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

Zaochen Ye (Rice University)

for the CMS Collaboration

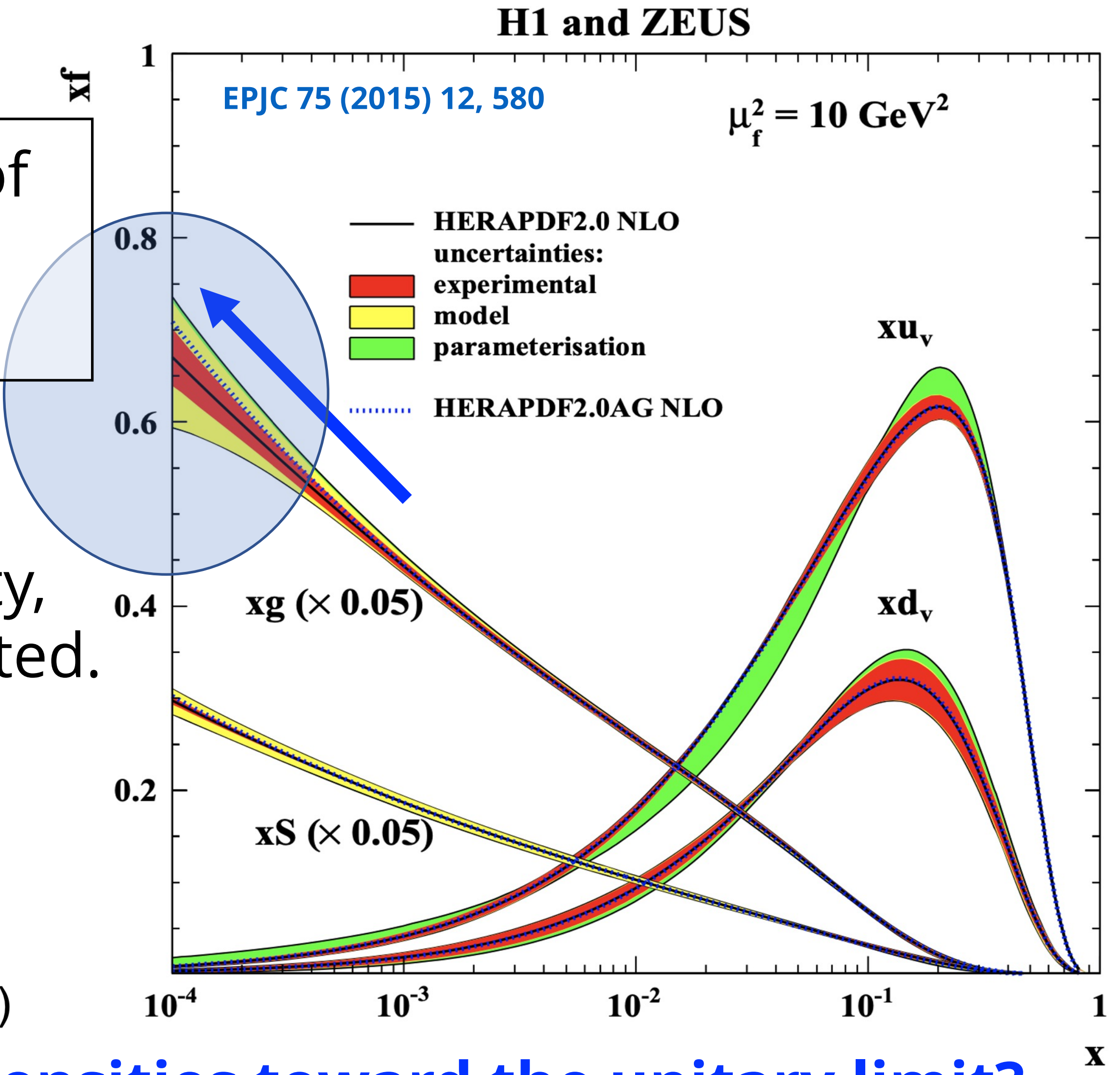
CMS: arXiv:2303.16984

Supported in part by the U.S. DEPARTMENT OF ENERGY Office of Science

Understand Nucleon Structure via DIS

e-p collider

Rapid increase of gluon density towards small x.



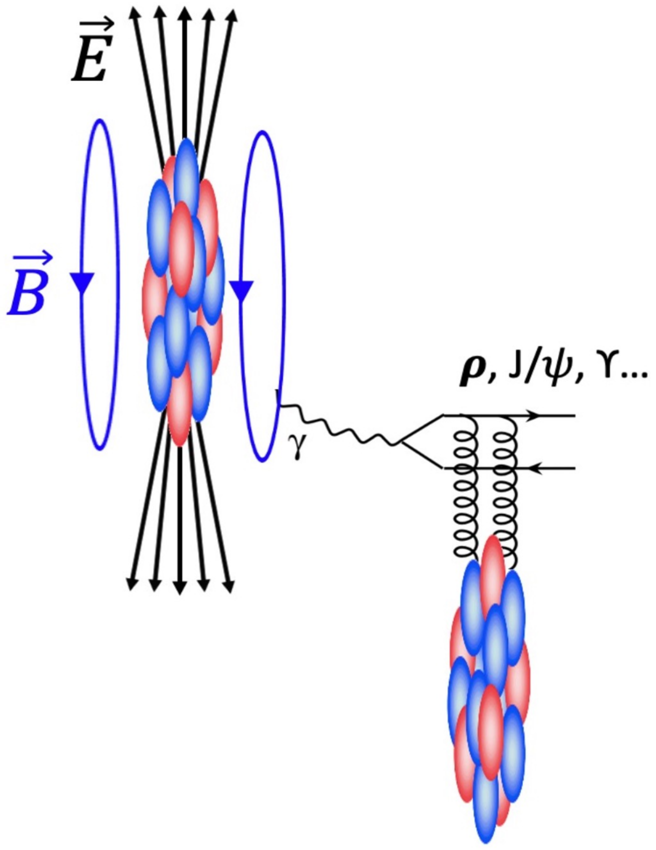
Indefinite growth at small-x violates unitarity, mechanism beyond gluon splitting is expected.

What is the fate of gluons at extreme densities toward the unitary limit?

Vector Meson Photoproduction in UPC

VM (e.g., J/Ψ) photoproduction directly probes gluonic structure of nucleus and nucleon.

At LO in pQCD, cross section ~ photon flux ⊗ $[xG(x)]^2$



Coherent production:

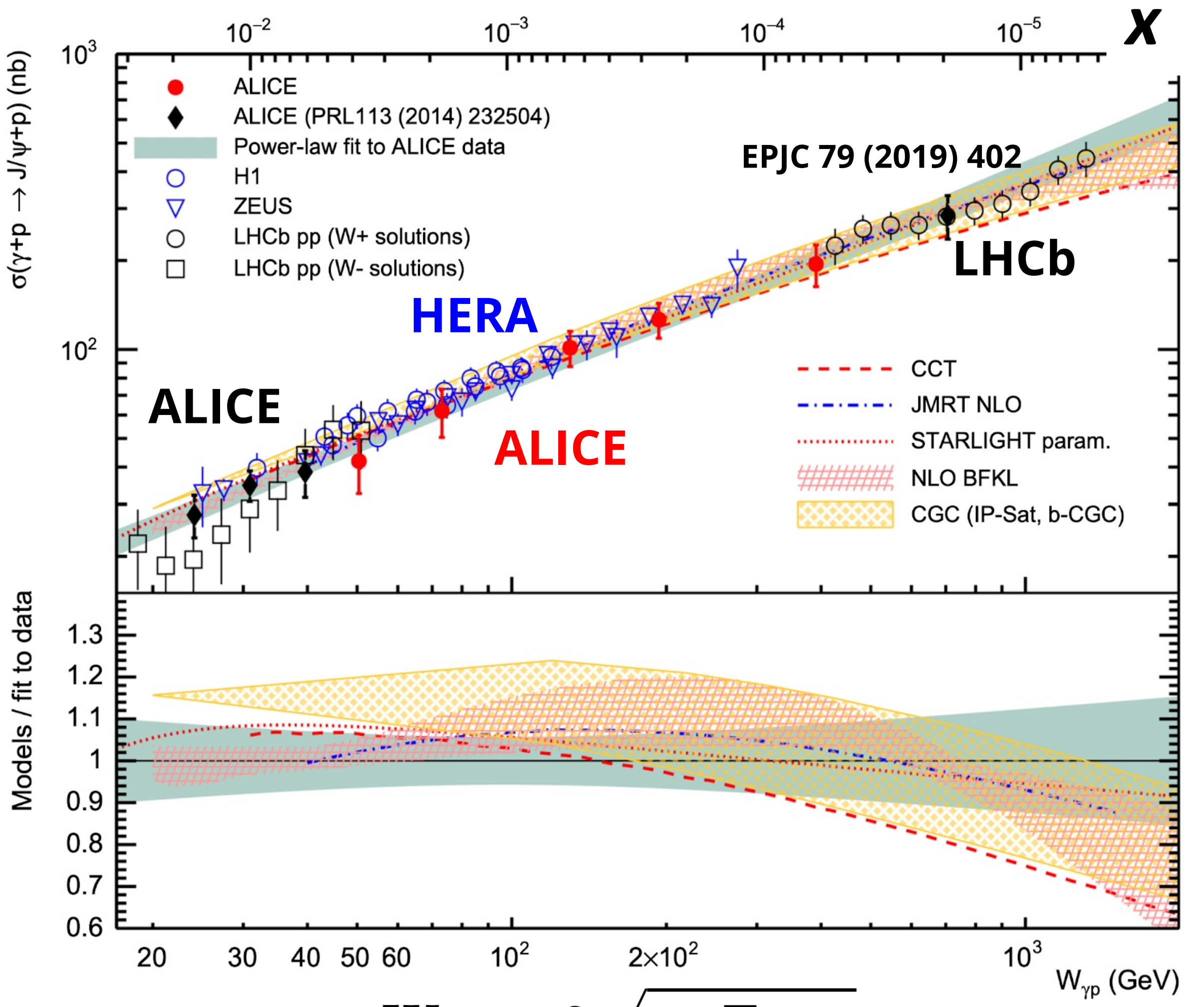
- Photon fluctuated dipole couples coherently to entire nucleus
- Target nucleus remains intact
- VM $\langle p_T \rangle$ ~ 50 MeV
- Probing the averaged gluon density

Incoherent production:

- Photon fluctuated dipole couples to individual nucleons
- Target nucleus usually breaks
- VM $\langle p_T \rangle$ ~ 500 MeV
- Probing the local gluon density fluctuation

$$\omega = \frac{M_{VM}}{2} e^{\pm y} \qquad x = \frac{M_{VM}}{\sqrt{s_{\mathrm{NN}}}} e^{\mp y} \qquad \mathrm{W}_{\gamma\mathrm{p}} = 2\sqrt{\omega \cdot \mathrm{E}_{\mathrm{beam}}}$$

Coherent J/Ψ Photoproduction via γ + Free Nucleon



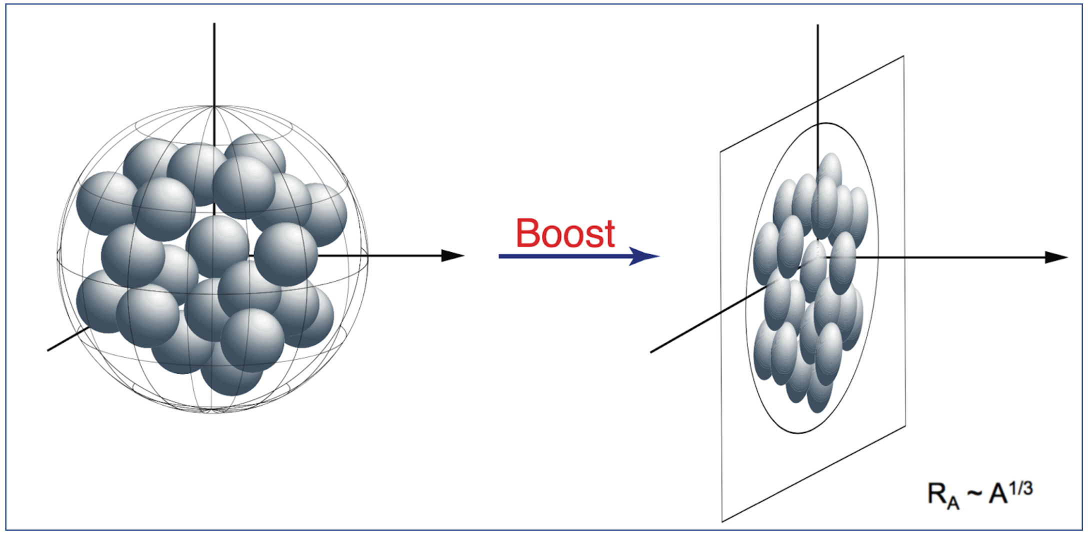
$$W_{\gamma p} = 2\sqrt{\omega \cdot E_{beam}}$$

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

- Data from **LHC** and **HERA** follow a **common** power-law trend, consistent with the expectation from the rapidly increasing gluon density in a proton

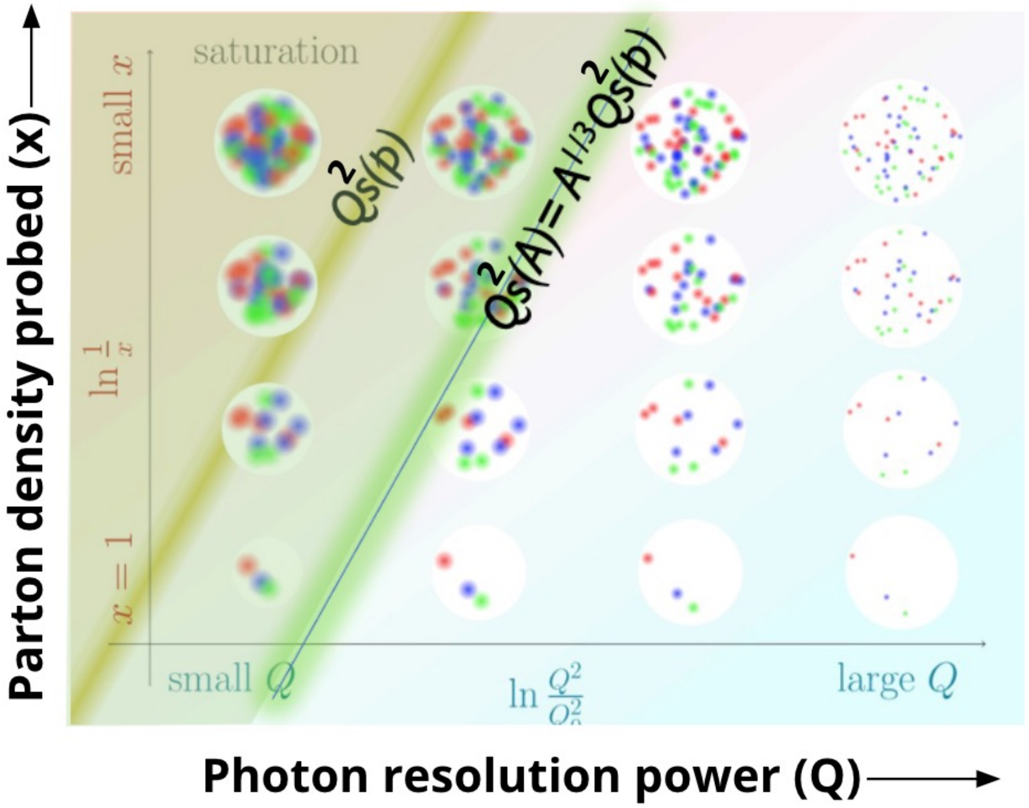
No clear indication of gluon saturation, even down to x~10^{-5} in a free nucleon.

Advantages of Gluon Saturation Search in Nucleus



Gluons is **enhanced** by a factor of $A^{1/3}$ in **nucleus** compared to what in free nucleon

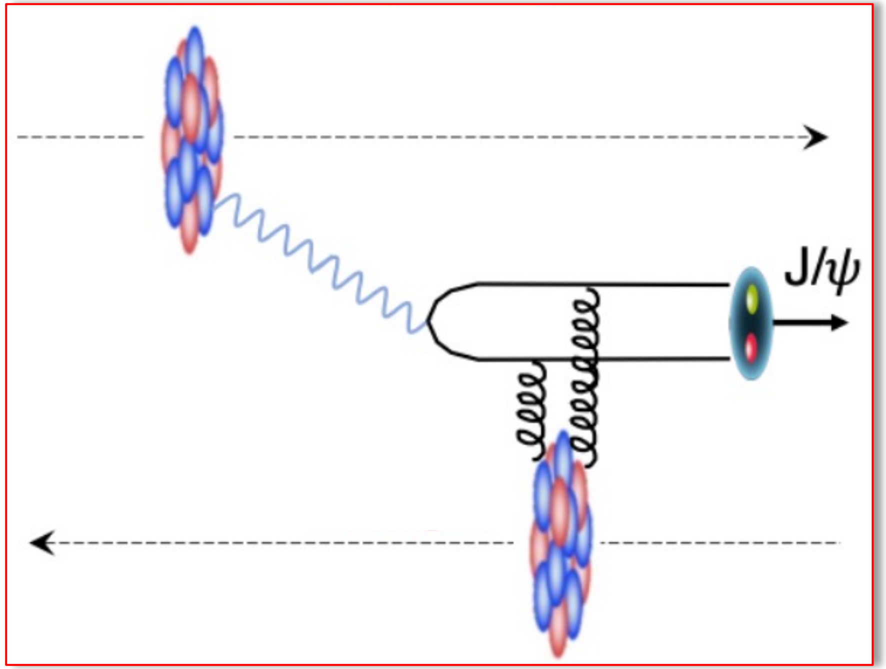
$$Q_s^2 \sim A^{1/3} \left(\frac{1}{x}\right)^{\lambda}$$

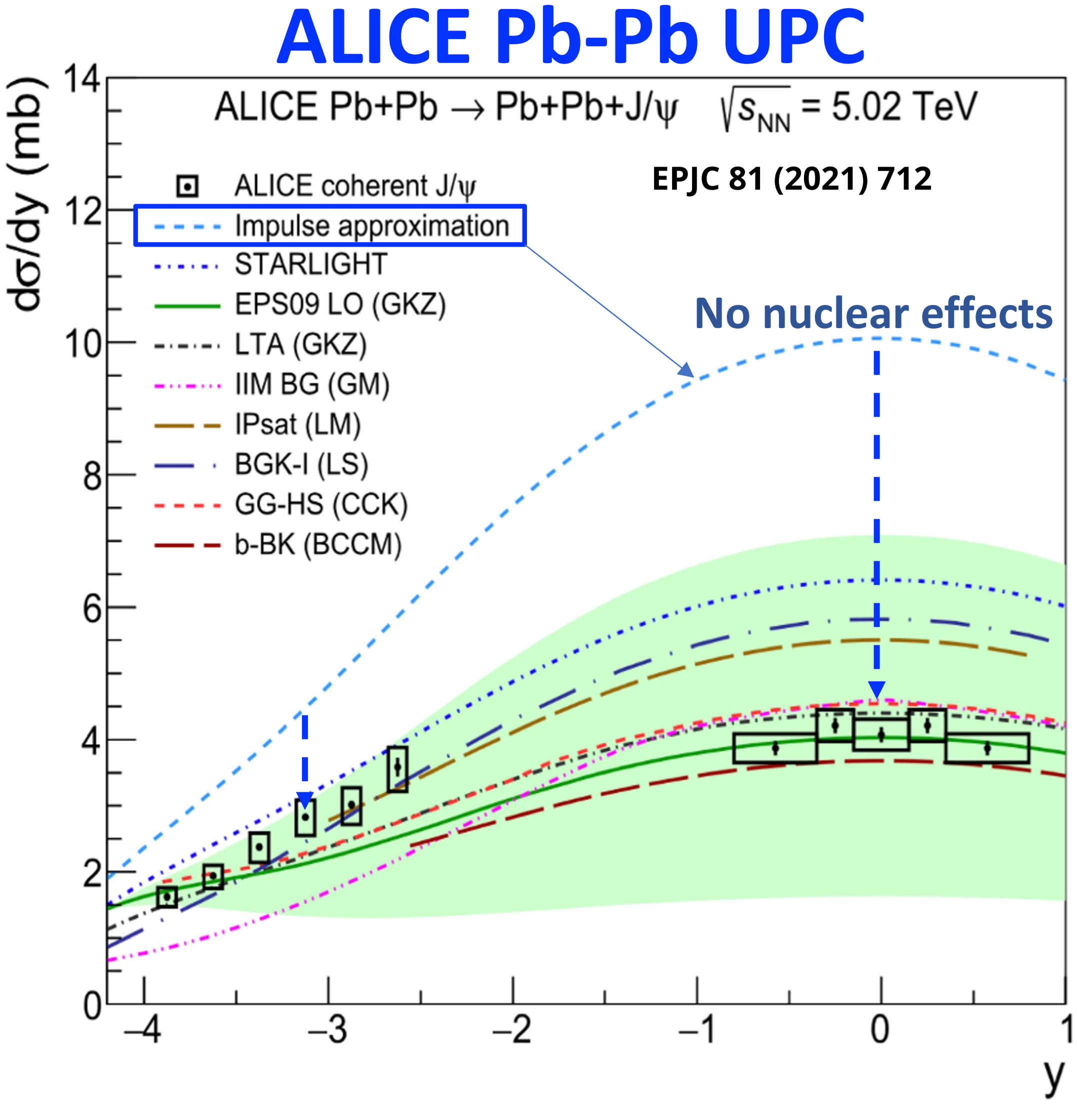


- Gluon saturation is expected to be easier to be reached **in nuclei**

Coherent J/Ψ Photoproduction in A-A UPCs

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





- **Strong suppression**, but the rapidity distribution is still **a puzzle** for theoretical studies (models considering gluon saturation or shadowing)

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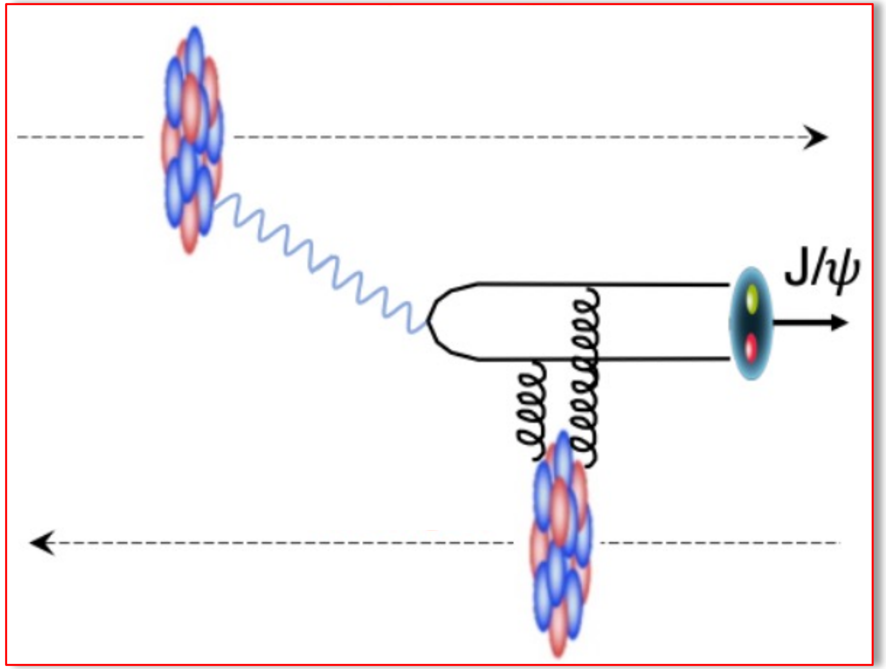

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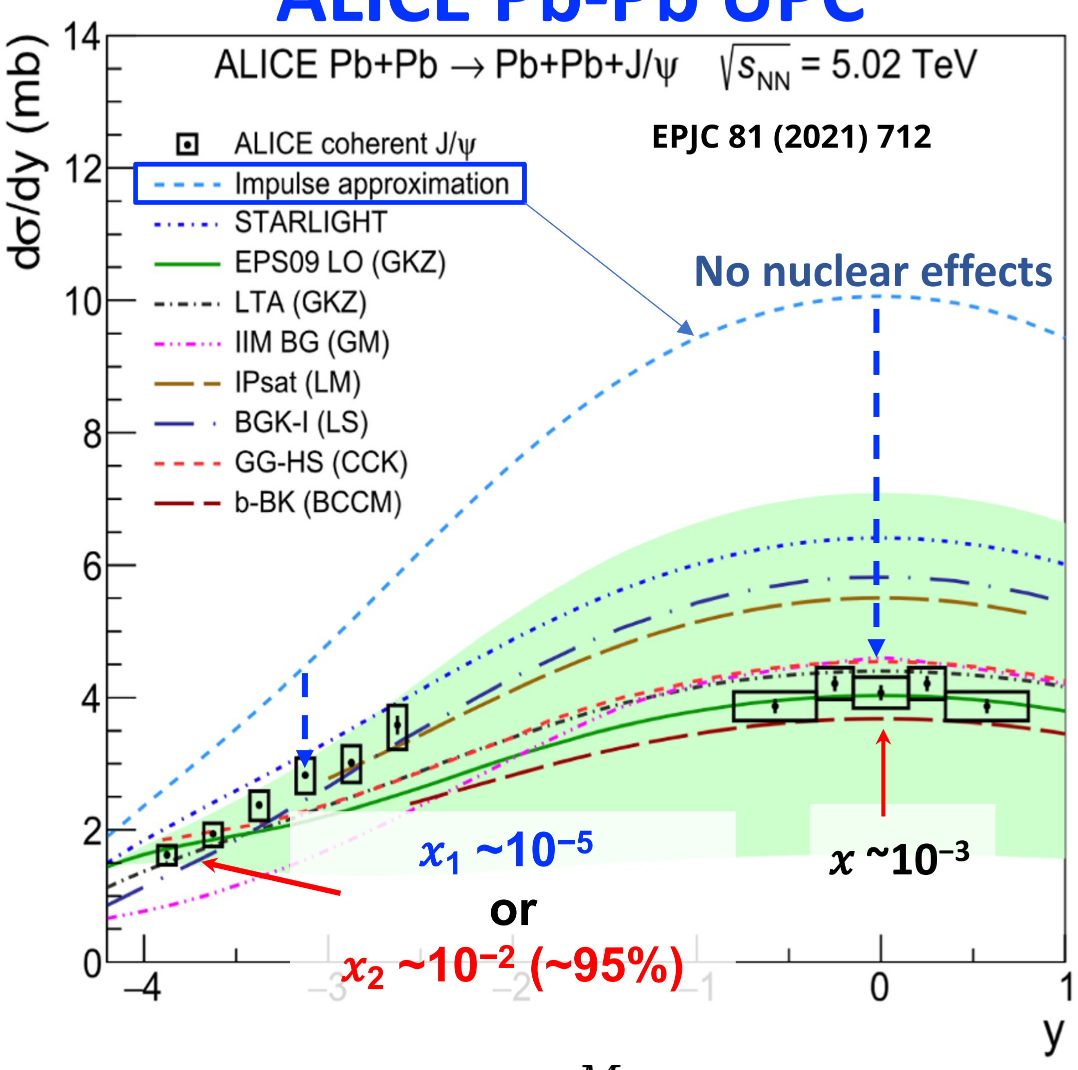
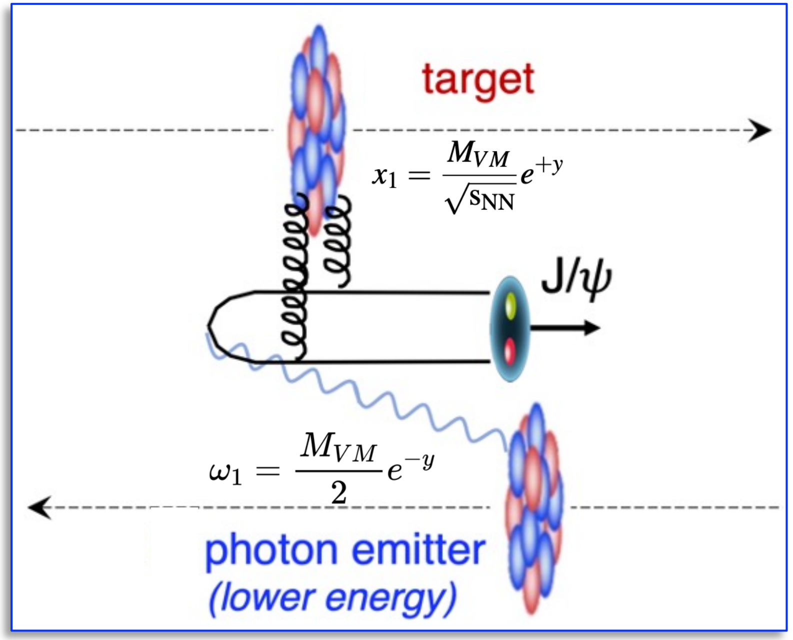
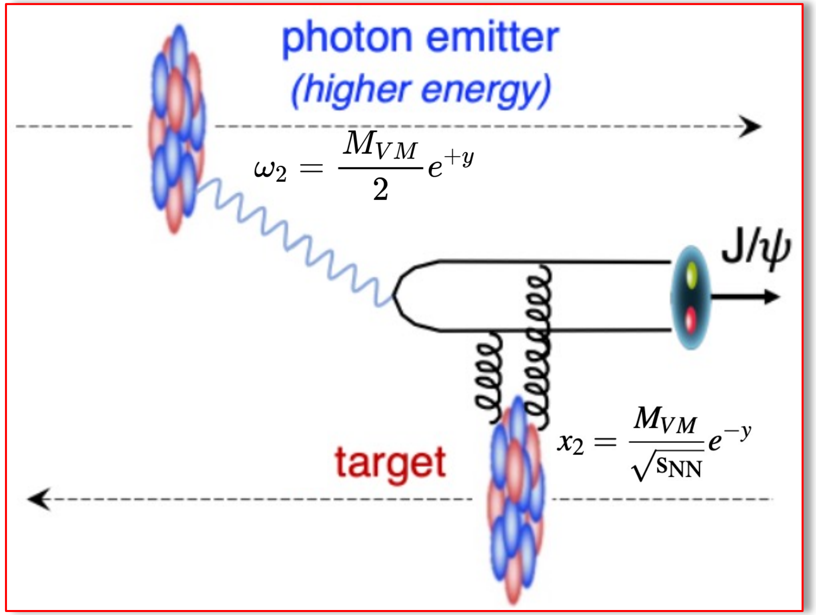
ALICE Pb-Pb UPC



$$x = \frac{M_{VM}}{\sqrt{s_{NN}}} e^{\mp y}$$

Two-Way Ambiguity in A-A UPC





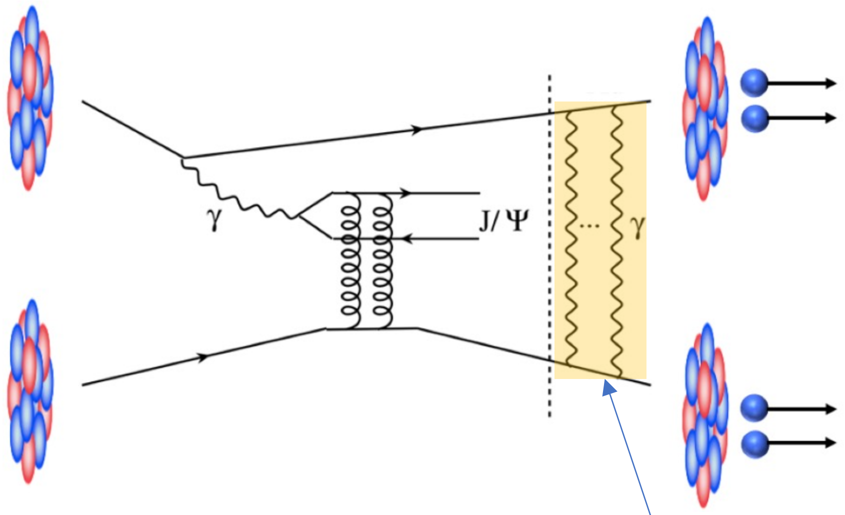
$$\frac{d\sigma_{AA \to AA' J/\psi}}{dy} = N_{\gamma/A}(\omega_1) \cdot \sigma_{\gamma A \to J/\psi A'}(\omega_1) + N_{\gamma/A}(w_2) \cdot \sigma_{\gamma A \to J/\psi A'}(w_2)$$

At least two equations for the solutions

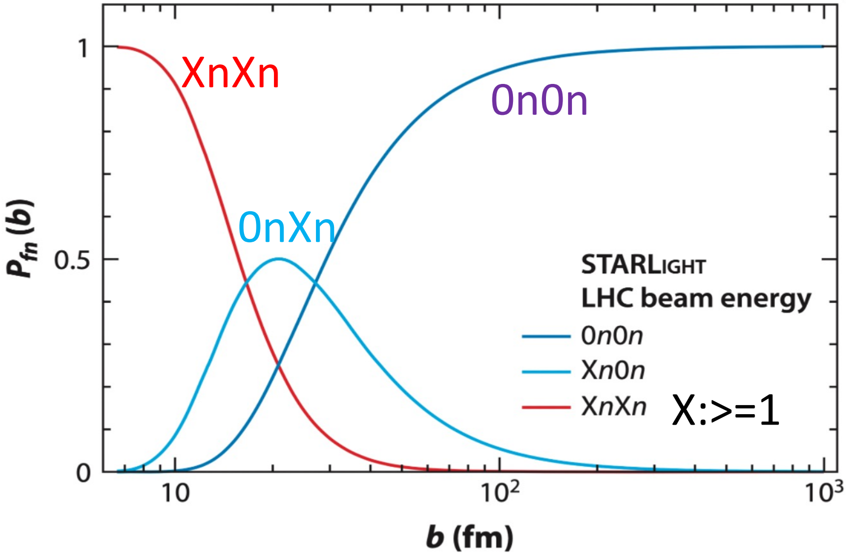
Method to Solve Two-Way Ambiguity in A-A UPC

V. Guzey, M. Strikman, M. Zhalov, EPJC (2014) 72 2942

- Control/select the impact parameter of UPCs via forward emitted neutrons



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



Neutron emission via EMD with additional photon exchange:

- Soft photons (energy ~10s MeV)
- Independent of interested physics process
- Large cross section ~200 b (single EMD)
- The smaller b → the more neutrons

- Analogous to centrality:
  - $b_{XnXn} < b_{0nXn} < b_{0n0n}$

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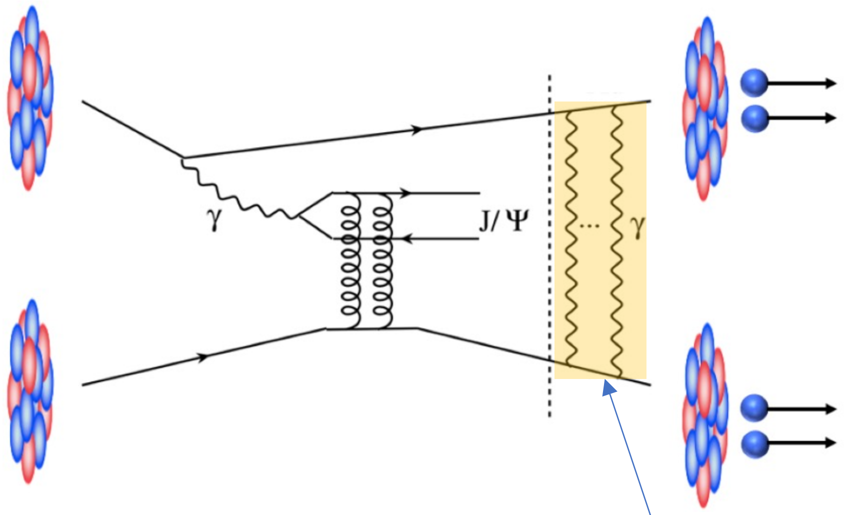

$$\frac{d\sigma^{0nXn}_{AA\to AA'J/\psi}}{dy} = N^{0nXn}_{\gamma/A}(\omega_1)\cdot\sigma_{\gamma A\to J/\psi A'(\omega_1)} + N^{0nXn}_{\gamma/A}(w_2)\cdot\sigma_{\gamma A\to J/\psi A'(w_2)}$$

from theoretical calculation

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

$$\sigma_{\gamma A\to J/\psi A'(\omega_1)}$$

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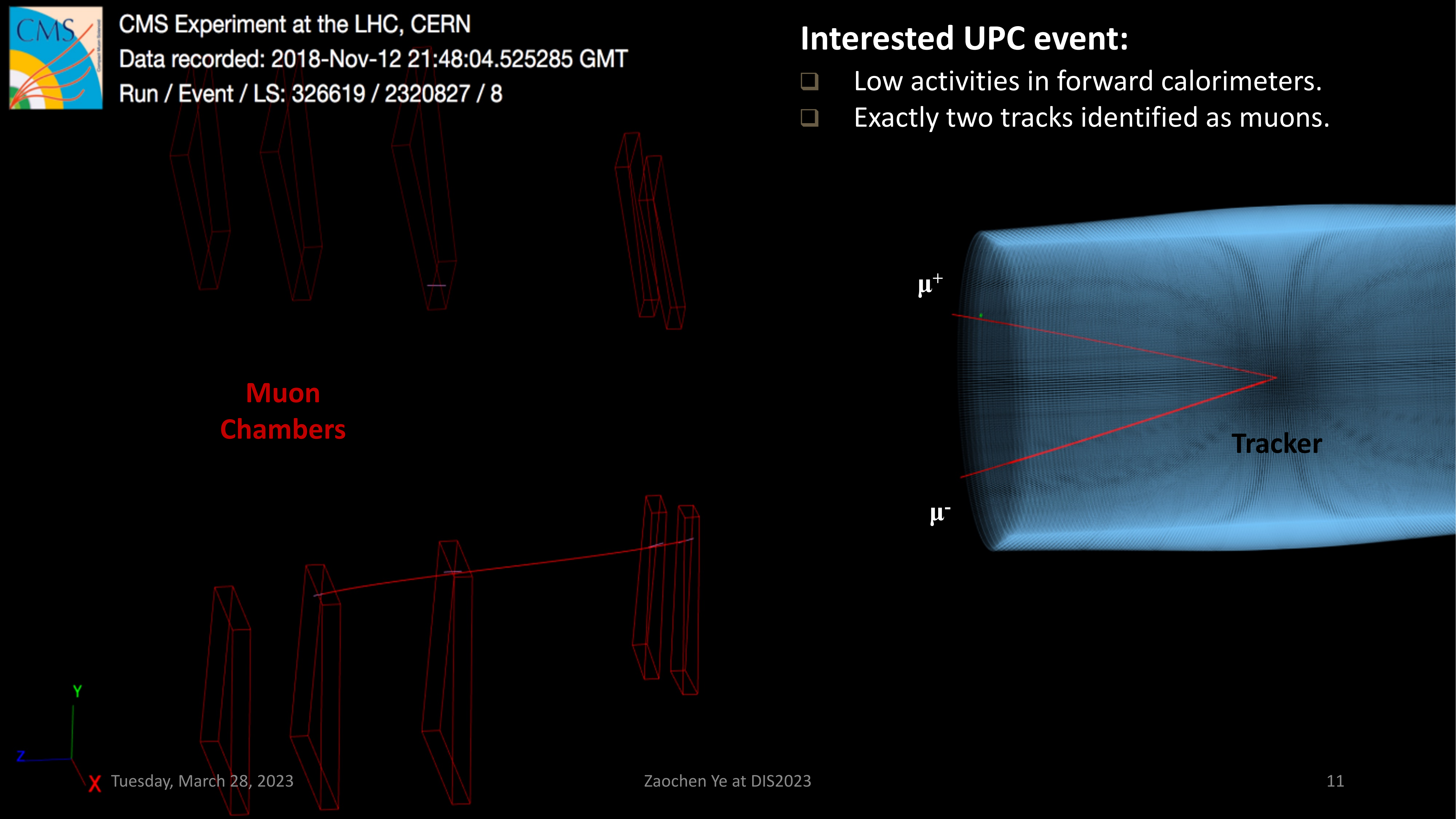
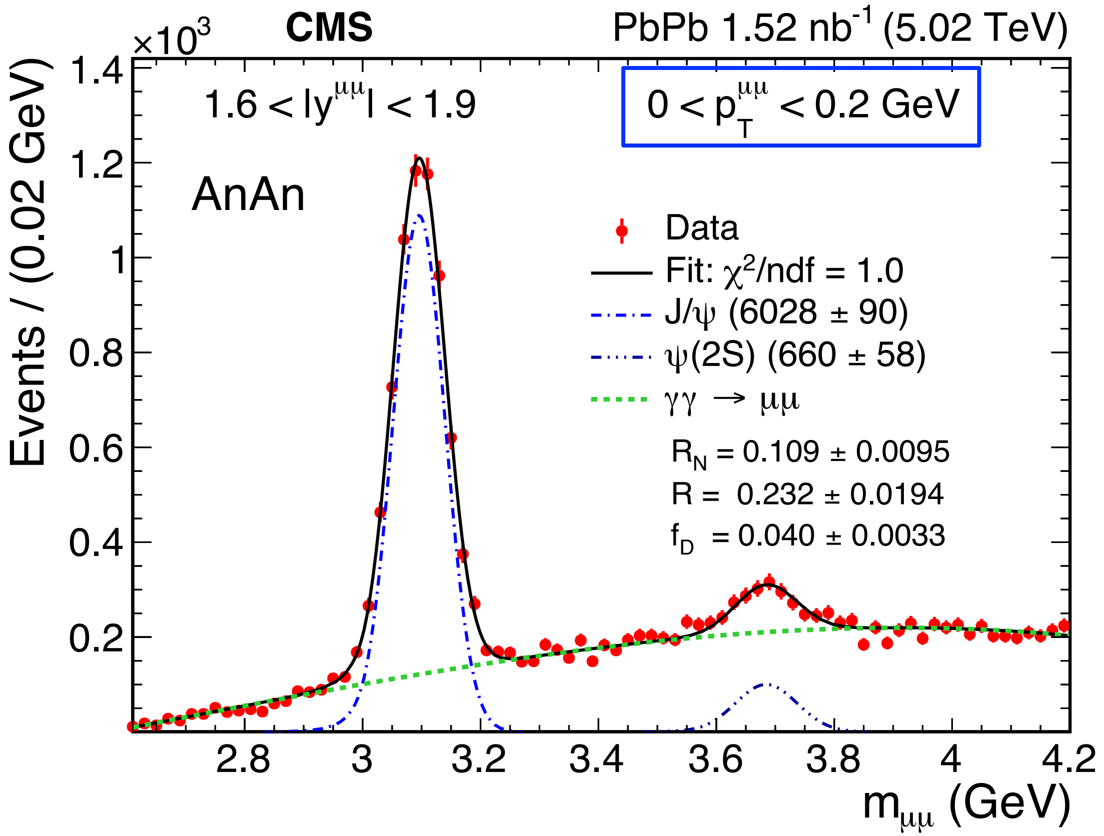
Interested UPC event:

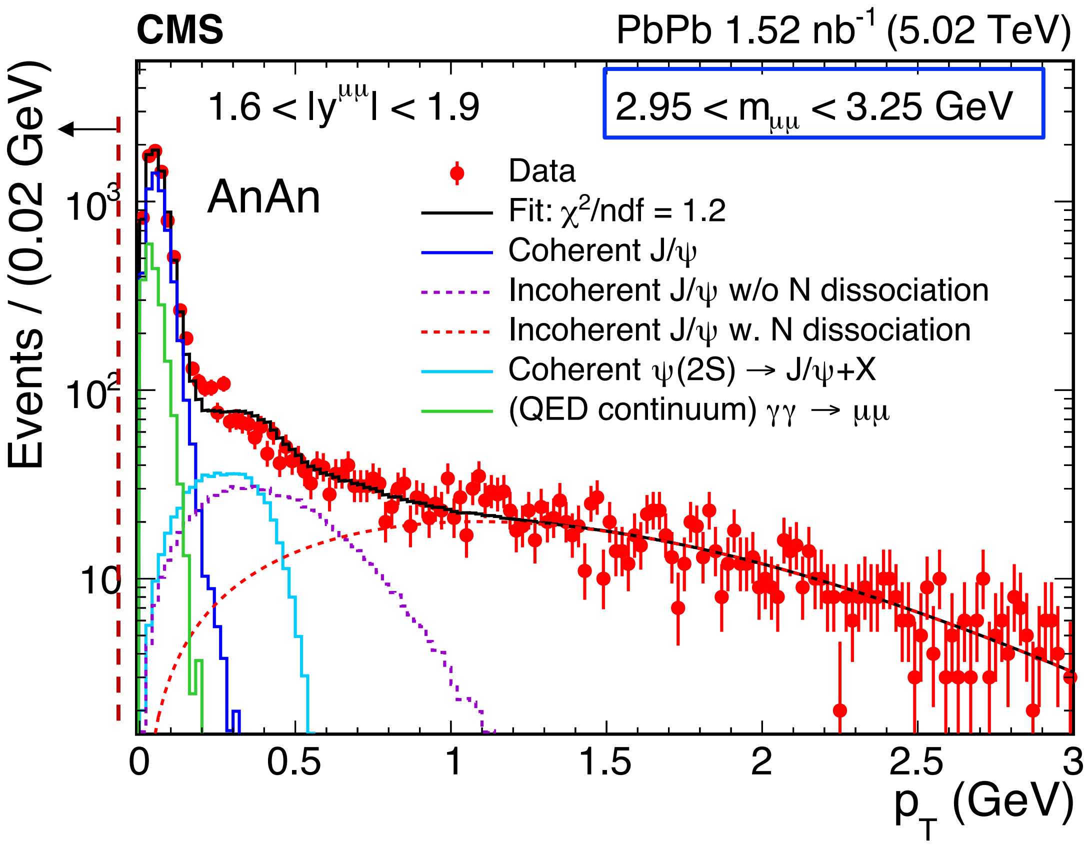
- Low activities in forward calorimeters.
- Exactly two tracks identified as muons.



Signal Extraction

CMS: arXiv:2303.16984





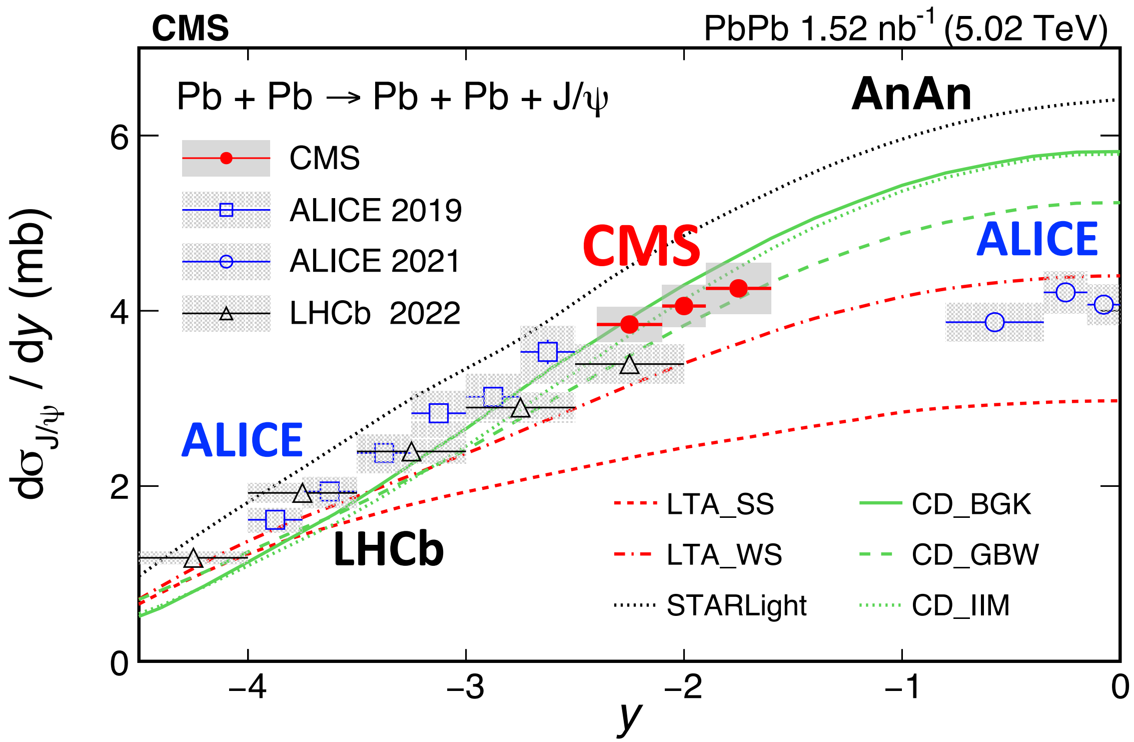
AnAn: All possible neutron emissions

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

Coherent J/Ψ in AnAn

CMS: arXiv:2303.16984

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



AnAn: All possible neutron emissions

CMS data cover a new *y* region and follow ALICE forward data trend

- A **tension** btw **ALICE**/**CMS** and **LHCb** data?
- **No theory** can describe data over **full y** region **– A puzzle?**

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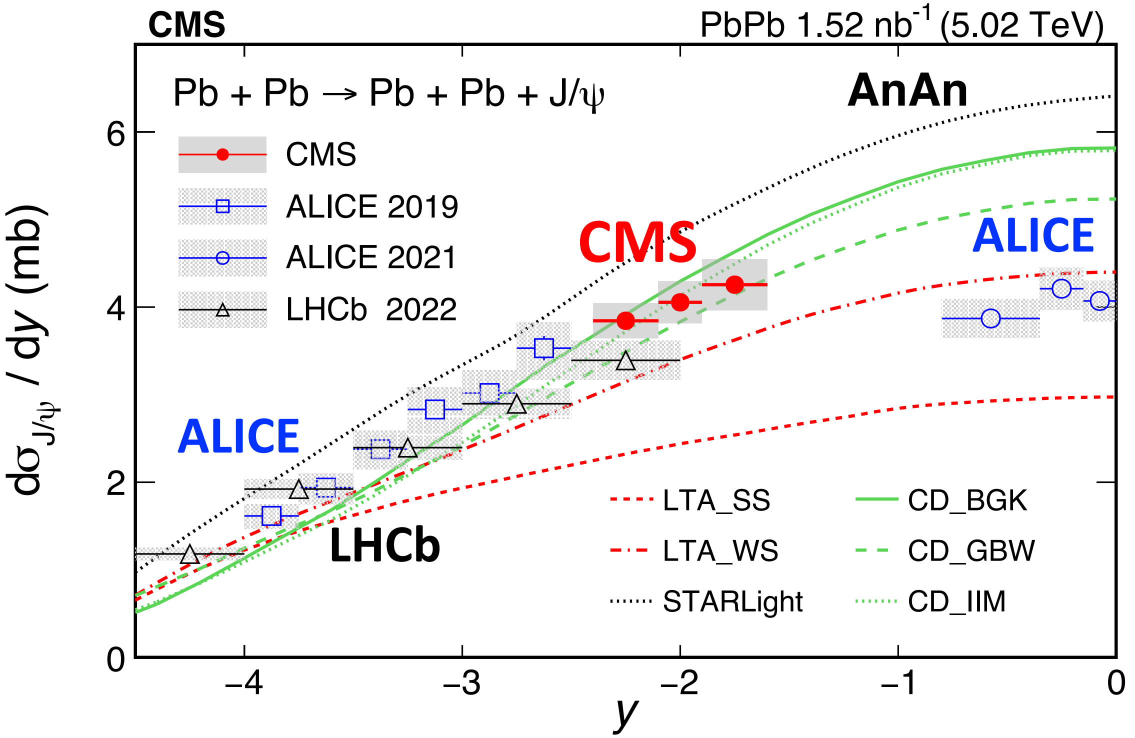

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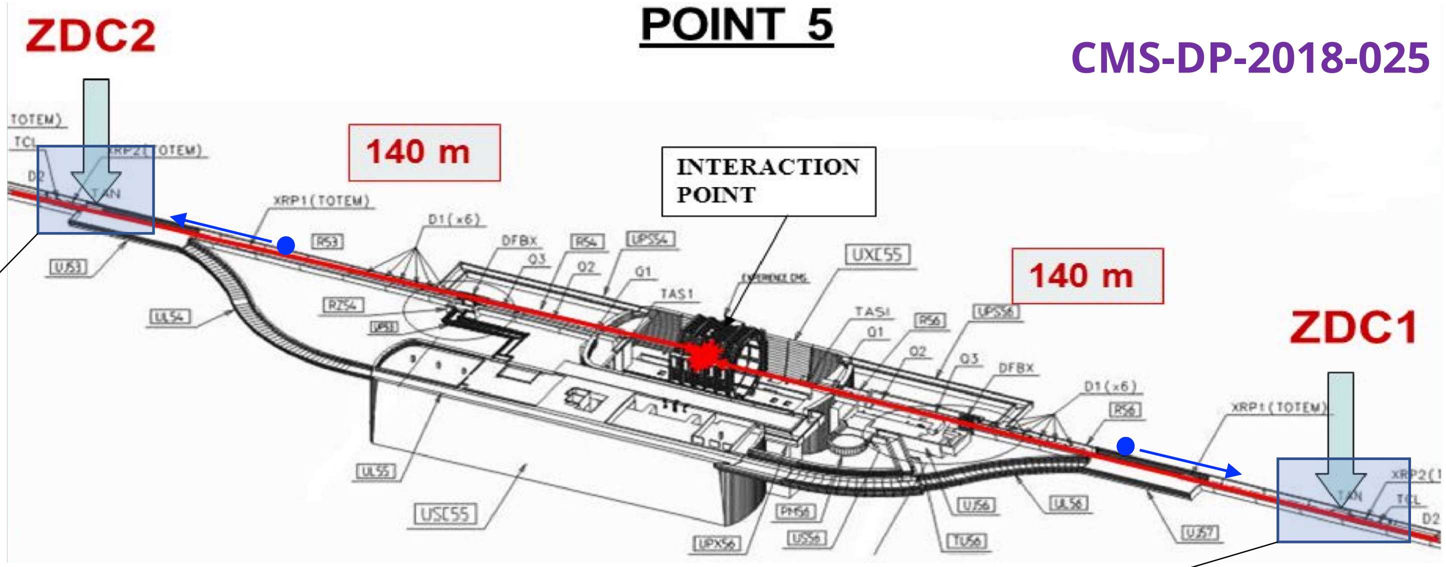
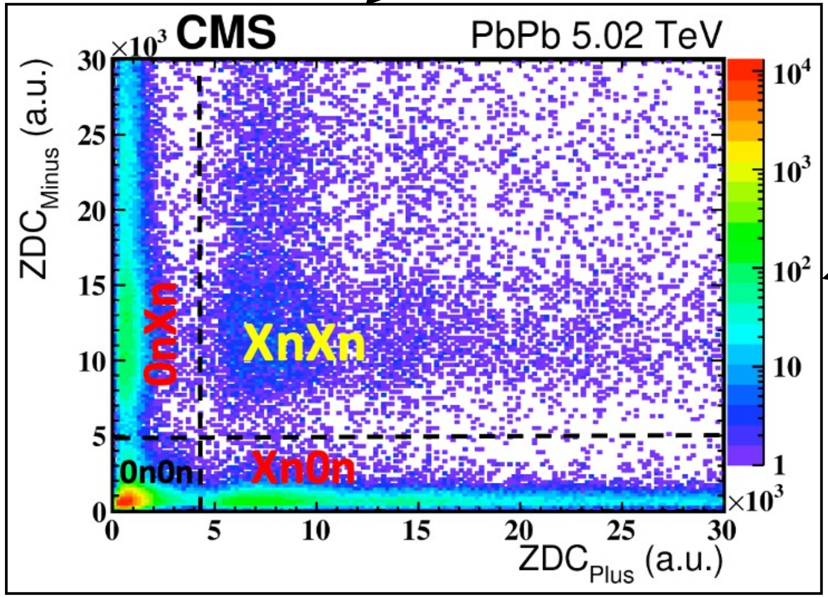
A **deeper** look at J/Ψ production from **single γ+Pb without** the **"two-way ambiguity"** will tell more.

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

Neutron Tag with Zero Degree Calorimeter



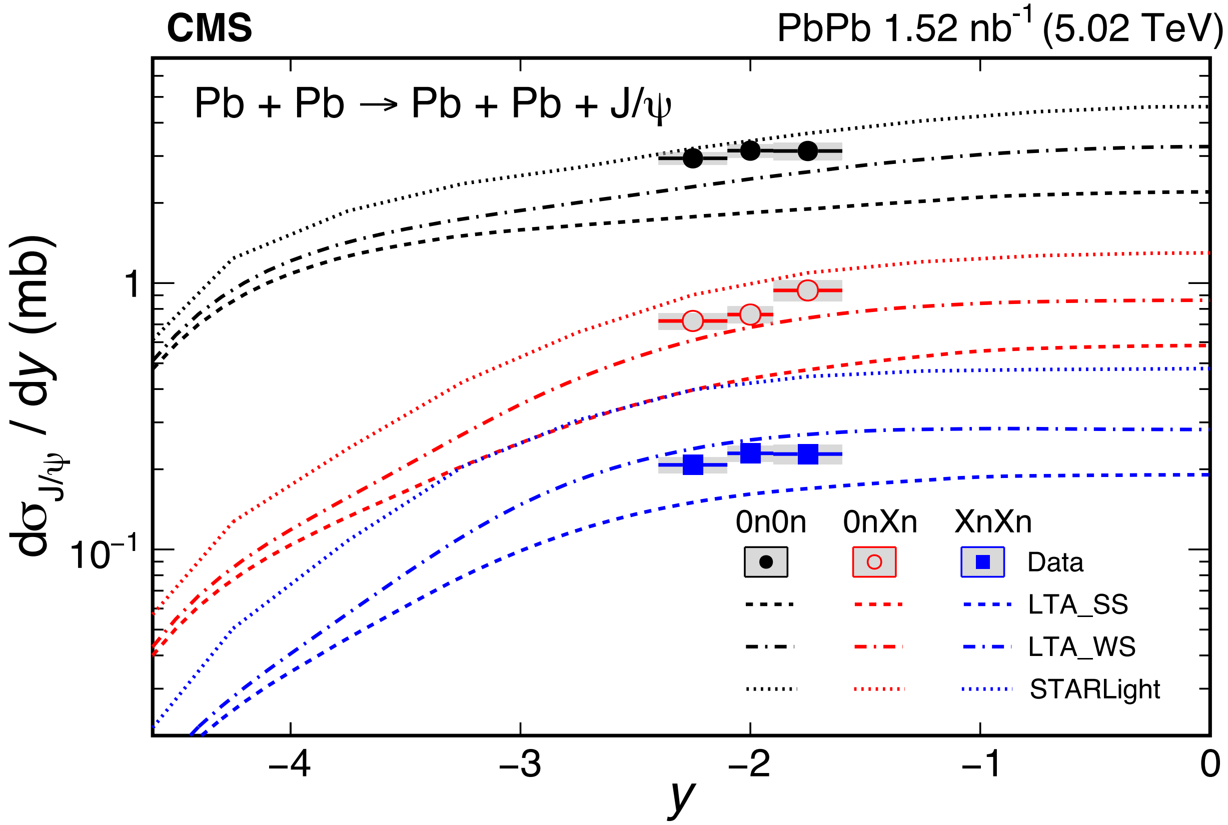


Tag events with **neutrons**:

- 0n0n, 0nXn, XnXn (X: ≥1)

Coherent J/Ψ in PbPb UPCs with Fwd Neutron Tag

CMS: arXiv:2303.16984

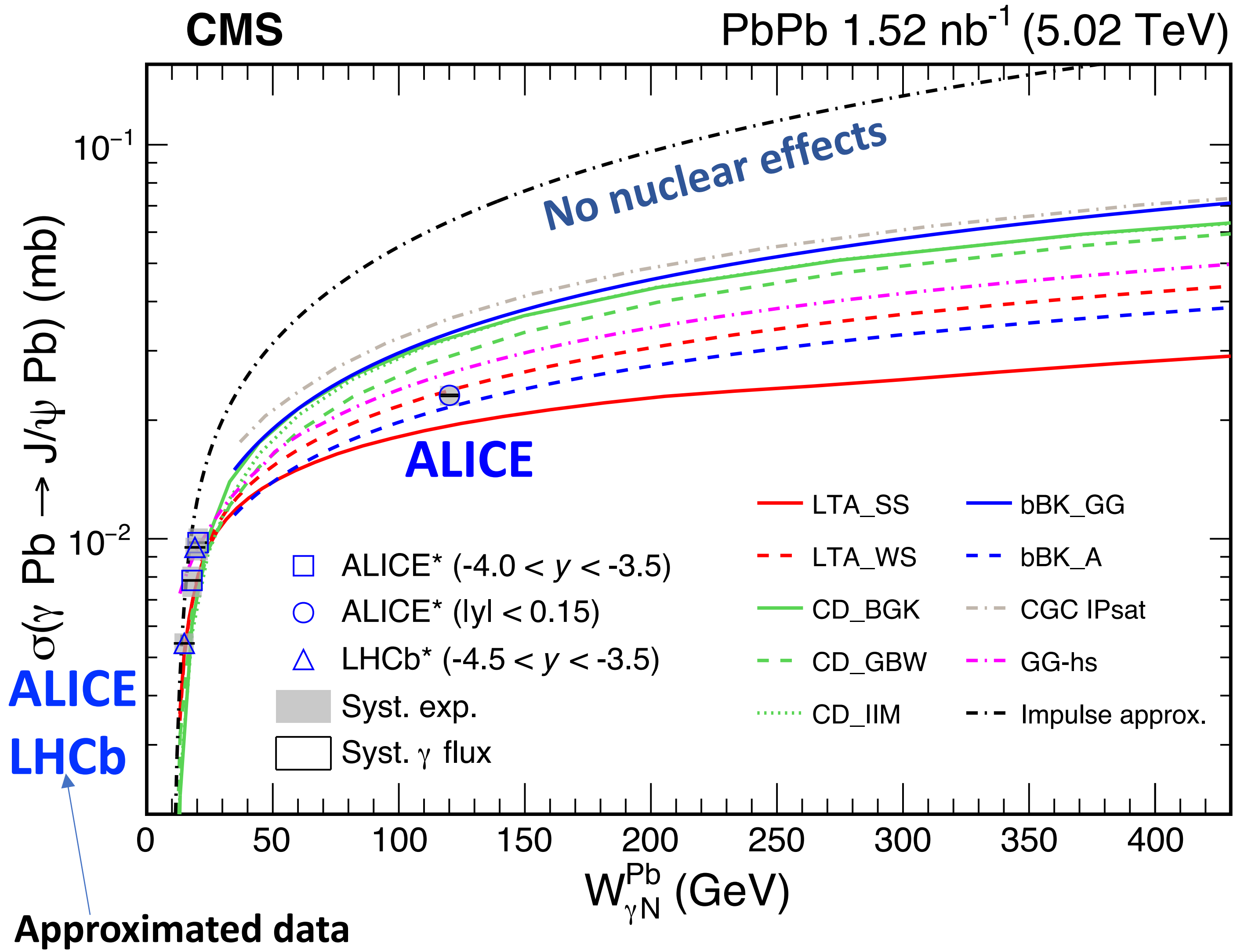


- First coherent J/Ψ measurement from different neutron classes
- No model can describe the data in different neutron classes

Allow to disentangle the low- and high- energy photon-nucleus contributions of a single γ+Pb.

Coherent J/Ψ Cross Section of Single **γ+Pb vs. W**

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

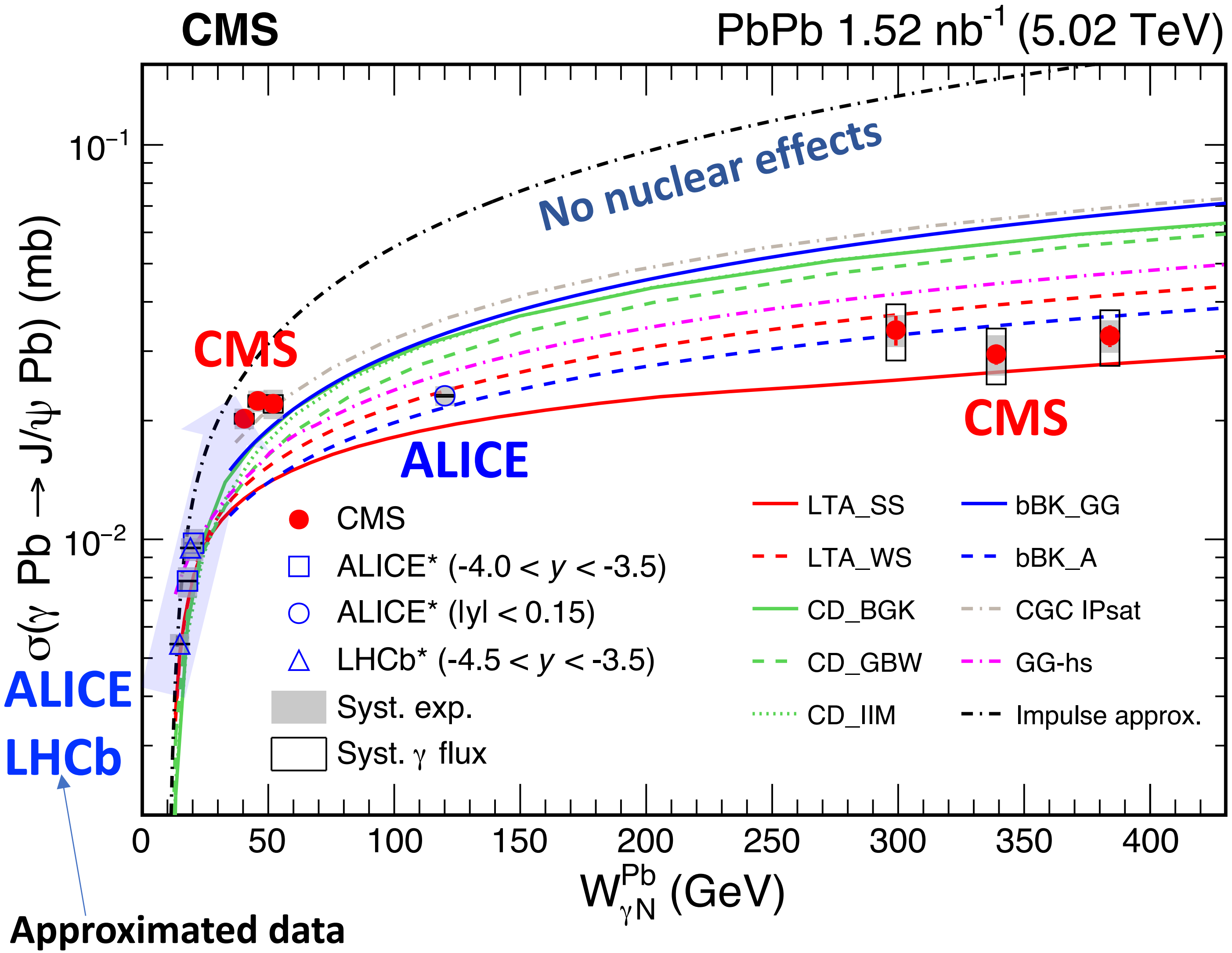


ALICE, LHCb vs. IA:

- Data is close to IA at low W.
- Data is significant lower than IA at W~125 GeV.

Coherent J/Ψ Cross Section of Single **γ+Pb** vs. W

CMS: arXiv:2303.16984



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New data from **CMS**:

- **Rapid increase** at W<40 GeV.

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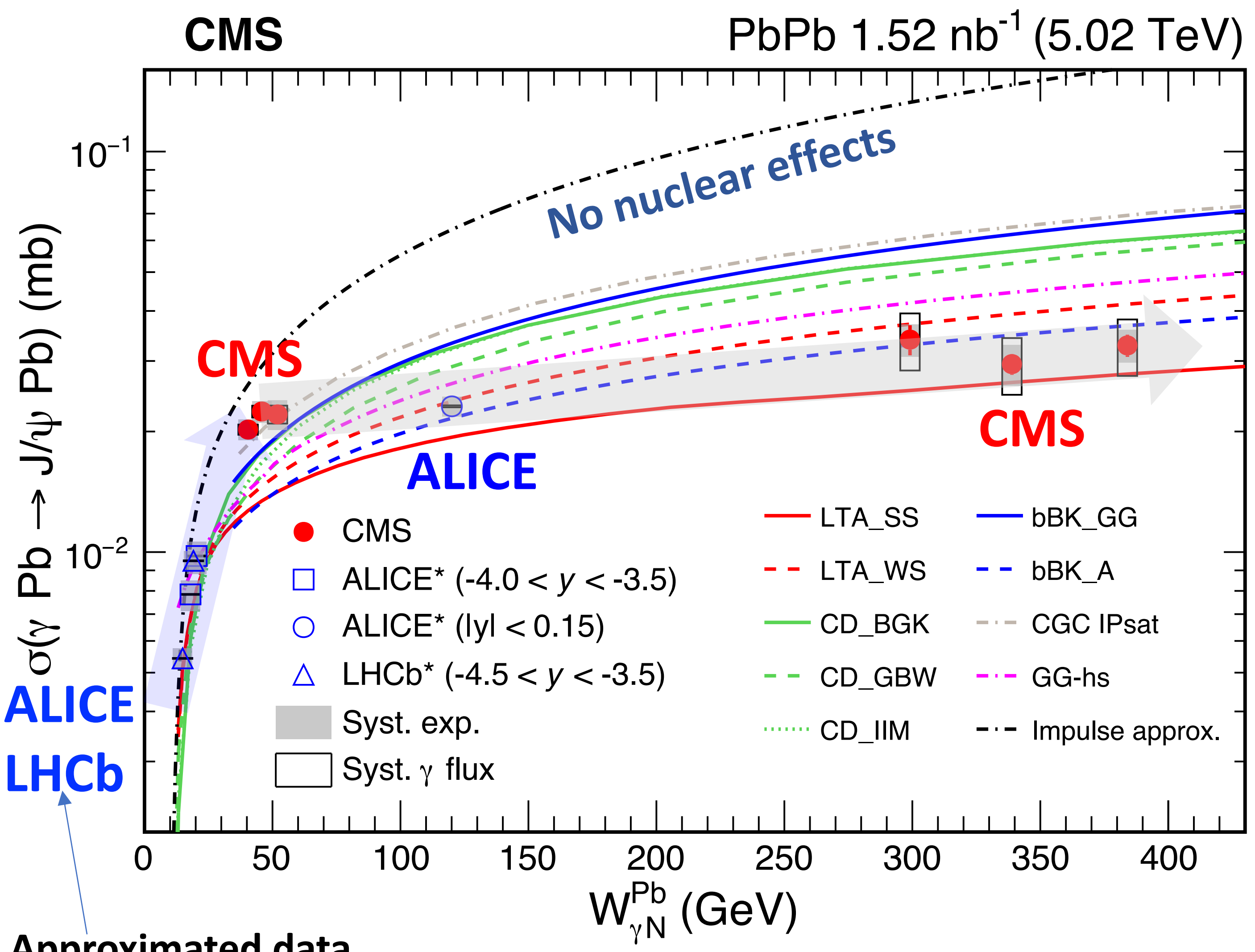

Approximated data

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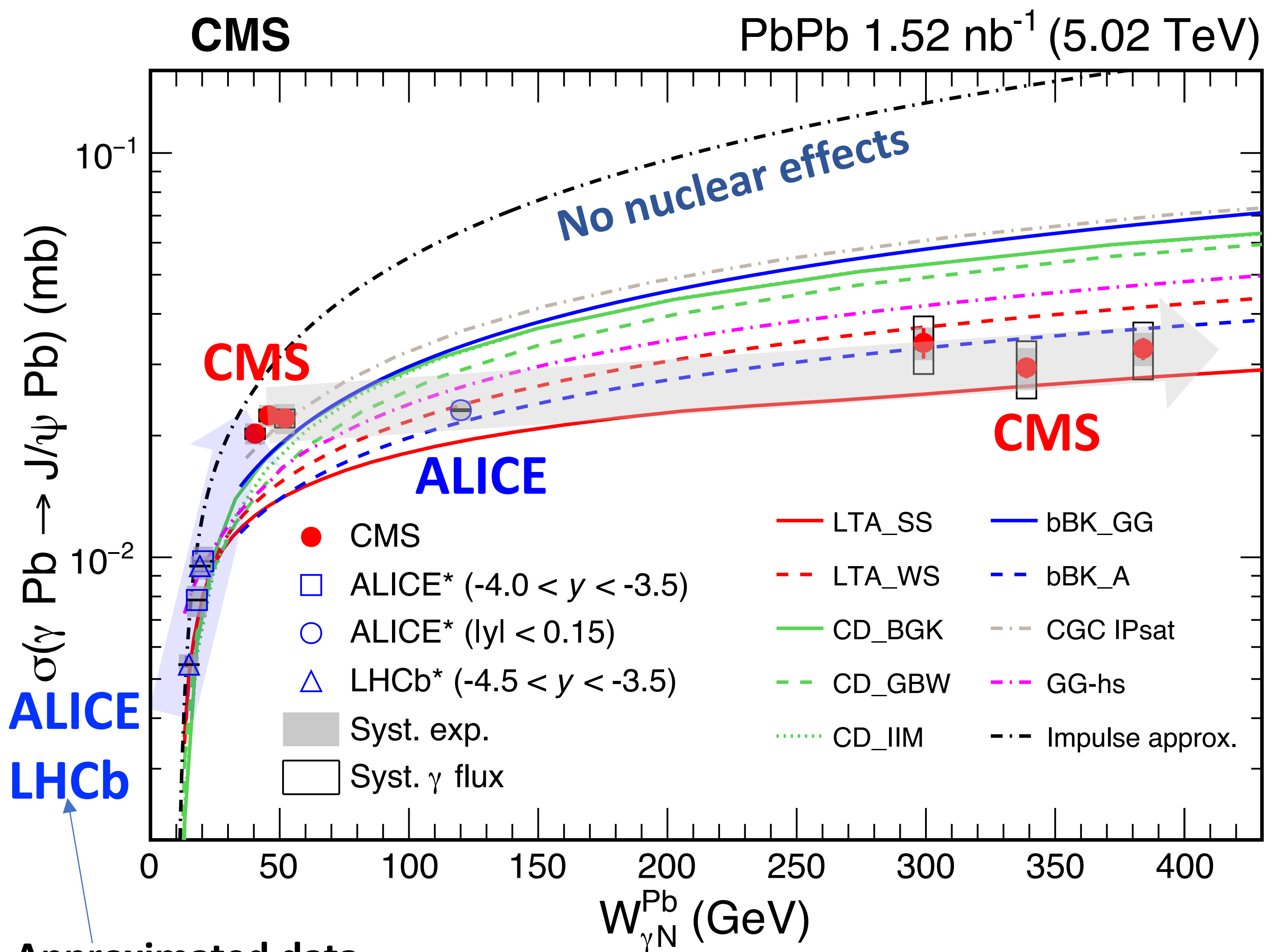

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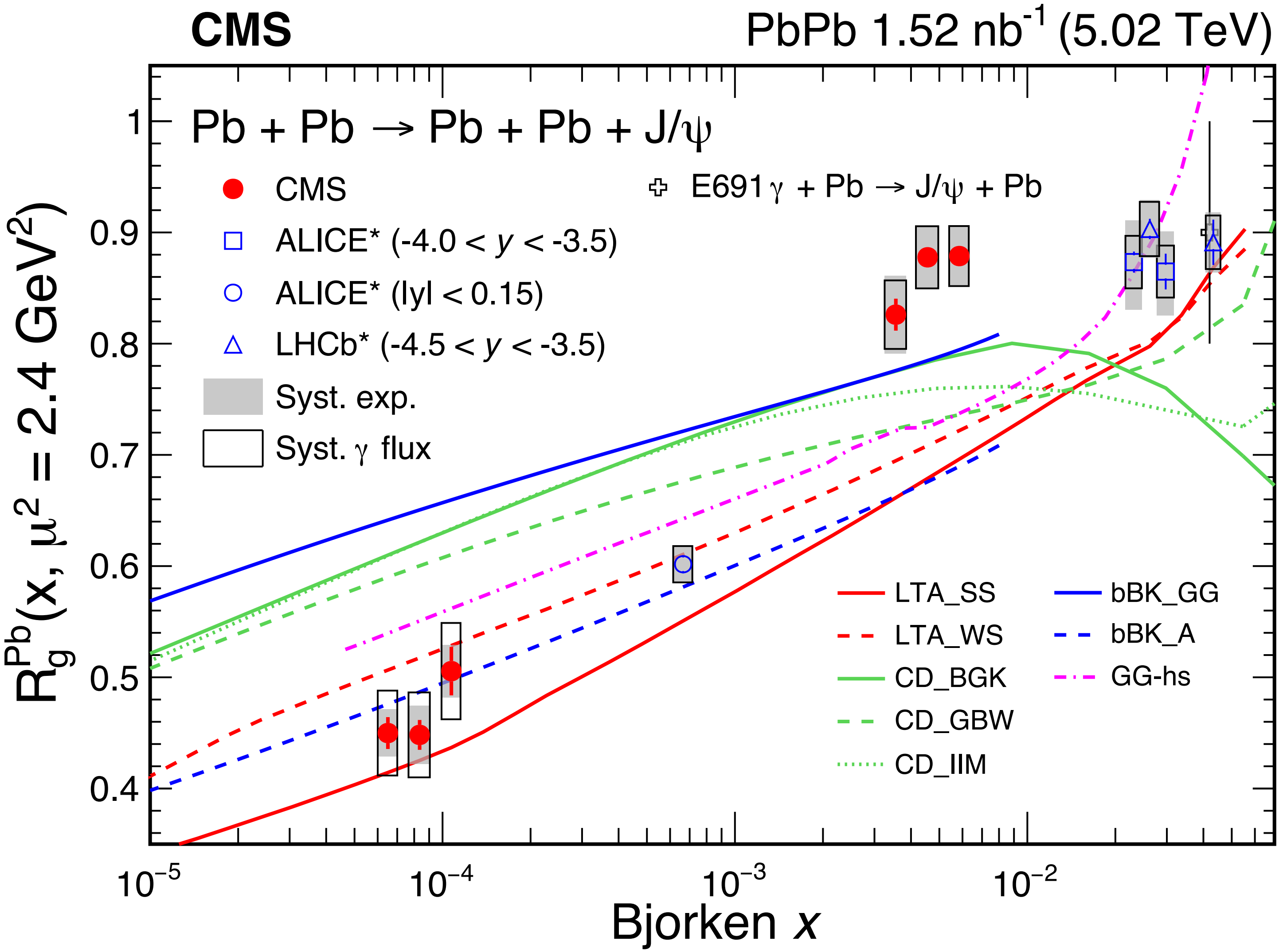
No models can describe the entire data distribution.

Nuclear Gluon Suppression Factor

CMS: arXiv:2303.16984



$$x = \frac{M_{VM}}{\sqrt{s_{NN}}} e^{\mp y}$$

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

Impulse approx. (IA) neglects all nuclear effects.

- R_g represents nuclear gluon suppression factor at LO.

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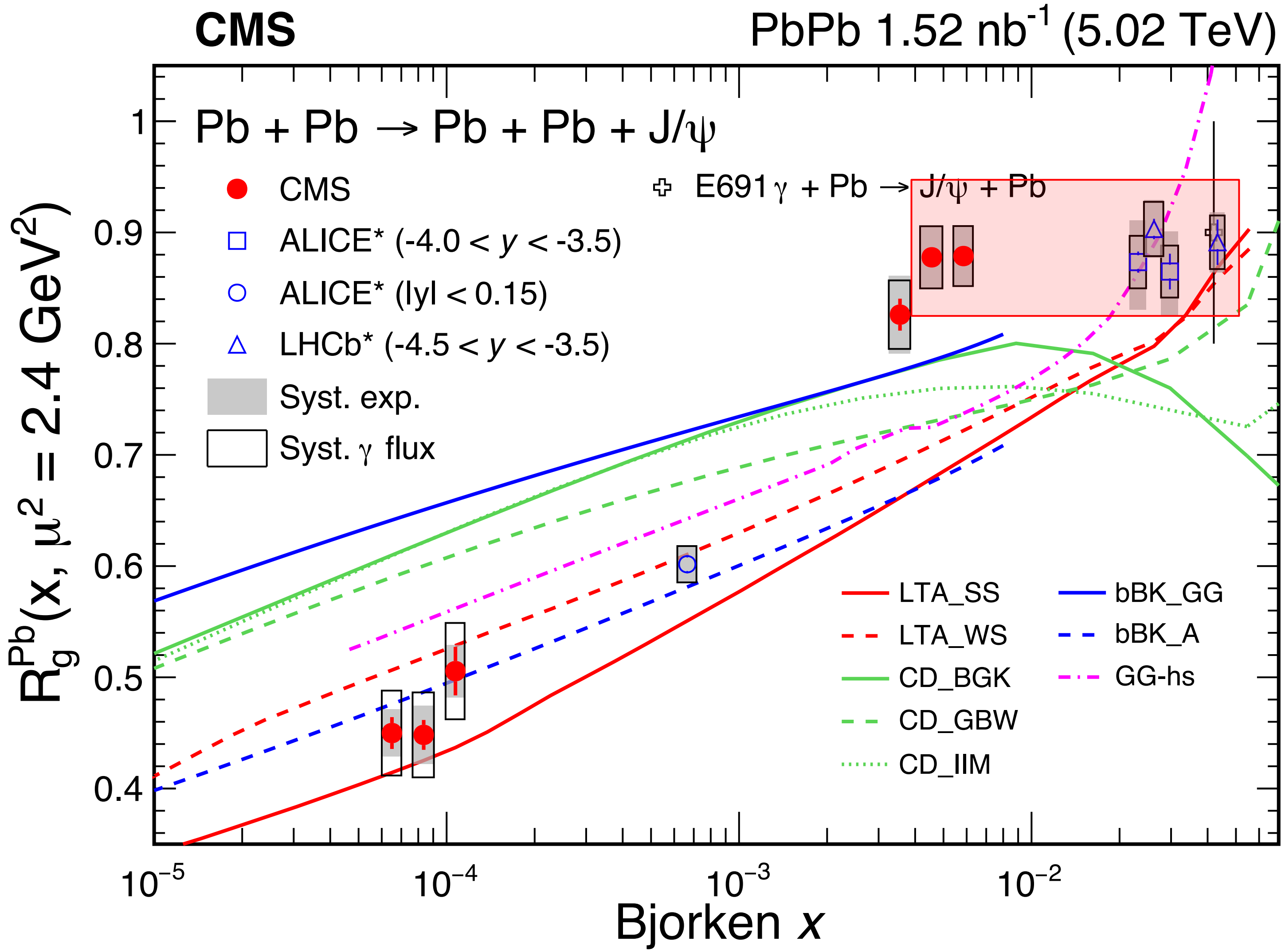

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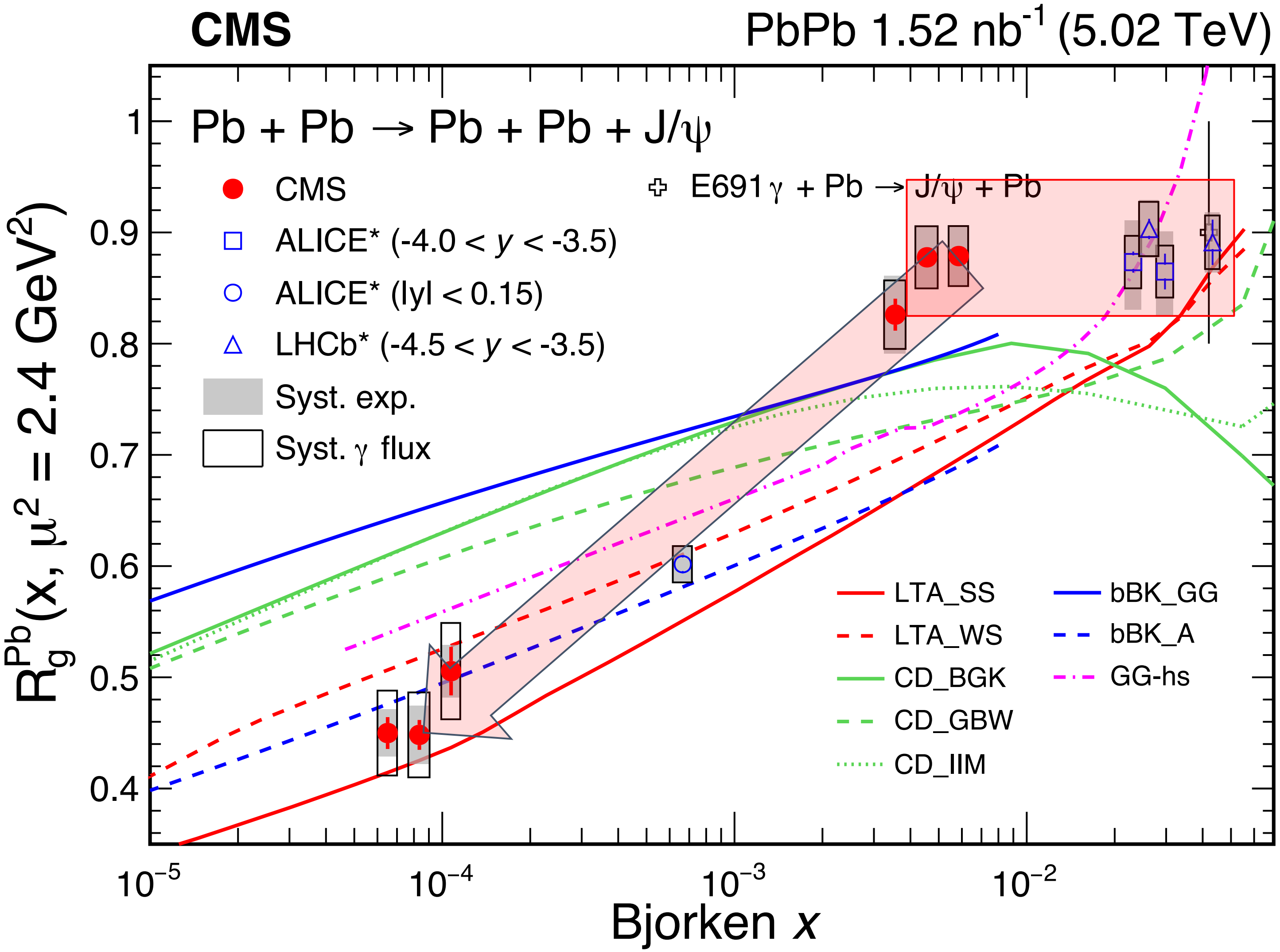

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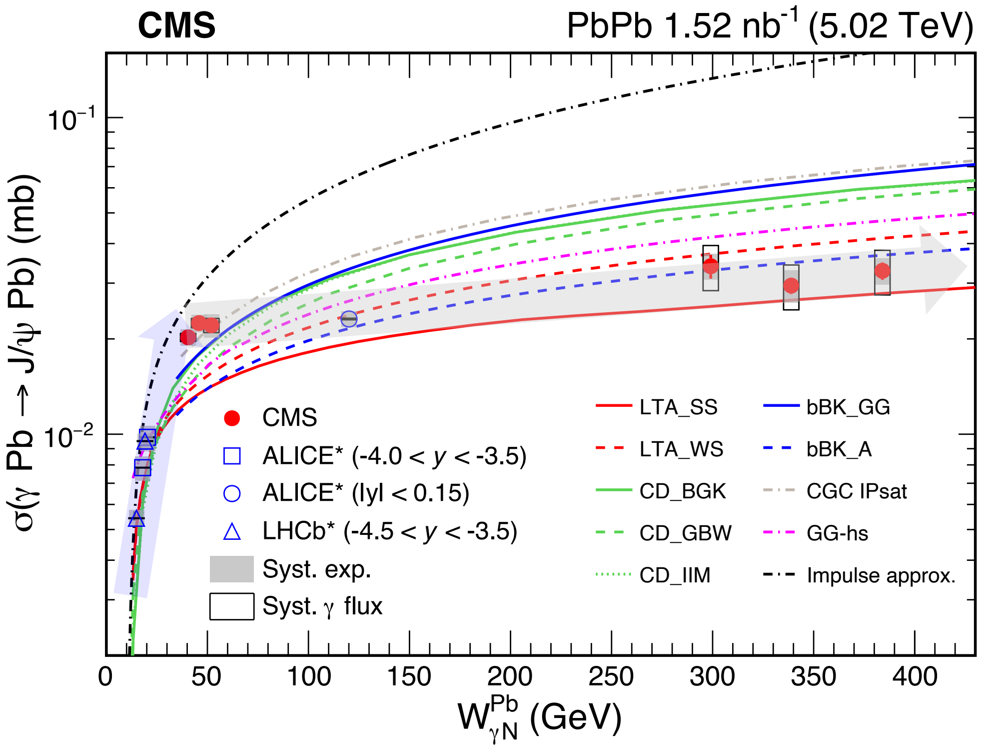
Impulse approx. (IA) neglects all nuclear effects.

- R_g represents nuclear gluon suppression factor at LO.
- At high-x region: **flat** trend.
- Quickly **decrease** towards lower x region.

Beyond model expectation

What Physics Behind?

CMS: arXiv:2303.16984



- σ stops rapid rising trend → splitting and recombination of gluons become equal
  - **Clear evidence for gluon saturation!!?**

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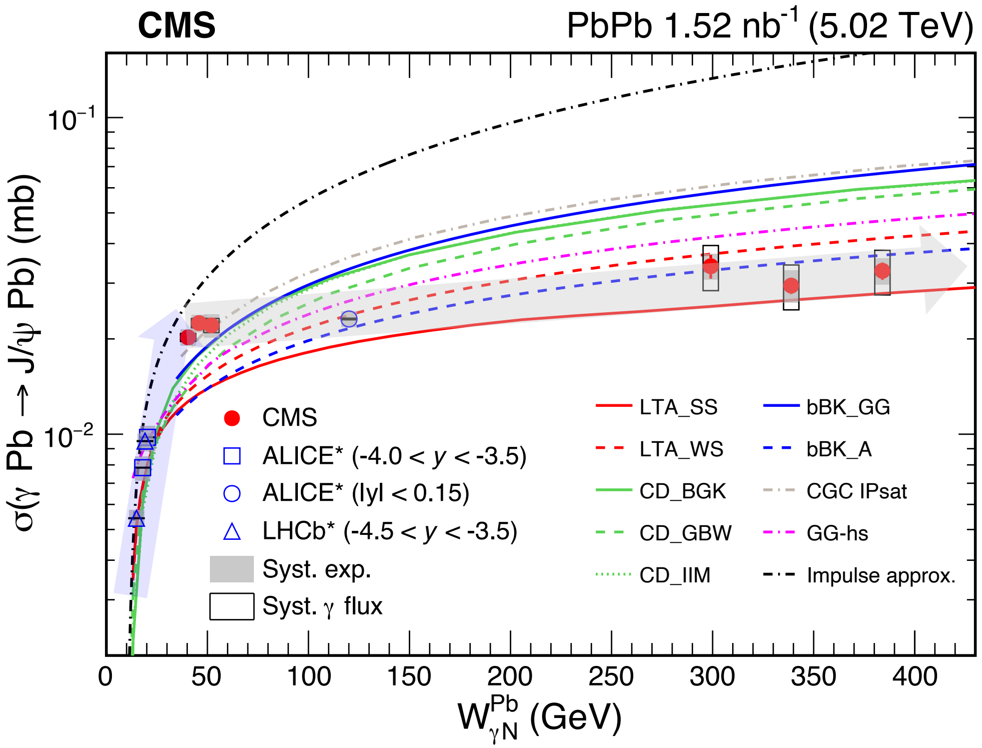
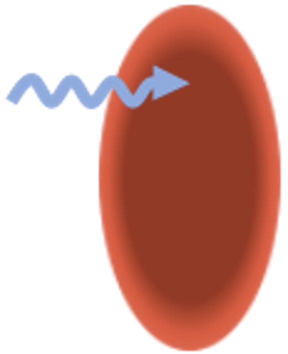




$$\hat{\sigma}^{\text{inel}}_{\text{PQCD}} \leq \hat{\sigma}_{\text{black}} = \pi R^2_{\text{target}}$$

L. Frankfurt **PRL 87 (2001)192301**
L. Frankfurt **PLB 537 (2002) 51**

- σ stops rapid rising trend → splitting and recombination of gluons become equal
  - **Clear evidence for gluon saturation!!?**

OR

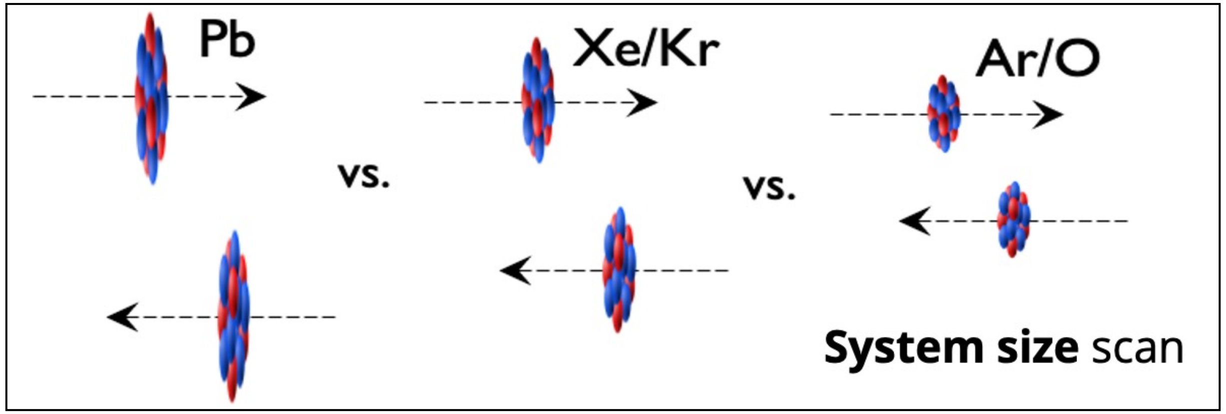
- Nucleus target becomes totally absorptive to incoming photons → **Black Disk Limit!!?**
  - **Nucleus becomes a black disk, internal structure is invisible.**

Future Opportunities

Various VMs in different nucleus-nucleus UPCs with **neutron taggings**

- ➢ Control of **dipole sizes** and **hard scales**.
- ➢ Variation of **saturation scales**
- ➢ **A dependences**
- ➢ **Incoherent** productions

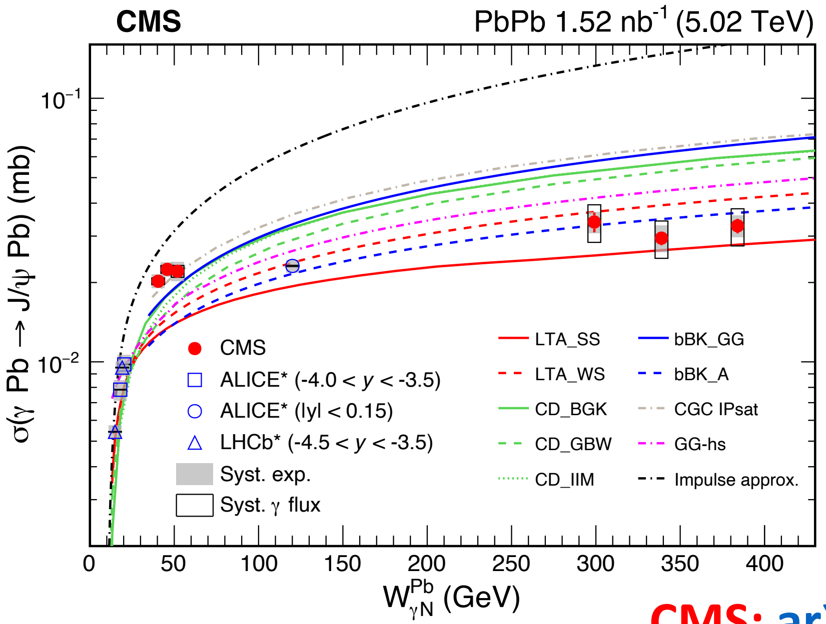
PbPb L_{int} = 13 nb^{-1}						
Meson	σ	All Total	Central 1 Total	Central 2 Total	Forward 1 Total 1	Forward 2 Total
$\rho \to \pi^+\pi^-$	5.2b	68 B	5.5 B	21B	4.9 B	13 B
$\rho' \to \pi^+\pi^-\pi^+\pi^-$	730 mb	9.5 B	210 M	2.5 B	190 M	1.2 B
$\phi \to K^+K^-$	0.22b	2.9 B	82 M	490 M	15 M	330 M
$J/\psi \to \mu^+\mu^-$	1.0 mb	14 M	1.1 M	5.7 M	600 K	1.6 M
$\psi(2S) \to \mu^+\mu^-$	30μb	400 K	35 K	180 K	19 K	47 K
$\Upsilon(1S) \to \mu^+\mu^-$	2.0 μb	26 K	2.8 K	14 K	880	2.0 K

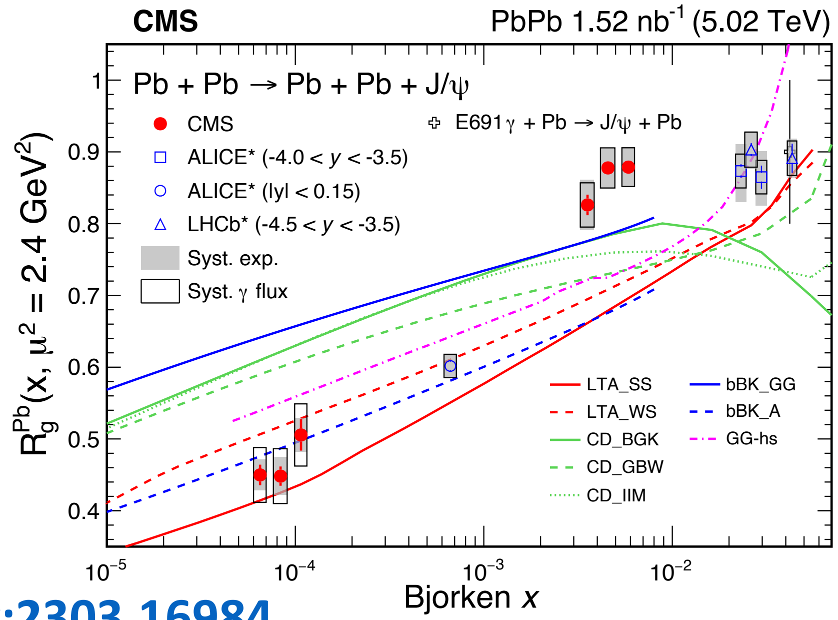


CERN yellow report, arXiv:1812.06772

Summary

- First time, **disentangled the low and high γ energy** contributions to coherent J/Ψ
- CMS measured coh. J/Ψ at a **new unprecedentedly low-x gluon regime** (10^{-4}-10^{-5})
- **σ(J/Ψ) vs. W** not predicted by state of the art models
  - **Gluon saturation?** or **black disk limit?** or **other physic effects**?
- **HL**-LHC including CMS **Phase-2 upgrades** will bring new exciting opportunities



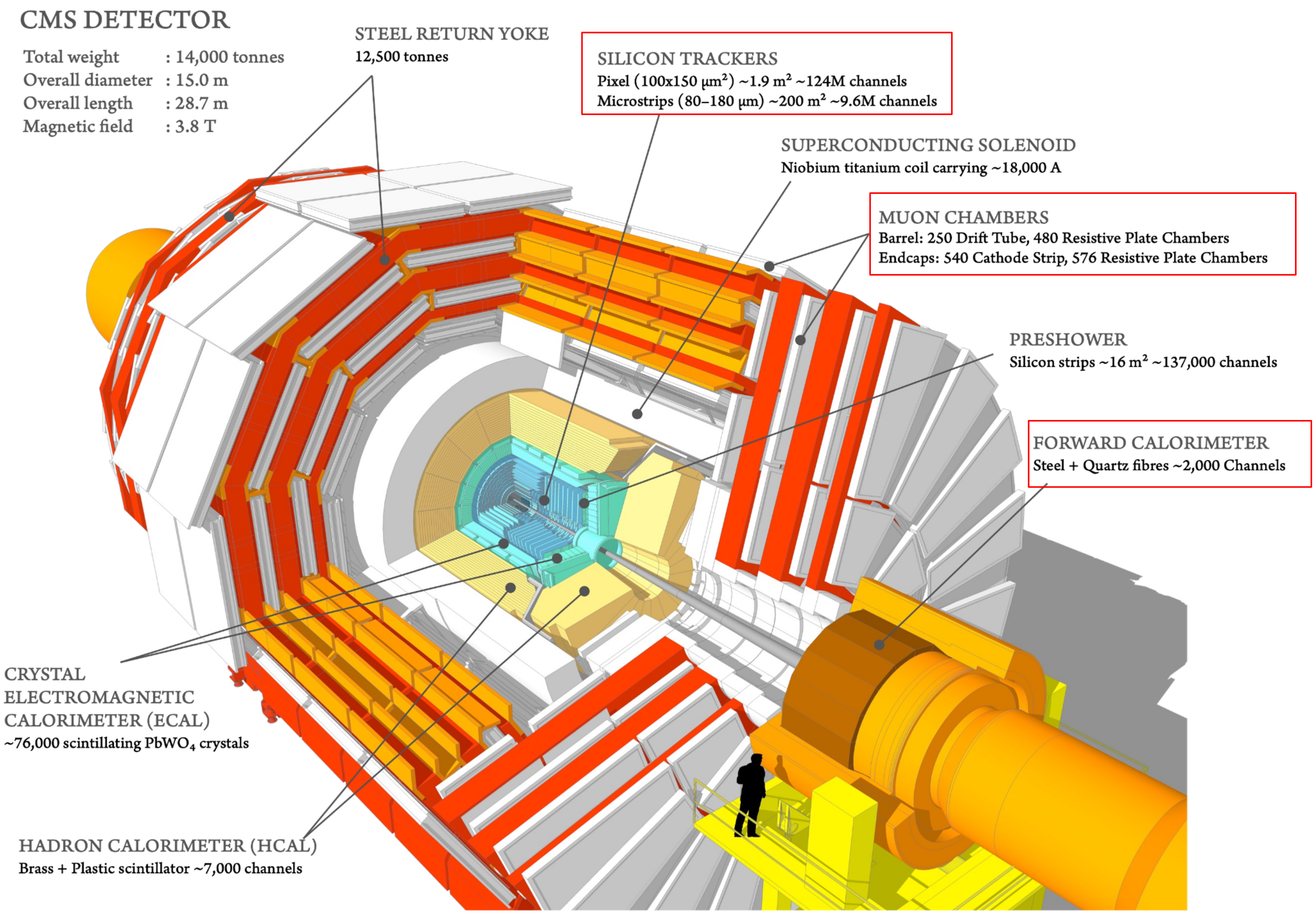


CMS: arXiv:2303.16984

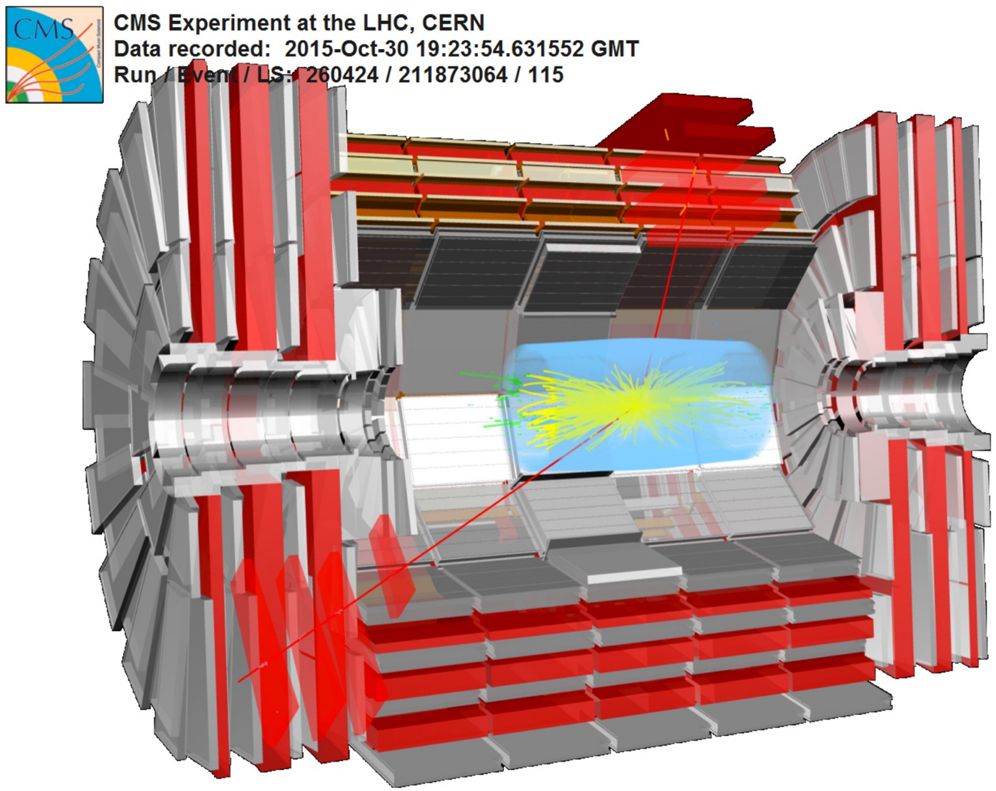
Thank you for your attention!

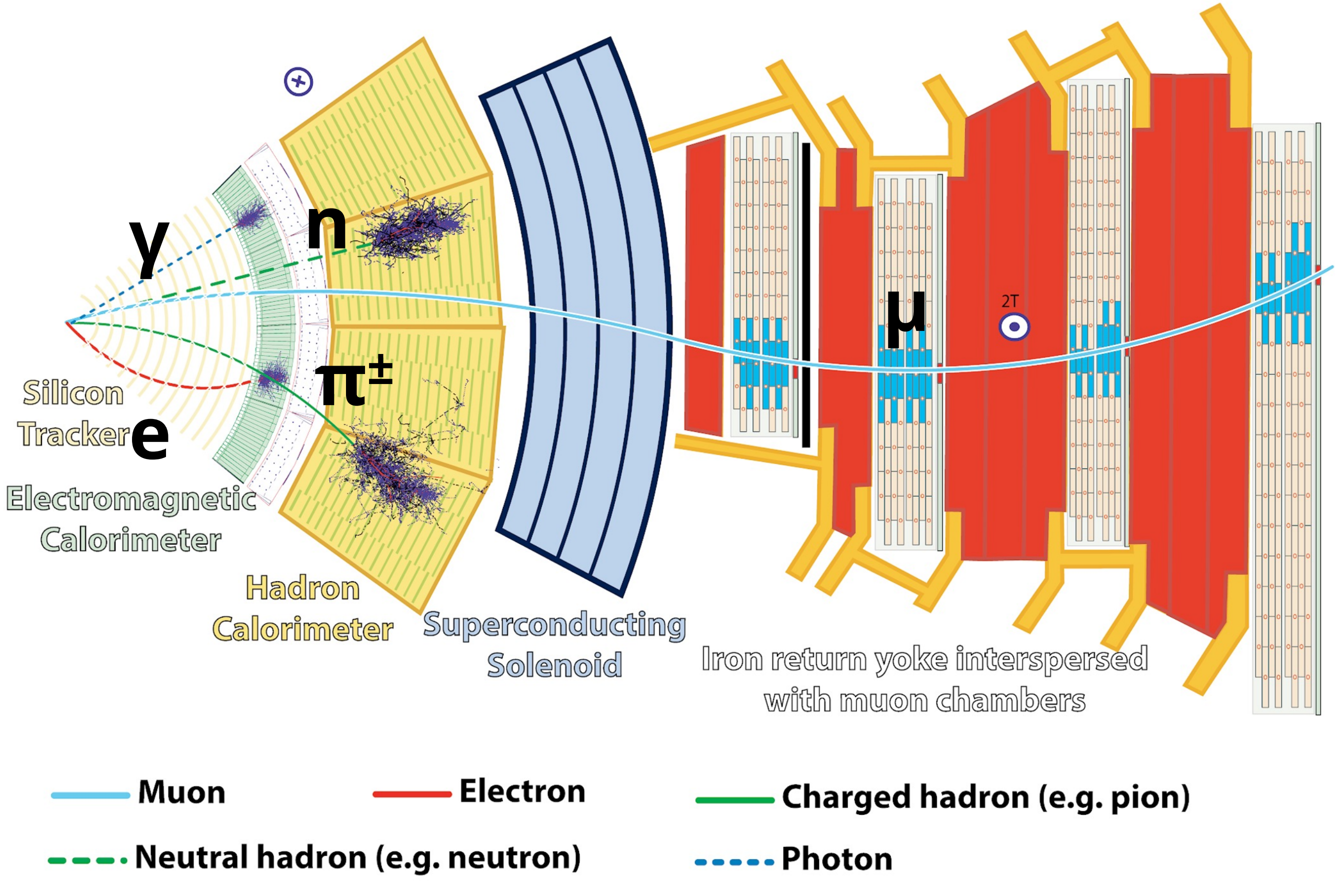
Backup Slides

Compact Muon Solenoid Detector



Muon Reconstruction



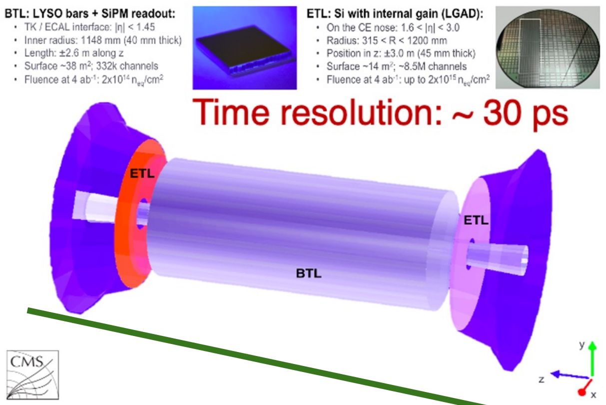


- Tracker and muon detectors used to reconstruct/identify muons.

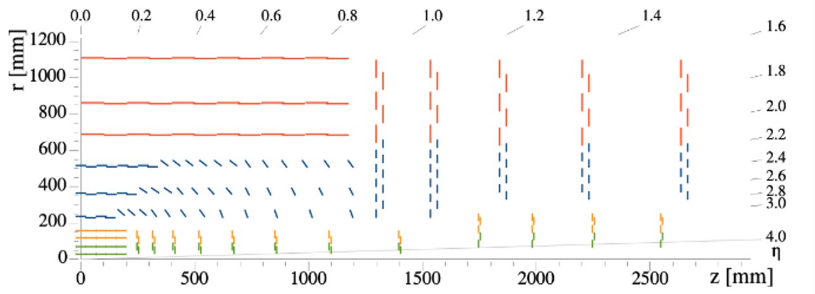
Understand Nucleon Structure via DIS

Future Opportunities

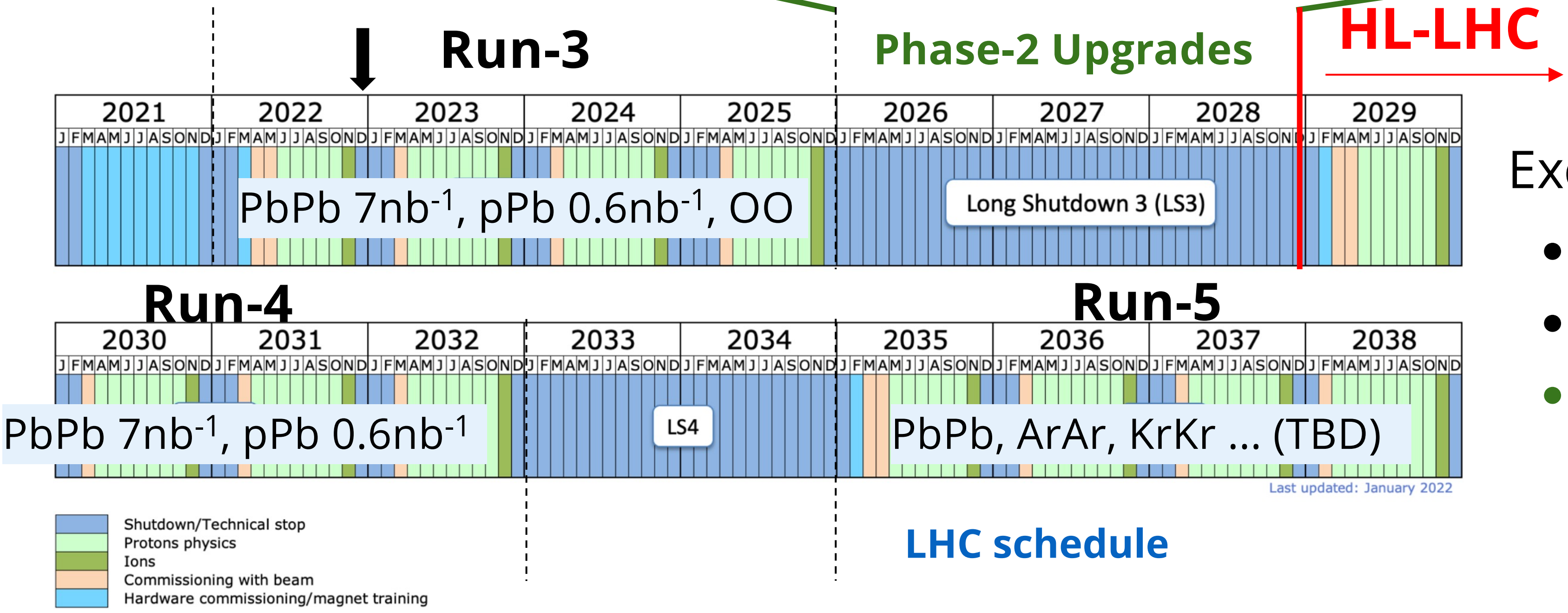
MIP Timing Detector for PID



Tracker with |η|<4 and better resolution, lighter materials



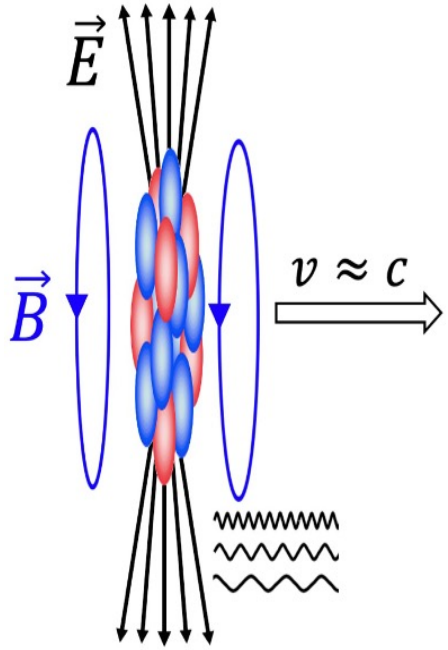
- Muon systems with |η|<**2.8**
- Trigger and DAQ rate: ~**10x**



Exciting opportunities ahead by:

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

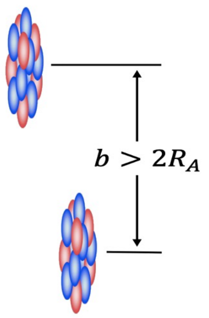
Ultra-Peripheral Collision (UPC)

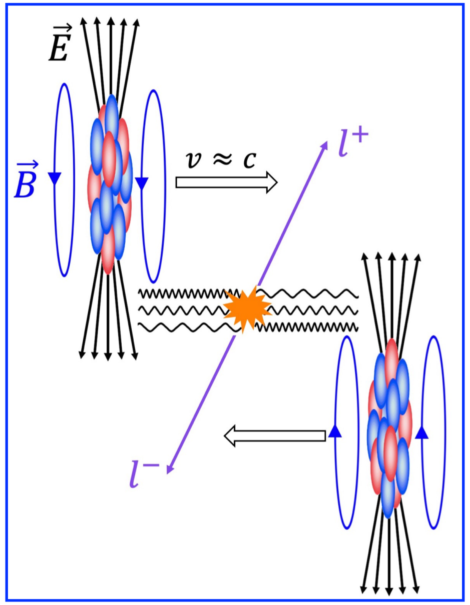


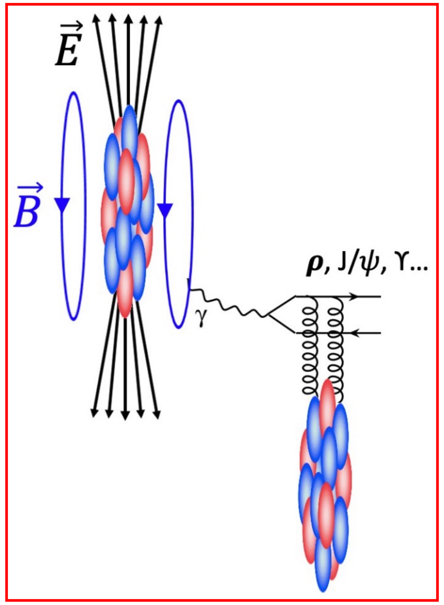
- Lorentz contracted EM fields → flux of quasi-real photons ($Q^2 < \hbar^2/R^2$).
- The photon flux $\propto Z^2$.
- Photon kinematics: $p_T < \hbar/R_A \sim 30$ MeV ($E_{max} \sim 80$ GeV) at LHC.

Heavy ion collider is also a Light-Light and Light-Nucleus collider

UPC:







...

Photon Flux: **Point-like** vs. **Realistic**

CPC 277 (2022) 108388

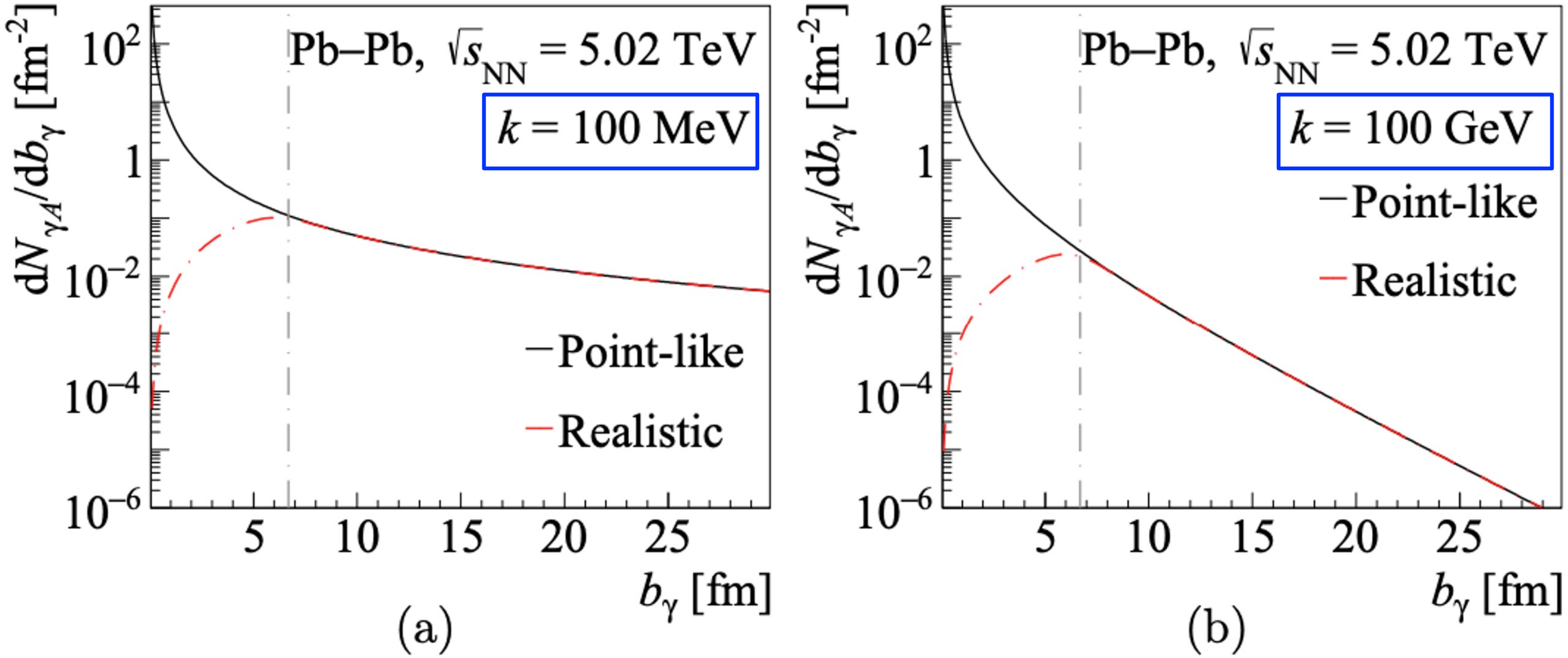
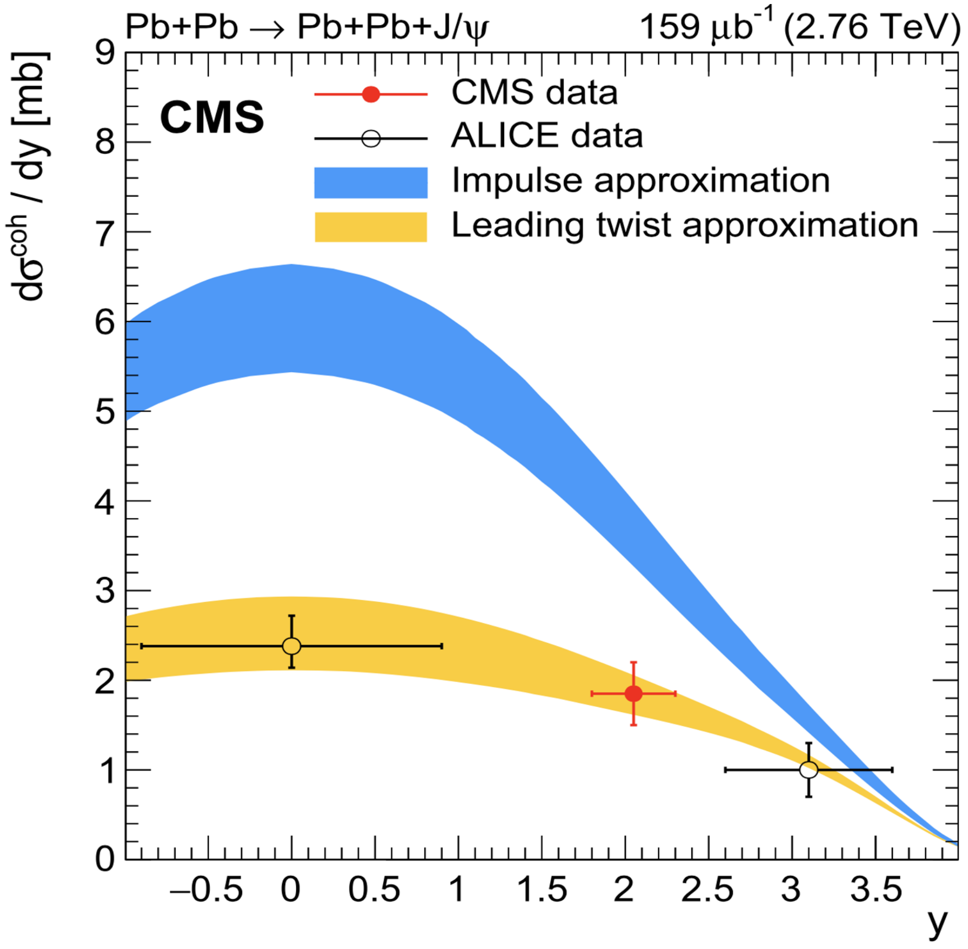


Figure 4: (Color online) Photon fluxes coming from a nucleus $N_{\gamma A}$ in the point-like source approximation and the realistic description as functions of impact parameter b_γ calculated at different photon energies: 100 MeV (a), 100 GeV (b).

Coh. Jpsi from LHC Run1 PbPb UPC

PLB 772 (2017) 489

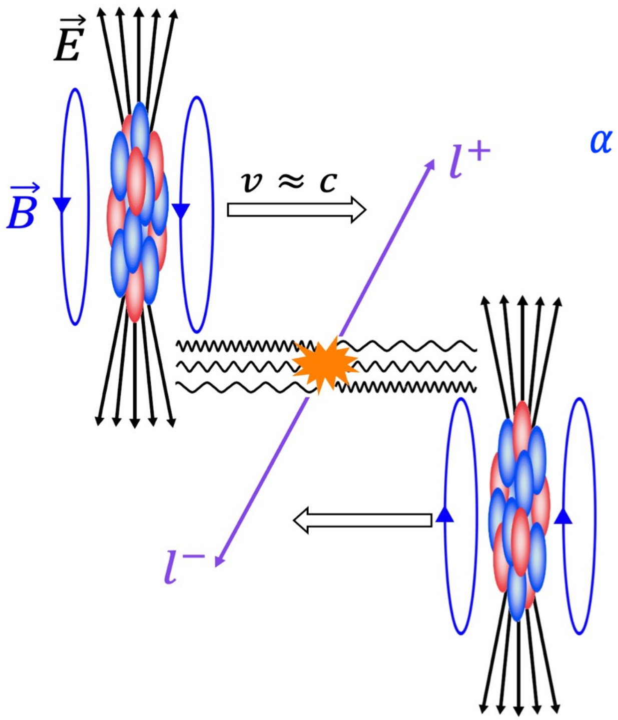


- Run 1 data from CMS and ALICE seem to be well consistent with LTA shadowing model calculations
- However,
  - large uncertainties
  - wide-y bins
  - Mixed low- and high- W contributions

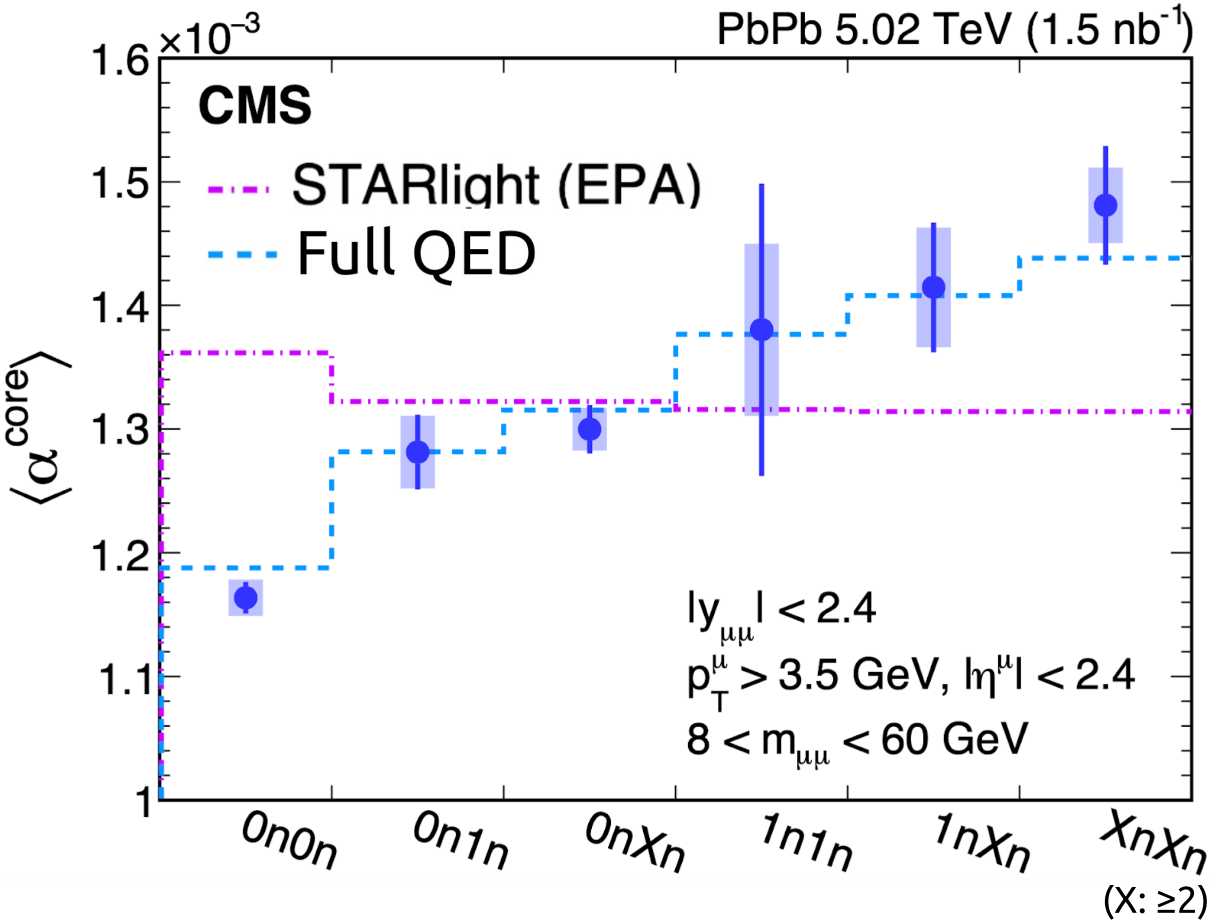
QED Dimuon with Neutron Tagging at CMS

PRL 127 (2021) 122001

$\gamma\gamma \rightarrow \mu^+\mu^-$



$\alpha = 1 - \frac{|\phi^+ - \phi^-|}{\pi}, \alpha \propto p_T^{l^+l^-}$



First direct evidence of b dependence of initial photon p_T, set strong base line for searching for possible QGP EM effects in heavy ion collisions