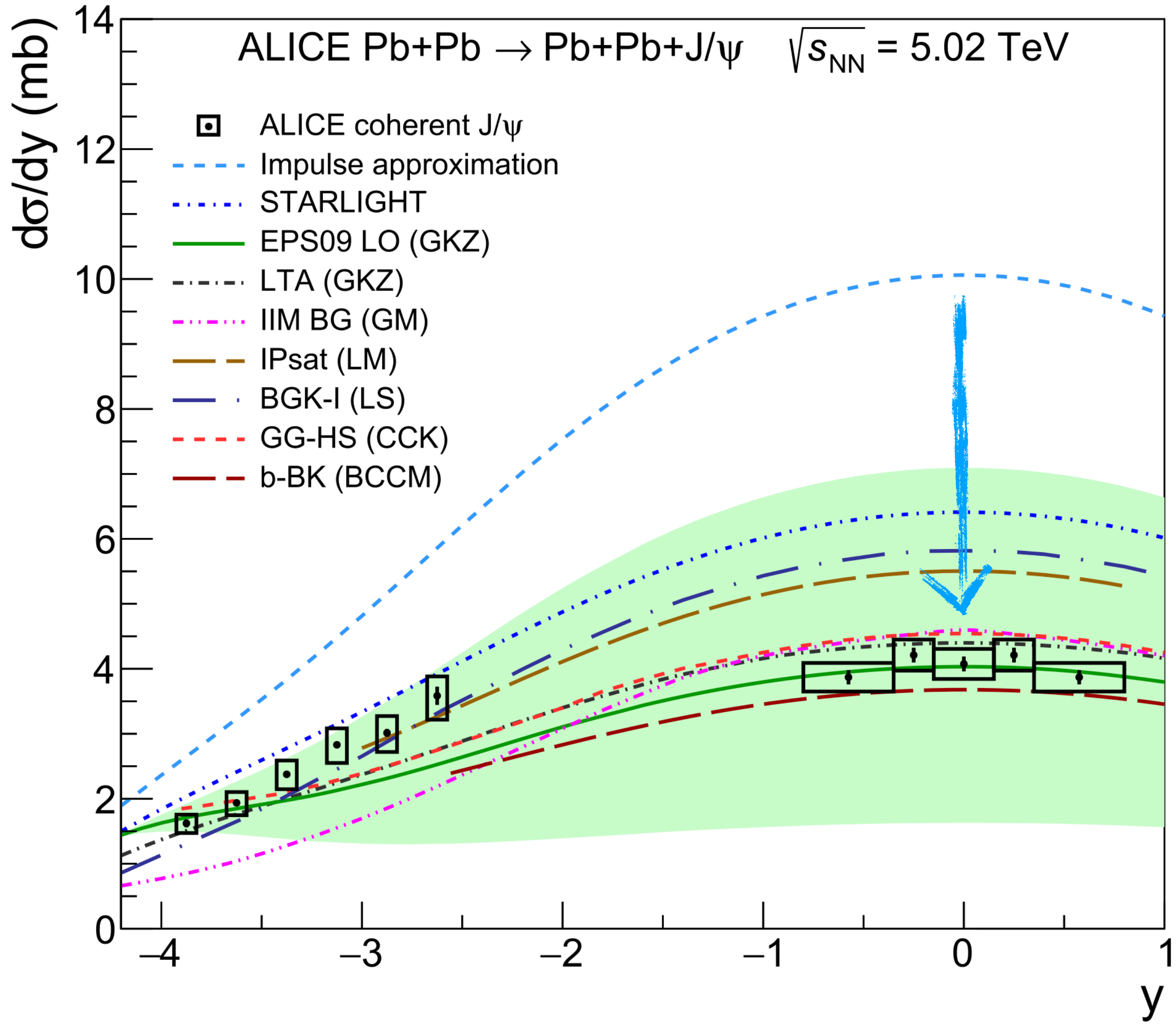
Ultra-dense gluonic matter



- 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

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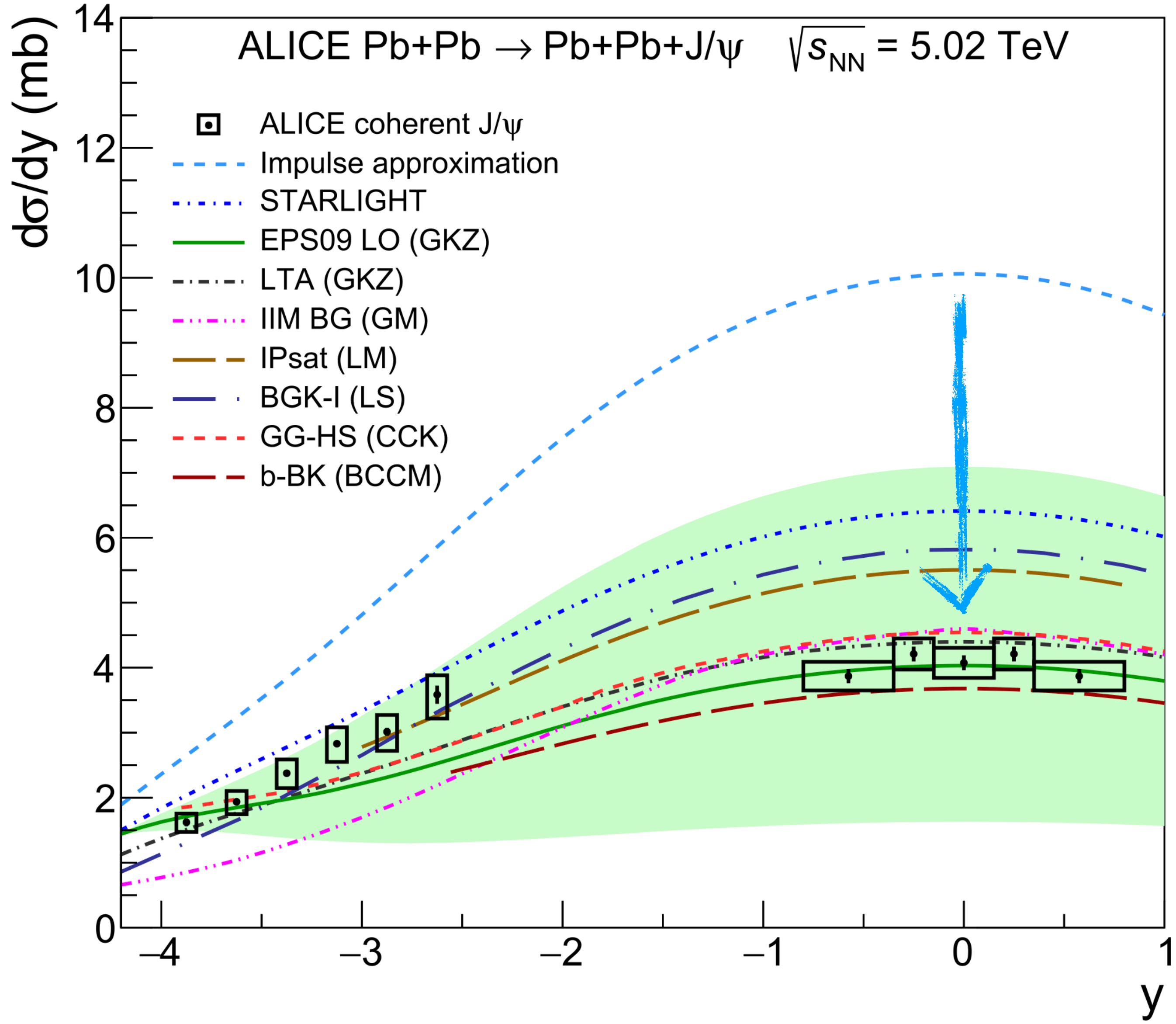

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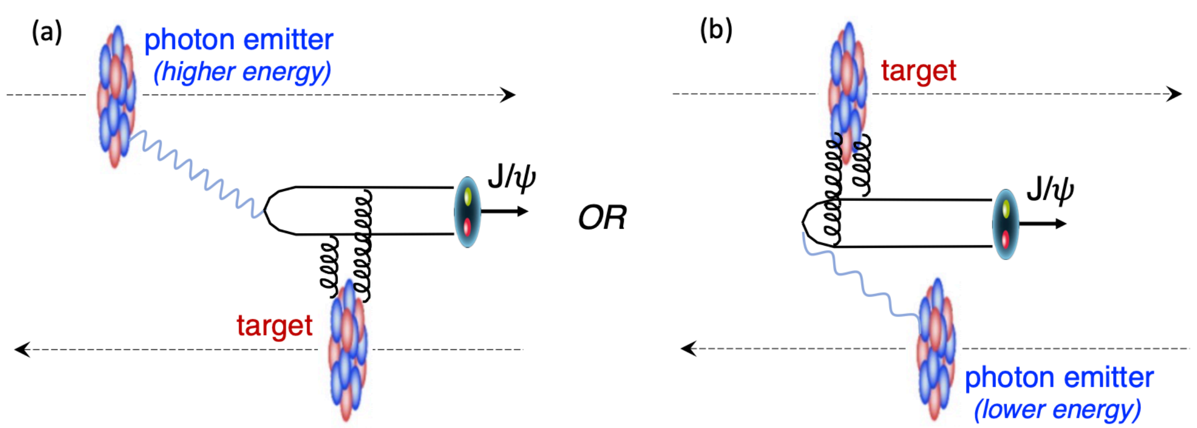
- Two-way ambiguity in A+A UPC

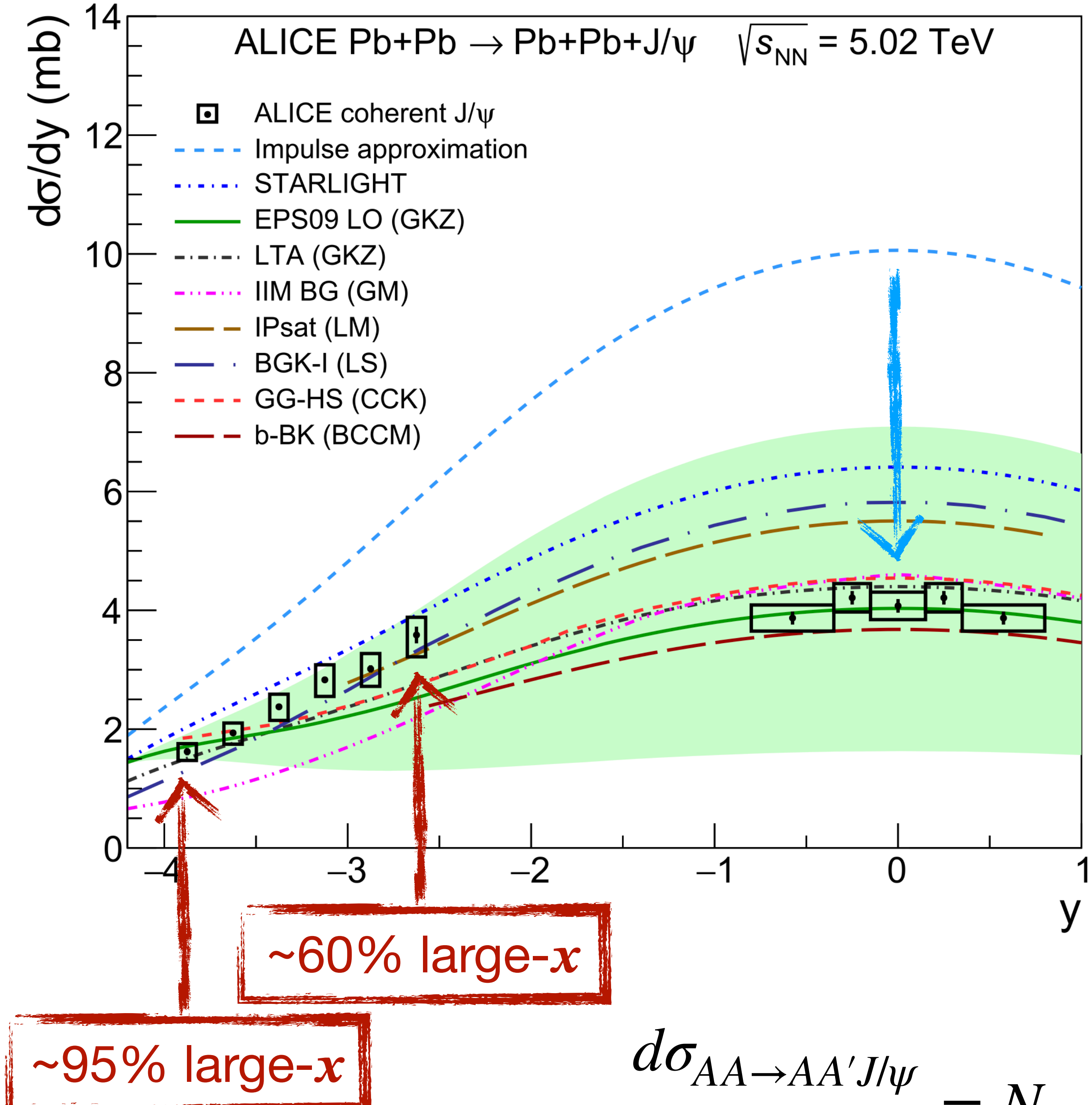


$$x = \frac{M_{J/\psi}}{2E_{beam}} e^{-y} \qquad x = \frac{M_{J/\psi}}{2E_{beam}} e^{+y}$$

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

Imaging heavy nucleus

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



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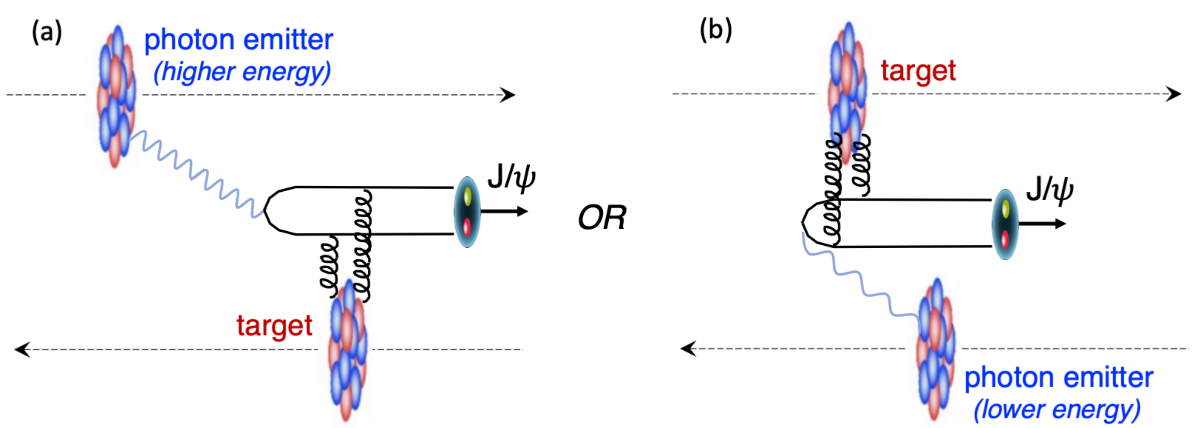

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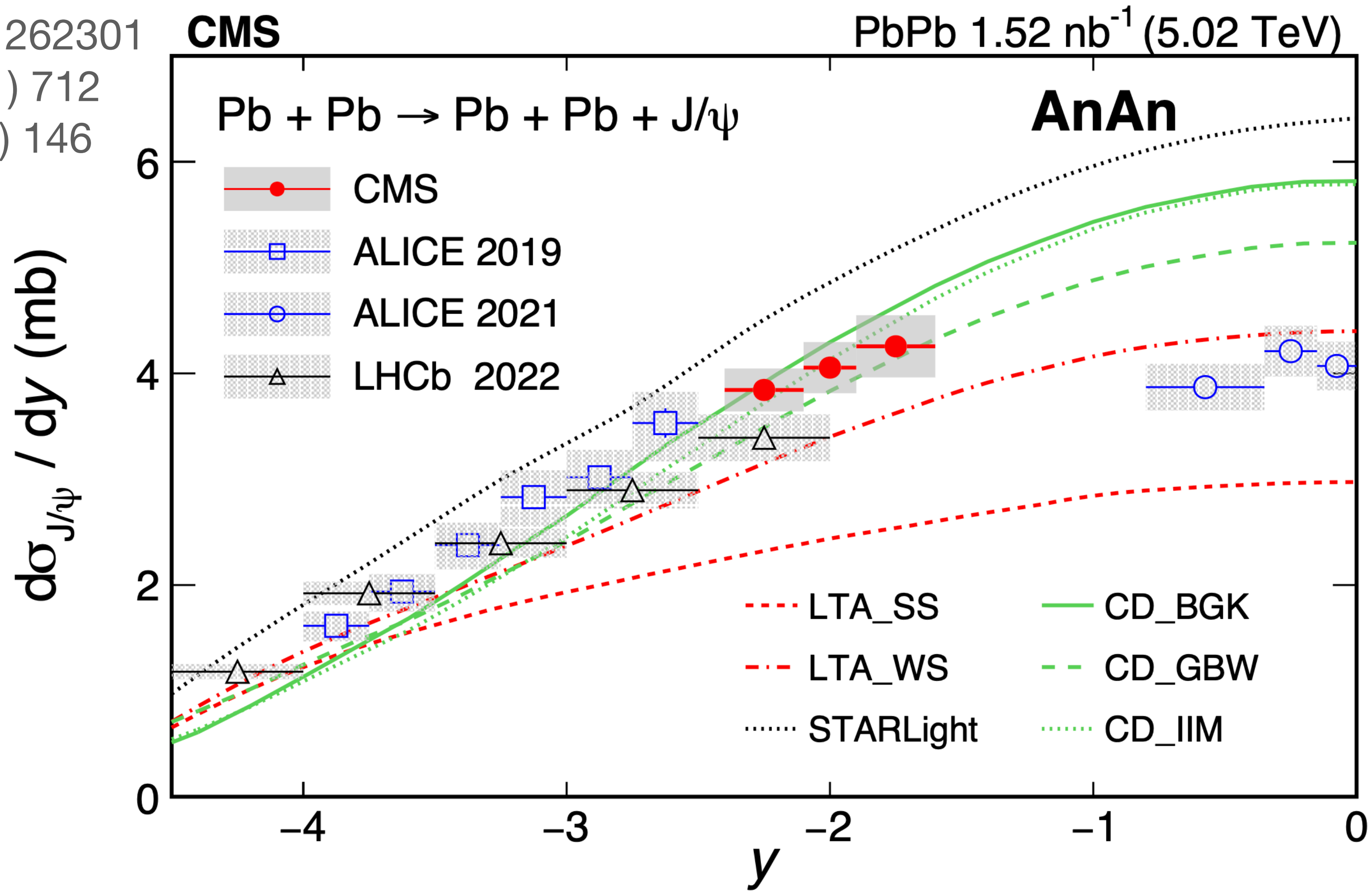
Imaging heavy nucleus

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

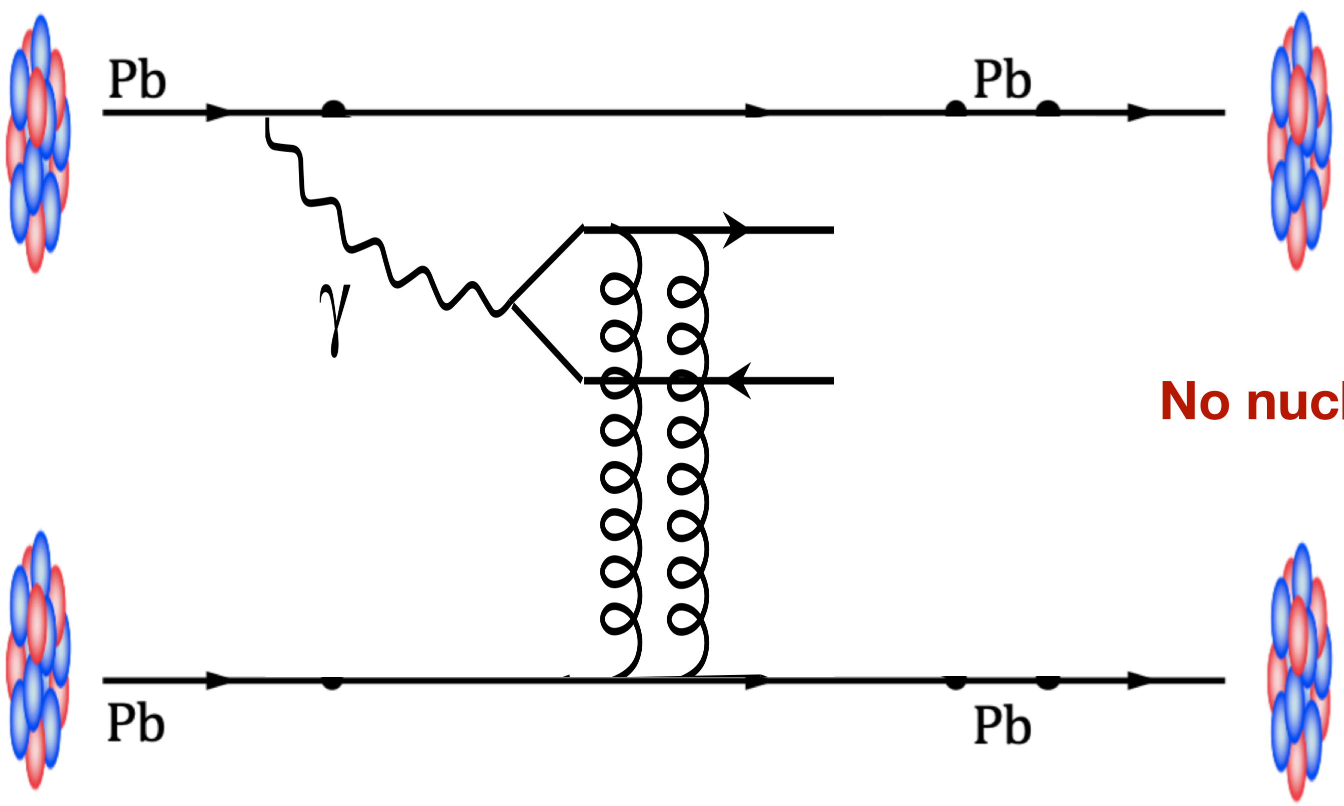


- LHC experiments complement each over a wide range of y region
  - No theory can describe data over full y region! What is missing?

Solving the “two-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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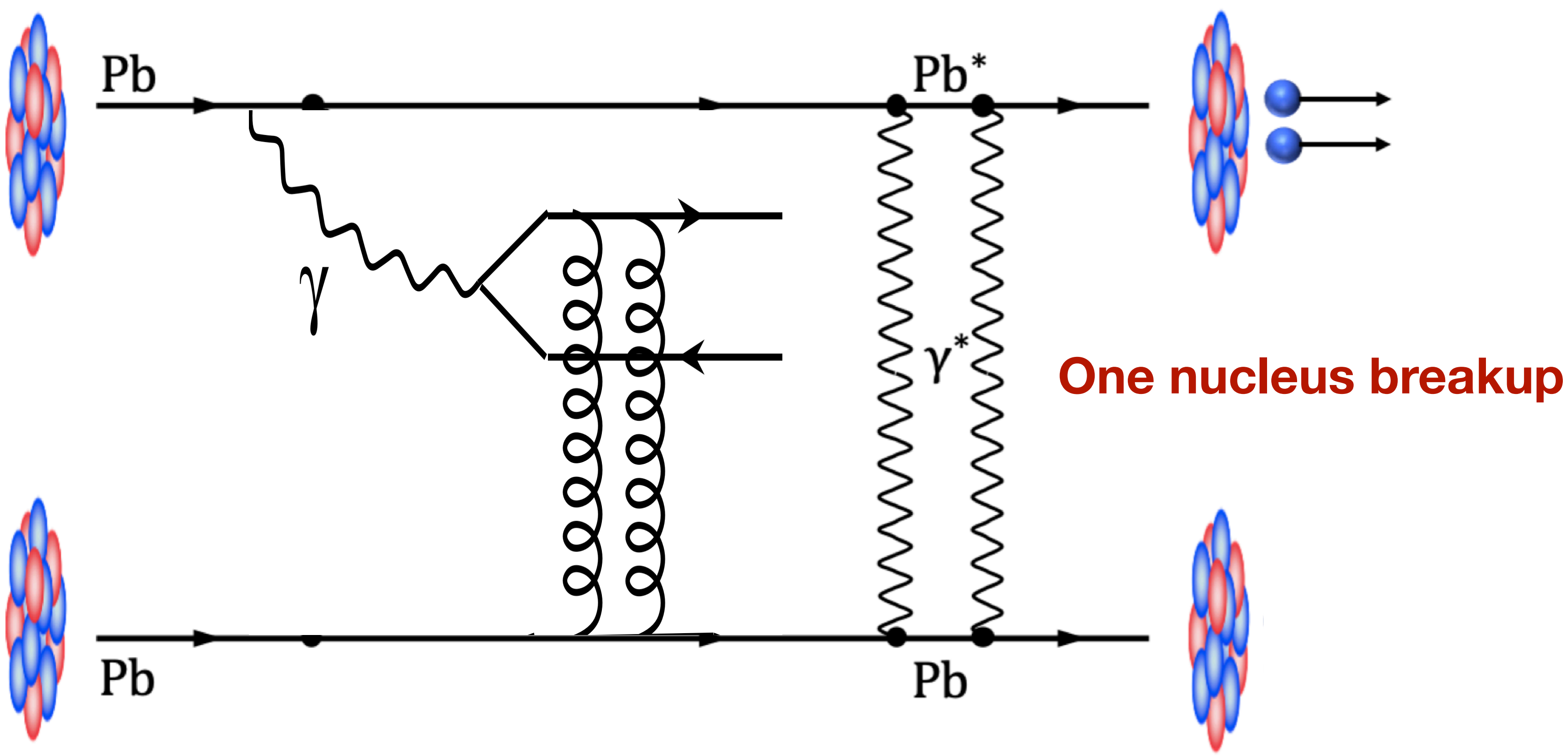

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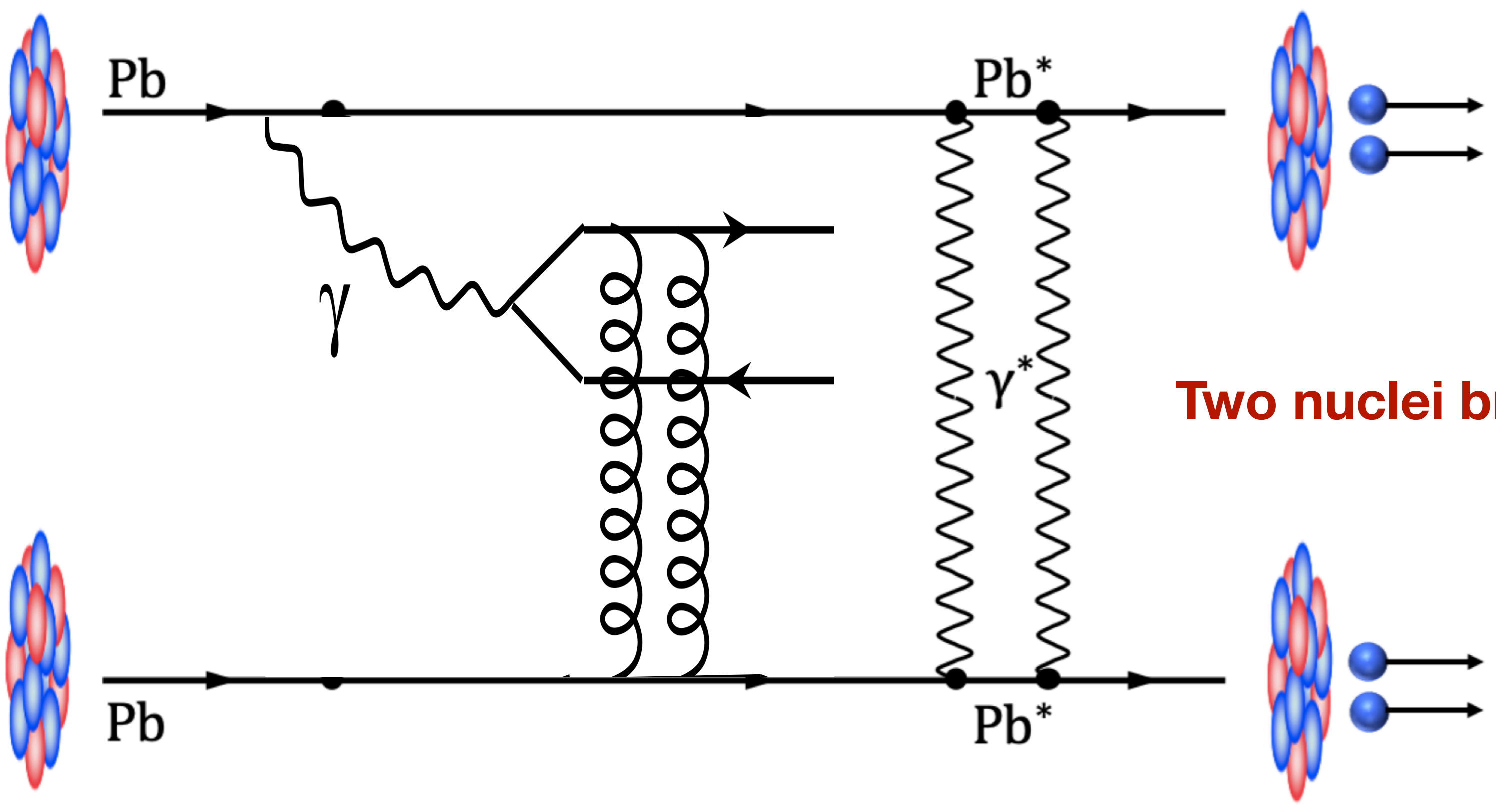

Two nuclei breakup

A solution to the “two-way ambiguity”

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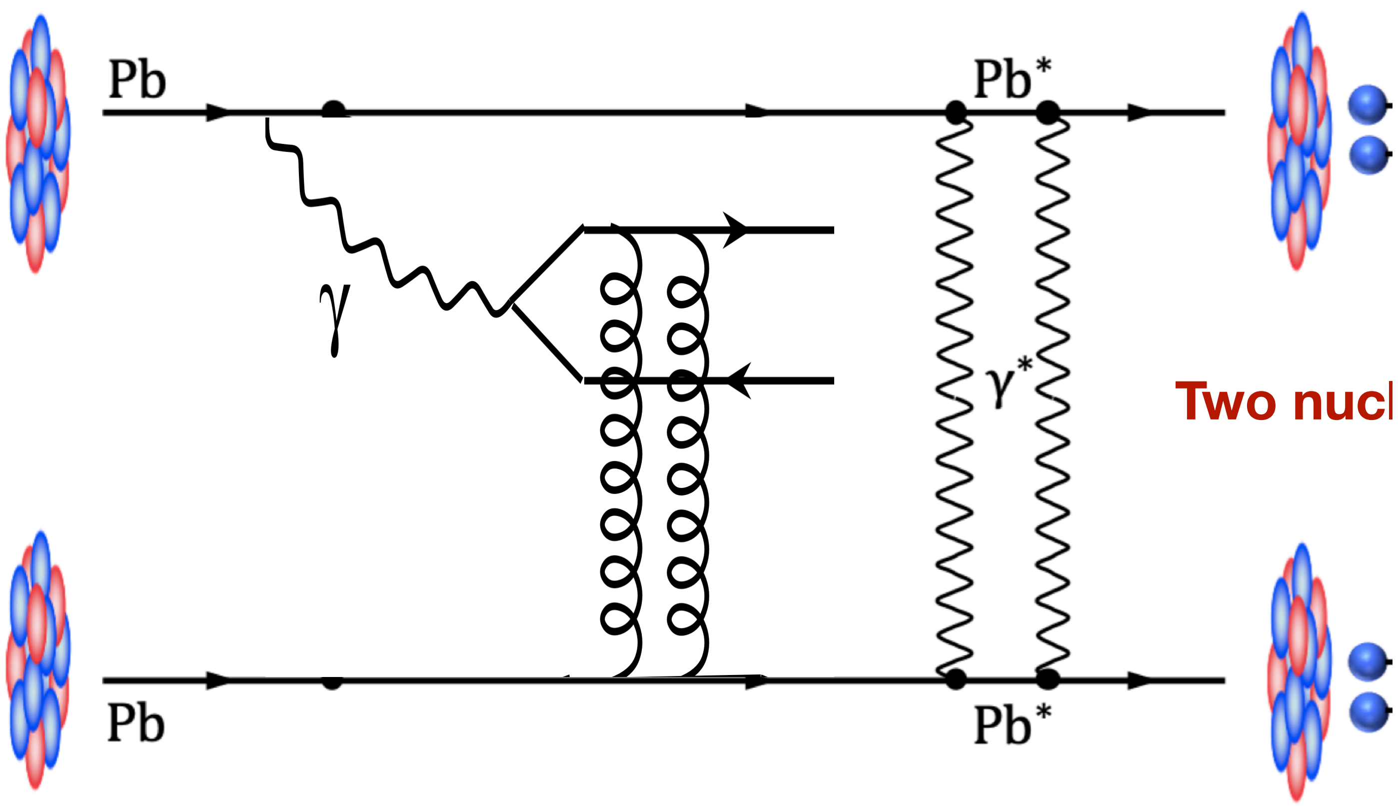
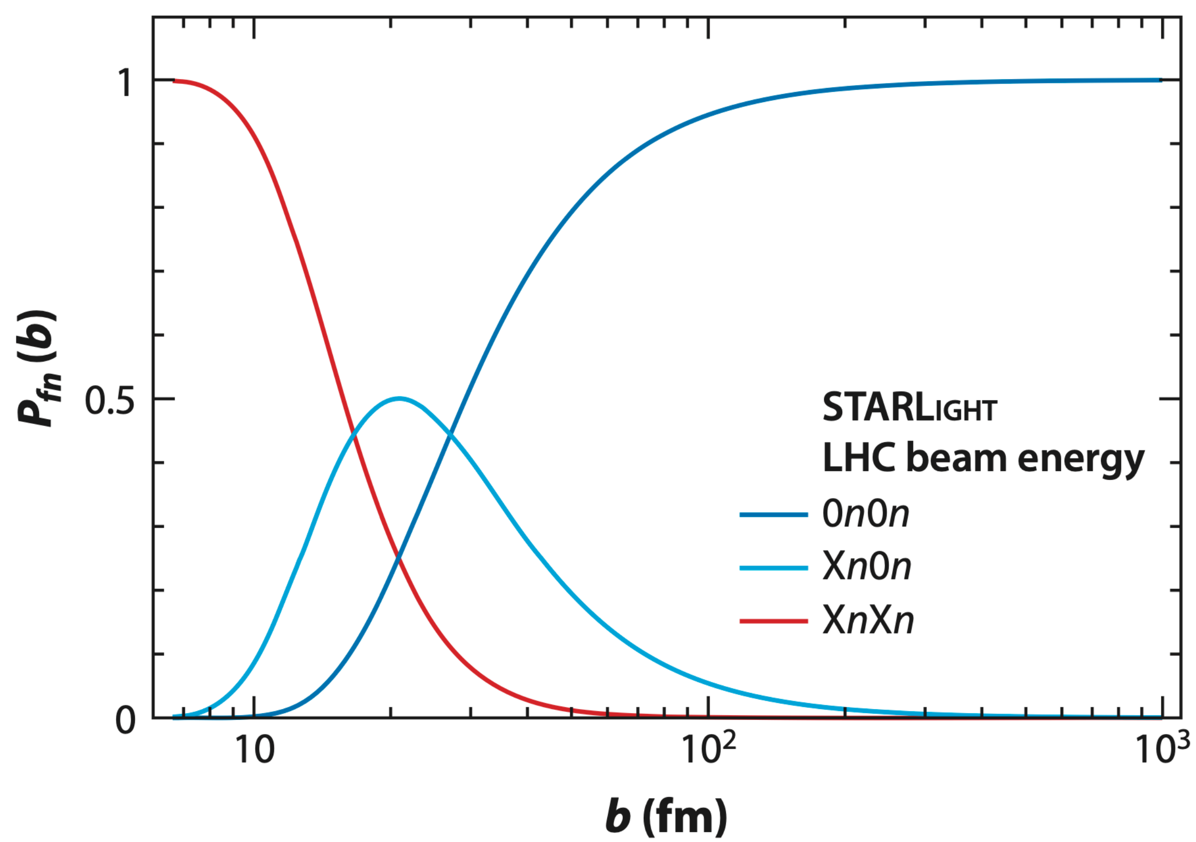
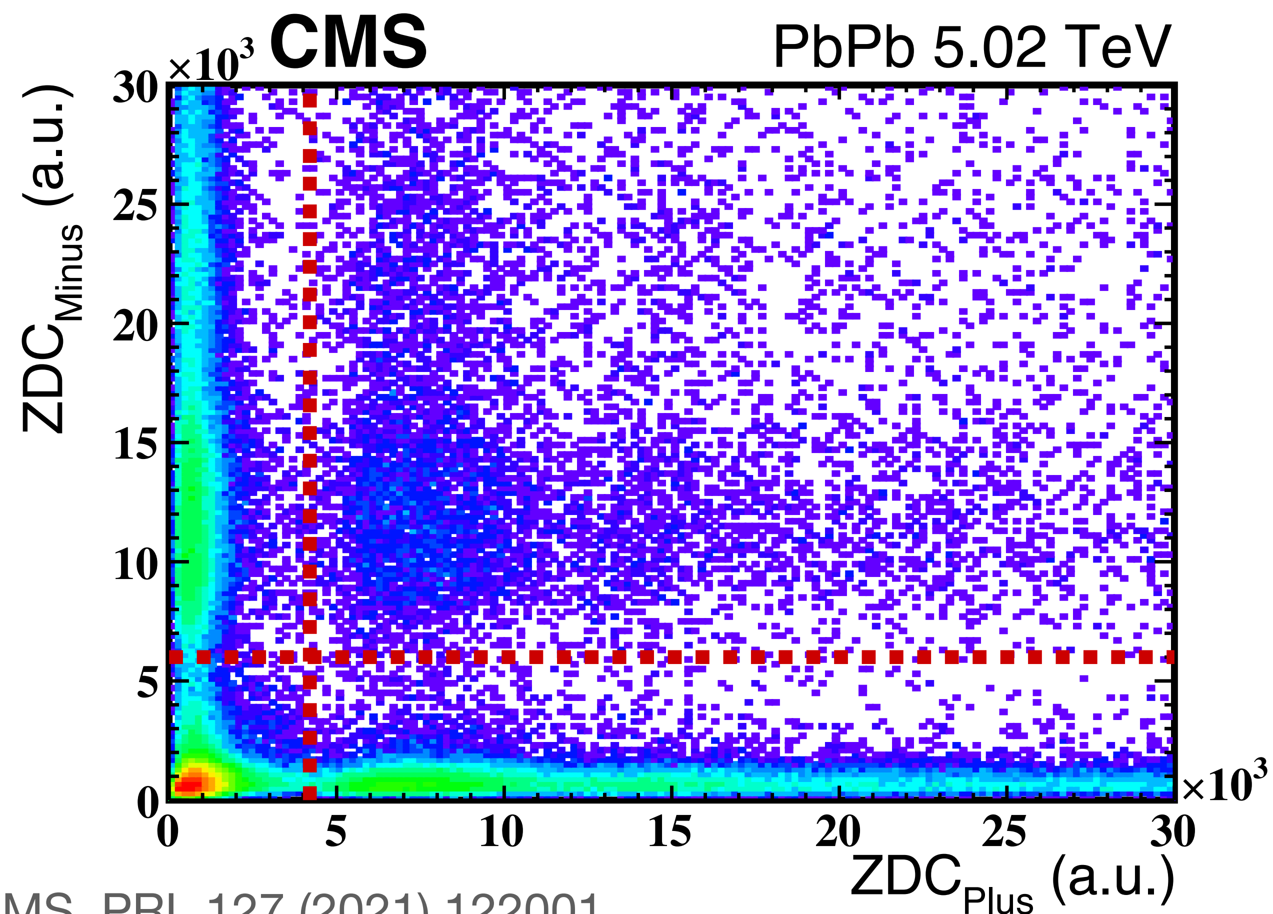


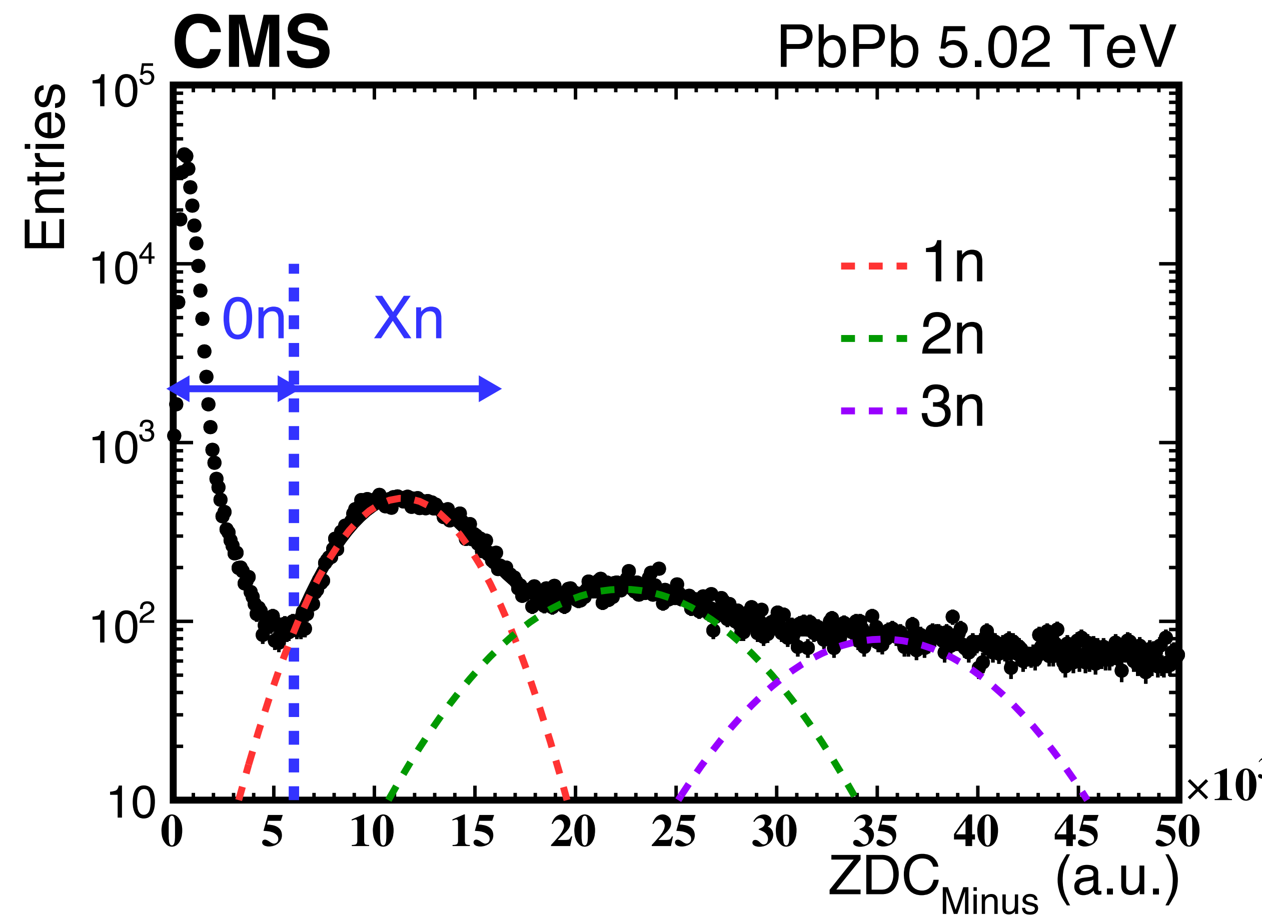


Klein and Steinberg, Ann. Rev. Nucl. Part. Sci. 70 (2020) 323

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

A solution to the "two-way ambiguity"



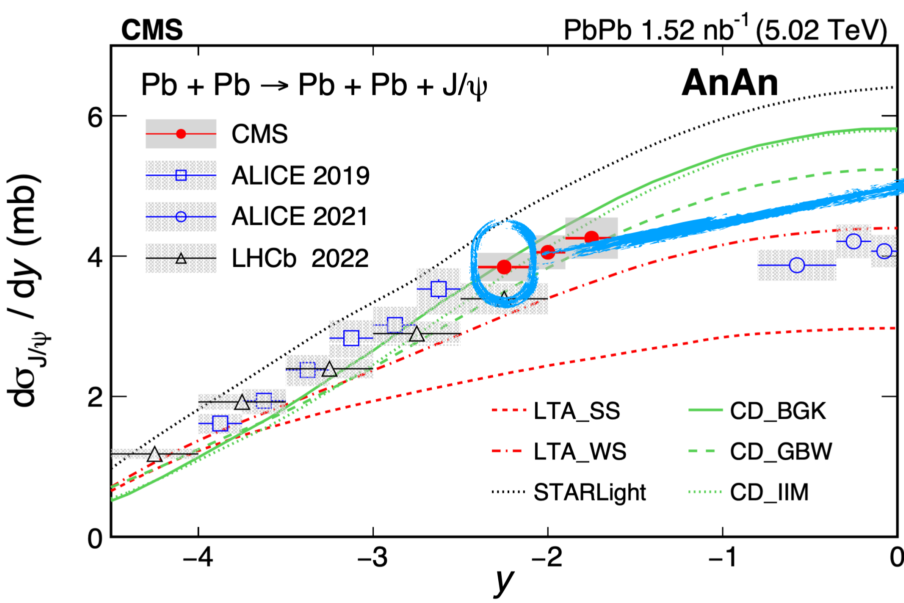


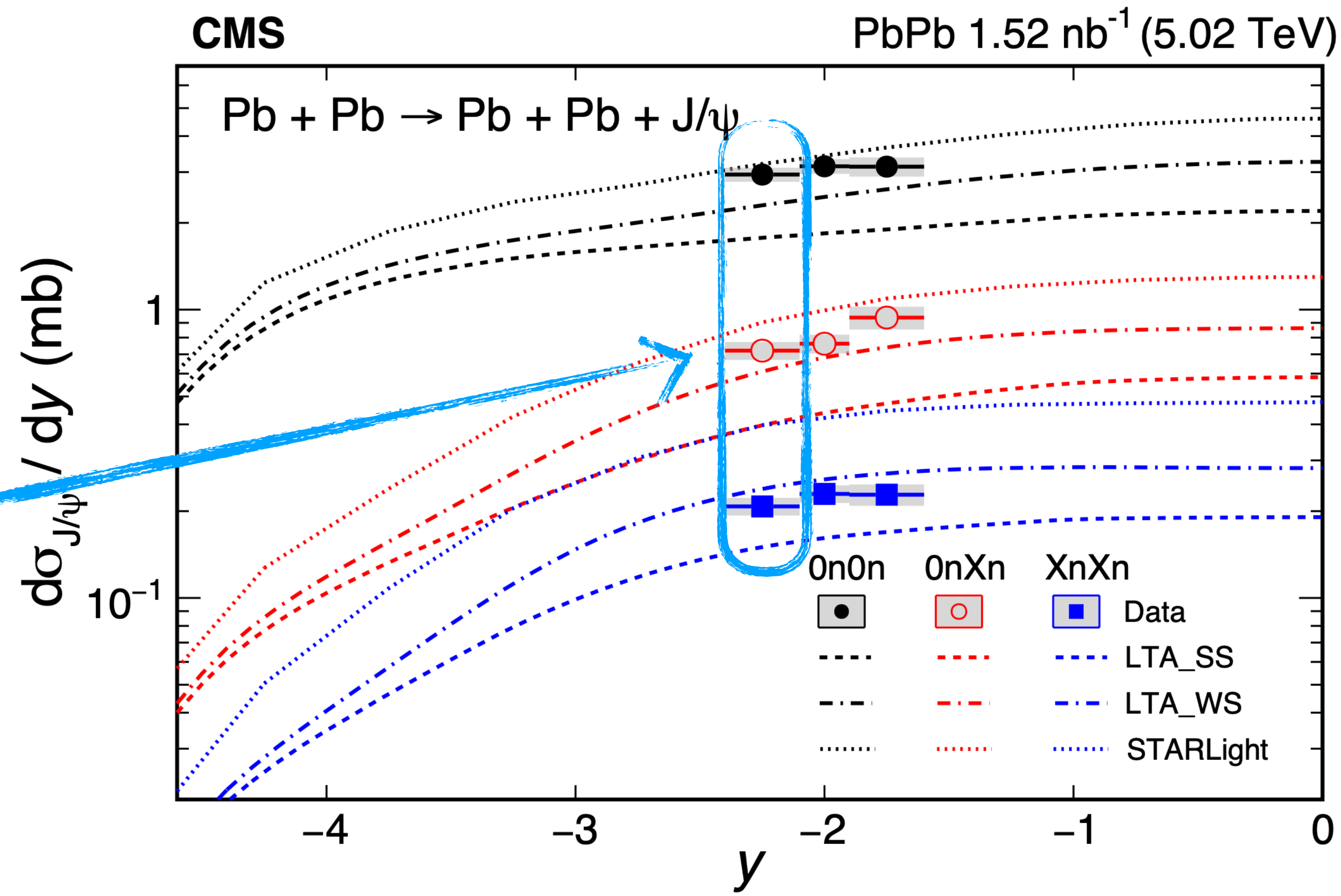
CMS, PRL 127 (2021) 122001

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

A solution to the “two-way ambiguity”

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





- 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”

A solution to the “two-way ambiguity”

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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Photon flux from theory

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What we need!

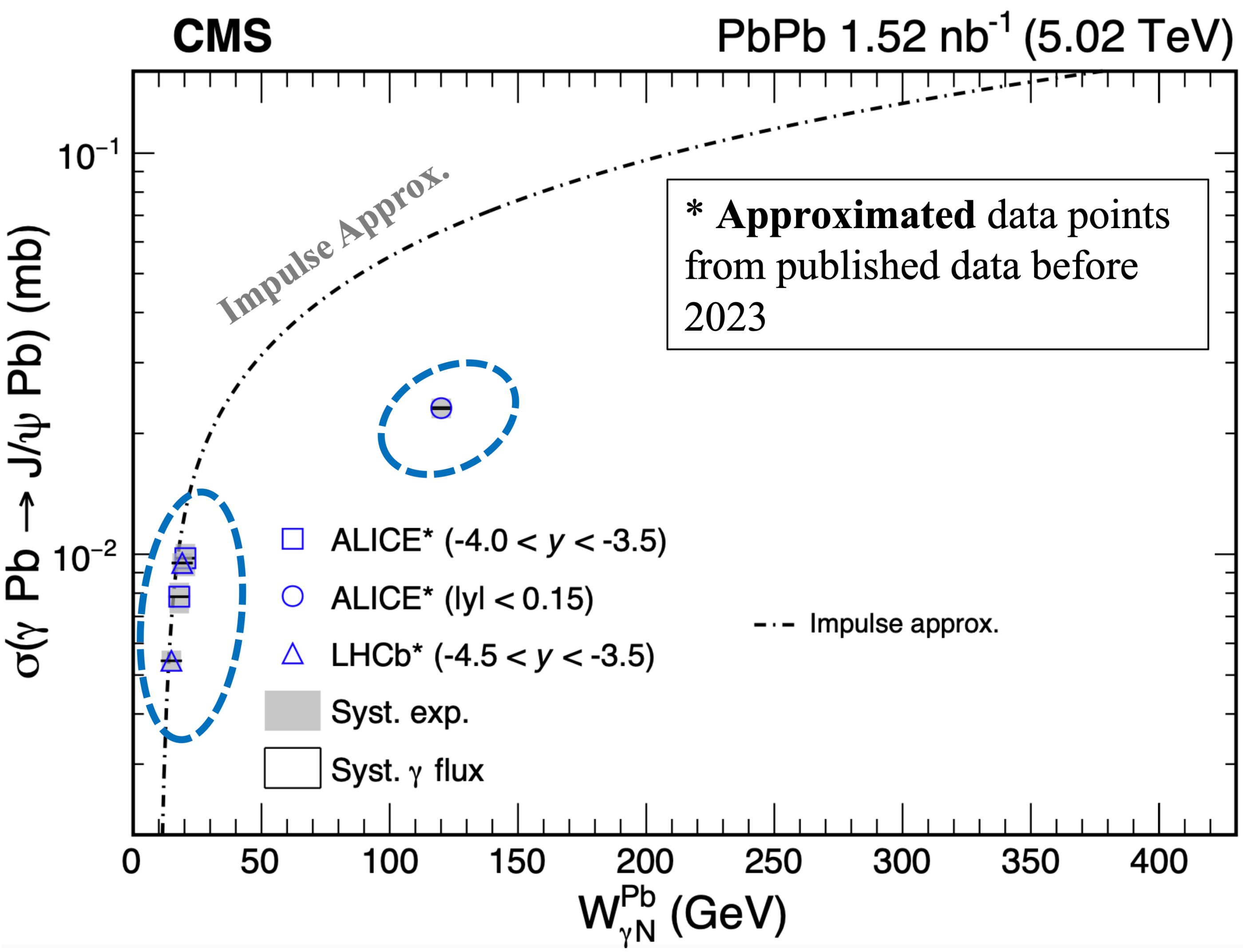
↓

Solve the "two-way ambiguity"

↓

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

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



- 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

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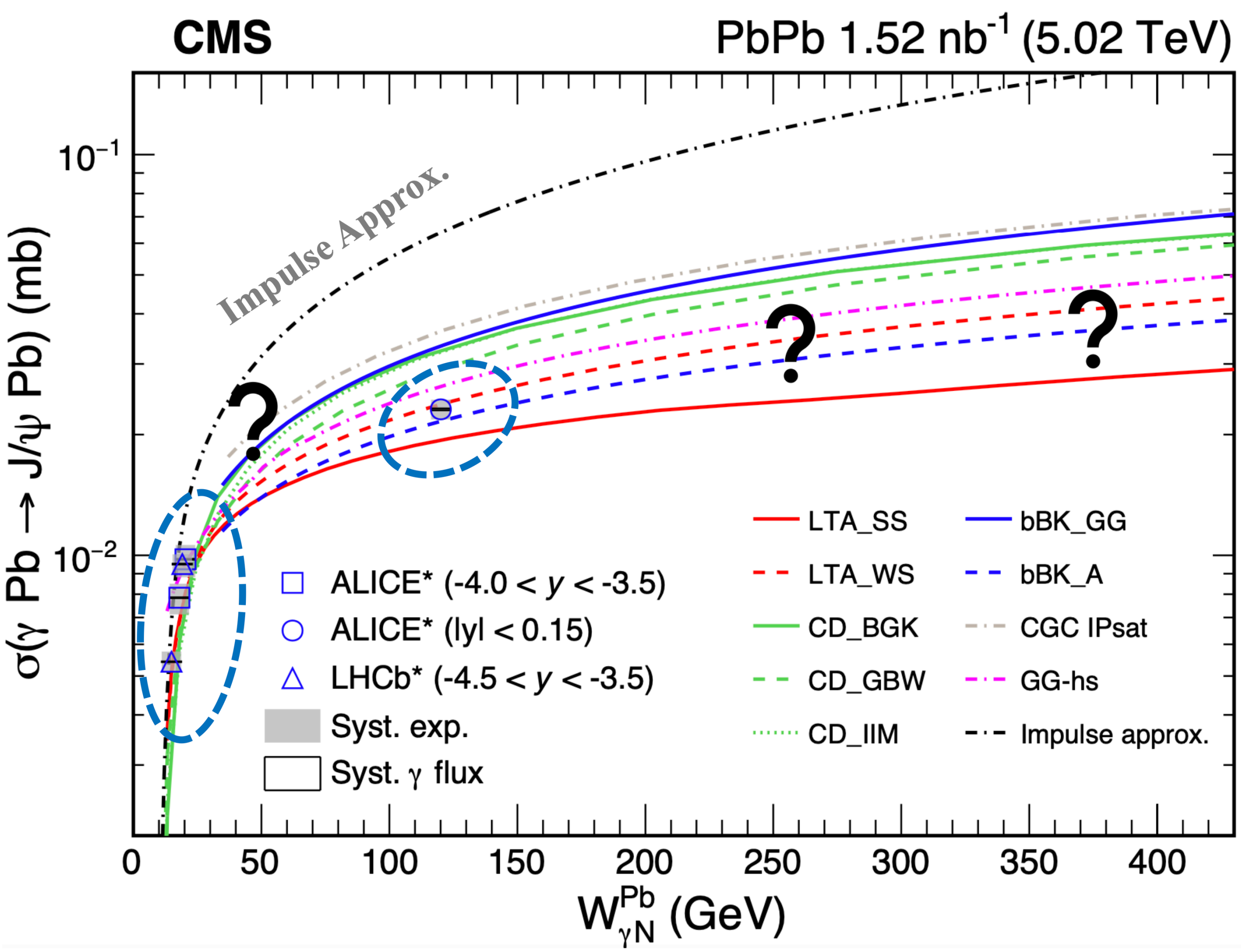

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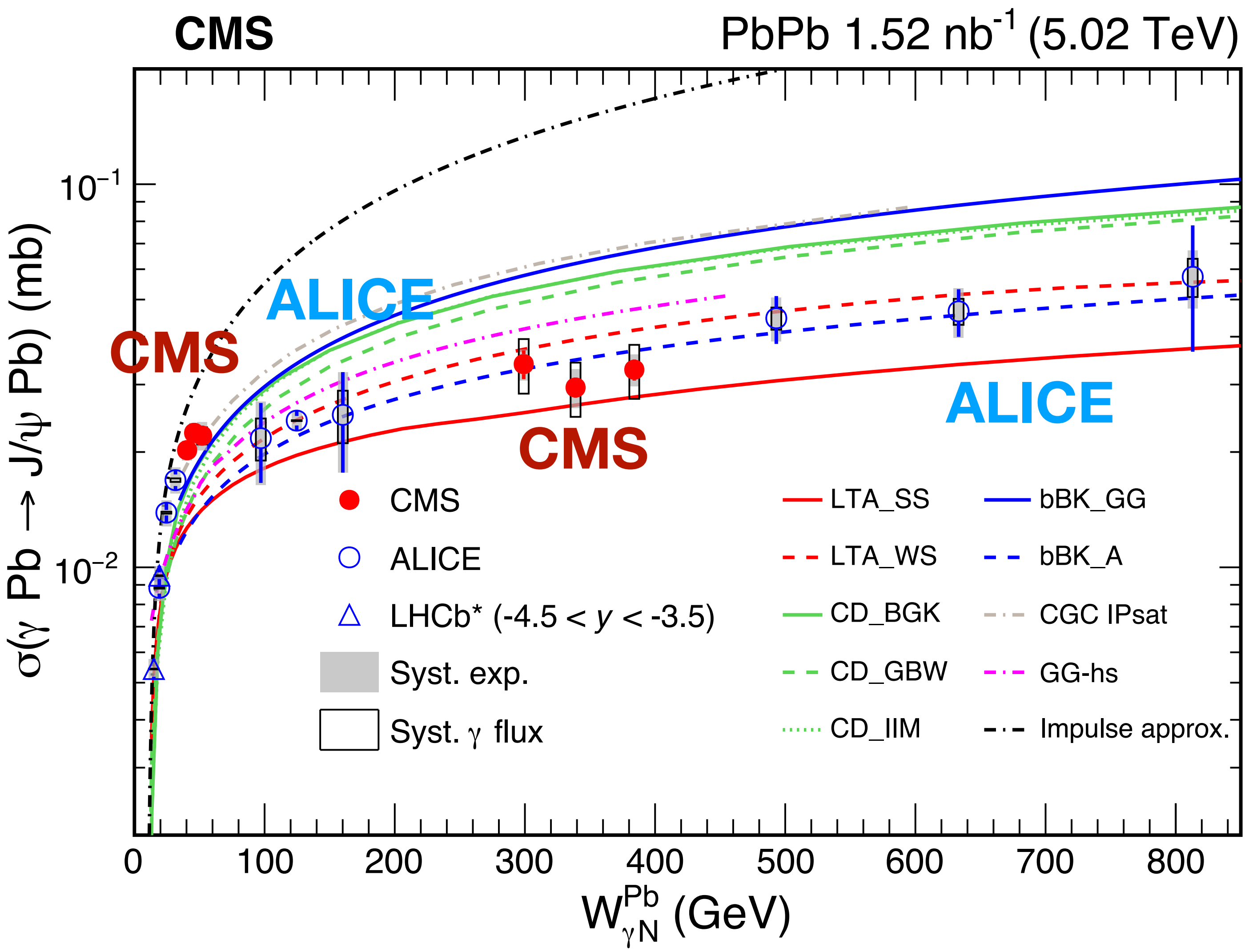
  - IA: neglects all nuclear effects
  - Data close to IA at low W
  - Data significant lower than IA at W~125 GeV ($x \sim 10^{-3}$)

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

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

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



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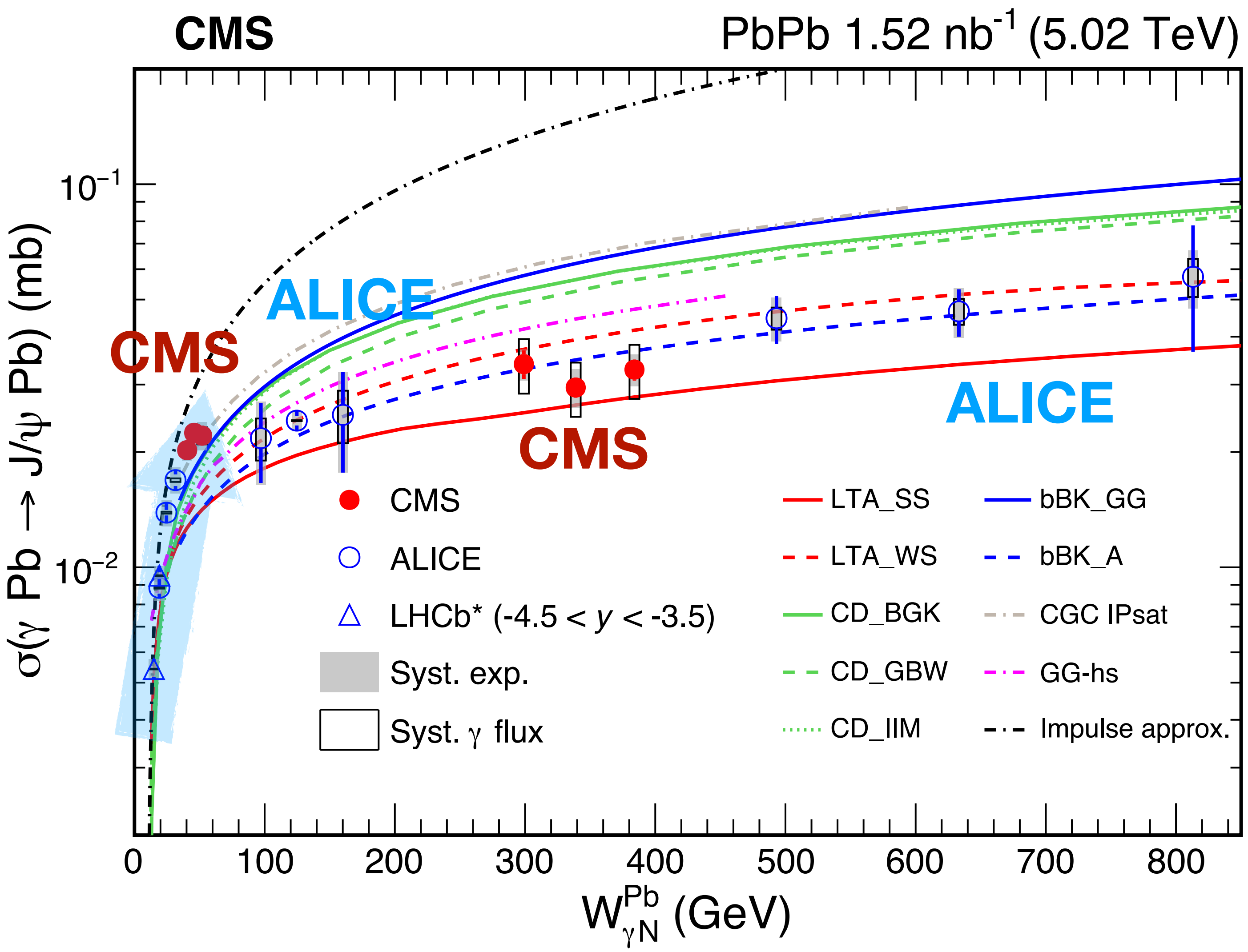

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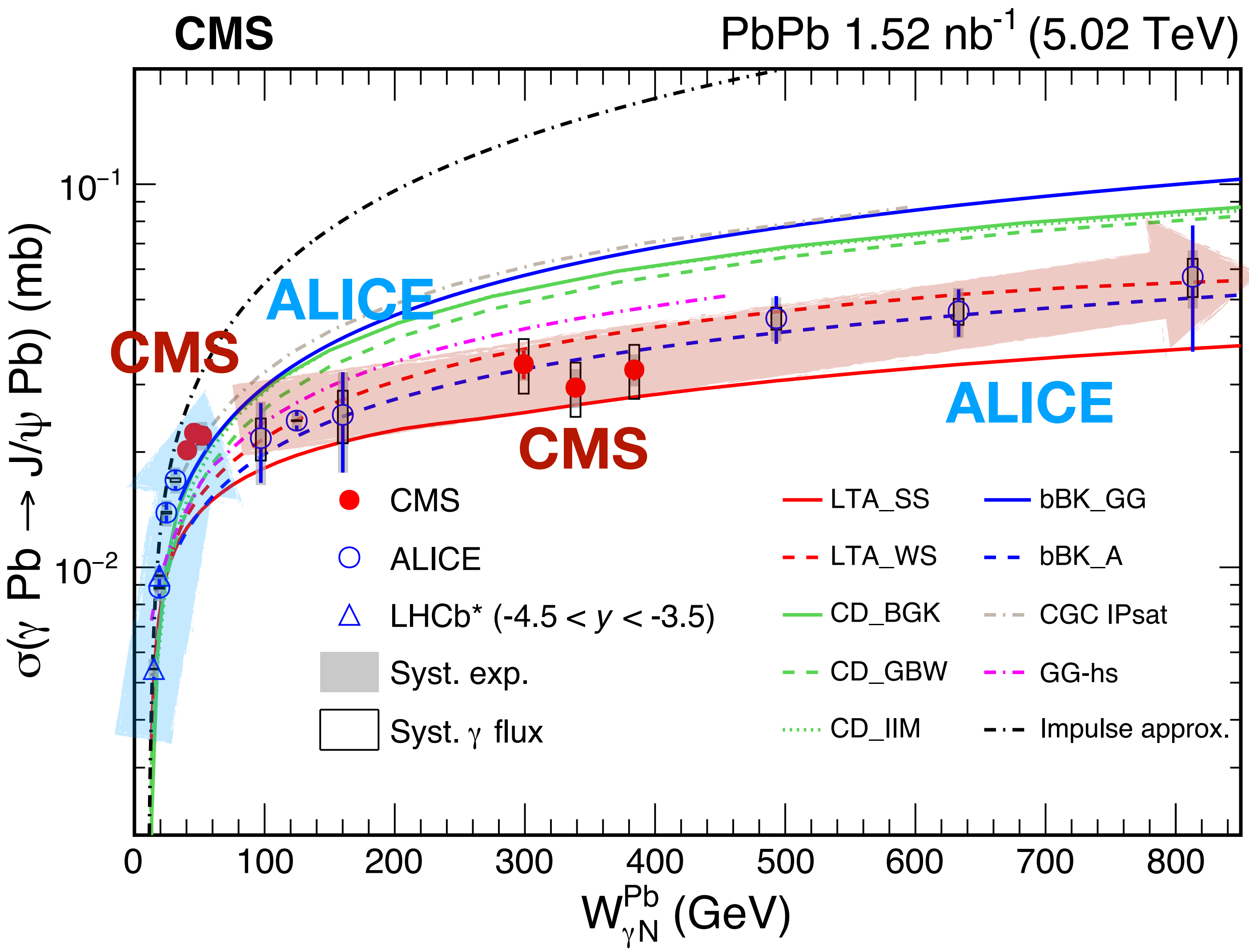

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- LHC measurements up to $W_{\gamma N}^{Pb} \approx 800$ GeV
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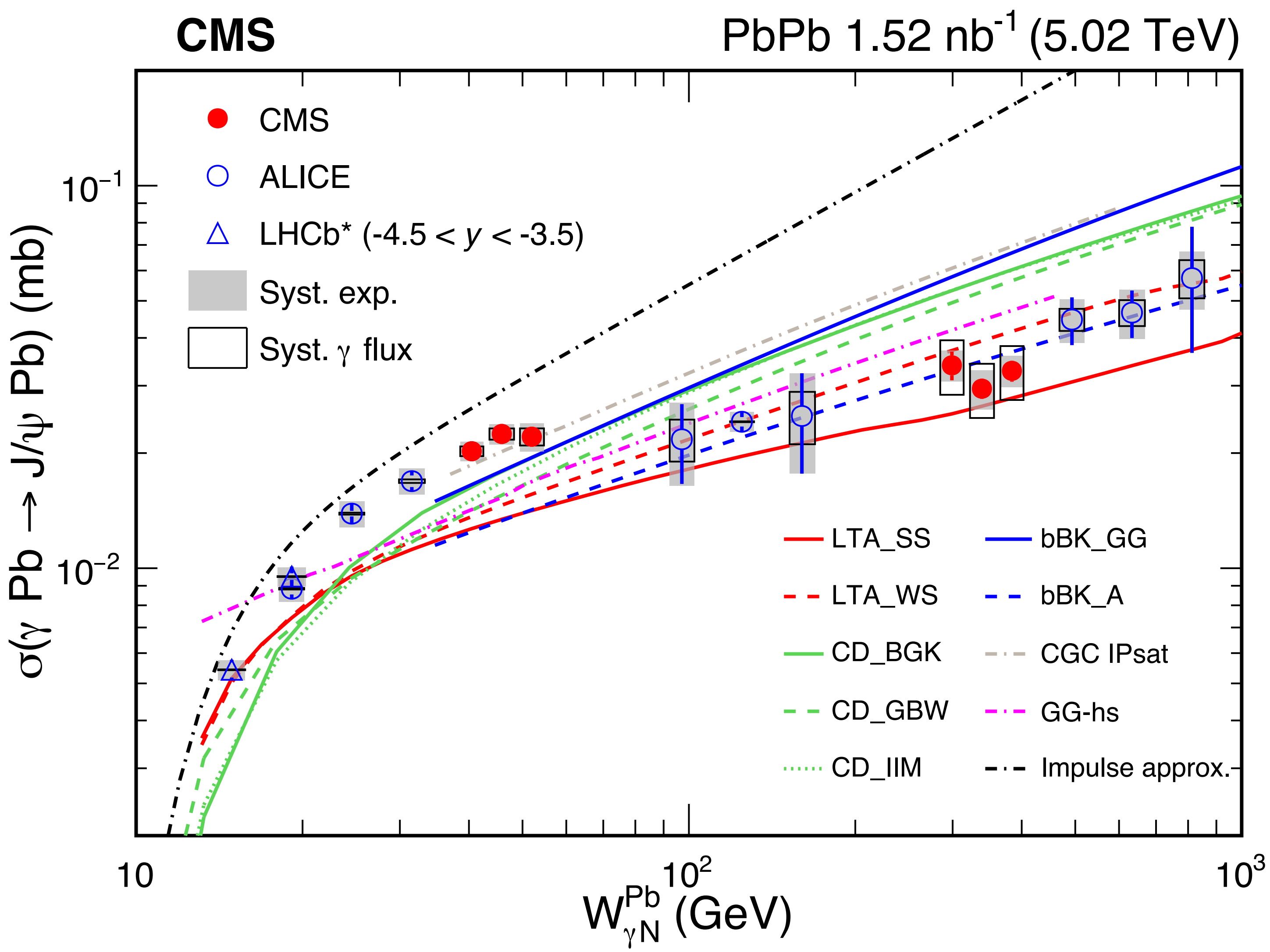
Coherent J/ψ production vs. $W_{\gamma N}^{Pb}$



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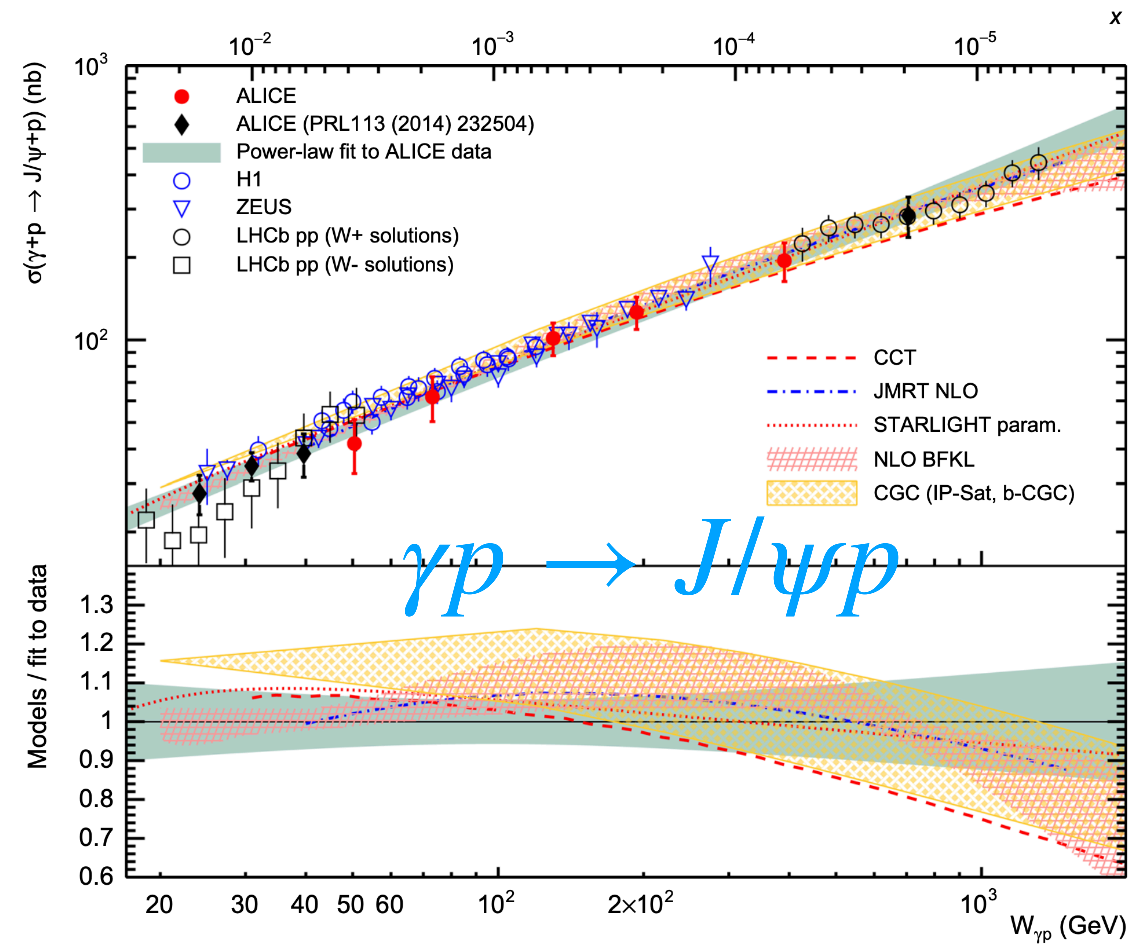
ALICE, EPJC 79 (2019) 402



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What physics could be behind?

CMS, PRL 131 (2023) 262301
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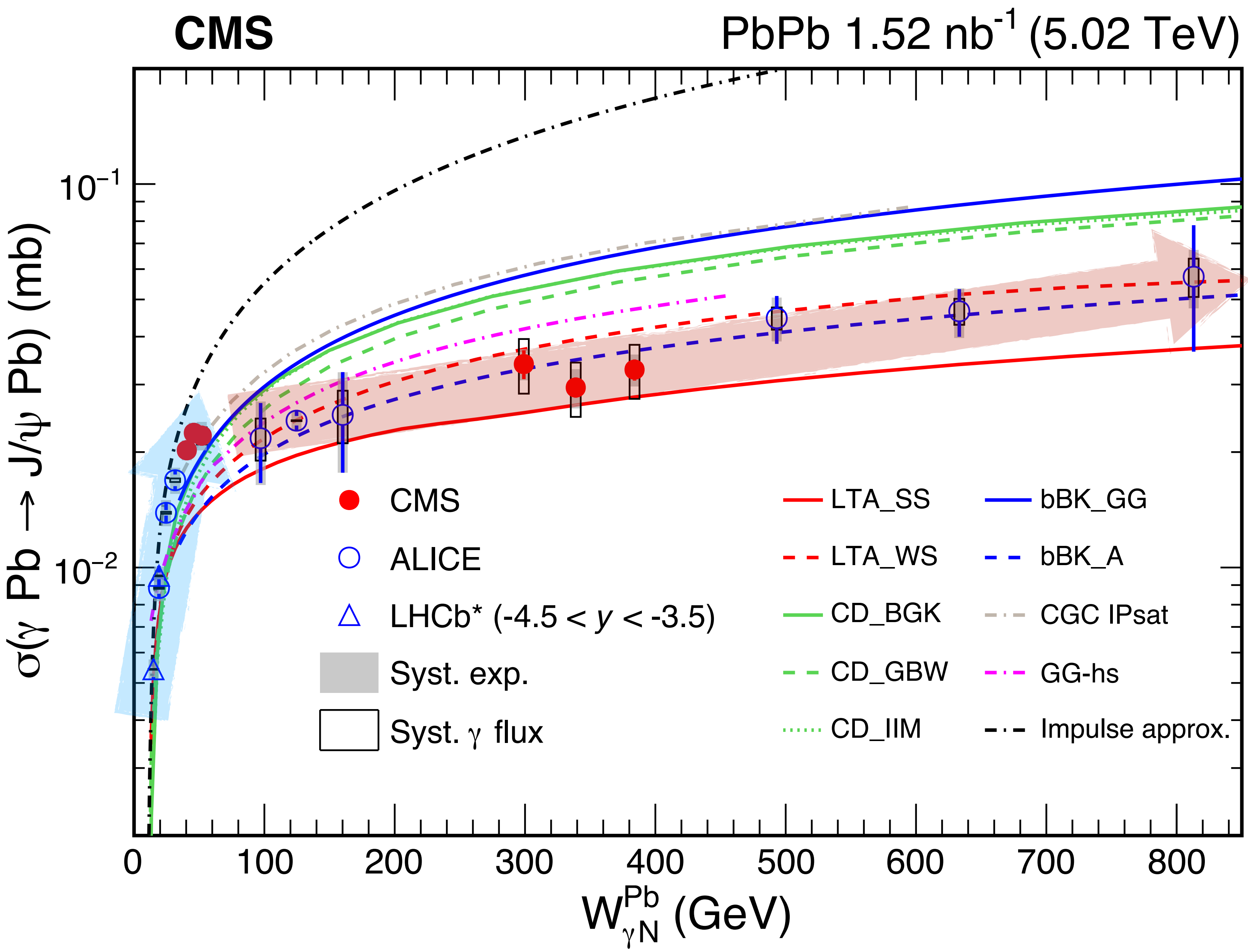
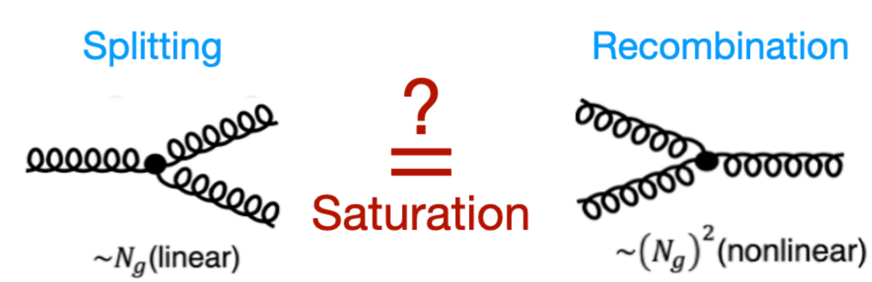
LO pQCD:
$\sigma^{VM} \propto [xG(x)]^2$

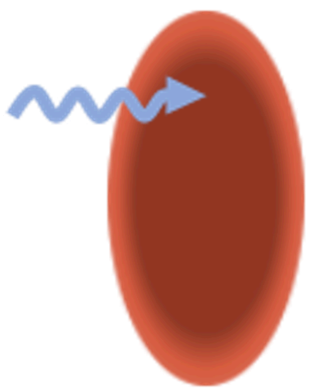


- Direct evidence of gluon saturation?



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

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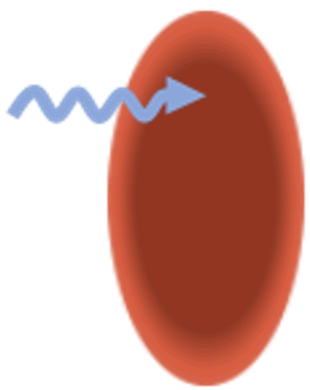

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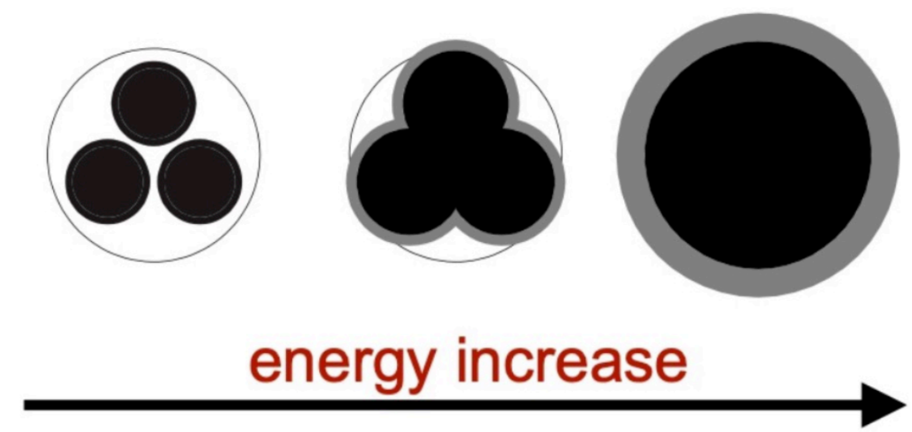

- Early onset is possible before gluon saturation if the dipole size is large
  - Depends on the weakly vs. strongly coupled regime and is not mutually exclusive with gluon saturation

Another novel regime of QCD: BDL

CMS, PRL 131 (2023) 262301
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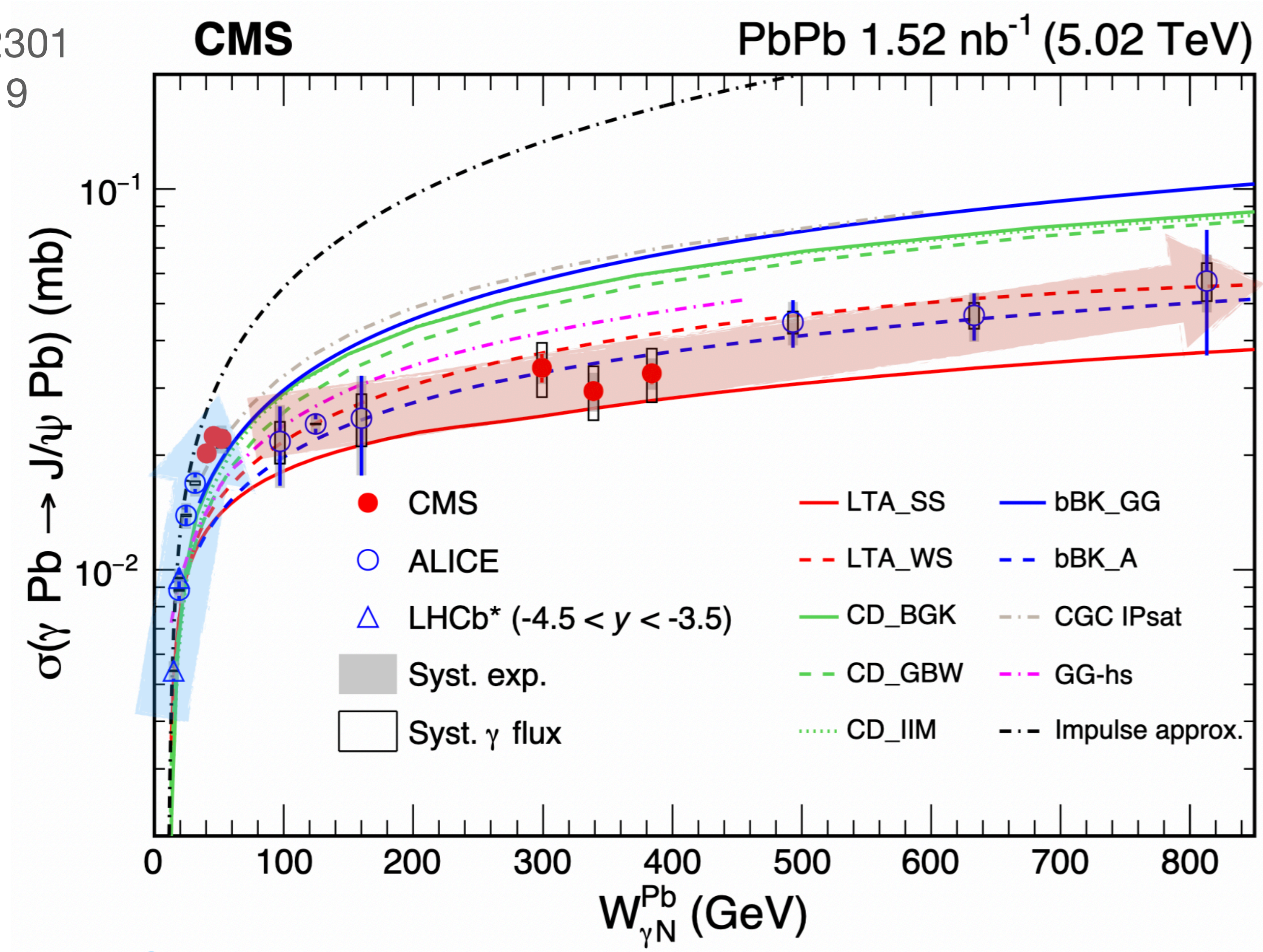

- Rapid grows reflect increased in gluon density
  - Amplitude of interaction is proportional to gluon density

Another novel regime of QCD: BDL

CMS, PRL 131 (2023) 262301
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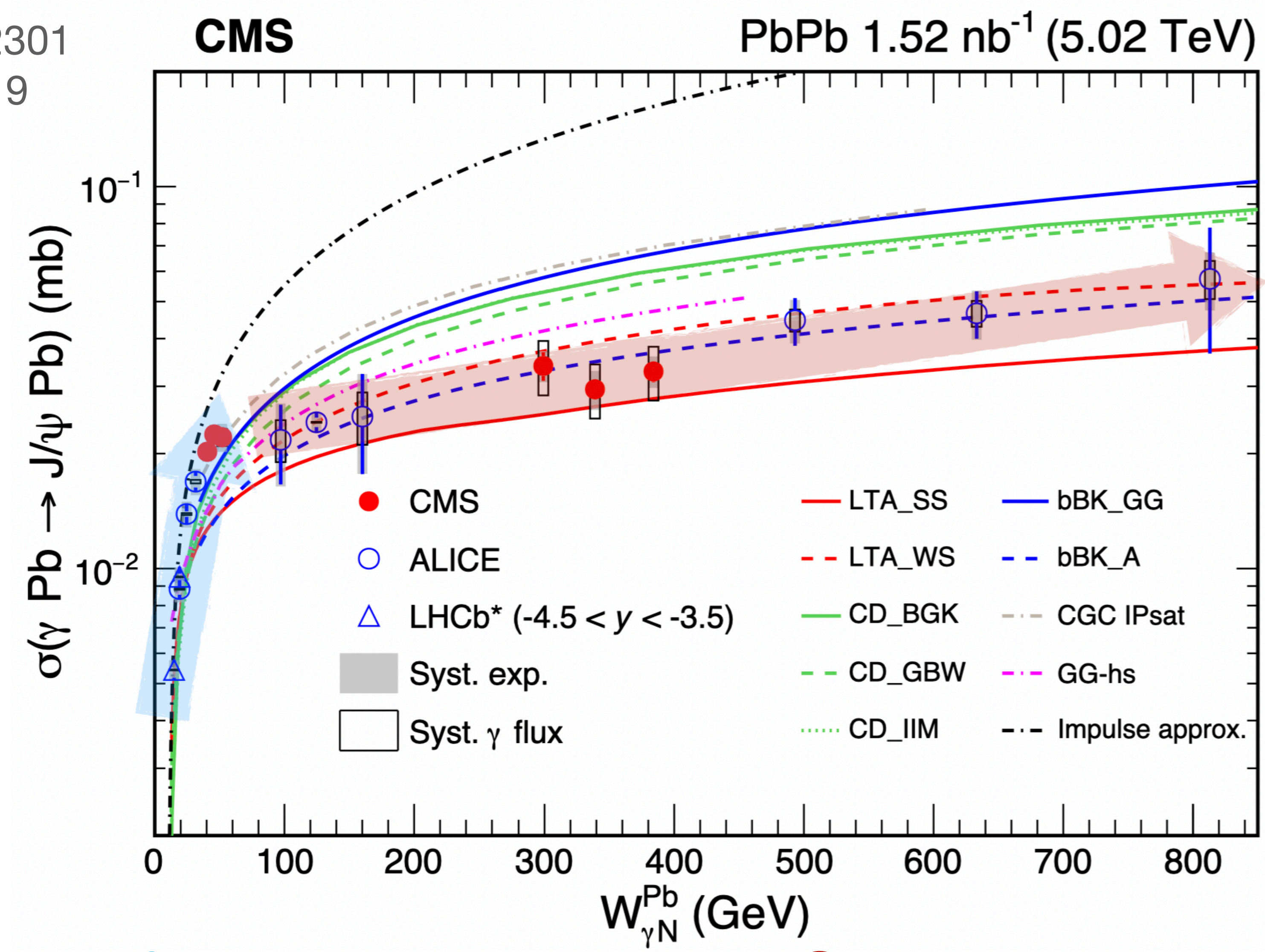
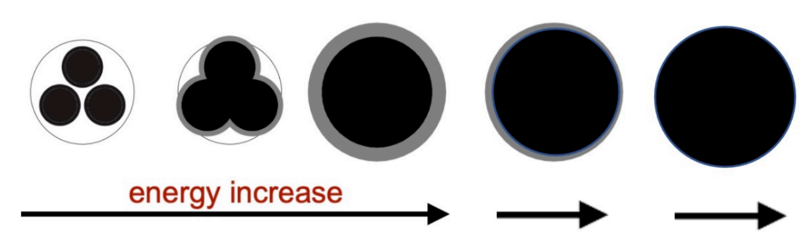
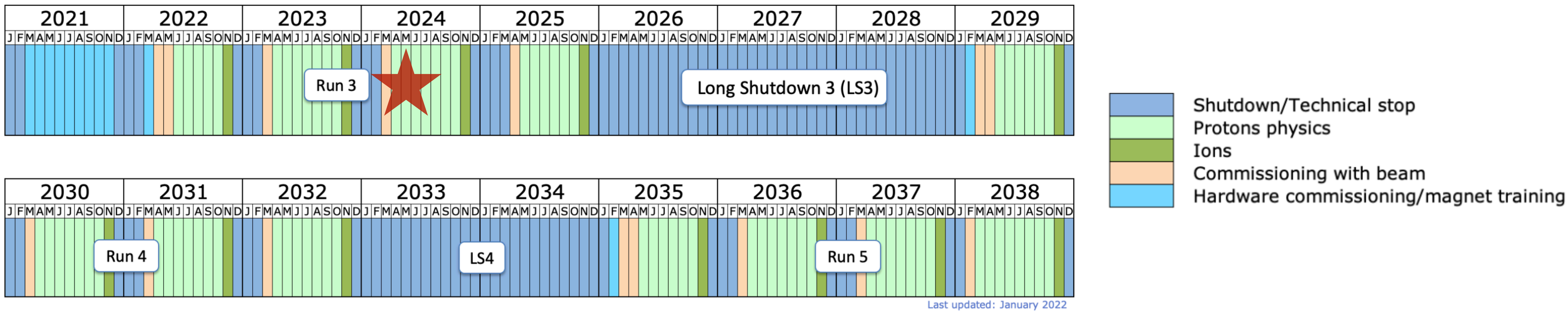


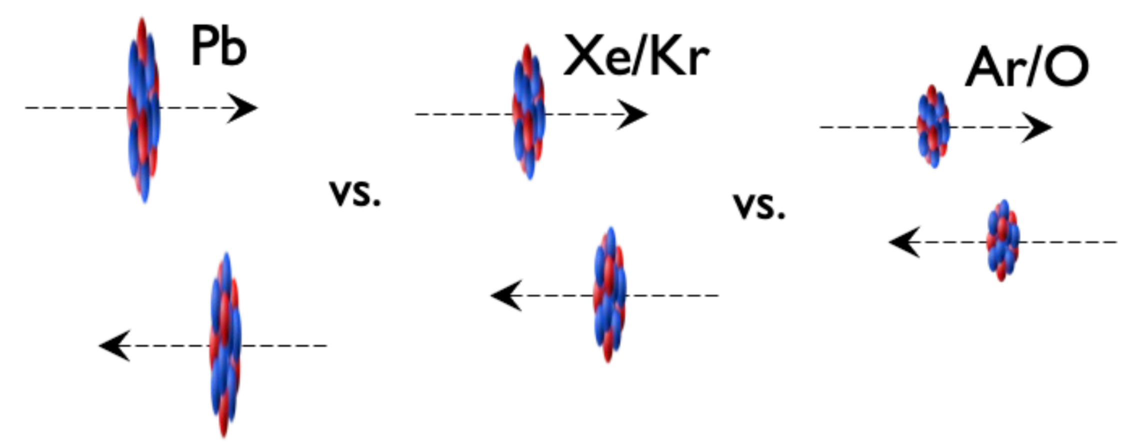
- Rapid grows reflect increased in gluon density
  - Amplitude of interaction is proportional to gluon density
- Slow grows may suggest the periphery of the nucleus has not become fully “black”



Future opportunities



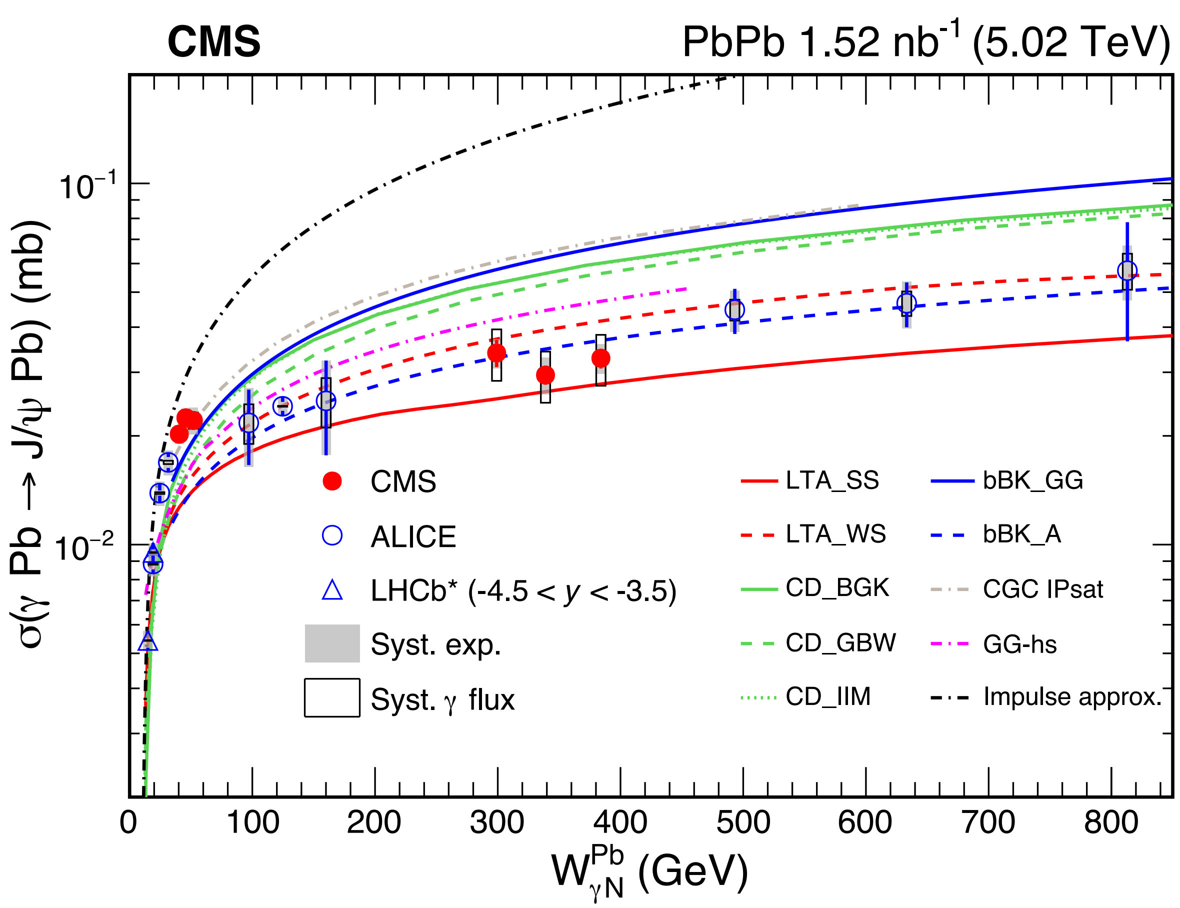
- Exciting opportunities ahead
  - Higher luminosities
  - Various ion species
  - Detector upgrade with new technologies



- UPC programs
  - Various vector meson productions in γPb with neutron tagging
  - System size scan with different ion species
  - Incoherent vector meson productions

Summary

- For the first time, directly disentangled coherent $\sigma_{\gamma A \rightarrow J/\psi A}$ in ultra-peripheral A+A collisions
- Probed a new low-x gluon regime (10^{-5}) in Pb nucleus
- Flattening of coherent $\sigma_{\gamma A \rightarrow J/\psi A}$ at high $W_{\gamma N}^{Pb}$ not predicted by theoretical models
  - Direct evidence of gluon saturation?
  - Near the "black disk limit"?
  - …?

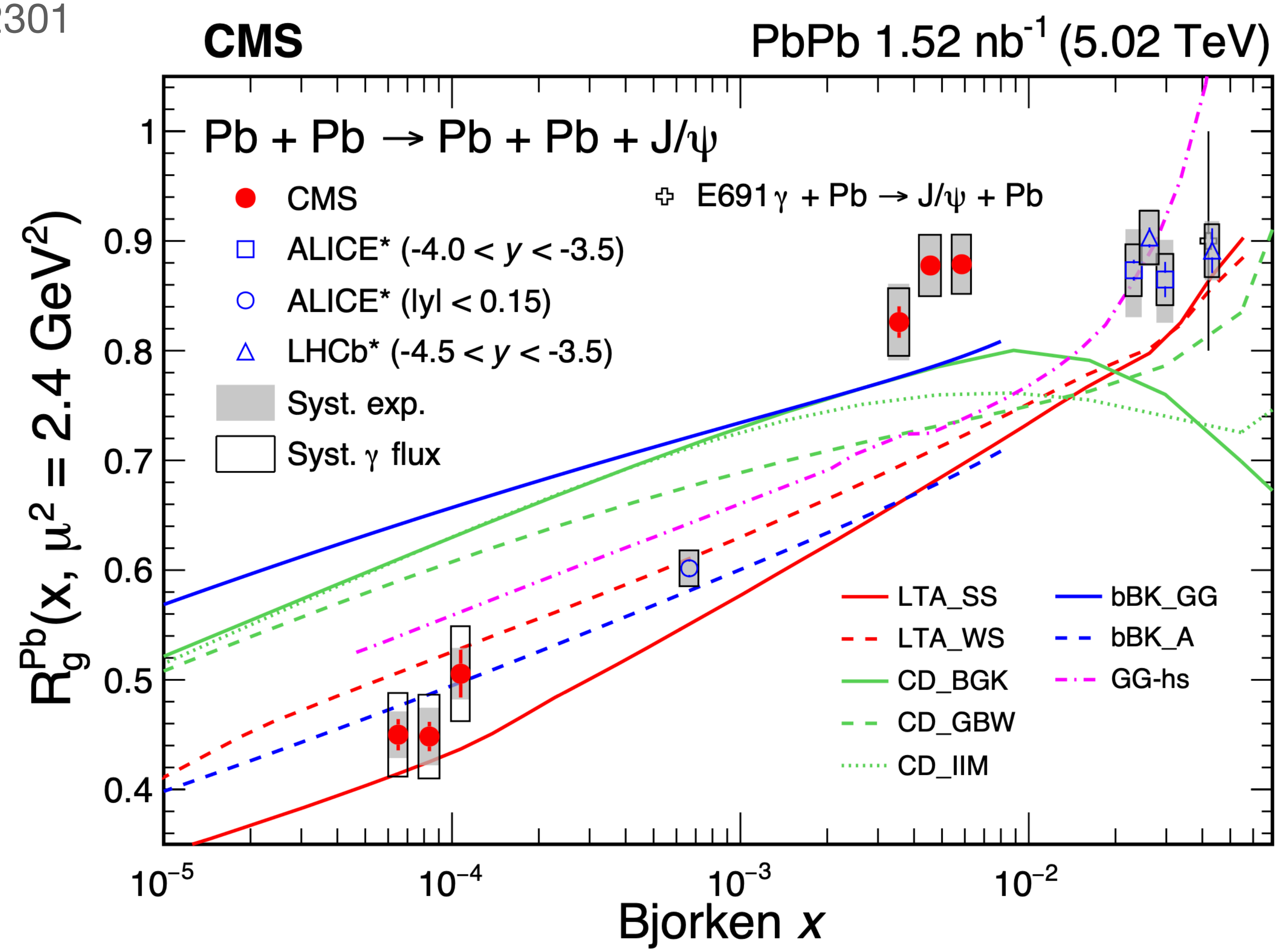


Thank you for your attention!

Nuclear gluon suppression factor

CMS, PRL 131 (2023) 262301

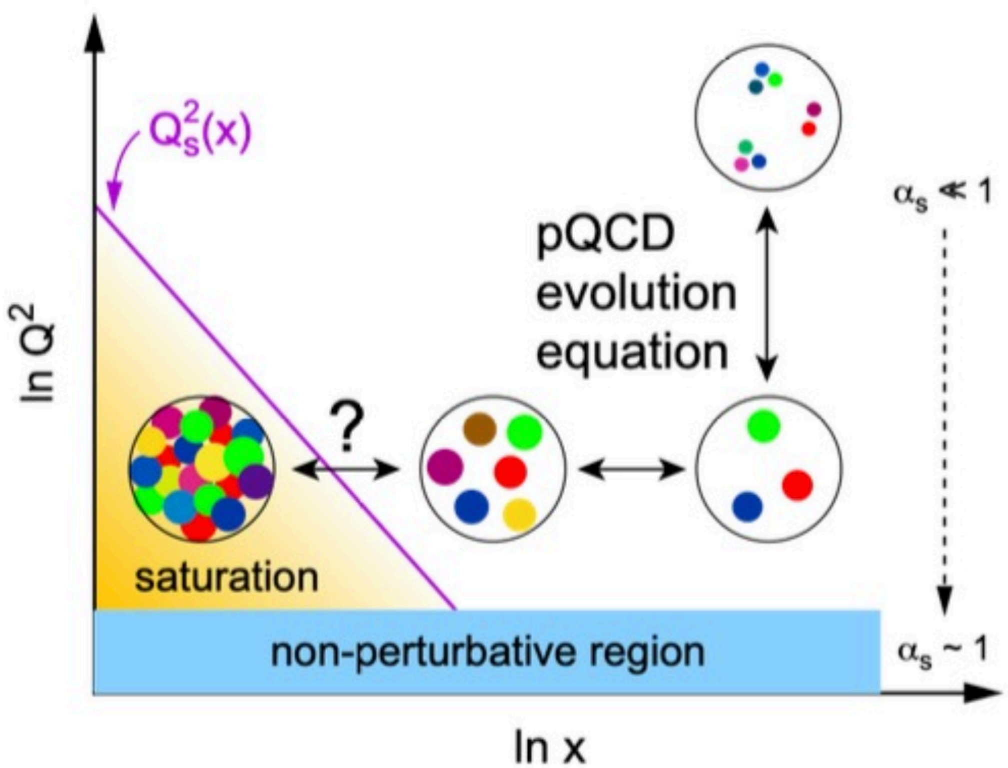
$$R_g^A = \frac{g_A(x, Q^2)}{A \cdot g_p(x, Q^2)} = \sqrt{\frac{\sigma^{exp}_{\gamma A \to J/\psi A}}{\sigma^{IA}_{\gamma A \to J/\psi A}}}$$

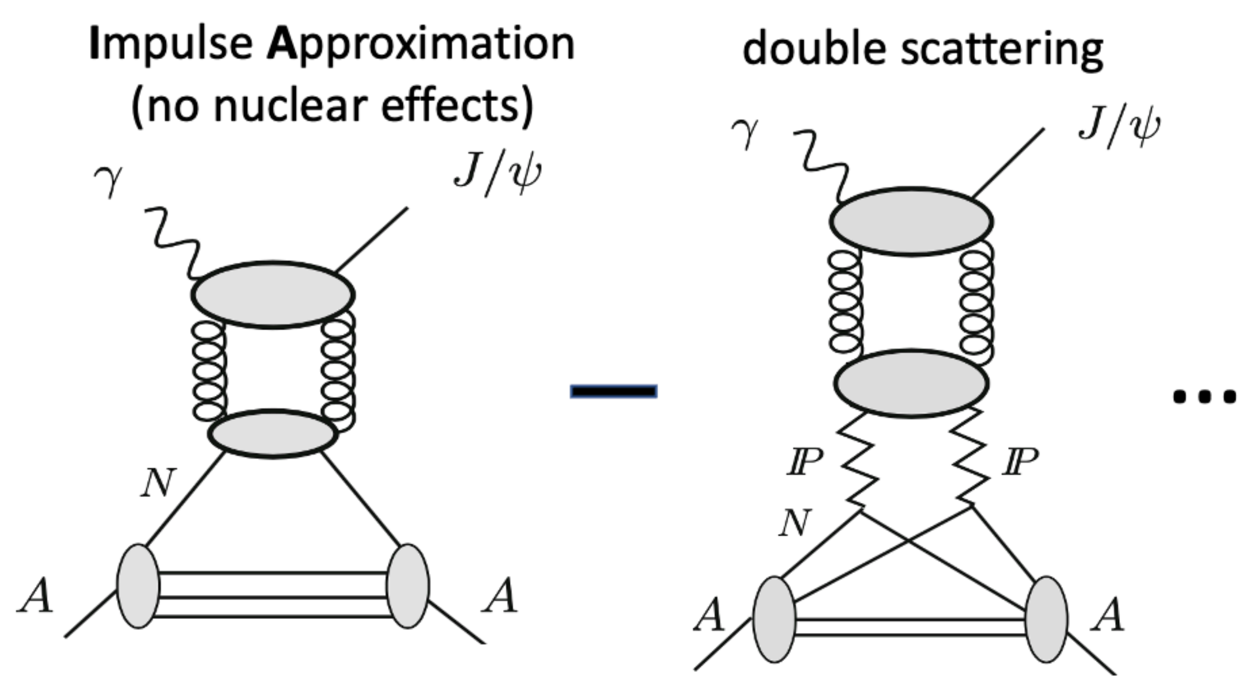


- R_g^A:nuclear suppression factor at LO approximation
  - A flat trend at high x (~3×10^{-3} - 5×10^{-2})
  - Rapidly decreasing towards very small x (~6×10^{-5})

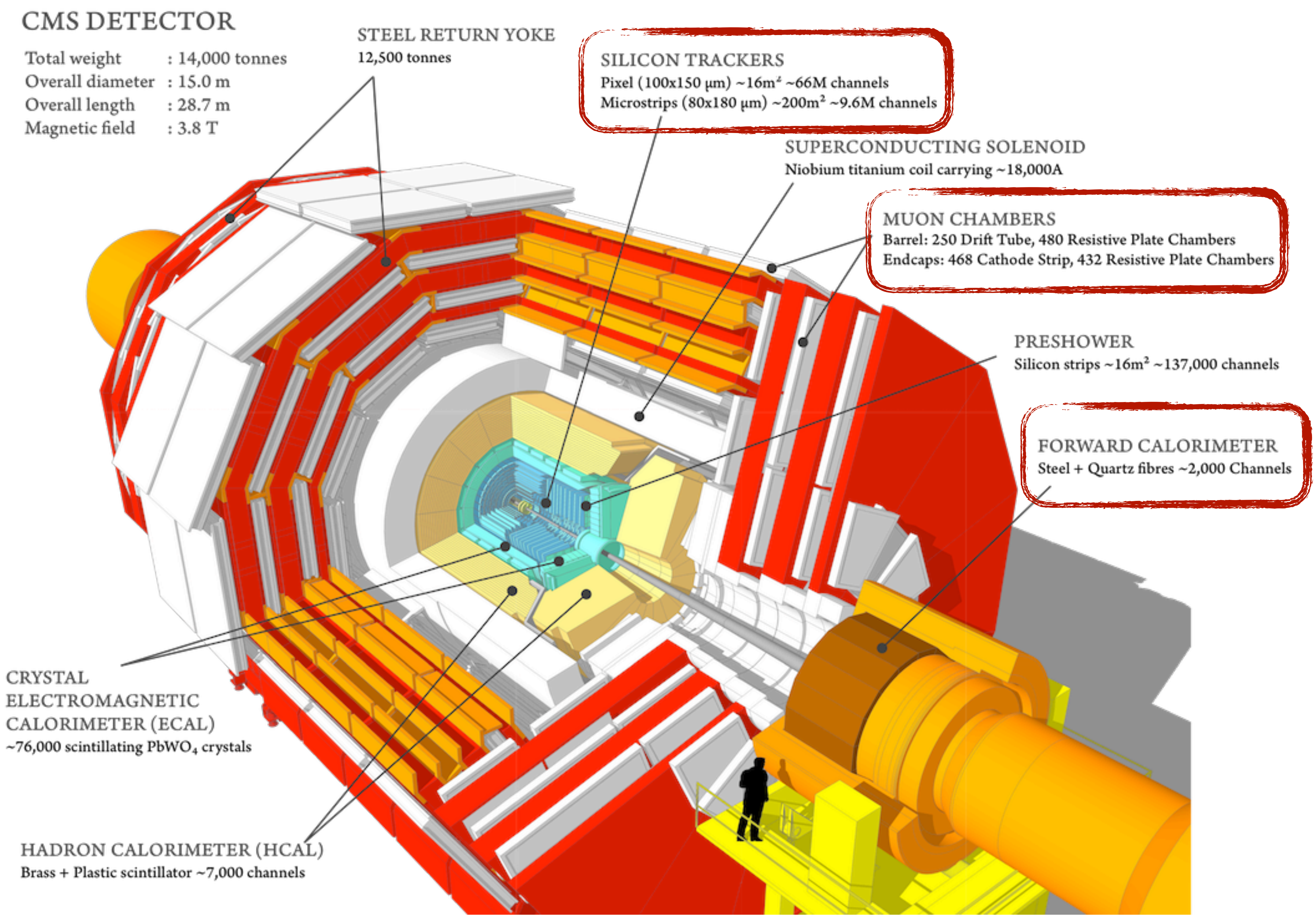
Saturation vs. shadowing

- 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

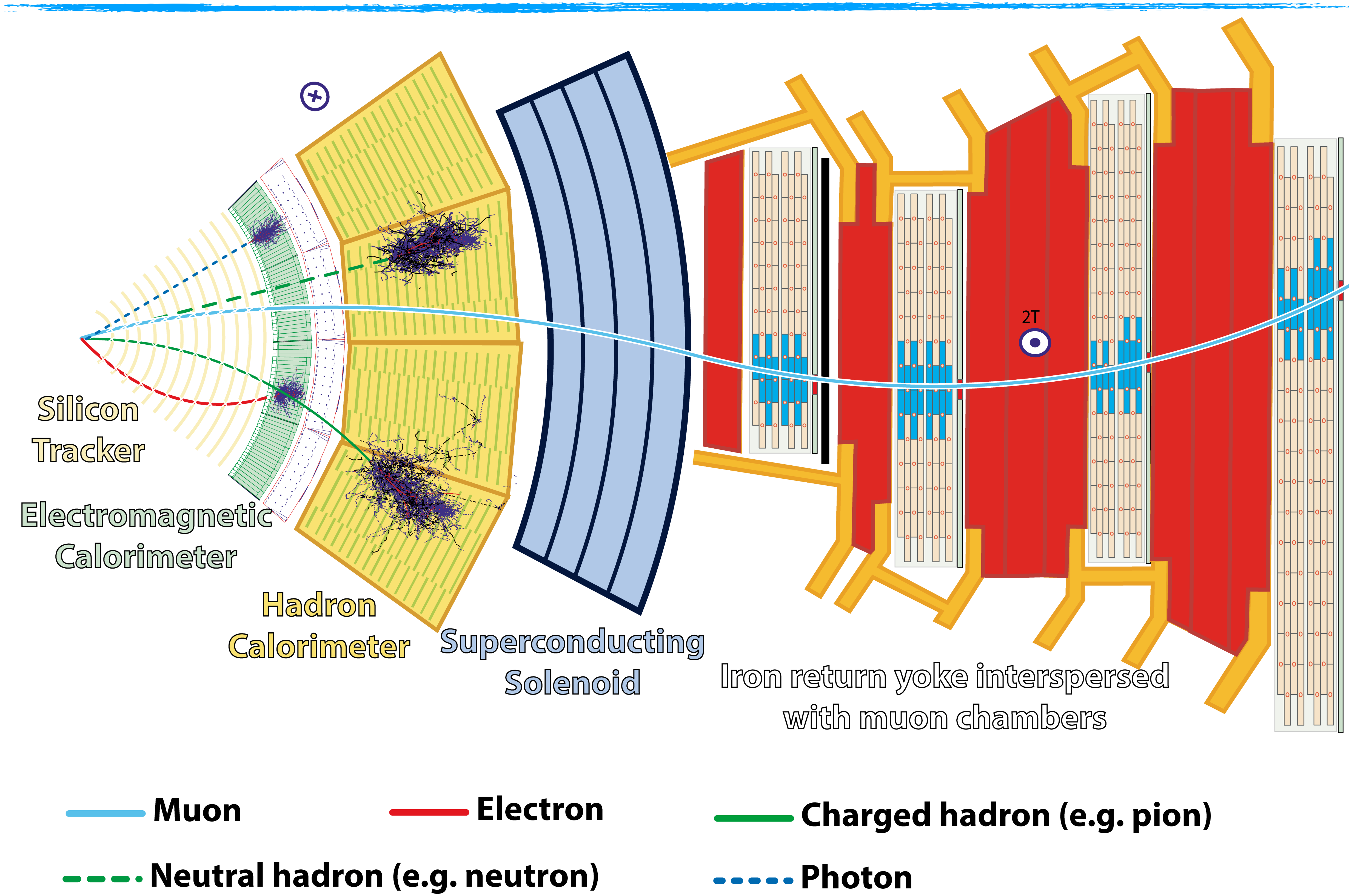




Compact Muon Solenoidal



Detection principle summary



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