Probing small-x nuclear gluonic structure via coherent J/ψ photoproduction in ultraperipheral PbPb collisions at CMS

Luis F. Alcerro
(On behalf of the CMS Collaboration)
l.alcerro@cern.ch

Department of Physics & Astronomy
University of Kansas

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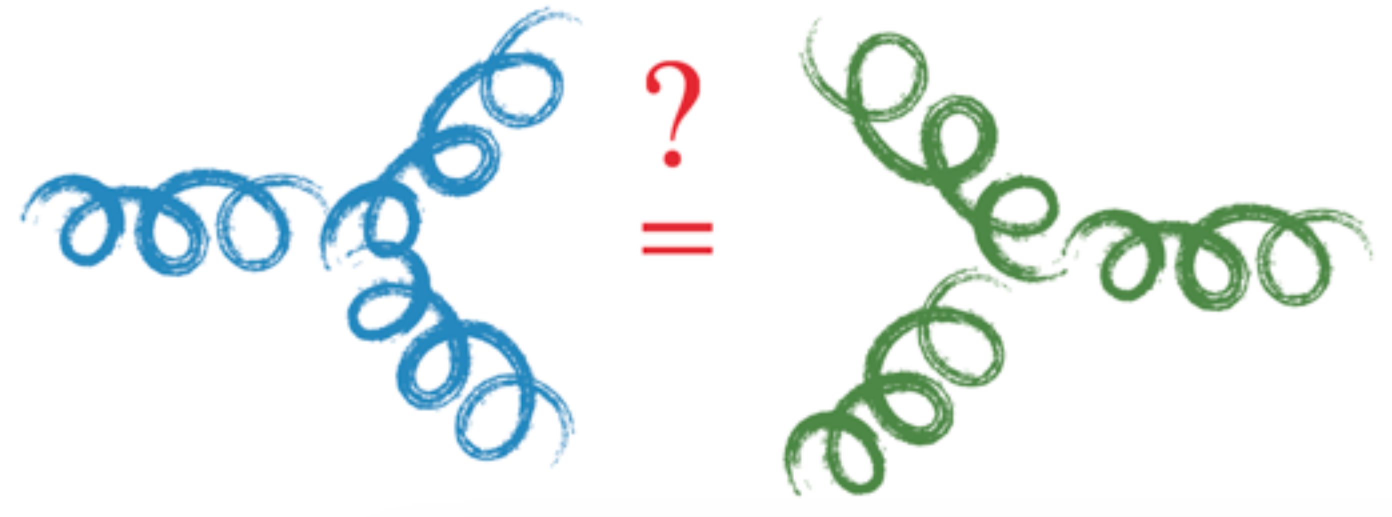
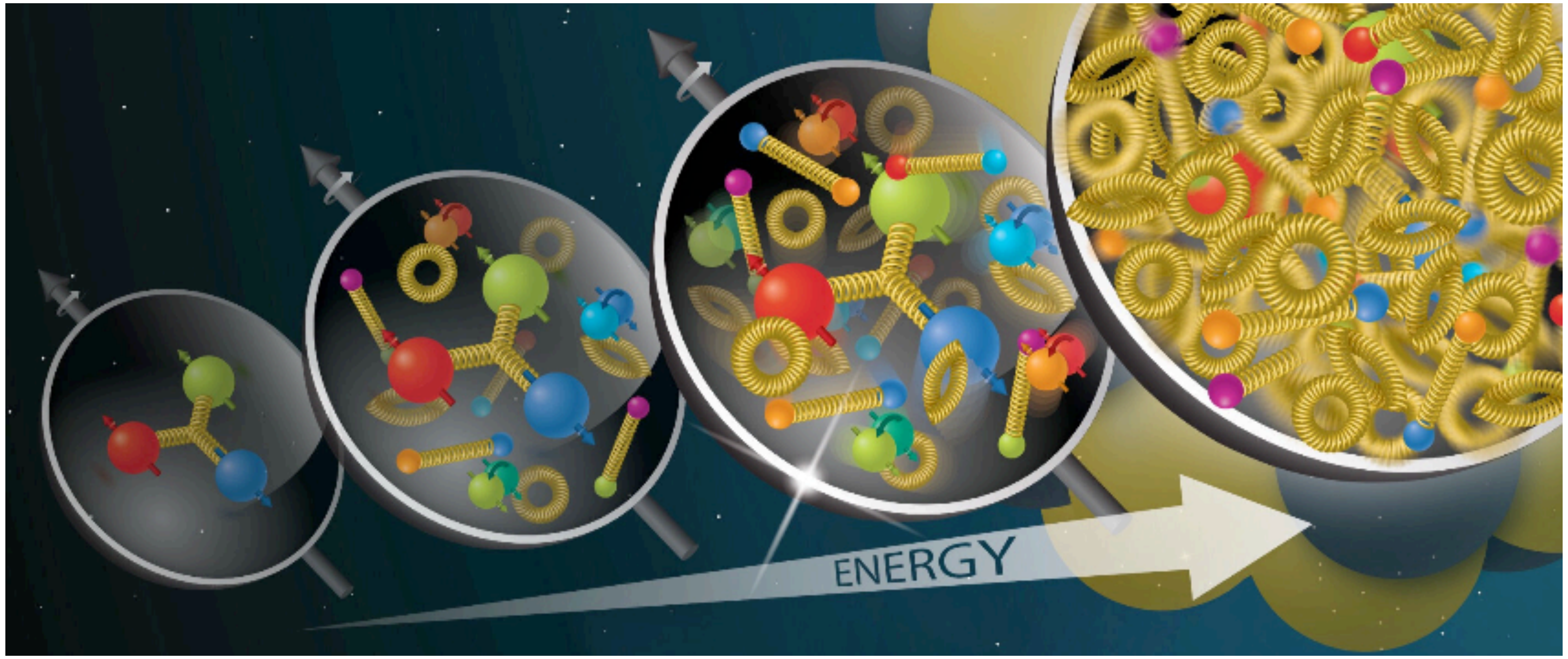
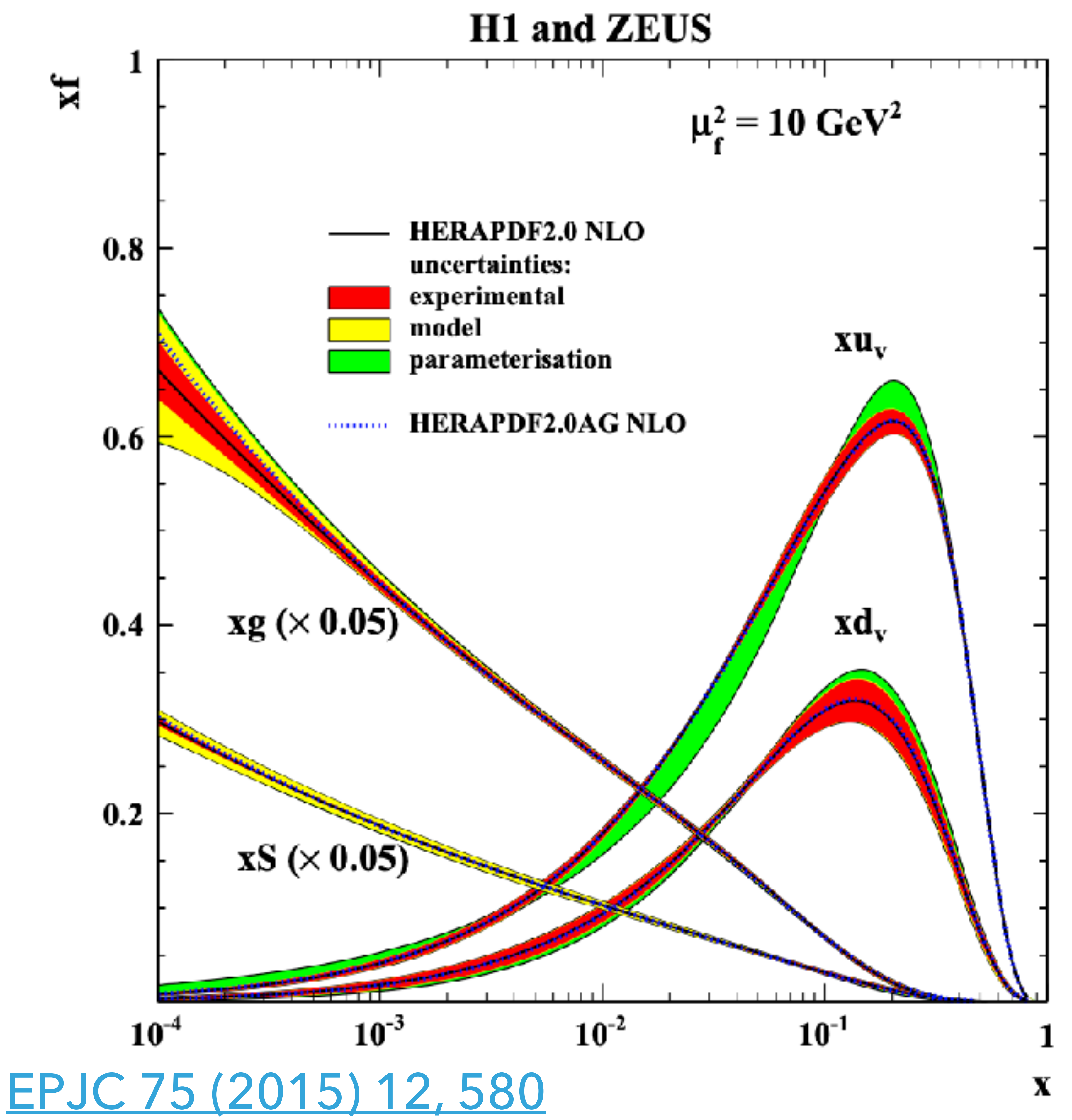
Motivation

- DIS experiments show gluons become rapidly dominant at high energies.
- Unitarity: This behavior cannot go forever!
- New QCD regime: compensation between gluon splittings and recombinations.
- No conclusive evidence of saturation to date!

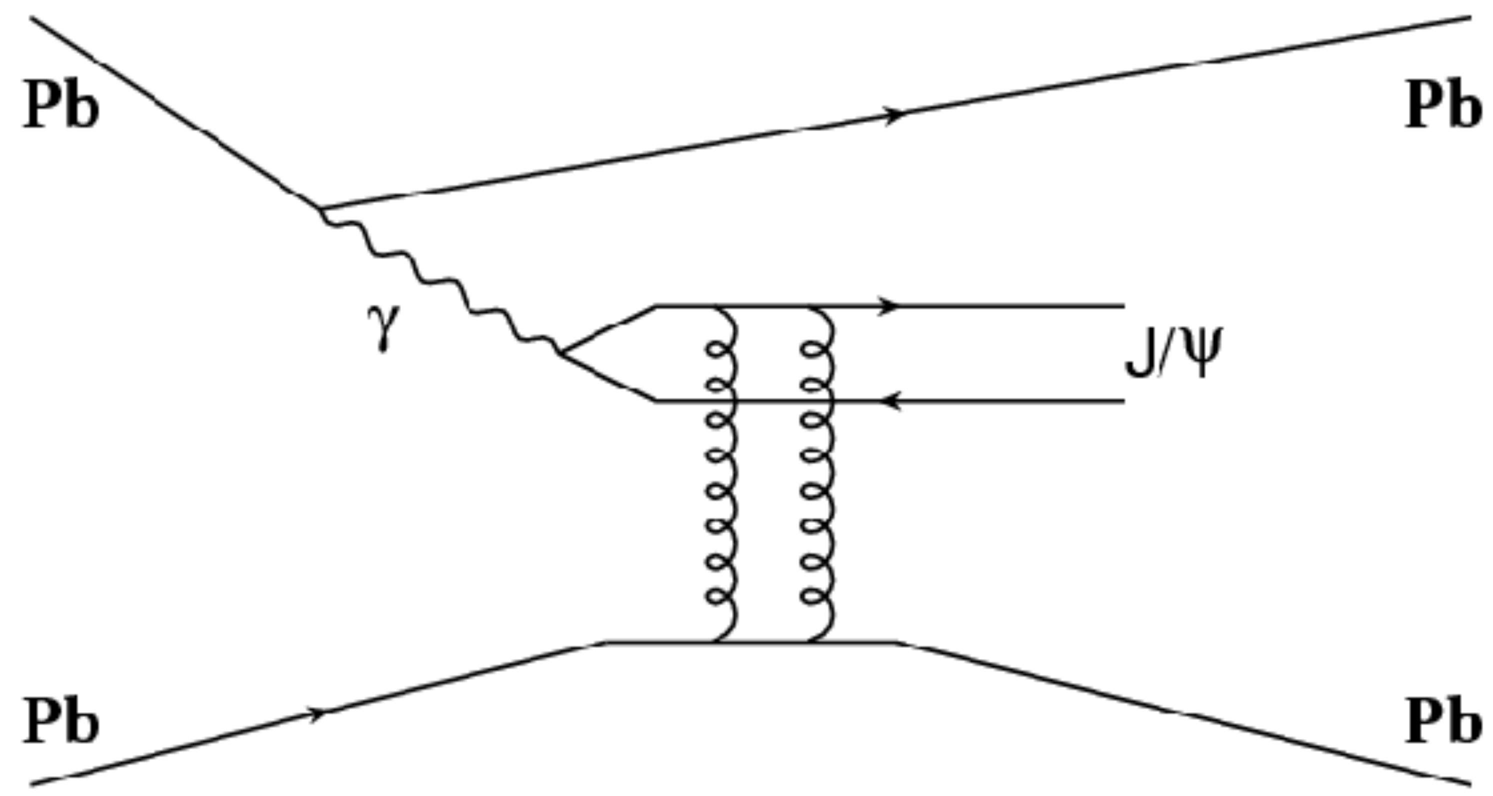






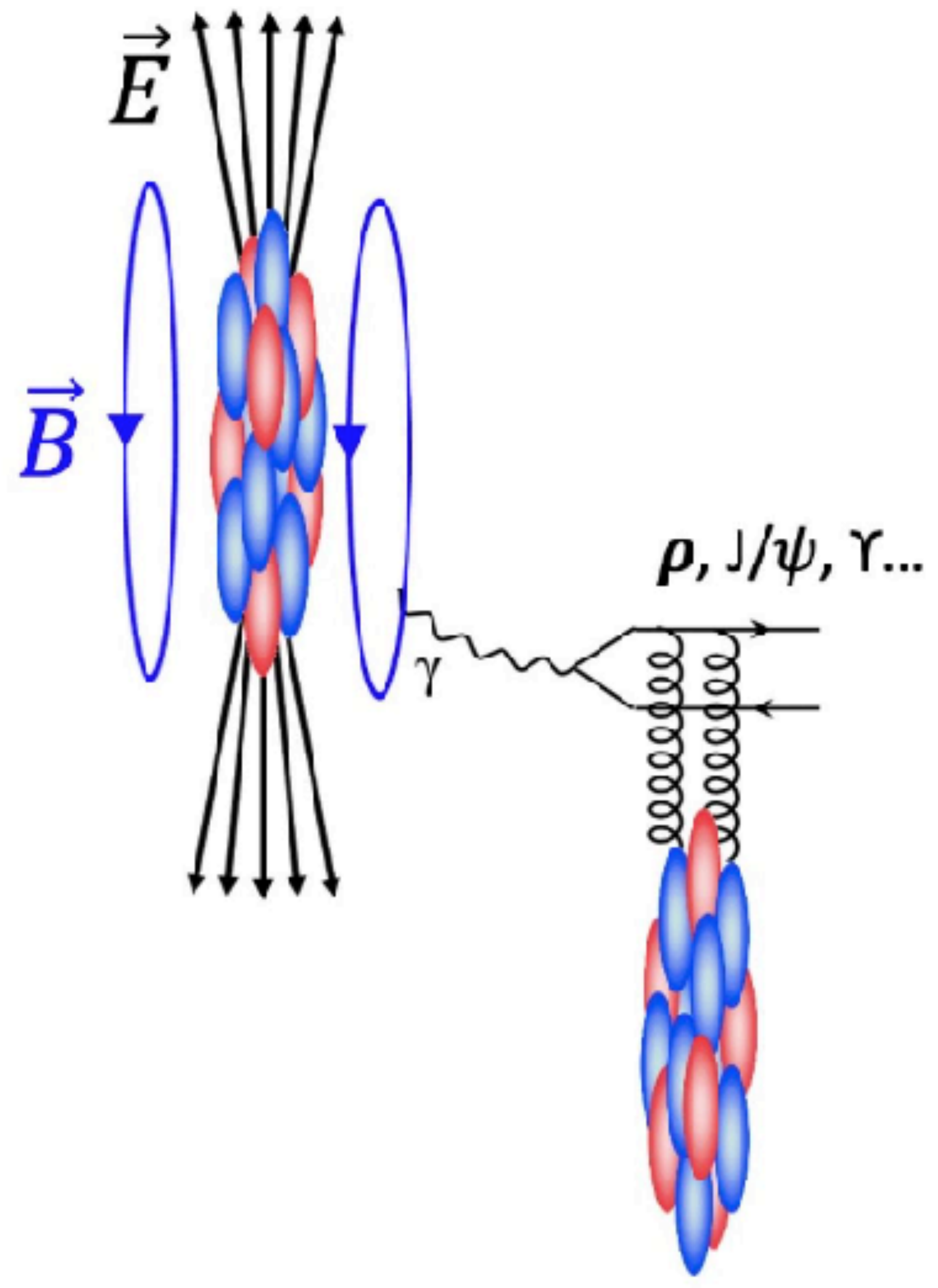
EPJC 75 (2015) 12, 580

Photoproduction of vector mesons (VM)



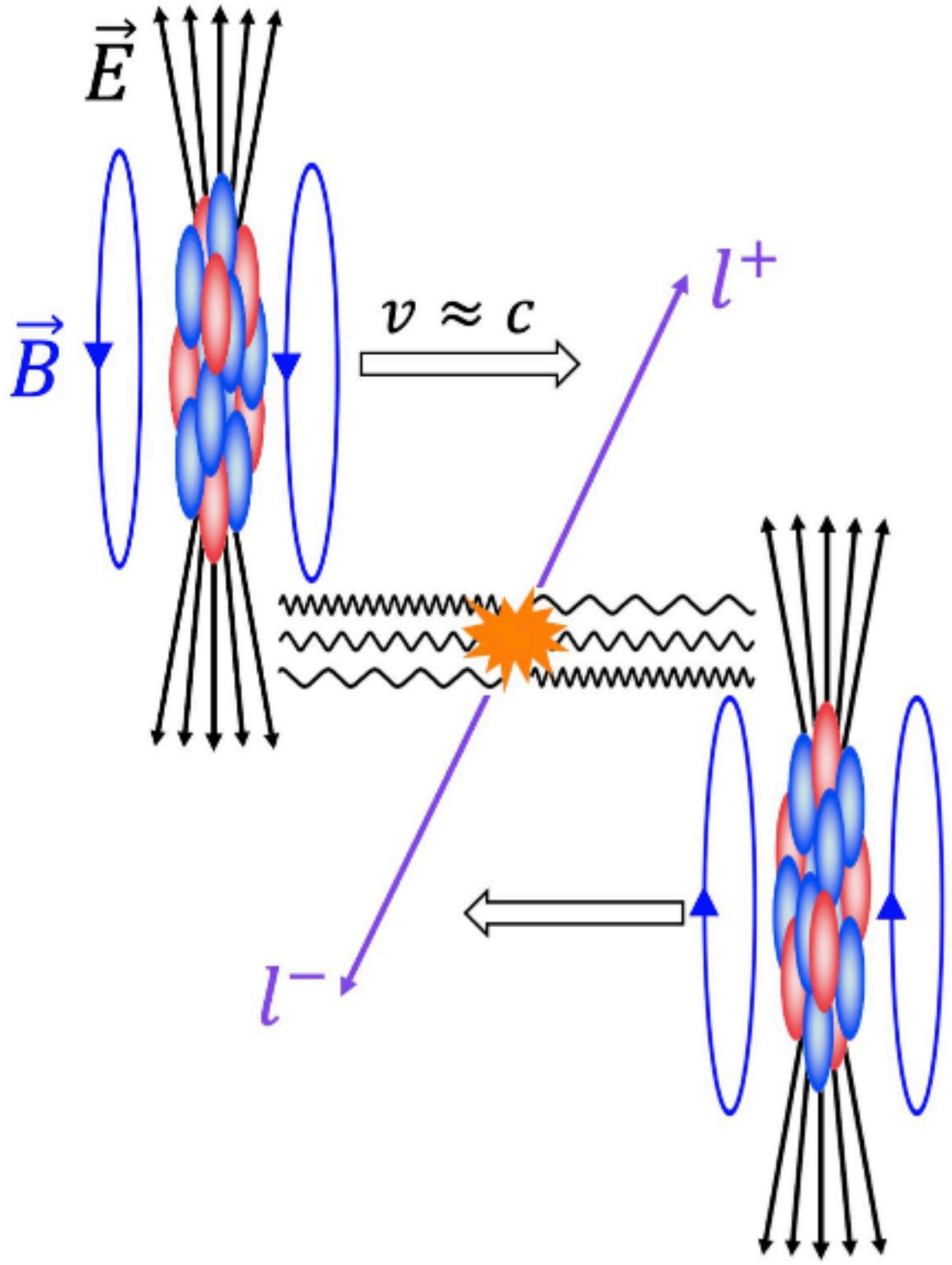
- Photon quantum numbers ($J^{PC} = 1^{--}$) same for VM → photon fluctuates into a VM !
- VM photoproduction cross section $\propto (xg(x, Q^2))^2$ at LO.
- Photoproduced VM cross section at small x can test gluon density.

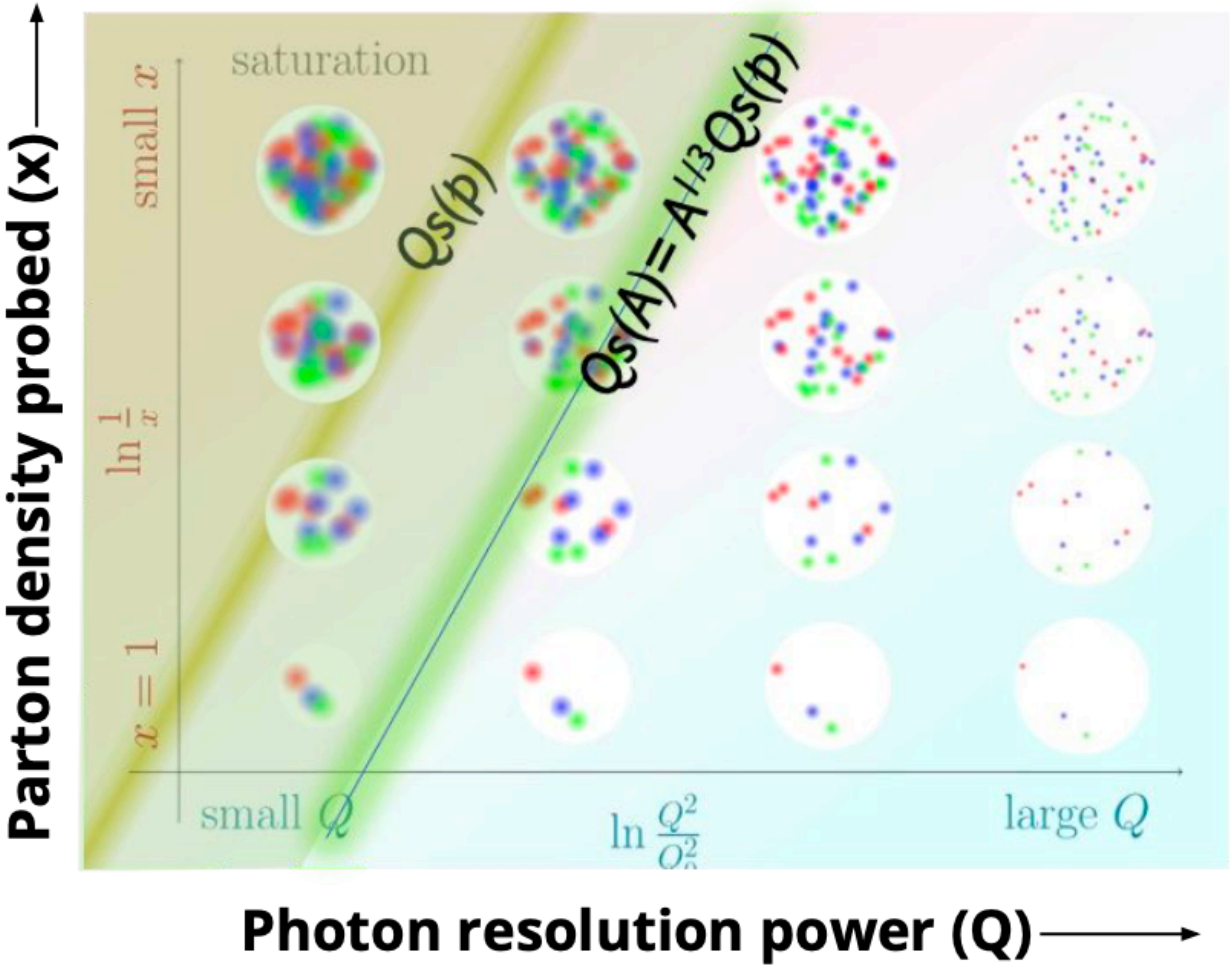
$$x = \left(\frac{M_{J/\psi}}{\sqrt{s_{\mathrm{NN}}}}\right) e^{\mp y}$$



How are HI UPCs collisions useful?

- In UPCs ($b > R_1 + R_2$), EM interactions dominate.
- Lorentz contracted EM fields produce fluxes of quasi-real photons.
- Photon fluxes enhanced $\propto Z^2$.
- Saturation region is expected to be easier to be accessed $Q_S \propto A^{1/3}$

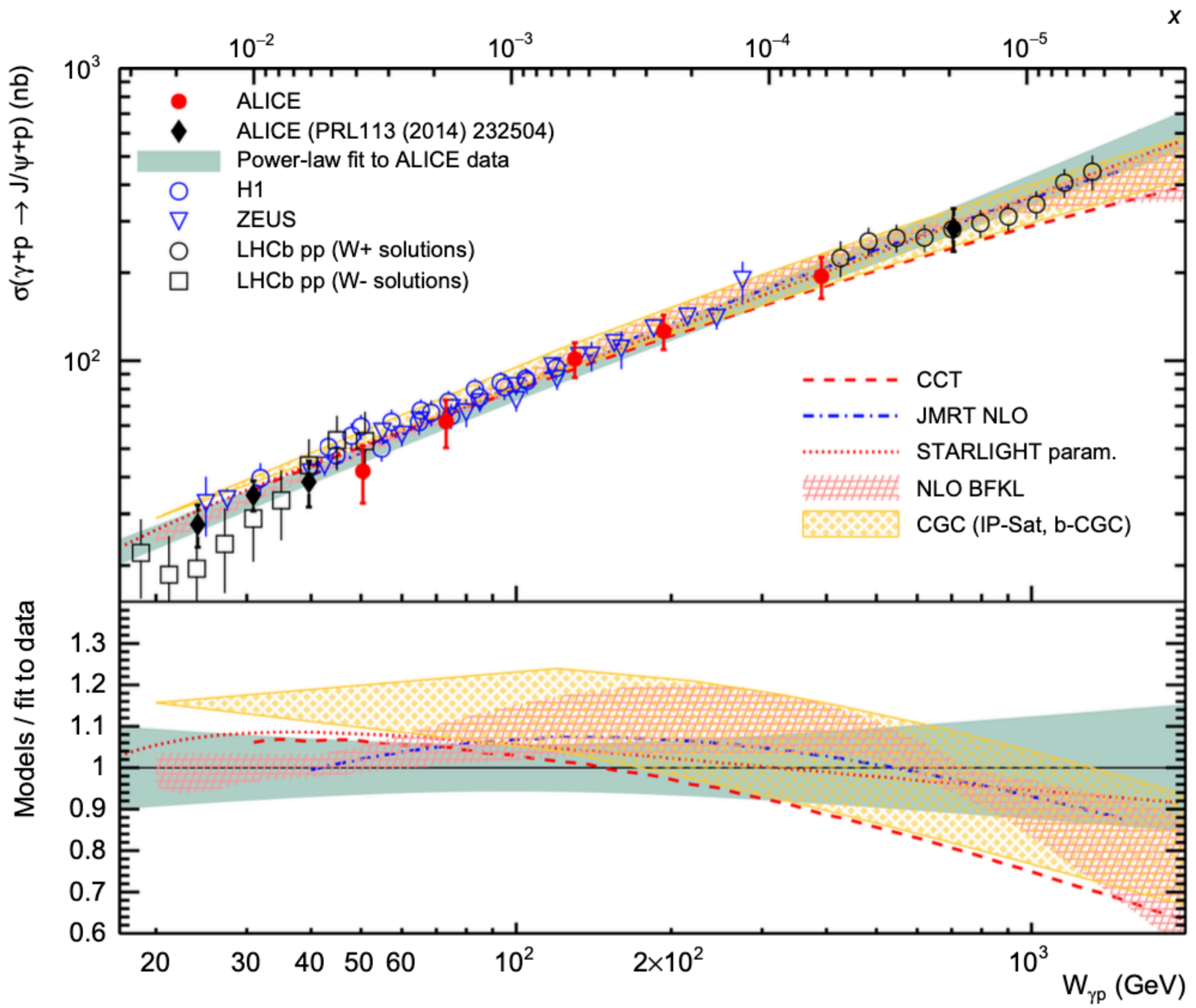




Photoproduction of J/ψ with protons

$$\gamma + p \rightarrow J/\psi + p$$

- Gluons inside a proton:
  - Investigated with ep, pPb and pp collisions by HERA and LHC
  - Consistent results between HERA and LHC data.
  - Data follow a power-law trend, consistent with the rapidly increasing gluon density.
  - No evidence for saturation !

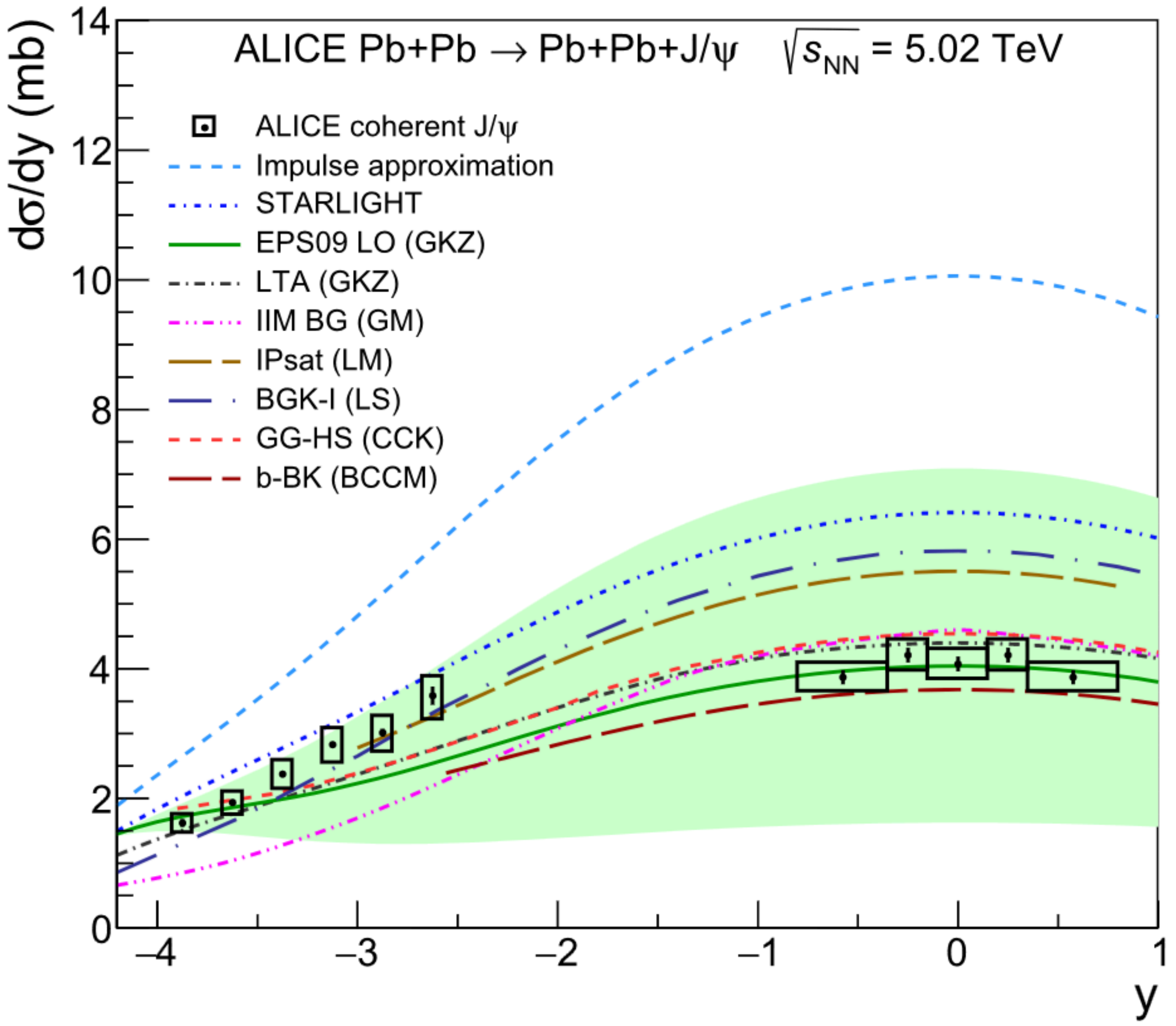


EPJC 79 (2019) 402

Photoproduction of J/ψ with heavy nuclei

$$\gamma + Pb \rightarrow J/\psi + Pb$$

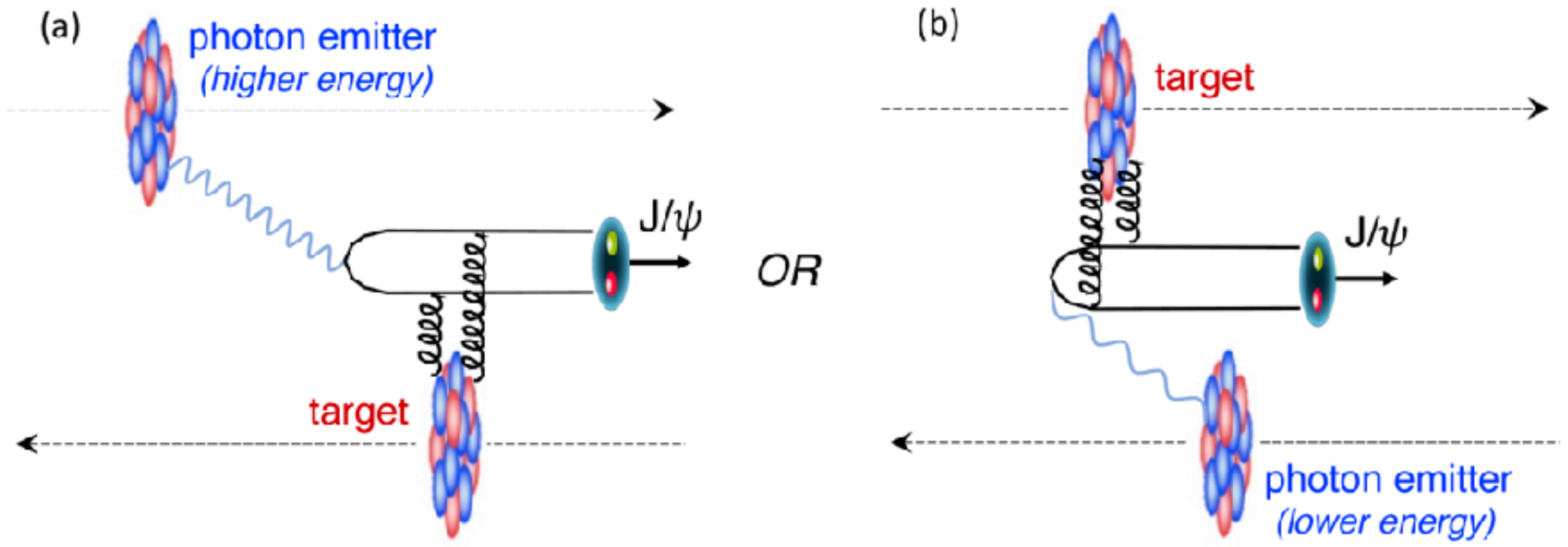
- Gluons inside Pb:
  - $\sigma(J/\psi)$ < I.A → strong nuclear modification in nuclei.
  - Data challenge all existing models.



EPJC 81 (2021) 712

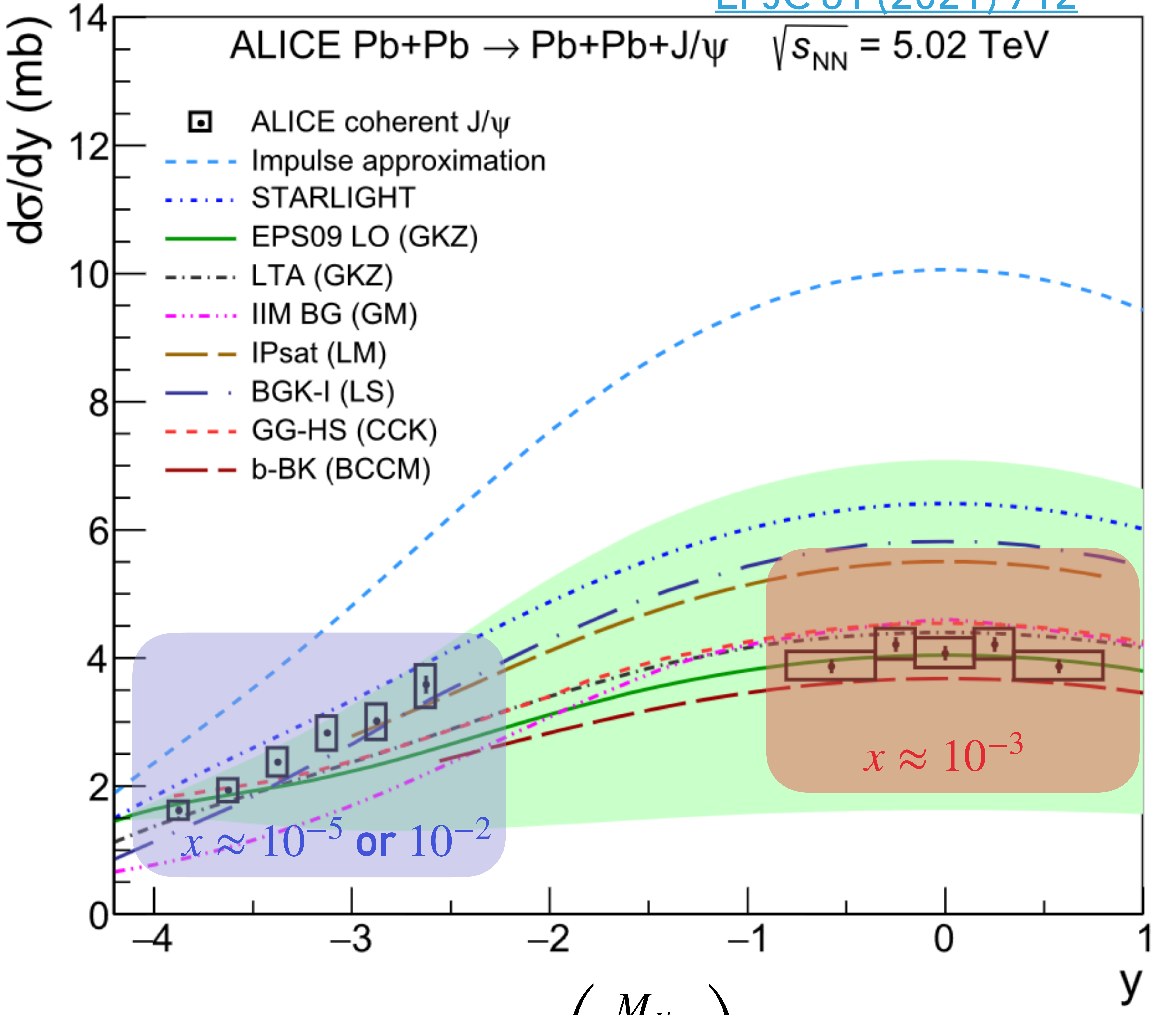
Photoproduction of J/ψ with heavy nuclei

- **Ambiguity in symmetric collisions:** either ion can serve as the emitter or target.
- Each data point has contributions from low and high energy photons.



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

EPJC 81 (2021) 712



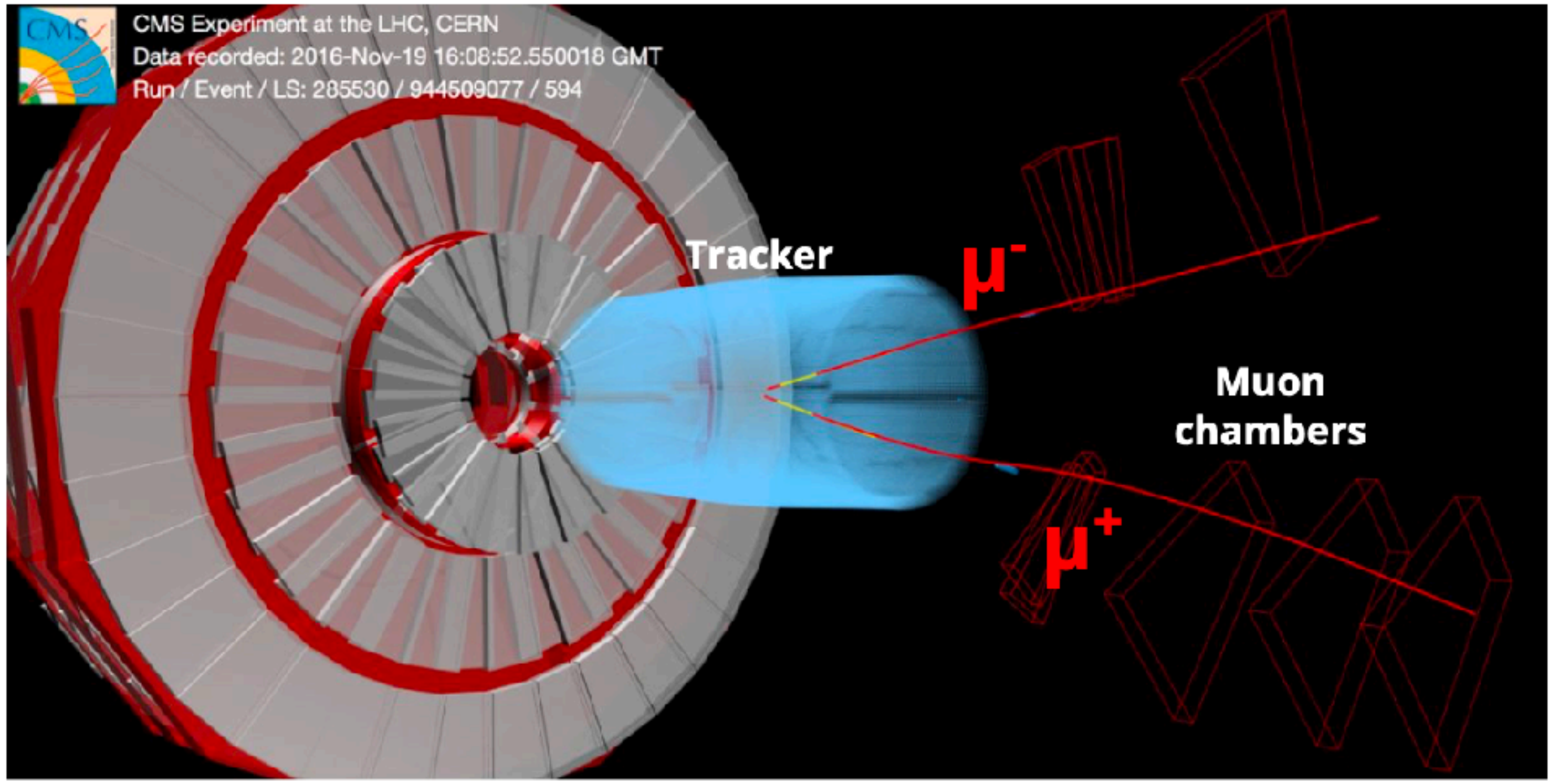
$$x = \left(\frac{M_{J/\psi}}{\sqrt{s_{NN}}}\right)e^{\mp y}$$

Coherent J/ψ photoproduction in UPC PbPb at 5.02 TeV

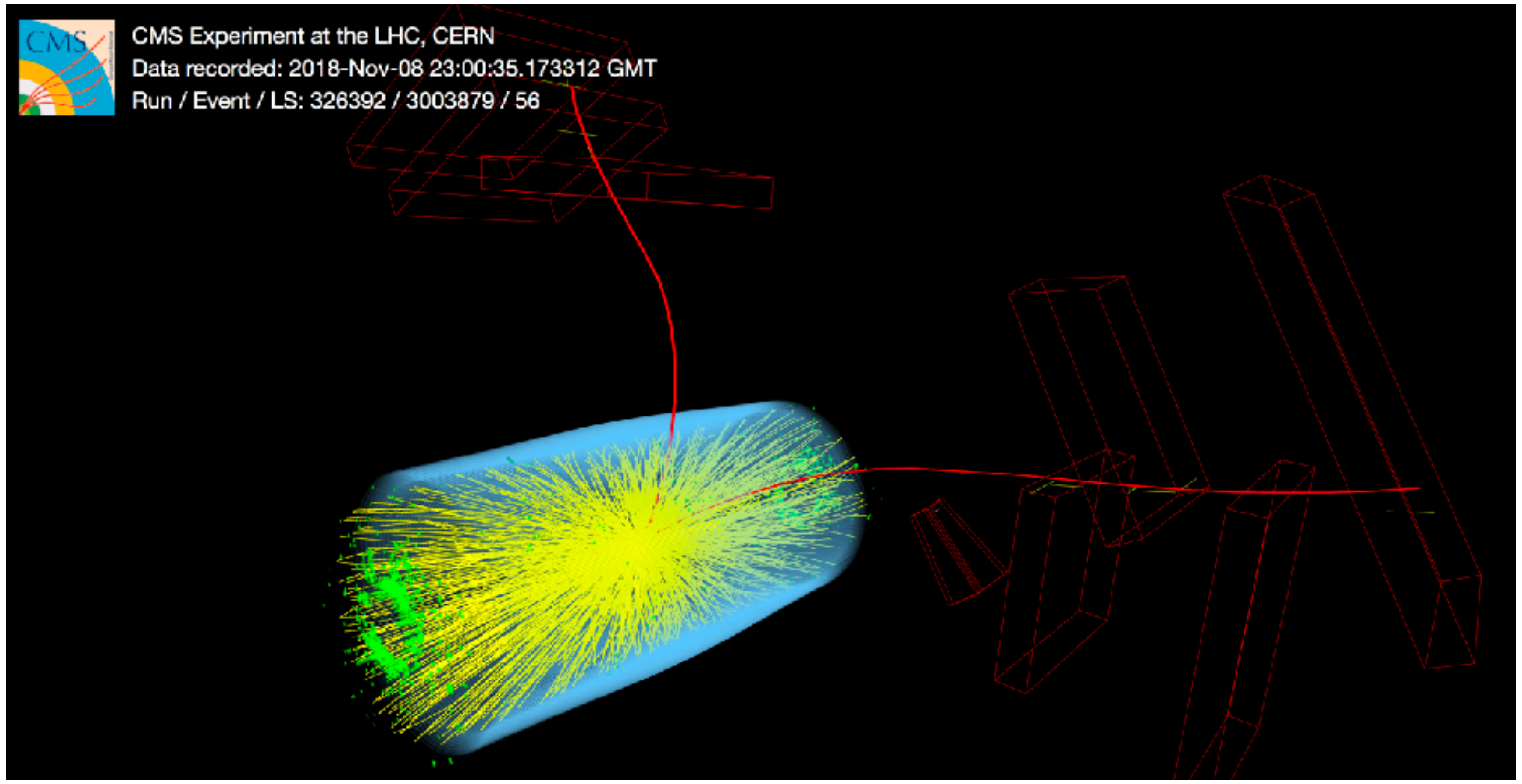
arXiv:2303.16984

- Data from 2018 PbPb UPC, $L_{int} \sim 1.52\ \mathrm{nb}^{-1}$
- Event selection:
  - Exactly two muons and nothing more!
  - Low energy depositions in hadronic calorimeter to suppress strong interactions.
  - Very clean events !

UPC

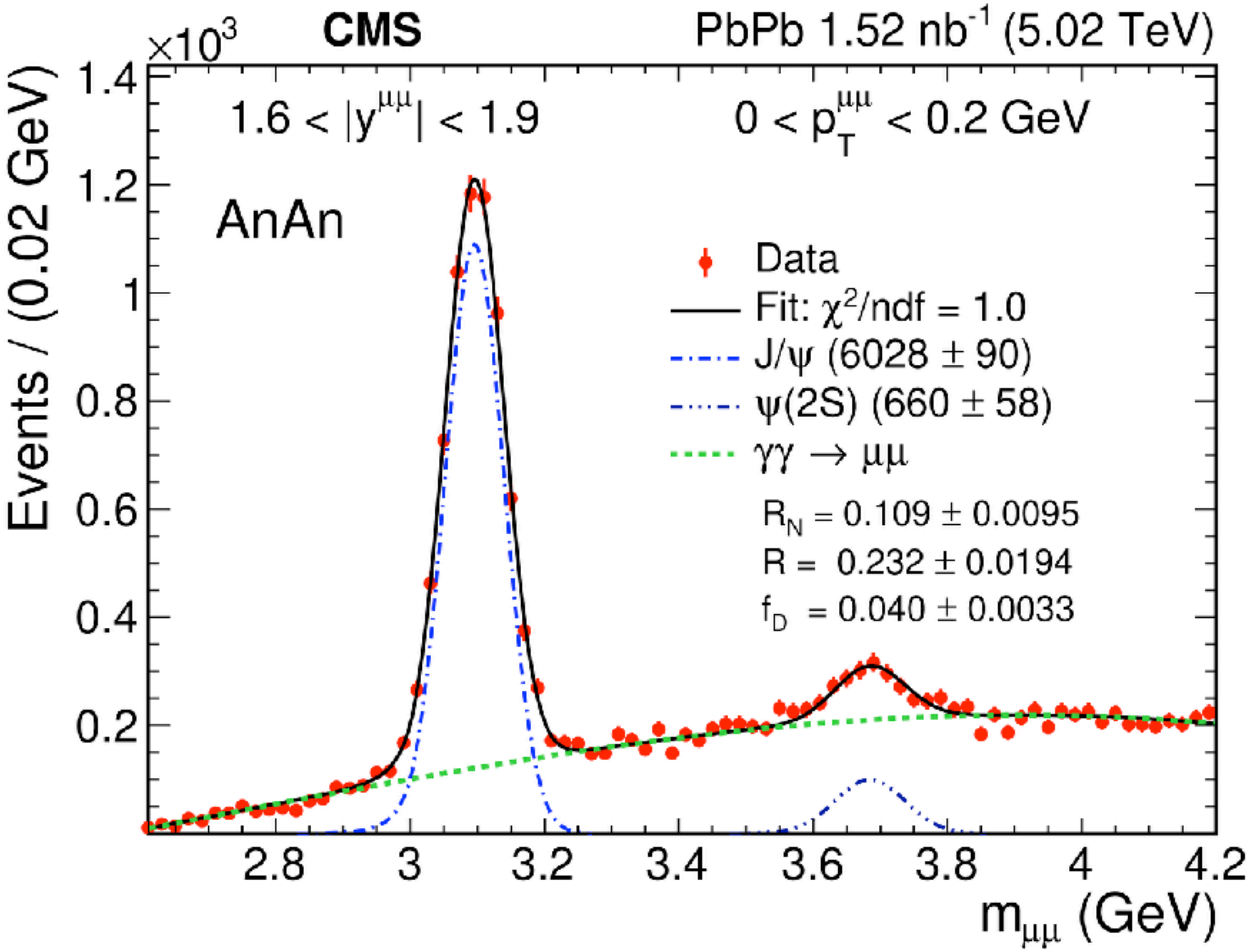


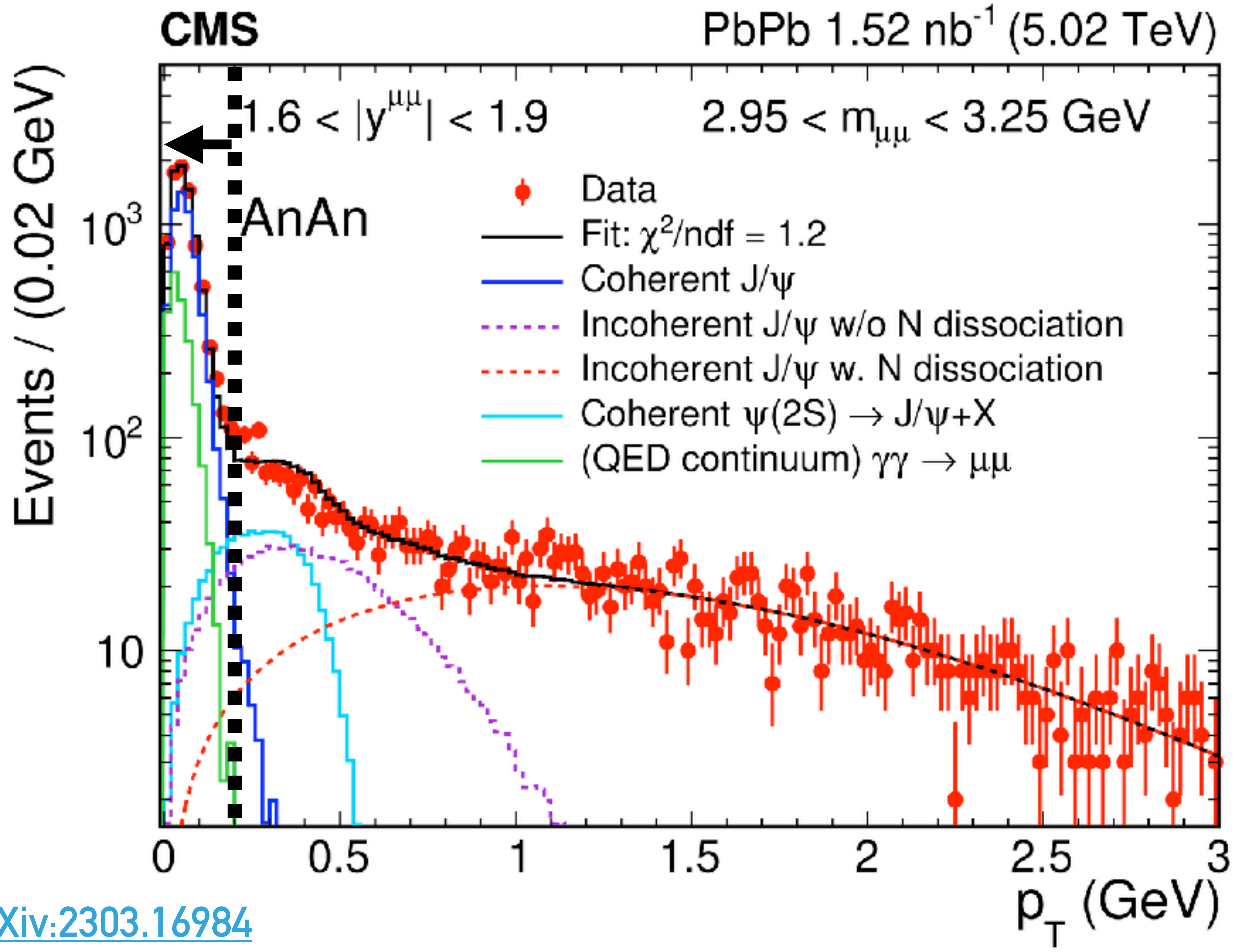
Central



Signal extraction

- Invariant mass fits filter J/ψ yields (coherent+incoherent) from QED background.
- Multi-template fits on J/ψ transverse momentum allows to separate coherent and incoherent contributions.



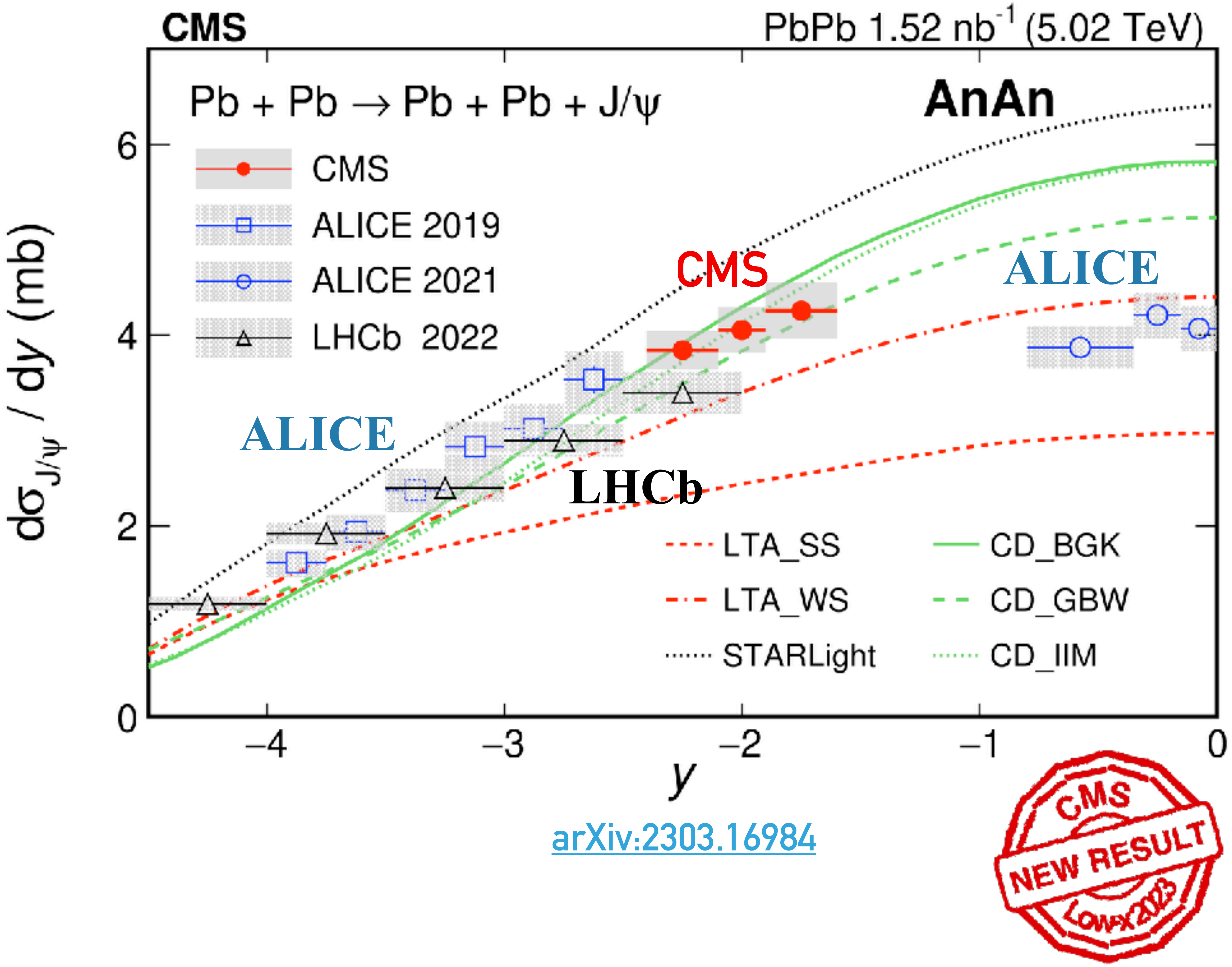


arXiv:2303.16984

Total Coh. J/ψ cross section

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

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



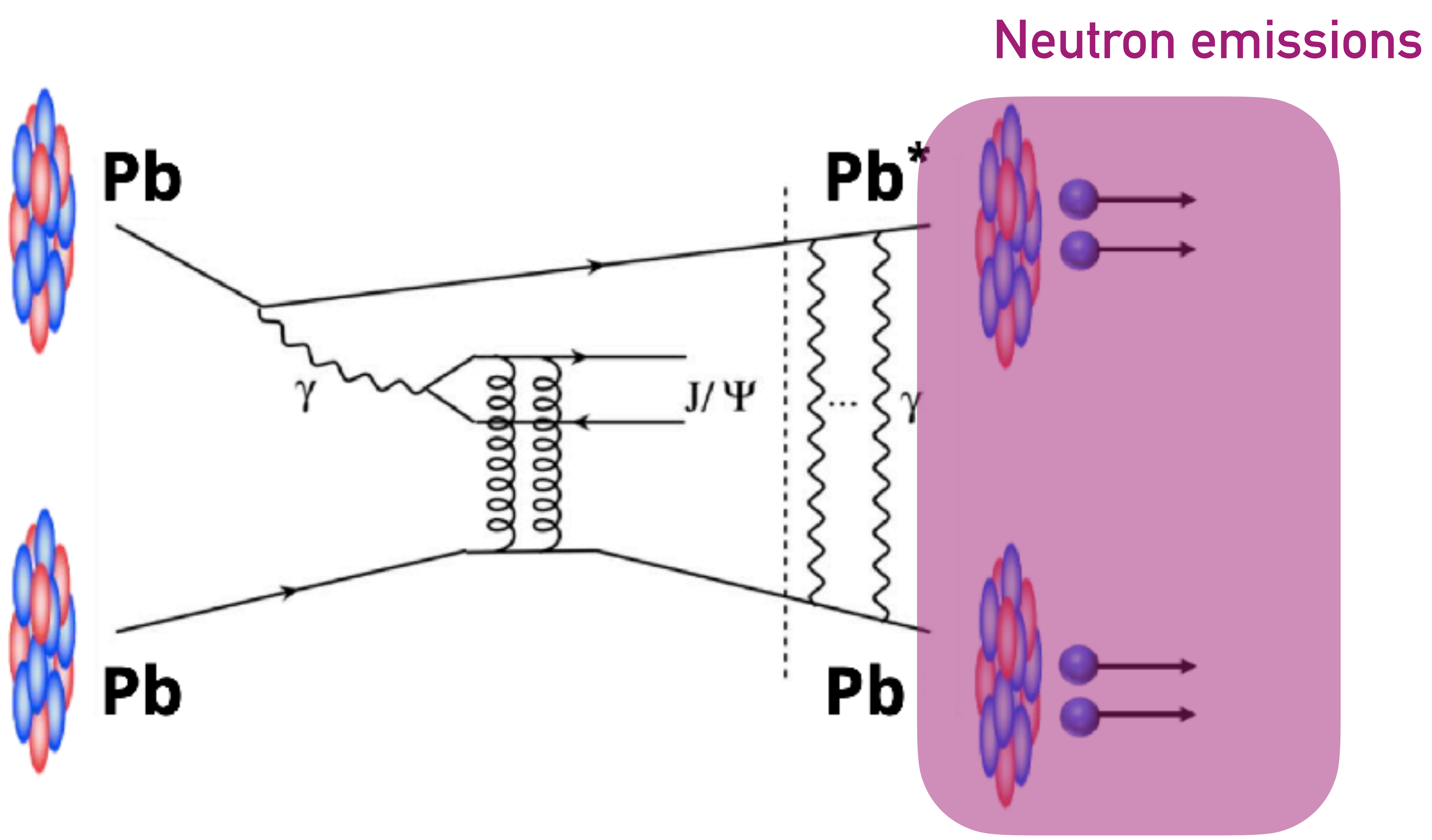
arXiv:2303.16984

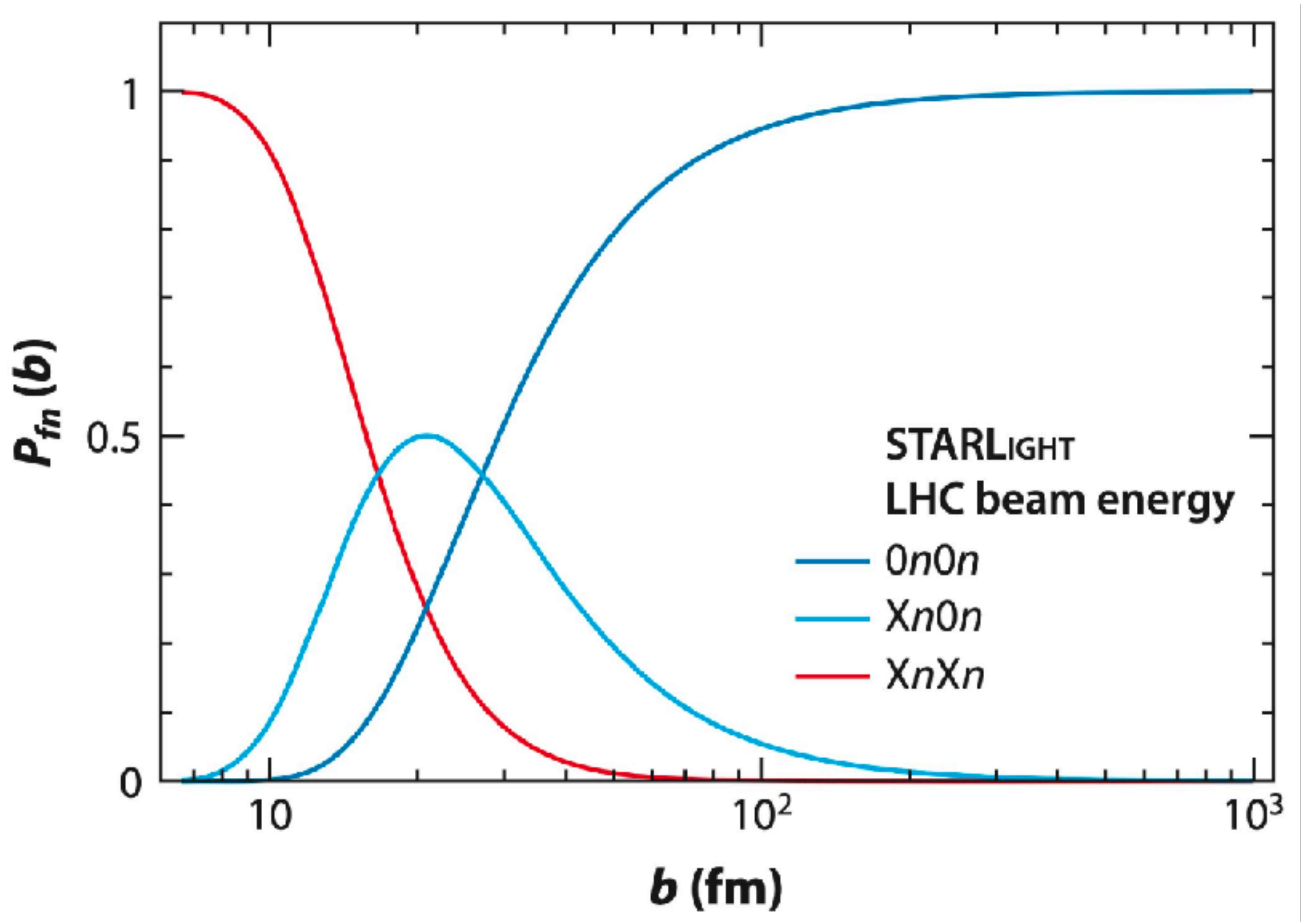
- LHC experiments complement each others over a wide range of rapidity.
- **CMS data covers a unique rapidity region, not previously accessed.**
- CMS data follow ALICE forward rapidity trend.
- Two-way ambiguity unsolved so far… wait for next slides!

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

A solution to the two-way ambiguity puzzle

Control impact parameter of UPCs via forward neutron emissions [Ann. Rev. Nucl. Part. Sci. 70 (2020) 323]

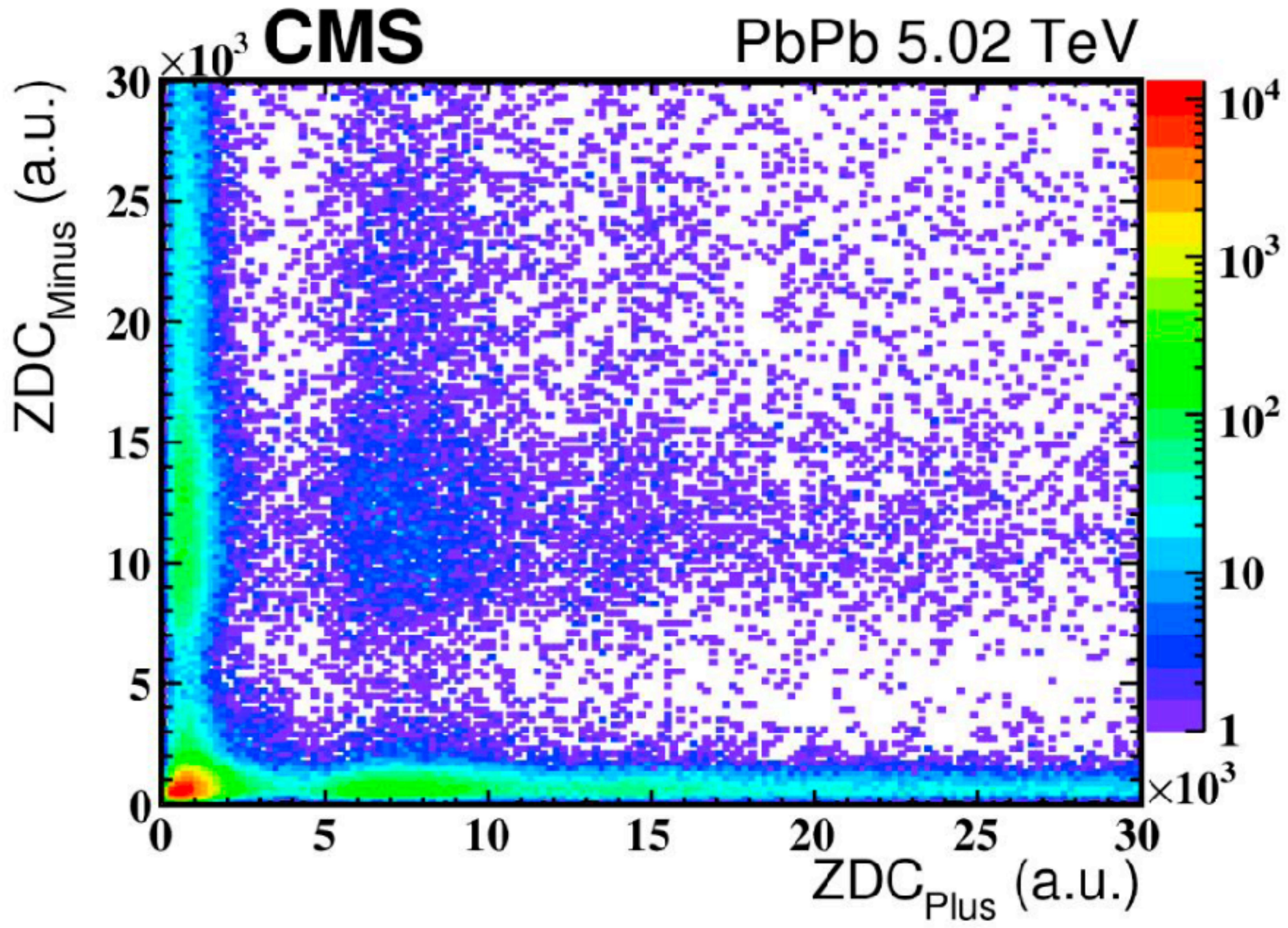


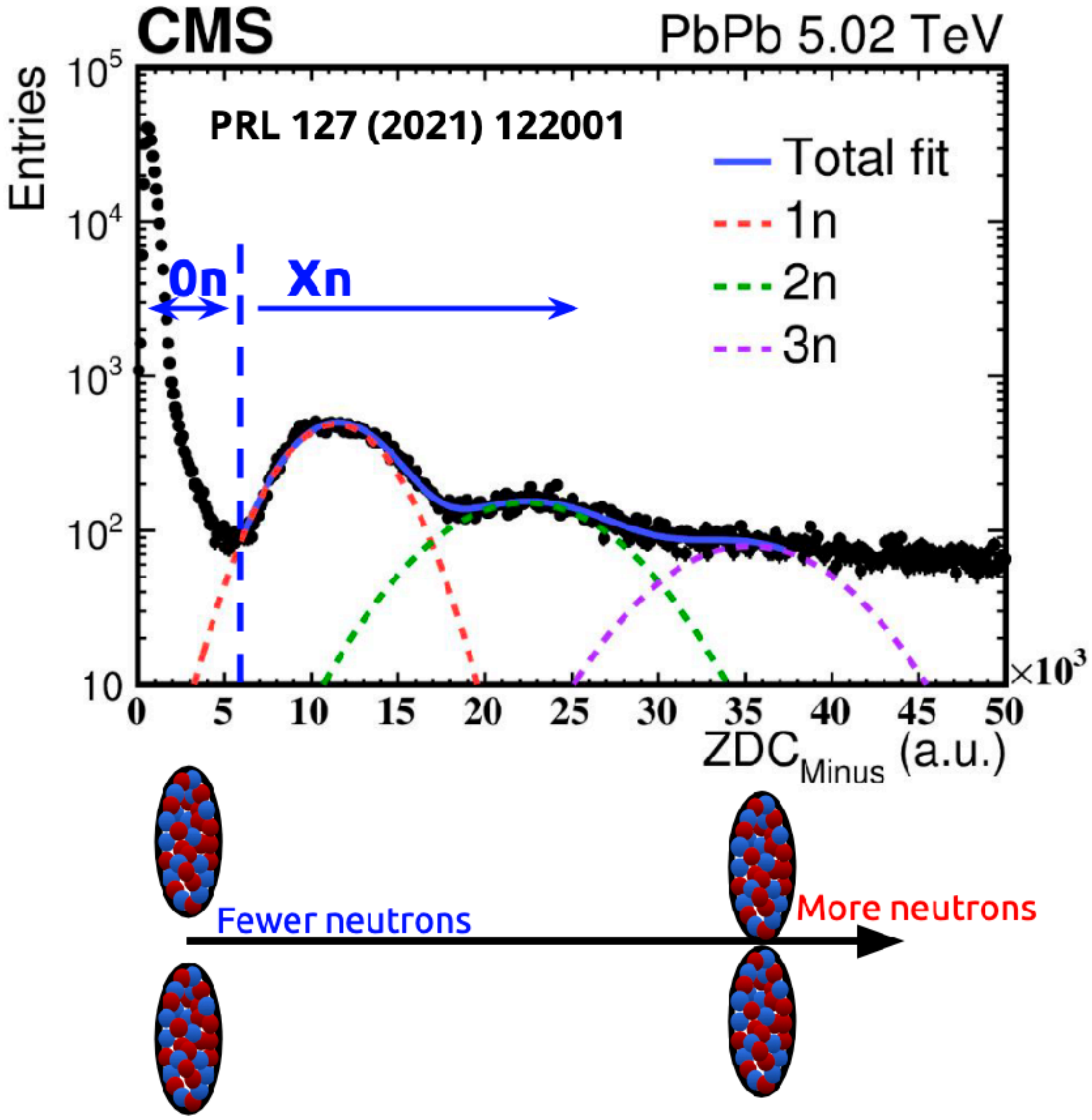


- Additional photon exchanges lead to neutron emissions via EMD.
- Analogous to centrality:
  - $b_{XnXn} < b_{0nXn} < b_{0n0n}$

Event classification via neutron multiplicity

- Energy depositions in ZDCs allow to classify events in neutron categories.





- XnXn → smaller b
- 0n0n → larger b

A solution to the two-way ambiguity puzzle

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

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

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

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

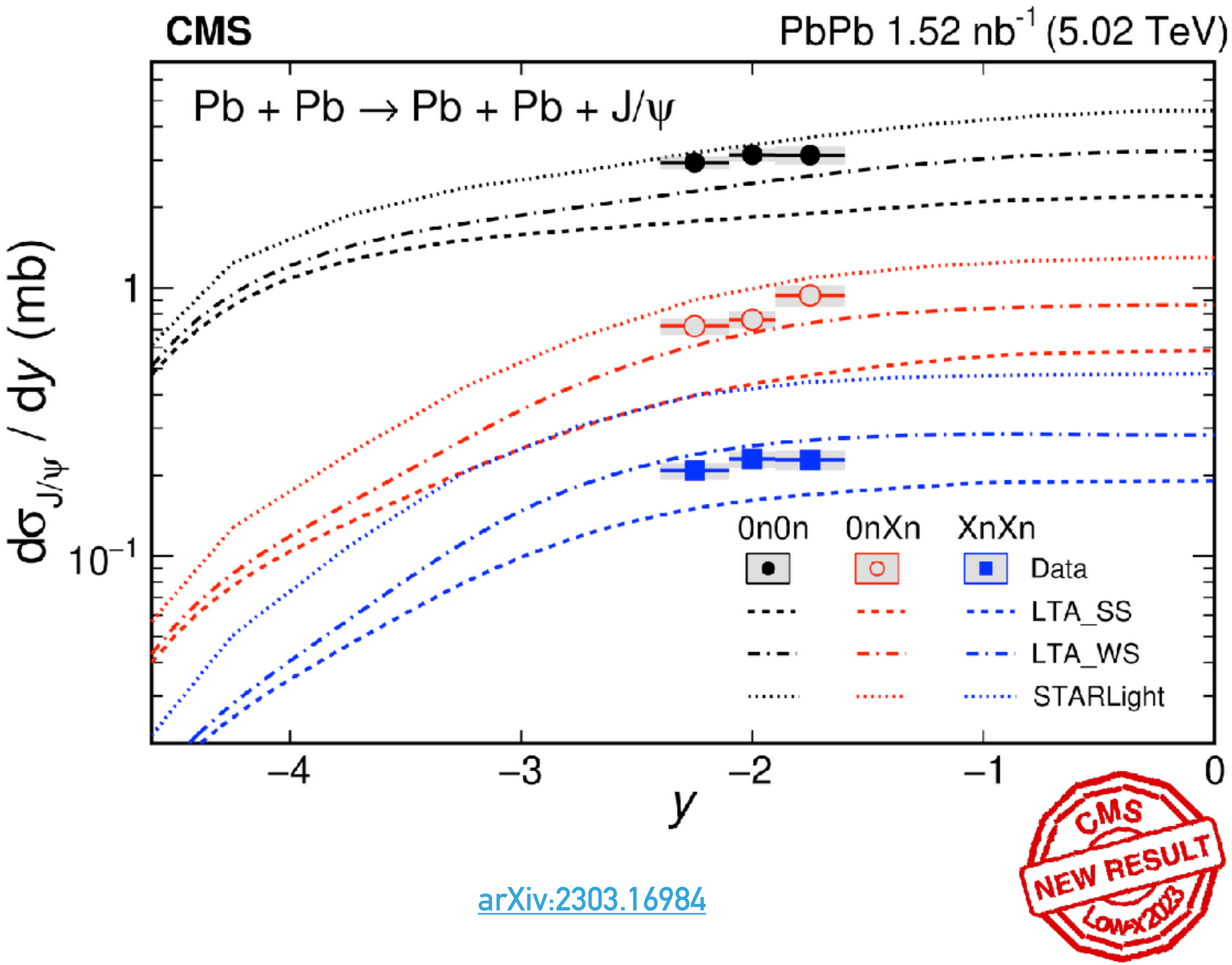
Dominant b ranges of different neutron classes:

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

→ Solve for $\sigma_{\gamma A\to J/\psi A'}(y)$ and $\sigma_{\gamma A\to J/\psi A'}(-y)$, and $x = \left(\frac{M_{VM}}{\sqrt{s_{NN}}}\right)e^{\mp y}$

Entering a new regime of small x ~ $10^{-4} - 10^{-5}$ in nuclei!

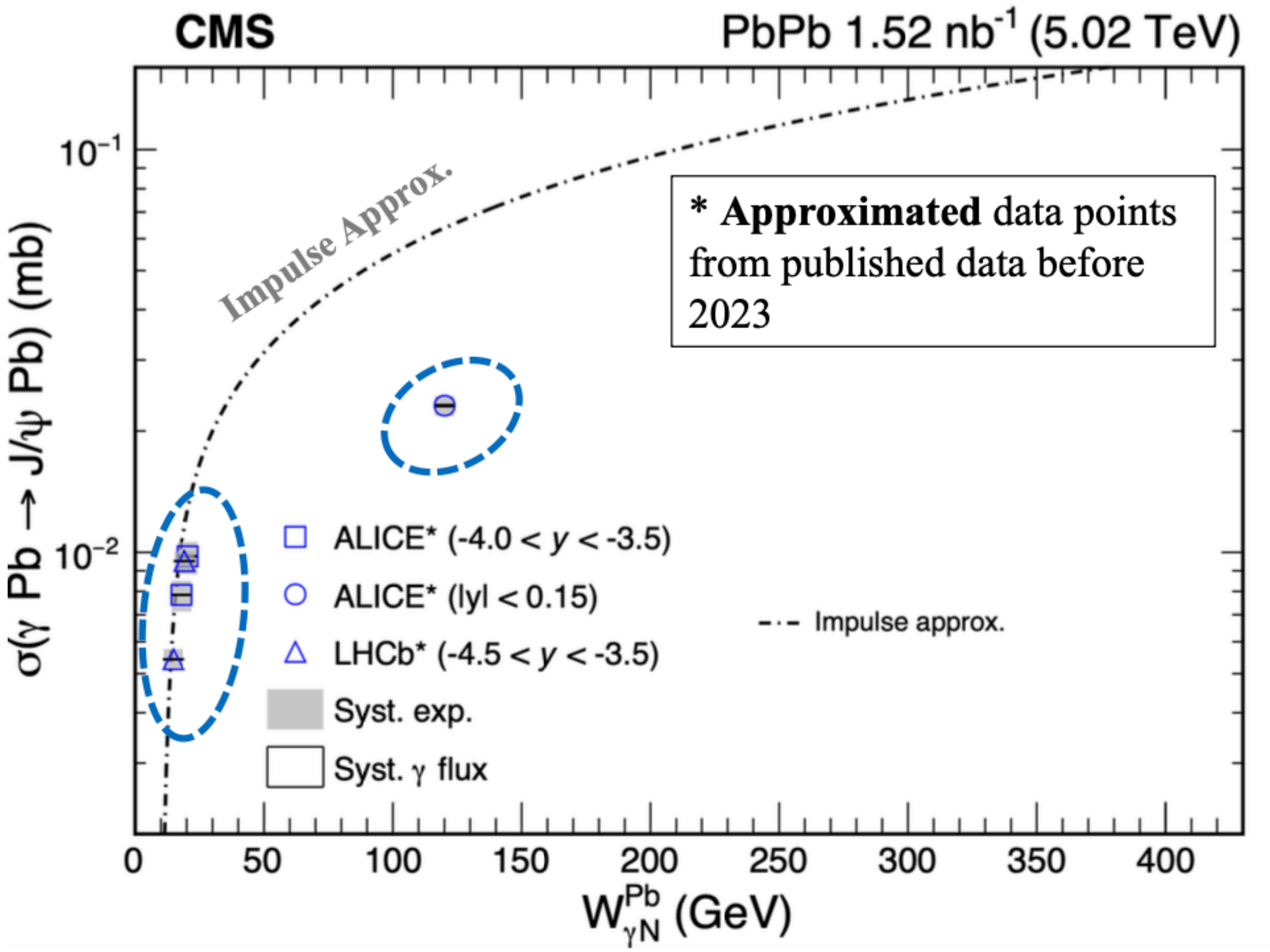
Total Coh. J/ψ cross section in neutron categories



arXiv:2303.16984

- ZDC allows to classify events in neutron categories.
- **First separation in different neutron categories.**

Coh. J/ψ photo nuclear cross section vs W



arXiv:2303.16984

- ALICE, LHCb vs I.A:
  - Impulse approx. (IA) neglects all nuclear effects.
  - Data close to IA at low W.
  - Data significantly lower than IA at W ~ 125 GeV.

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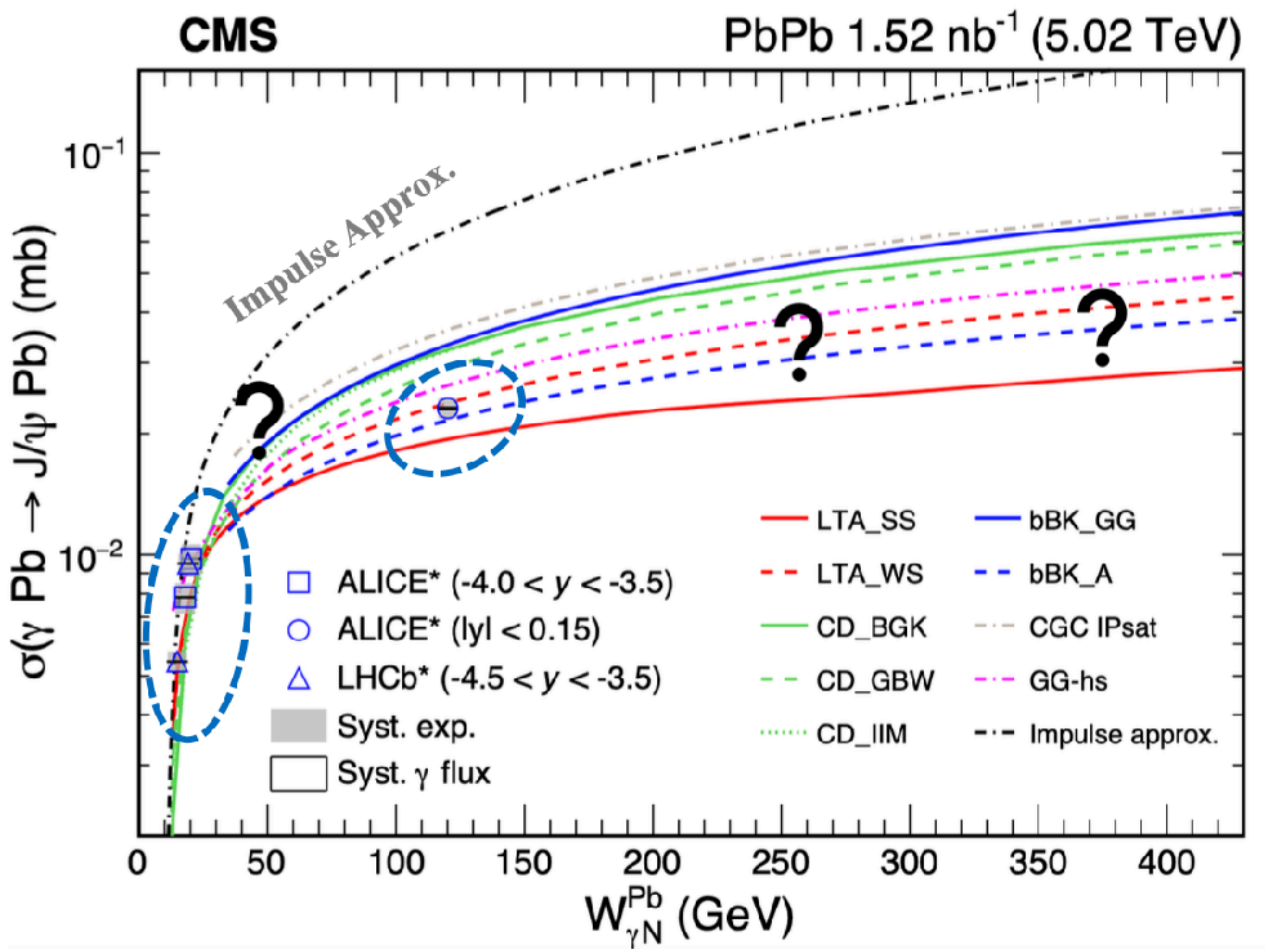

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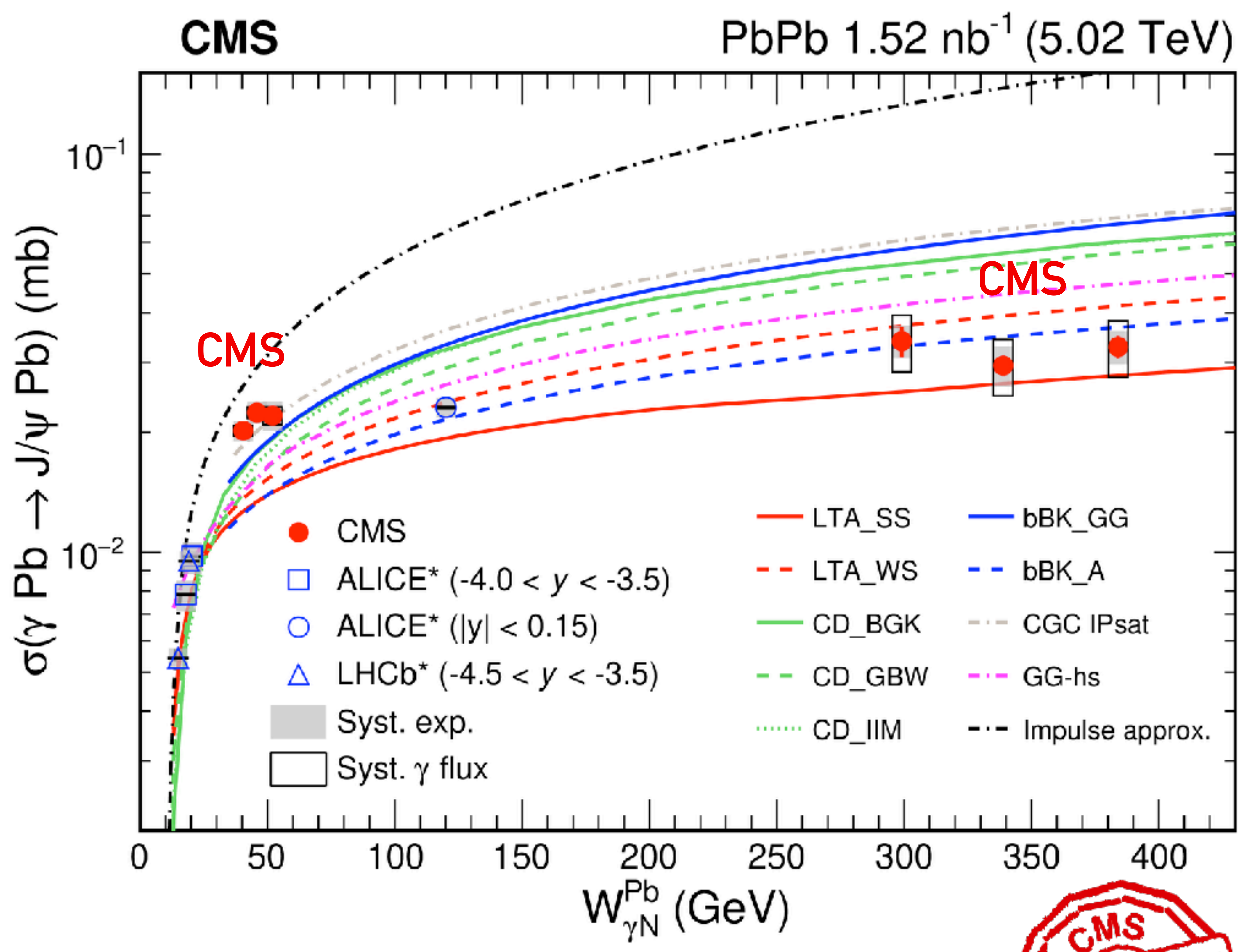
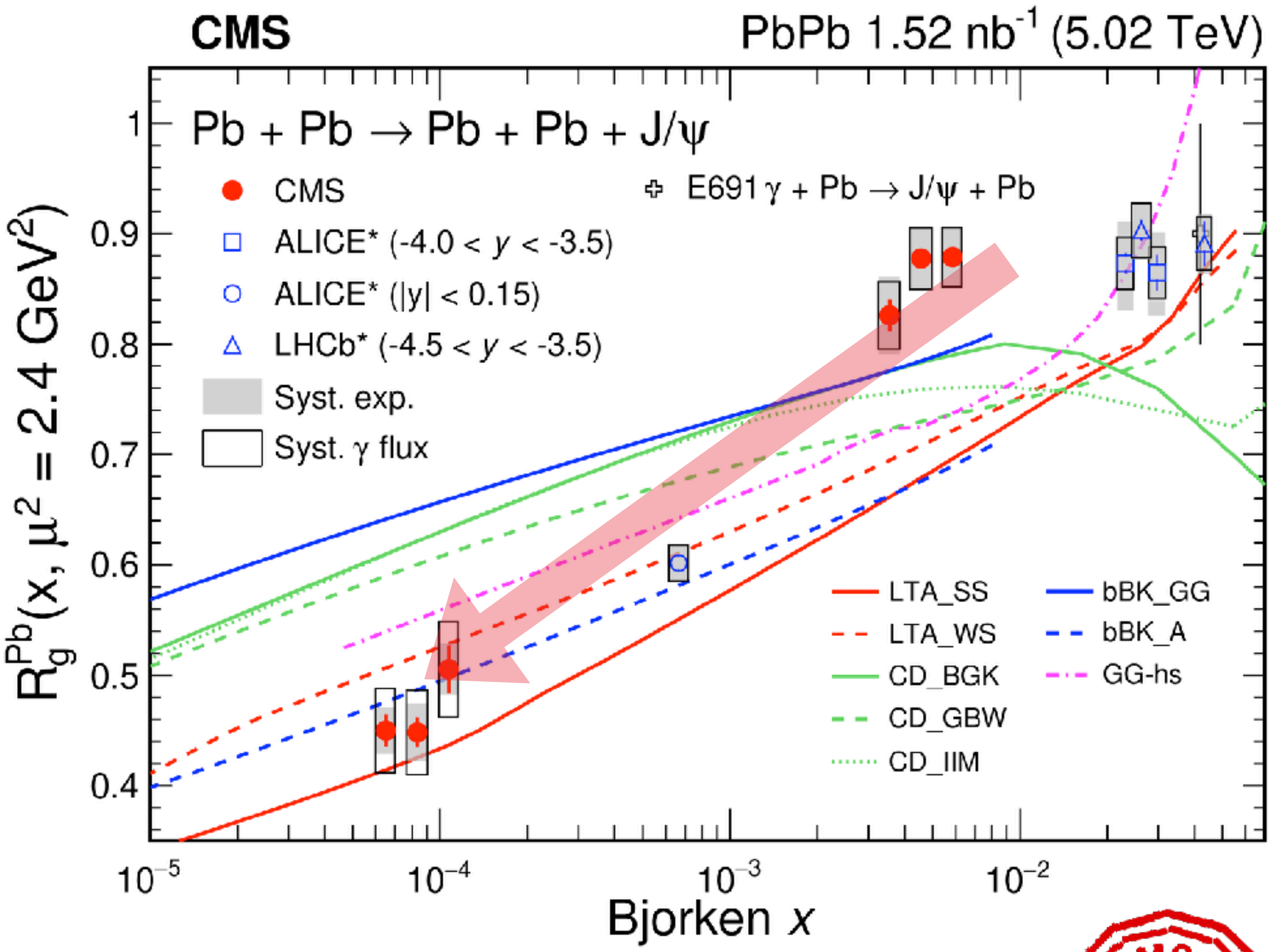


[arXiv:2303.16984](https://arxiv.org/abs/2303.16984)

CMS NEW RESULT LowX2023

- ALICE, LHCb vs I.A:
  - Impulse approx. (IA) neglects all nuclear effects.
  - Data close to IA at low W.
  - Data significantly lower than IA at W ~ 125 GeV.
  - Shadowing/saturation models predict larger suppression at higher W.
- **First measurement by CMS:**
  - W< 40 GeV: rapidly increasing
  - 40<W<400 GeV: slowly raising -- underlying physics changed!
  - No models can describe the entire data distribution!

Nuclear suppression factor

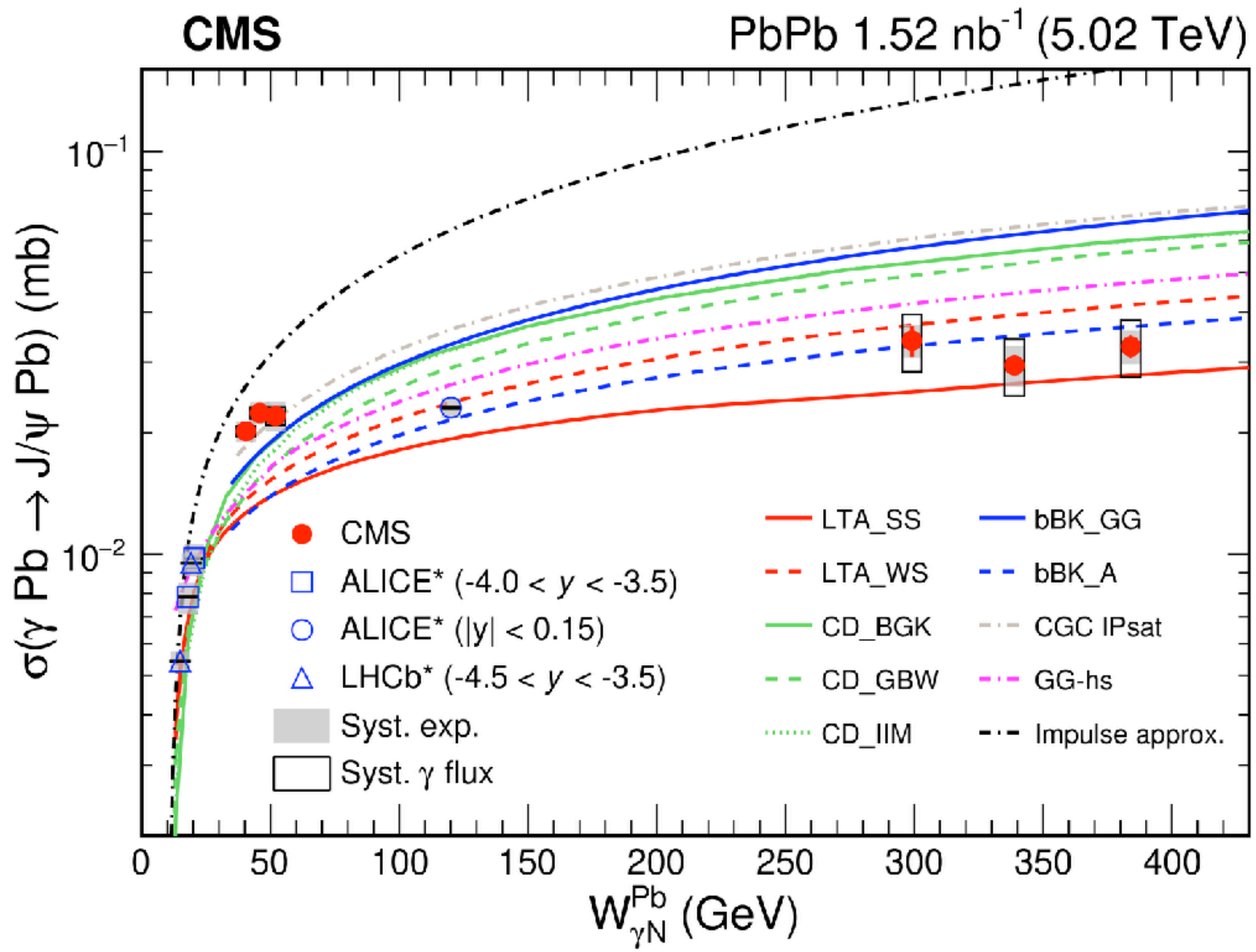


arXiv:2303.16984

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

- Represents nuclear gluon suppression factor at LO.
- x ~ 10^{-2} - 10^{-3} : flat trend
- Quickly decrease towards lower x region.

What physics could be behind?



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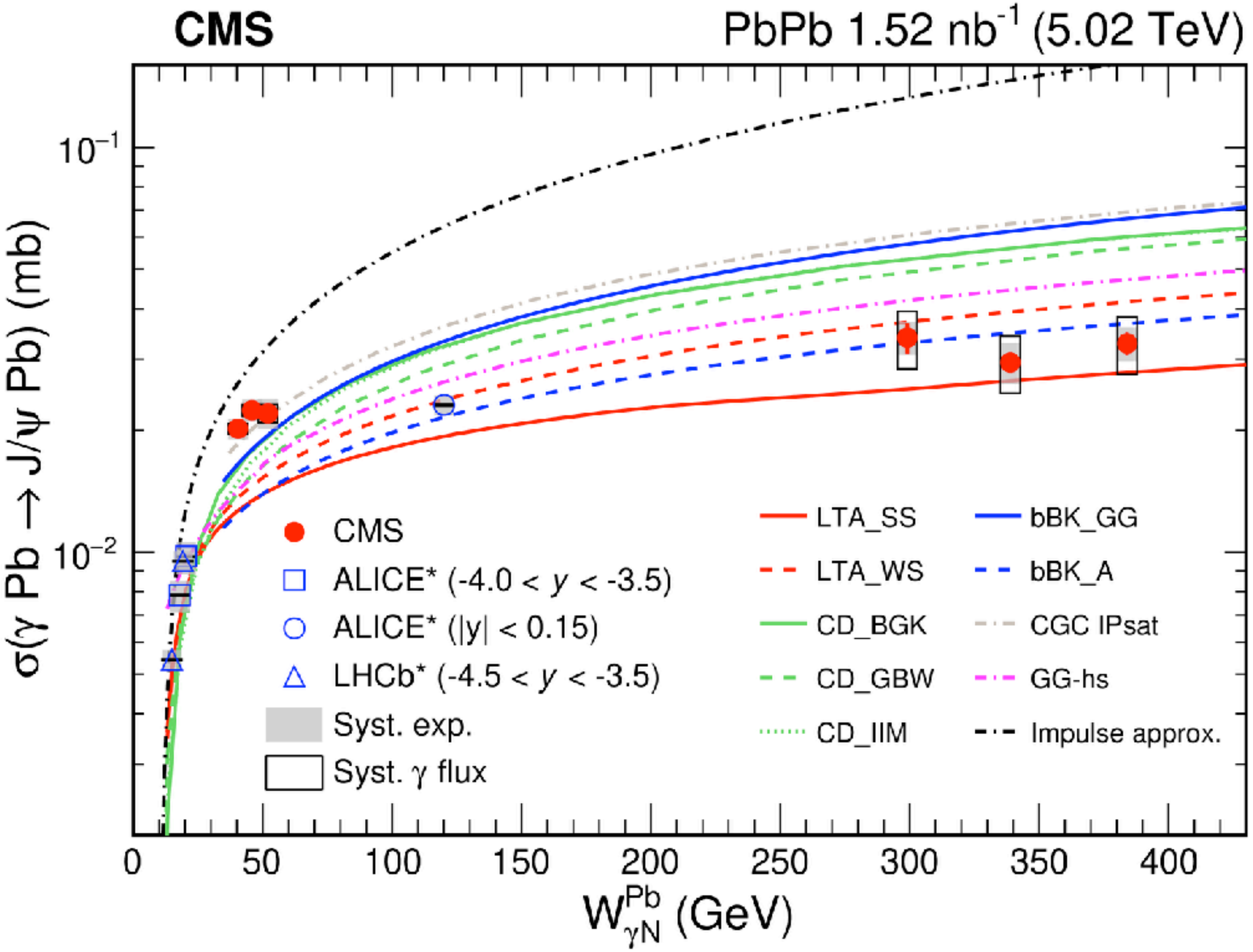
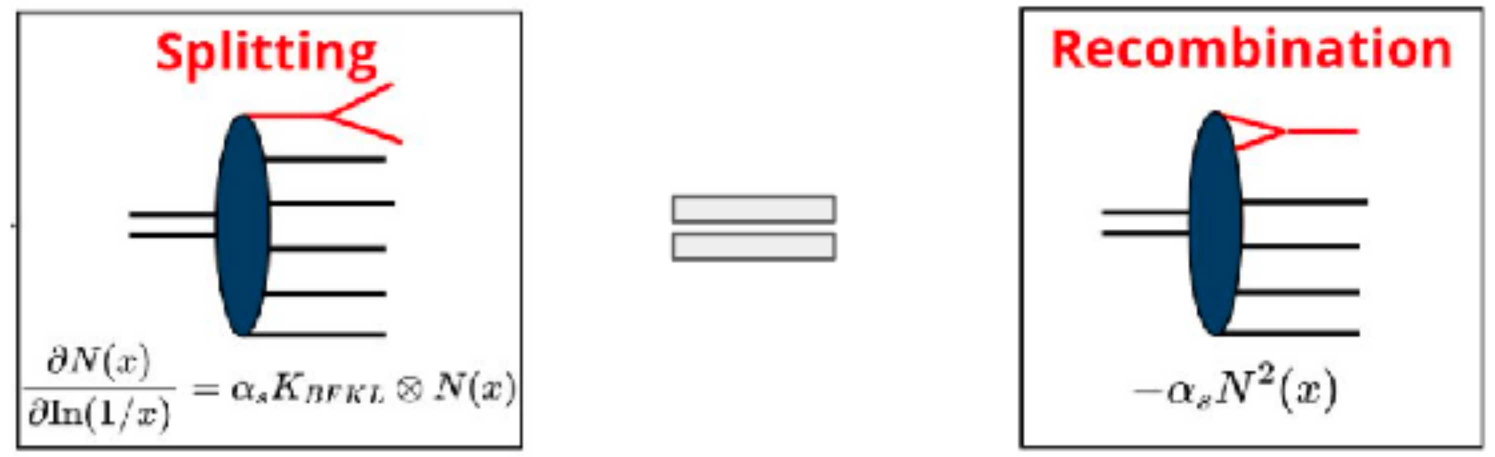


arXiv:2303.16984

- $\sigma(\gamma Pb \to J/\psi Pb)$ rapidly increases → splitting and recombination of gluons become equal.
  - Evidence for gluon saturation ?



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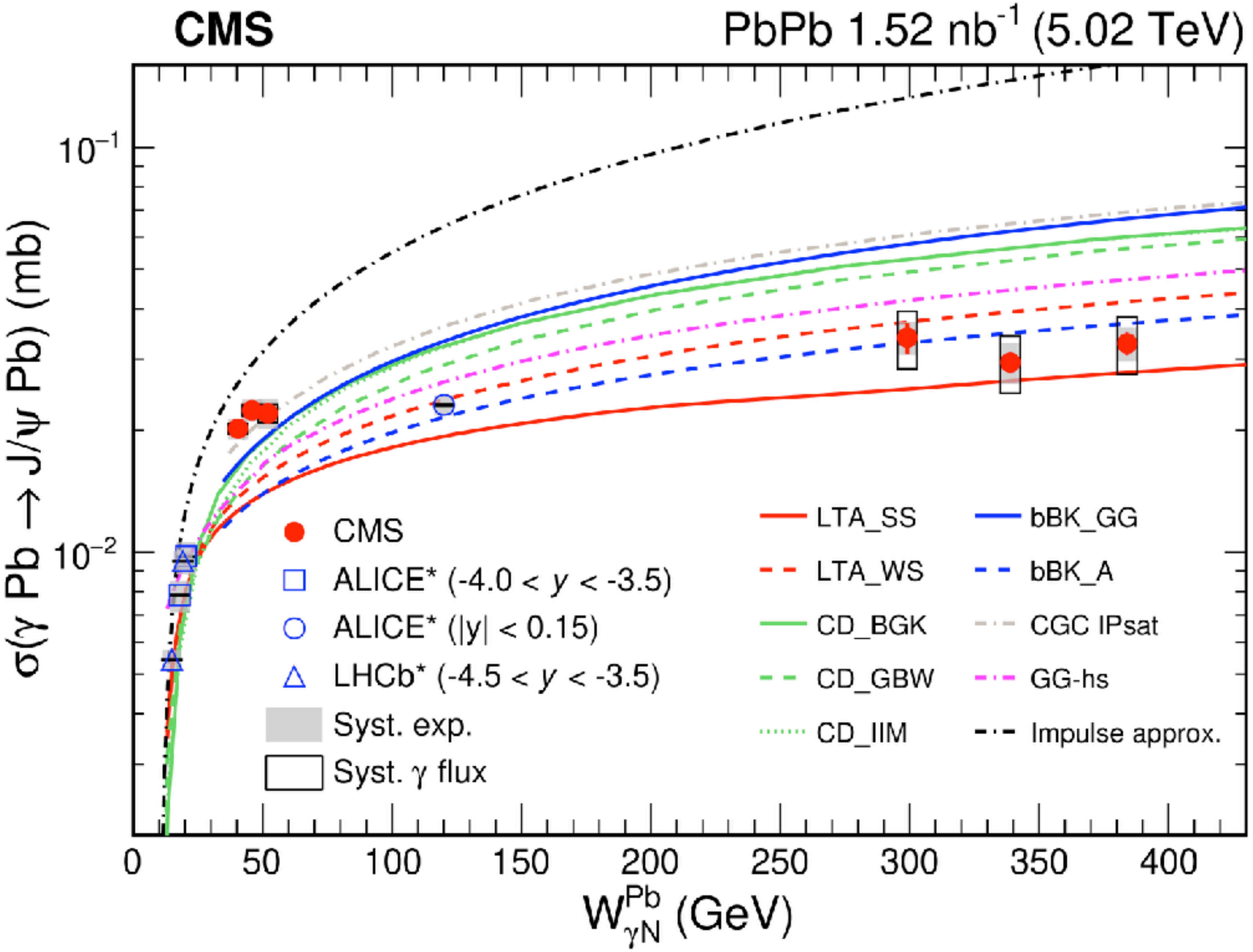

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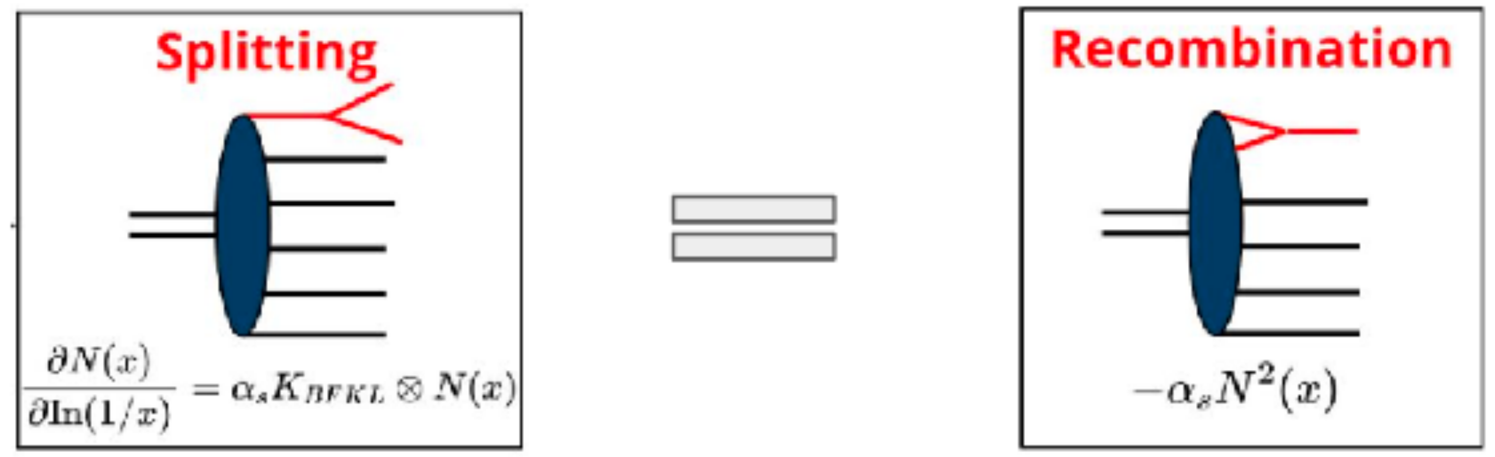
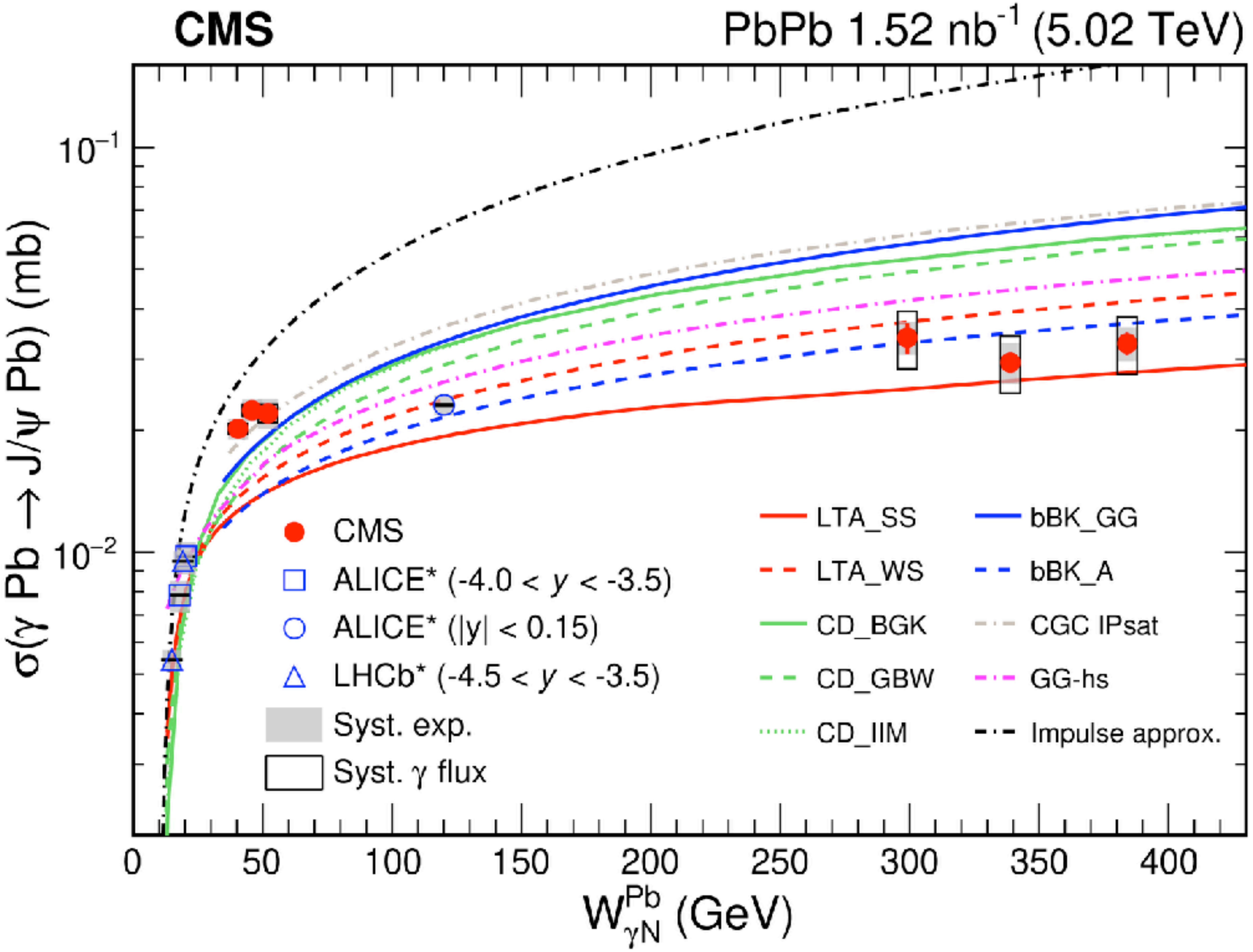


Other scenario (not mutually exclusive)

What physics could be behind?



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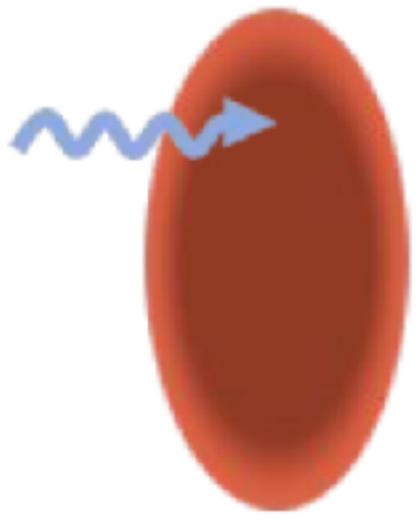
- $\sigma(\gamma Pb \to J/\psi Pb)$ rapidly increases → splitting and recombination of gluons become equal.
  - Evidence for gluon saturation ?

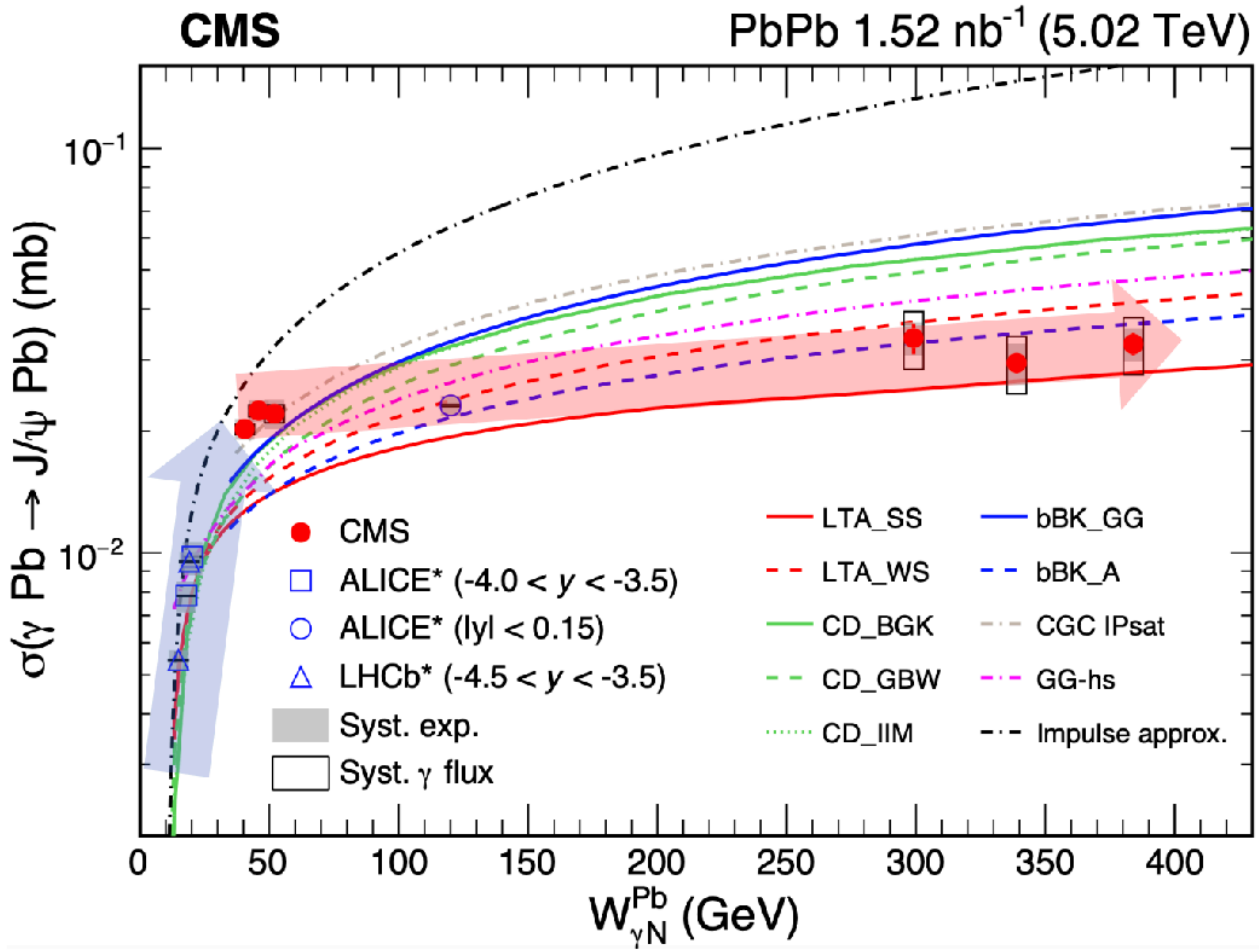
Other scenario (not mutually exclusive)

- Nuclear target becomes totally absorptive to incoming photons:
  - Black Disk Limit interpretation?



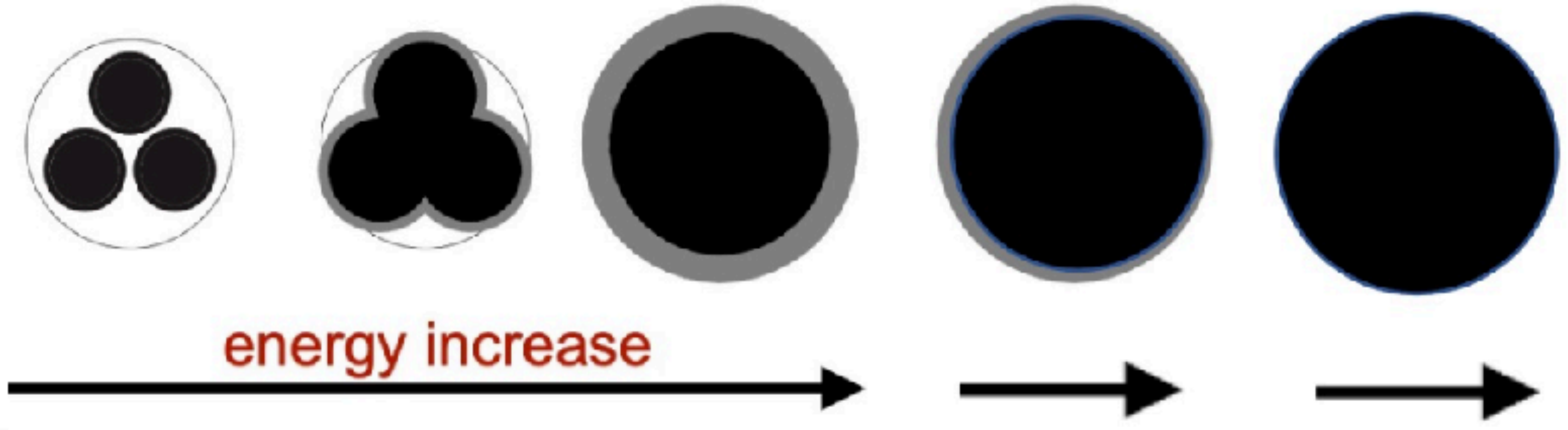
$$\hat{\sigma}^{\text{inel}}_{\text{PQCD}} \leq \hat{\sigma}_{\text{black}} = \pi R^2_{\text{target}}$$

What physics could be behind?



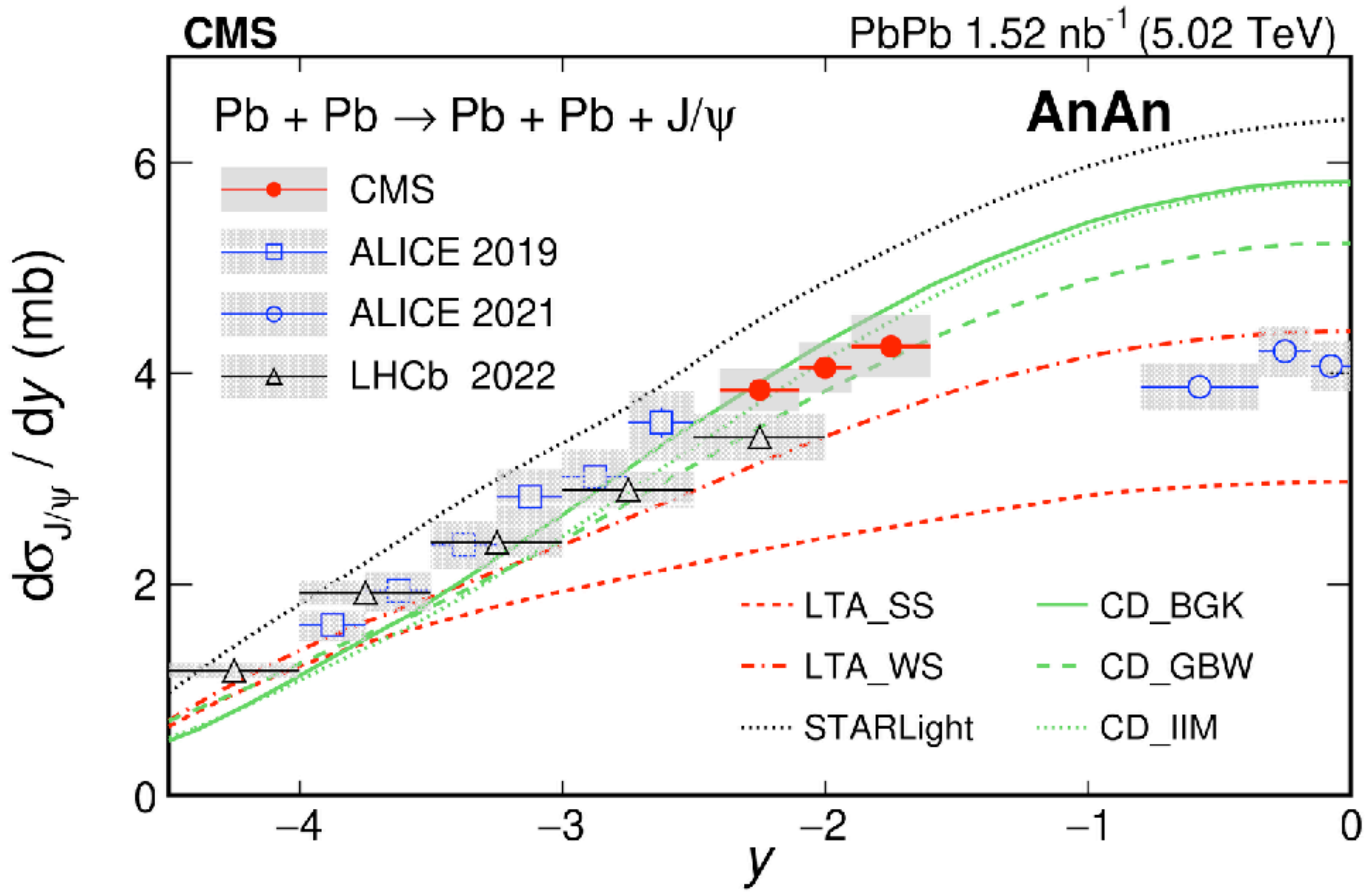
- Rapid grows reflect increased in gluon density
  - Amplitude of interaction is proportional to gluon density

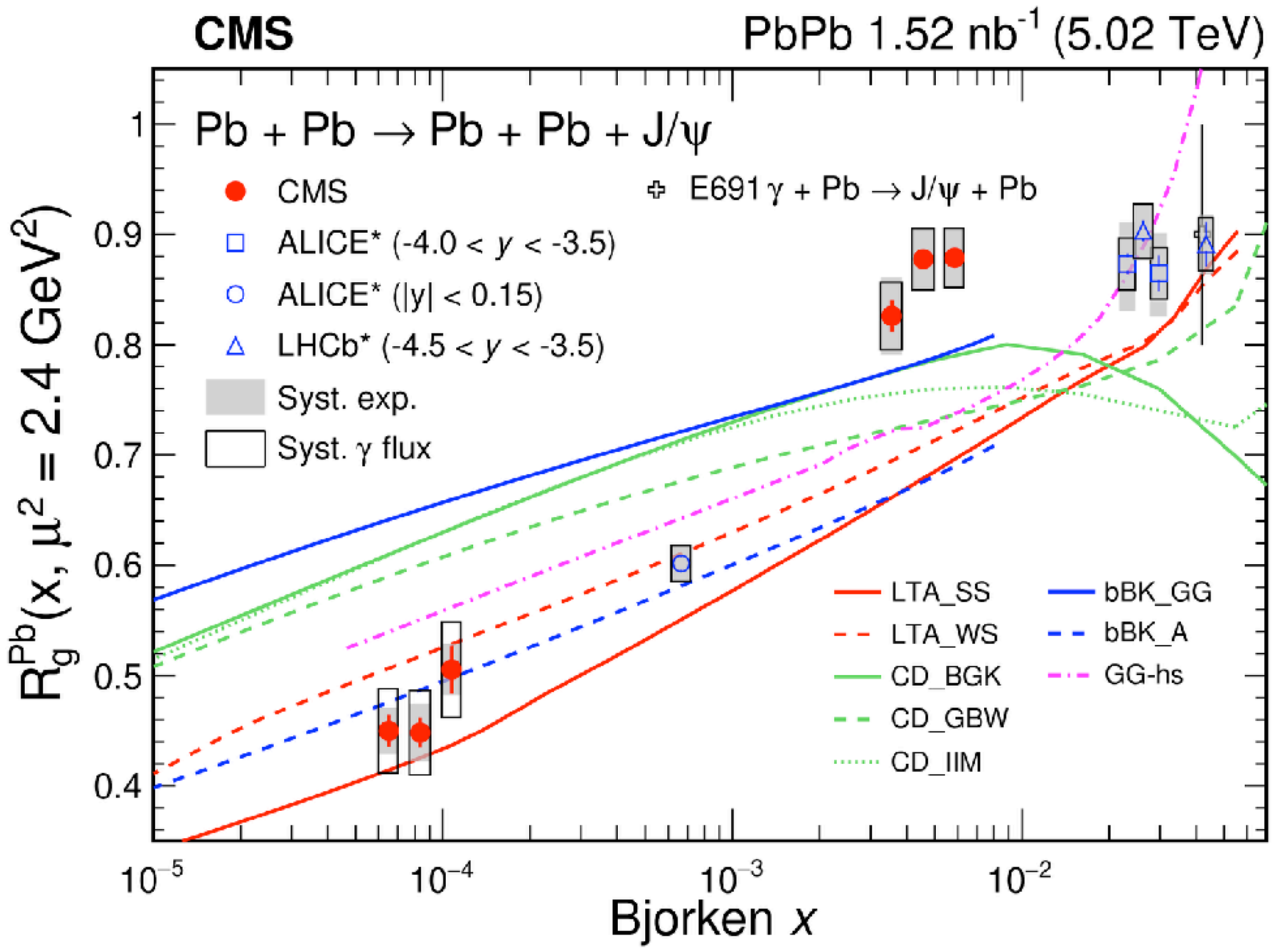
- Slow growth may suggest the periphery of the nucleus has not become fully “black”

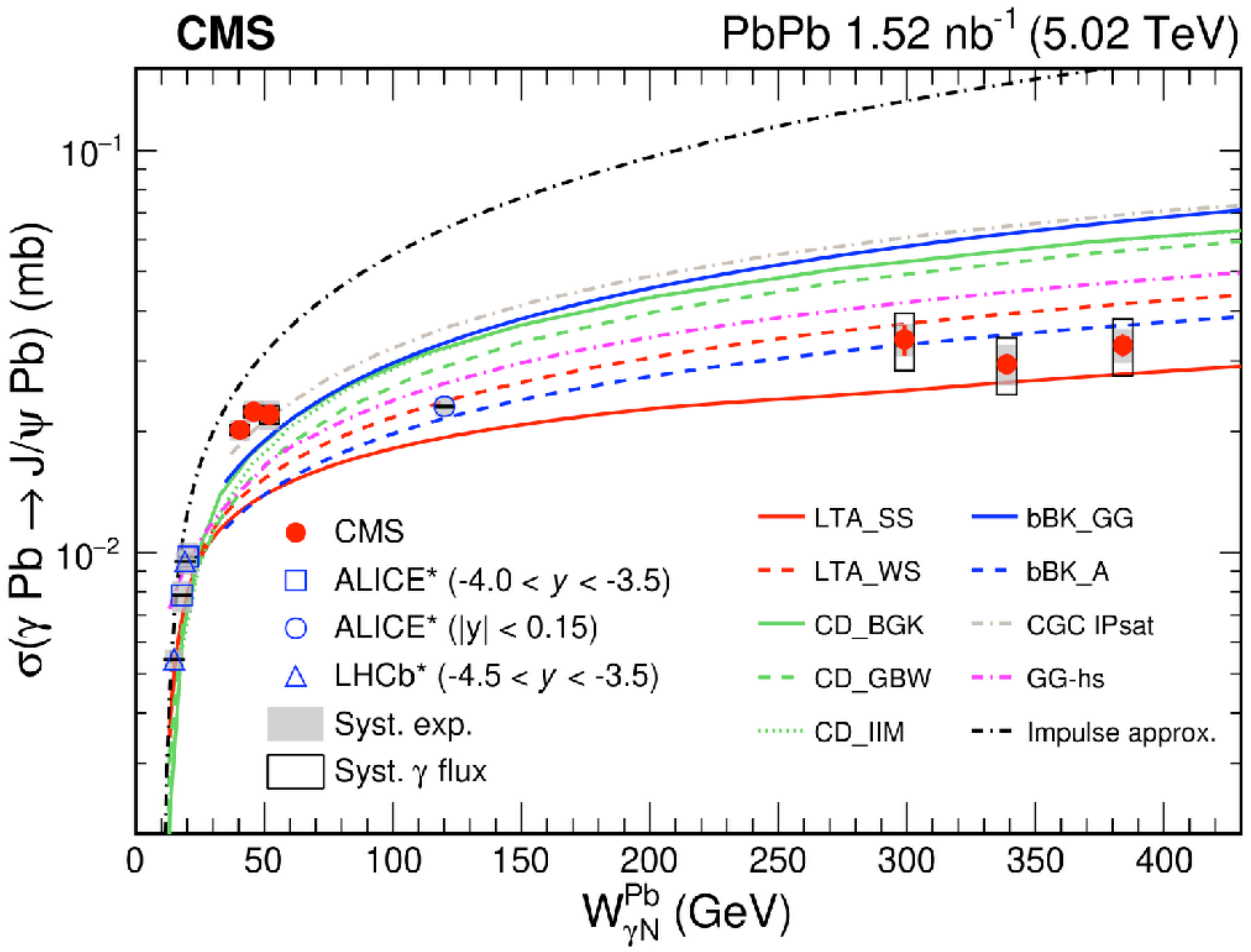


Summary

- Directly disentangled coh. $\sigma_{\gamma A \to J/\psi A'}(W)$ in UPC **for the first time.**
- CMS measured coh. $\sigma_{\gamma A \to J/\psi A'}(W)$ to a new unprecedentedly low-x gluon regime $(10^{-4} - 10^{-5})$.
- No model can completely describe the data at low and high W.
  - Gluon saturation? , Black disc limit? , other physics?

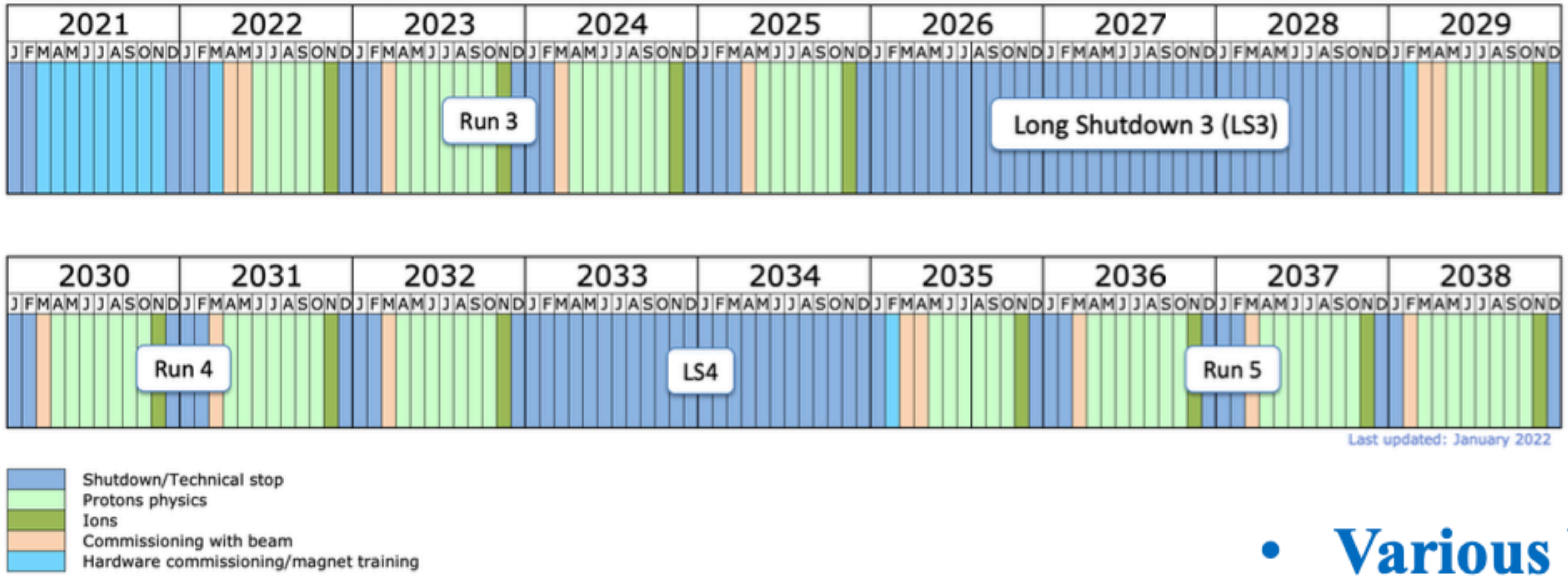






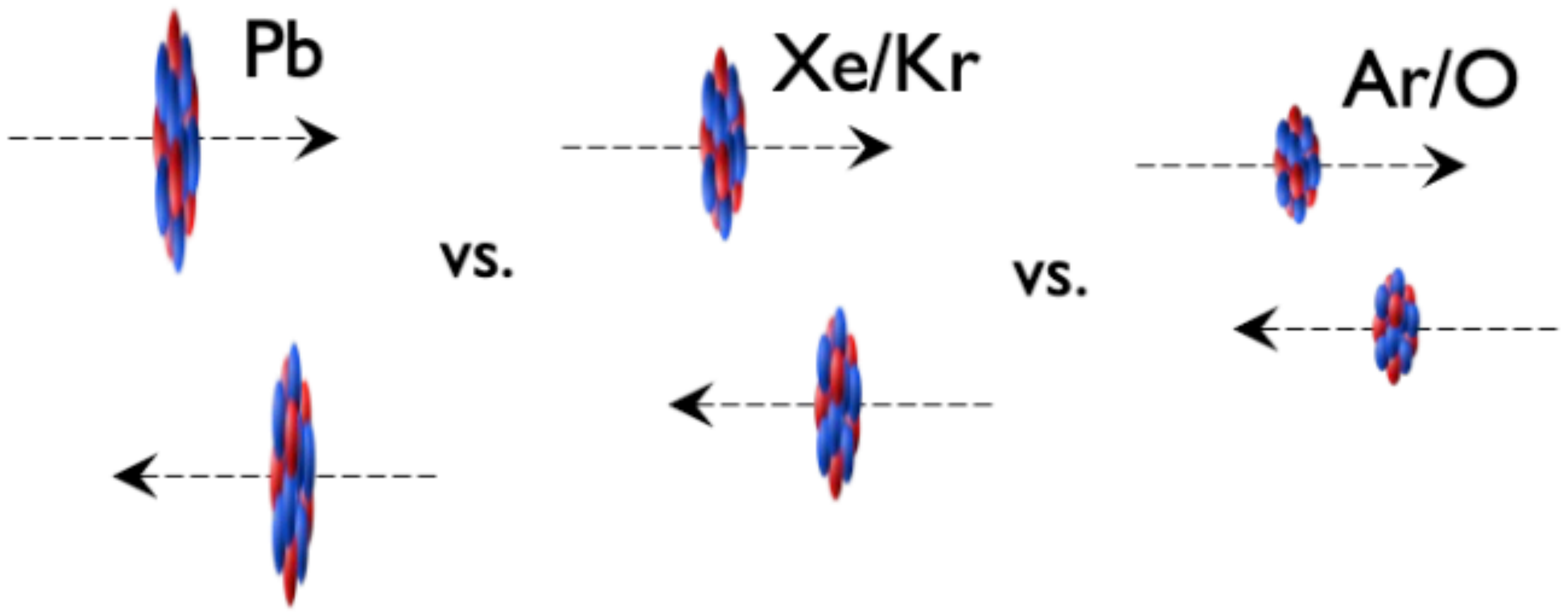
Backup slides

Future opportunities



Exciting opportunities ahead

- Higher luminosities.
- A variety of ion species.
- Upgrades enabled by new technologies!



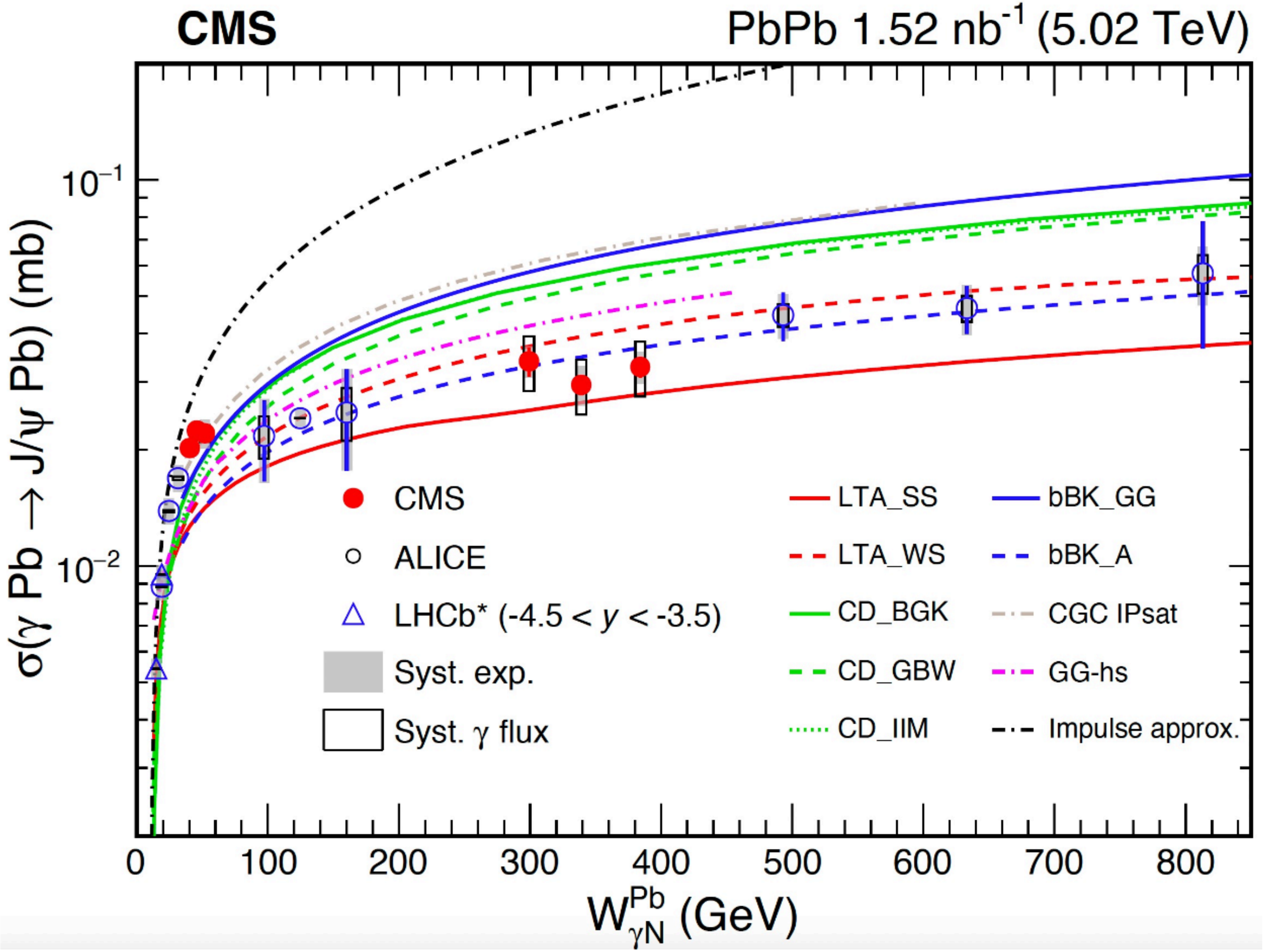
- **Various VM species in γPb with neutron tagging**
- **System size scan with different ion species**

When approaching the BDL

- Coh. cross section scales with $A^{2/3}$
- Incoh. cross section strongly suppressed; internal substructure becomes invisible

Comparison with new ALICE result since the CMS submission

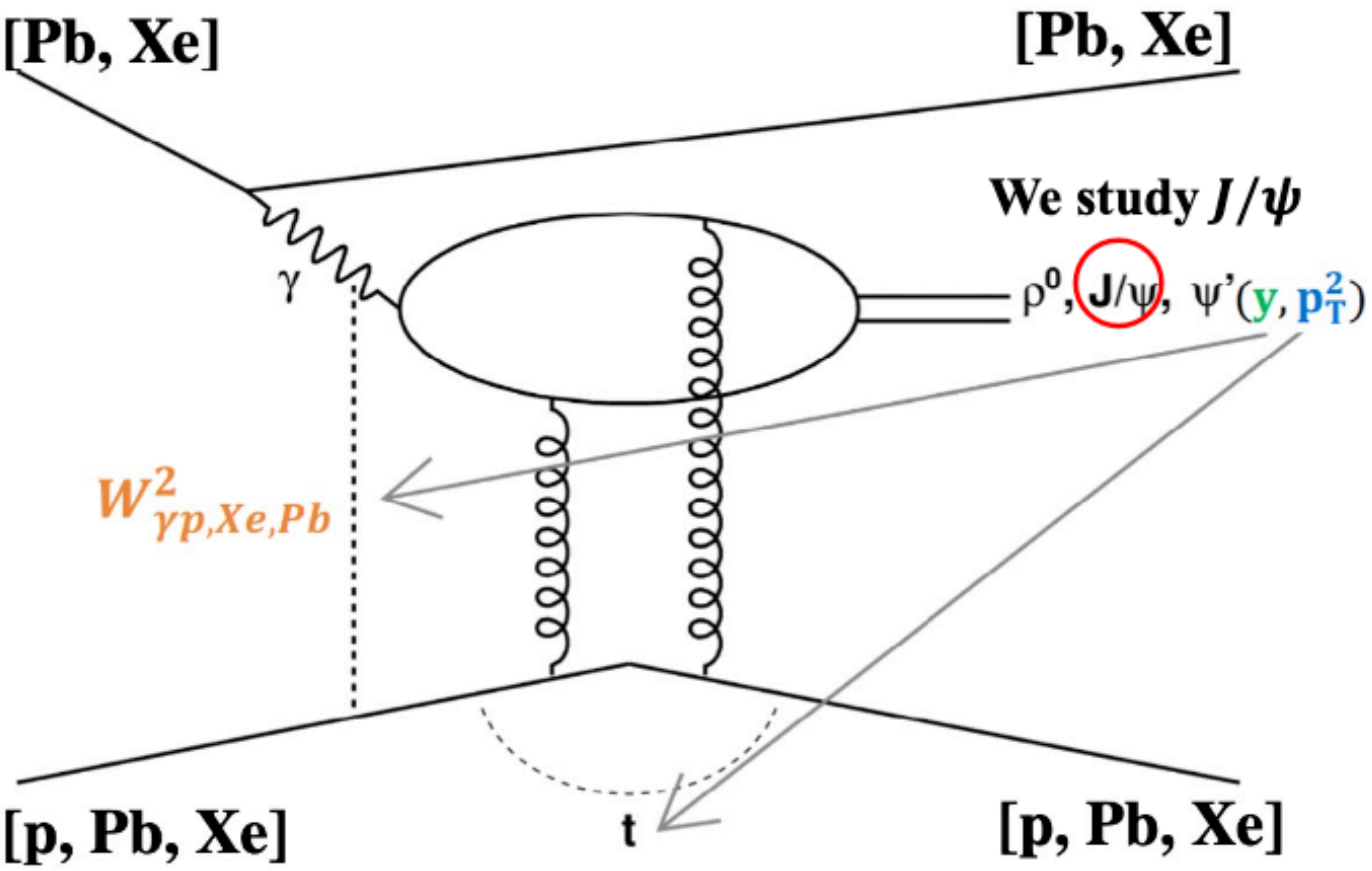
arXiv:2305.19060



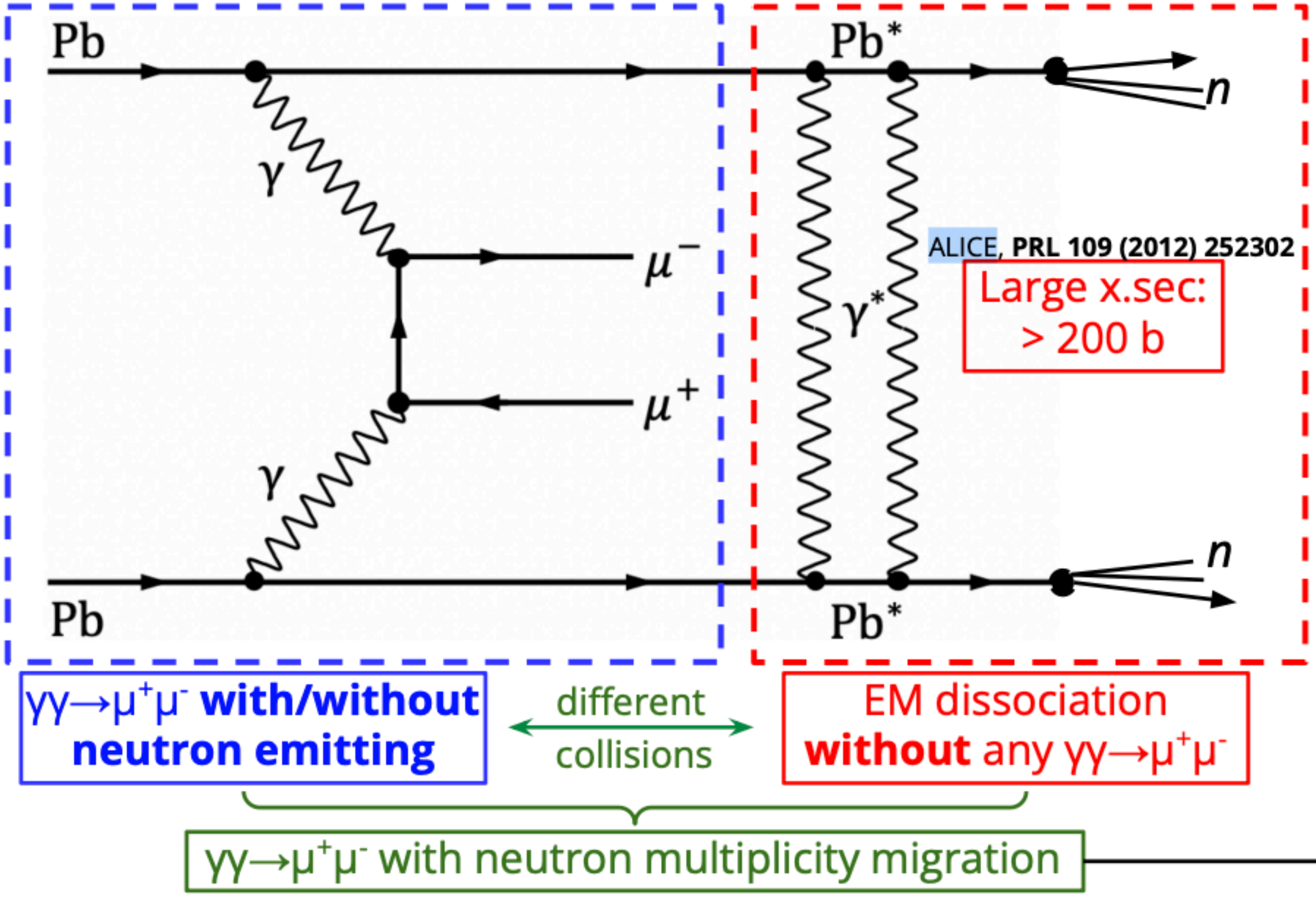
VM photoproduction kinematics

- A given y → Fixes ω, x, W

- $\omega = \frac{M_{VM}}{2} e^{\pm y}$
  - y: Rapidity of the VM
  - ω: Photon energy
  - M_{VM}: Mass of the VM
- $x = \left(\frac{M_{VM}}{\sqrt{s_{NN}}}\right) e^{\mp y}$
- $W^2 = M_{VM}\sqrt{s_{NN}} \cdot e^{\pm y}$
  - W: Centre-of-mass energy of the photon–target system



EMD pileup correction



Impact of dissociative PU corrected by measuring neutron multiplicity in events without any activity in CMS tracker.