



CMS光致产生矢量介子研究进展

杨 帅

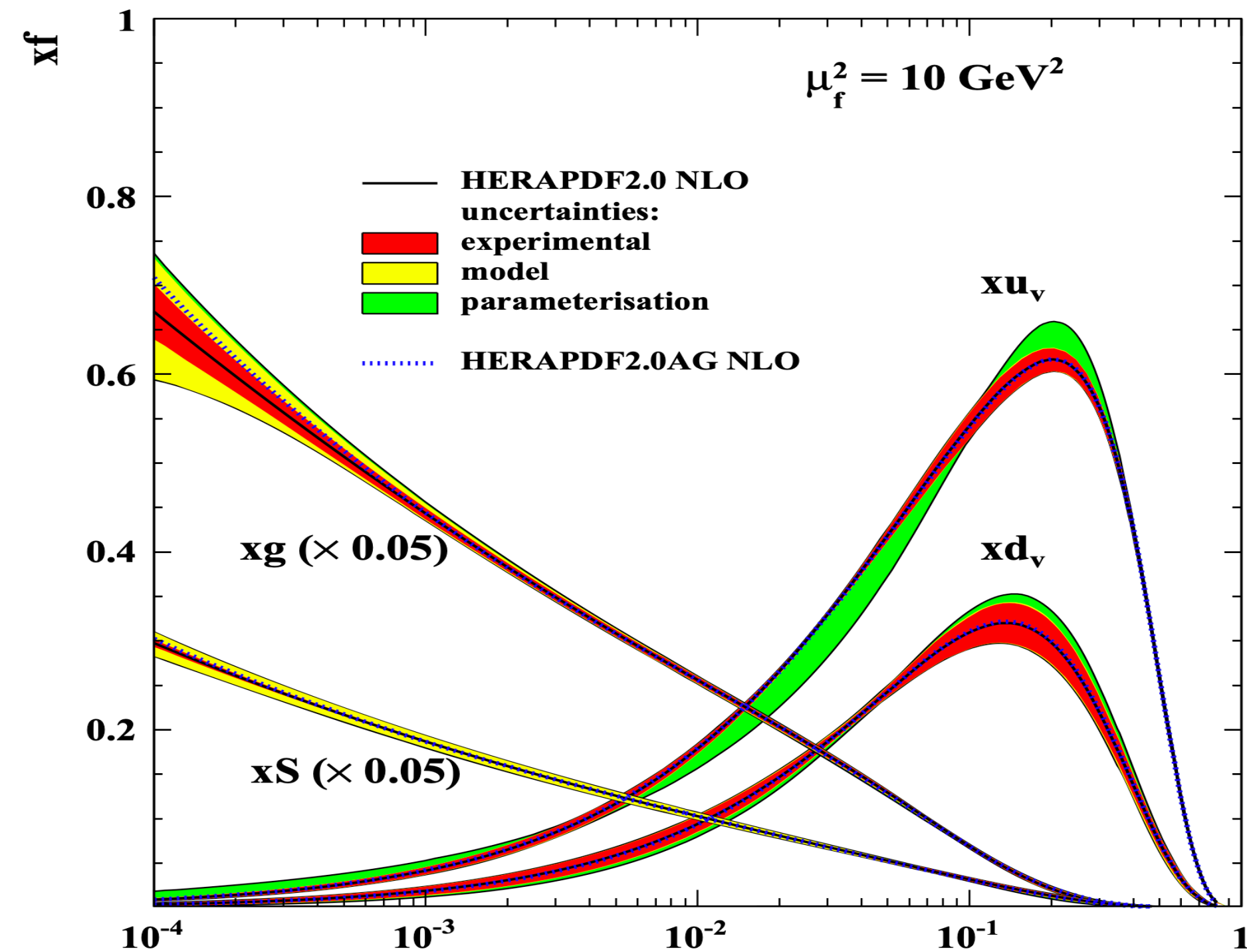
华南师范大学

“极端等离子体: 从夸克-胶子到聚变能”研讨会

复旦大学, 上海, 8月12-13日, 2025

Explore internal structure of matter

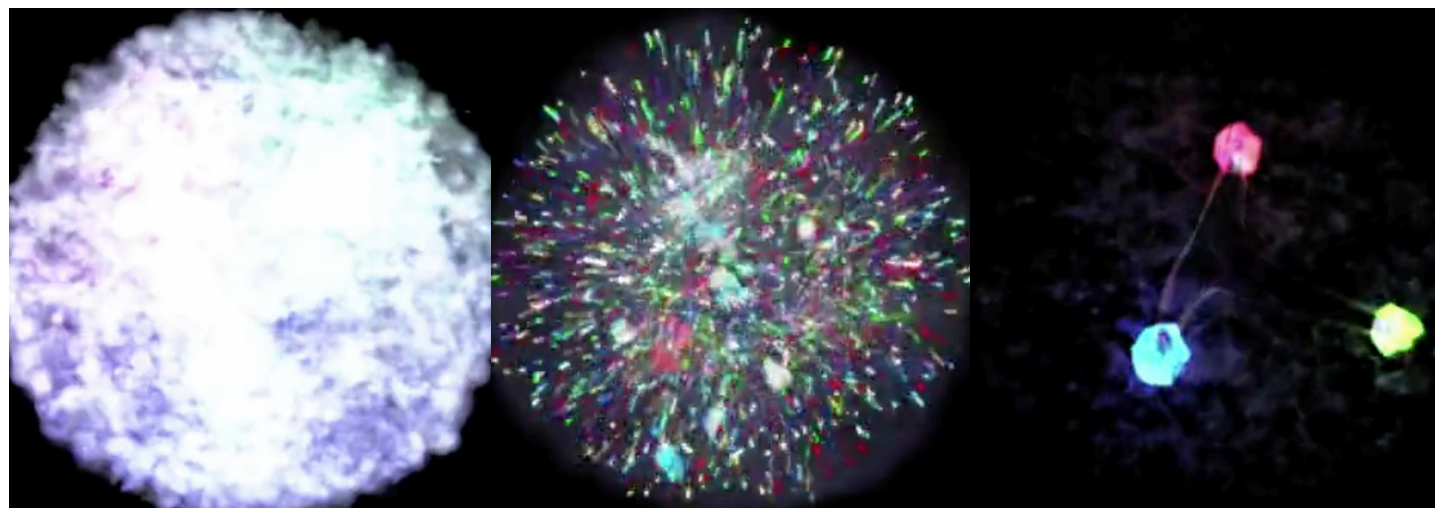
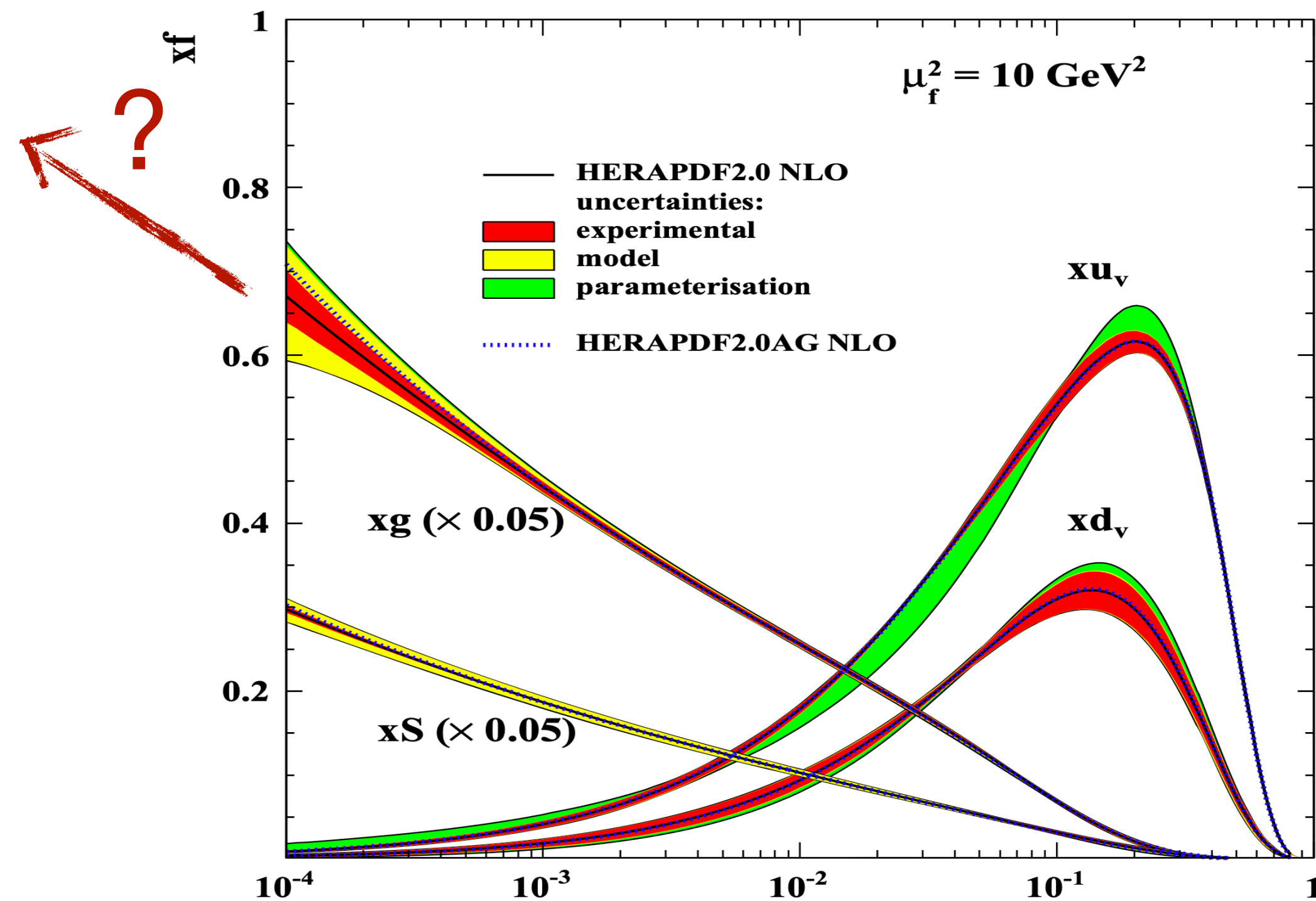
H1 and ZEUS, EPJC 75 (2015) 580



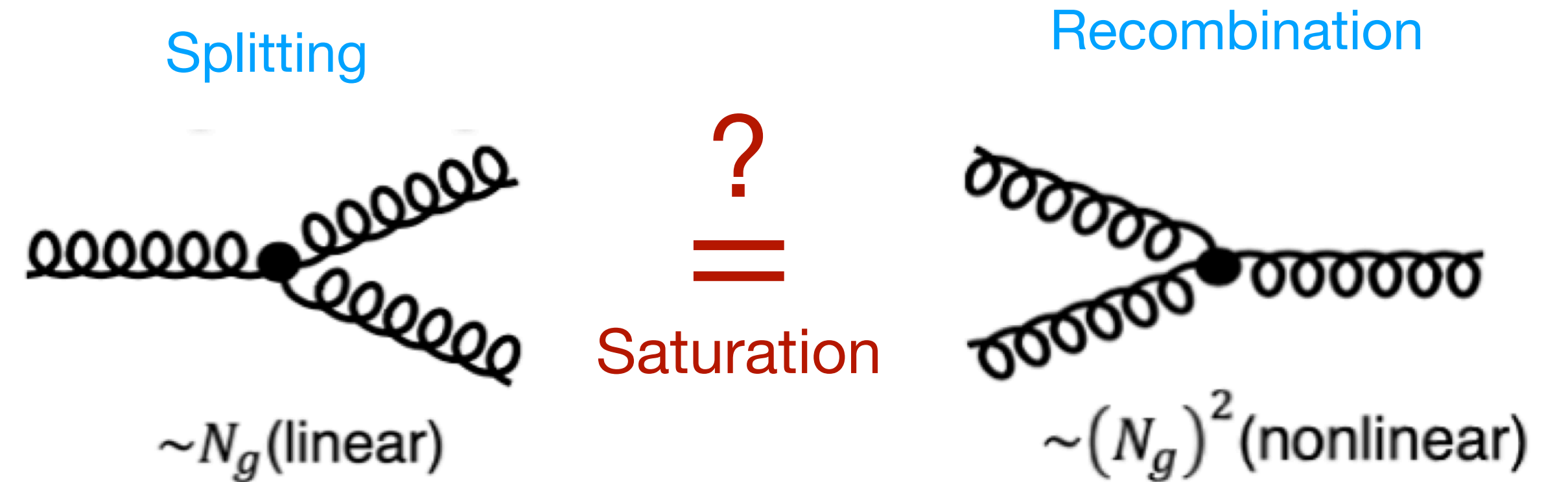
Small x $\leftarrow$ $\rightarrow$ Large x

Explore internal structure of matter

H1 and ZEUS, EPJC 75 (2015) 580

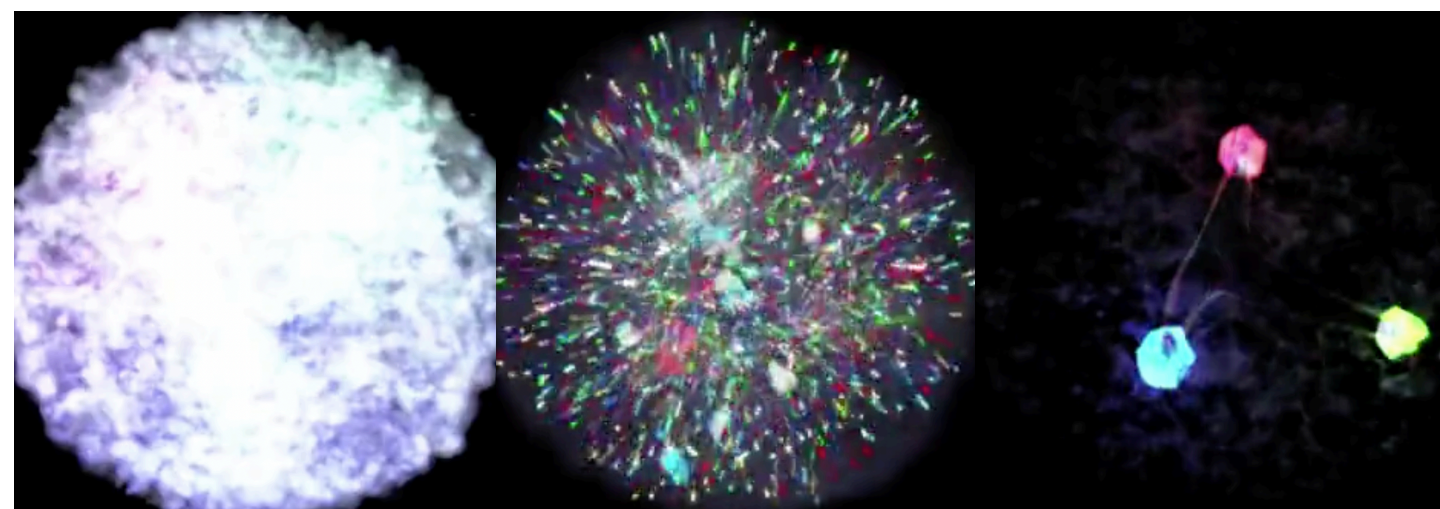
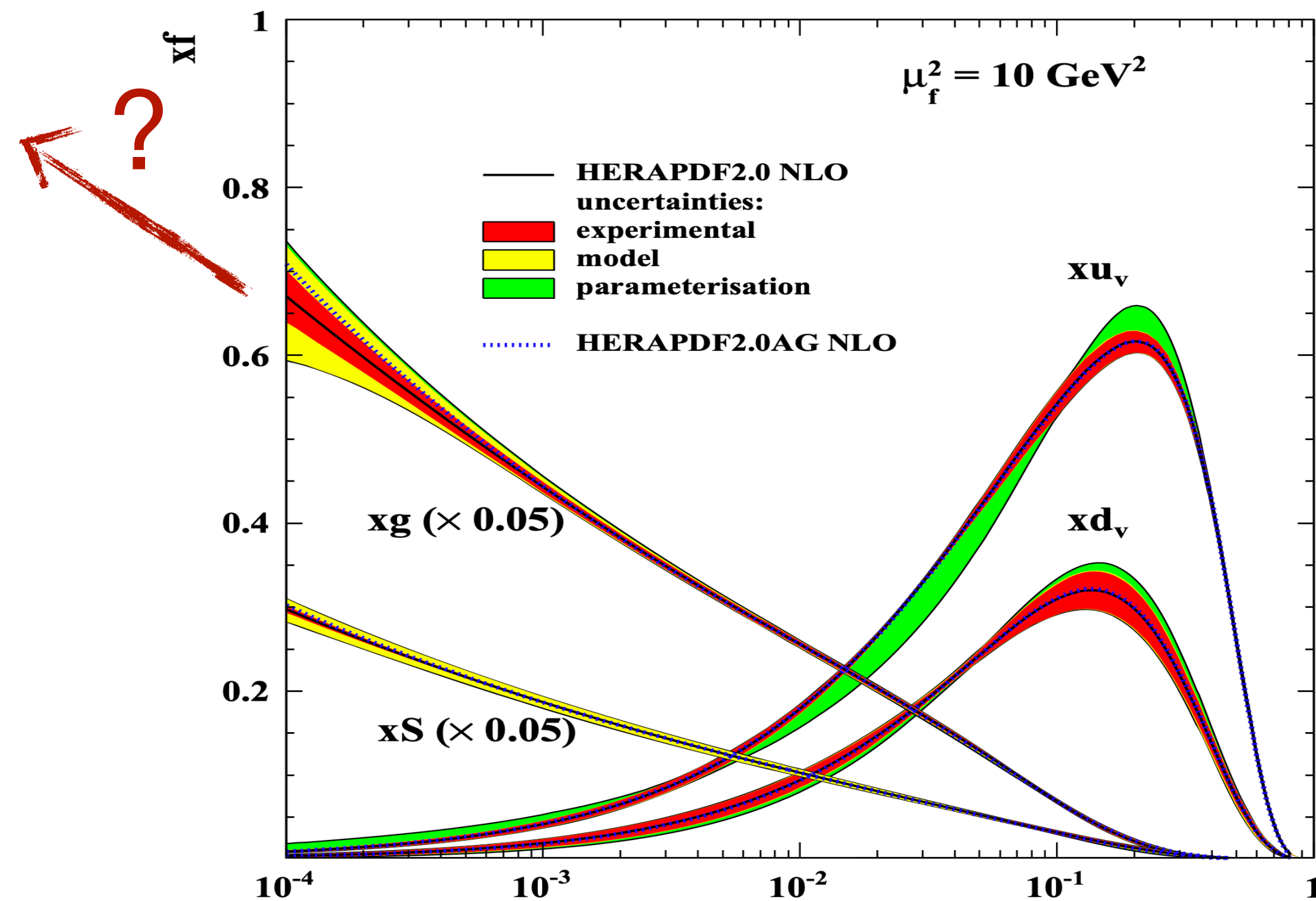


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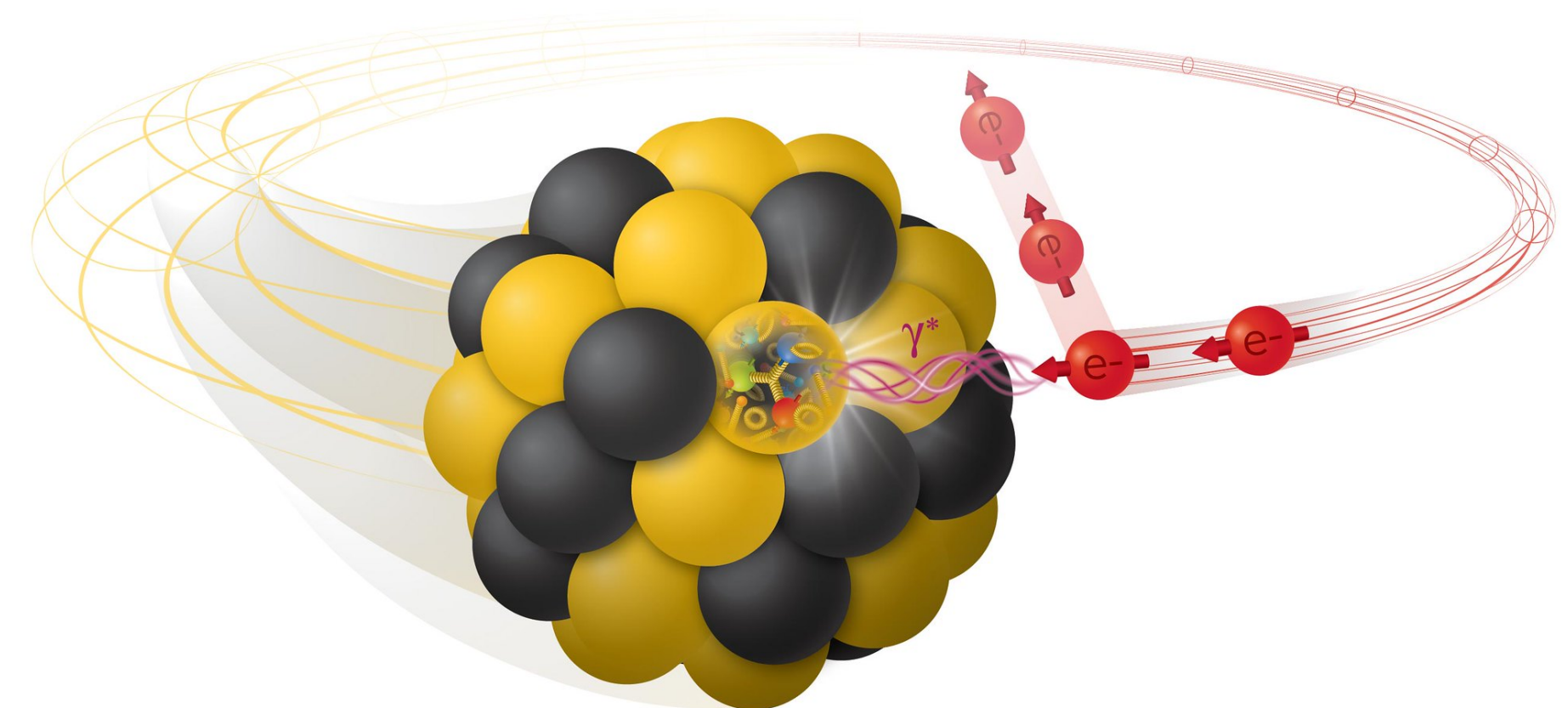
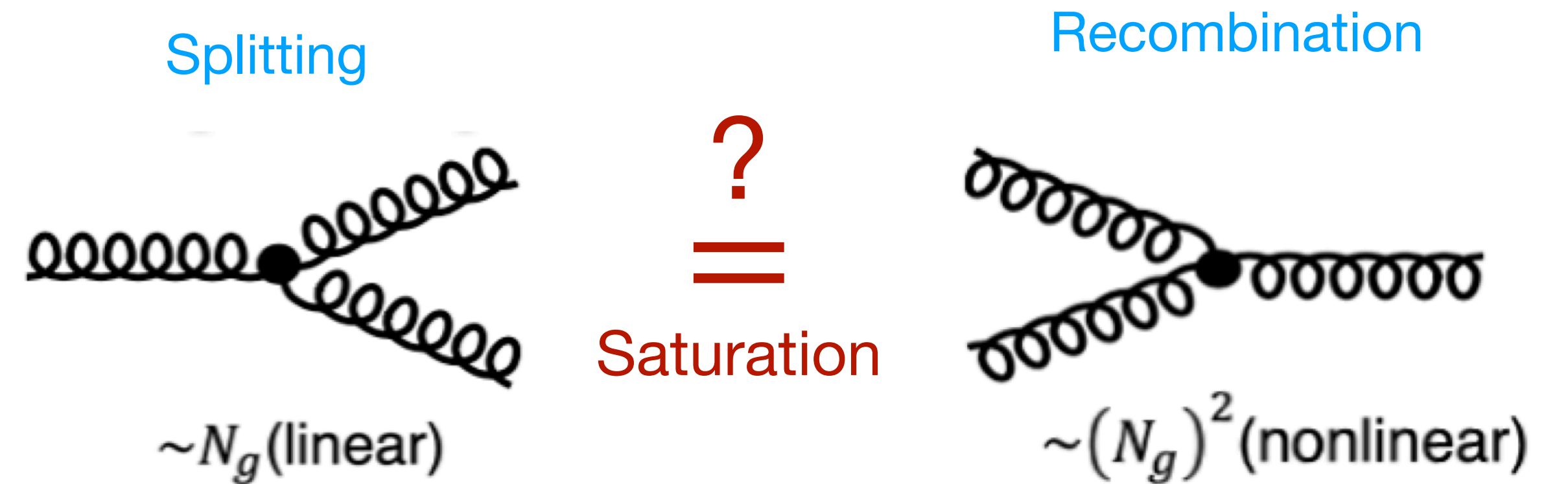


Explore internal structure of matter

H1 and ZEUS, EPJC 75 (2015) 580

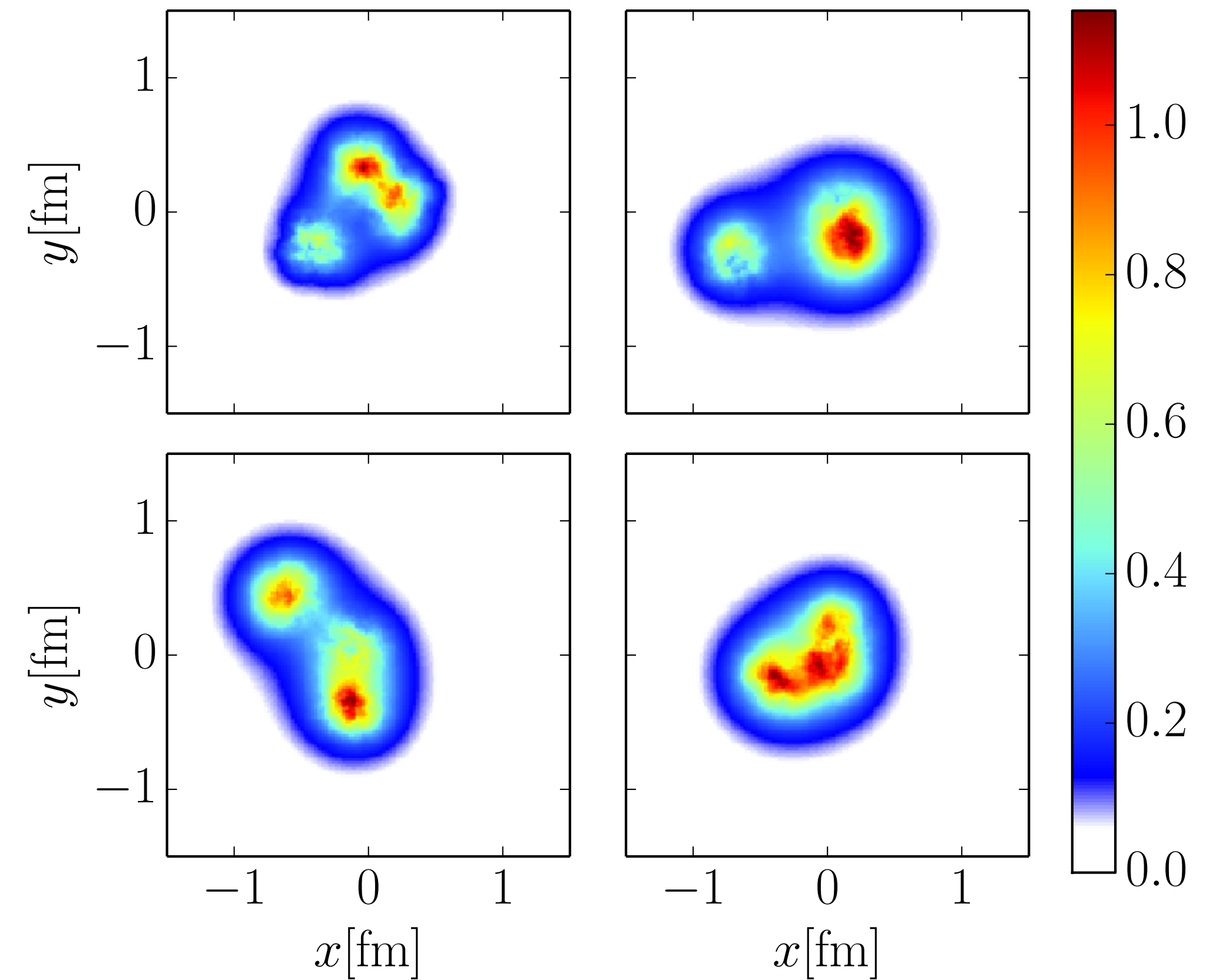
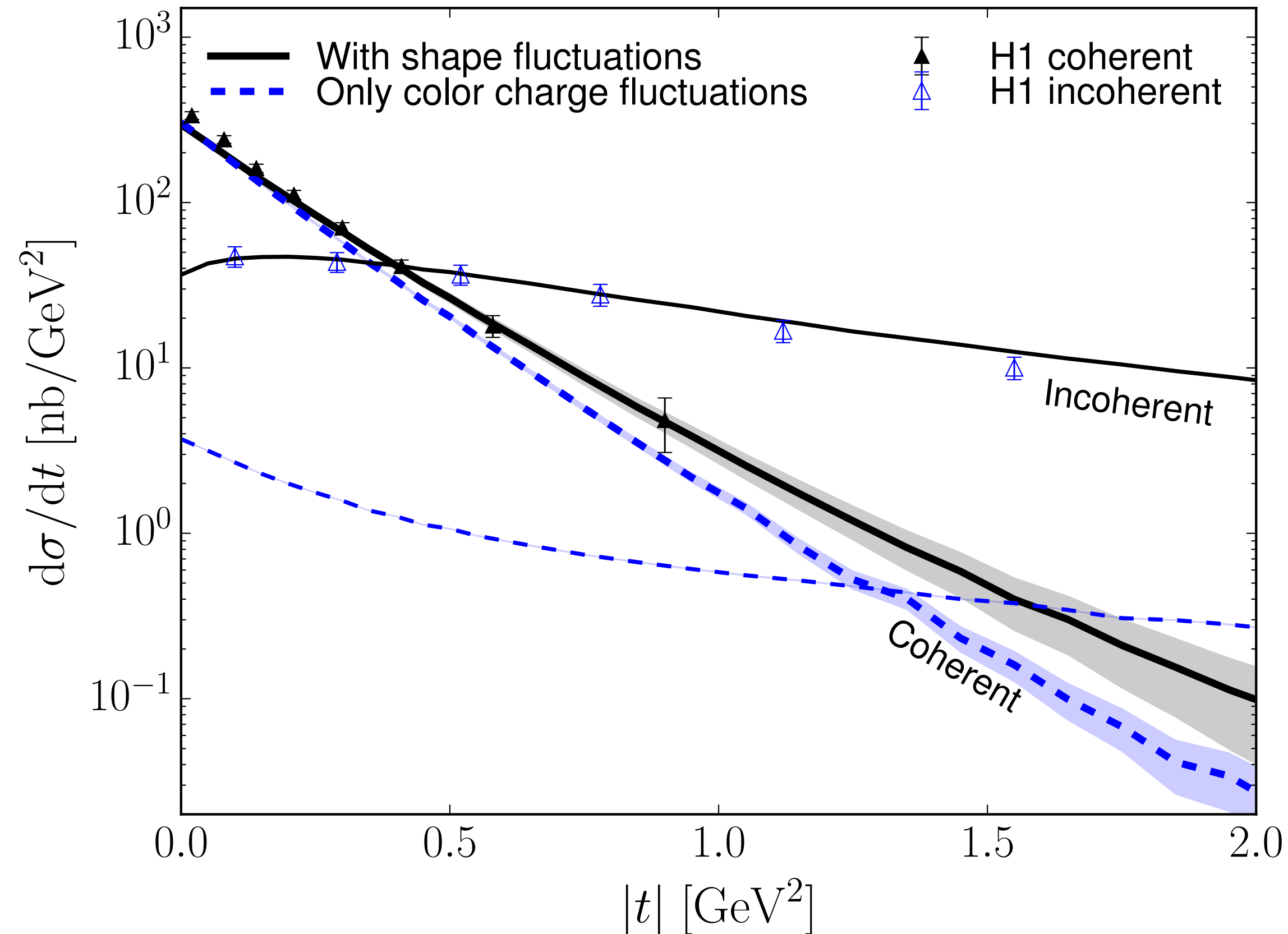


Small x $\leftarrow$ $\rightarrow$ Large x



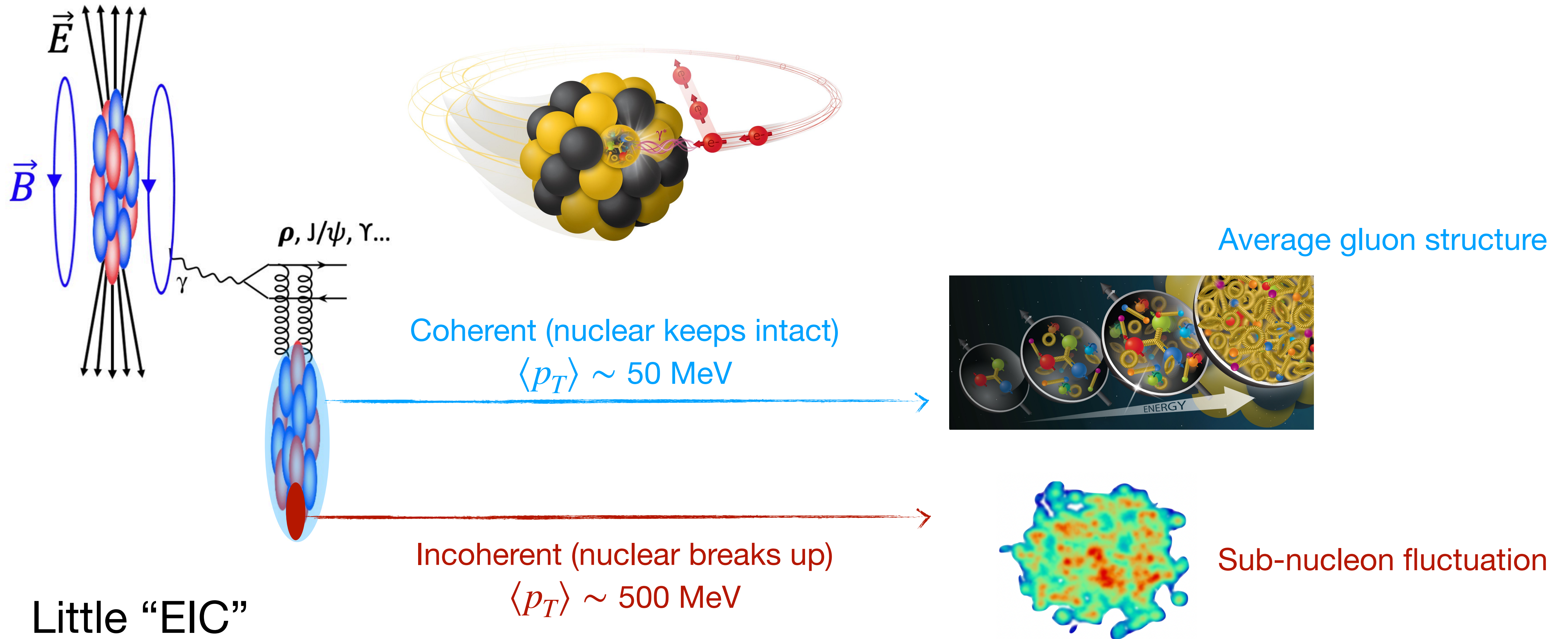
The critical role of gluon fluctuation

Mantysaari, Rep. Prog. Phys. 83 (2020) 082201

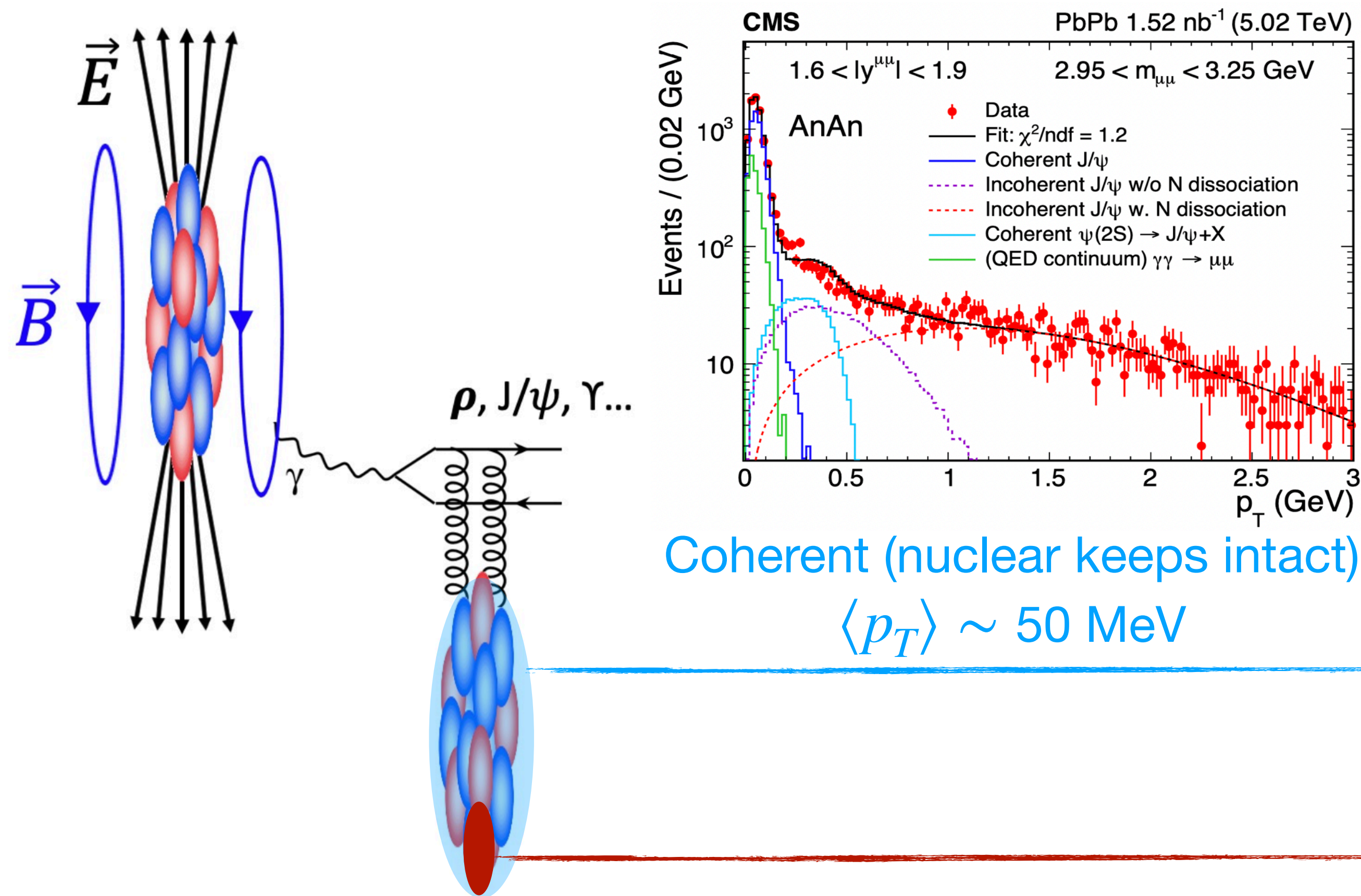


- Only CGC considering gluon fluctuations can describe HERA data
 - Geometry, energy density, local saturation scale and color charge

Photon-nuclear interactions in UPC

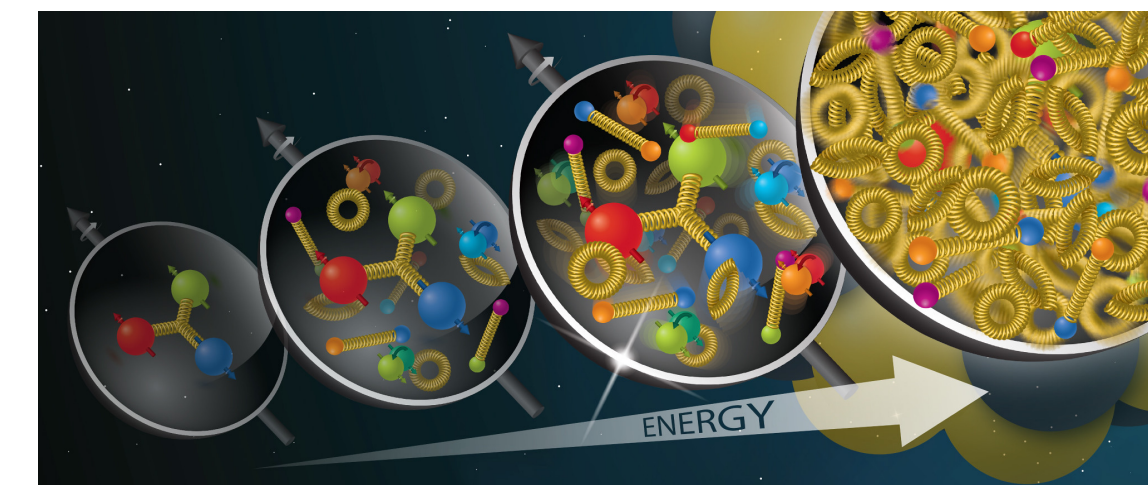


Photon-nuclear interactions in UPC



Coherent (nuclear keeps intact)

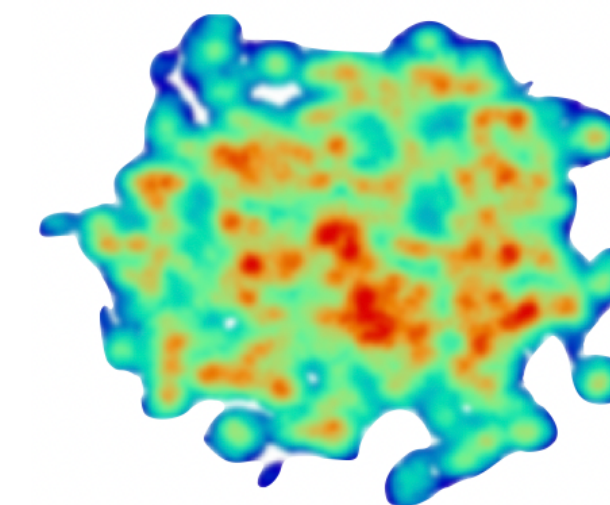
$$\langle p_T \rangle \sim 50 \text{ MeV}$$



Average gluon structure

Incoherent (nuclear breaks up)

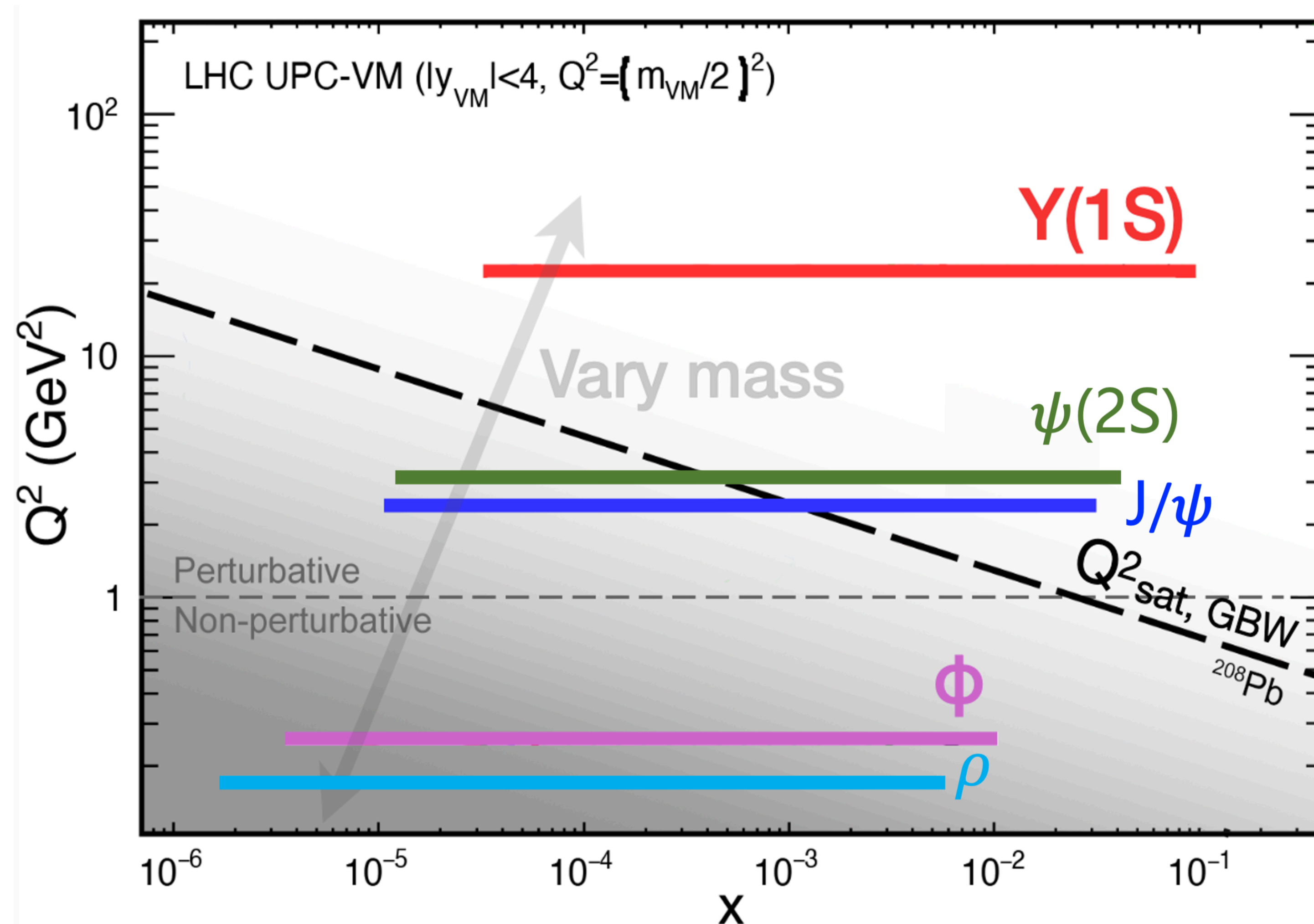
$$\langle p_T \rangle \sim 500 \text{ MeV}$$



Sub-nucleon fluctuation

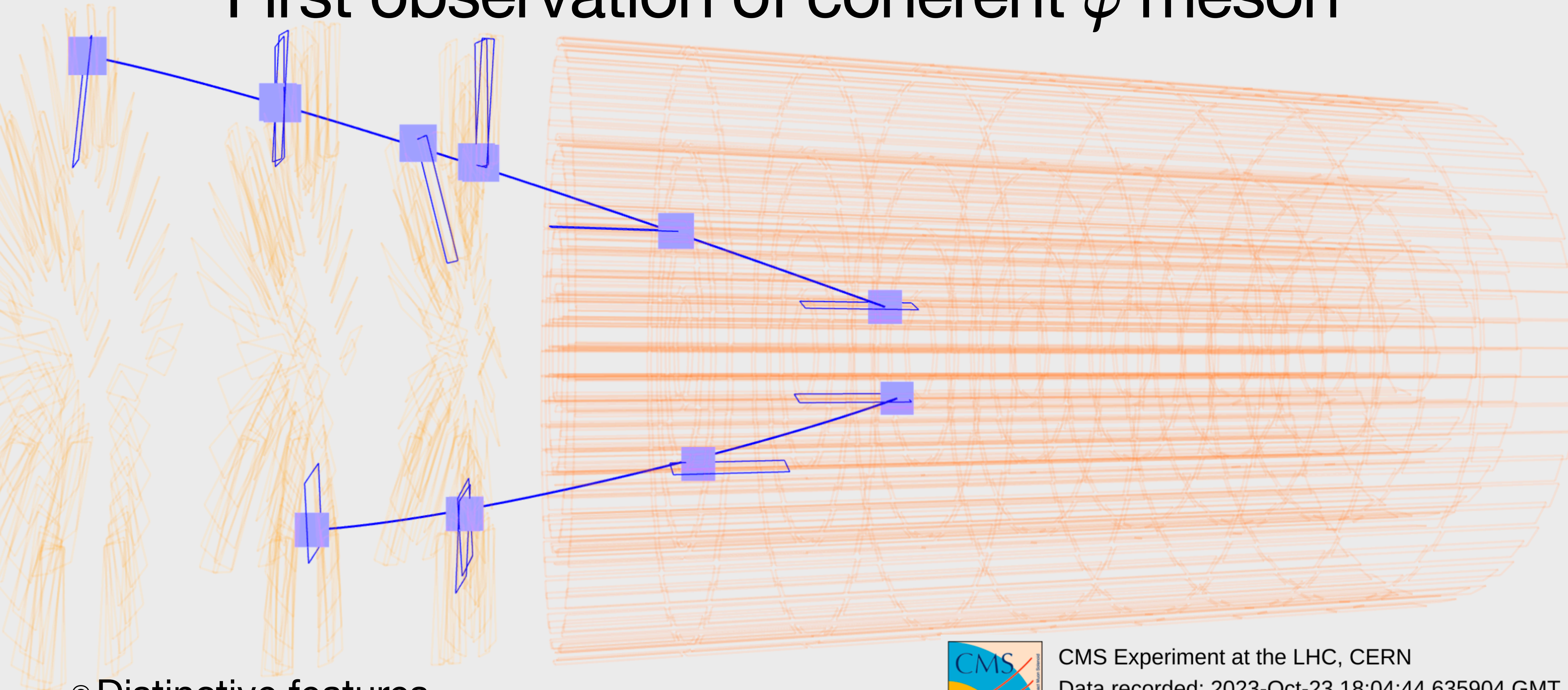
Little "EIC"

What can we do with photoproduced VM?



Probe gluon structure at various x and Q^2

First observation of coherent ϕ meson



● Distinctive features

- Low activities in forward calorimeters
- Exactly two tracks identified as daughters of photoproduced VM



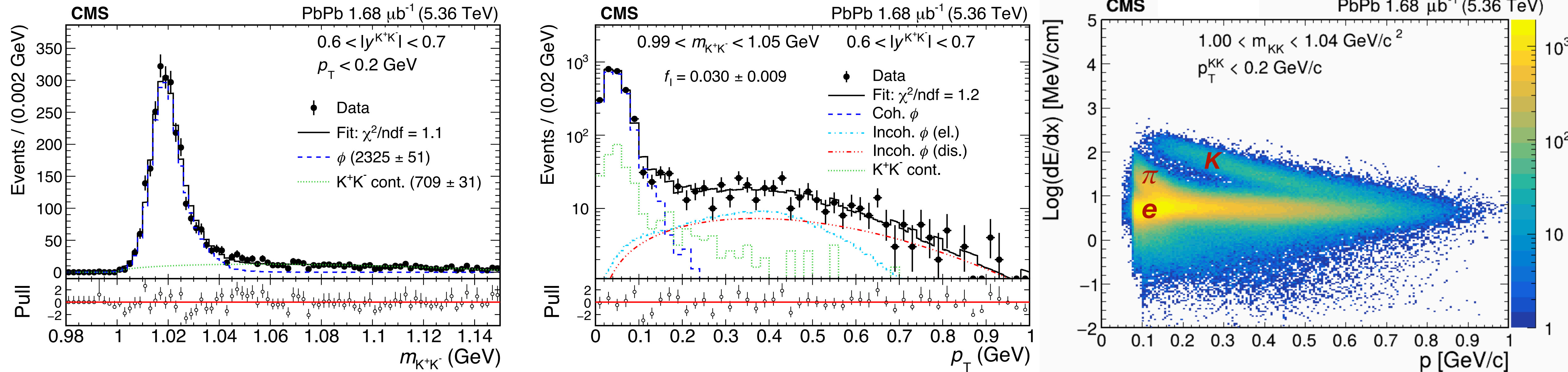
CMS Experiment at the LHC, CERN

Data recorded: 2023-Oct-23 18:04:44.635904 GMT

Run / Event / LS: 375531 / 526831649 / 370

First observation of coherent ϕ meson

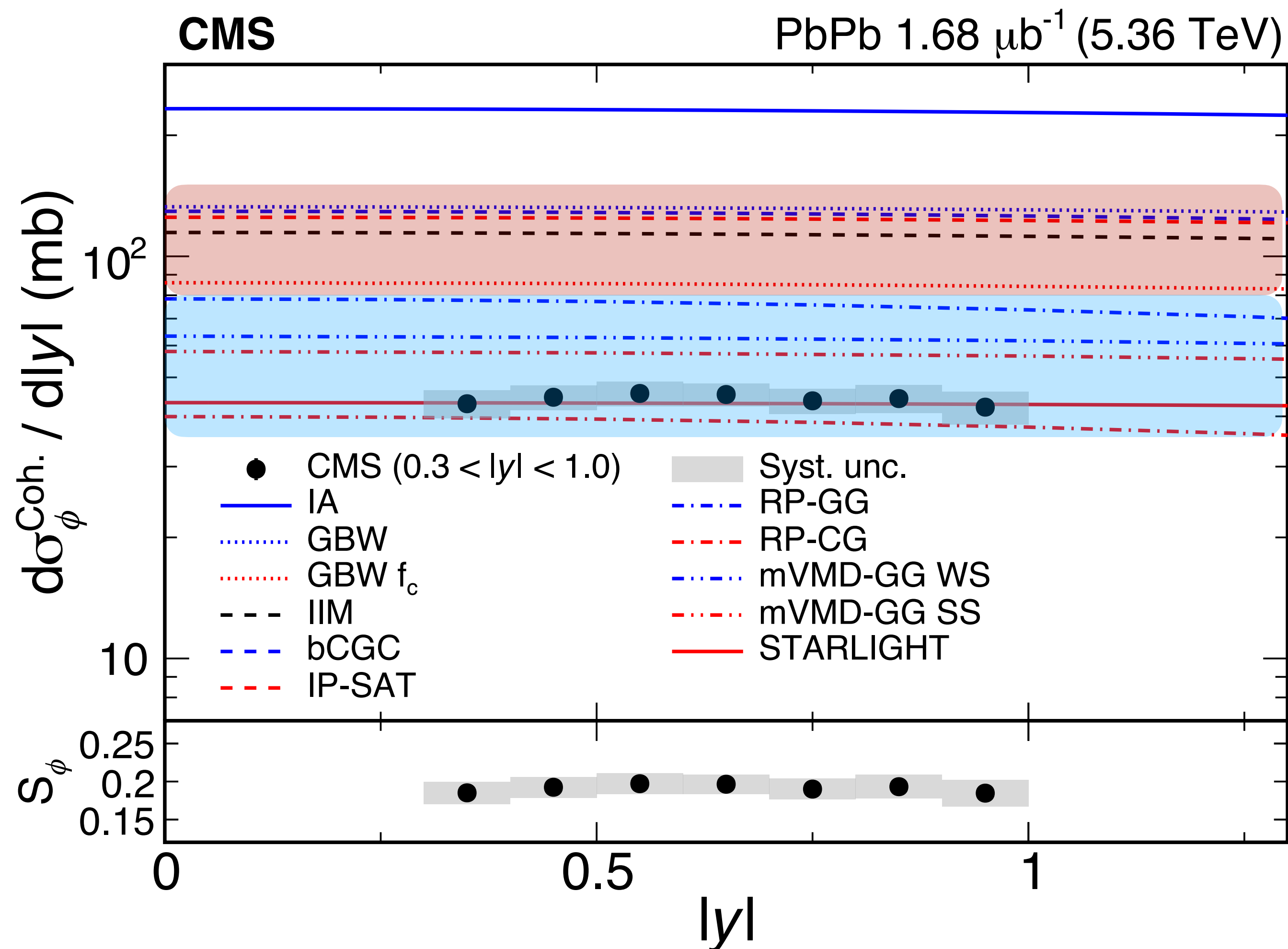
CMS, arXiv:2504.05193



- Super challenging for coherent ϕ measurements for all experiments
 - The p_T of daughter kaon is $\sim 0.05 - 0.1$ GeV/c
 - CMS can perform PID at low momentum
 - Similar signal extraction strategy for all photoproduced vector mesons

First observation of coherent ϕ meson

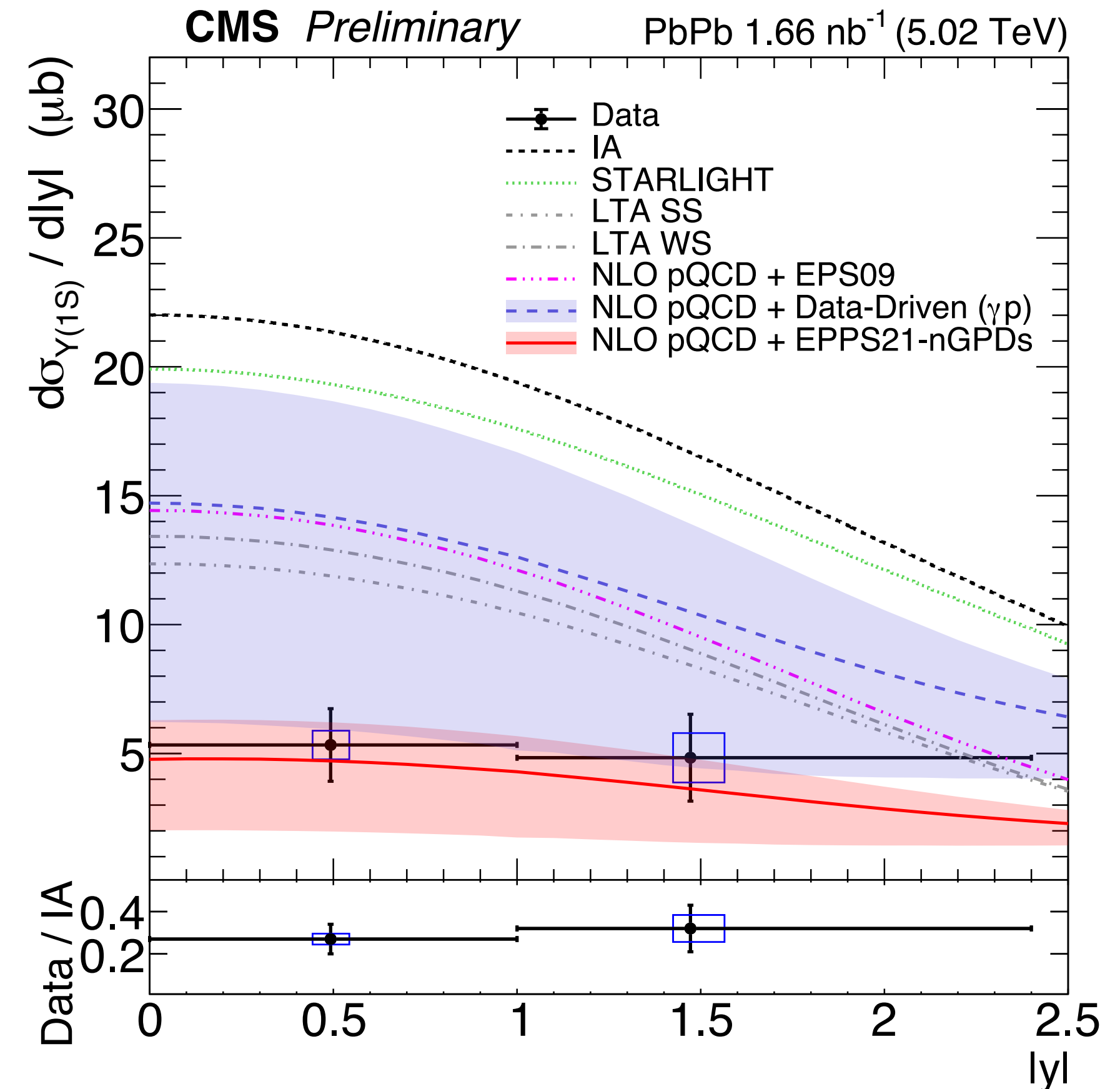
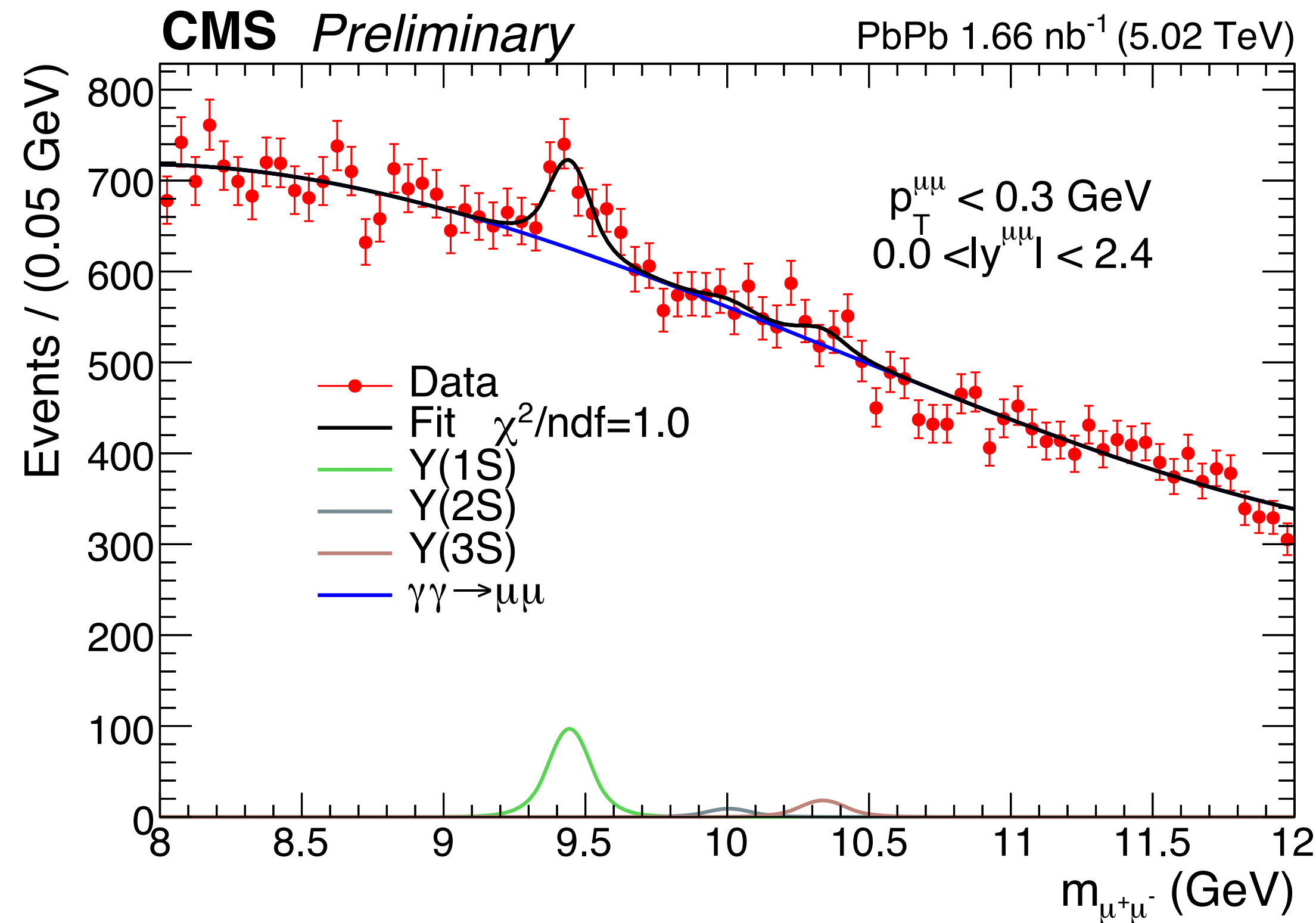
CMS, arXiv:2504.05193



- Strong ($\sim 5\times$) suppression is observed
- Gluon saturation models over predict data by a factor of 2-3
- Nuclear shadowing models generally better describe data
 - VMD + Gribov Glauber (GG) over predict data
 - VMD + Classical Glauber (CG) best describe data
 - STARlight can describe ϕ but not for J/ψ and ρ results

First observation of coherent $\Upsilon(1S)$ meson

CMS-PAS-HIN-24-013

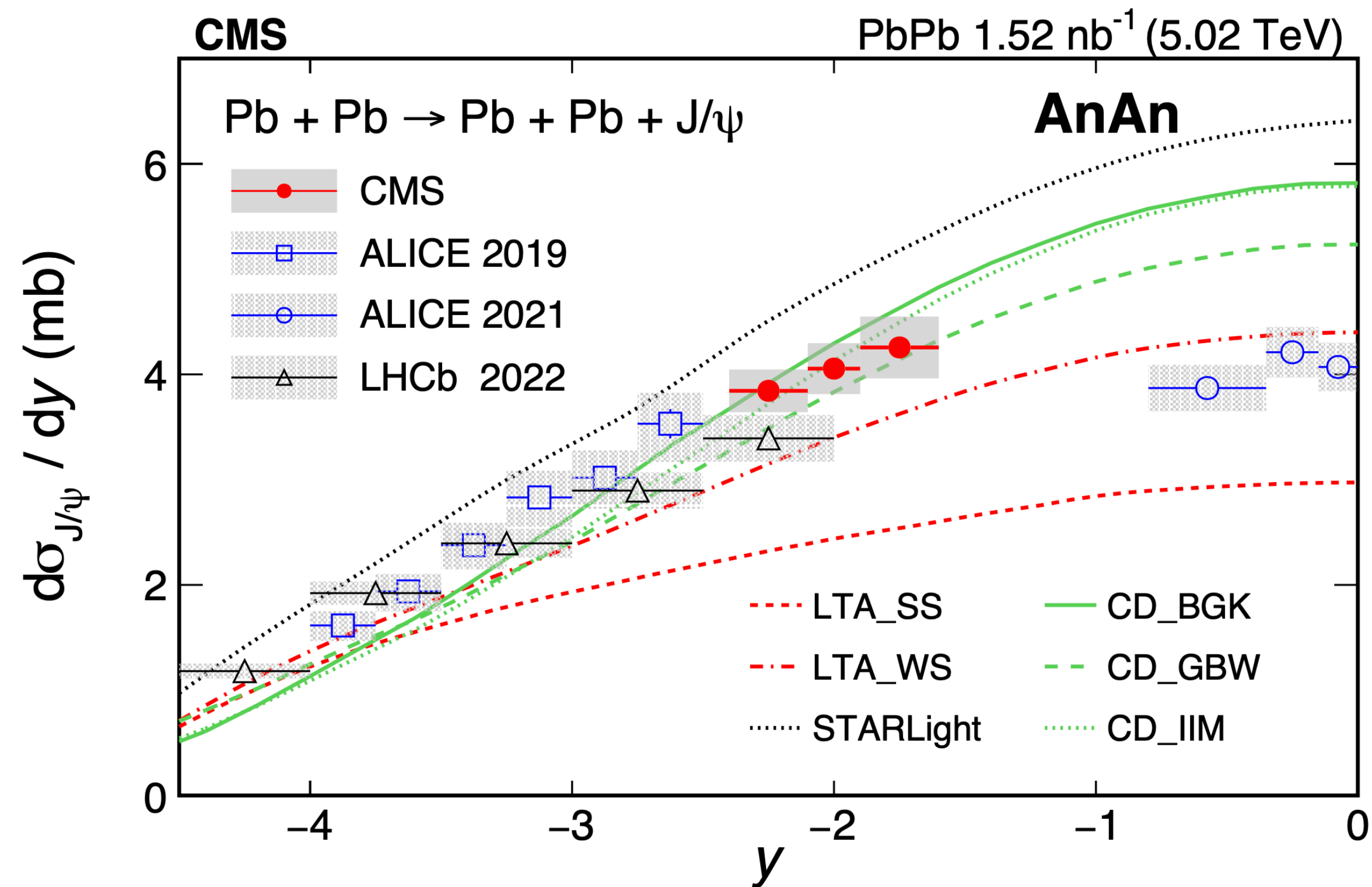


- $\Upsilon(1S)$ is expected to be less sensitive to the non-linear QCD effects
 - However, strongly ($\sim 3\text{-}4\times$) suppressed is observed!

Imaging heavy nuclear with coherent J/ψ

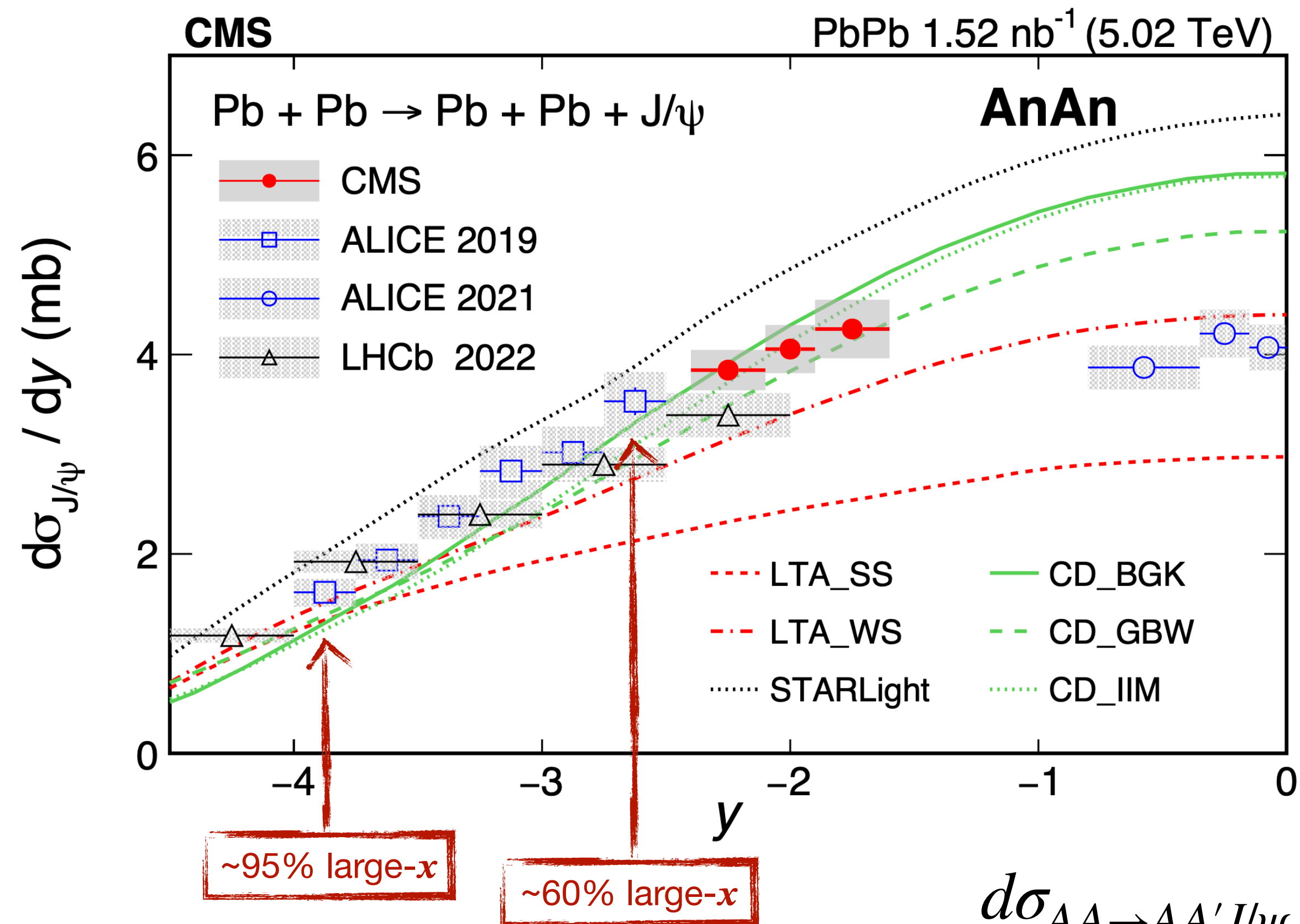
ALICE, EPJC 81 (2021) 712
CMS, PRL 131 (2023) 262301
LHCb, JHEP 06 (2023) 146

- ◉ LHC experiments complement each over a wide range of y region
 - Around $\sim 3\times$ suppression at $x\sim 10^{-3}$ ($y=0$)



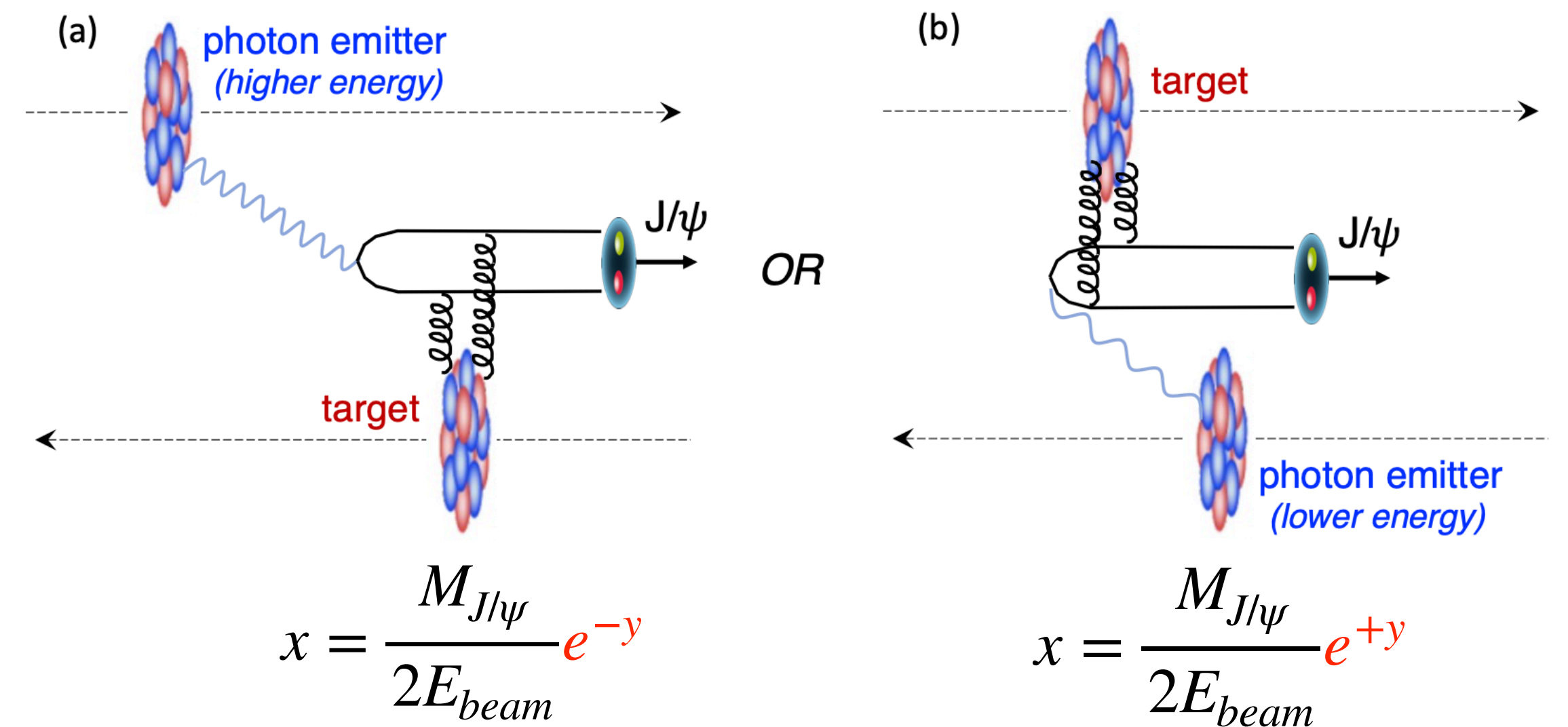
Imaging heavy nuclear with coherent J/ψ

ALICE, EPJC 81 (2021) 712
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◉ LHC experiments complement each over a wide range of y region

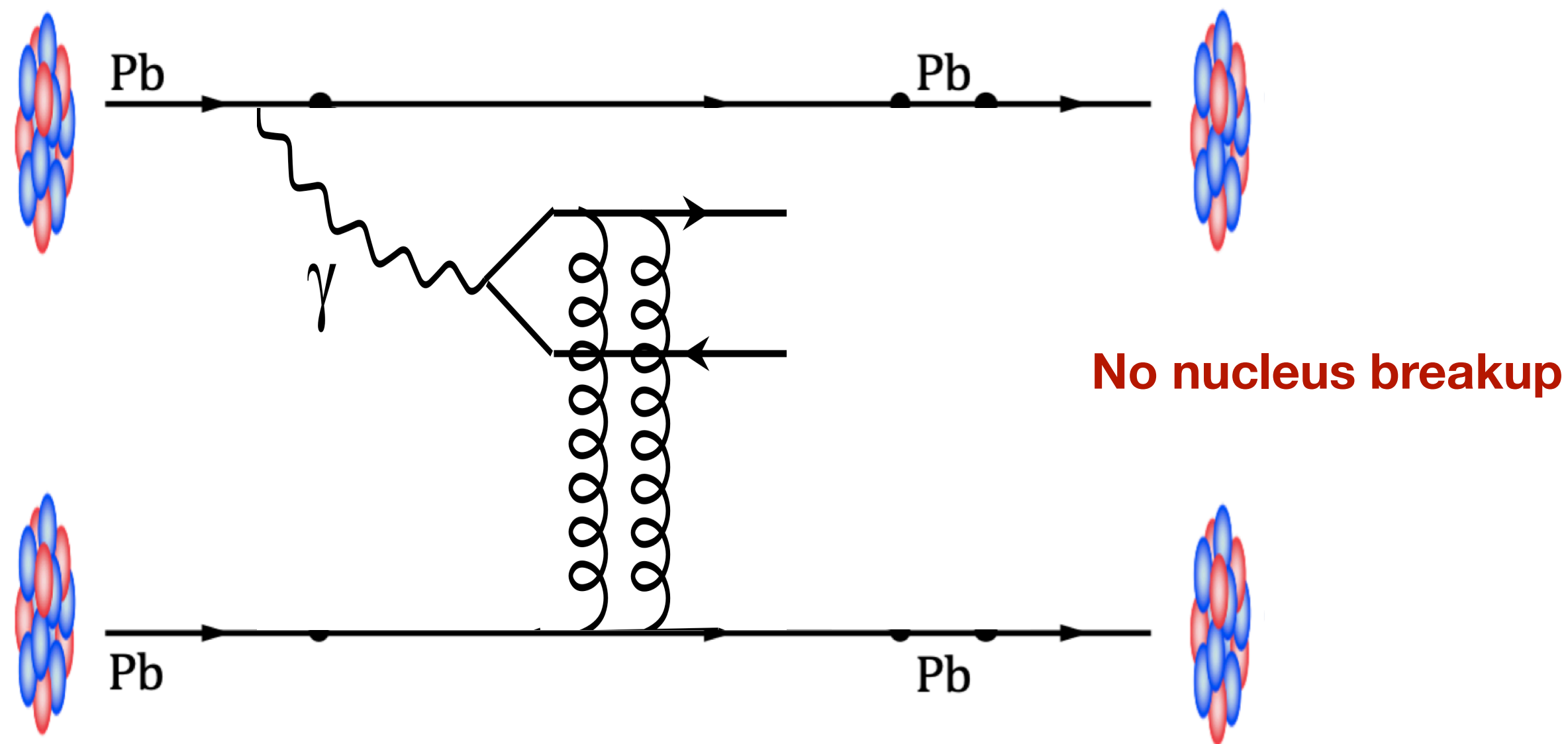
- Around $\sim 3\times$ suppression at $x \sim 10^{-3}$ ($y=0$)



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

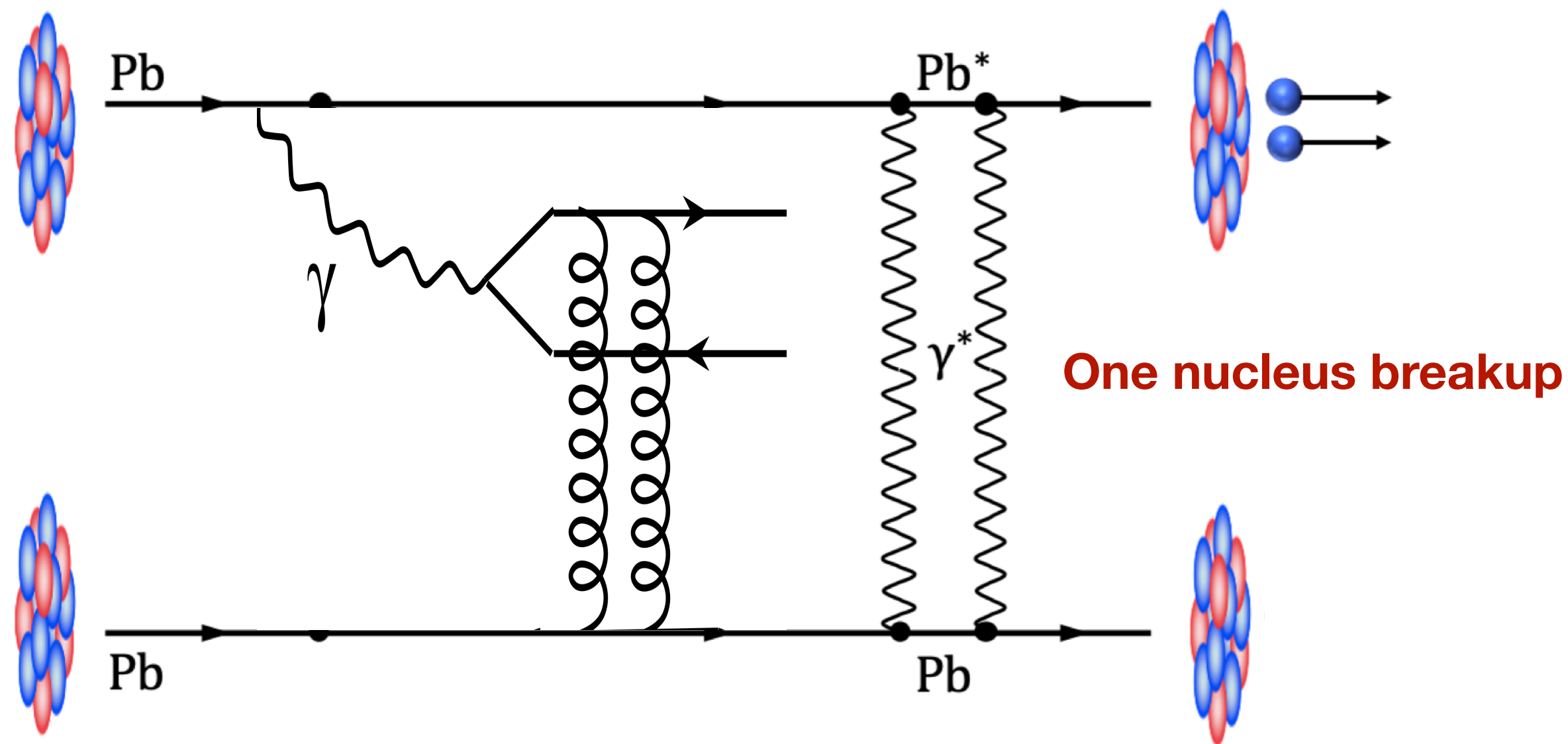
A solution to the “two-way ambiguity”

Nuclei **may** exchange soft photon(s) $\Rightarrow$ **nuclear dissociation**



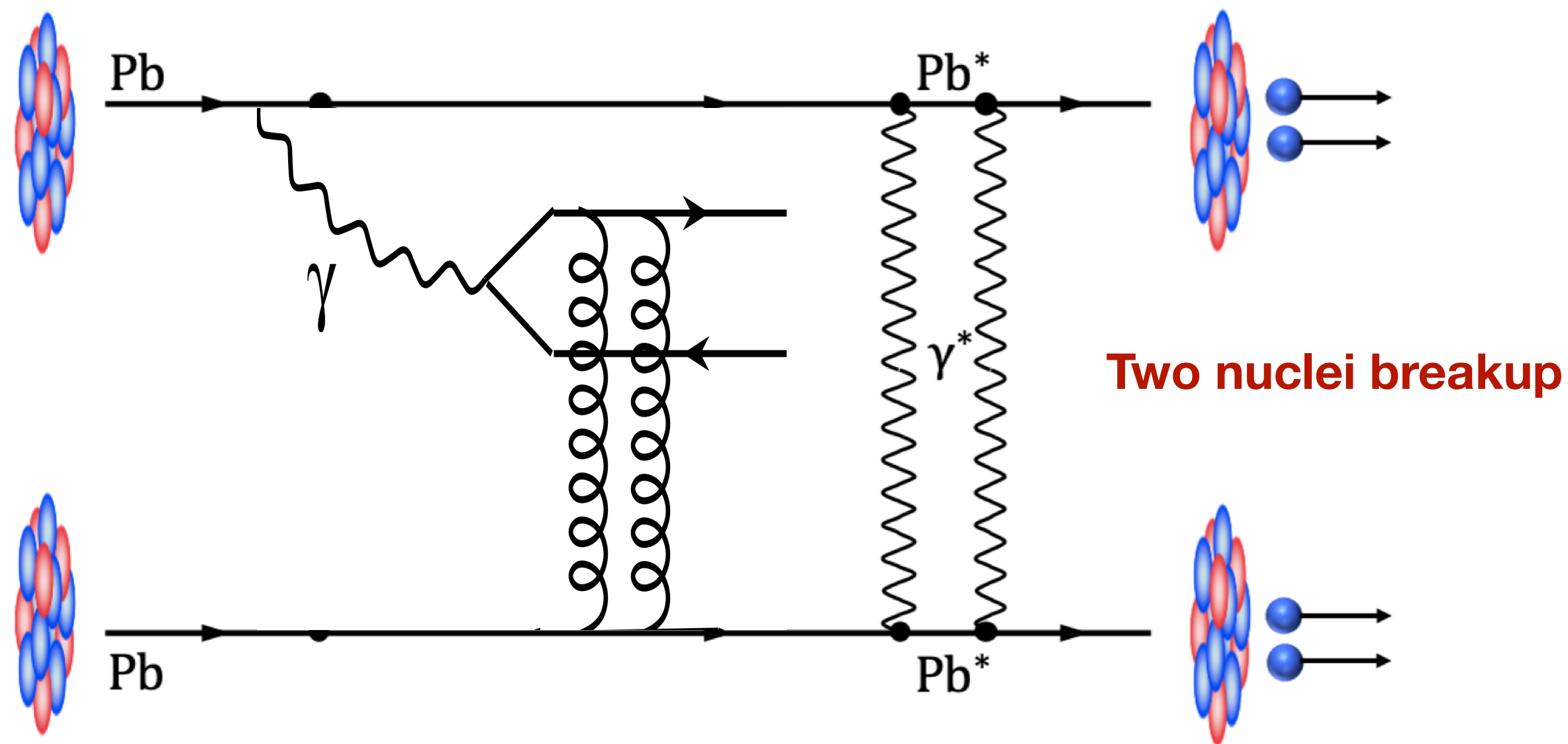
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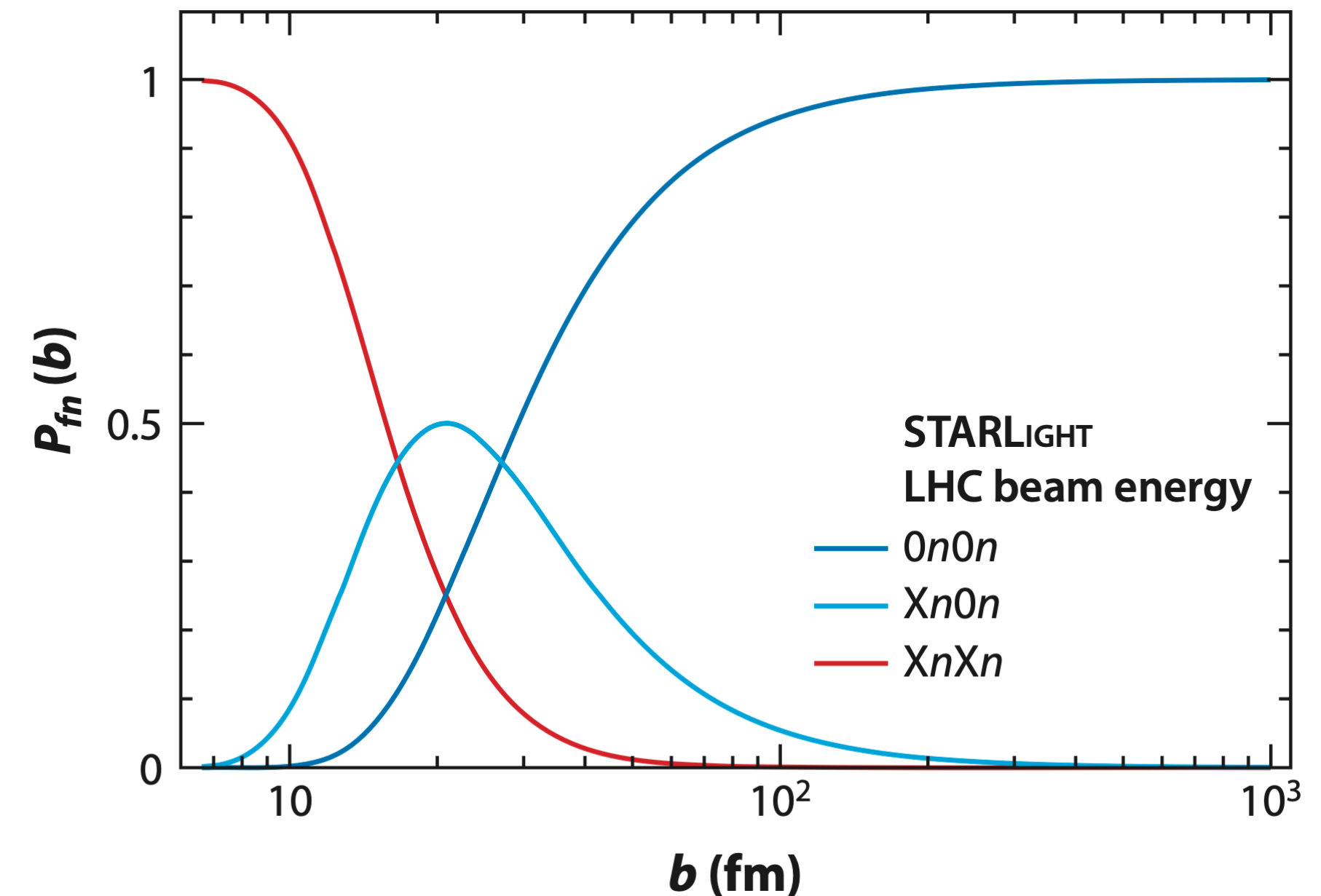
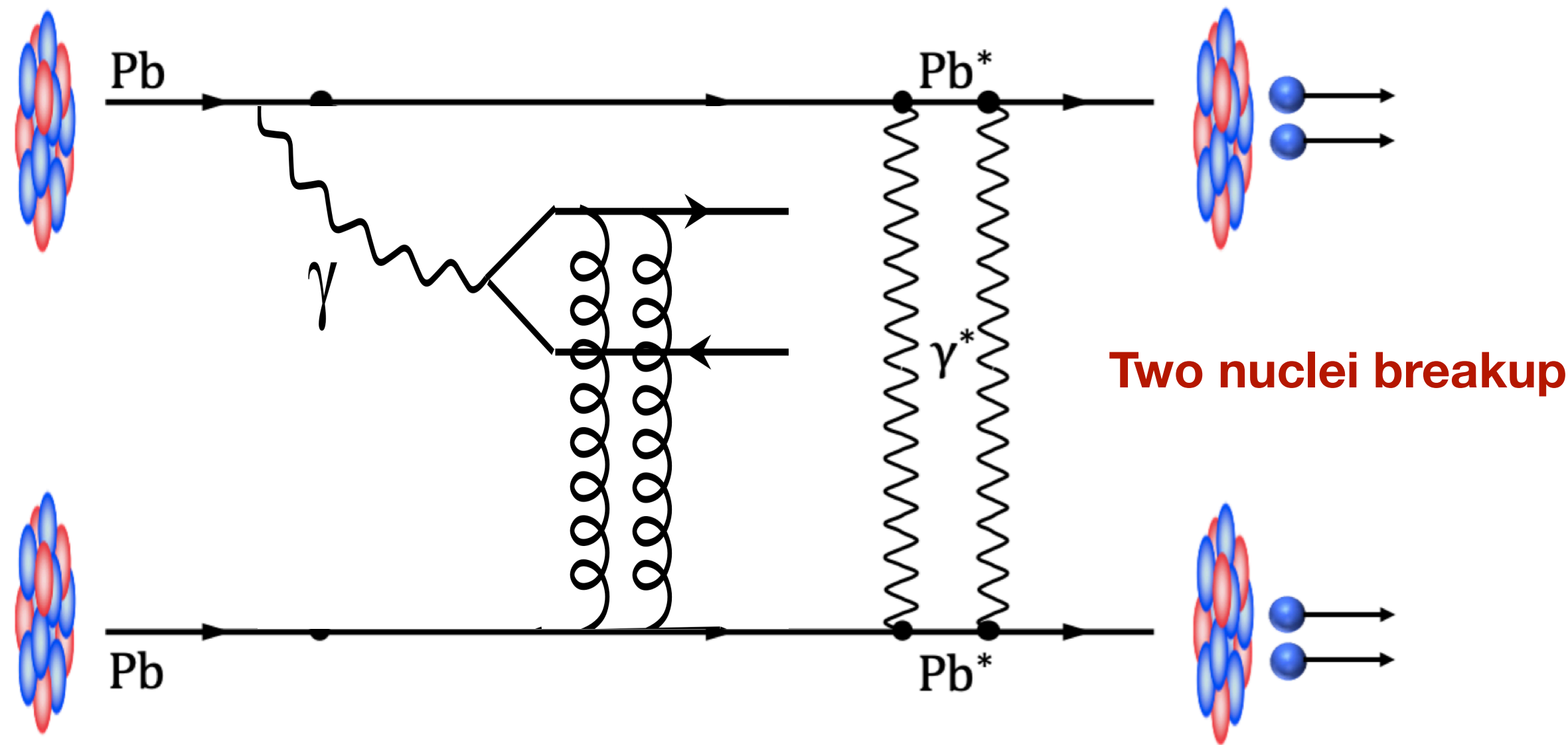
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A solution to the “two-way ambiguity”

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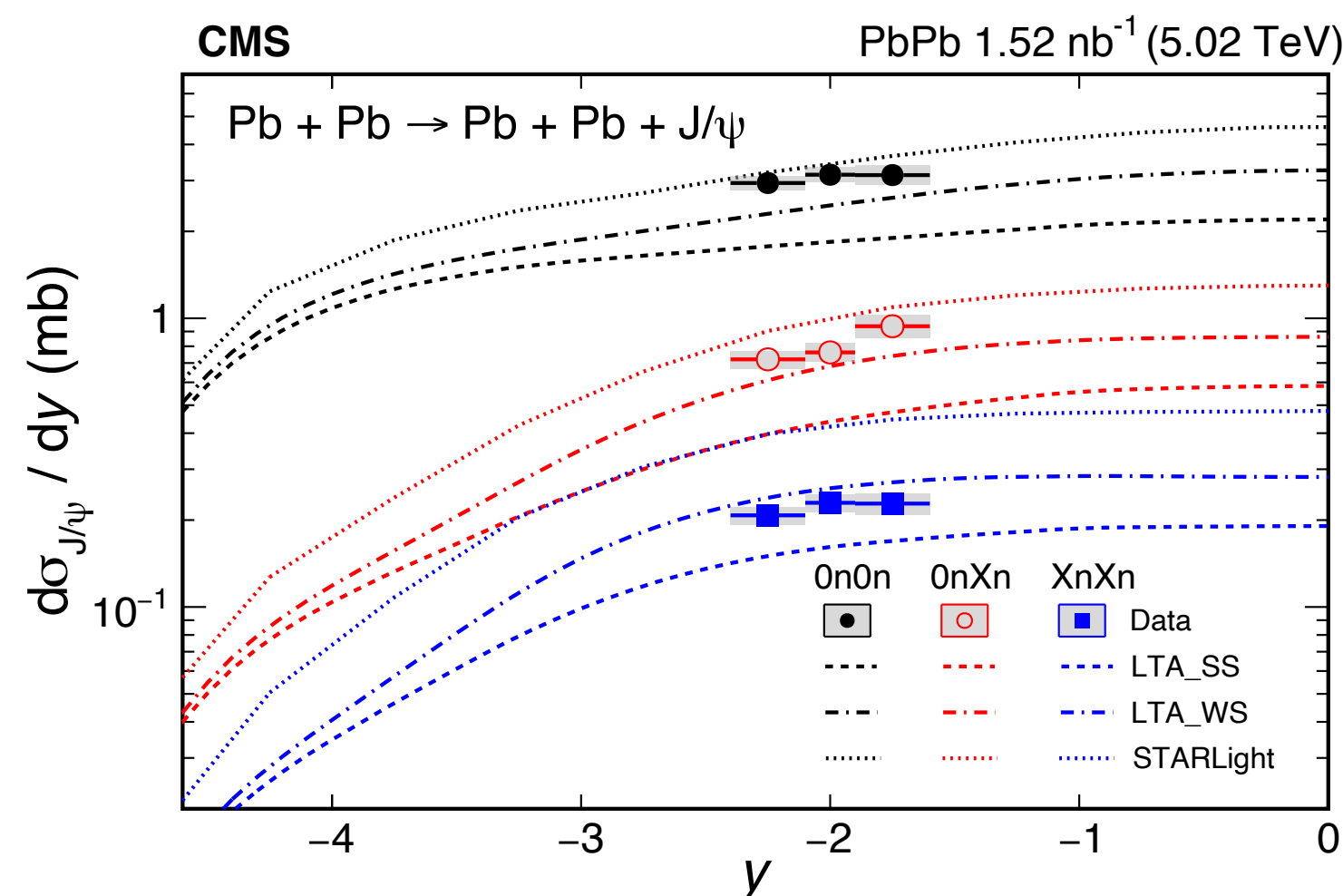
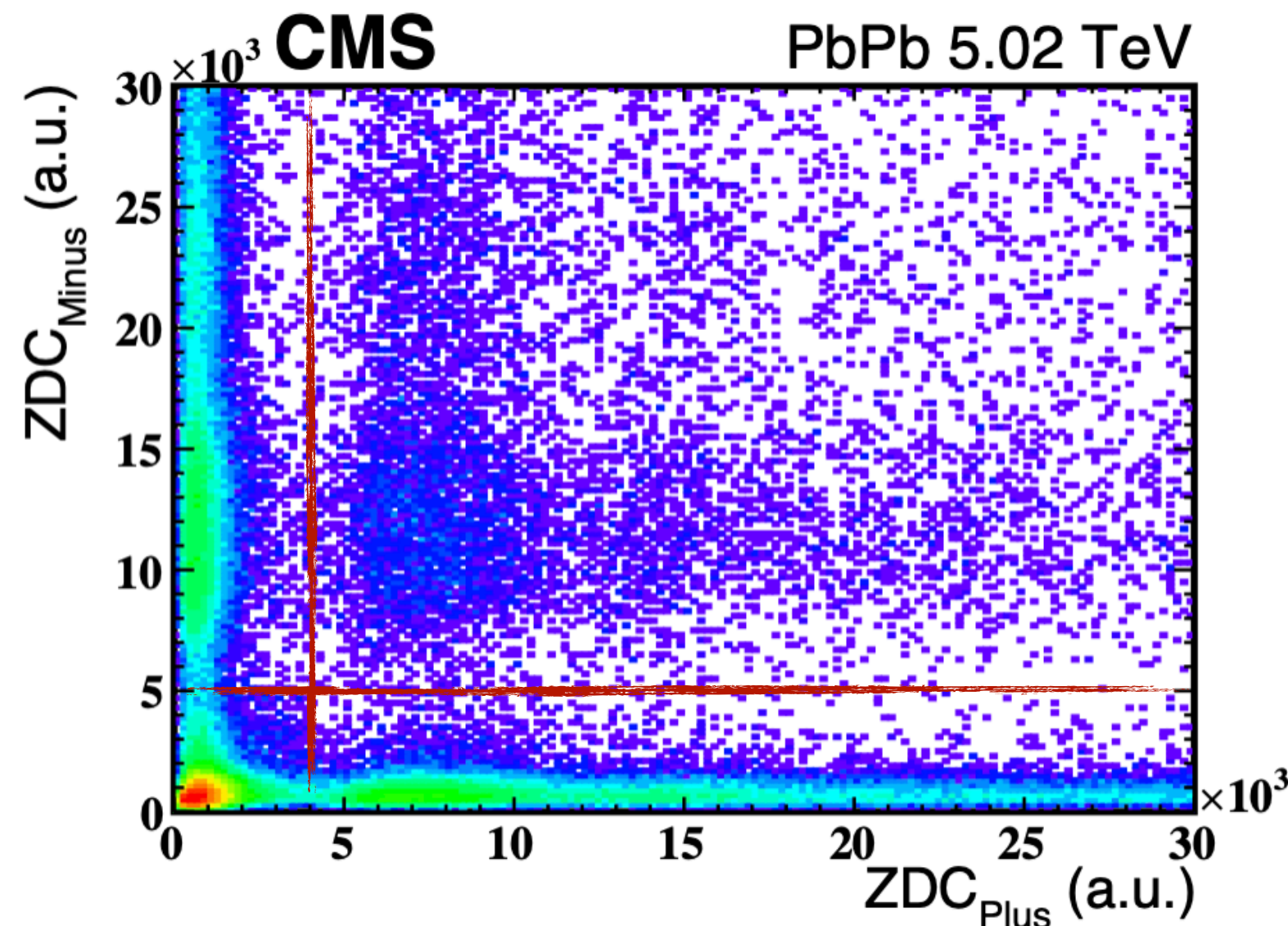
Klein and Steinberg, Ann. Rev. Nucl. Part. Sci. 70 (2020) 323

◎ Control the impact parameter via forward neutron multiplicity

- $\langle b \rangle_{XnXn} < \langle b \rangle_{0nXn} < \langle b \rangle_{0n0n}$

A solution to the “two-way ambiguity”

Guzey et al., EPJC 74 (2014) 2942



Experimental
measurements

$$\begin{aligned} \frac{d\sigma_{AA \rightarrow AA' J/\psi}^{0n0n}}{dy} &= N_{\gamma/A}^{0n0n}(\omega_1) \cdot \sigma_{\gamma A \rightarrow J/\psi A'}(\omega_1) + N_{\gamma/A}^{0n0n}(\omega_2) \cdot \sigma_{\gamma A \rightarrow J/\psi A'}(\omega_2) \\ \frac{d\sigma_{AA \rightarrow AA' J/\psi}^{0nXn}}{dy} &= N_{\gamma/A}^{0nXn}(\omega_1) \cdot \sigma_{\gamma A \rightarrow J/\psi A'}(\omega_1) + N_{\gamma/A}^{0nXn}(\omega_2) \cdot \sigma_{\gamma A \rightarrow J/\psi A'}(\omega_2) \\ \frac{d\sigma_{AA \rightarrow AA' J/\psi}^{XnXn}}{dy} &= N_{\gamma/A}^{XnXn}(\omega_1) \cdot \sigma_{\gamma A \rightarrow J/\psi A'}(\omega_1) + N_{\gamma/A}^{XnXn}(\omega_2) \cdot \sigma_{\gamma A \rightarrow J/\psi A'}(\omega_2) \end{aligned}$$

Photon flux
from theory

What we need!

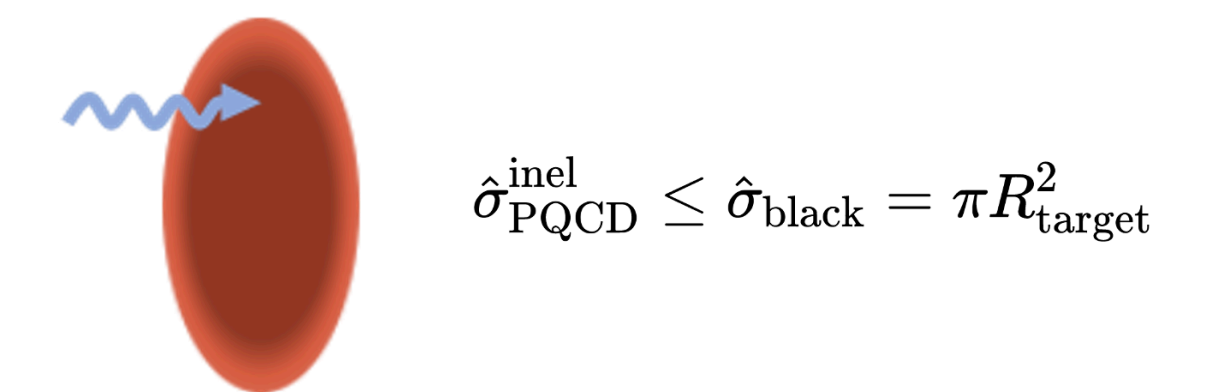
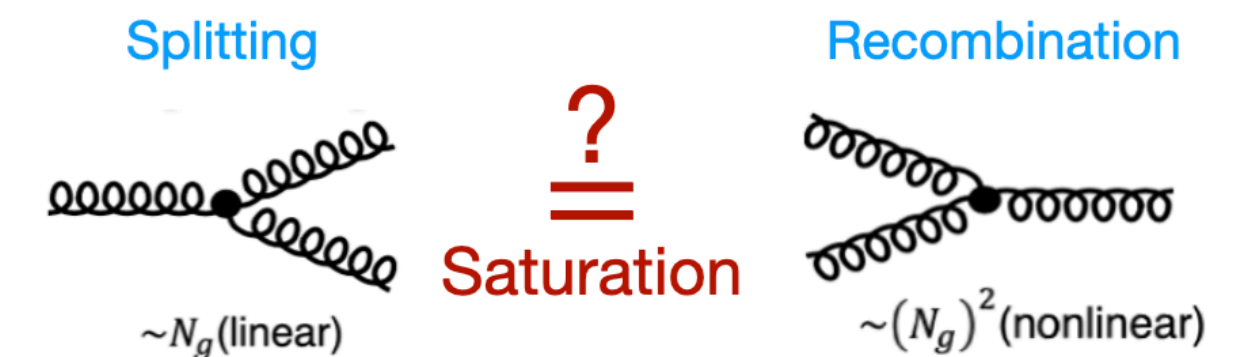
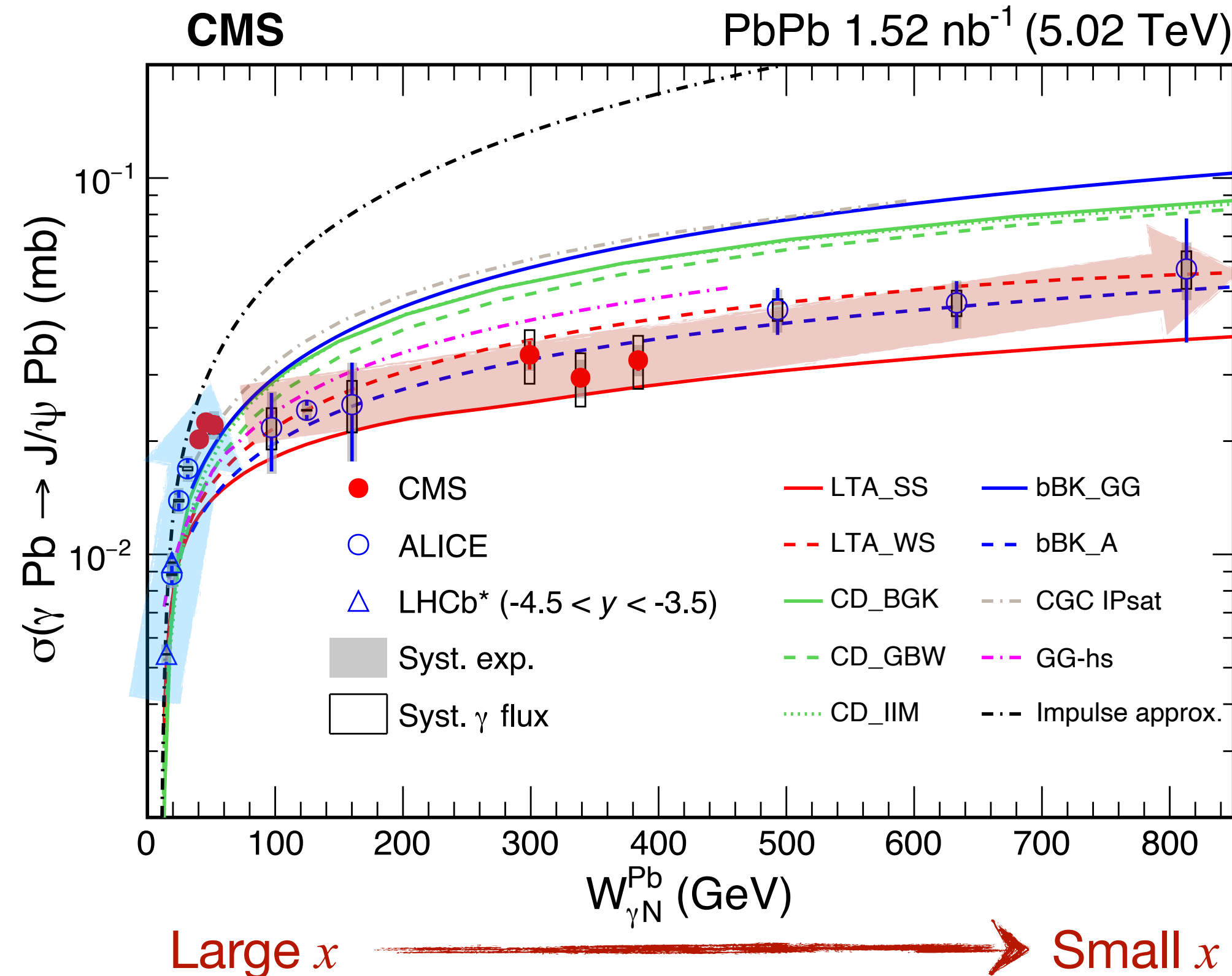
Solve the “two-way ambiguity”

Probe gluons at $x \sim 10^{-5} - 10^{-4}$ in heavy nucleus!

Energy dependence of coherent J/ ψ

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

LO pQCD:
 $\sigma^{VM} \propto [xG(x)]^2$

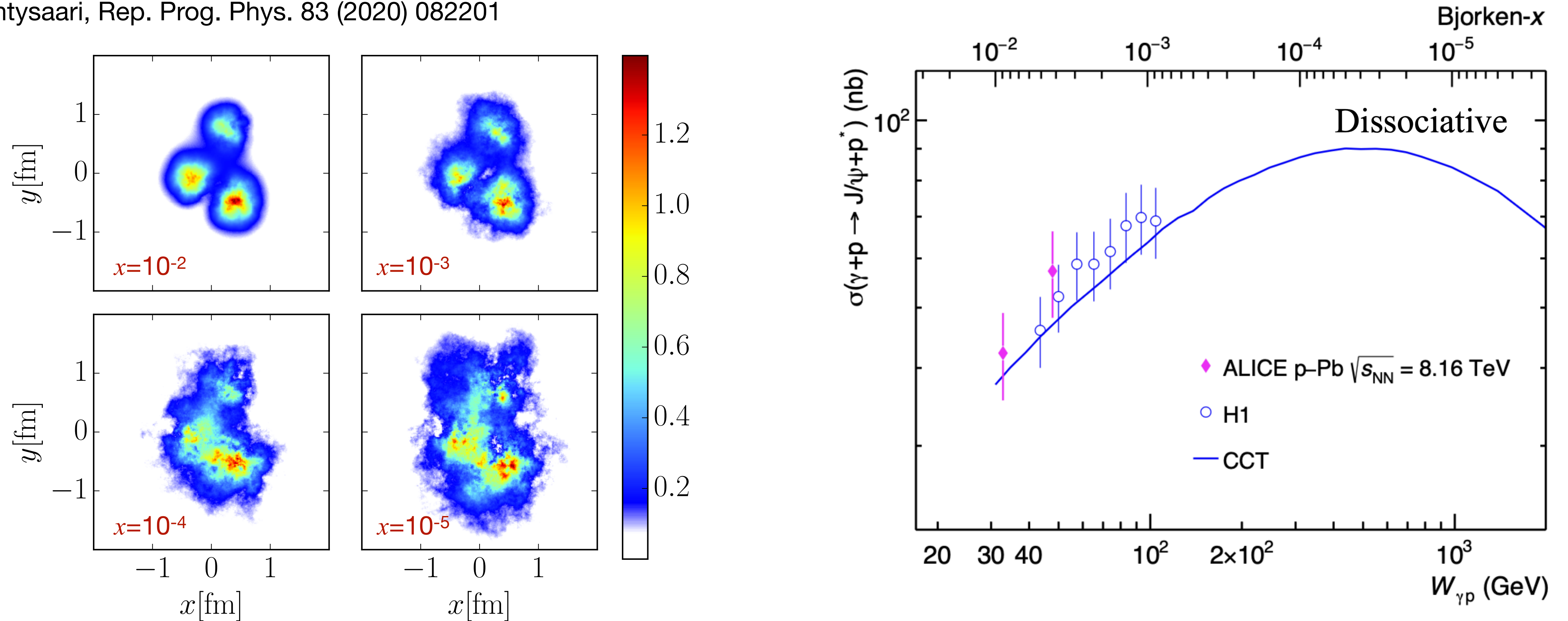


Frankfurt, PRL 87 (2001)192301
Frankfurt, PLB 537 (2002) 51

- Forward neutron tagging is employed to solve the “two-way” ambiguity
- Direct evidence of gluon saturation inside heavy nuclei?
 - $W_{\gamma N}^{Pb} < 40$ GeV: rapidly rising
 - $40 < W_{\gamma N}^{Pb} < 800$ GeV: nearly flat with a much slower rising

The role of energy dependence of incoherent J/ψ

Mantysaari, Rep. Prog. Phys. 83 (2020) 082201

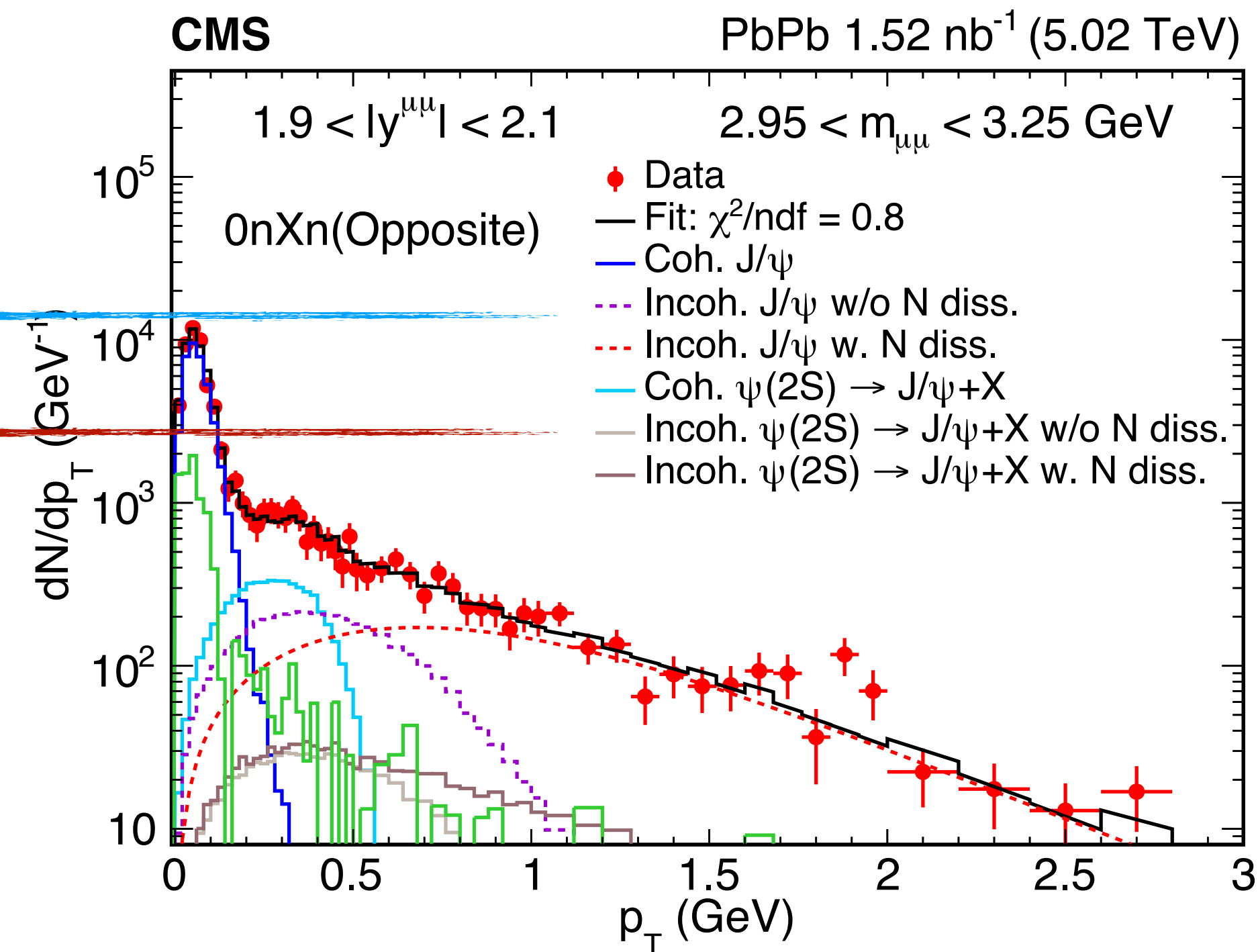
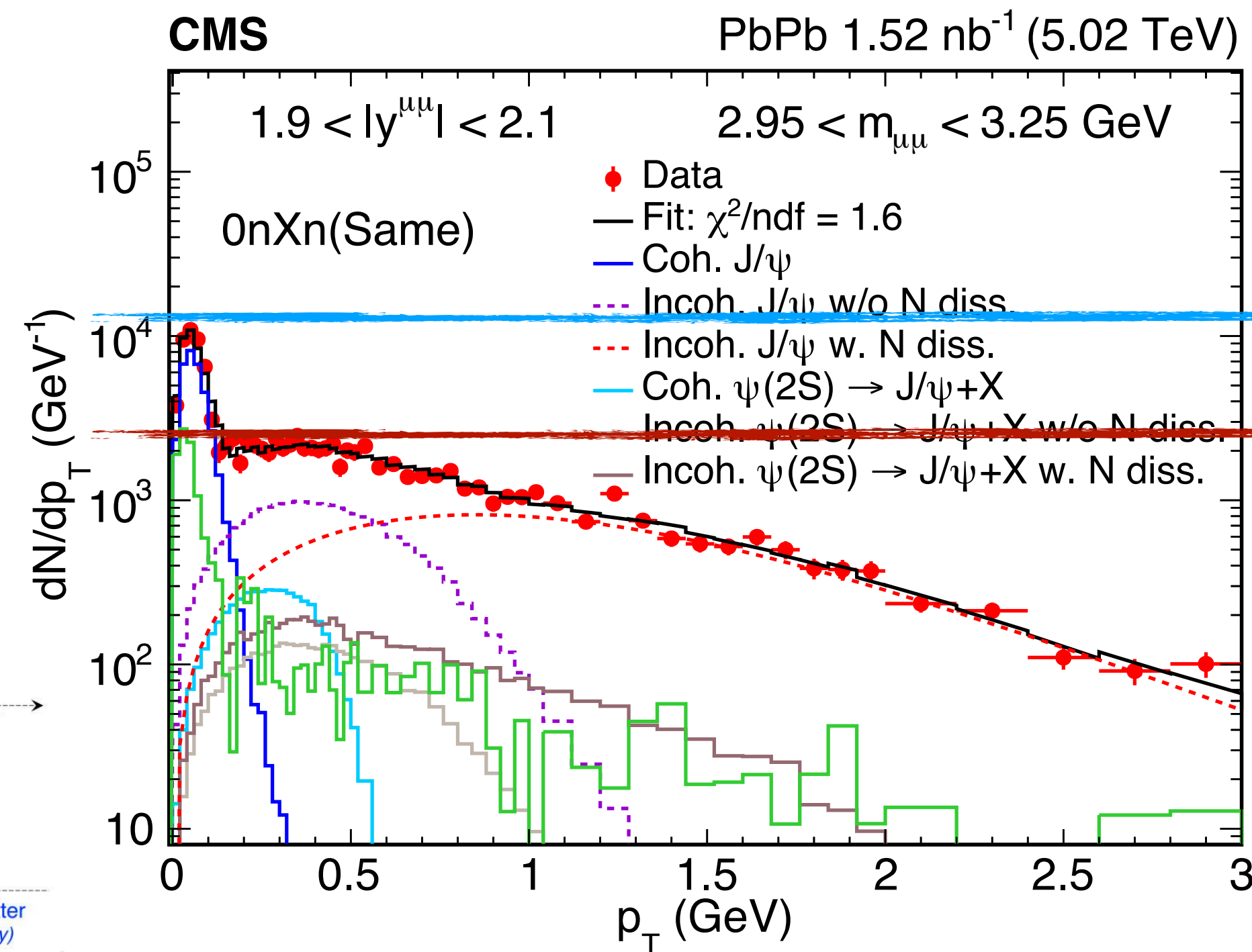


● Increasing energy, probing lower- x gluons

- Gluons eventually largely overlap $\rightarrow$ reduce variance over configurations $\rightarrow$ reduce the incoherent J/ψ cross section $\rightarrow$ signature of gluon saturation

Extract energy dependence of **incoherent** J/ψ

CMS, arXiv:2503.08903 (accepted by PRL)

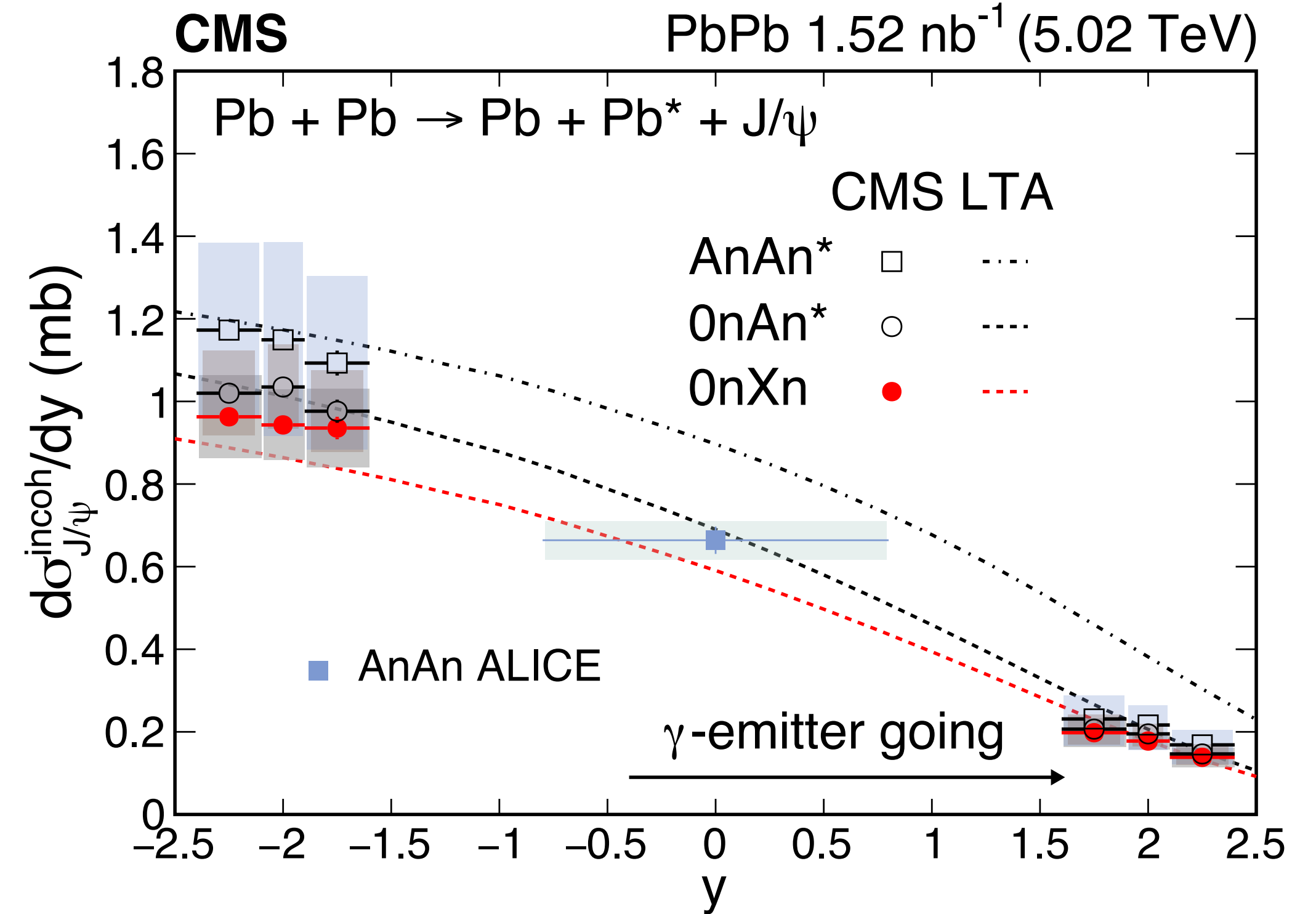
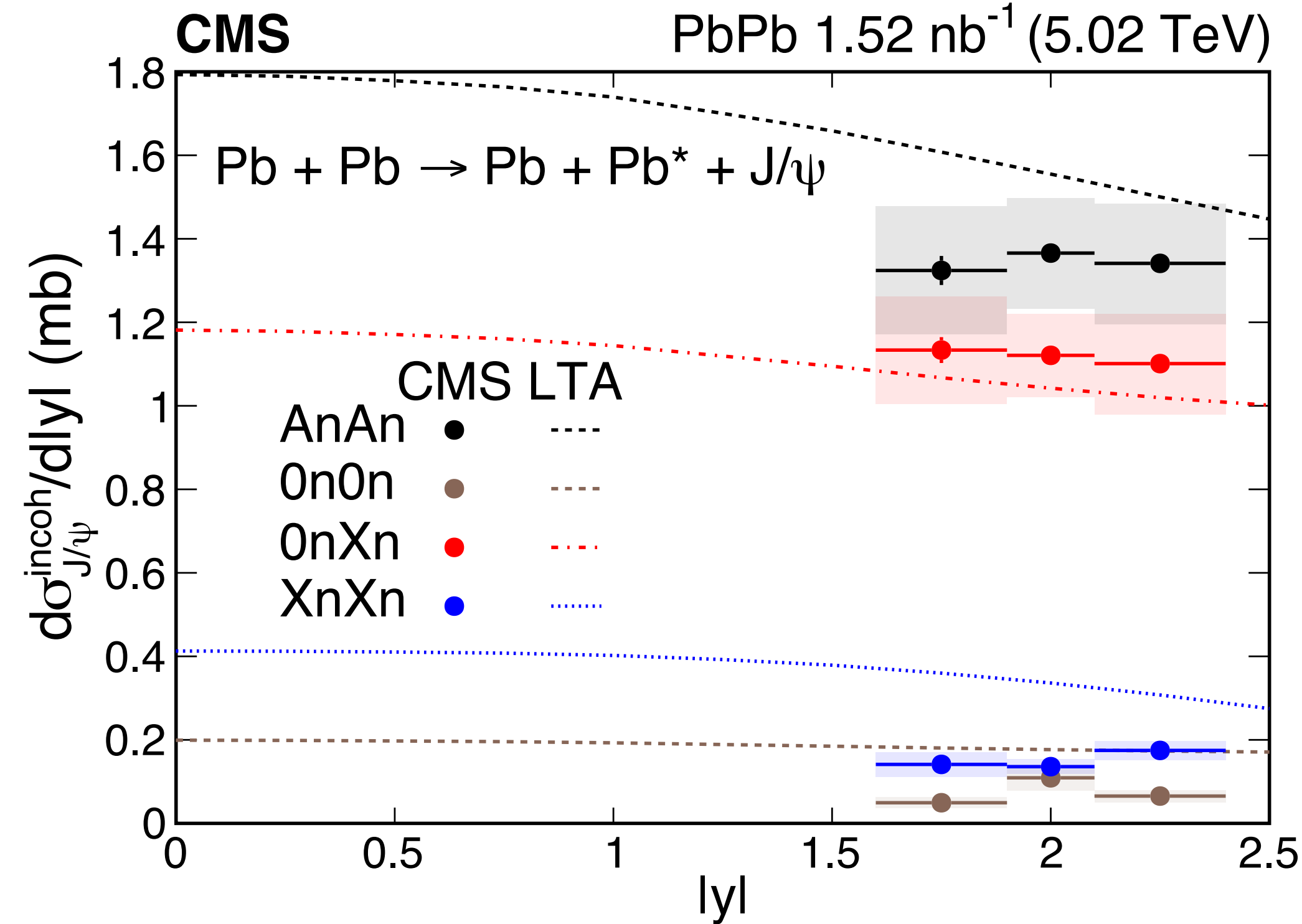


⊙ Coherent J/ψ : no correlation with neutron emissions

⊙ Incoherent J/ψ : strong correlation with neutron emissions

Incoherent J/ψ cross section vs. rapidity

CMS, arXiv:2503.08903 (accepted by PRL)

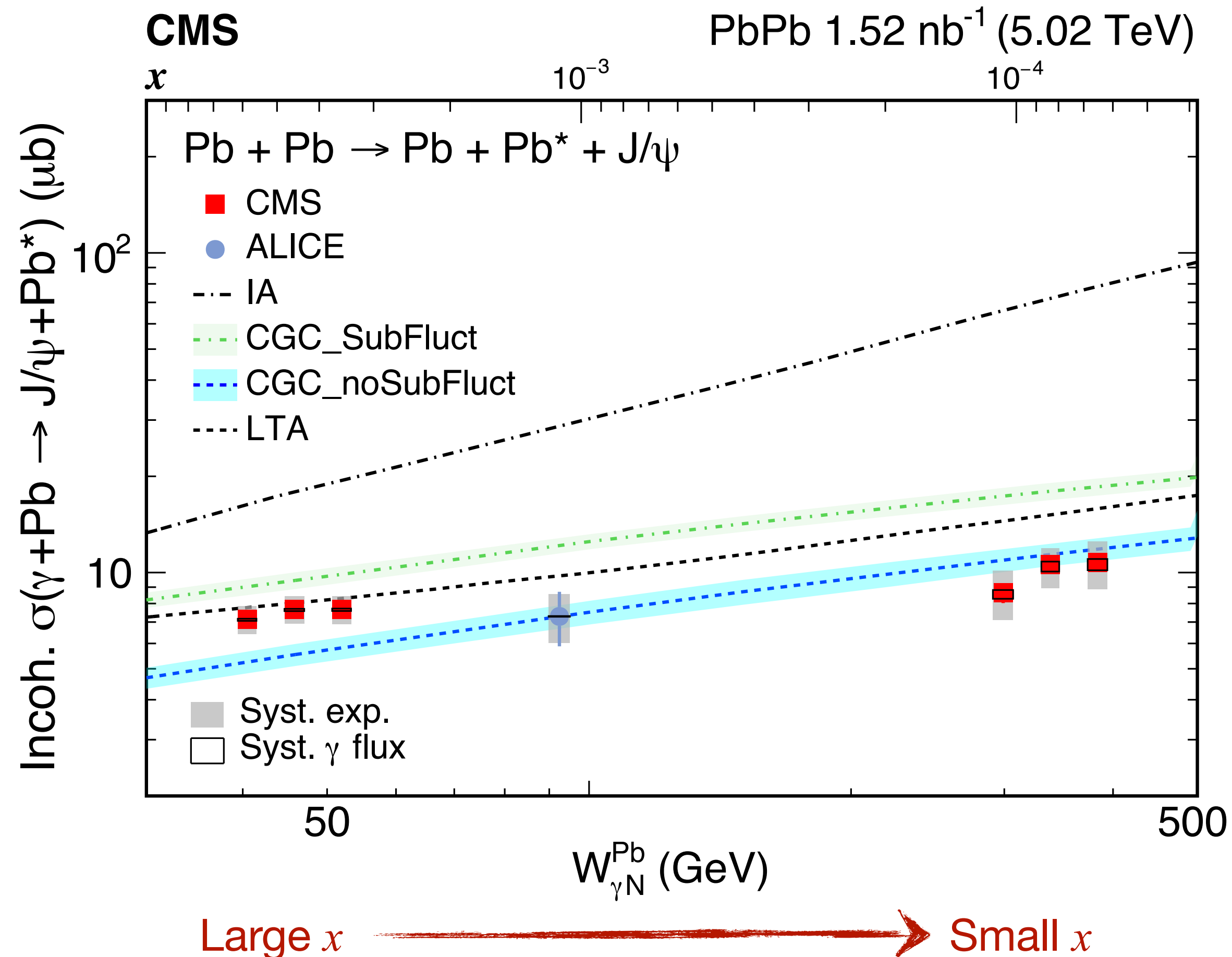


$$\frac{d\sigma_{PbPb \rightarrow PbPb' J/\psi}^{0nAn^*}(y)}{dy} = \frac{d\sigma_{PbPb \rightarrow PbPb' J/\psi}^{0nXn}(y)}{dy} + \frac{d\sigma_{PbPb \rightarrow PbPb' J/\psi}^{0n0n}(y)}{dy}$$

- Relative yield ratio between positive over negative rapidity in 0n0n are assumed to be same as that in 0nXn events

Probing gluon fluctuations with incoherent J/ψ

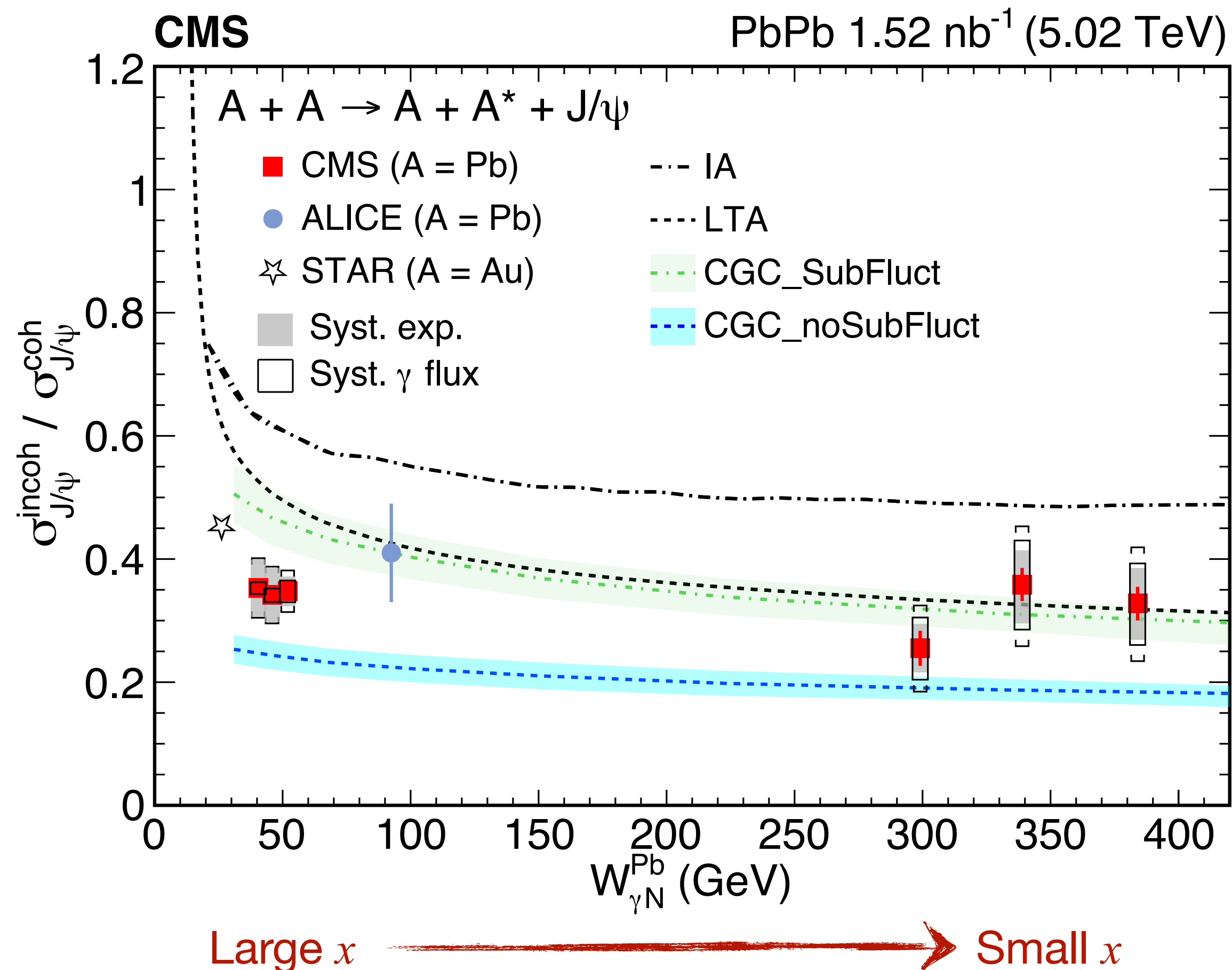
CMS, arXiv:2503.08903 (accepted by PRL)



- First measurement of incoherent J/ψ as a function of energy
- Strong suppression compared to impulse approximation model
- LTA describe the data with $W_{\gamma N}^{\text{Pb}} < 60$ GeV, while CGC without gluon fluctuations is consistent with data with $W_{\gamma N}^{\text{Pb}} > 90$ GeV

Comparisons of coherent and incoherent J/ψ

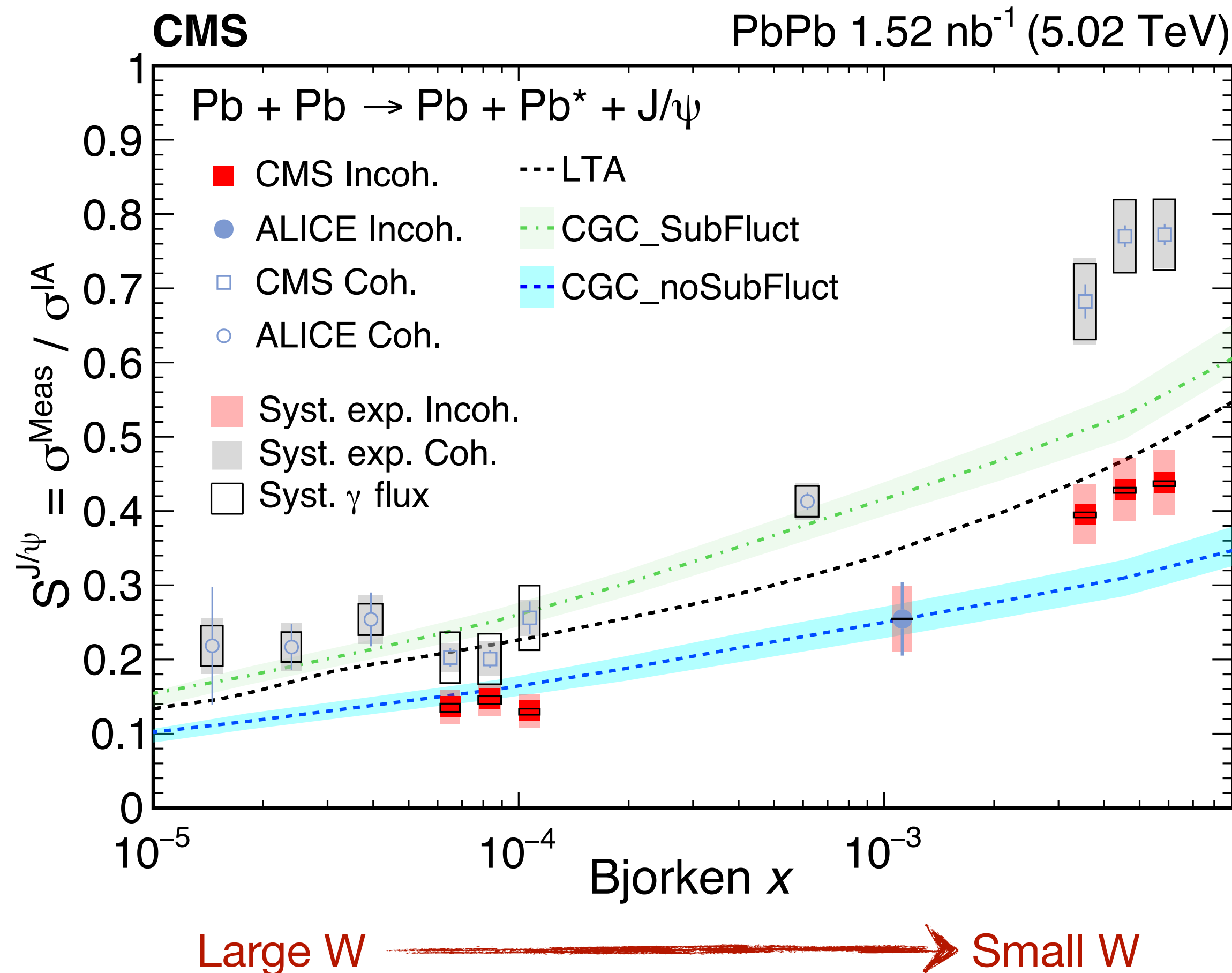
CMS, arXiv:2503.08903 (accepted by PRL)



- ◎ Uncertainties are largely cancelled
 - Experimental wise: correlated systematic uncertainties
 - Theoretical wise: VM wave function, nucleon PDFs, photon flux, nuclear shape etc
- Incoherent J/ψ is more suppressed compared to coherent J/ψ
- ◎ Data are consistent CGC incorporating gluon fluctuations
 - Overestimates data at low energy

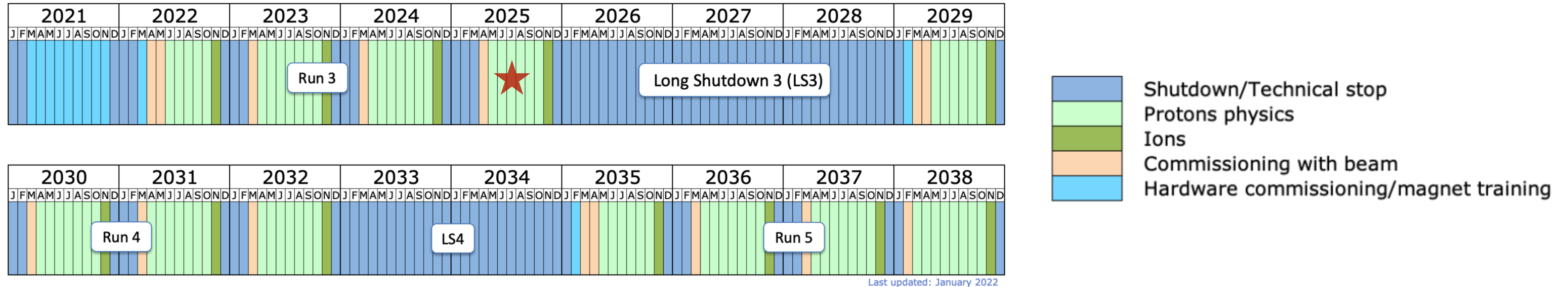
Comparisons of coherent and incoherent J/ψ

CMS, arXiv:2503.08903 (accepted by PRL)



- Strong suppression towards low x region for both coherent and incoherent J/ψ
 - Flatten out at $x < 10^{-4}$
- Compare to coherent J/ψ , incoherent is J/ψ more suppressed at large x but remains consistent at small x
- No theoretical model can consistently describe the whole photoproduced J/ψ measurements

Future opportunities

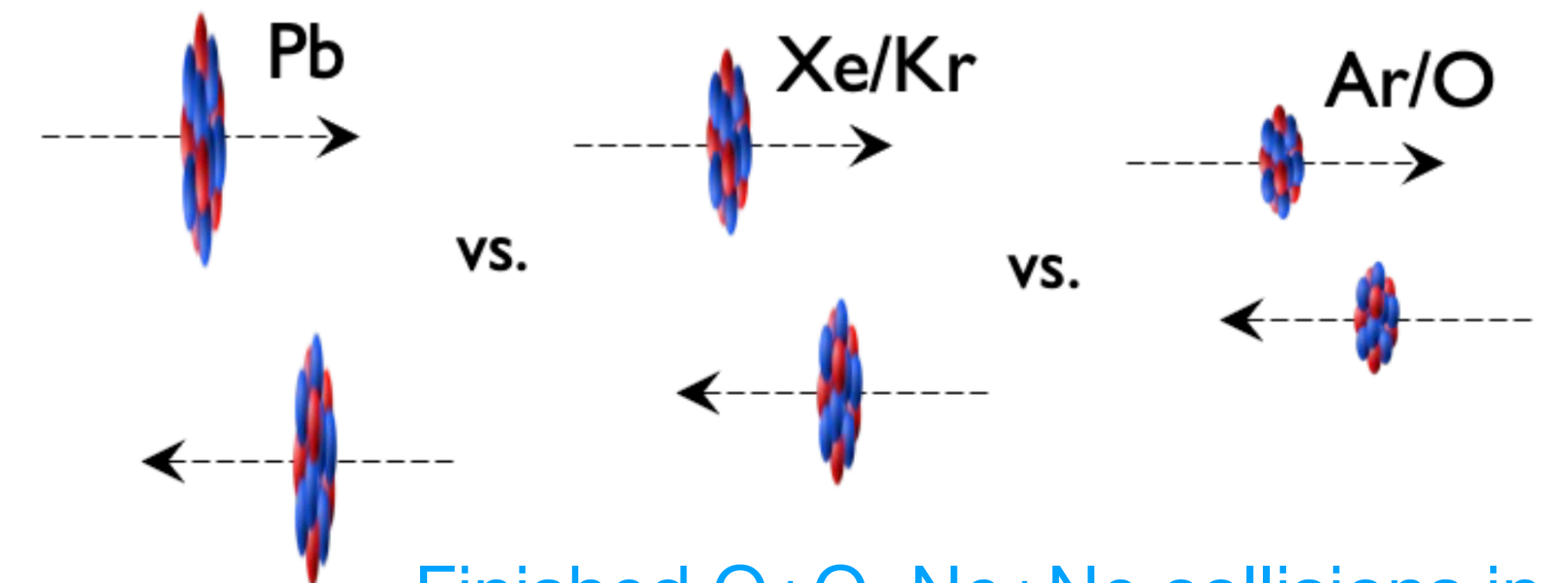


Exciting opportunities ahead

- System size scan with different ion species
- Detector upgrade with new technologies

UPC programs

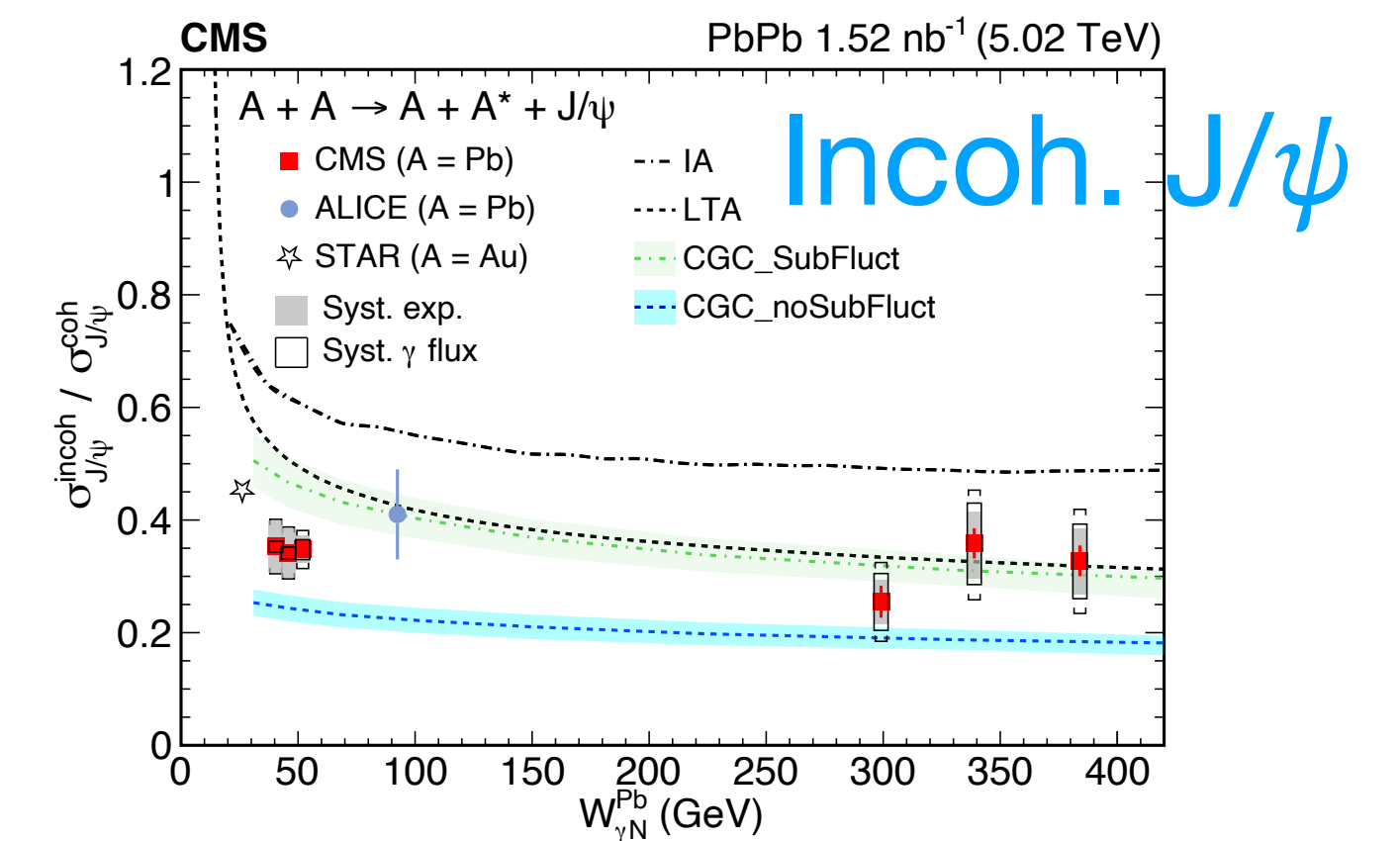
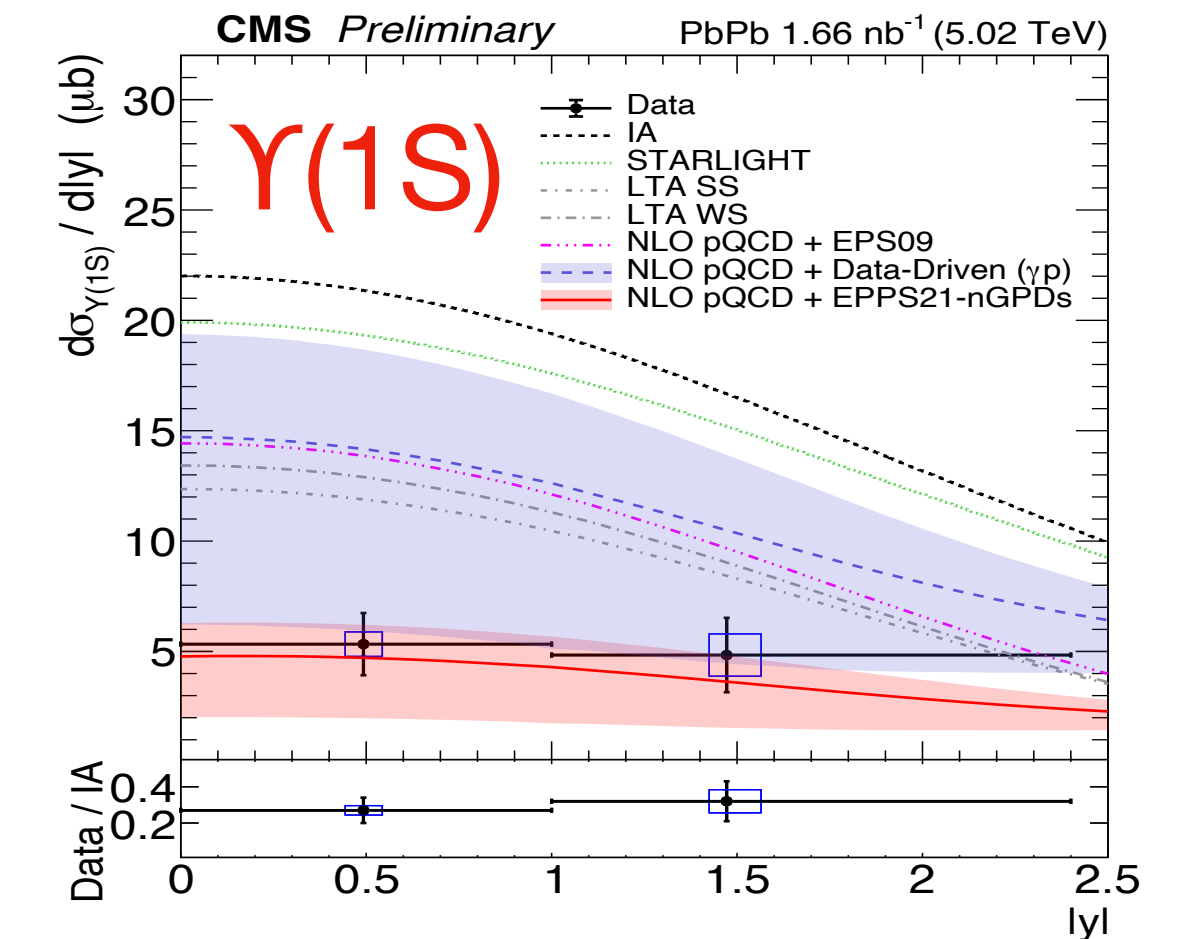
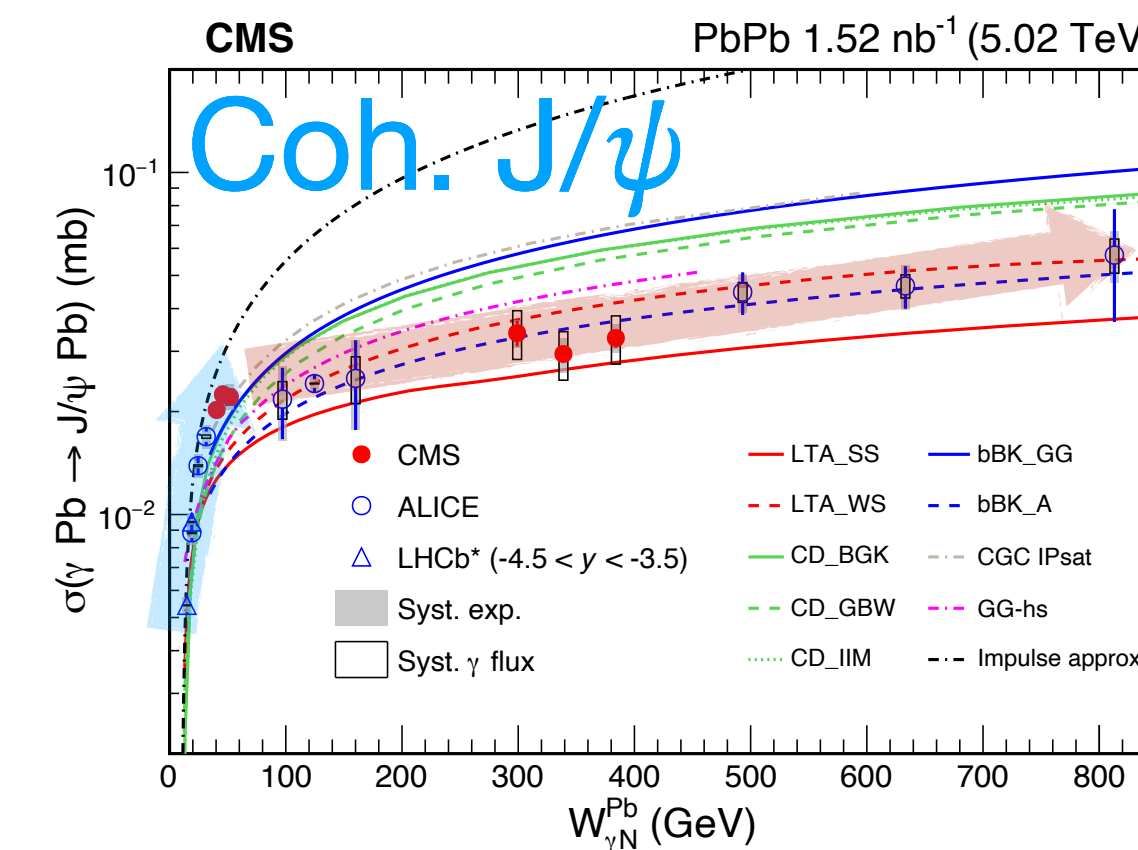
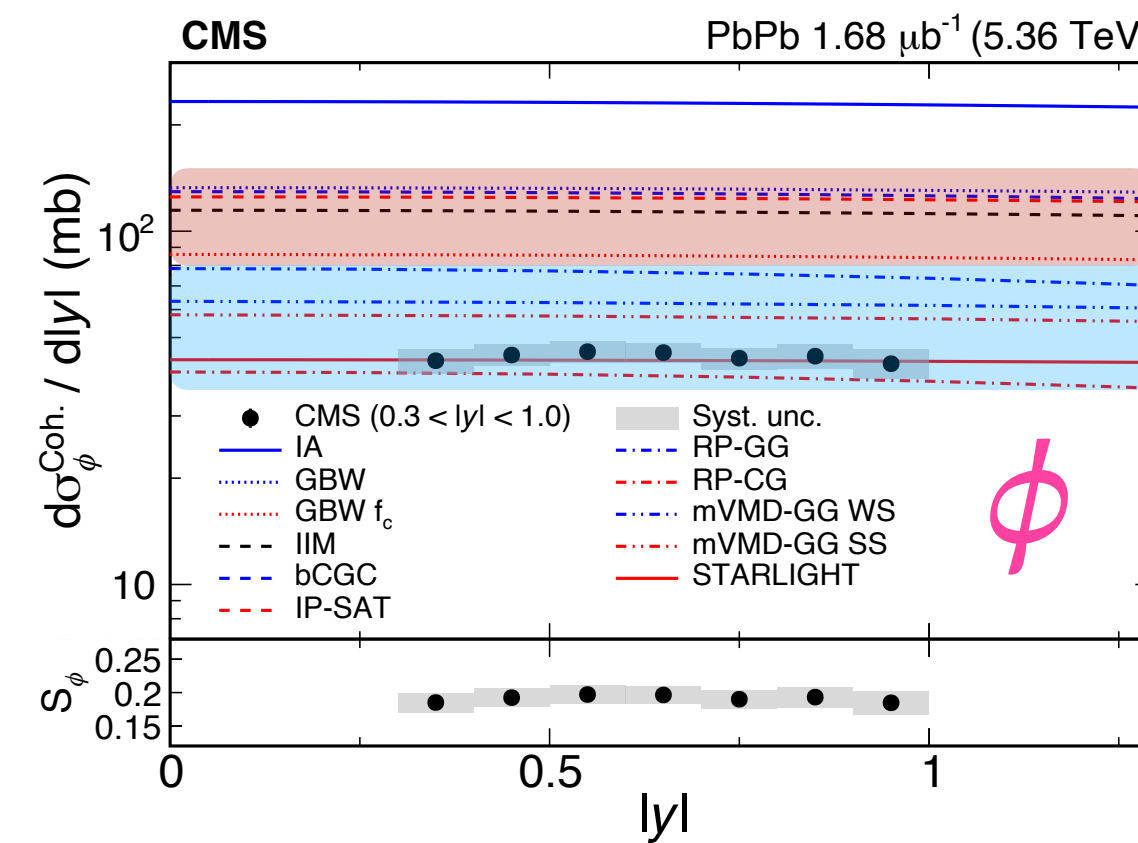
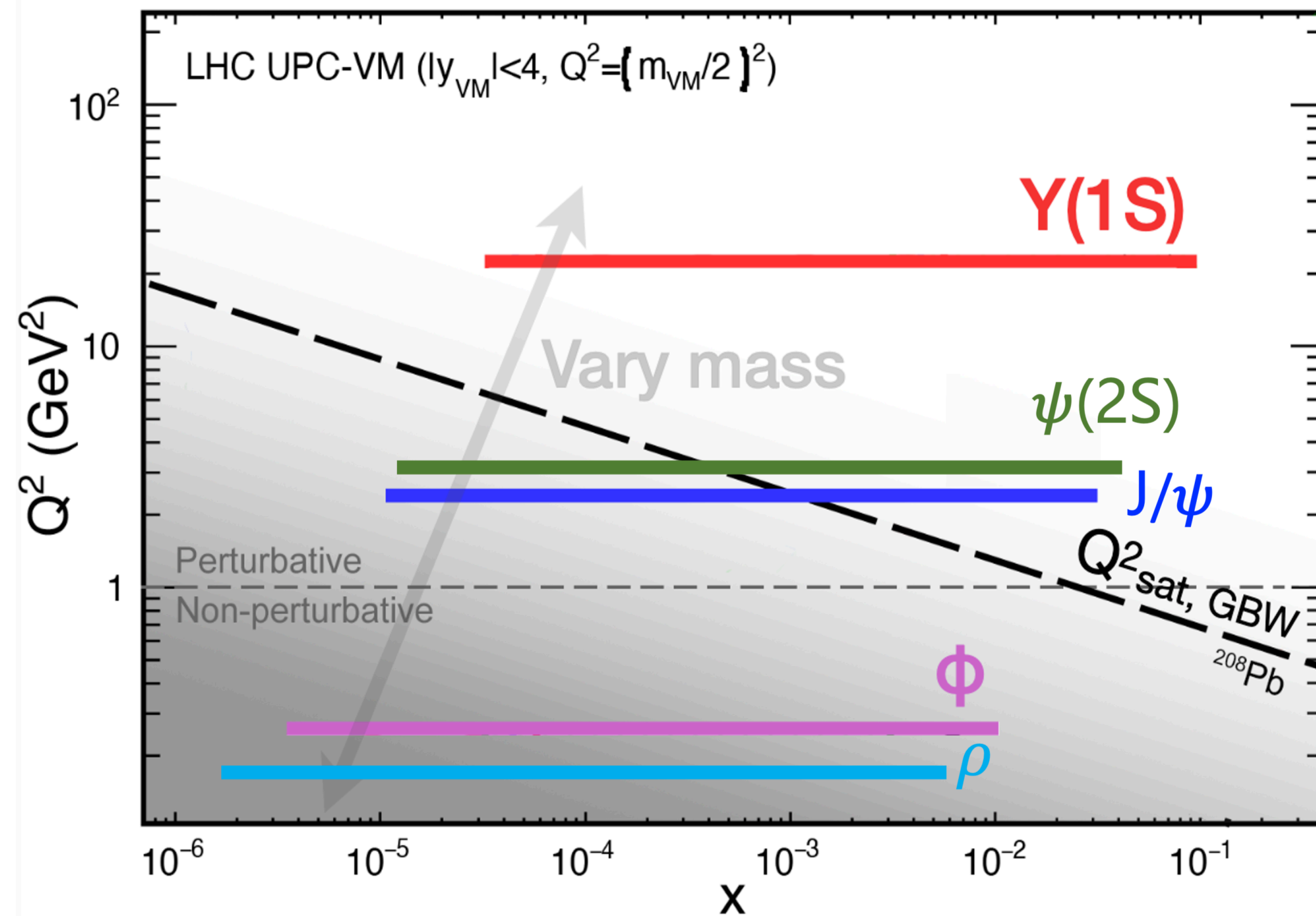
- Various vector meson photoproductions
 - Energy dependence of photoproduced vector meson cross sections
- Open HF and (di-)jet photoproductions



Finished O+O, Ne+Ne collisions in July

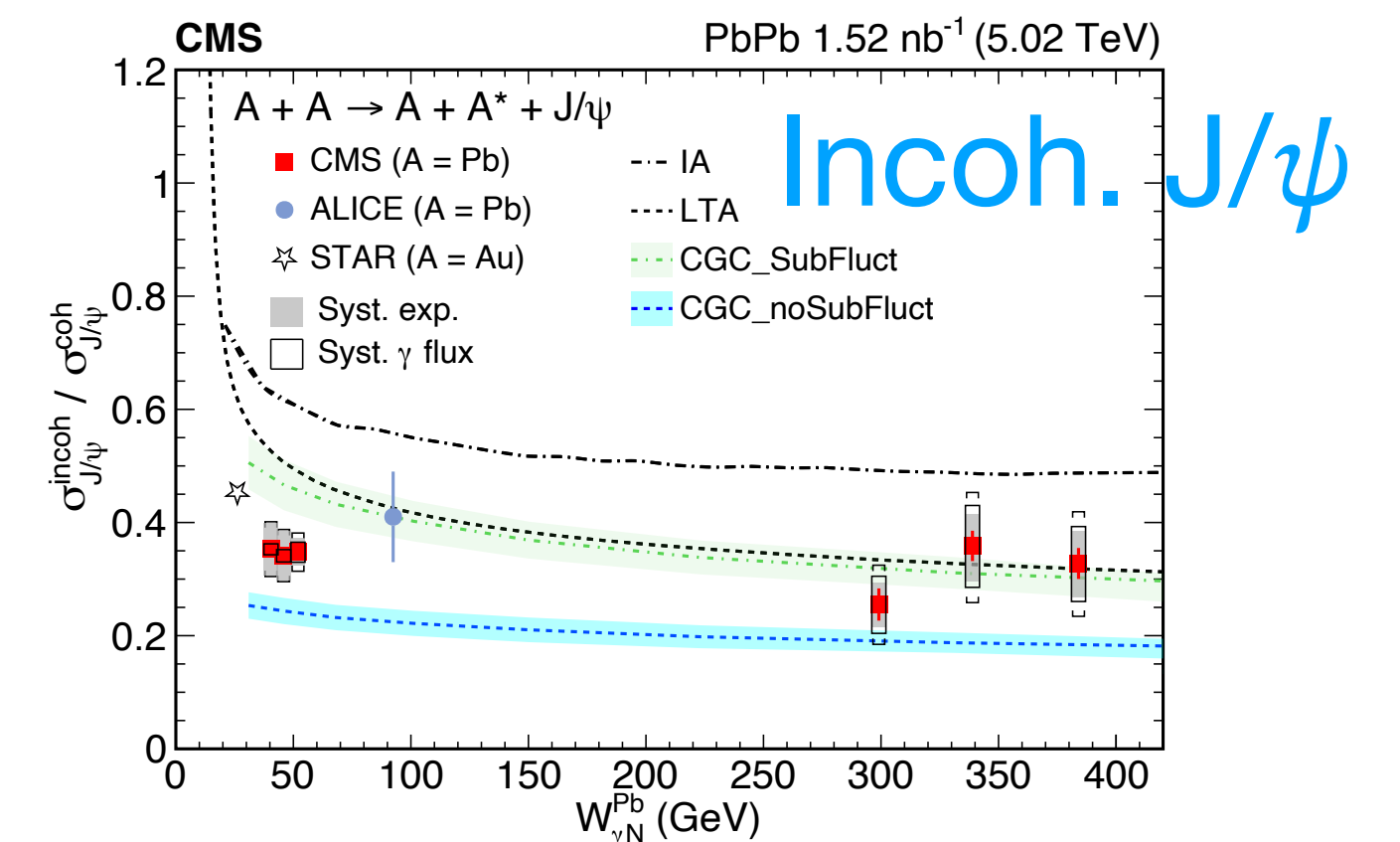
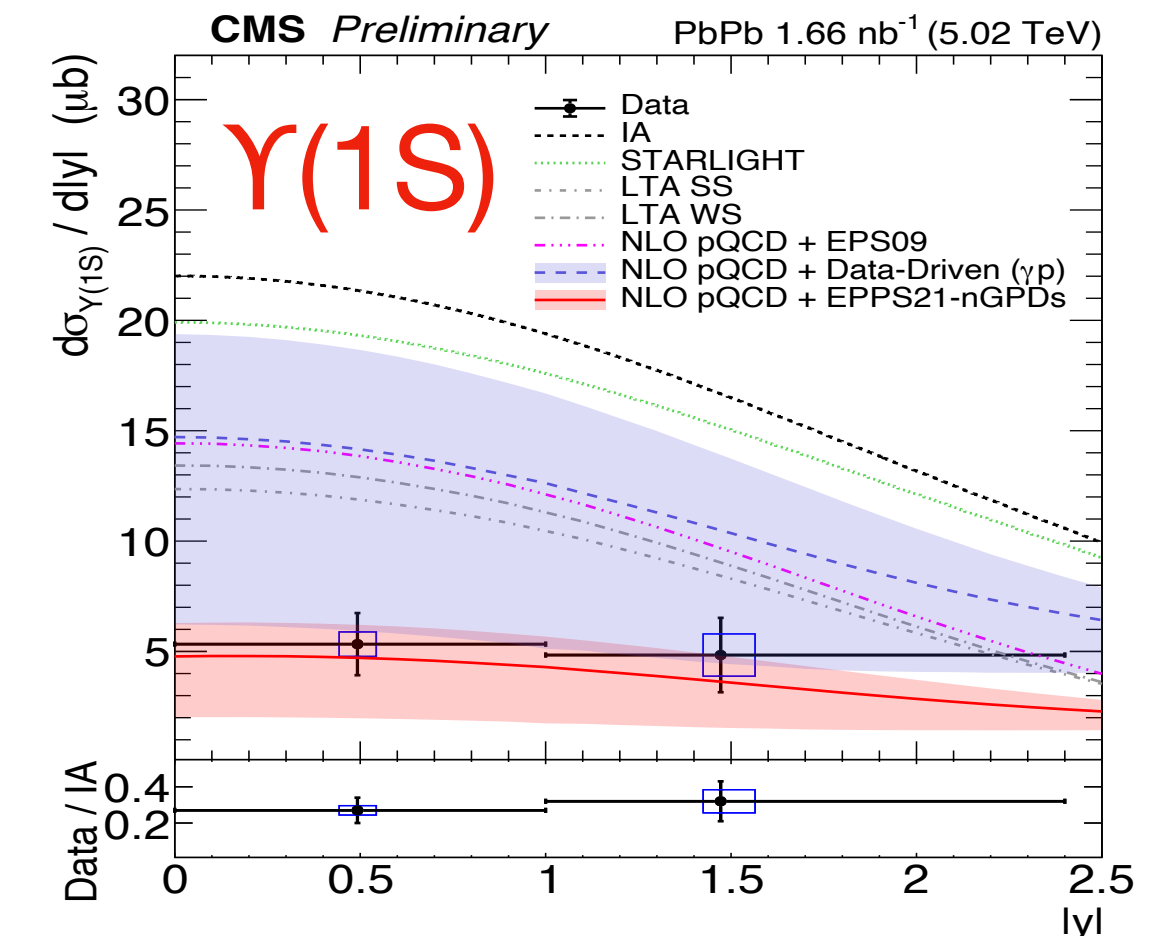
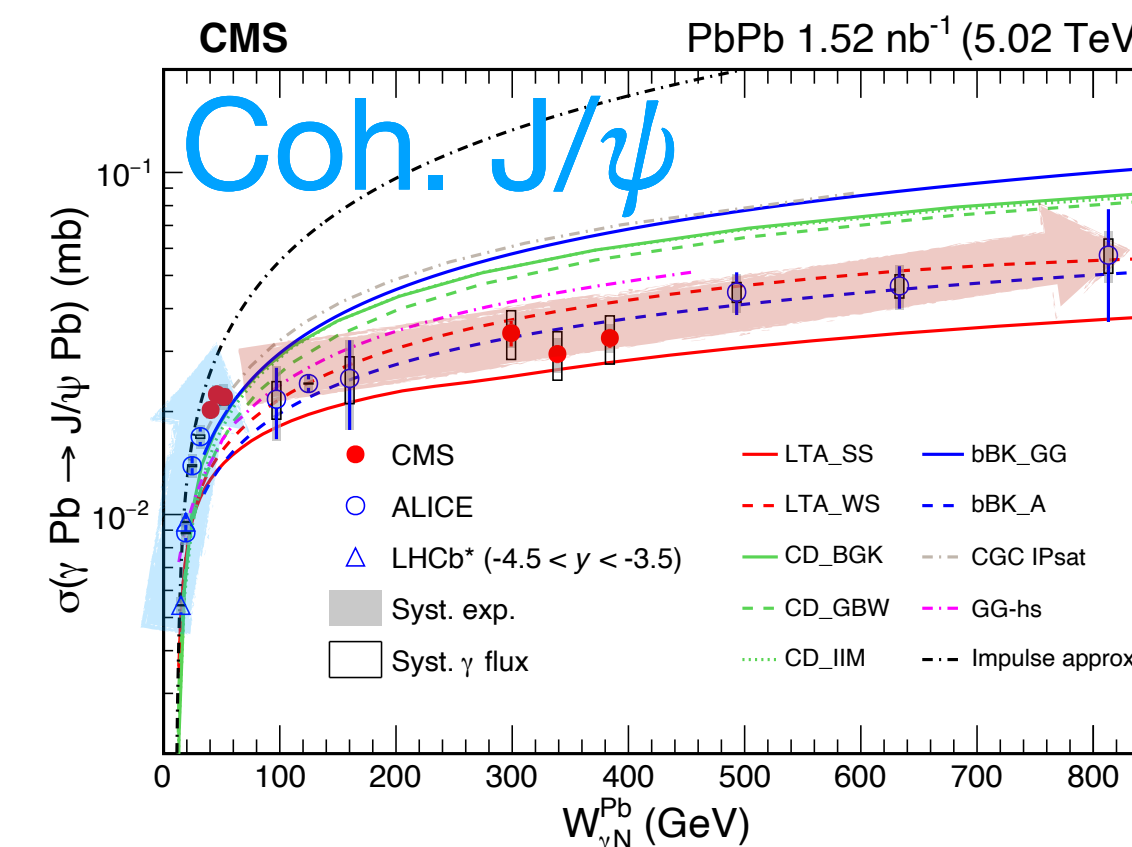
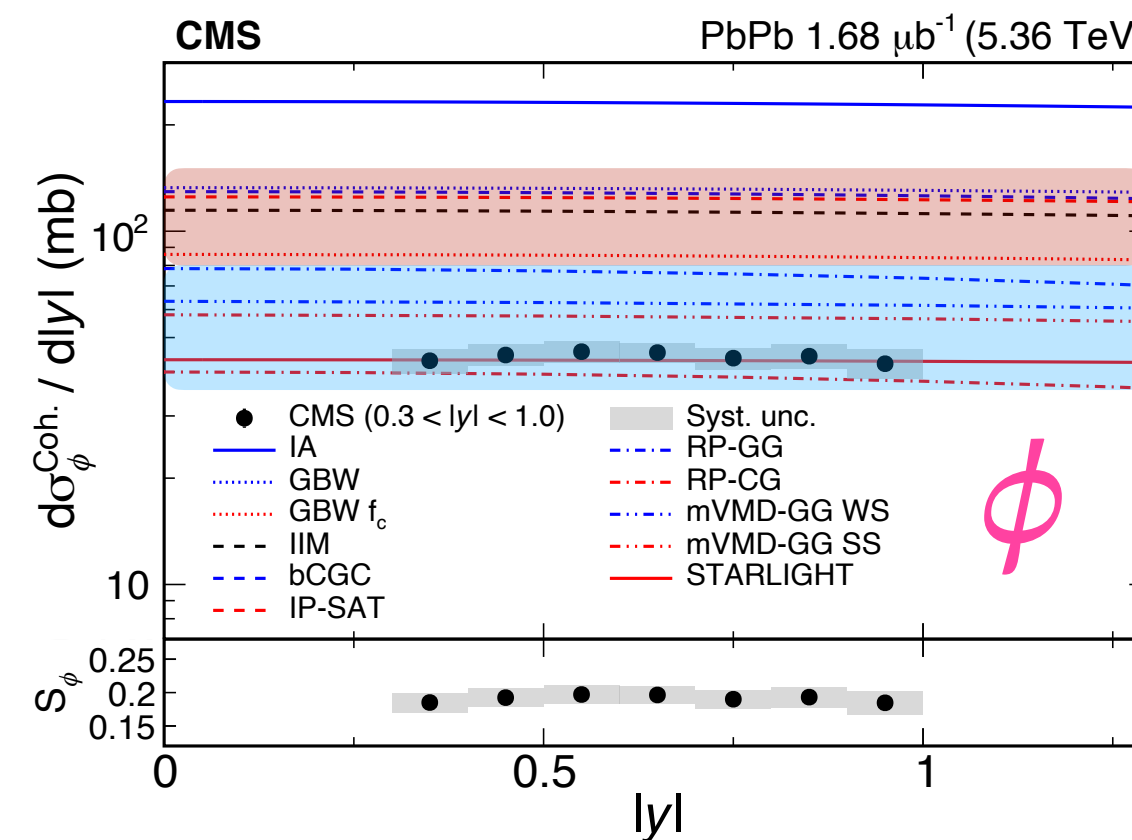
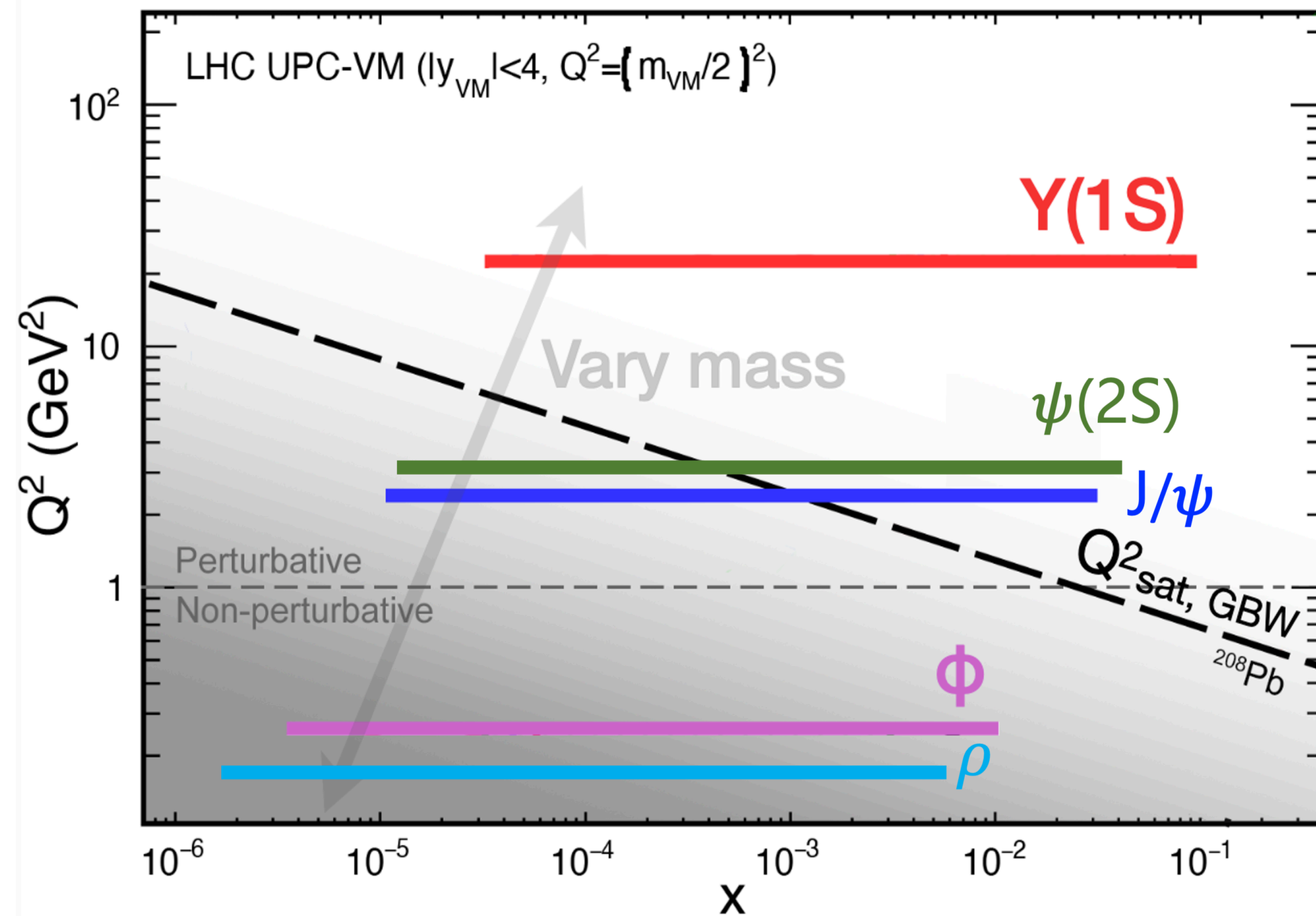
Summary

● Multidimensional imaging of nuclei with photon-nuclear interactions at CMS



Summary

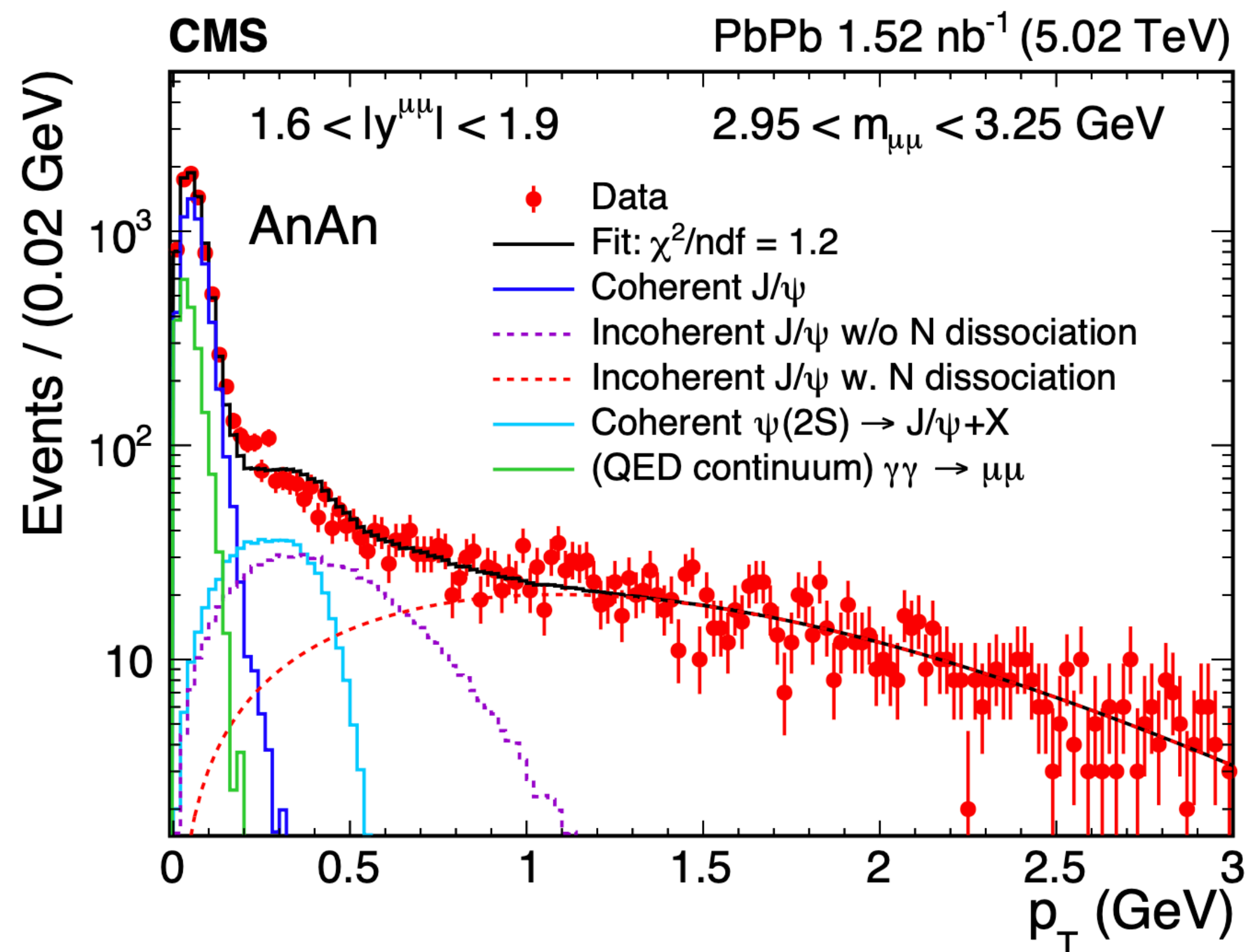
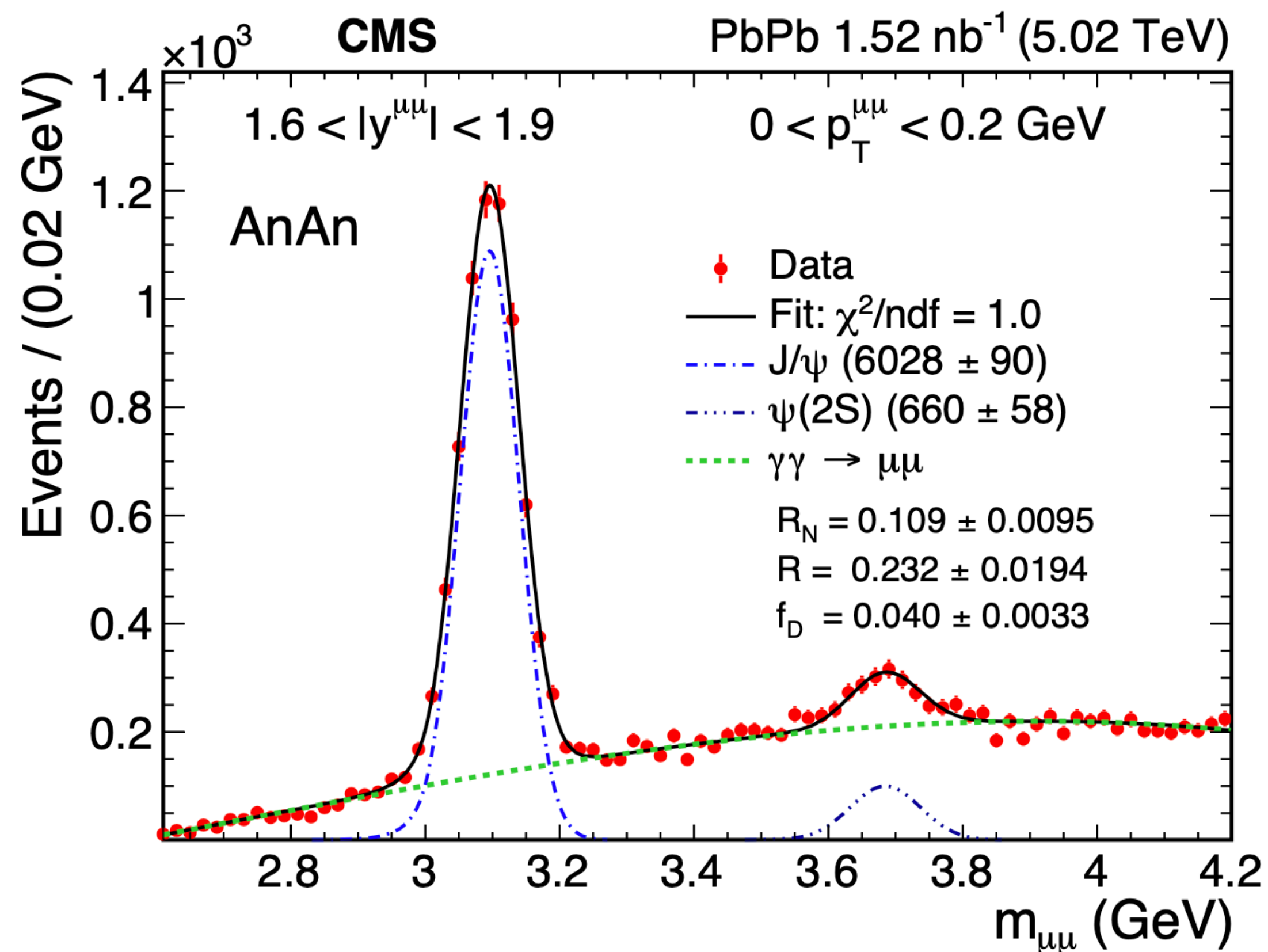
● Multidimensional imaging of nuclei with photon-nuclear interactions at CMS



感谢大家的聆听!

Backups

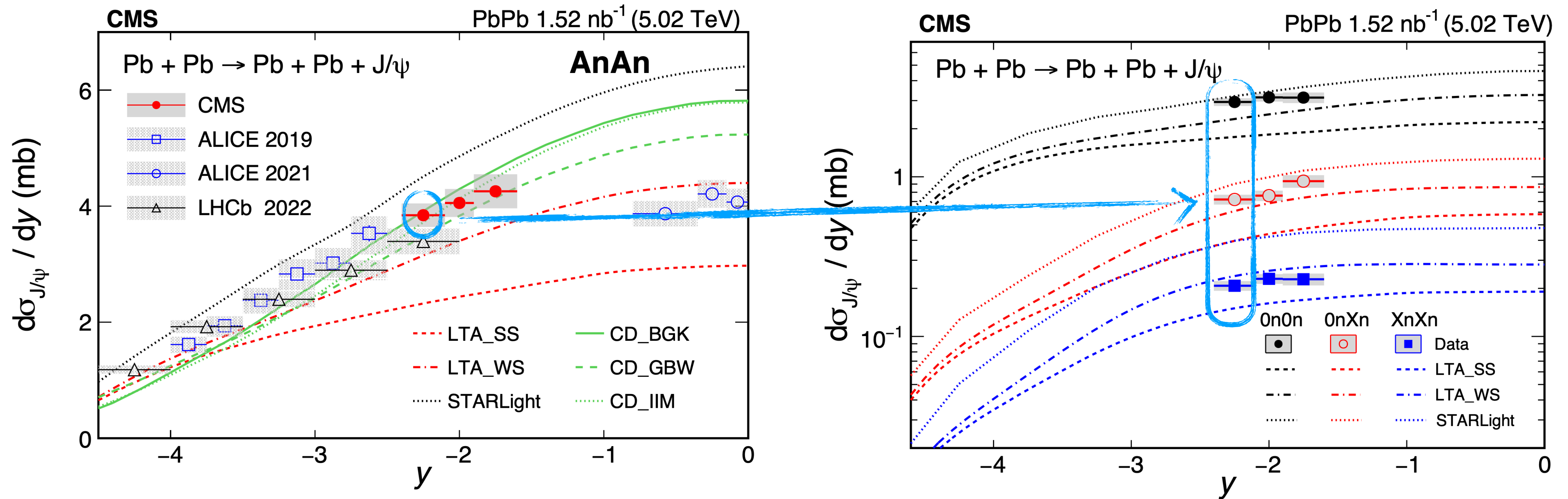
Imaging heavy nuclear with coherent J/ψ



- ◉ Extract coherent J/ψ signal by simultaneously fit the mass and p_T spectra
 - Same strategy for incoherent J/ψ signal extraction

A solution to the “two-way ambiguity”

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



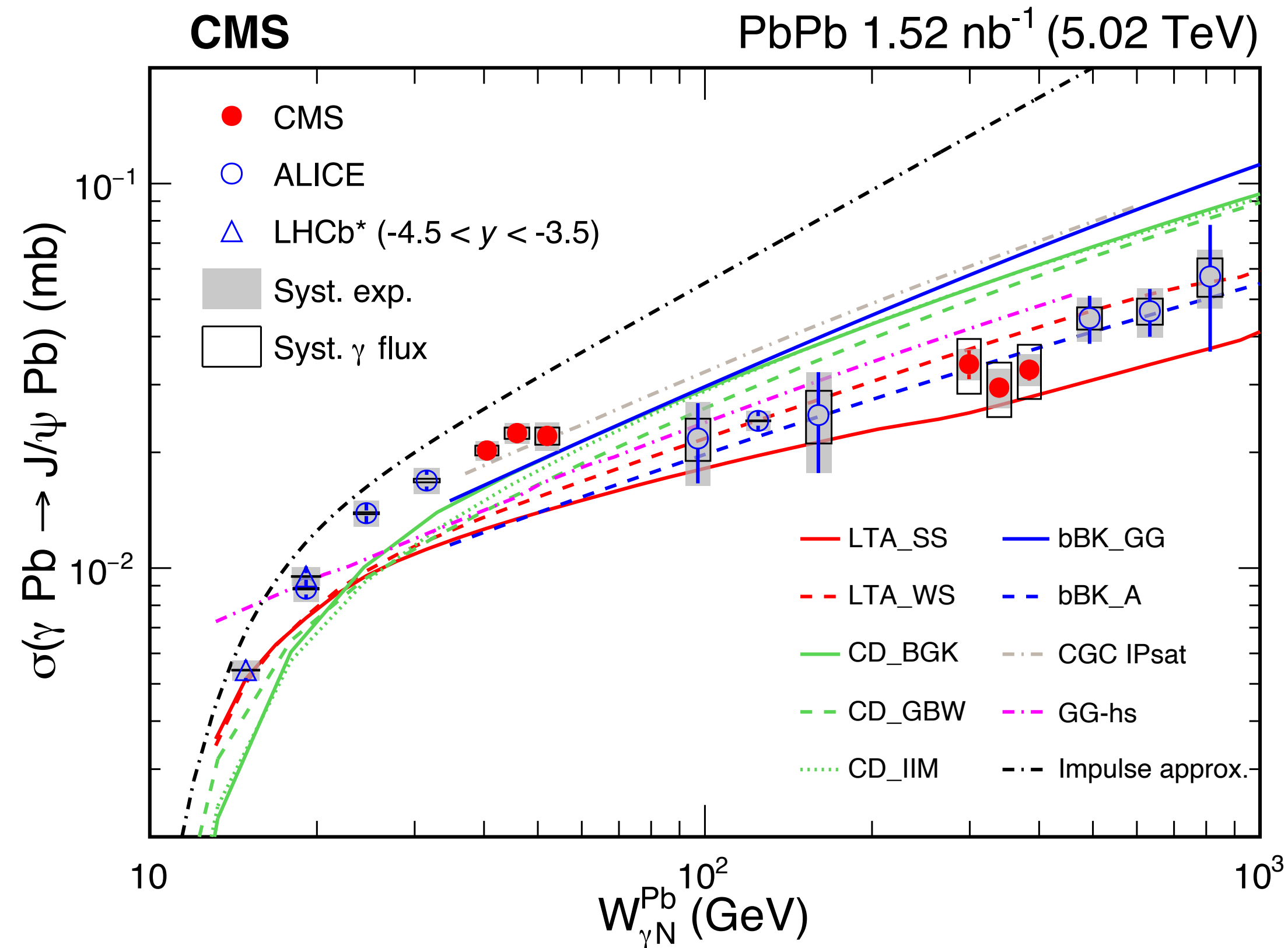
- First measurement of neutron multiplicity dependence of coherent J/ψ production
 - Enable to solve the “two-way ambiguity”

Coherent J/ψ production vs. $W_{\gamma N}^{Pb}$

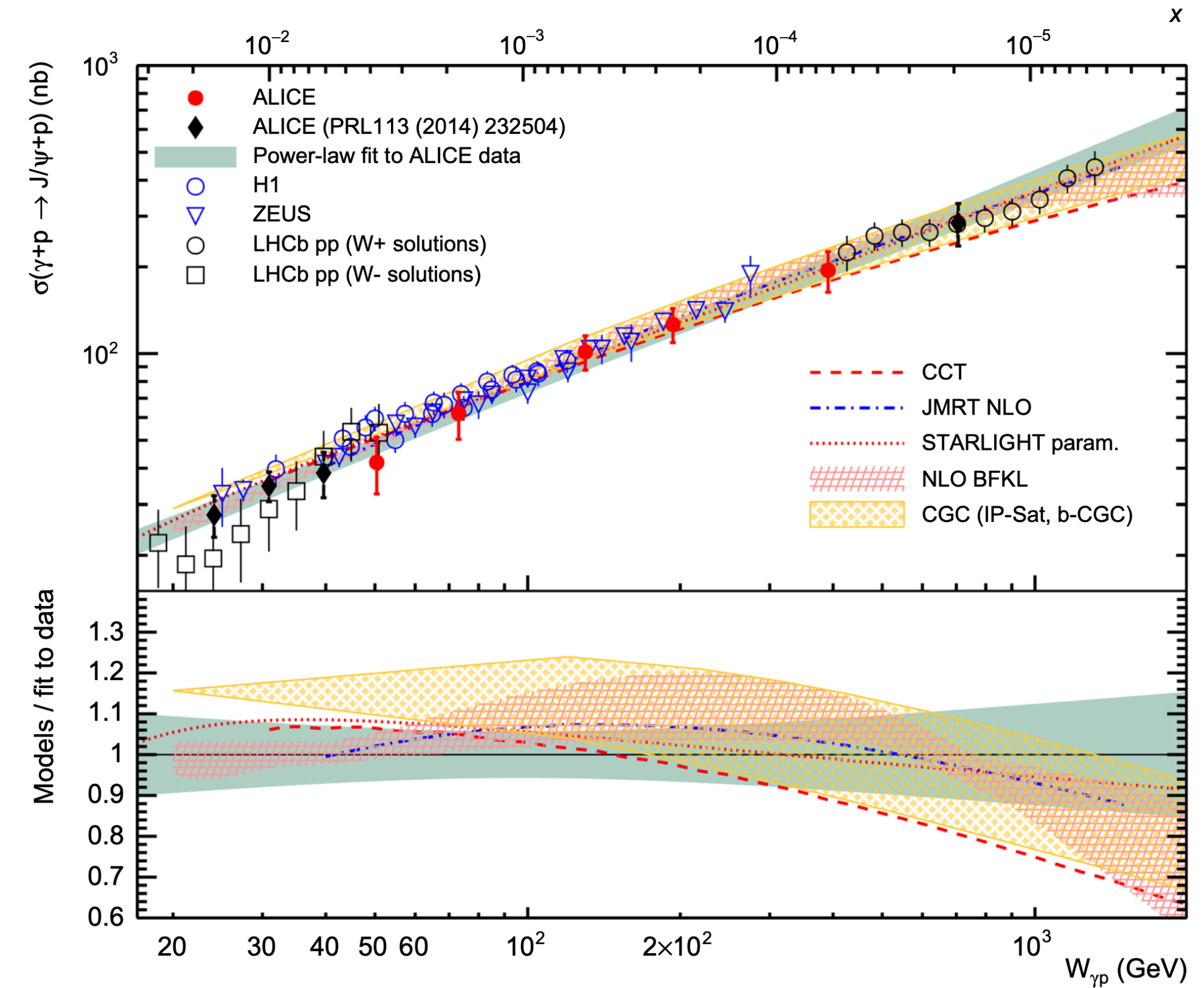
ALICE, JHEP 10 (2023) 119
ALICE, EPJC 81 (2021) 712
ALICE, PLB 798 (2019) 134926

CMS, PRL 131 (2023) 262301
LHCb, JHEP 06 (2023) 146

ALICE, EPJC 79 (2019) 402



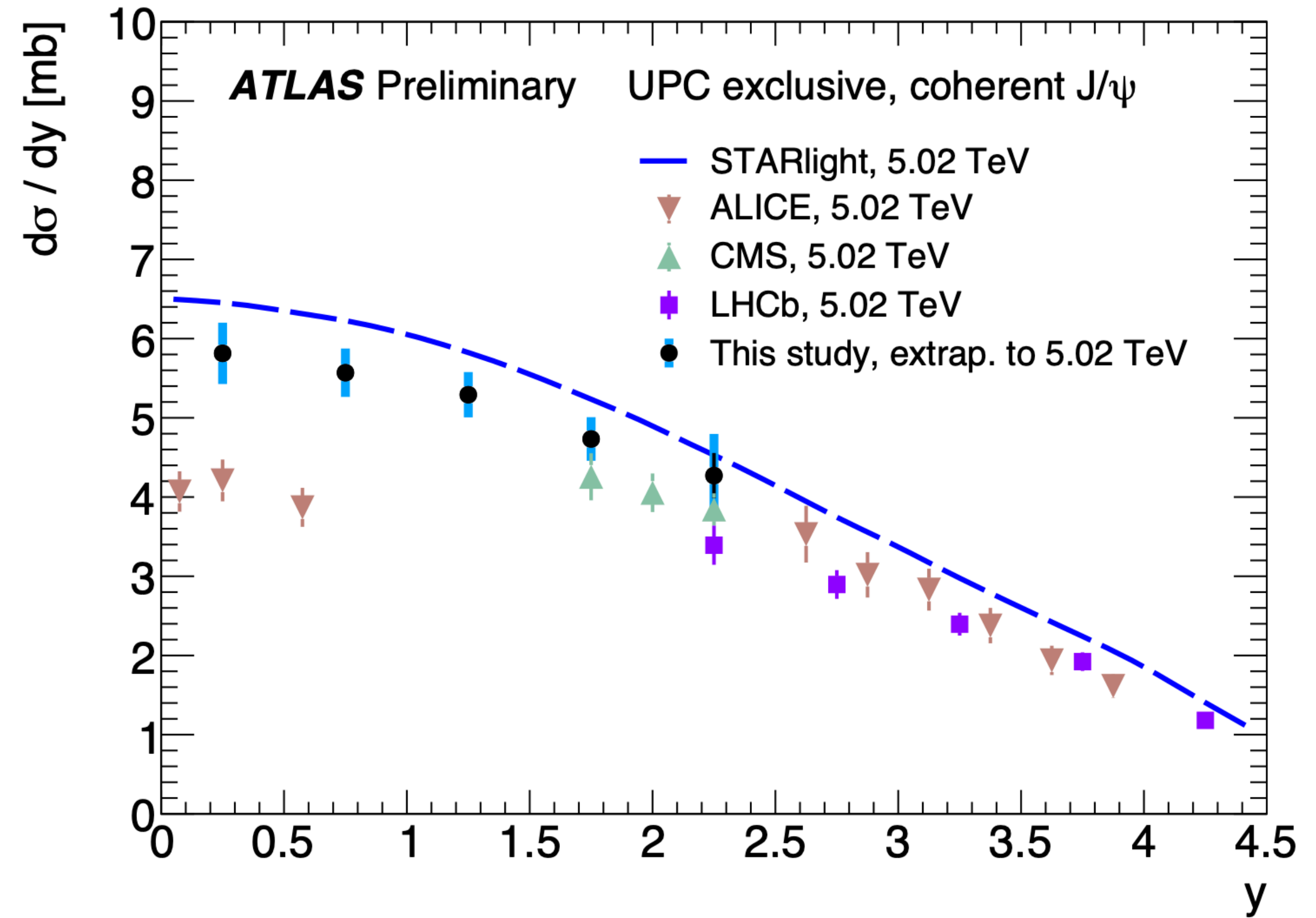
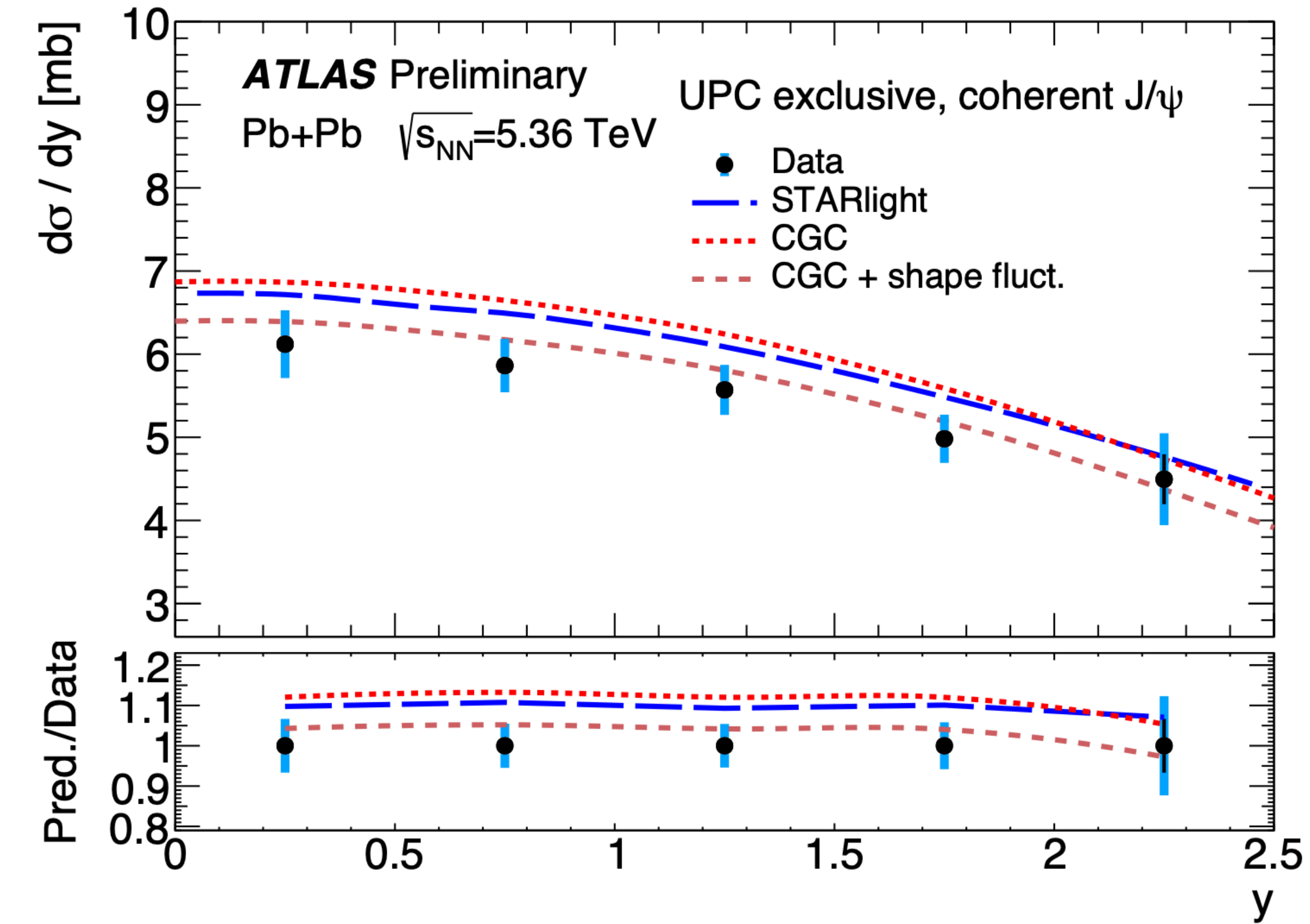
$$\gamma A \rightarrow J/\psi A$$



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

Coherent J/ψ photoproduction at LHC

ATLAS-CONF-2025-003



Extract energy dependence of incoherent J/ ψ

- Incoherent cross section accounted for in 0nAn*

$$\frac{d\sigma_{\text{PbPb} \rightarrow \text{PbPb}' J/\psi}^{0\text{nAn}^*}(y)}{dy} = \frac{d\sigma_{\text{PbPb} \rightarrow \text{PbPb}' J/\psi}^{0\text{nXn}}(y)}{dy} + \frac{d\sigma_{\text{PbPb} \rightarrow \text{PbPb}' J/\psi}^{0\text{n0n}}(y)}{dy}$$

- Photon flux calculated with STARLIGHT

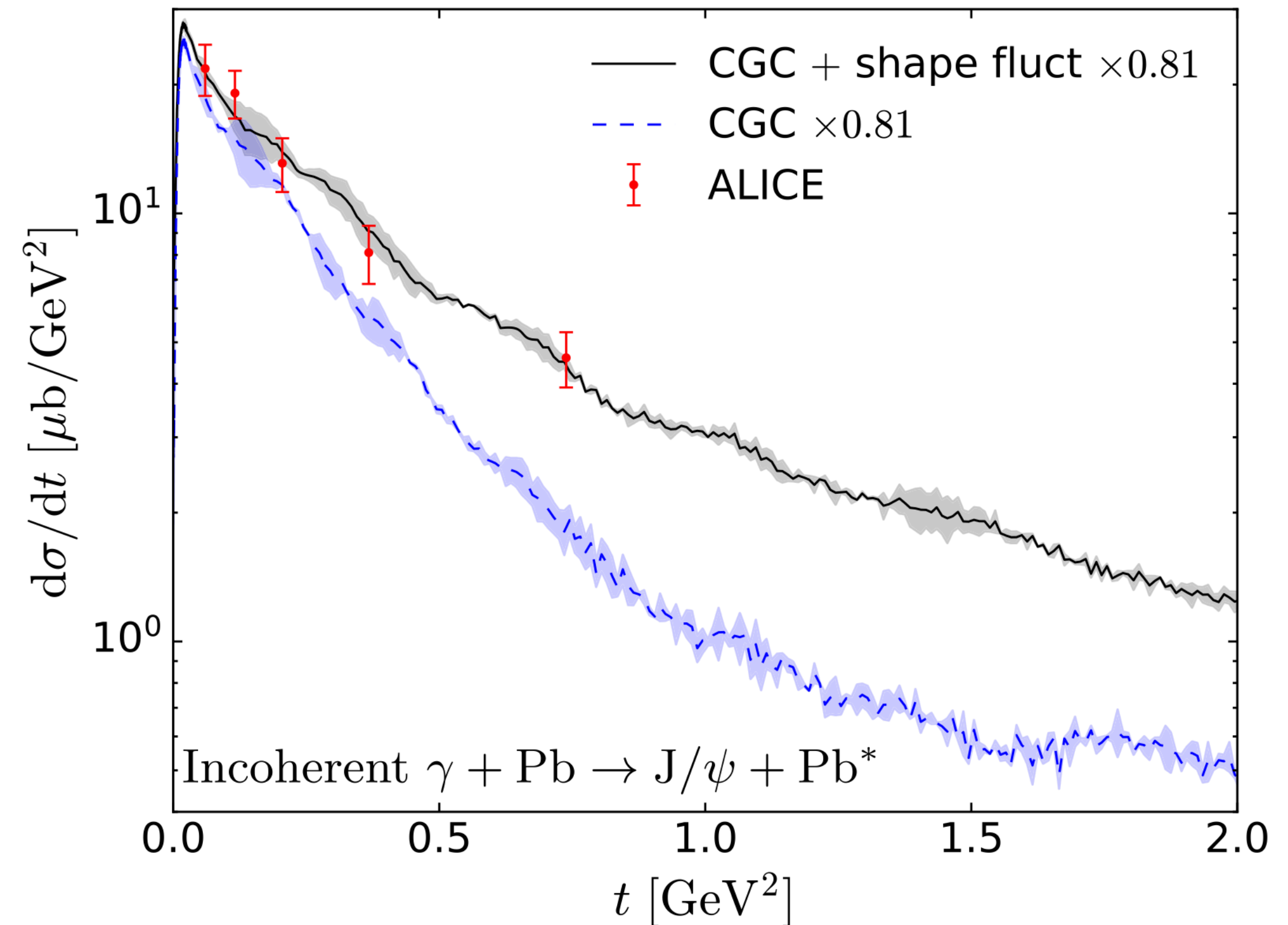
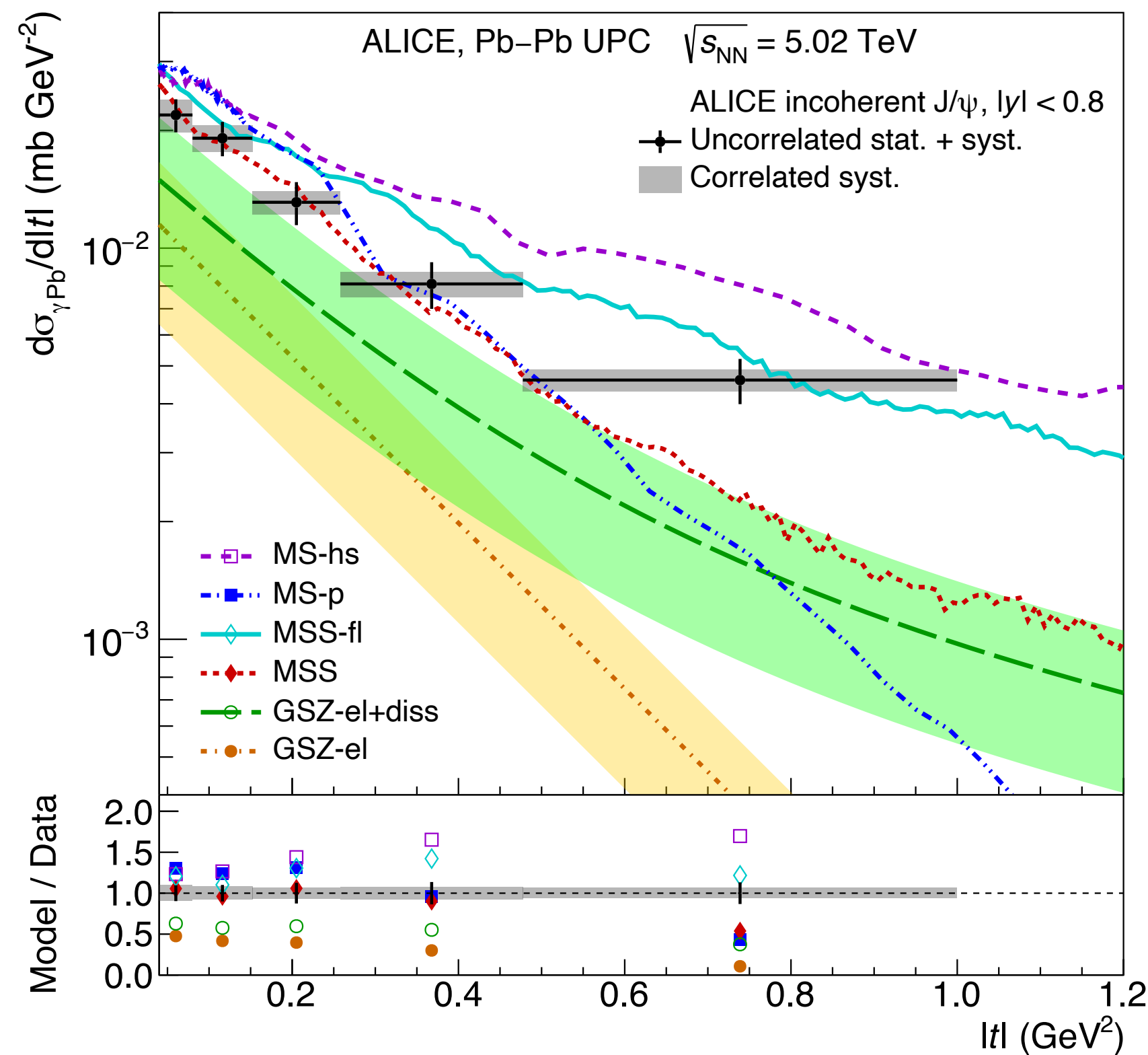
$$n_{\gamma/\text{Pb}}^{0\text{nAn}^*}(\omega) = n_{\gamma/\text{Pb}}^{0\text{n0n(EMD)}}(\omega) + \frac{1}{2} n_{\gamma/\text{Pb}}^{0\text{nXn(EMD)}}(\omega)$$

$$\sigma_{\gamma\text{Pb} \rightarrow J/\psi\text{Pb}'}(W) = \frac{d\sigma_{\text{PbPb} \rightarrow \text{PbPb}' J/\psi}^{0\text{nAn}^*}(y)}{dy} / n_{\gamma/\text{Pb}}^{0\text{nAn}^*}(\omega)$$

Incoherent J/ψ production with ALICE

ALICE, PRL 132 (2024) 162302

Mäntysaari et al., PRD 109 (2024) L071504



- CGC model with sub-nucleon fluctuations can describe the $|t|$ spectrum shape of incoherent J/ψ but not for the magnitude