Probing nuclear gluon structure with photoproduced J/ψ in ultra-peripheral collisions

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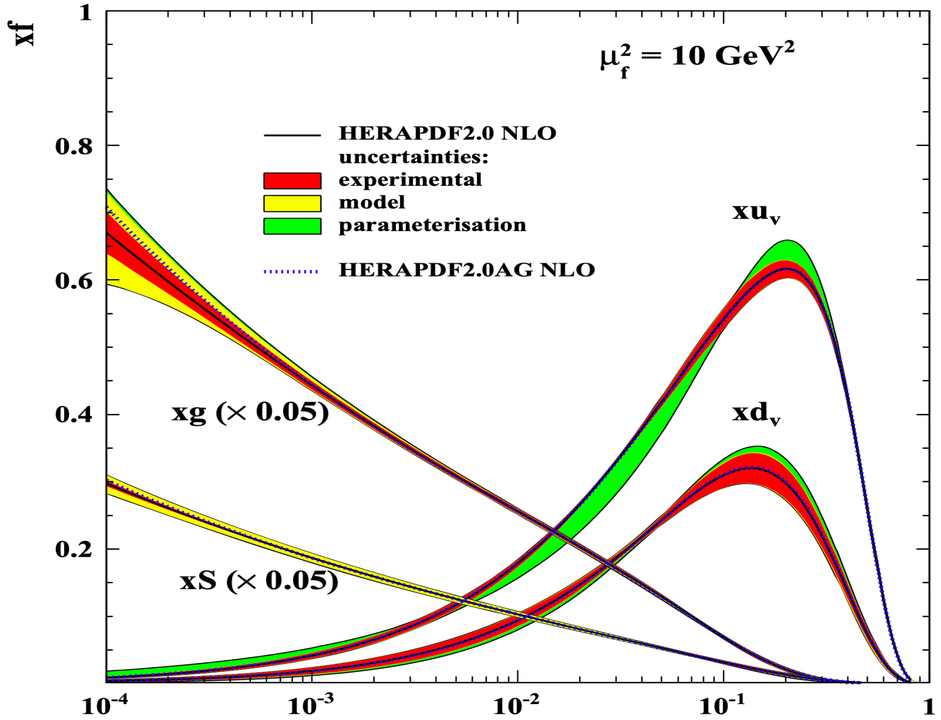
What's the ultimate destiny of gluon?

H1 and ZEUS, EPJC 75 (2015) 580



Small x ⟵ Large x

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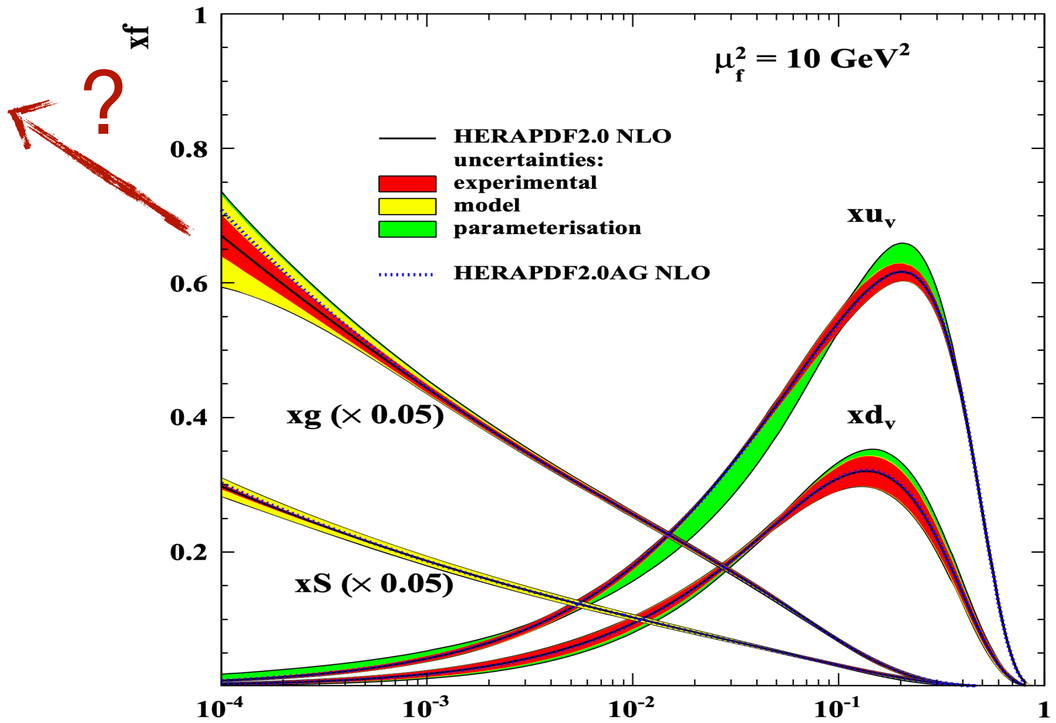
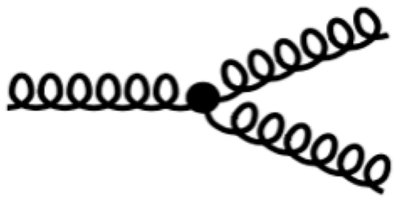


Small x ⟵ Large x

Splitting

Recombination



?

=

Saturation

$\sim N_g$(linear)

$\sim (N_g)^2$(nonlinear)

QCD unitarity: growth of gluon density can't continue indefinitely!

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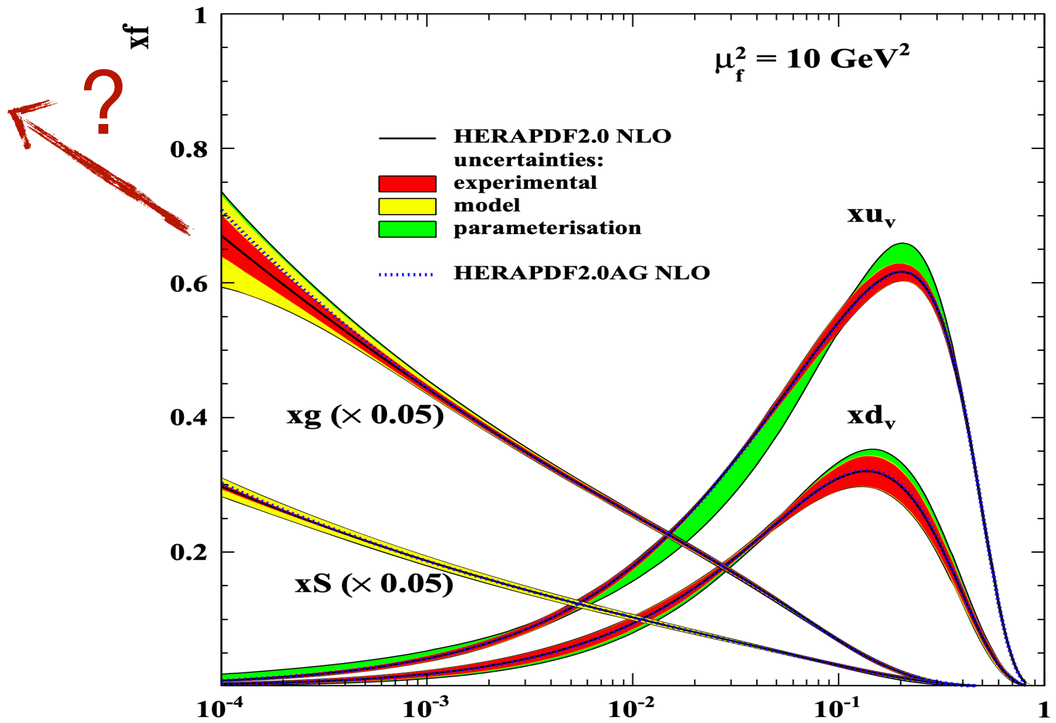

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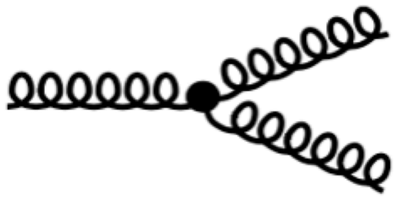

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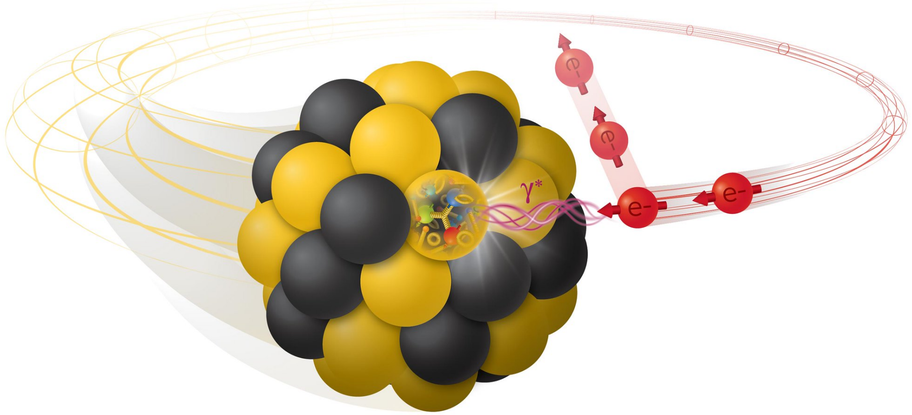
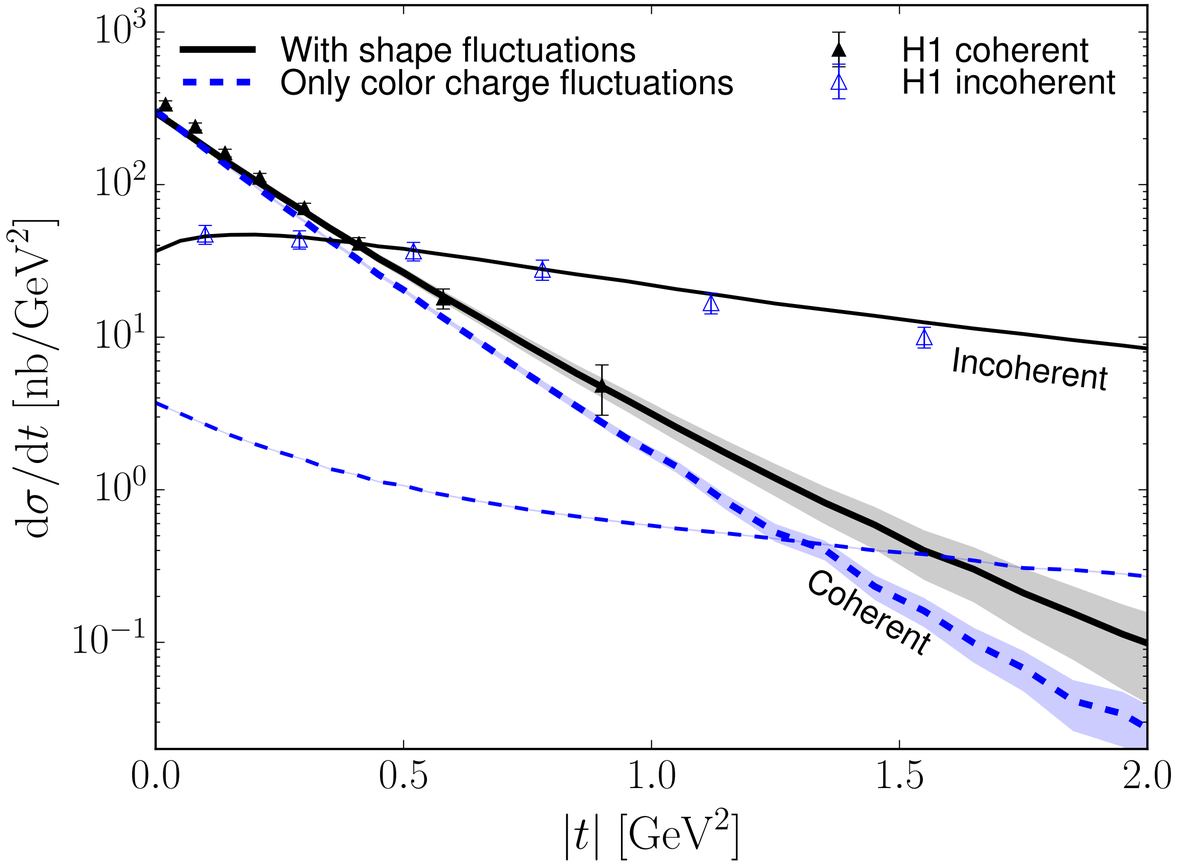
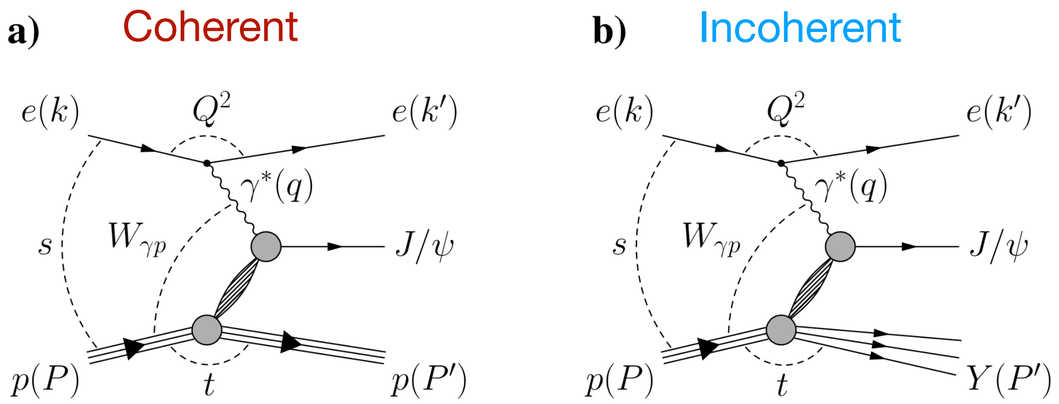


The critical role of gluon fluctuation

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

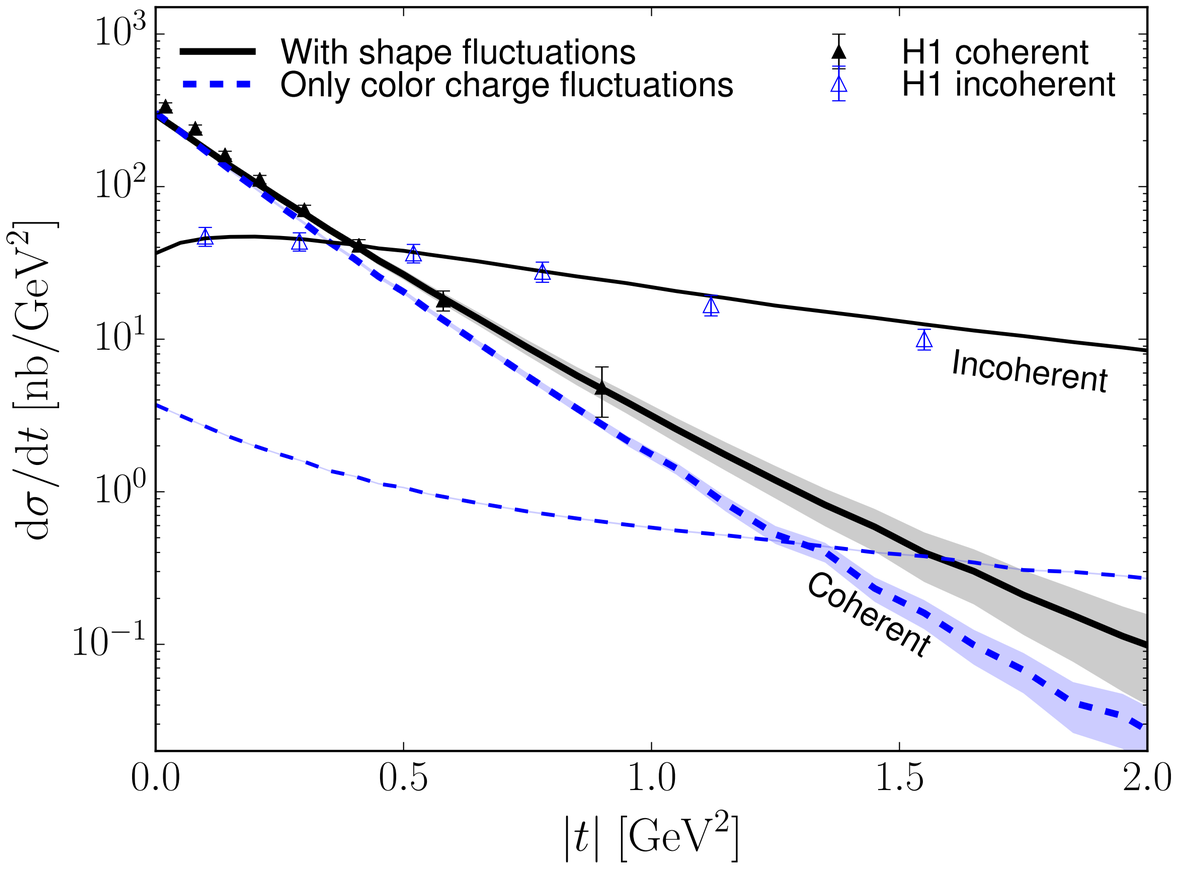


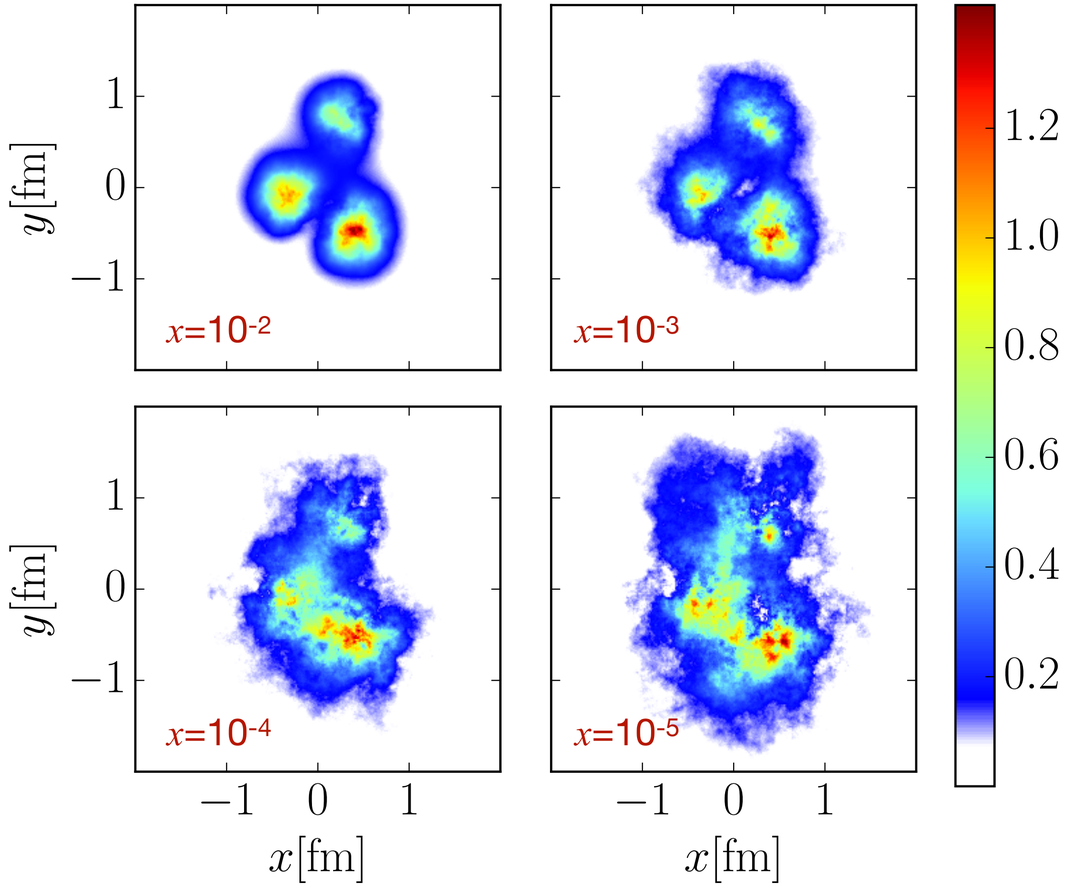


- The critical role of gluon fluctuations
  - Only CGC considering gluon fluctuations can describe HERA data

The critical role of gluon fluctuation

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





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The critical role of gluon fluctuation

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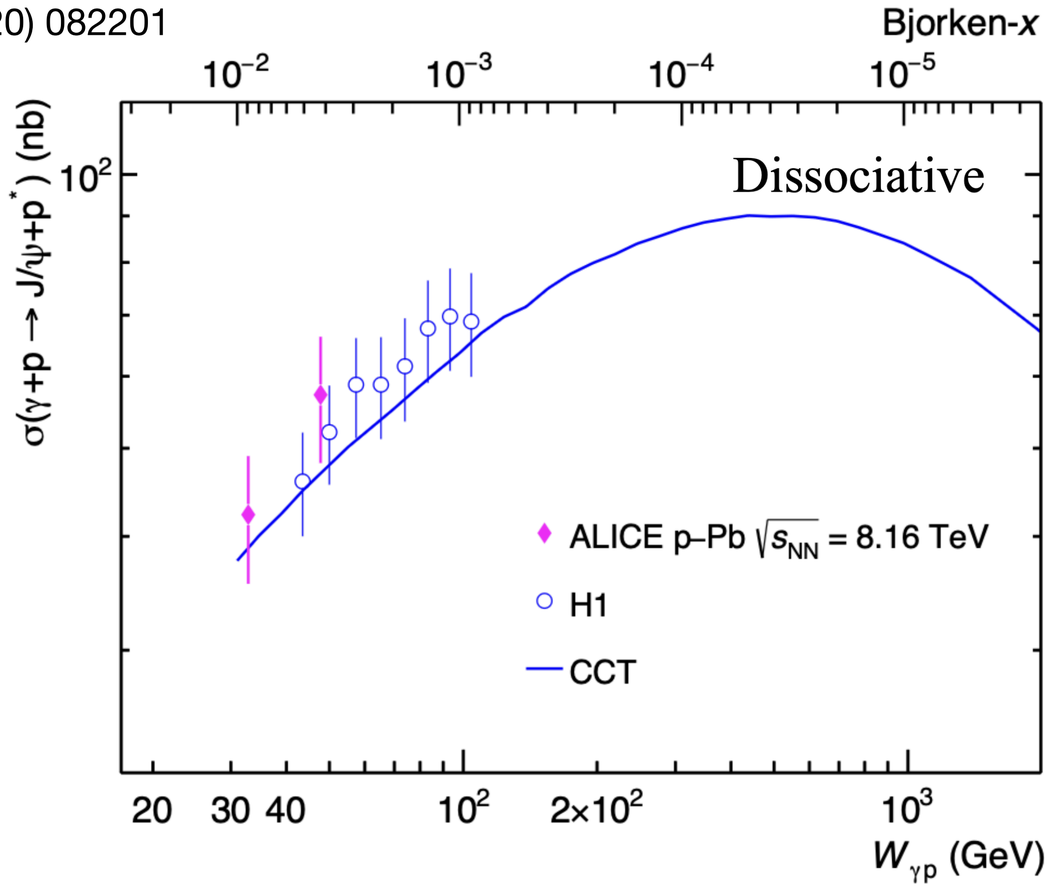
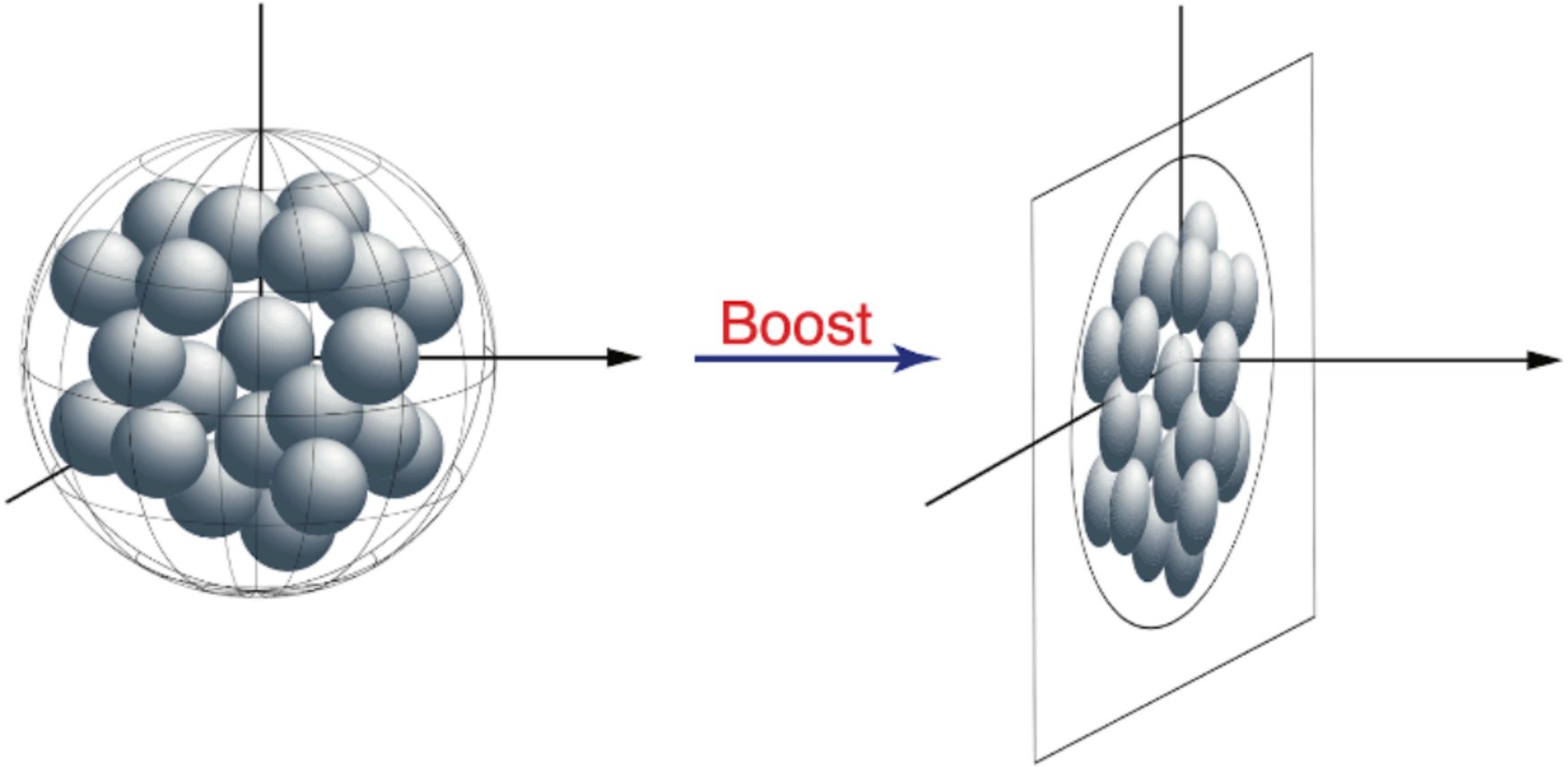


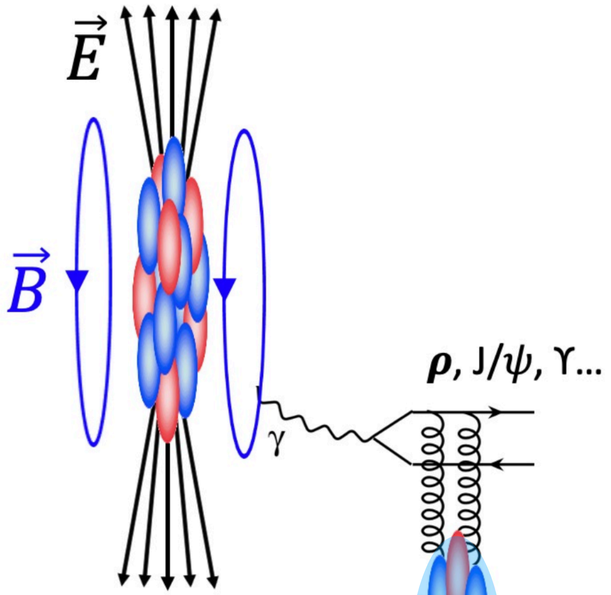
- Increasing energy, probing lower-x gluons
  - Reduce variance over configurations → reduce the incoherent vector meson cross section → signature of gluon saturation

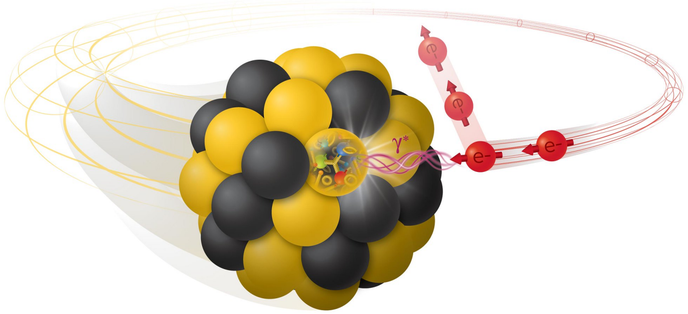
Ultra-dense gluonic matter



Gluon saturation is expected to be easier to be achieved inside heavy nuclei

Photon-nuclear interactions in UPC

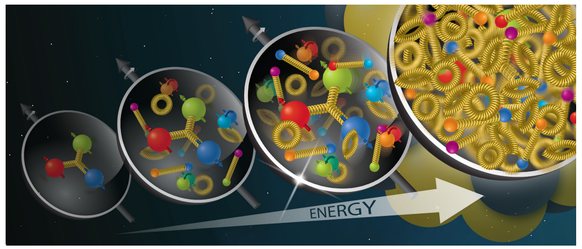




Average gluon structure

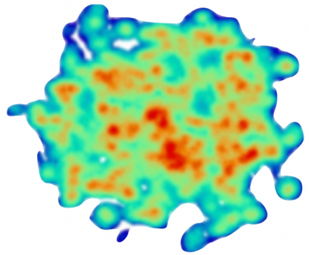
Coherent (nuclear keeps intact)

$\langle p_T \rangle \sim 50$ MeV



Incoherent (nuclear breaks up)

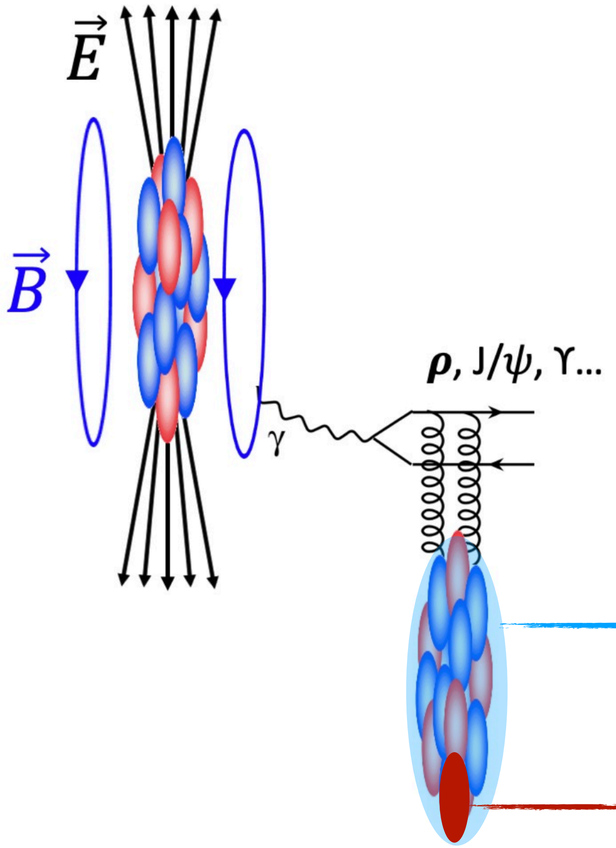
$\langle p_T \rangle \sim 500$ MeV

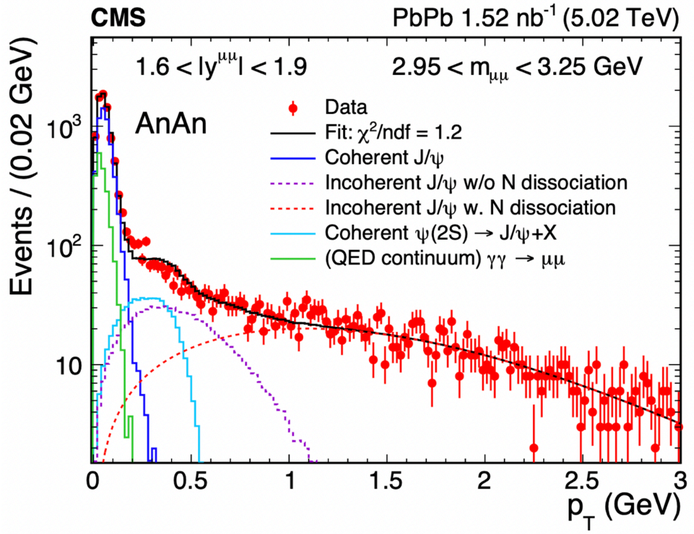


Sub-nucleon fluctuation

Little “EIC”

Photon-nuclear interactions in UPC





CMS, PRL 131 (2023) 262301

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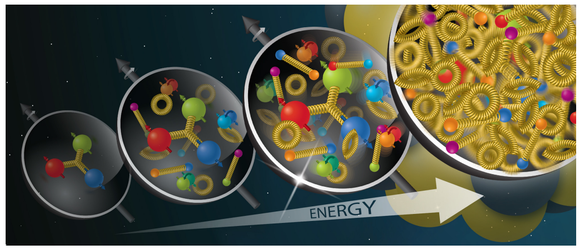

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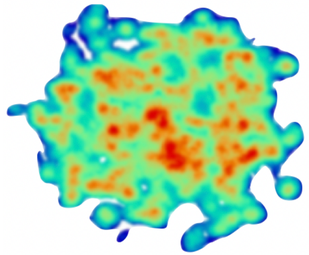
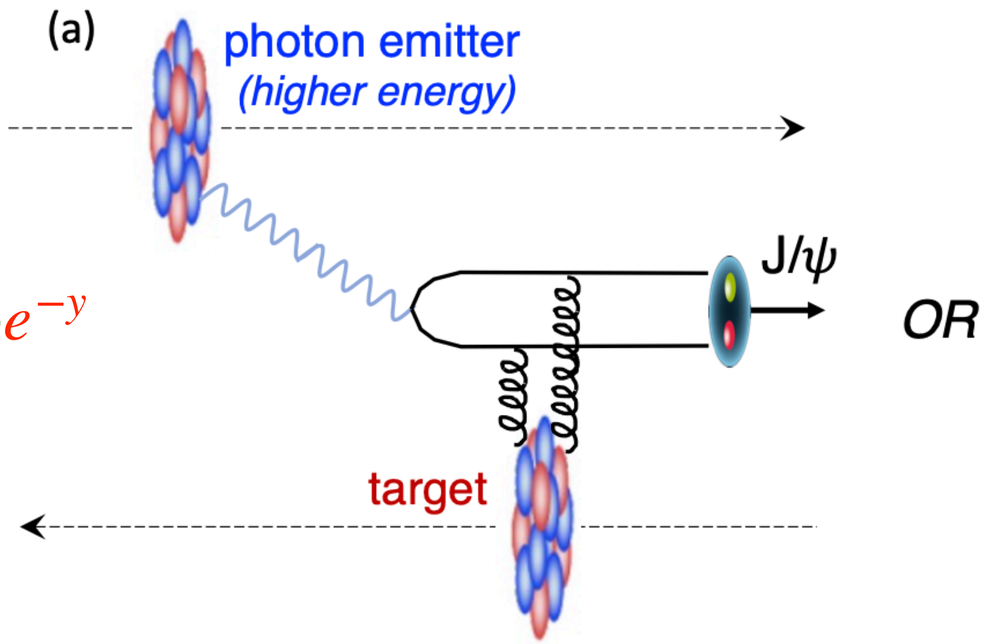


Sub-nucleon fluctuation

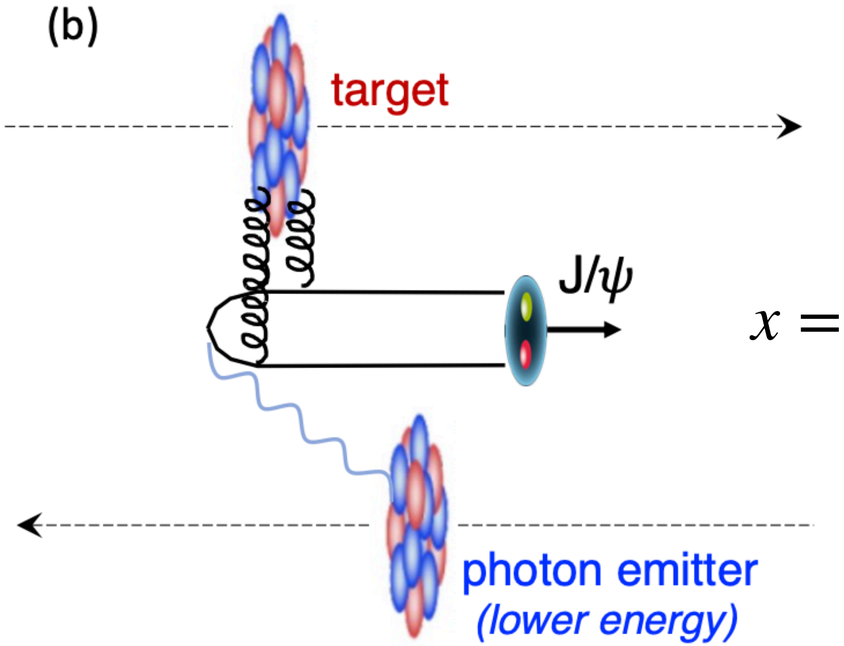
Little “EIC”

The “two-way ambiguity” problem



$$x = \frac{M_{J/\psi}}{2E_{beam}} e^{-y}$$

OR



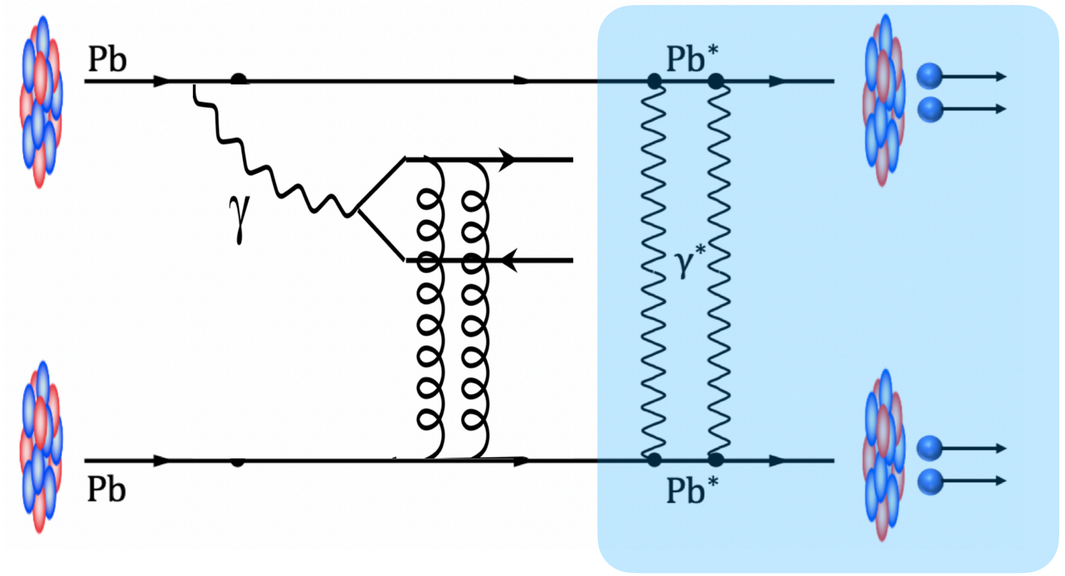
$$x = \frac{M_{J/\psi}}{2E_{beam}} e^{+y}$$

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

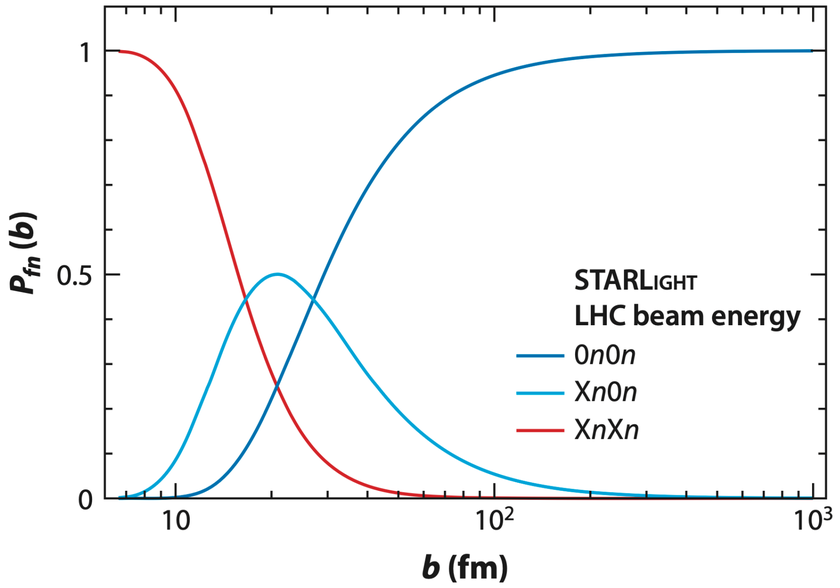
A solution to the “two-way ambiguity”

- Employ **neutron tagging** to measure the energy dependence of photoproduced vector mesons

Coherent photoproduction



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



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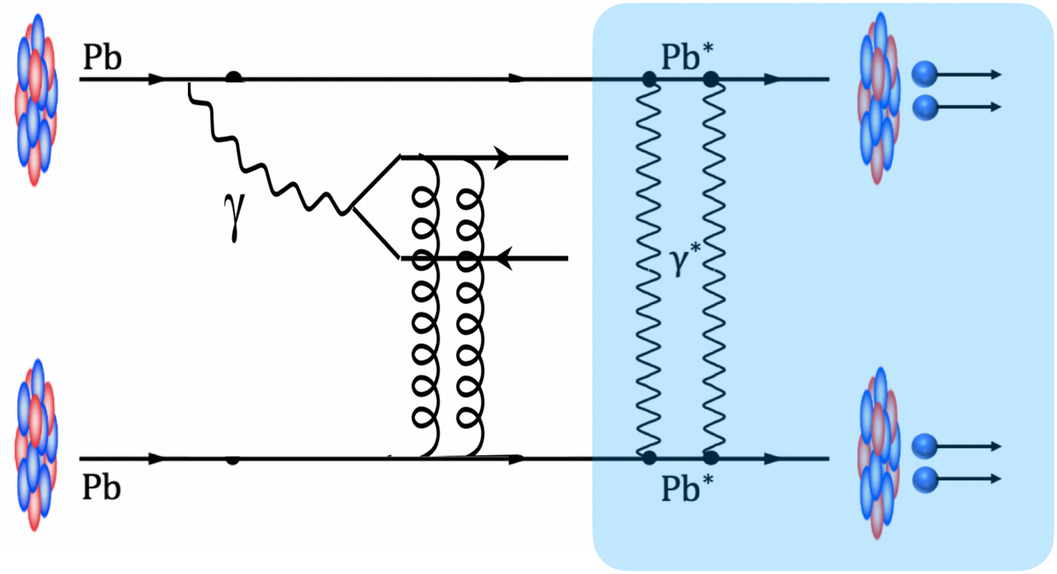

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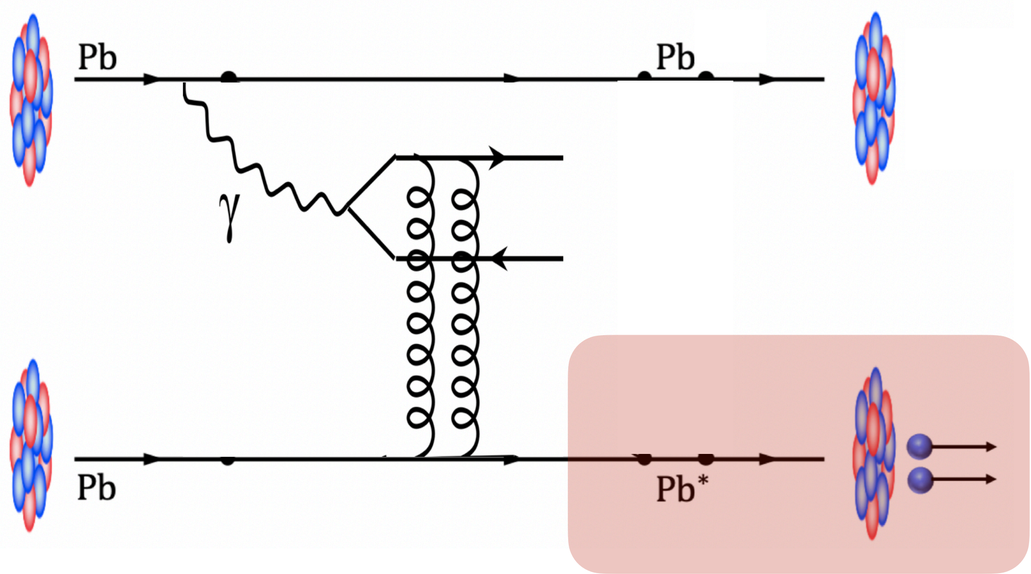

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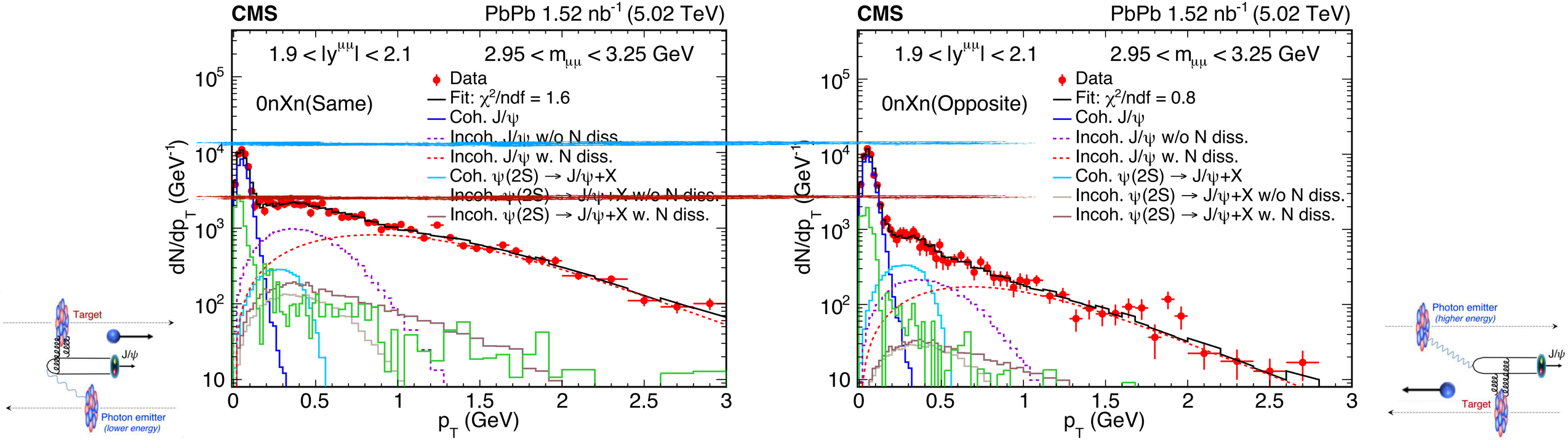
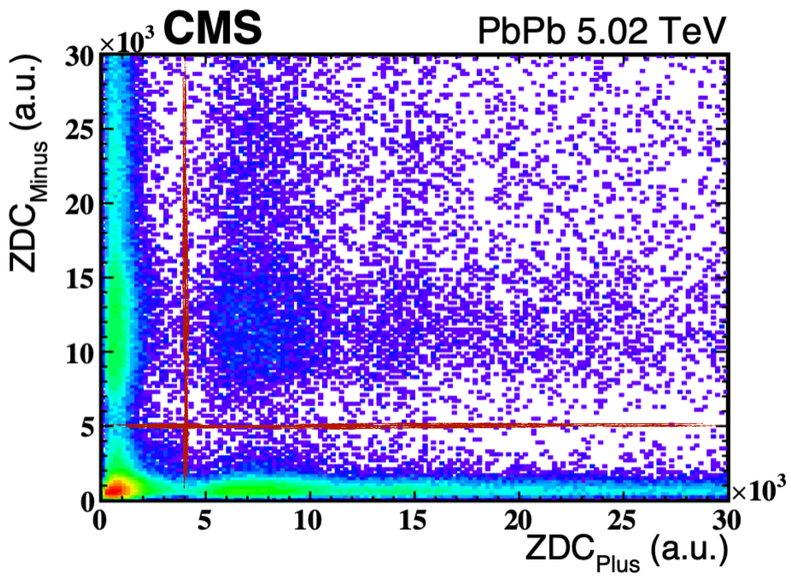
A solution to the “two-way ambiguity”

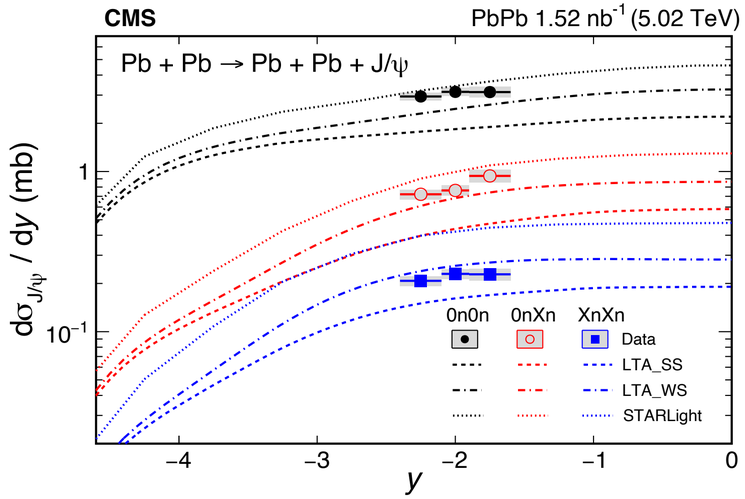
CMS, PRL 135 (2025) 112301



- Coherent J/ψ: no correlation with neutron emissions
- Incoherent J/ψ: strong correlation with neutron emissions

Solve the “two-way ambiguity” for coherent J/ψ





Guzey et al., EPJC 74 (2014) 2942

Experimental measurements

Photon flux from theory

$$\frac{d\sigma^{0n0n}_{AA\to AA'J/\psi}}{dy} = N^{0n0n}_{\gamma/A}(\omega_1)\cdot\sigma_{\gamma A\to J/\psi A'(\omega_1)} + N^{0n0n}_{\gamma/A}(\omega_2)\cdot\sigma_{\gamma A\to J/\psi A'(\omega_2)}$$

$$\frac{d\sigma^{0nXn}_{AA\to AA'J/\psi}}{dy} = N^{0nXn}_{\gamma/A}(\omega_1)\cdot\sigma_{\gamma A\to J/\psi A'(\omega_1)} + N^{0nXn}_{\gamma/A}(\omega_2)\cdot\sigma_{\gamma A\to J/\psi A'(\omega_2)}$$

$$\frac{d\sigma^{XnXn}_{AA\to AA'J/\psi}}{dy} = N^{XnXn}_{\gamma/A}(\omega_1)\cdot\sigma_{\gamma A\to J/\psi A'(\omega_1)} + N^{XnXn}_{\gamma/A}(\omega_2)\cdot\sigma_{\gamma A\to J/\psi A'(\omega_2)}$$

What we need!

↓

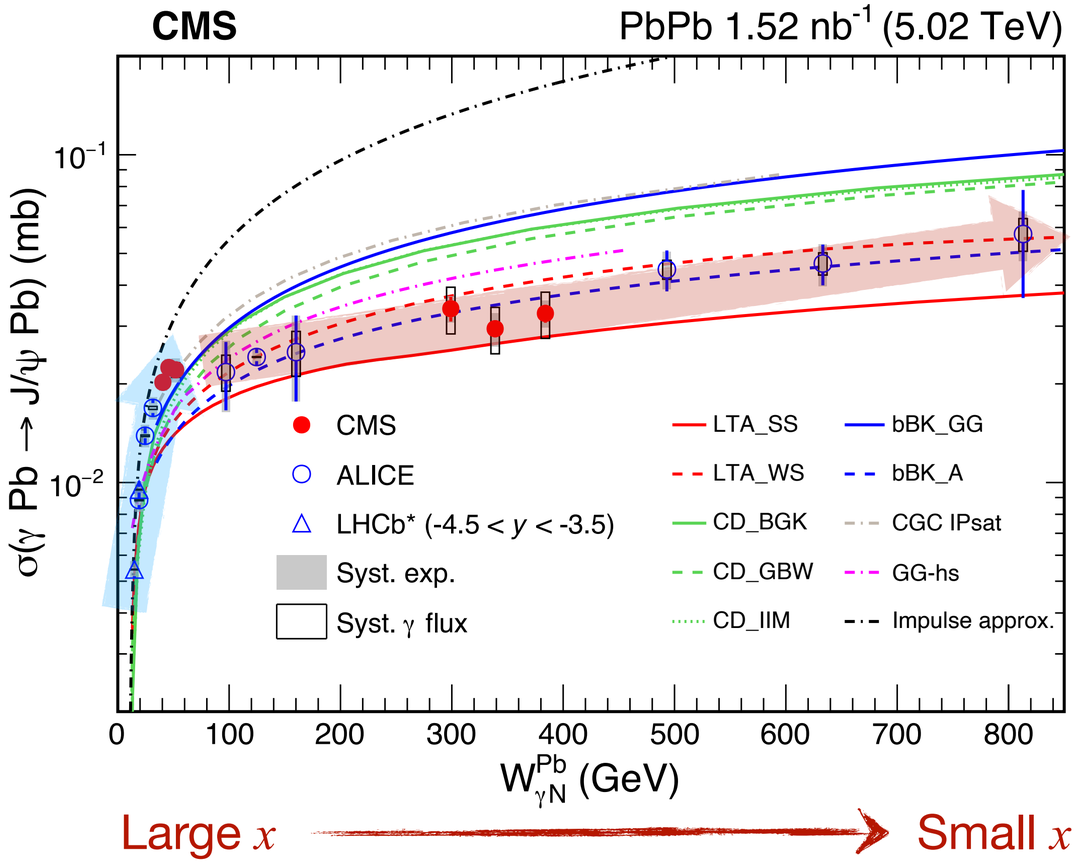
Solve the “two-way ambiguity”

↓

Probe gluons at x~10^{-5}-10^{-4} in heavy nucleus!

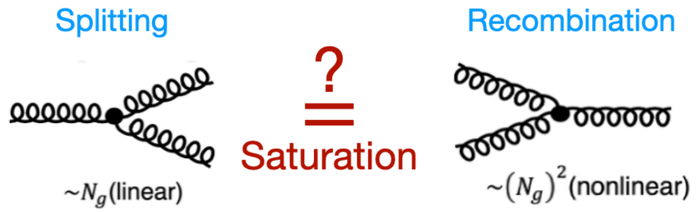
Energy dependence of coherent J/ψ

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



Large x → Small x

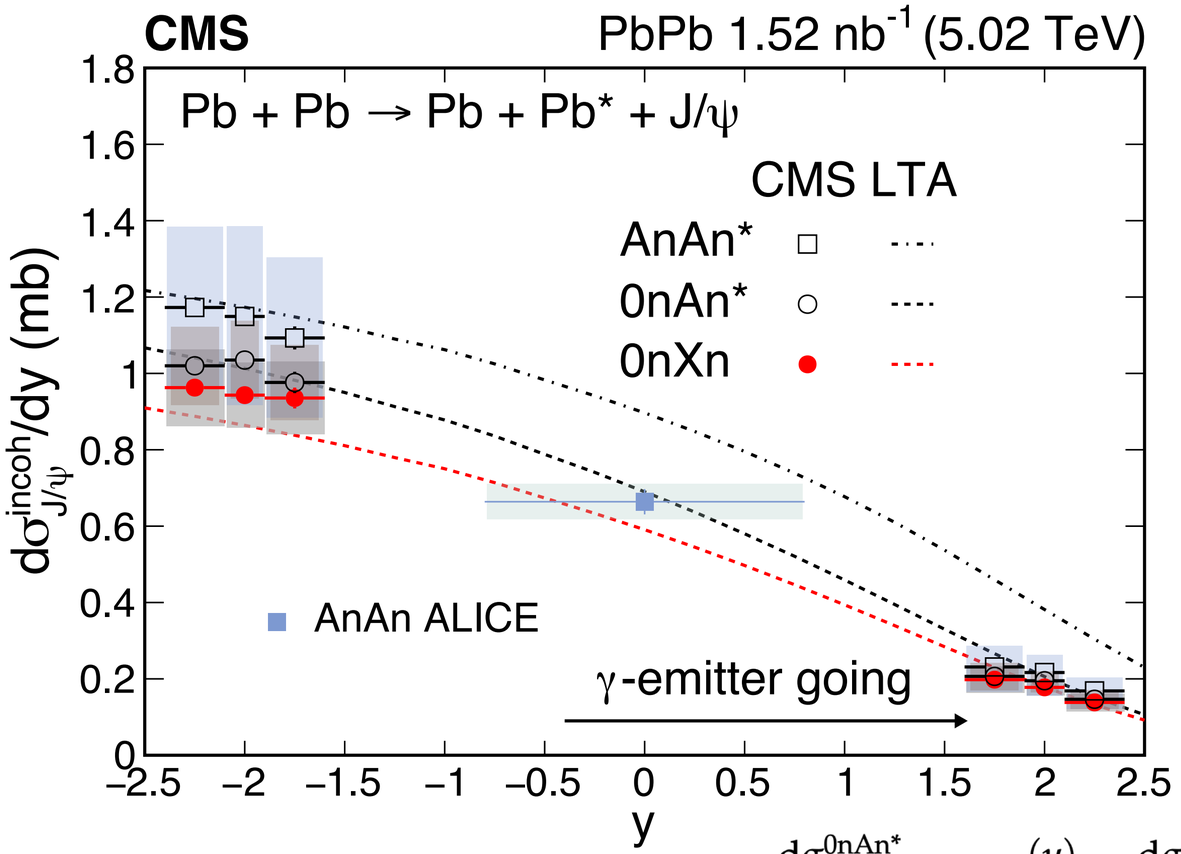
CMS, PRL 131 (2023) 262301
ALICE, JHEP 10 (2023) 119



- 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

Solve the “two-way ambiguity” for incoherent J/ψ

CMS, PRL 135 (2025) 112301

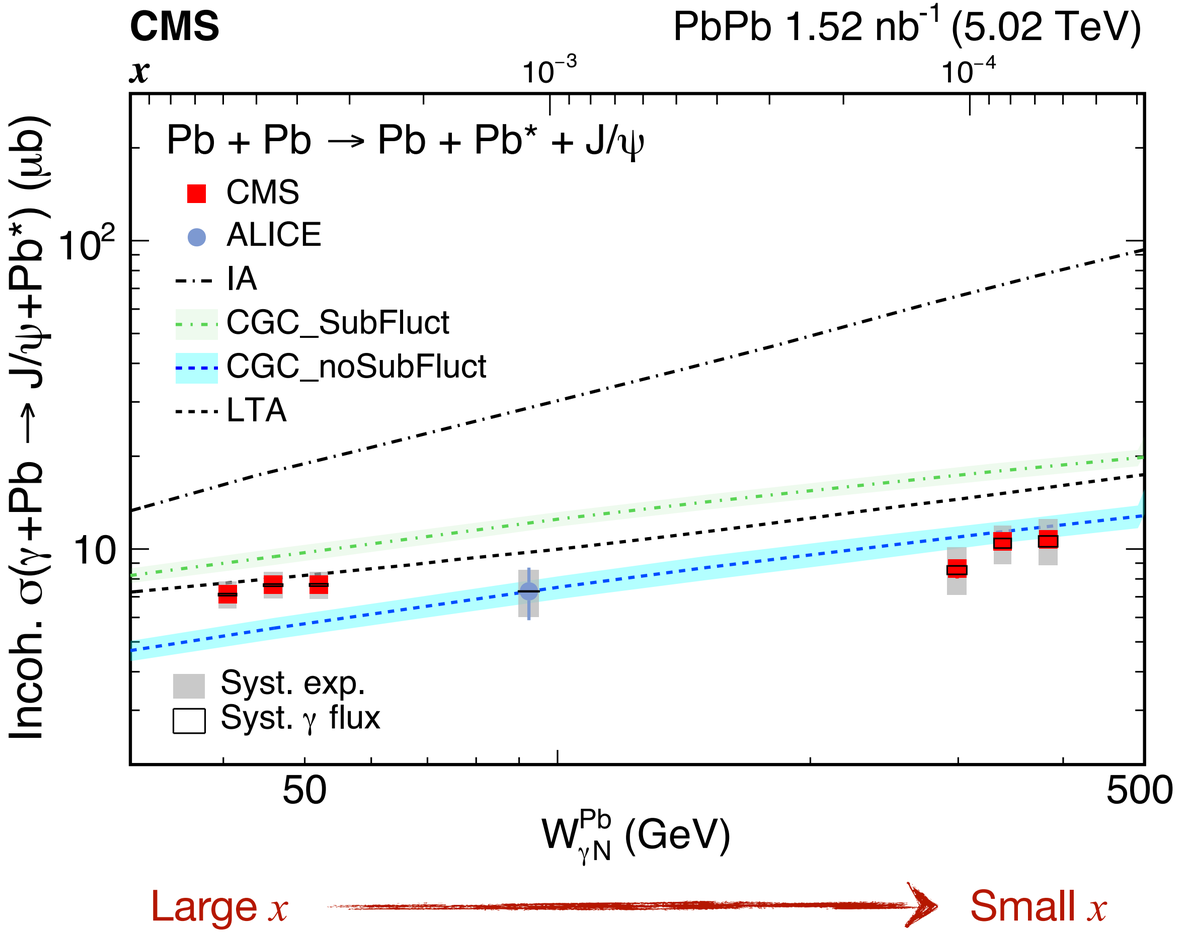


$$\frac{d\sigma^{0nAn^*}_{PbPb\to PbPb'J/\psi}(y)}{dy} = \frac{d\sigma^{0nXn}_{PbPb\to PbPb'J/\psi}(y)}{dy} + \frac{d\sigma^{0n0n}_{PbPb\to PbPb'J/\psi}(y)}{dy}$$

- 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

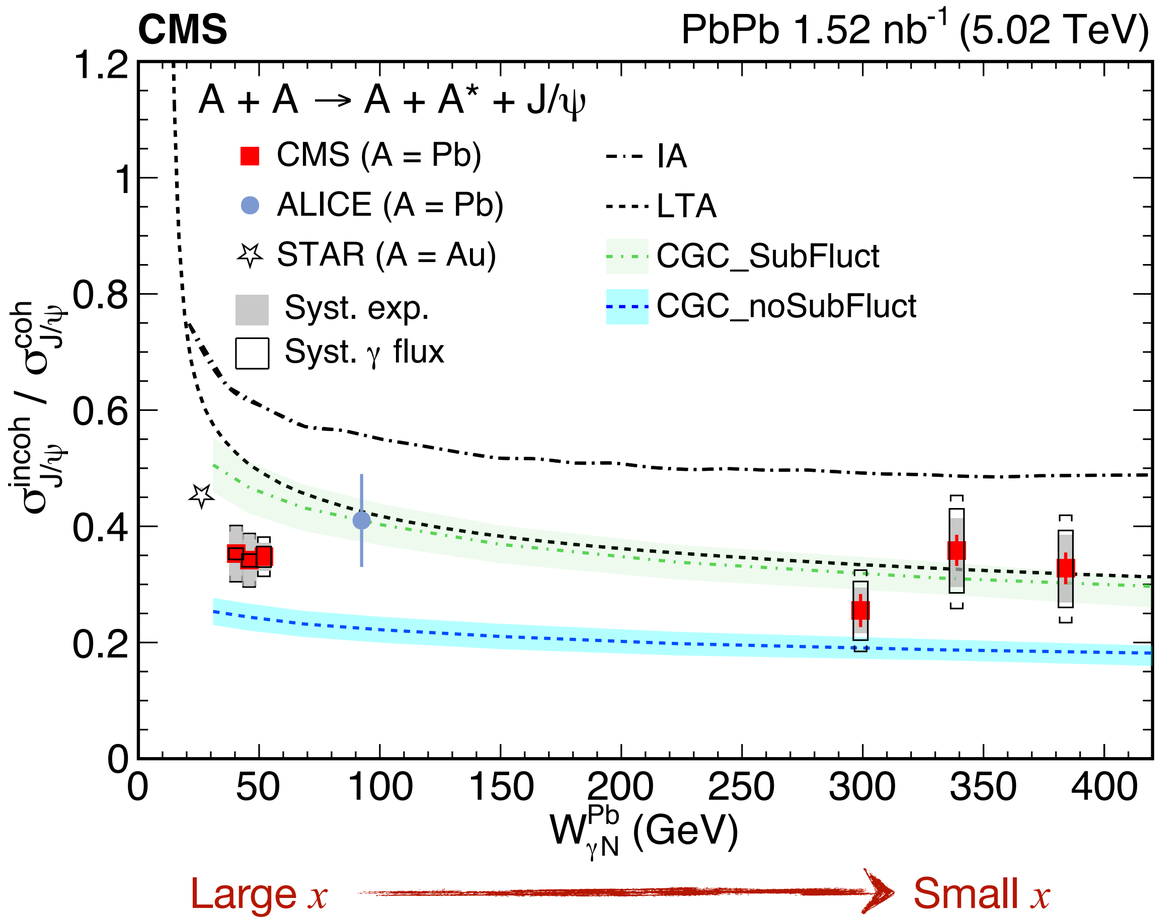
CMS, PRL 135 (2025) 112301



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

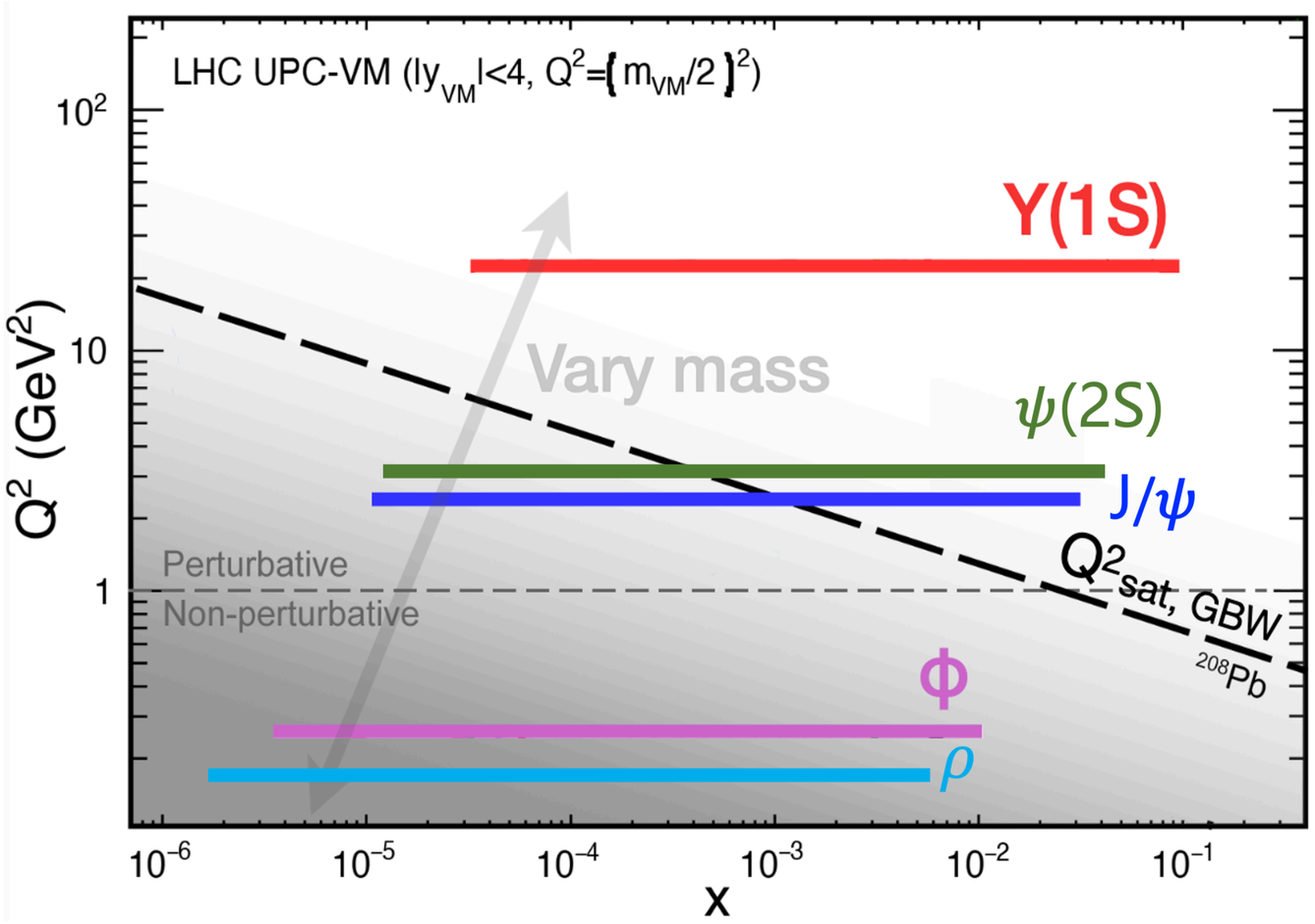
Comparisons of coherent and incoherent J/ψ

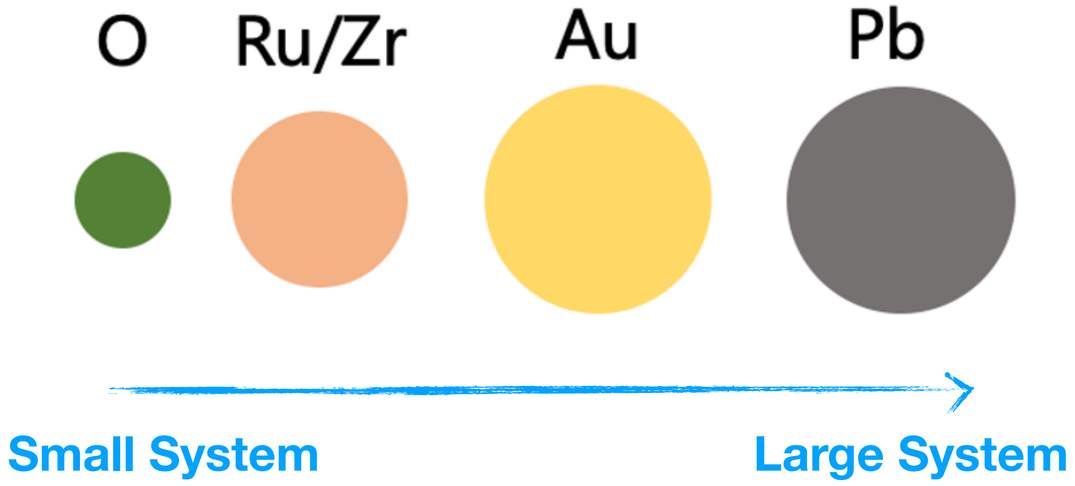
CMS, PRL 135 (2025) 112301
CMS, PRL 131 (2023) 262301



- Experimental and theoretical uncertainties are largely cancelled
- Ratio of incoherent/coherent J/ψ has no energy dependence
- Data are consistent CGC incorporating gluon fluctuations
  - Overestimates data at low energy

The roadmap of probing gluon structure

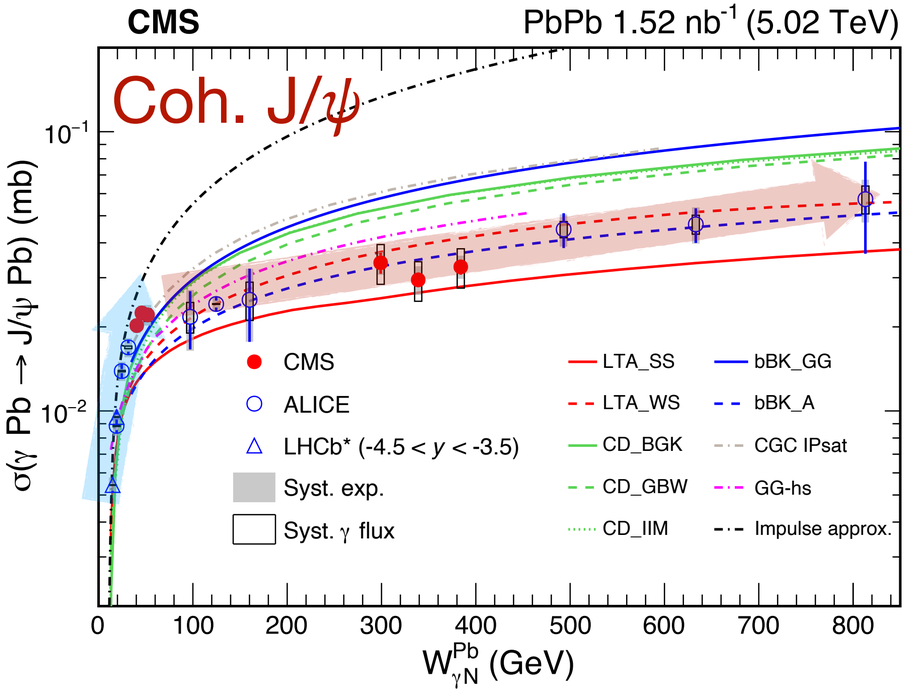


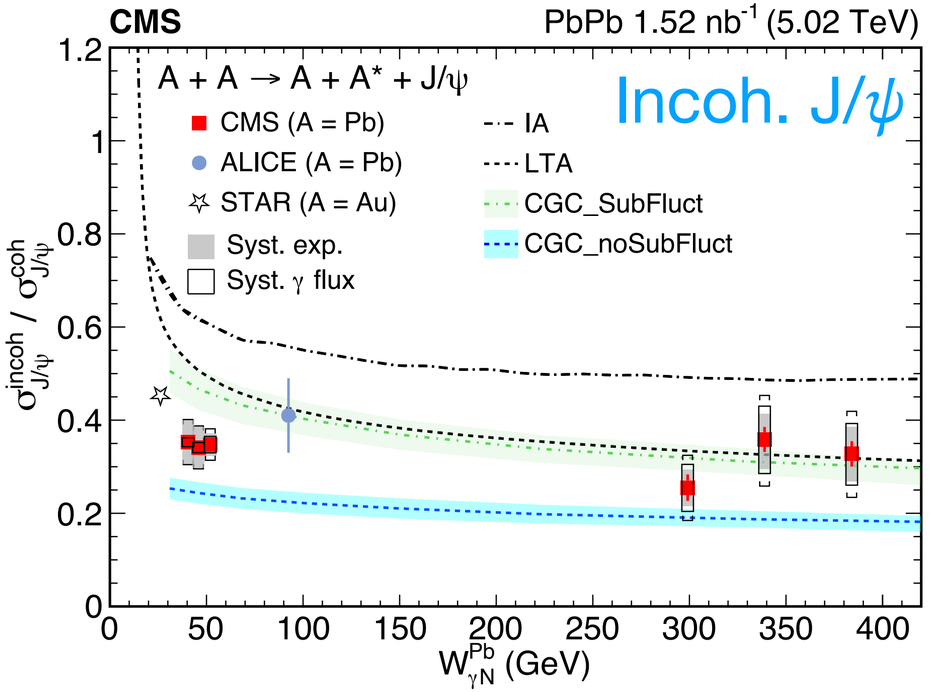


Probe gluon structure at $x - Q^2 - Q^2_{S,A}$

Summary

- First energy-dependent measurement of coherent and incoherent J/ψ production off nucleus
  - Cross-section of coherent J/ψ gradually approaches saturation at high energy
  - Ratio of incoherent/coherent J/ψ has no energy dependence





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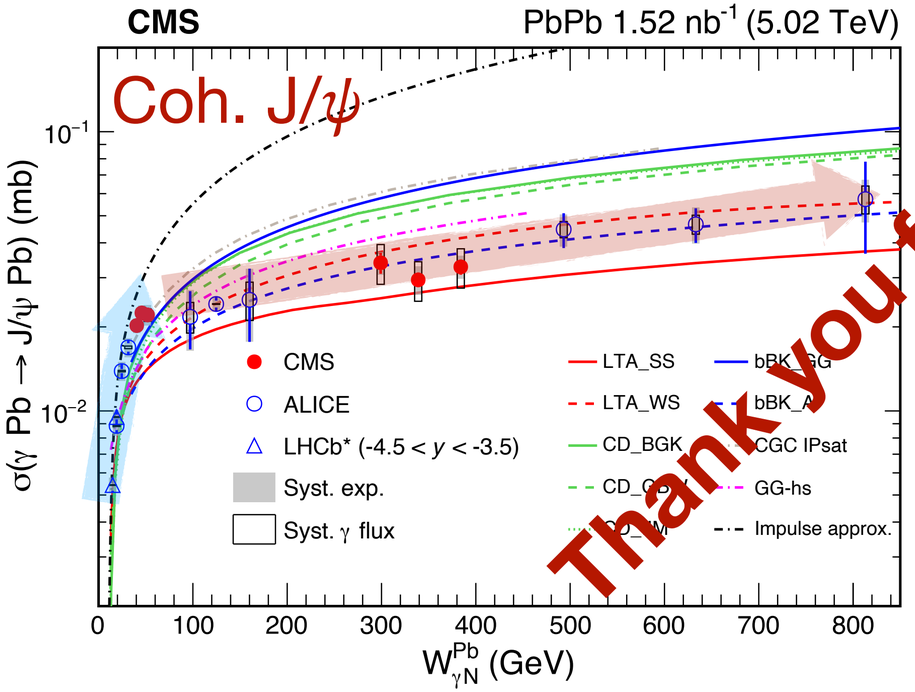
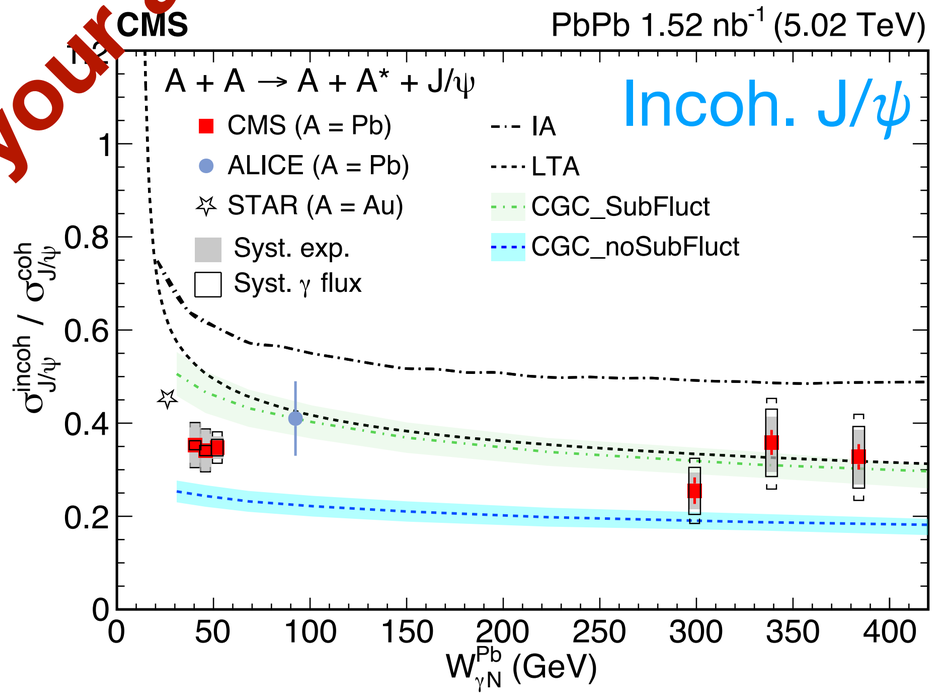


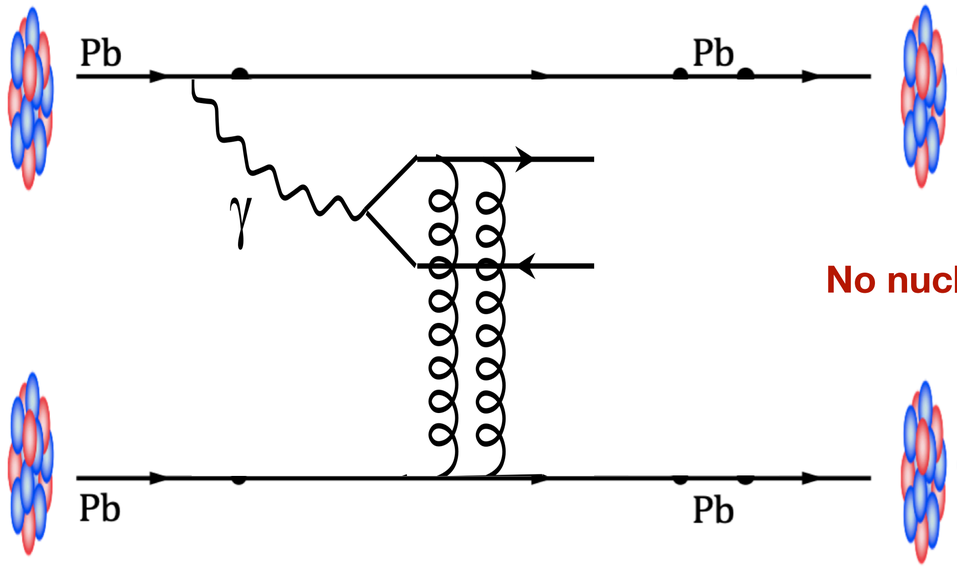


Thank you for your attention!

Backups

A solution to the “two-way ambiguity”

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



No nucleus breakup

A solution to the “two-way ambiguity”

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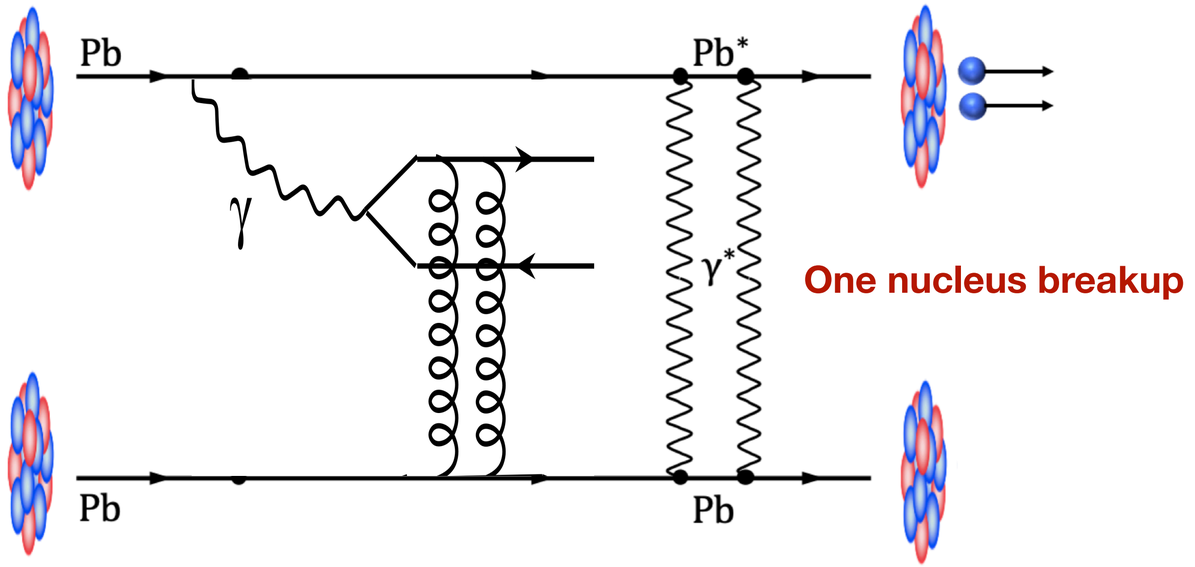

One nucleus breakup

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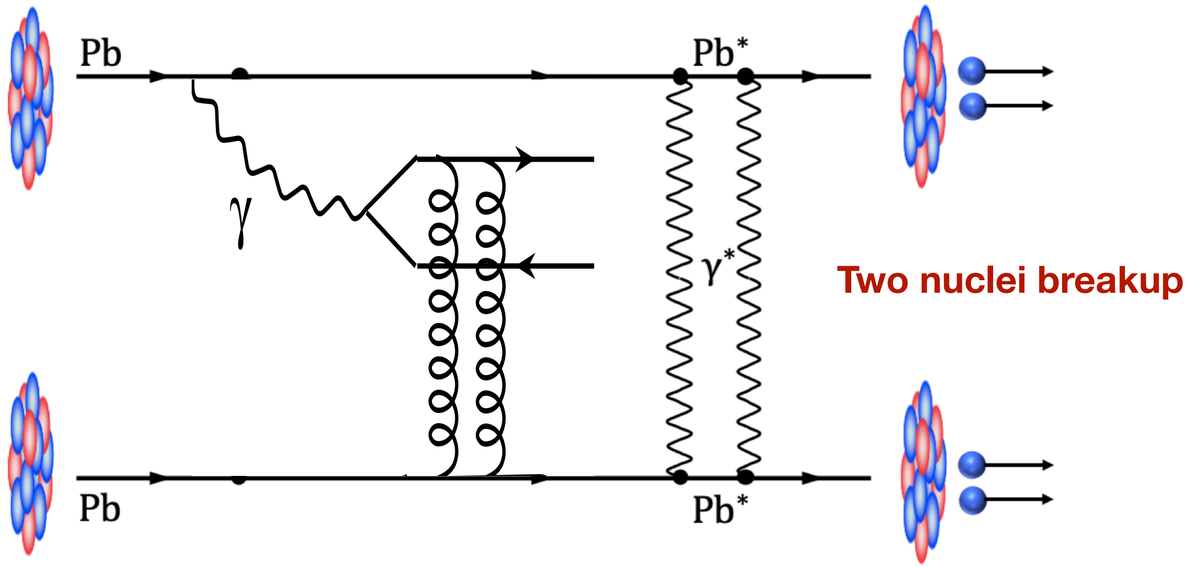
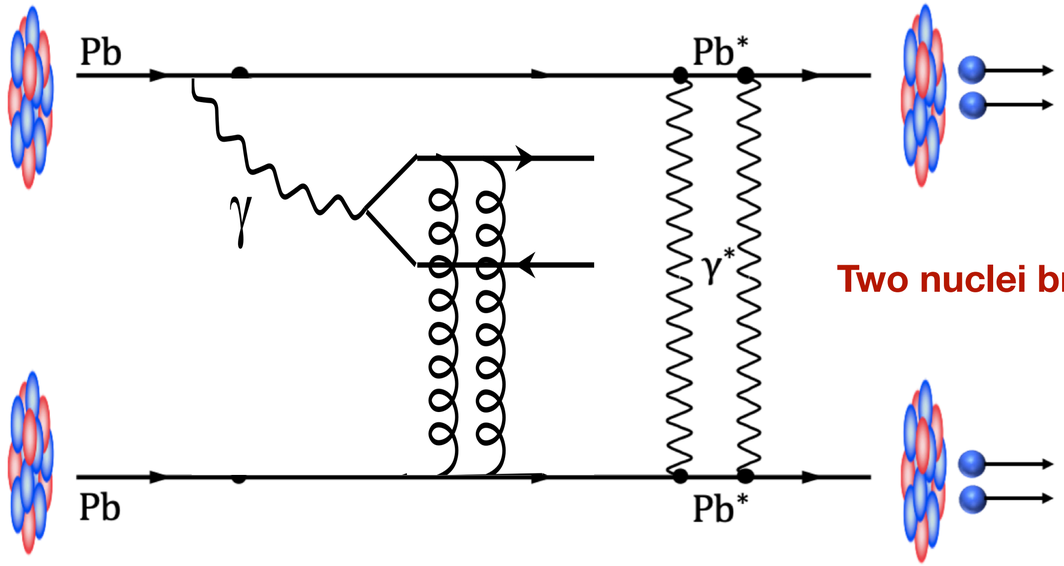


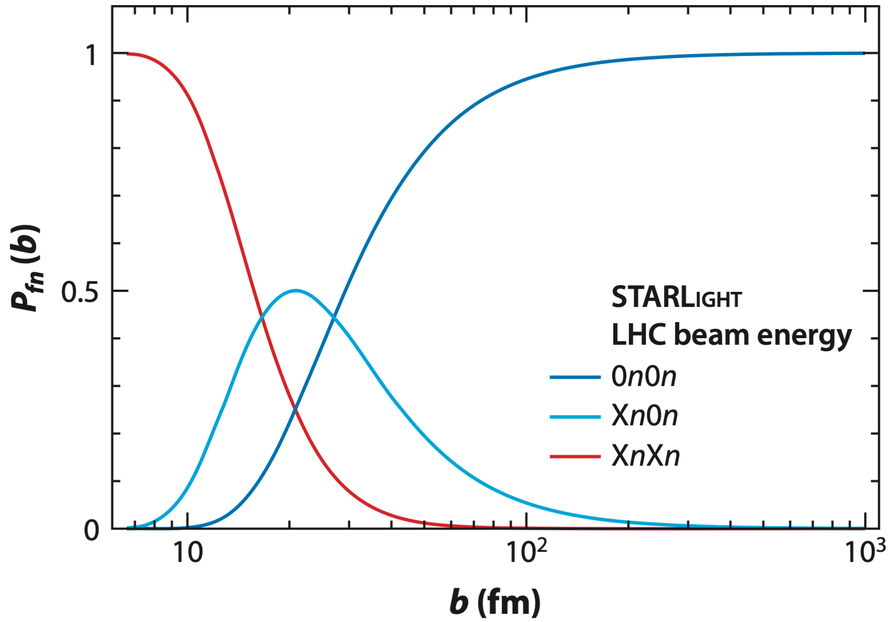
Two nuclei breakup

A solution to the “two-way ambiguity”

Nuclei **may** exchange soft photon(s) ⟹ nuclear dissociation



Two nuclei breakup

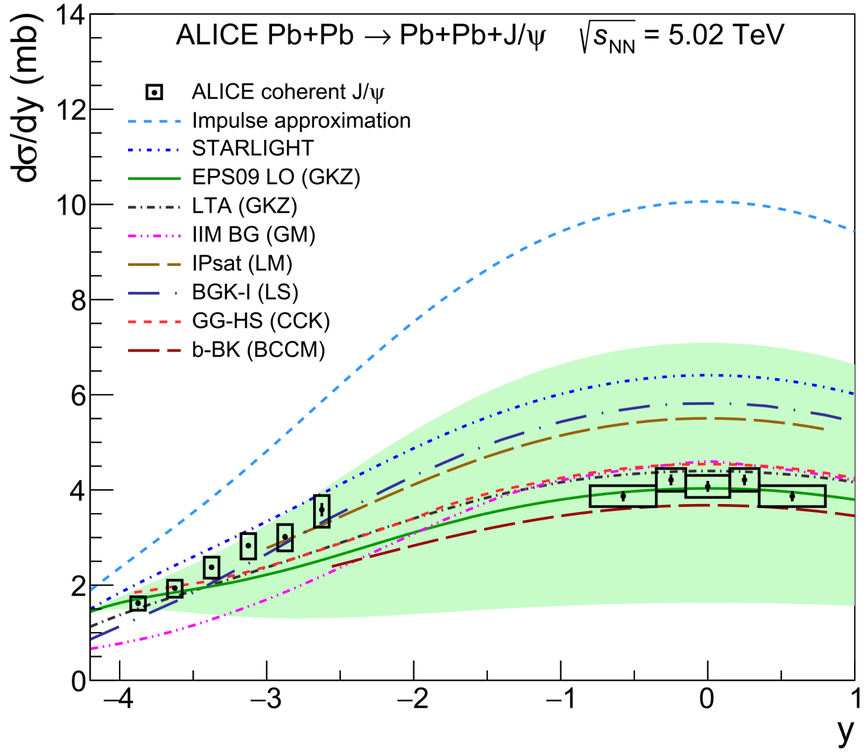


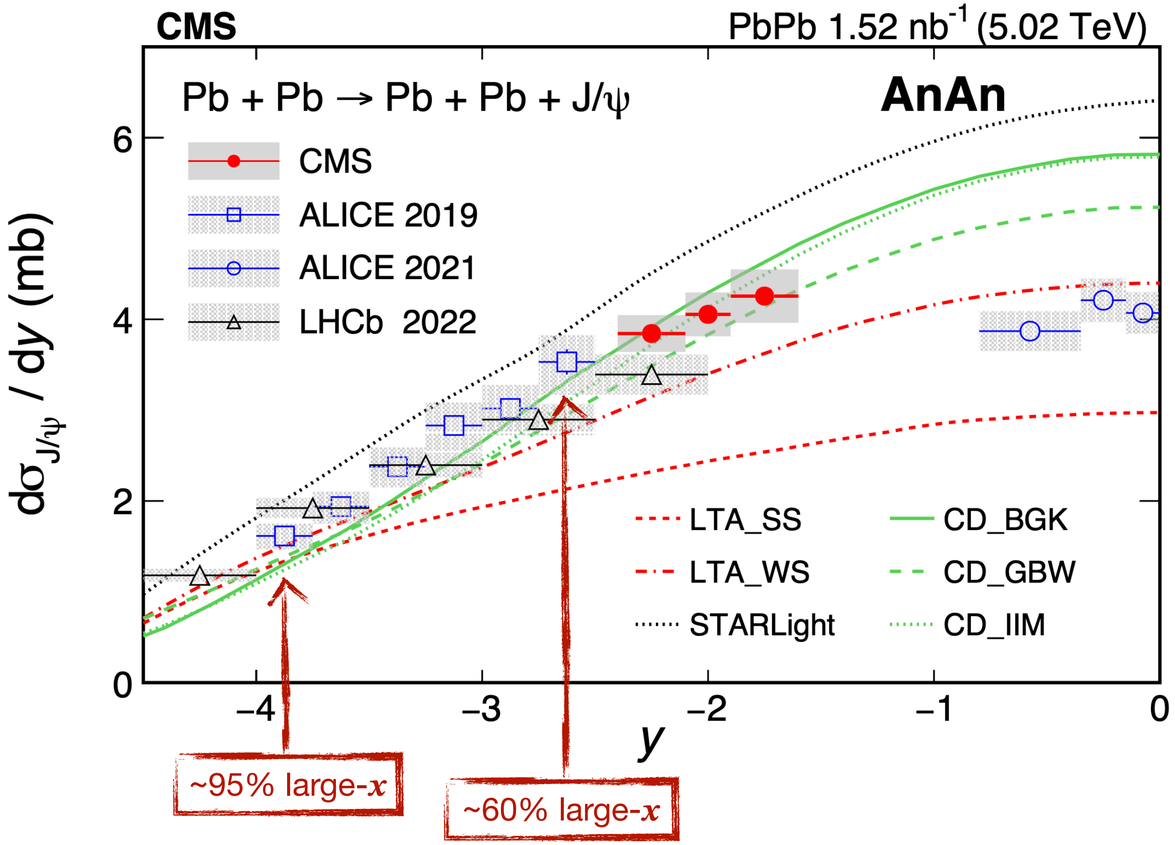
Klein and Steinberg, Ann. Rev. Nucl. Part. Sci. 70 (2020) 323

- Control the impact parameter via forward neutron multiplicity
  - $\langle b \rangle_{XnXn} < \langle b \rangle_{0nXn} < \langle b \rangle_{0n0n}$

Imaging heavy nuclear with coherent J/ψ

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



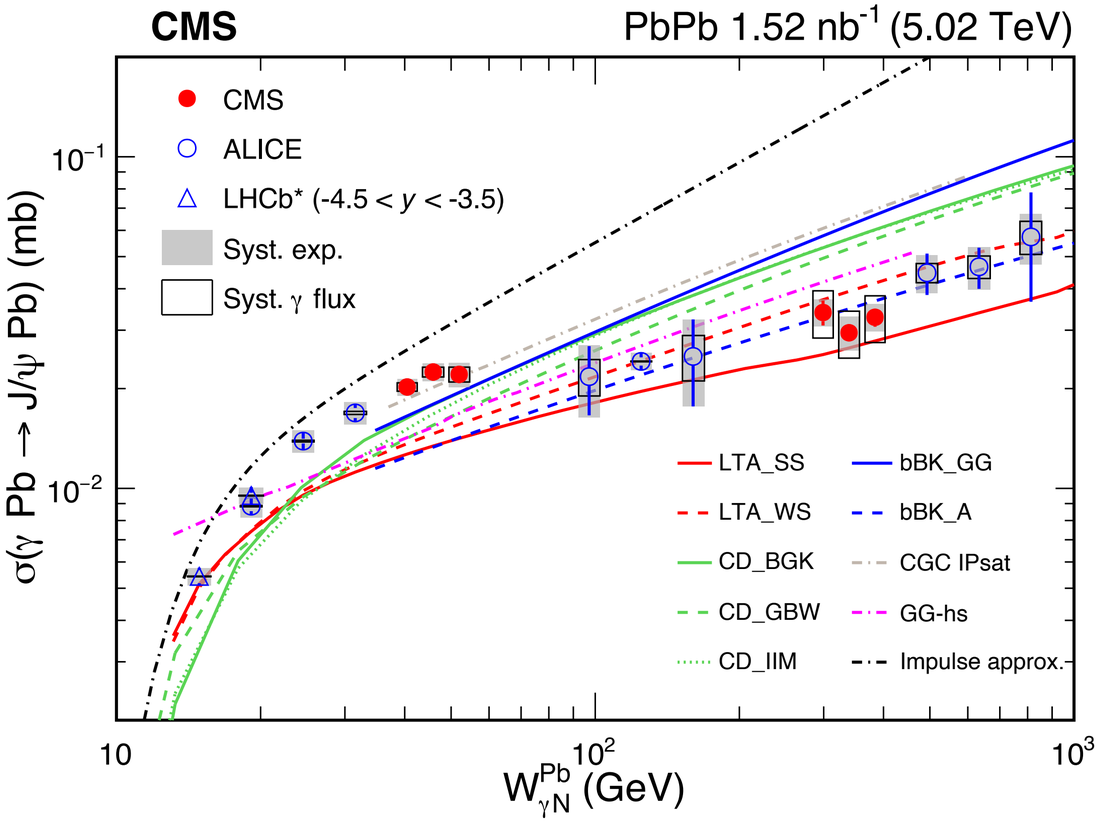


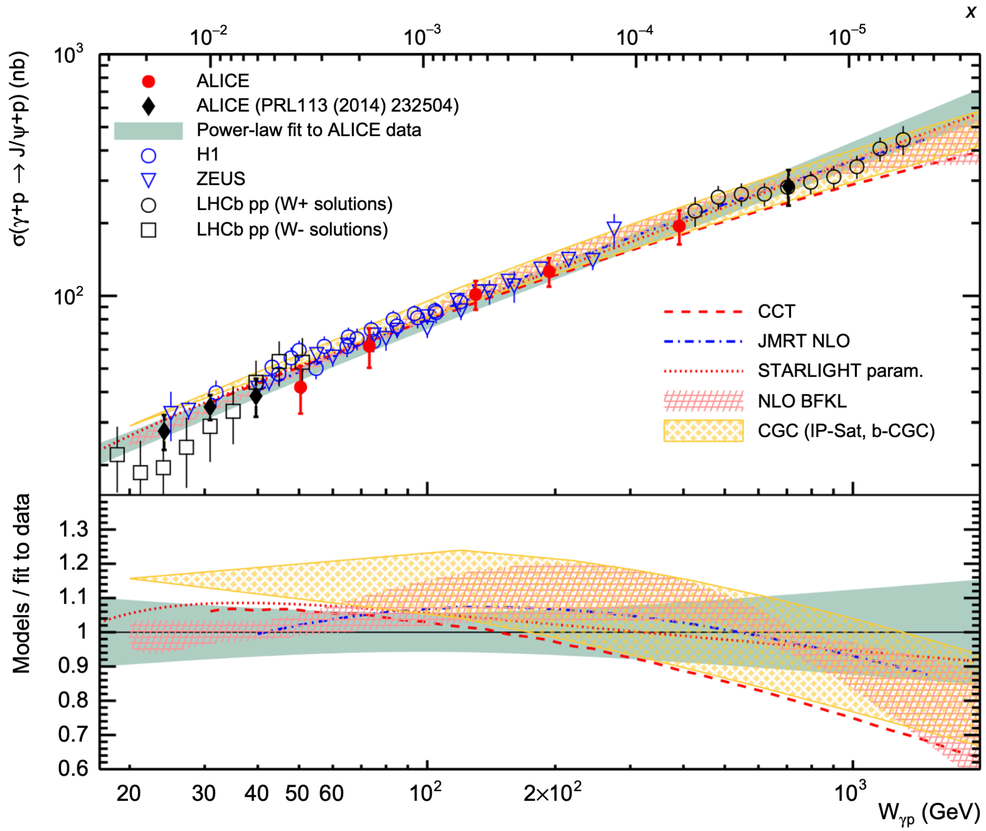
Coherent J/ψ production vs. $W_{\gamma N}^{Pb}$

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



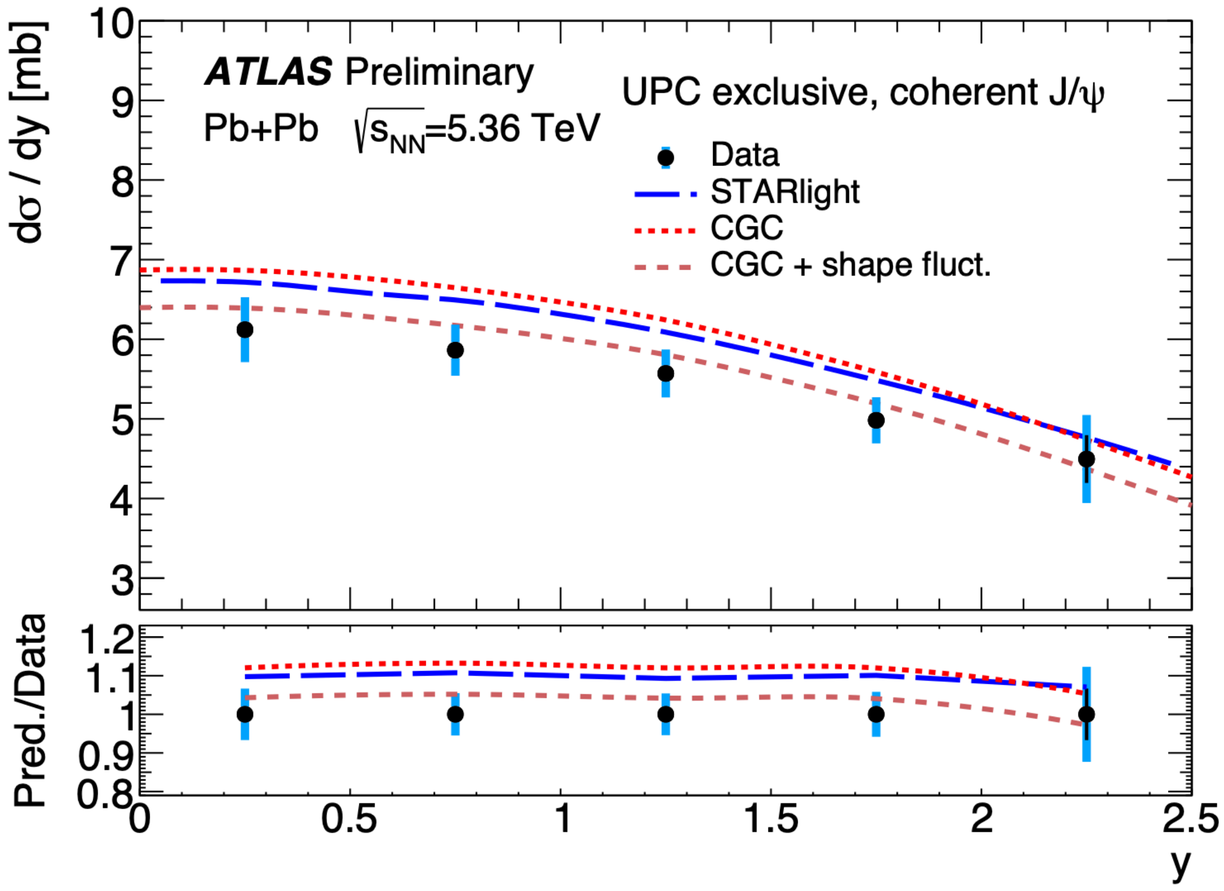


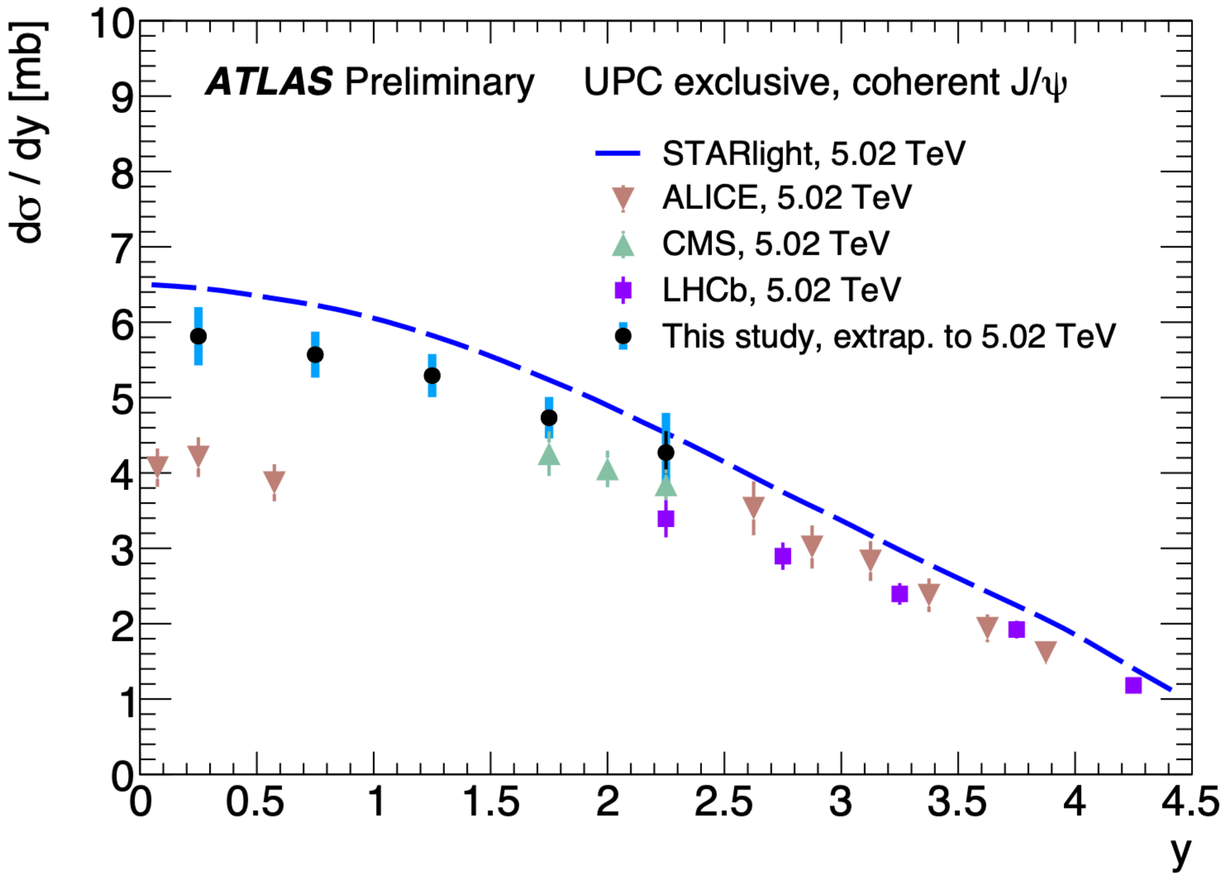
$\gamma A \rightarrow J/\psi A$

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

Coherent J/ψ photoproduction at LHC

ATLAS-CONF-2025-003





Extract energy dependence of incoherent J/ψ

- Incoherent cross section accounted for in 0nAn*

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

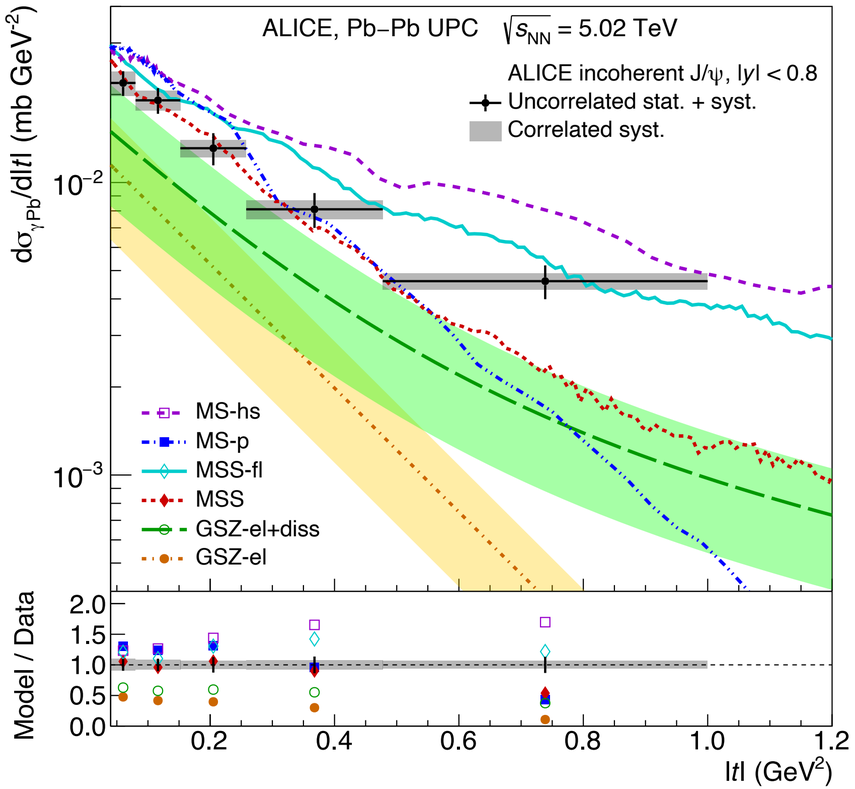
- Photon flux calculated with STARLIGHT

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

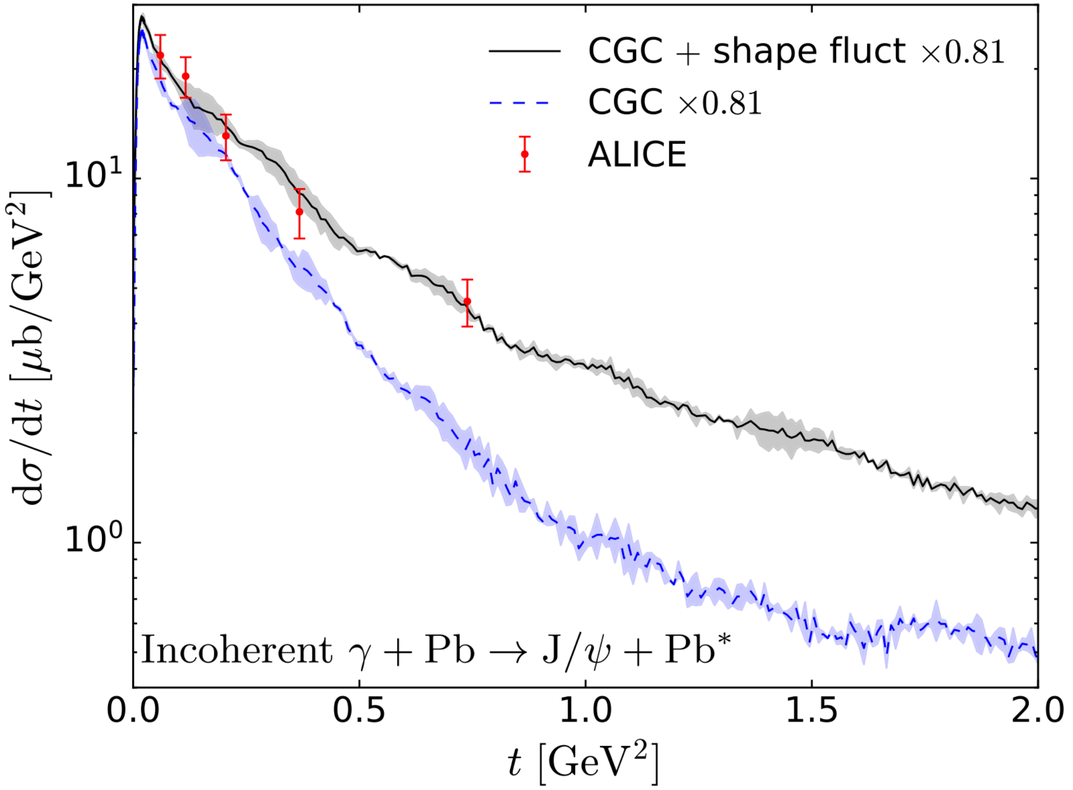
$$\sigma_{\gamma Pb\to J/\psi Pb'}(W) = \frac{d\sigma^{0nAn^*}_{PbPb\to PbPb'J/\psi}(y)}{dy} / n^{0nAn^*}_{\gamma/Pb}(\omega)$$

Incoherent J/ψ production with ALICE

ALICE, PRL 132 (2024) 162302



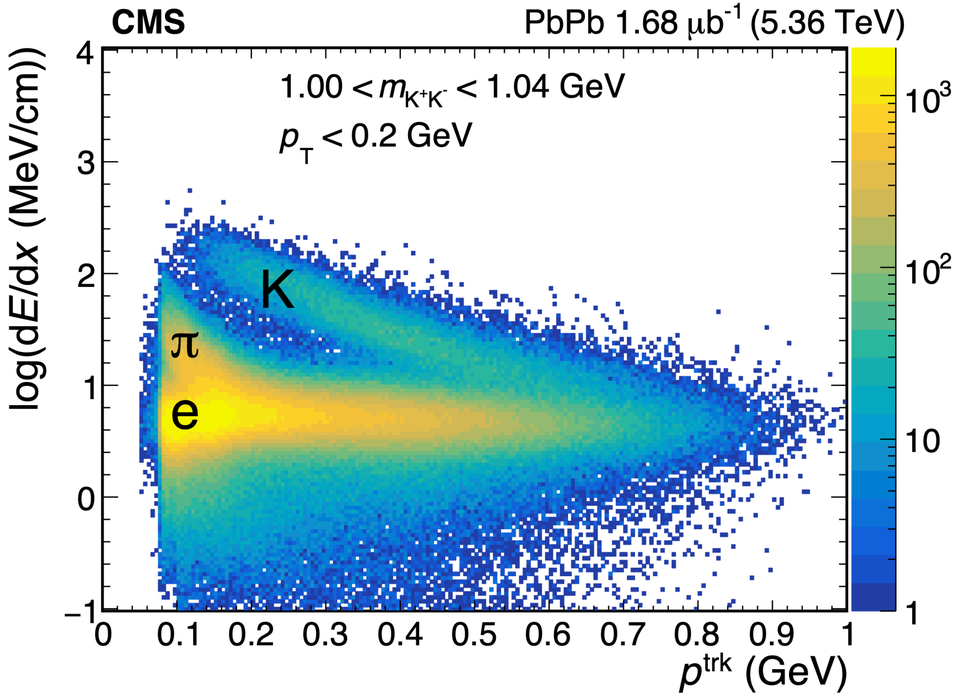
Mäntysaari et al., PRD 109 (2024) L071504

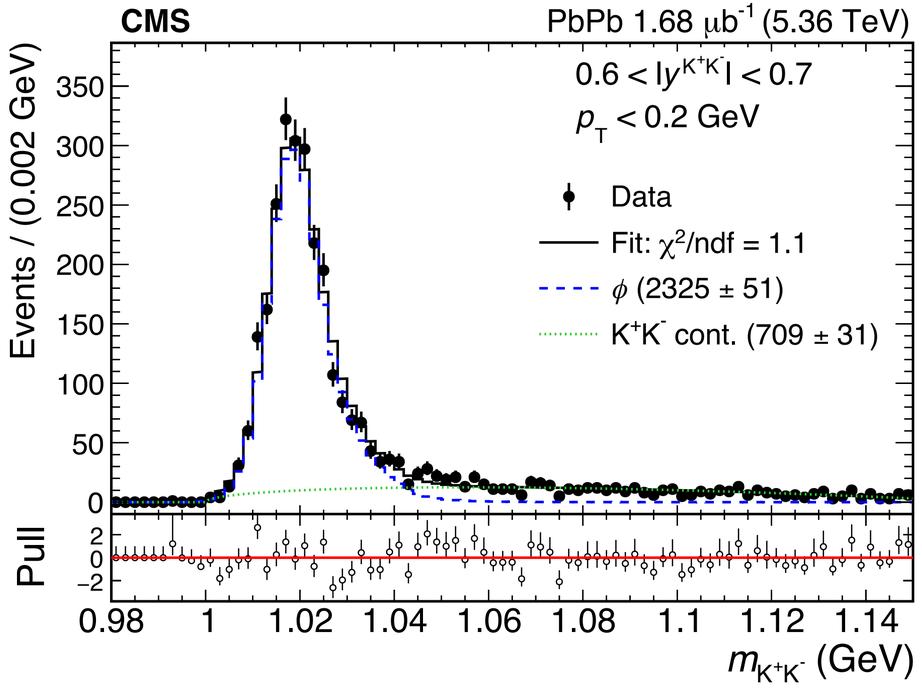


- CGC model with sub-nucleon fluctuations can describe the |t| spectrum shape of incoherent J/ψ but not for the magnitude

First observation of coherent ϕ meson

PRL 135 (2025) 262301

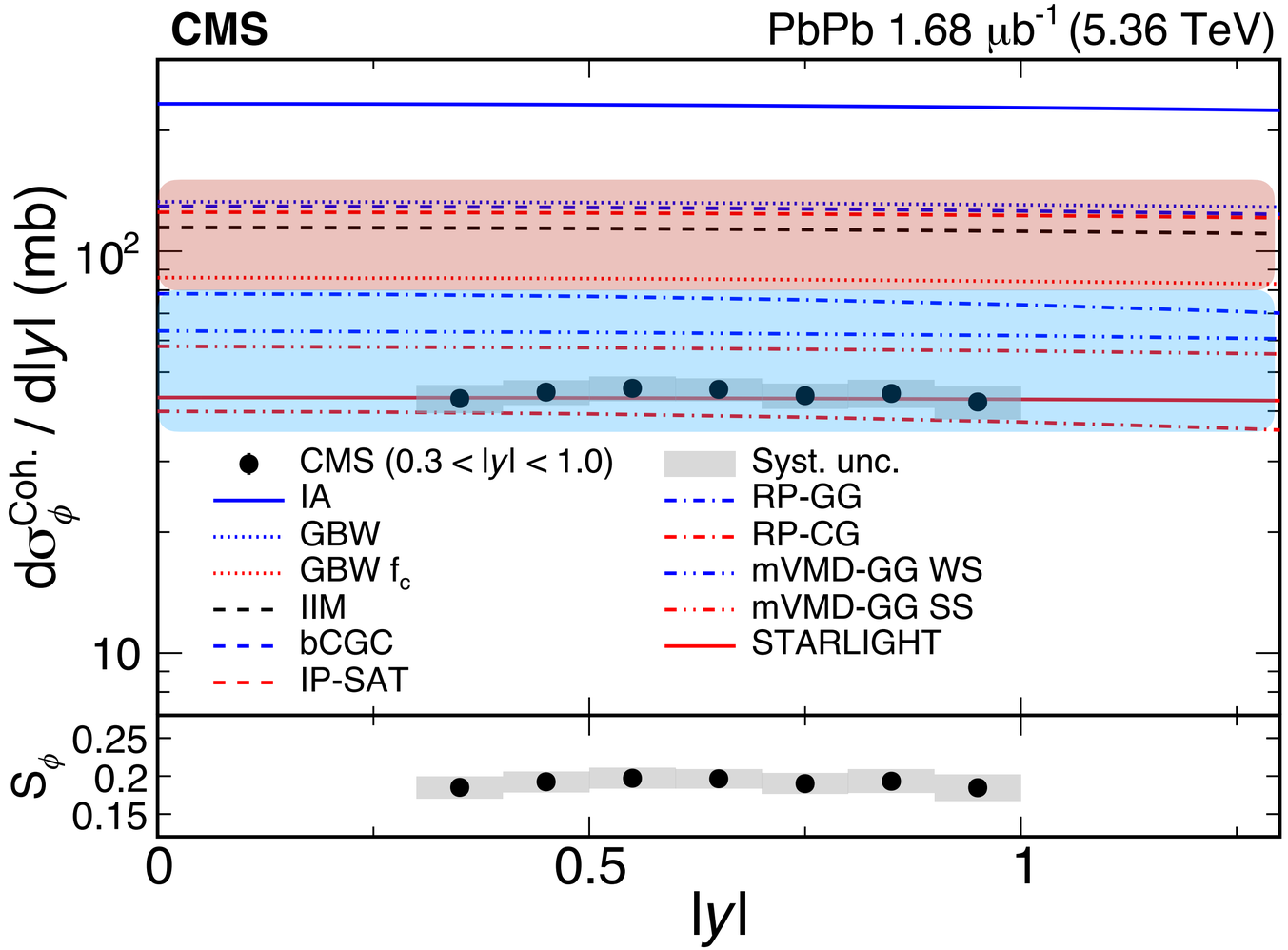




- Super challenging for coherent ϕ measurements for all experiments
  - The p_T of daughter kaon is ~ 0.05 - 0.1 GeV/c
  - CMS can perform PID at low momentum

First observation of coherent ϕ meson

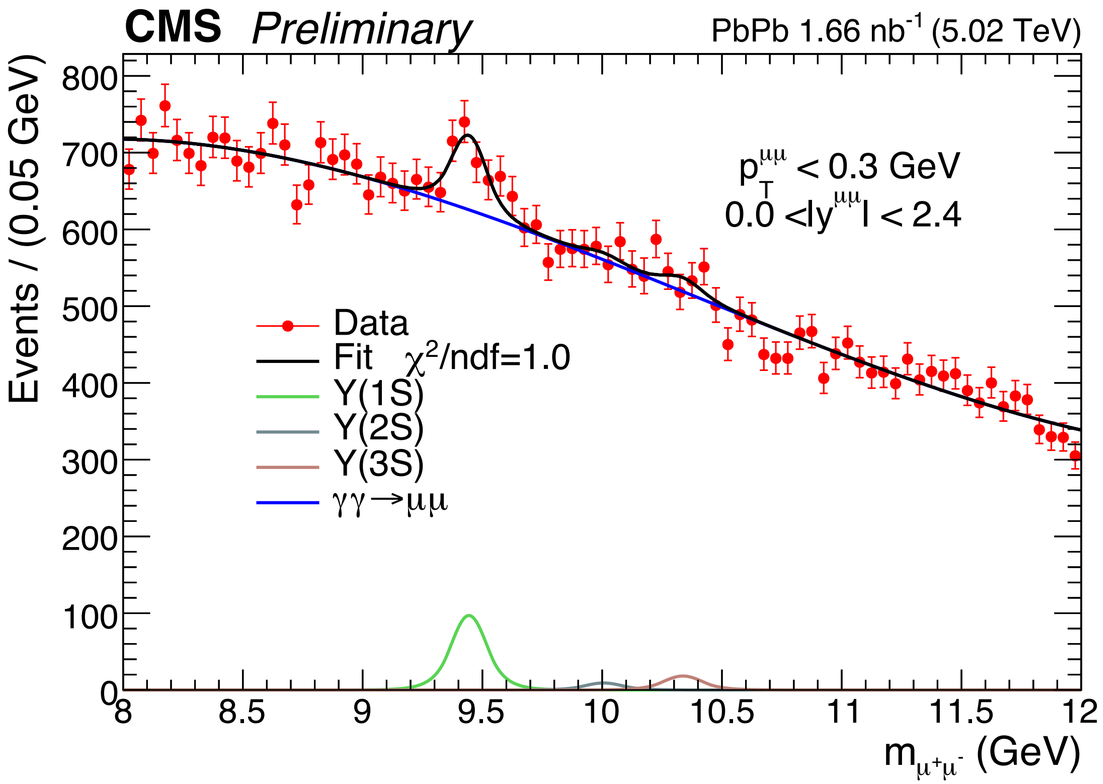
PRL 135 (2025) 262301

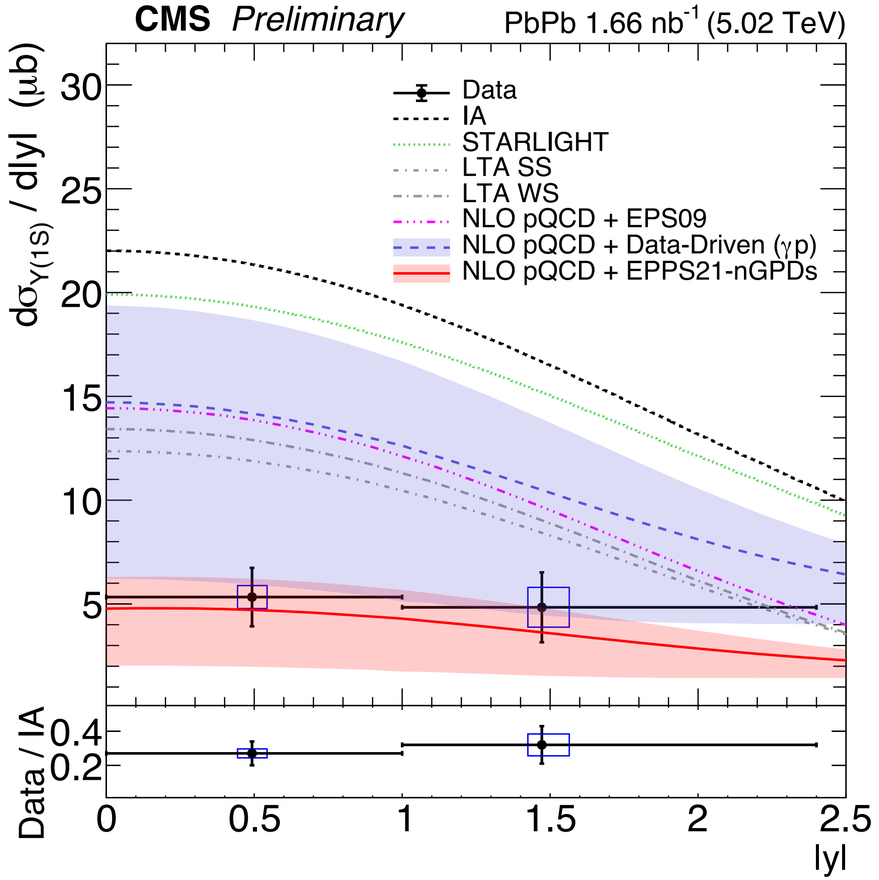


- Strong (~5×) suppression is observed
- Gluon saturation models over predict data by a factor of 2-3
- Nuclear shadowing models generally better describe data

First observation of coherent Υ(1S) meson

CMS-PAS-HIN-24-013





- Υ(1S) is expected to be less sensitive to the non-linear QCD effects
  - However, strongly (~3-4×) suppressed is observed!