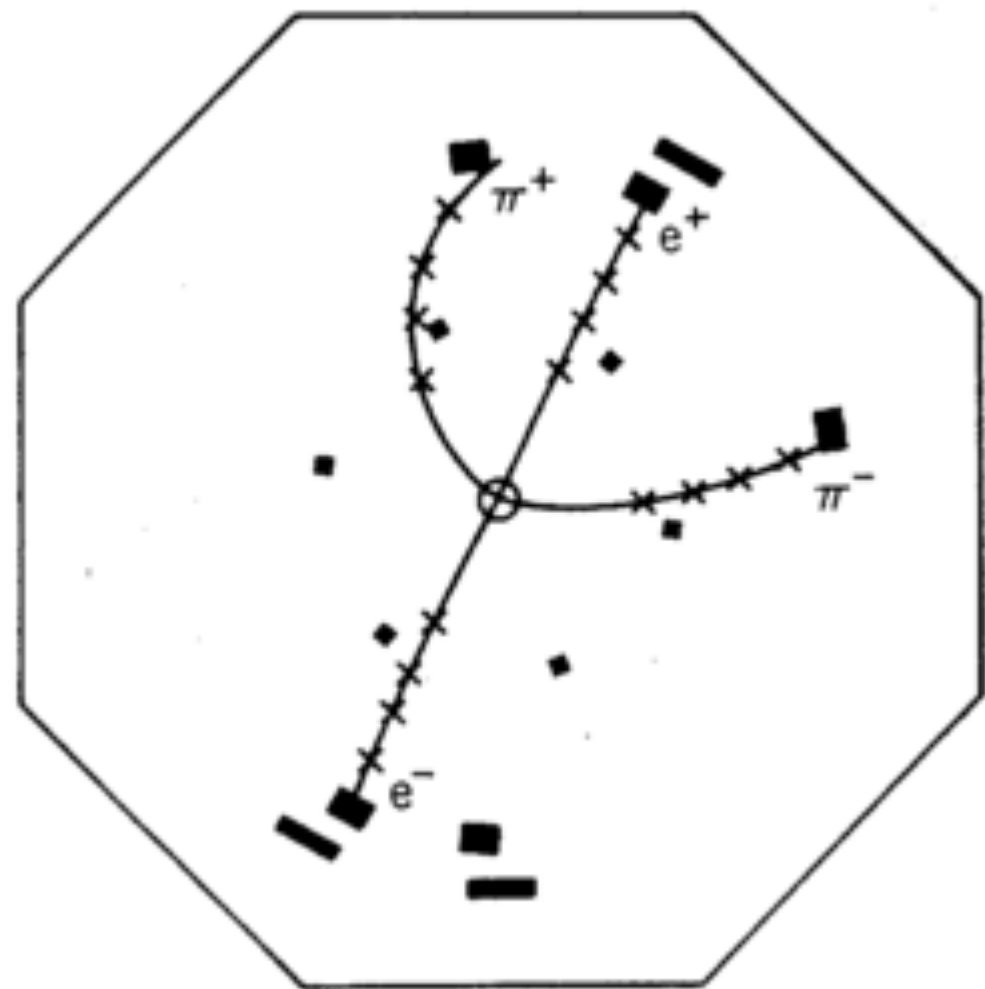




One particle, many stories: exploring heavy-ion collisions with J/ψ

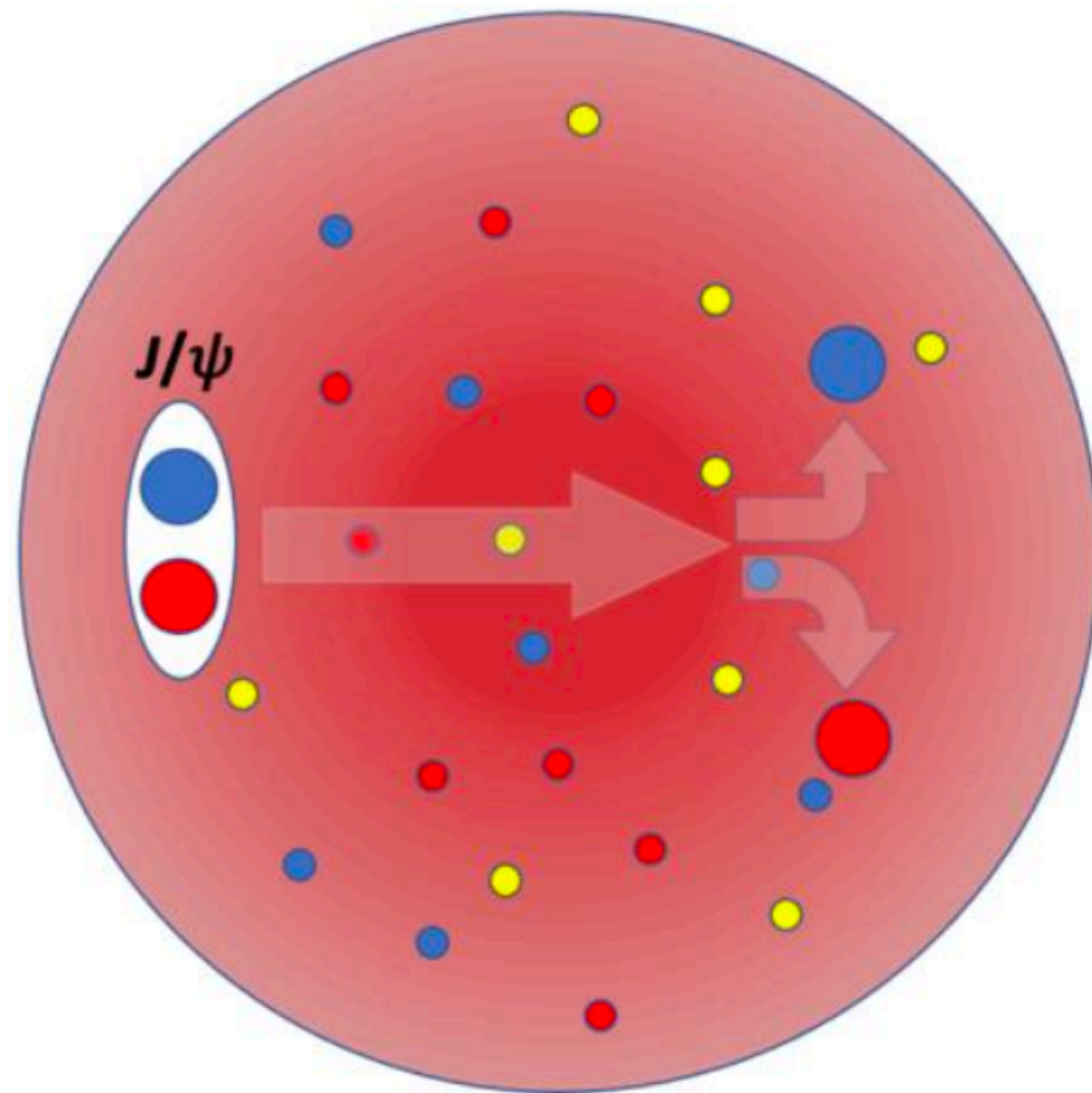
Shuai Yang (杨帅)

South China Normal University

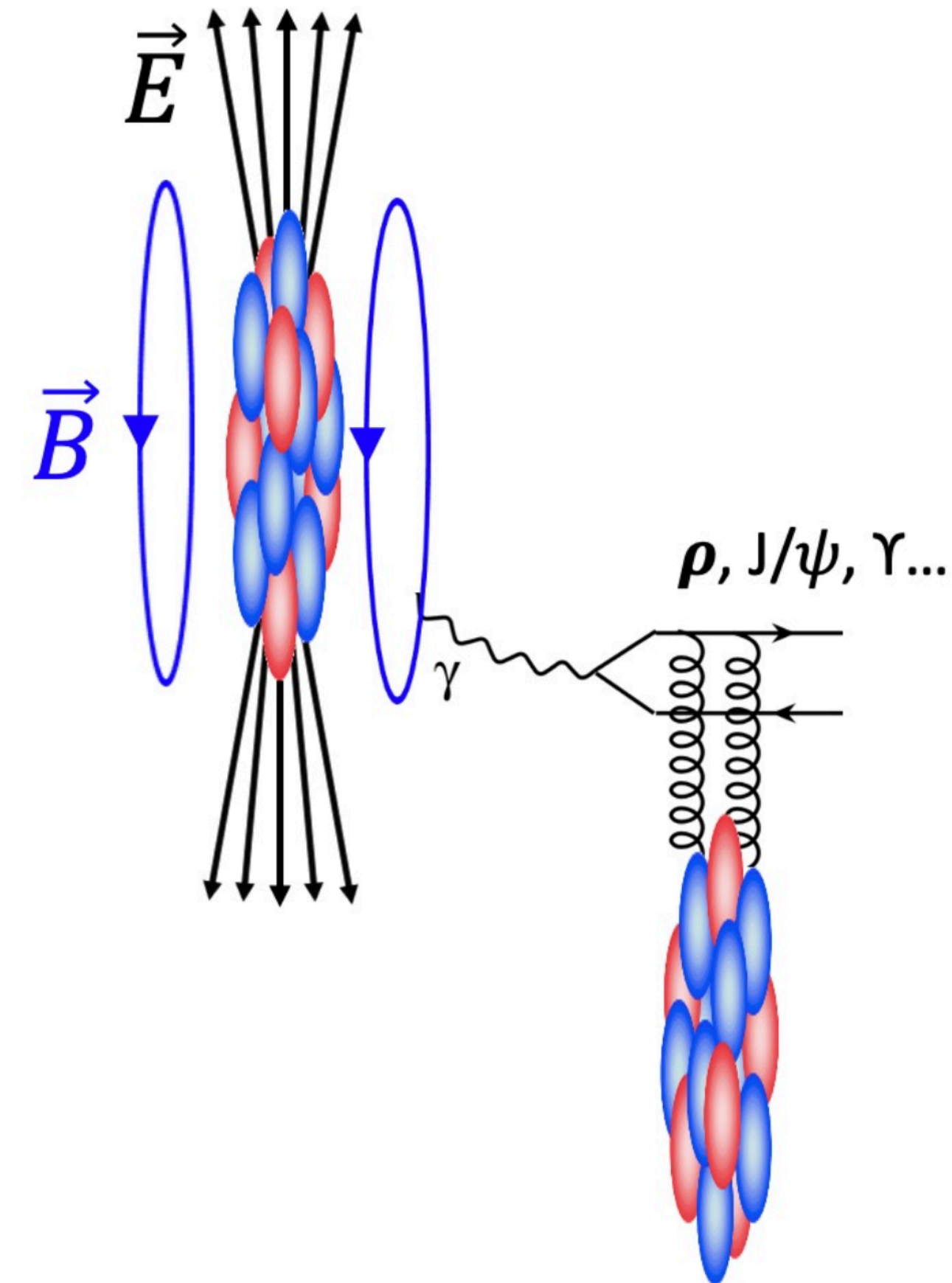


The critical role of J/ψ in heavy-ion collisions

Probe of hot medium



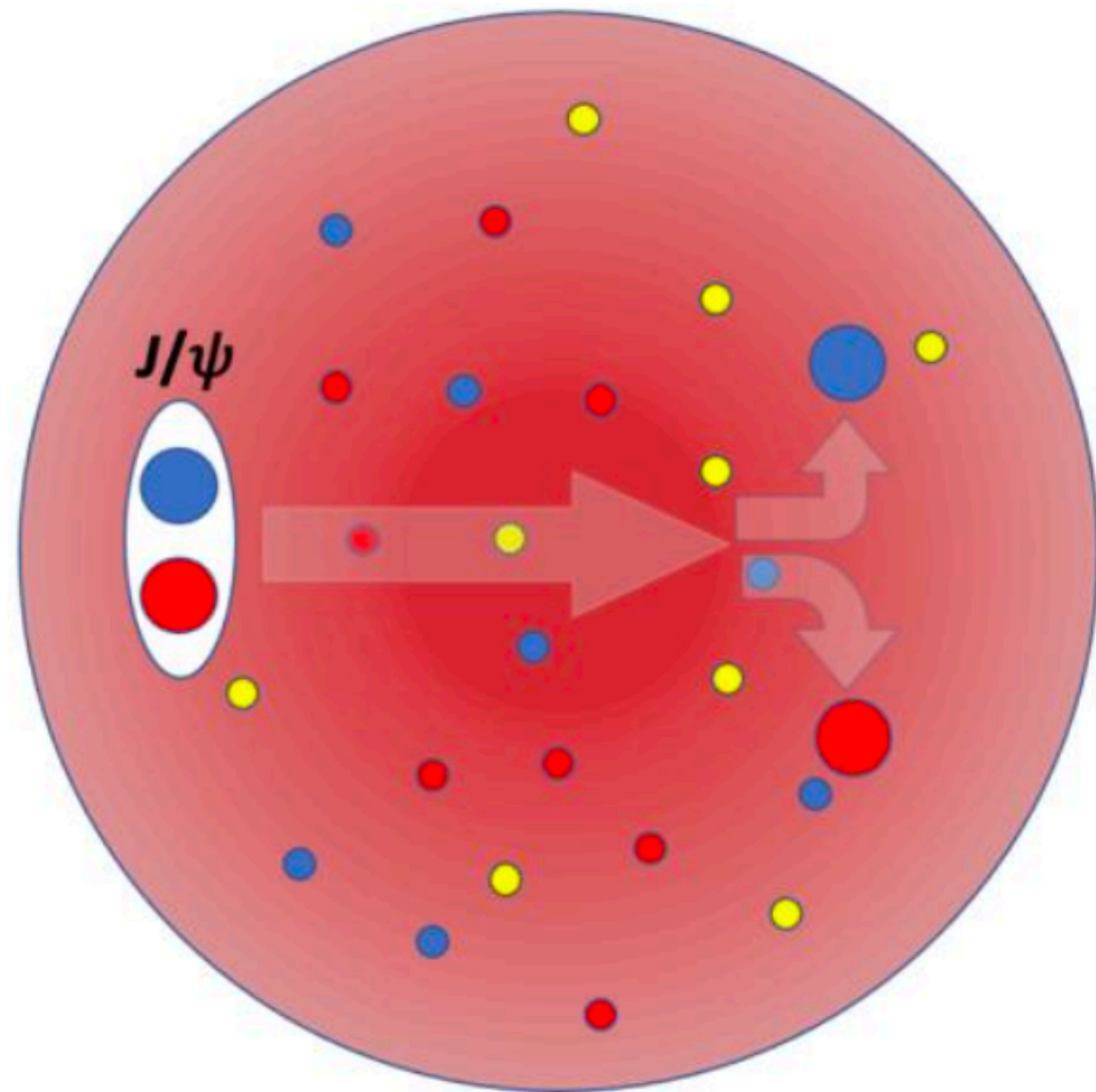
Courtesy: Q. Yang



Probe of gluon structure and polarization

A sensitive probe of QGP

Probe of hot medium



Courtesy: Q. Yang

- Quarkonia suppression was proposed as a sensitive probe of QGP properties

Satz, PLB 178 (1986) 416

- Hot medium effects**

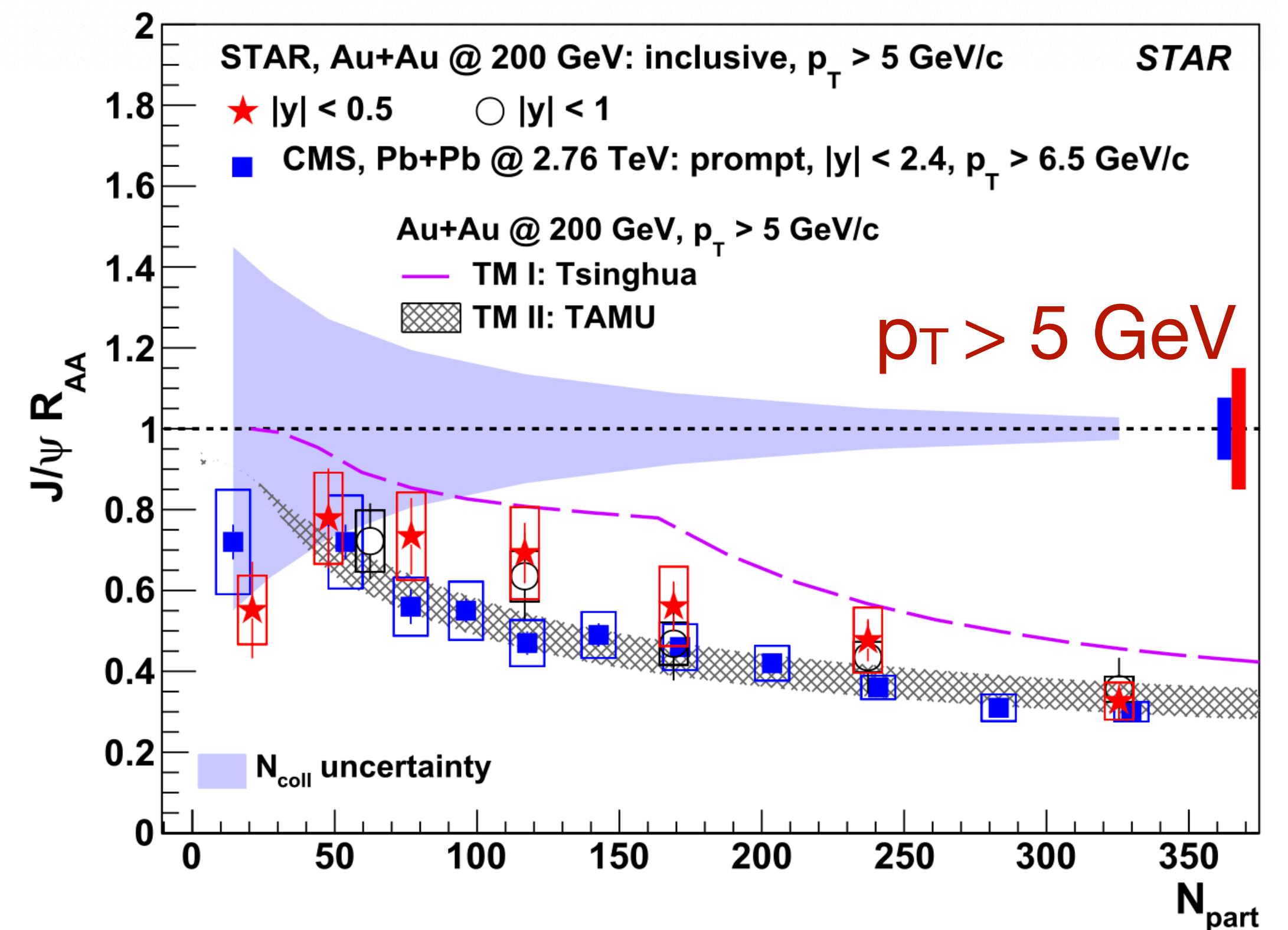
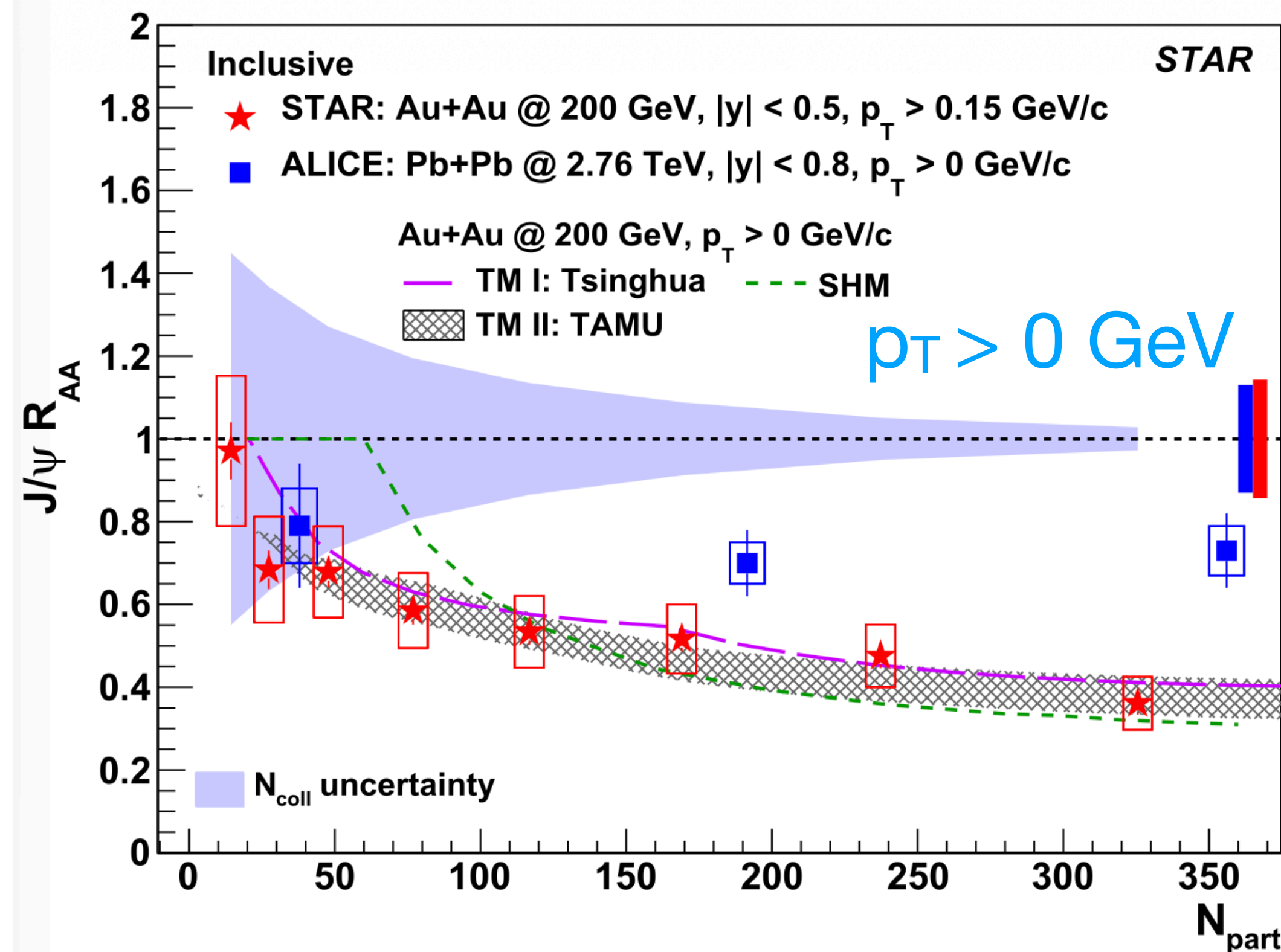
- Static and dynamic dissociation
- Regeneration

- Cold nuclear matter effects**

- Nuclear PDF
- Nuclear absorption
- Initial-state parton energy loss
- Co-mover effects

*J. Zhao, K. Zhou, S. Chen and **P. Zhuang**, PPNP 114 (2020) 103801*

J/ψ suppression at top RHIC and LHC energies

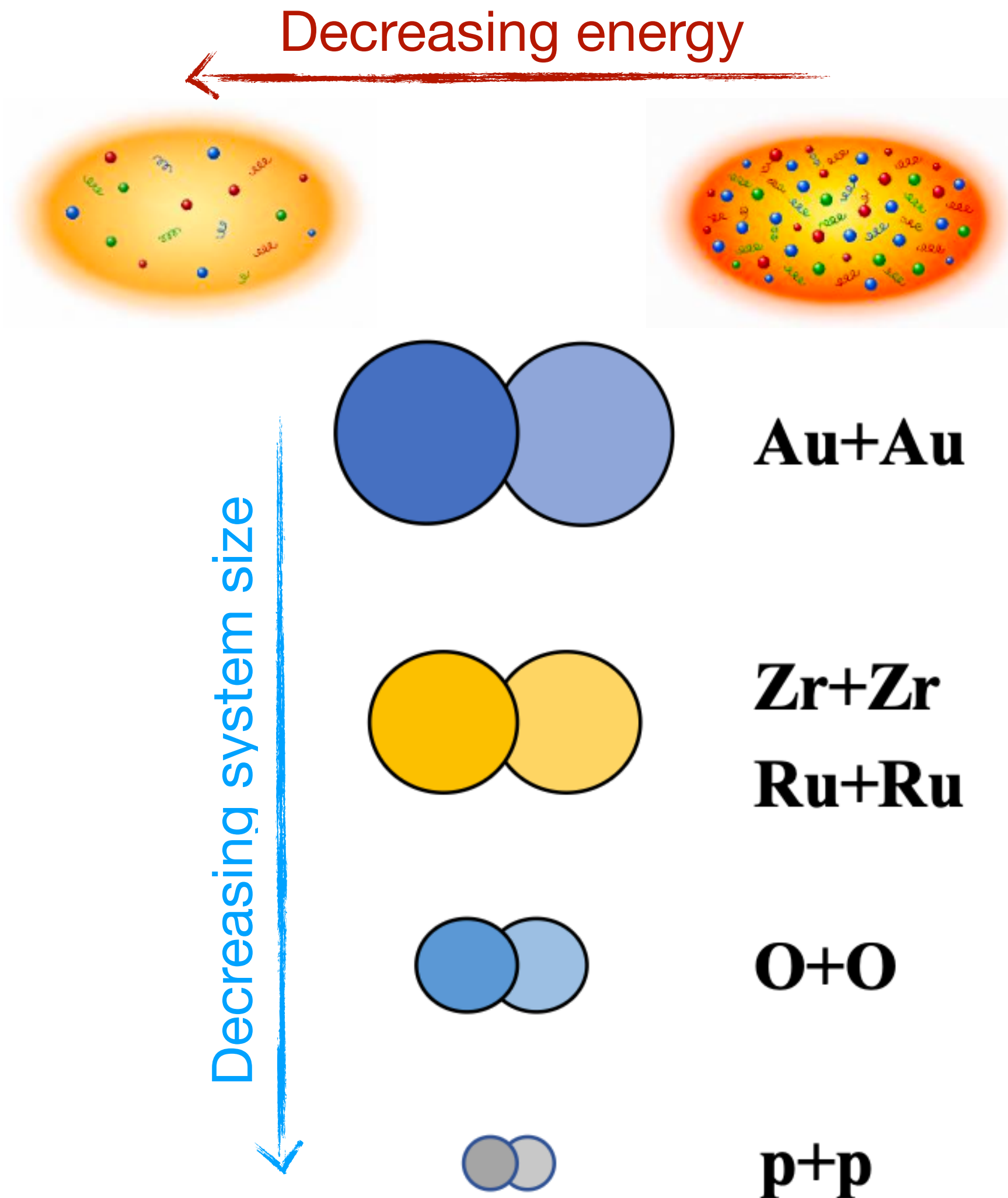


- Significant J/ψ suppression towards central collisions at RHIC
- Transport models qualitatively describe the data

STAR, PLB 797 (2019) 134917
 ALICE, JHEP 07 (2015) 051
 CMS, EPJC 77 (2017) 252

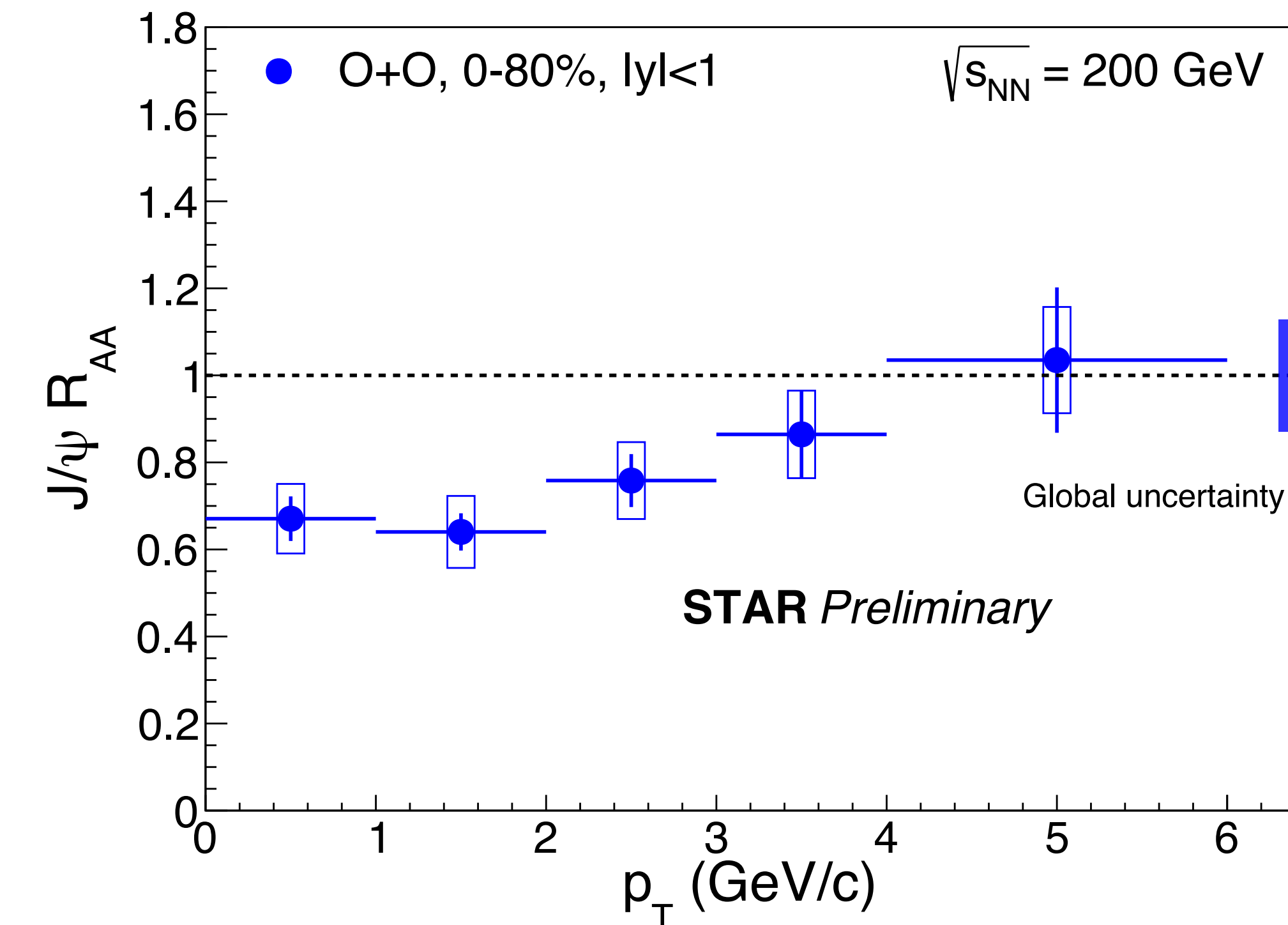
L. Yan, **P. Zhuang**, N. Xu, PRL 97 (2006) 232301
 K. Zhou, N. Xu, Z. Xu, **P. Zhuang**, PRC 89 (2014) 054911
 Zhao, Rapp, PRC 82 (2010) 064905
 Andronic et al., Nature 561 (2018) 321

System-size and energy dependence of J/ψ production



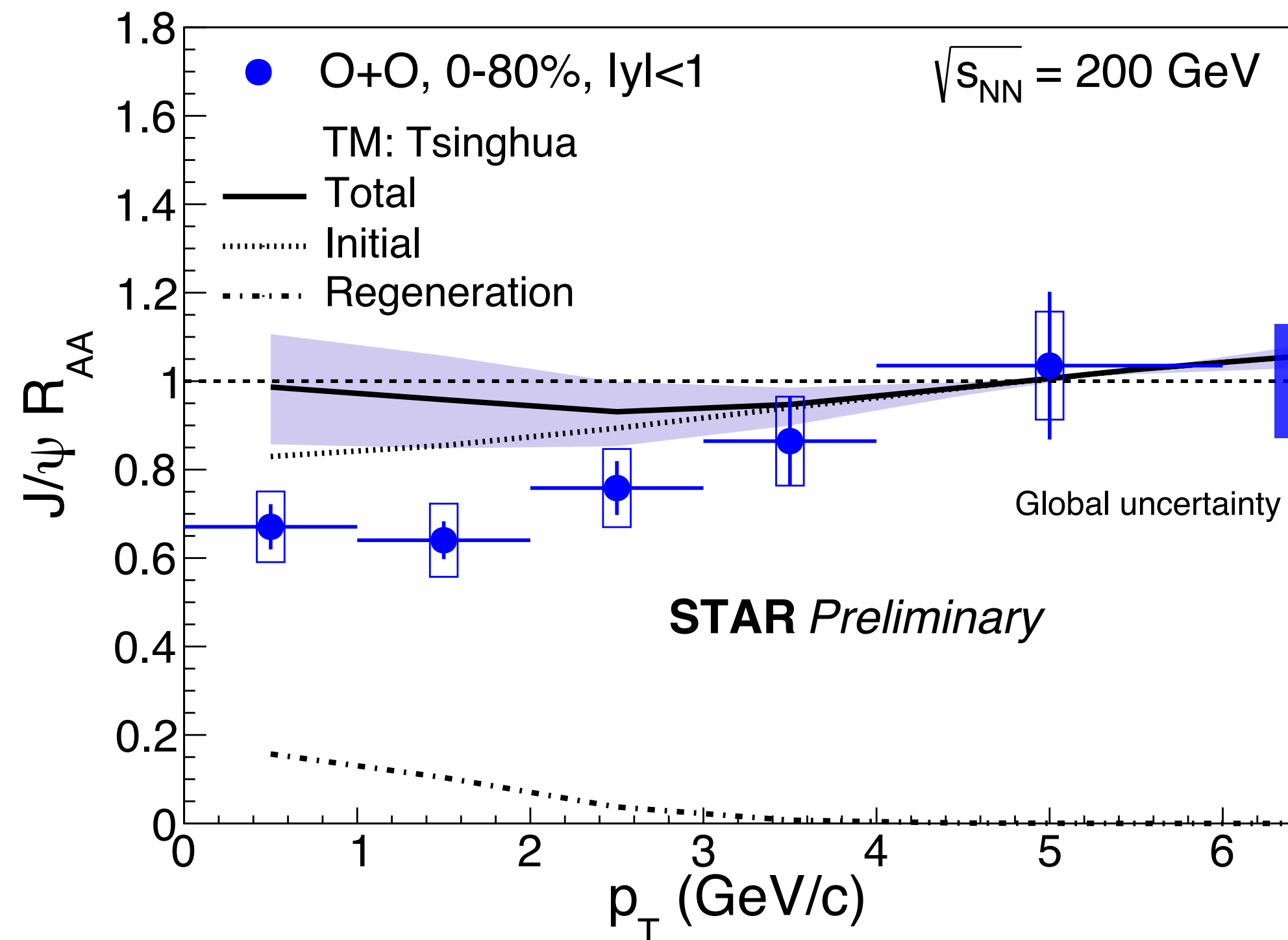
- Strong J/ψ suppression is observed in large systems at top RHIC and LHC energies
- The presence of J/ψ suppression in small systems has yet to be established
- The behavior of J/ψ production at low energy is still poorly determined

Inclusive J/ψ production in O+O collisions



- Strong J/ψ suppression at low p_T , consistent with 1 at high p_T

Inclusive J/ψ production in O+O collisions

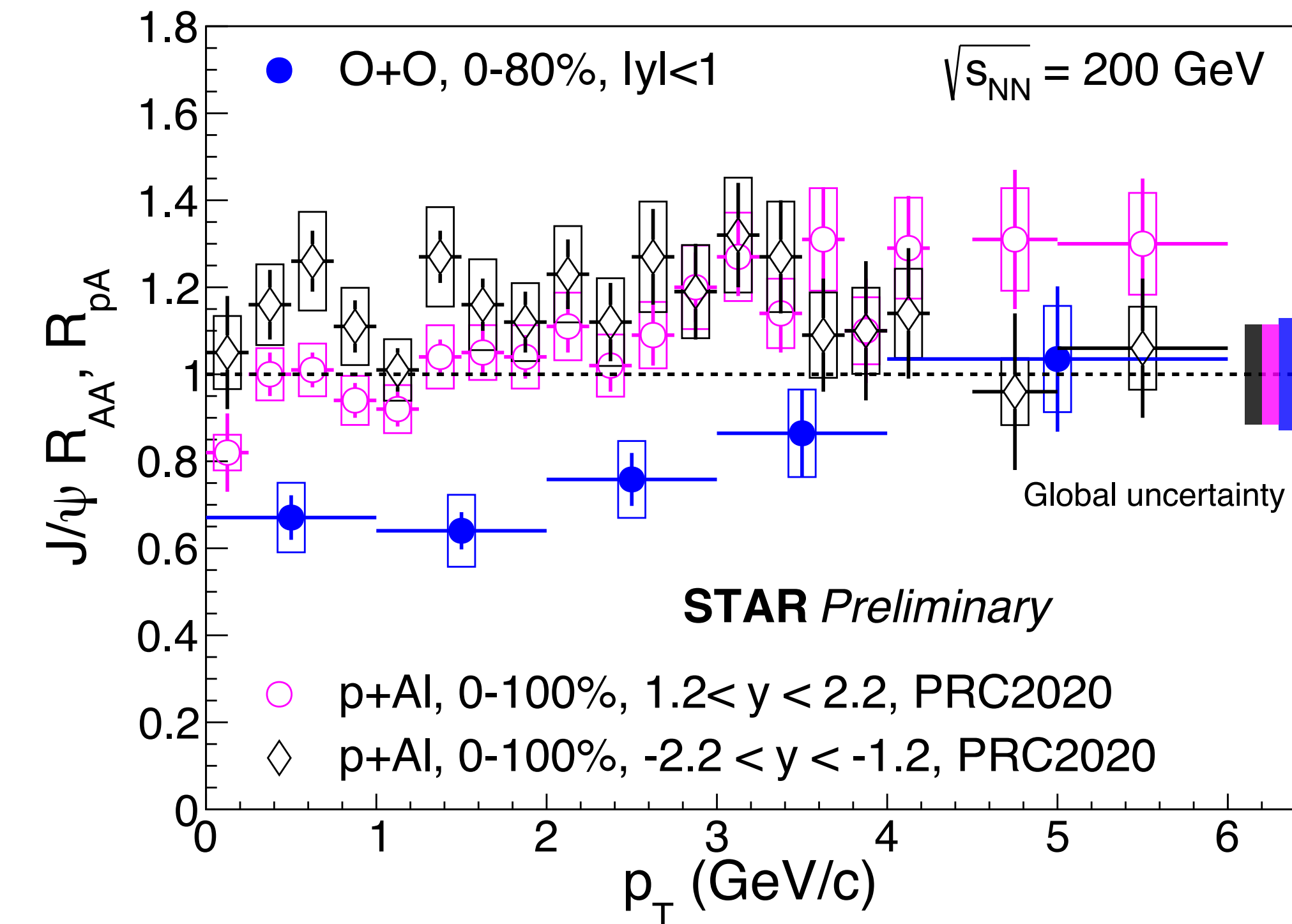


- Strong J/ψ suppression at low p_T , consistent with 1 at high p_T
- Model underestimates the suppression at low p_T , but describes the data at high p_T
 - Primordial: QGP dissociation + nPDF + nuclear absorption
 - Regeneration: charm is assumed to be fully thermalized

J. Zhao and P. Zhuang, PRC 105 (2022) 064907 (private communications)

Inclusive J/ψ production in OO collisions

PHENIX., PRC 102 (2020) 014902

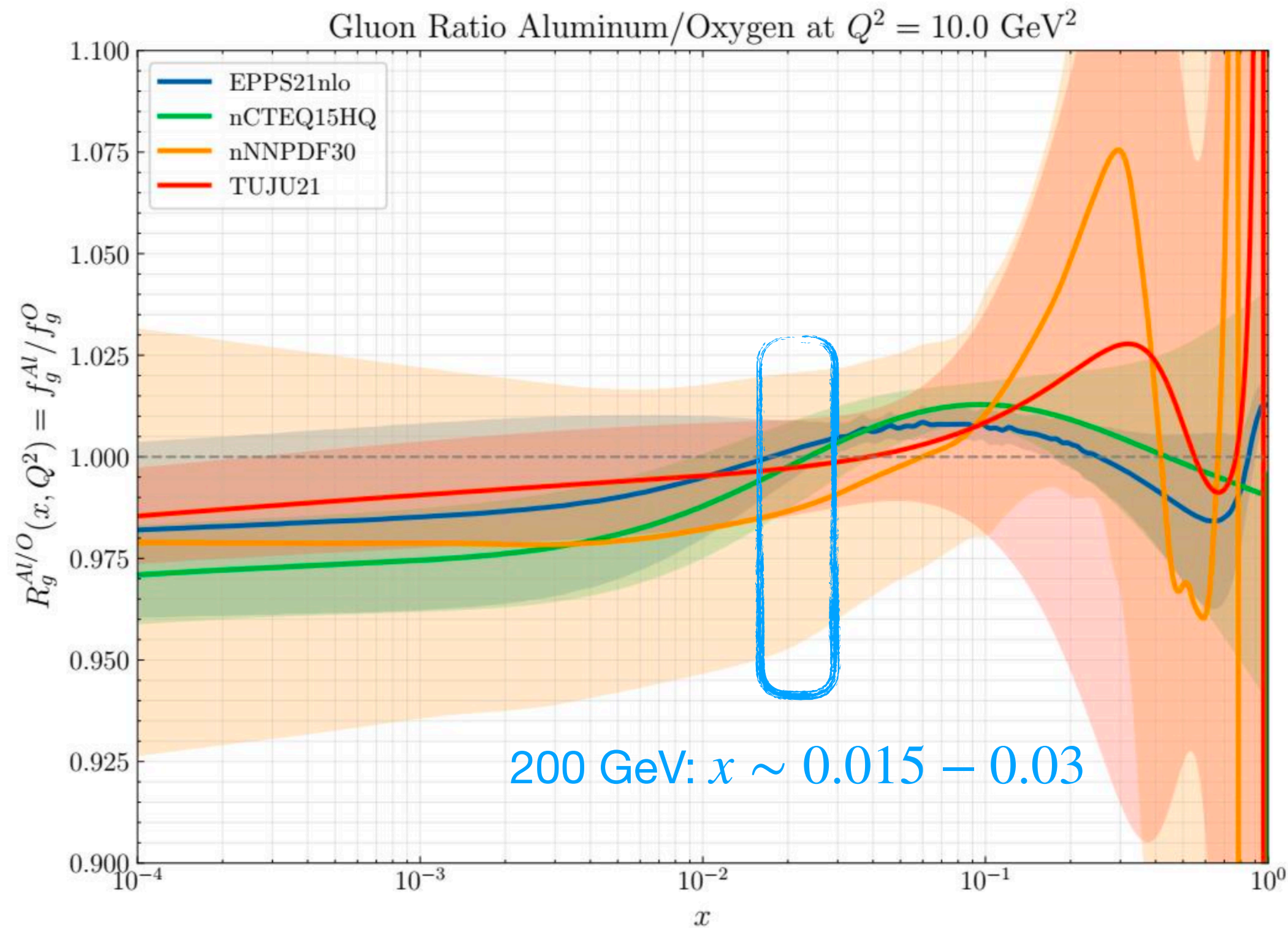


- Strong J/ψ suppression at low p_T , consistent with 1 at high p_T
- The R_{pA} is consistent with 1 in p+Al

nPDF in aluminum and oxygen

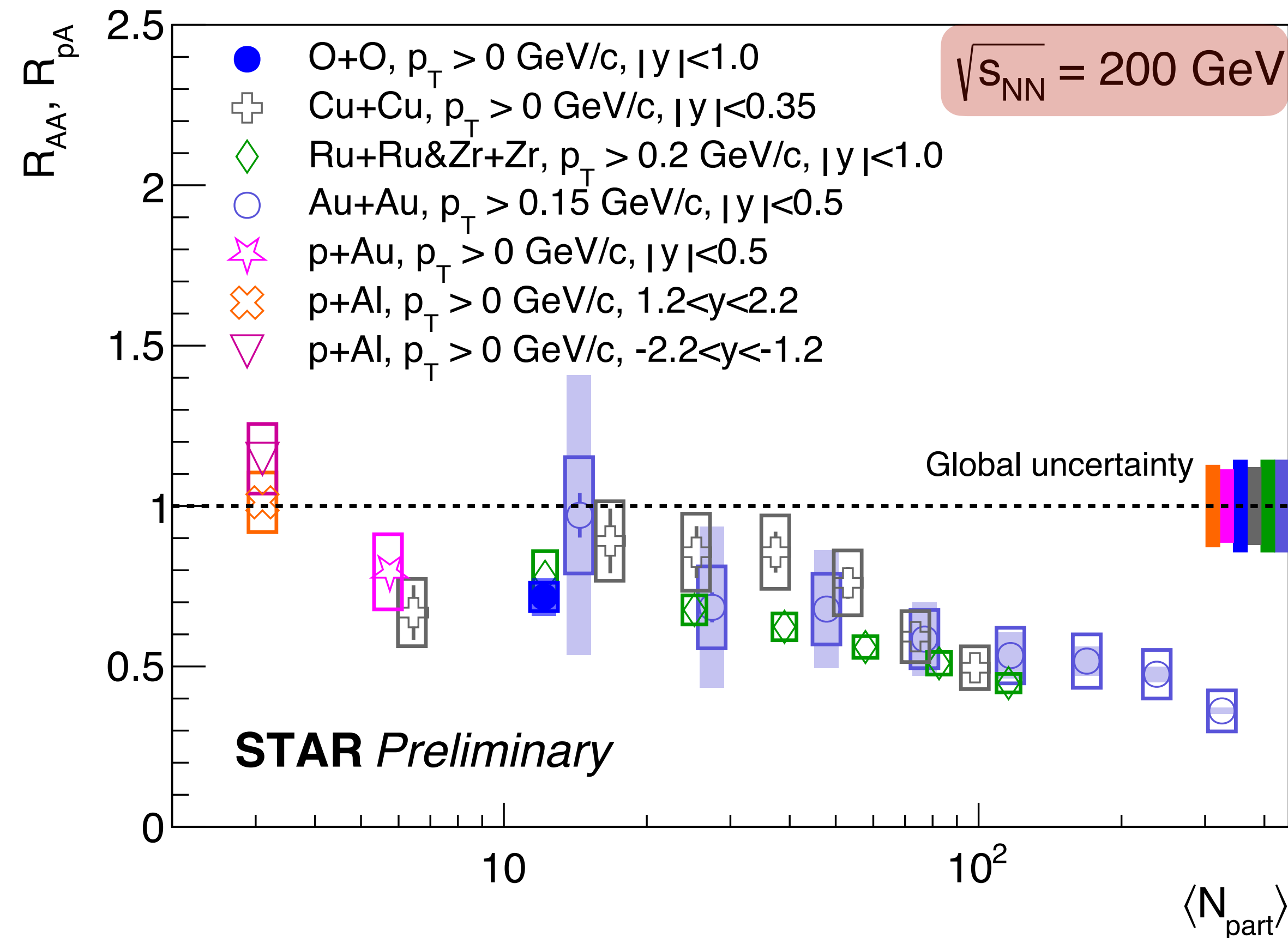
Buckley et al., EPJC 75 (2015) 132

Jonas et al., arXiv:2602.15928



- Strong J/ψ suppression at low p_T , consistent with 1 at high p_T
- The R_{pA} is consistent with 1 in p+Al
 - nPDF calculations suggest similar CNM effects in p+O and p+Al collisions
 - Additional suppression in O+O relative to p+Al is consistent with QGP-induced suppression

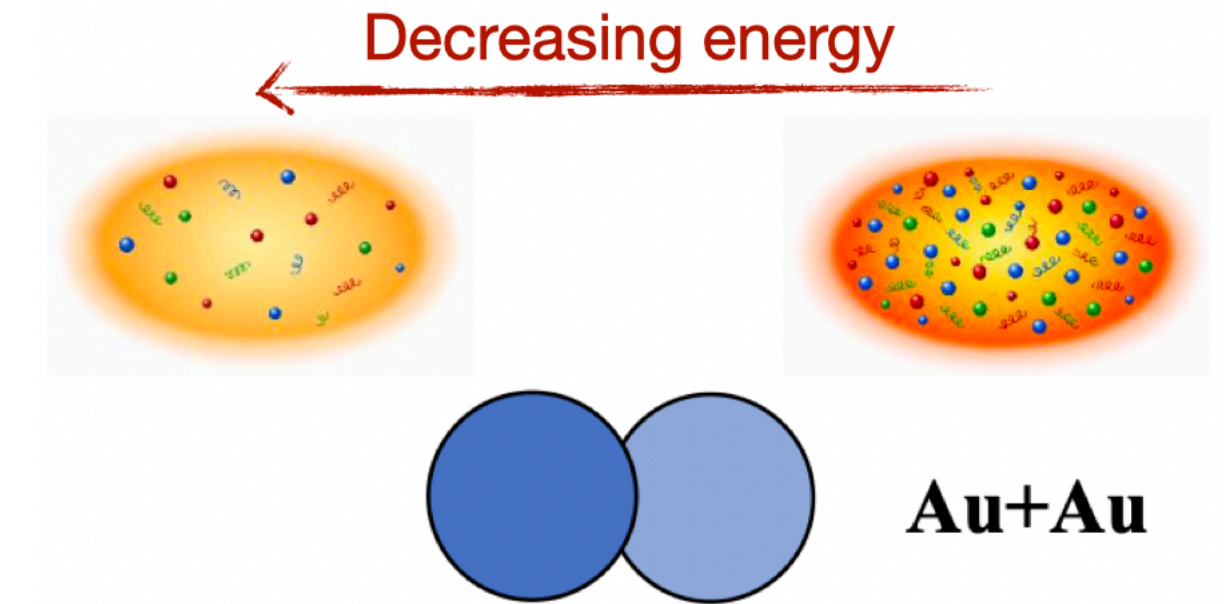
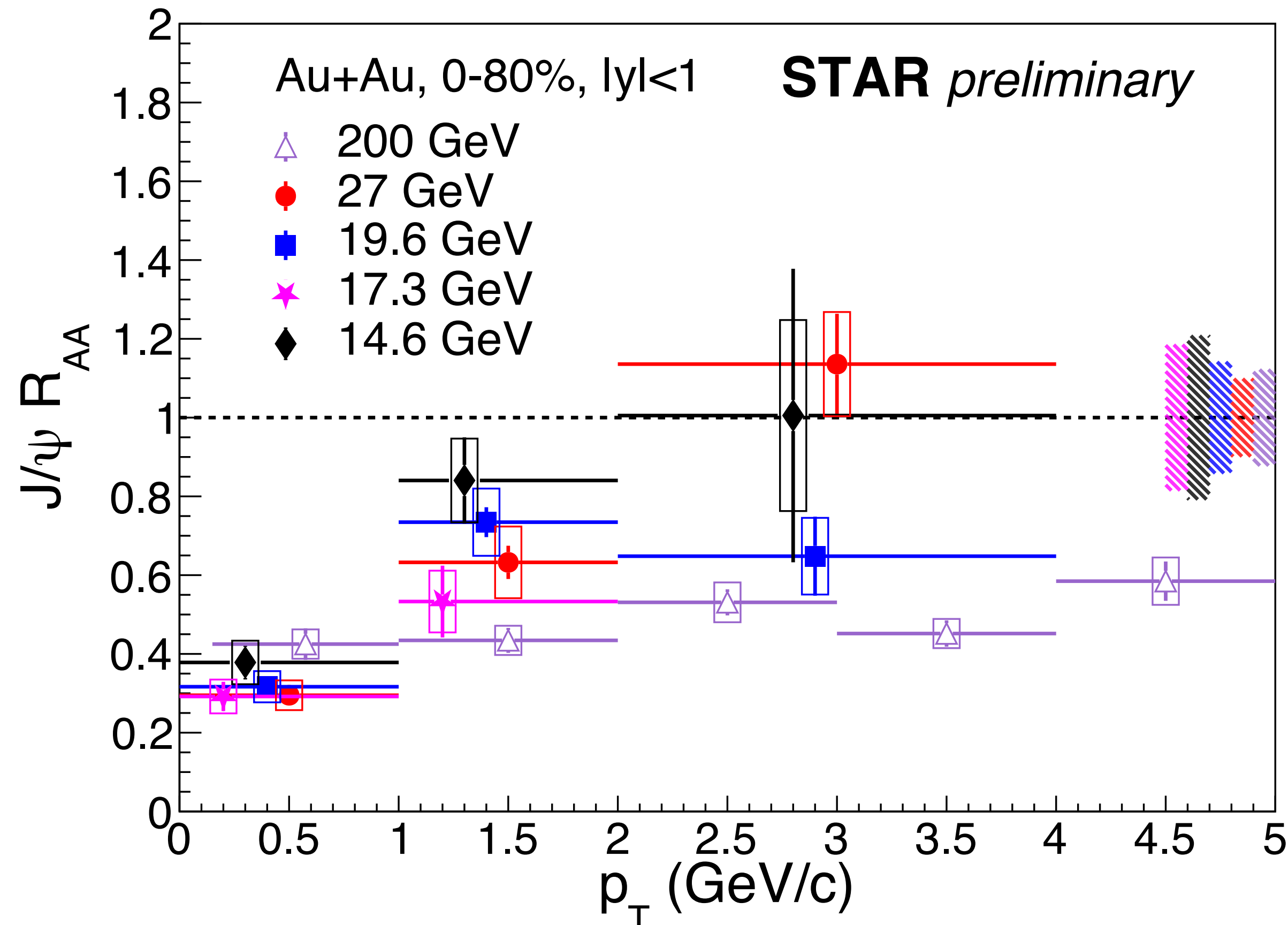
System size dependence of inclusive J/ψ R_{AA}



STAR, PLB 797 (2019) 134917
 STAR, PLB 825 (2022) 136865
 PHENIX, PRL 101 (2008) 122301
 PHENIX, PRC 102 (2020) 014902

© Smooth decrease of R_{AA} with increasing $\langle N_{part} \rangle$ for different colliding systems

p_T and energy dependence of inclusive J/ψ R_{AA}



- Au+Au at BESII: R_{AA} is significantly below 1 at low p_T , but rises with p_T
- No significant p_T dependence at 200 GeV

Energy dependence of inclusive J/ψ R_{AA}

NA50, PLB 477 (2000) 28

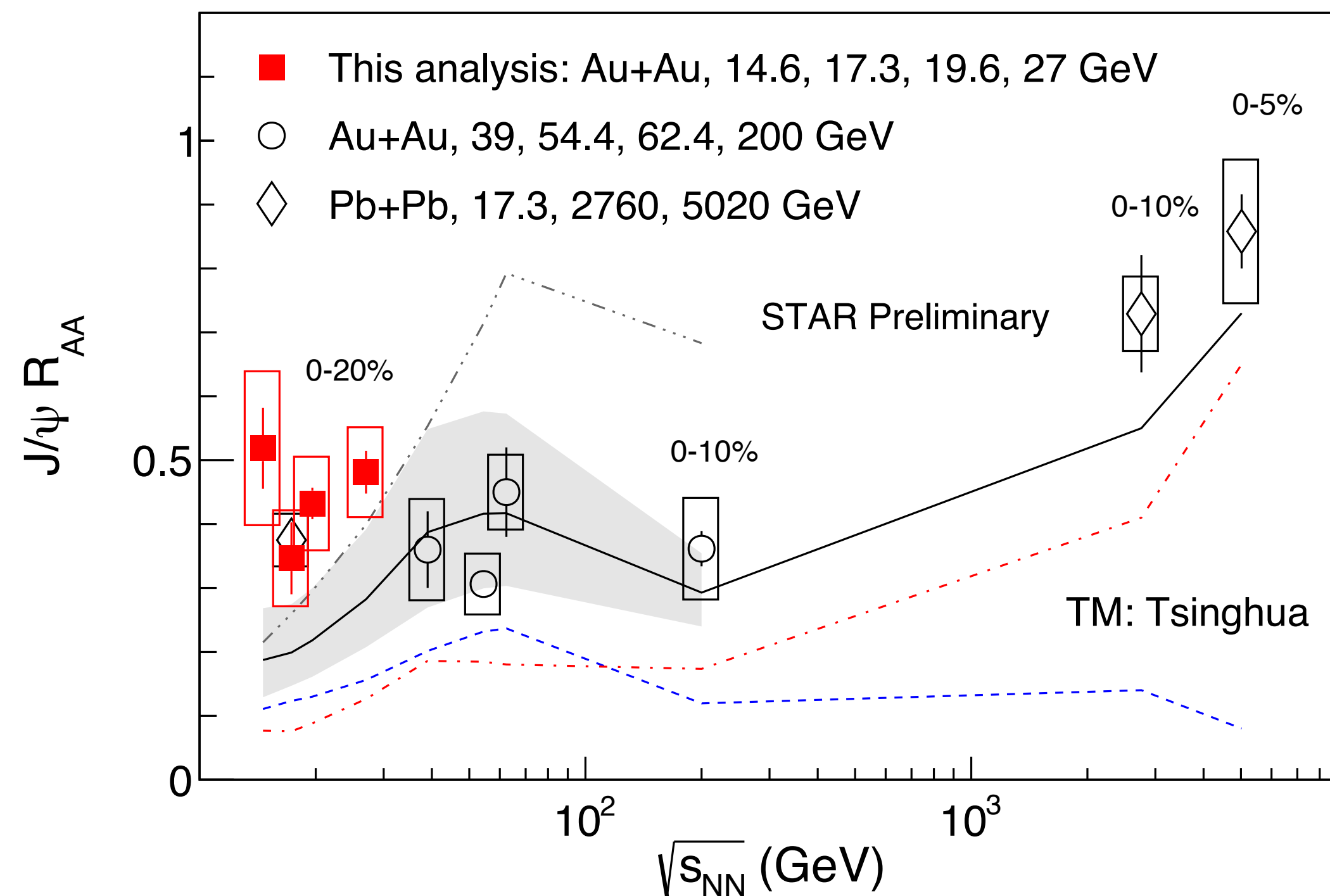
ALICE, PLB 734 (2014) 314

ALICE, NPA 1005 (2021) 121769

STAR, PLB 771 (2017) 13

STAR, PLB 797 (2019) 134917

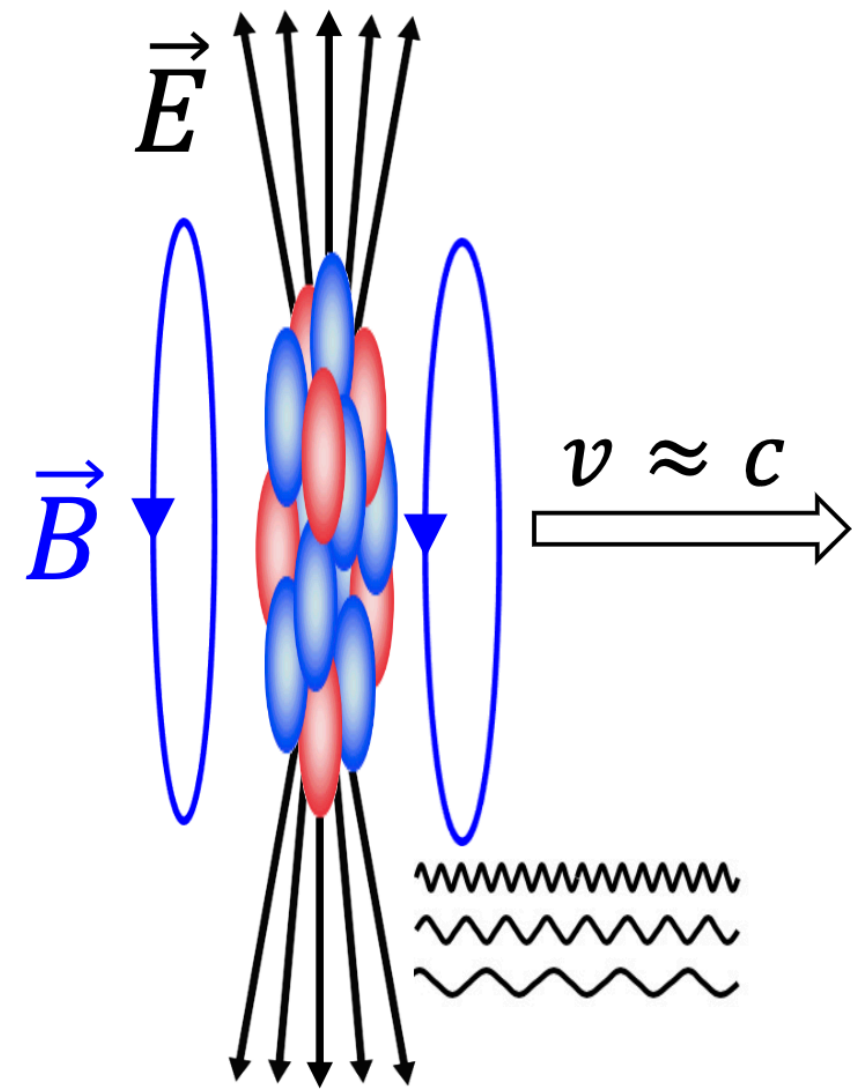
— · · · · CNM
 - - - - Primordial
 - · - · Regeneration



- No significant energy dependence of J/ψ R_{AA} in central collisions is observed up to 200 GeV
- J/ψ suppression is weaker at LHC energy
 - Regeneration dominates at LHC energy
- Tsinghua transport model captures the energy dependence, but slightly overestimates the data at lowest energies

J. Zhao and P. Zhuang, PRC 105 (2022) 064907 (private communications)

Linearly polarized photon



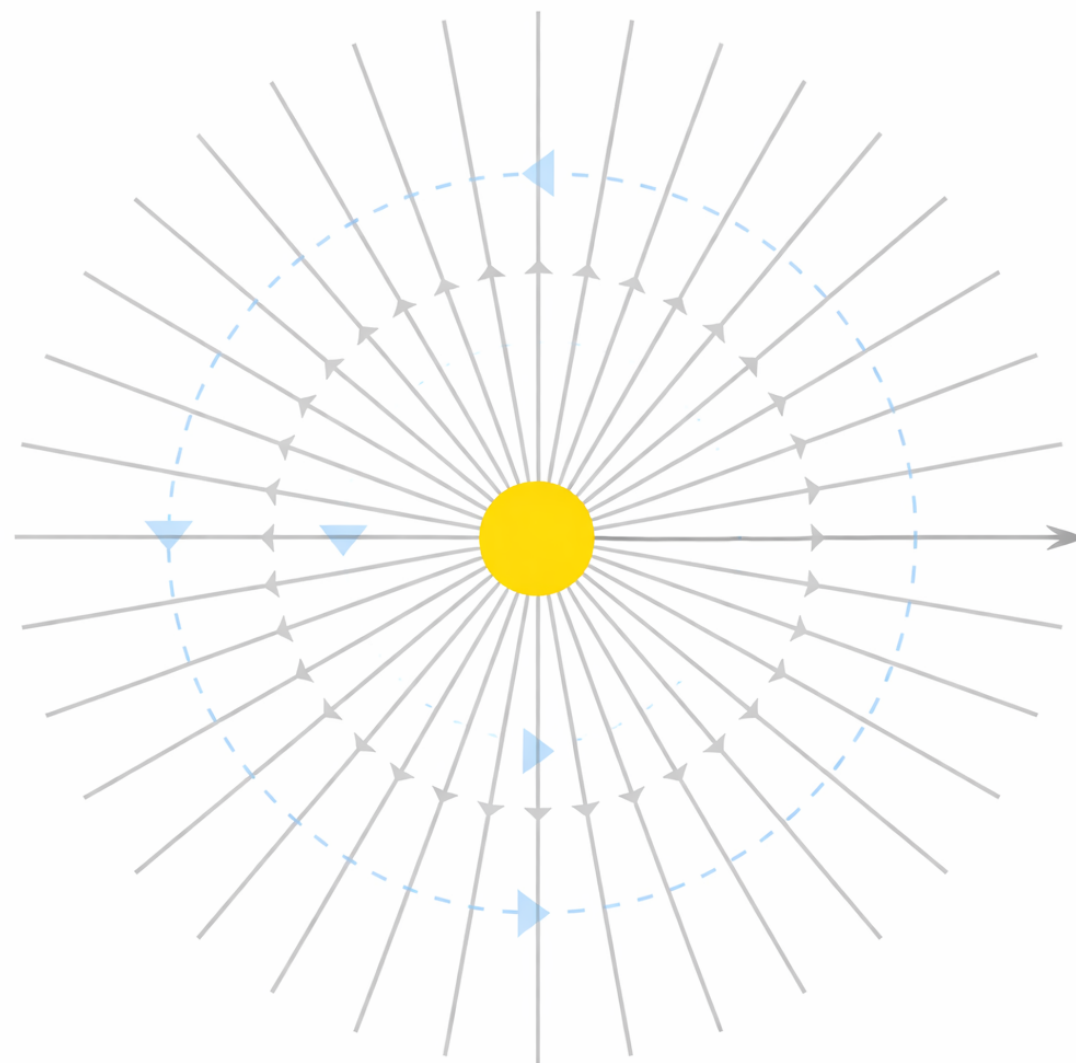
● Equivalent Photon Approximation

- Photon Flux $\propto Z^2$
- $p_T < \sim 30 \text{ MeV}$ ($Q^2 \sim 0$)

Fermi, Z. Phys. 29 (1924) 315

Williams, Phys. Rev. 45 (1934) 729

Weizsacker, Z. Phys. 88 (1934) 612



● The photon is linearly polarized

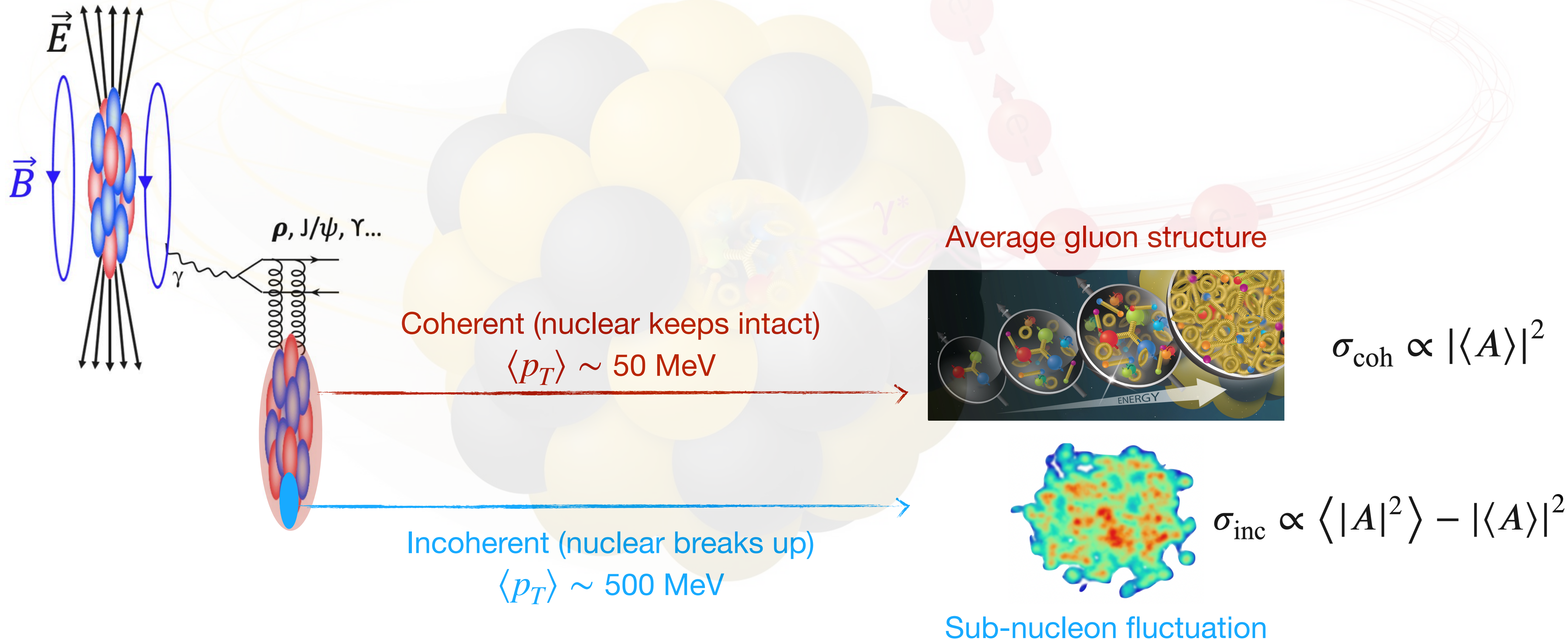
- Polarization direction ($\vec{\xi}$) is parallel to $\vec{E}$
- $\vec{E} \perp \vec{B} \perp \vec{v}$

Zhou et al., PLB 88 (2019) 576

Photon-nuclear interactions

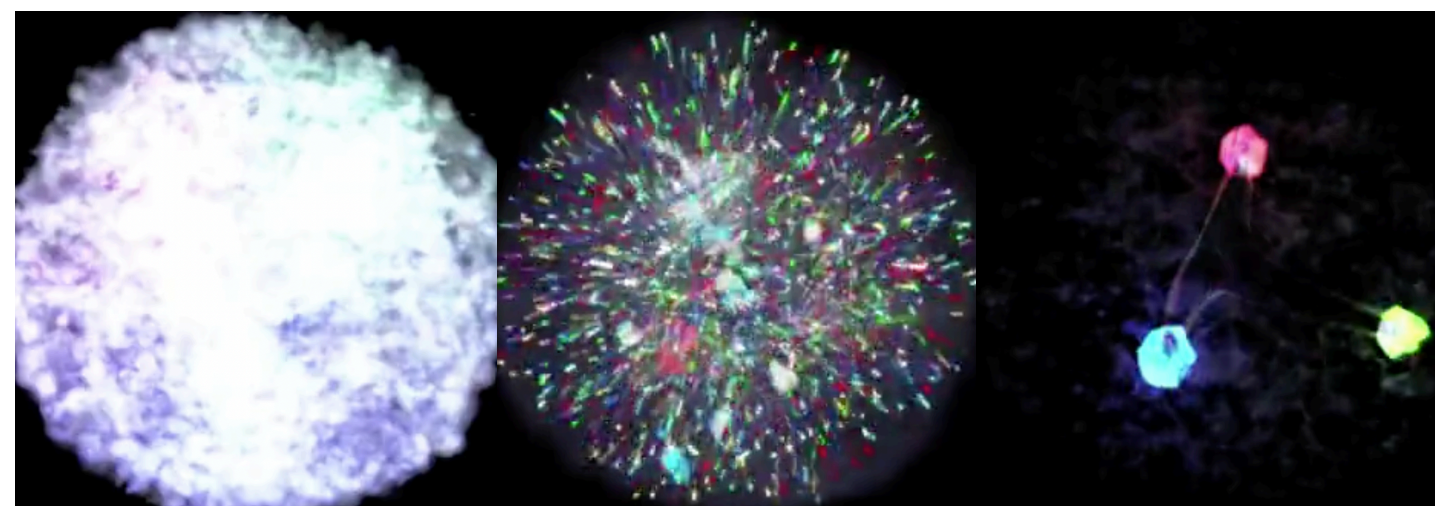
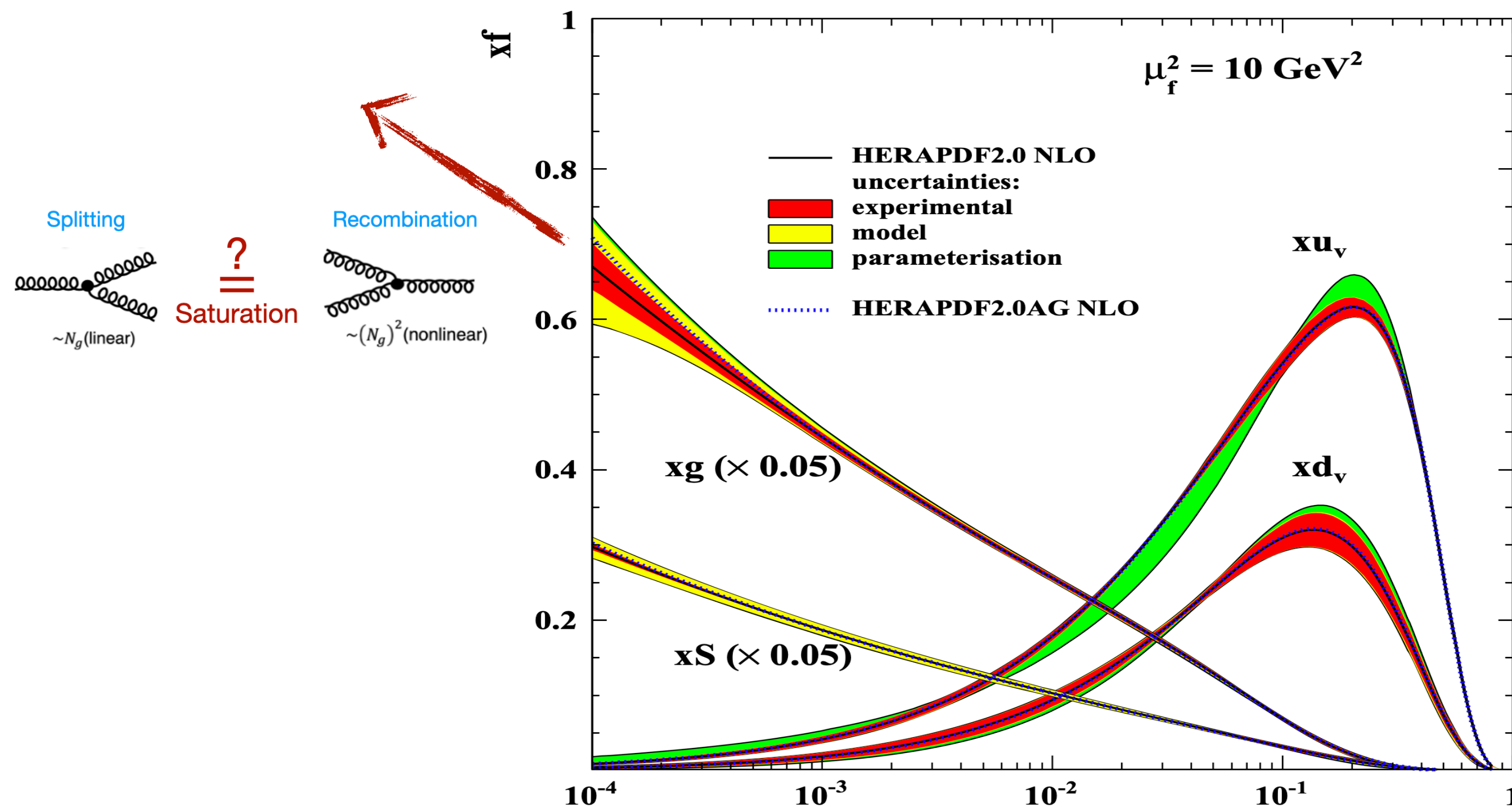
Ultra Peripheral Collisions

Good and Walker, Phys. Rev. 120 (1960) 1857



Physics goal of coherent and incoherent J/ ψ

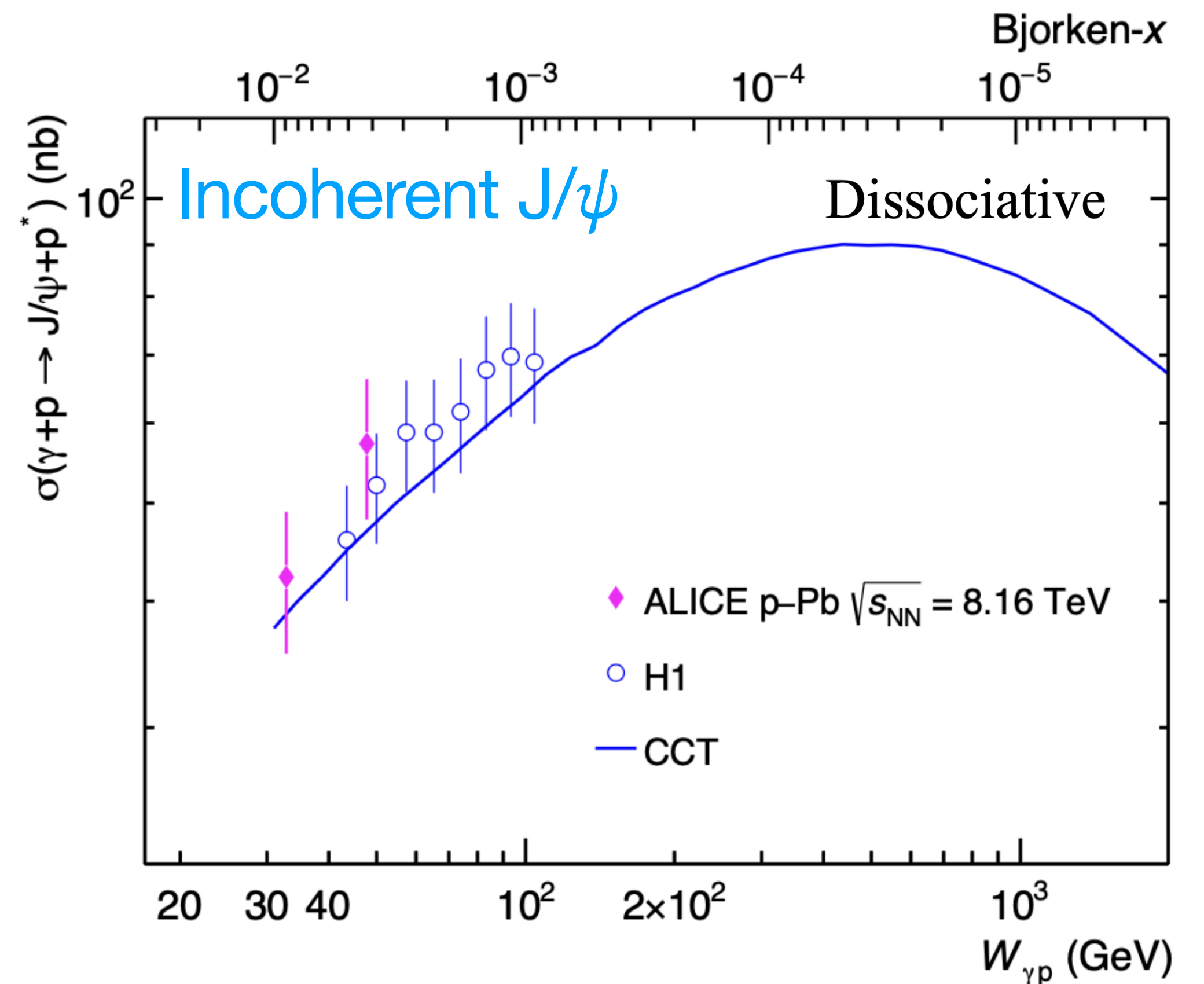
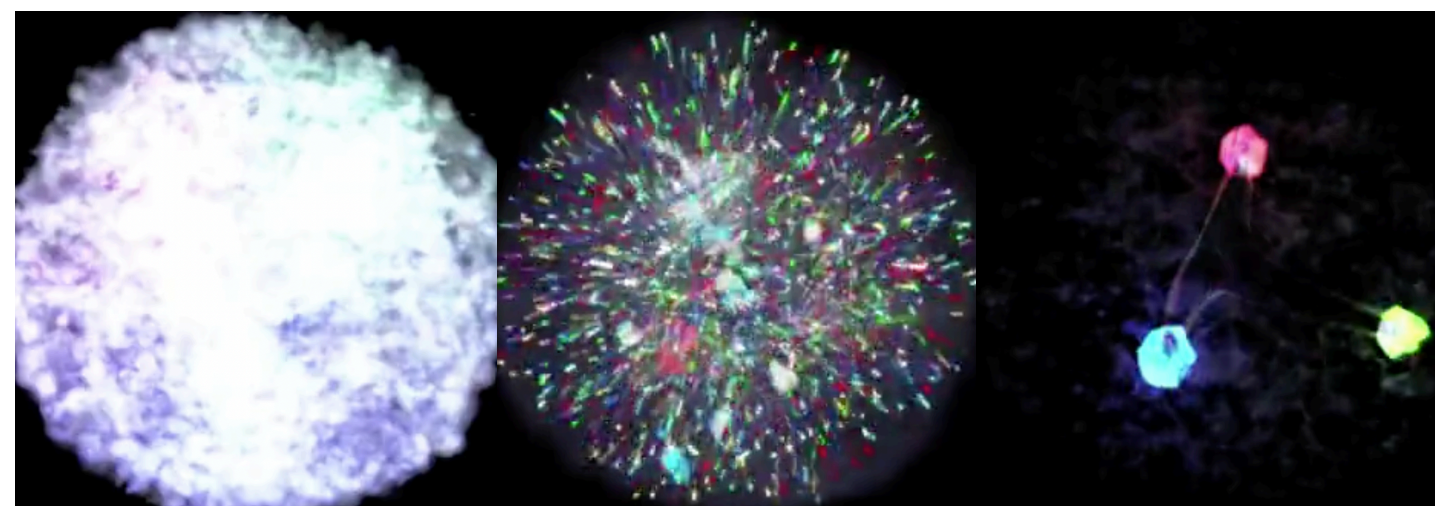
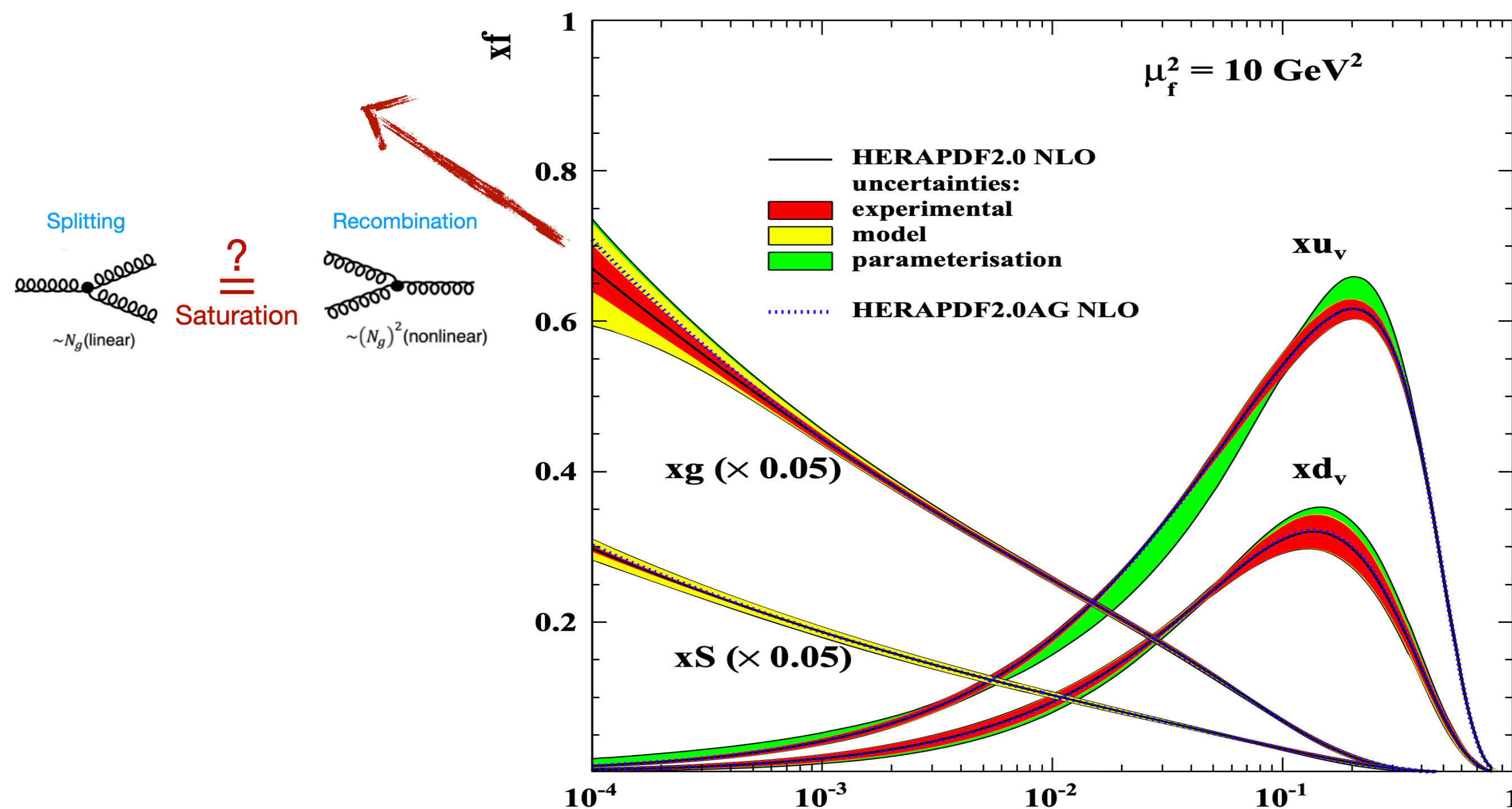
H1 and ZEUS, EPJC 75 (2015) 580



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

Physics goal of coherent and incoherent J/ψ

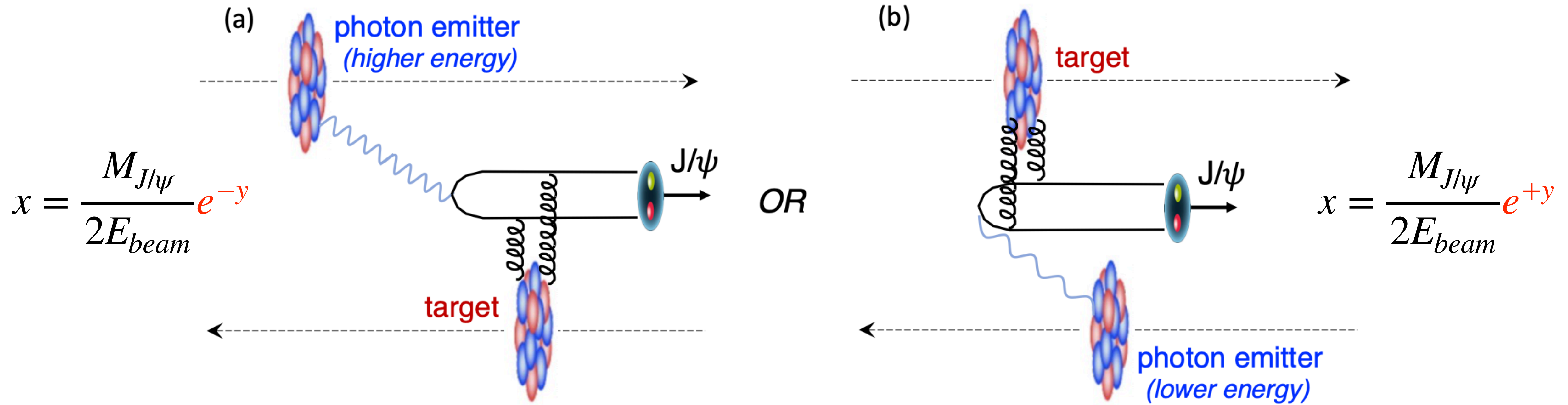
H1 and ZEUS, EPJC 75 (2015) 580



- Reduced gluon fluctuations also serve as a signature of gluon saturation

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

The “two-component ambiguity” problem

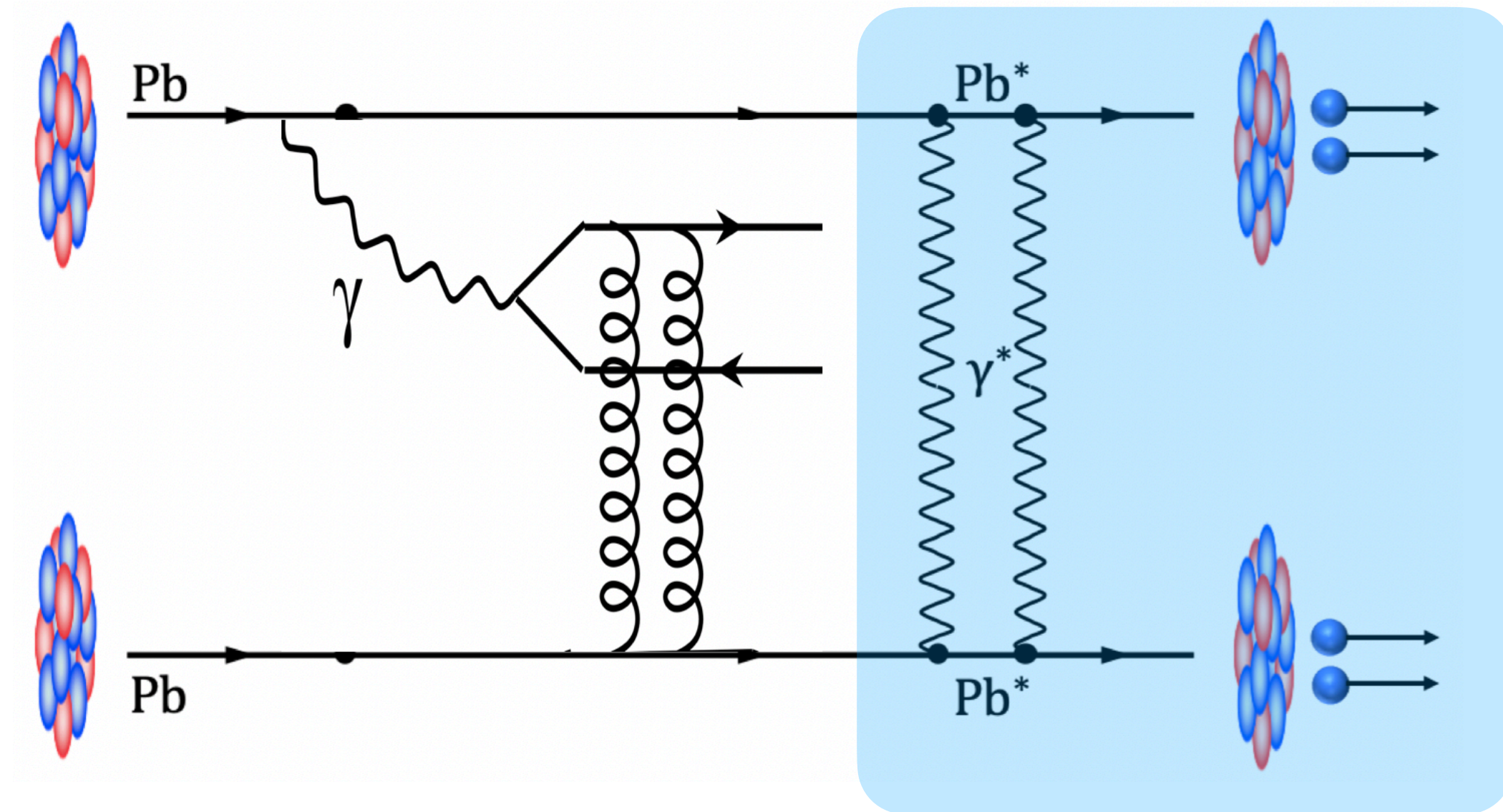


$$\frac{d\sigma_{AA \rightarrow AA' J/\psi}}{dy} = N_{\gamma/A}(\omega_1) \cdot \sigma_{\gamma A \rightarrow J/\psi A'}(\omega_1) + N_{\gamma/A}(\omega_2) \cdot \sigma_{\gamma A \rightarrow J/\psi A'}(\omega_2)$$

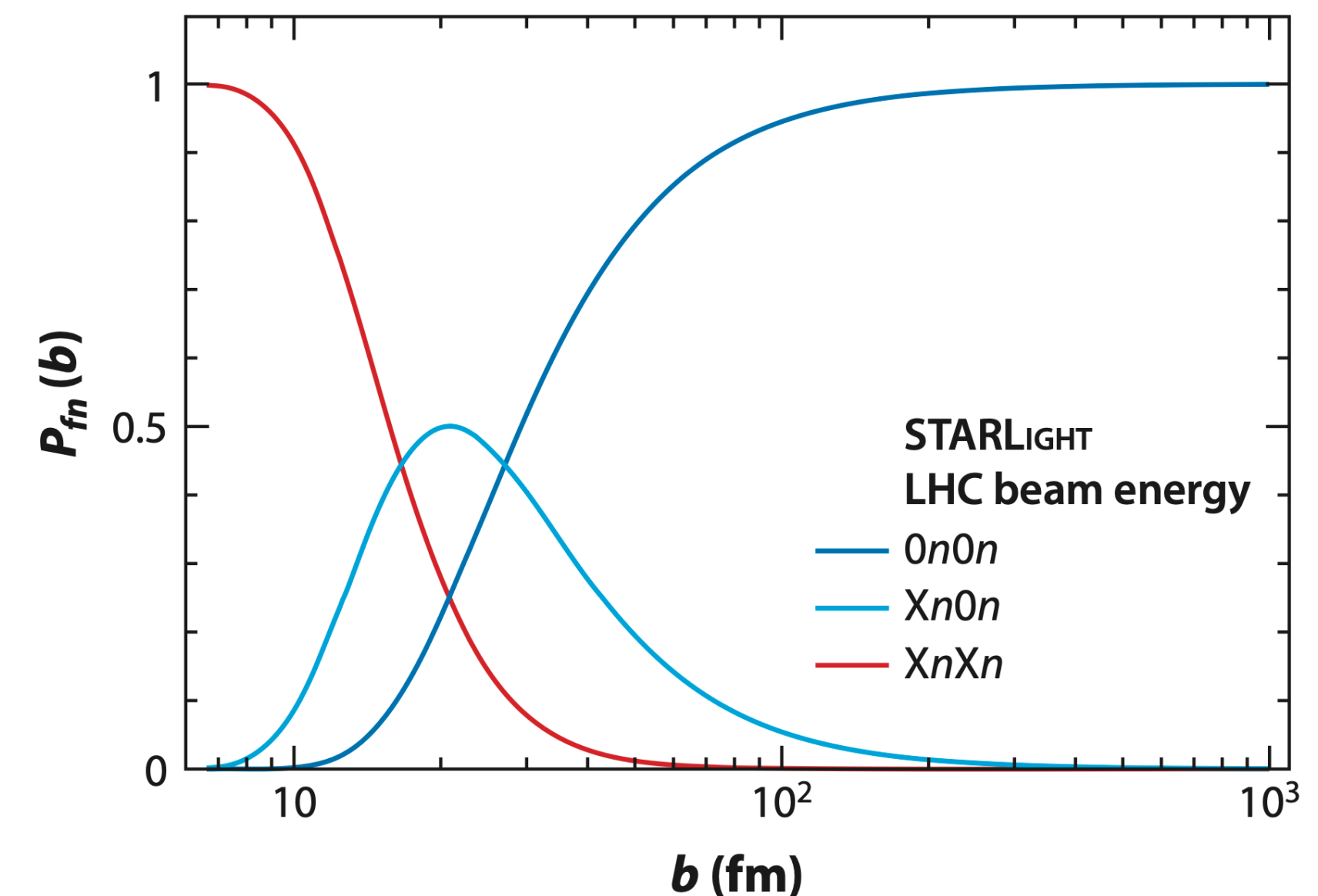
A solution to the “two-component ambiguity”

- 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

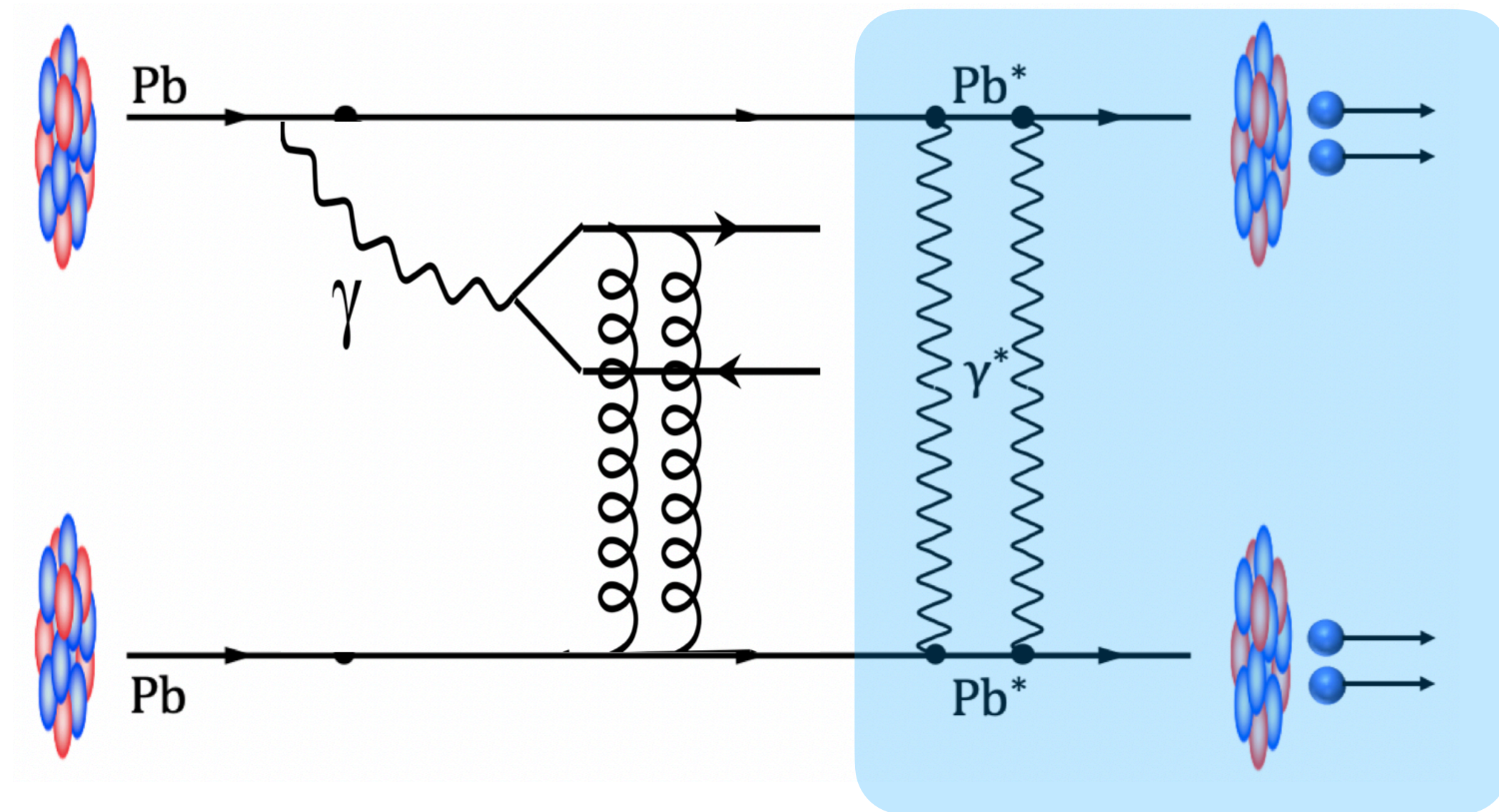


$$\frac{d\sigma_{AA \rightarrow AA' J/\psi}}{dy} = N_{\gamma/A}(\omega_1) \cdot \sigma_{\gamma A \rightarrow J/\psi A'}(\omega_1) + N_{\gamma/A}(\omega_2) \cdot \sigma_{\gamma A \rightarrow J/\psi A'}(\omega_2)$$

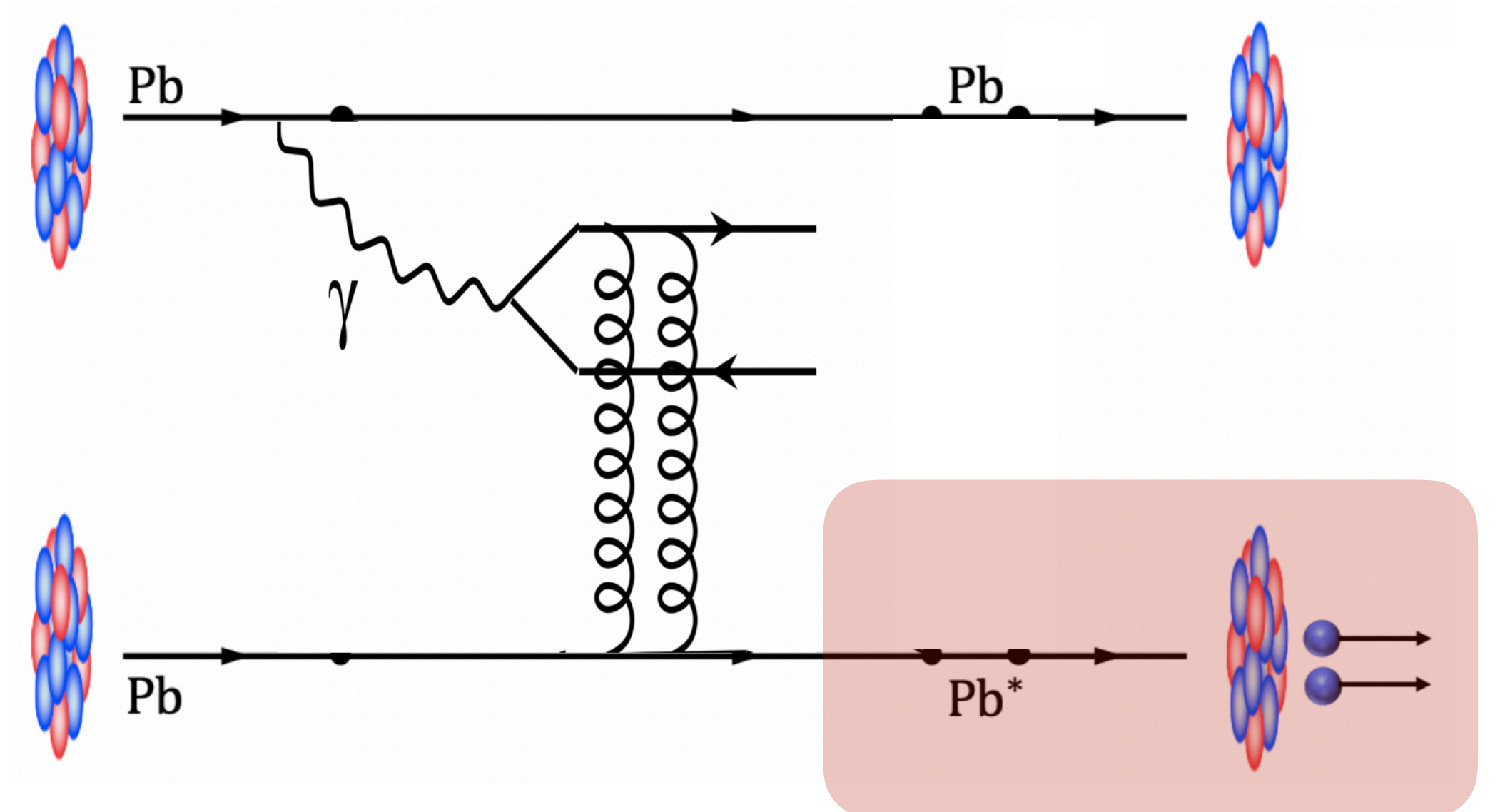
A solution to the “two-component ambiguity”

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

Coherent photoproduction



Incoherent photoproduction

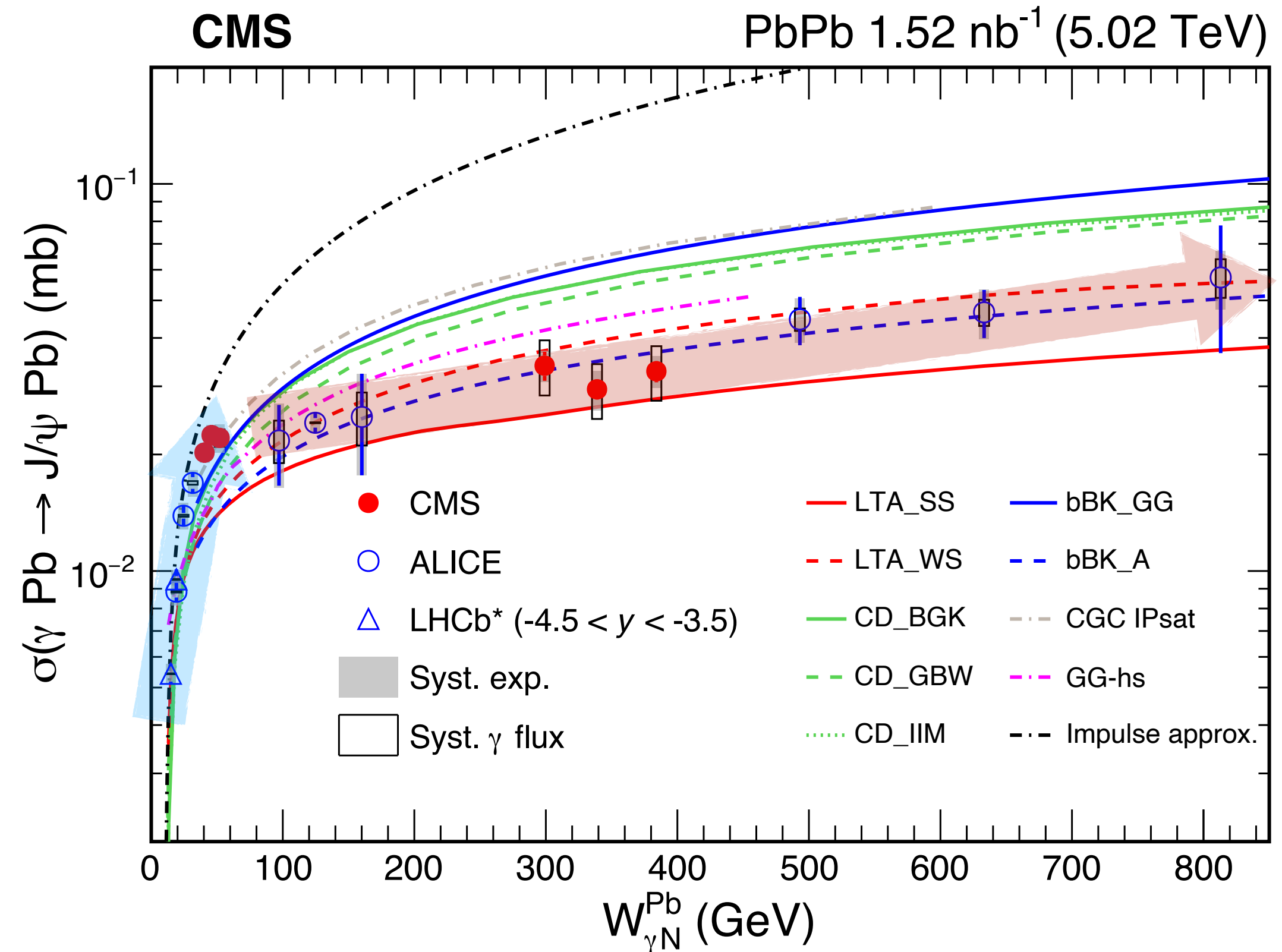


$$\frac{d\sigma_{AA \rightarrow AA' J/\psi}}{dy} = N_{\gamma/A}(\omega_1) \cdot \sigma_{\gamma A \rightarrow J/\psi A'}(\omega_1) + N_{\gamma/A}(\omega_2) \cdot \sigma_{\gamma A \rightarrow J/\psi A'}(\omega_2)$$

Energy dependence of coherent J/ ψ

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

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



Large x $\longrightarrow$ Small x

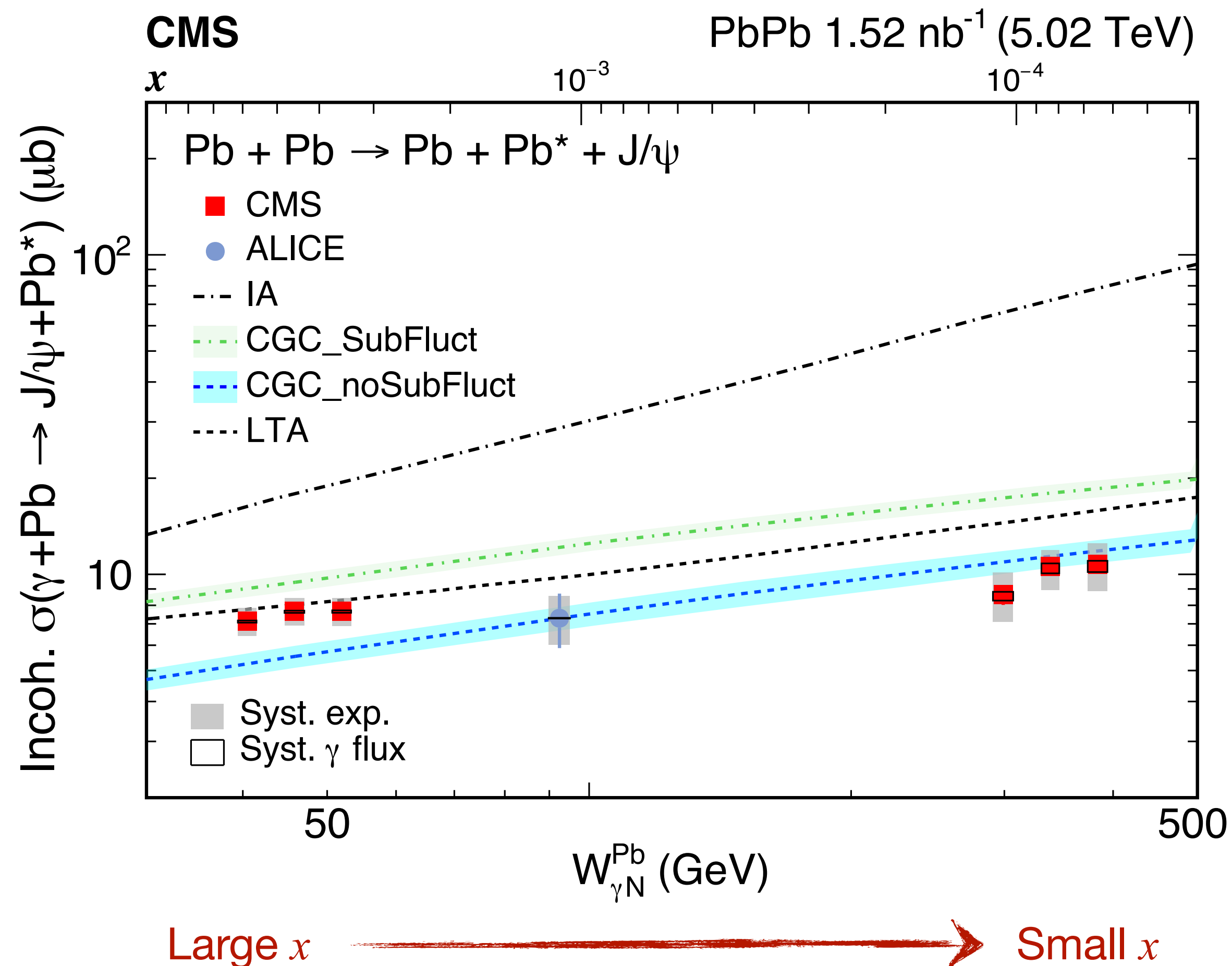


◎ Direct evidence of gluon saturation inside heavy nuclei?

- $W_{\gamma N}^{Pb} < 40$ GeV: rapidly rising
- $40 < W_{\gamma N}^{Pb} < 800$ GeV: nearly flat with a much slower rising

Probing gluon fluctuations with incoherent J/ψ

CMS, PRL 135 (2025) 112301

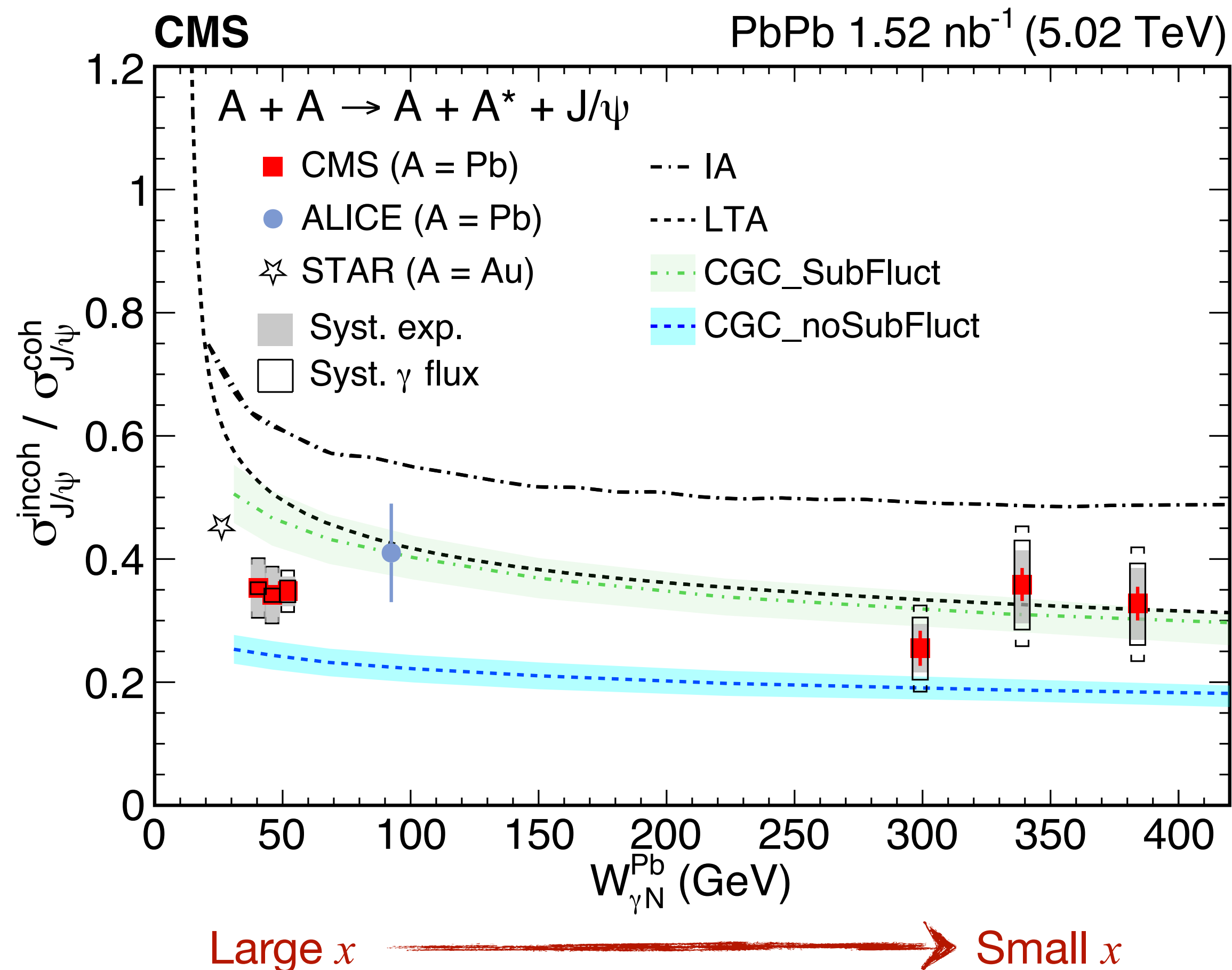


- First measurement of incoherent J/ψ as a function of energy
- Strong suppression compared to impulse approximation model
- LTA describes the data with $W_{\gamma N}^{\text{Pb}} < 60$ GeV, while CGC without gluon fluctuations is consistent with data with $W_{\gamma N}^{\text{Pb}} > 90$ GeV

Comparisons of coherent and incoherent J/ψ

CMS, PRL 135 (2025) 112301

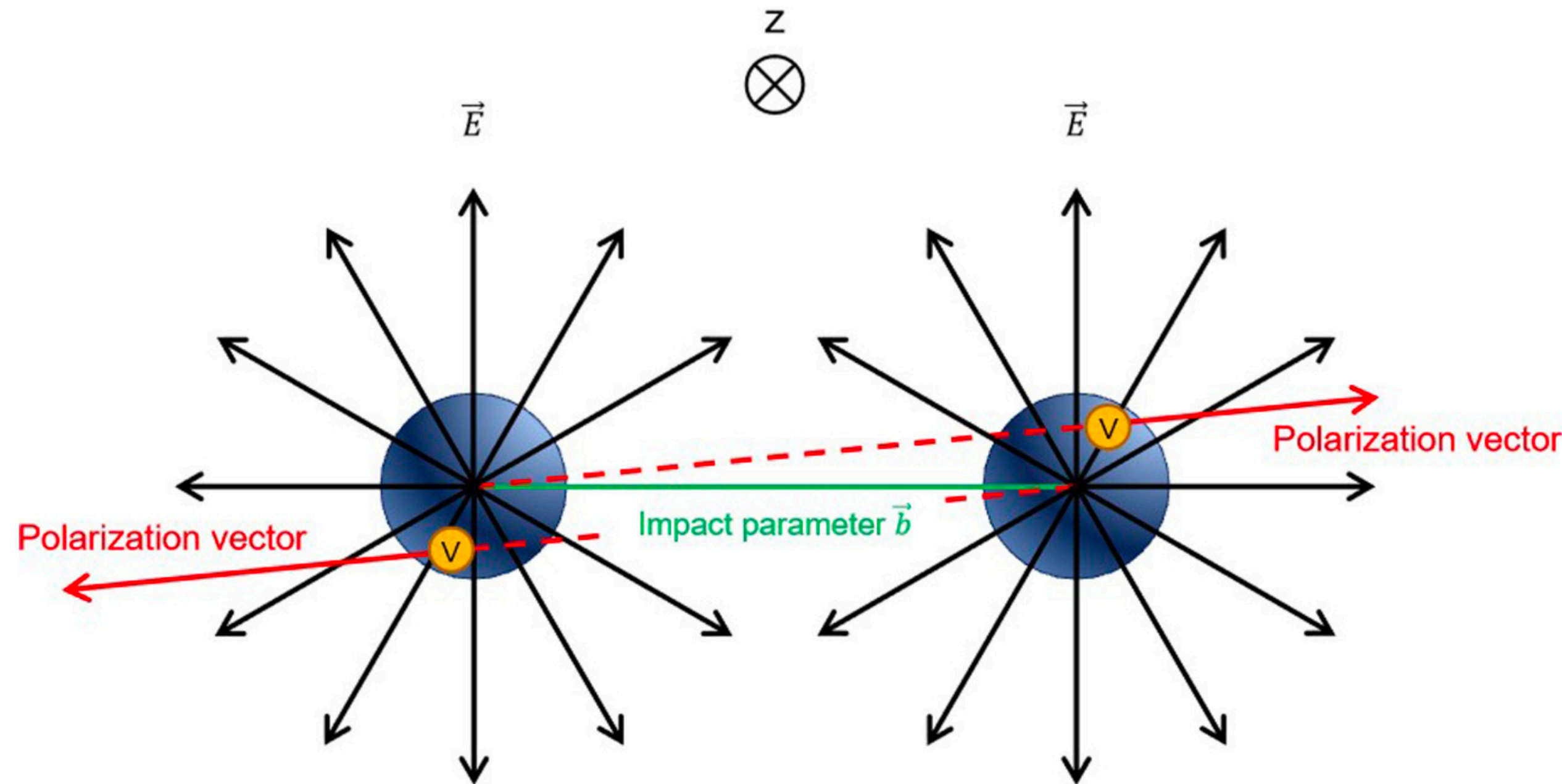
CMS, PRL 131 (2023) 262301



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

Modulation of photoproduced vector meson

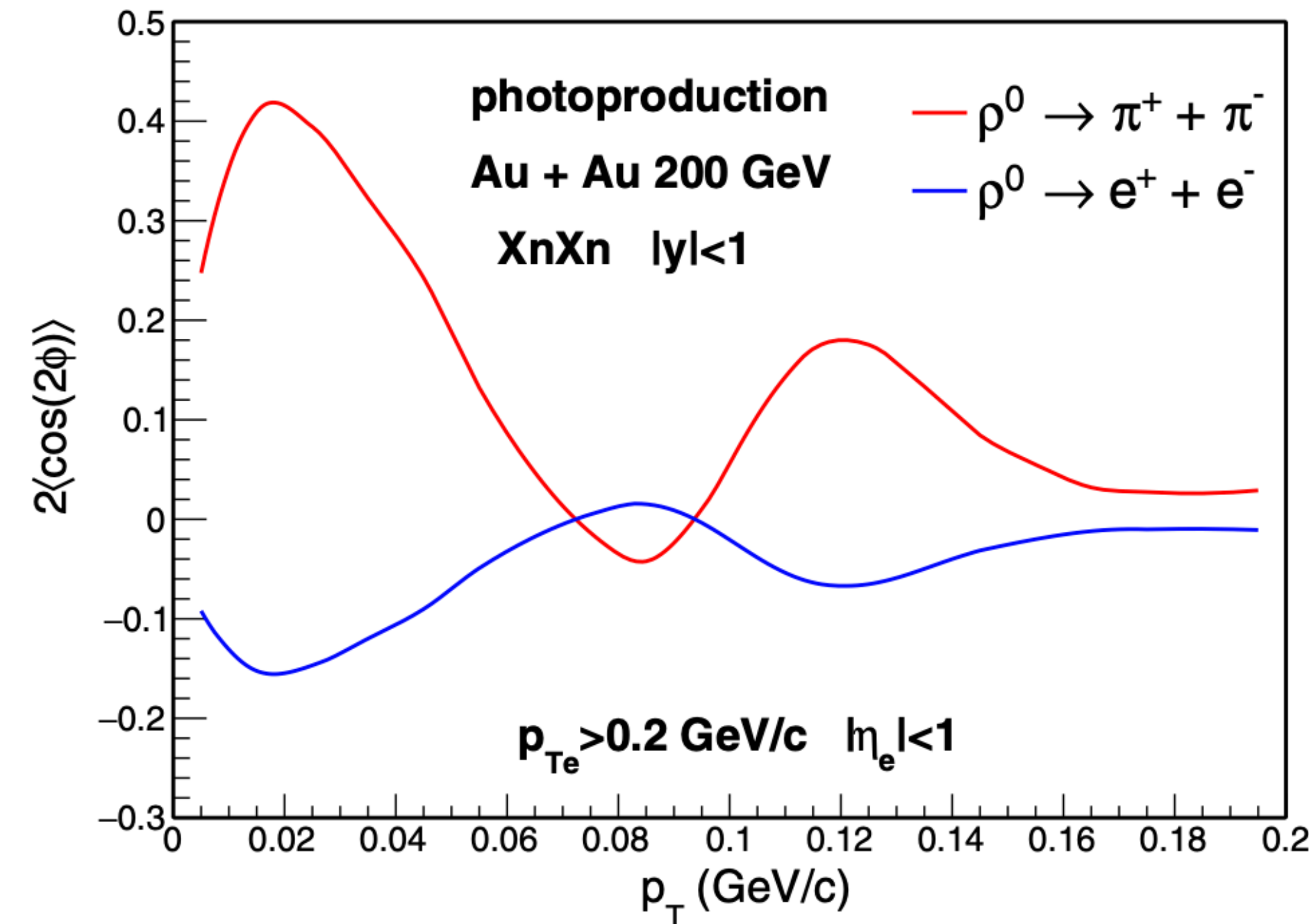
Wu et al., PRR 4 (2022) L042048
Xing et al., JHEP 10 (2020) 064
Zha et al., PRD 103 (2021) 033007



- VM inherits the polarization because of s-channel helicity conservation
- $\cos(2\Delta\phi)$ azimuthal modulation of decayed daughter **w.r.t. the polarization direction**
- Impact parameter (**b**): a robust estimator of polarization direction

Spin state dependence of $\cos(2\Delta\phi)$ modulation

Zha et al., PRD 103 (2021) 033007
 STAR, Sci. Adv. 9 (2023) abq3903
 STAR, PRL 136 (2026) 242302



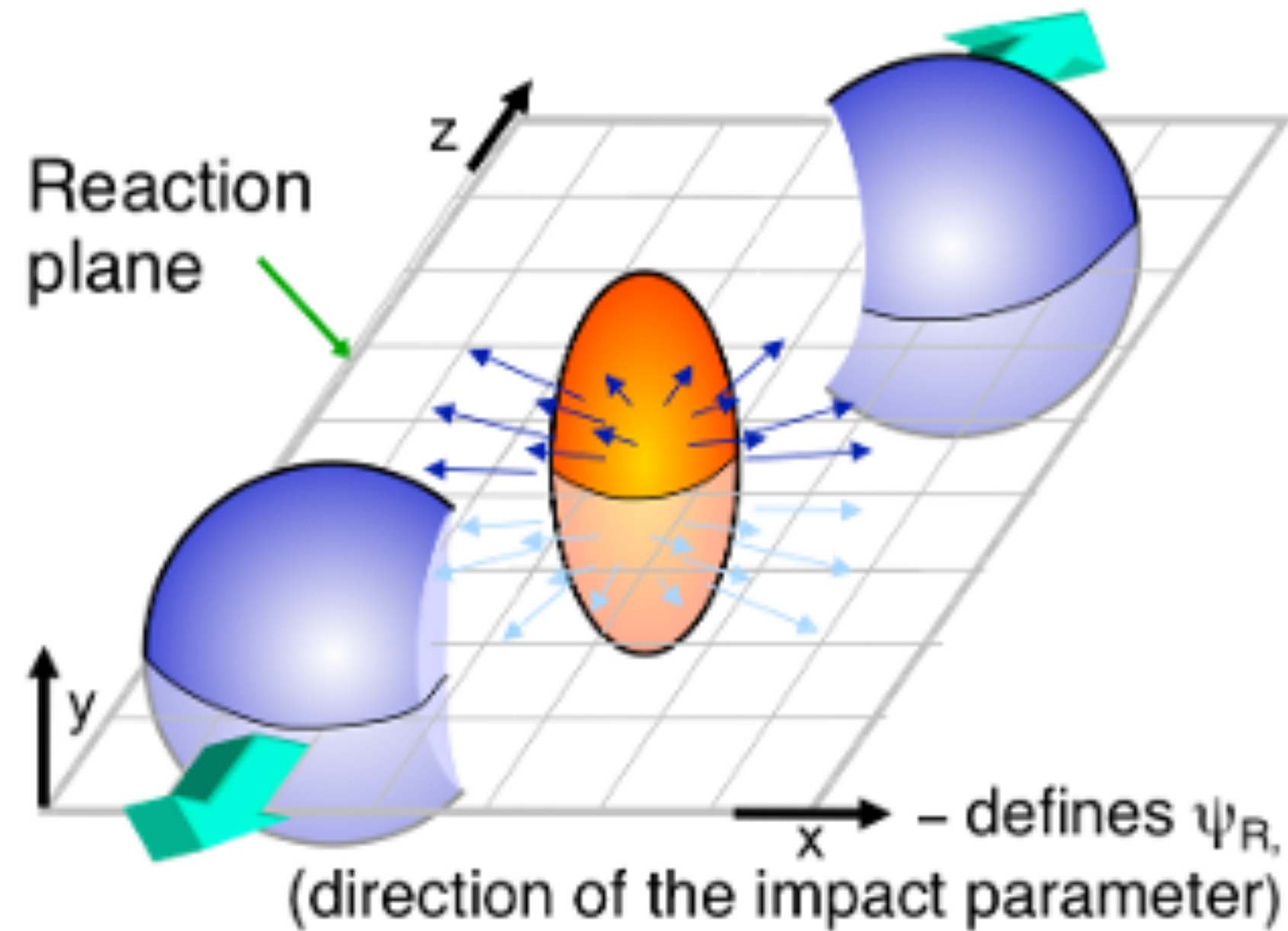
● Spin-0 final states ($\rho^0 \rightarrow \pi^+ \pi^-$)

$$\propto \frac{3}{8\pi} \sin^2 \theta [1 + \cos 2(\phi - \Phi)].$$

● Spin-1/2 final states ($J/\psi/\rho^0 \rightarrow l^+ l^-$)

$$\propto \frac{3}{16\pi} (1 + \cos^2 \theta) \left[1 - \frac{\sin^2 \theta}{1 + \cos^2 \theta} \cos 2(\phi - \Phi) \right]$$

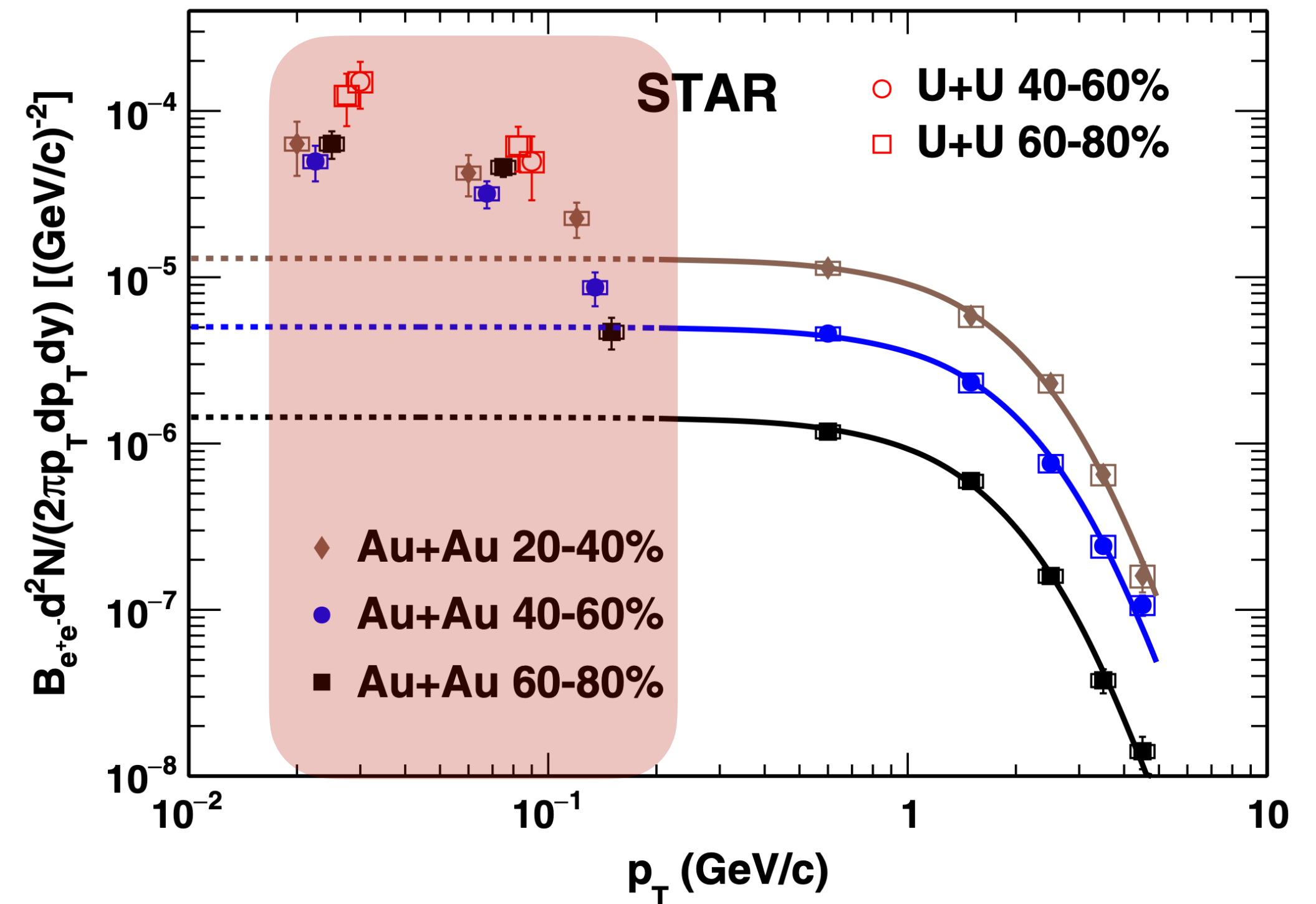
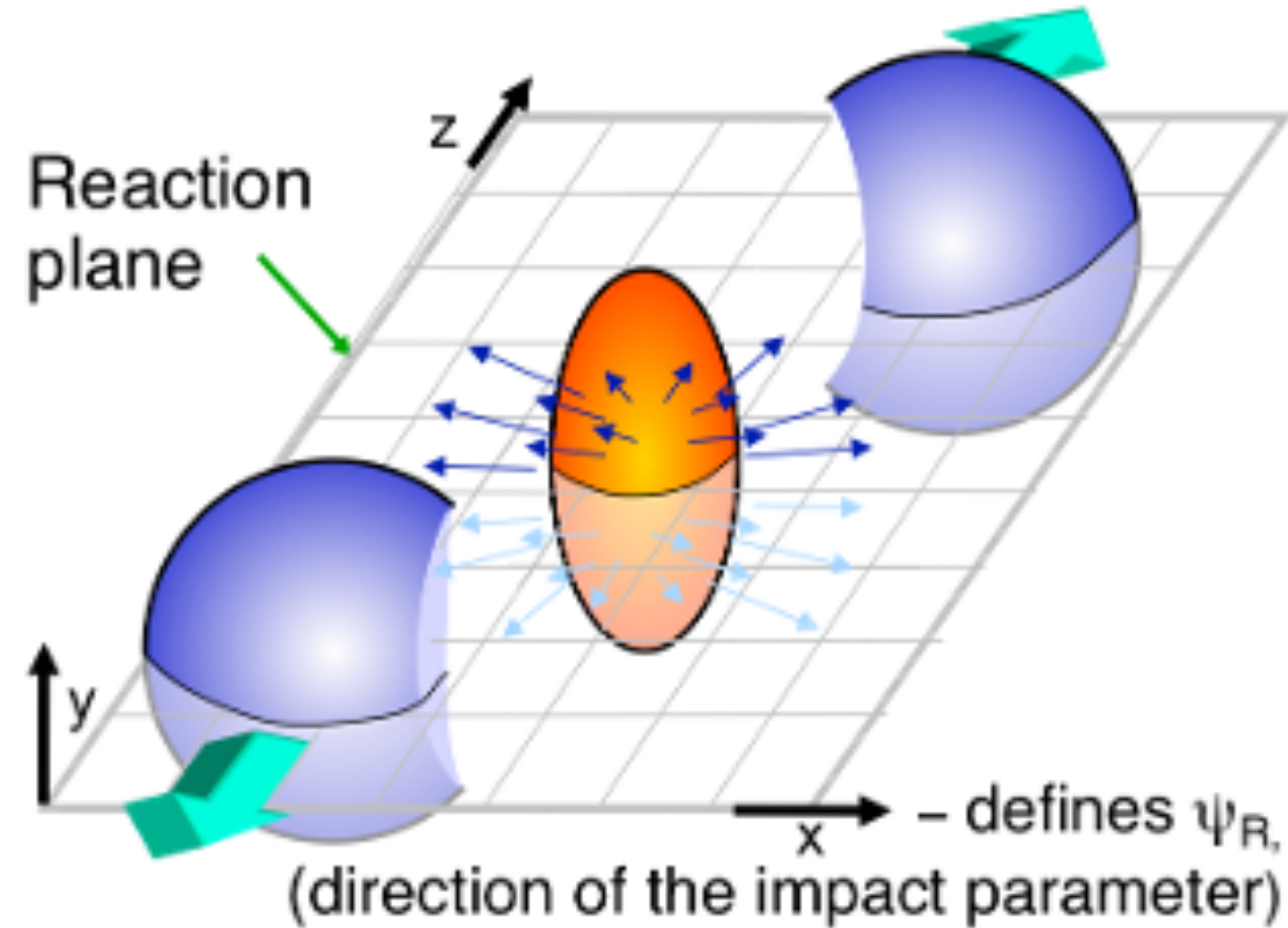
Study the modulation in hadronic collisions



- $\mathbf{b}$ is estimated by the second order event plane technique

Study the modulation in hadronic collisions

ALICE, PRL 116 (2016) 222301
STAR, PRL 123 (2019) 132302



- b is estimated by the second order event plane technique

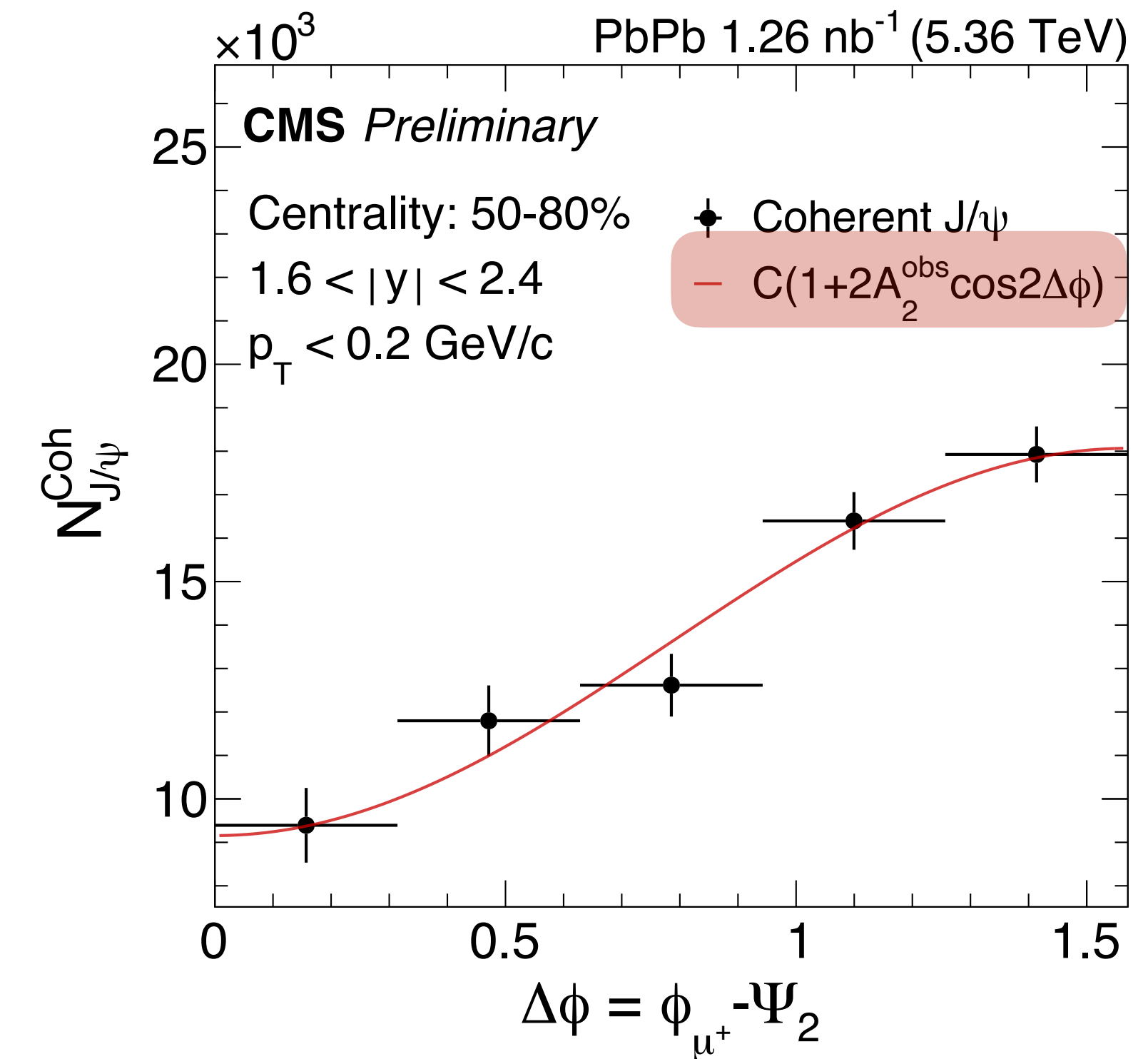
[STAR, QM 2025](#)

- Coherent J/ψ was observed in hadronic collisions

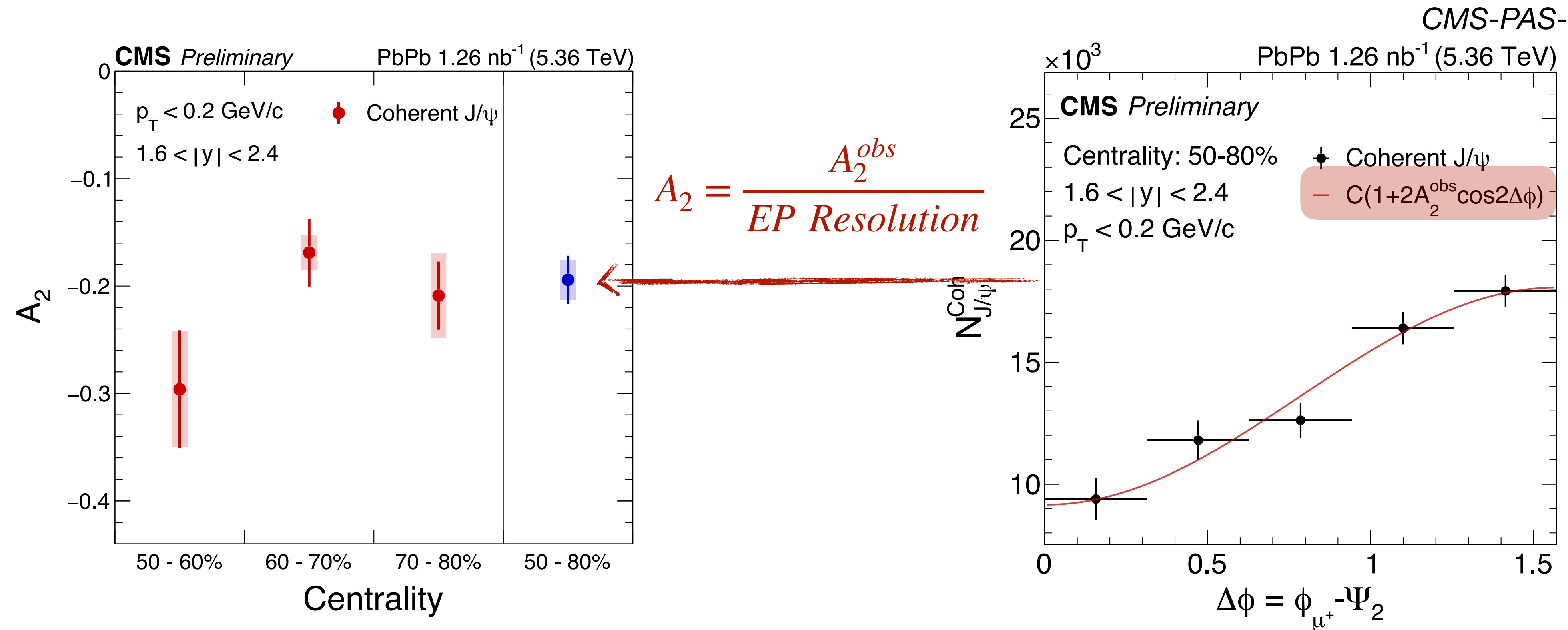
[CMS-PAS-HIN-25-006](#)

$\cos(2\Delta\phi)$ modulation in coherent $J/\psi \rightarrow \mu^+\mu^-$

CMS-PAS-HIN-25-006

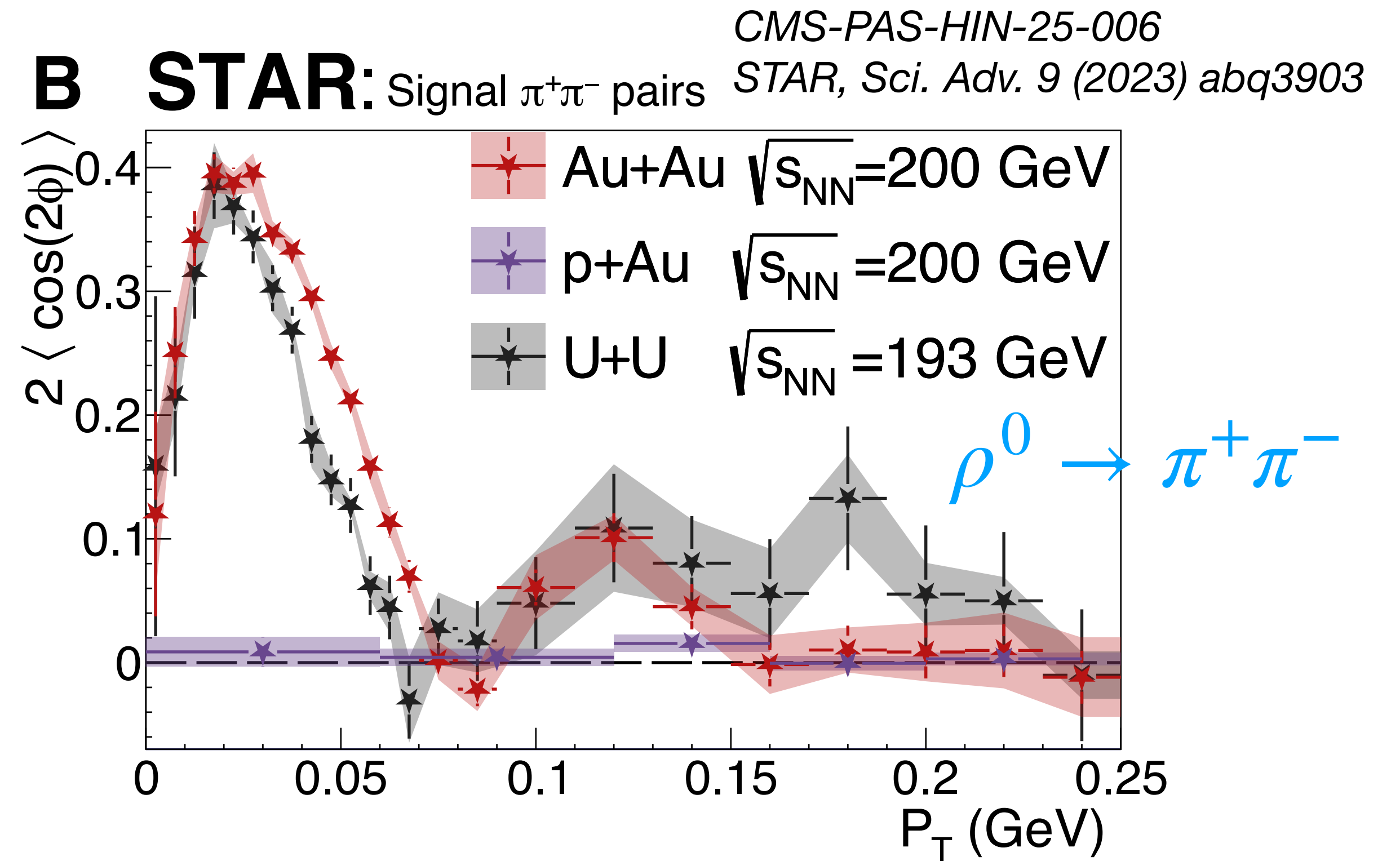
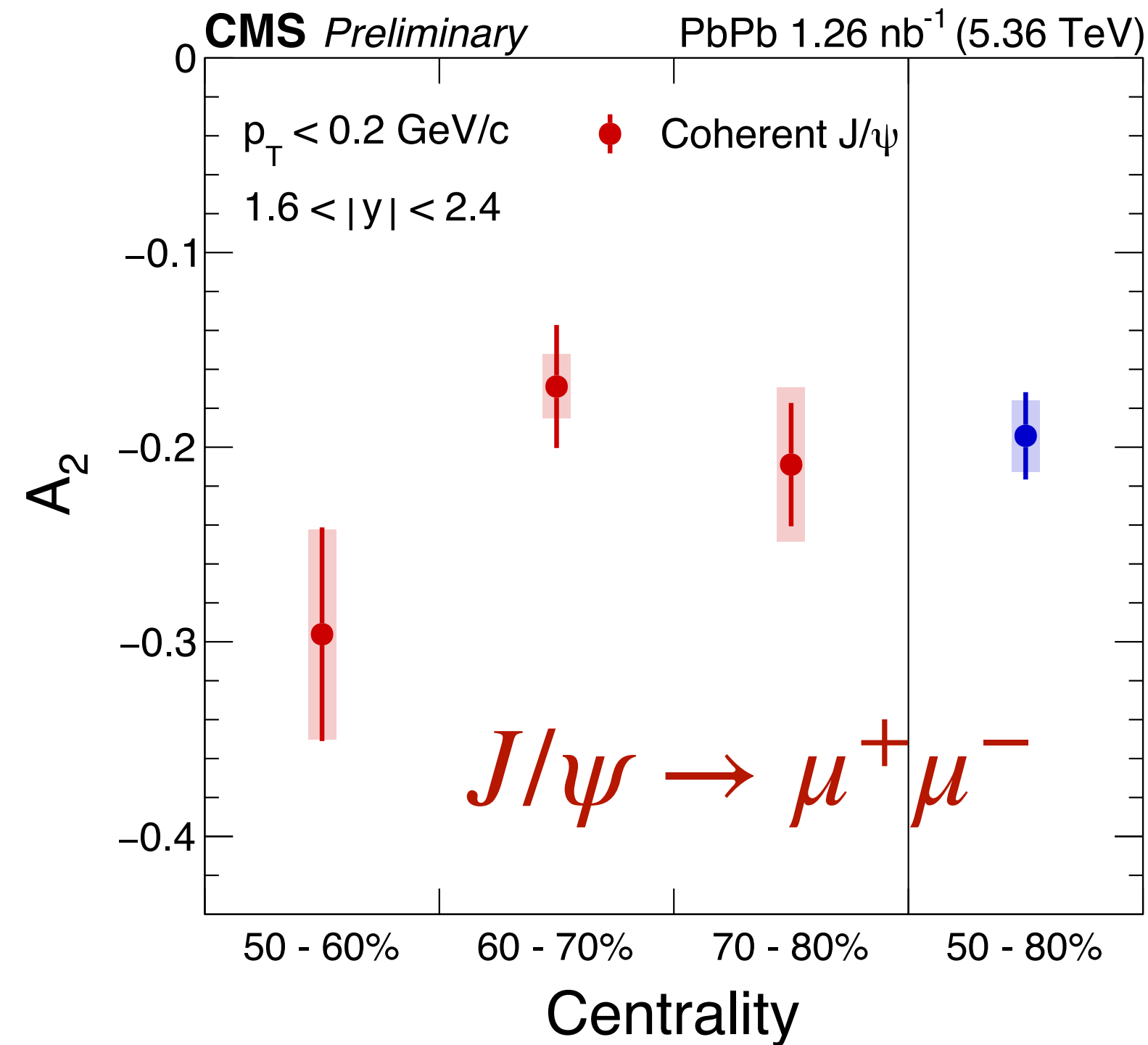


$\cos(2\Delta\phi)$ modulation in coherent $J/\psi \rightarrow \mu^+\mu^-$



- ⊙ A negative modulation is observed in coherent $J/\psi \rightarrow \mu^+\mu^-$ (**spin-1/2**)
 - $A_2 = -0.194 \pm 0.022$ (stat) ± 0.018 (syst), with a significance of 6.8σ
 - No significant centrality dependence in 50-80% centrality class

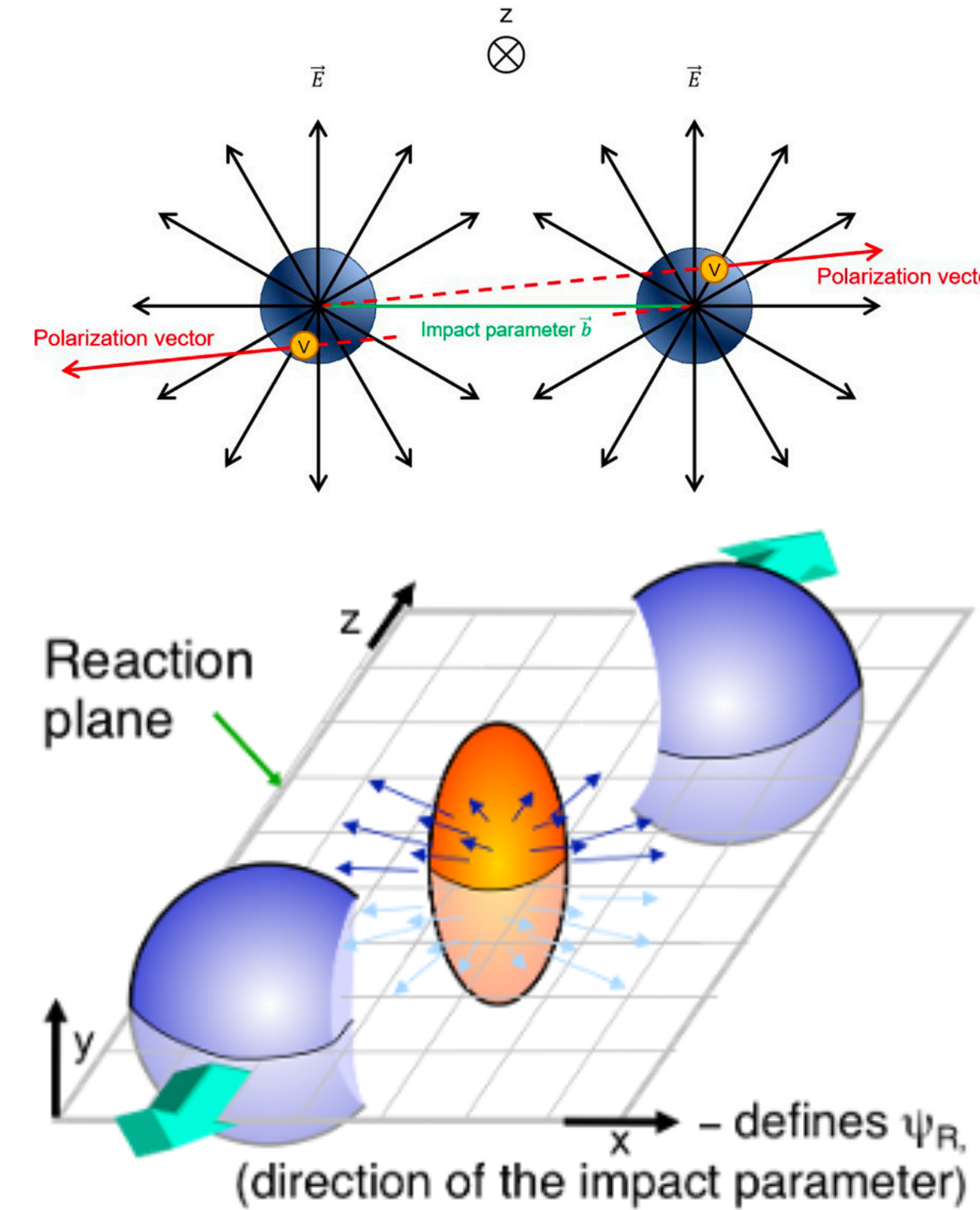
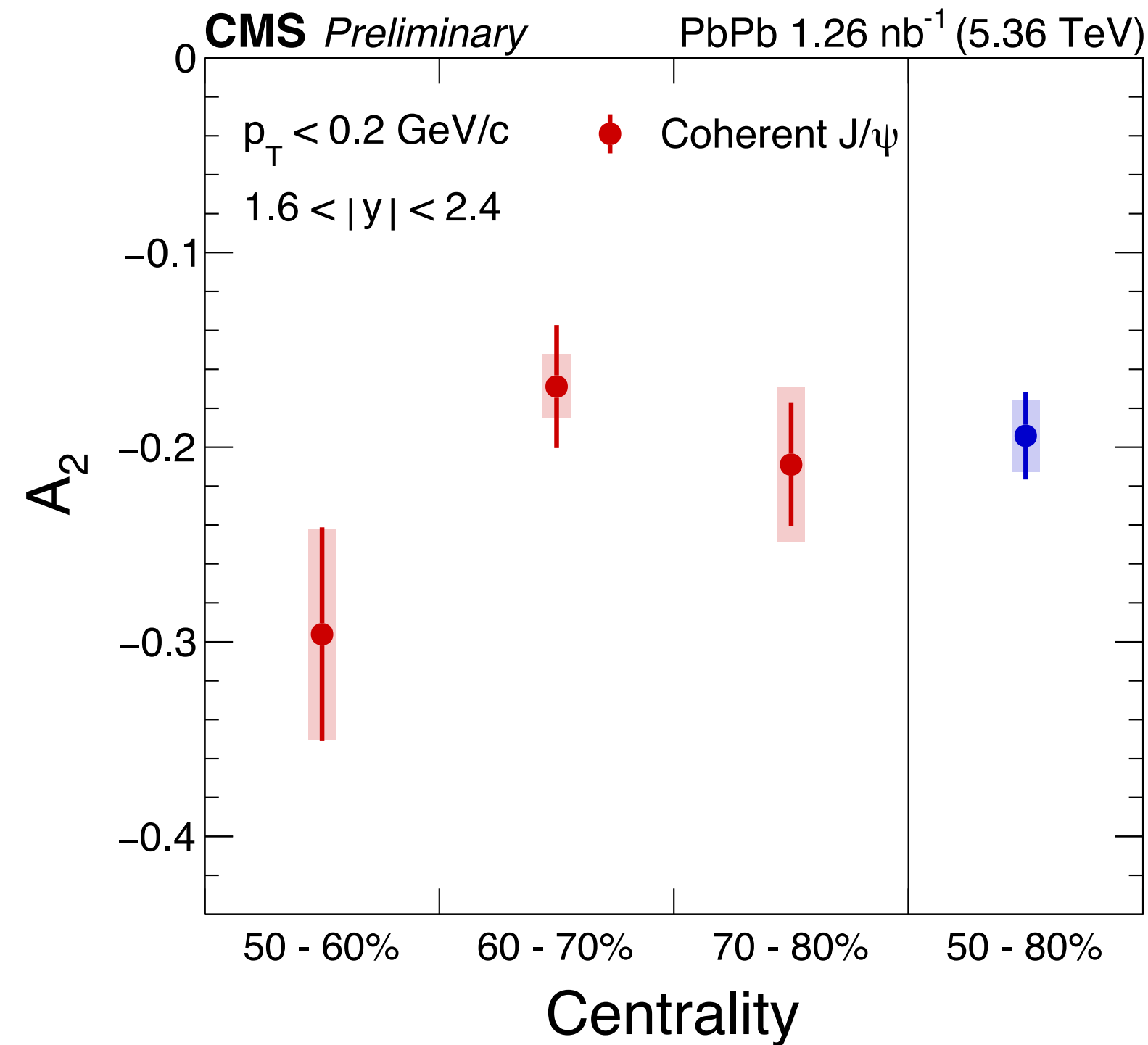
$\cos(2\Delta\phi)$ modulation in coherent $J/\psi \rightarrow \mu^+\mu^-$



- A negative modulation is observed in coherent $J/\psi \rightarrow \mu^+\mu^-$ (spin-1/2)
- Provide the first observation of spin-state dependence in azimuthal asymmetry

$\cos(2\Delta\phi)$ modulation in coherent $J/\psi \rightarrow \mu^+\mu^-$

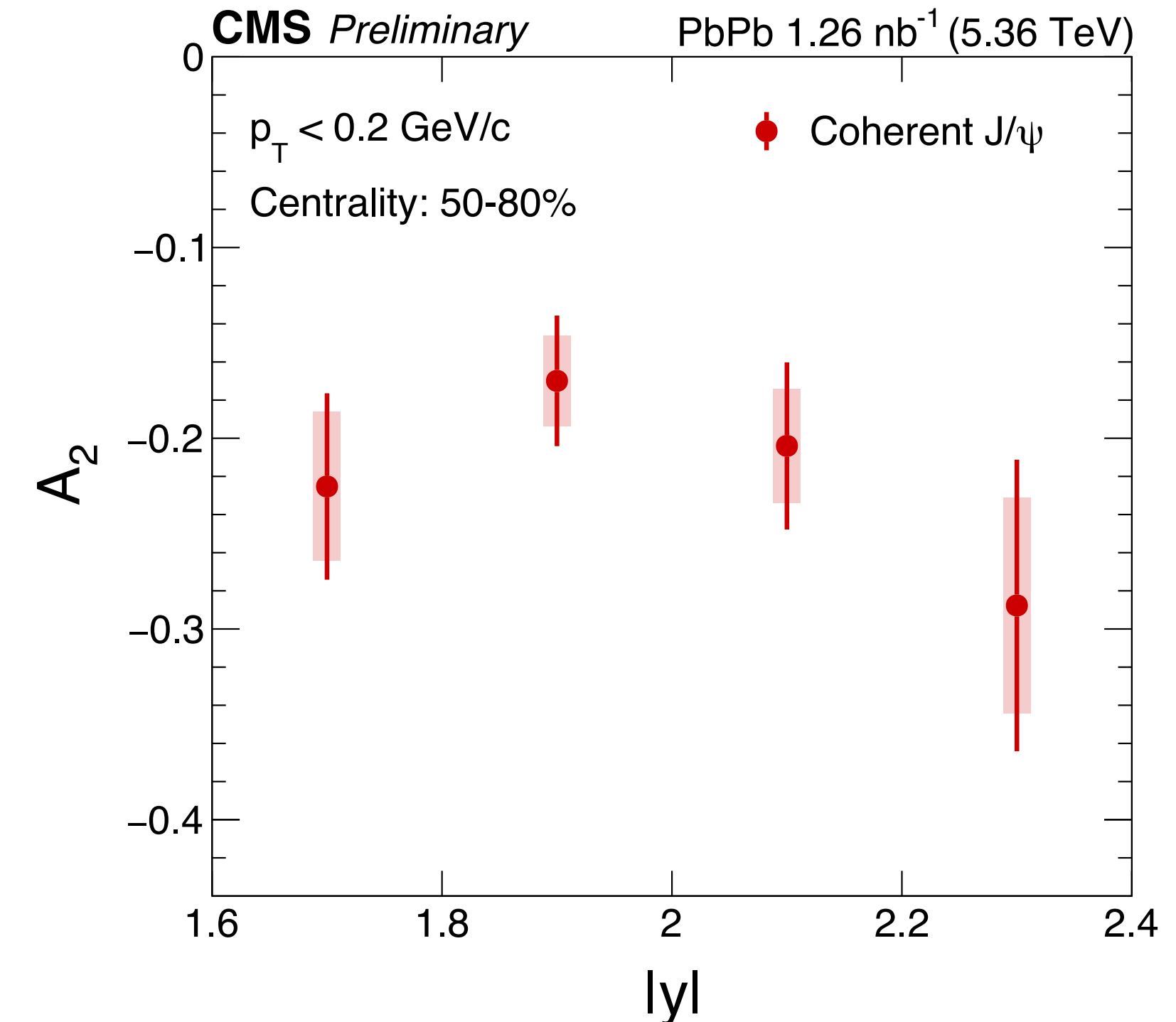
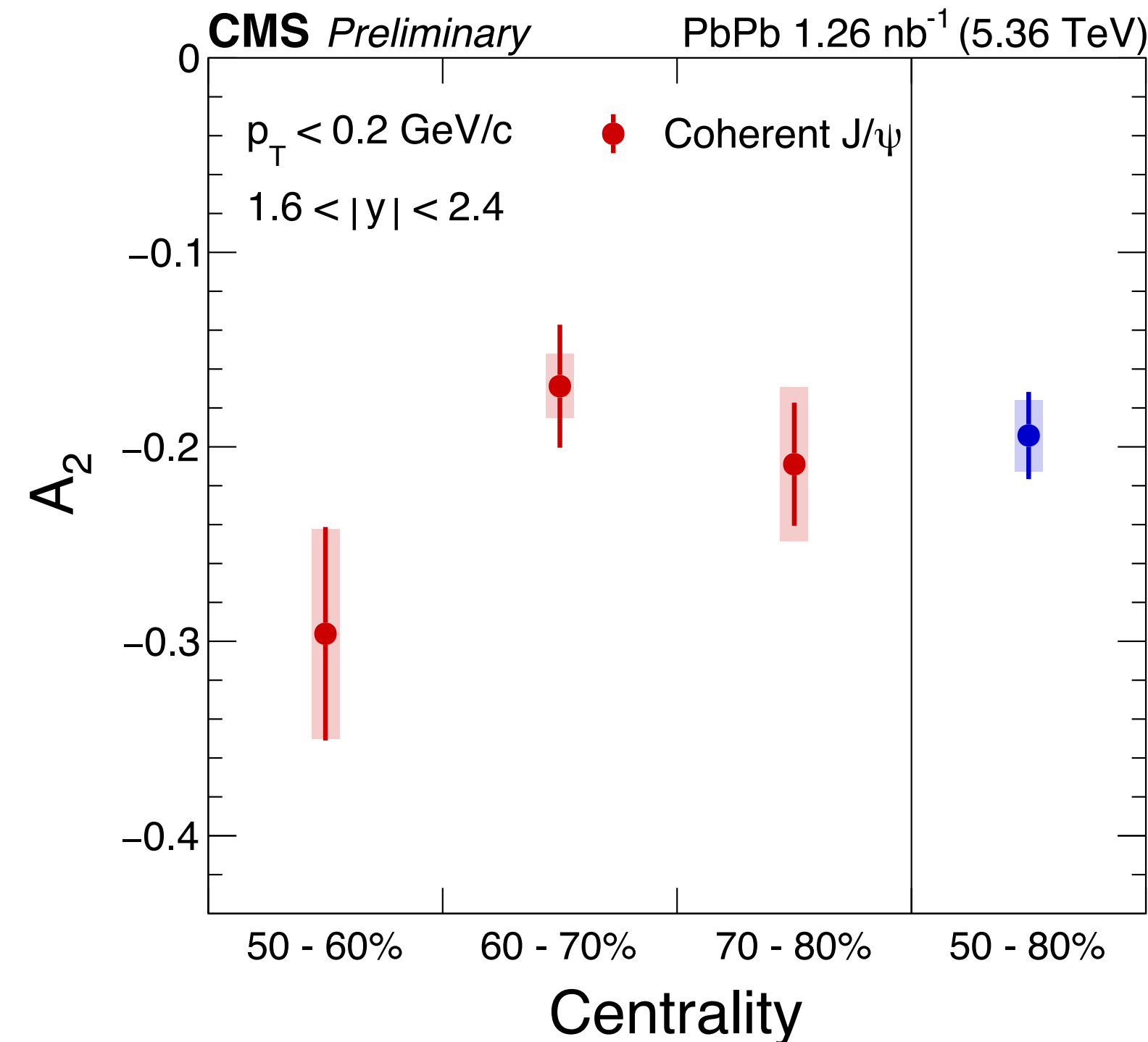
CMS-PAS-HIN-25-006



- A negative modulation is observed in coherent $J/\psi \rightarrow \mu^+\mu^-$ (spin-1/2)
- Provide the first observation of spin-state dependence in azimuthal asymmetry
- **Demonstrate the feasibility of a complementary reaction plane probe**

$\cos(2\Delta\phi)$ modulation in coherent $J/\psi \rightarrow \mu^+\mu^-$

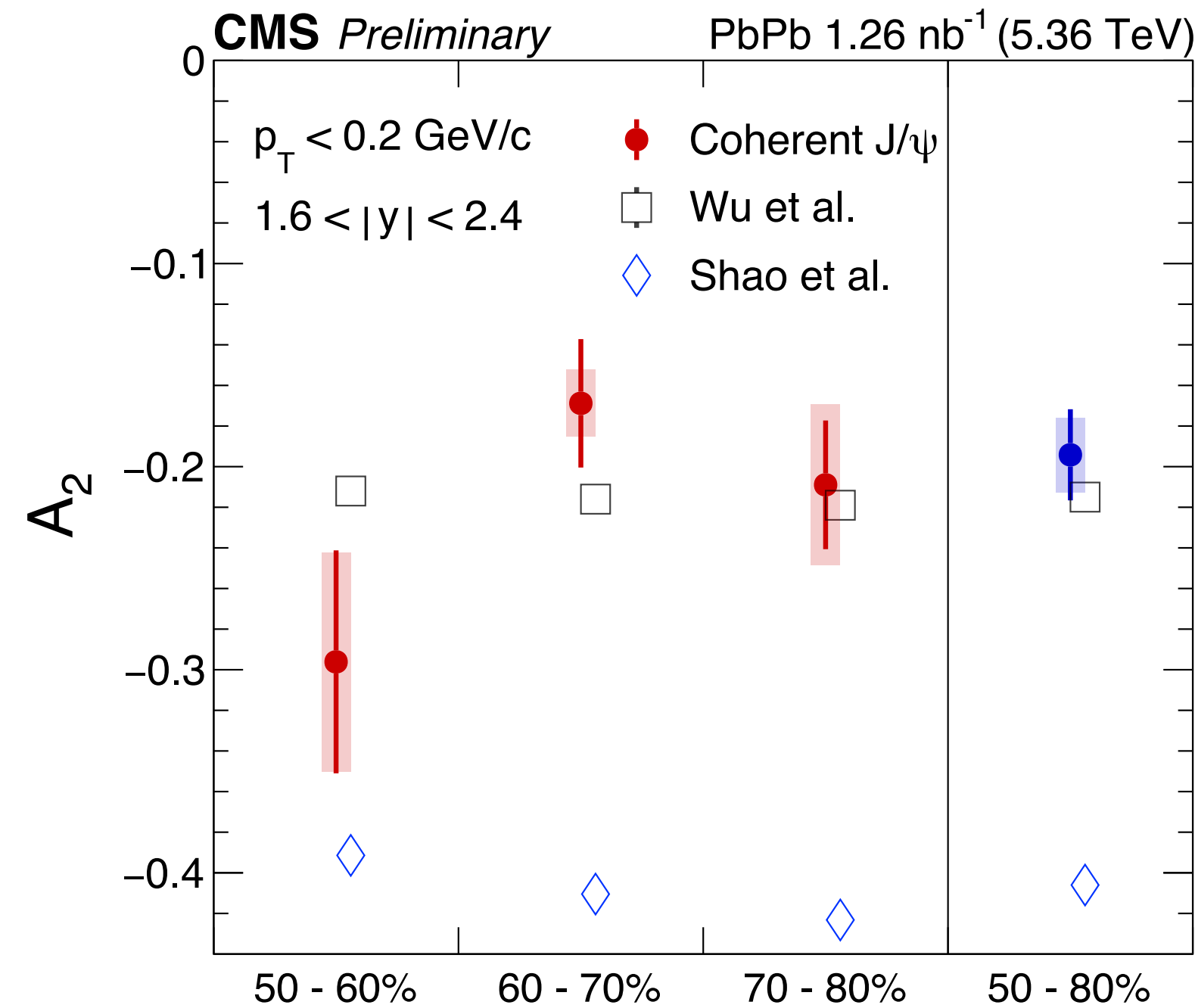
CMS-PAS-HIN-25-006



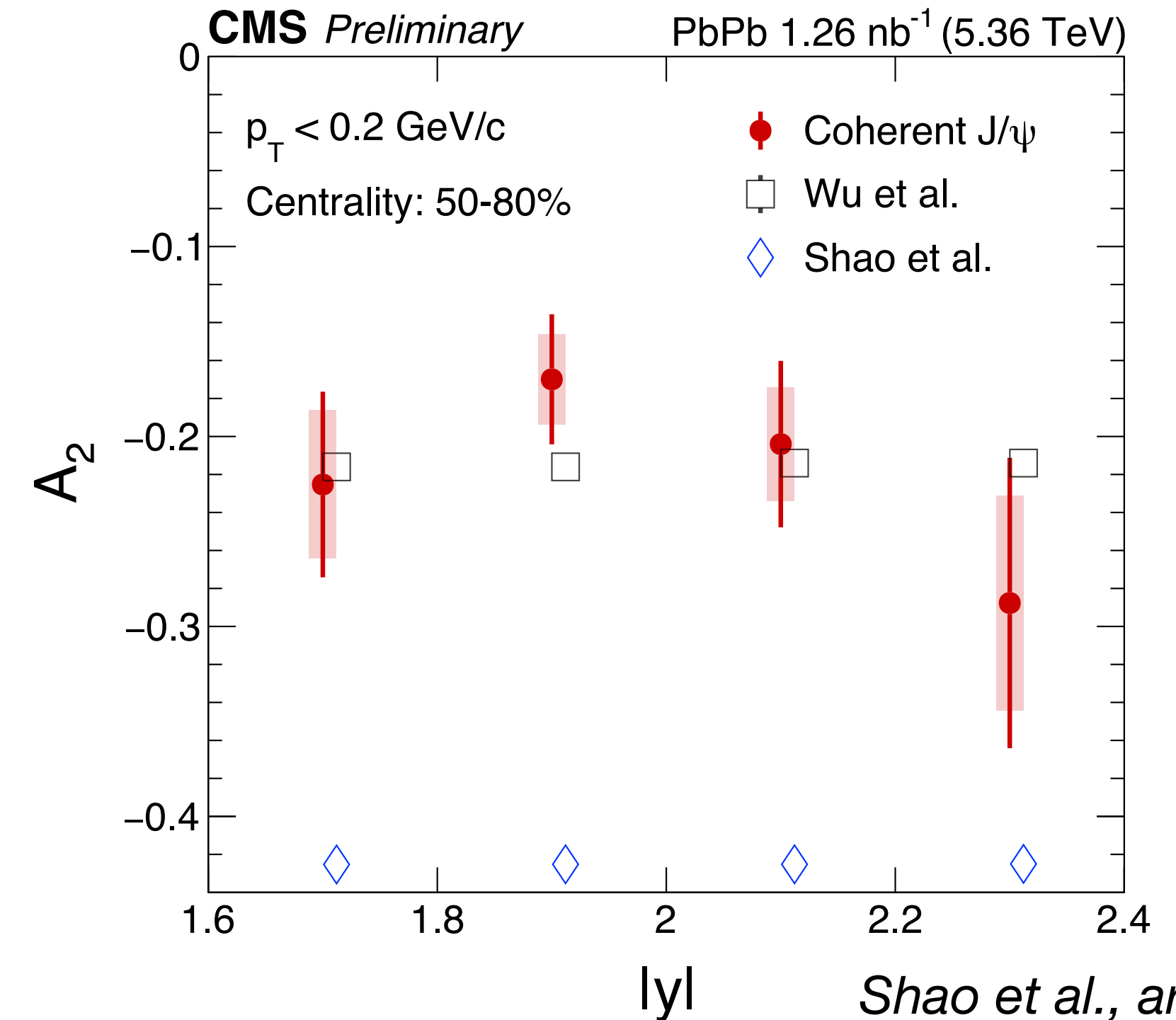
- A negative modulation is observed in coherent $J/\psi \rightarrow \mu^+\mu^-$ (spin-1/2)
- Provide the first observation of spin-state dependence in azimuthal asymmetry
- Demonstrate the feasibility of a complementary reaction plane probe
- **No significant rapidity dependence in $1.6 < |y| < 2.4$**

$\cos(2\Delta\phi)$ modulation in coherent $J/\psi \rightarrow \mu^+\mu^-$

CMS-PAS-HIN-25-006



Wu et al., PRR 4 (2022) L042048 Centrality

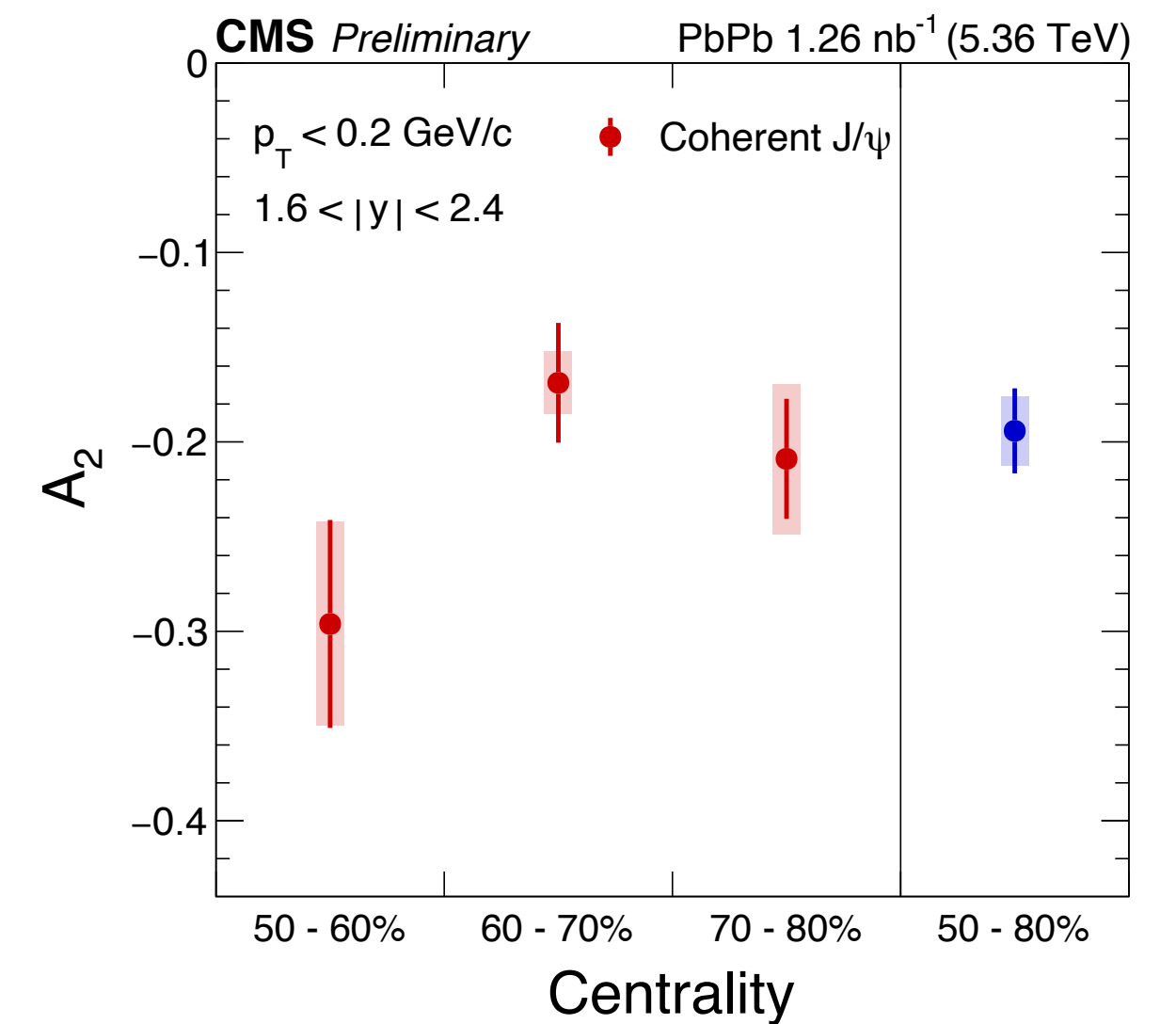
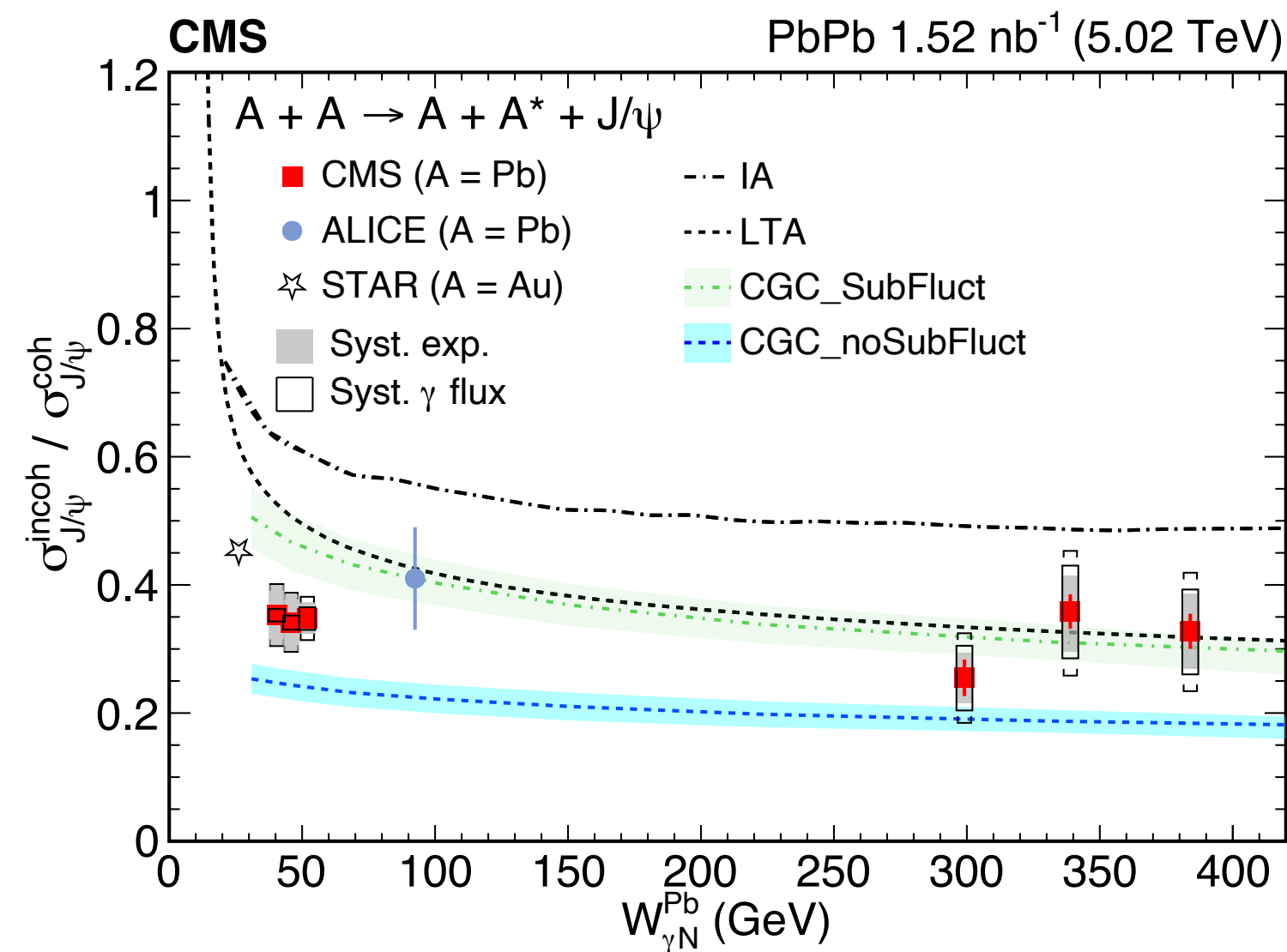
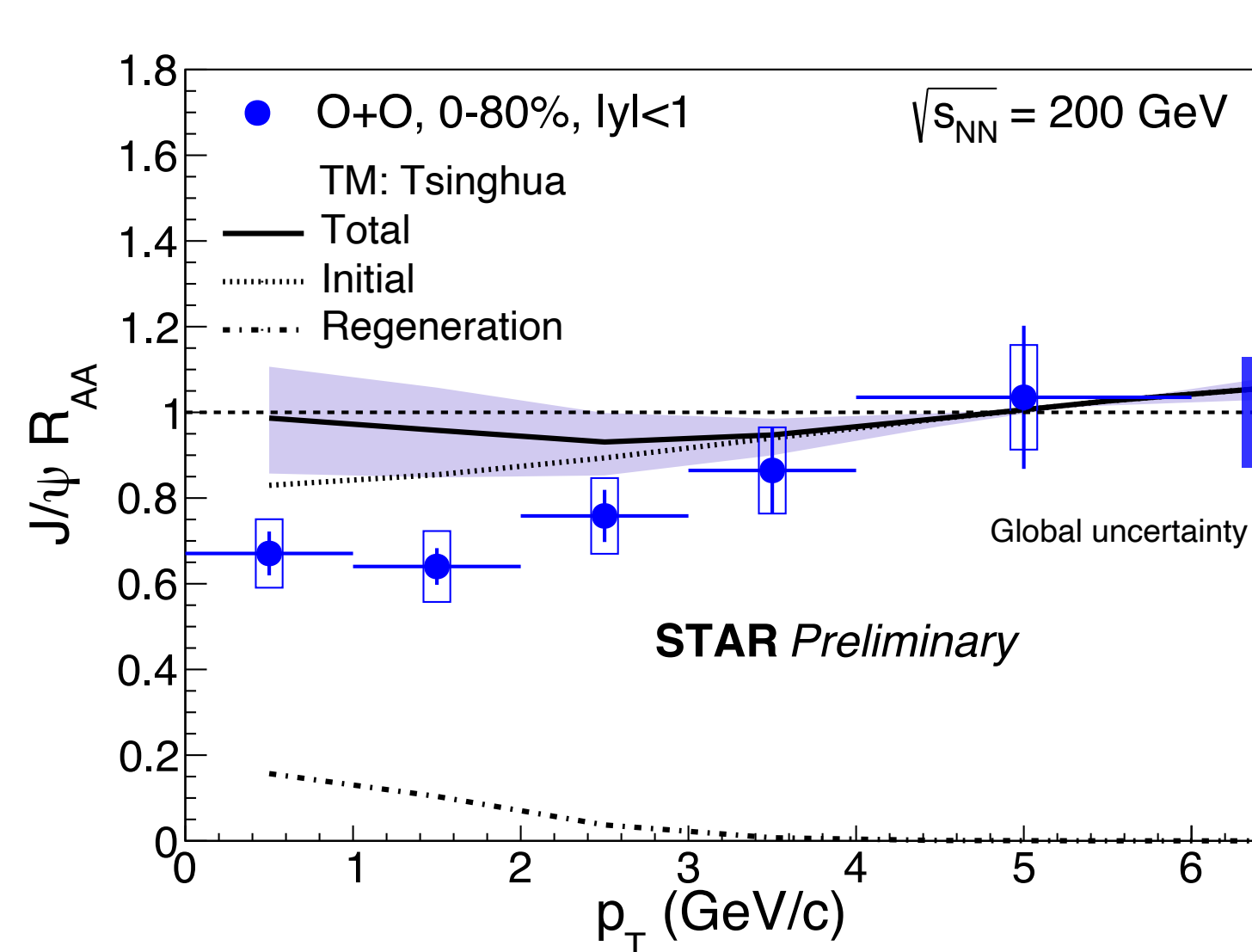


Shao et al., arXiv:2511.17670

- Both models consider the correlations between polarization and ***b*** directions
- The model by Wu et al.
 - Vector meson dominance framework
 - Accounts for the effects of participating nucleons
- The model by Shao et al.
 - Color dipole framework
 - Ignoring the effects of participating nucleons

Summary

- J/ψ serves as a sensitive probe for studying the dynamics of QGP
- J/ψ can probe the gluon structure of heavy nuclei
- J/ψ can probe the linear polarization of equivalent photons and the initial collision geometry

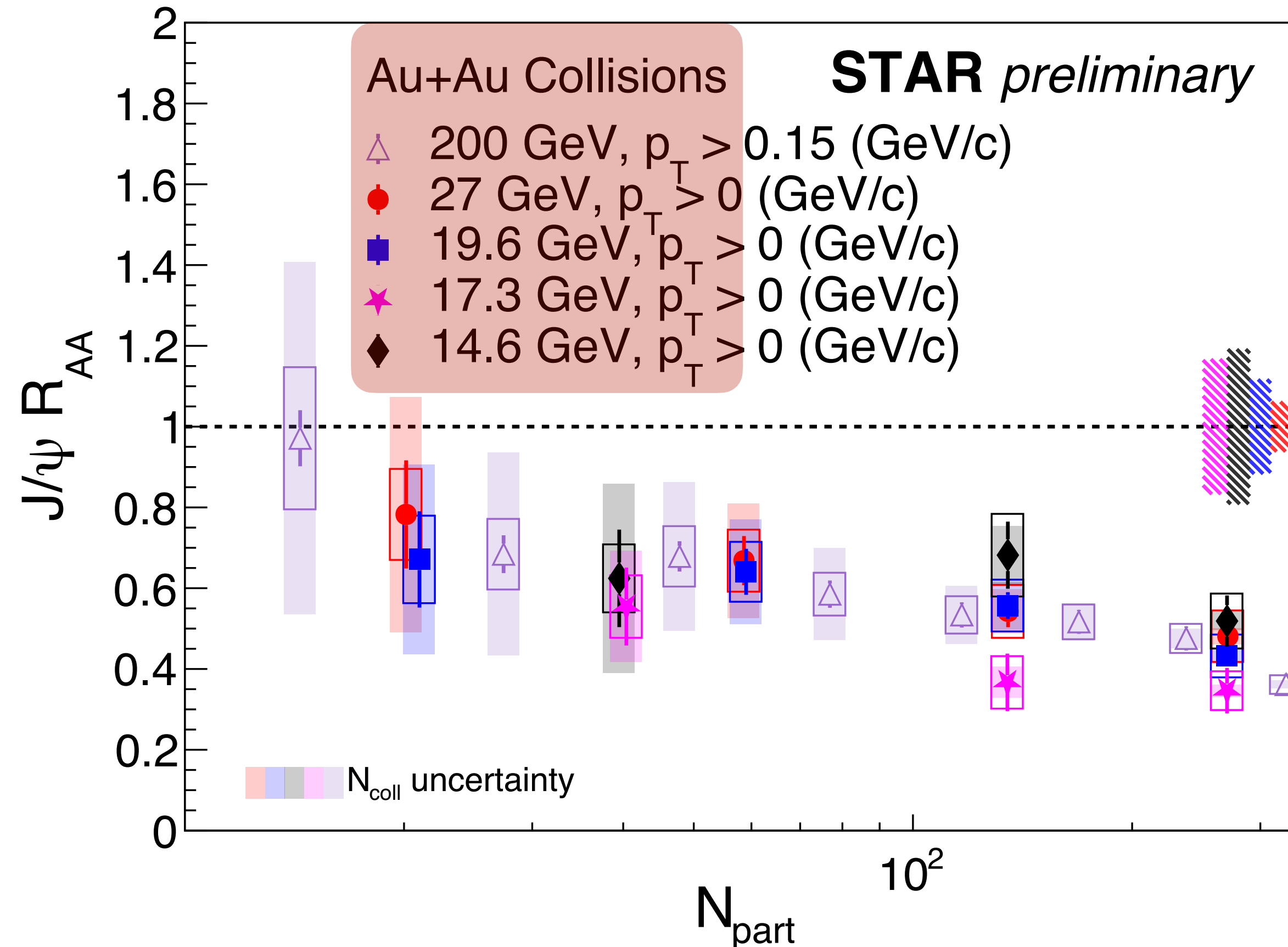




卅载厚德载物，七旬乘风破浪
祝庄老师生日快乐！

Backups

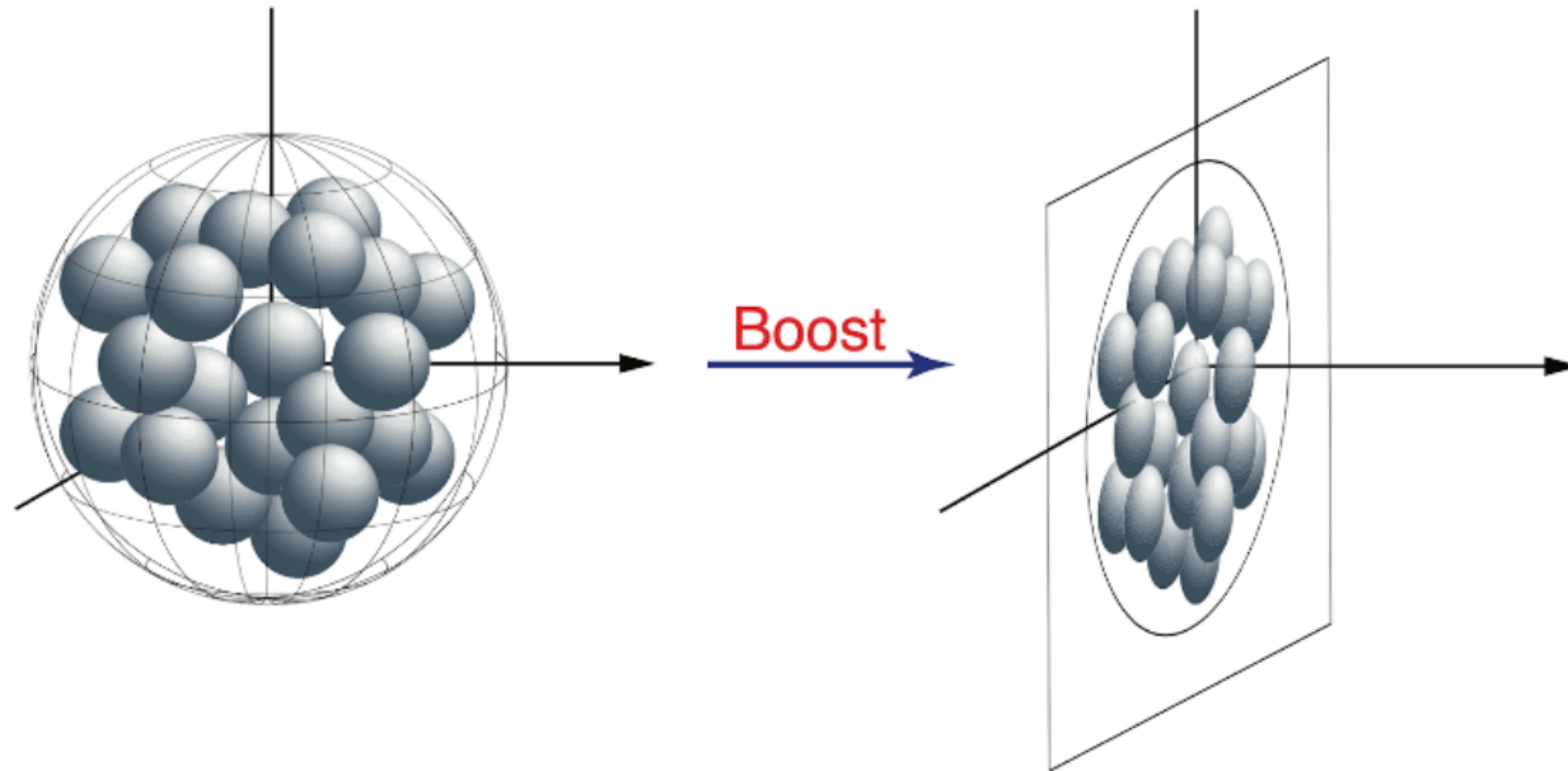
Centrality dependence of inclusive J/ψ R_{AA}



STAR, PLB 797 (2019) 134917
 STAR, PLB 825 (2022) 136865
 PHENIX, PRL 101 (2008) 122301
 PHENIX, PRC 102 (2020) 014902

- ◉ Hint of decreasing trend as a function of centrality
- ◉ R_{AA} shows no significant energy dependence at RHIC for similar $\langle N_{\text{part}} \rangle$

Ultra-dense gluonic matter

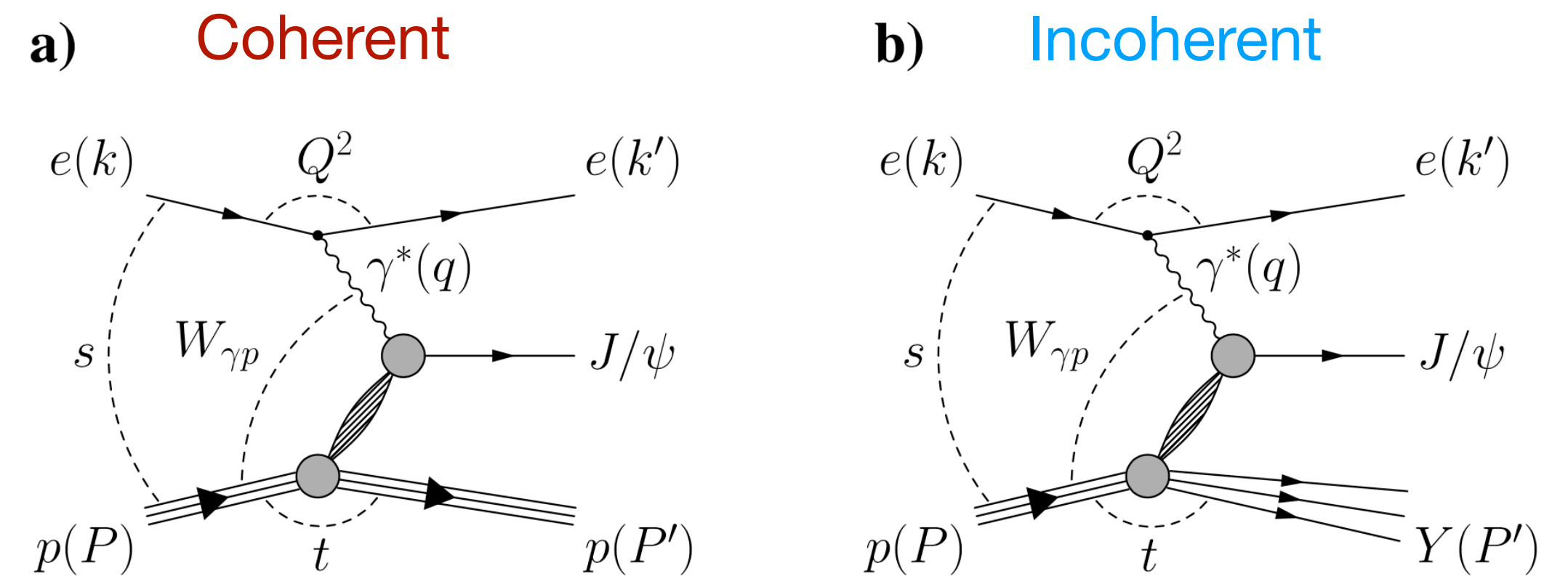
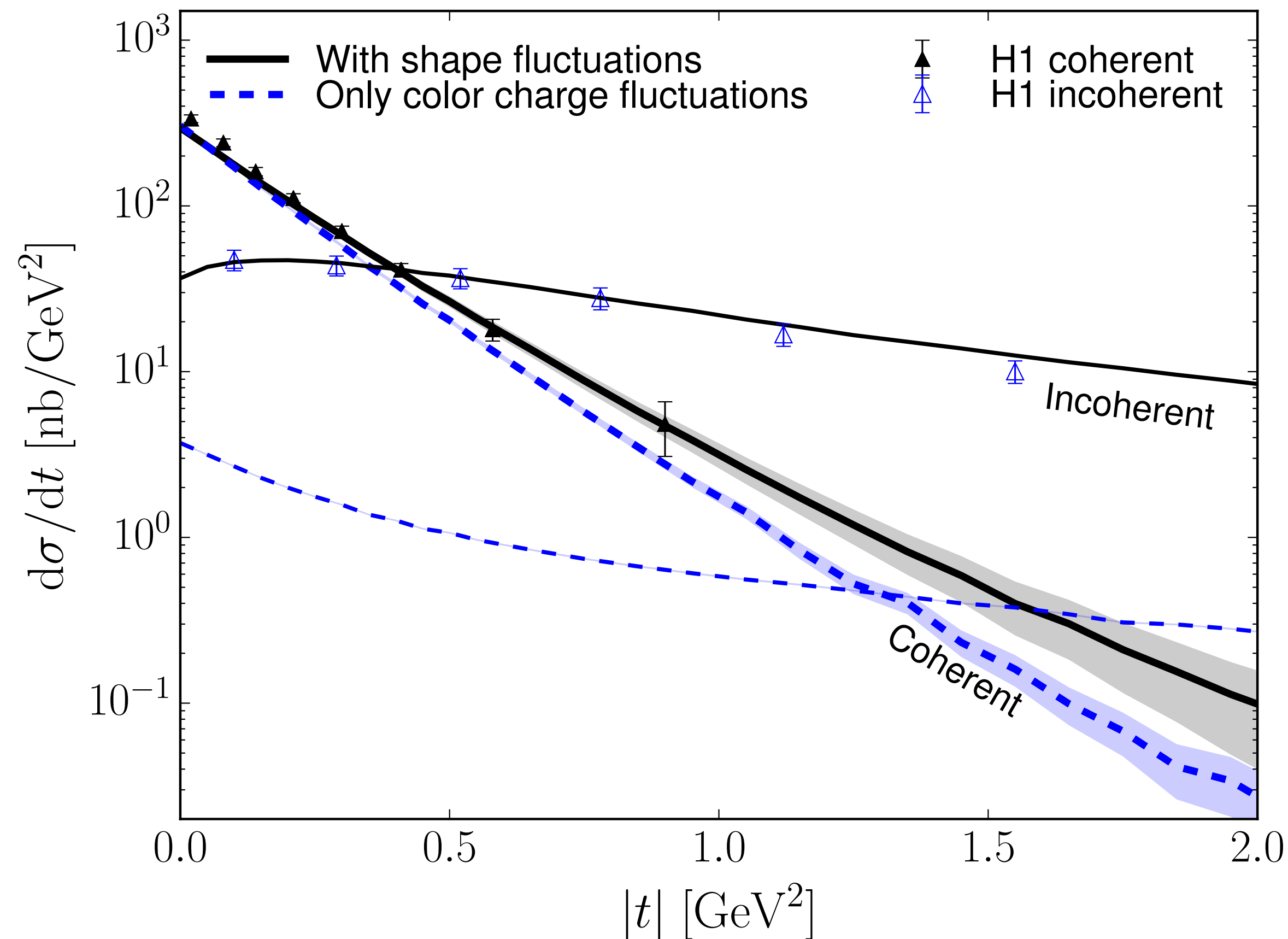


- Gluon is **enhanced by a factor of $A^{1/3}$ in nucleus** w.r.t free nucleon
 - $Q_s^2 \sim A^{1/3} \left(\frac{1}{x}\right)^\lambda$
- Onset of gluon saturation is expected at higher x , Q^2 in nuclei

The critical role of gluon fluctuations

Mantysaari and Schenke, PRD 94 (2016) 034042

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

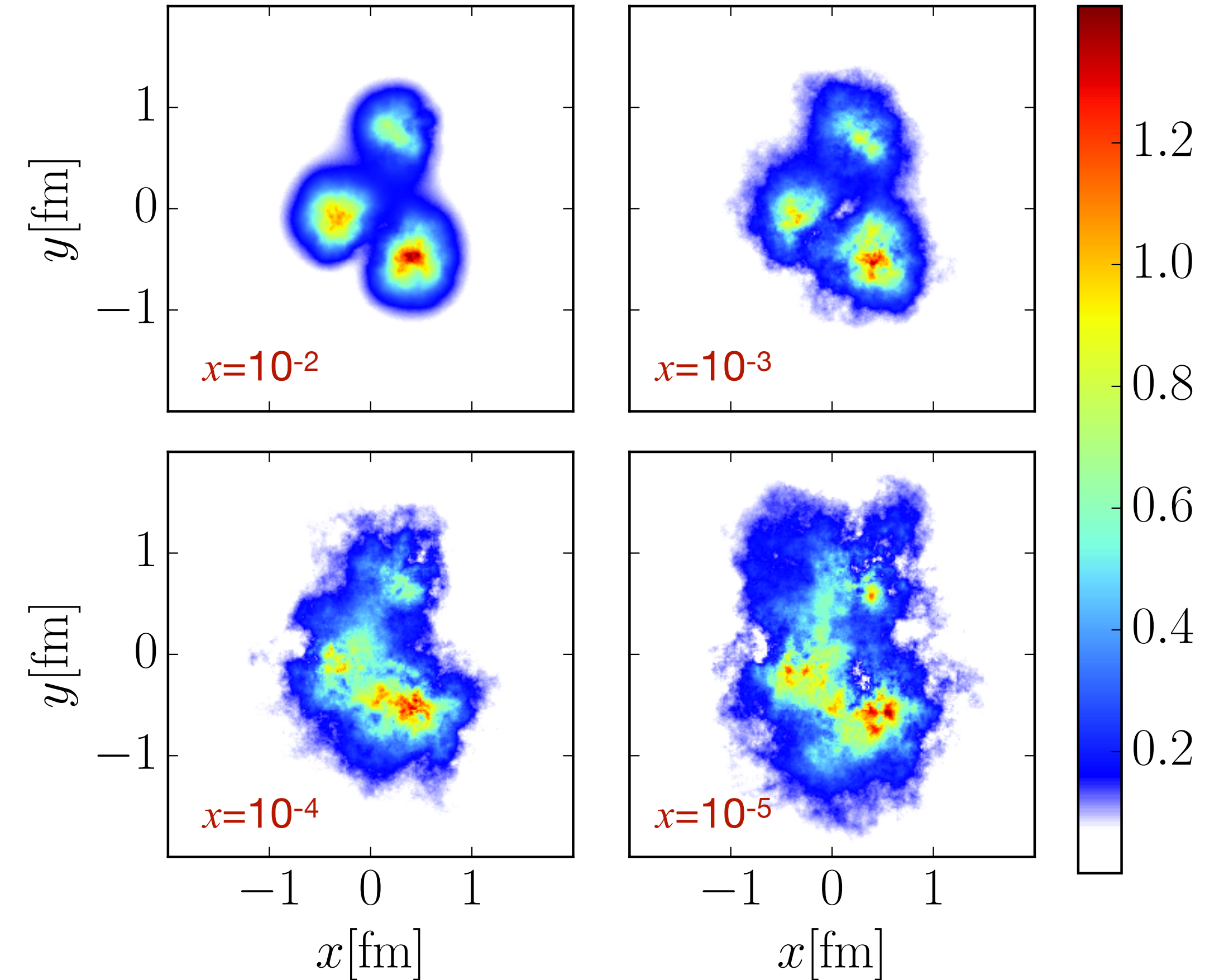
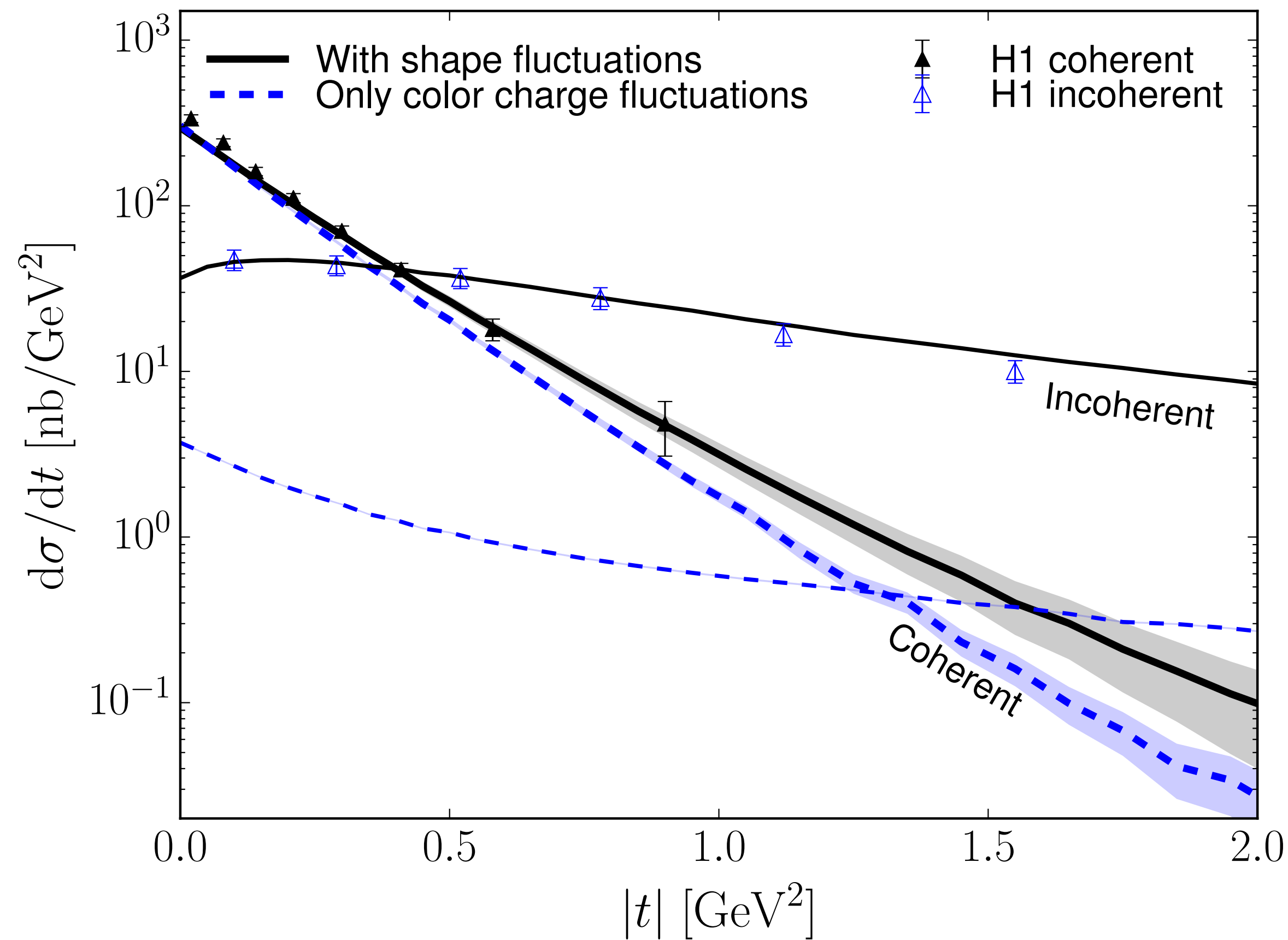


● CGC can only describe HERA data when gluon fluctuations are included

The critical role of gluon fluctuations

Mantysaari and Schenke, PRD 94 (2016) 034042

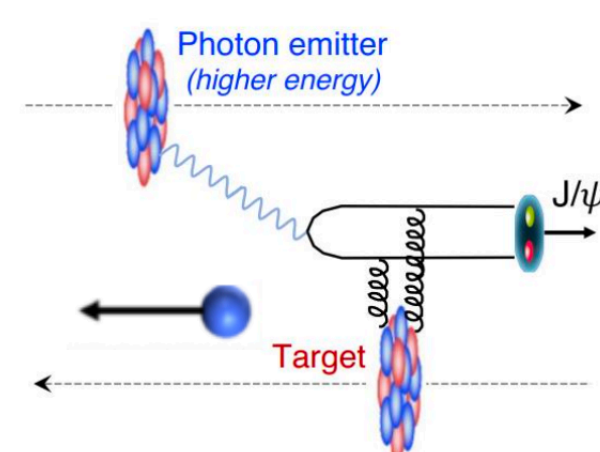
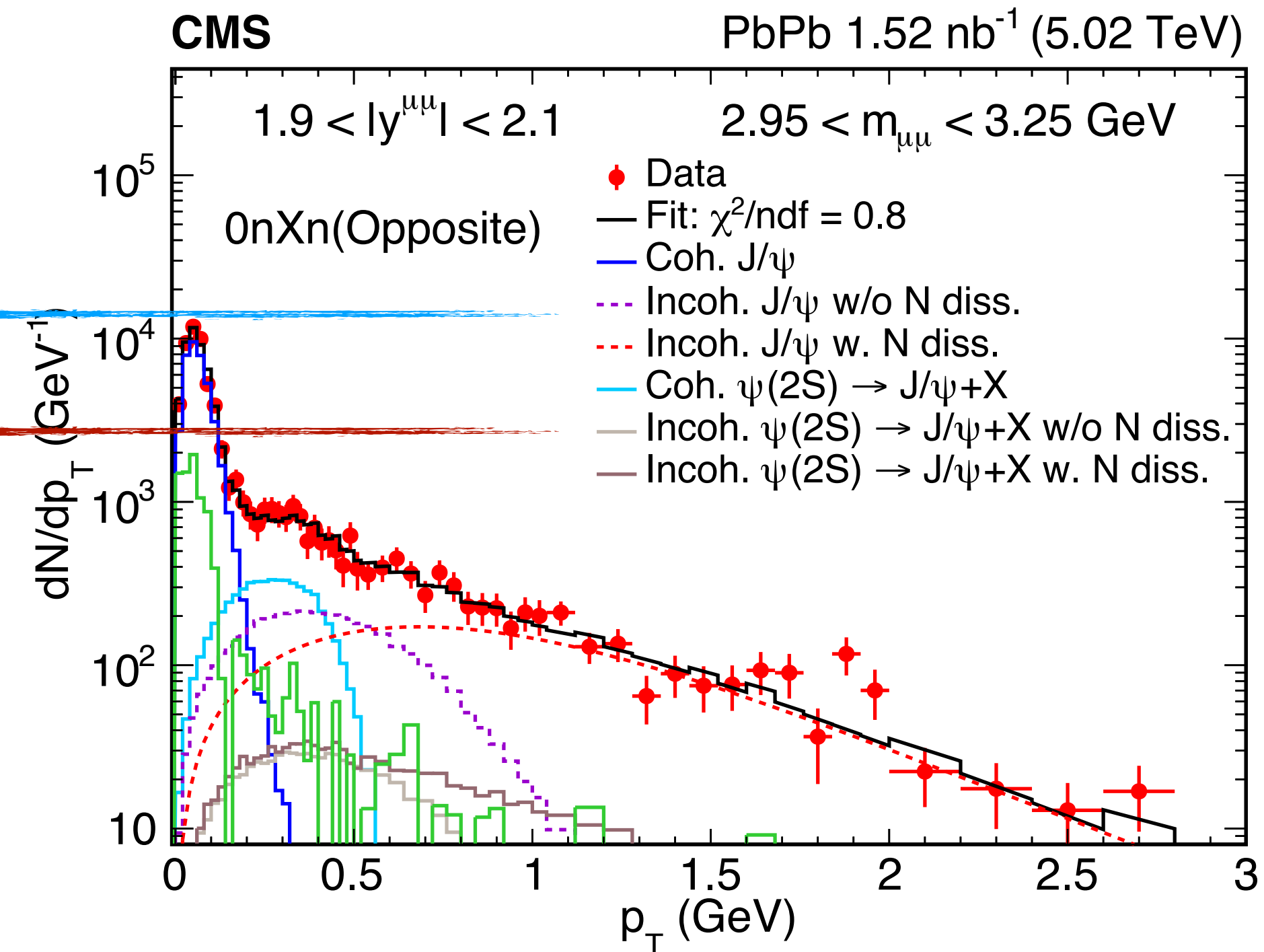
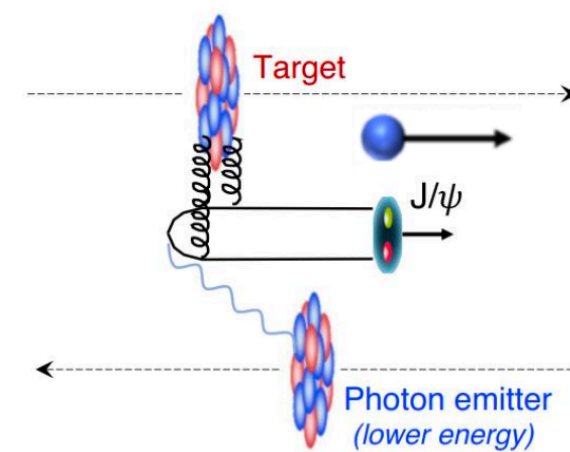
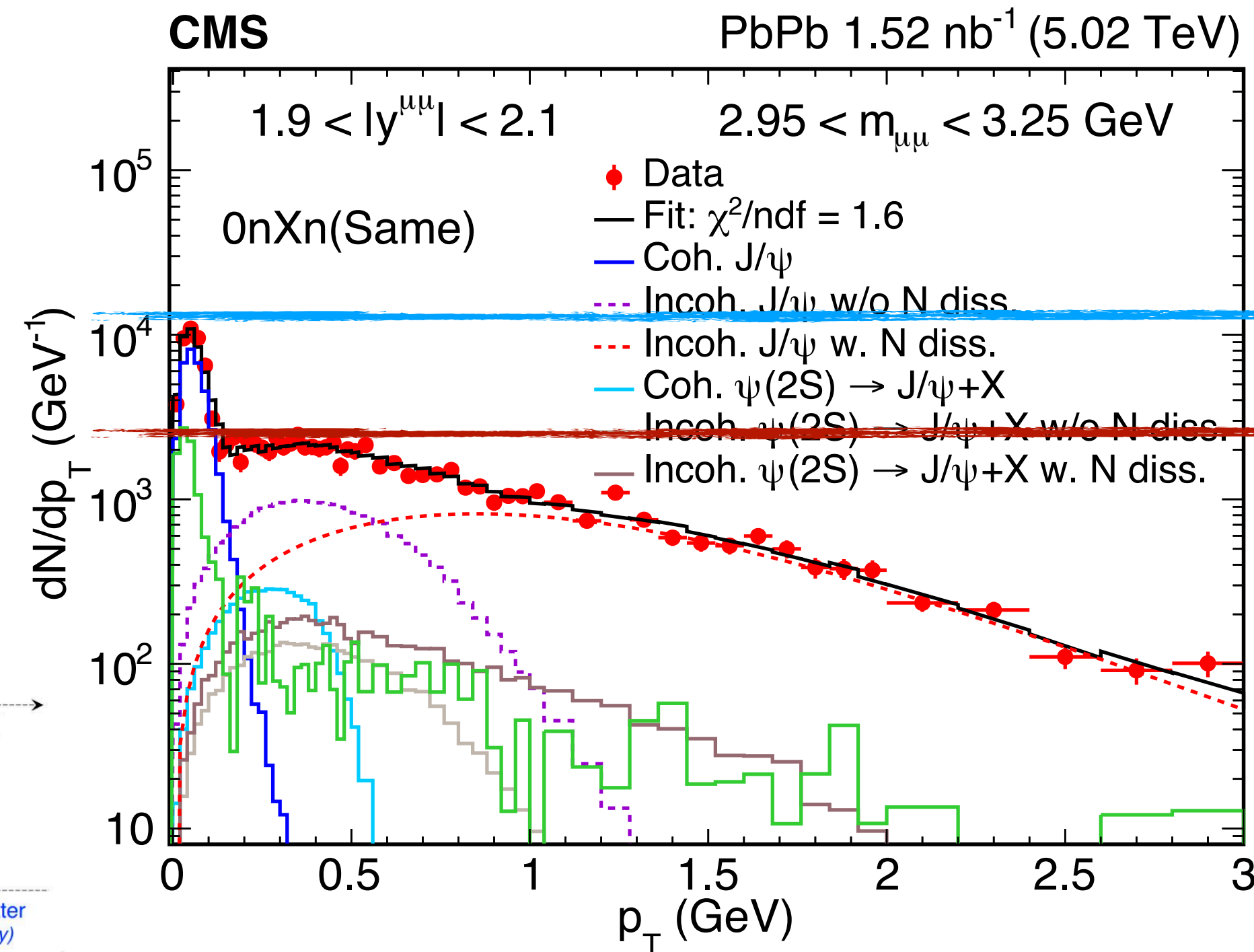
Mantysaari, Rep. Prog. Phys. 83 (2020) 082201



- CGC can only describe HERA data when gluon fluctuations are included

A solution to the “two-way ambiguity”

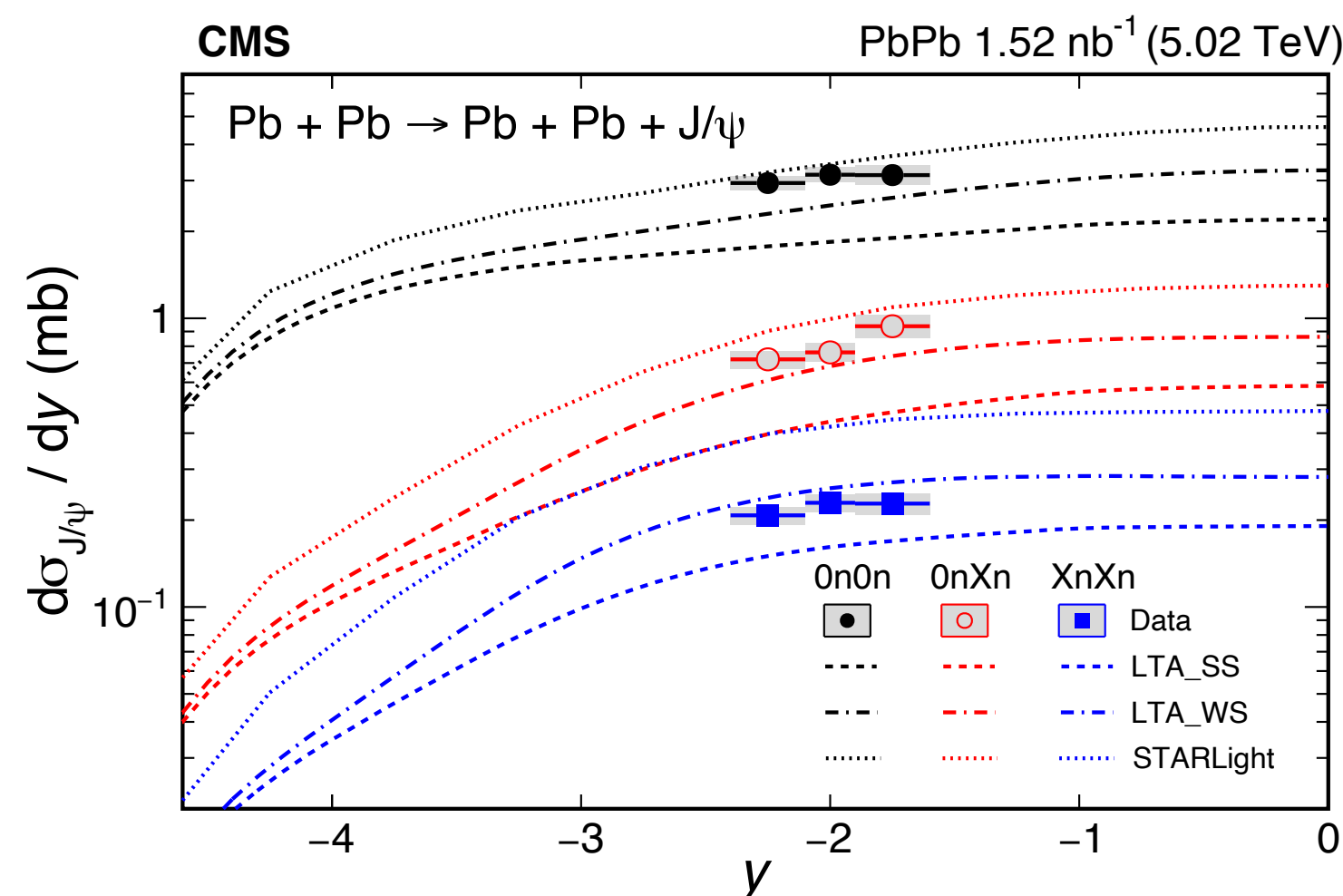
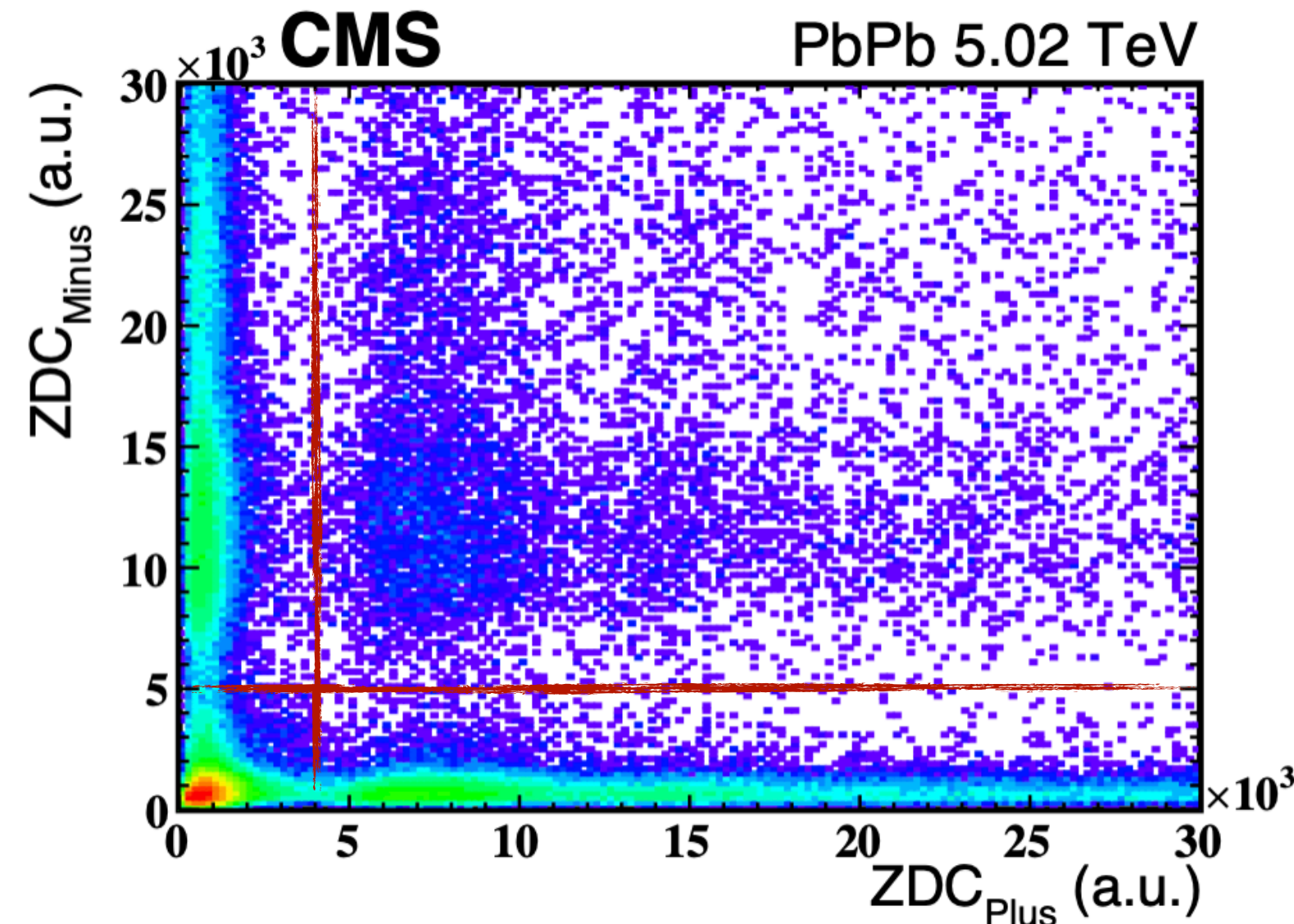
CMS, PRL 135 (2025) 112301



- 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

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

Photon flux from theory

What we need!

Solve the “two-way ambiguity”

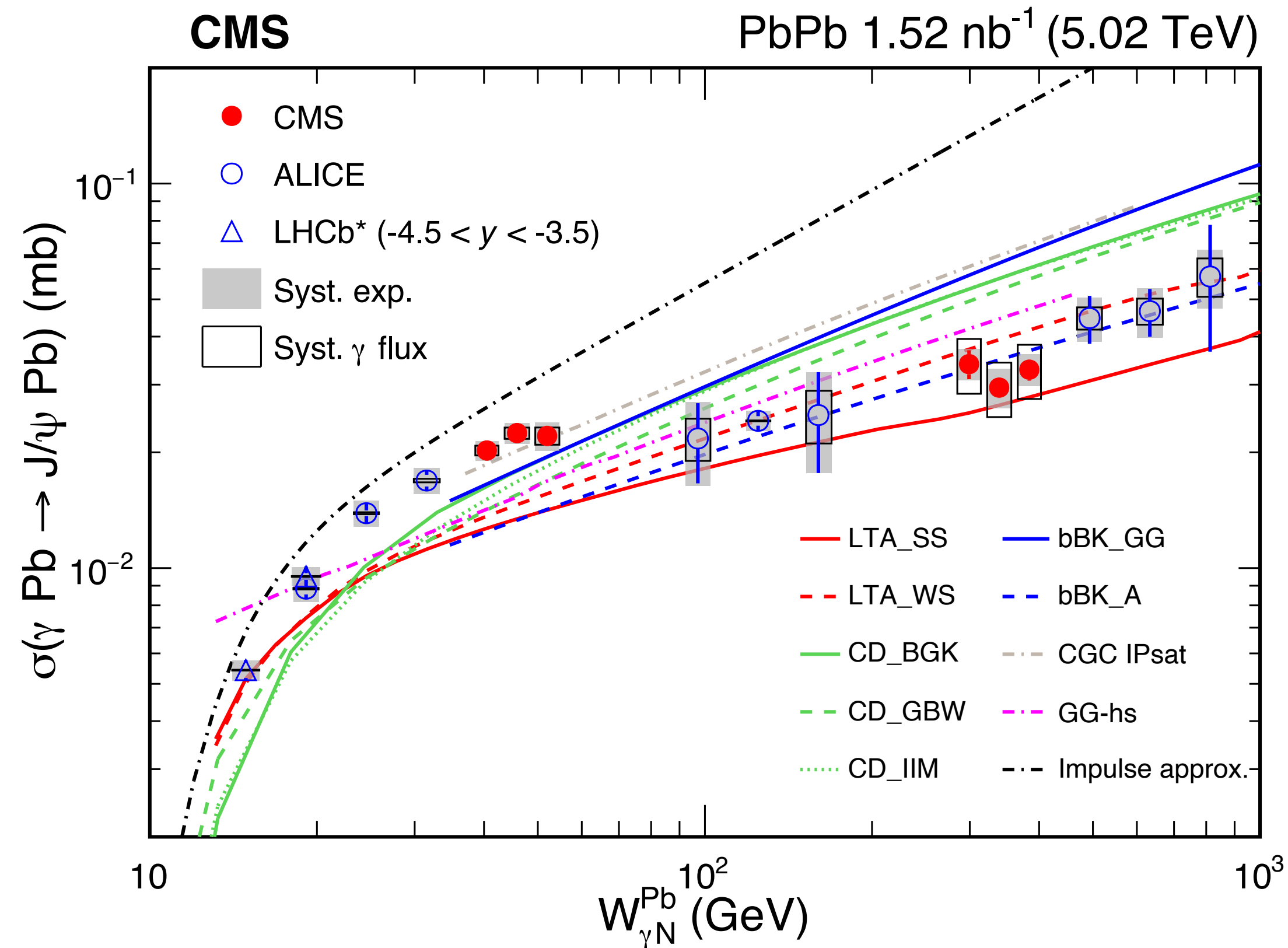
Probe gluons at $x \sim 10^{-5} - 10^{-4}$ in heavy nucleus!

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

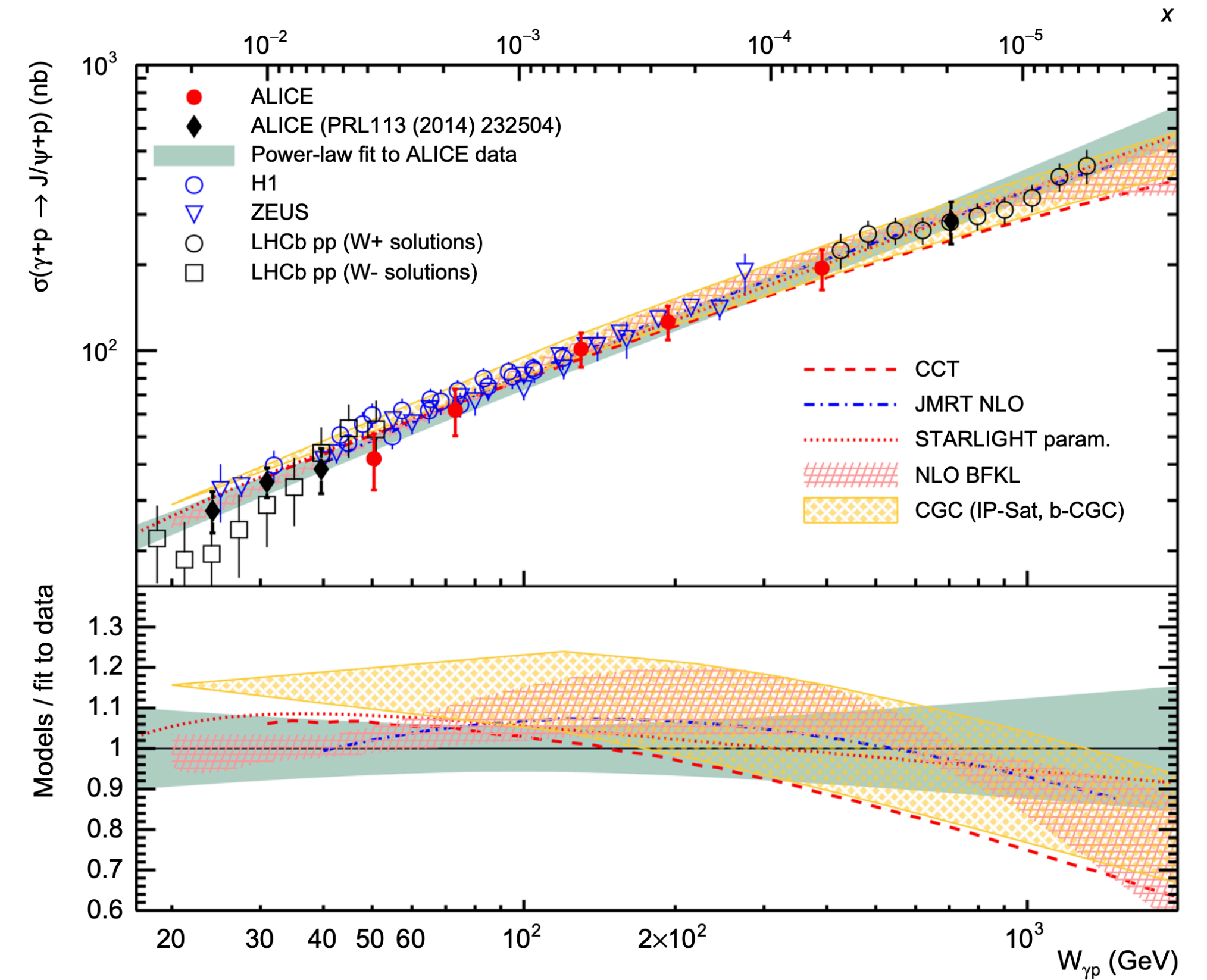
ALICE, JHEP 10 (2023) 119
ALICE, EPJC 81 (2021) 712
ALICE, PLB 798 (2019) 134926

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

ALICE, EPJC 79 (2019) 402



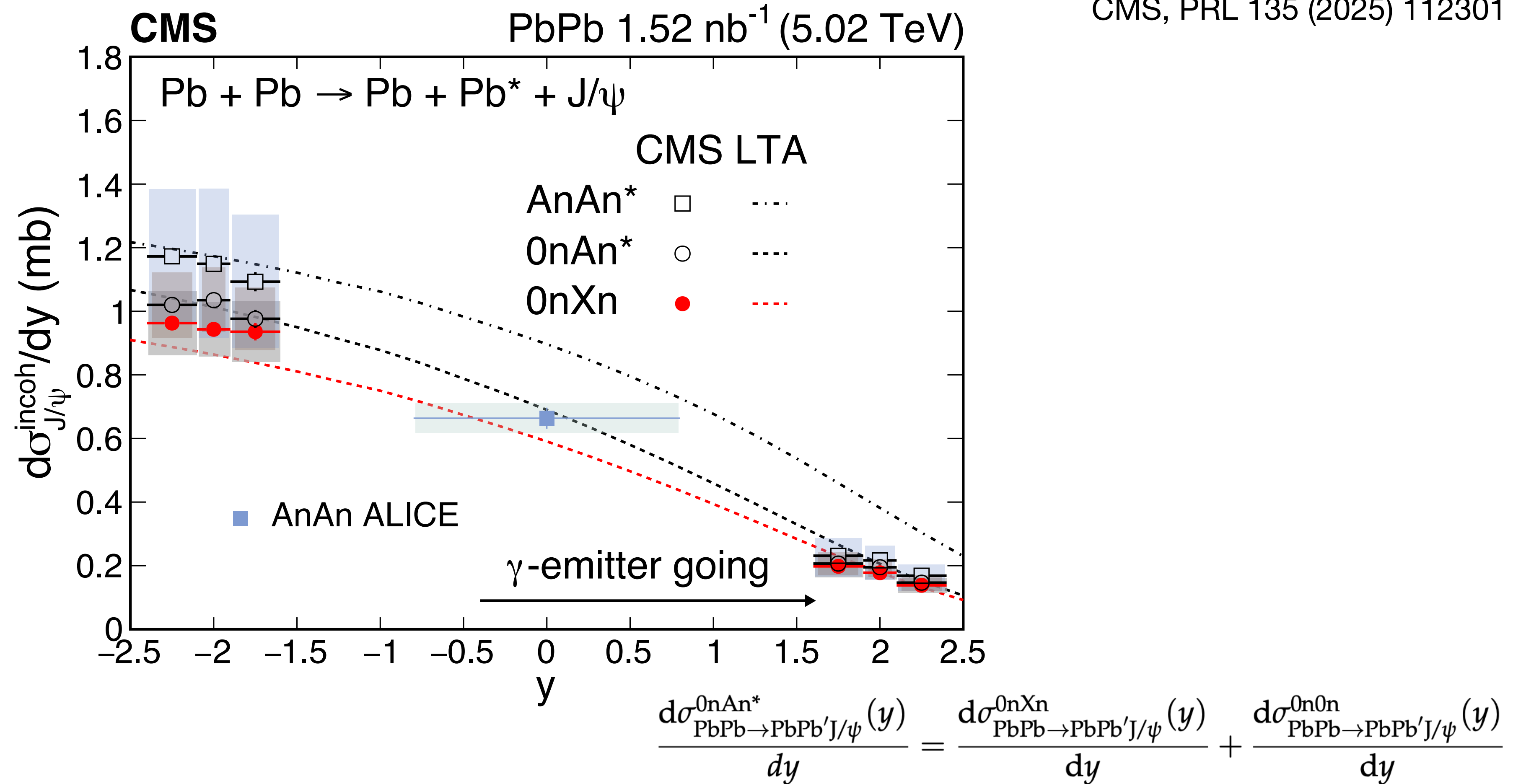
$$\gamma A \rightarrow J/\psi A$$



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

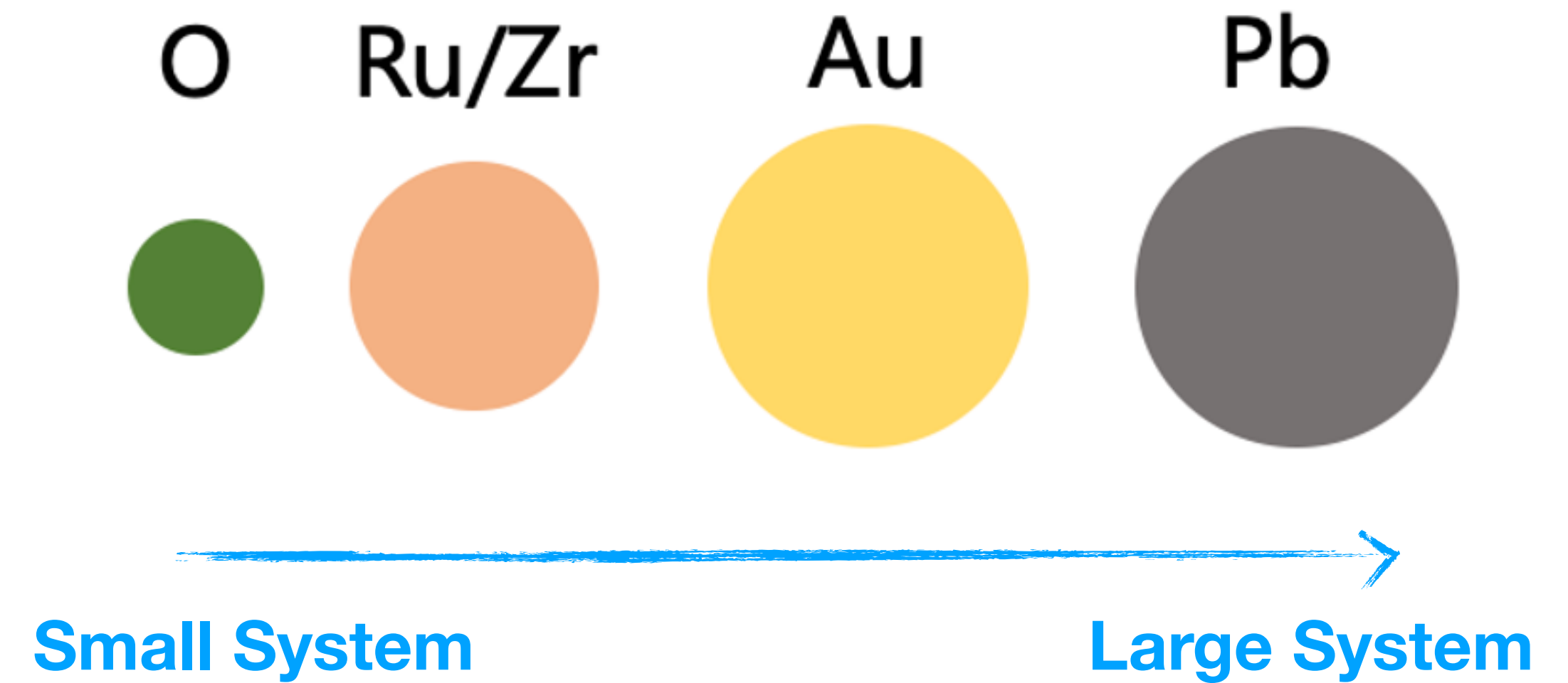
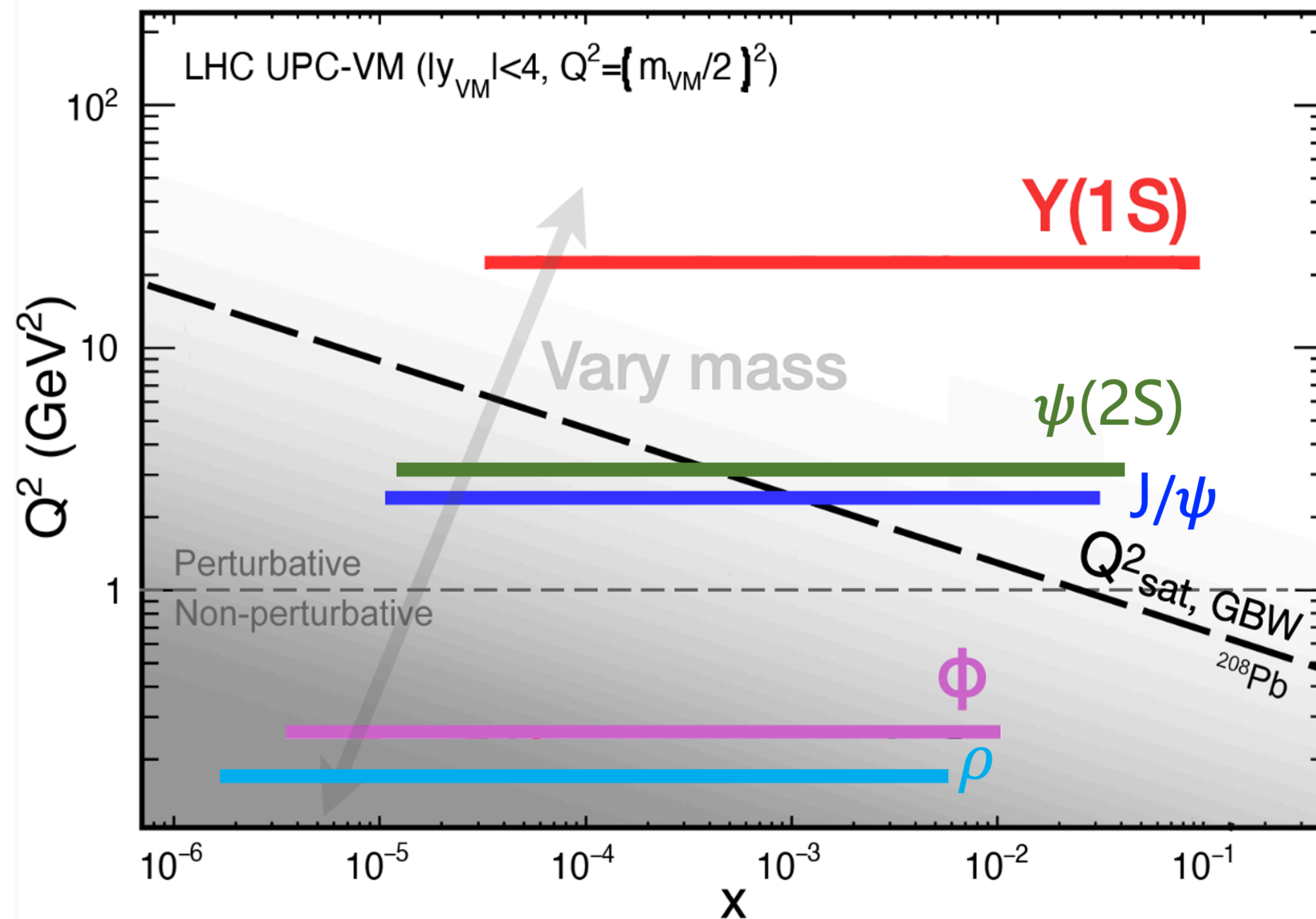
Solve the “two-way ambiguity” for incoherent J/ψ

CMS, PRL 135 (2025) 112301



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

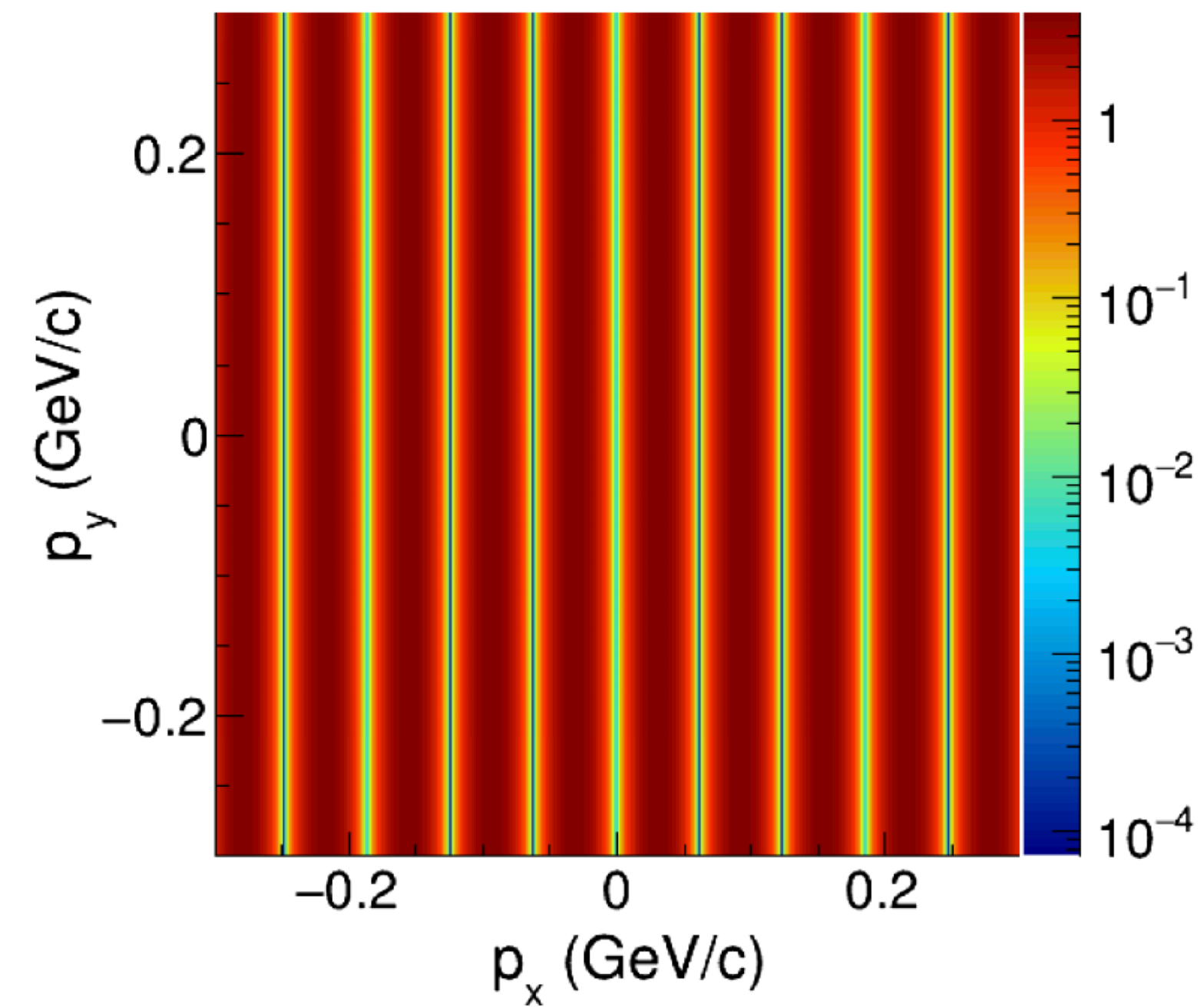
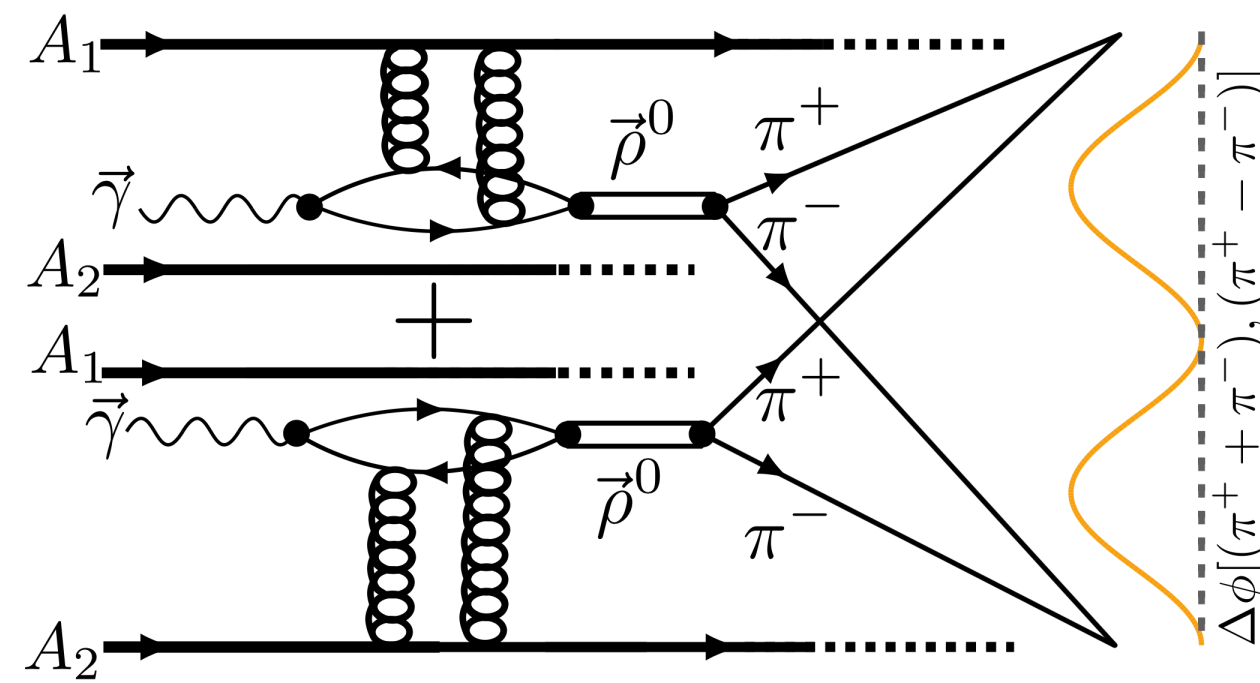
The roadmap of probing gluon structure



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

Observed $\cos(2\Delta\phi)$ modulation of coherent ρ^0 in UPC

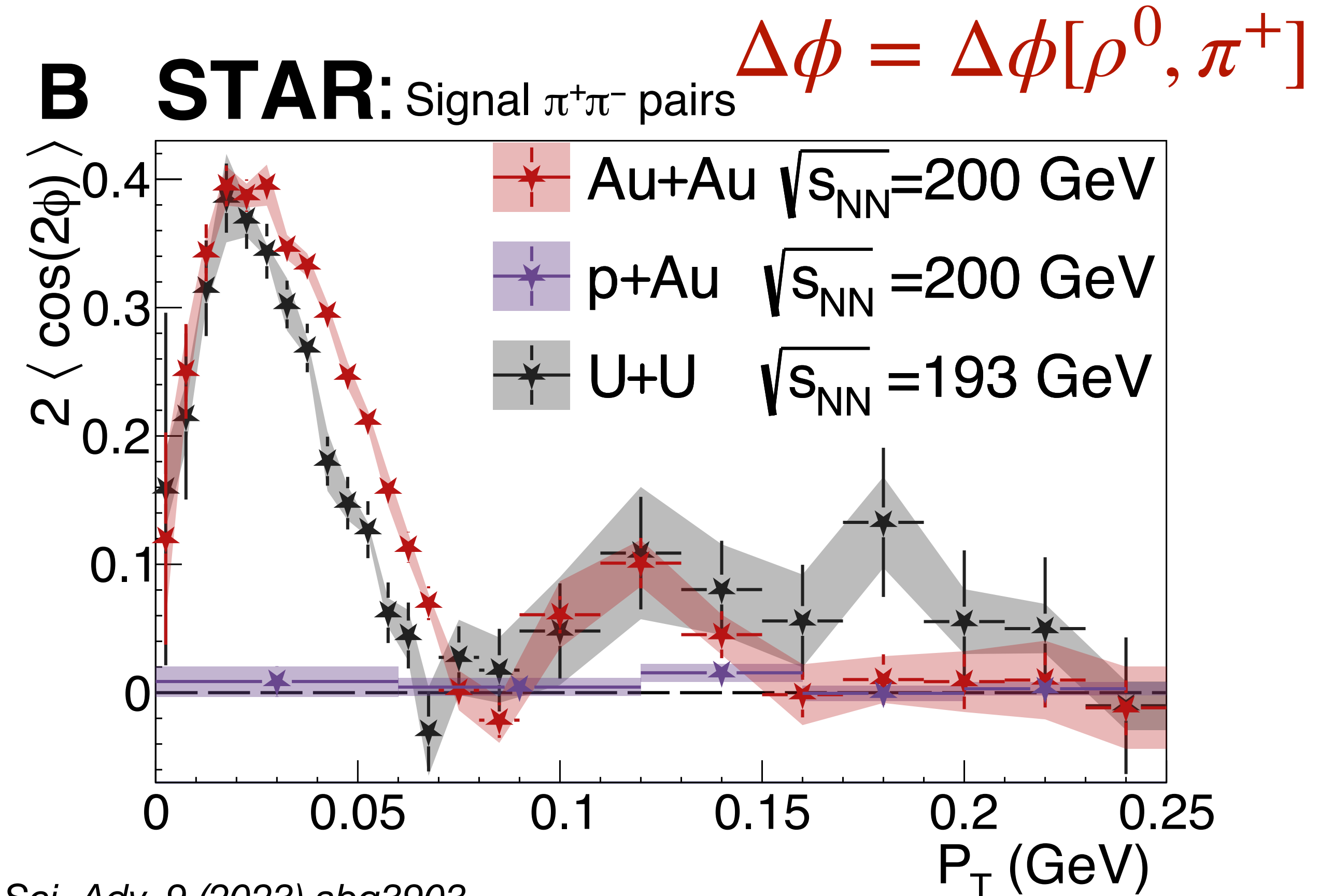
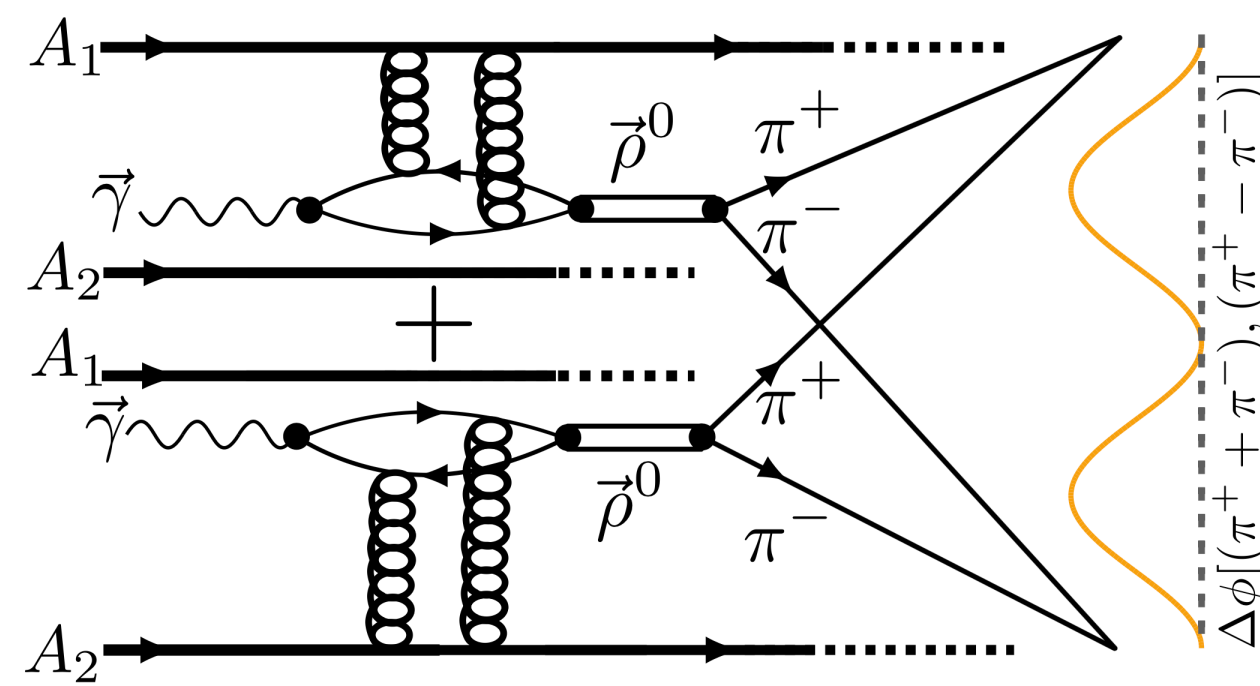
- © **Symmetric A+A collisions:** **Strong correlation** between the p_T and polarization directions



STAR, Sci. Adv. 9 (2023) abq3903

Observed $\cos(2\Delta\phi)$ modulation of coherent ρ^0 in UPC

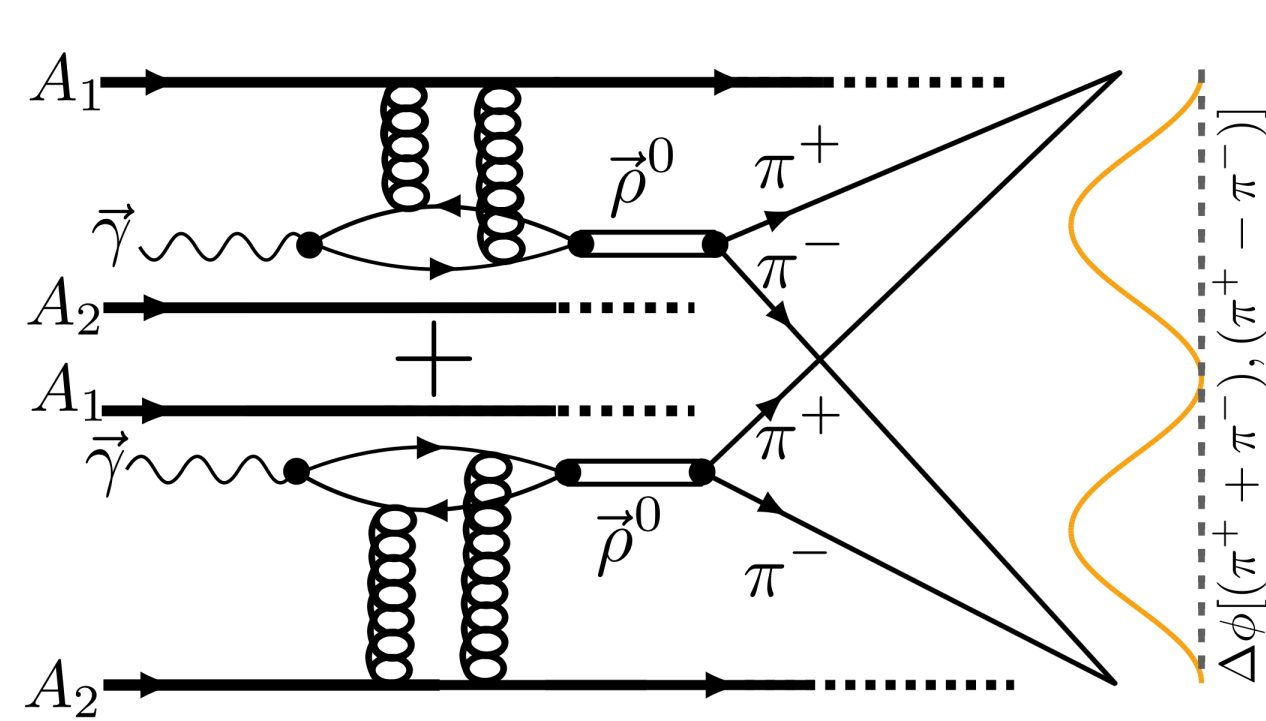
- ◎ **Symmetric A+A collisions:** **Strong correlation** between the p_T and polarization directions



STAR, Sci. Adv. 9 (2023) abq3903

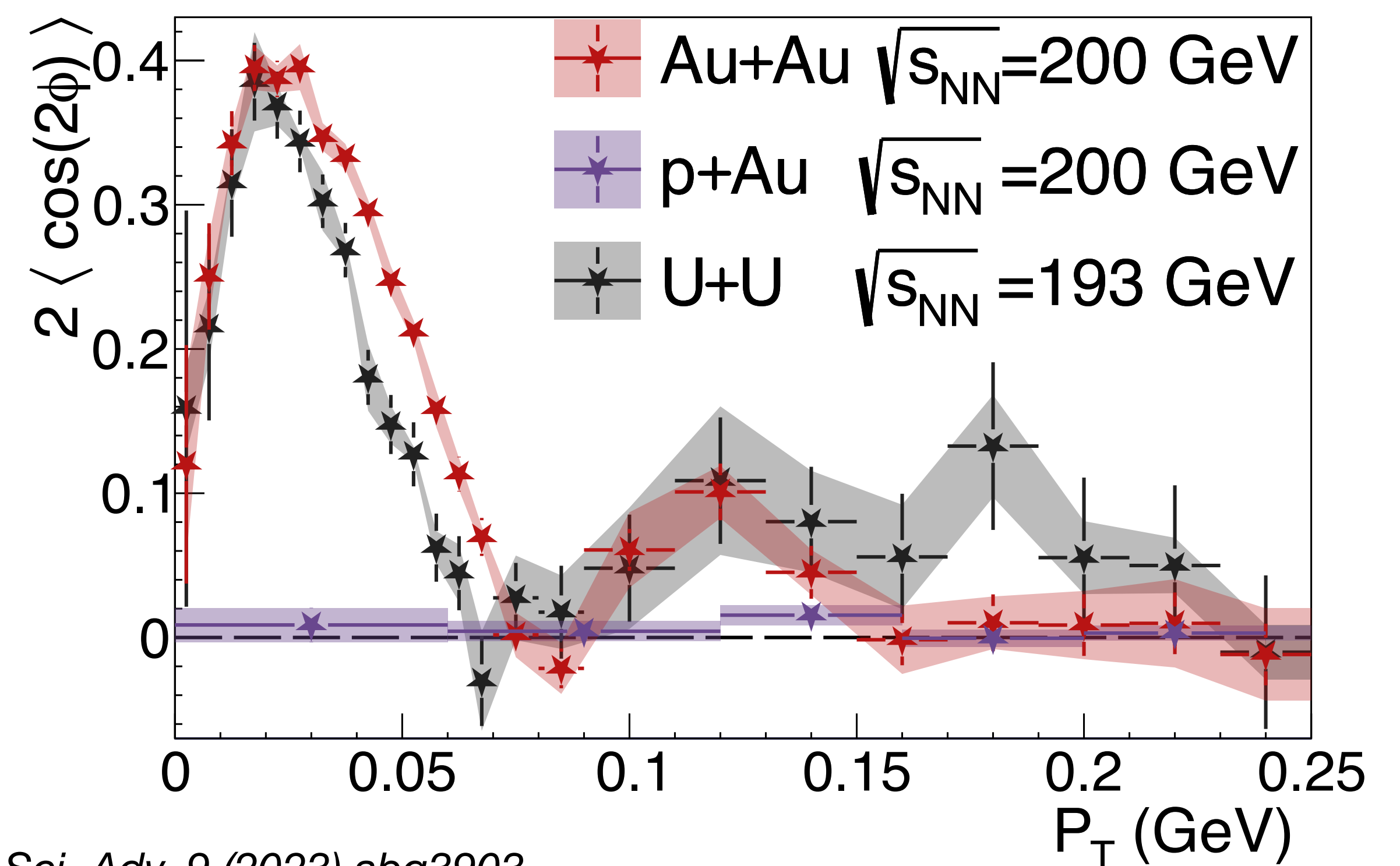
Observed $\cos(2\Delta\phi)$ modulation of coherent ρ^0 in UPC

- Symmetric A+A collisions:** Strong correlation between the p_T and polarization directions



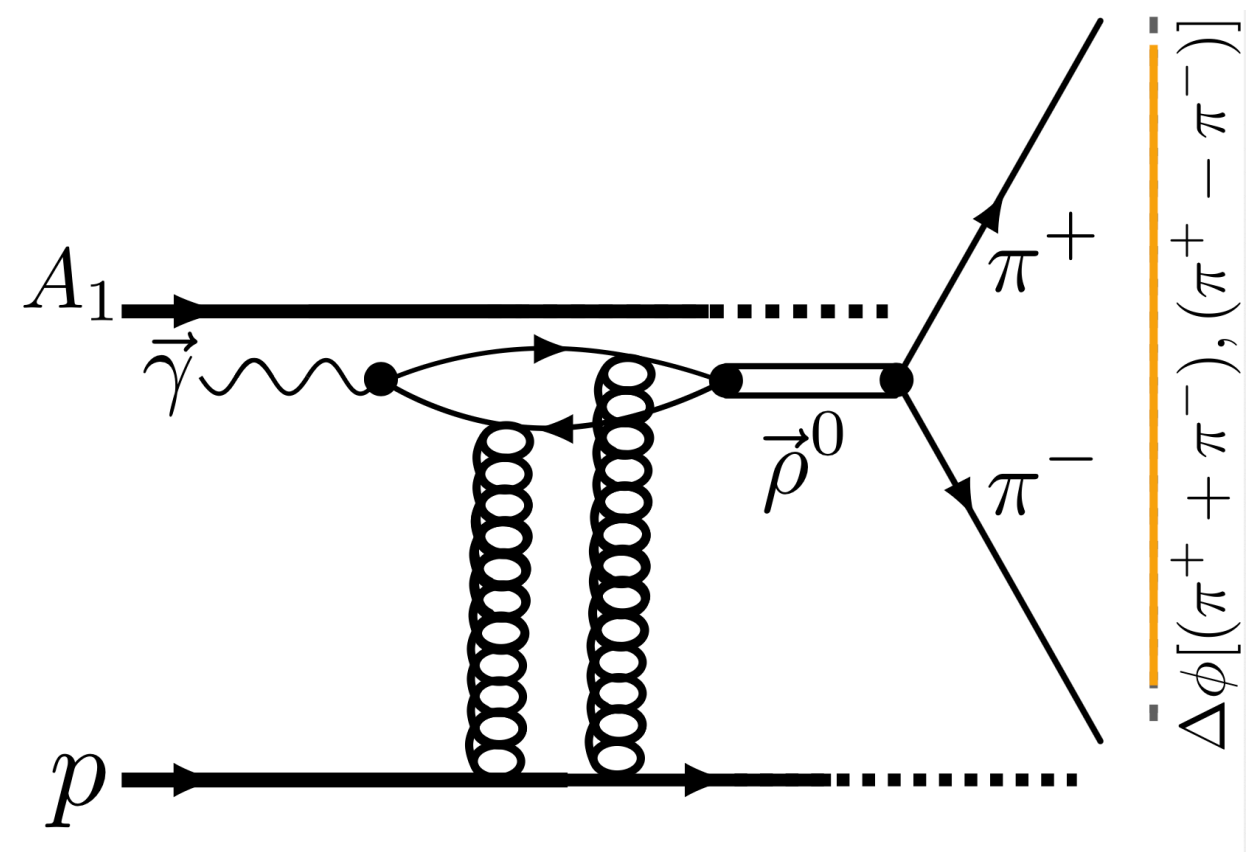
$$\Delta\phi = \Delta\phi[\rho^0, \pi^+]$$

B STAR: Signal $\pi^+\pi^-$ pairs



STAR, Sci. Adv. 9 (2023) abq3903

Interference matters for p_T proxy!

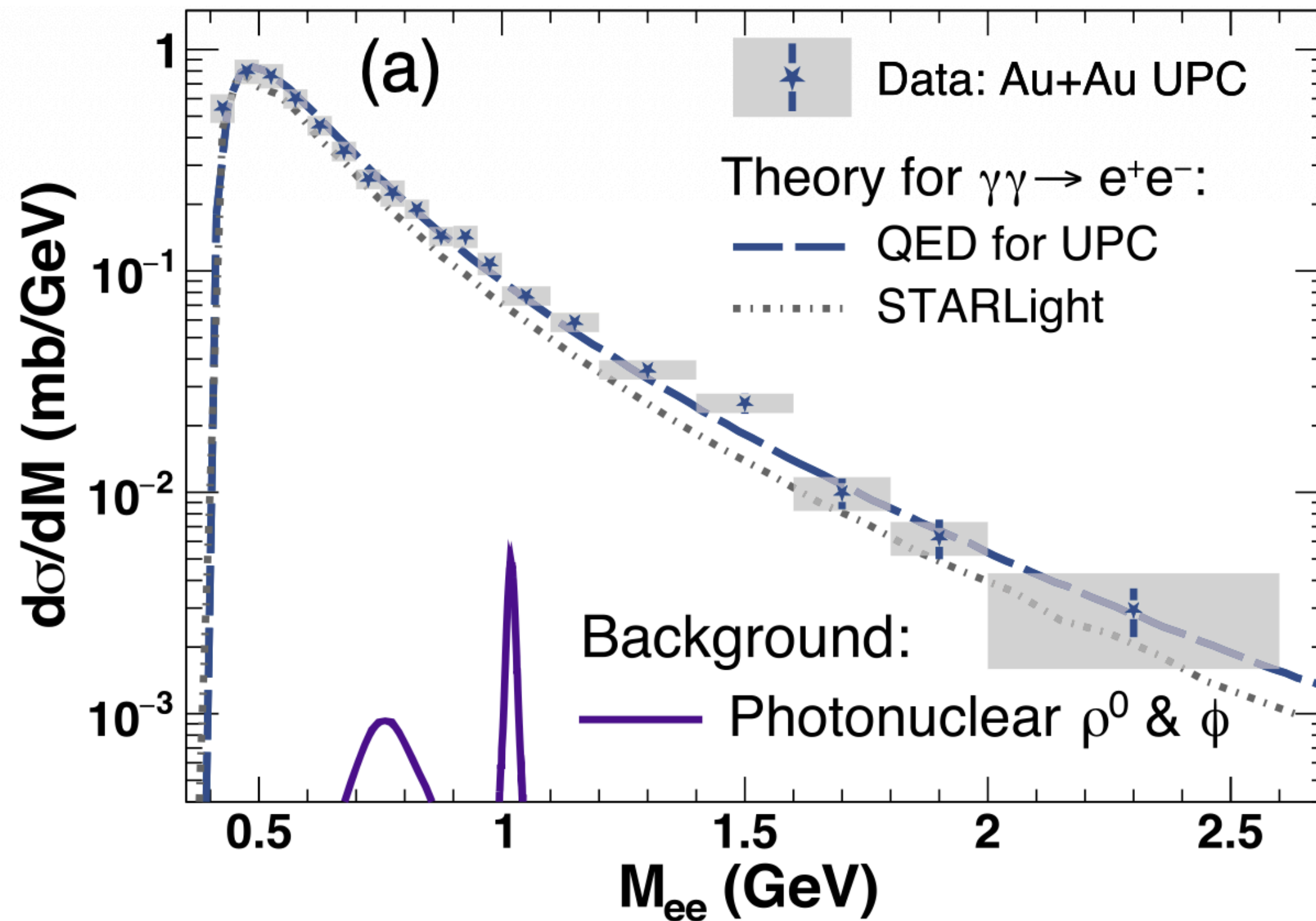


- Asymmetric collisions:** No/weak correlation between the p_T and polarization direction

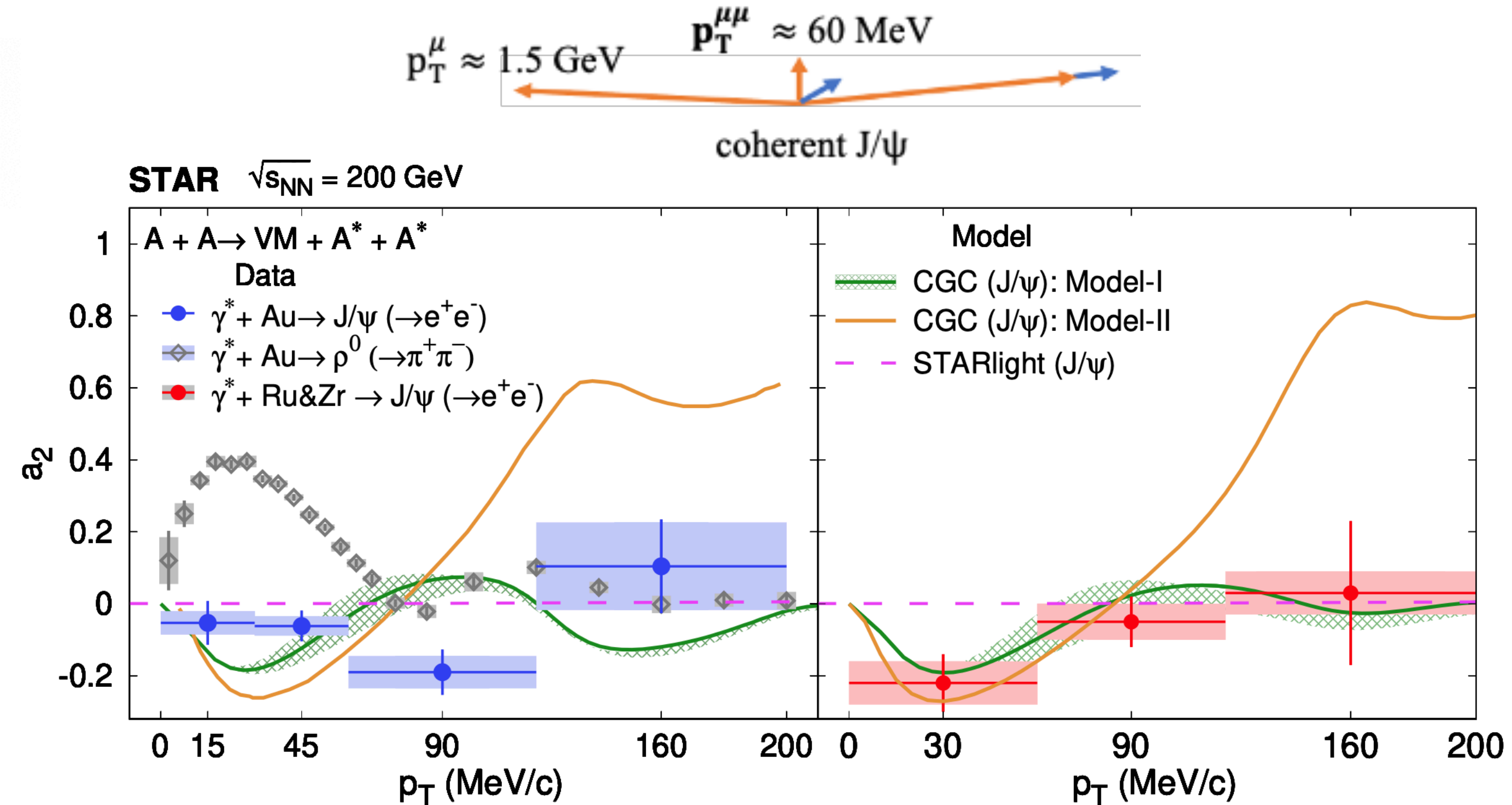
Challenge of spin-1/2 measurement

Zha et al., PRD 103 (2021) 033007

STAR, PRL 136 (2026) 242302



⊙ $\rho^0/\phi \rightarrow e^+e^-$ is overwhelmed by two-photon interactions



⊙ $J/\psi \rightarrow e^+e^-$ is suffered by the detector resolution and soft photon radiation

Extraction of $\cos(2\Delta\phi)$ amplitude (A_2)

CMS-PAS-HIN-25-006

J/ ψ signal extraction in each $\Delta\phi = \phi_{\mu^-} - \Psi_2$ bin



Hadronic subtraction in each $\Delta\phi$ bin



$\cos(2\Delta\phi)$ amplitude A_2^{obs} extraction

