Probing Ultra-Dense Gluonic Matter via UPCs at CMS

Zaochen Ye (South China Normal University)

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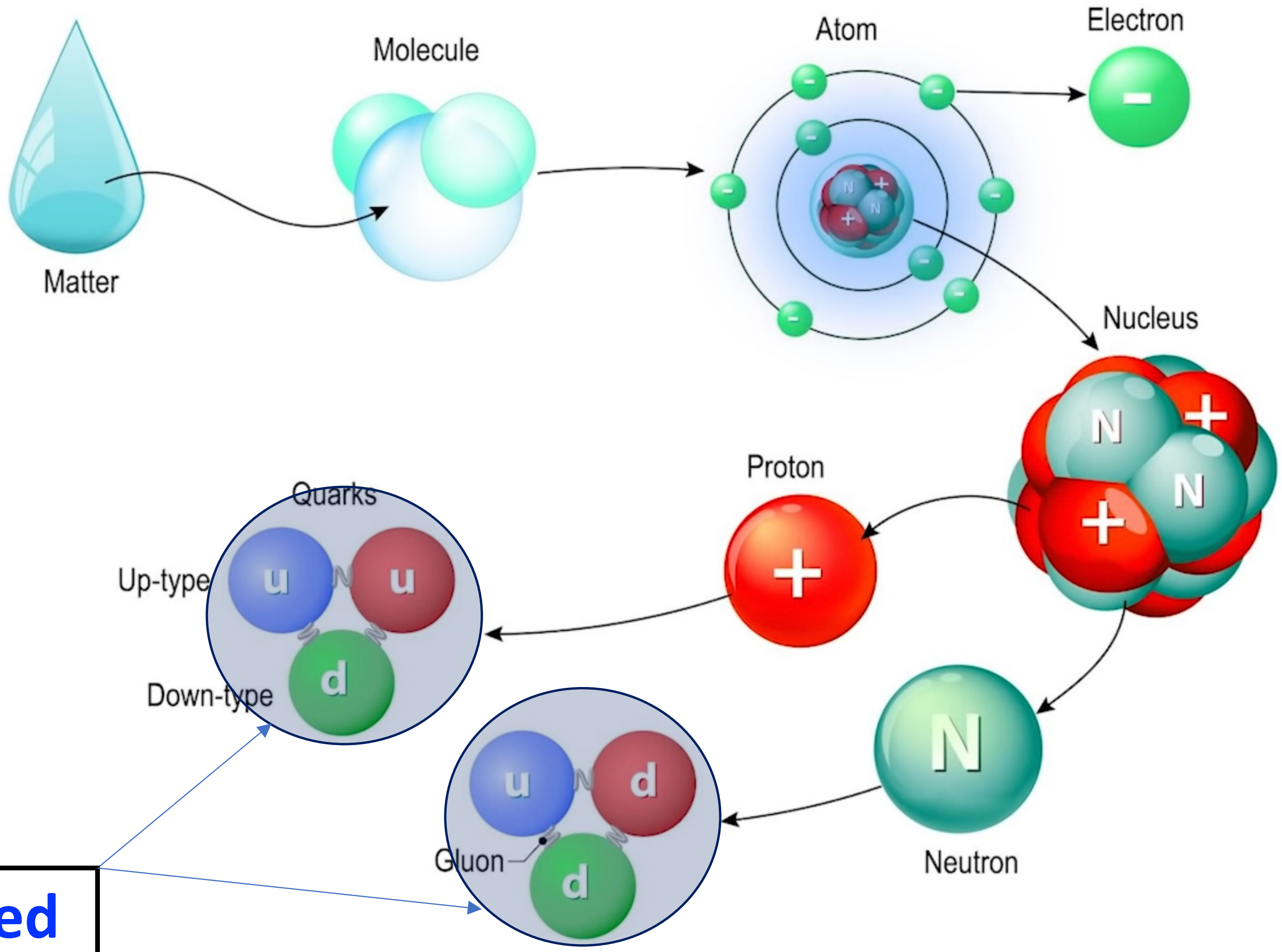
In collaboration with Wei Li, Jiazhao Lin and Shuai Yang

中国科学技术大学核物理系列小型研讨会
USTC-PNP-Nuclear Physics Mini Workshop Series

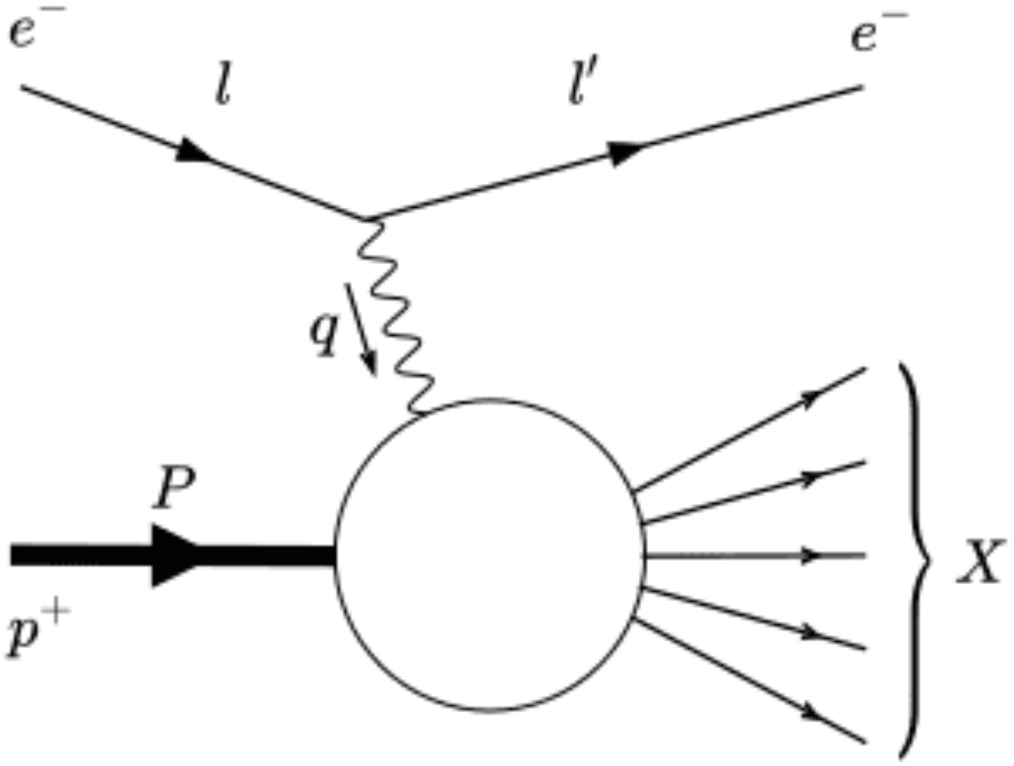
Understand Fundamental Structure of Matter



Confined

Understand Nucleon Structure via DIS

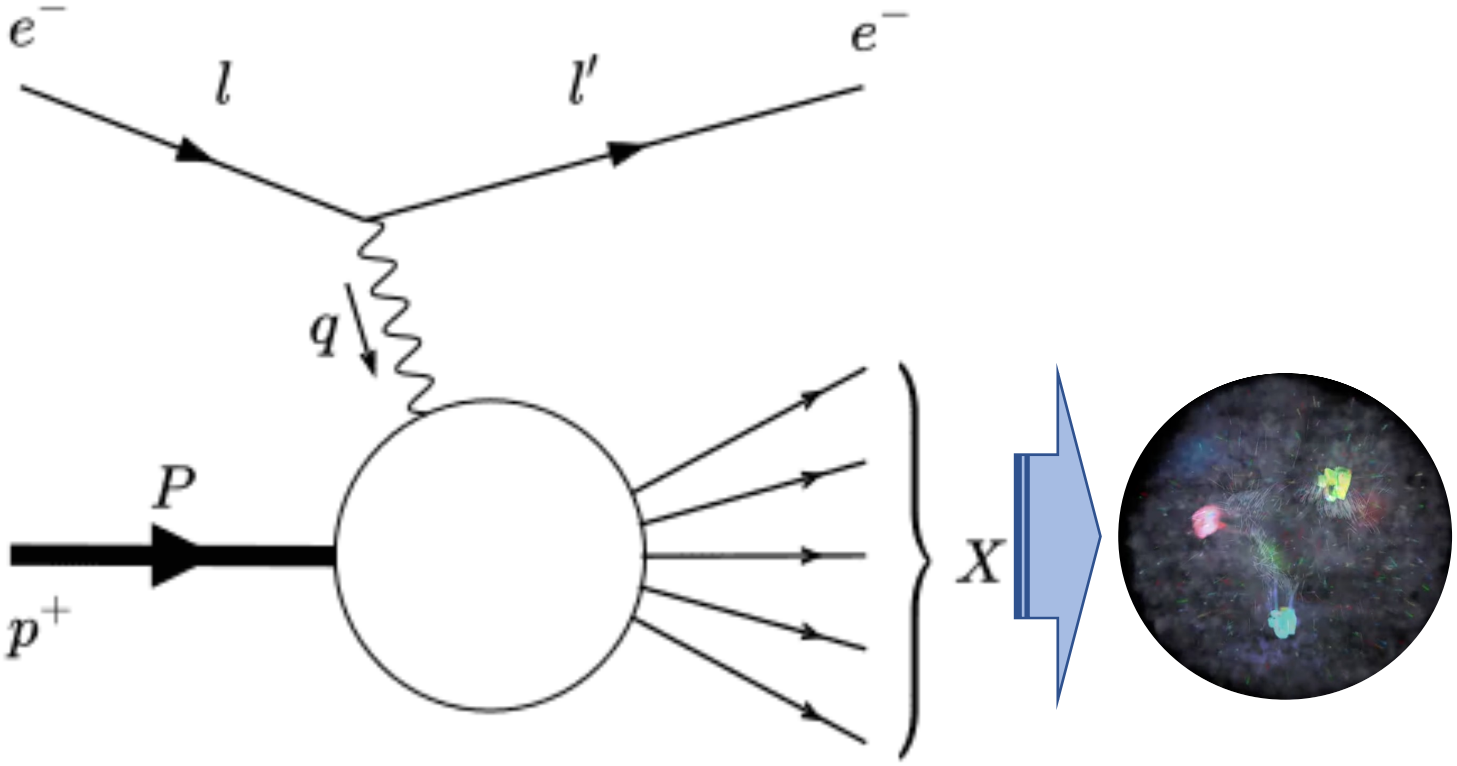
Smash them!!!



Deep Inelastic Scattering

Understand Nucleon Structure via DIS

Smash them!!!



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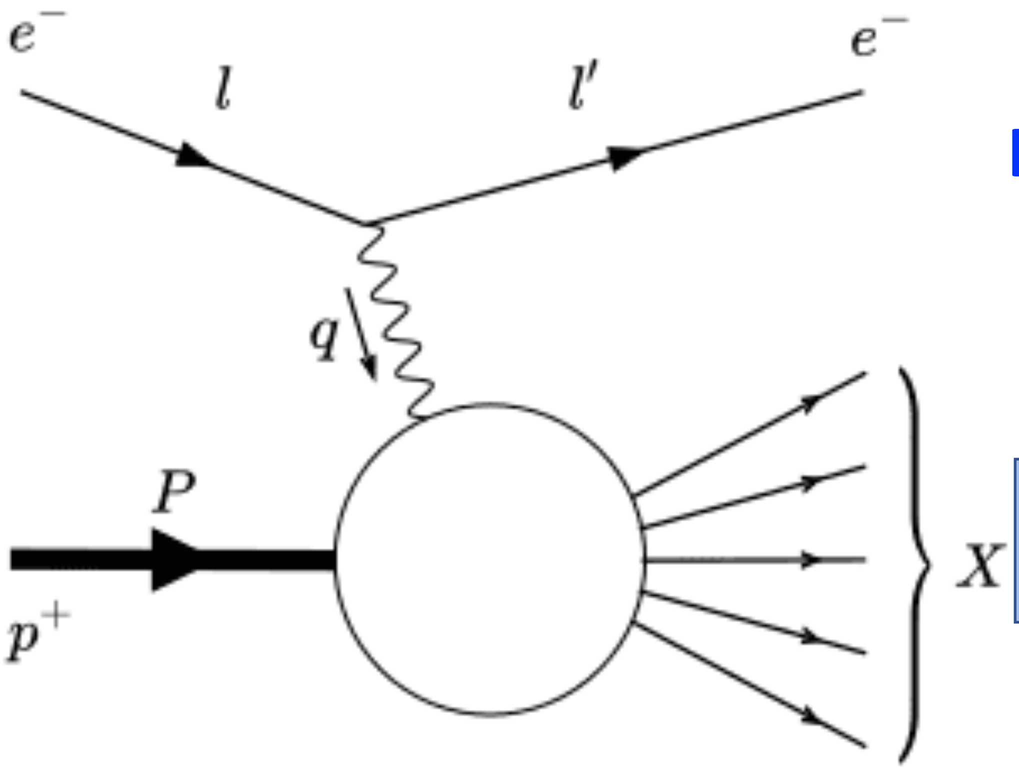
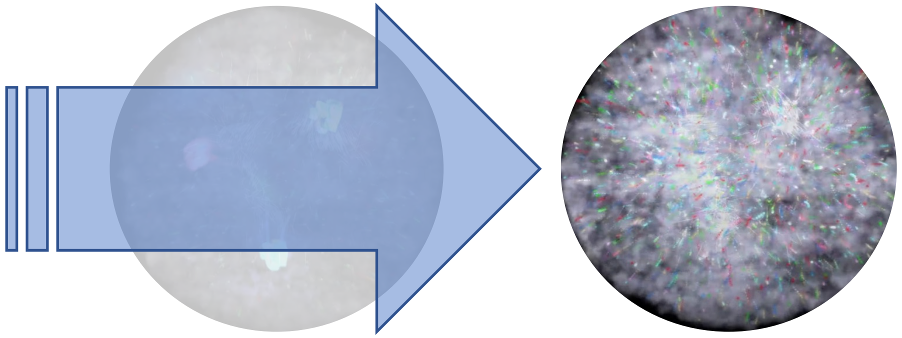


Higher energy, probing lower-x partons



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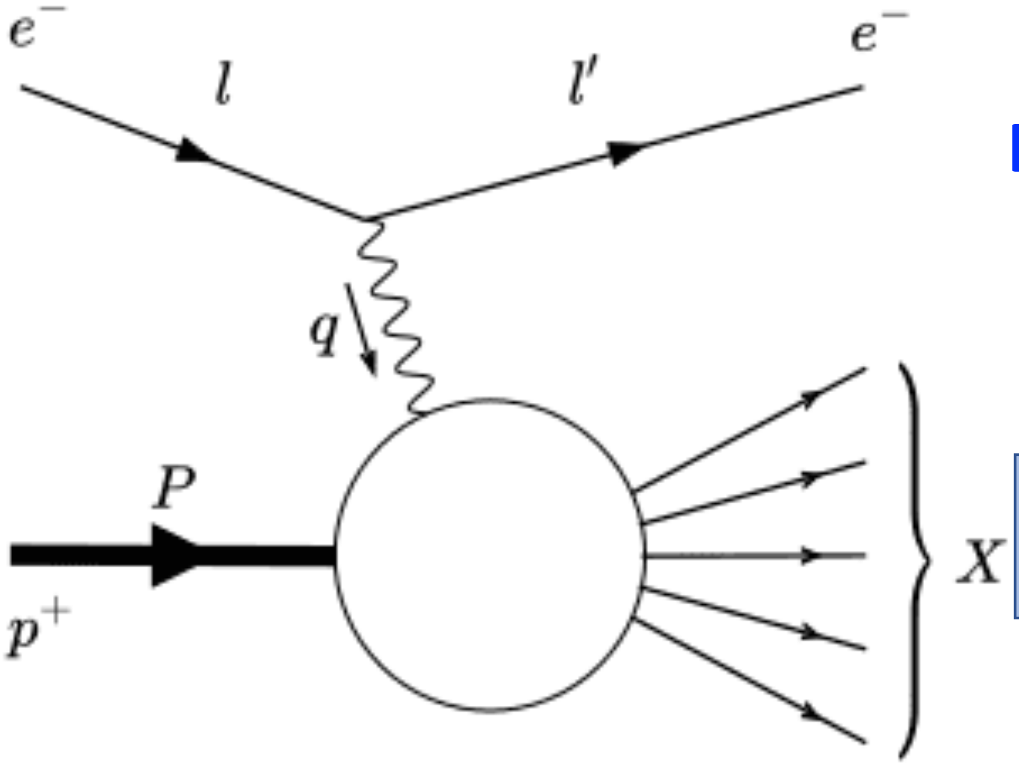

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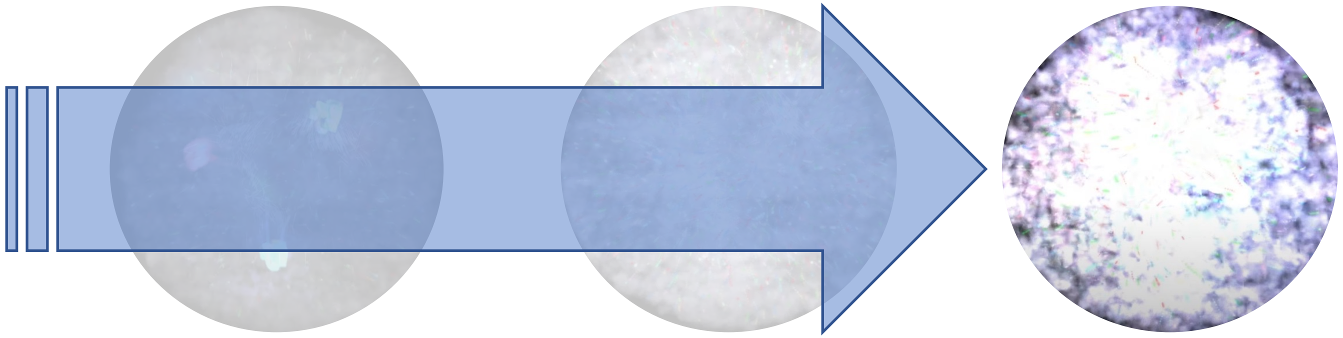
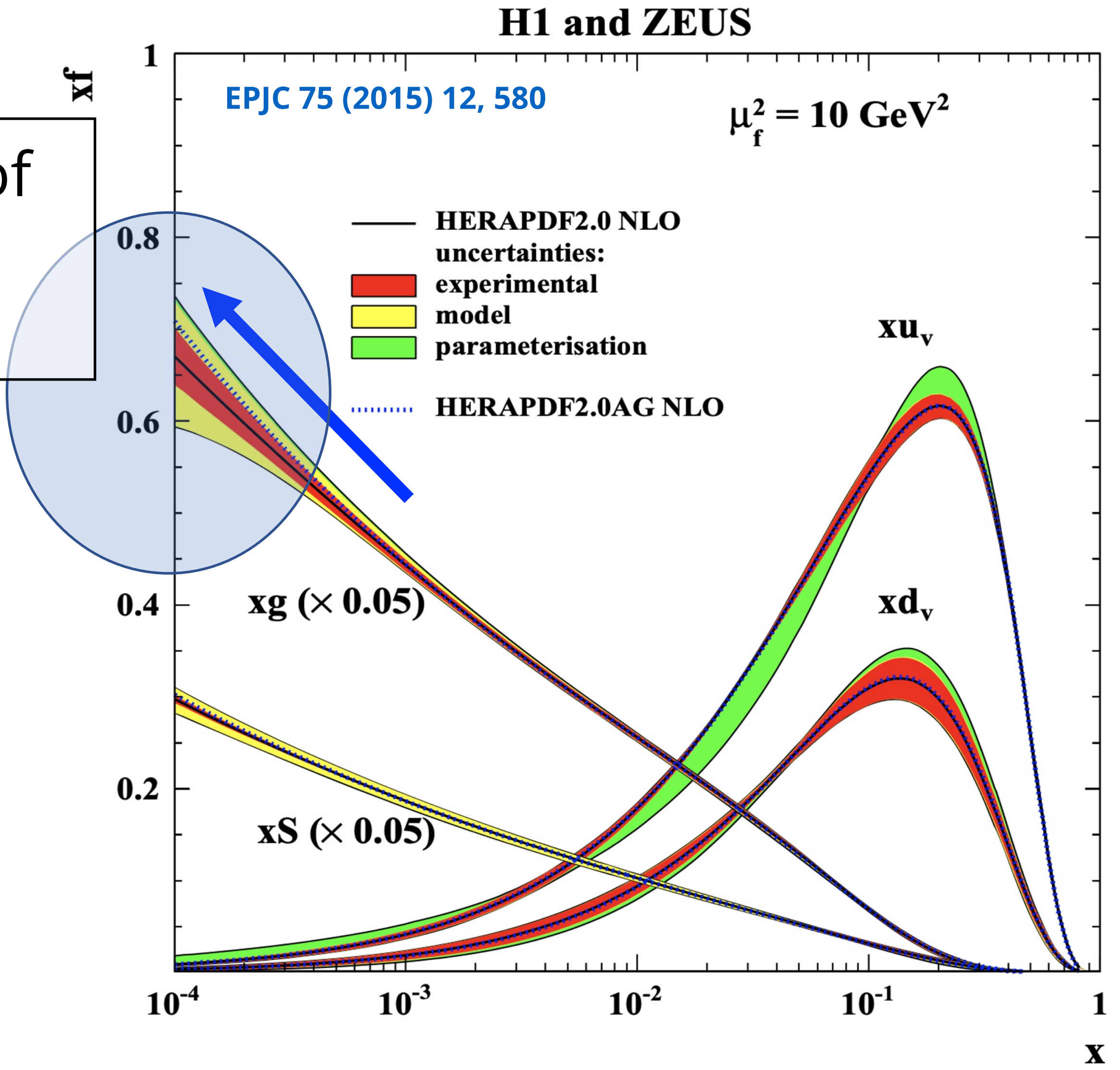


Deep Inelastic Scattering

Understand Nucleon Structure

e-p collider

Rapid increase of gluon density towards small x.



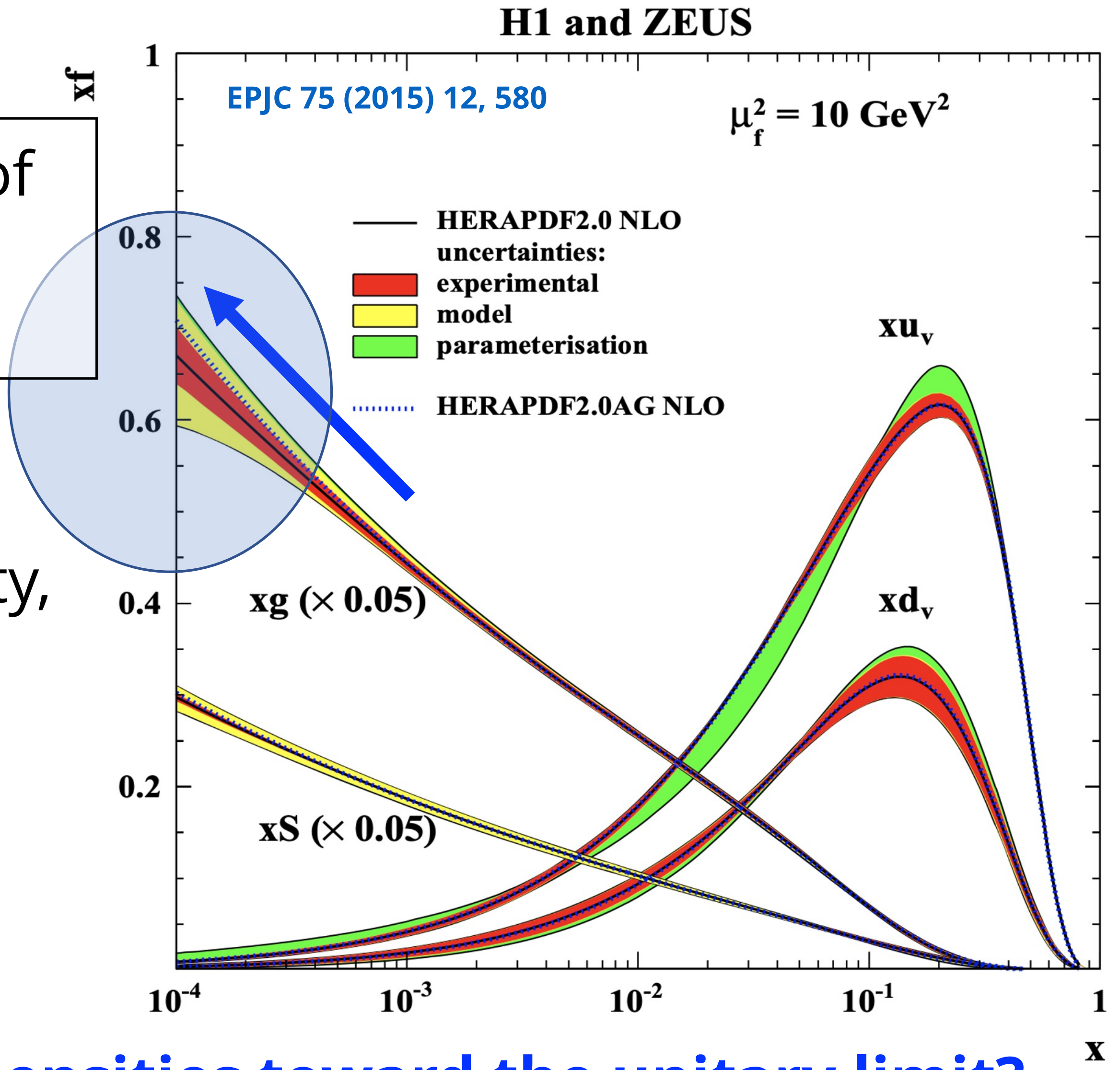
Understand Nucleon Structure

e-p collider

Rapid increase of gluon density towards small x.

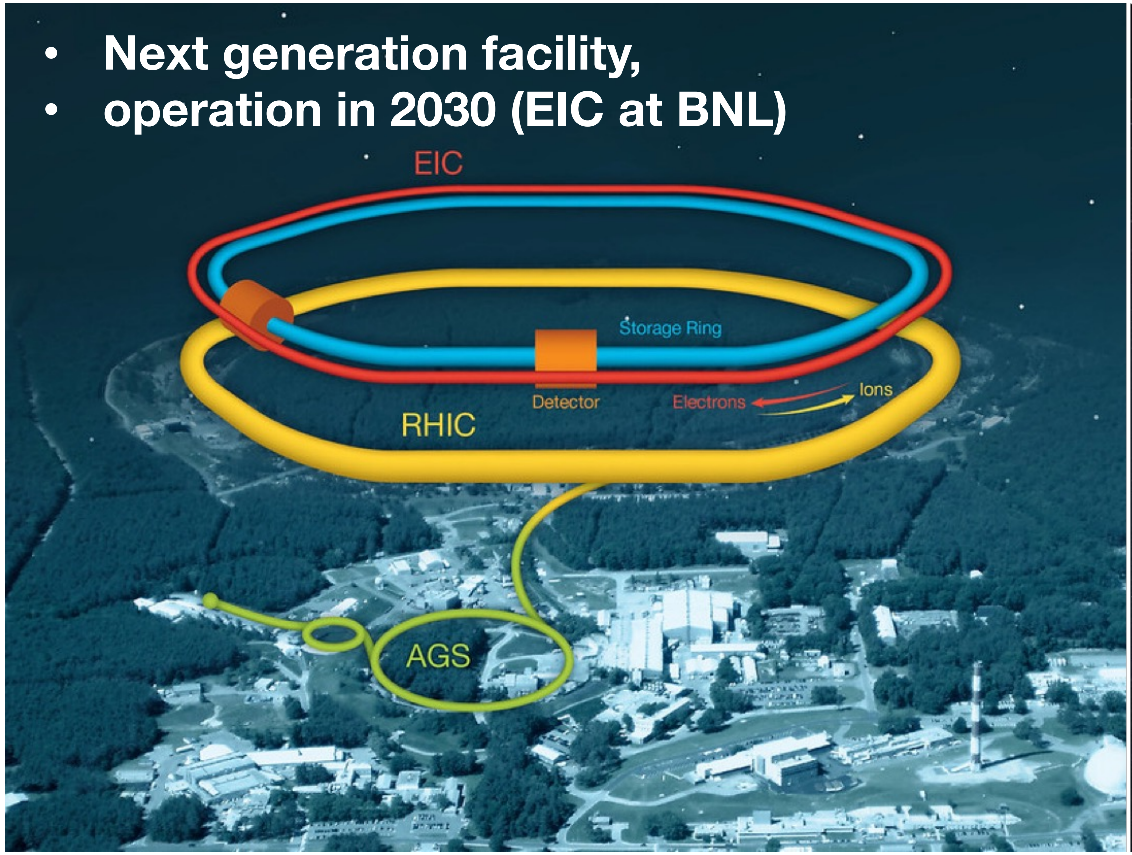
Indefinite growth at small-x violates unitarity, new mechanism is expected.

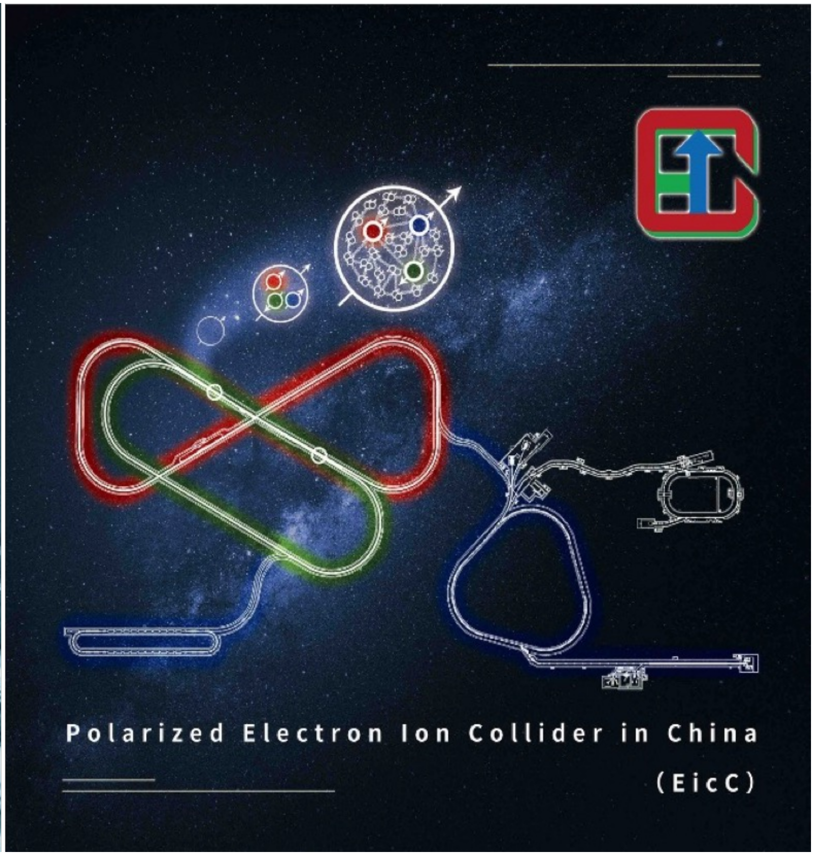
Saturation?



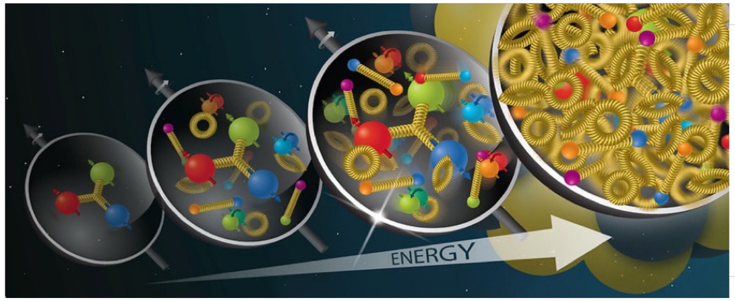
What is the fate of gluons at extreme densities toward the unitary limit?

Understand Nucleon Structure at EIC





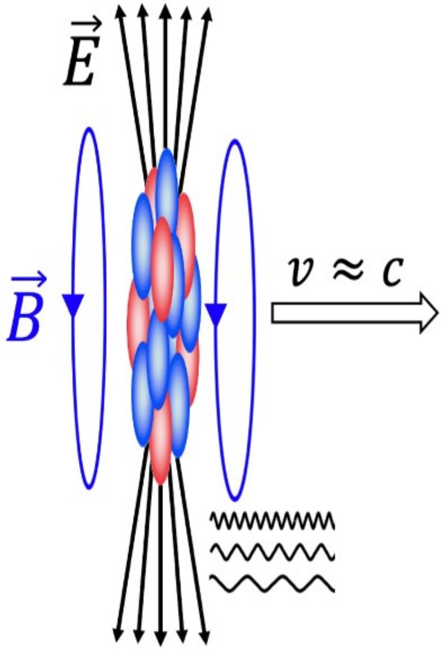
Confinement & Gluon Saturation



Spin Crisis

Mass Origin

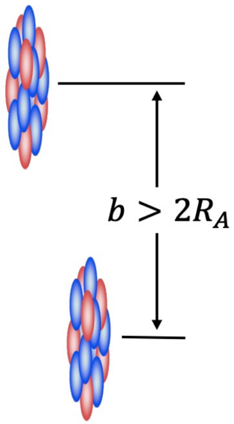
Ultra-Peripheral Collision (UPC)

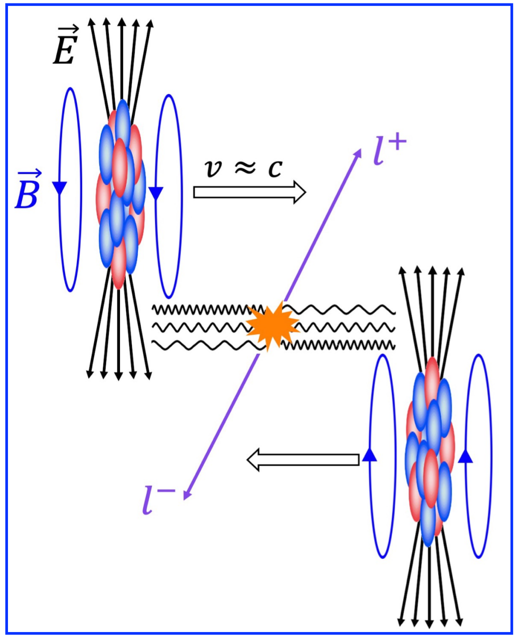


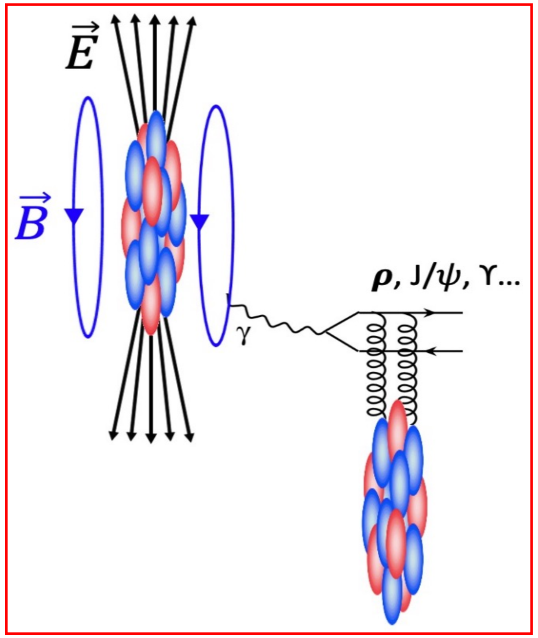
- **Lorentz contracted EM fields → flux of quasi-real photons ($Q^2<\hbar^2/R^2$).**
- **The photon flux ∝ Z^2.**
- **Photon kinematics: $p_T < \hbar/R_A$ ~ 30 MeV (E_{max} ~ 80 GeV) at LHC.**

Heavy ion collider is also a Photon-Photon and Photon-Ion collider !!!

UPC:





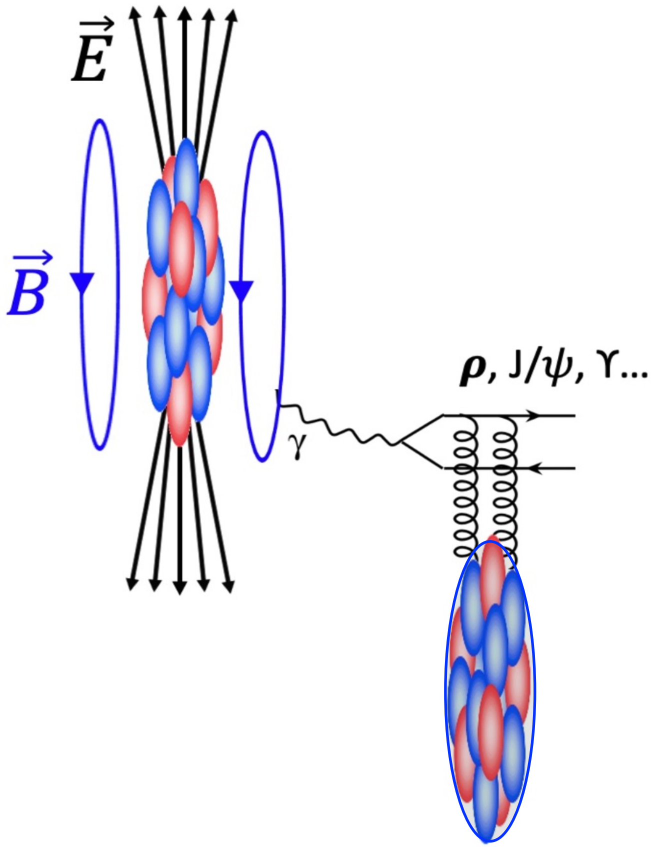


...

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 ⊗ $[xG(x)]^2$



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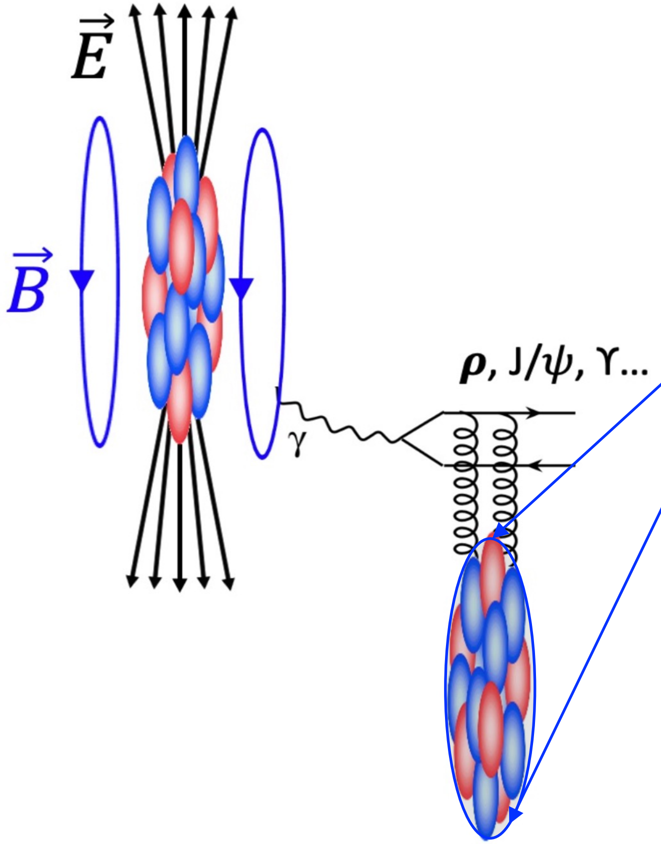

Coherent production:

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

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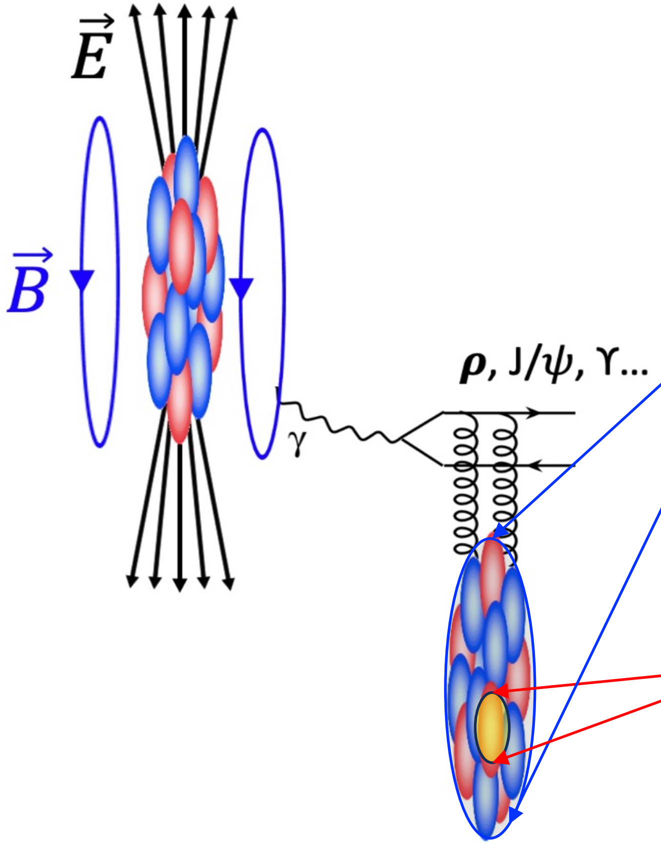

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Incoherent production:

- Photon fluctuated dipole couples to individual nucleons
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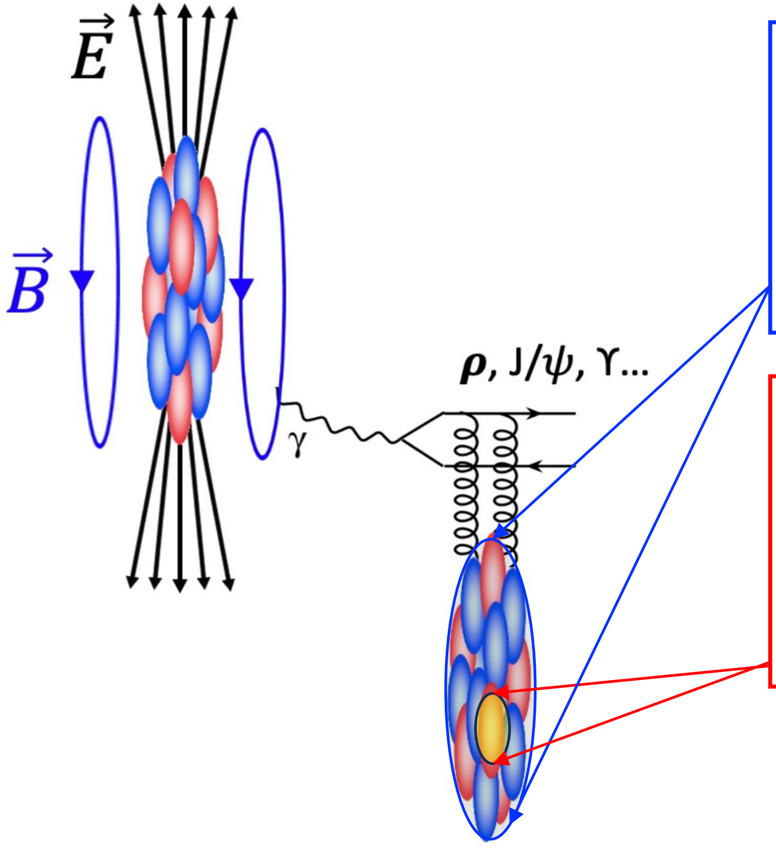

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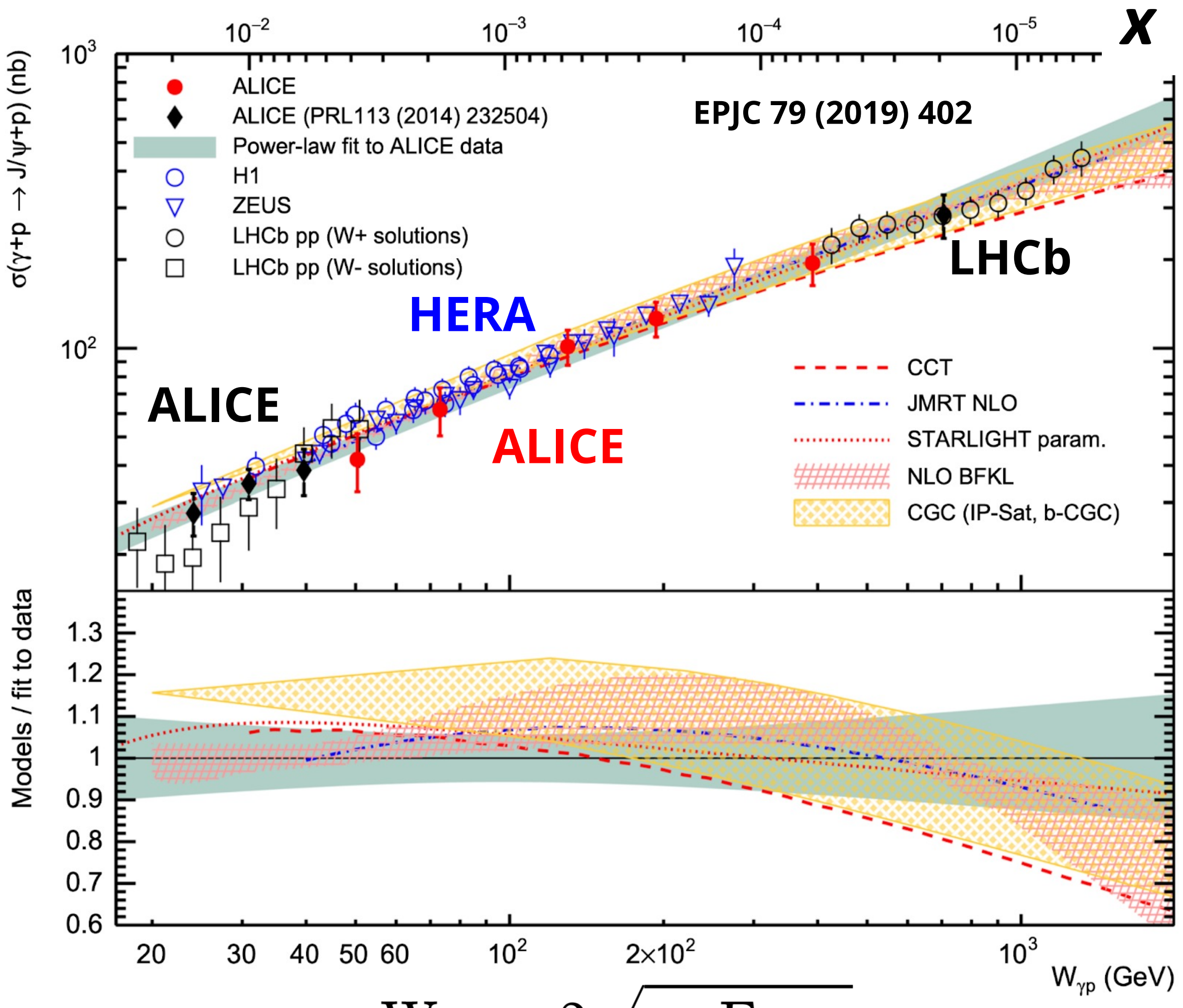
$$\omega = \frac{M_{VM}}{2} e^{\pm y} \qquad x = \frac{M_{VM}}{\sqrt{s_{NN}}} e^{\mp y} \qquad W_{\gamma p} = 2\sqrt{\omega \cdot E_{beam}}$$

Exclusive J/Ψ Photoproduction via γ + **p (Free Nucleon)**



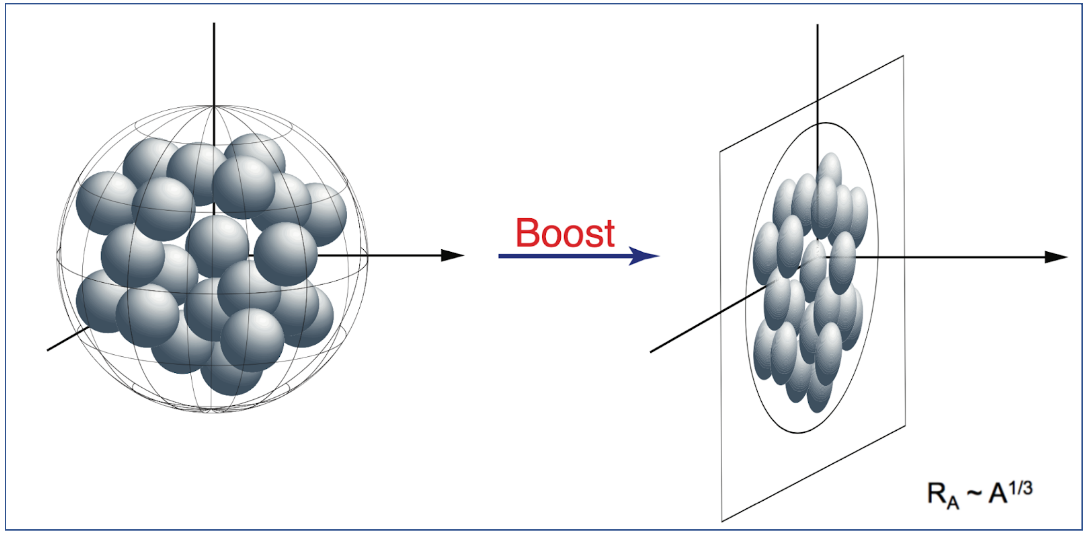
$$W_{\gamma p} = 2\sqrt{\omega \cdot E_{beam}}$$

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

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

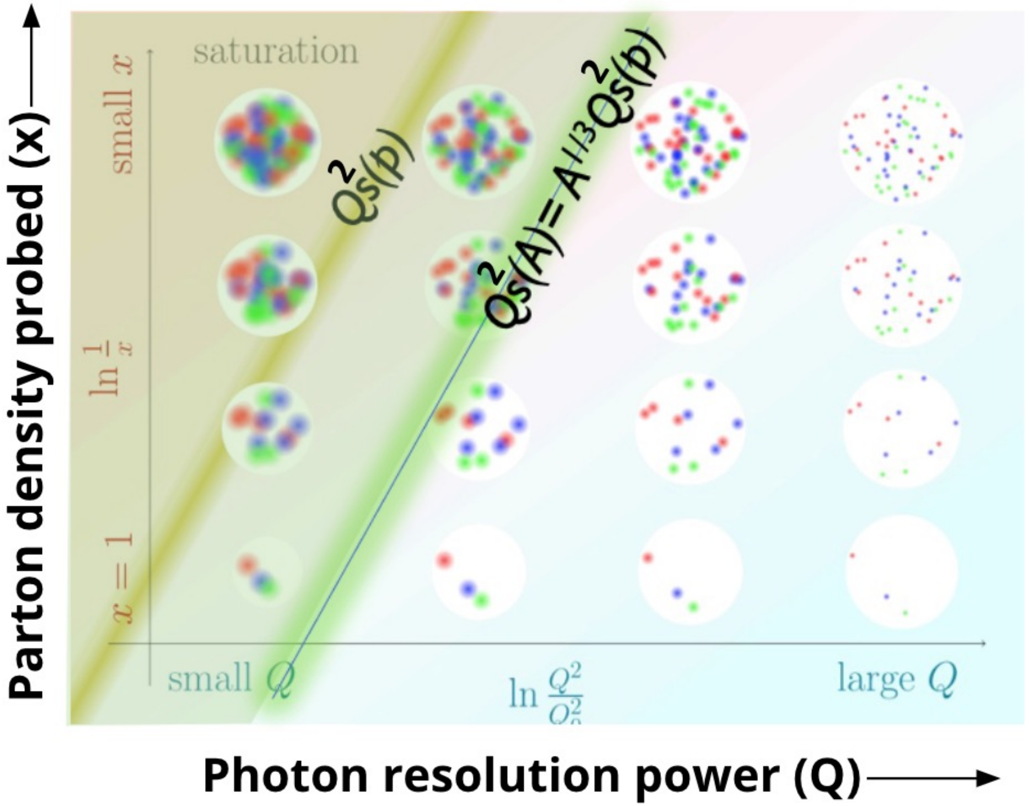
No clear indication of gluon saturation, even down to x~10^{-5} in a free nucleon.

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

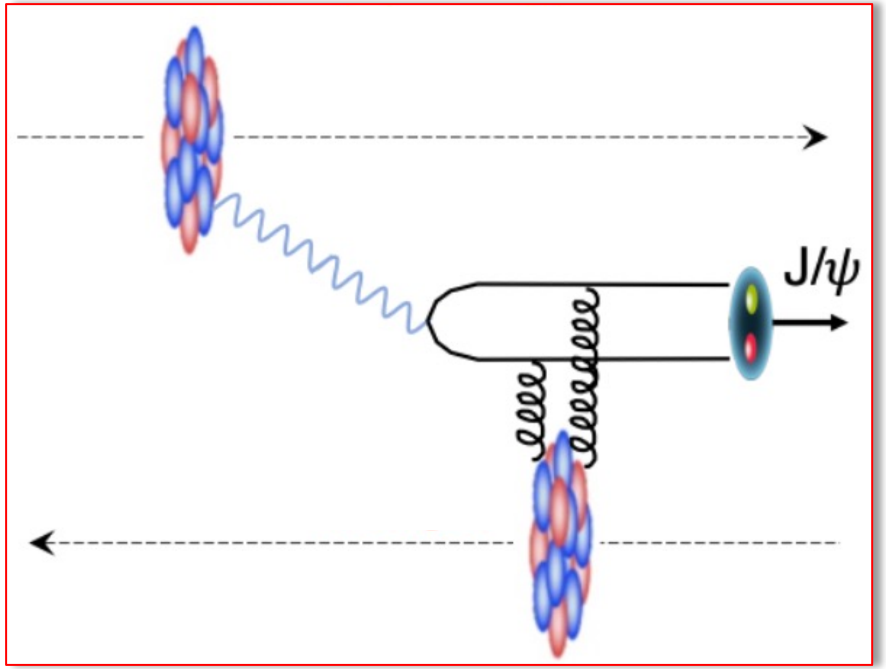
$$Q_s^2 \sim A^{1/3} \left(\frac{1}{x}\right)^{\lambda}$$



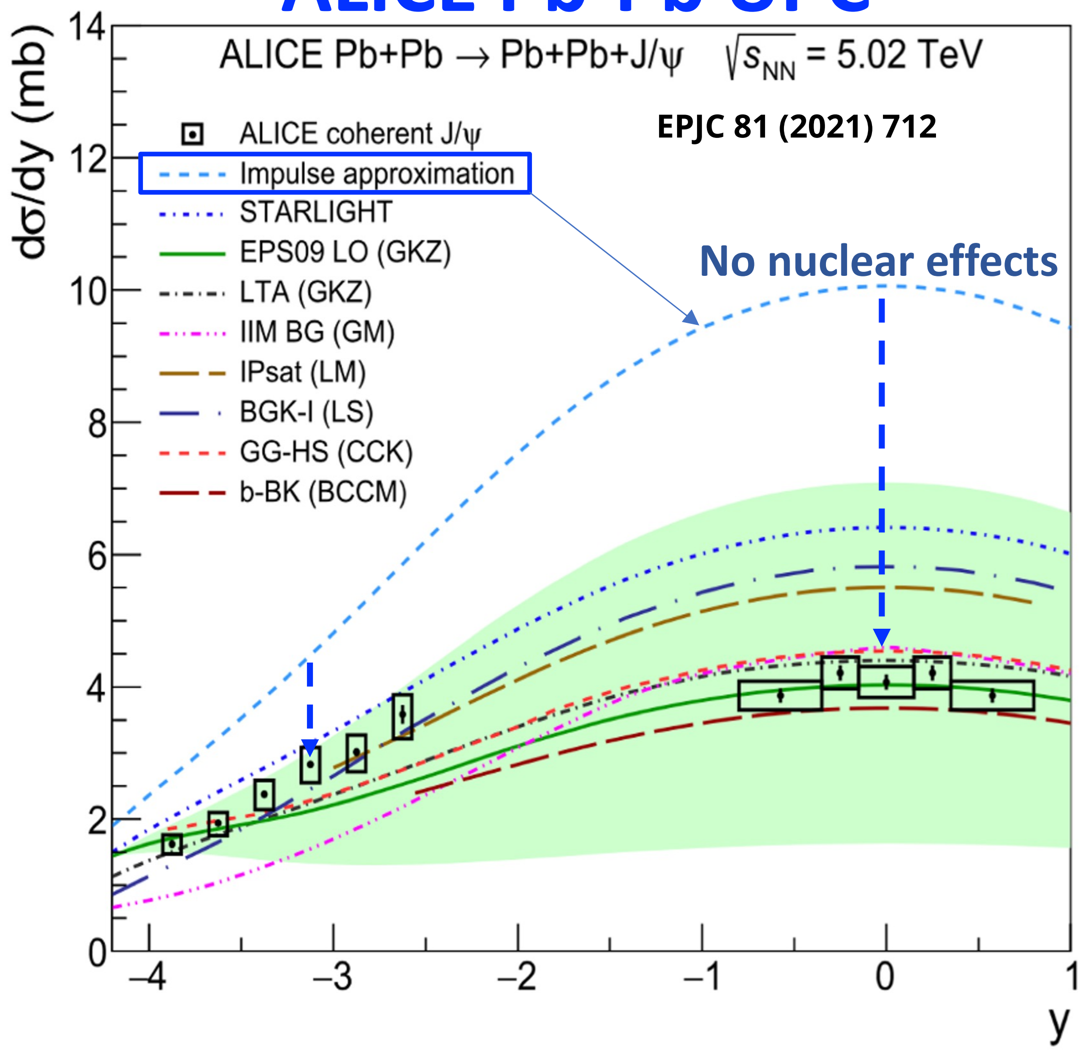
- Gluon saturation is expected to be **easier** to be reached **in nuclei**

Coherent J/Ψ Photoproduction in A-A UPCs

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



ALICE Pb-Pb UPC



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

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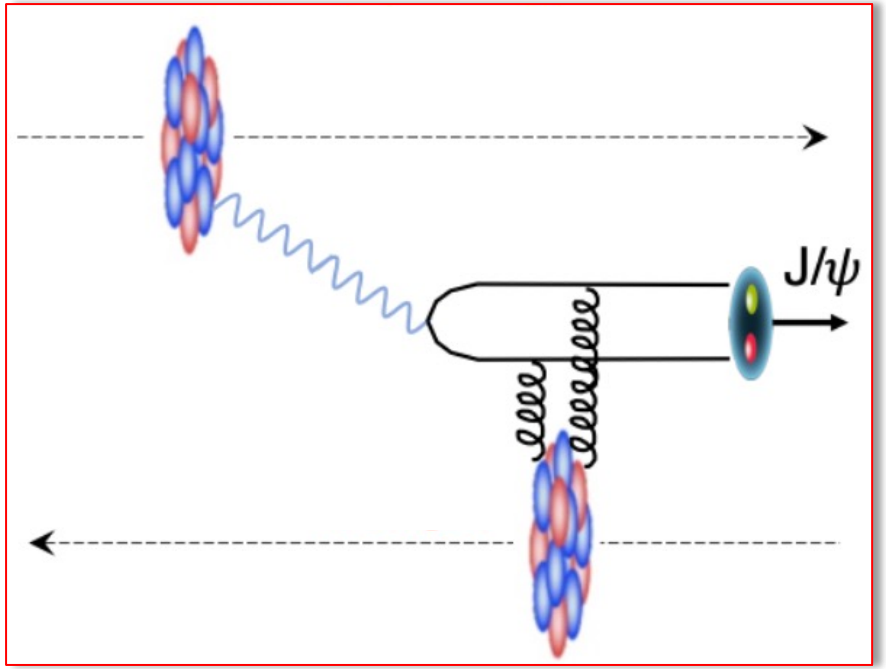

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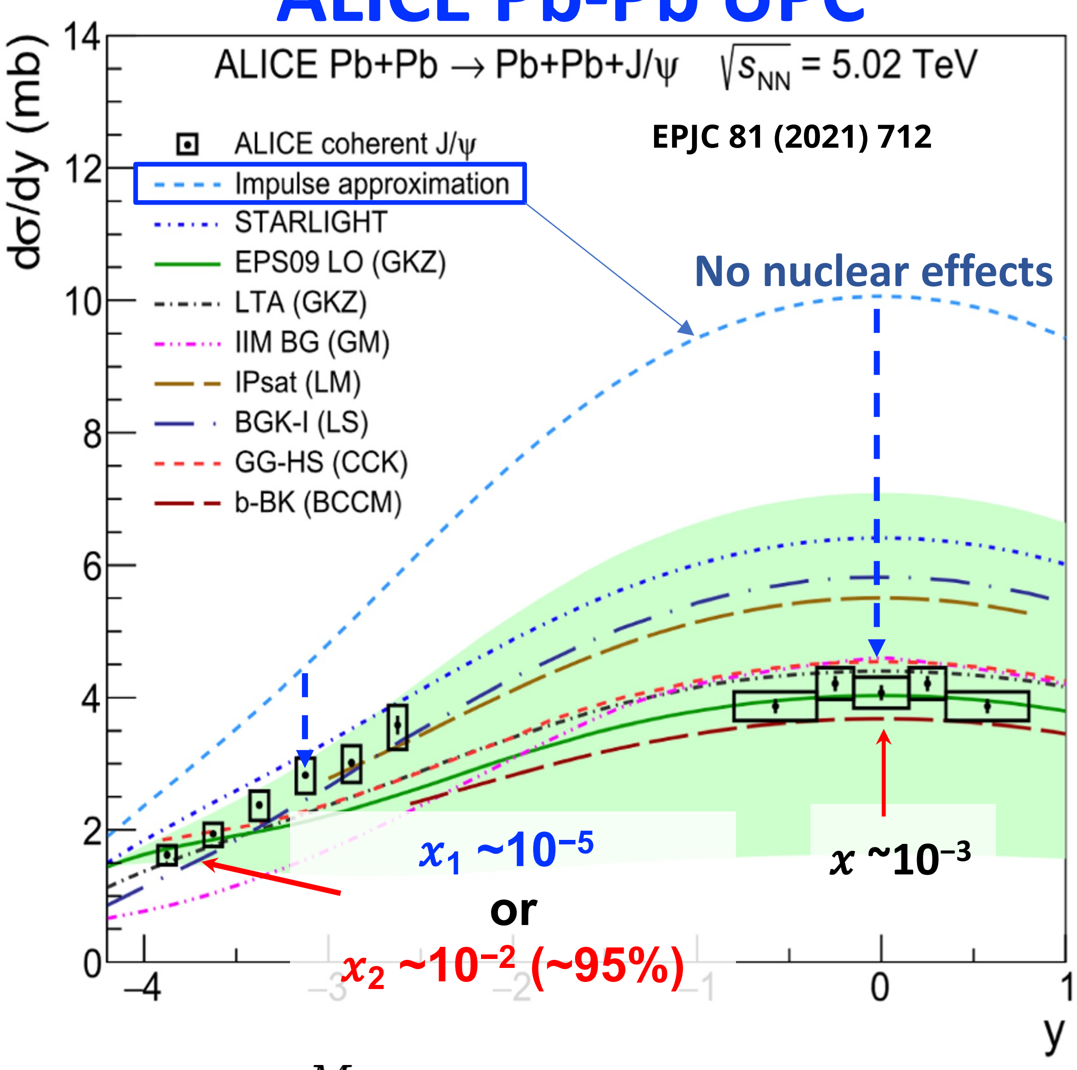
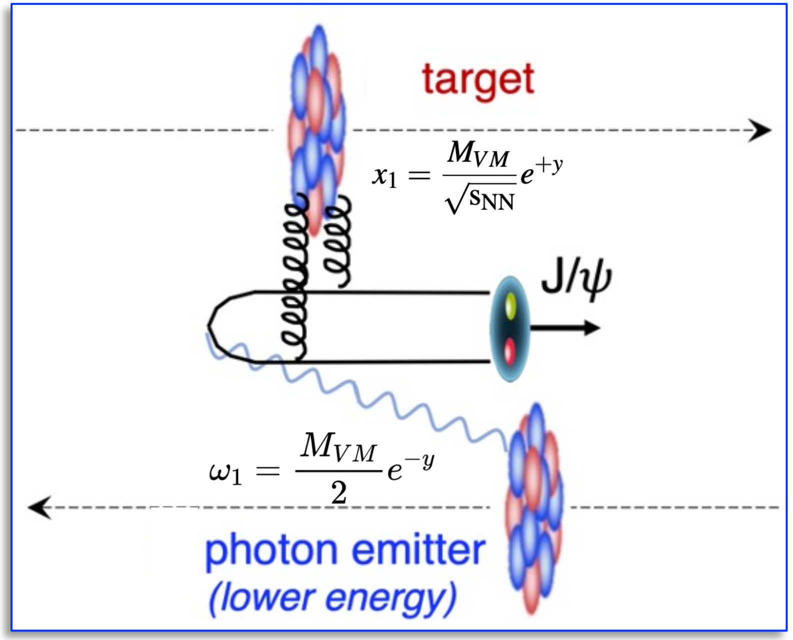
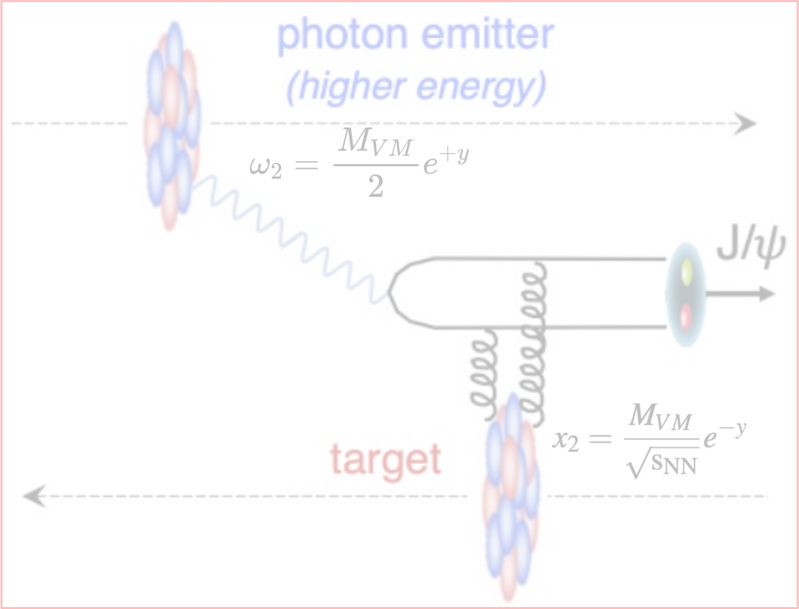


$$x = \frac{M_{VM}}{\sqrt{s_{NN}}} e^{\mp y}$$

low-energy photons dominant

Two-Way Ambiguity in A-A UPC

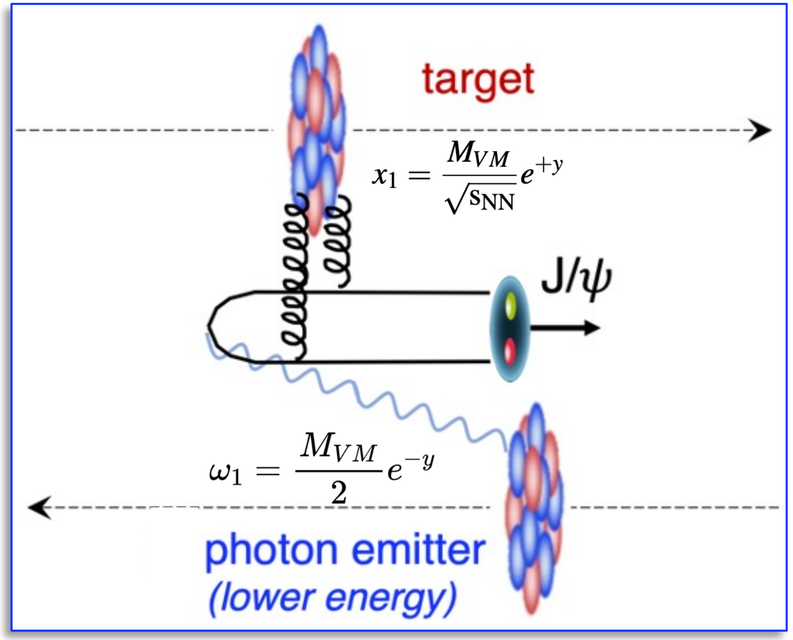


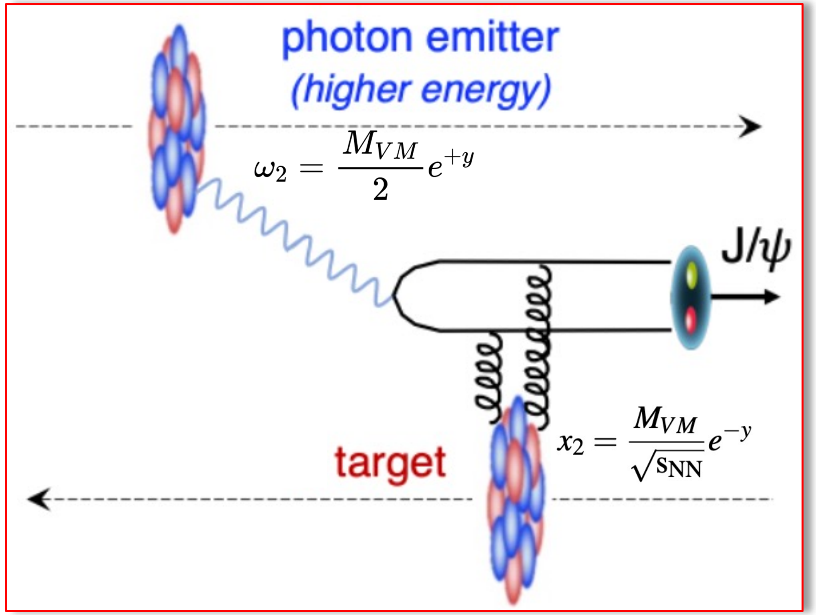


$$\frac{d\sigma_{AA\to AA'J/\psi}}{dy} = N_{\gamma/A}(\omega_1)\cdot\sigma_{\gamma A\to J/\psi A'}(\omega_1) + N_{\gamma/A}(w_2)\cdot\sigma_{\gamma A\to J/\psi A'}(w_2)$$

At least two equations for the solutions

Two-Way Ambiguity in A-A UPC





Smaller-*x*

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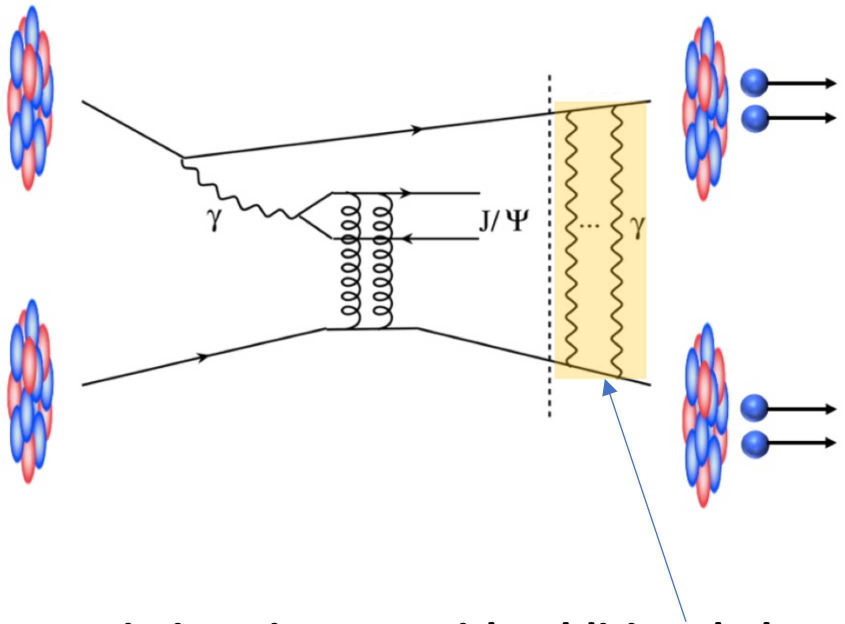
At least two equations for the solutions

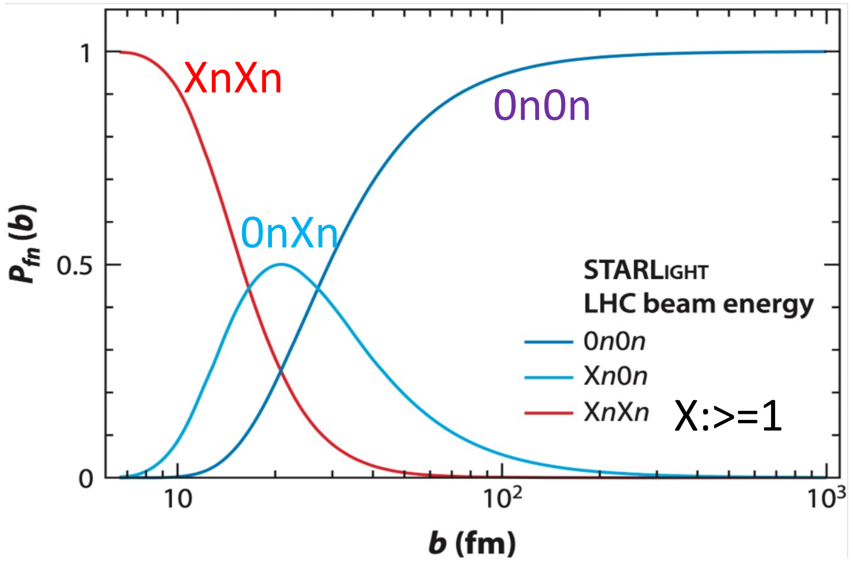
Method to Solve Two-Way Ambiguity in A-A UPC

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)
- Smaller b → More neutrons

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

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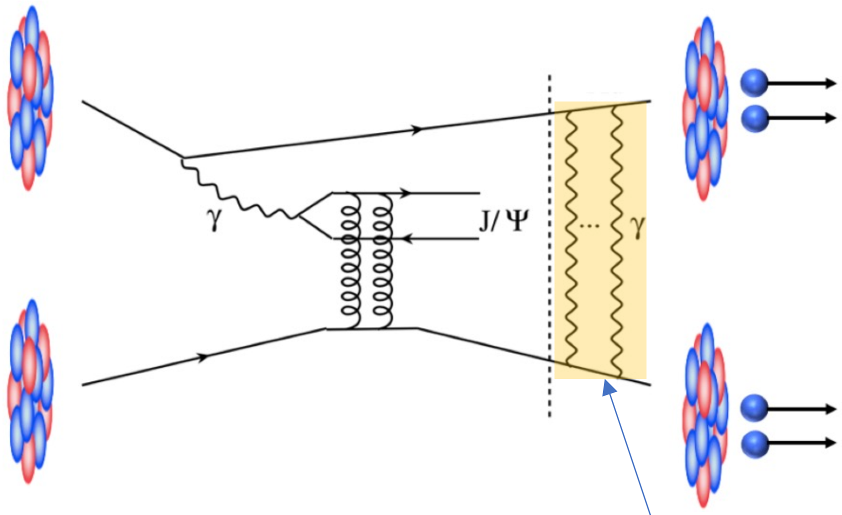


$$\frac{d\sigma^{0nXn}_{AA\to AA'J/\psi}}{dy} = N^{0nXn}_{\gamma/A}(\omega_1)\cdot\sigma_{\gamma A\to J/\psi A'(\omega_1)} + N^{0nXn}_{\gamma/A}(w_2)\cdot\sigma_{\gamma A\to J/\psi A'(w_2)}$$

from theoretical calculation

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

Neutron emission via EMD with <u>additional photon exchange</u>:

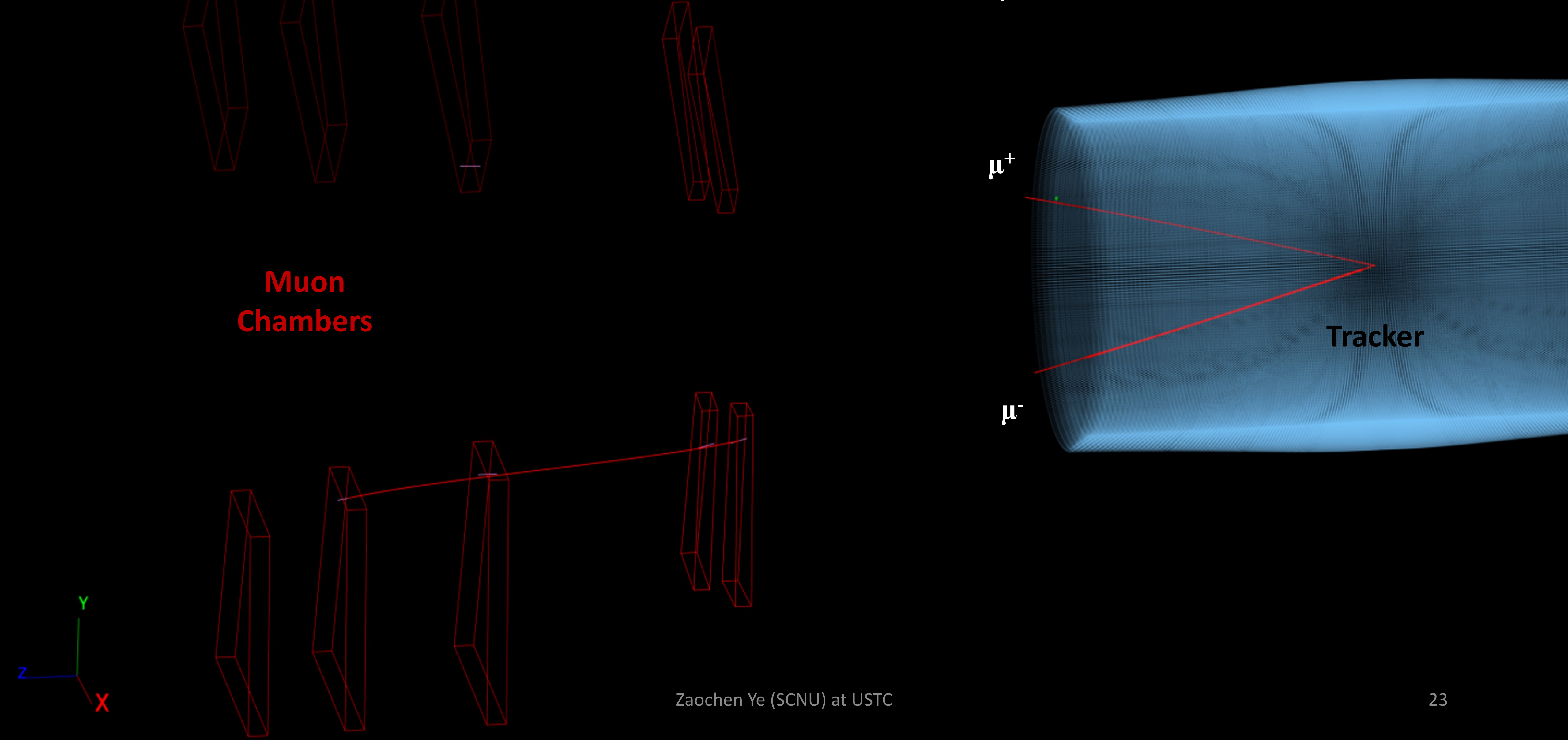
- Soft photons (energy ~10s MeV)
- Independent of interested physics process
- Large cross section ~200 b (single EMD)
- The smaller b → the more neutrons

$\sigma_{\gamma A\to J/\psi A'(\omega_1)}$ **Larger-x**

$\sigma_{\gamma A\to J/\psi A'(w_2)}$ **Smaller-x**

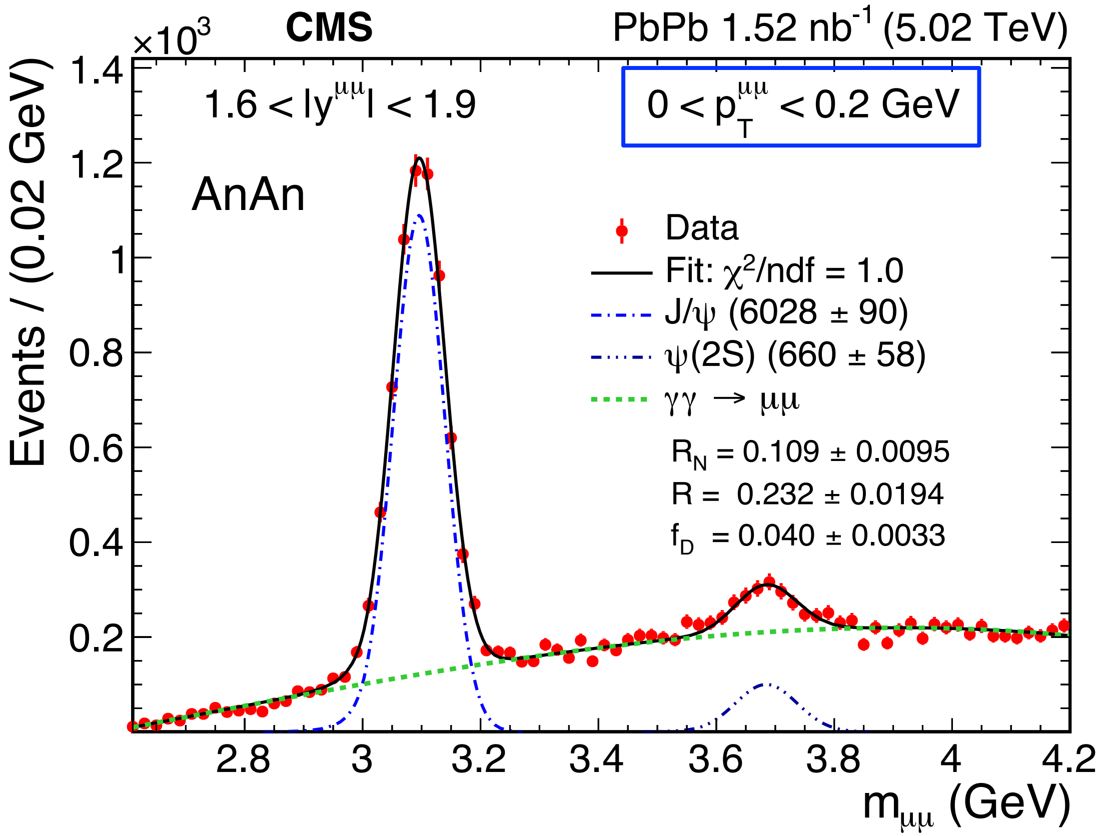
Interested UPC event:

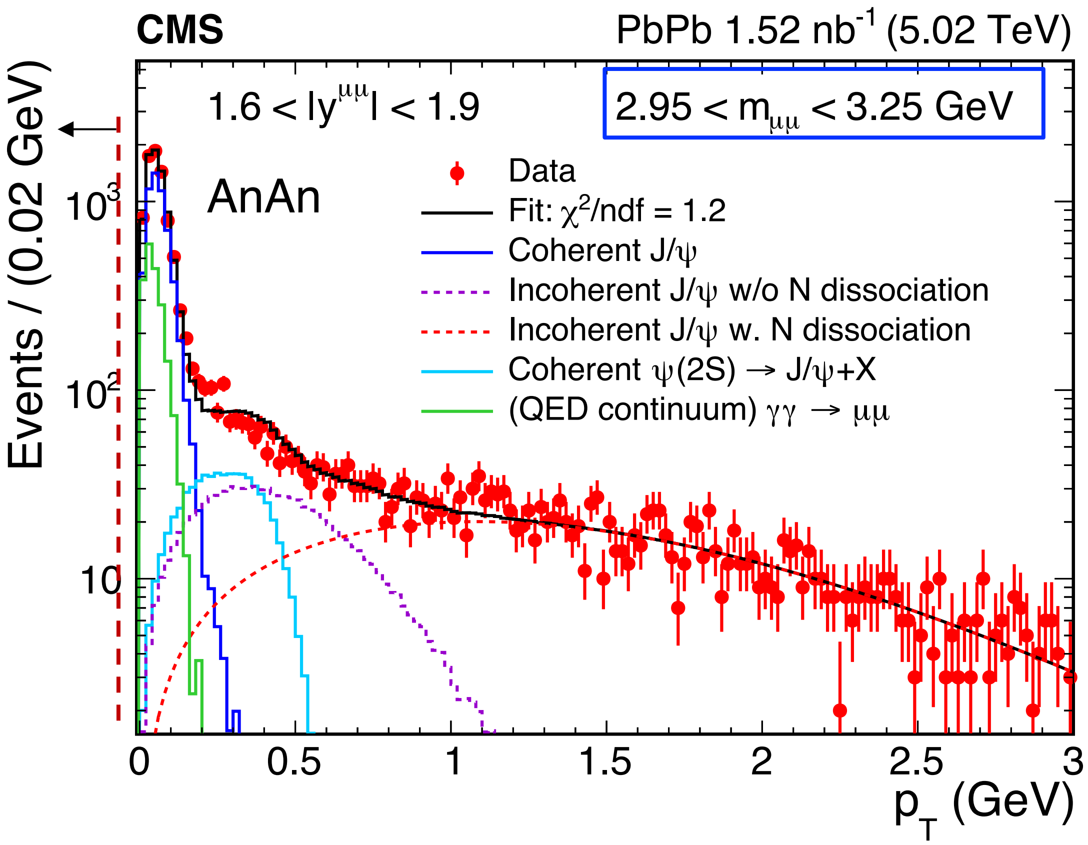
- ❑ Low activities in forward calorimeters.
- ❑ Exactly two tracks identified as muons.



Signal Extraction

CMS: PRL 131, 262301 (2023)





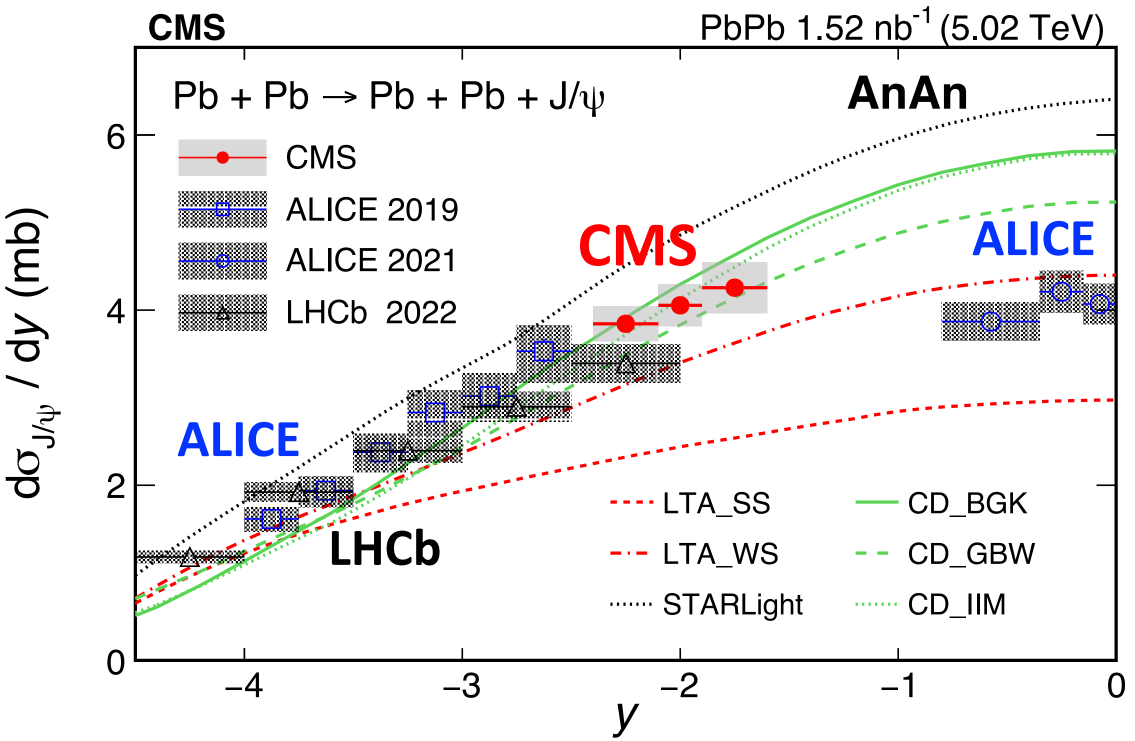
AnAn: All possible neutron emissions

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

Coherent J/Ψ in AnAn

CMS: PRL 131, 262301 (2023)

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



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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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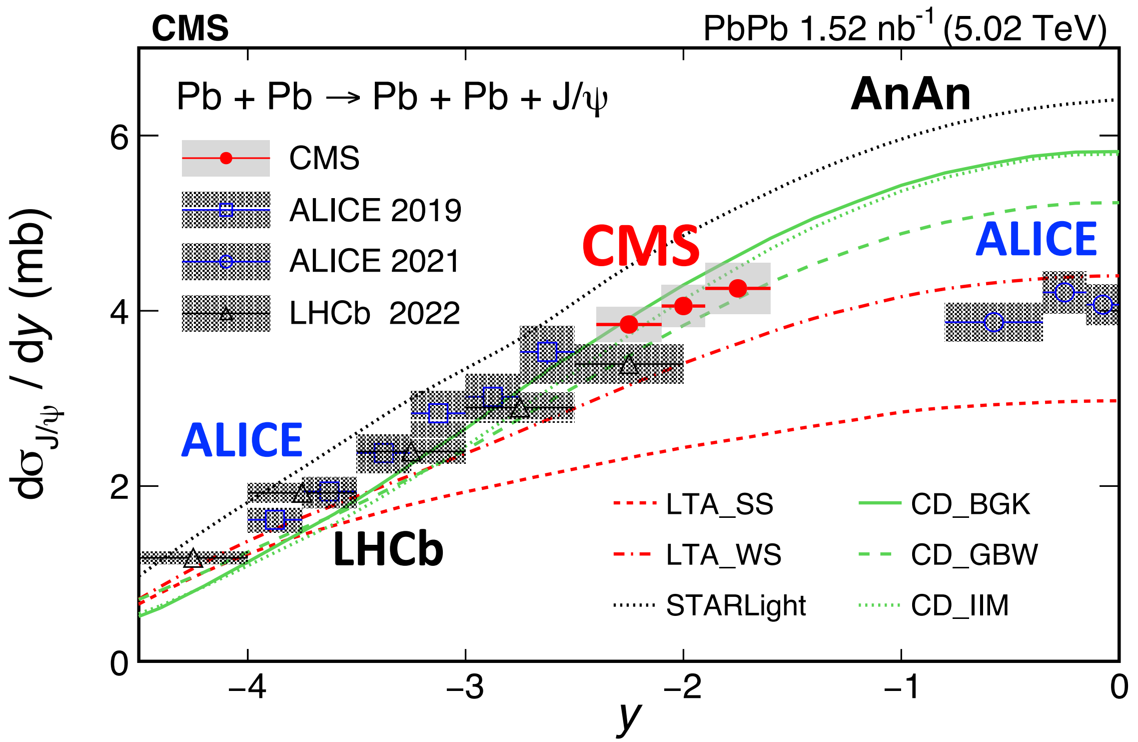

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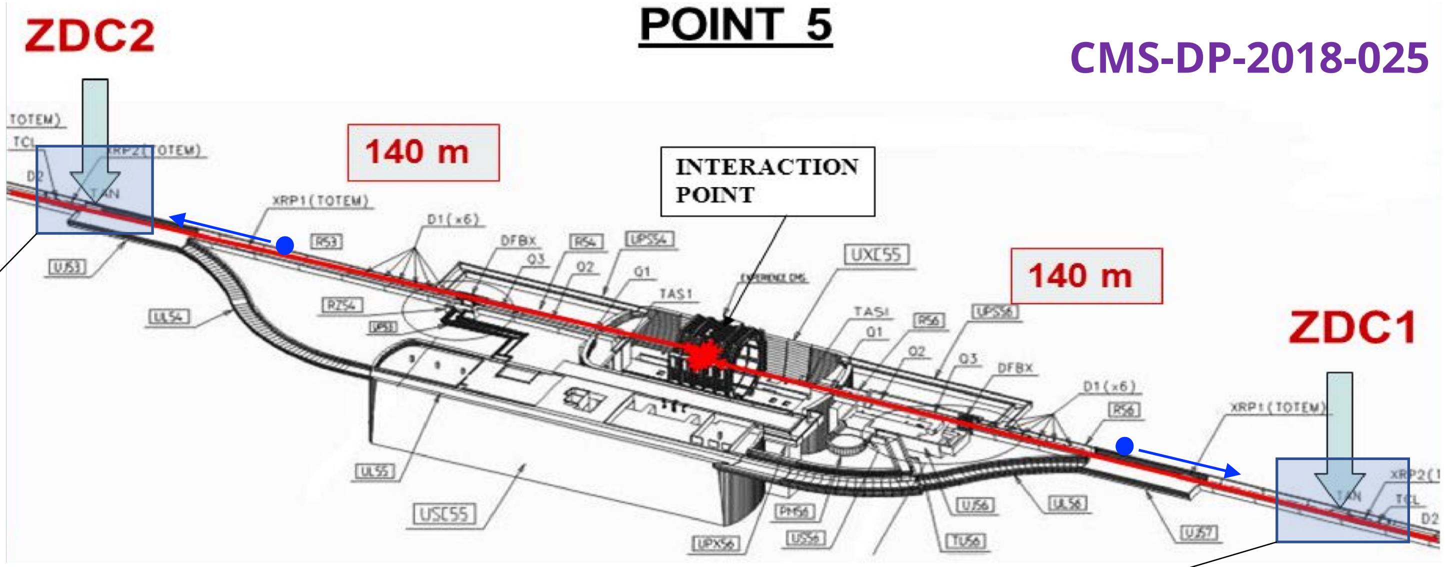
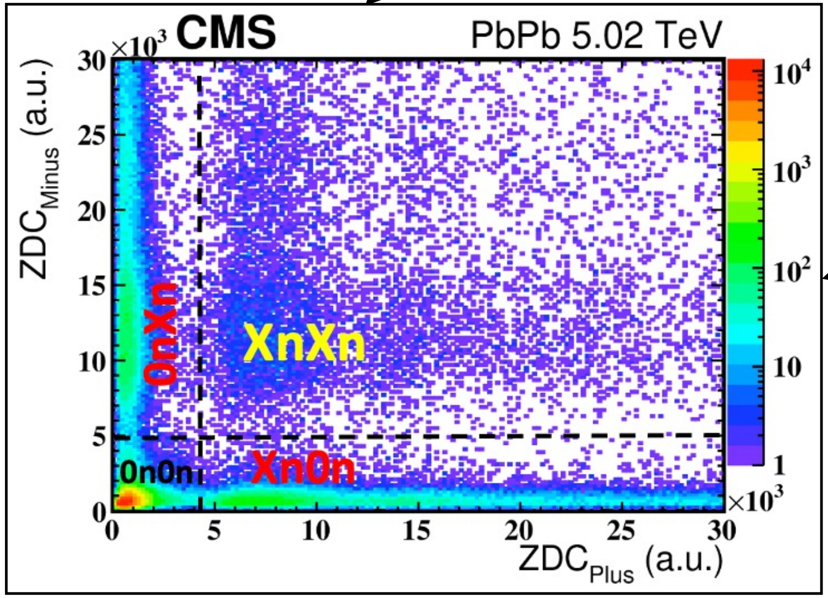
A **deeper** look at J/Ψ production from **single γ+Pb without** the **"two-way ambiguity"** will tell more.

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

Neutron Tag with Zero Degree Calorimeter



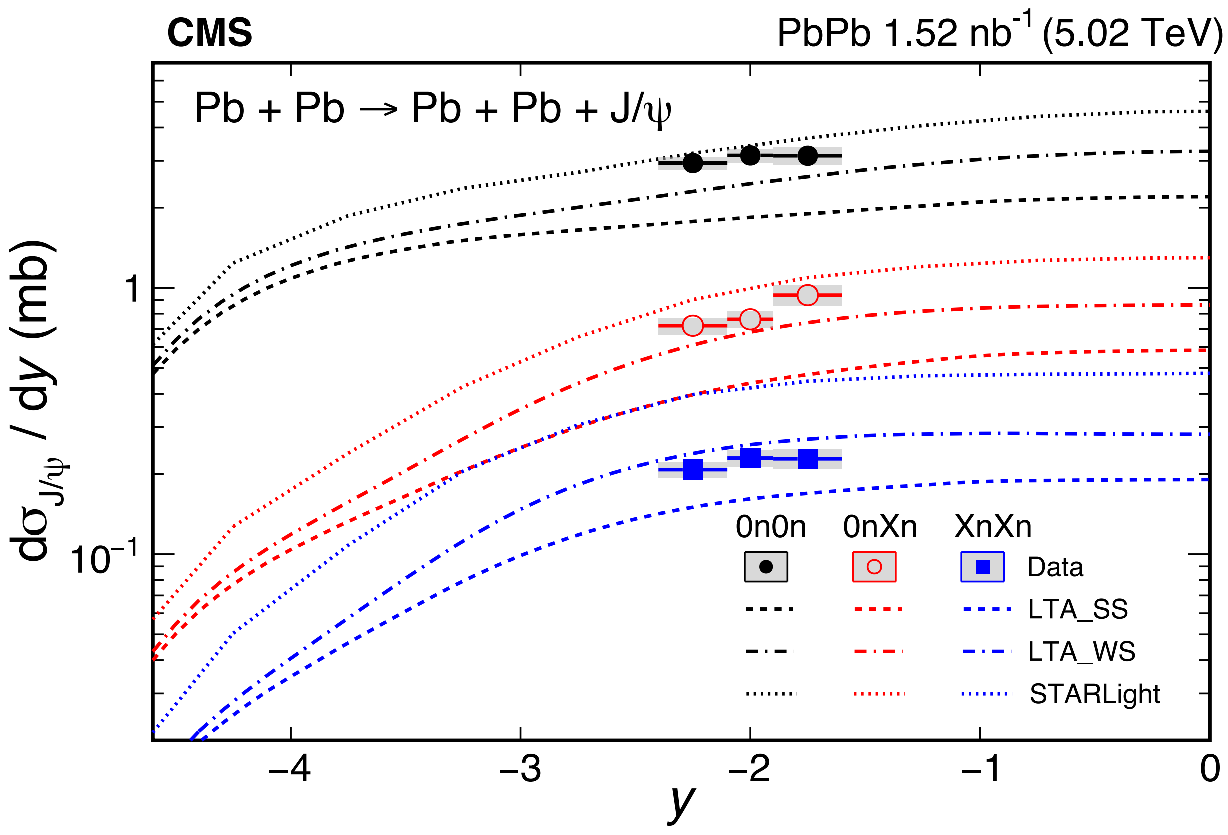


Tag events with **neutrons**:

- 0n0n, 0nXn, XnXn (X: ≥1)

Coherent J/Ψ in PbPb UPCs with Fwd Neutron Tag

CMS: PRL 131, 262301 (2023)



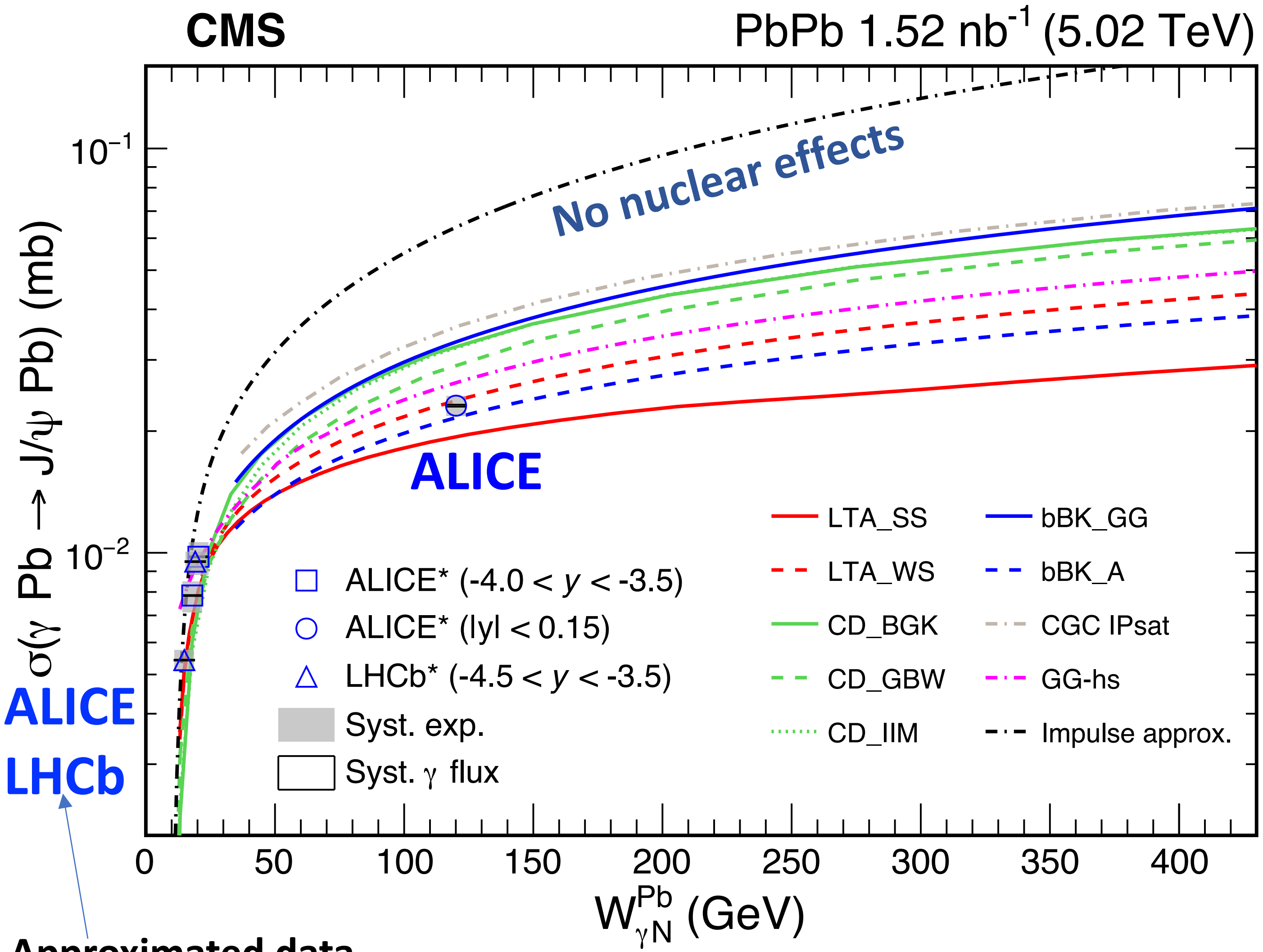
Neutron migration effects are corrected

- 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**



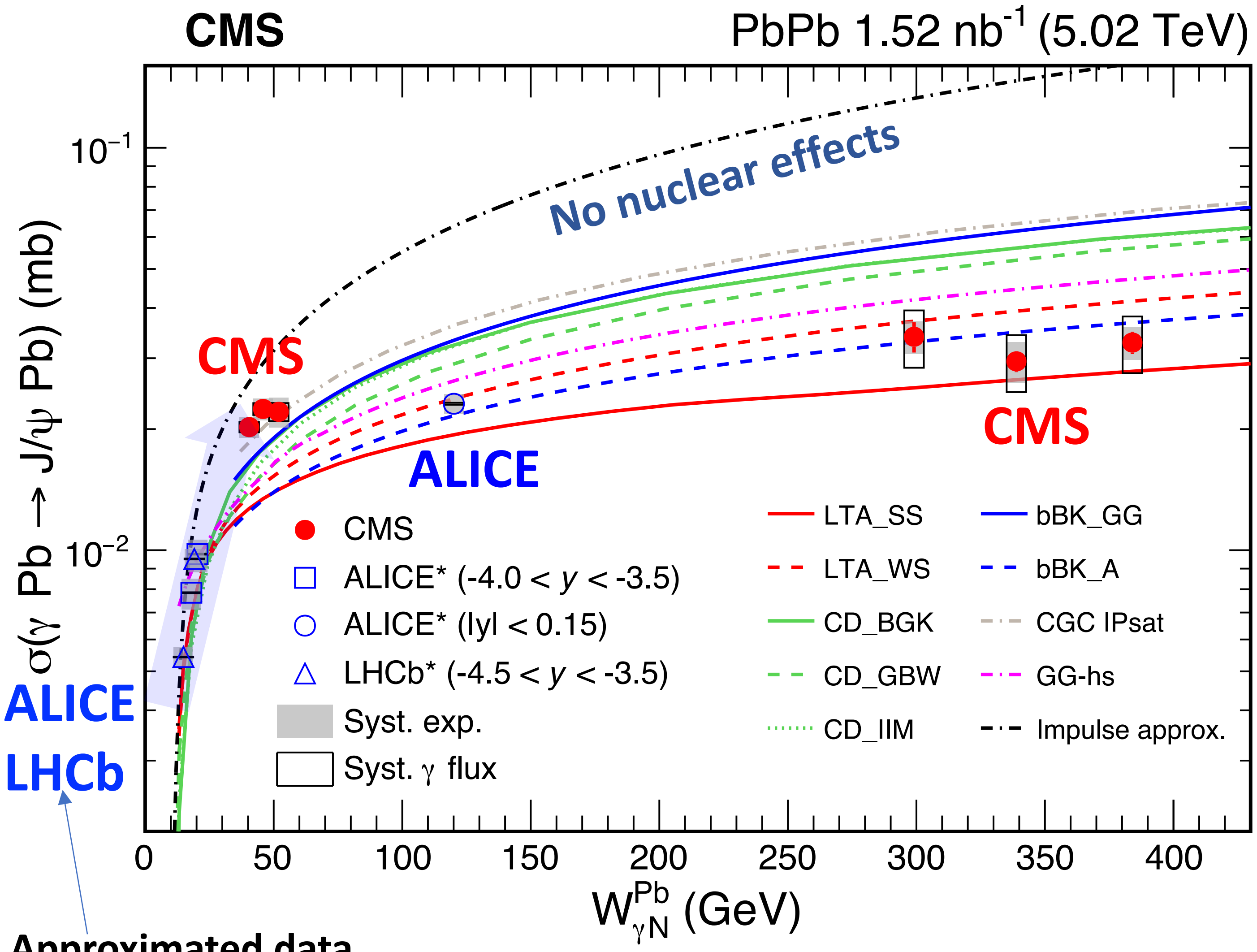
Approximated data

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: PRL 131, 262301 (2023)



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New data from CMS:

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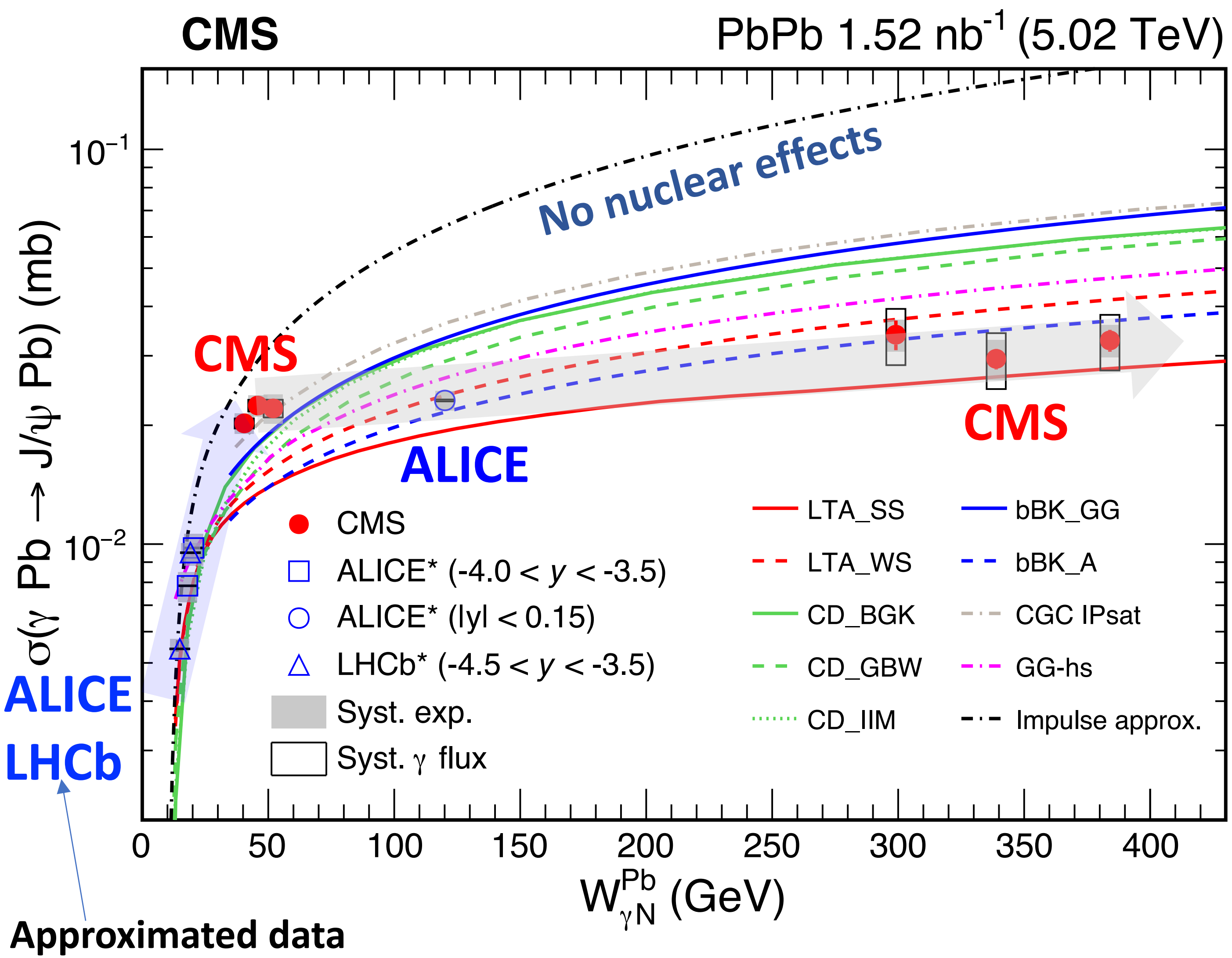

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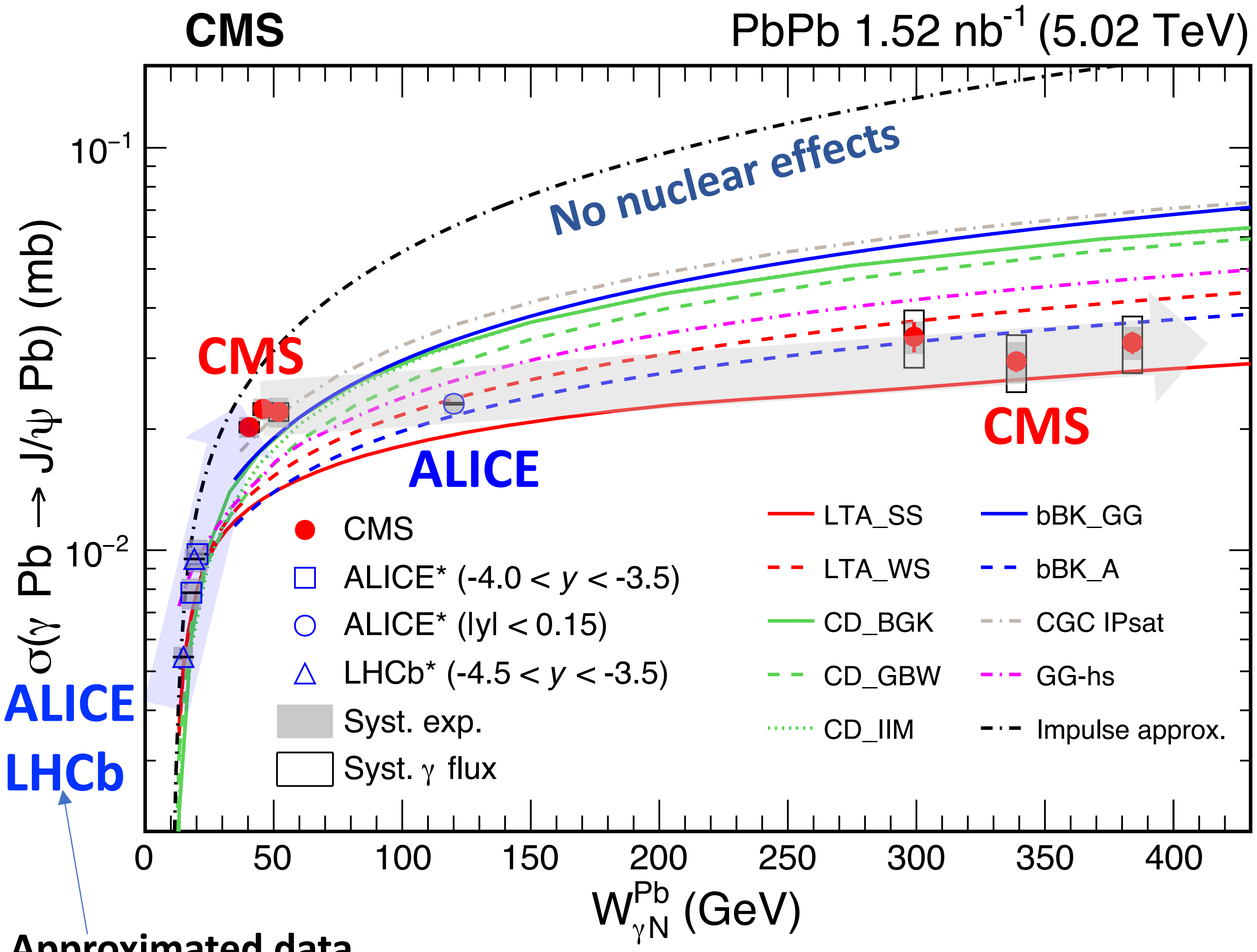
CMS: **PRL 131, 262301 (2023)**



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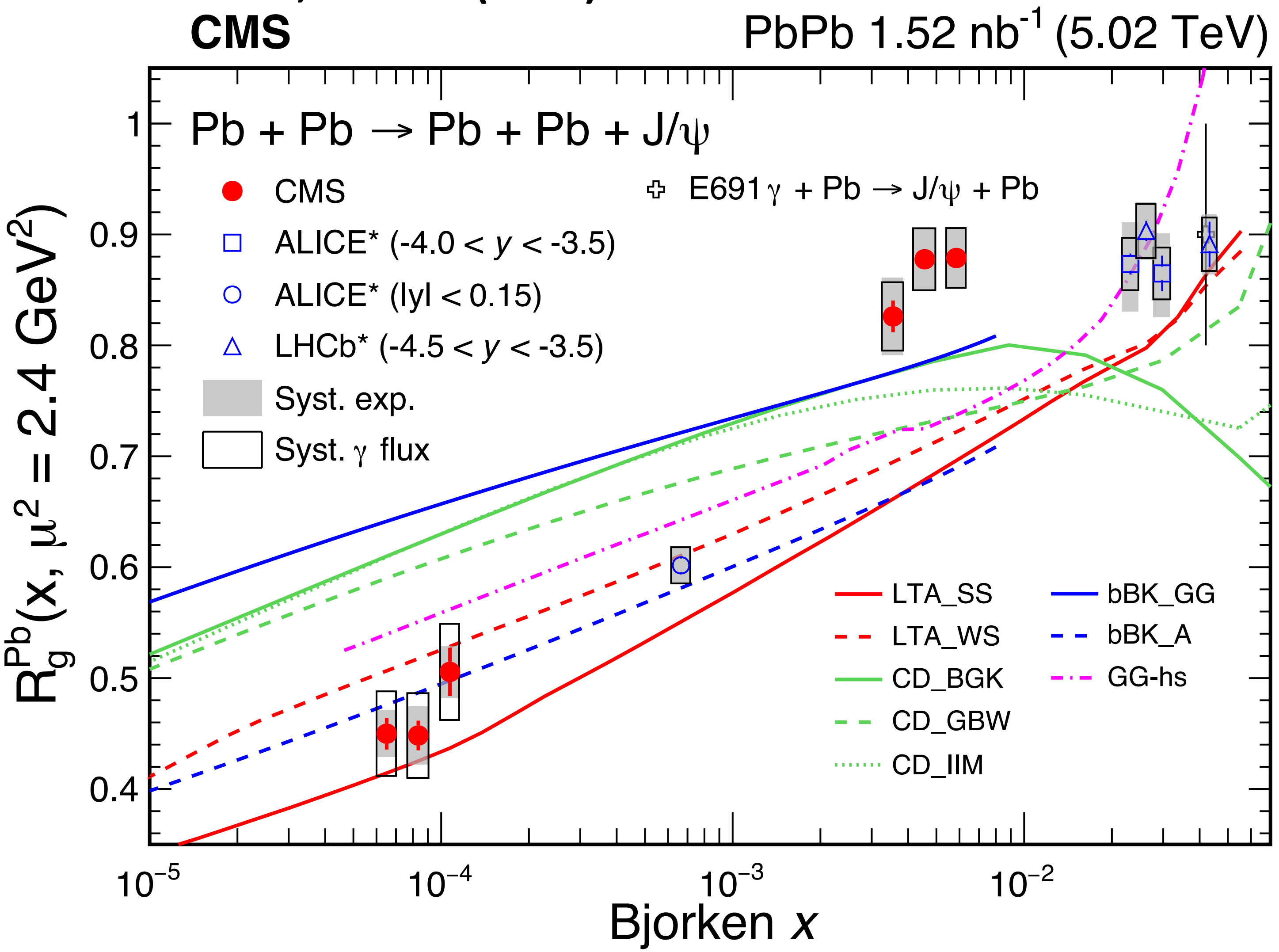
No models can describe the entire data distribution.

ALICE new data follows the same trend, see Simone Ragoni' QM23 talk

arXiv:2305.19060

Nuclear Gluon Suppression Factor

CMS: PRL 131, 262301 (2023)



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

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

Impulse approx. (IA) neglects all nuclear effects.

- R_g represents nuclear gluon suppression factor at LO.

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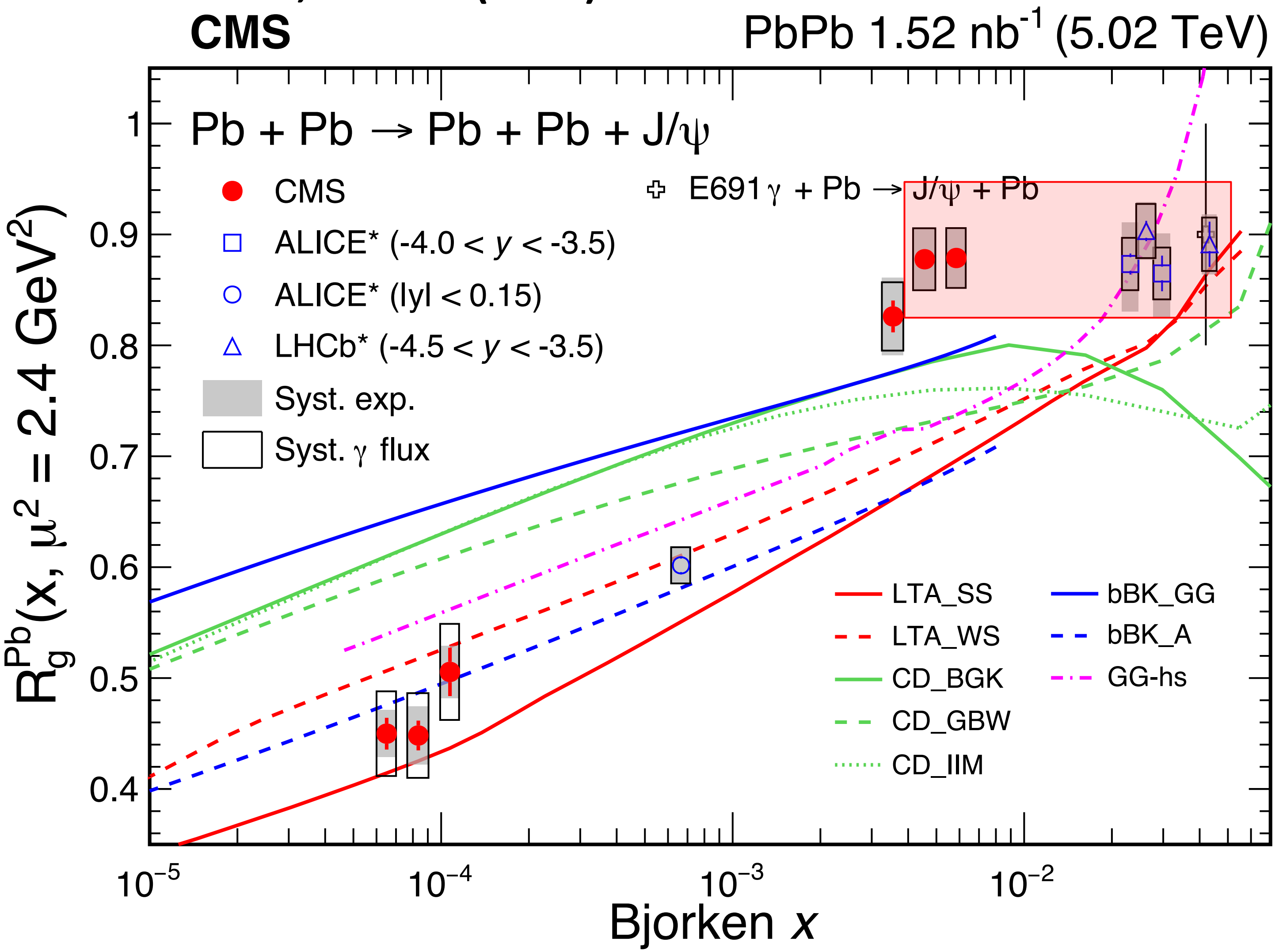

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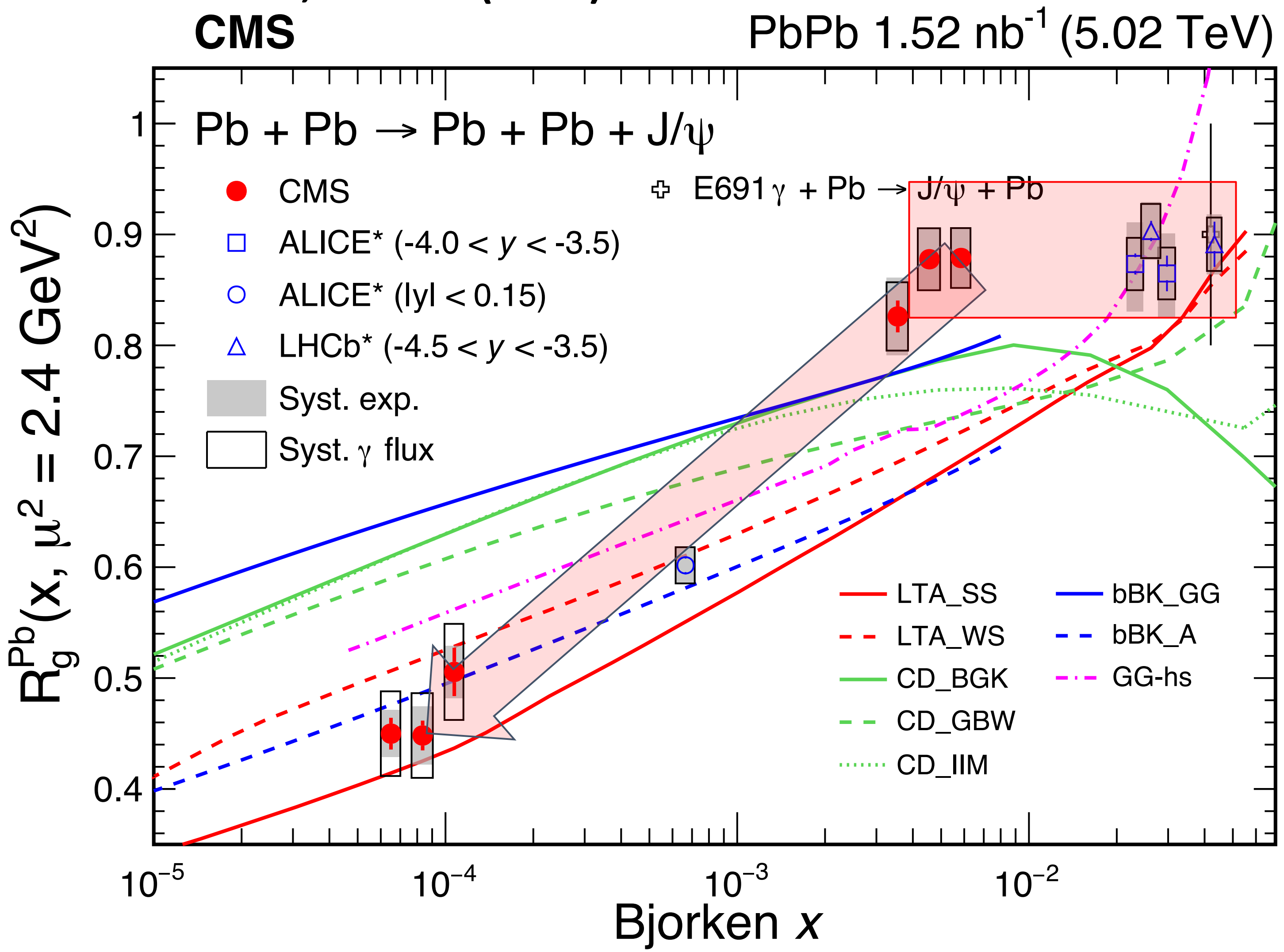

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Impulse approx. (IA)
neglects all nuclear effects.

- 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?

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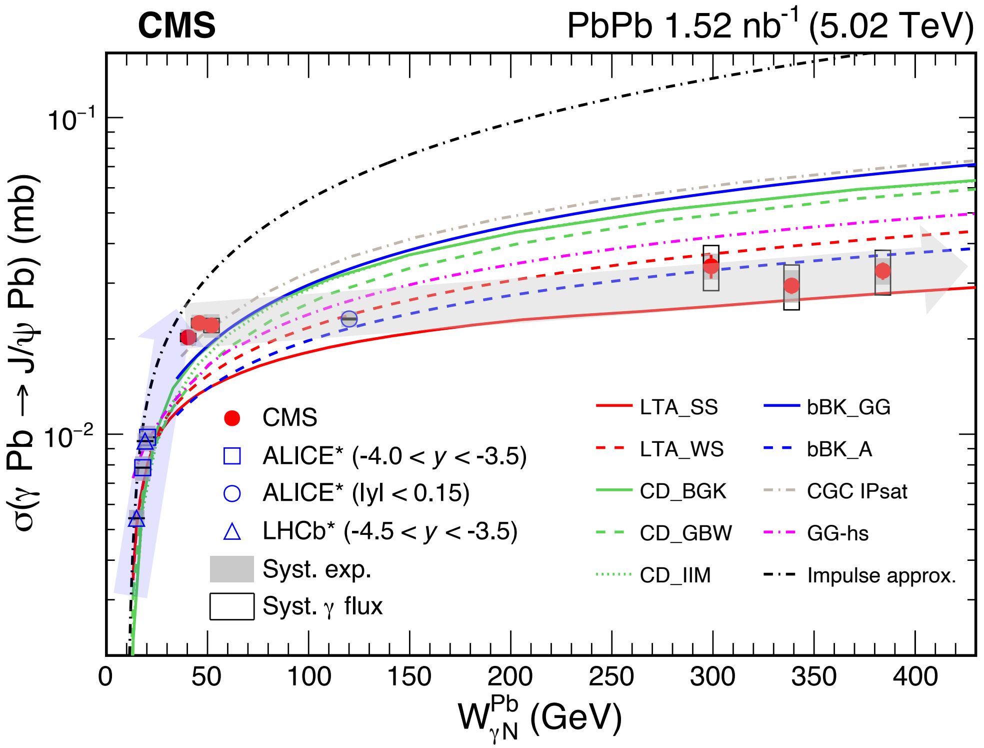
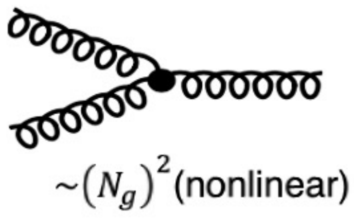
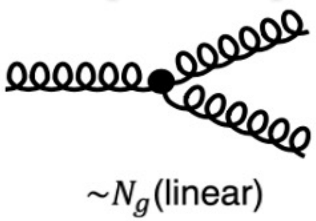




Gluon Saturation?



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

What Physics Behind?

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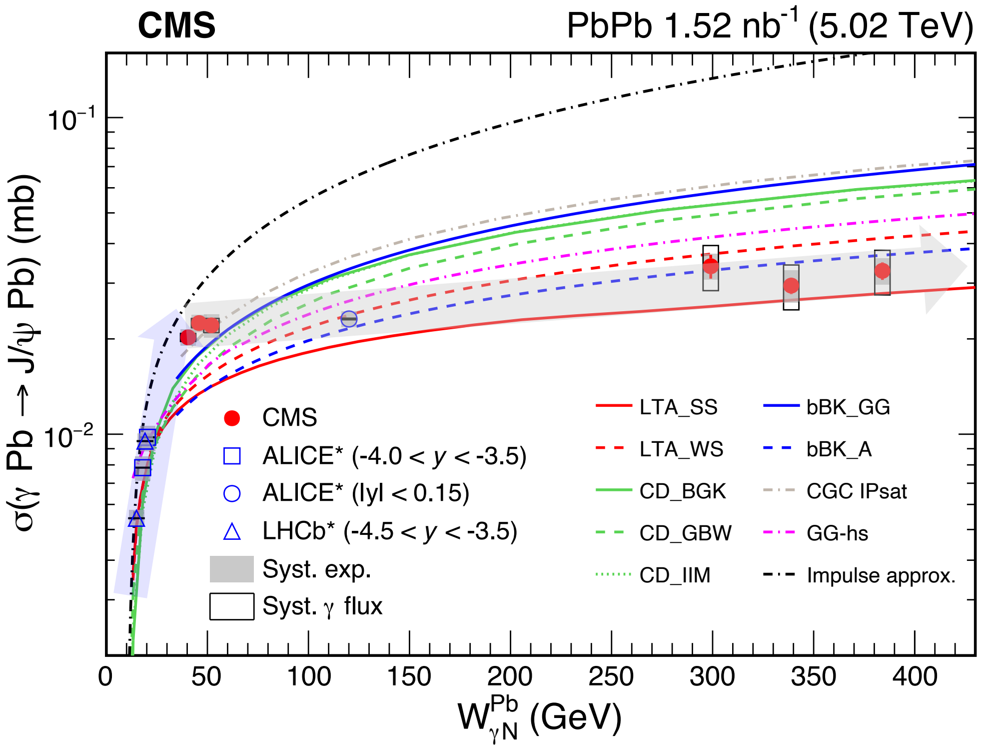
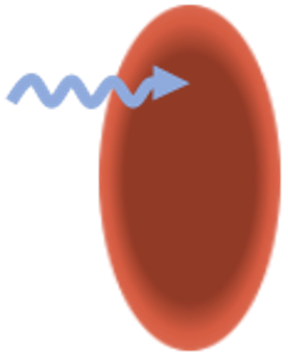




Black Disk Limit?

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

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!!?**

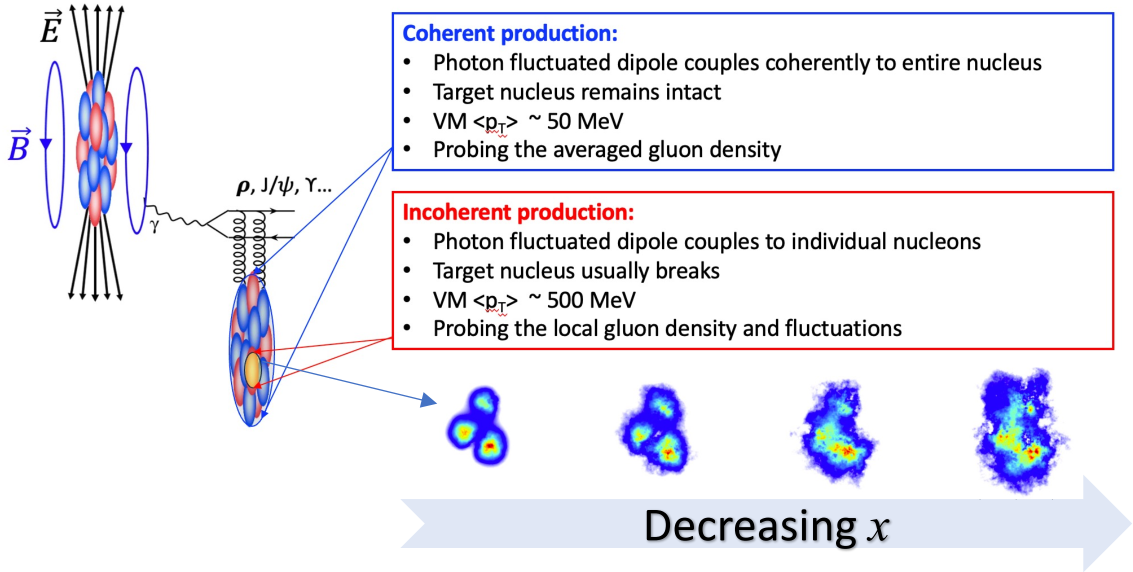
OR

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

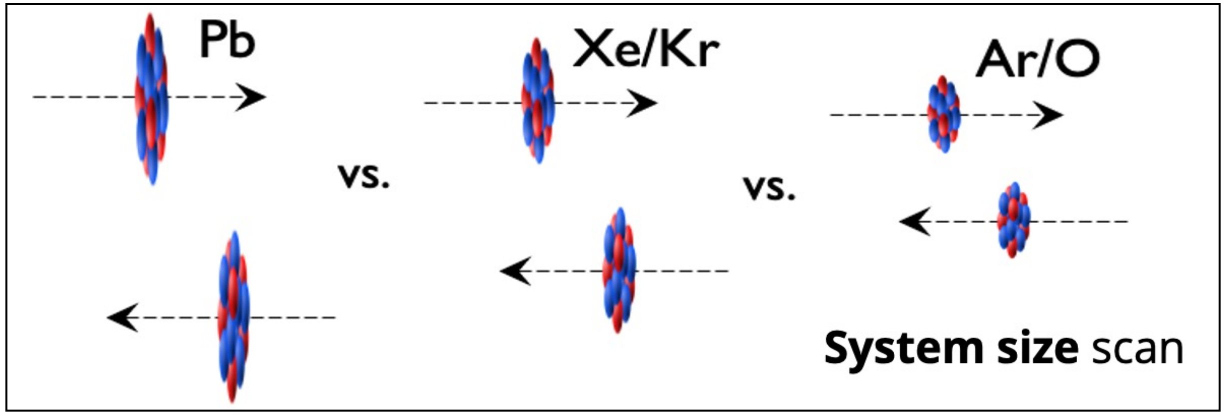
Future Opportunities

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

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



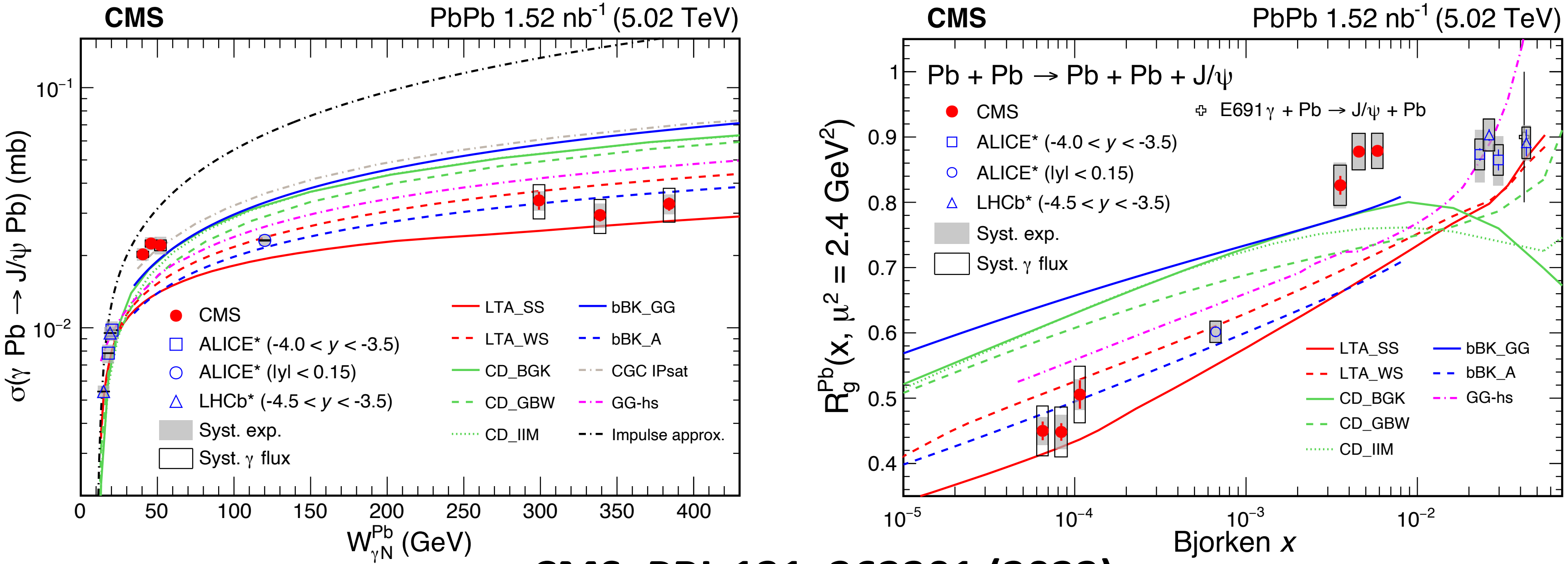
PbPb L_{int} = 13 nb^{-1}						
Meson	σ	All Total	Central 1 Total	Central 2 Total	Forward 1 Total 1	Forward 2 Total
$\rho \to \pi^+\pi^-$	5.2b	68 B	5.5 B	21B	4.9 B	13 B
$\rho' \to \pi^+\pi^-\pi^+\pi^-$	730 mb	9.5 B	210 M	2.5 B	190 M	1.2 B
$\phi \to K^+K^-$	0.22b	2.9 B	82 M	490 M	15 M	330 M
$J/\psi \to \mu^+\mu^-$	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 low-x gluon regime** (10^{-4}-10^{-5}) in nucleus
- **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



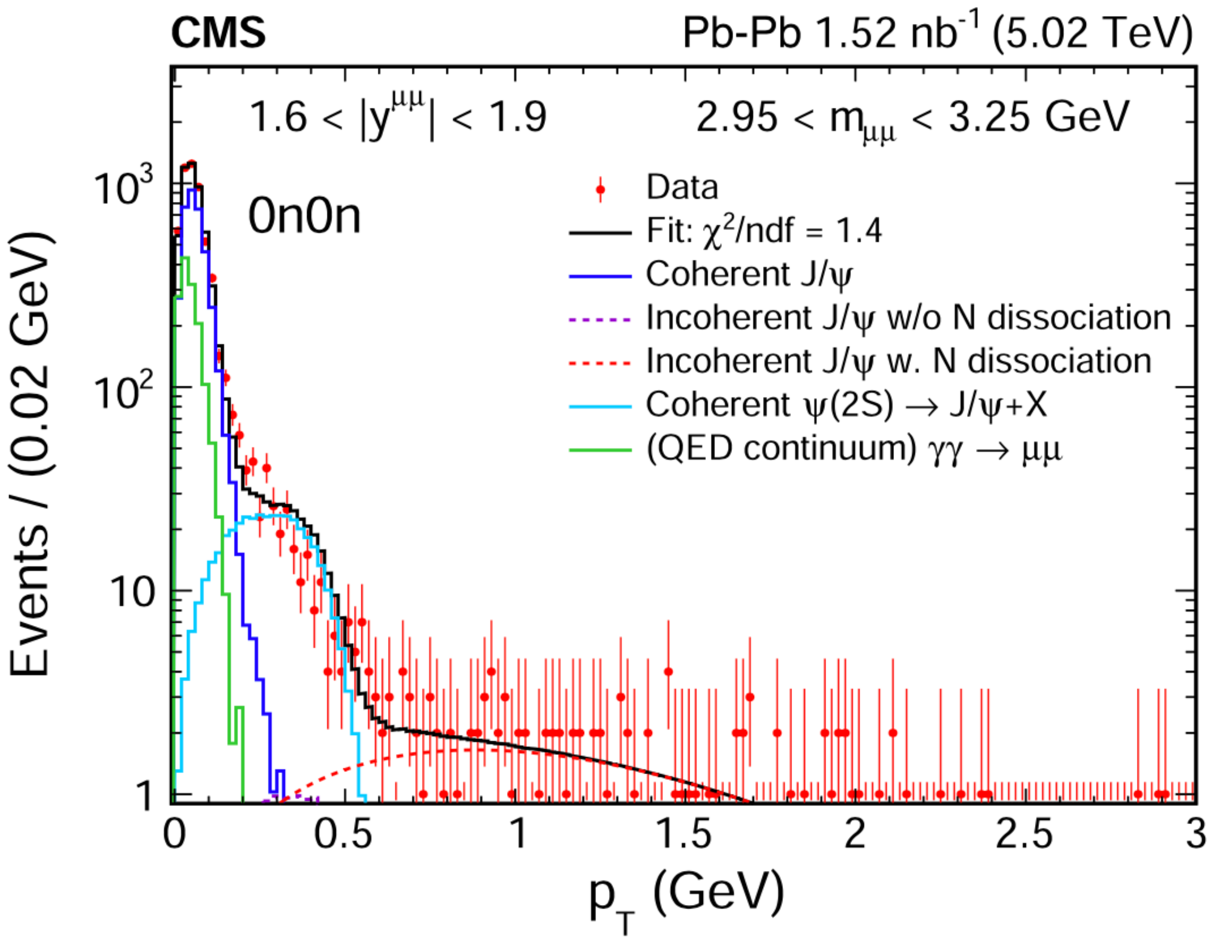
CMS: PRL 131, 262301 (2023)

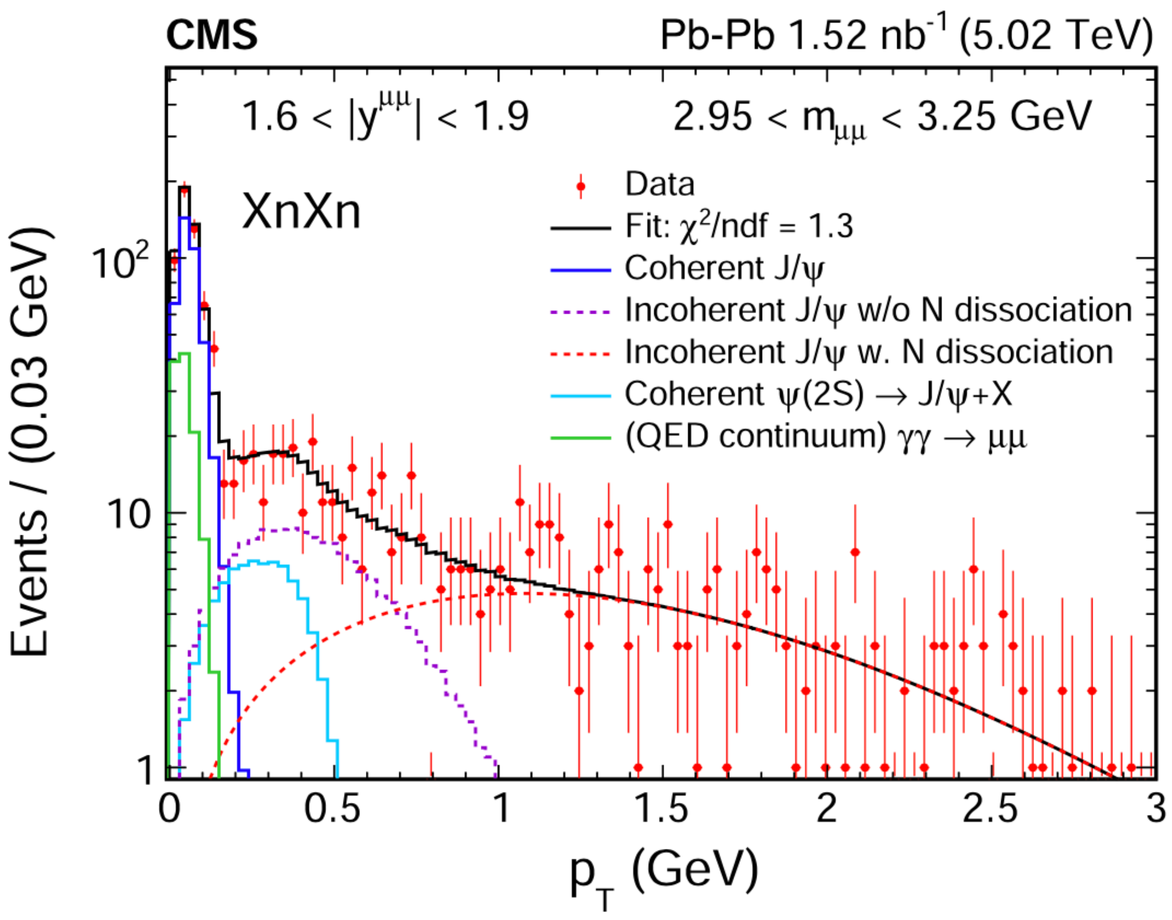
Thank you for your attention!

Special thanks to:
Nuclear shadowing: Vadim Guzey, Mark Strikman, Michael Zhalov
CGC IpSat: Heikki Mantysaari, Bjorn Schenke
Hot spot: Jesus Guillermo Contreras Nuno
b-BK-**G**lauber-**G**ribov: Dagmar Bendova
CD+CGC: Agnieszka Luszczak, Wolfgang Schafer
For their valuable discussions and theoretical inputs.

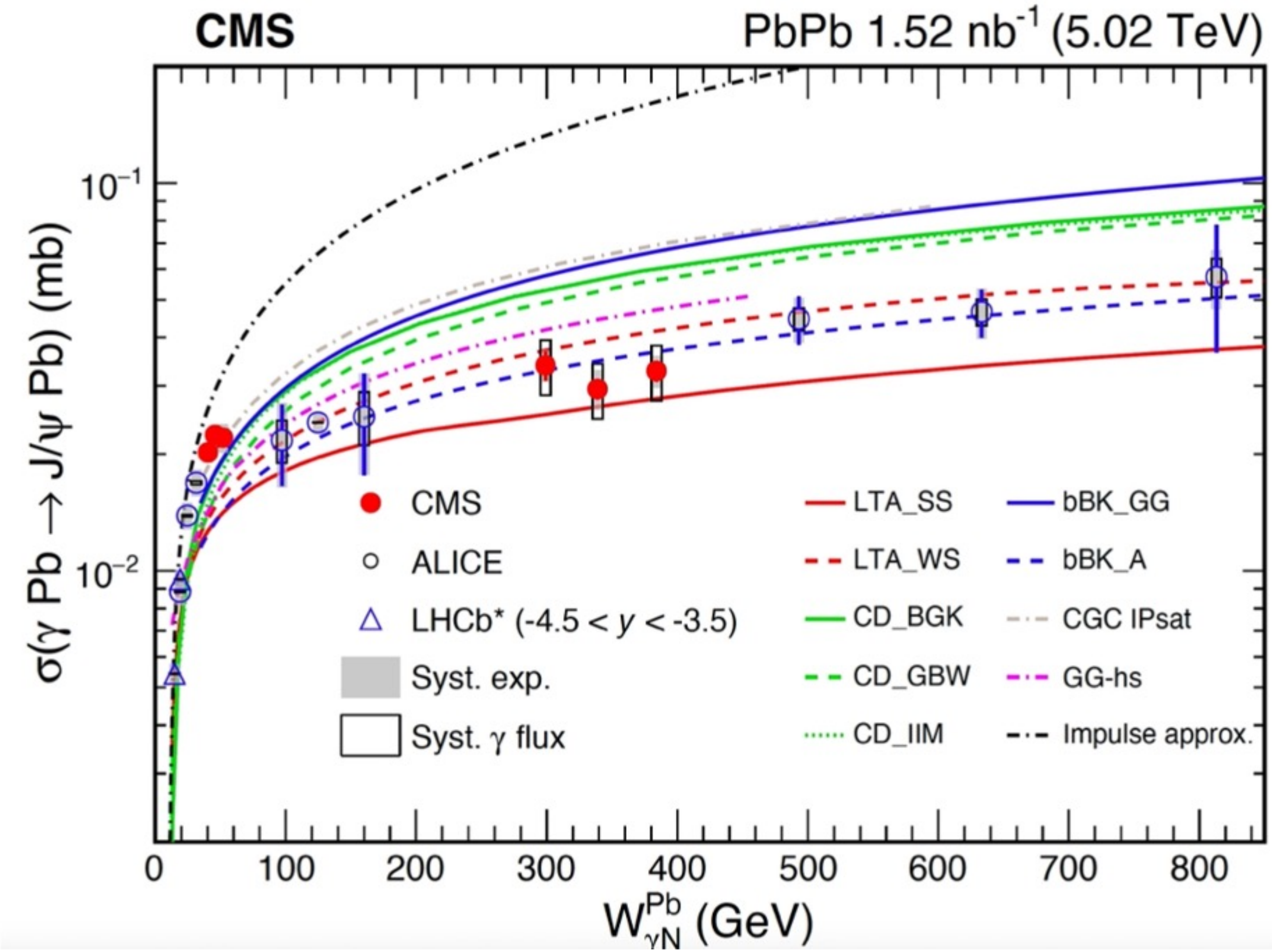
Backup Slides

Pt Distribution in 0n0n and XnXn



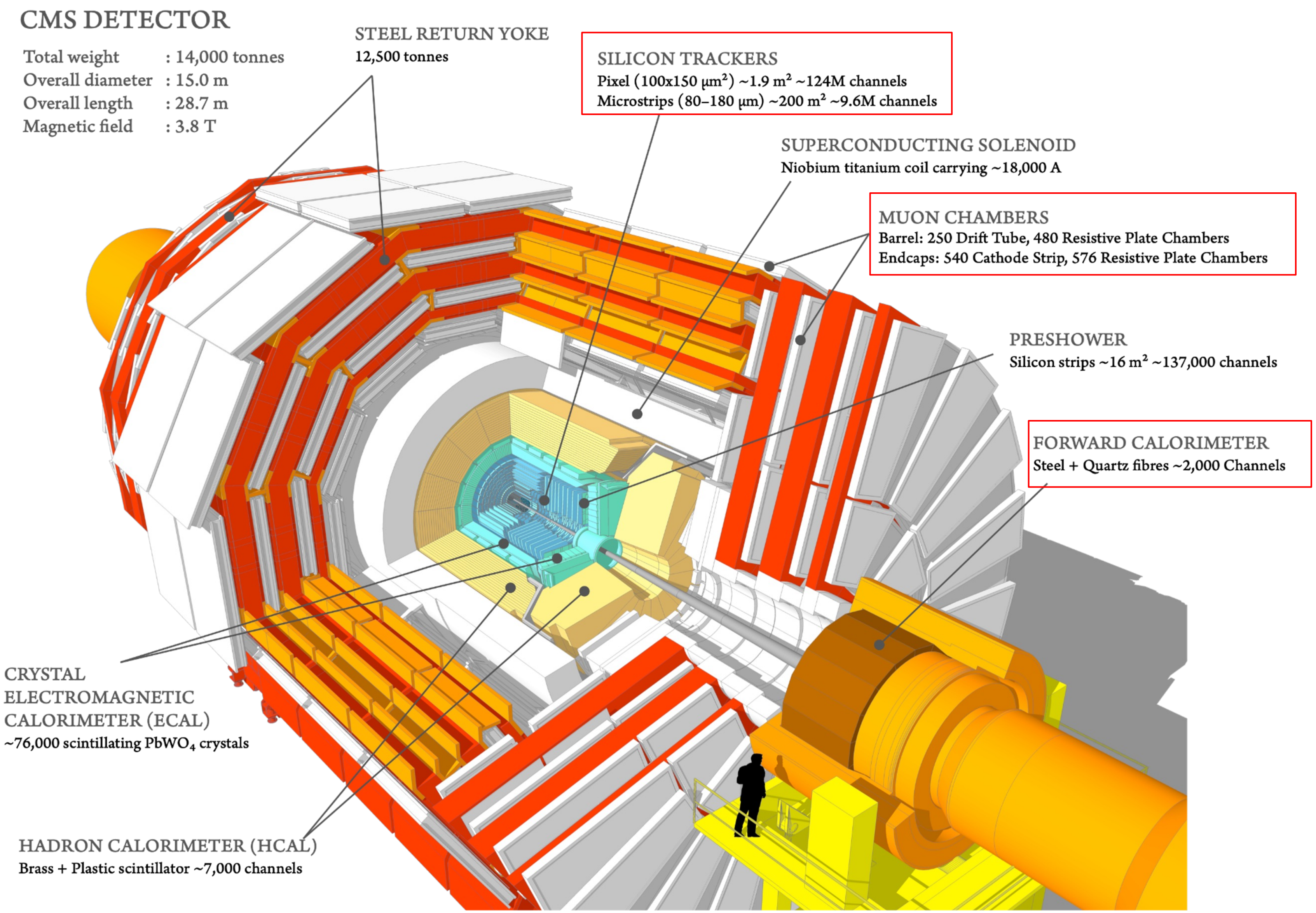


CMS and ALICE data follows the same trend

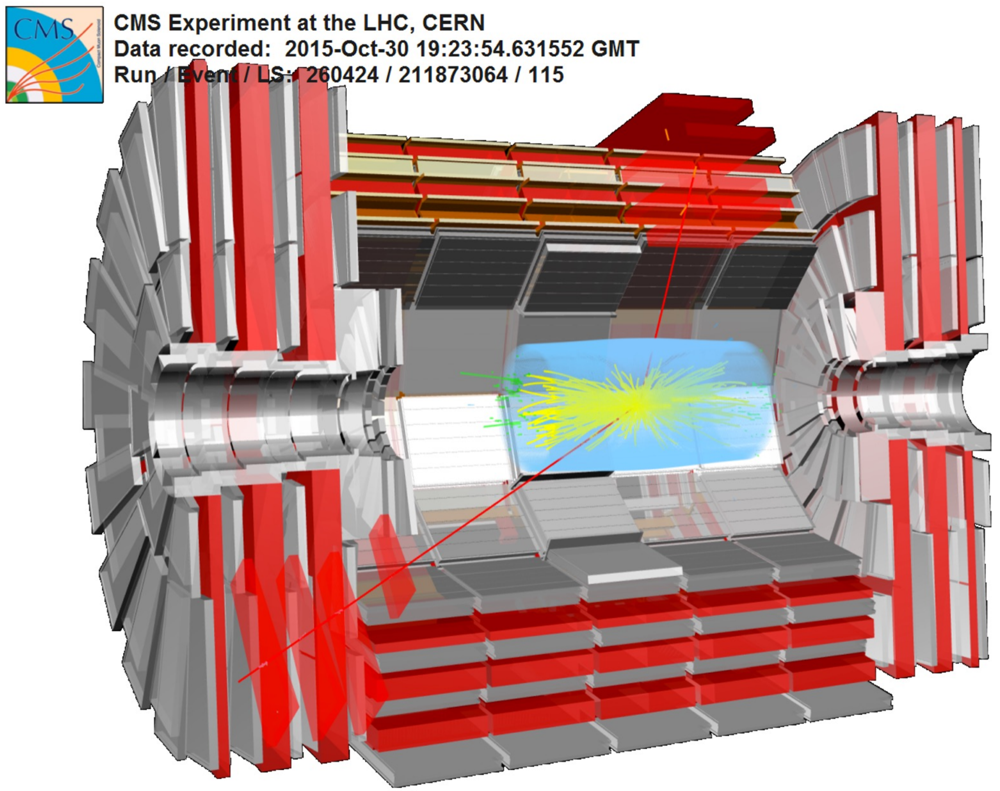


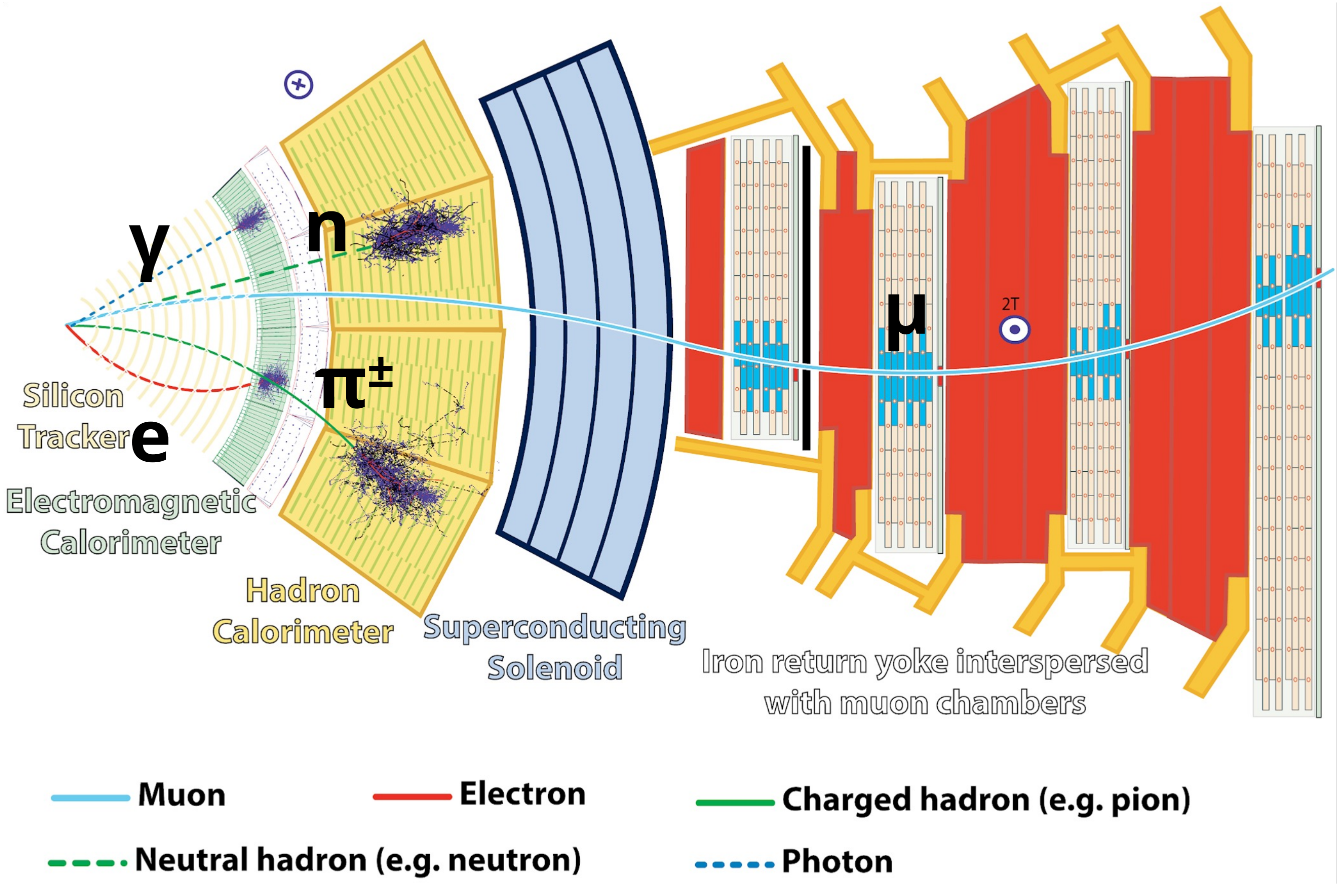
CMS: PRL 131, 262301 (2023) **ALICE: JHEP 10, (2023) 119**

Compact Muon Solenoid Detector



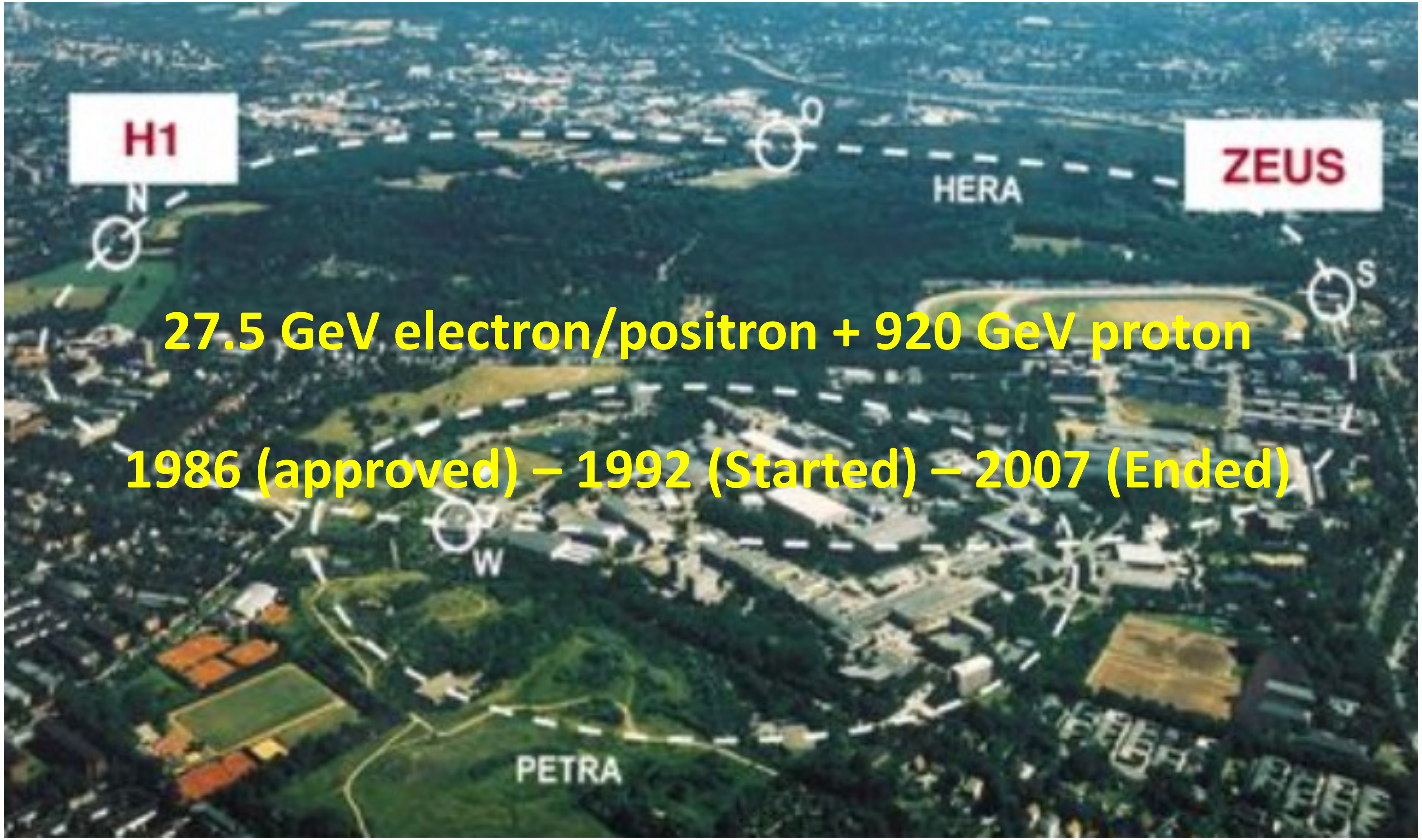
Muon Reconstruction





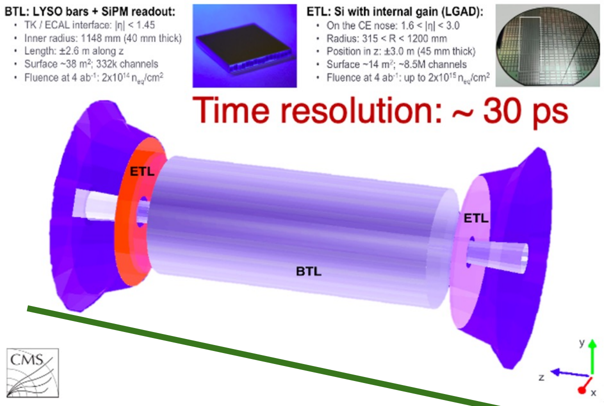
- Tracker and muon detectors used to reconstruct/identify muons.

Understand Nucleon Structure at HERA

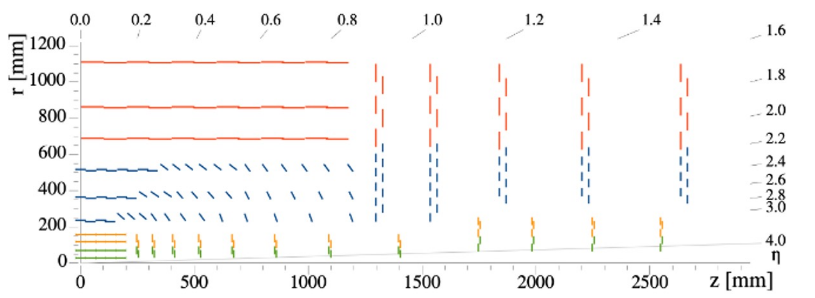


Future Opportunities

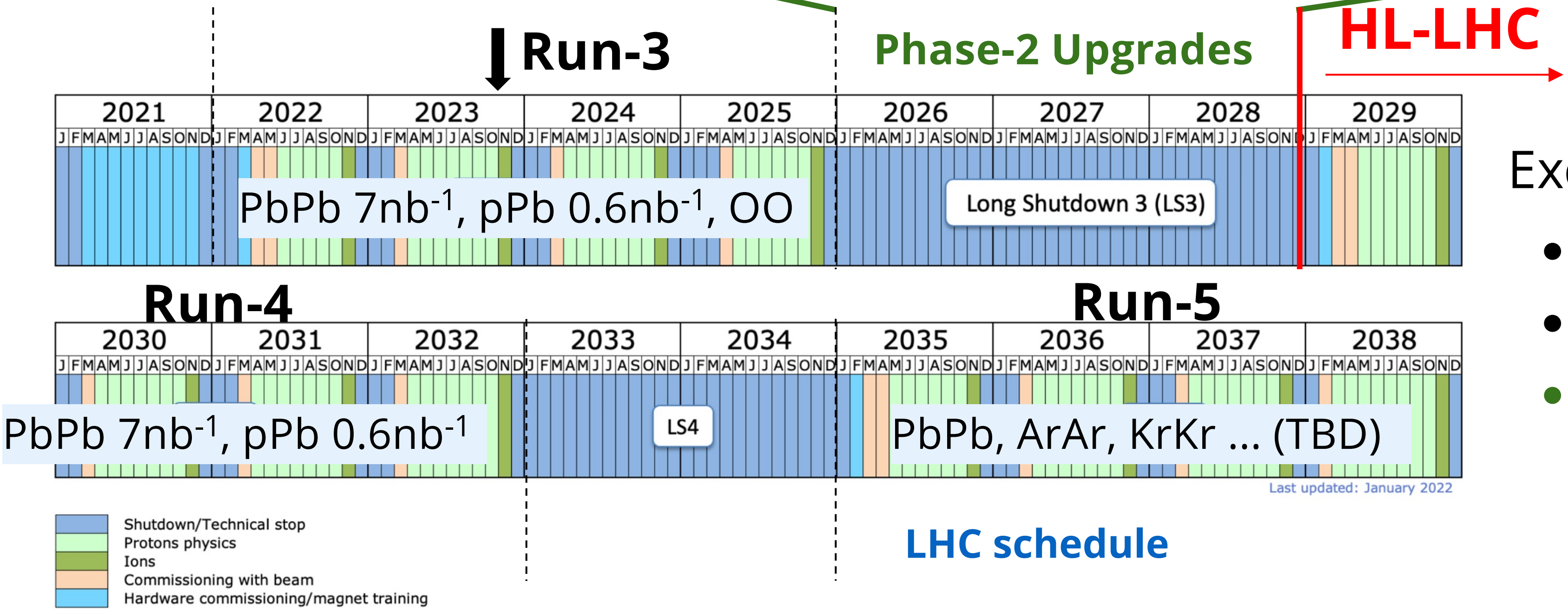
MIP Timing Detector for PID



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!

Photon Flux: Point-like vs. Realistic

CPC 277 (2022) 108388

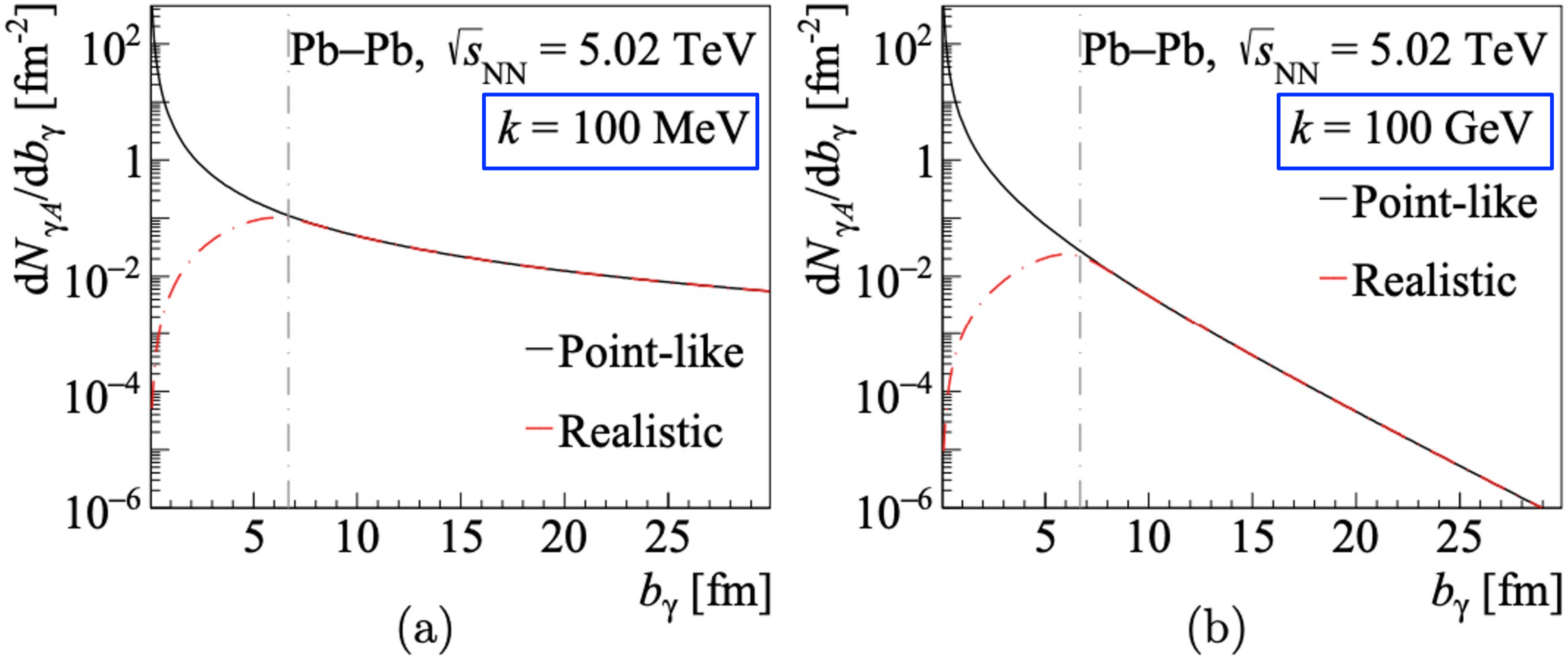
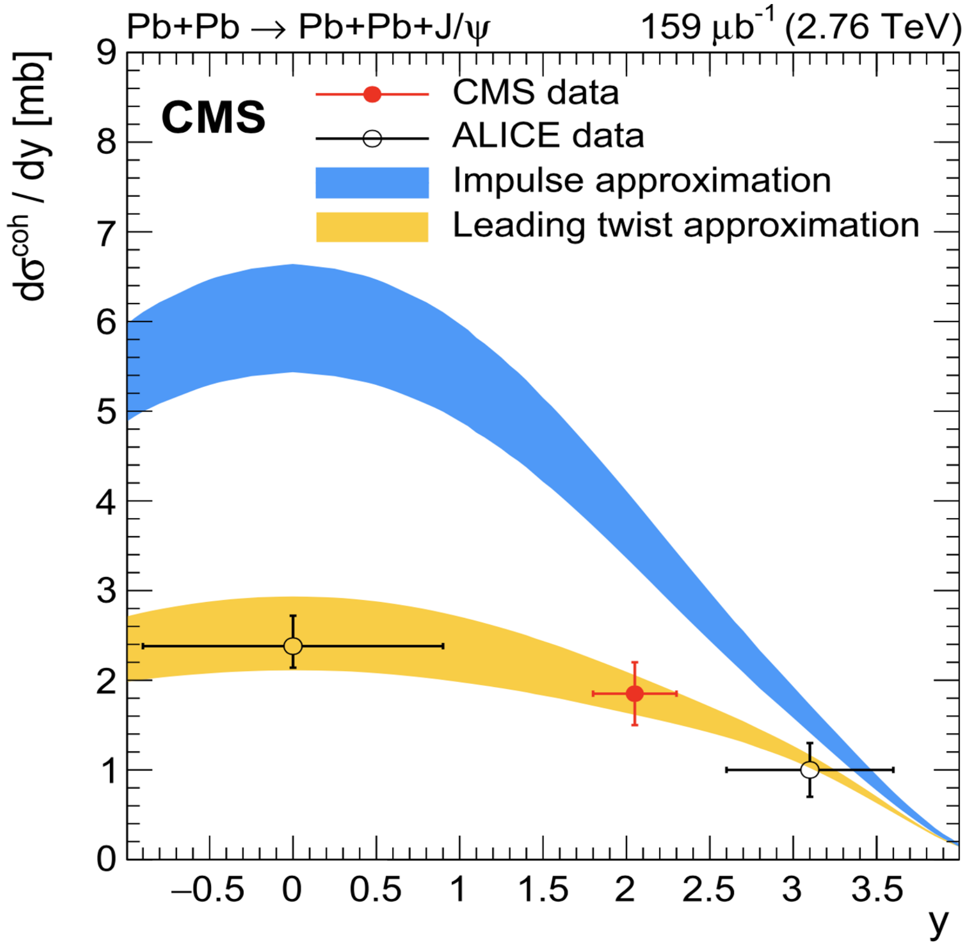


Figure 4: (Color online) Photon fluxes coming from a nucleus $N_{\gamma A}$ in the point-like source approximation and the realistic description as functions of impact parameter b_γ calculated at different photon energies: 100 MeV (a), 100 GeV (b).

Coh. Jpsi from LHC Run1 PbPb UPC

PLB 772 (2017) 489

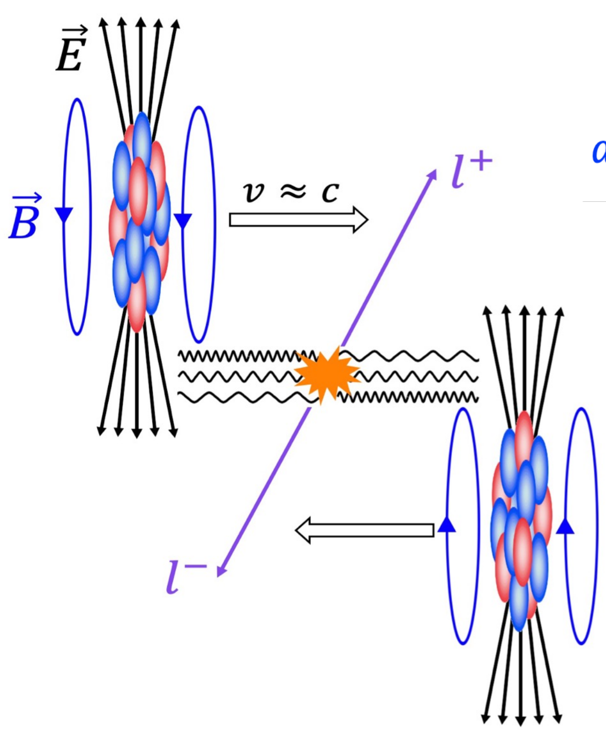


- Run 1 data from CMS and ALICE seem to be well consistent with LTA shadowing model calculations
- However,
  - large uncertainties
  - wide-y bins
  - Mixed low- and high- W contributions

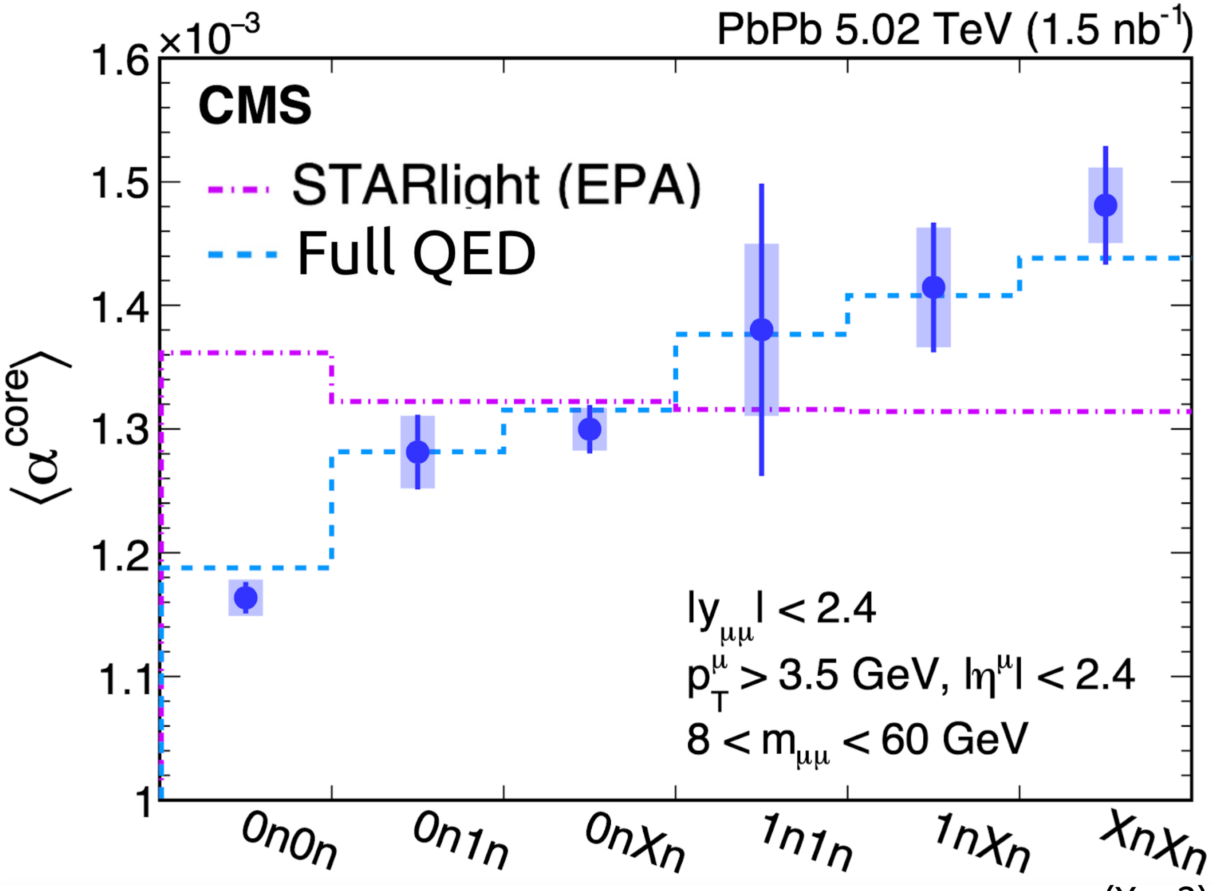
QED Dimuon with Neutron Tagging at CMS

PRL 127 (2021) 122001

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



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



(X: ≥2)

First direct evidence of b-dependent initial photon p_T, set strong base line for observe QGP EM effects in heavy ion collisions