

Vector Meson Photoproduction in UPCs with the CMS Experiment

Zaochen Ye (Rice University)
for the CMS Collaboration

CMS: [arXiv:2303.16984](https://arxiv.org/abs/2303.16984), accepted by PRL

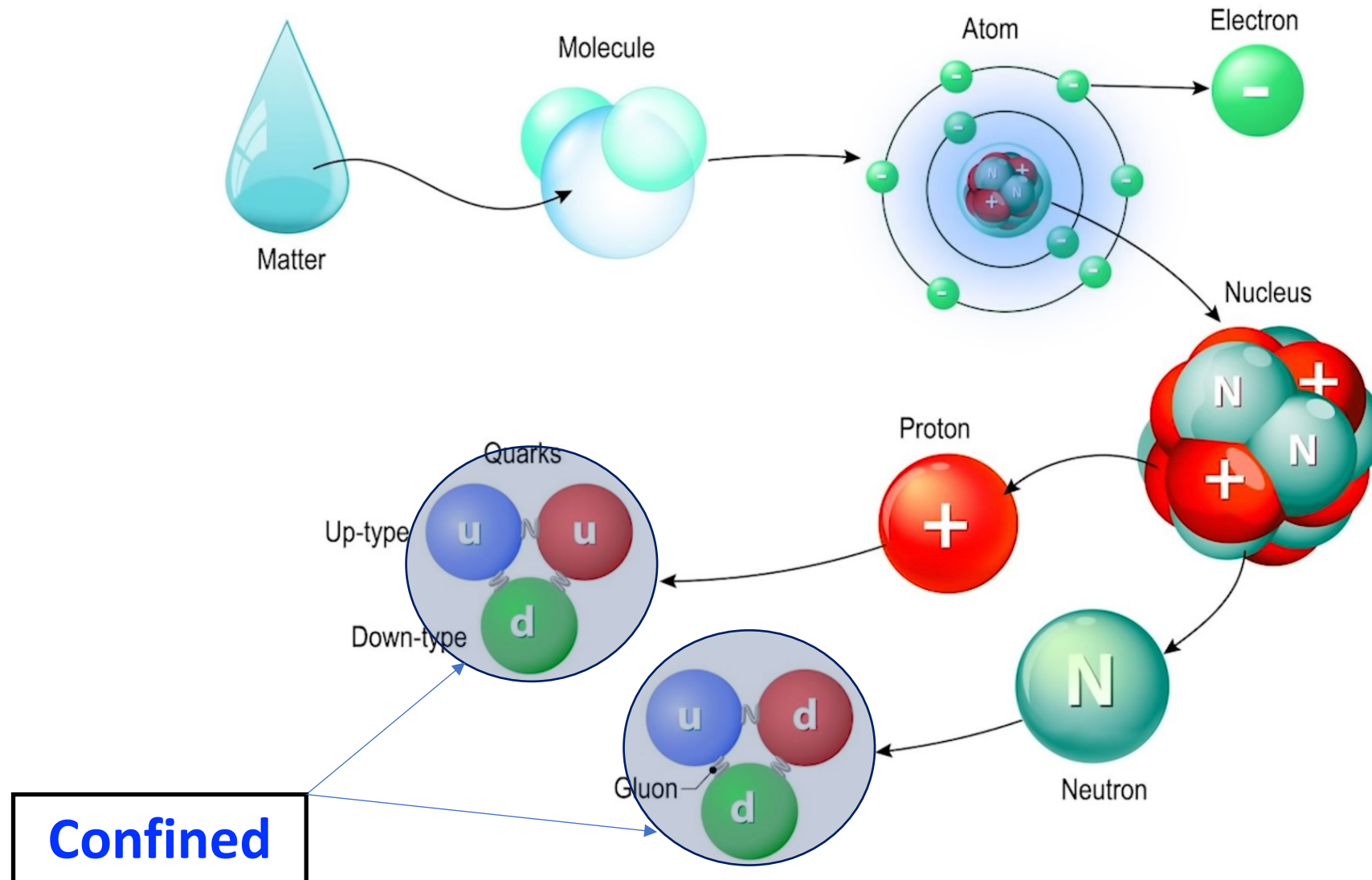
2nd CFNS Workshop on Advancing
the Understanding of Non-pQCD
Using Energy Flow



RICE

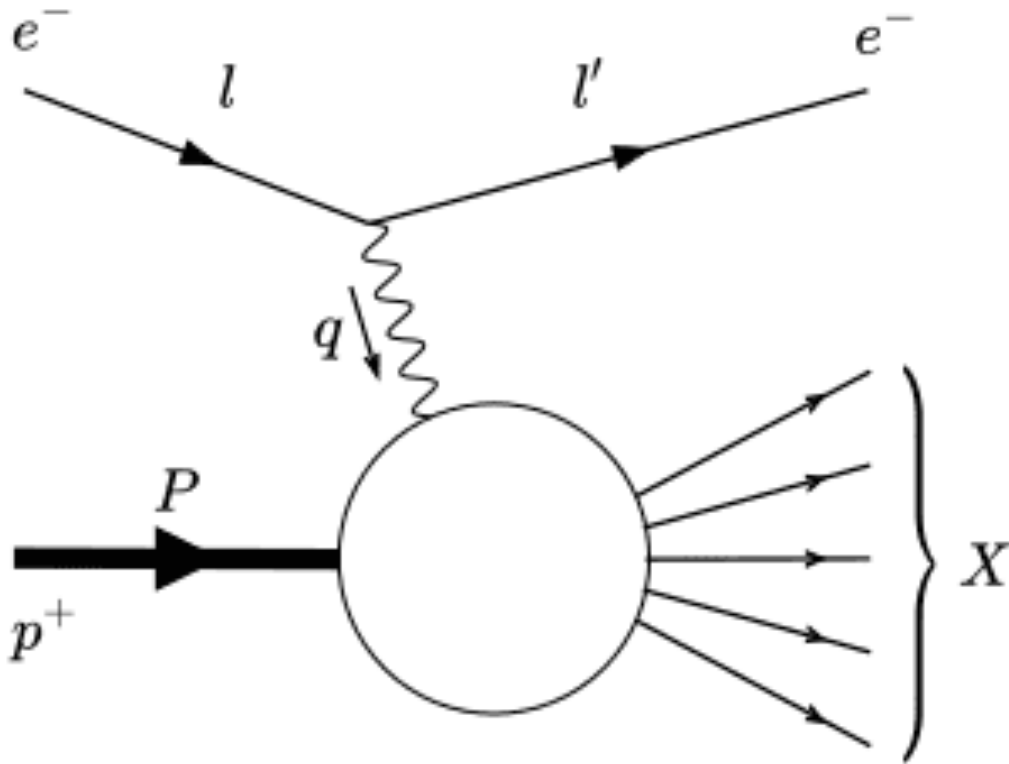


Understand Fundamental Structure of Matter



Understand Nucleon Structure via DIS

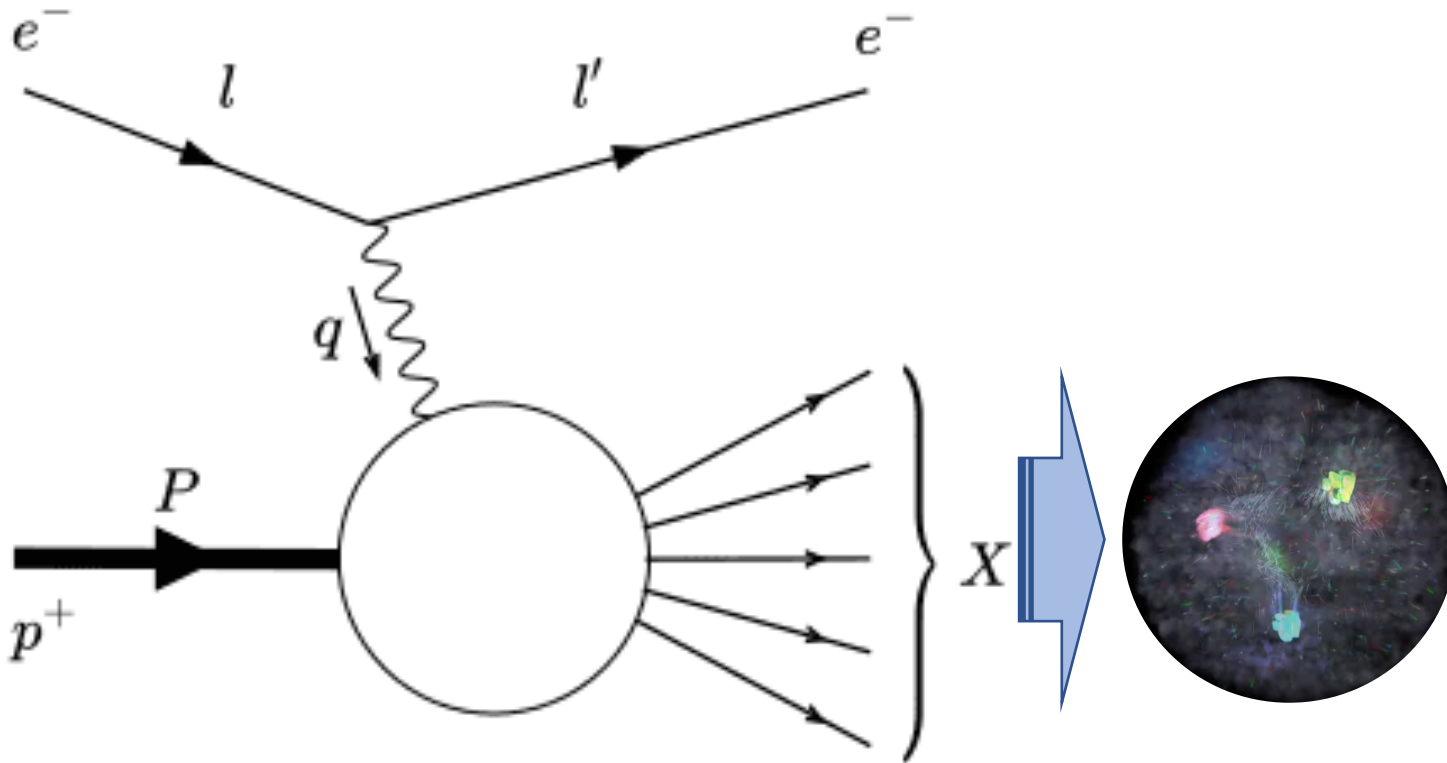
Smash them!!!



Deep Inelastic Scattering

Understand Nucleon Structure via DIS

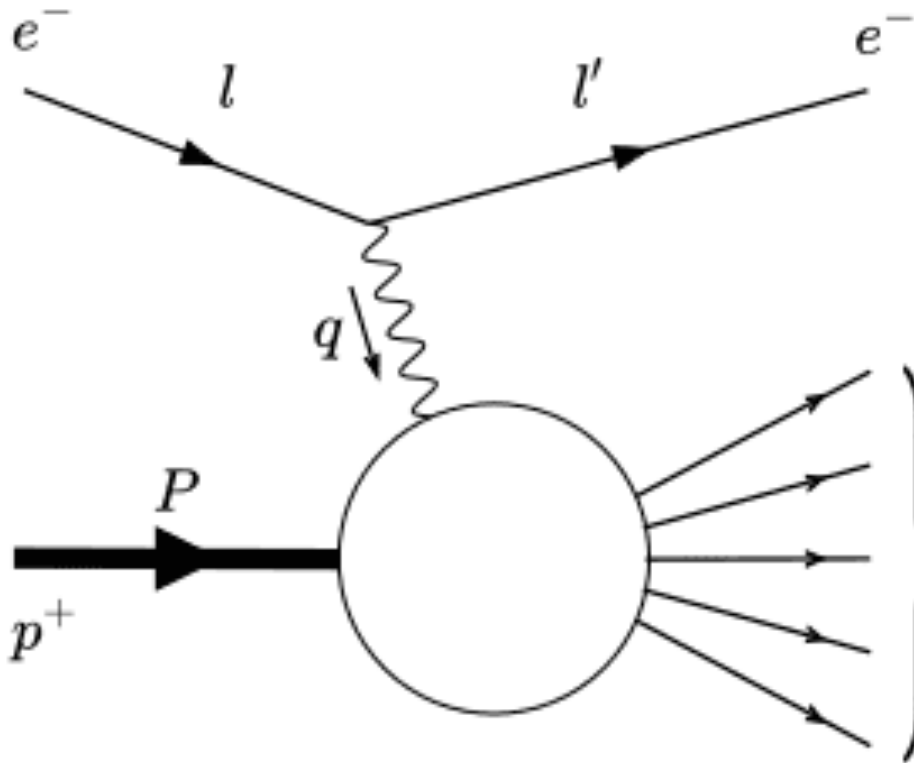
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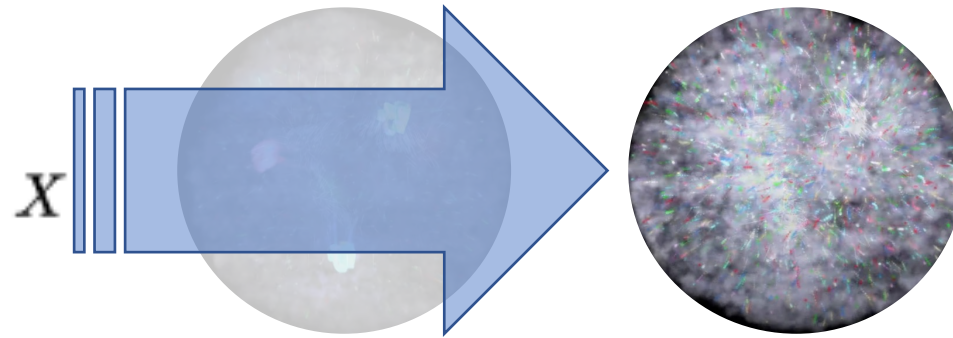
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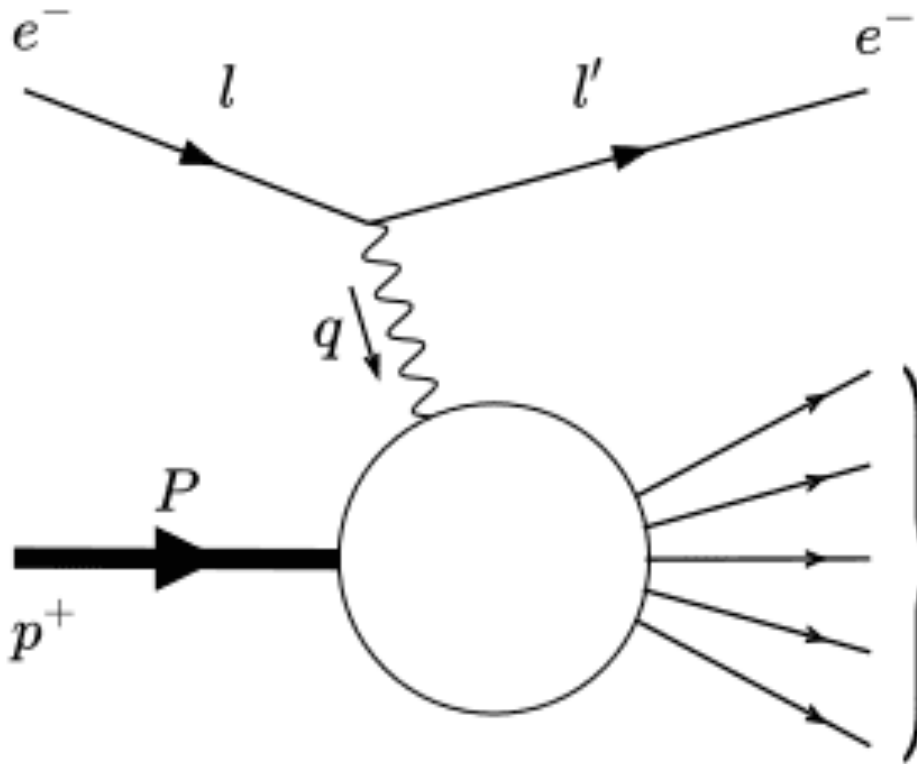
Higher energy, probing lower-x partons



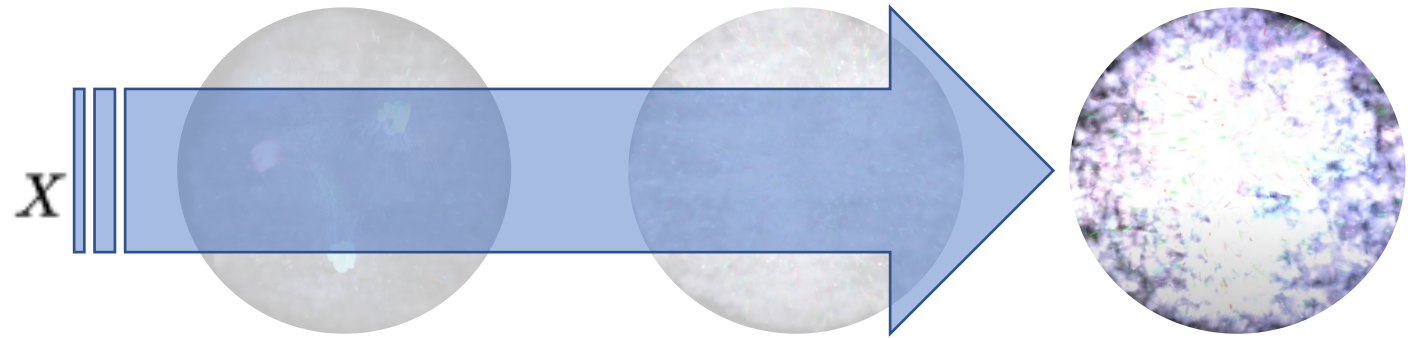
Deep Inelastic Scattering

Understand Nucleon Structure via DIS

Smash them!!!



Higher energy, probing lower-x partons



Deep Inelastic Scattering

Understand Nucleon Structure

e-p collider



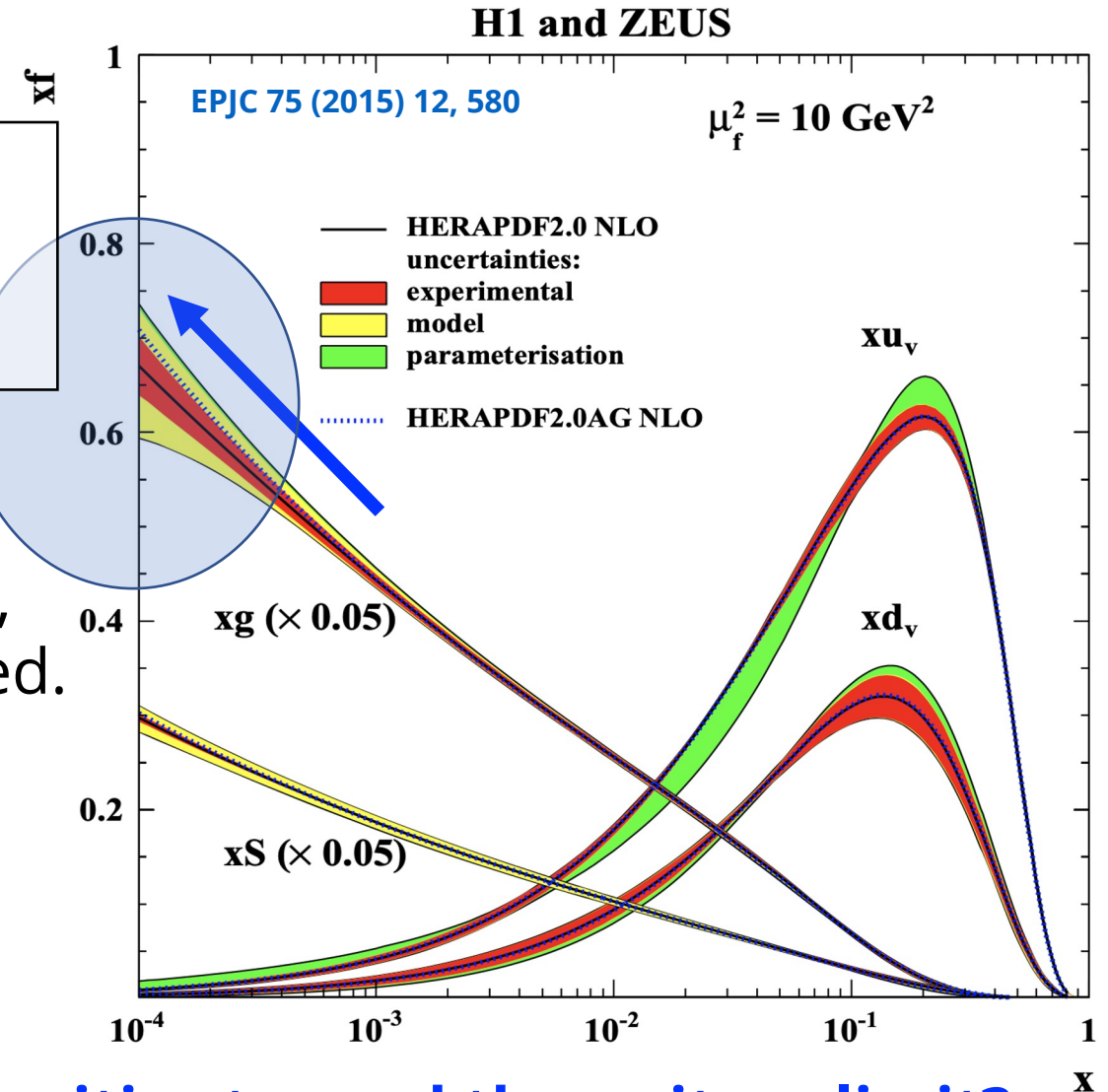
Rapid increase of gluon density towards small x .

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

$$\sim (N_g)^2 \text{ (nonlinear)}$$

Saturation?

$$\sim N_g \text{ (linear)}$$

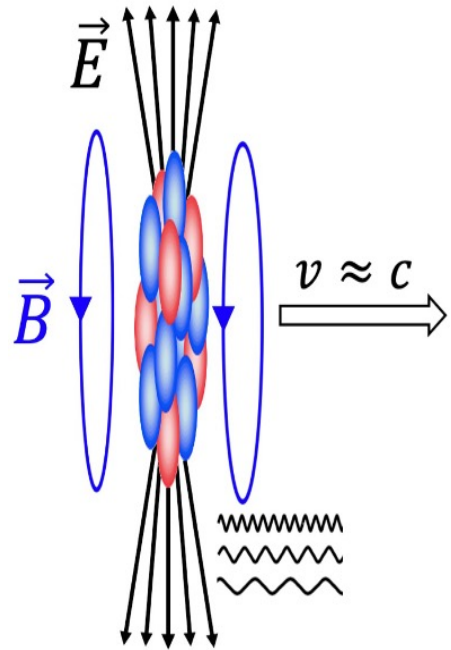


What is the fate of gluons at extreme densities toward the unitary limit?

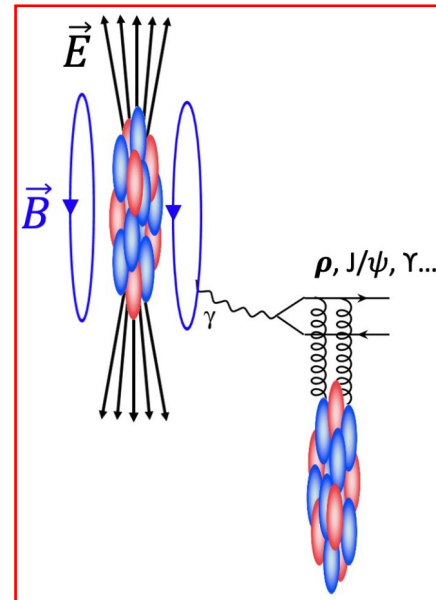
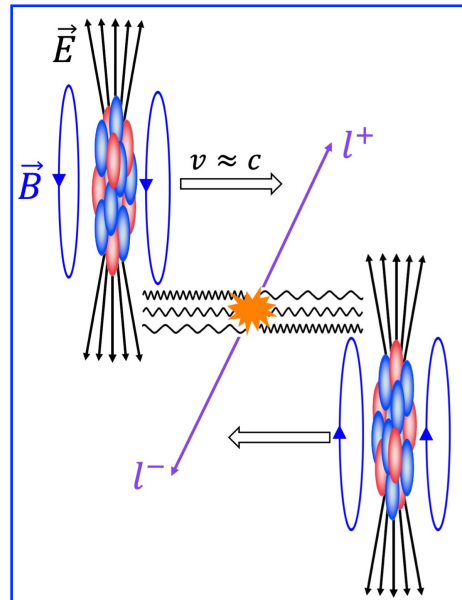
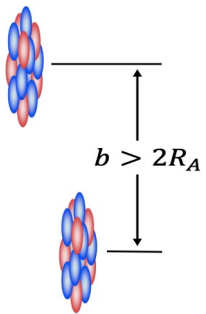
Ultra-Peripheral Collision (UPC)

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

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



UPC:

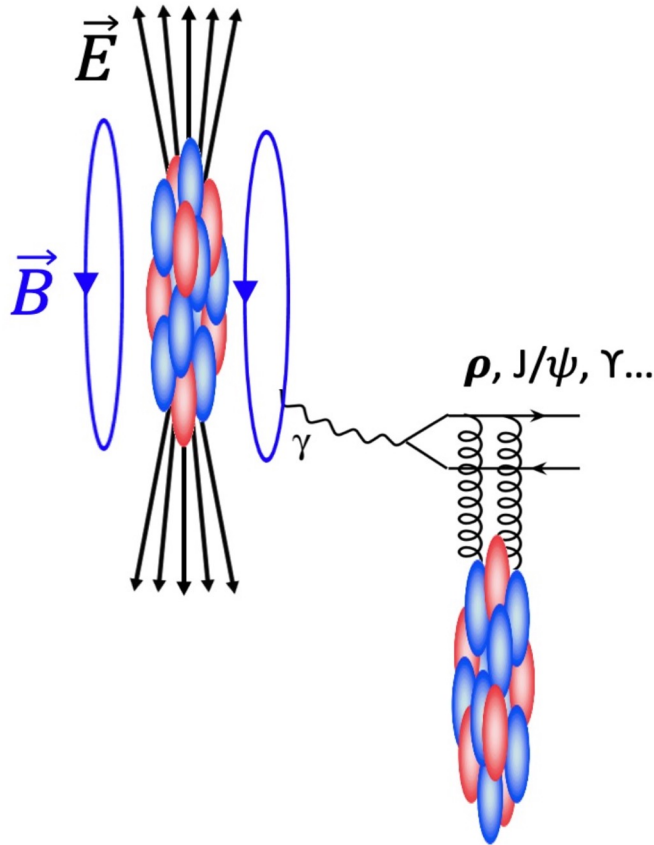


...

Vector Meson Photoproduction in UPC

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

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



Coherent production:

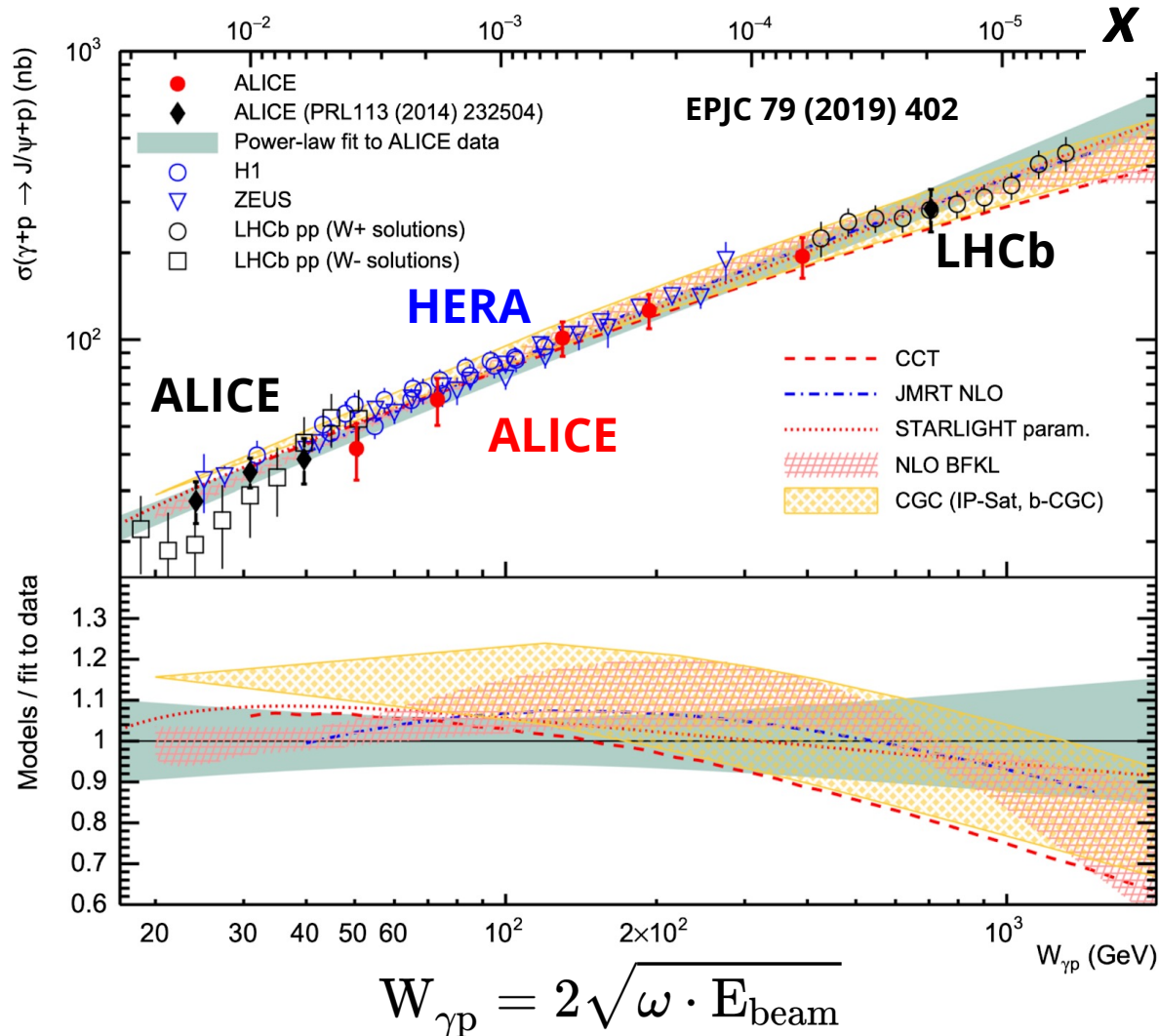
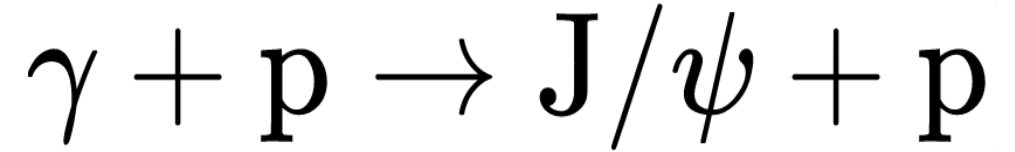
- Photon fluctuated dipole couples coherently to entire nucleus
- Target nucleus remains intact
- VM $\langle p_T \rangle \sim 50$ MeV
- Probing the averaged gluon density

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

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

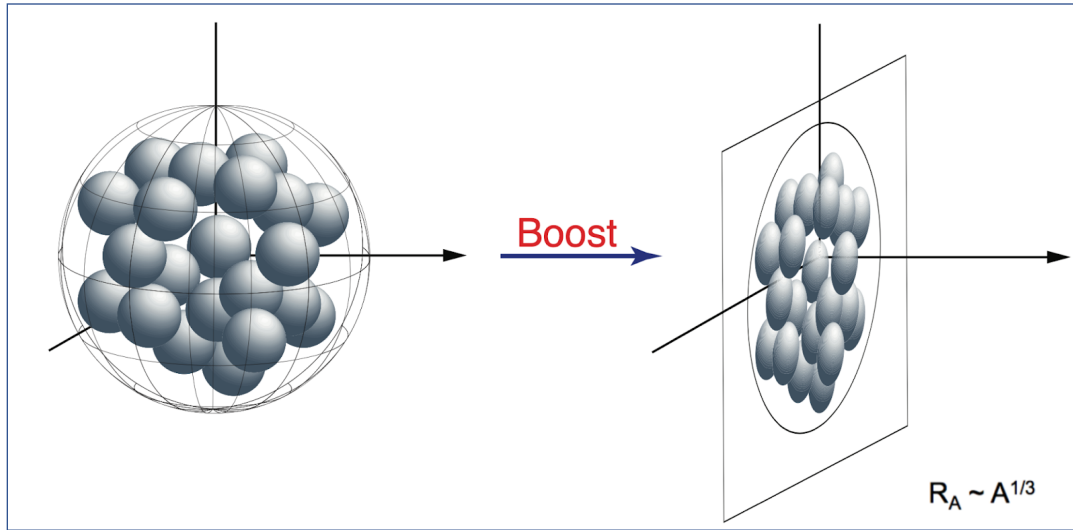
J/ψ Photoproduction via γ + Free Nucleon



- 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.

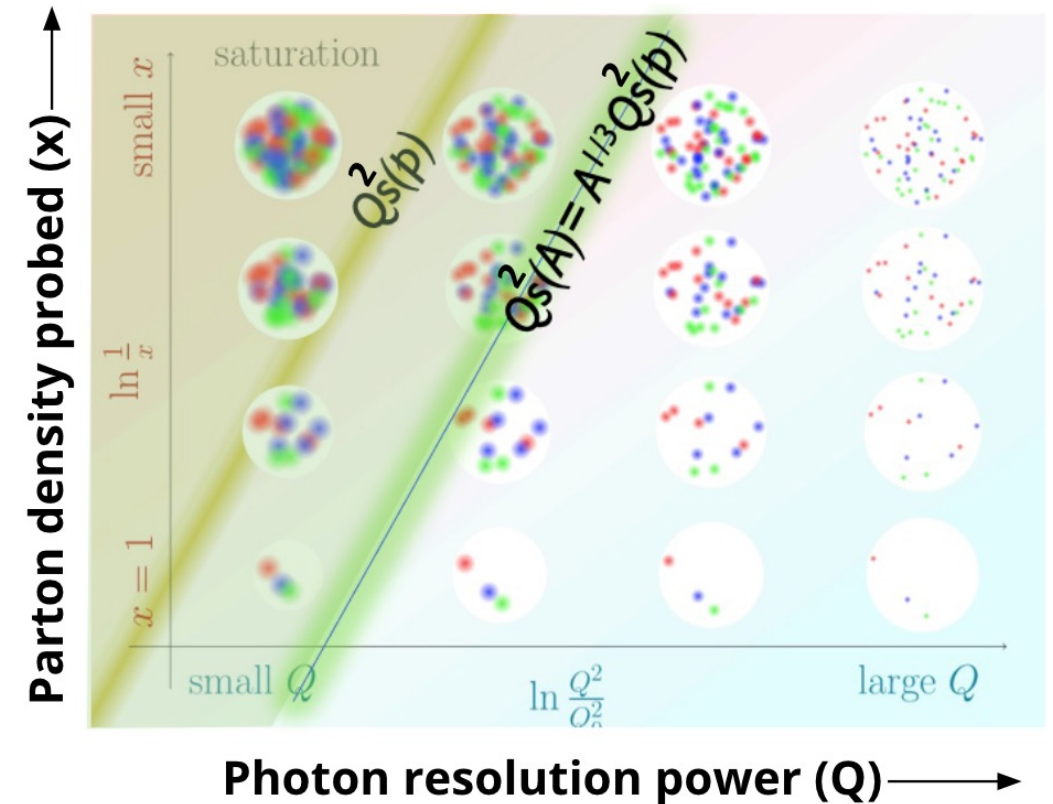
Advantages of Gluon Saturation Search in Nucleus



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

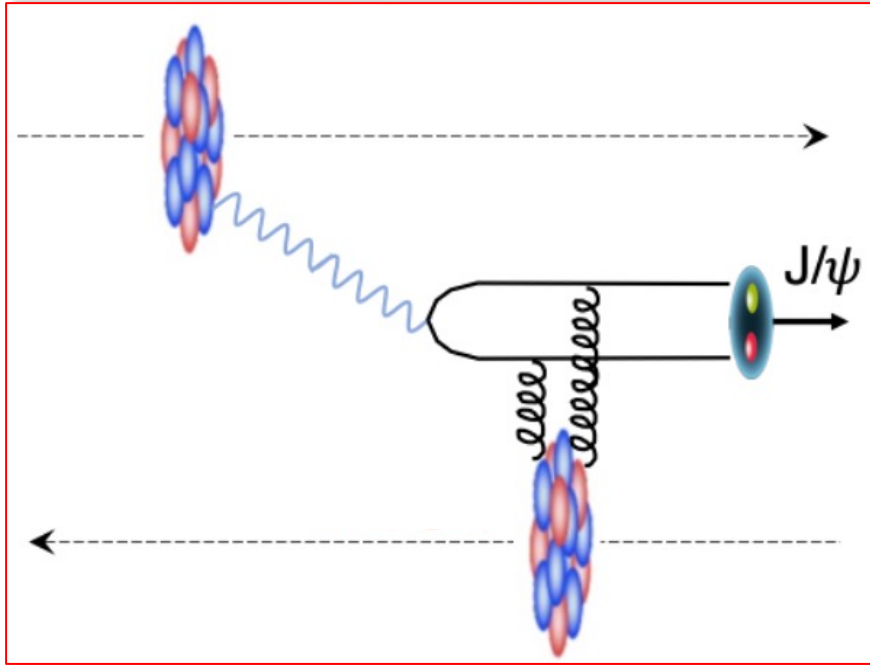
$$Q_s^2 \sim A^{1/3} \left(\frac{1}{x} \right)^\lambda$$

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



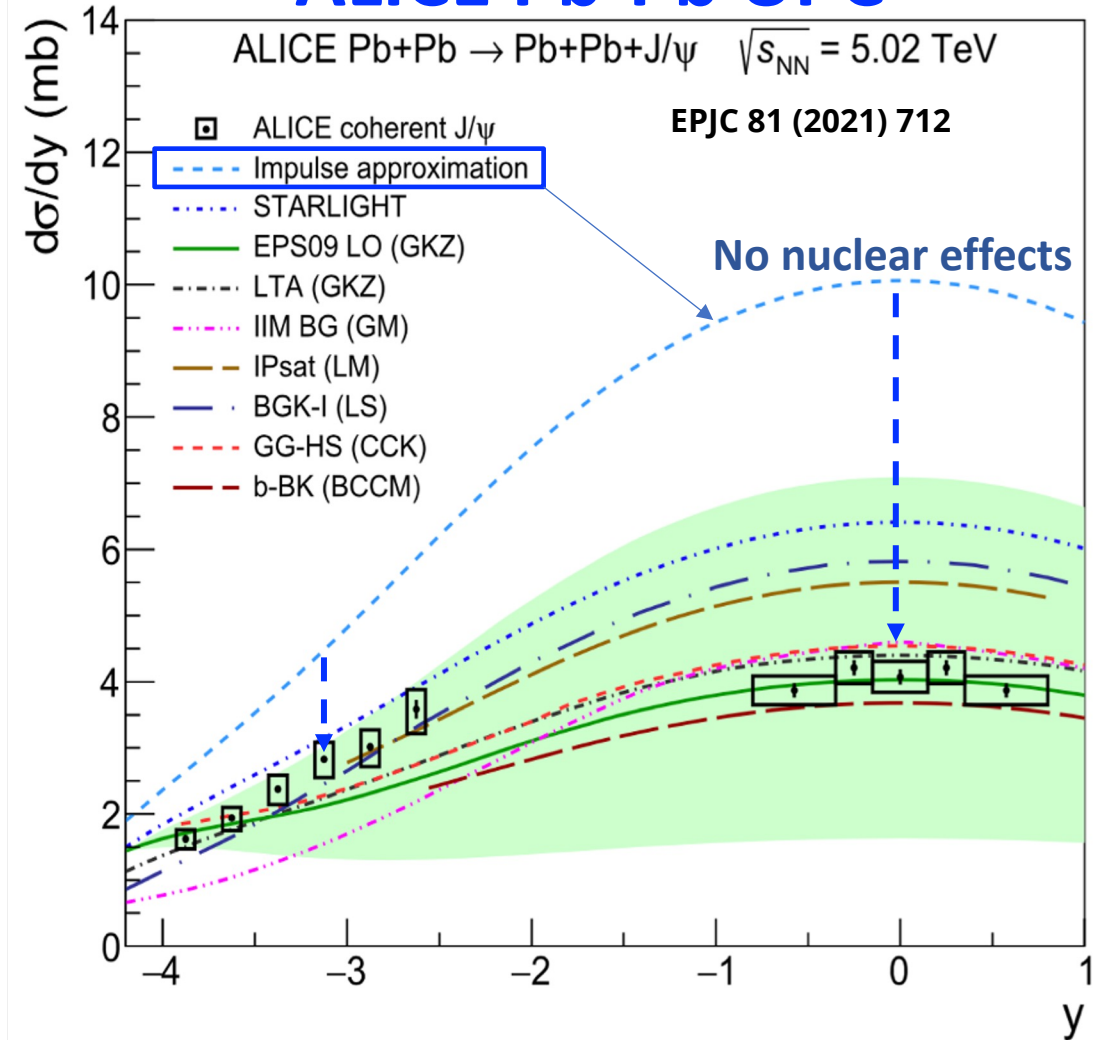
Coherent J/ψ Photoproduction in A-A UPCs

$$\gamma + \text{Pb} \rightarrow \text{J}/\psi + \text{Pb}$$

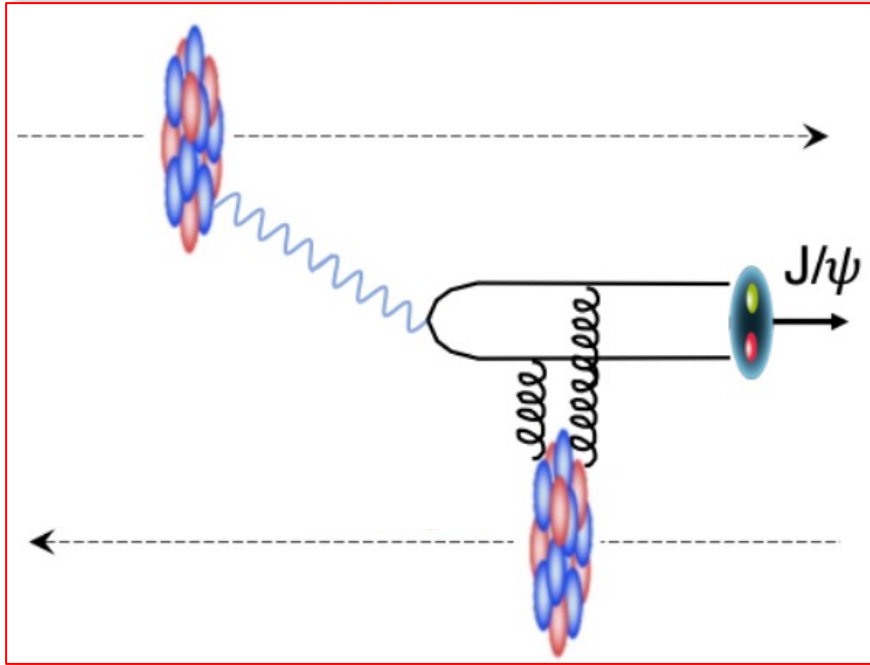
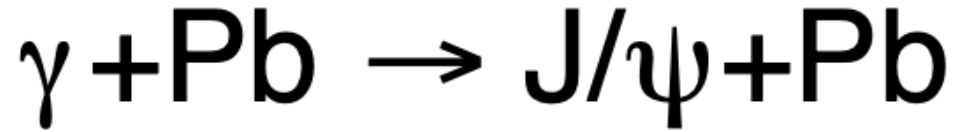


- **Strong suppression**, but the rapidity distribution is still **a puzzle** for theoretical studies (models considering gluon saturation or shadowing)

ALICE Pb-Pb UPC

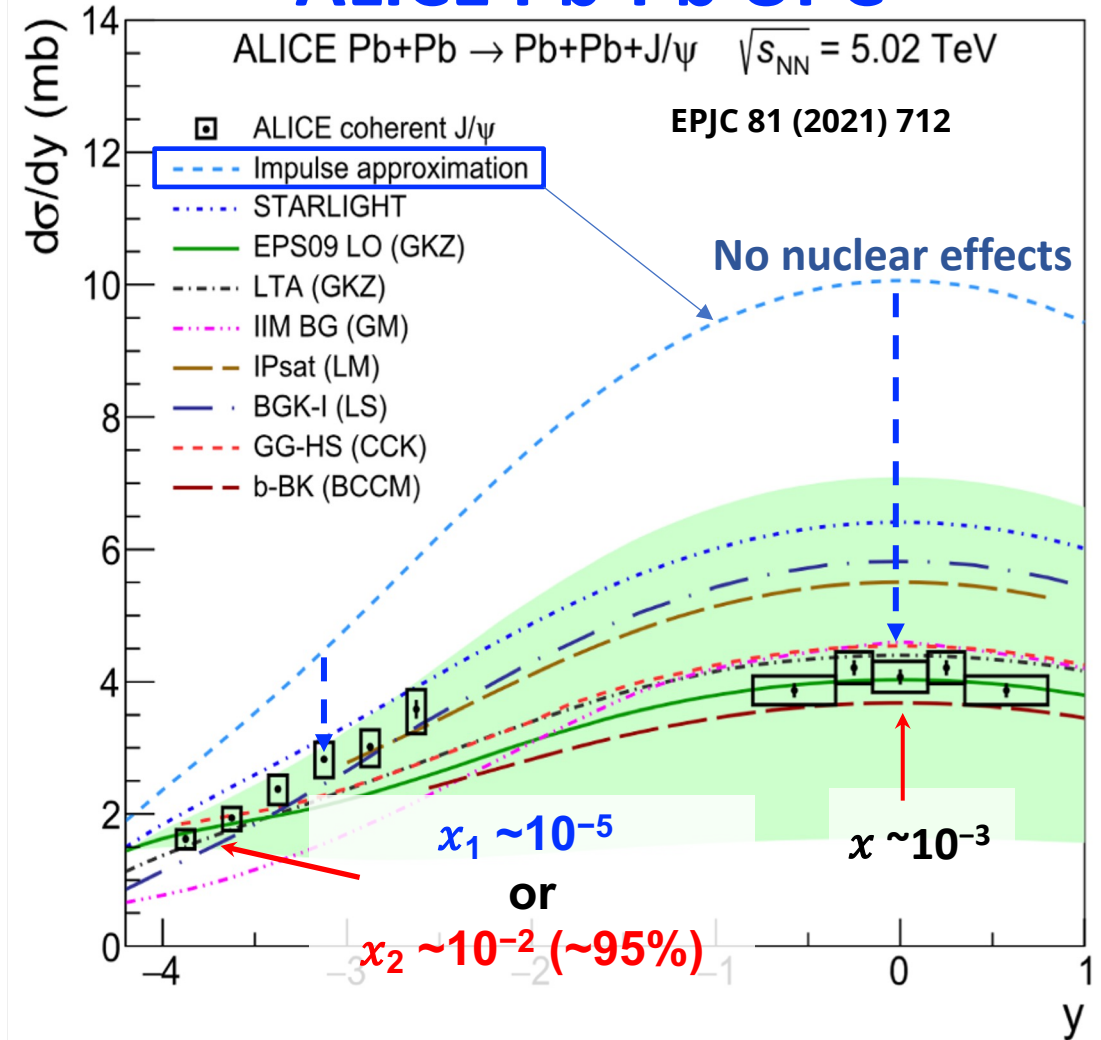


Coherent J/ψ Photoproduction in A-A UPCs



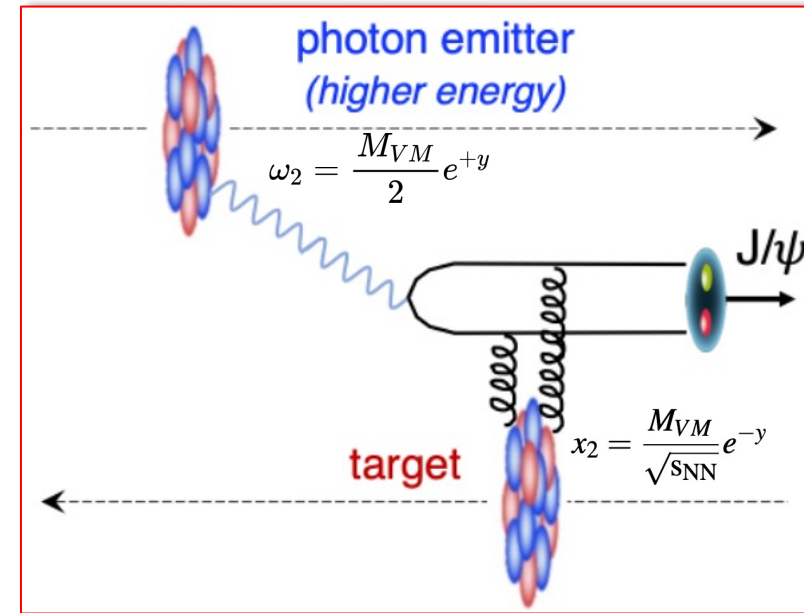
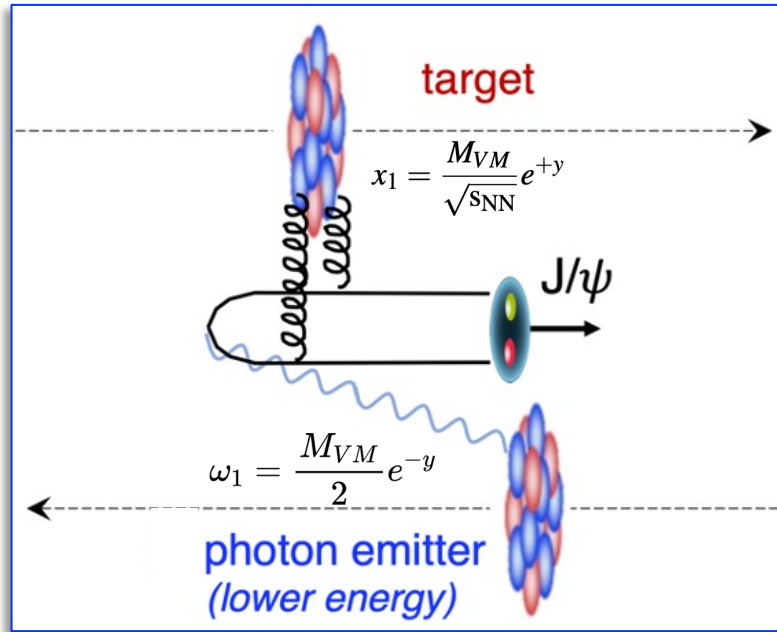
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ALICE Pb-Pb UPC



$$x = \frac{M_{V\psi}}{\sqrt{s_{NN}}} e^{\pm y}$$

Two-Way Ambiguity in A-A UPC



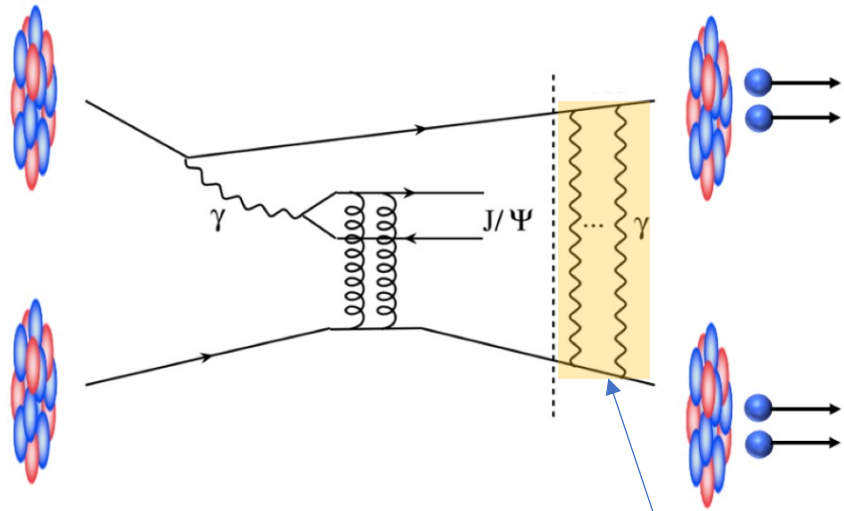
$$\frac{d\sigma_{AA \rightarrow AA' J/\psi}}{dy} = N_{\gamma/A}(\omega_1) \cdot \sigma_{\gamma A \rightarrow J/\psi A'}(\omega_1) + N_{\gamma/A}(\omega_2) \cdot \sigma_{\gamma A \rightarrow J/\psi A'}(\omega_2)$$

At least two equations for the solutions

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

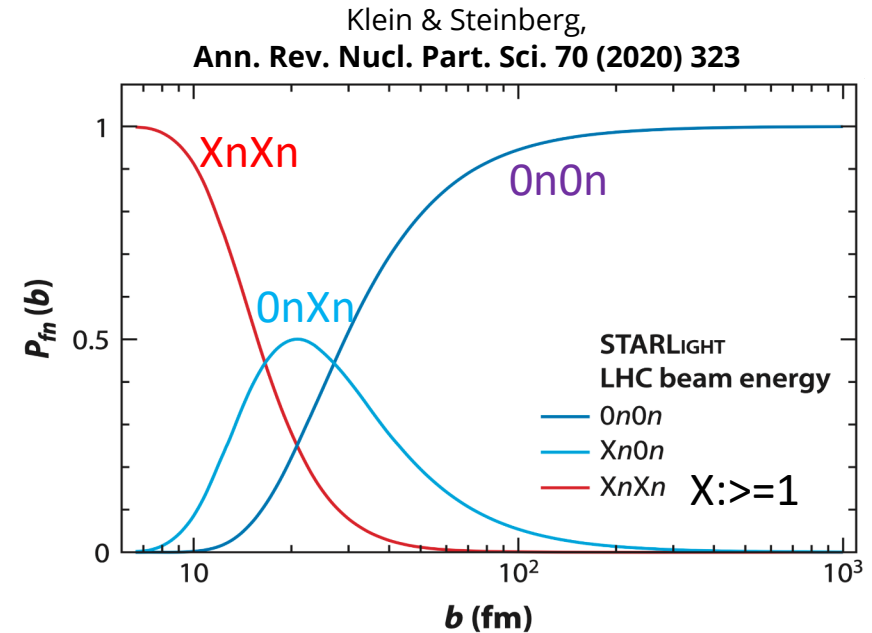
V. Guzey, M. Strikman, M. Zhalov, EPJC (2014) 72 2942

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



Neutron emission via EMD with additional photon exchange:

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

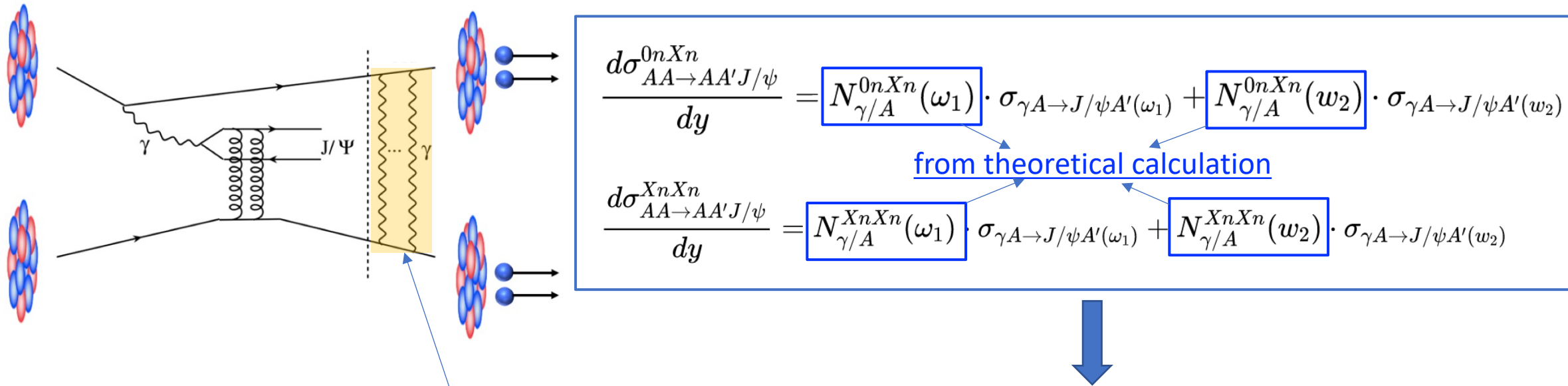


- Analogous to centrality:
 - $b_{XnXn} < b_{0nXn} < b_{0n0n}$ in UPC

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CMS Experiment at the LHC, CERN

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

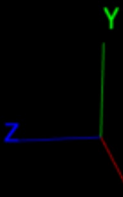
Run / Event / LS: 326619 / 2320827 / 8

**Muon
Chambers**

μ^+

μ^-

Tracker



Wednesday, November 8, 2023

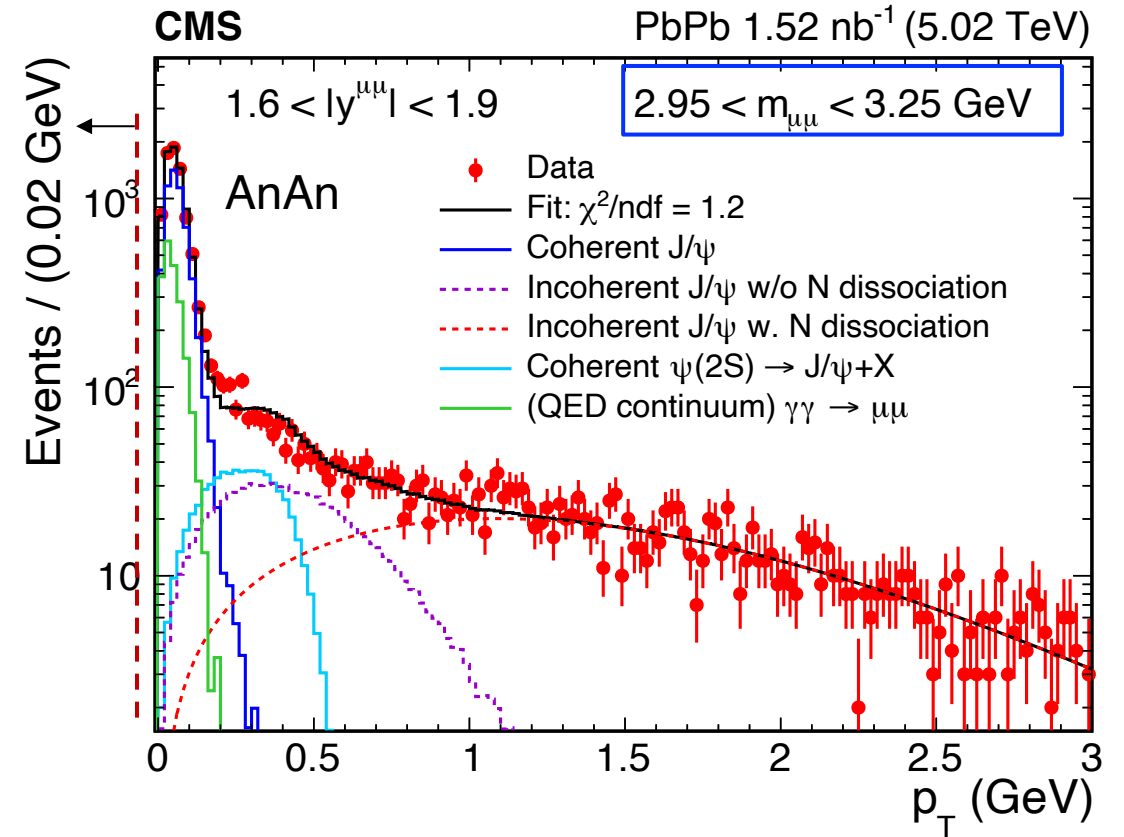
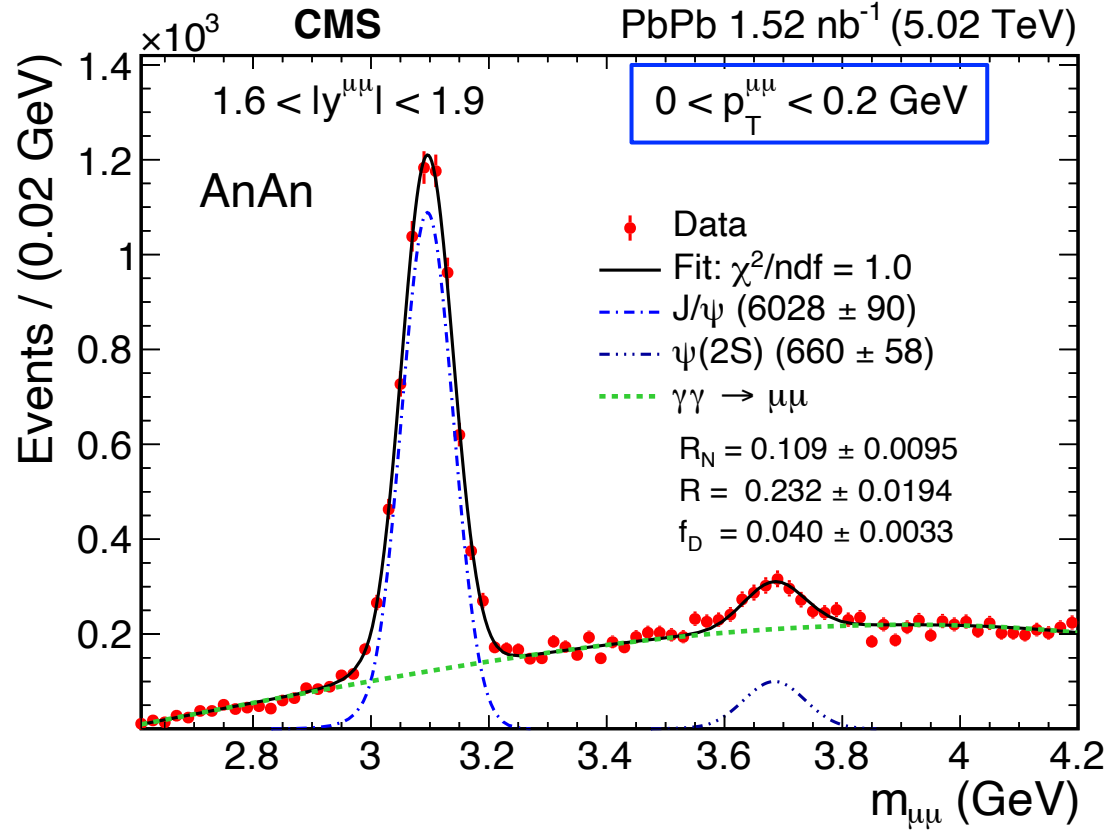
Zaochen Ye at CFNS Workshop 2023

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)



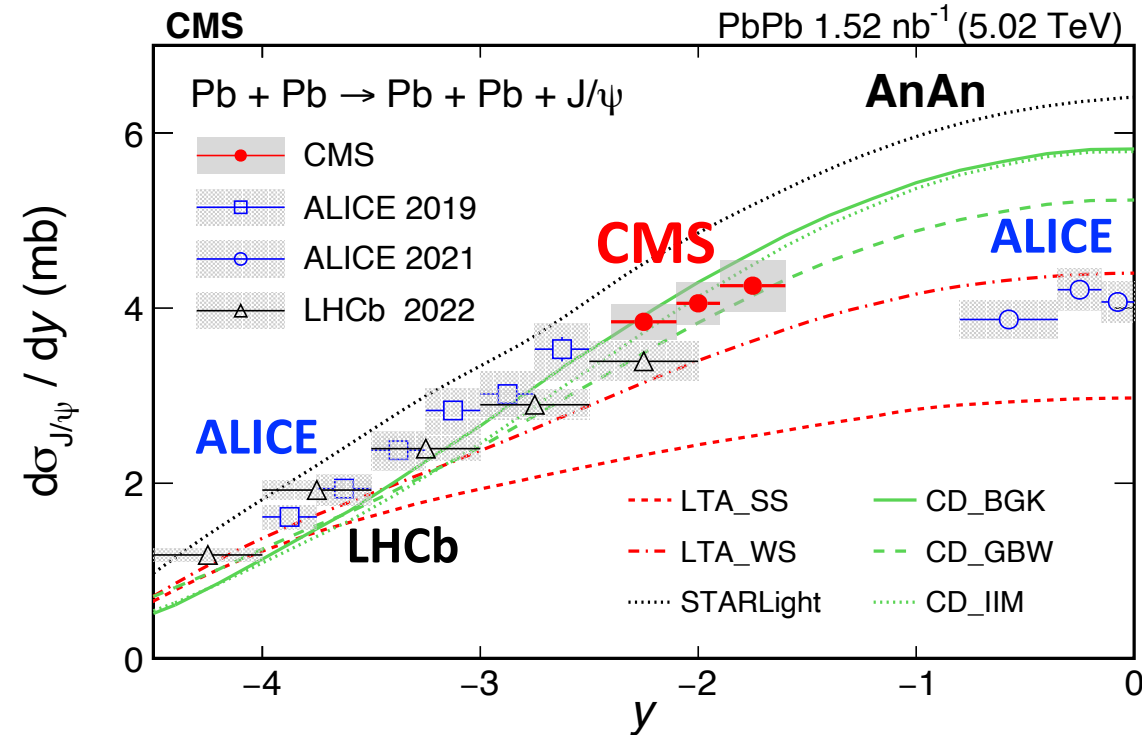
AnAn: All possible neutron emissions

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)

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



AnAn: All possible neutron emissions

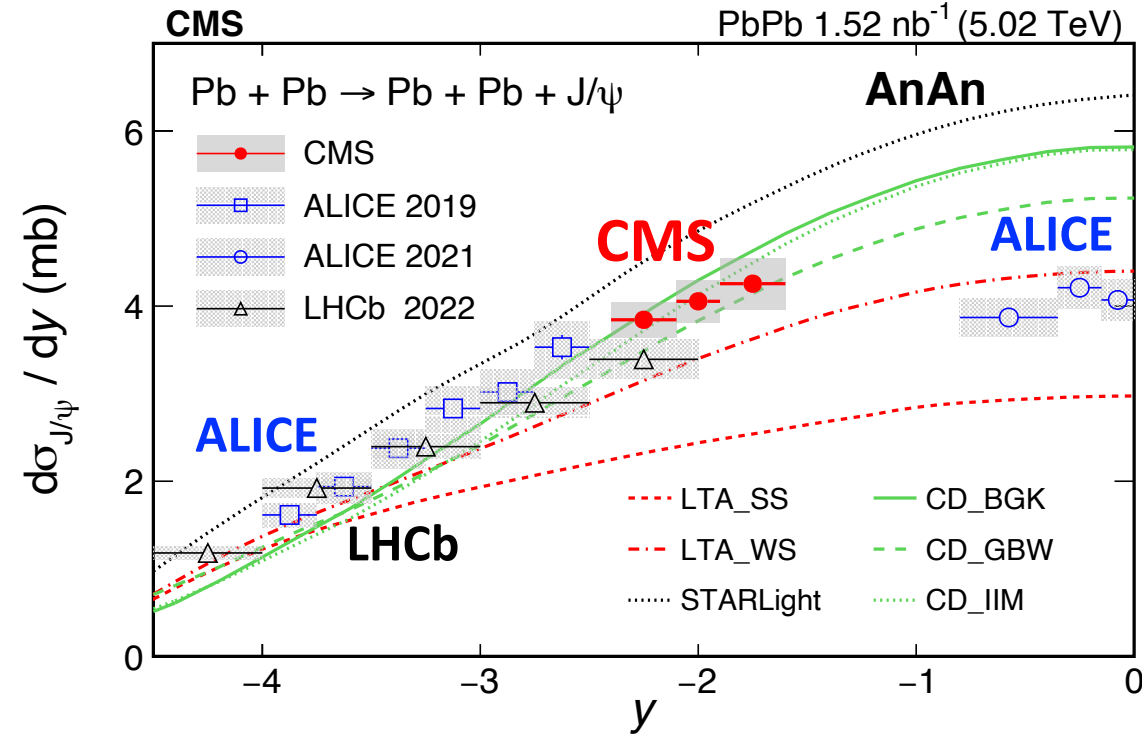
CMS data cover a new y region and follow ALICE forward data trend

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

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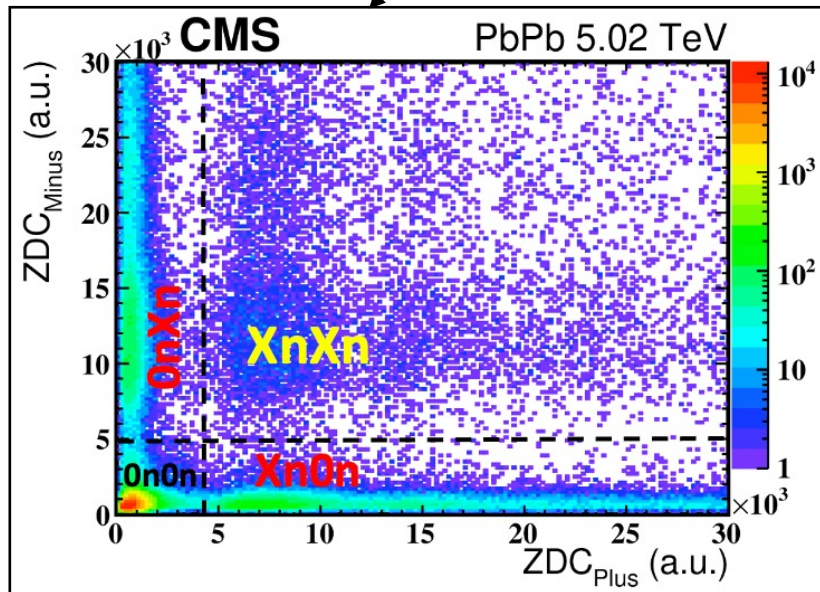
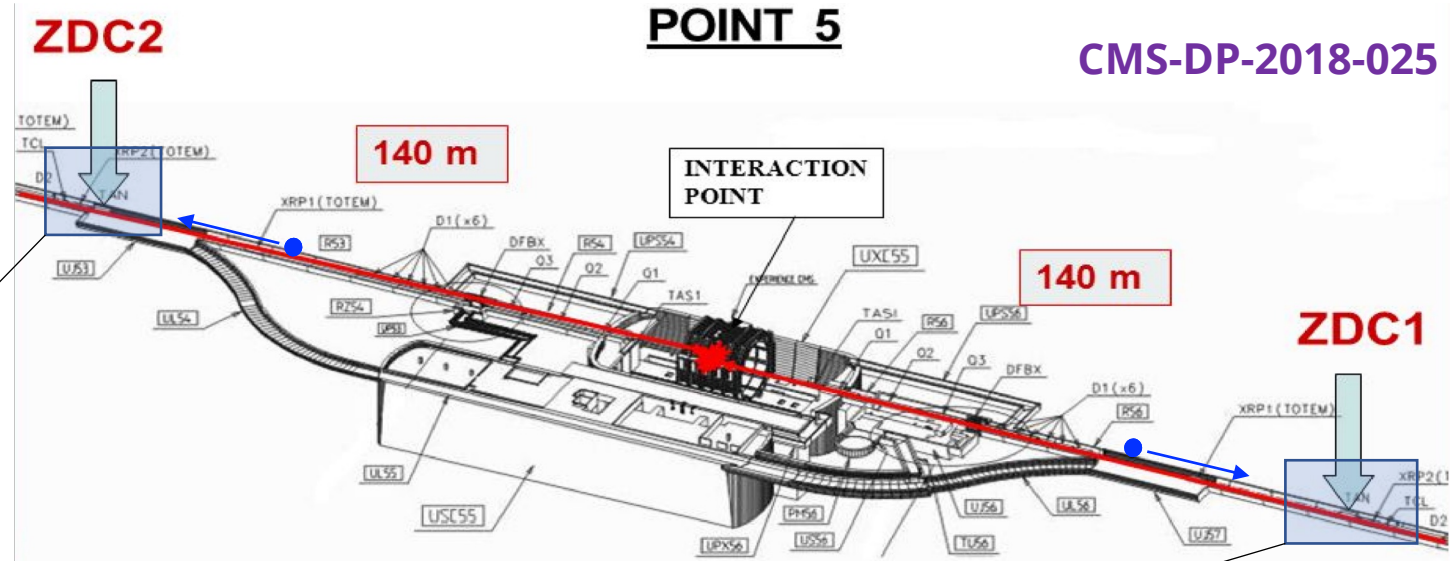
A deeper look at J/ψ production from **single γ +Pb** without the “two-way ambiguity” will tell more.

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

Neutron Tag with Zero Degree Calorimeter

POINT 5

CMS-DP-2018-025

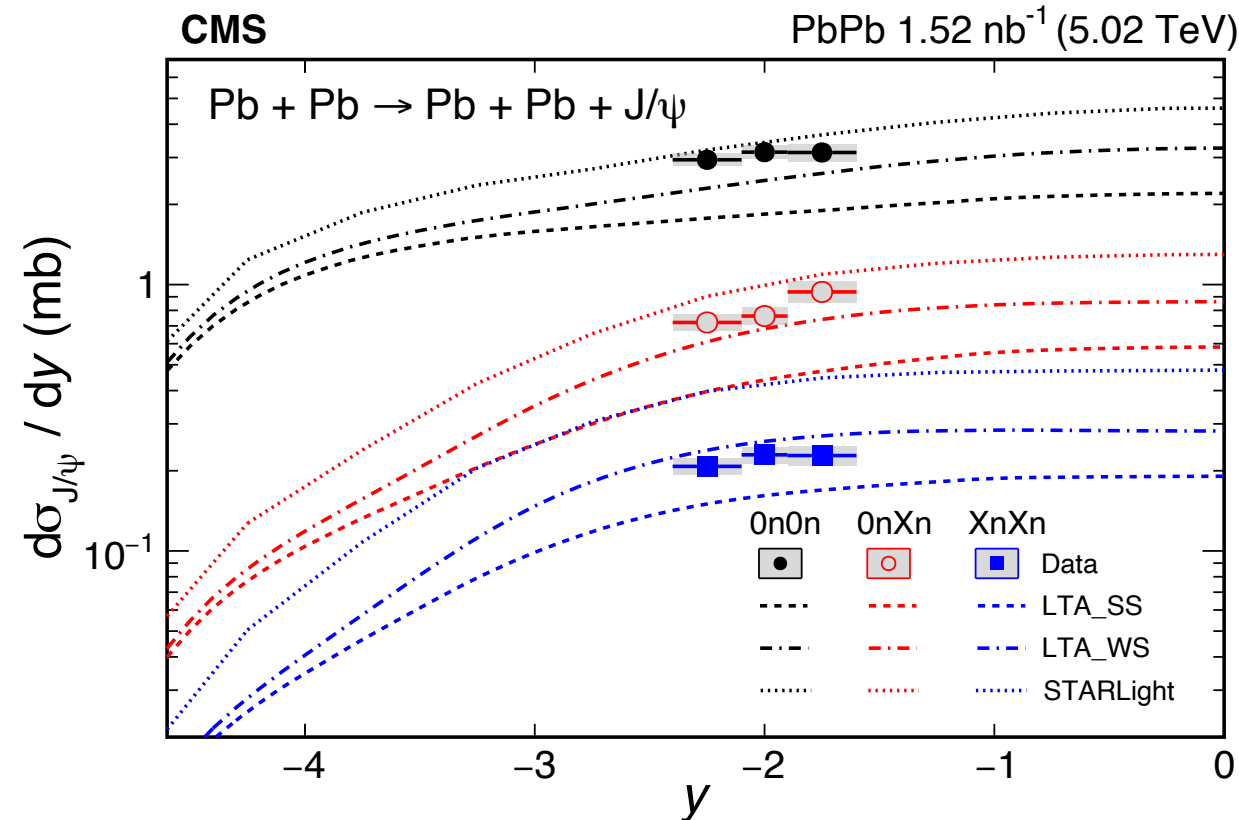


Tag events with **neutrons**:

- 0n0n, **0nXn**, **XnXn** (X: ≥ 1)

Coherent J/ψ in PbPb UPCs with Fwd Neutron Tag

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



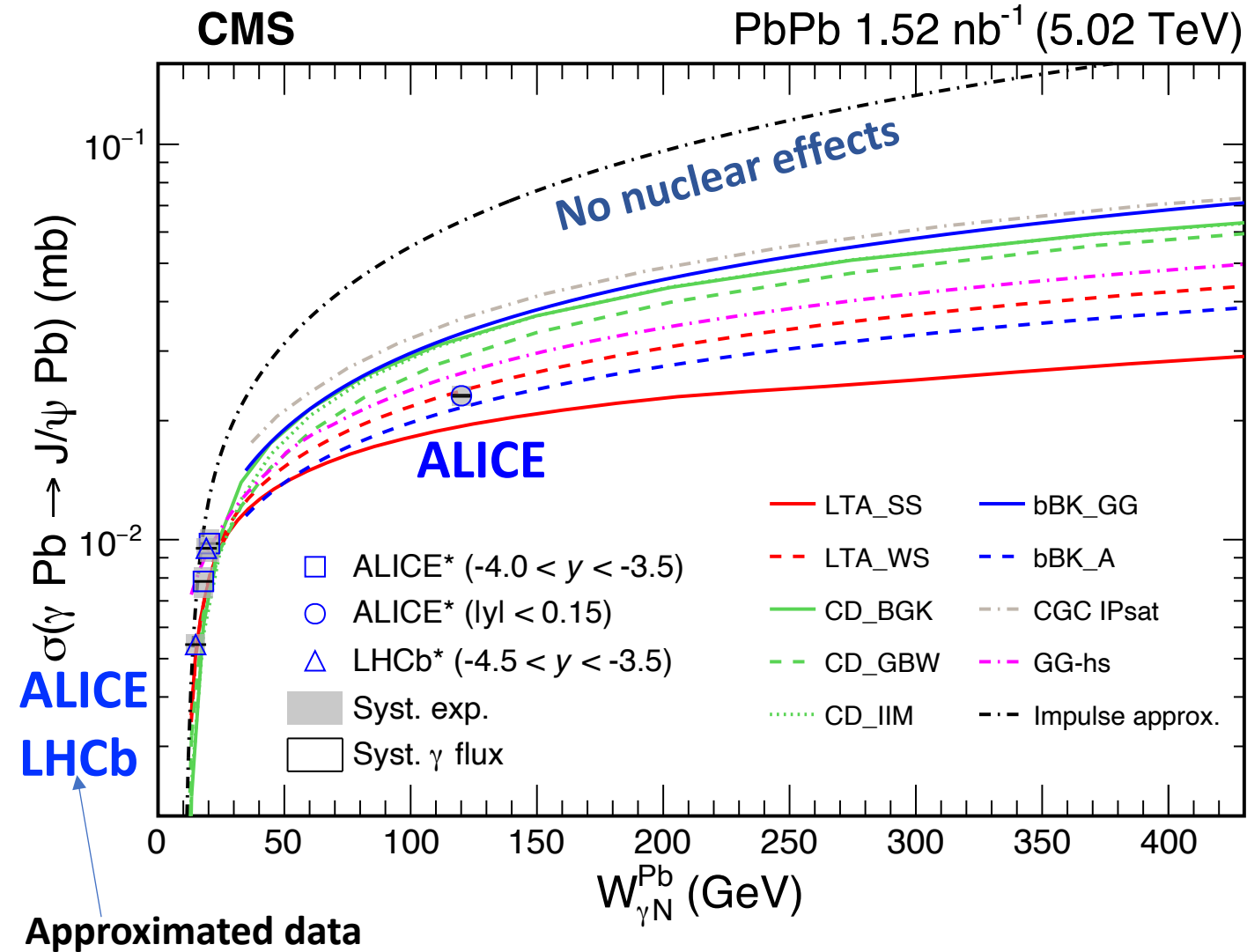
Neutron migration effects are corrected

- 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](#)

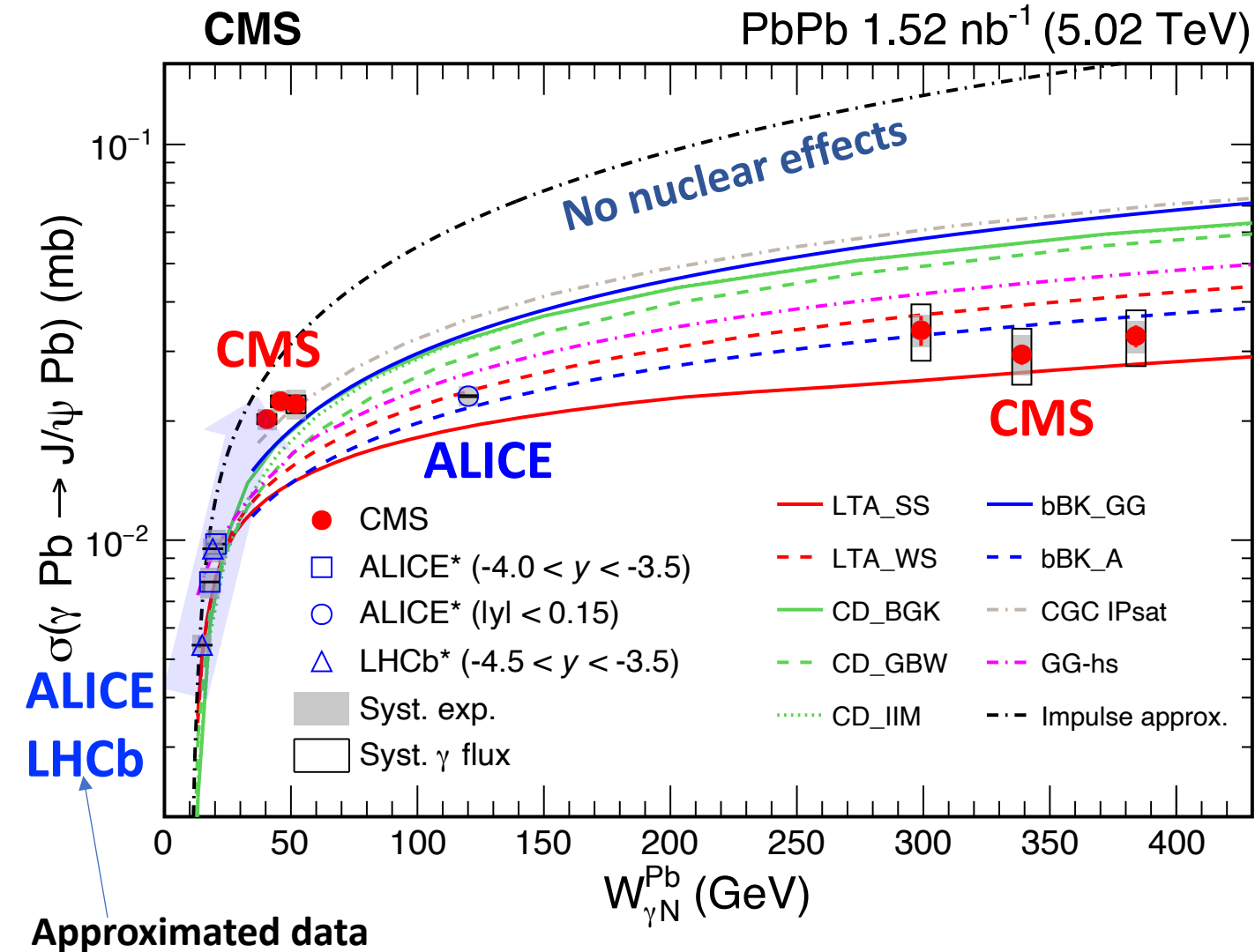


ALICE, LHCb vs. IA:

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

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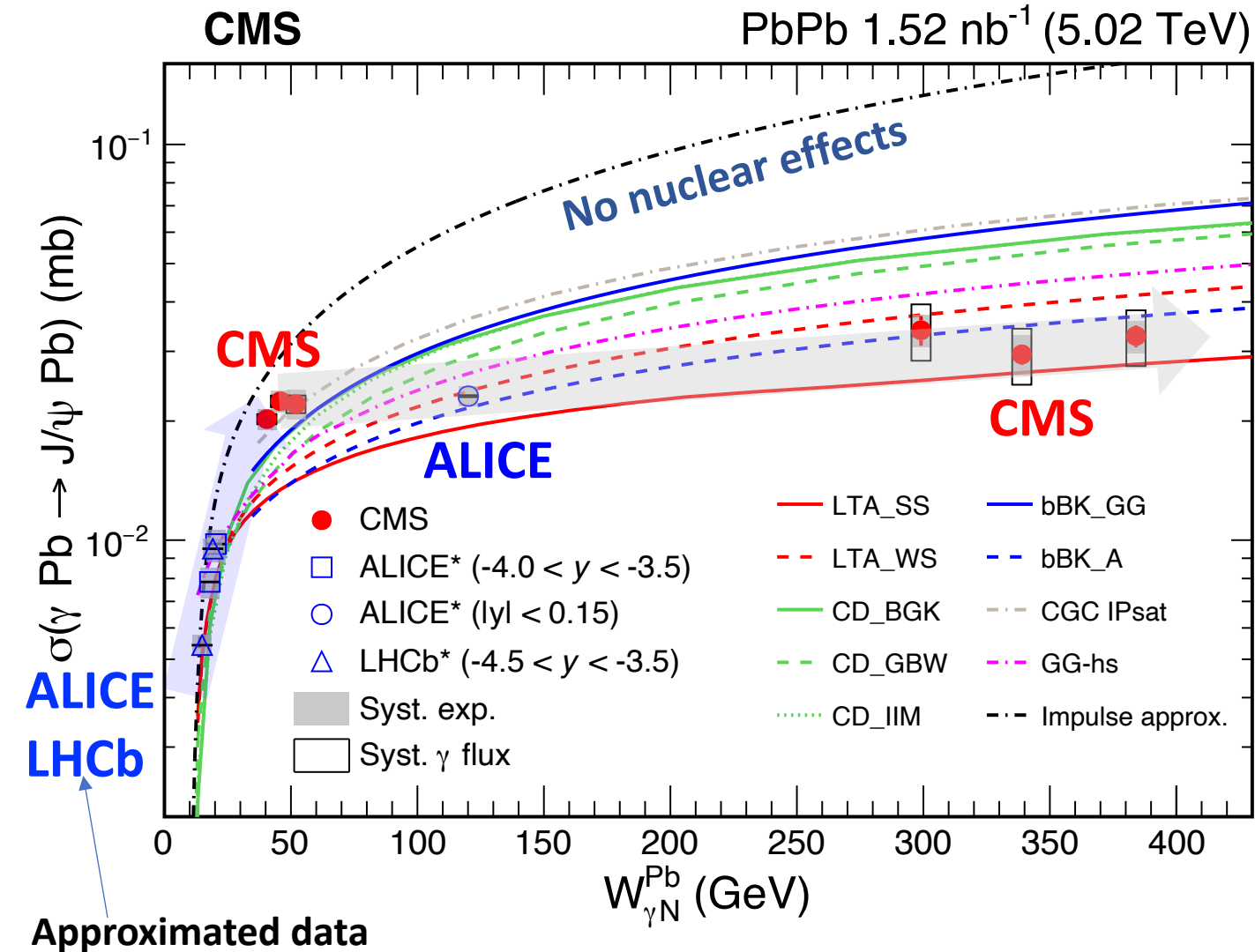
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New data from **CMS**:

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

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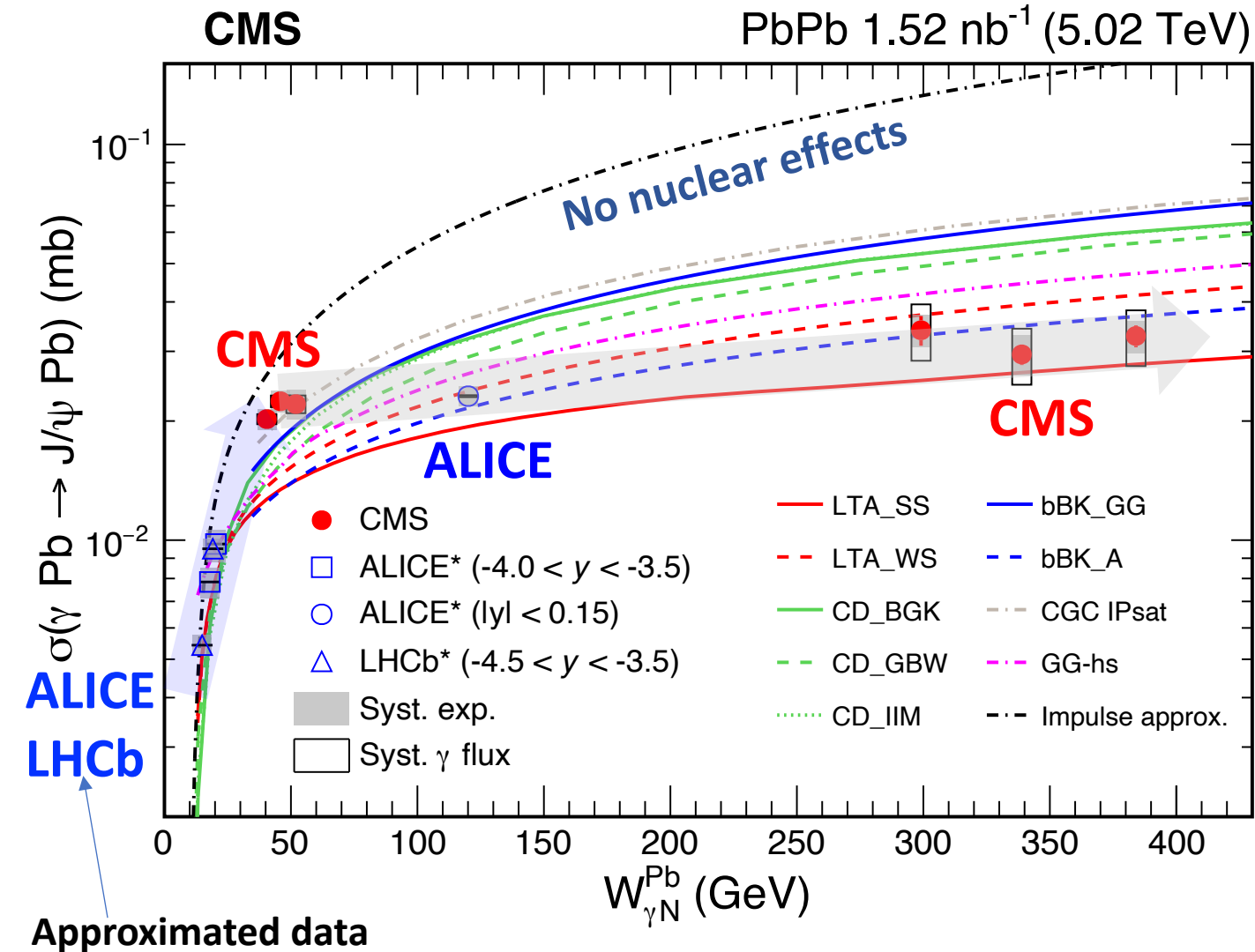
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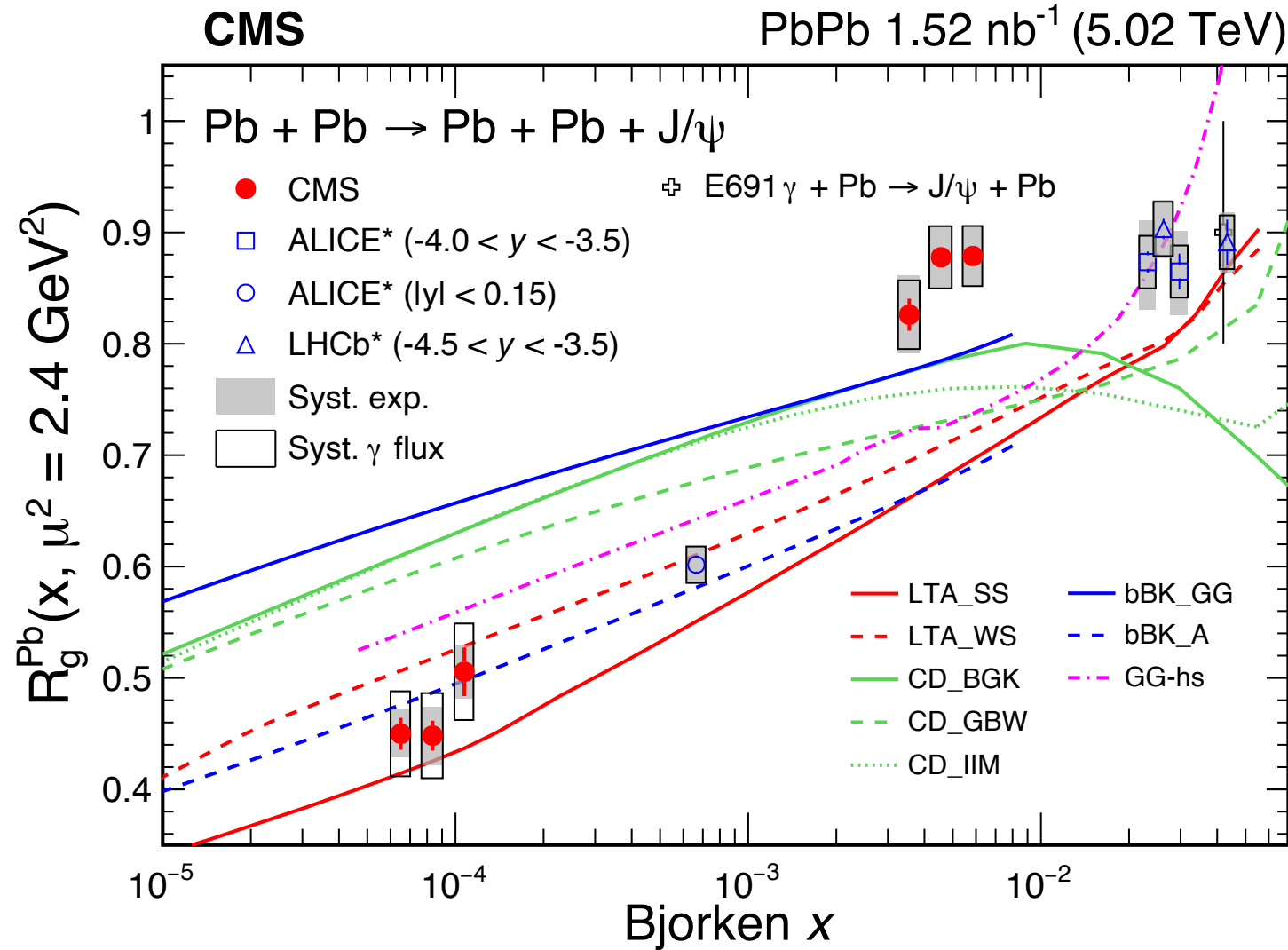
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No models can describe the entire data distribution.

ALICE new data follows the same trend, see Simone Ragoni' [QM23 talk](#)

Nuclear Gluon Suppression Factor

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



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

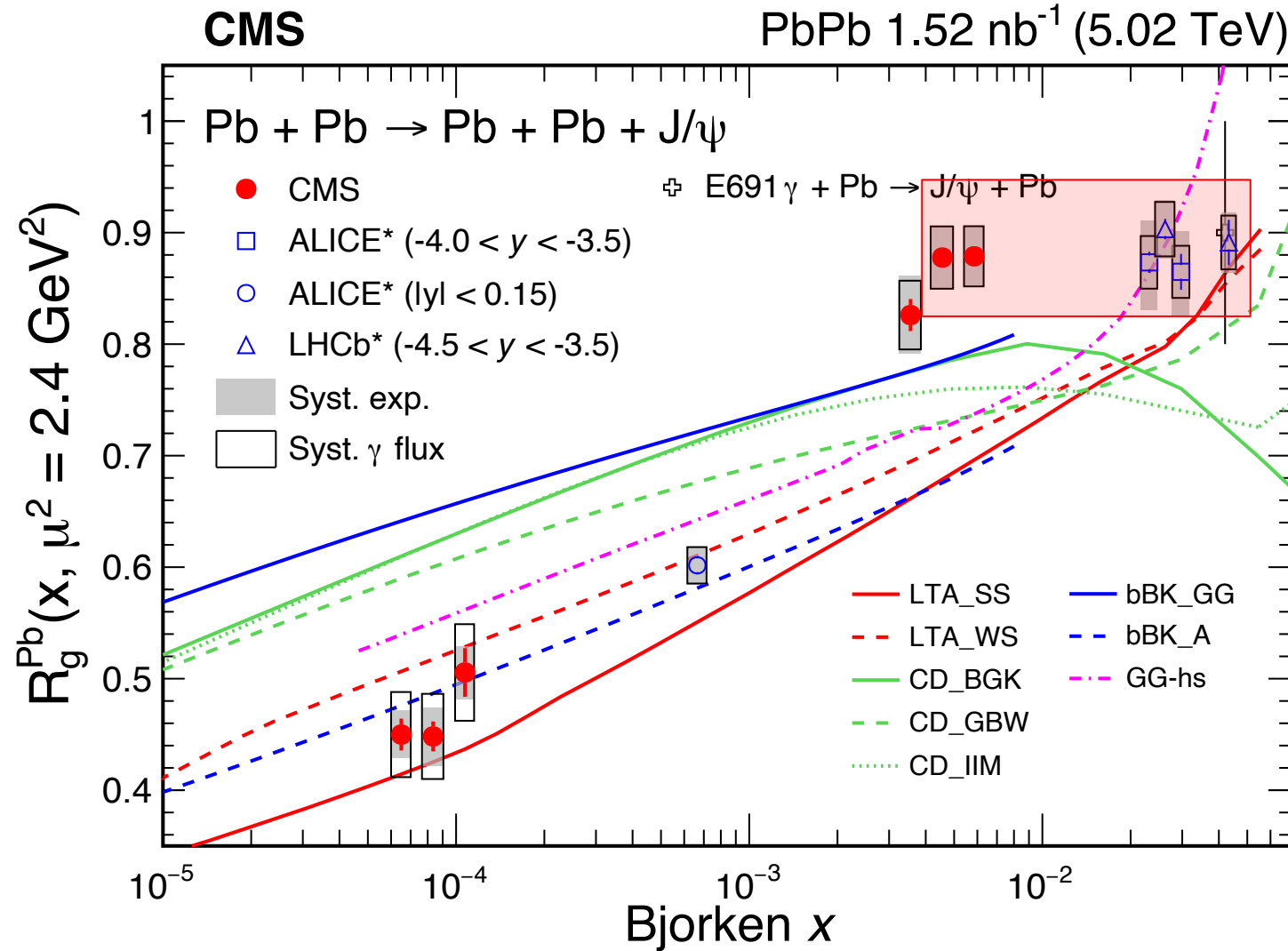
Impulse approx. (IA)
neglects all nuclear effects.

- R_g represents nuclear gluon suppression factor at LO.

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

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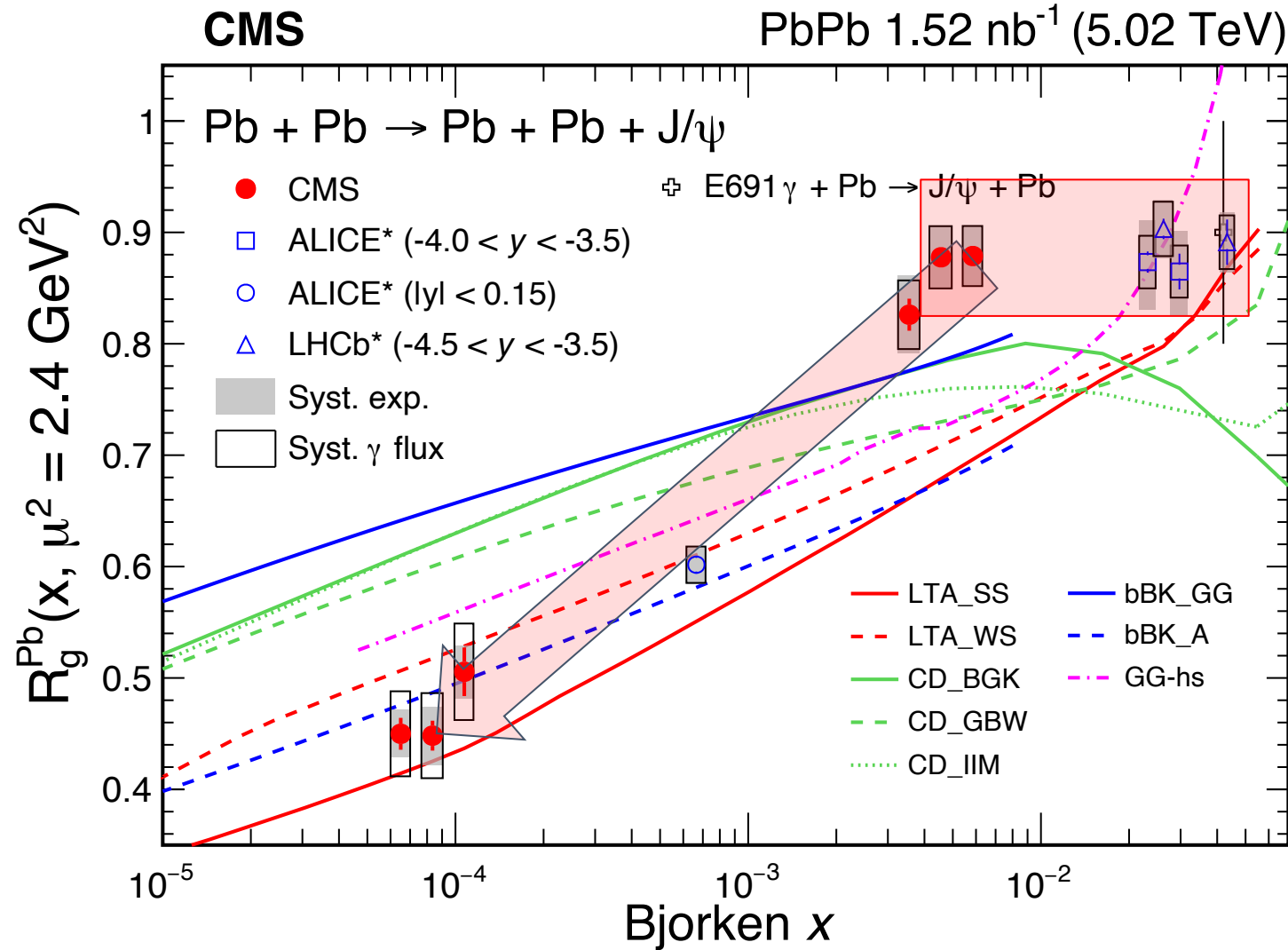
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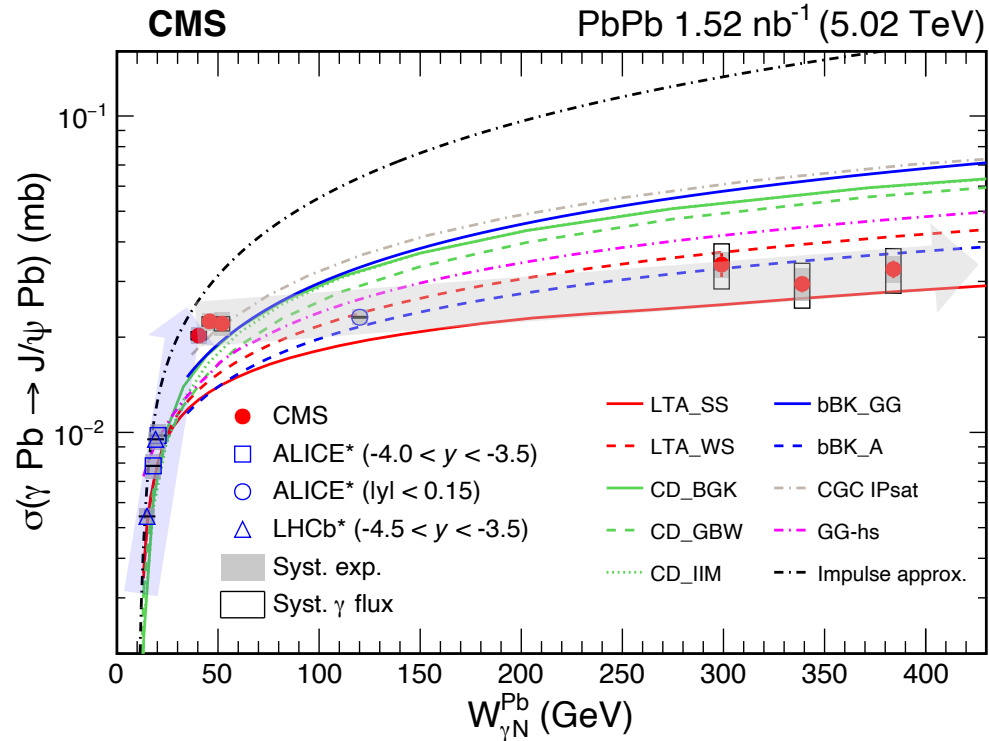
Impulse approx. (IA)
neglects all nuclear effects.

- 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?

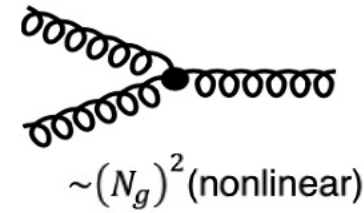
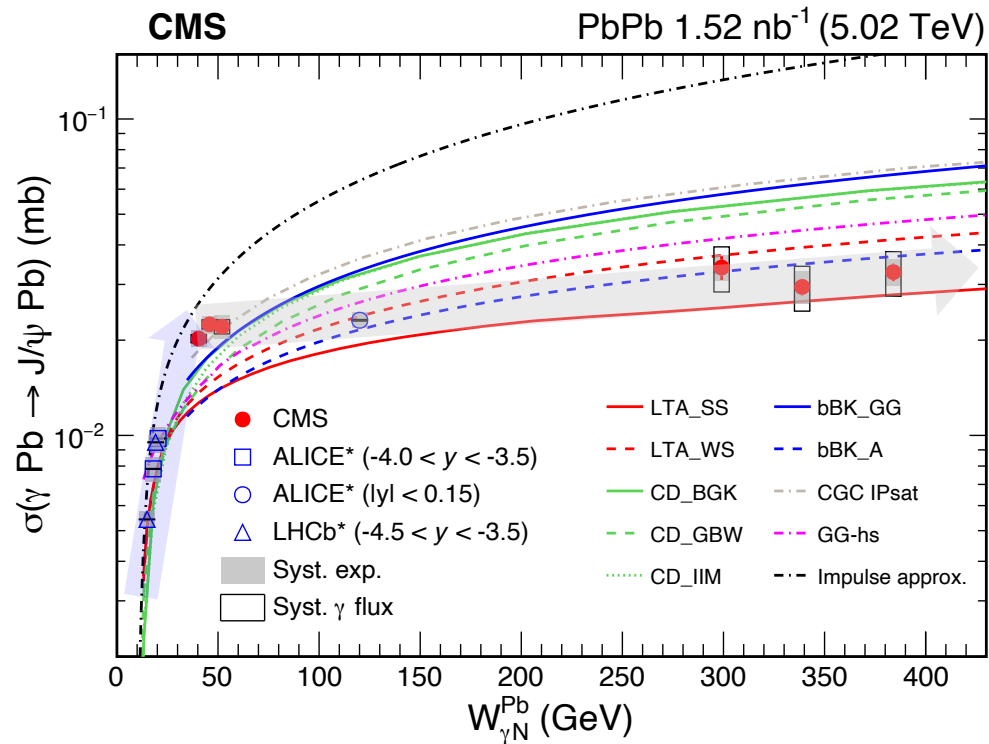
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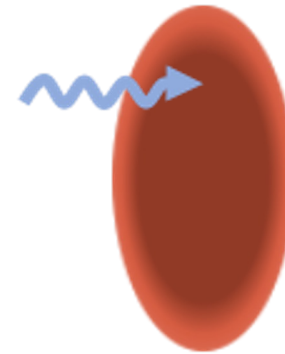
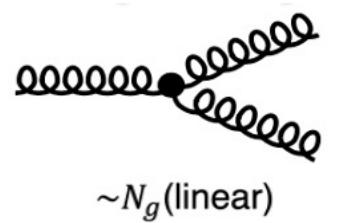
- σ stops rapid rising trend $\rightarrow$ splitting and recombination of gluons become equal
 - **Clear evidence for gluon saturation!!?**

What Physics Behind?

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Gluon Saturation?



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](#)

- σ stops rapid rising trend $\rightarrow$ splitting and recombination of gluons become equal
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OR

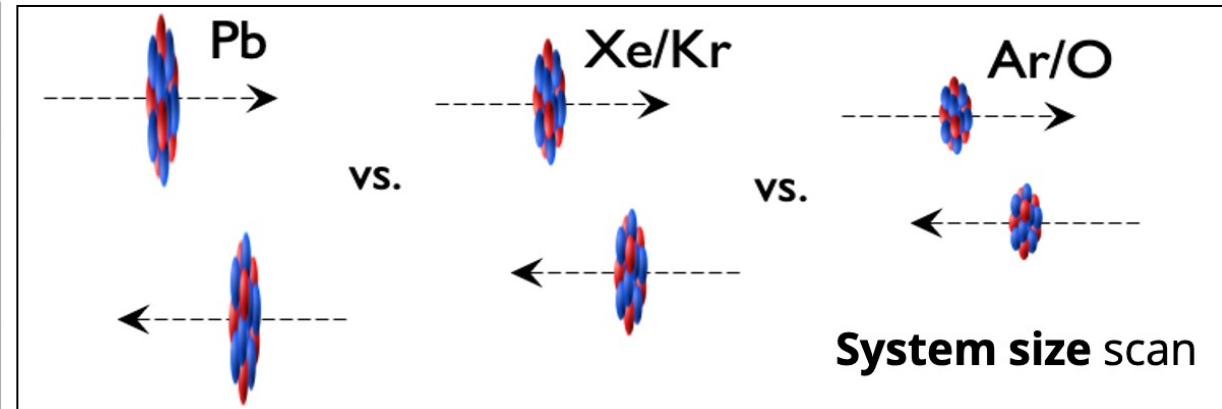
- Nucleus target becomes totally absorptive to incoming photons $\rightarrow$ **Black Disk Limit!!?**
 - **Nucleus becomes a black disk, internal structure is invisible.**

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

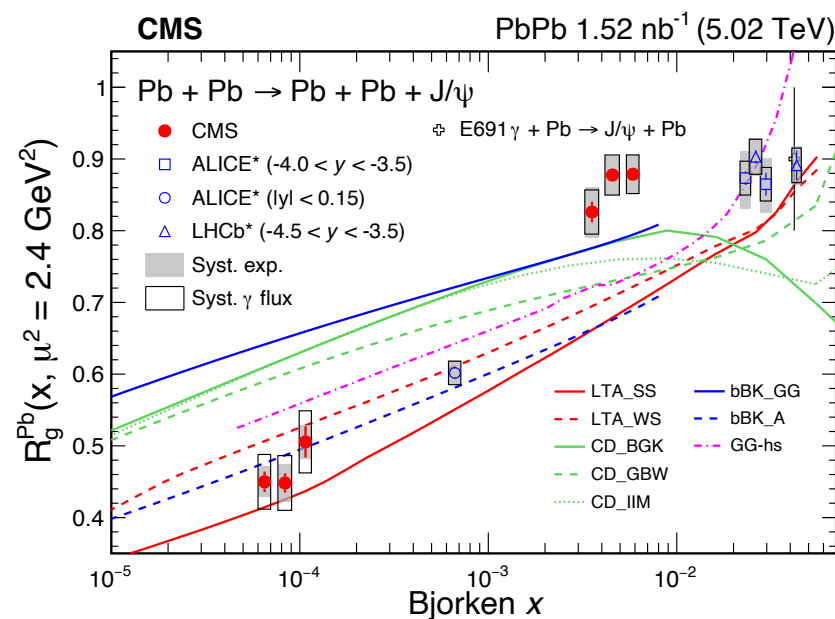
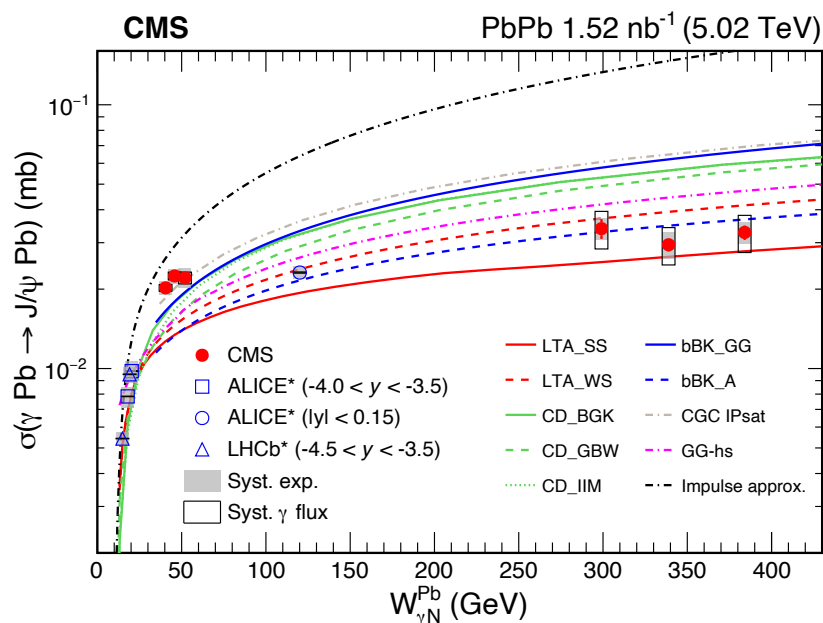
Meson	σ	PbPb $L_{\text{int}} = 13 \text{ nb}^{-1}$				
		All Total	Central 1 Total	Central 2 Total	Forward 1 Total 1	Forward 2 Total
$\rho \rightarrow \pi^+ \pi^-$	5.2b	68 B	5.5 B	21B	4.9 B	13 B
$\rho' \rightarrow \pi^+ \pi^- \pi^+ \pi^-$	730 mb	9.5 B	210 M	2.5 B	190 M	1.2 B
$\phi \rightarrow K^+ K^-$	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 μ b	400 K	35 K	180 K	19 K	47 K
$Y(1S) \rightarrow \mu^+ \mu^-$	2.0 μ 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 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
- **$\sigma(\text{J}/\Psi)$ 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), accepted by 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

STEEL RETURN YOKE
12,500 tonnes

SILICON TRACKERS

Pixel ($100 \times 150 \mu\text{m}^2$) $\sim 1.9 \text{ m}^2 \sim 124\text{M}$ channels
Microstrips ($80\text{--}180 \mu\text{m}$) $\sim 200 \text{ m}^2 \sim 9.6\text{M}$ channels

SUPERCONDUCTING SOLENOID

Niobium titanium coil carrying $\sim 18,000 \text{ A}$

MUON CHAMBERS

Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 540 Cathode Strip, 576 Resistive Plate Chambers

PRESHOWER

Silicon strips $\sim 16 \text{ m}^2 \sim 137,000$ channels

FORWARD CALORIMETER

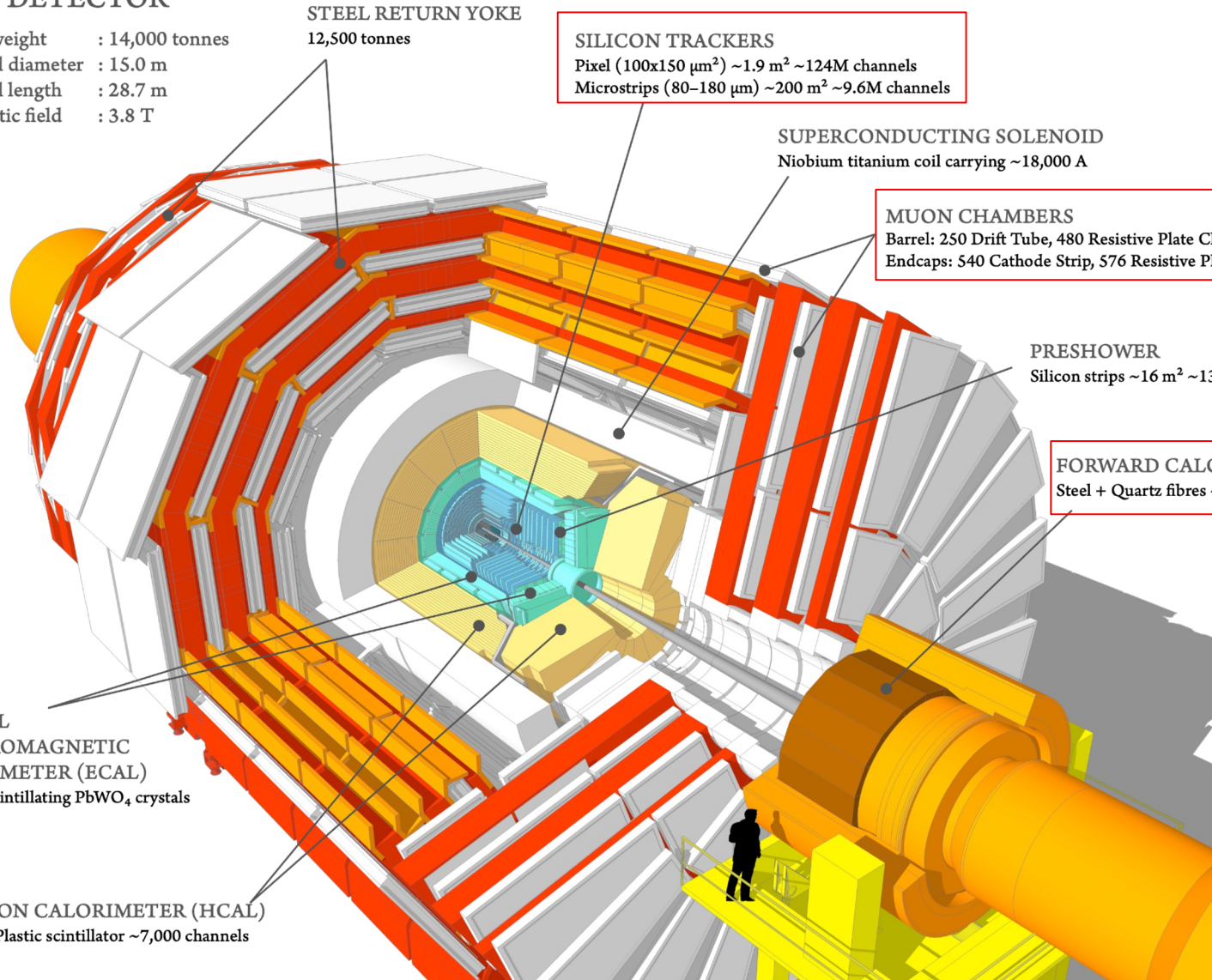
Steel + Quartz fibres $\sim 2,000$ Channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)

$\sim 76,000$ scintillating PbWO_4 crystals

HADRON CALORIMETER (HCAL)

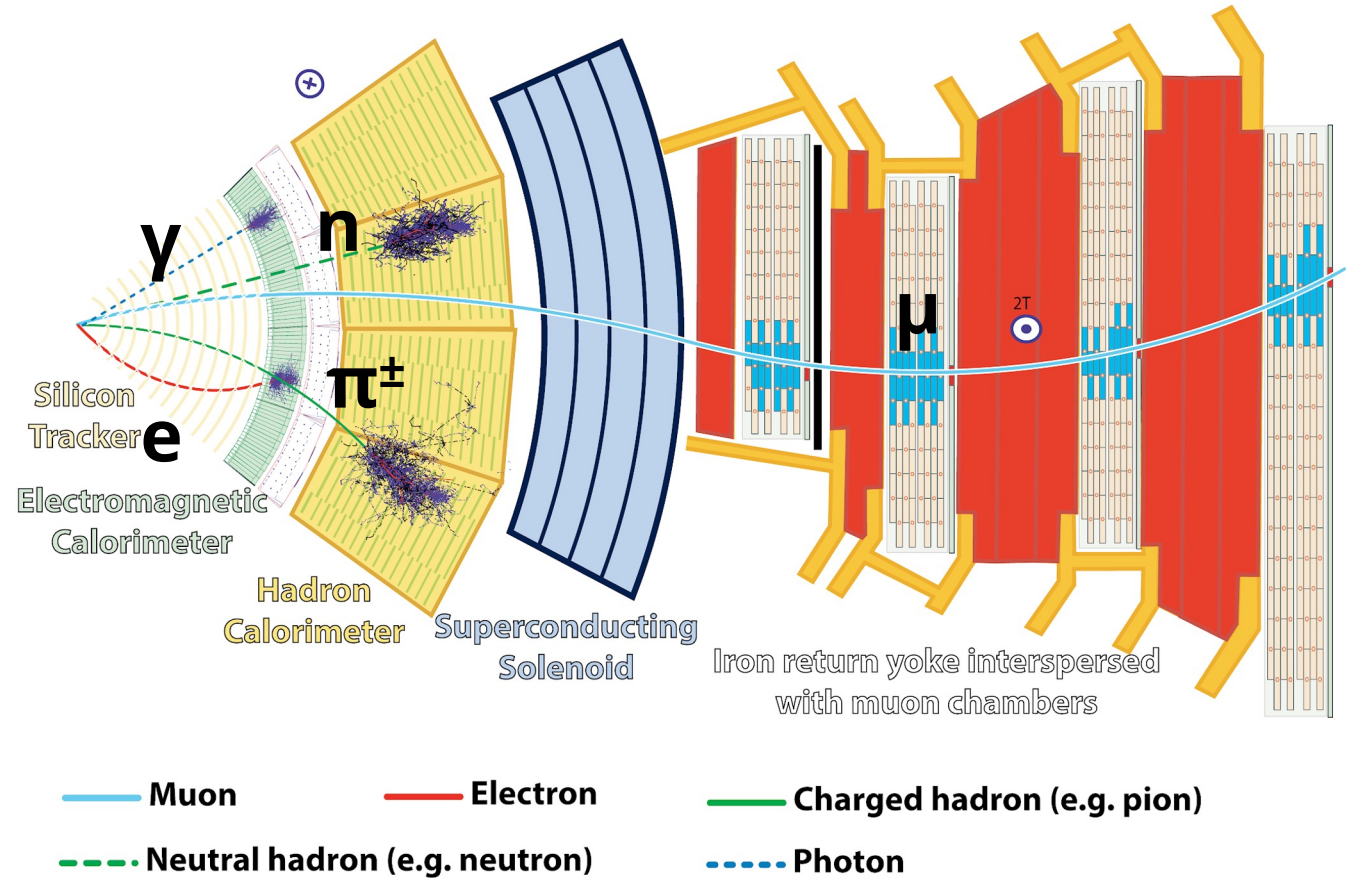
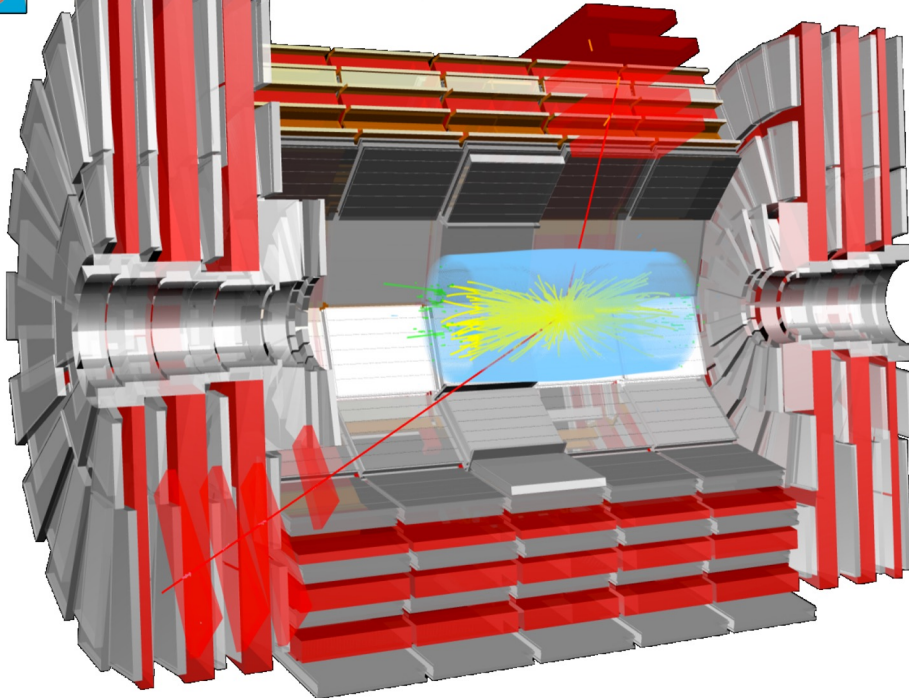
Brass + Plastic scintillator $\sim 7,000$ channels



Muon Reconstruction

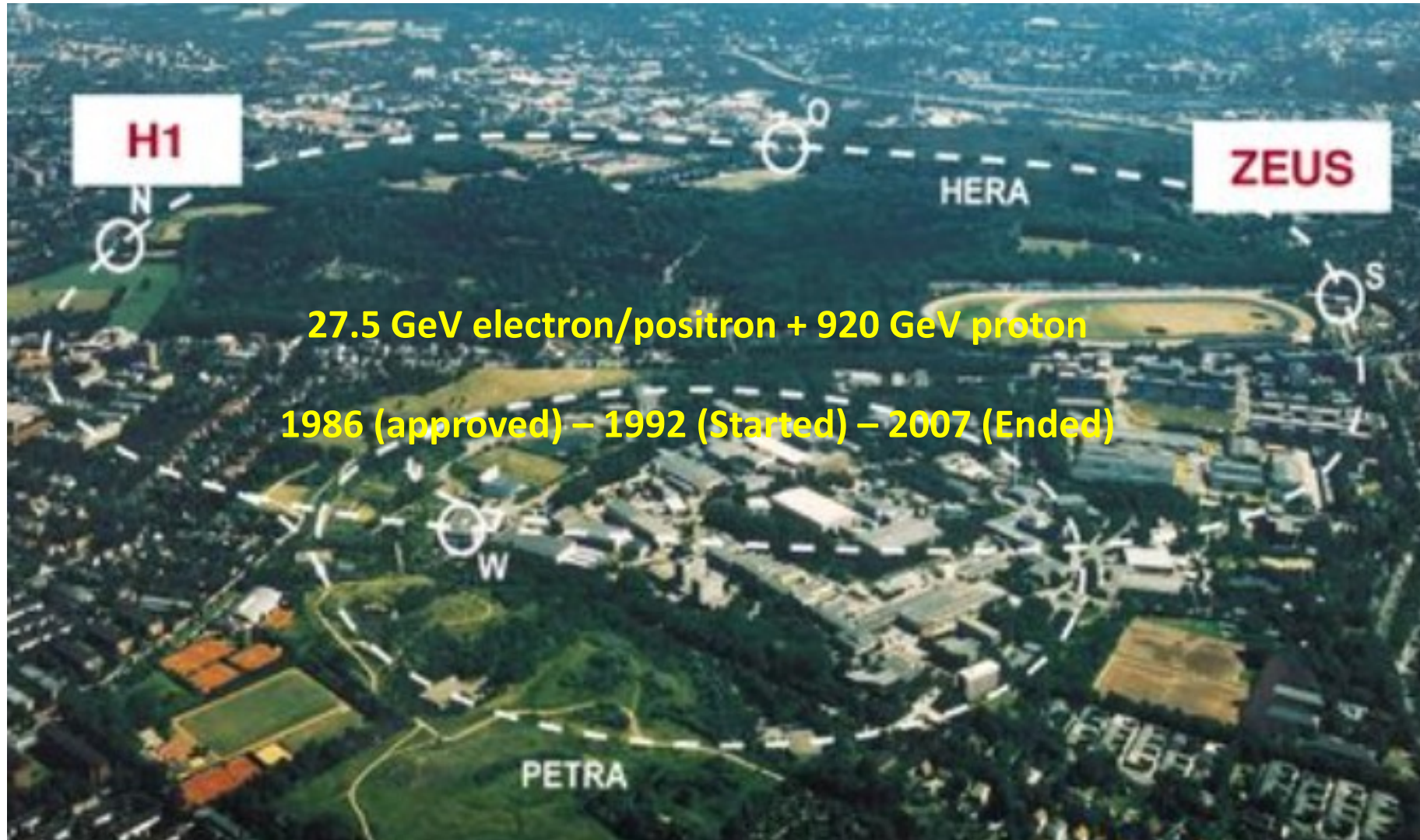


CMS Experiment at the LHC, CERN
Data recorded: 2015-Oct-30 19:23:54.631552 GMT
Run / Event / LS: 260424 / 211873064 / 115



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

Understand Nucleon Structure at HERA

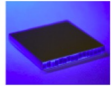


Future Opportunities

MIP Timing Detector for PID

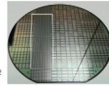
BTL: LYSO bars + SiPM readout:

- TK / ECAL interface: $|\eta| < 1.45$
- Inner radius: 1148 mm (40 mm thick)
- Length: ± 2.6 m along z
- Surface ~ 38 m², 332k channels
- Fluence at 4 ab⁻¹: $2 \times 10^{11} n_{\text{eq}}/\text{cm}^2$

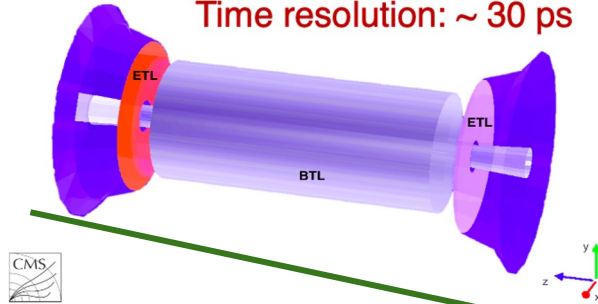


ETL: Si with internal gain (LGAD):

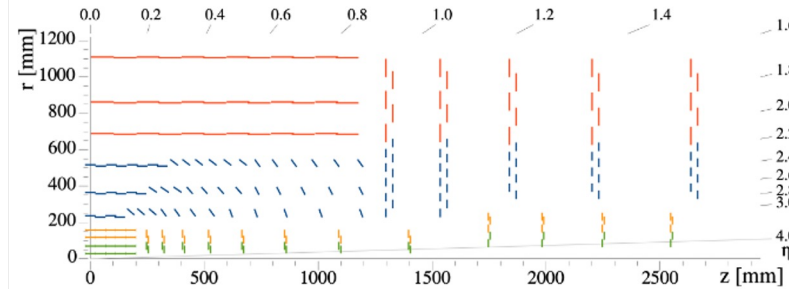
- On the CE nose: $1.6 < |\eta| < 3.0$
- Radius: $315 < R < 1200$ mm
- Position in z: ± 3.0 m (45 mm thick)
- Surface ~ 14 m², ~ 8.5 M channels
- Fluence at 4 ab⁻¹: up to $2 \times 10^{11} n_{\text{eq}}/\text{cm}^2$



Time resolution: ~ 30 ps



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

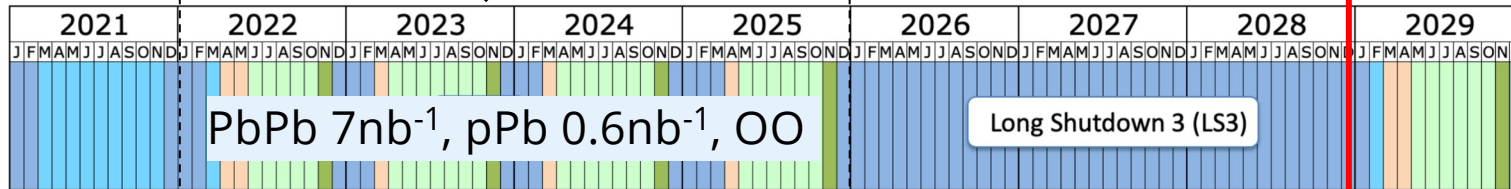


- Muon systems with $|\eta| < 2.8$
- Trigger and DAQ rate: $\sim 10\times$

↓ Run-3

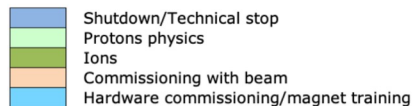
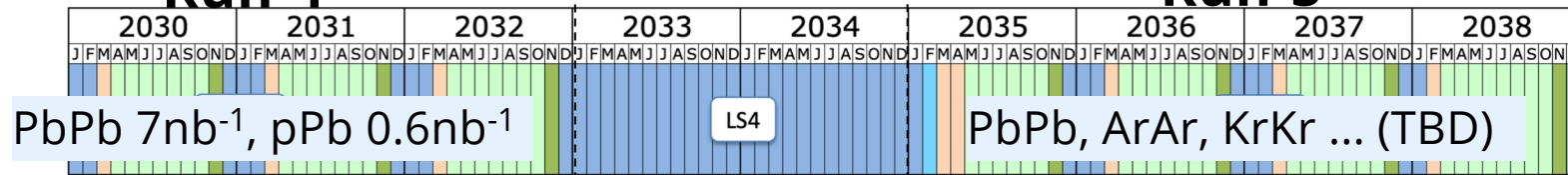
Phase-2 Upgrades

HL-LHC



Run-4

Run-5



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

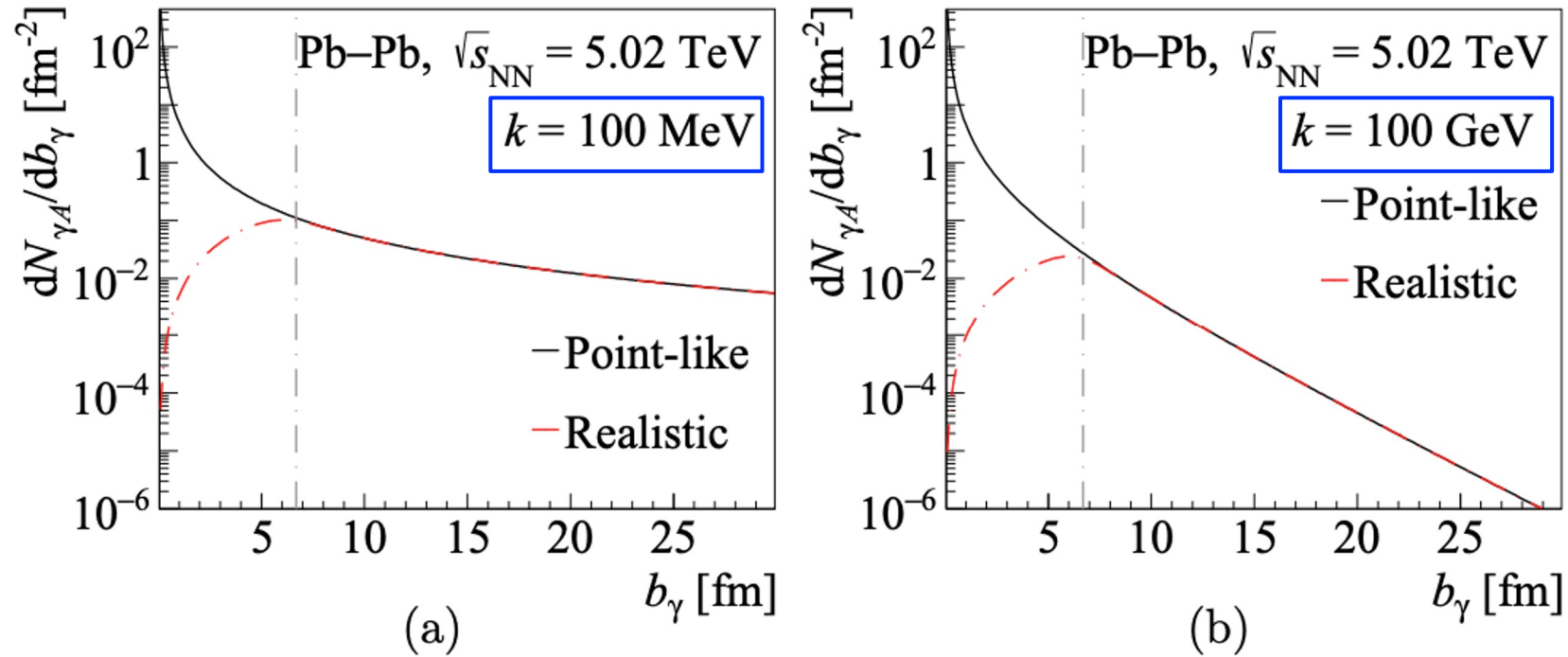
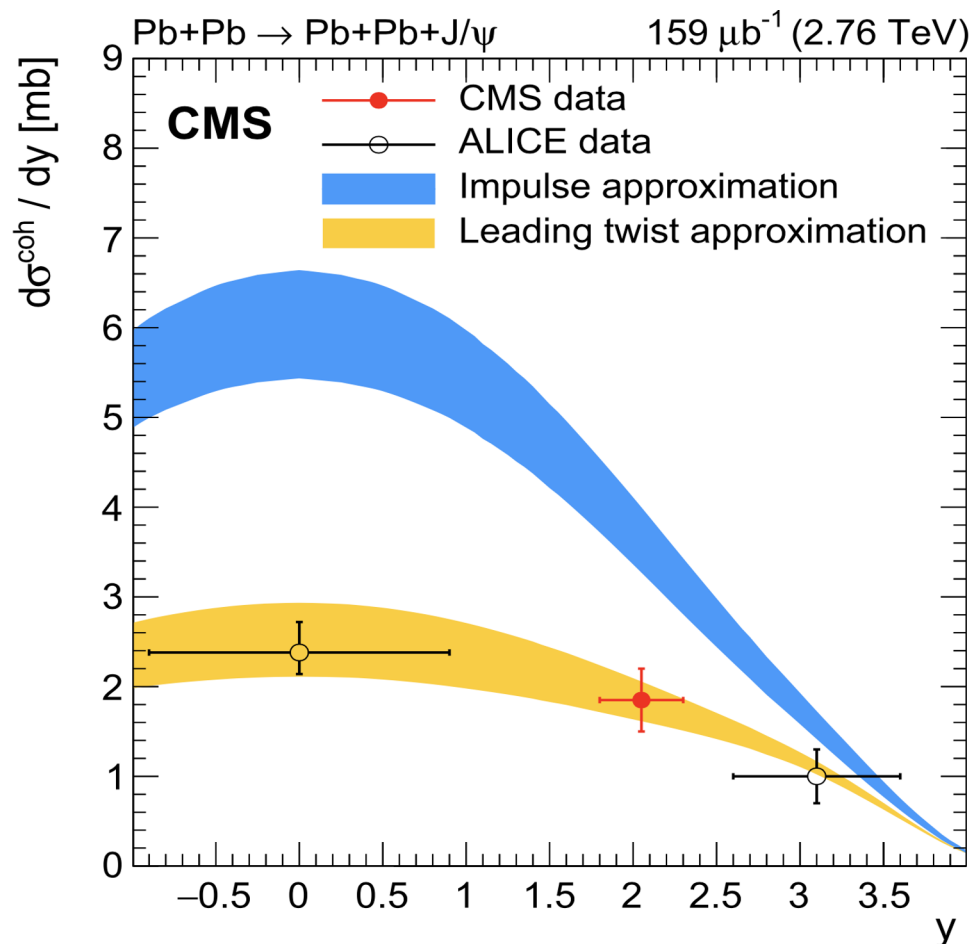


Figure 4: (Color online) Photon fluxes coming from a nucleus $N_{\gamma A}$ in the point-like source approximation and the realistic description as functions of impact parameter b_{γ} calculated at different photon energies: 100 MeV (a), 100 GeV (b).

Coh. Jpsi from LHC Run1 PbPb UPC

PLB 772 (2017) 489



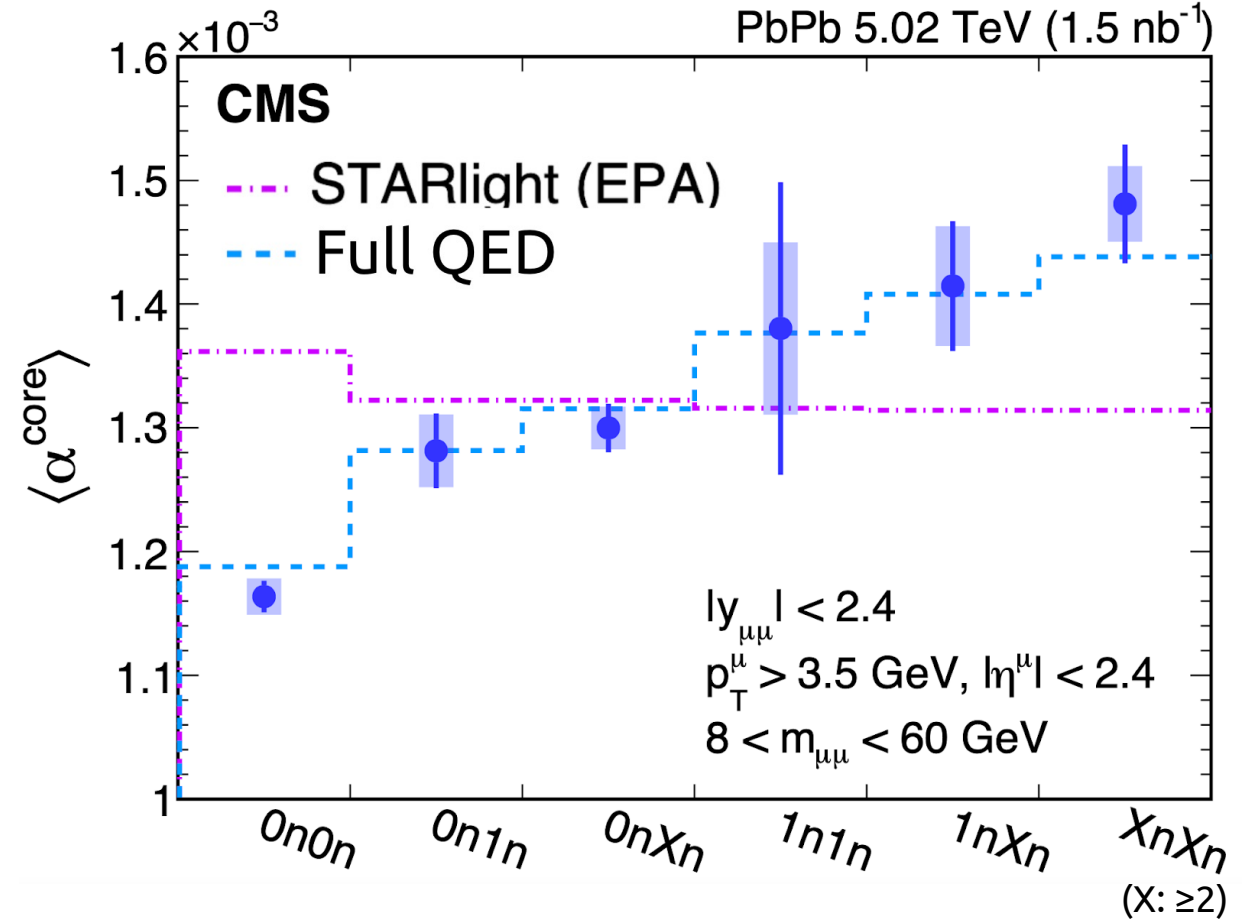
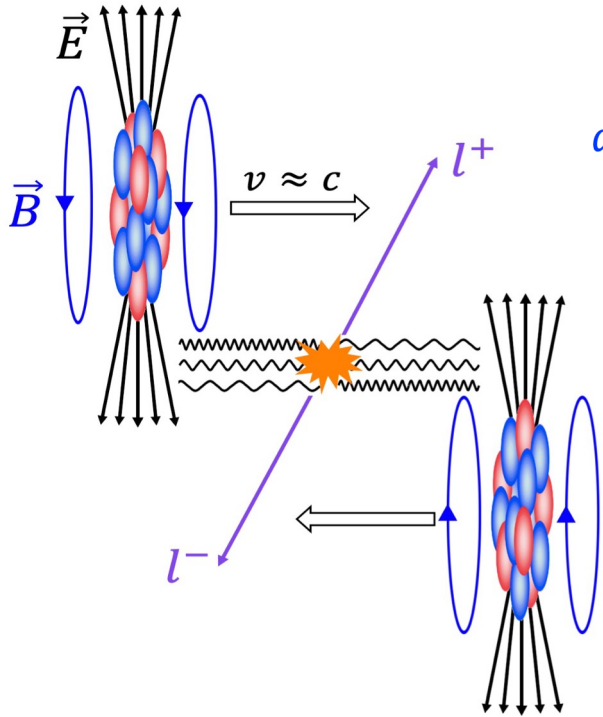
- Run 1 data from CMS and ALICE seem to be well consistent with LTA shadowing model calculations
- However,
 - large uncertainties
 - wide- y bins
 - Mixed low- and high- W contributions

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

Nuclear suppression factor from CMS and ALICE

