

# Probing Ultra-Dense Gluonic Matter via UPCs with the CMS Experiment

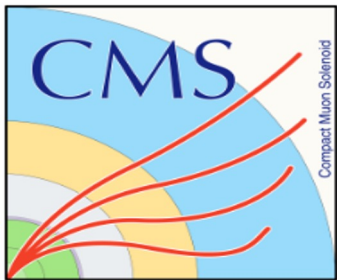
Zaochen Ye (Rice University)  
for the CMS Collaboration

**CMS:** [arXiv:2303.16984](https://arxiv.org/abs/2303.16984), submitted to PRL



Topical Group on  
Hadronic Physics  
GHP

April 12-14 2023, Minneapolis Minnesota



RICE

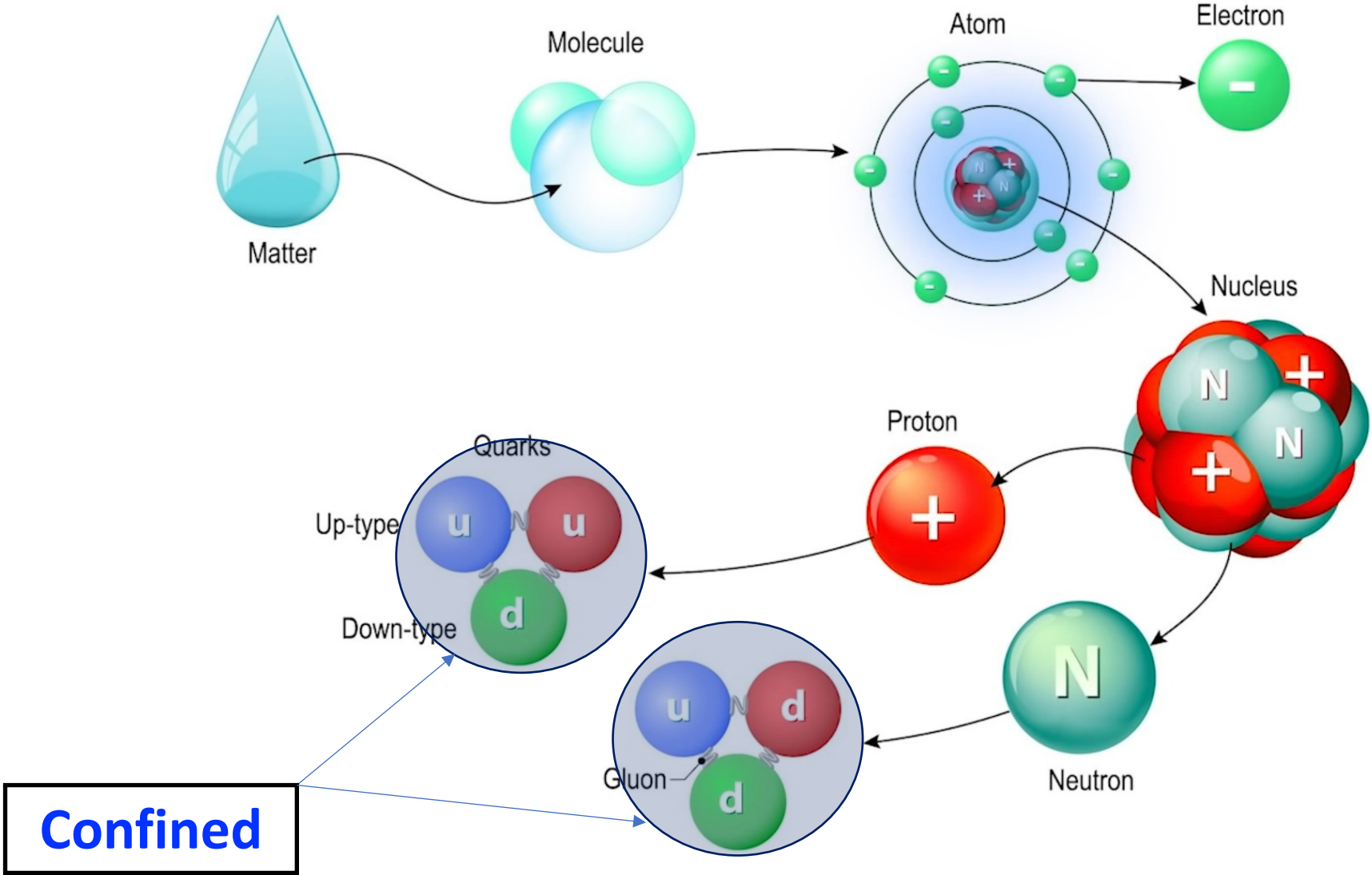


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**ENERGY**

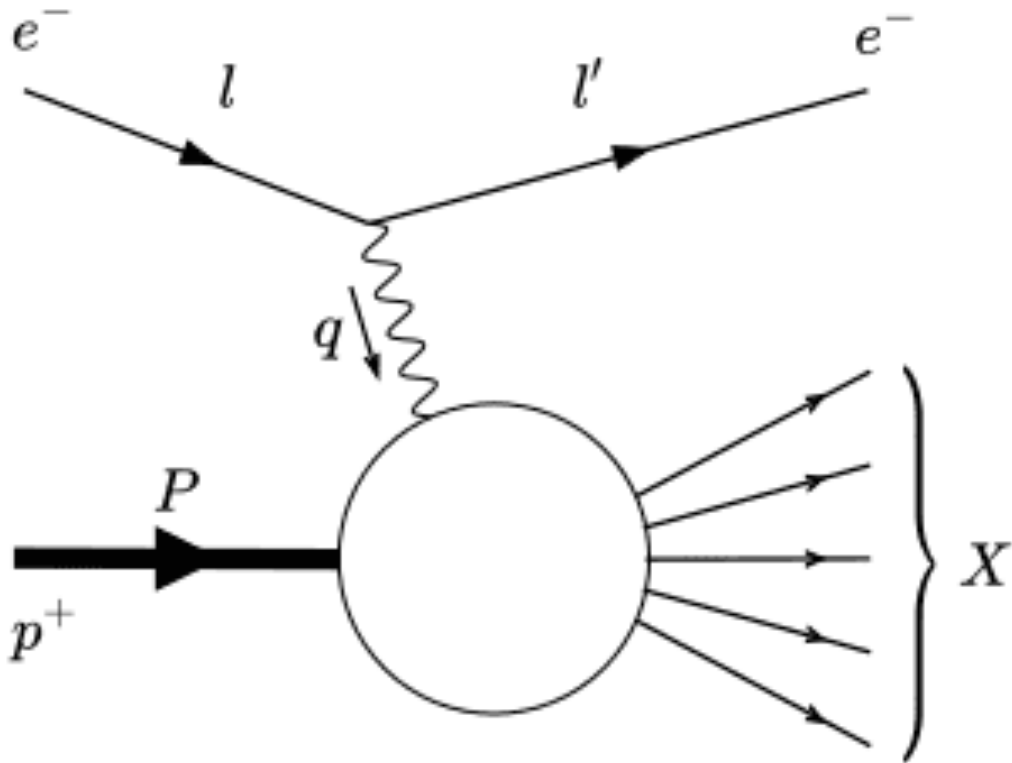
Office of  
Science

# Understand Fundamental Structure of Matter



# Understand Nucleon Structure via DIS

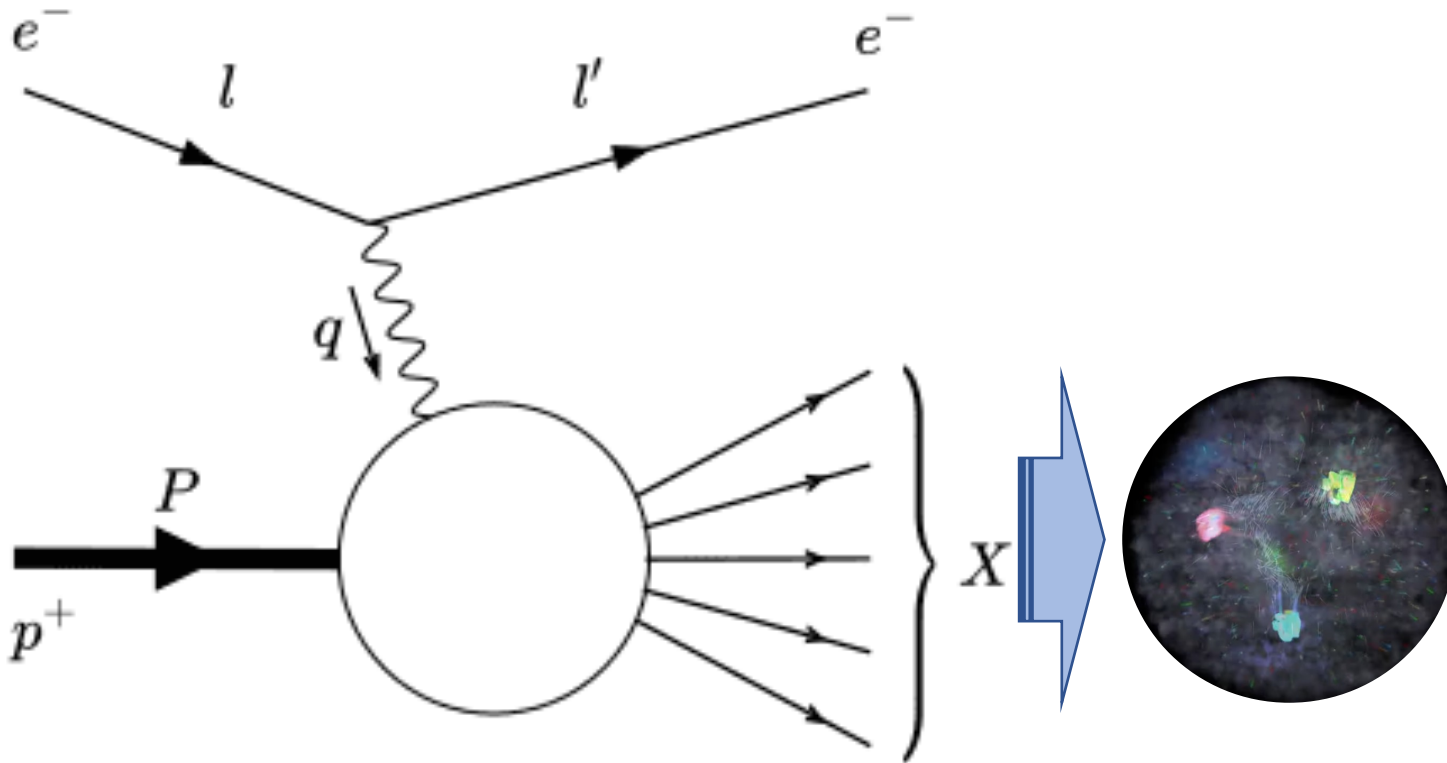
**Smash them!!!**



**Deep Inelastic Scattering**

# Understand Nucleon Structure via DIS

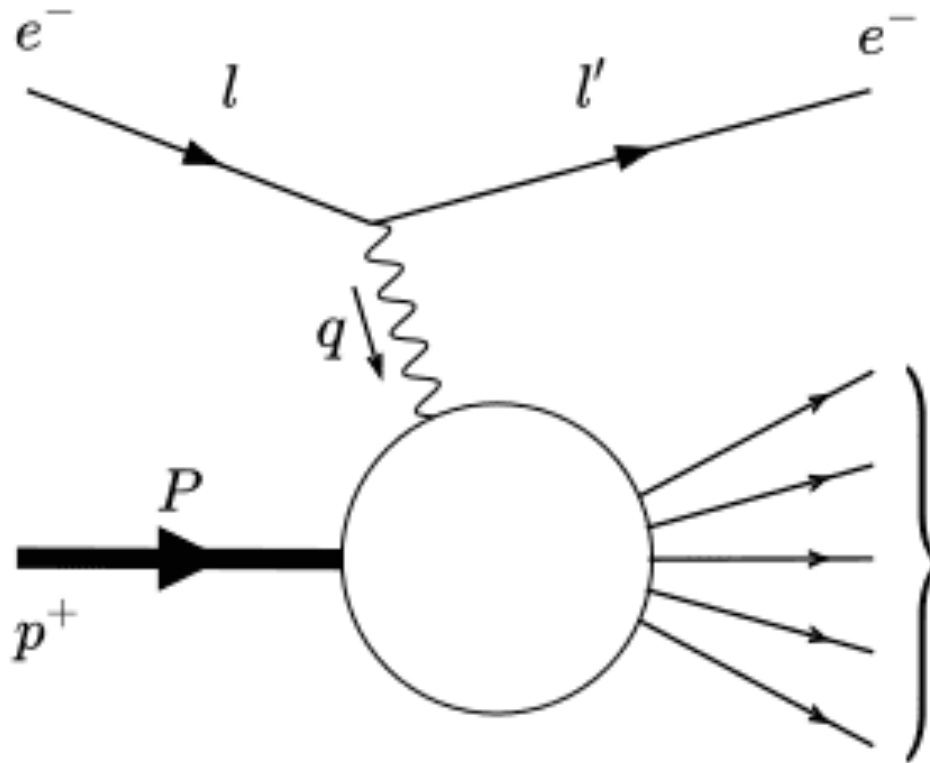
**Smash them!!!**



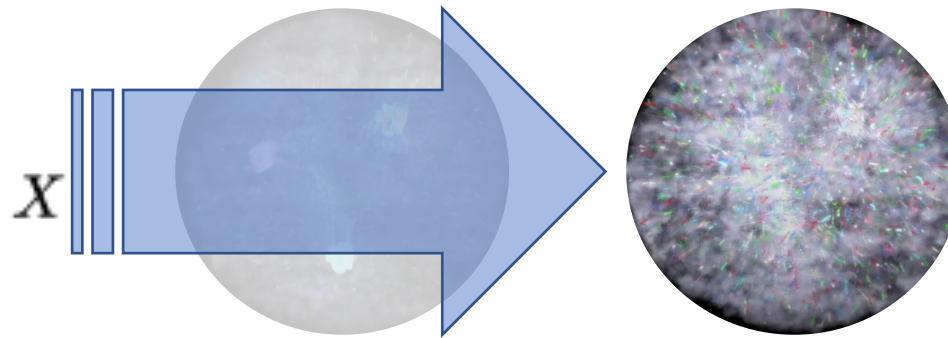
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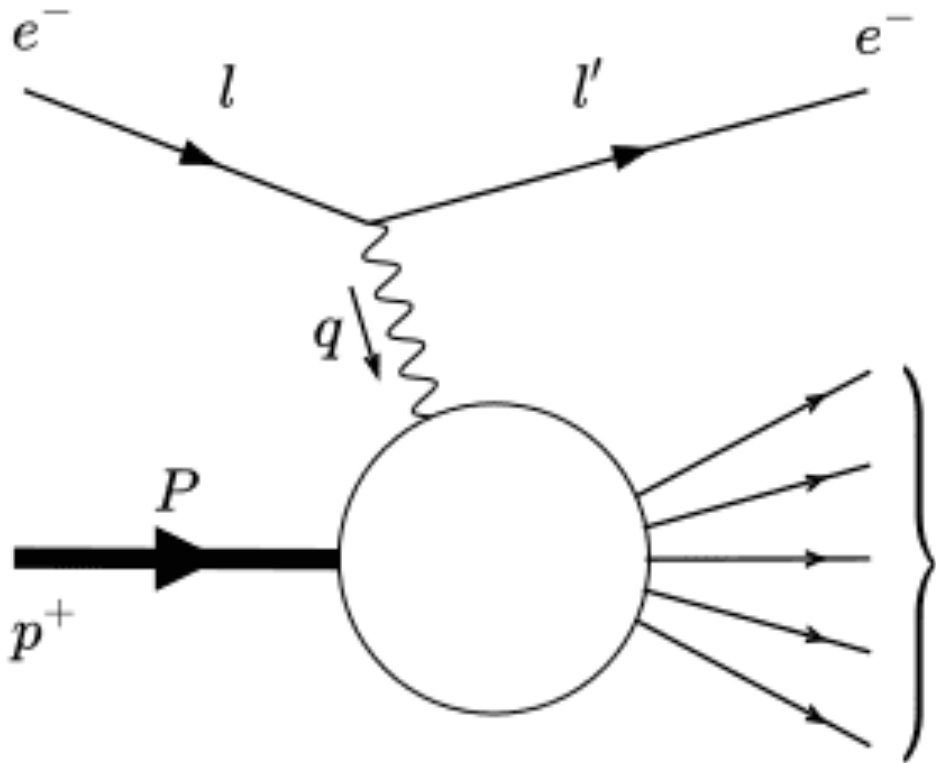
**Higher energy, probing lower-x partons**



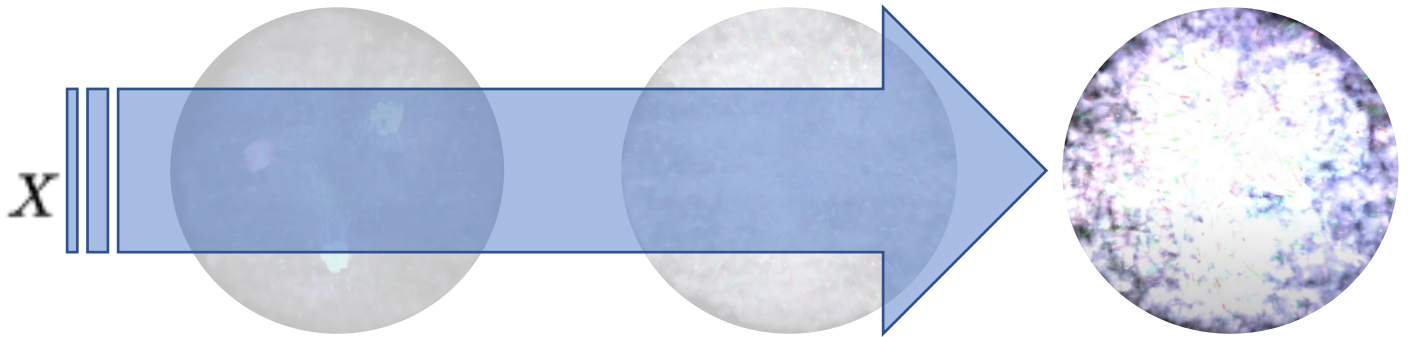
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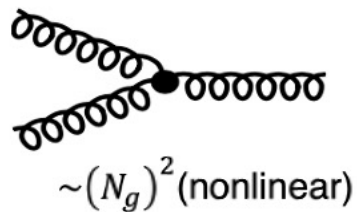
# Understand Nucleon Structure

e-p collider

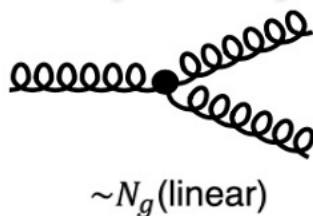


Rapid increase of gluon density towards small  $x$ .

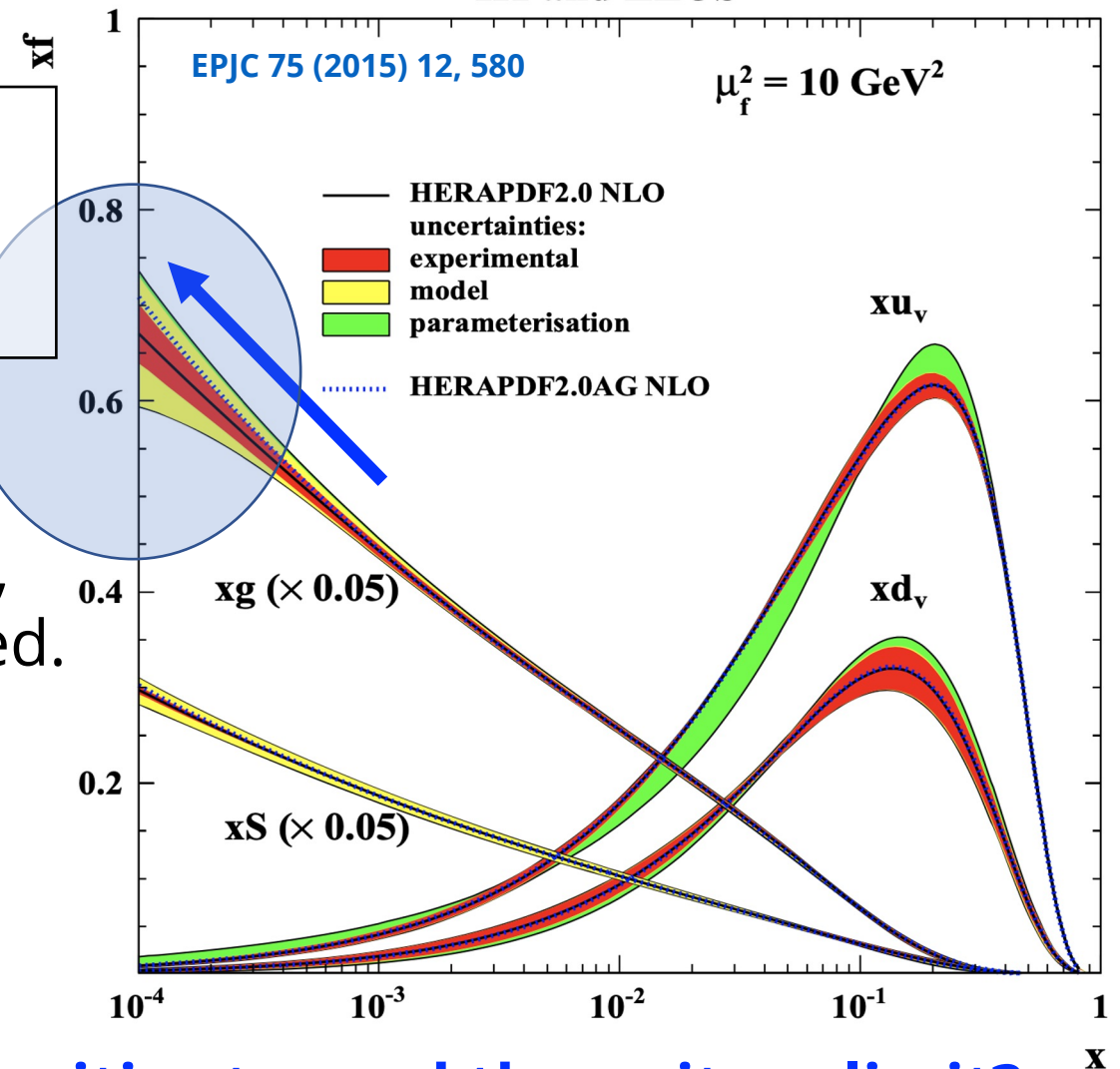
Indefinite growth at small- $x$  violates unitarity, mechanism beyond gluon splitting is expected.



Saturation?



H1 and ZEUS

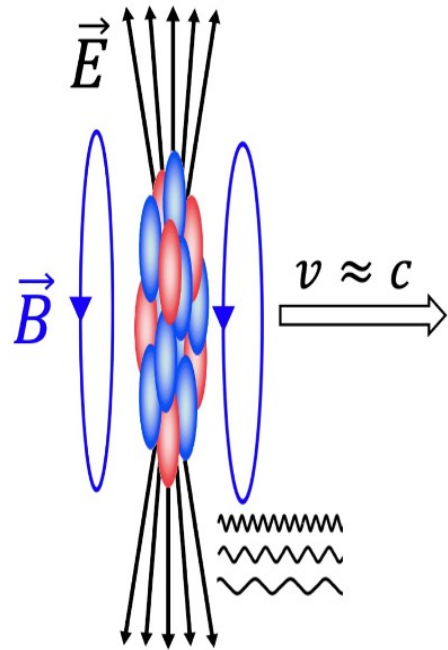


What is the fate of gluons at extreme densities toward the unitary limit?

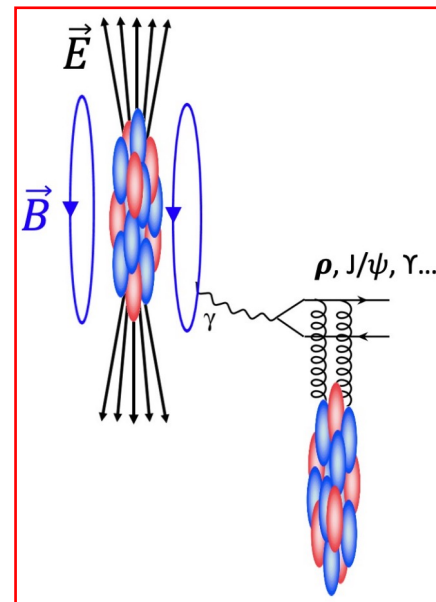
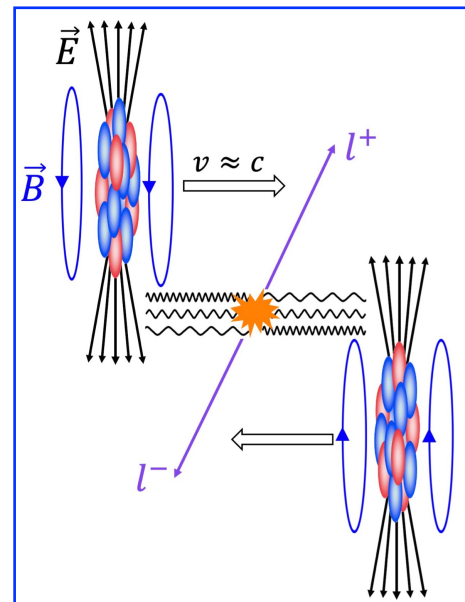
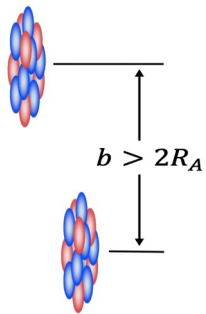
# Ultra-Peripheral Collision (UPC)

- Lorentz contracted EM fields  $\rightarrow$  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:



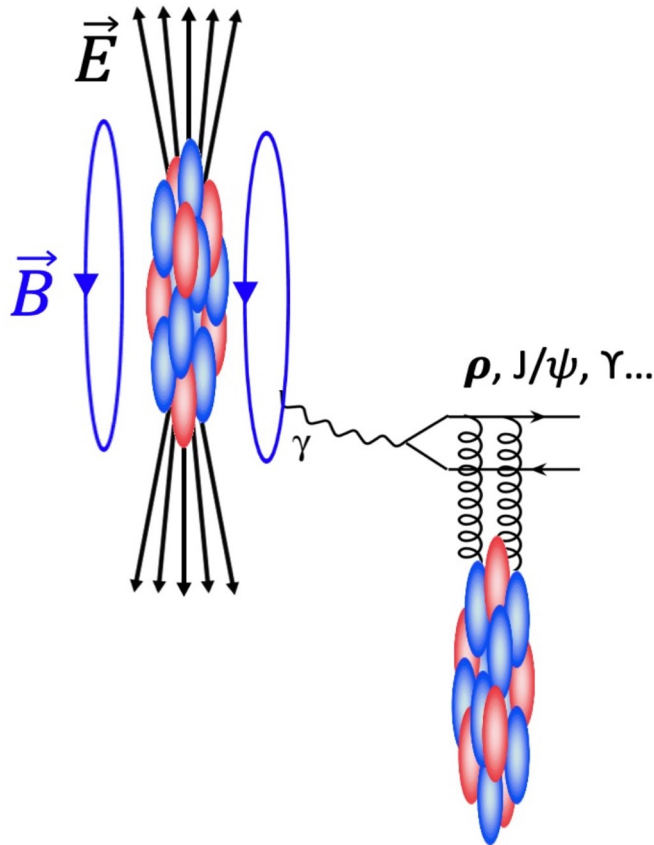
...



# Vector Meson Photoproduction in UPC

VM (e.g.,  $J/\psi$ ) photoproduction directly **probes gluonic structure** of nucleus and nucleon.

At LO in pQCD, cross section  $\sim$  photon flux  $\otimes$   $[xG(x)]^2$



## Coherent production:

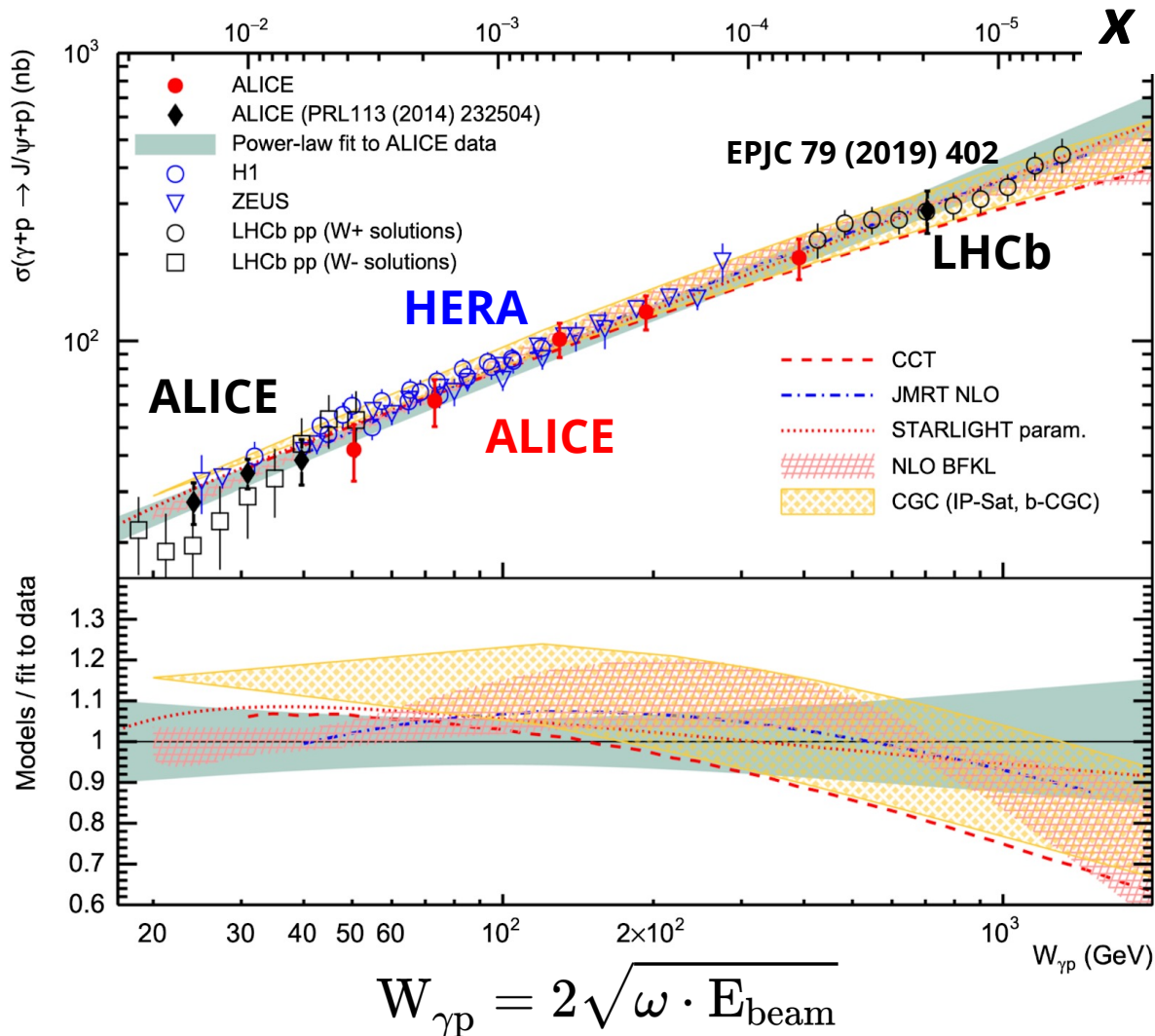
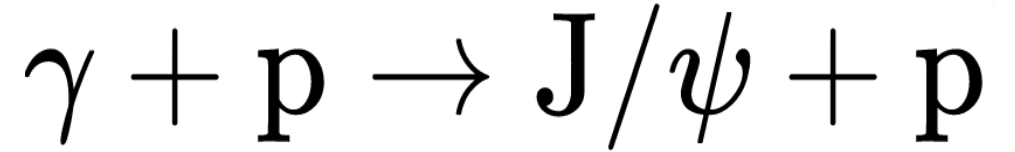
- Photon fluctuated dipole couples coherently to entire nucleus
- Target nucleus remains intact
- VM  $\langle p_T \rangle \sim 50$  MeV
- Probing the averaged gluon density

## Incoherent production:

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

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

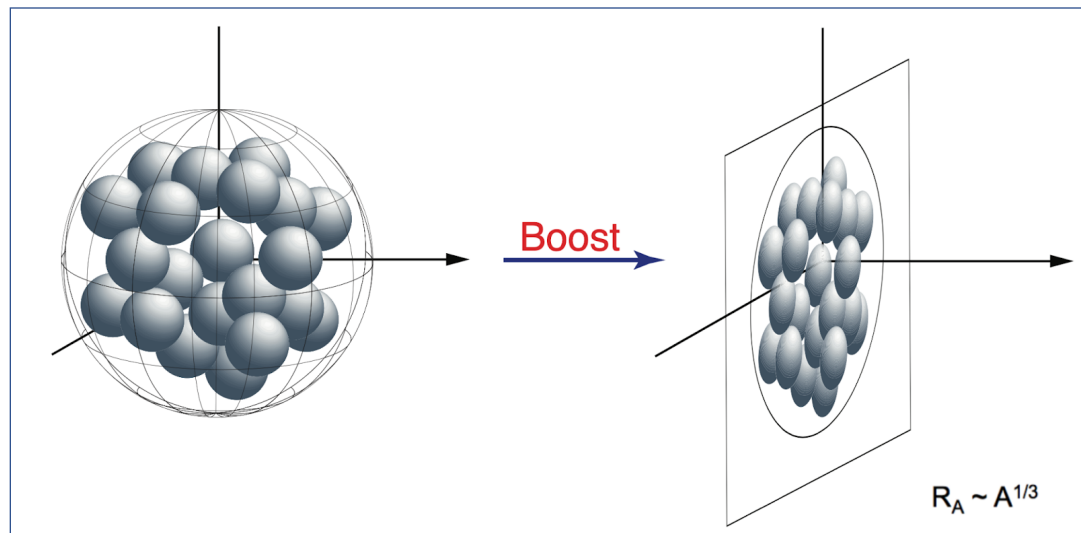
# Coherent J/ψ Photoproduction via $\gamma$ + Free Nucleon



- 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  $x \sim 10^{-5}$  in a free nucleon.**

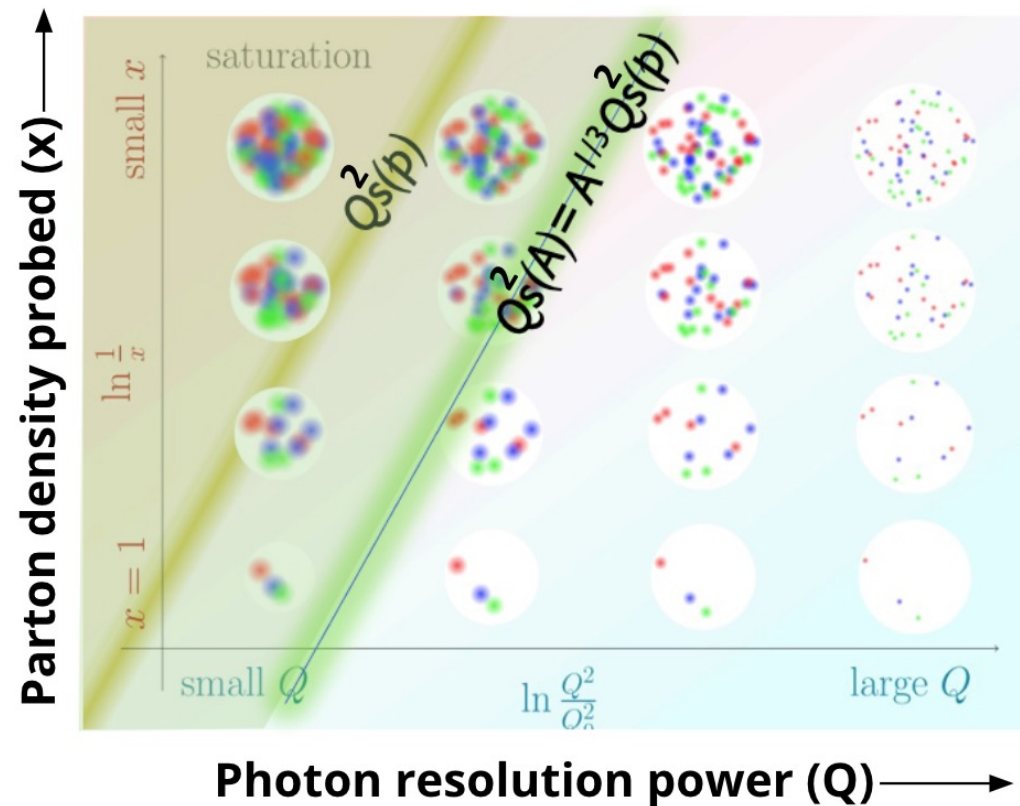
# Advantages of Gluon Saturation Search in Nucleus



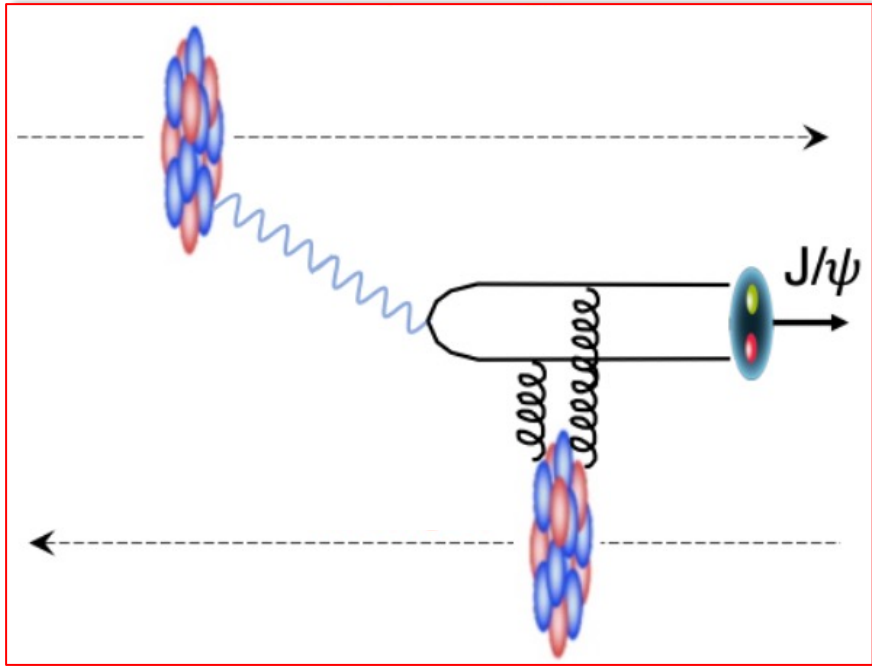
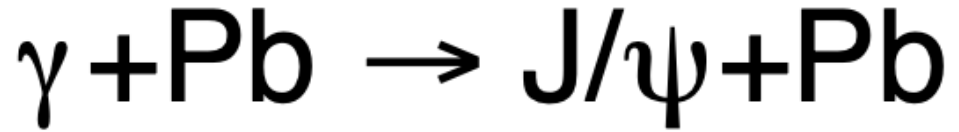
Gluons is **enhanced** by a factor of  $A^{1/3}$  in **nucleus** compared to what in free nucleon

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

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

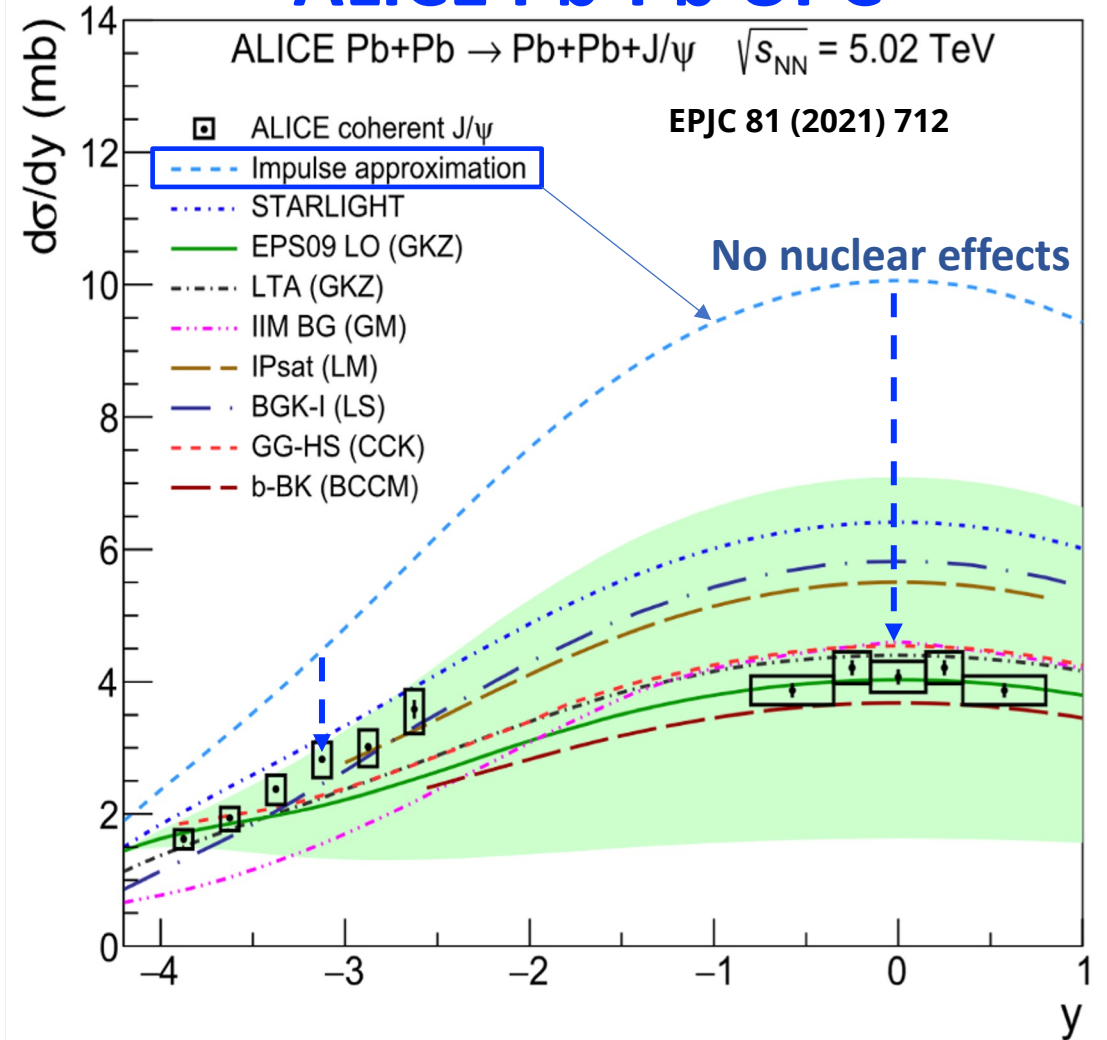


# Coherent J/ψ Photoproduction in A-A UPCs

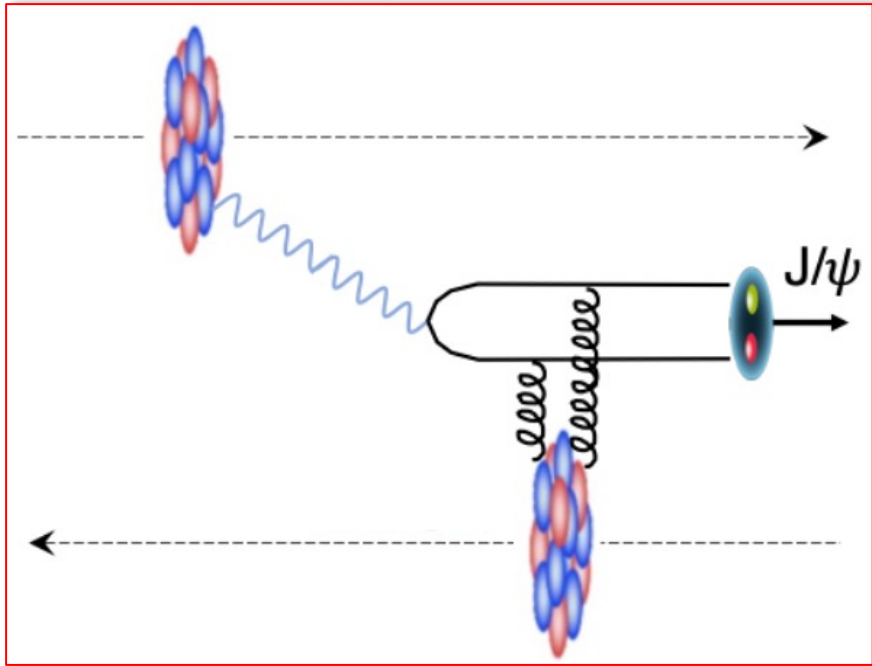
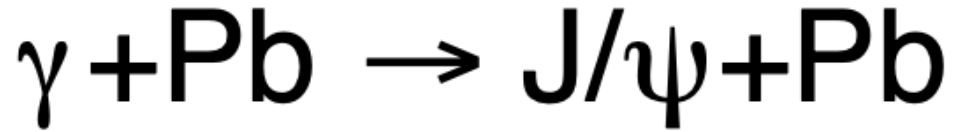


- **Strong suppression**, but the rapidity distribution is still **a puzzle** for theoretical studies (models considering gluon saturation or shadowing)

## ALICE Pb-Pb UPC

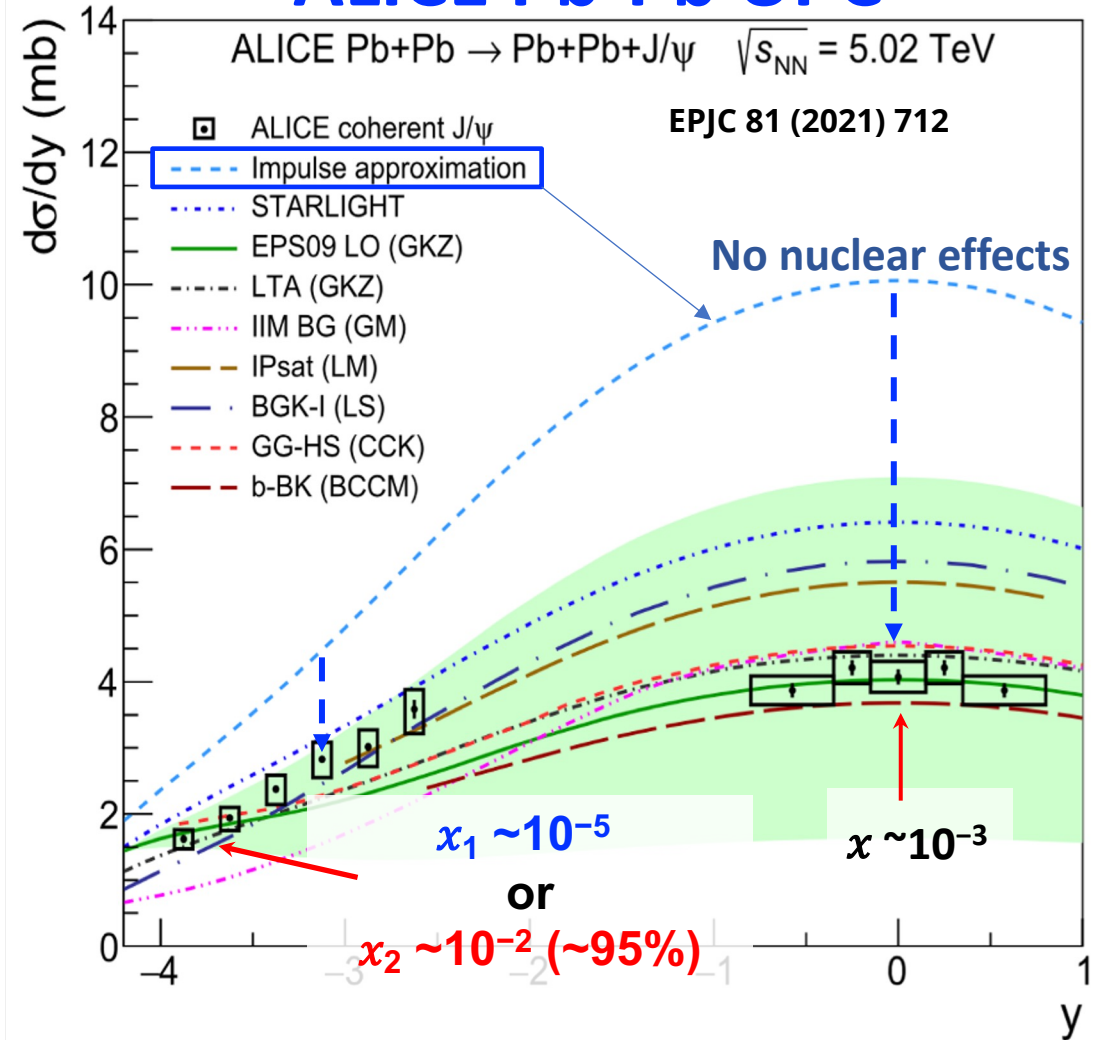


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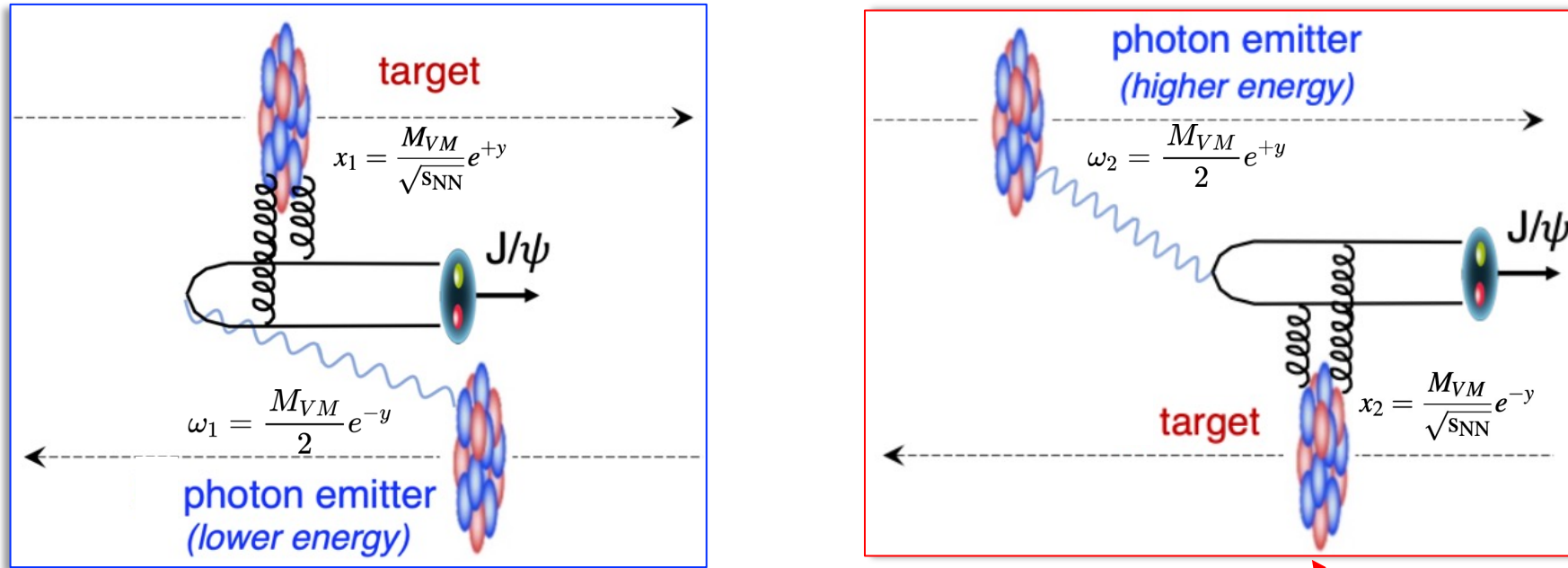
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## ALICE Pb-Pb UPC



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

# Two-Way Ambiguity in A-A UPC



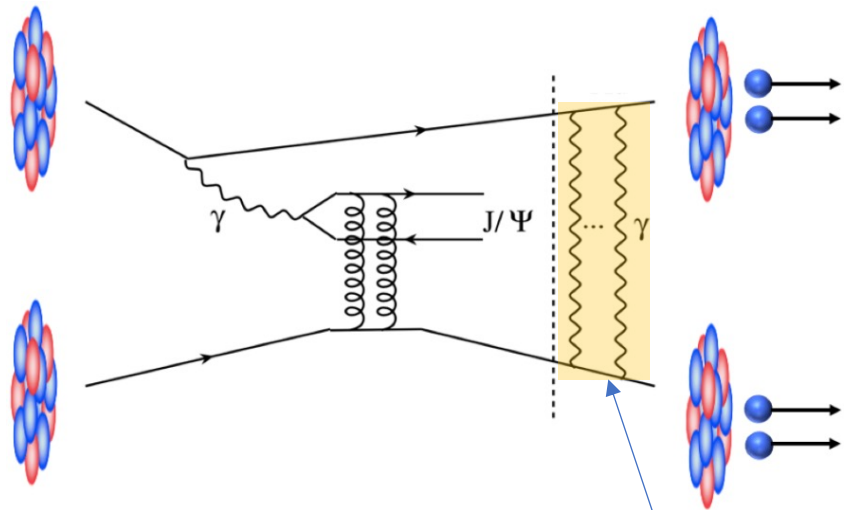
$$\frac{d\sigma_{AA \rightarrow AA' J/\psi}}{dy} = N_{\gamma/A}(\omega_1) \cdot \sigma_{\gamma A \rightarrow J/\psi A'}(\omega_1) + N_{\gamma/A}(\omega_2) \cdot \sigma_{\gamma A \rightarrow J/\psi A'}(\omega_2)$$

**At least two equations for the solutions**

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

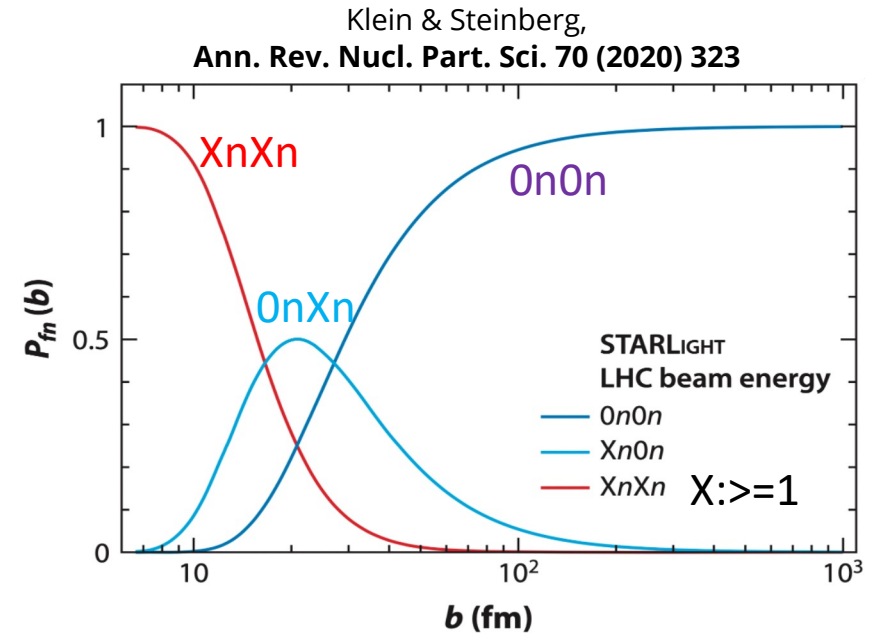
V. Guzey, M. Strikman, M. Zhalov, EPJC (2014) 72 2942

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



## Neutron emission via EMD with additional photon exchange:

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



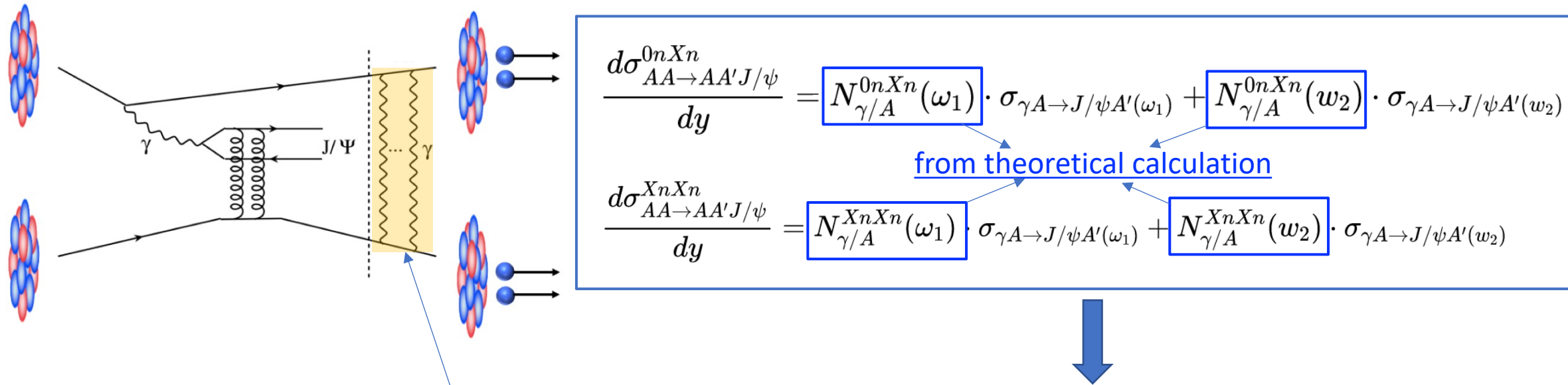
- Analogous to centrality:

- $b_{XnXn} < b_{0nXn} < b_{0n0n}$  in UPC

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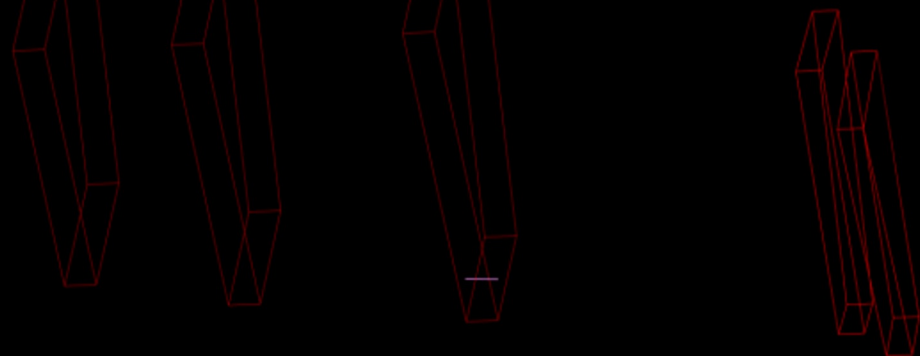




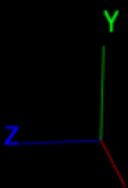
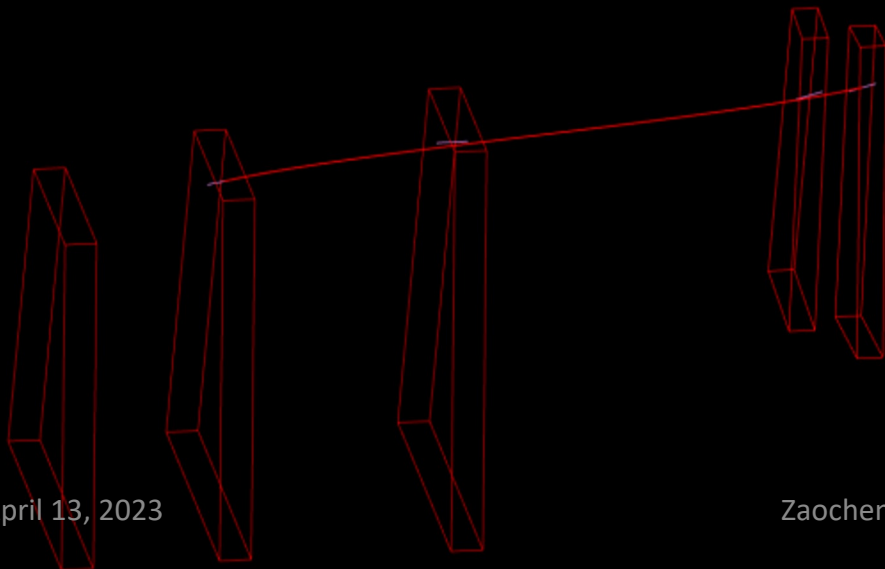
CMS Experiment at the LHC, CERN

Data recorded: 2018-Nov-12 21:48:04.525285 GMT

Run / Event / LS: 326619 / 2320827 / 8



**Muon Chambers**

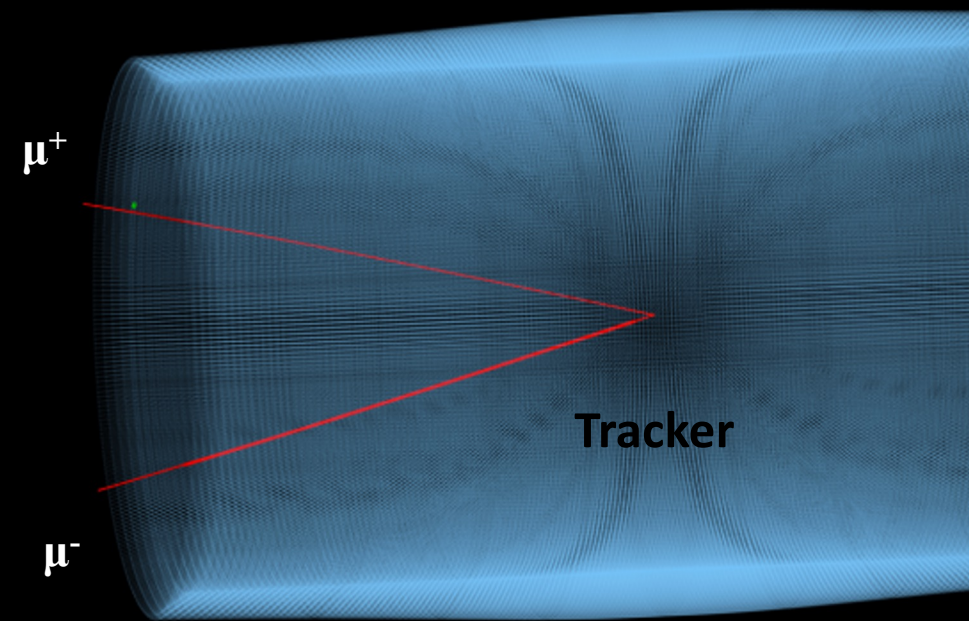


Thursday, April 13, 2023

Zaochen Ye at GHP2023

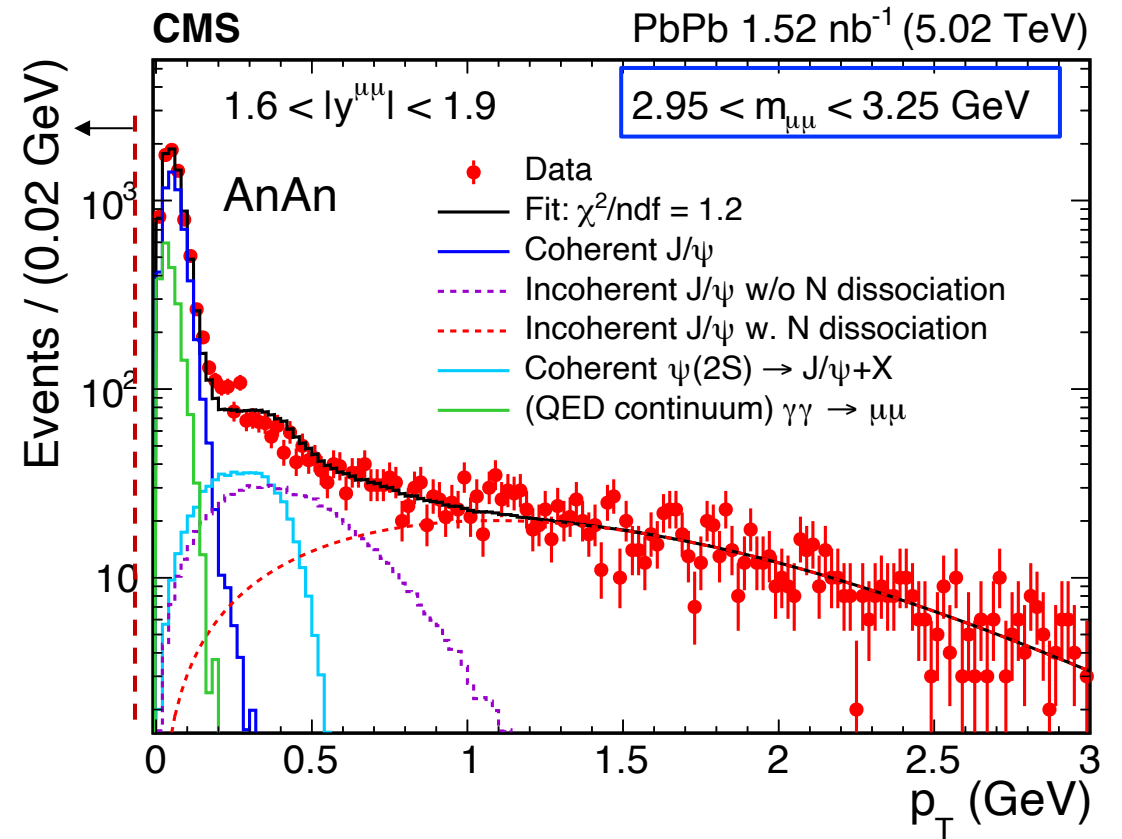
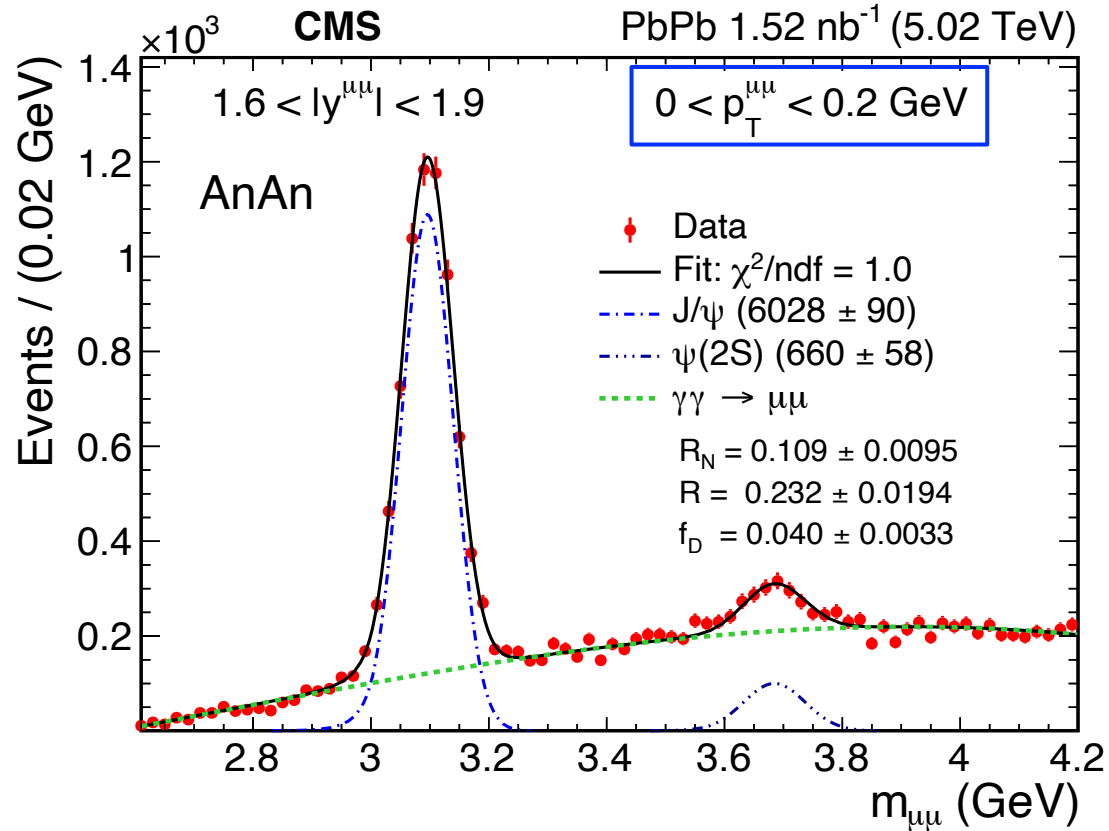
## Interested UPC event:

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



# Signal Extraction

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



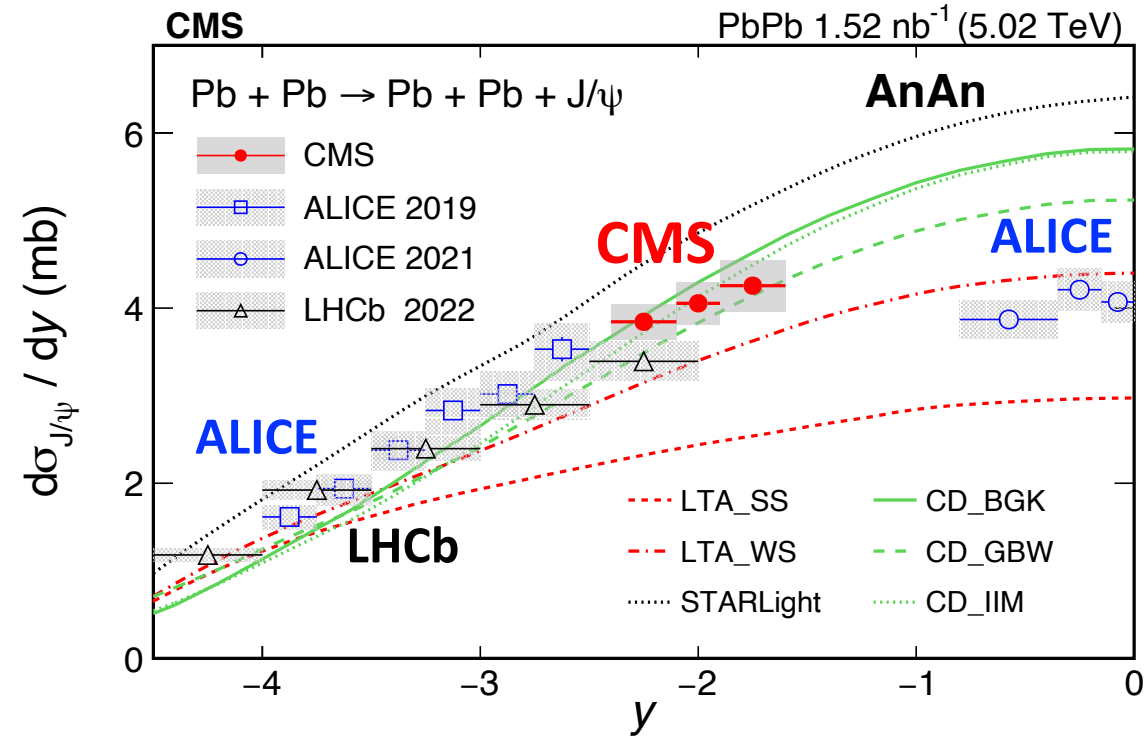
**AnAn:** All possible neutron emissions

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

# Coherent J/ψ in AnAn

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

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



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

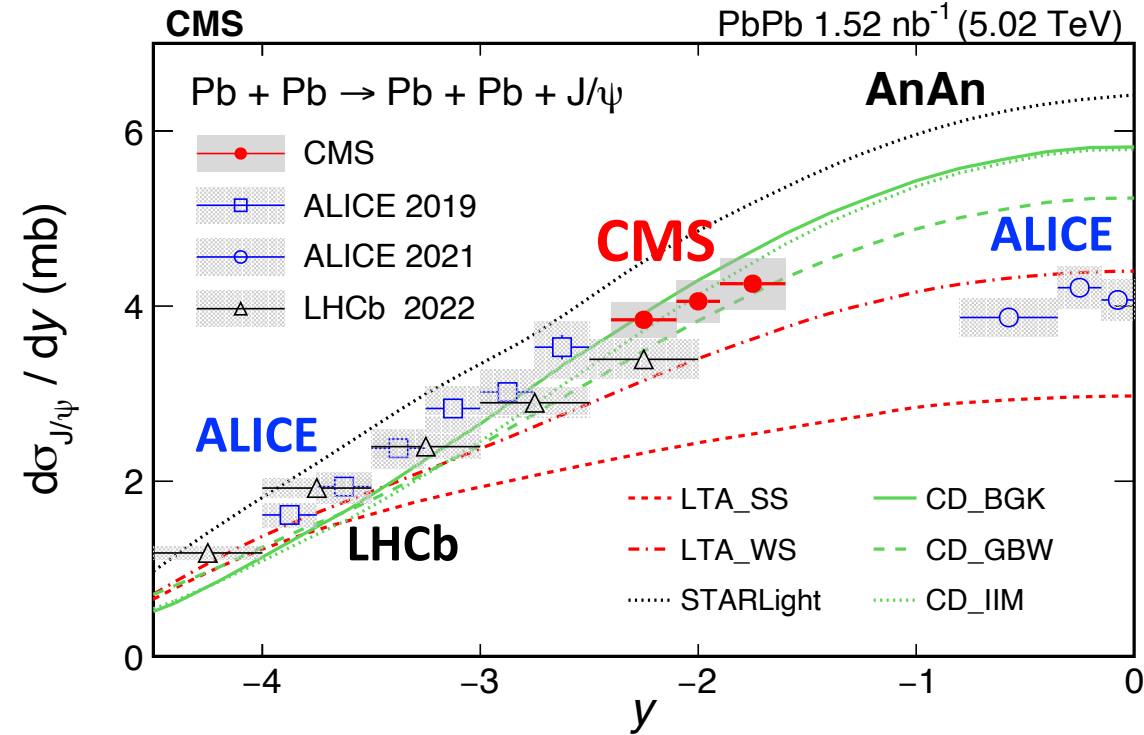
- A **tension** btw **ALICE/CMS** and **LHCb** data?
- **No theory** can describe data over **full  $y$**  region – **A puzzle?**

**AnAn: All possible neutron emissions**

# Coherent J/ψ in AnAn

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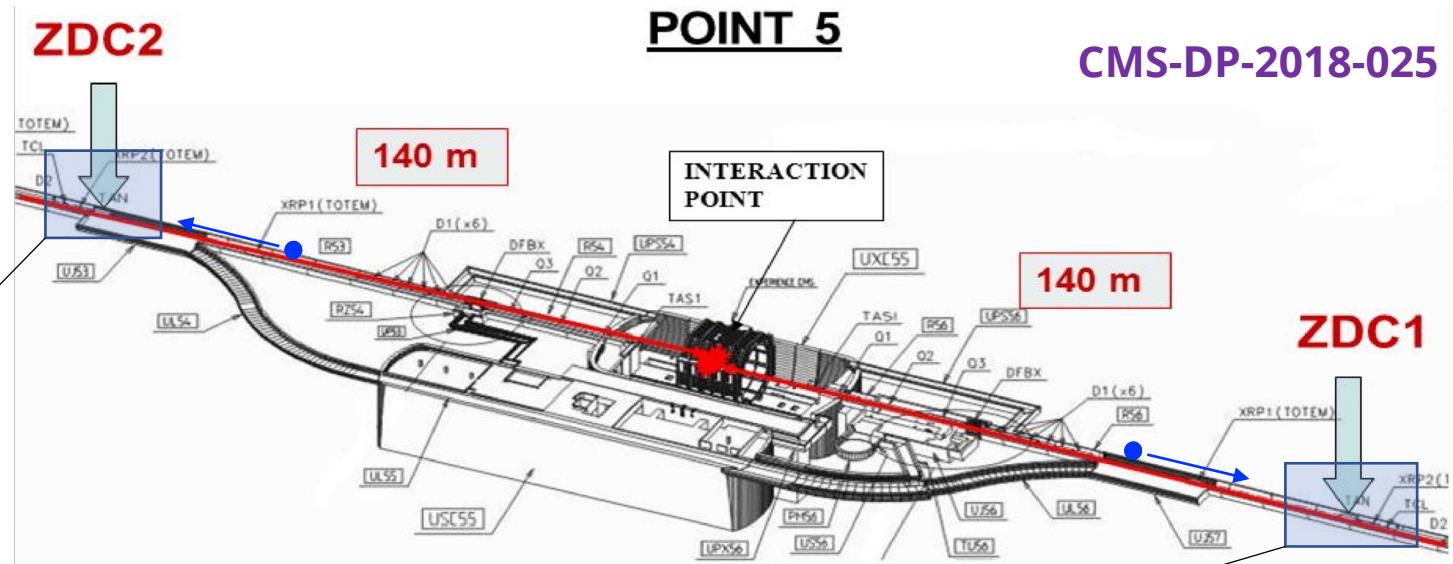
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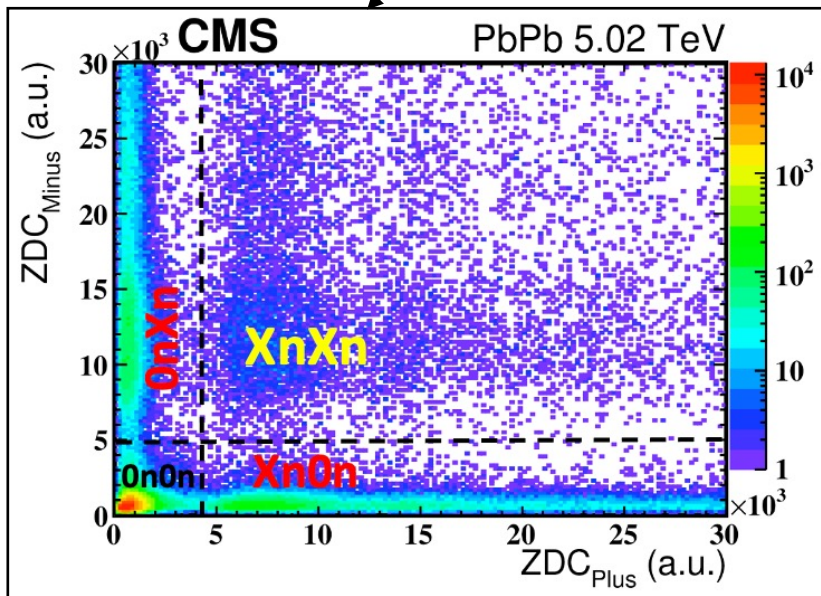
A deeper look at J/ψ production from **single γ+Pb** without the “two-way ambiguity” will tell more.

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

# Neutron Tag with Zero Degree Calorimeter



CMS-DP-2018-025

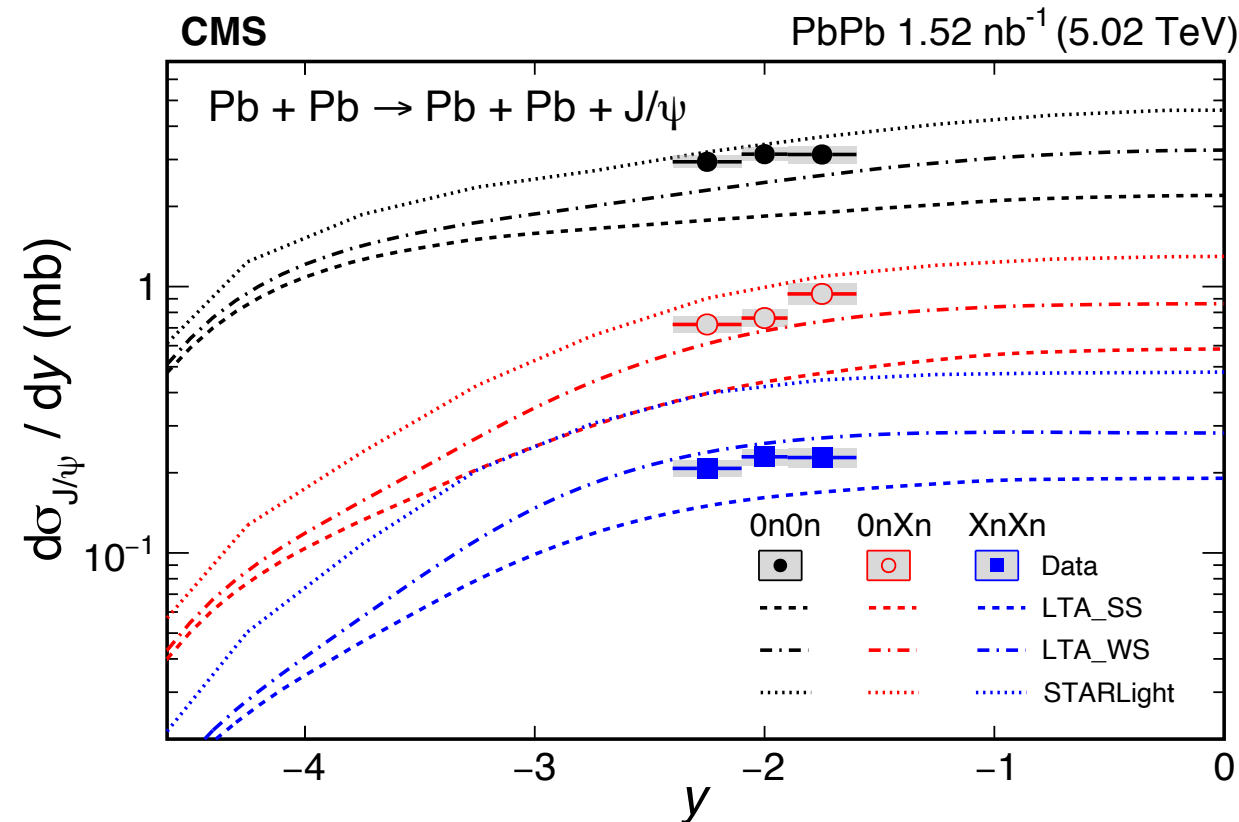


Tag events with neutrons:

- 0n0n, 0nXn, XnXn (X:  $\geq 1$ )

# Coherent $J/\psi$ in PbPb UPCs with Fwd Neutron Tag

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



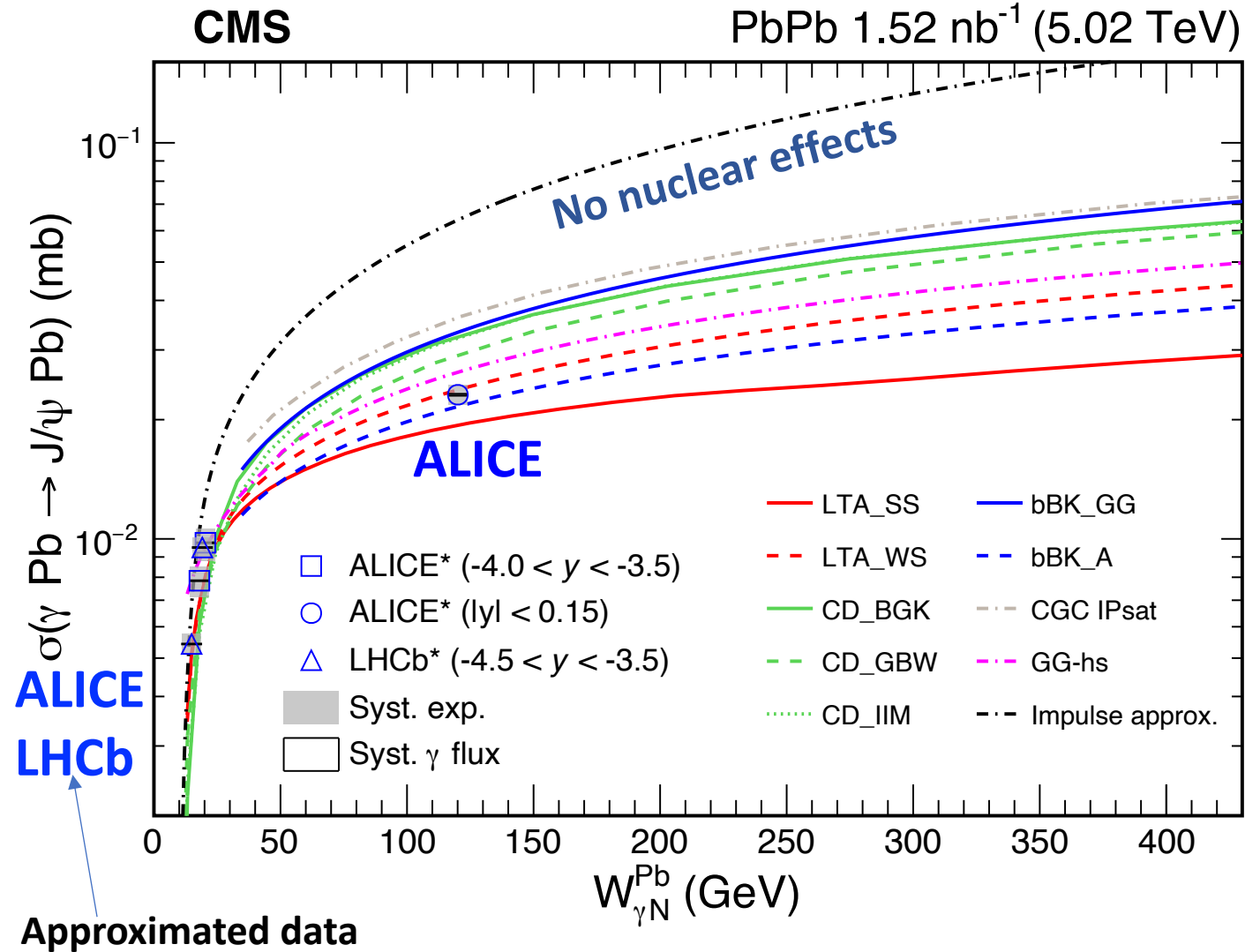
Neutron migration effects are corrected

- First coherent  $J/\psi$  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  $\gamma$ +Pb.**

# Coherent $J/\psi$ Cross Section of Single $\gamma$ +Pb vs. $W$

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

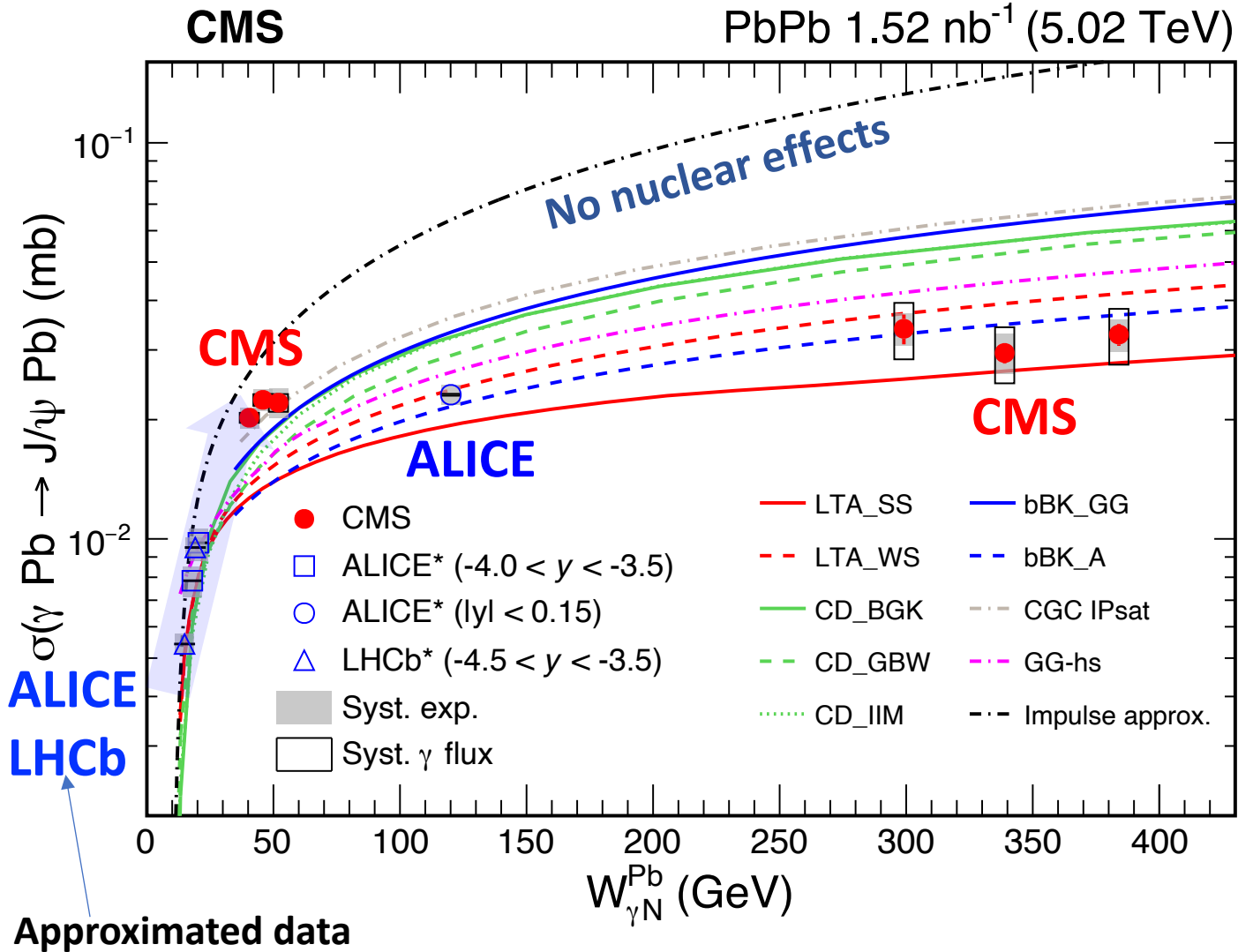


ALICE, LHCb vs. IA:

- Data is close to IA at low  $W$ .
- Data is significant lower than IA at  $W \sim 125$  GeV.

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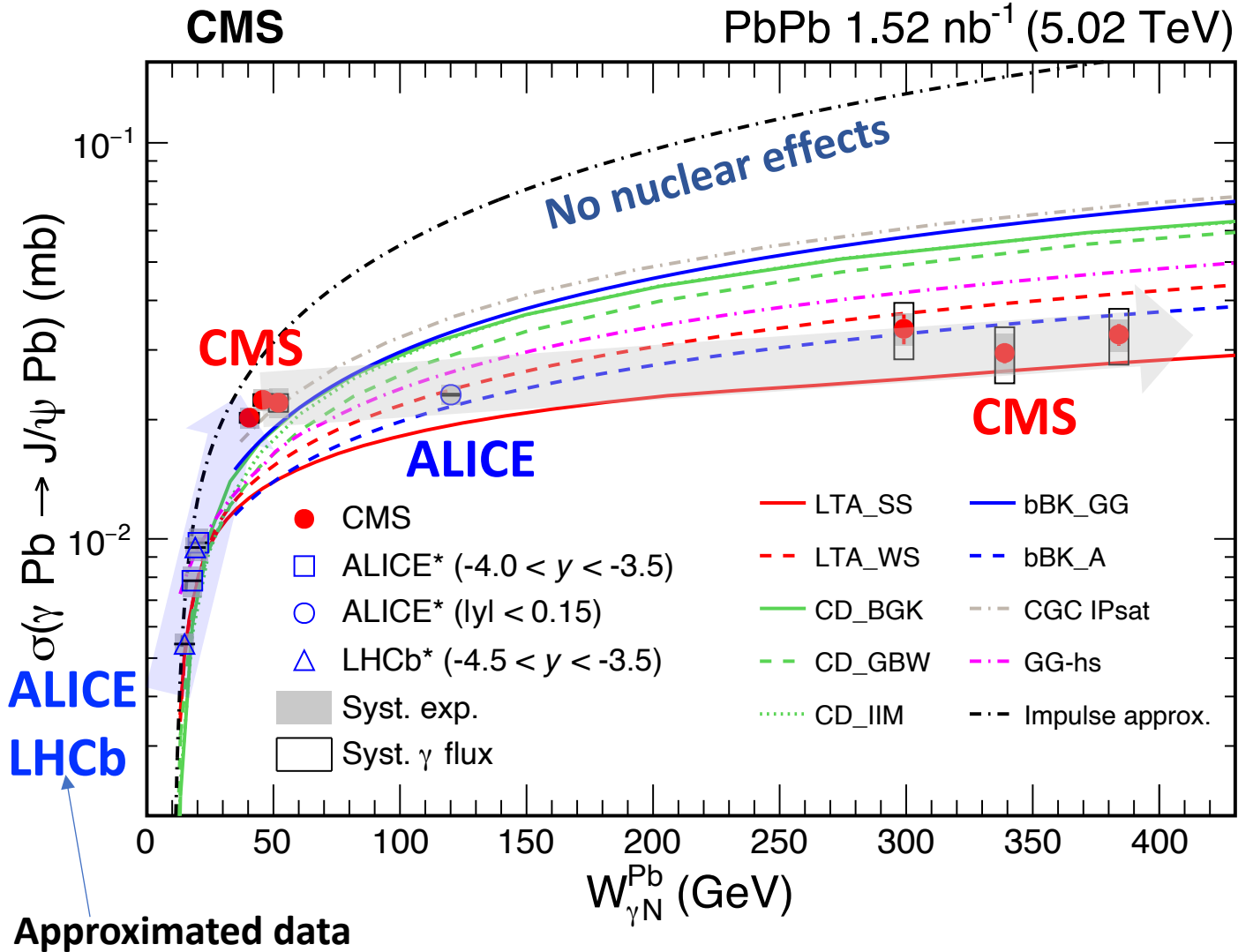
New data from **CMS**:

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



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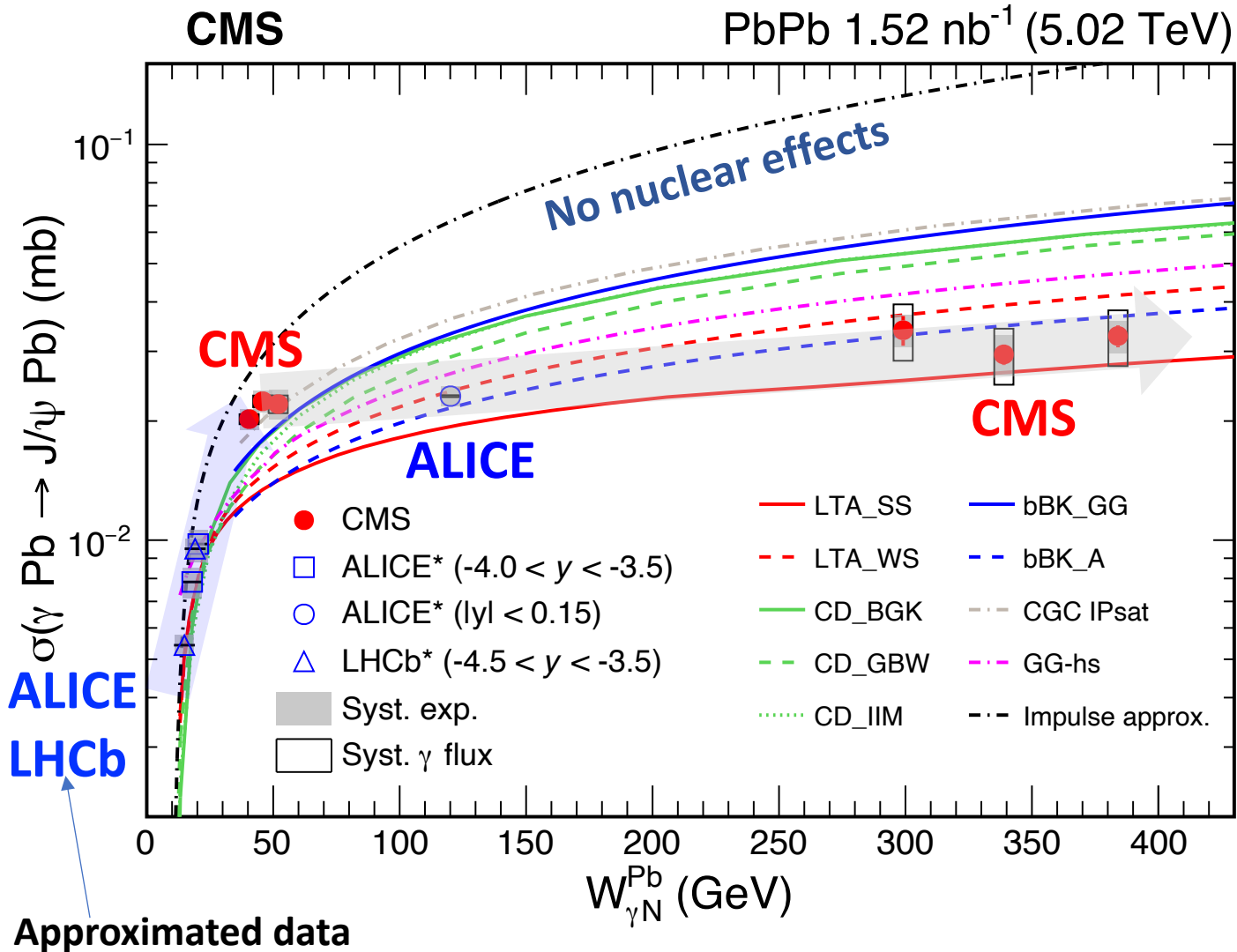
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- Turn into a **nearly flat** (slower rising) trend for  $W > 40$  GeV.

Approximated data

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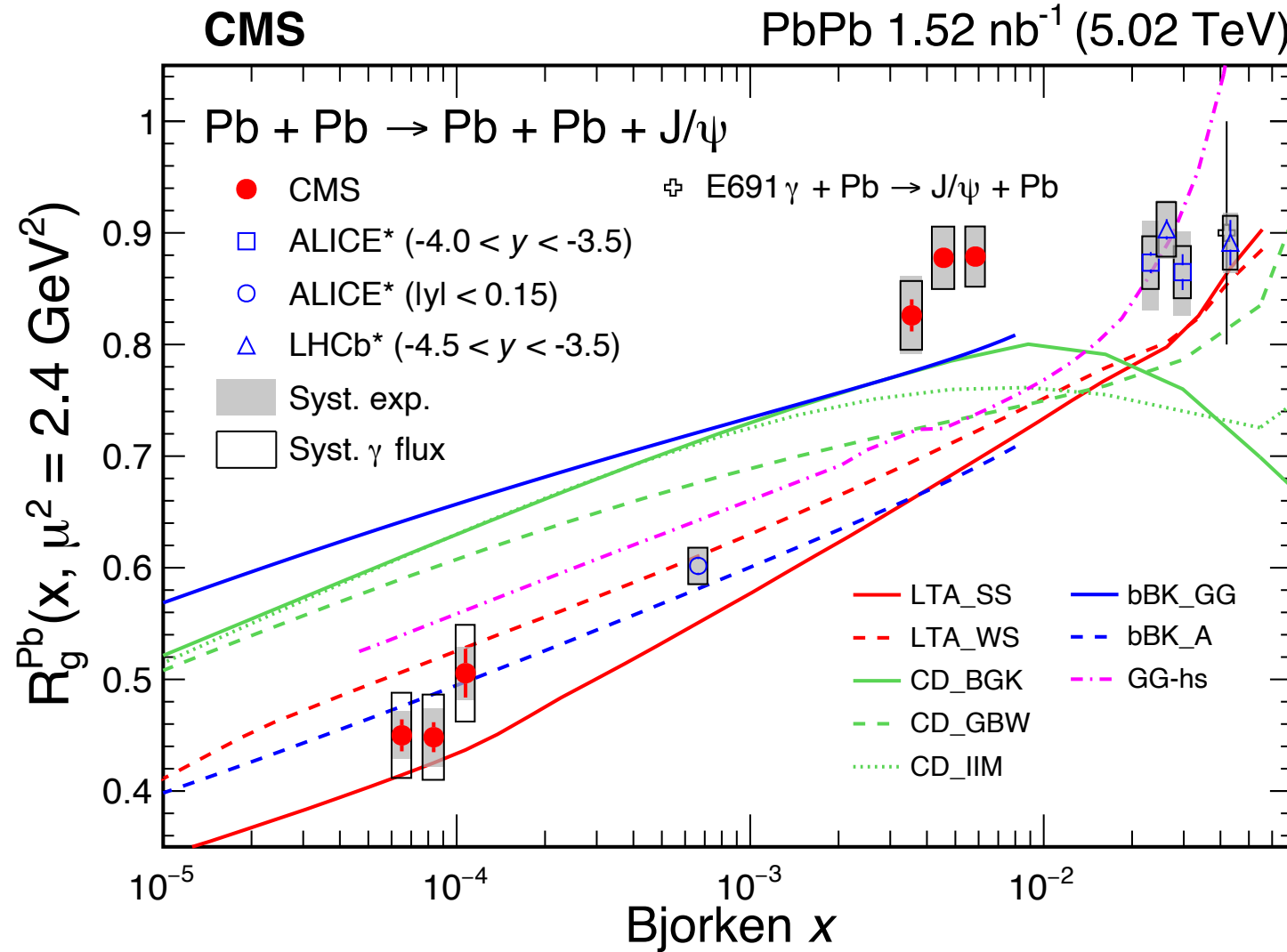
- **Rapid increase** at  $W < 40$  GeV.
- Turn into a **nearly flat** (slower rising) trend for  $W > 40$  GeV.

**No models can describe the entire data distribution.**

ALICE new data follows the same trend, see D. T. Takaki' [talk](#): Wed 16:00

# Nuclear Gluon Suppression Factor

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



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

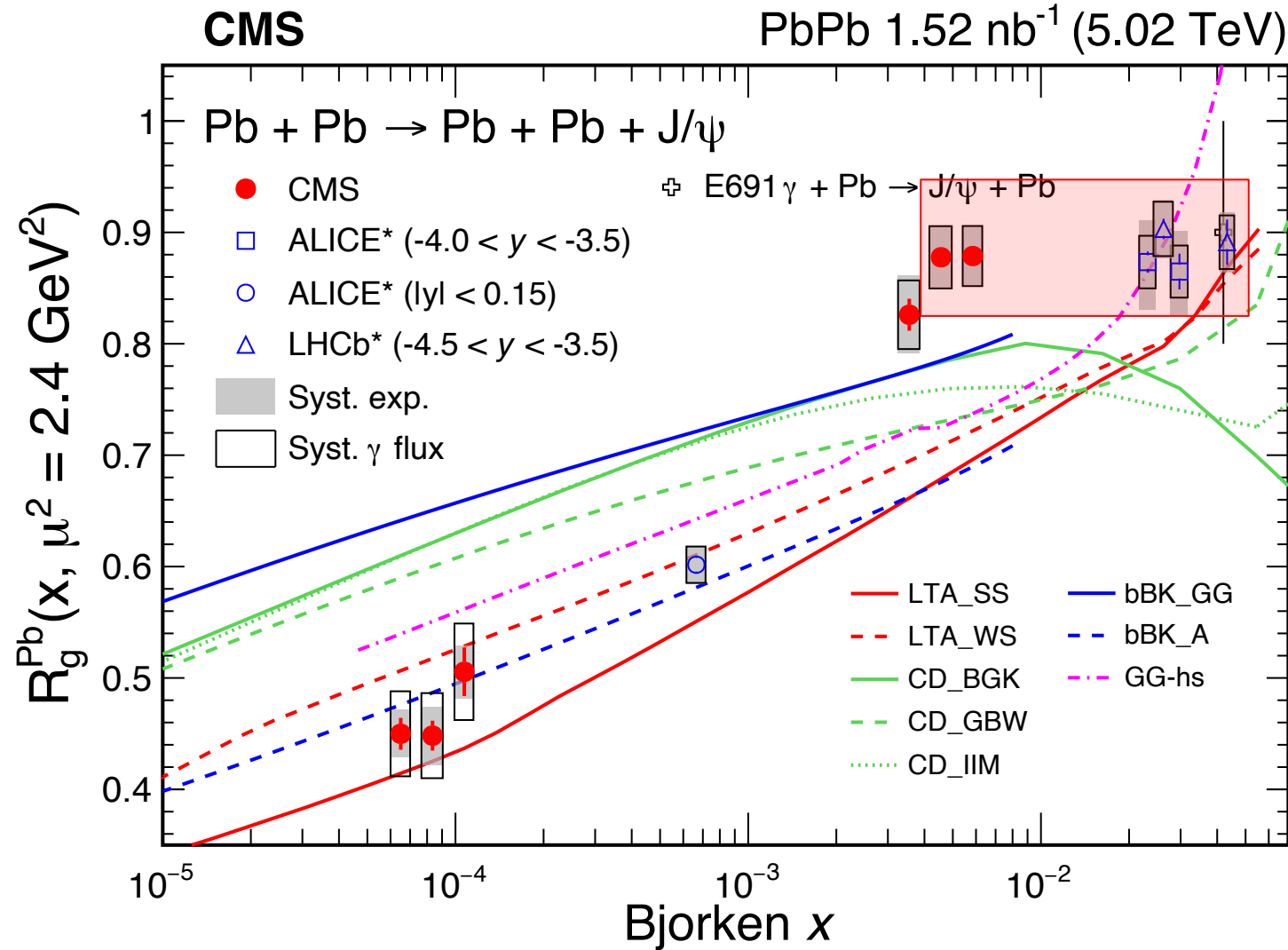
Impulse approx. (IA)  
neglects all nuclear effects.

- $R_g$  represents nuclear gluon suppression factor at LO.

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

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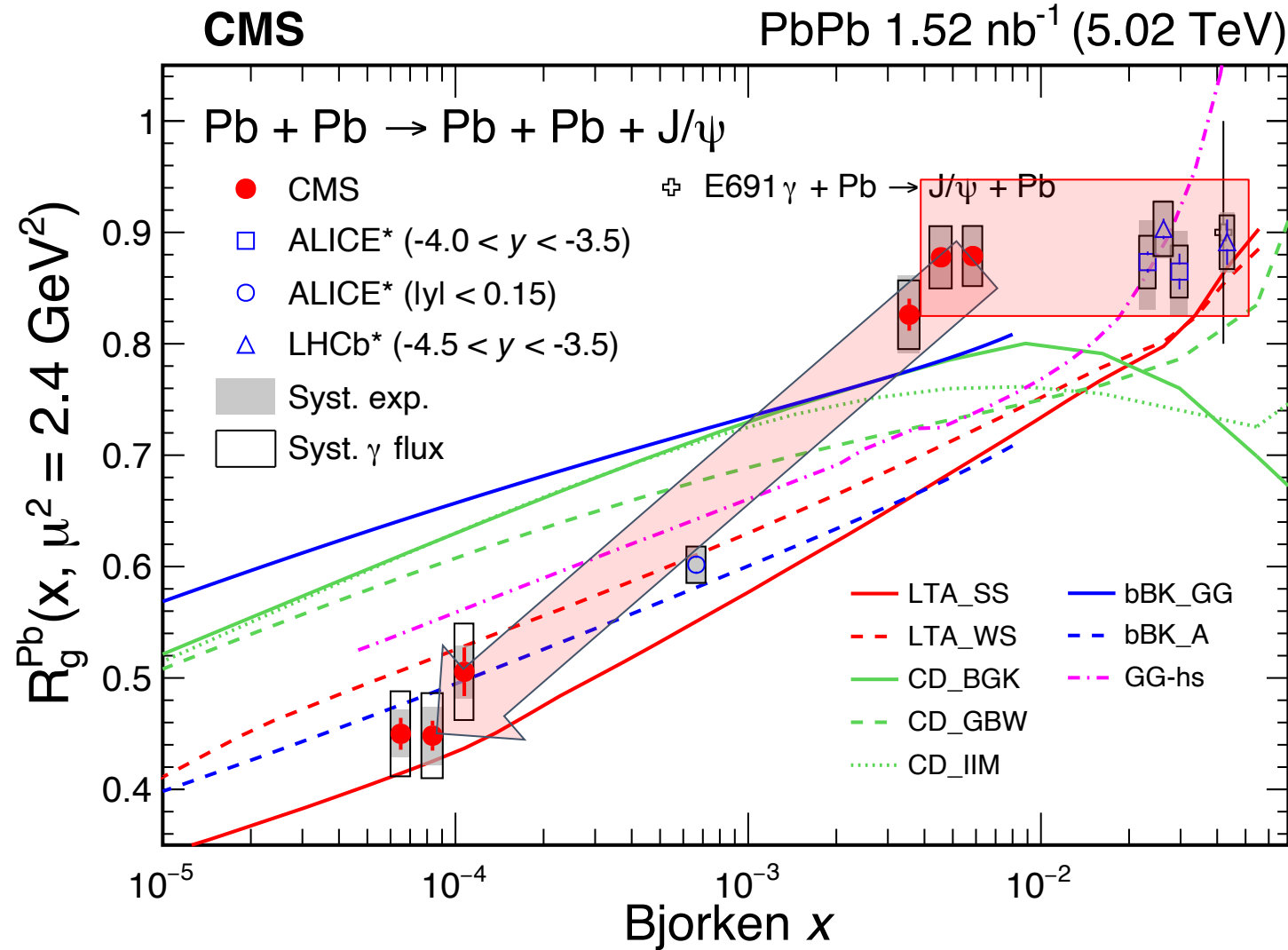
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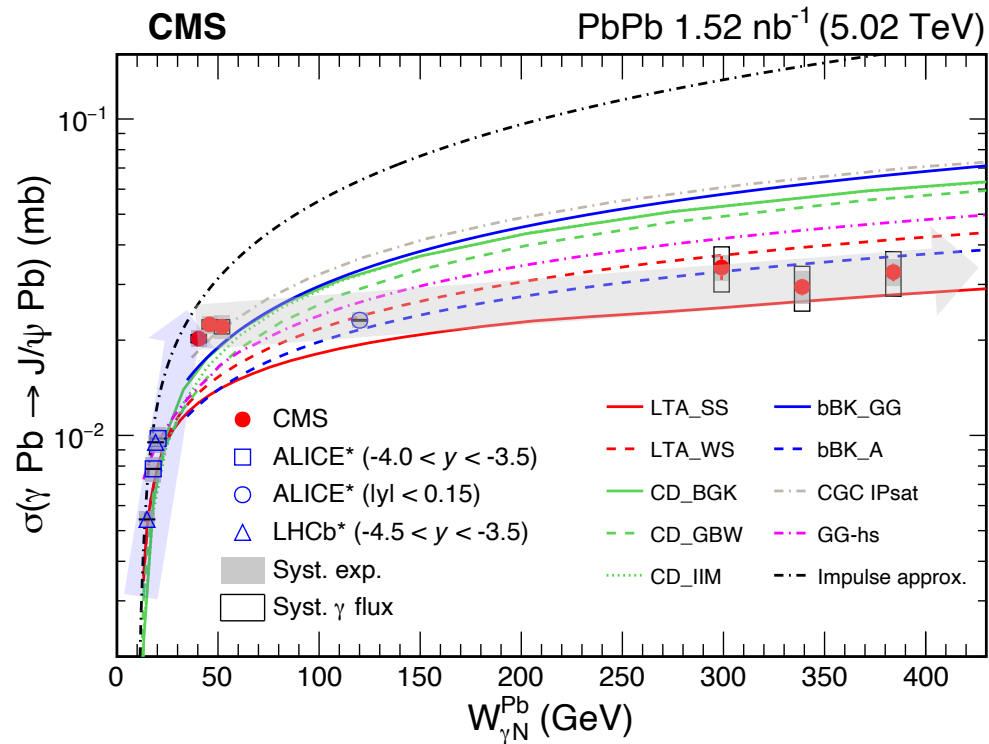
- $R_g$  represents nuclear gluon suppression factor at LO.
- At high-x region: **flat** trend.
- Quickly **decrease** towards lower x region.

**Beyond model expectation**

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

# What Physics Behind?

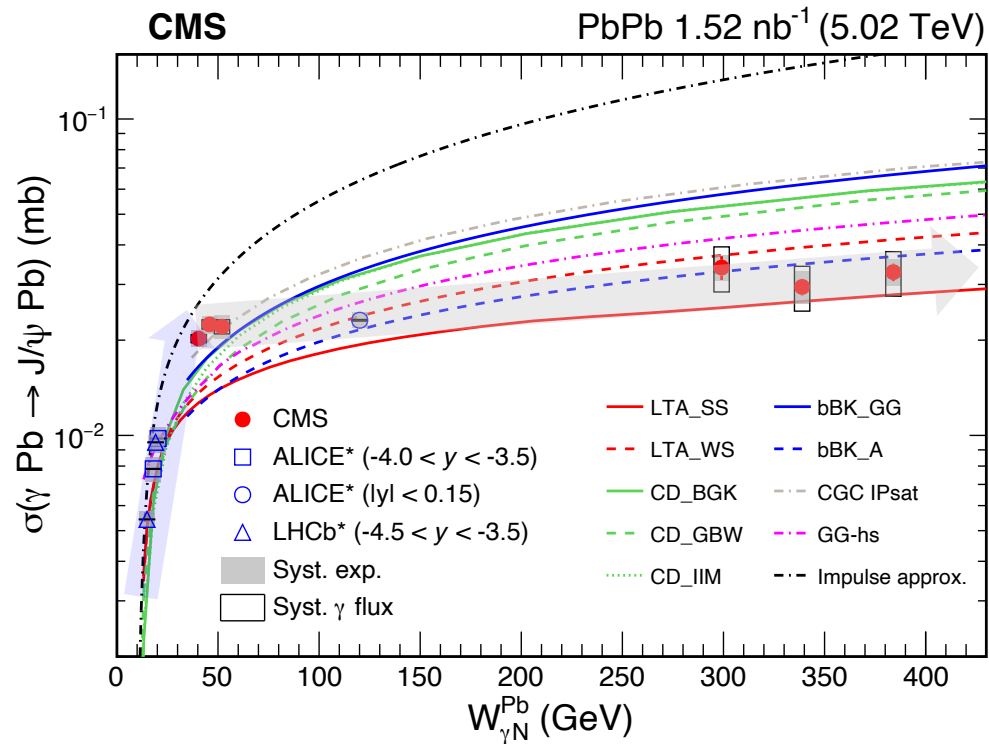
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- $\sigma$  stops rapid rising trend → splitting and recombination of gluons become equal
  - **Clear evidence for gluon saturation!!?**

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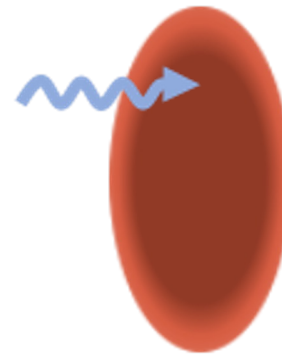


## Black Disk Limit?

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

L. Frankfurt [PRL 87 \(2001\)192301](#)

L. Frankfurt [PLB 537 \(2002\) 51](#)



- $\sigma$  stops rapid rising trend  $\rightarrow$  splitting and recombination of gluons become equal
  - **Clear evidence for gluon saturation!!?**

OR

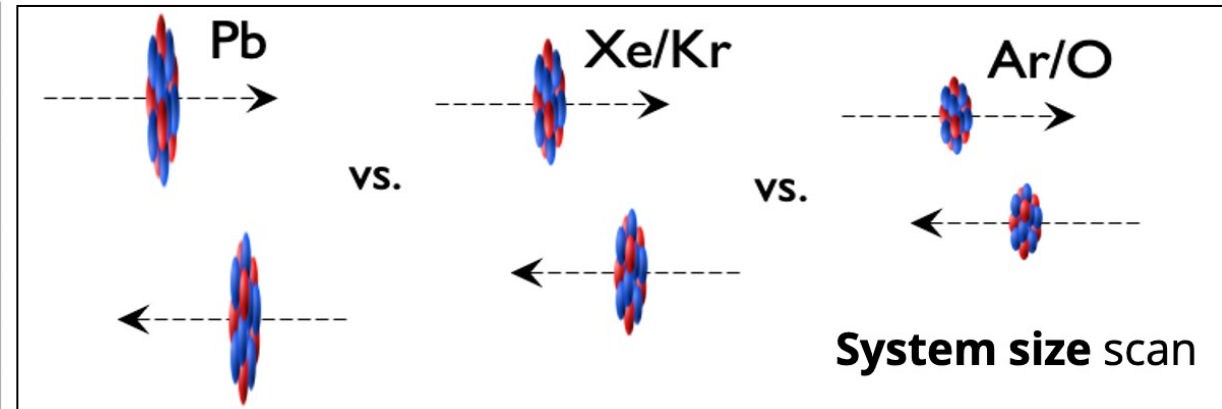
- Nucleus target becomes totally absorptive to incoming photons  $\rightarrow$  **Black Disk Limit!!?**
  - **Nucleus becomes a black disk, internal structure is invisible.**

# 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

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

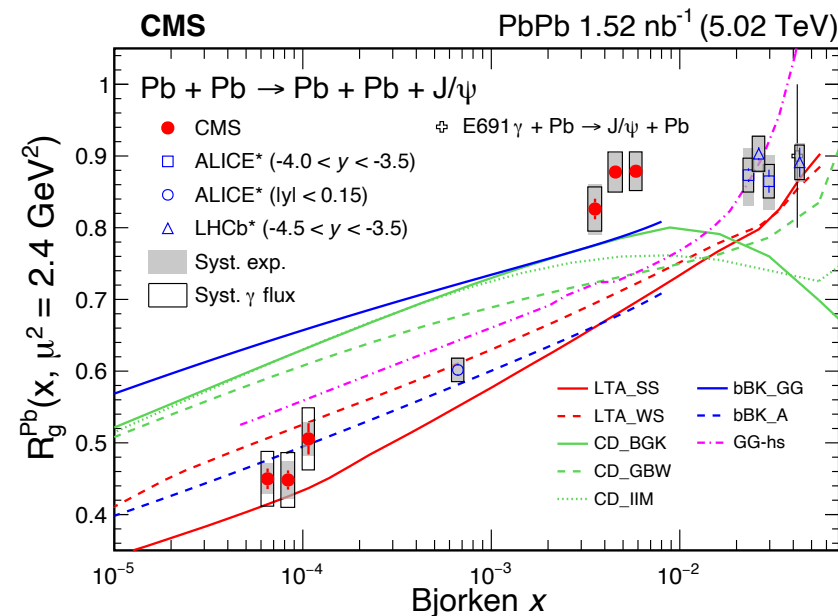
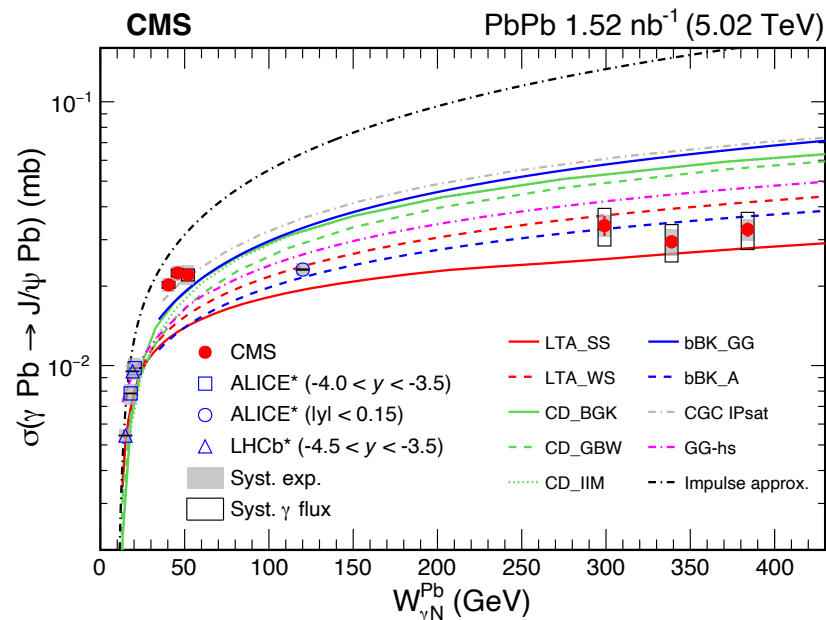


CERN yellow report, [arXiv:1812.06772](https://arxiv.org/abs/1812.06772)



# Summary

- First time, **disentangled the low and high  $\gamma$  energy** contributions to coherent J/ $\Psi$
- CMS measured coh. J/ $\Psi$  at a **new unprecedentedly low-x gluon regime** ( $10^{-4}$ - $10^{-5}$ )
- $\sigma(\text{J}/\Psi)$  vs.  $W$  not predicted by state of the art models
  - **Glue 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](https://arxiv.org/abs/2303.16984), submitted to PRL**

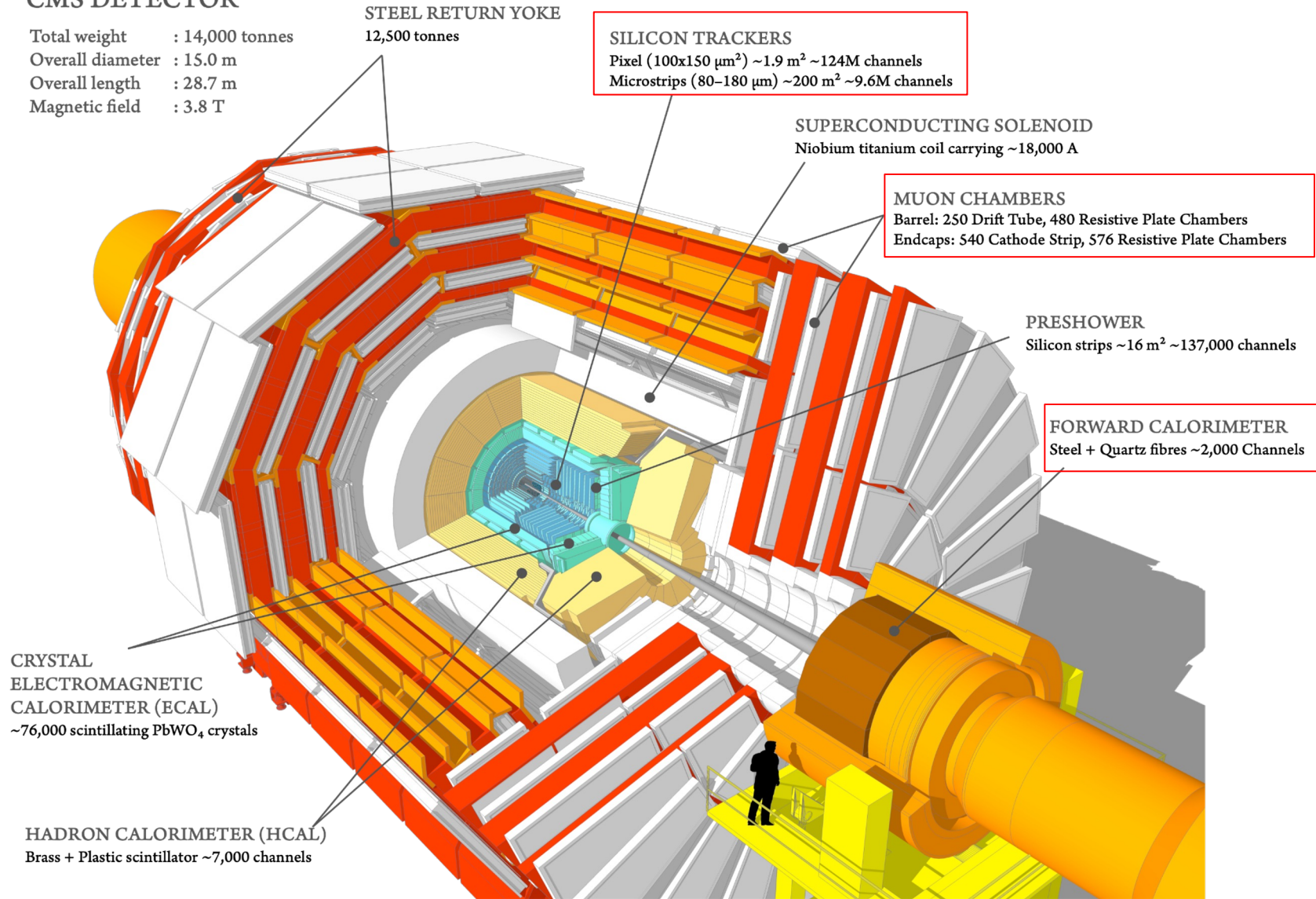
**Thank you for your attention!**

# Backup Slides

# Compact Muon Solenoid Detector

## CMS DETECTOR

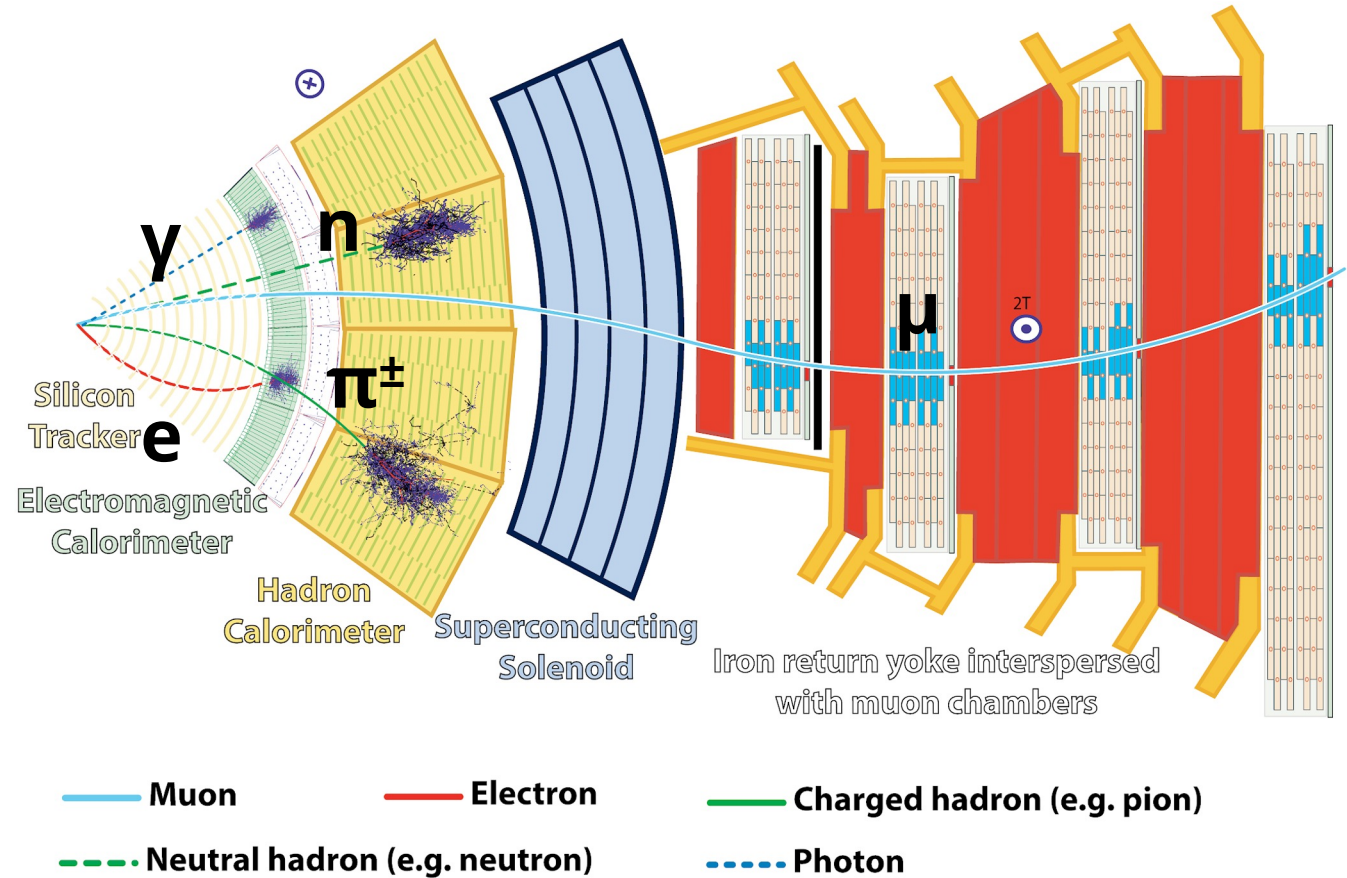
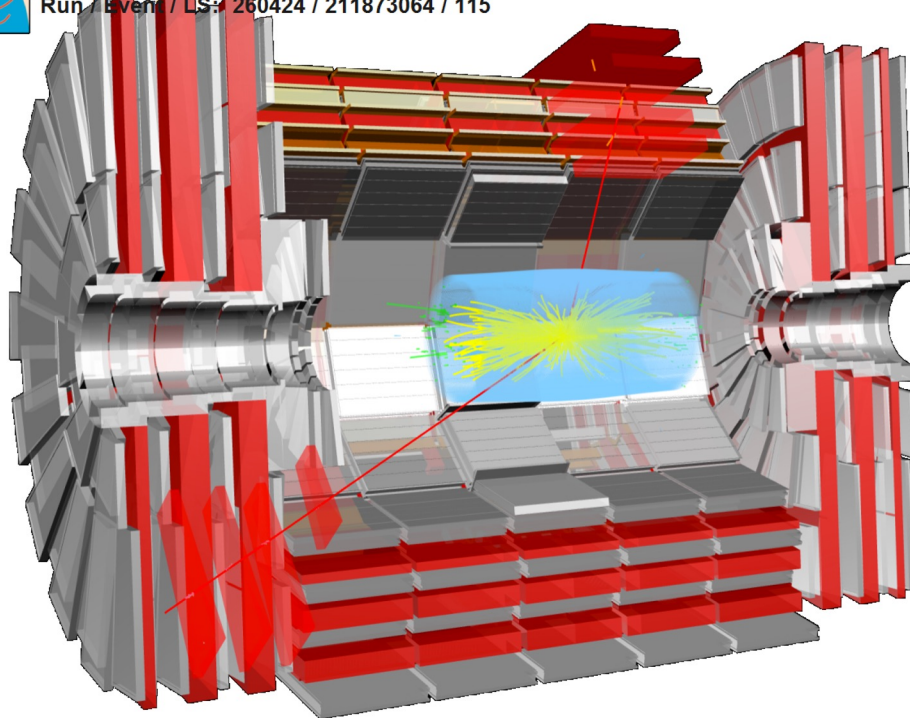
Total weight : 14,000 tonnes  
Overall diameter : 15.0 m  
Overall length : 28.7 m  
Magnetic field : 3.8 T



# Muon Reconstruction

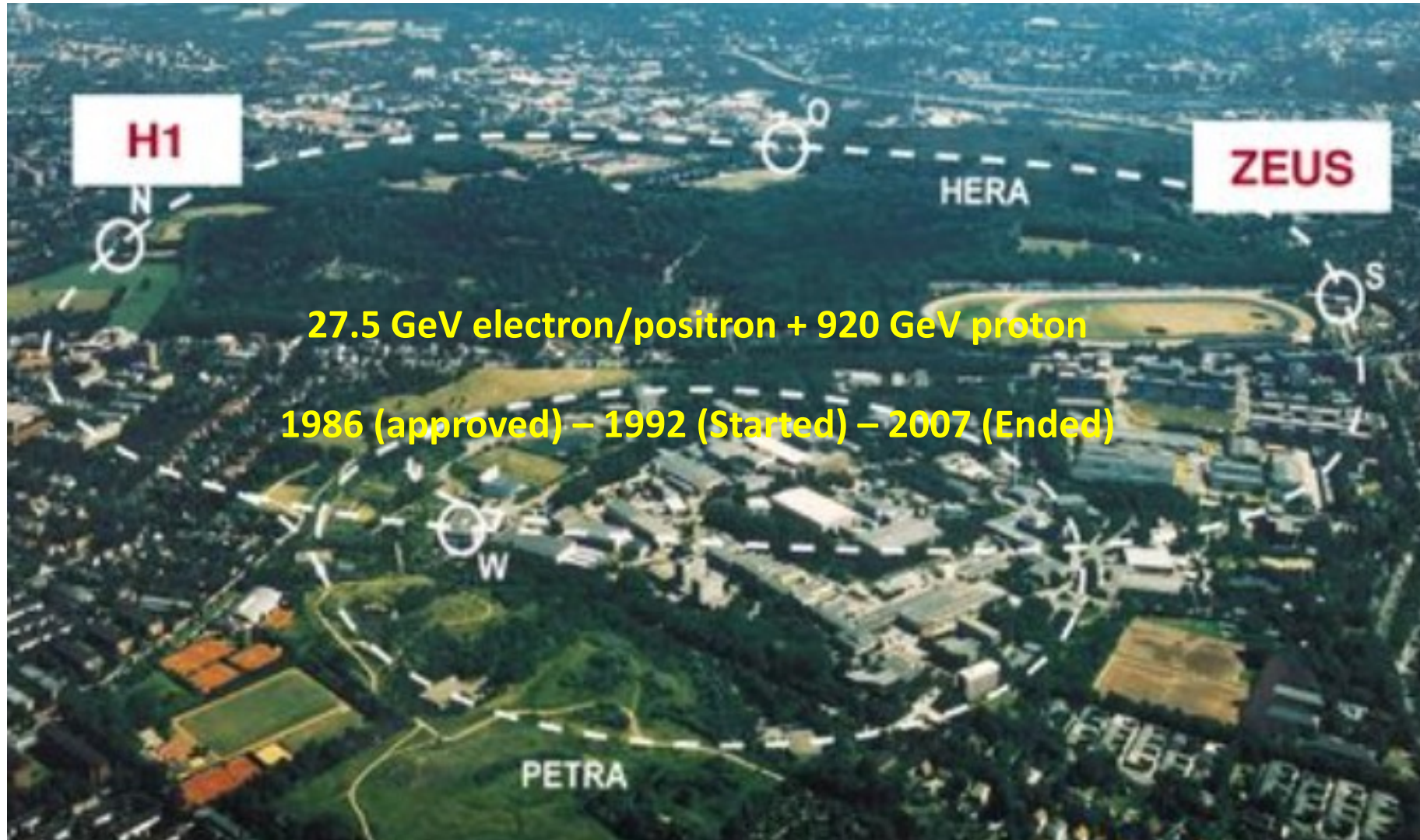


CMS Experiment at the LHC, CERN  
Data recorded: 2015-Oct-30 19:23:54.631552 GMT  
Run / Event / LS: 260424 / 211873064 / 115



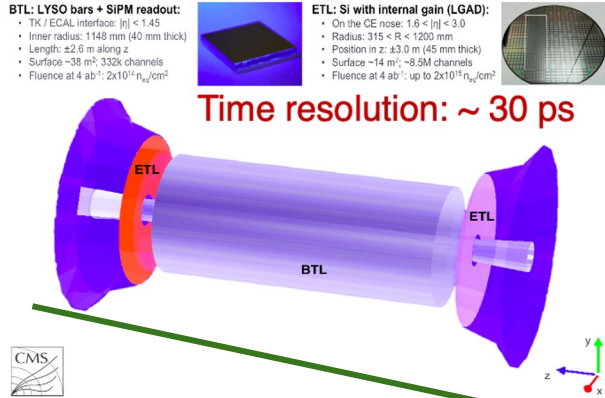
- Tracker and muon detectors used to reconstruct/identify muons.

# Understand Nucleon Structure at HERA

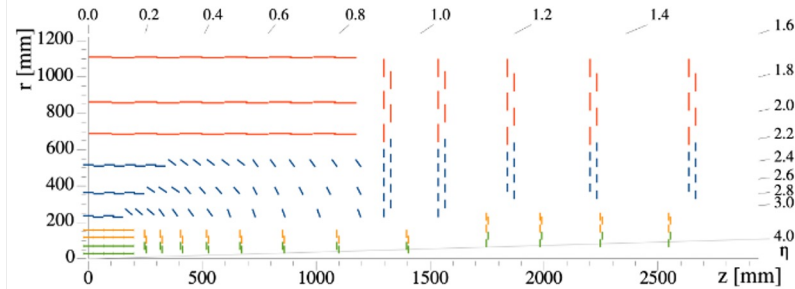


# Future Opportunities

## MIP Timing Detector for PID



## Tracker with $|\eta| < 4$ and better resolution, lighter materials

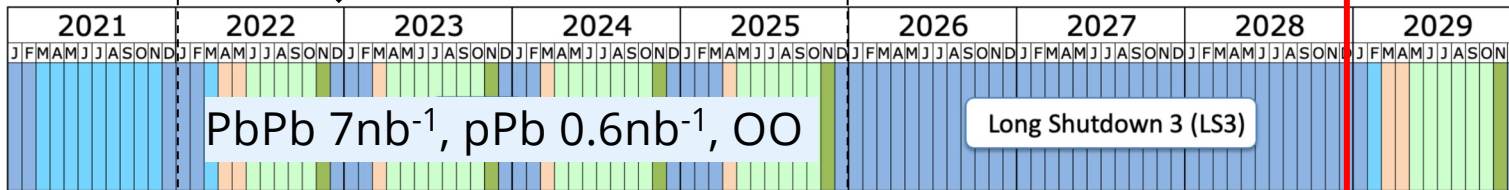


- Muon systems with  $|\eta| < 2.8$
- Trigger and DAQ rate:  $\sim 10 \times$

### Run-3

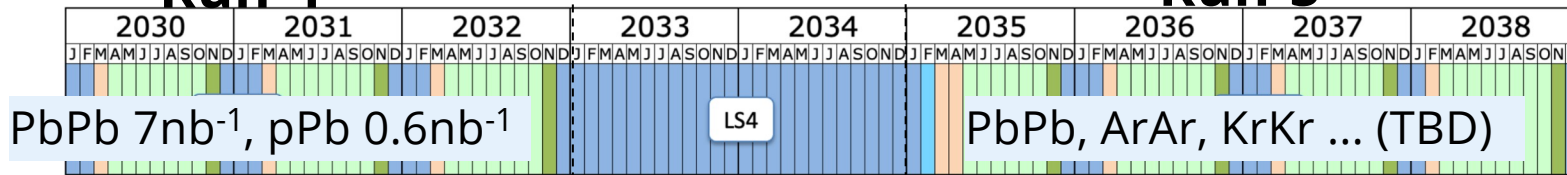
### Phase-2 Upgrades

### HL-LHC



### Run-4

### Run-5



- Shutdown/Technical stop
- Protons physics
- Ions
- Commissioning with beam
- Hardware commissioning/magnet training

### LHC schedule

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

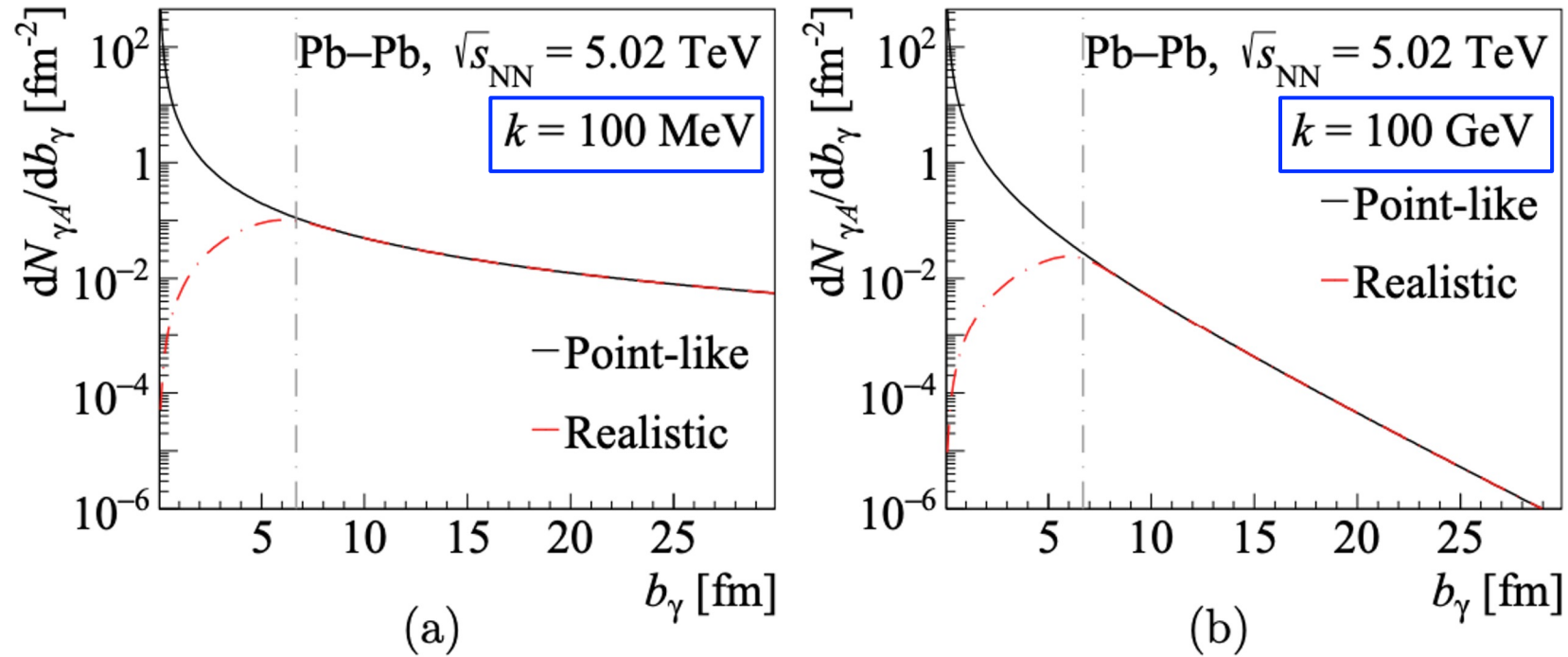
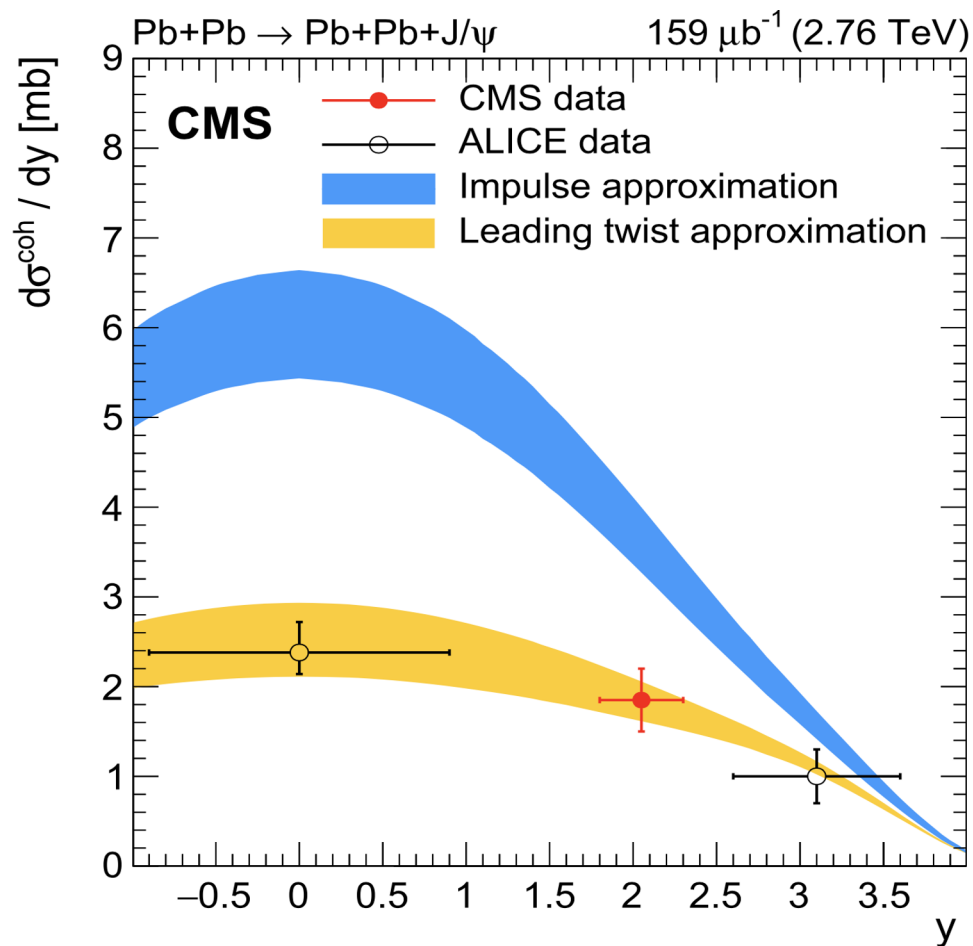


Figure 4: (Color online) Photon fluxes coming from a nucleus  $N_{\gamma A}$  in the point-like source approximation and the realistic description as functions of impact parameter  $b_{\gamma}$  calculated at different photon energies: 100 MeV (a), 100 GeV (b).



# Coh. Jpsi from LHC Run1 PbPb UPC

PLB 772 (2017) 489



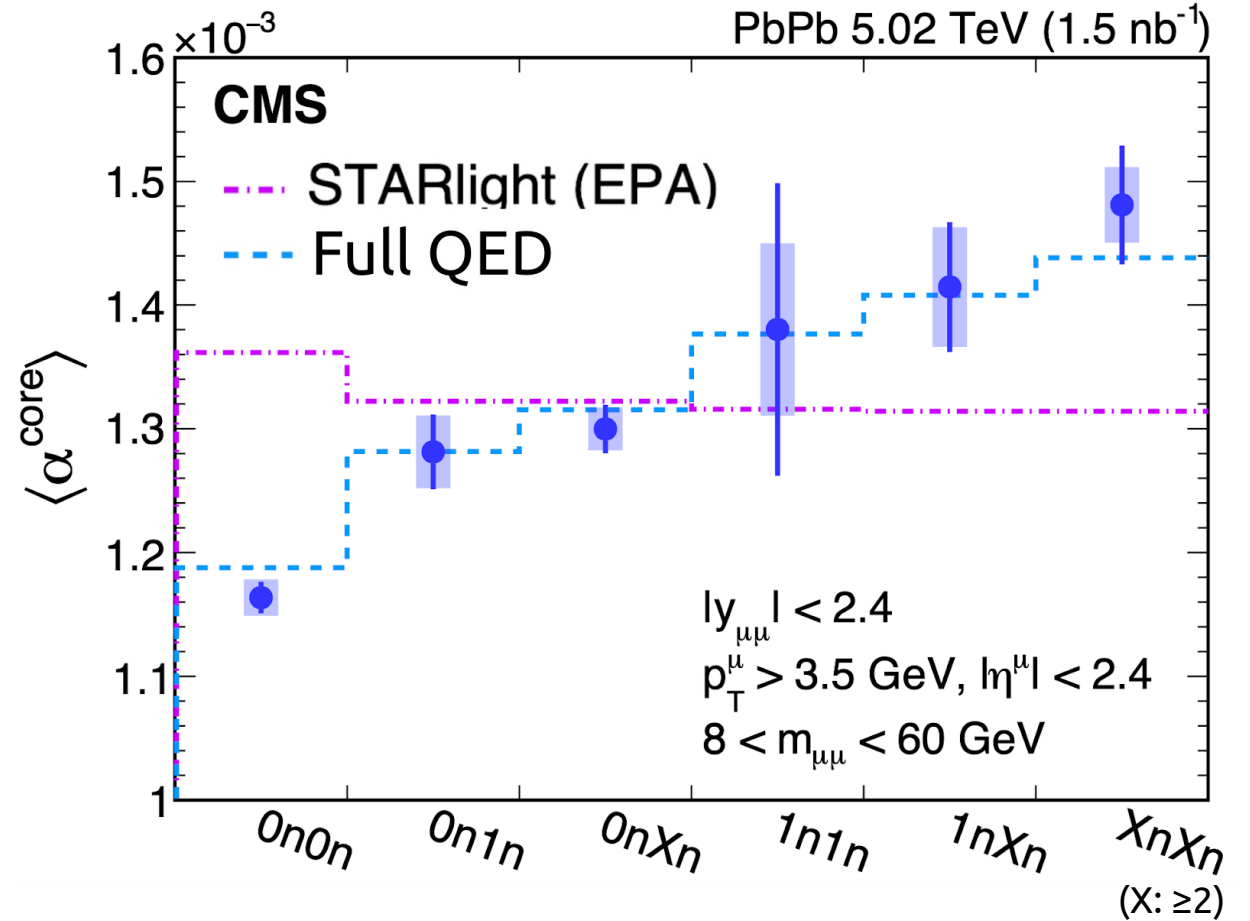
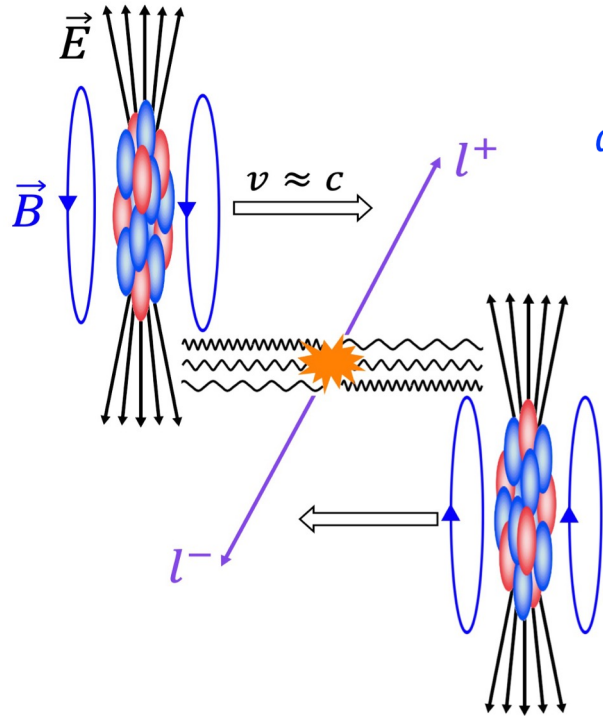
- Run 1 data from CMS and ALICE seem to be well consistent with LTA shadowing model calculations
- However,
  - large uncertainties
  - wide-y bins
  - Mixed low- and high-  $W$  contributions

# 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