The recent measurements of ultra-peripheral collisions
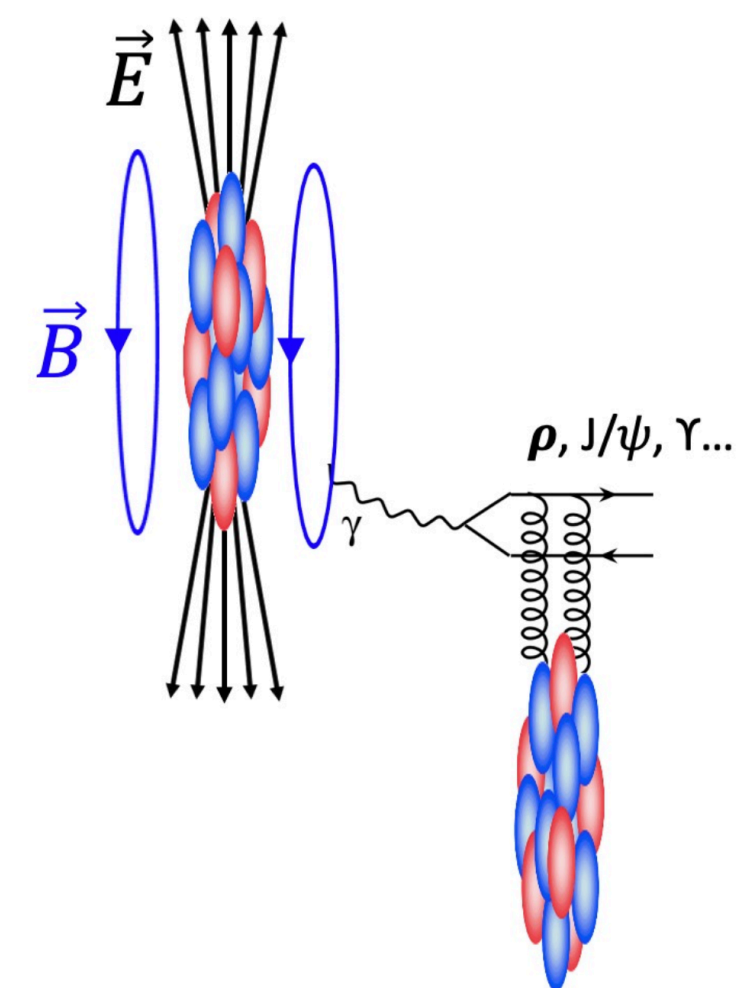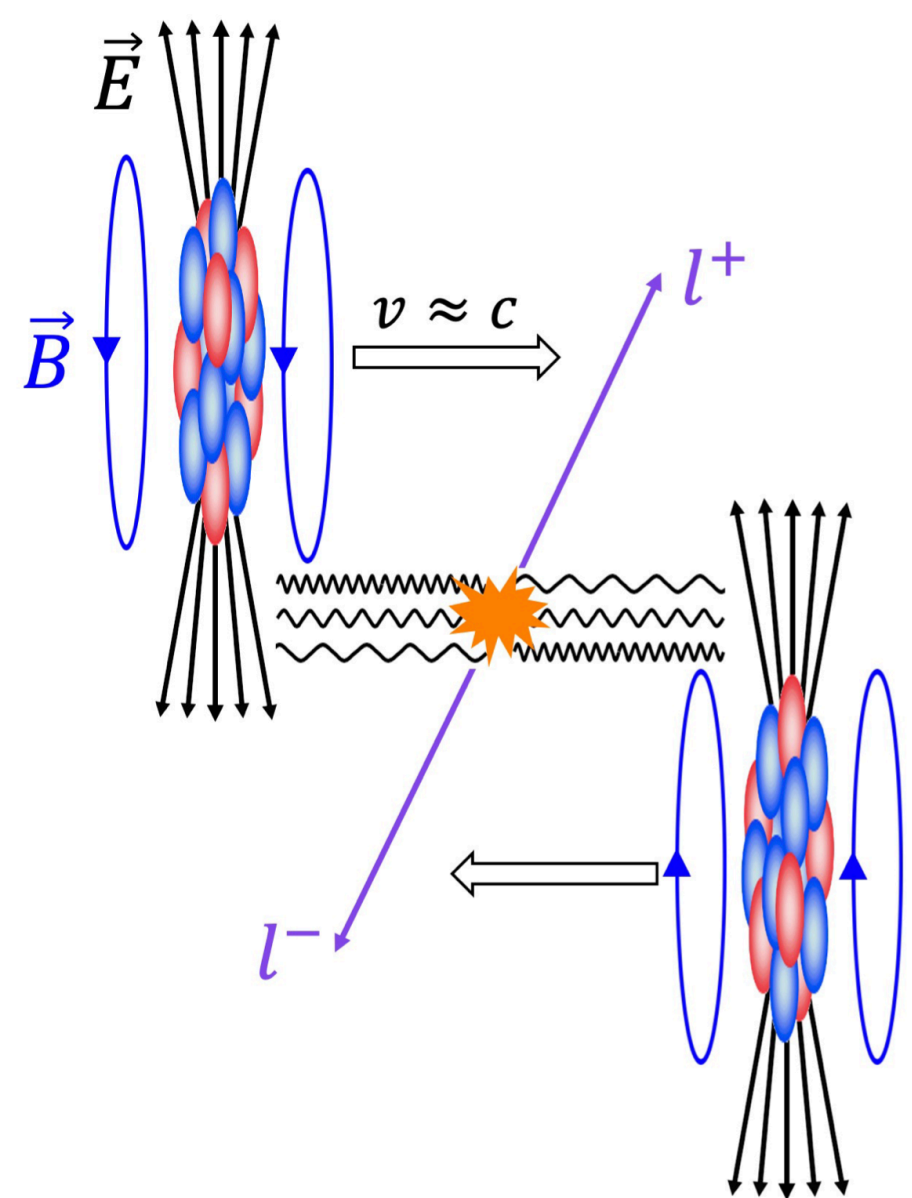
杨 帅

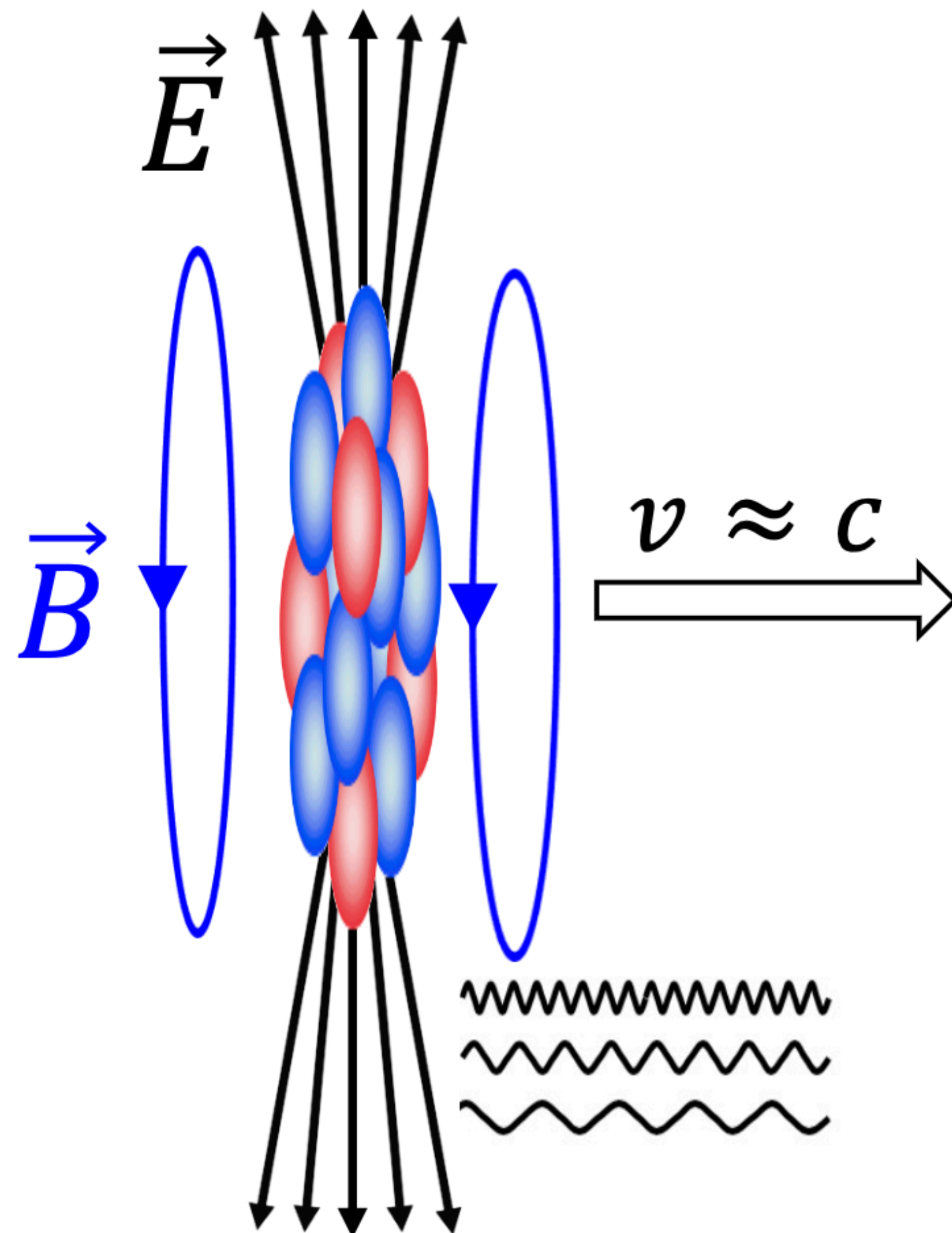华南师范大学

第十四届全国粒子物理学术会议, 青岛, 2024年8月14日-18日

Equivalent photon

◉ **E**quivalent **P**hoton **A**pproximation
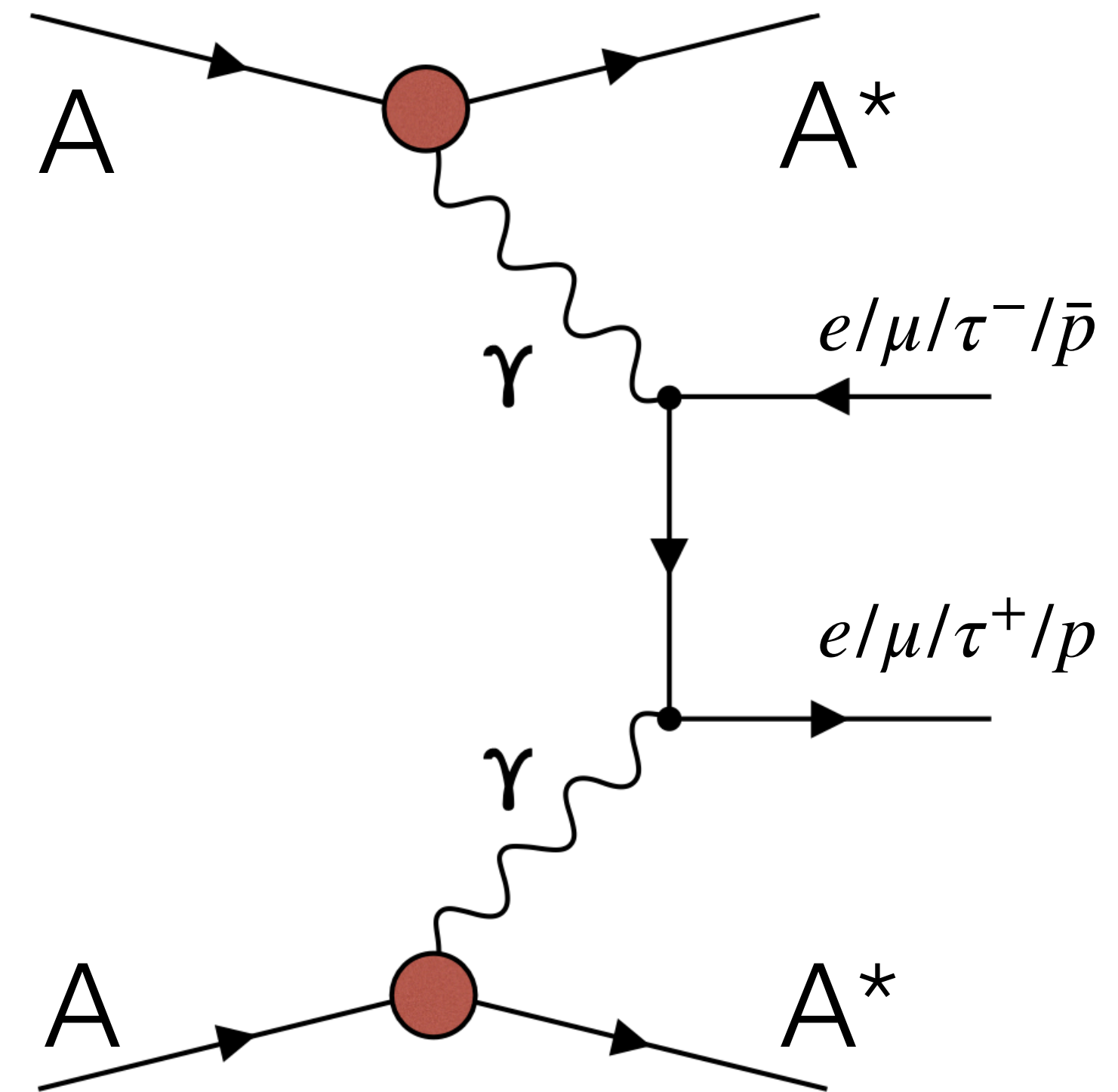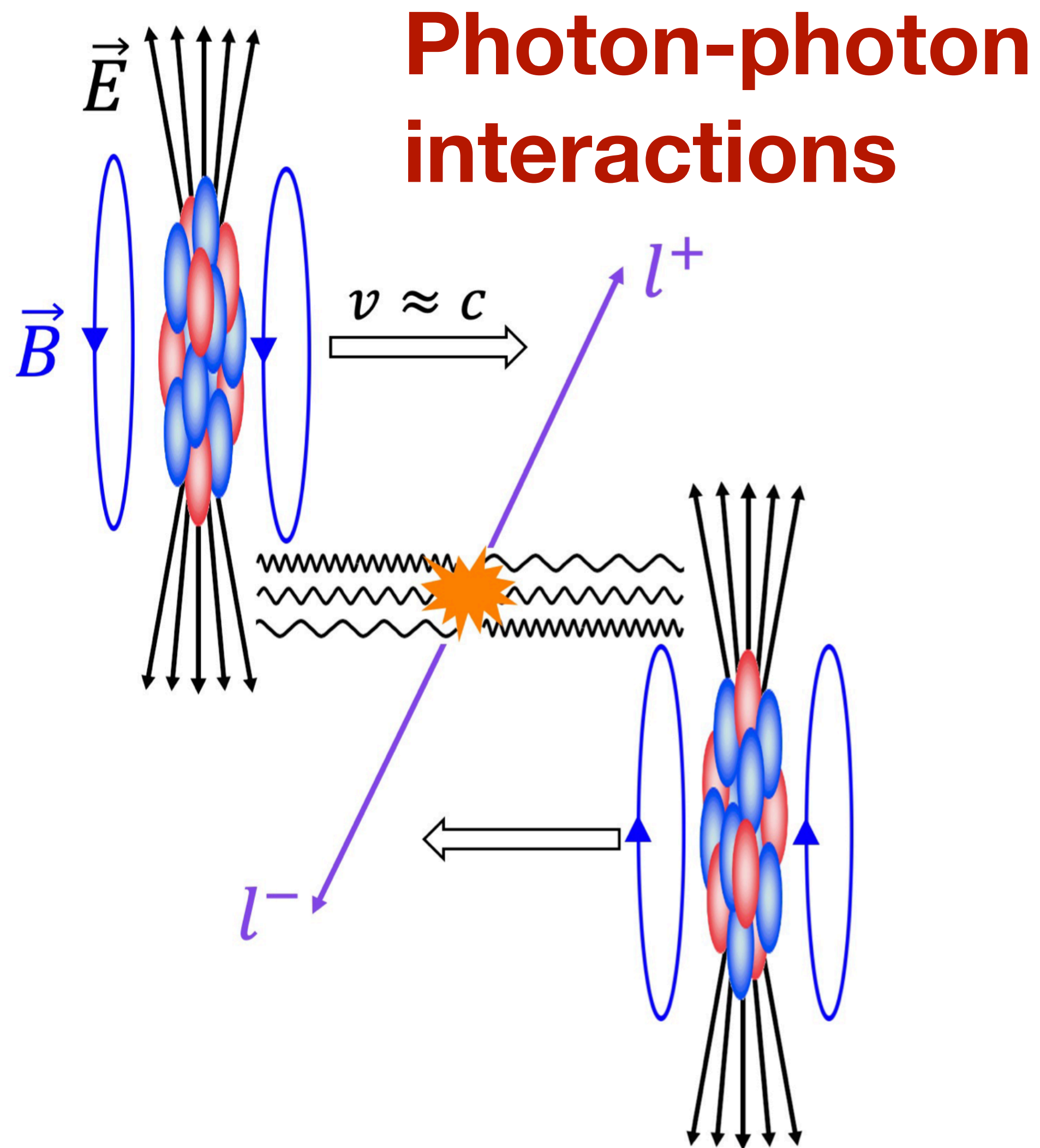- Photon Flux ∝ Z^2
- $Q^2 \sim 0$ (quasi real photon)

Fermi, Z. Phys. 29 (1924) 315
Williams, Phys. Rev. 45 (1934) 729
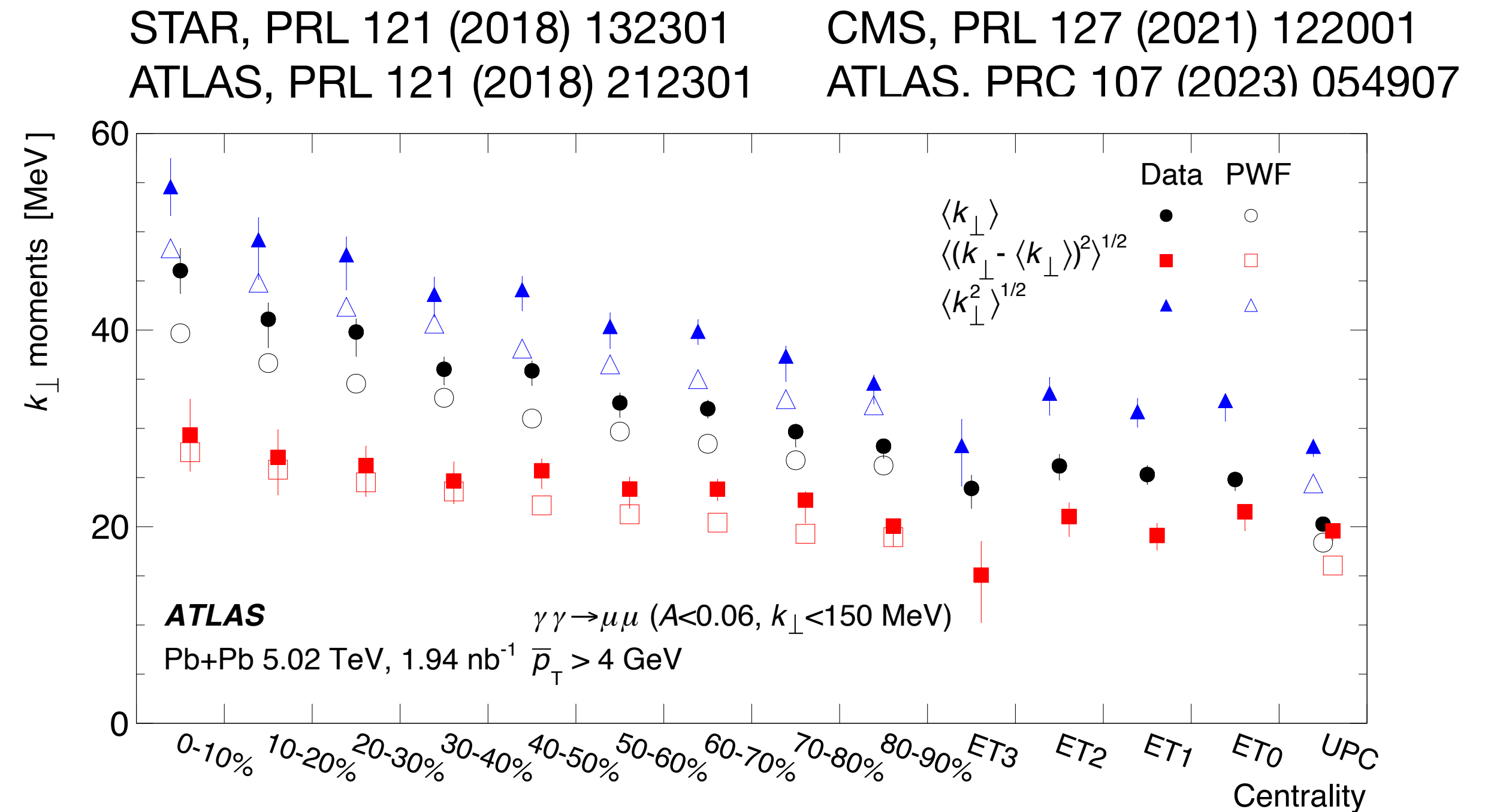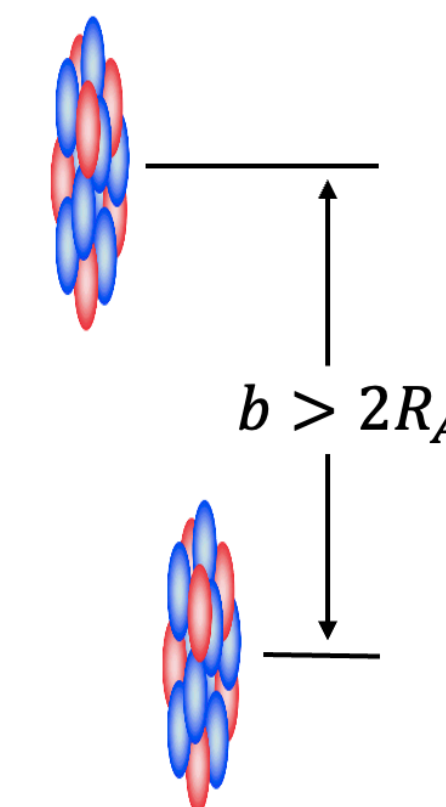Weizsacker, Z. Phys. 88 (1934) 612

◉ **Photon kinematics**

maximum energy $E_{\gamma,max} \sim \gamma(\hbar c/R)$	80 GeV in Pb+Pb@LHC 3 GeV in Au+Au@RHIC
typical p_T (& virtuality) $p_{Tmax} \sim \hbar c/R$	O(30) MeV @ RHIC & LHC
Coherent strengths (rates) scale as Z^2: nuclei >> protons	Flux of photons on other nucleus ~ Z^2, flux of photons on photons ~ Z^4 (45M!)

Photon-photon interactions

Photon-photon interactions

⊙ QED

⊙ BSM physics

Concluded the *b* dependence of photon p$_T$

STAR, PRL 121 (2018) 132301
ATLAS, PRL 121 (2018) 212301

CMS, PRL 127 (2021) 122001
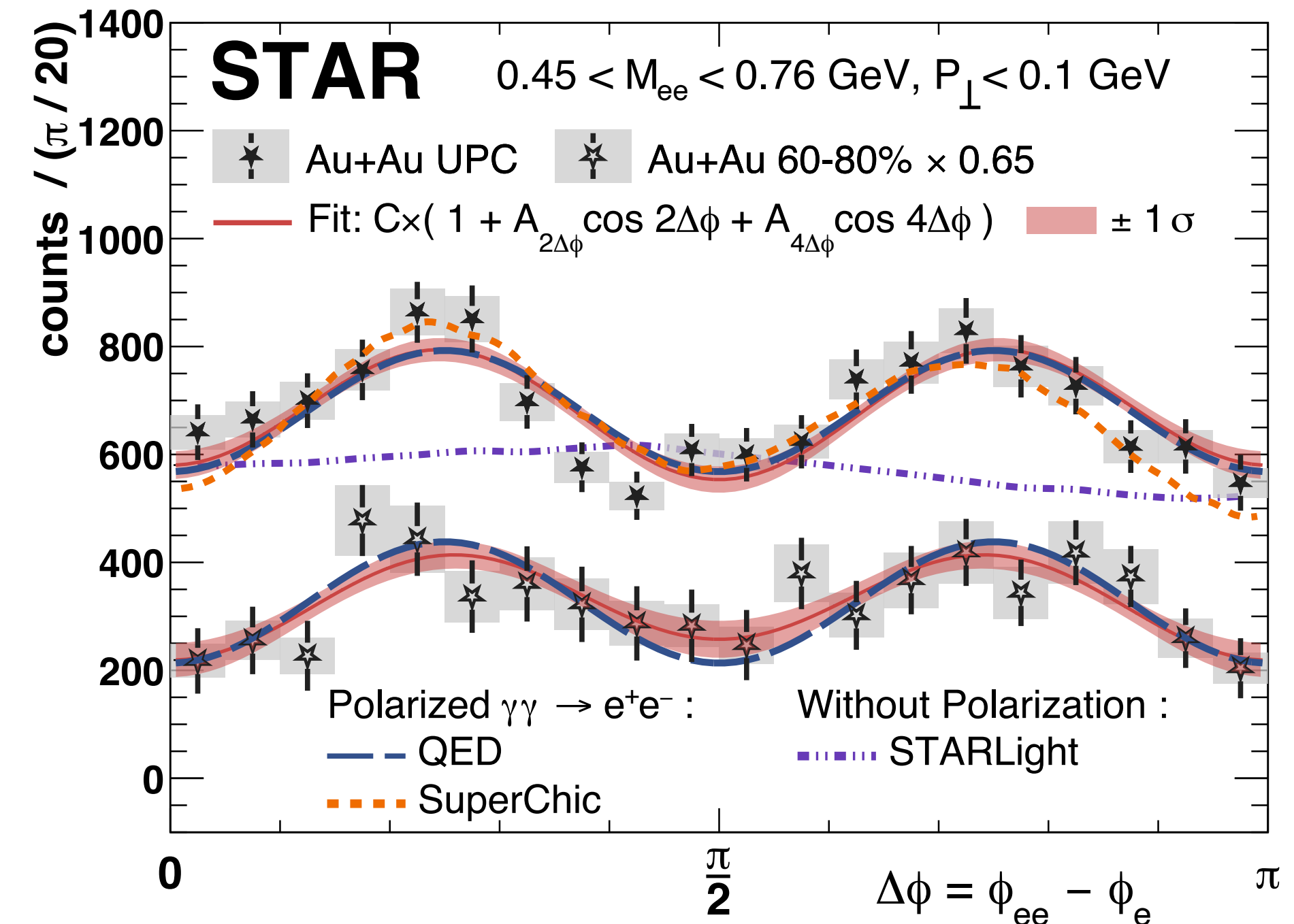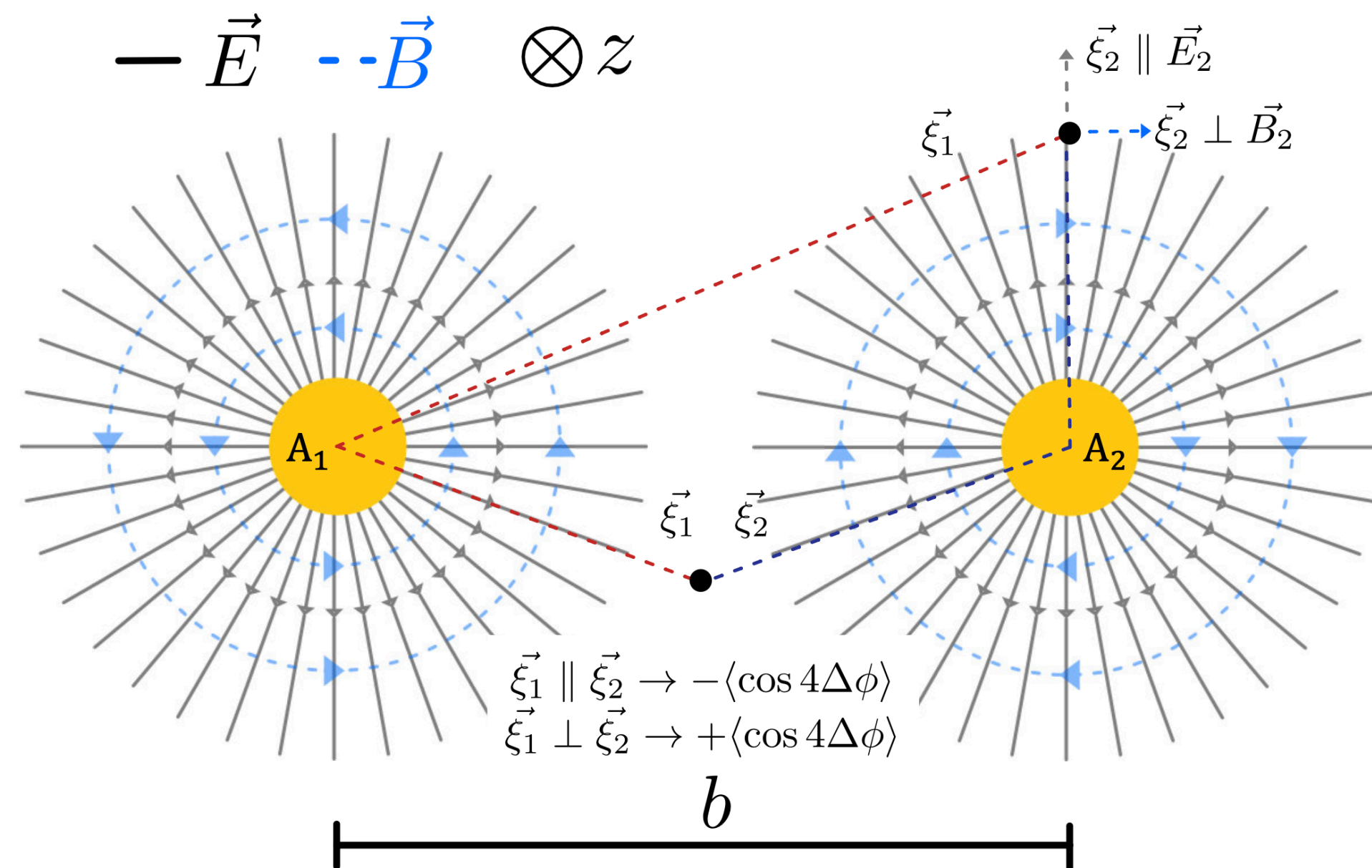ATLAS. PRC 107 (2023) 054907
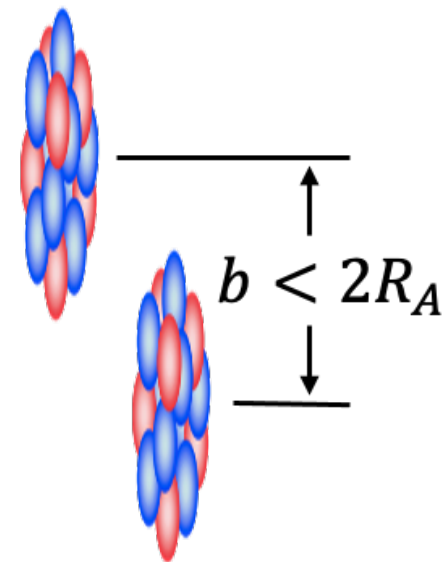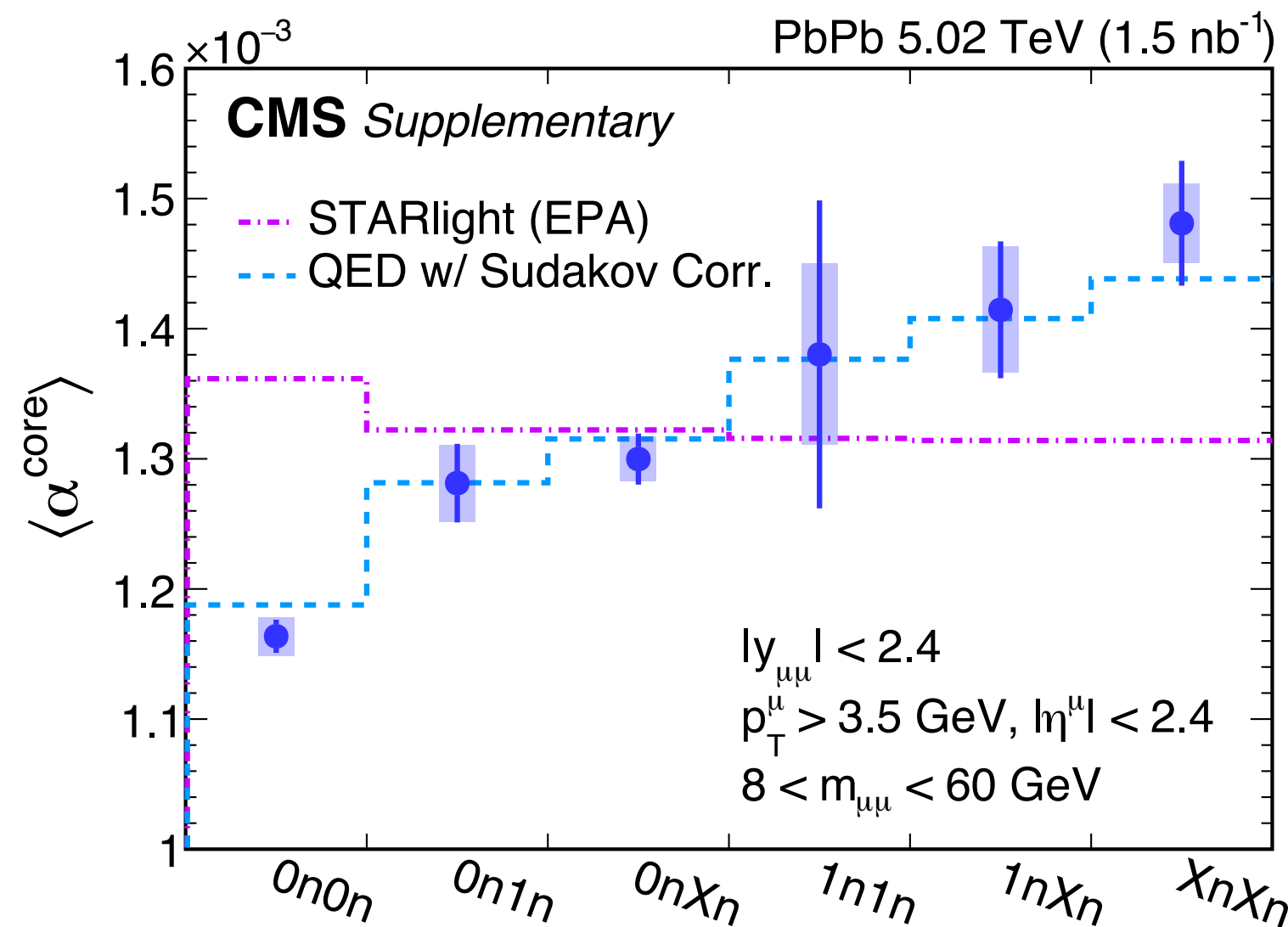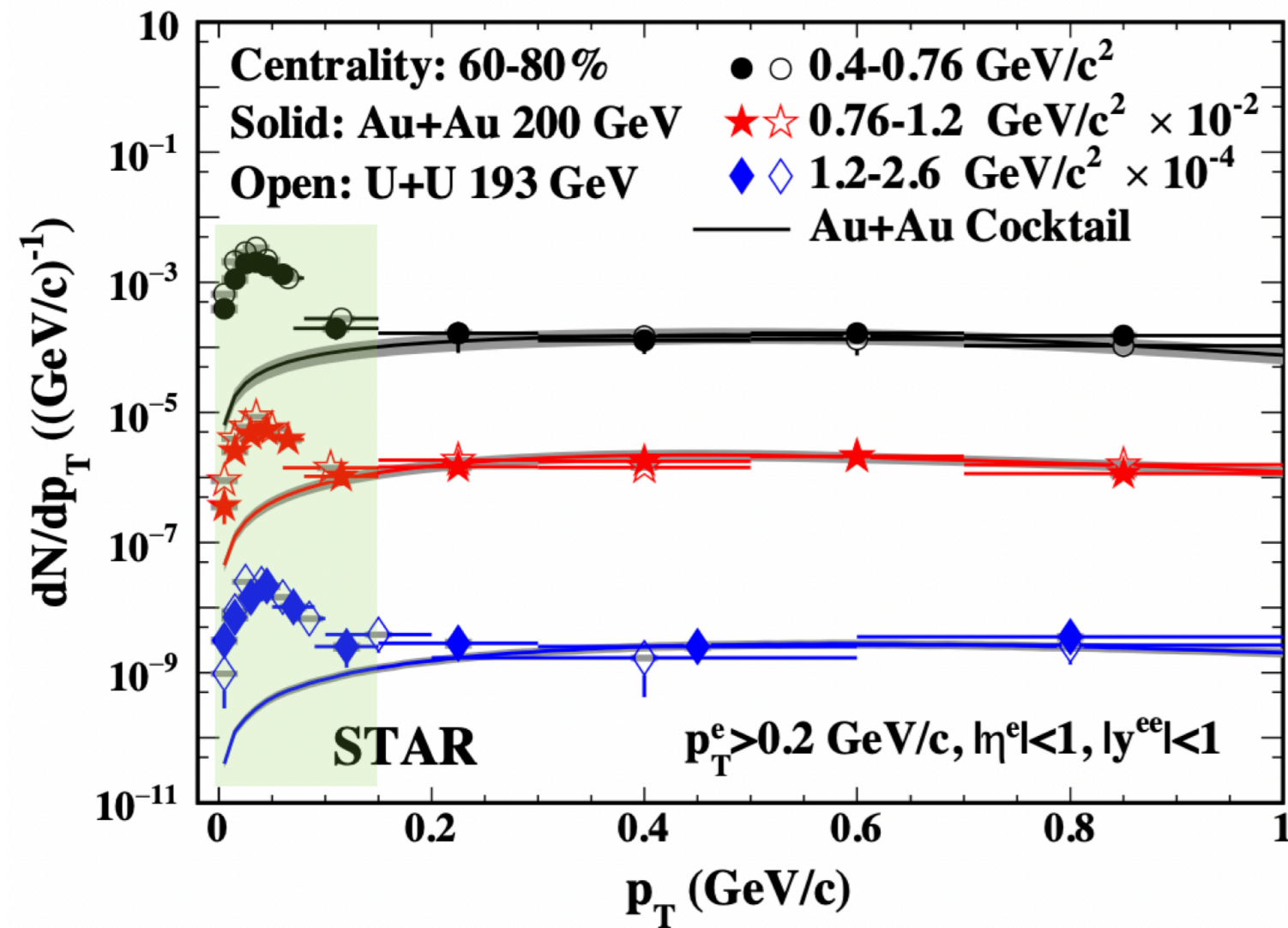
smaller *b* ⟵ **larger *b***

◉ Observed Breit-Wheeler process in non-UPC

- Probe QGP medium with $\gamma\gamma \rightarrow l^+l^-$

◉ Demonstrated the b dependent of photon p$_T$

- Precise reference for probing QGP EM effects

Experimental signature of linearly polarized photons

Li, Zhou, and Zhou, PLB 795 (2019) 576

STAR, PRL 127 (2021) 052302

- ◉ Different helicity amplitude combinations for linearly polarized photons lead to a splitting of angular modulation
- ◉ Experimentally observe that photons are linearly polarized
  - UPC: $A_{4\Delta\phi}$ observed with $> 6\sigma$
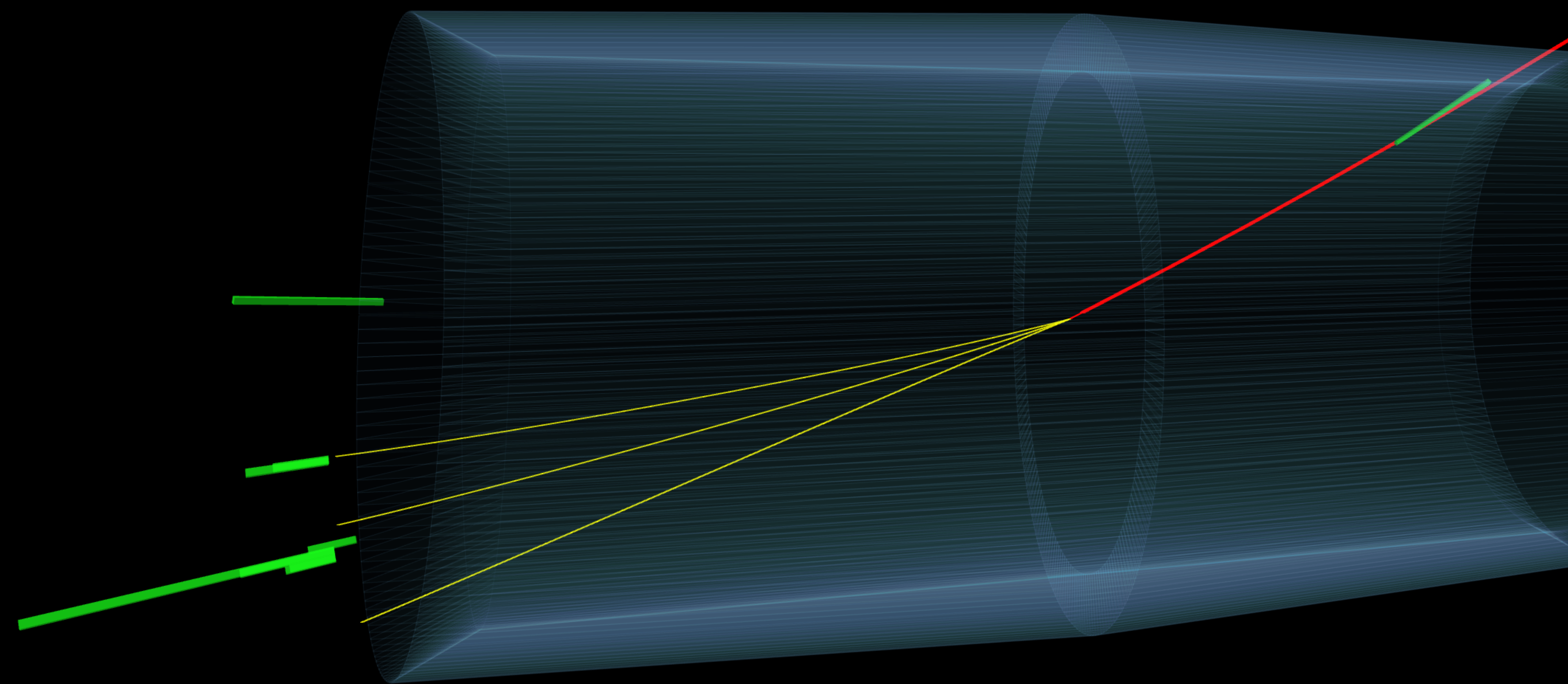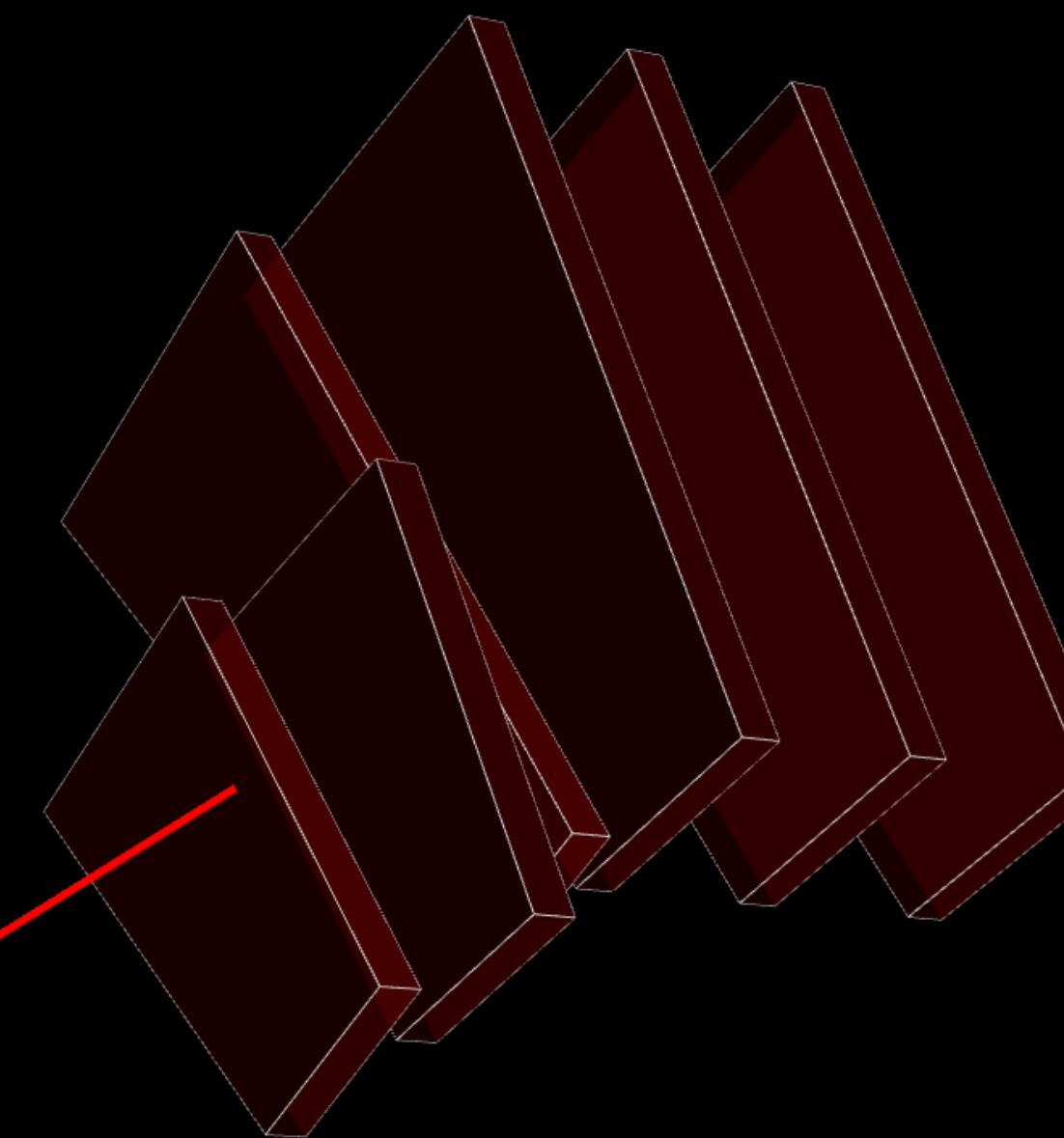 - non-UPC: $A_{4\Delta\phi}$ observed with $> 4\sigma$

Observation of $\gamma\gamma \rightarrow \tau\tau$ in AA

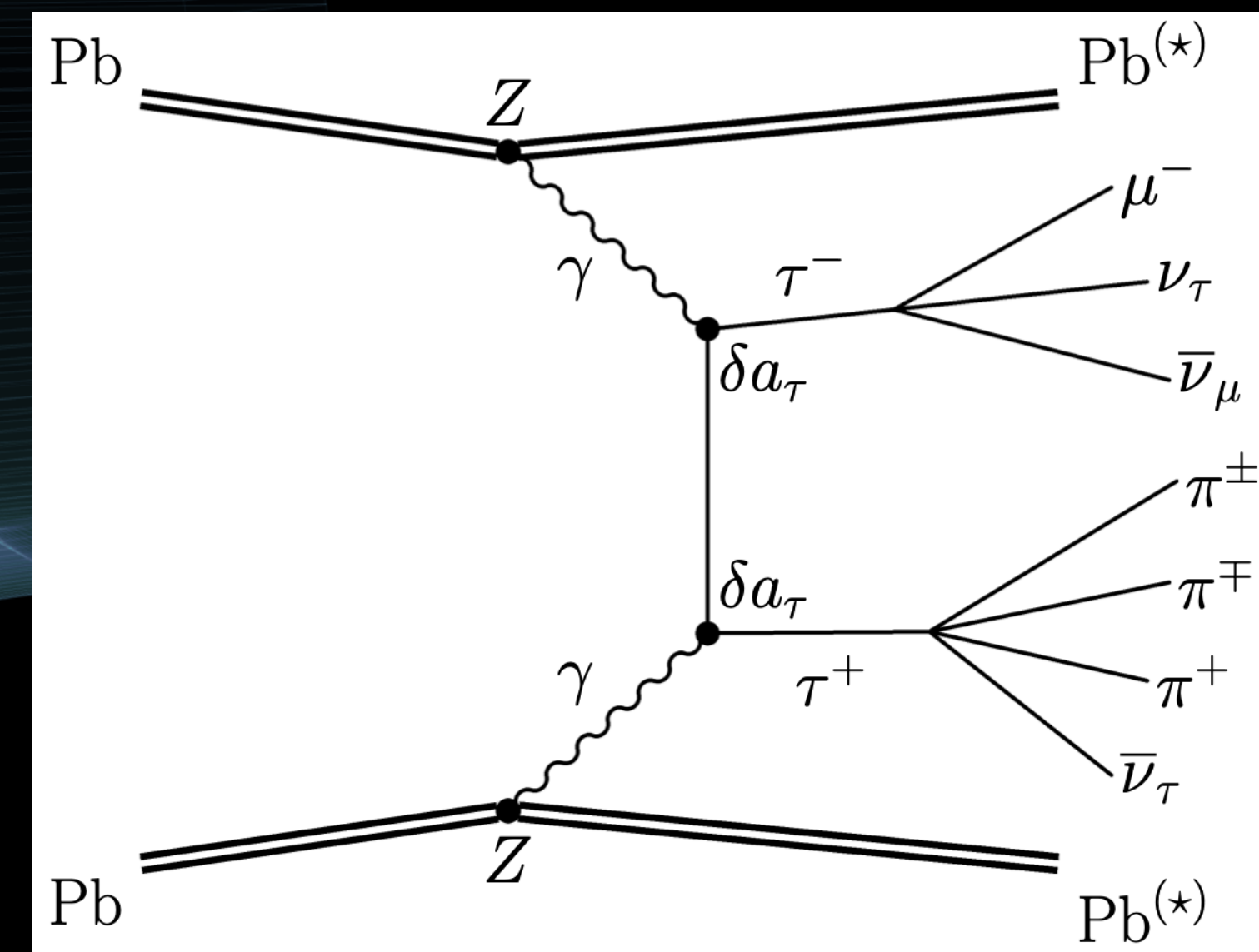CMS Experiment at the LHC, CERN
Data recorded: 2015-Dec-06 21:41:27.033612 GMT
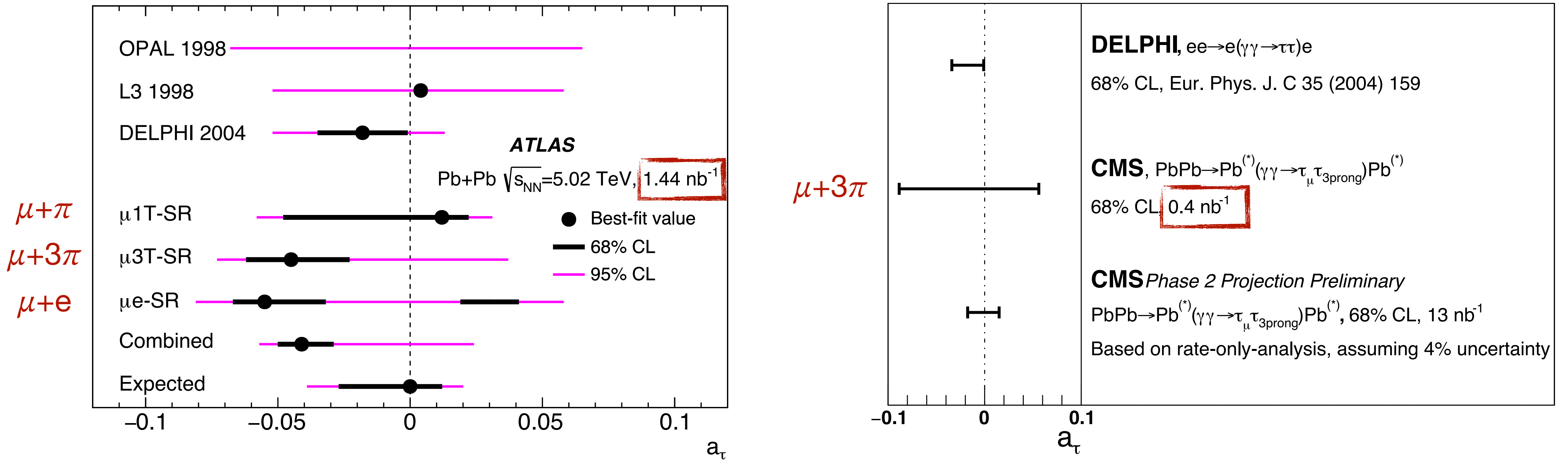Run / Event / LS: 263400 / 88515785 / 849

ATLAS, PRL 131 (2023) 151802
CMS, PRL 131 (2023) 151803

Constrain $a_\tau = (g_\tau - 2)/2$

ATLAS, PRL 131 (2023) 151802

CMS, PRL 131 (2023) 151803

$\mu+\pi$

$\mu+3\pi$

$\mu+e$

◉ Sensitivity to the BSM physics

- Model-dependent value of a_τ
- Comparable with DELPHI result

Higher excitation of QED vacuum

Zhang, Zhang, and Shao, arxiv: 2406.05618
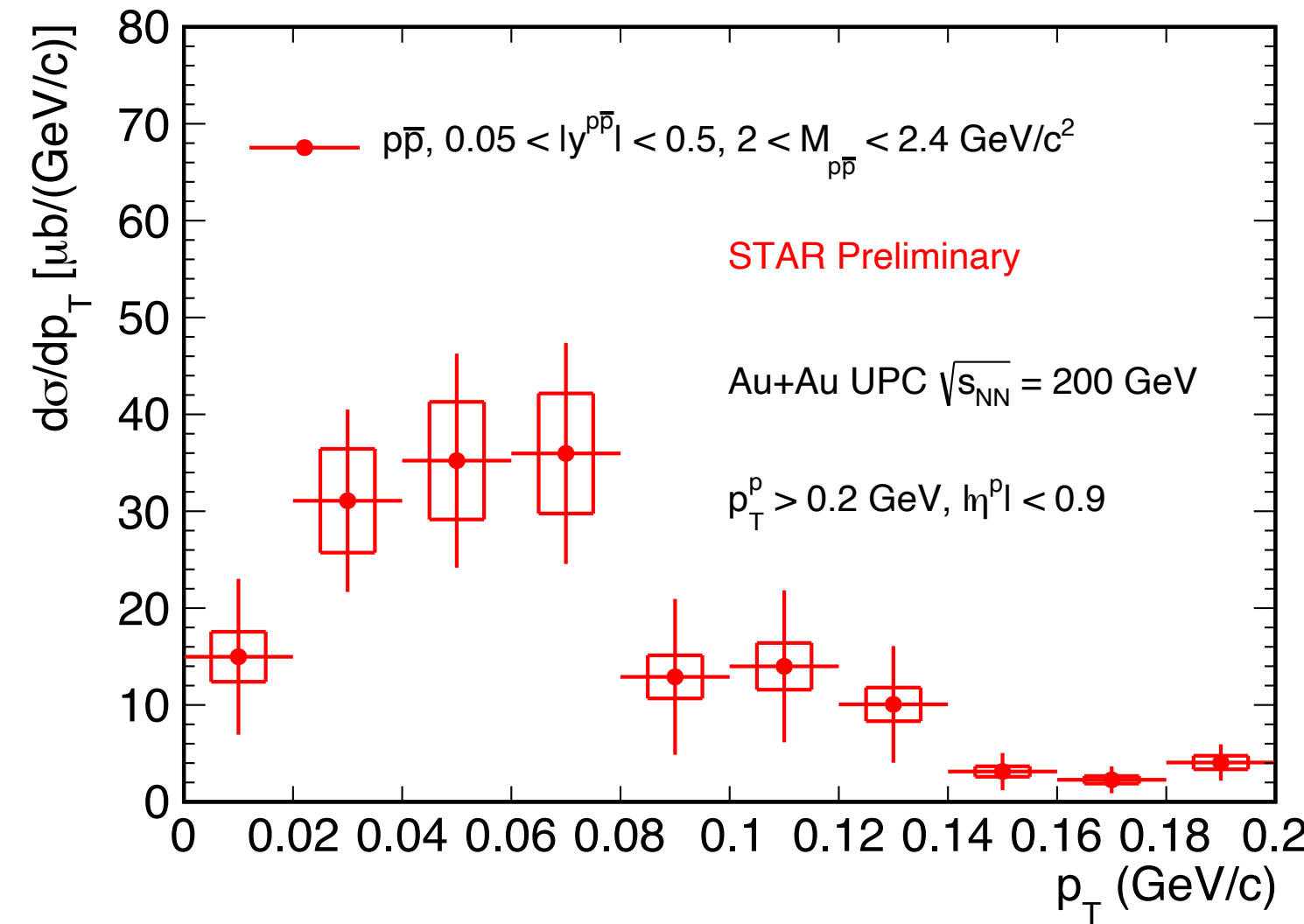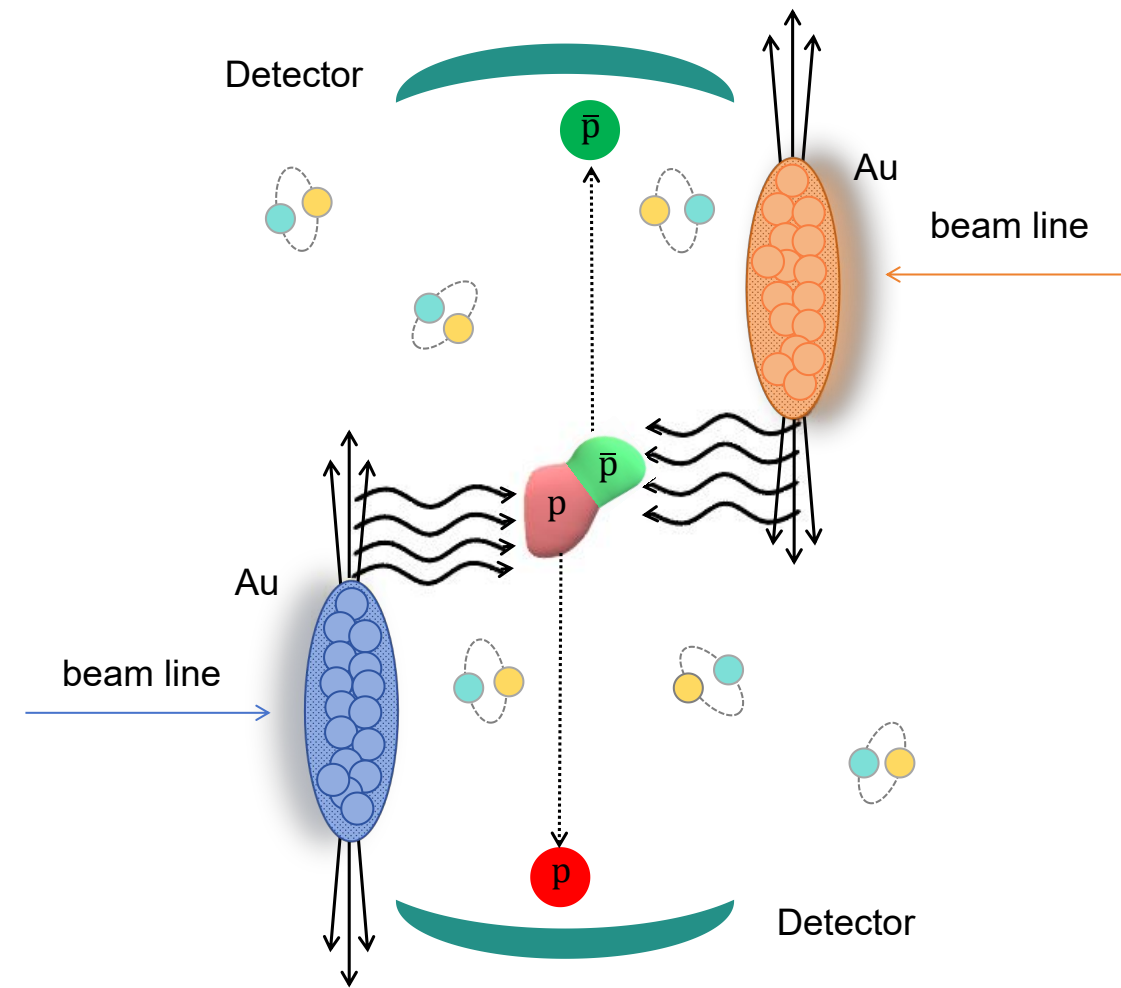
⊙ First observation of $\gamma\gamma \to$ dibaryon production in UPC

• Contribution of Drell-Söding process is significantly lower than data

• Consistent with $\gamma\gamma \to p\bar{p}$ production

Drell-Söding process
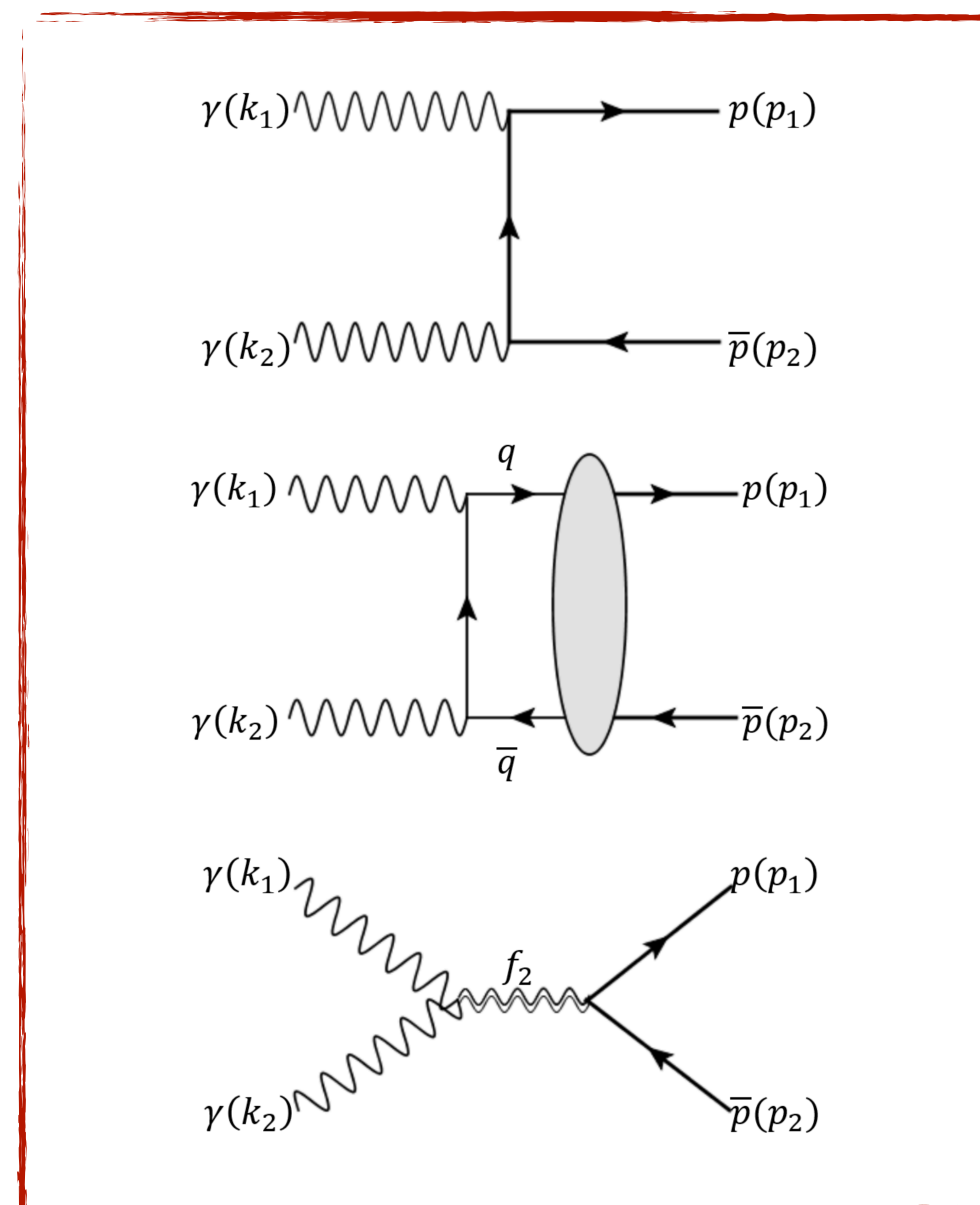
Photon-nuclear interactions

Photon-nuclear interactions

$\vec{E}$

$\vec{B}$

ρ, J/ψ, Υ...

γ

Drell-Söding process

γ

$- - hadron$

$\rightarrow - - anti - hadron$

$\mathbb{P}, f_{2\mathbb{R}}$

γ

$hadron$

$anti - hadron$

$\mathbb{P}, f_{2\mathbb{R}}$

Coherent (nuclear keeps intact)

gluonic structure

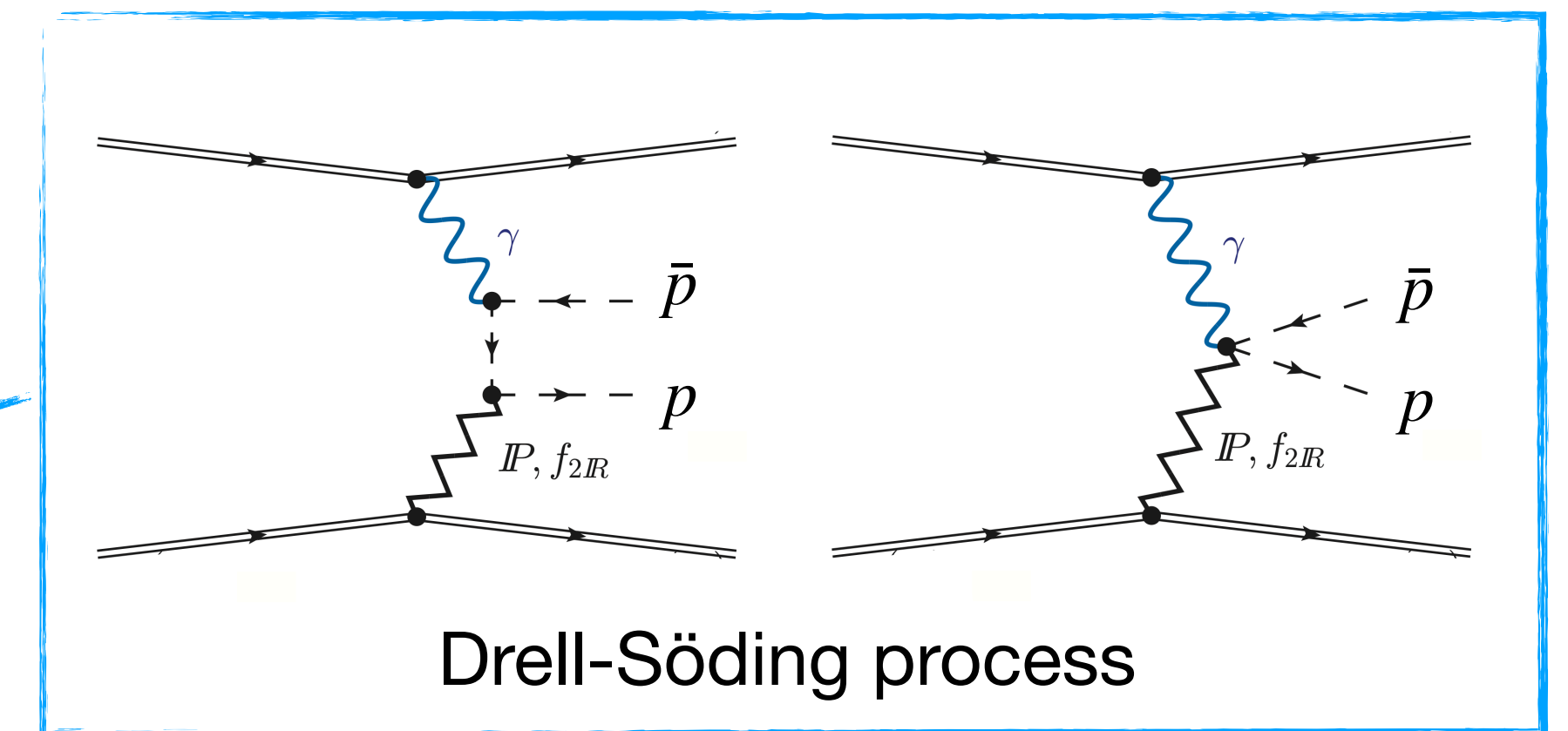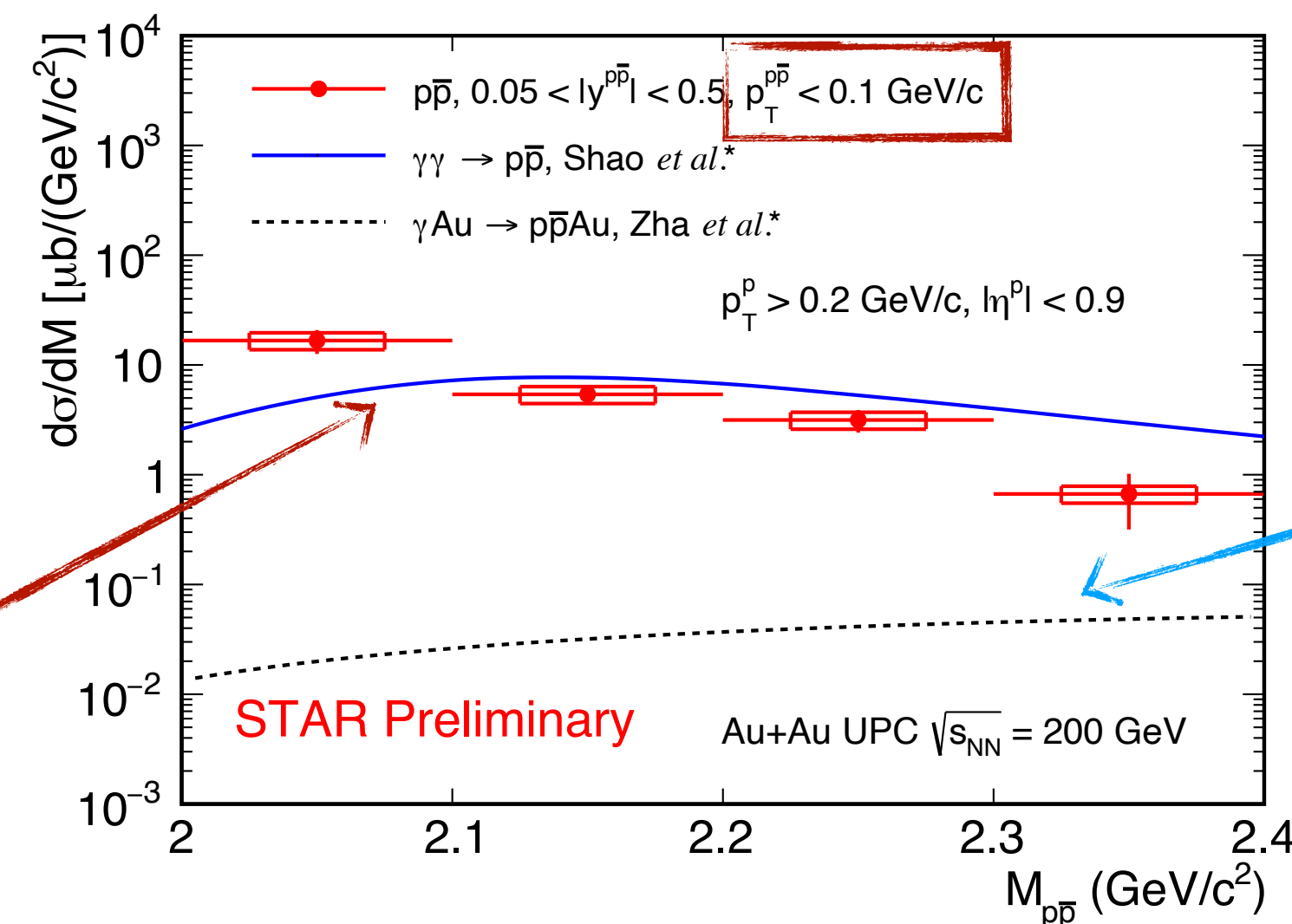Incoherent (nuclear breaks up)
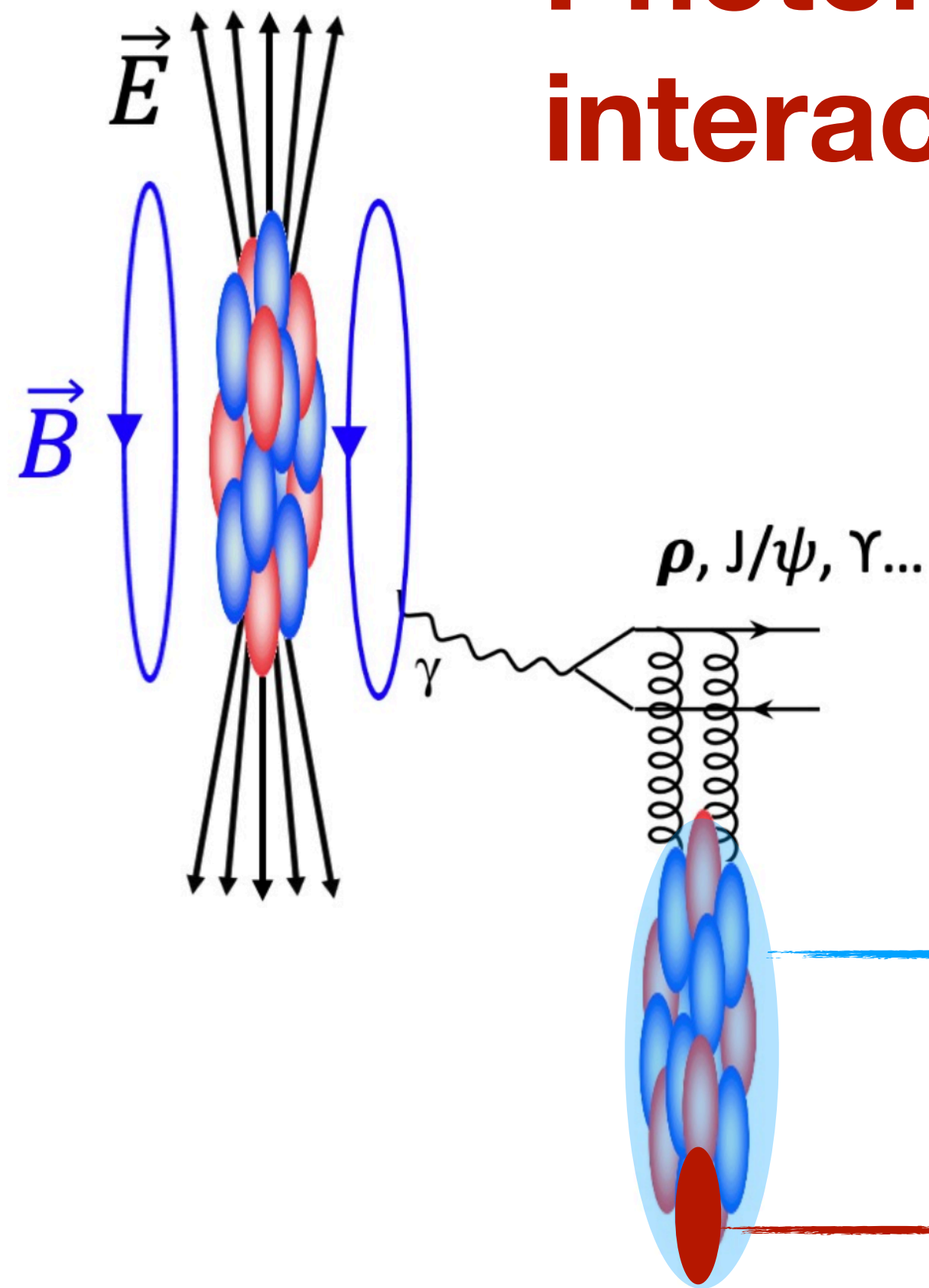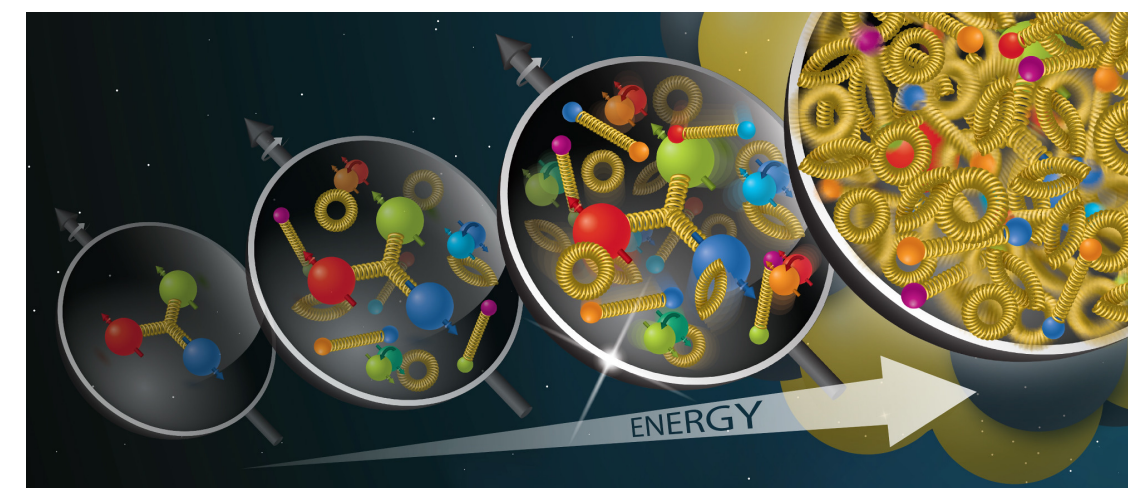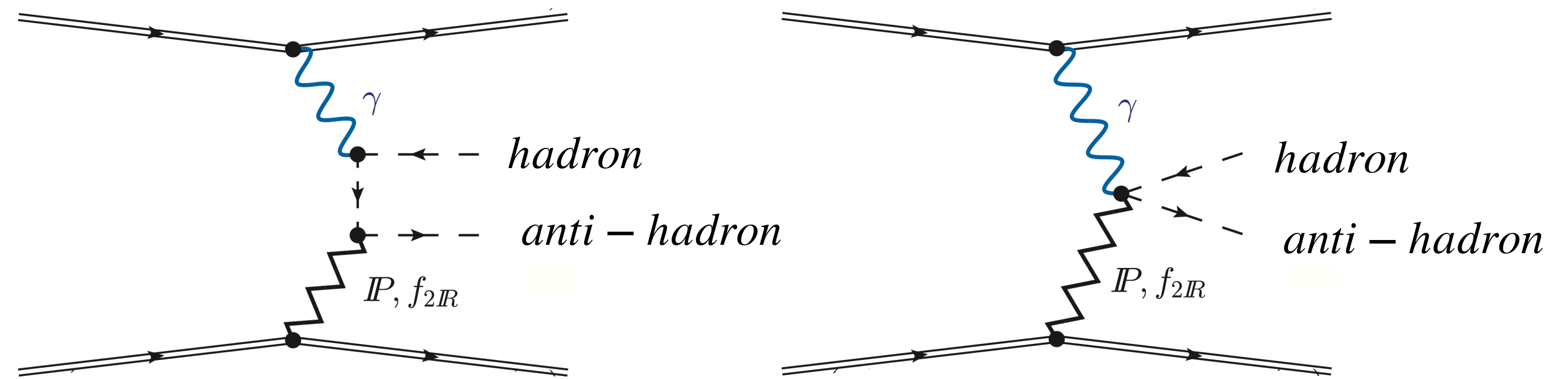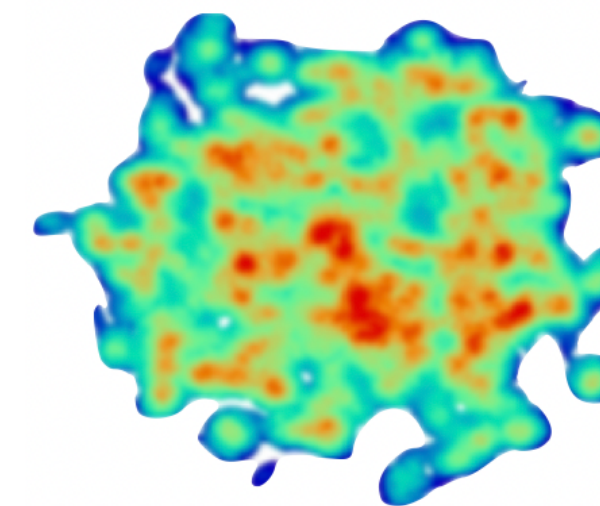
sub-nucleon fluctuation

⊙ Little "EIC"

Photoproduction of K^+K^- pairs

ALICE, PRL 132 (2024) 222303
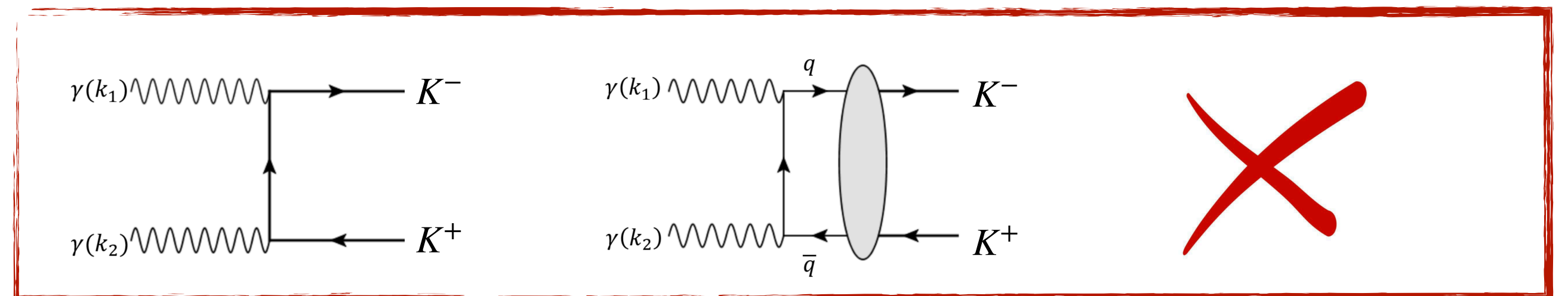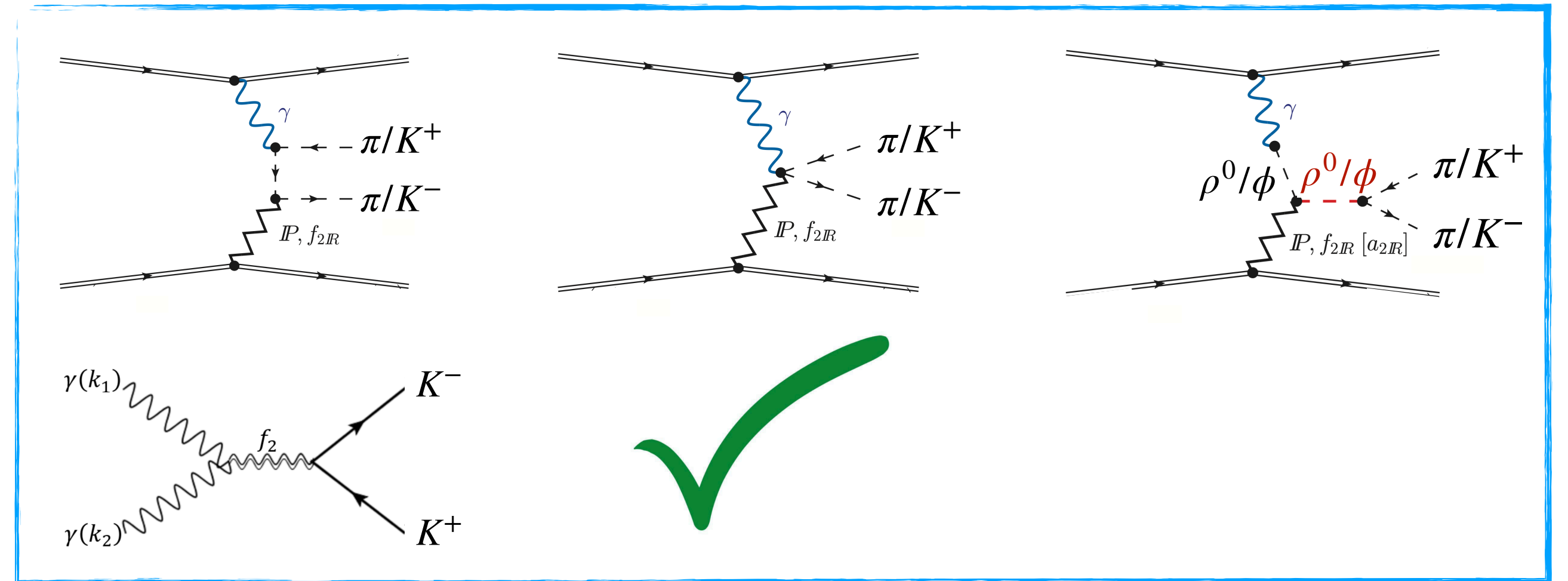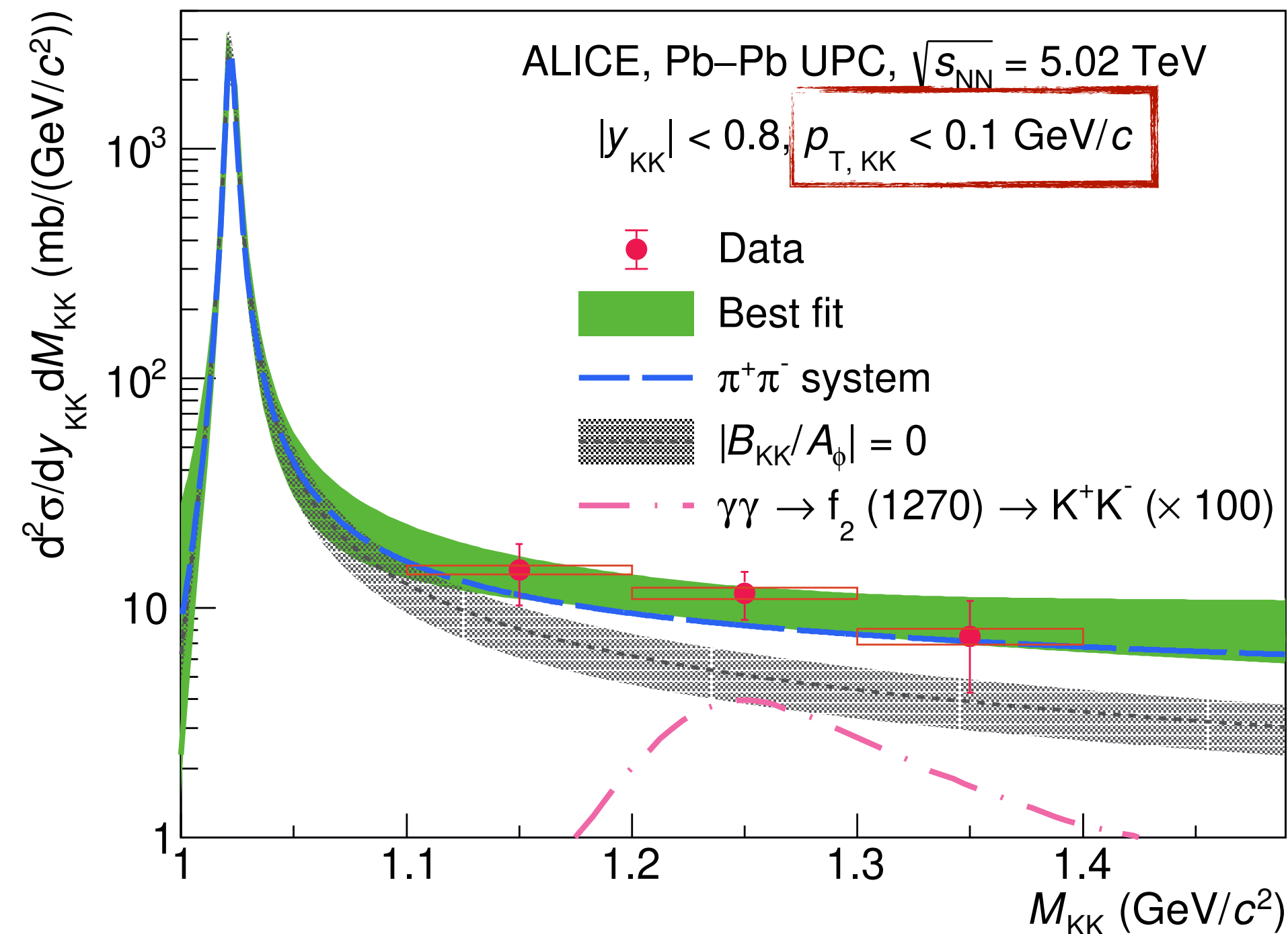
- ◉ Data favor the coherent $\phi(1020) \to K^+K^-$ + direct K^+K^- photoproduction, with interference considered
  - The contribution of $\gamma\gamma \to K^+K^-$ is not estimated

Imaging heavy nuclear with coherent J/ψ

⊙ LHC experiments complement each over a wide range of y region

- $R_g^{Pb} = 0.64 \pm 0.04$ at $x \sim 10^{-3}$ (y=0)

Imaging heavy nuclear with coherent J/ψ

ALICE, EPJC 81 (2021) 712
CMS, PRL 131 (2023) 262301
LHCb, JHEP 06 (2023) 146
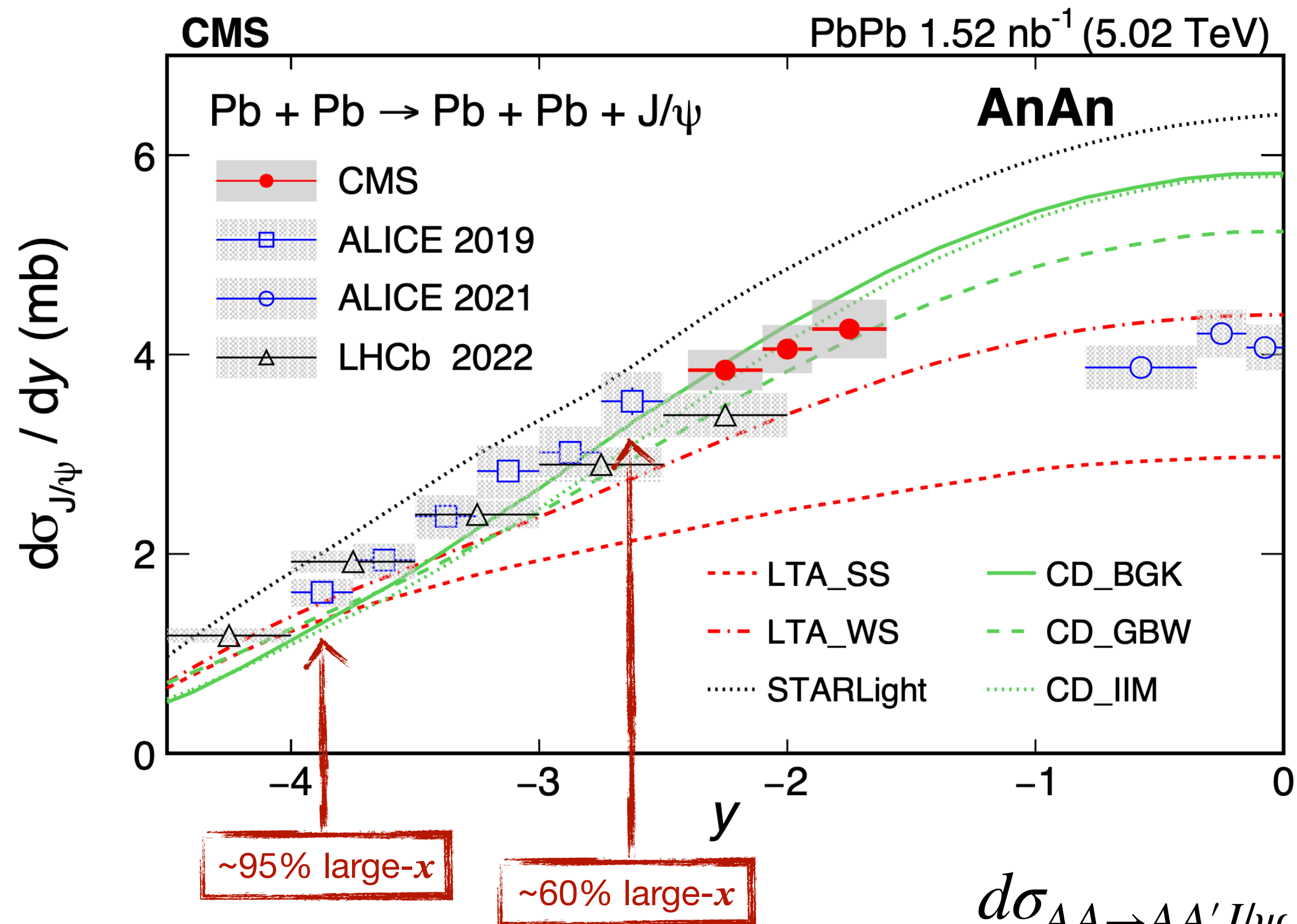
- ◉ LHC experiments complement each over a wide range of y region
  - $R_g^{Pb} = 0.64 \pm 0.04$ at $x \sim 10^{-3}$ (y=0)

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

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

CMS

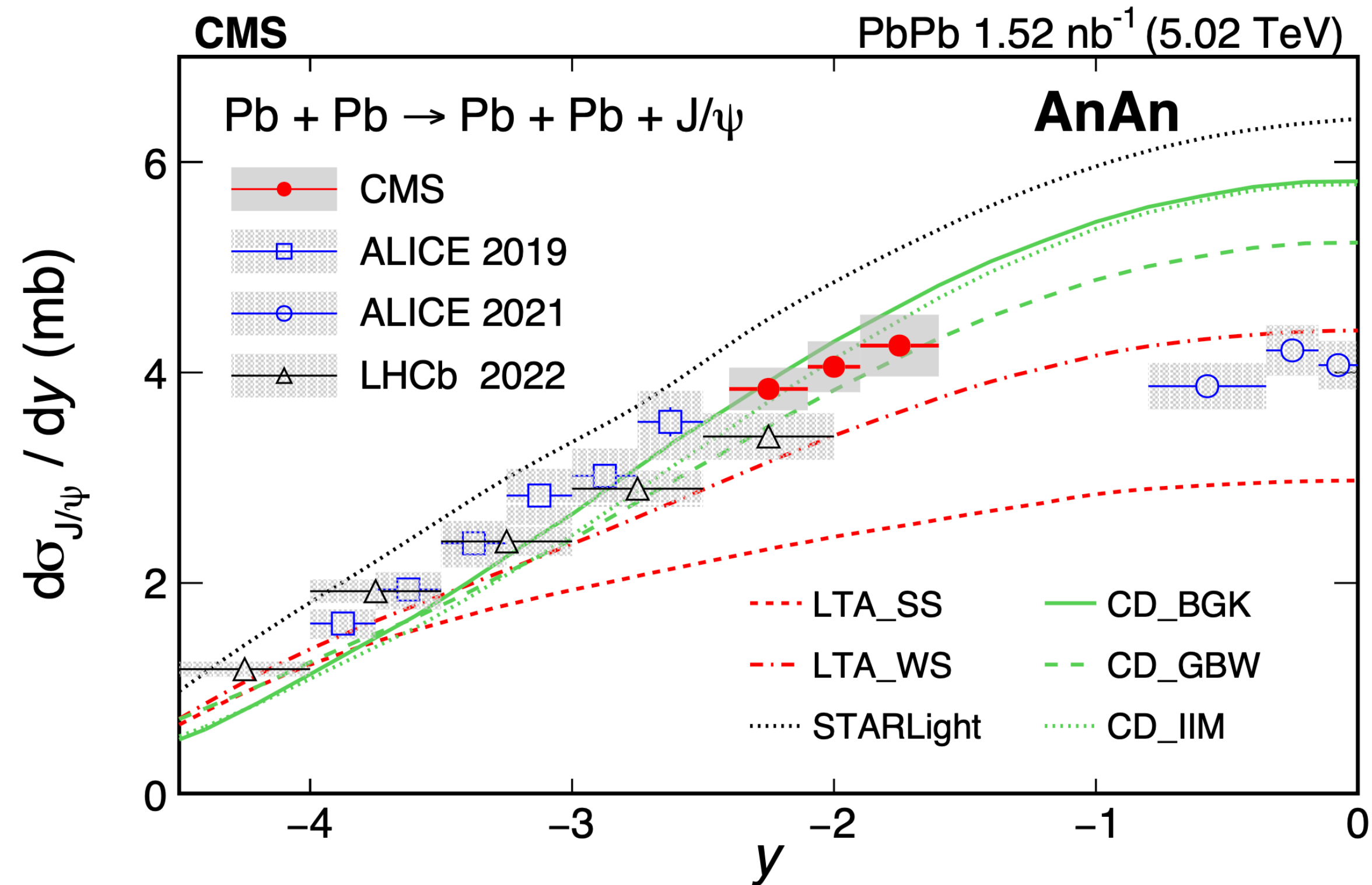PbPb 1.52 nb^{-1} (5.02 TeV)

Pb + Pb → Pb + Pb + J/ψ **AnAn**

- CMS
- ALICE 2019
- ALICE 2021
- LHCb 2022

d$\sigma_{J/\psi}$ / dy (mb)

---- LTA_SS   —— CD_BGK
—·— LTA_WS   ---- CD_GBW
····· STARLight   ····· CD_IIM

~95% large-x

~60% large-x
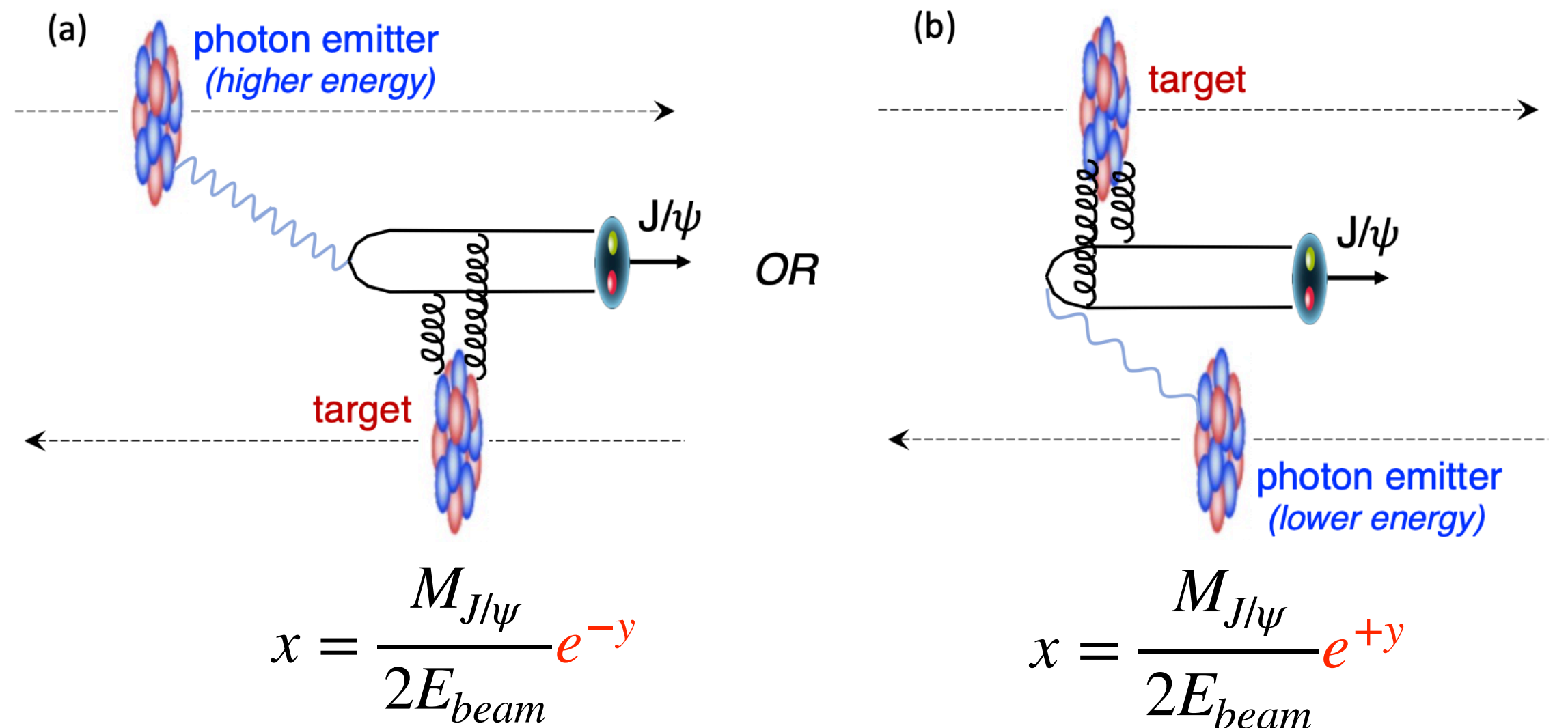
$$\frac{d\sigma_{AA \to AA'J/\psi}}{dy} = N_{\gamma/A}(\omega_1) \cdot \sigma_{\gamma A \to J/\psi A'}(\omega_1) + N_{\gamma/A}(\omega_2) \cdot \sigma_{\gamma A \to J/\psi A'}(\omega_2)$$

Imaging heavy nuclear with coherent J/ψ

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

LO pQCD:
$\sigma^{VM} \propto [xG(x)]^2$
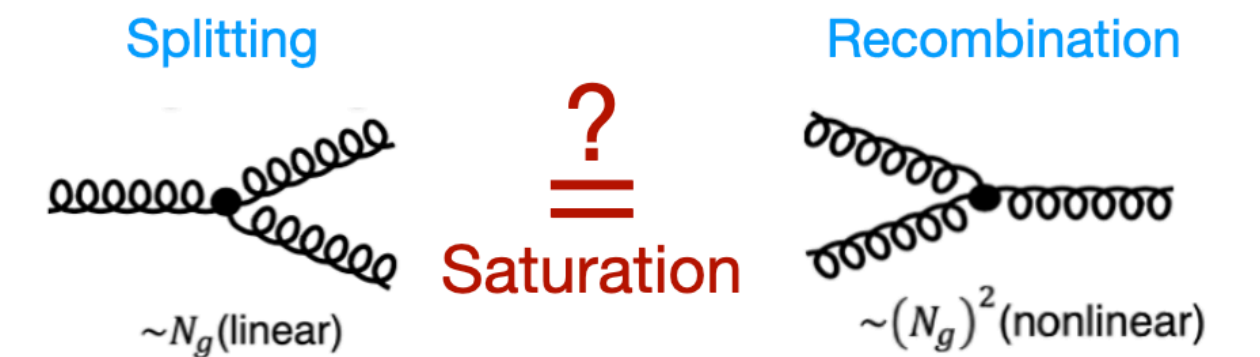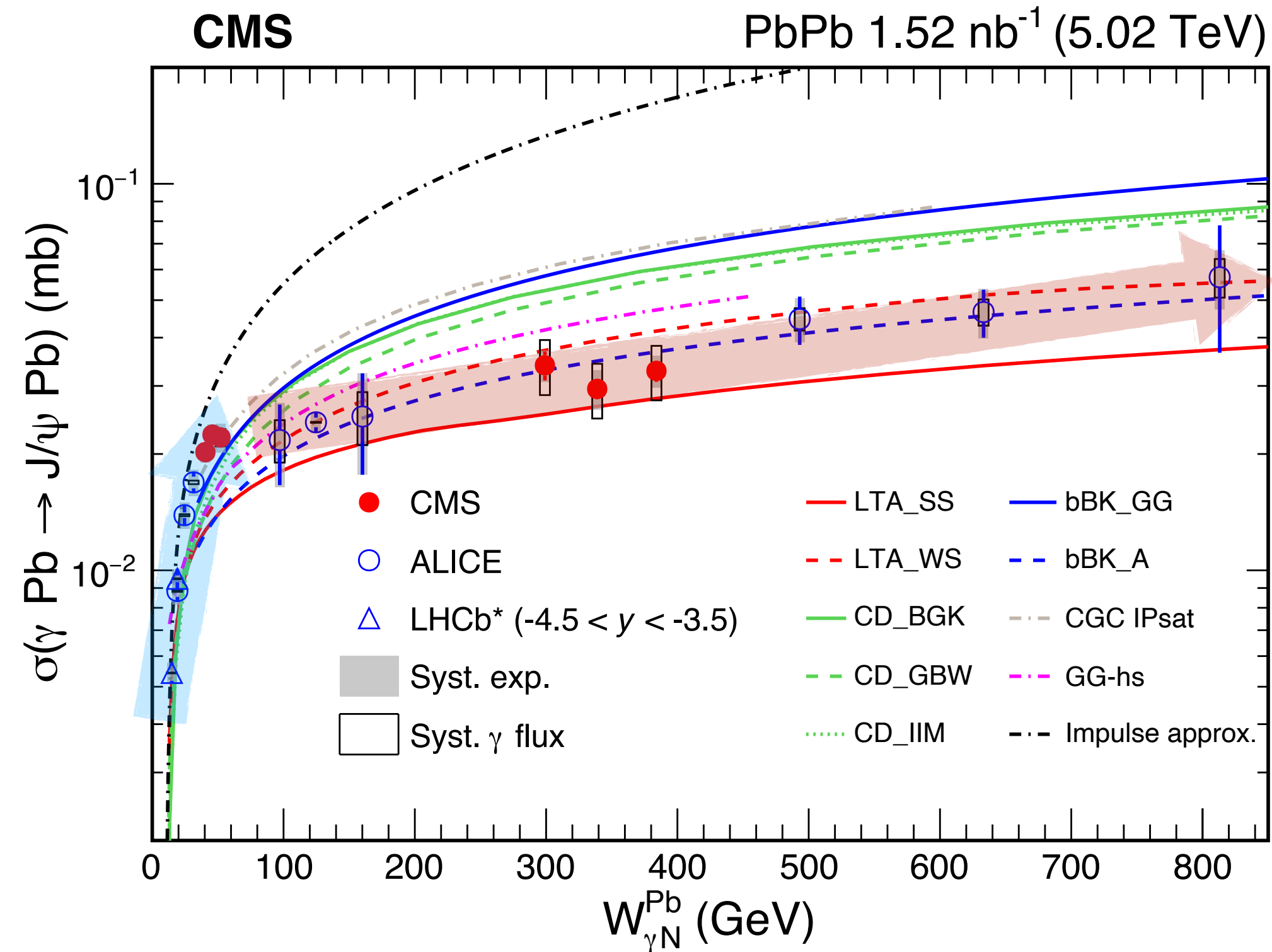
- ◉ Forward neutron tagging is employed to solve the "two-way" ambiguity
- ◉ Direct evidence of gluon saturation inside heavy nuclei?
  - $W_{\gamma N}^{Pb} < 40$ GeV: rapidly rising
  - $40 < W_{\gamma N}^{Pb} < 800$ GeV: nearly flat with a much slower rising

Incoherent J/ψ production at LHC

ALICE, PRL 132 (2024) 162302
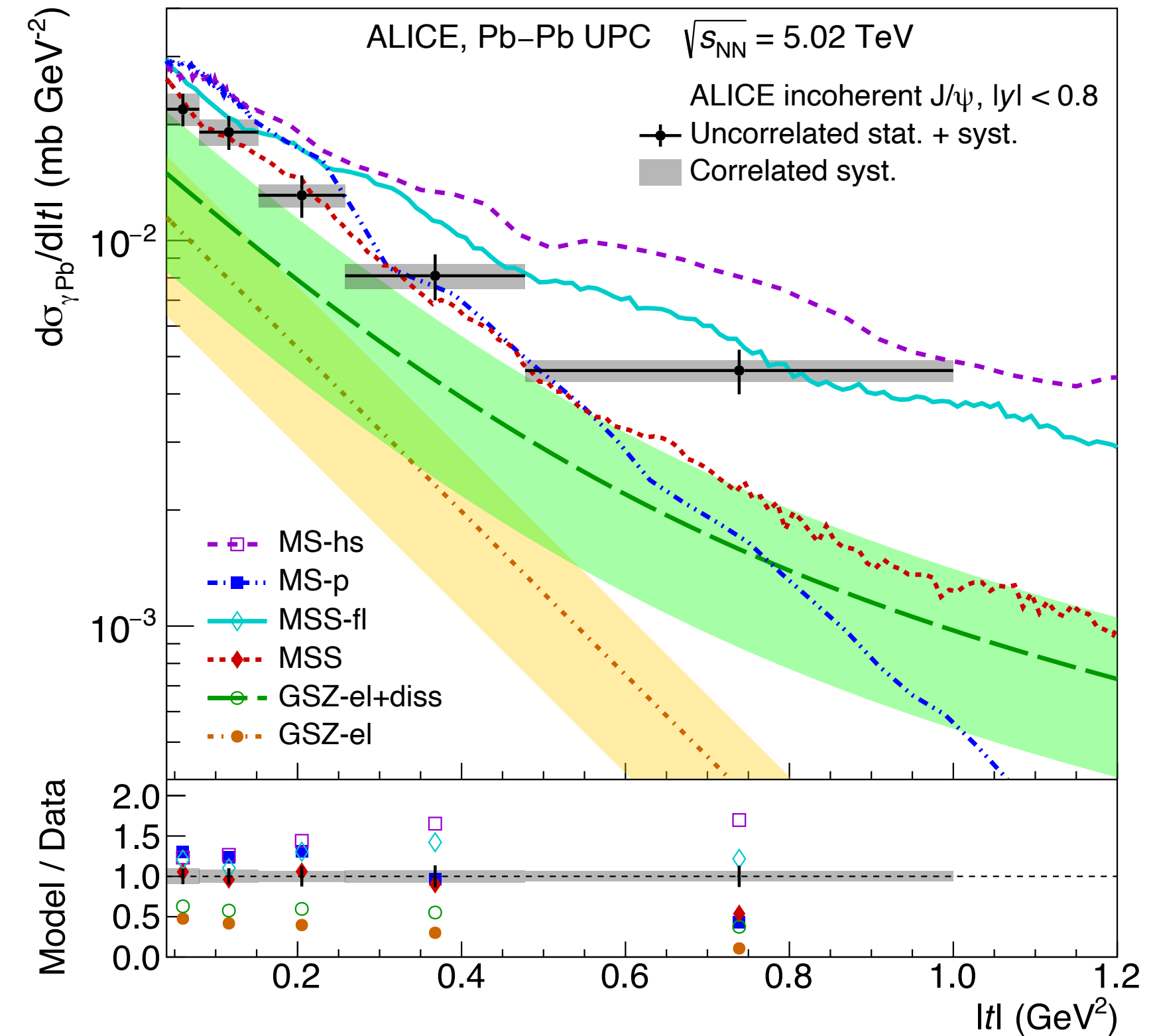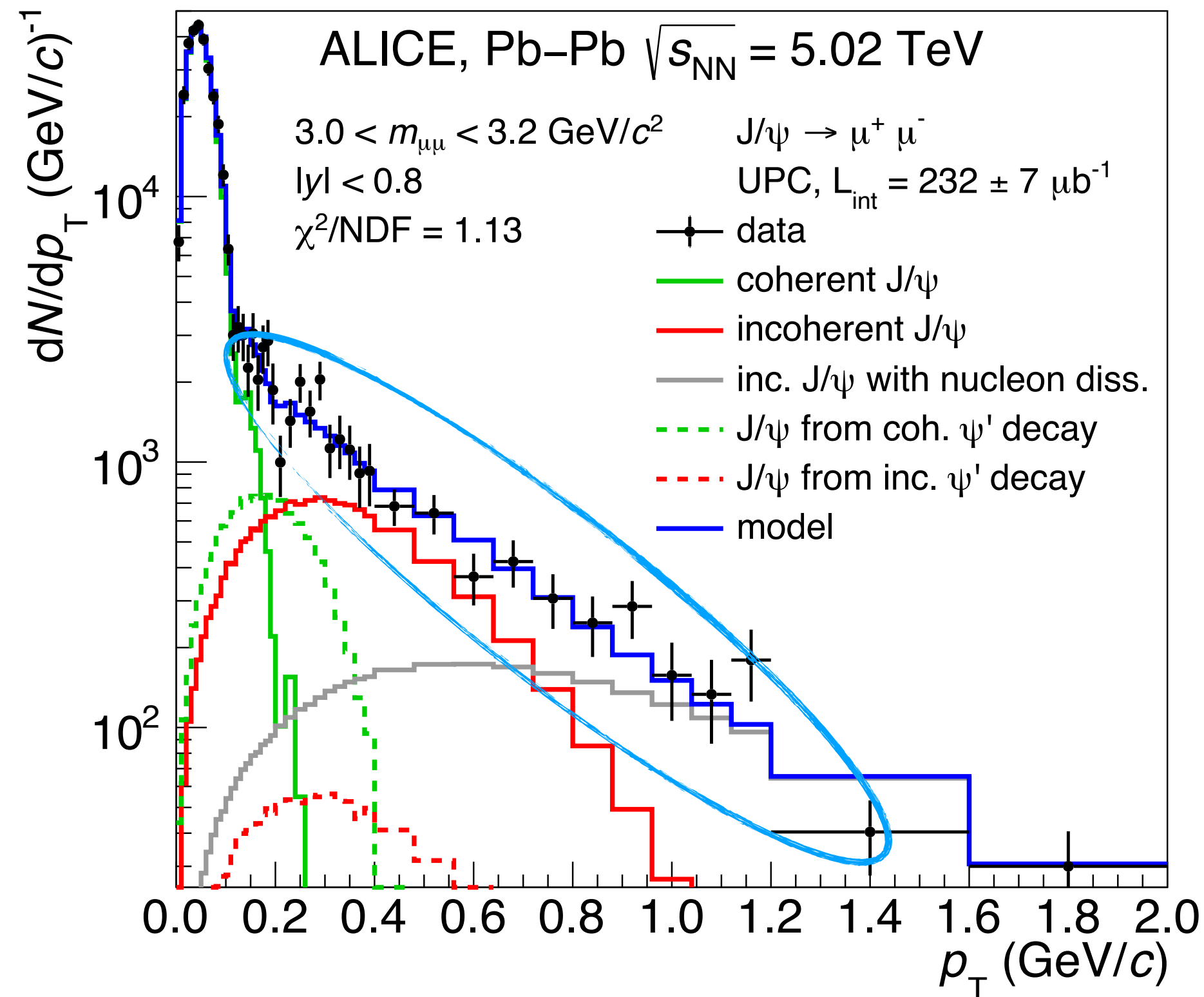
- ◉ The first measurement of |t| spectrum of incoherent J/ψ

  - No model describes both the absolute yield and the shape of |t| spectrum
  - A reasonably good description of the |t| spectrum is achieved when models incorporate sub-nucleon fluctuation

Incoherent J/ψ production at RHIC
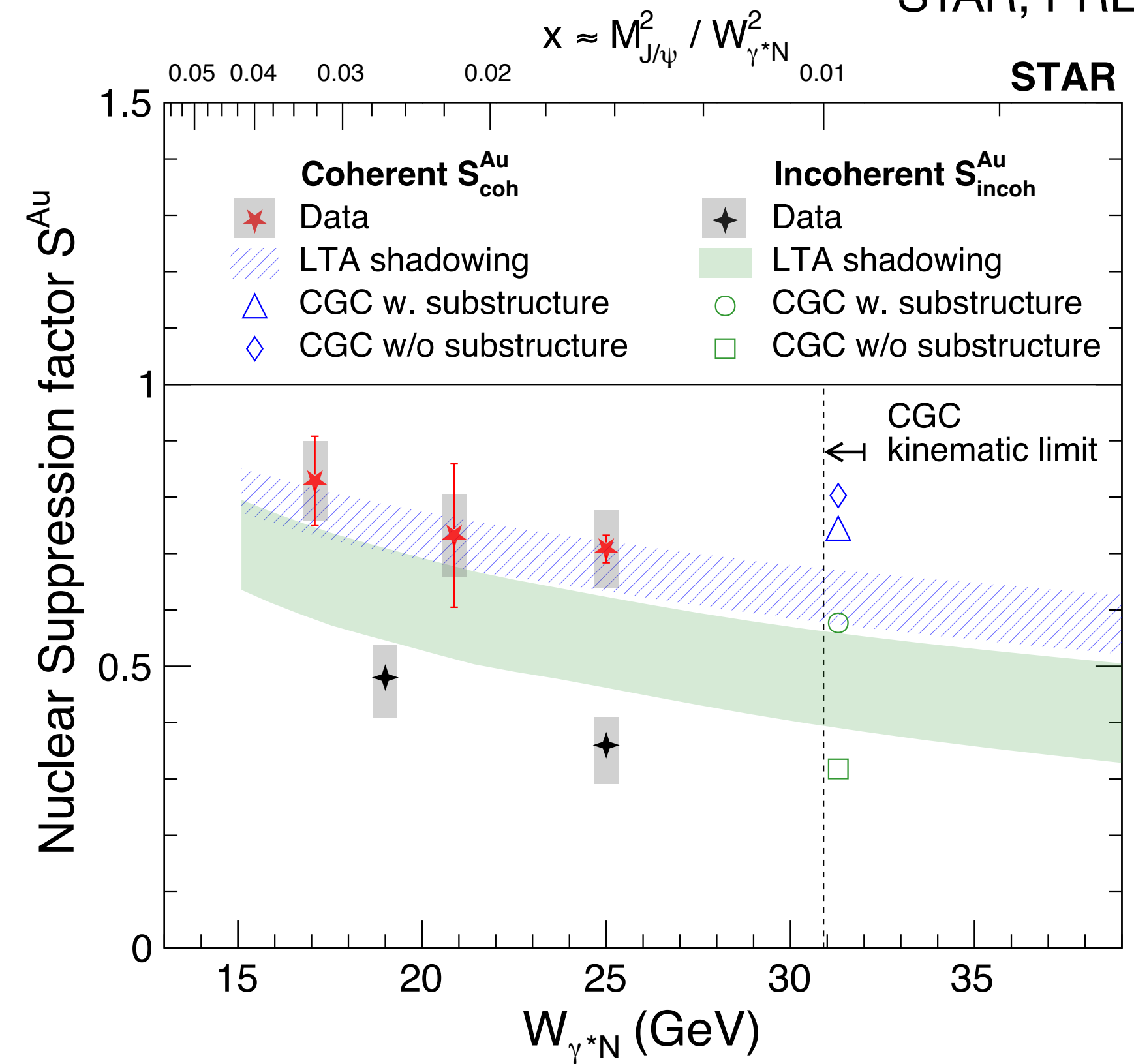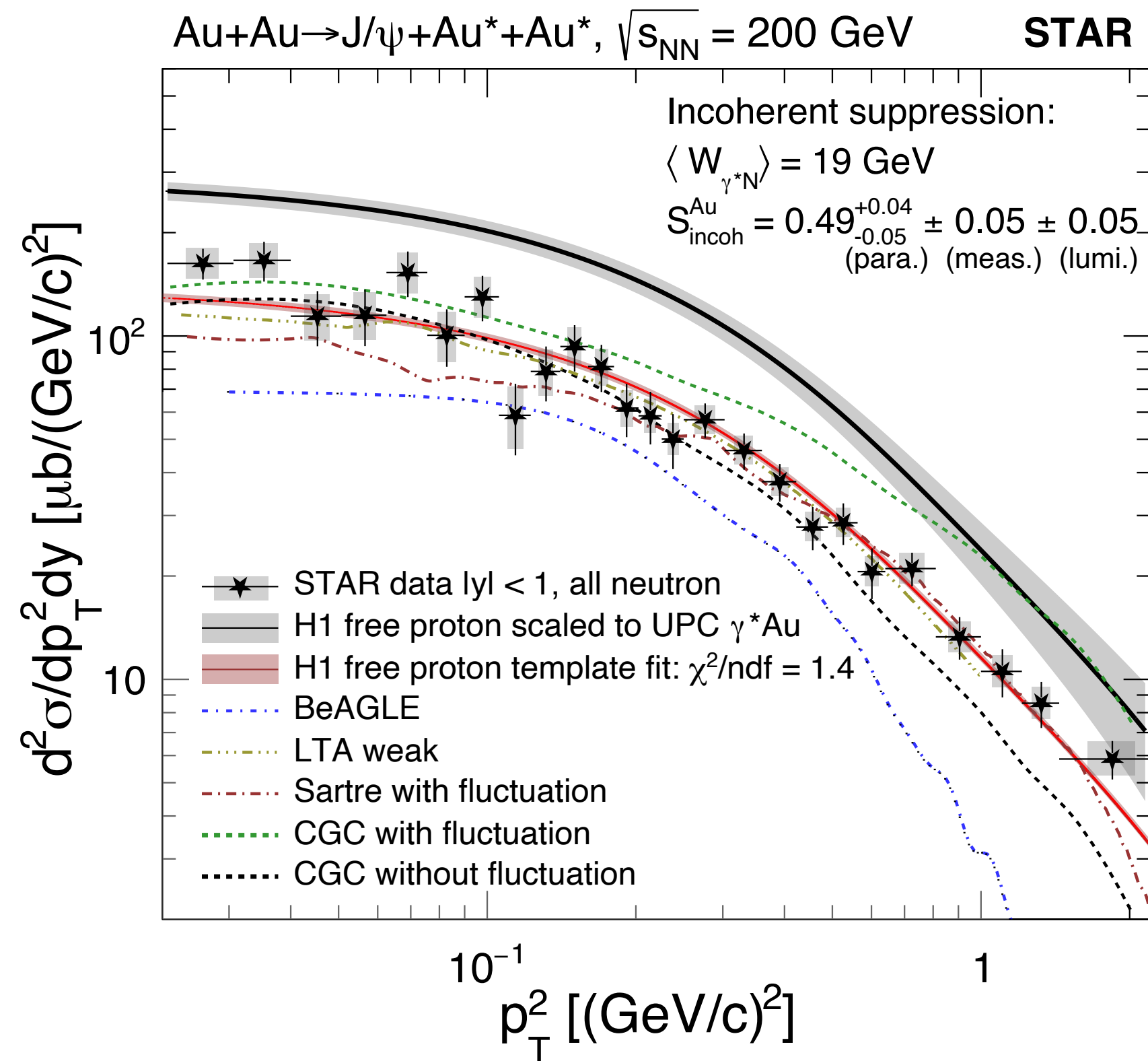
- ◉ The |t| shapes of incoherent J/ψ are similar between bound and free nucleons
- ◉ The incoherent suppression factor is less than that of the coherent production
  - Cannot conclude if sub-nucleon fluctuation is present in the incoherent photoproduction

Spin-interference for photoproduced ρ^0

STAR, Sci. Adv. 9 (2023) eabq3903

$$\Delta\phi = \phi(\vec{e}^+ + \vec{e}^-) - \phi(\vec{e}^+ - \vec{e}^-)$$

Xing et al., JHEP 10 (2020) 064
Zha et al., PRD 103 (2021) 033007

A **STAR:** Signal $\pi^+\pi^-$ pairs with $P_T < 60$ MeV

$f(\phi) = 1 + A\cos(2\phi)$ Syst. Uncert.

Au+Au : A = (29.1 ±0.4 ±0.4)×10^{-2}
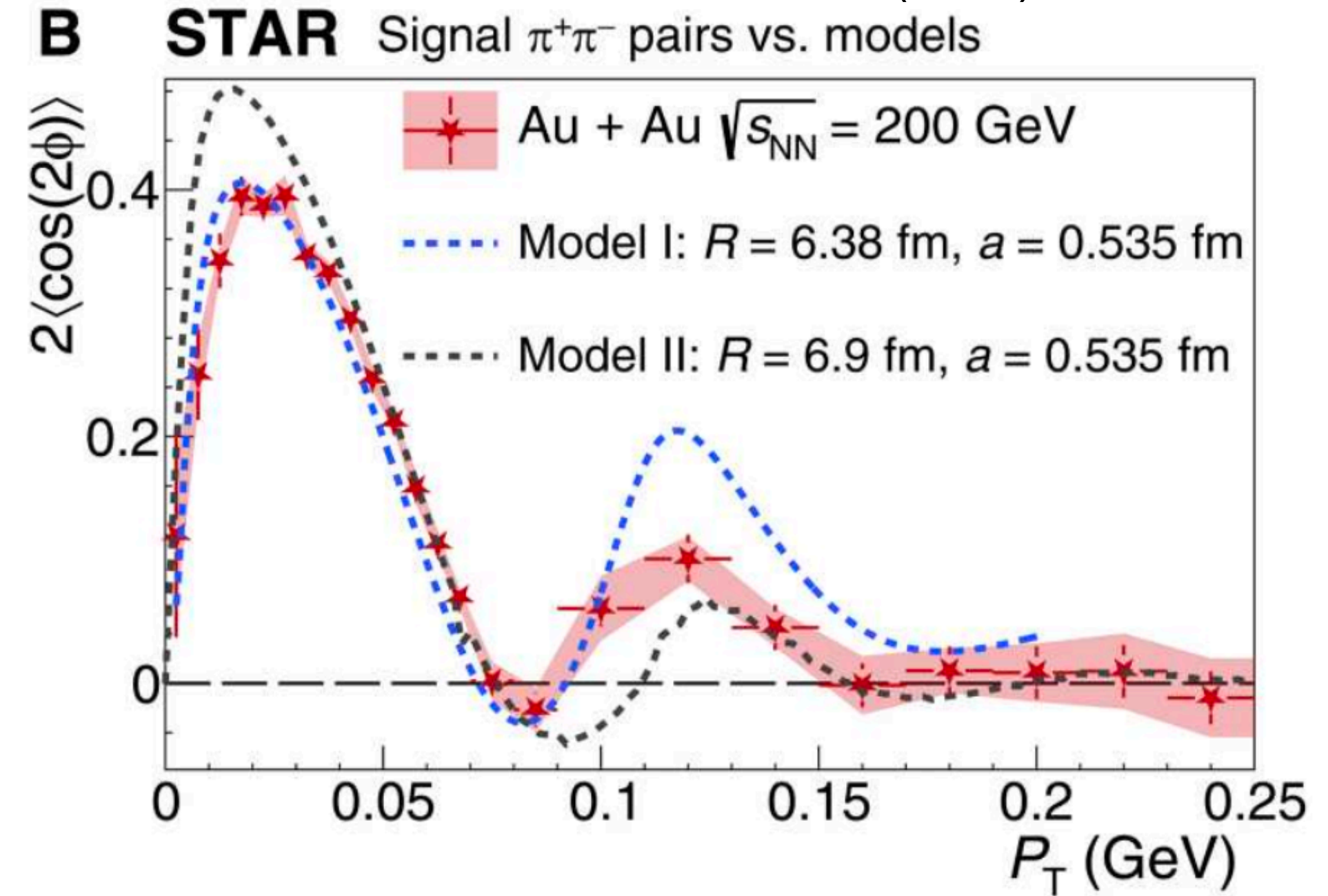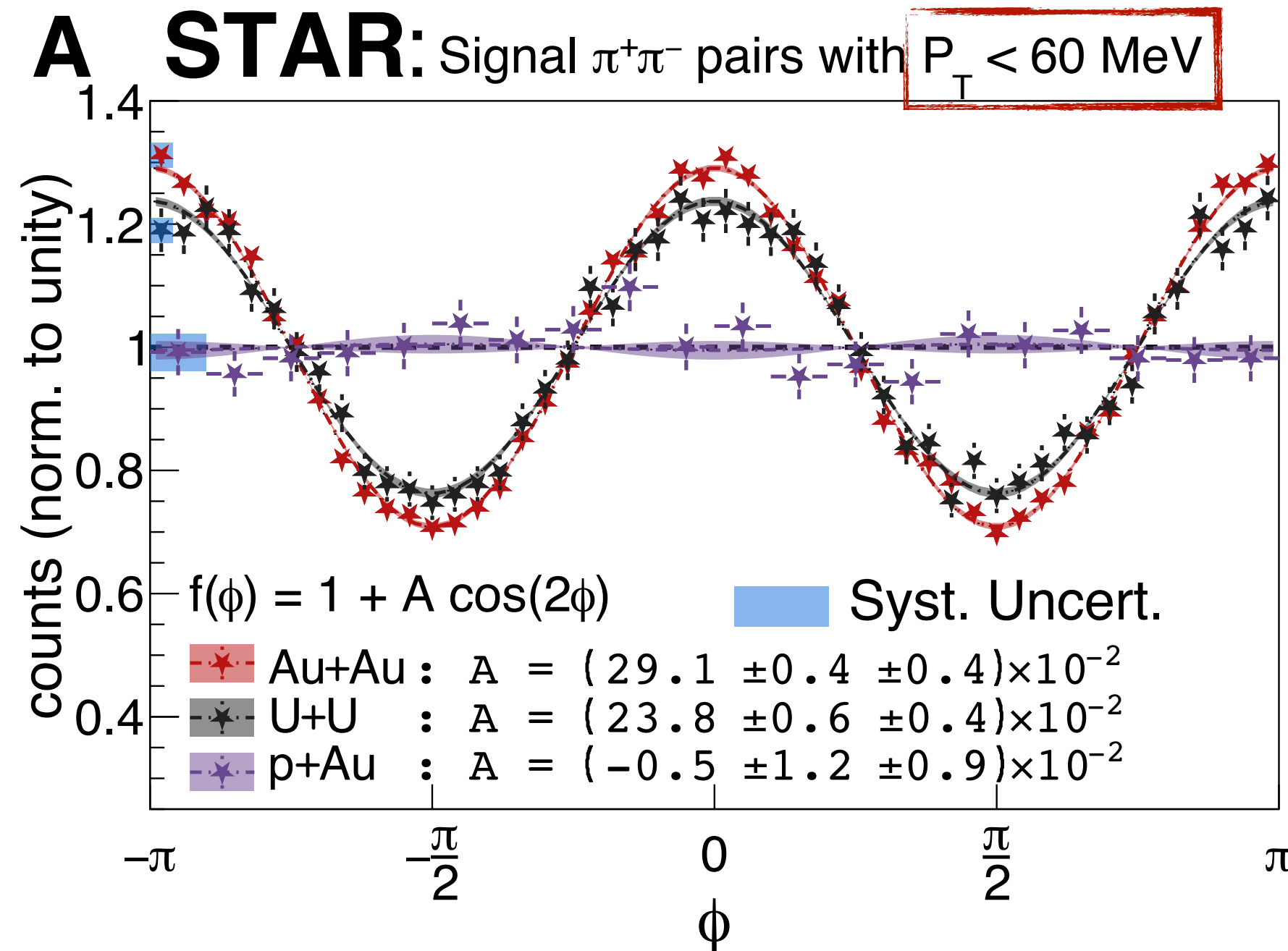U+U   : A = (23.8 ±0.6 ±0.4)×10^{-2}
p+Au : A = (−0.5 ±1.2 ±0.9)×10^{-2}

B **STAR** Signal $\pi^+\pi^-$ pairs vs. models

Au + Au $\sqrt{s_{NN}} = 200$ GeV
Model I: $R = 6.38$ fm, $a = 0.535$ fm
Model II: $R = 6.9$ fm, $a = 0.535$ fm
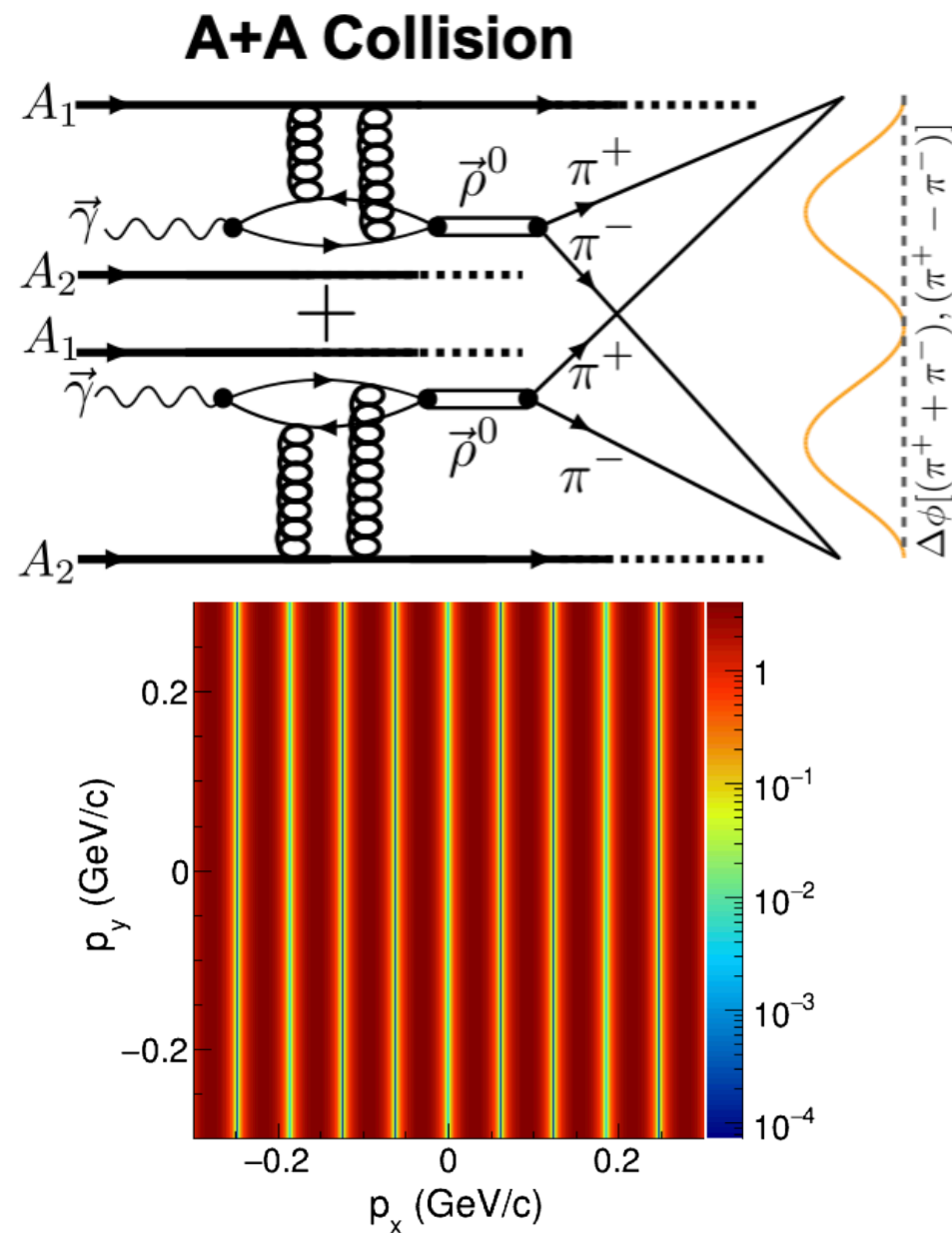
- ◉ Strong cos2$\Delta\phi$ modulations due to photon polarization
  - • "Double-slit" interference is critical to this observable
- ◉ Sensitive to nuclear geometry → strong interaction radius
  - • New techniques for multidimensional imaging of nuclei

Spin-interference for photoproduced J/ψ

⦿ Negative modulation predicted for J/ψ

   • Decay daughters are fermions → different angular momentum projection along z-axis

⦿ Need to consider the effect of soft photon radiation
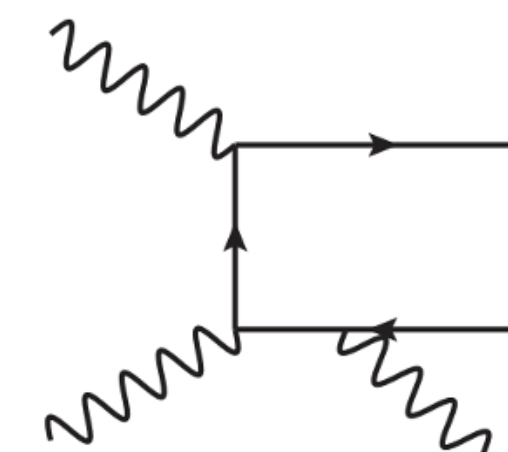
Spin-interference for photoproduced J/ψ
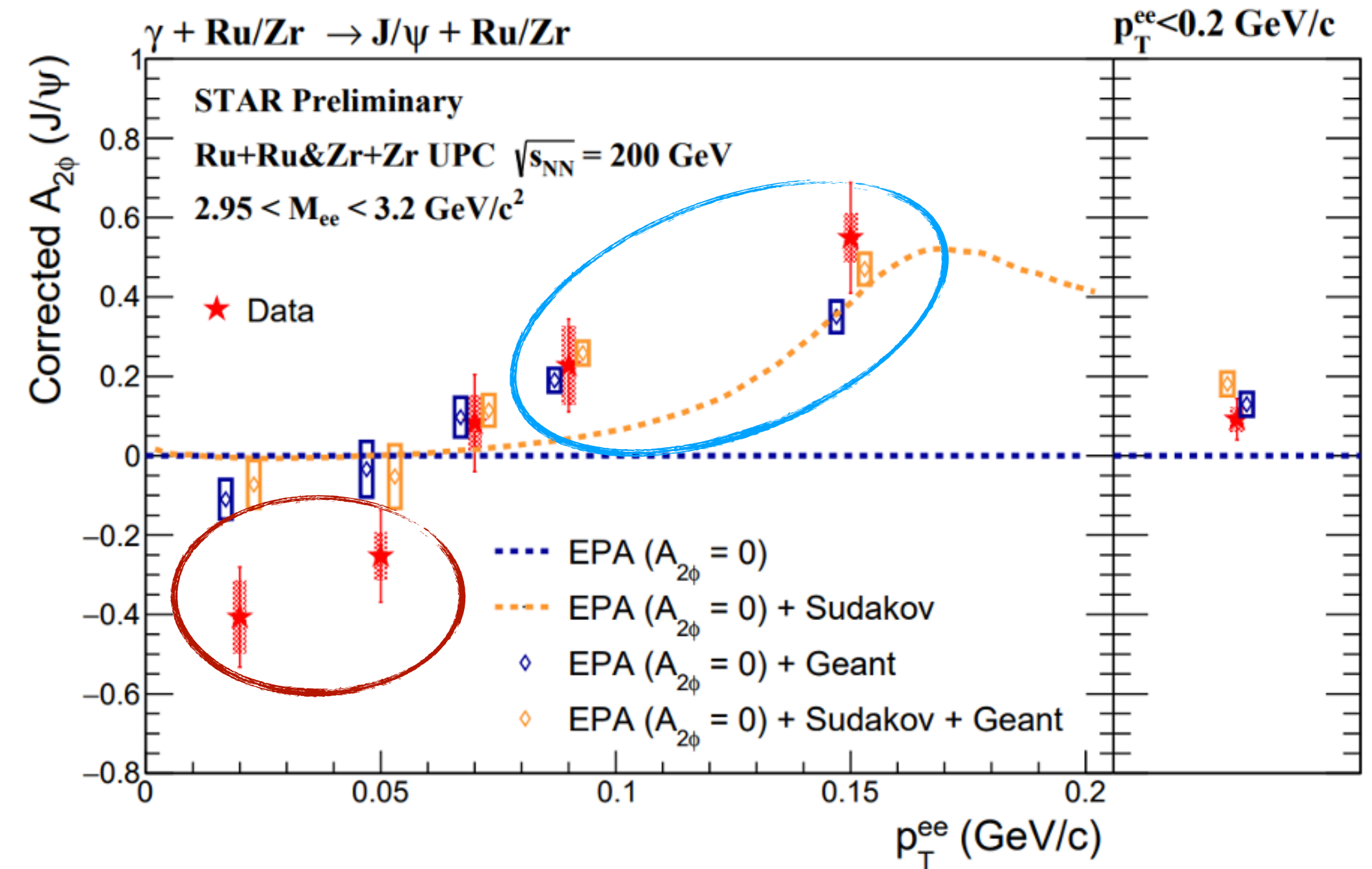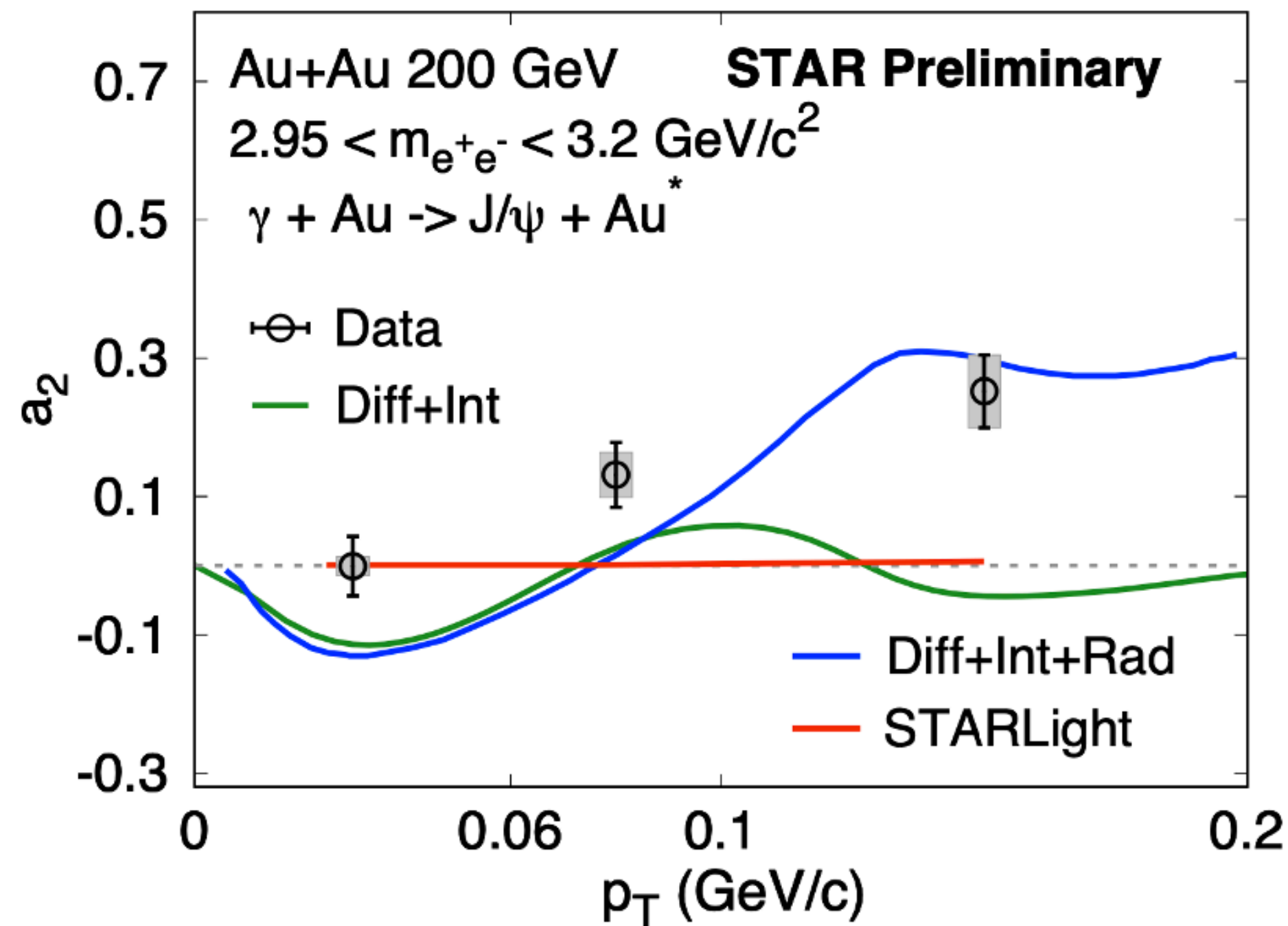
- **Experimental challenges** of photoproduced J/ψ

  - $\gamma\gamma \rightarrow e^+e^-$ background
  - Soft photon radiation
  - Bremsstrahlung & detector effects

- **Indication of negative spin interference of photoproduced J/ψ at low p_T**

Summary

◉ **Significant experimental progress of two-photon interactions**

- Demonstrated the *b*-dependence of photon p_T → baseline to probe QGP EM effects
- Experimental signal of linearly polarized photon → new techniques to image nuclear
- Observed $\gamma\gamma \to \tau\tau$ in UPC and showed the sensitivity to BSM physics
- Observed $\gamma\gamma \to p\bar{p}$ production → higher excitation of QED vacuum

◉ **Multidimensional imaging of nuclei with photon-nuclear interactions**

- Direct experimental evidence of gluon saturation?
- Observed spin interference of photoproduced vector meson → strong interactions radius
- First measurement of the |t|-spectra of incoherent J/ψ → sub-nucleon fluctuation
- Observed Drell-Söding process?

Summary

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  - Observed Drell-Söding process?

感谢大家聆听！

Backups

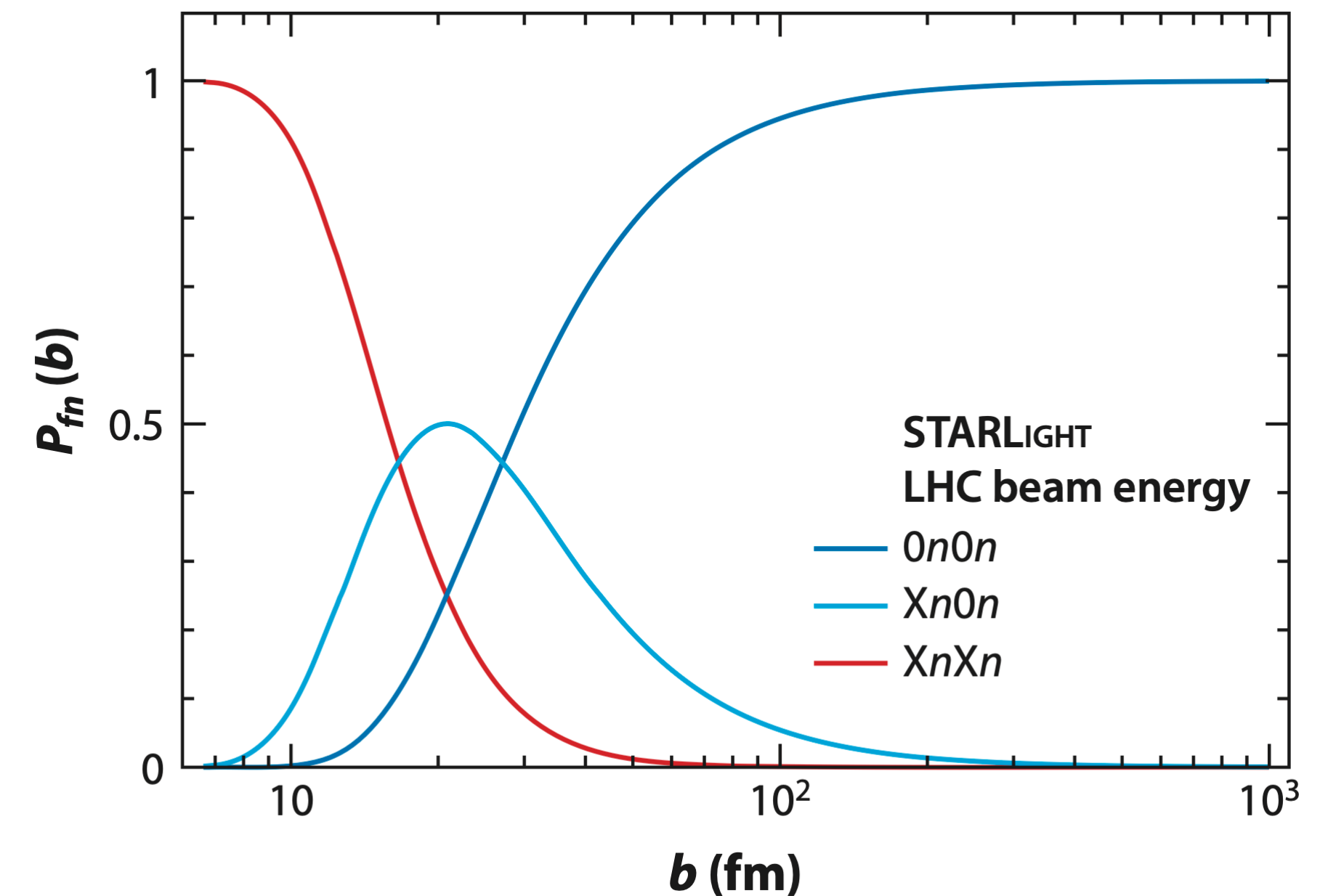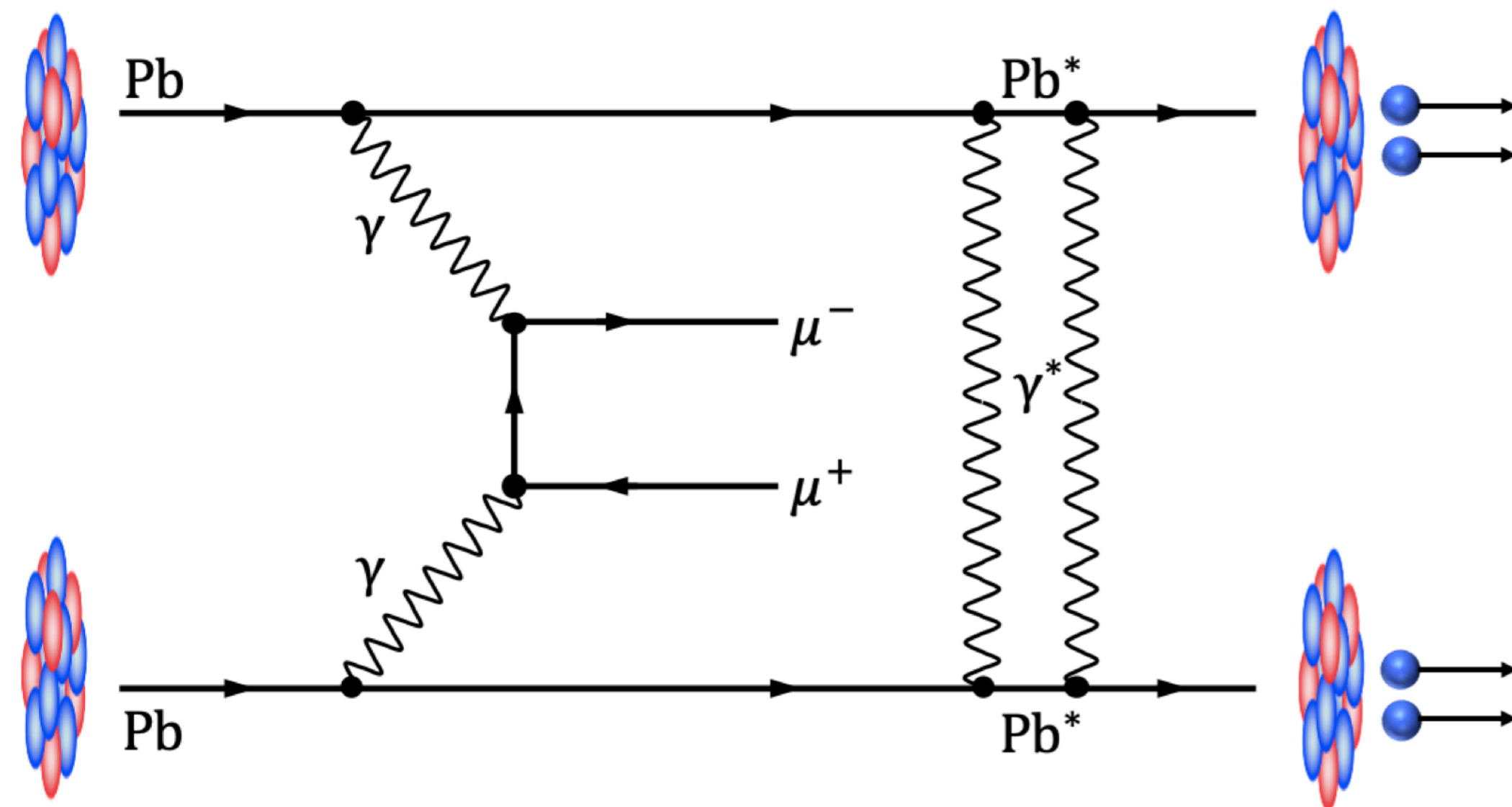# Energy dependence of $\gamma\gamma \rightarrow e^+e^-$ production

STAR, arXiv:2407.14821
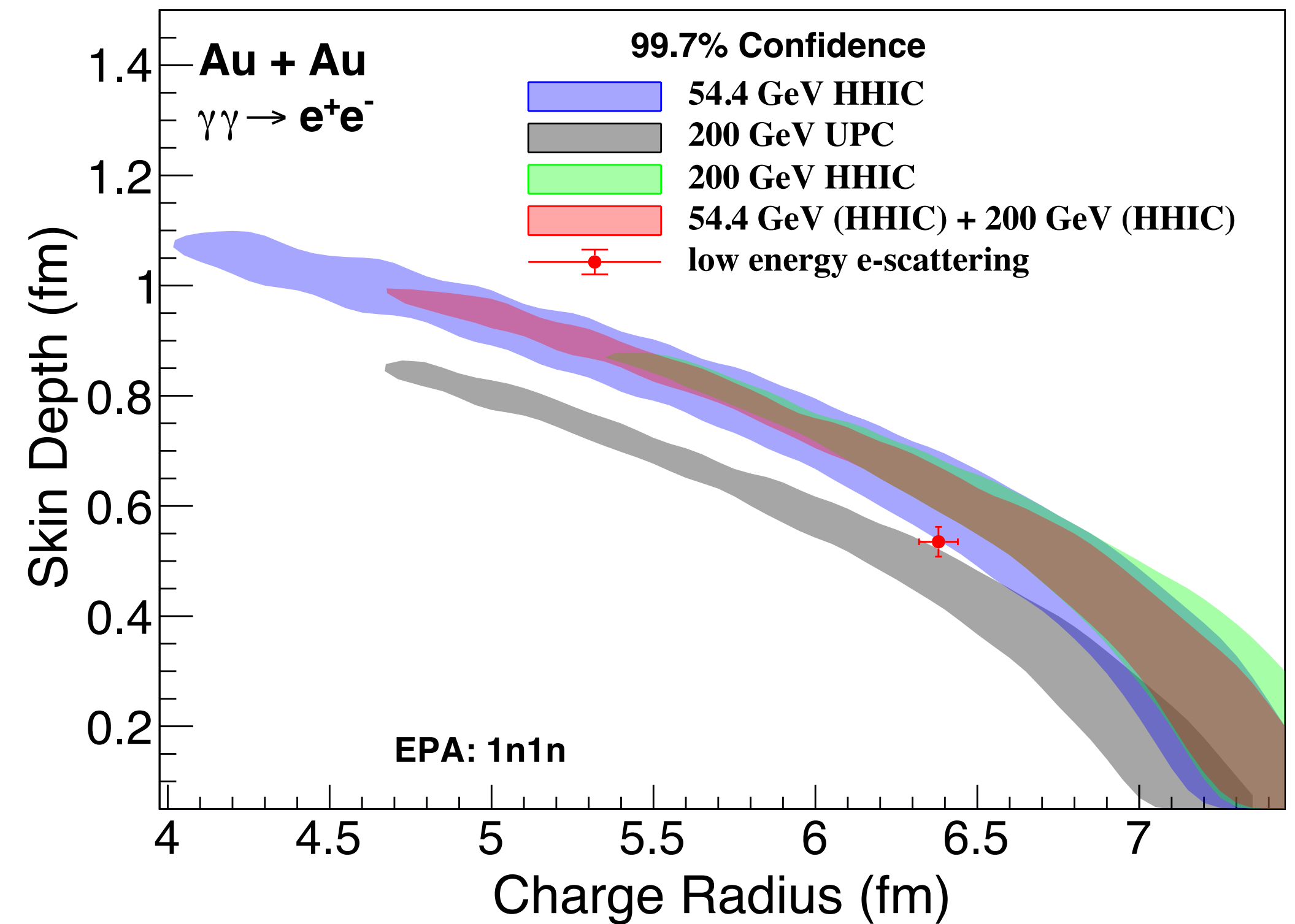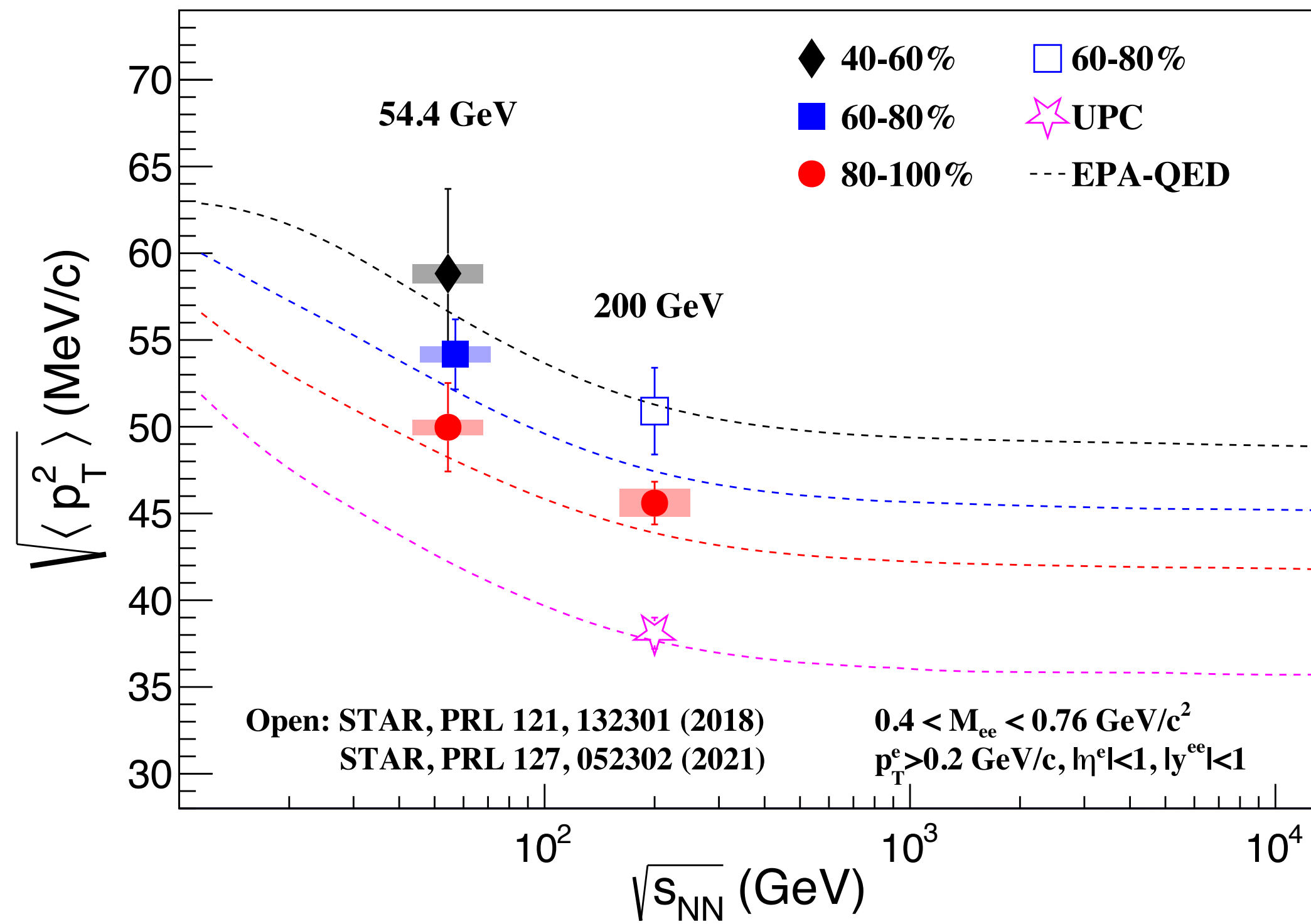
- ◉ Clear energy and centrality (*b*) dependence of $\gamma\gamma \rightarrow e^+e^-$ production
  - Consistent with EPA-QED baseline

- ◉ Constrain the nuclear charge distribution with $\gamma\gamma \rightarrow e^+e^-$ production

Control impact parameter in UPC

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

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

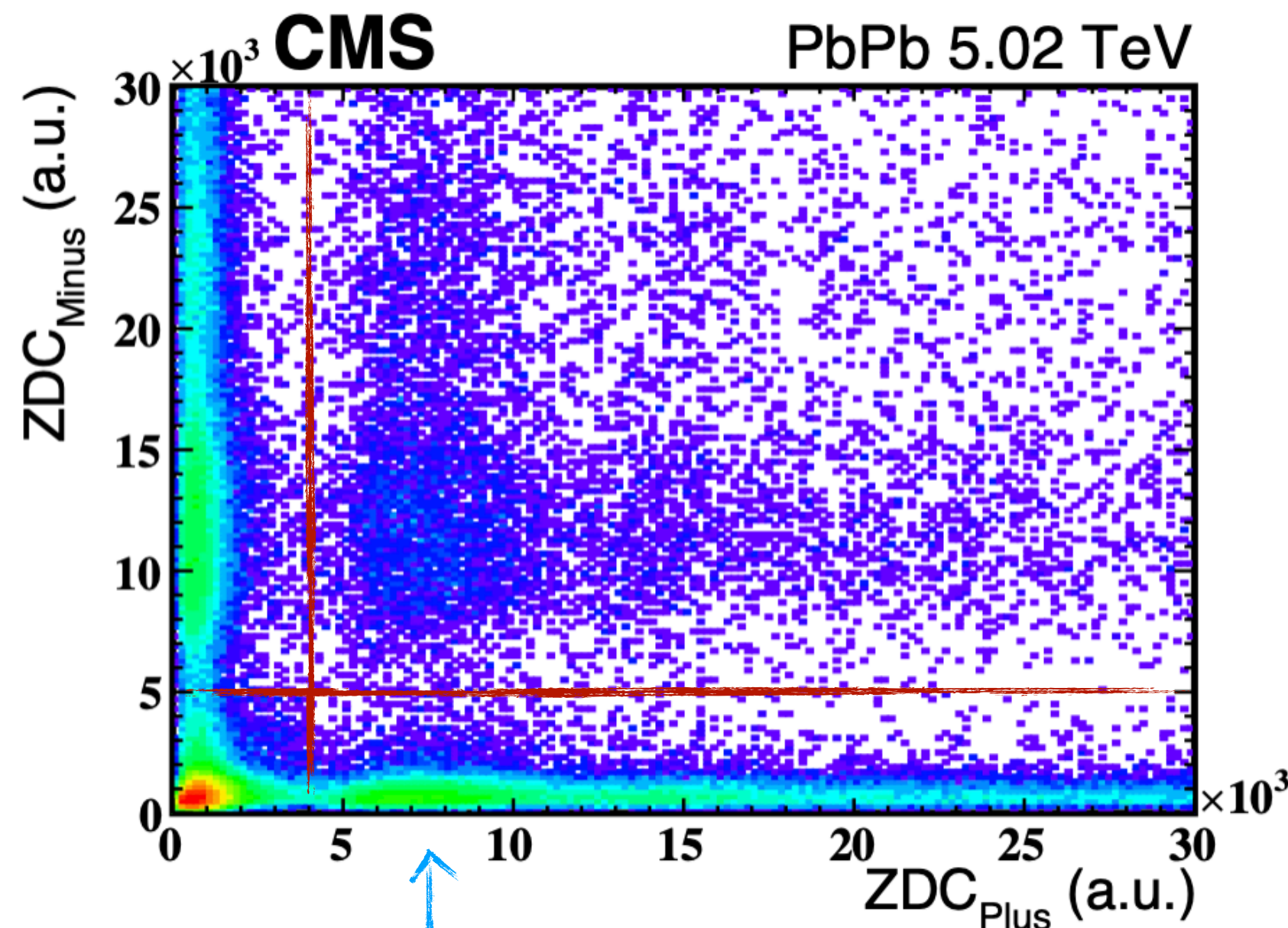◉ Control the impact parameter via forward neutron multiplicity
- $b_{XnXn} < b_{0nXn} < b_{0n0n}$

A solution to the "two-way ambiguity"

Single neutron peak

Experimental measurements

Photon flux from theory

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

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

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

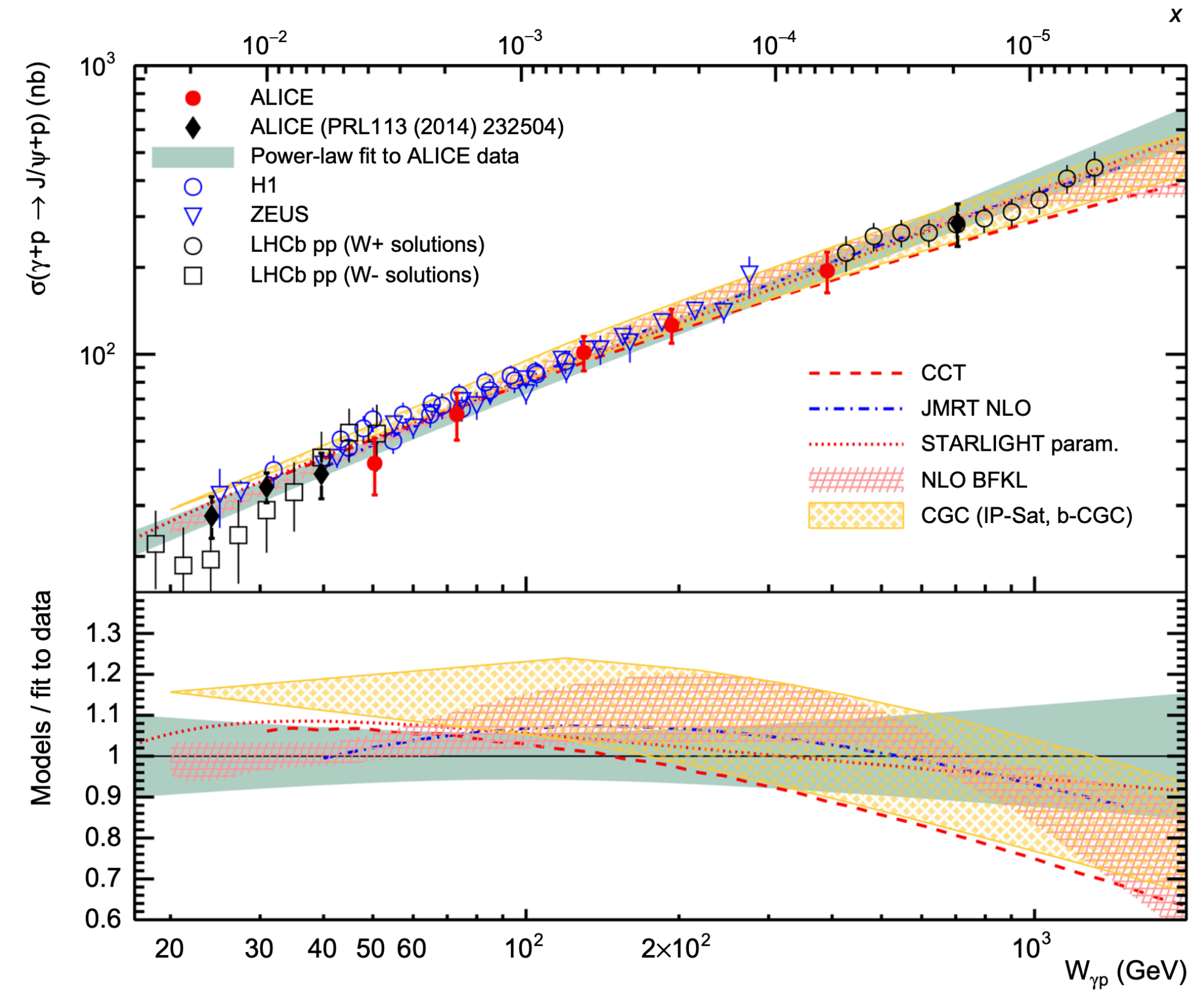What we need!
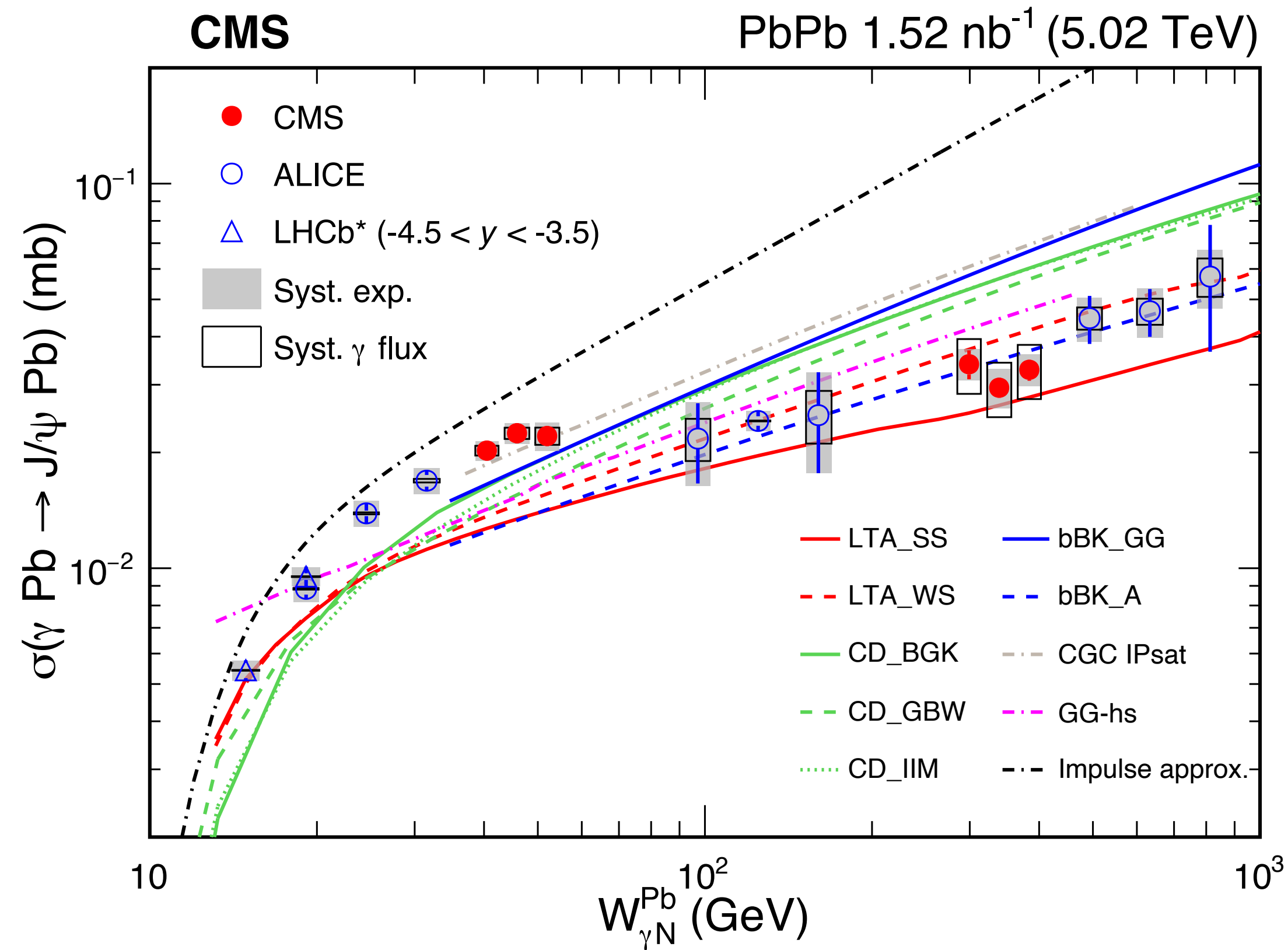
Solve the "two-way ambiguity"

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

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

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