Probing a new regime of ultra-dense gluonic matter using high-energy photons with CMS

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CMS FINAL HP23

CMS NEW RESULT HP23

submitted for publication
arXiv:2303.16984

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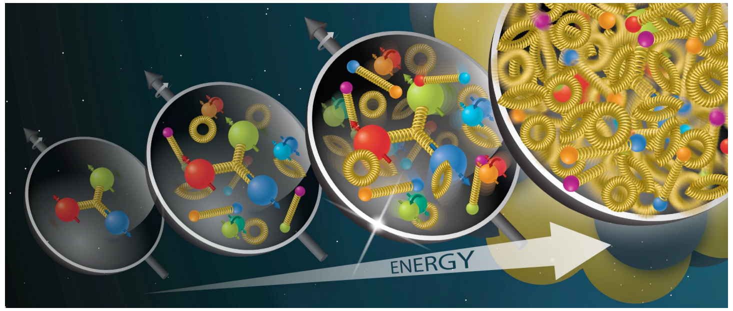
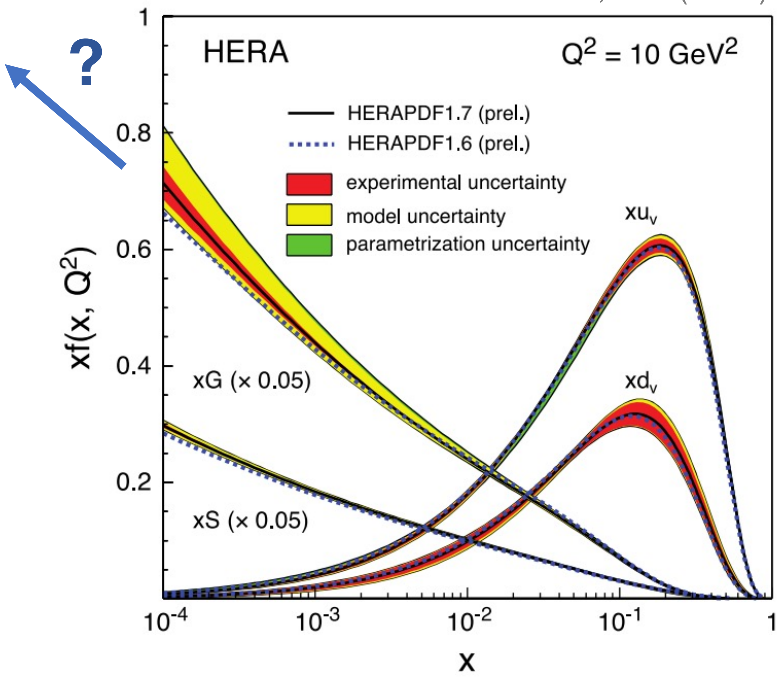
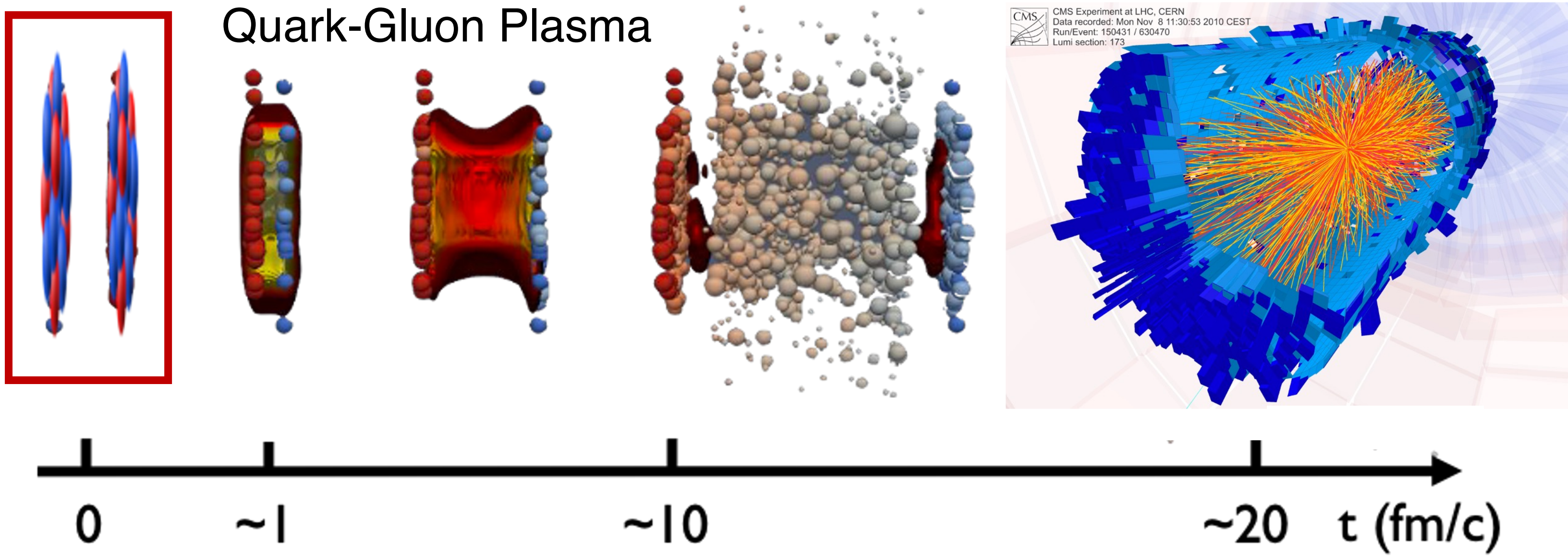
Ultra-dense Gluonic Matter in Nuclear Collisions



EPJC 75, 580 (2015)



Initial state



Ultra-dense gluonic state is the form of matter inside heavy nuclei at high energies (or small x)

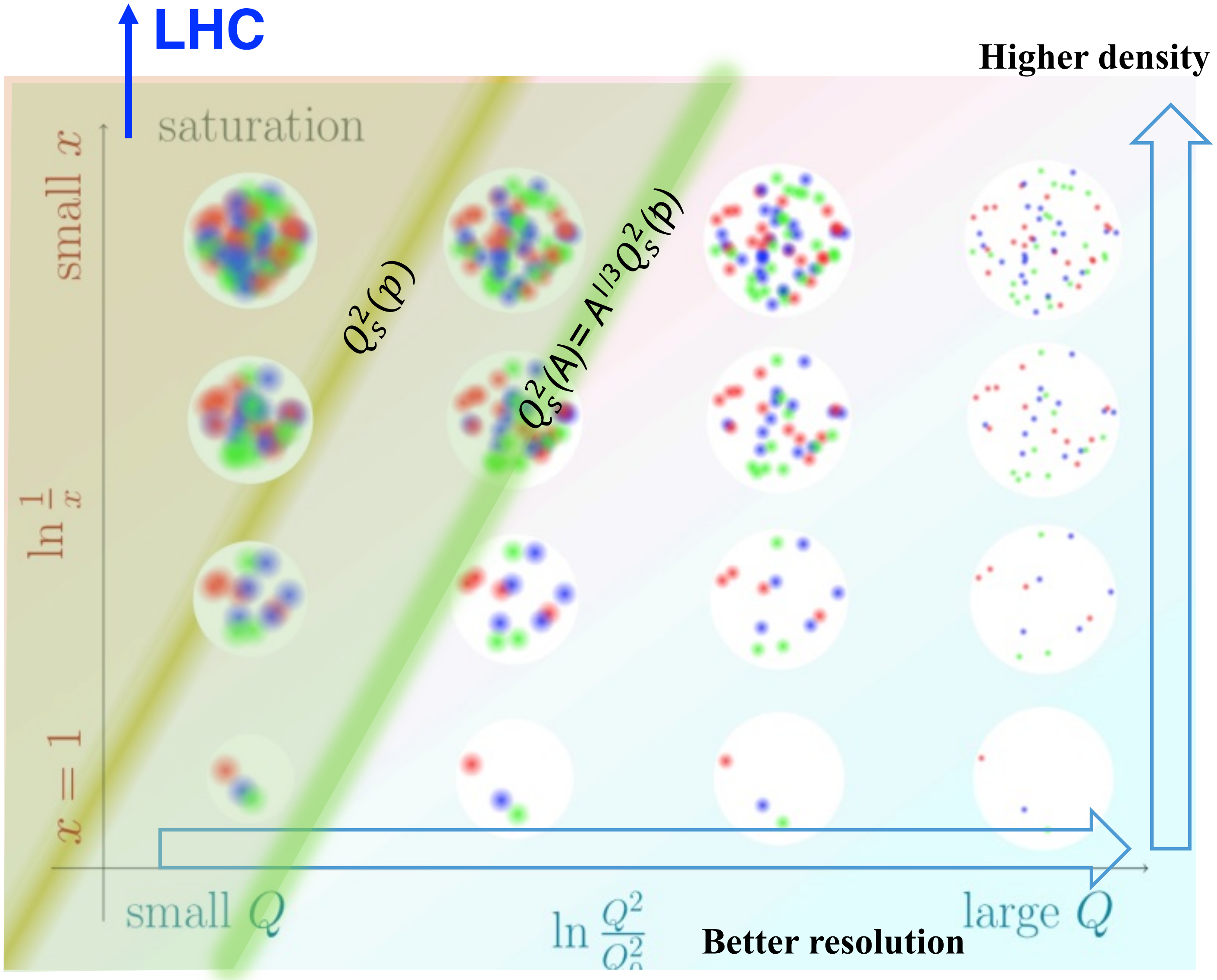
Ultra-dense Gluonic Matter in Nuclear Collisions

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

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

– No conclusive evidence yet!

Better chance of observing the gluon saturation in heavy nuclei!

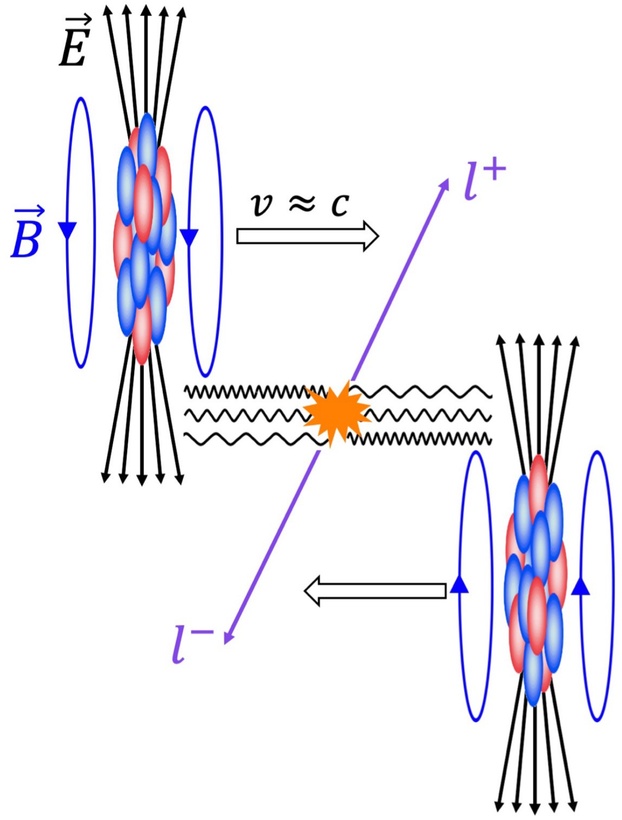


Ultra-Peripheral Collision (UPC)

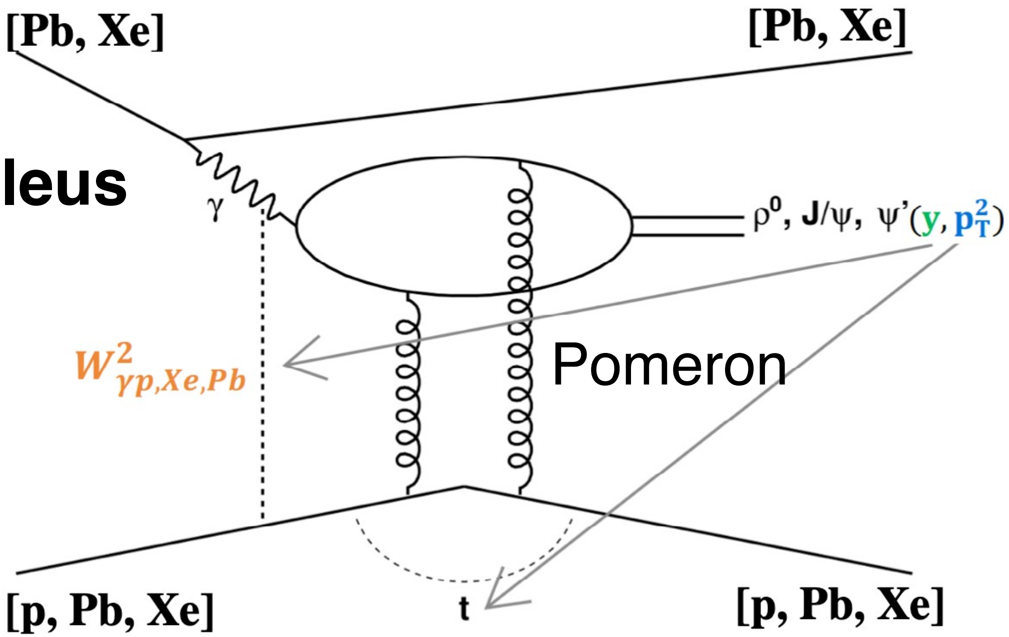
Nuclei “miss” each other (b > $R_A + R_B$)

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

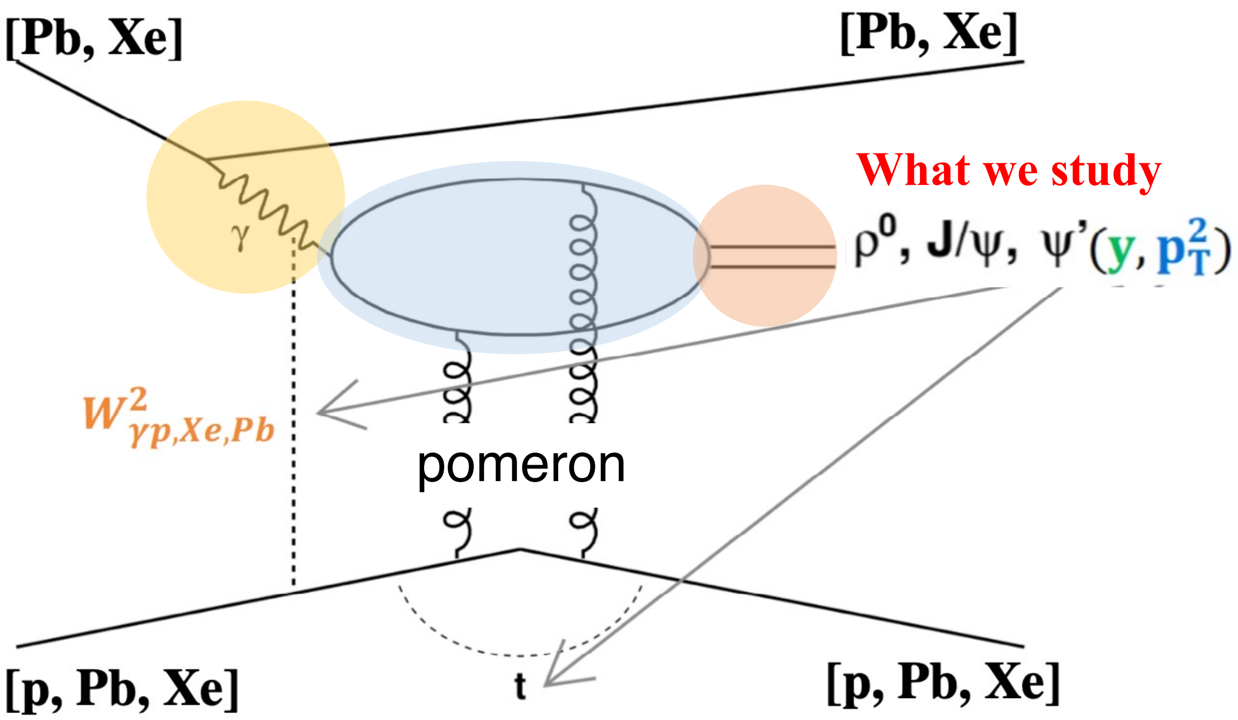
Photon-photon



Photon-nucleus



UPC VMs as a clean probe of gluonic structure



Well-defined kinematics:

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

$$W^2 = M_{VM}\sqrt{s_{NN}} \cdot e^{\pm y} \qquad x = \frac{M_{VM}}{\sqrt{s_{\mathrm{NN}}}} e^{\mp y}$$

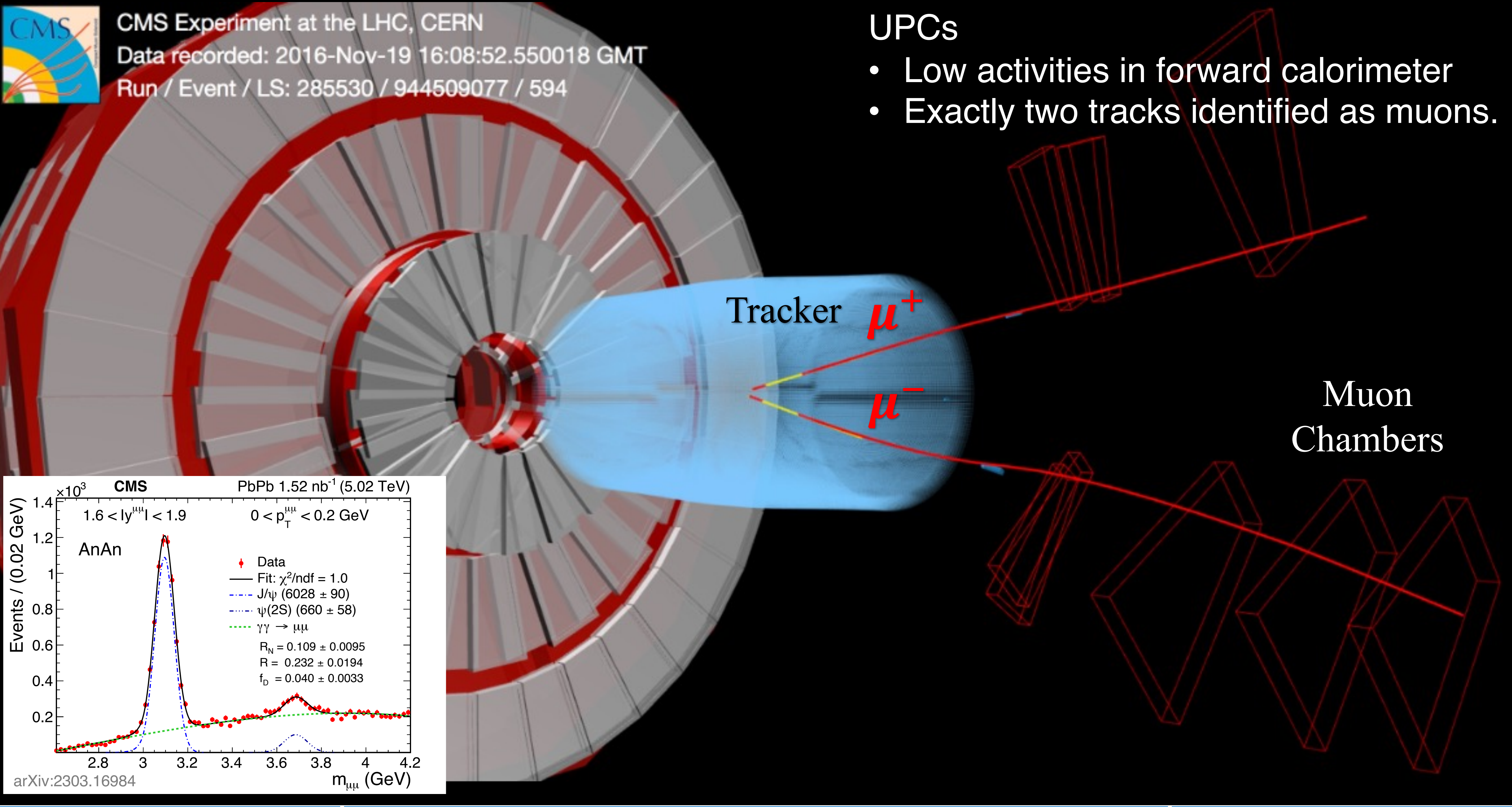
Low $Q^2 \sim 0$ but heavy quark mass can provide a hard scale for pQCD.

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

- Coherent: average distribution ⟸ Focus of this talk
- Incoherent: event-by-event fluctuations

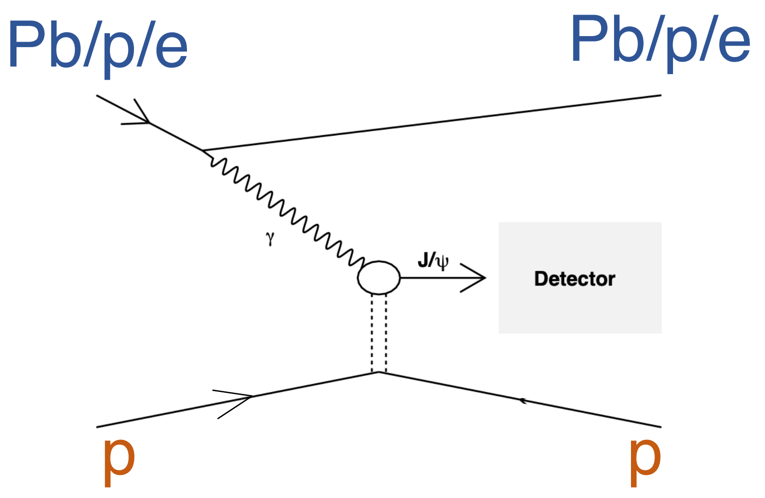
UPCs

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



arXiv:2303.16984

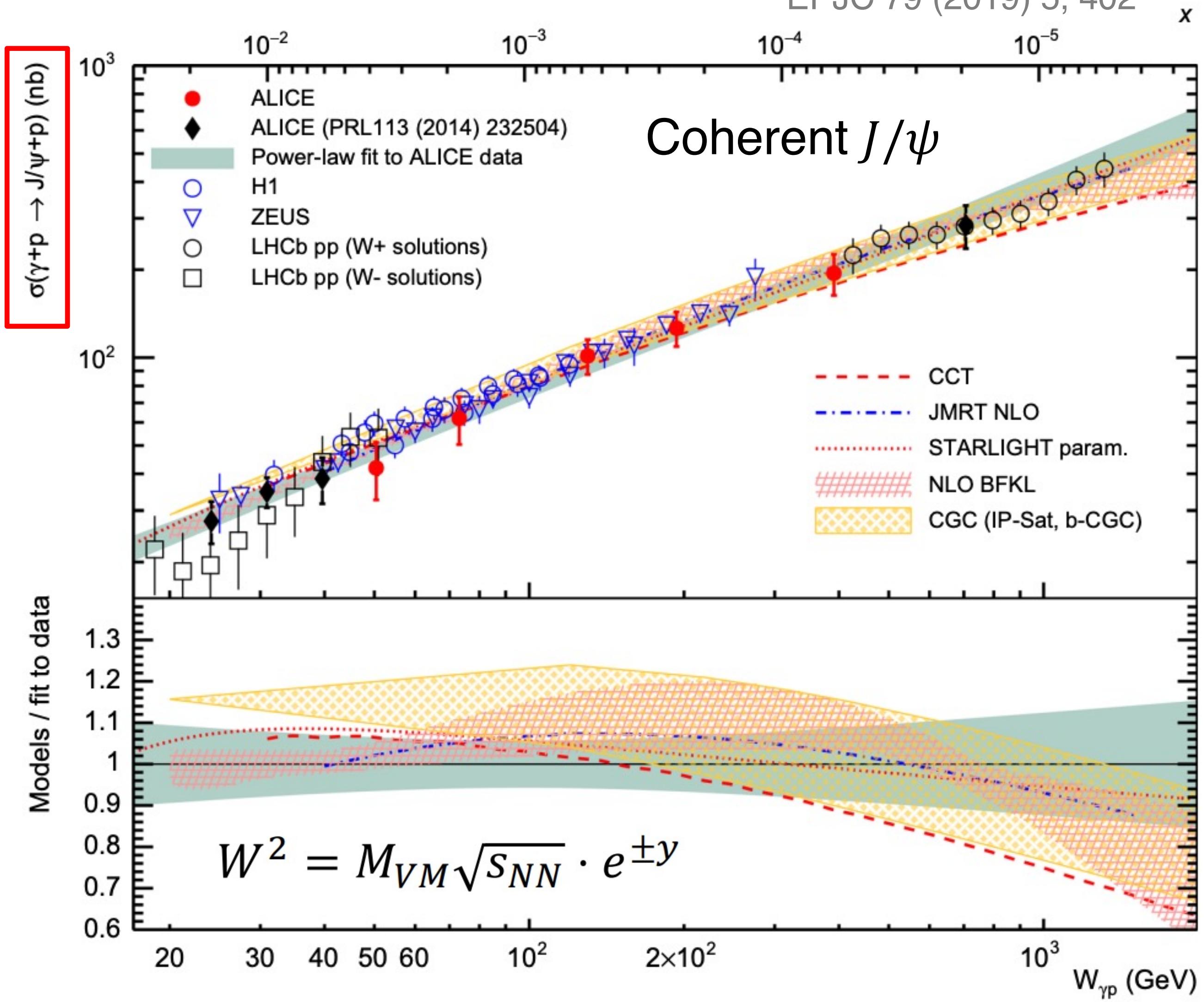
Coherent J/ψ photoproduction via γp



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

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

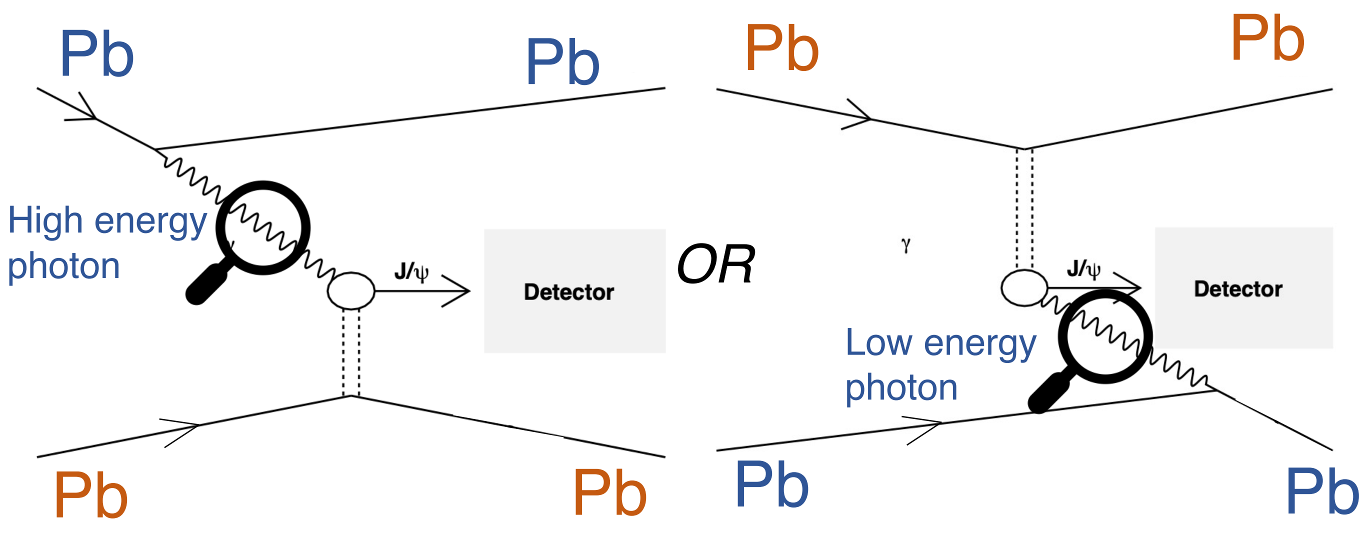
EPJC 79 (2019) 5, 402



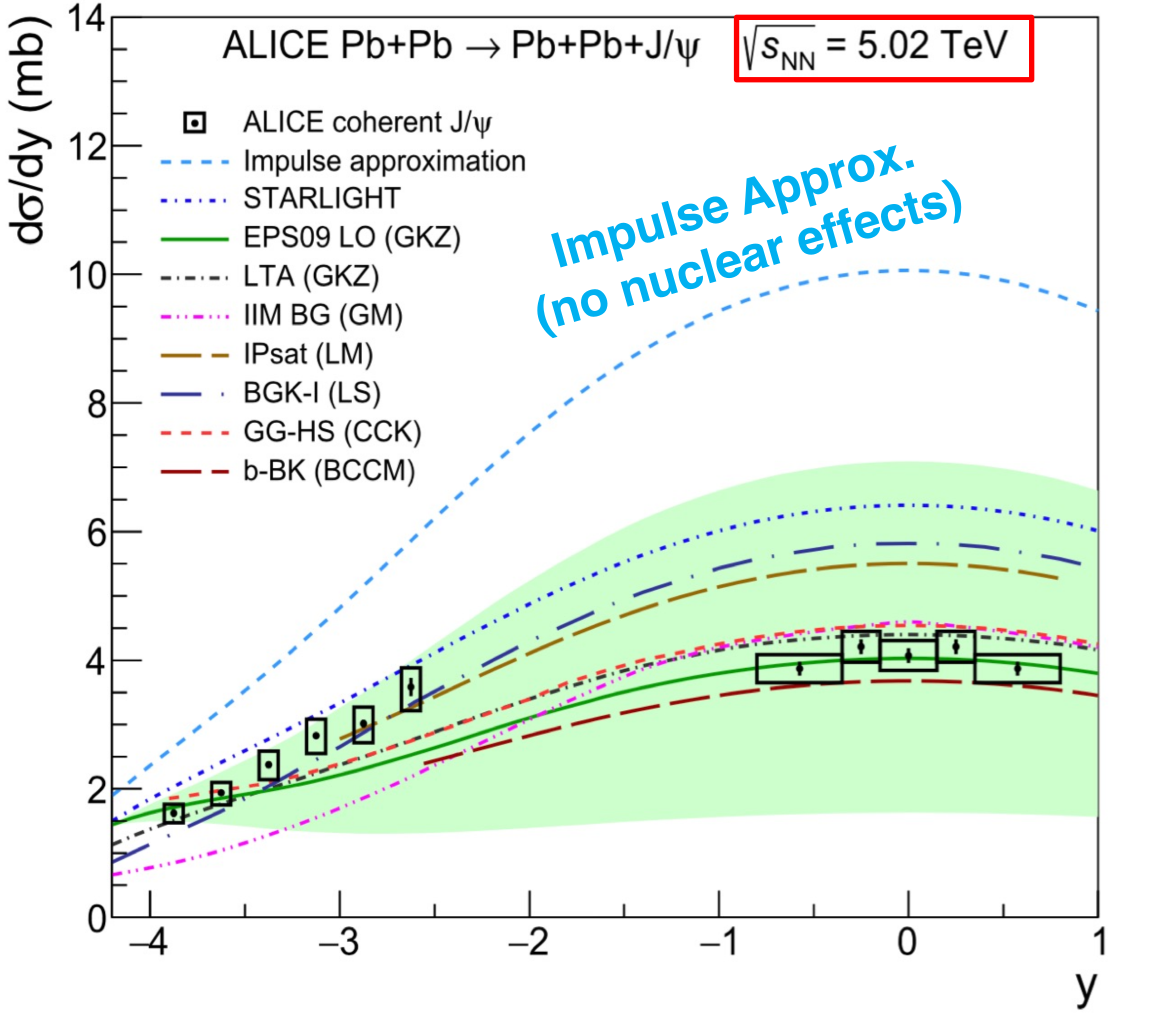
$$W^2 = M_{VM}\sqrt{s_{NN}} \cdot e^{\pm y}$$

Coherent J/ψ photoproduction in γPb

A "two-way ambiguity" in symmetric systems

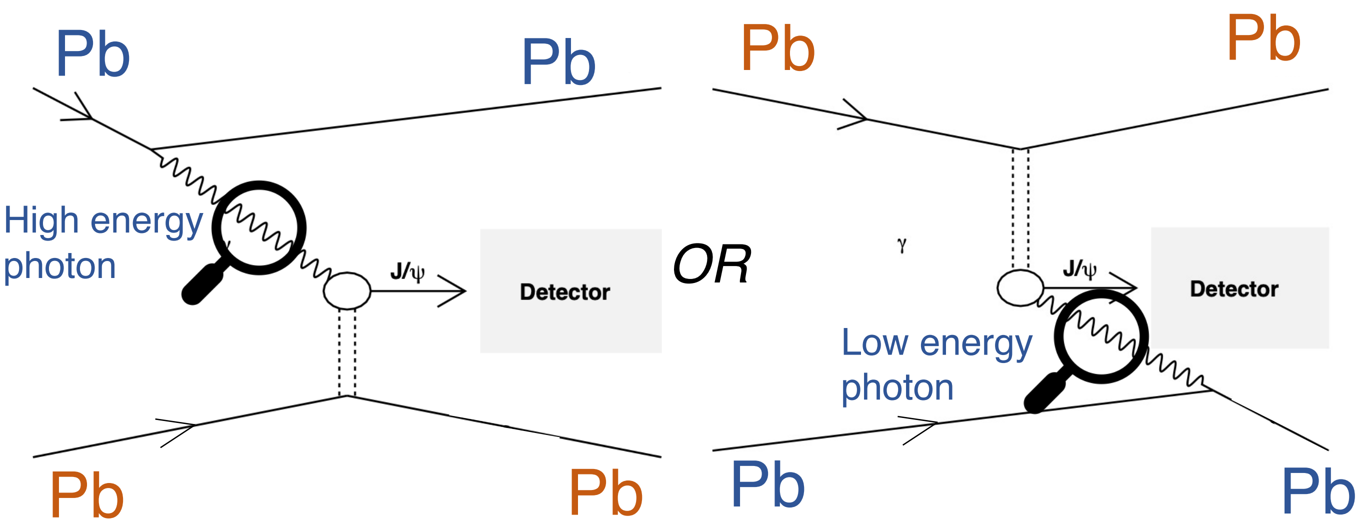


Eur. Phys. J. C (2021) 81:712



Coherent J/ψ photoproduction in γPb

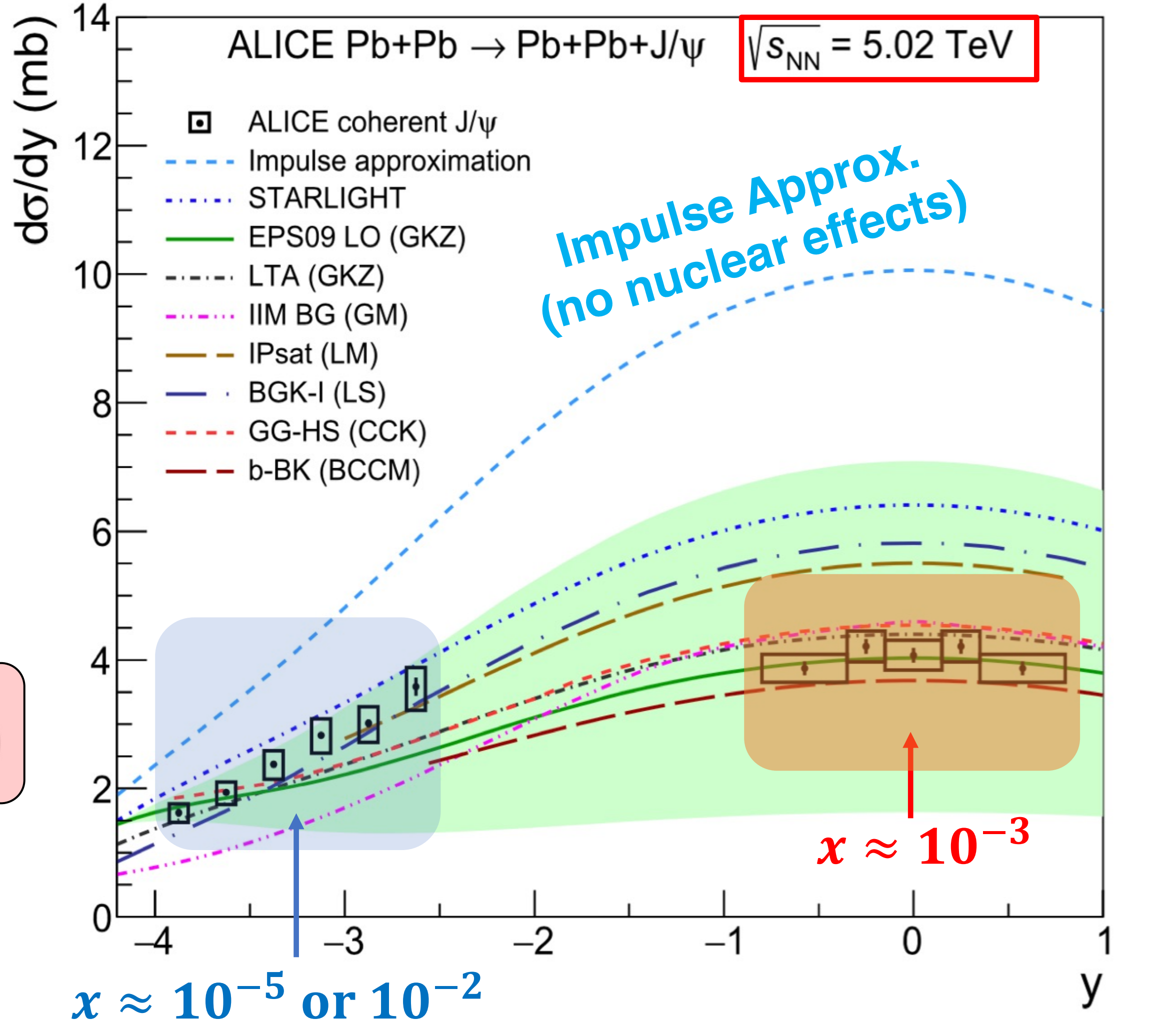
A "two-way ambiguity" in symmetric systems



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

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

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

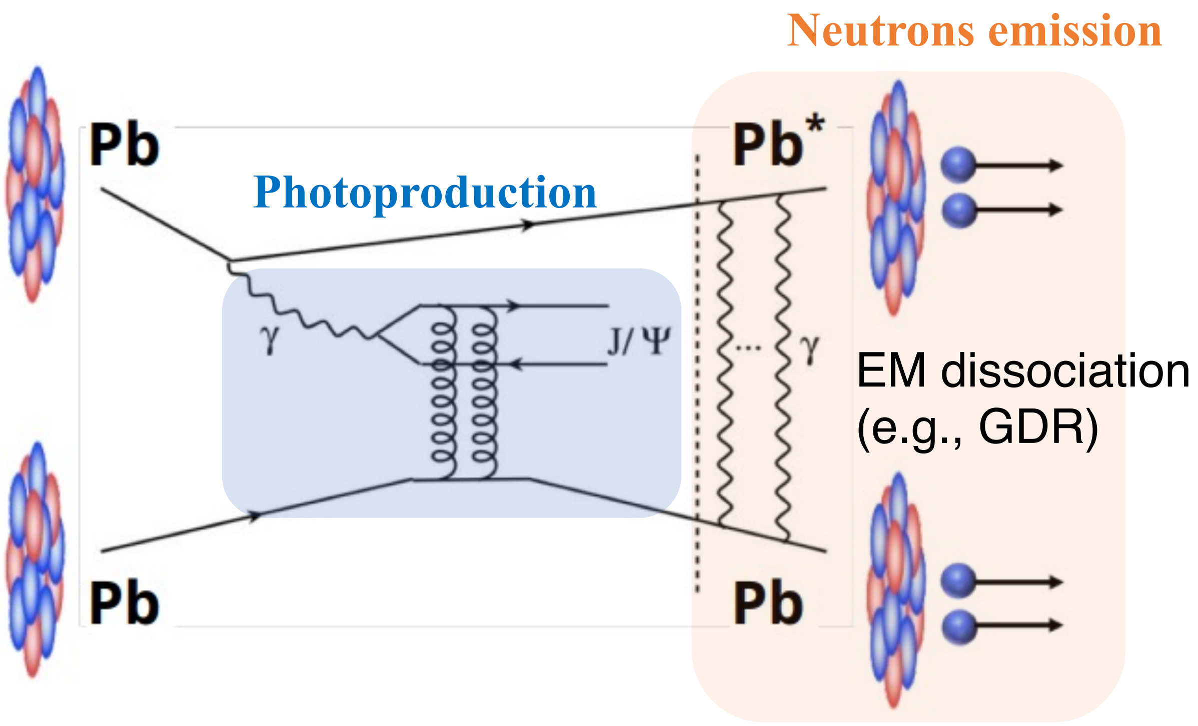


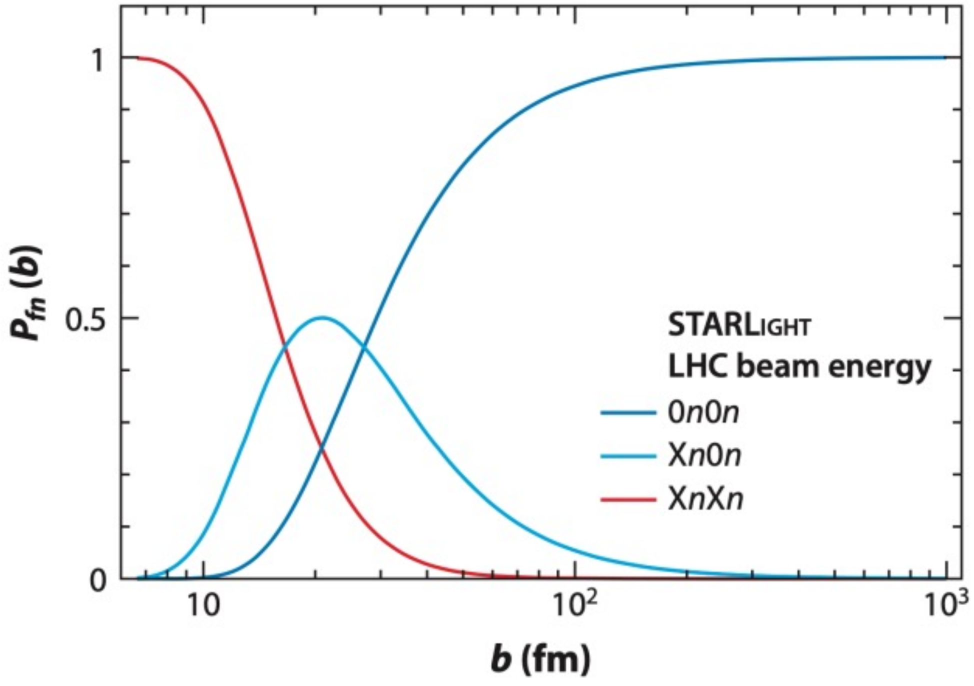
$x \approx 10^{-5}$ or 10^{-2}
(>95% high x!)

A Solution To The “Two-way Ambiguity”

Proposed by Guzey et al., EPJC 74 (2014) 2942

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





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

Nucleus excitation probability:

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

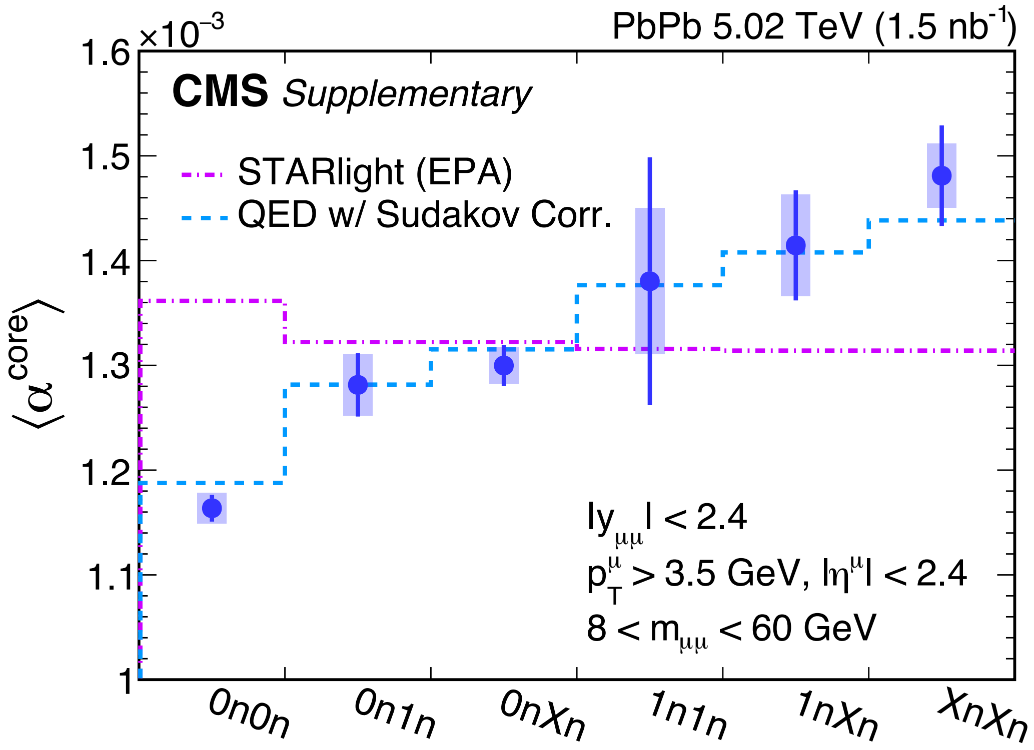
•Analogous to centrality:

- b_{XnXn} < b_{0nXn} < b_{0n0n}

A Solution To The "Two-way Ambiguity"

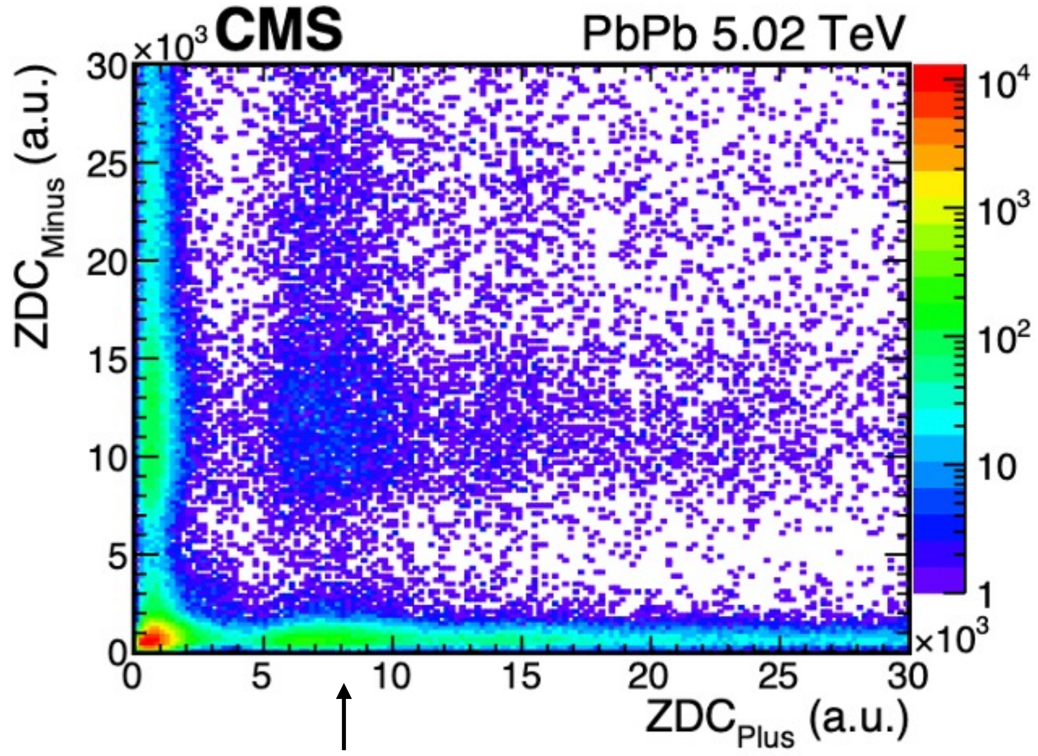
Control the impact parameter or "centrality" of UPCs via forward neutron multiplicity

Dimuon acoplanarity from $\gamma\gamma \rightarrow \mu^+\mu^-$



PRL 127 (2021) 12, 122001

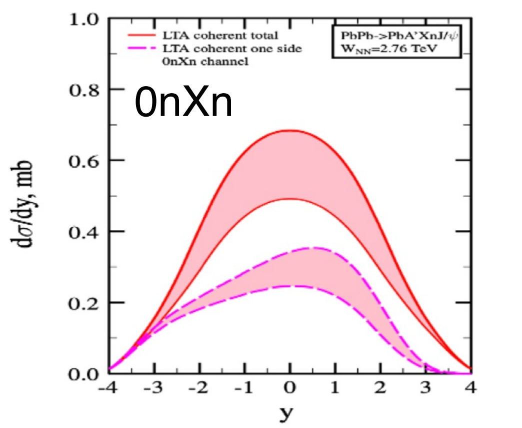
Energy distribution of ZDC+ vs ZDC-

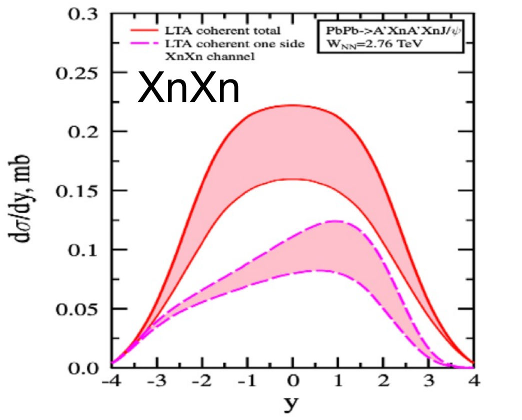


Single neutron peak

A Solution To The "Two-way Ambiguity"

For each J/ψ |y| bin,





Guzey et al., EPJC 74 (2014) 2942

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

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

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

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

⇩

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

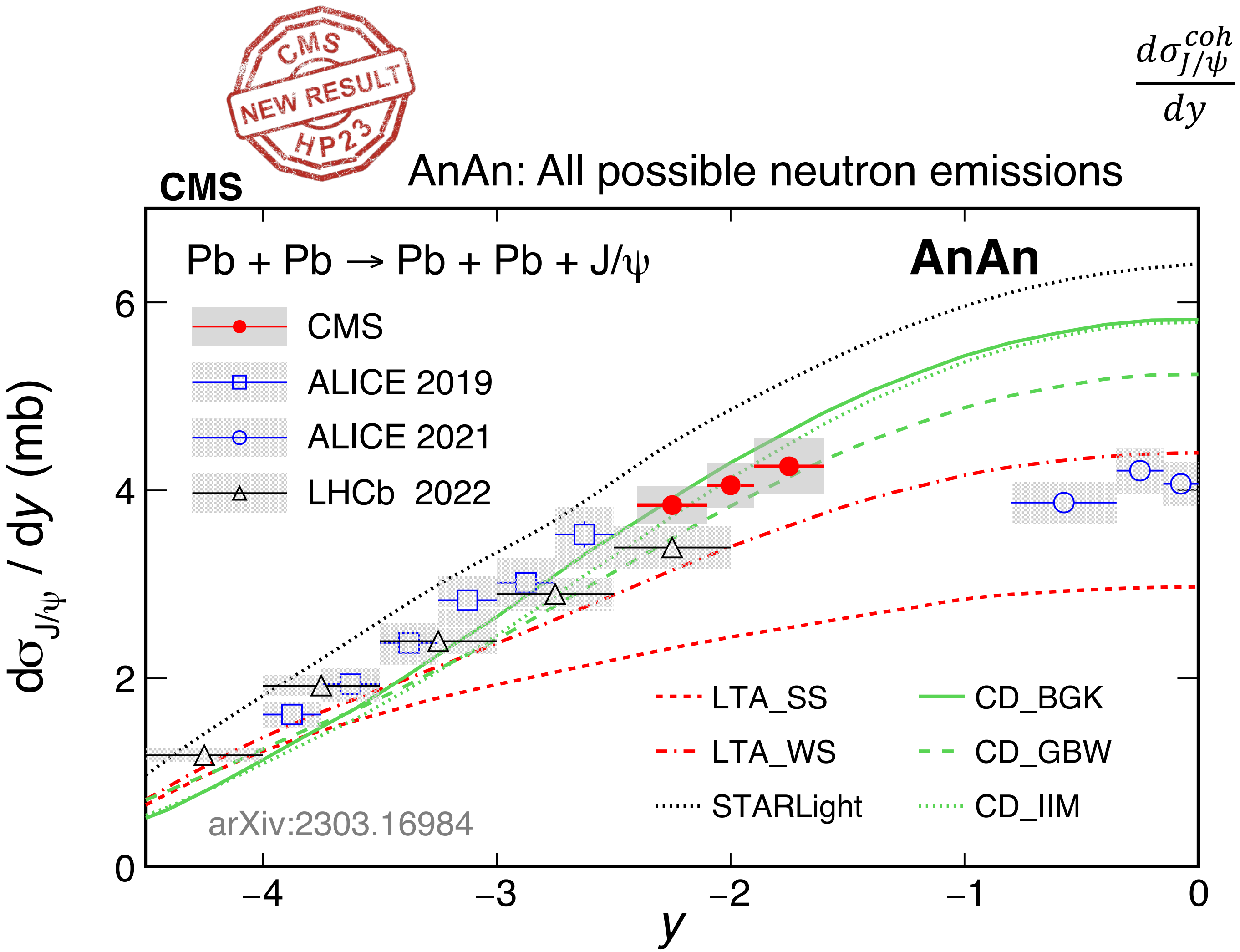
⇩

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

Coherent J/ψ in UPC PbPb w/o neutron selections

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

AnAn: All possible neutron emissions



* will be able to cover full |y|<2.4 in the future

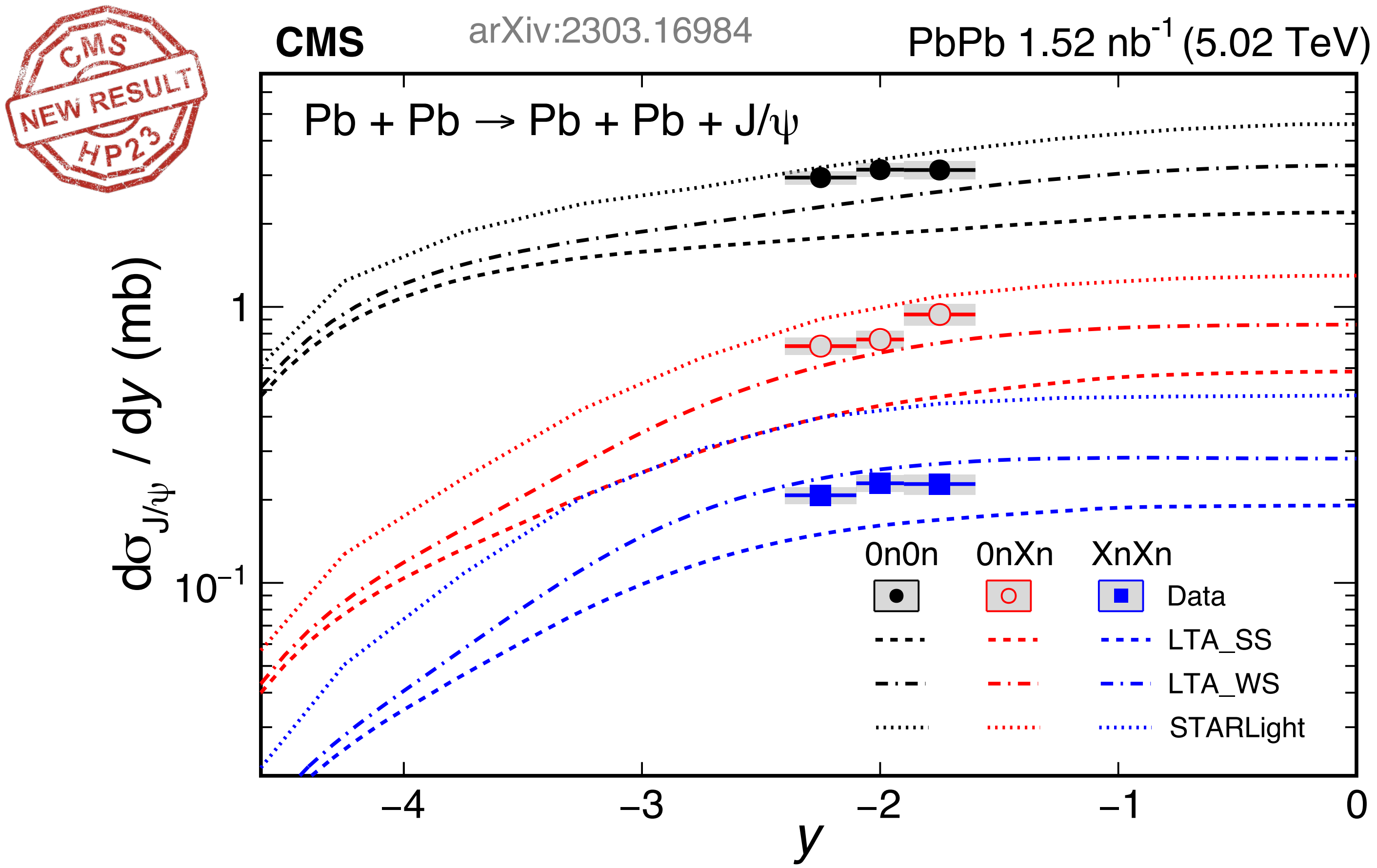
CMS data cover a new y region and follow ALICE high-y trend

- A tension between ALICE/CMS and LHCb forward data?

No theory described the data over the full y range – ***a puzzle? what's missing?***

Solving the two-way ambiguity is the key!

Coherent J/ψ in each "UPC centrality" class

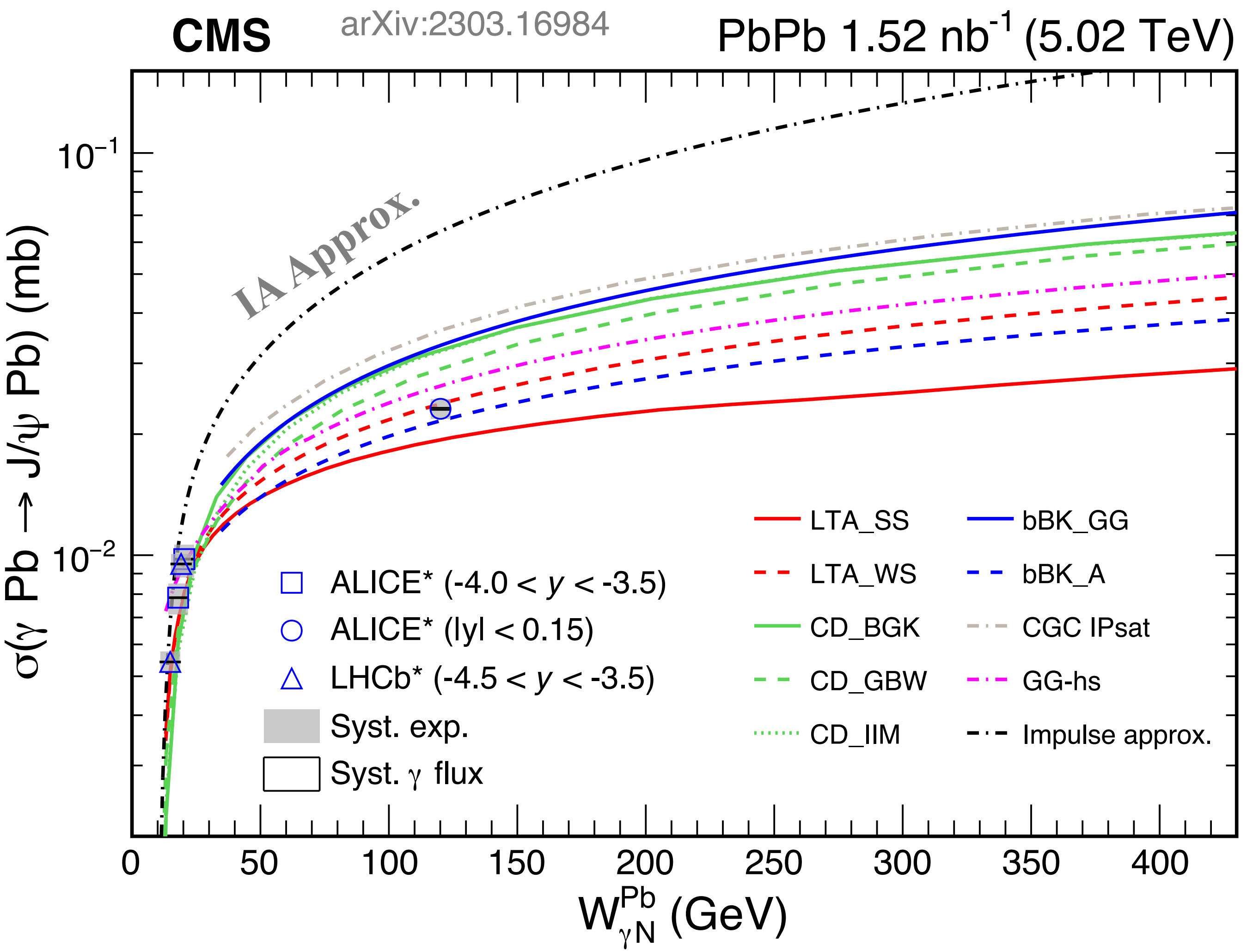


- 0n0n: b > 40 fm
- 0nXn: b ~ 20 fm
- XnXn: b < 15 fm

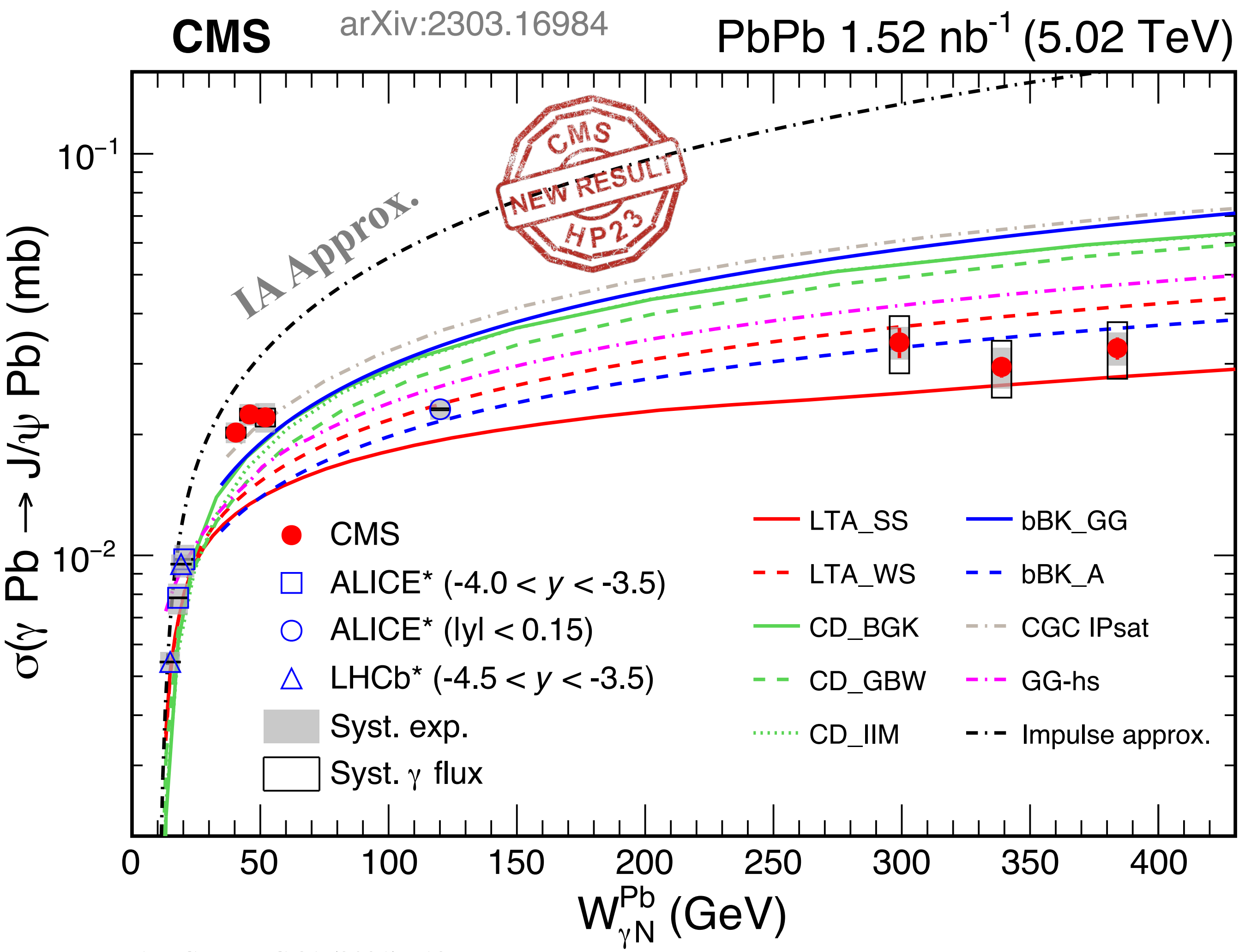
EMD pileups corrected

- First separation in different UPC centrality classes!
- LTA or STARLight cannot describe data in all neutron classes

Coherent J/ψ cross section v.s. $W_{\gamma N}^{Pb}$



Coherent J/ψ cross section v.s. $W_{\gamma N}^{Pb}$



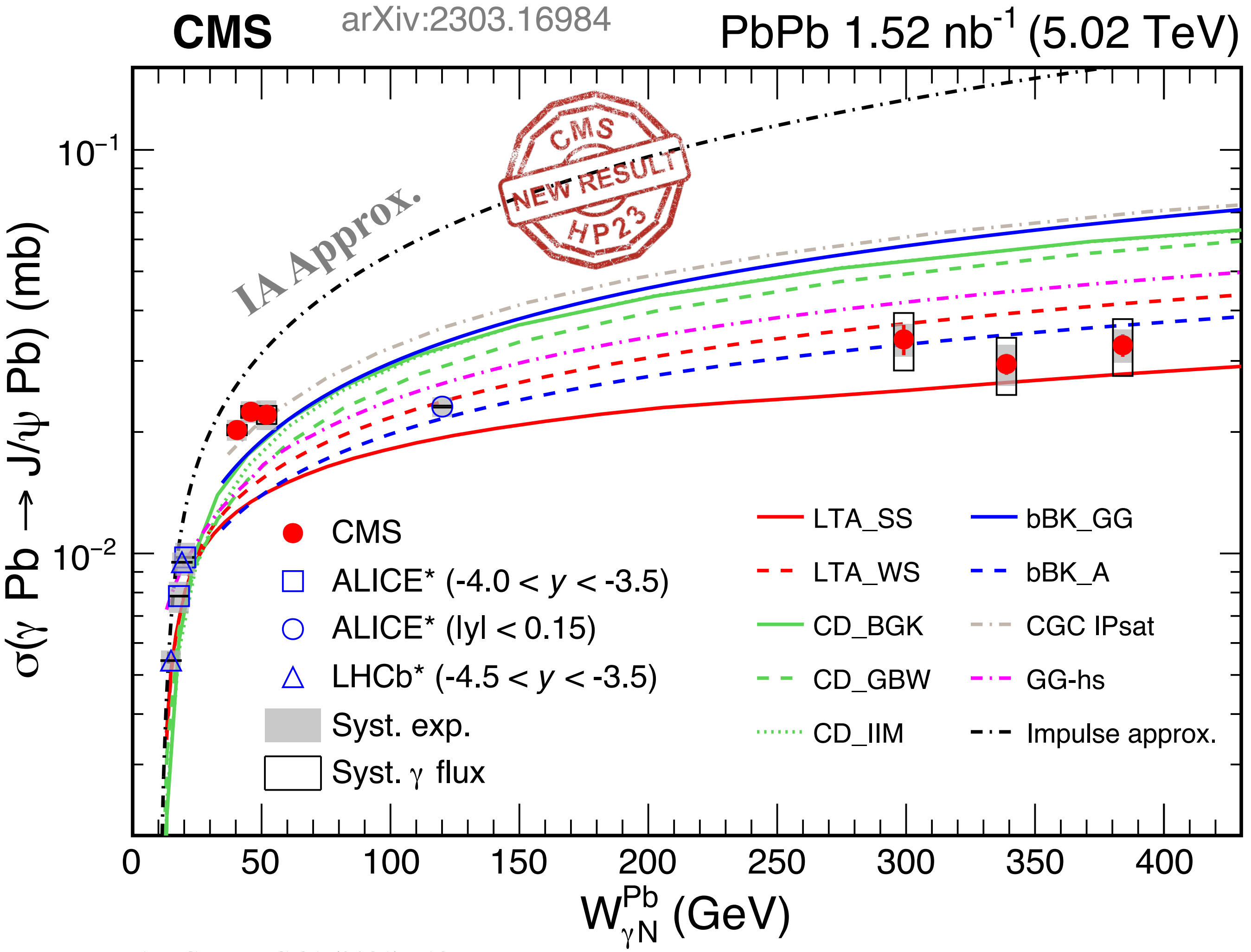
ALICE, EPJC 81 (2021) 712
LHCb, arXiv:2206.08221

CMS measurement up to W ~ 400 GeV

- W < 40 GeV: rapidly rising
- **40 < W < 400GeV: nearly plateaued with a much slower increase**

The observed trend in data is not predicted by theoretical models (e.g., gluon saturations, LTA shadowing)

Coherent J/ψ cross section v.s. $W_{\gamma N}^{Pb}$

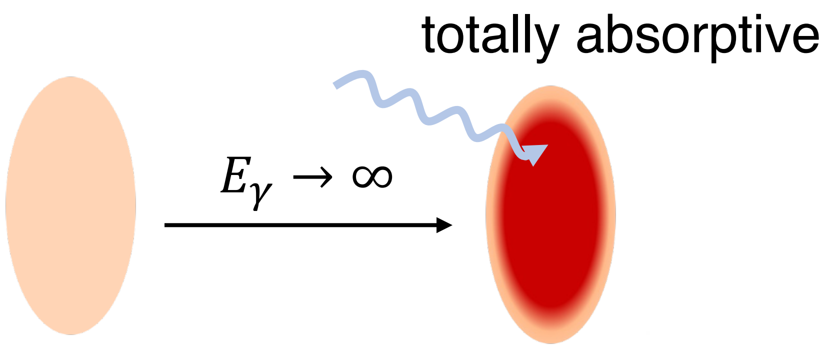


ALICE, EPJC 81 (2021) 712
LHCb, arXiv:2206.08221

- **Direct evidence for strong gluon saturation!!?**

OR

- **Near the "Black Disk Limit"**

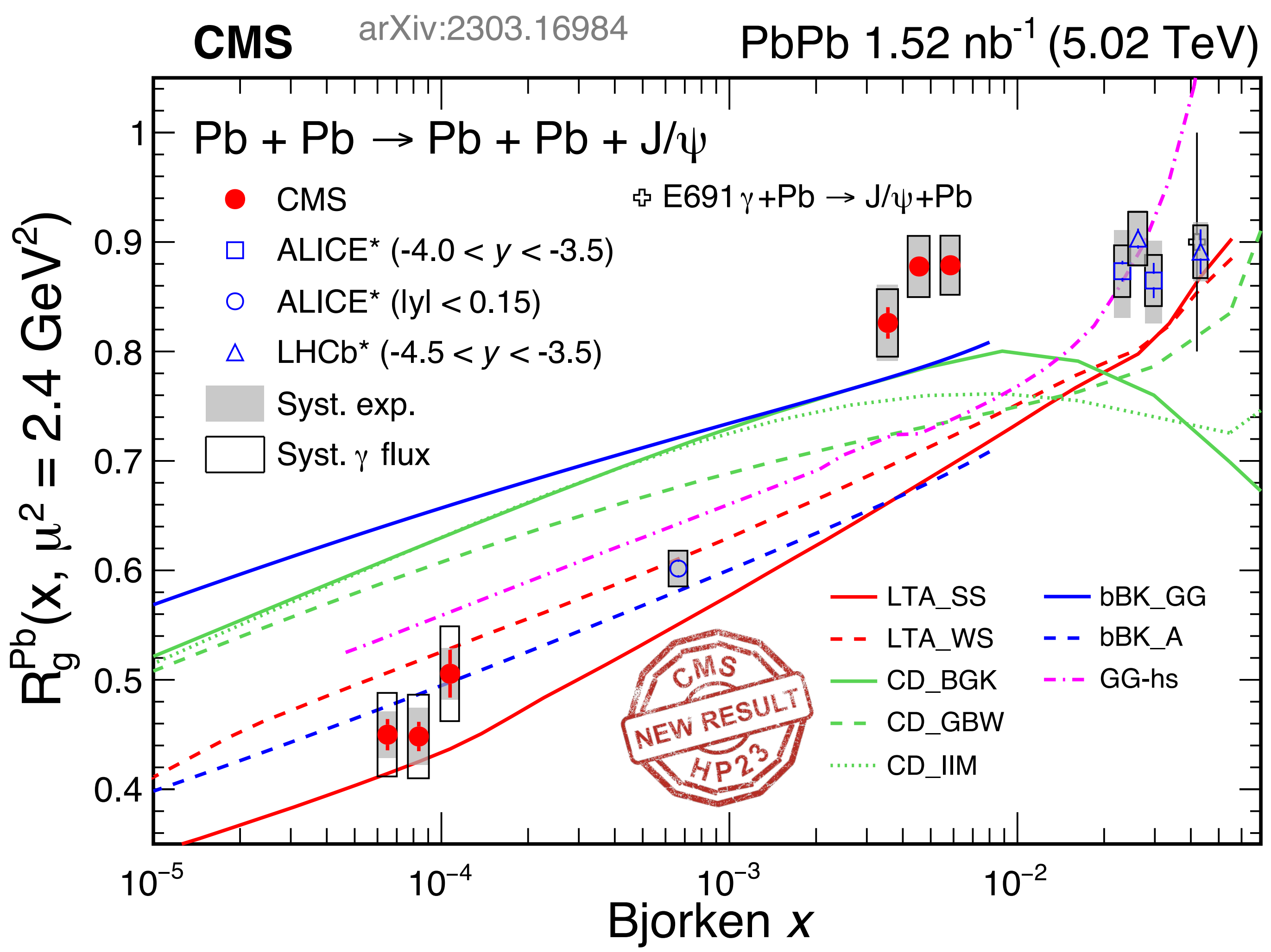


$$\hat{\sigma}^{\text{inel}}_{\text{PQCD}} \leq \hat{\sigma}_{\text{black}} = \pi R^2_{\text{target}}$$

Physics Reports 512 (2012) 255

OR …

Nuclear suppression for gluon PDF



Nuclear gluon suppression factor (valid at LO approx.)

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

- A flat trend at x ~ $10^{-2} - 10^{-3}$
- Rapidly decrease towards very small x (~6x10^{-5}) region.

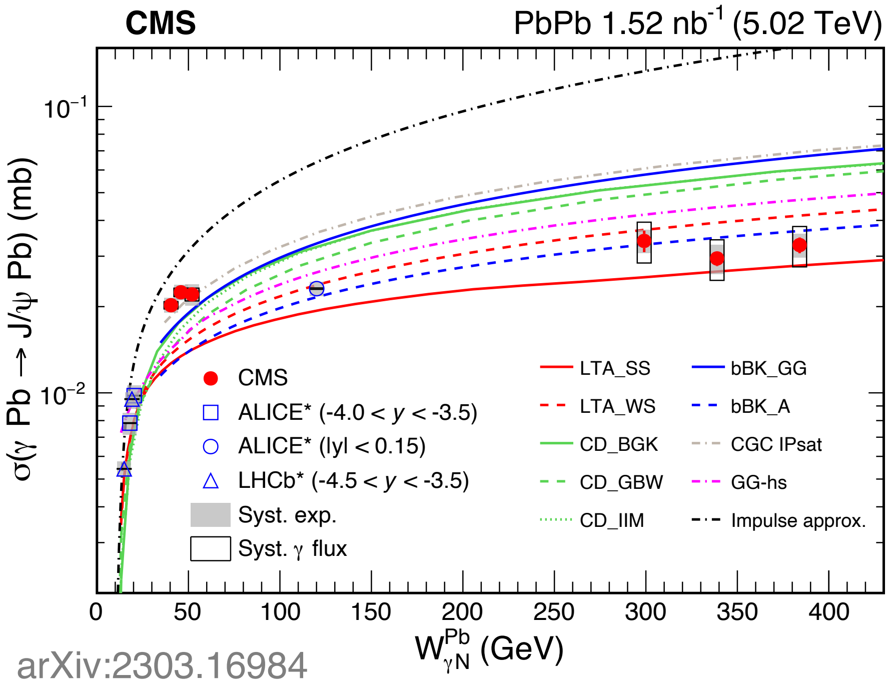
→ Not described by any model

NLO contributions important?

K. Eskola, PRC 106 (2022) 035202, arXiv:2210.16048

Summary

- For the first time, **directly disentangled coh. $\sigma_{\gamma A \to J/\psi A'}(W)$** in UPC AA
- Probed a **new low-x gluon regime ($10^{-4} - 10^{-5}$) in lead nuclei.**
- Flattening of coh. $\sigma_{\gamma A \to J/\psi A'}(W)$ at high W not predicted by theoretical models
  - **Direct evidence for gluon saturation**? Or Near the **black-disk limit**? Or …?



arXiv:2303.16984

New insights to ultra-dense gluonic matter!

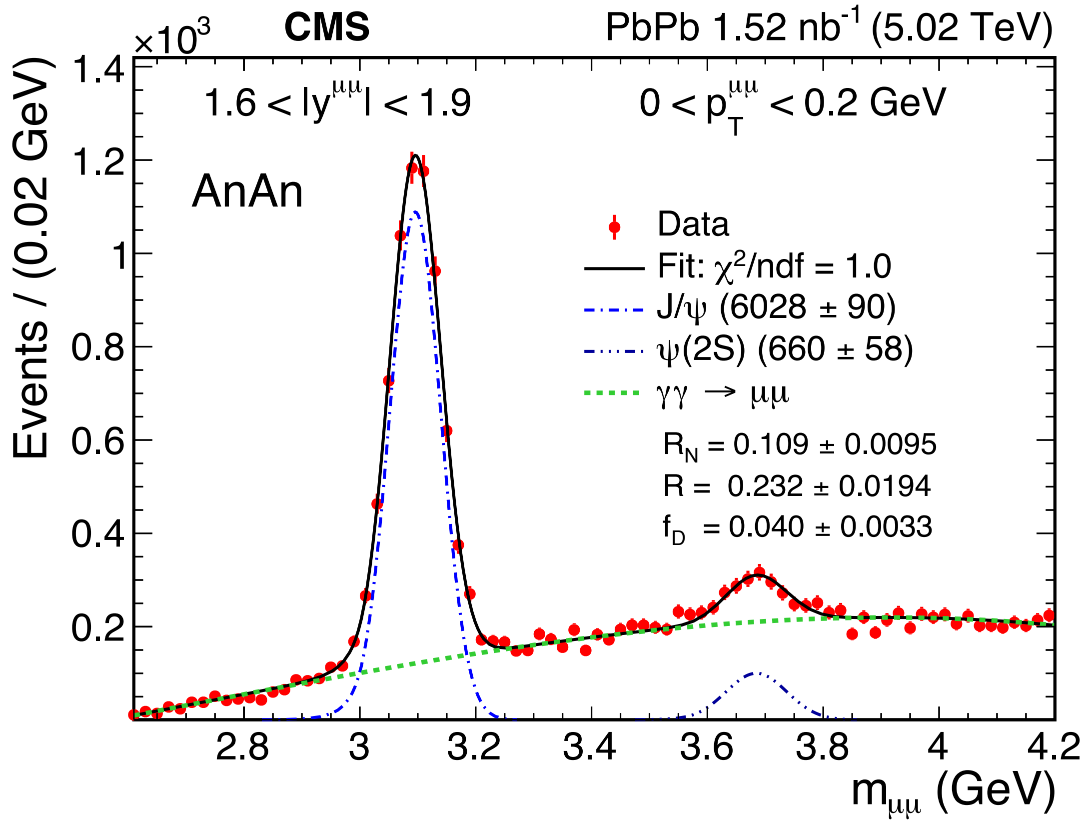
A rich future program ahead:

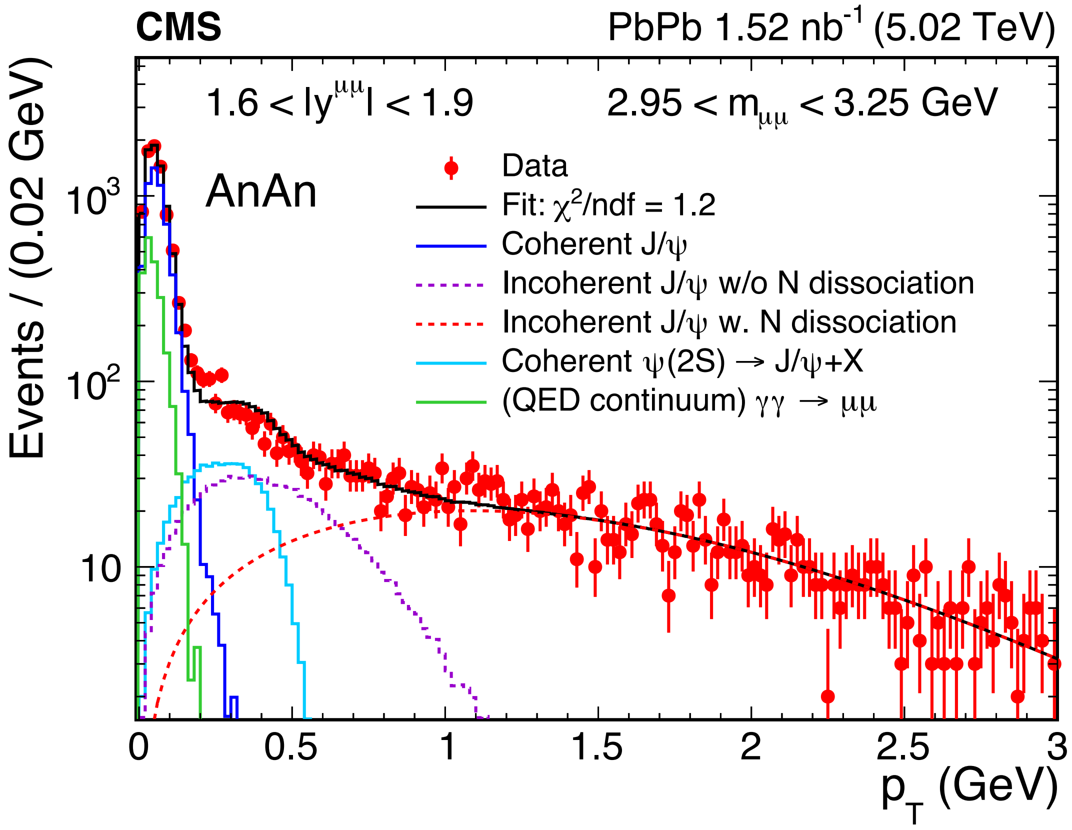
- A variety of VMs (ϕ, $\psi(2S)$, Υ)
- More ion species (OO, XeXe, ArAr, …)
- Coherent vs incoherent
- …

CMS NEW RESULT HP23

EXTRA

Coherent J/ψ signal extraction





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

AnAn: All possible neutron emissions

EM Diss. Correction

- The correction can be obtained by inverting migration matrix

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

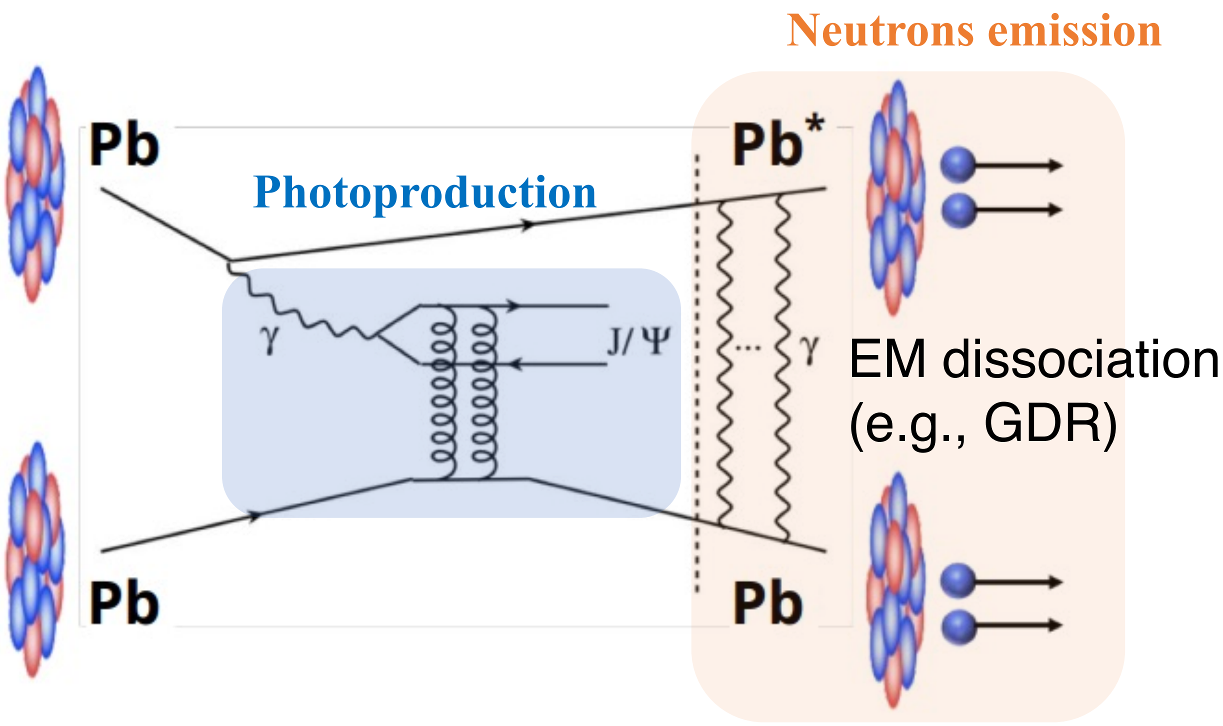
- The matrix element can be obtained from ZB fraction

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

A Solution To The "Two-way Ambiguity"

Guzey et al., EPJC 74 (2014) 2942

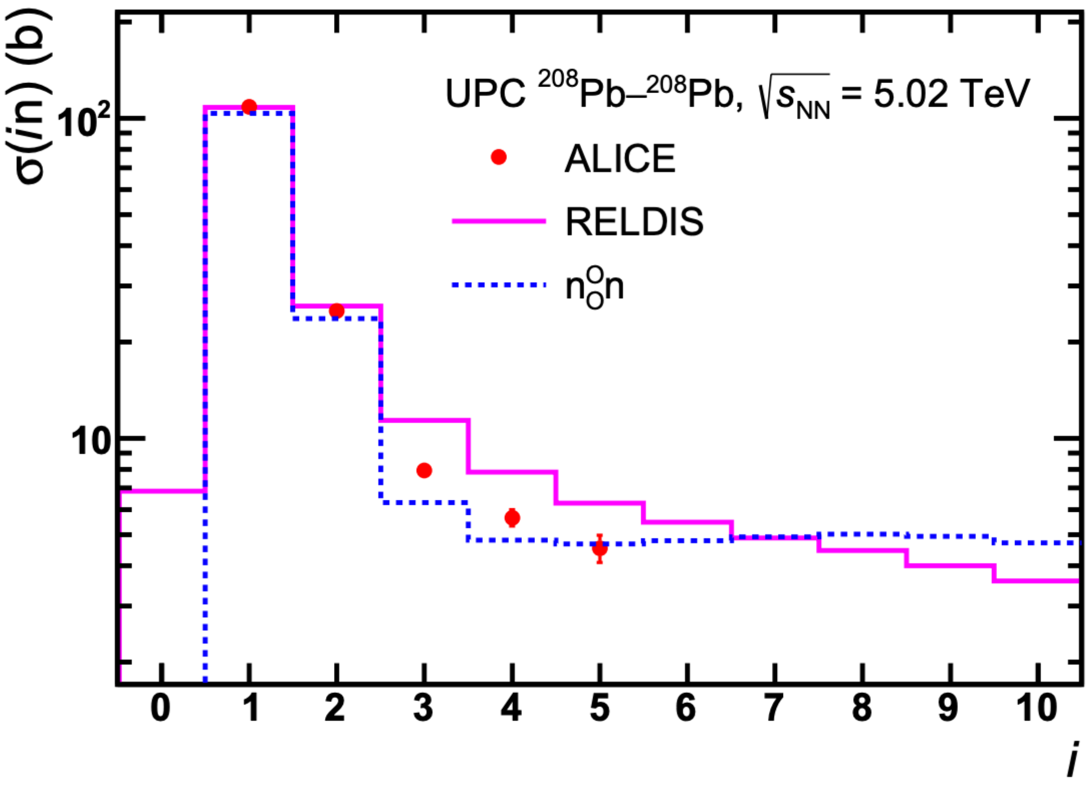
Control the impact parameter or "centrality" of UPCs via forward neutron multiplicity



Nucleus excitation probability:

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

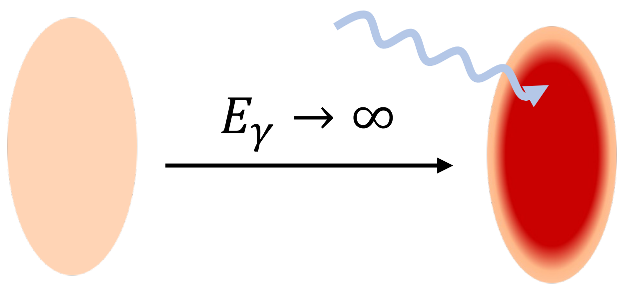
ALICE, arXiv:2209.04250



Neutrons from EMD reasonably understood

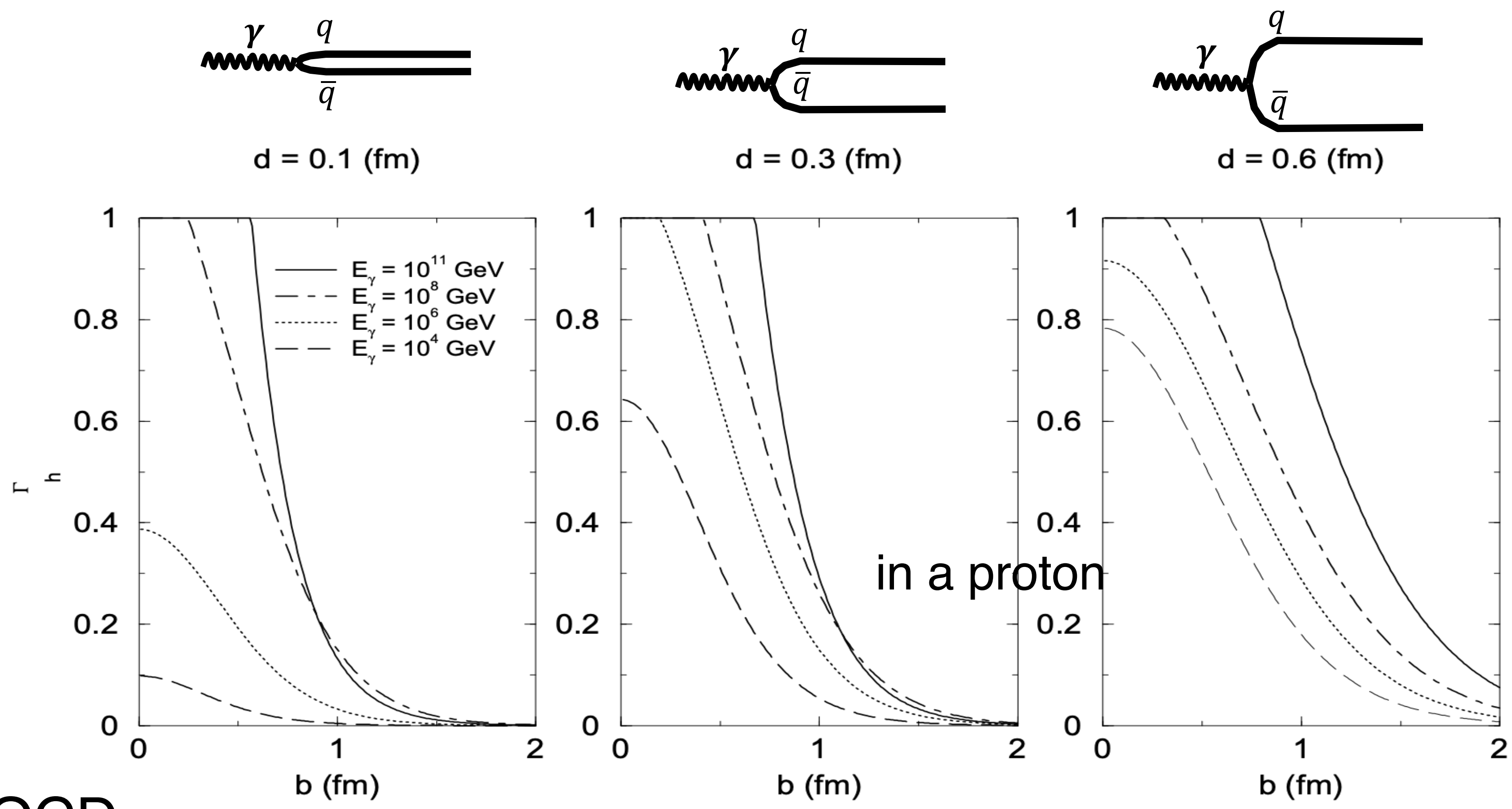
A Novel Regime Of QCD: Black Disk Limit

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



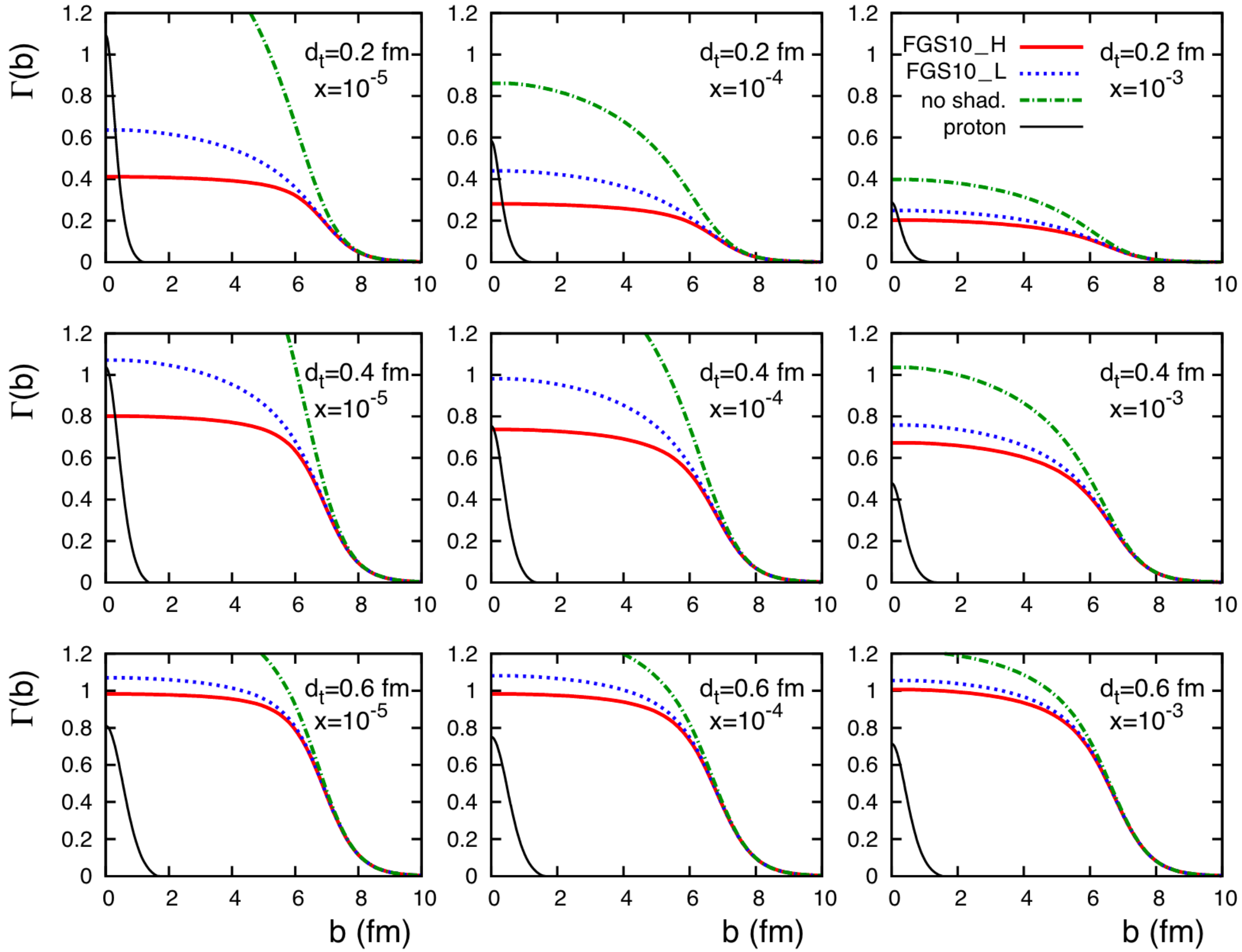
$$\hat{\sigma}^{\text{inel}}_{\text{PQCD}} \leq \hat{\sigma}_{\text{black}} = \pi R^2_{\text{target}}$$

– **"Black Disk Limit (BDL)"**



"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



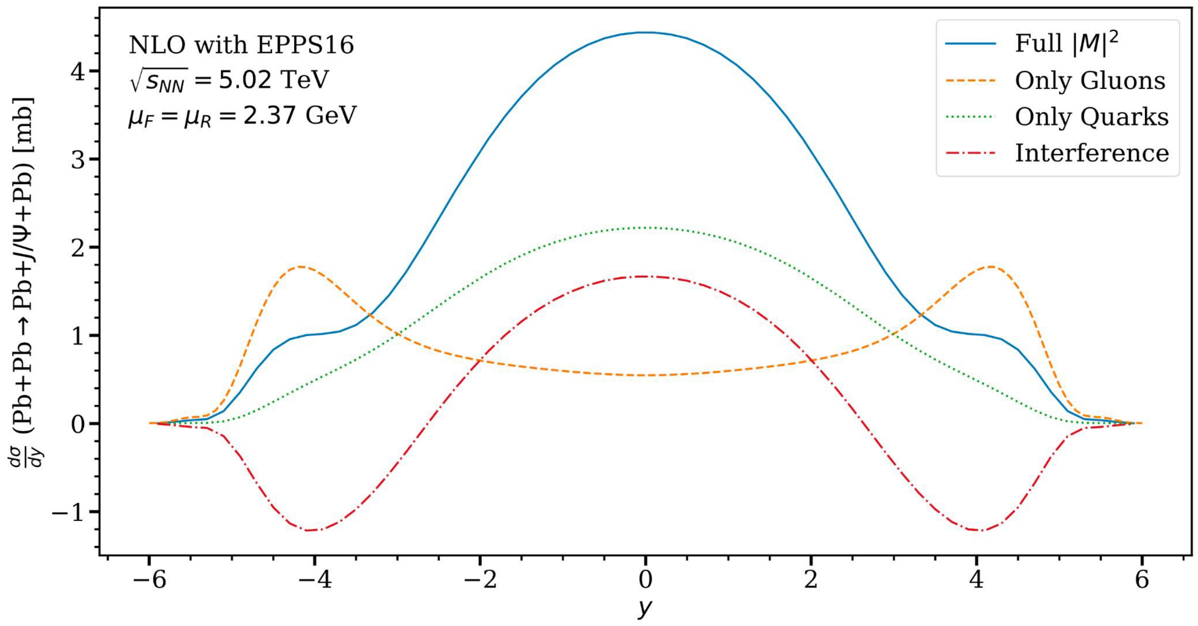
Physics Reports 512 (2012) 255

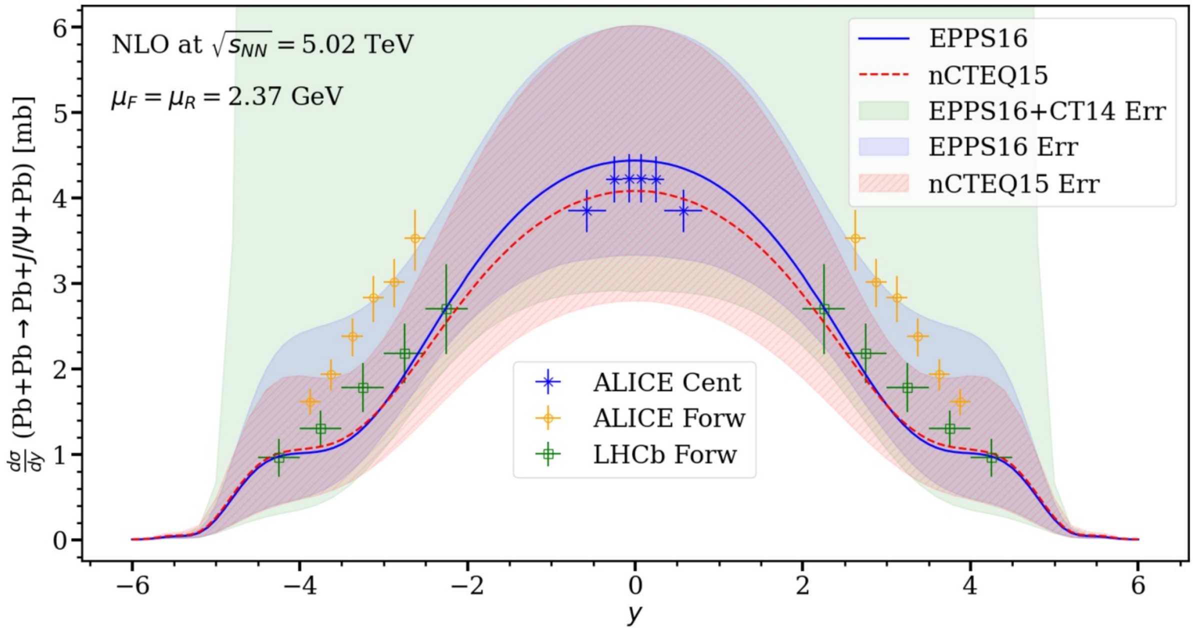
Fig. 99. The impact factor $\Gamma_A(x, b, d_\perp)$ for ^{208}Pb at $Q^2 = 4$ GeV^2 as a function of the impact parameter b for different values of x and dipole sizes $d_\perp$. The solid (red) curves correspond to model FGS10_H; the dotted curves correspond to FGS10_L. For comparison, we also give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

NLO contributions

Quark contributions at NLO + cancellations between LO and NLO gluons may lead to strong modifications to LO results, although uncertainties are still large.

PRC 106 (2022) 035202

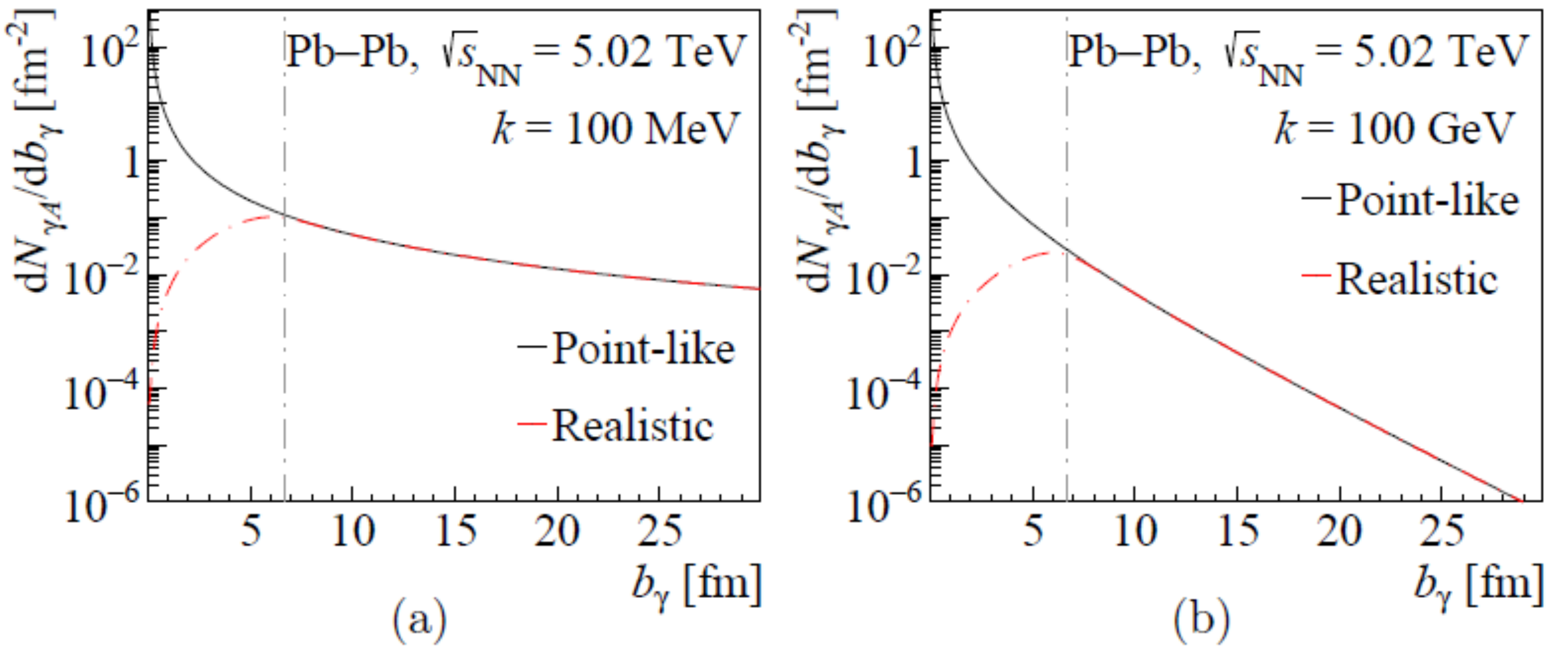




Flux From StarLight

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

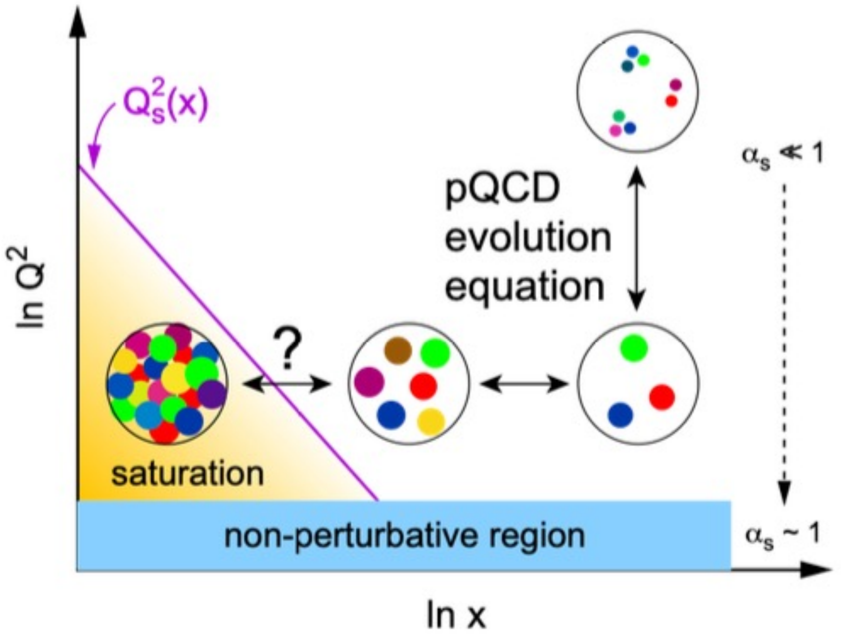
arXiv:2111.11383



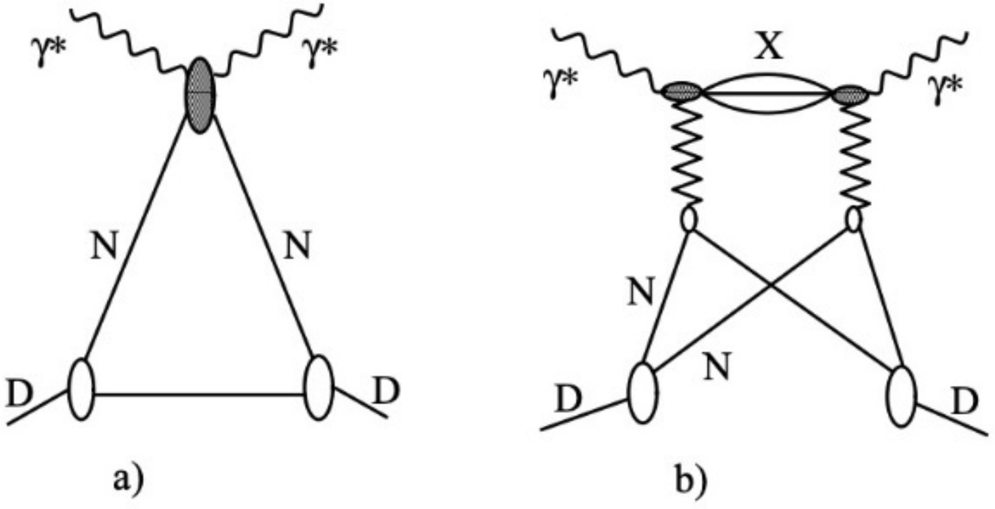
(Color online) Photon fluxes coming from a nucleus in the point-like source approximation and the realistic description as functions of impact parameter b calculated at different photon energies: 100 MeV (a), 100 GeV (b)

Saturation vs Shadowing

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



Gluon saturation



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

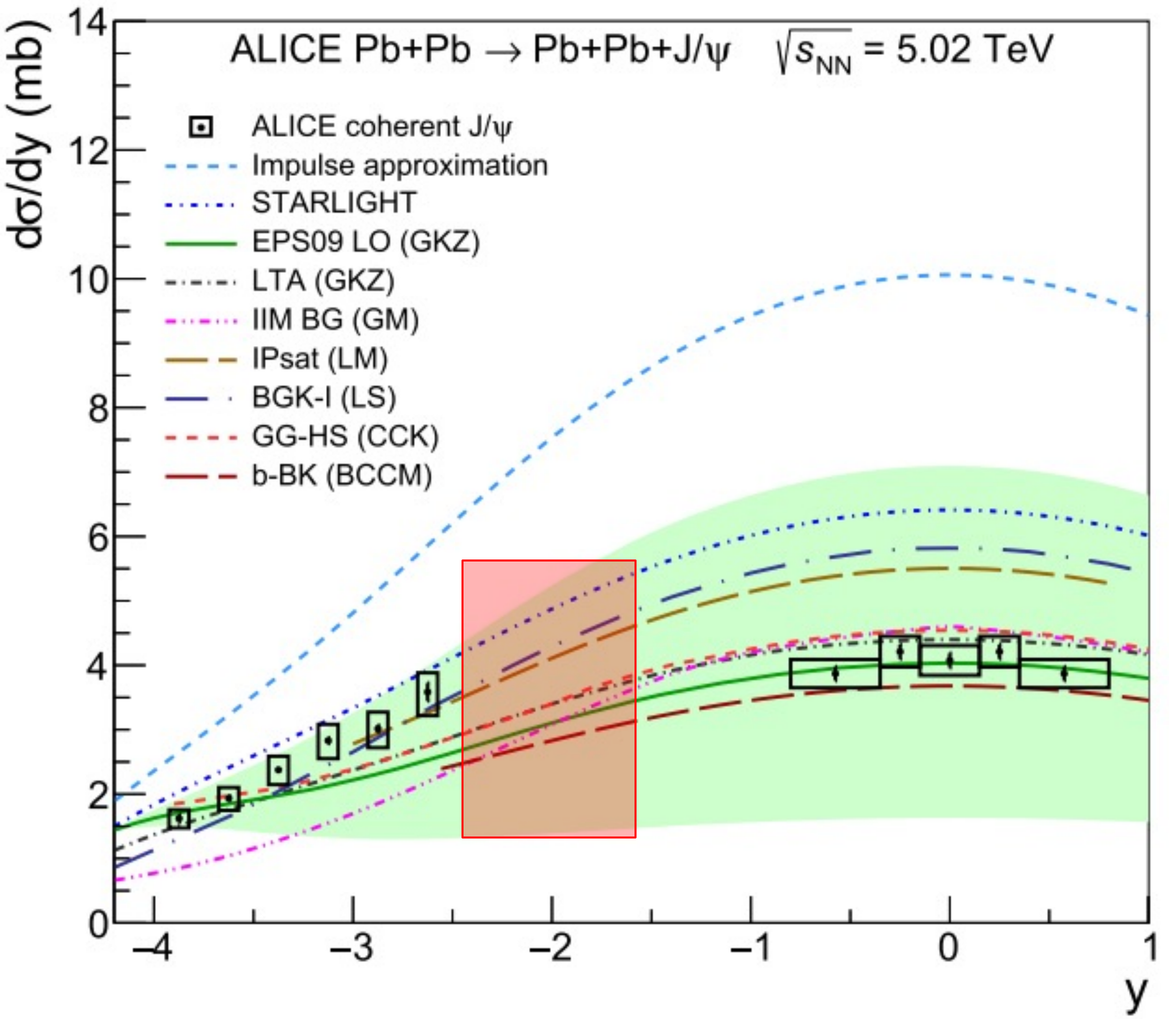
Nuclear shadowing

Theory Description

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



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