



# Spin-dependent azimuthal asymmetry of coherent vector meson photoproduction in relativistic heavy-ion collisions

杨 帅

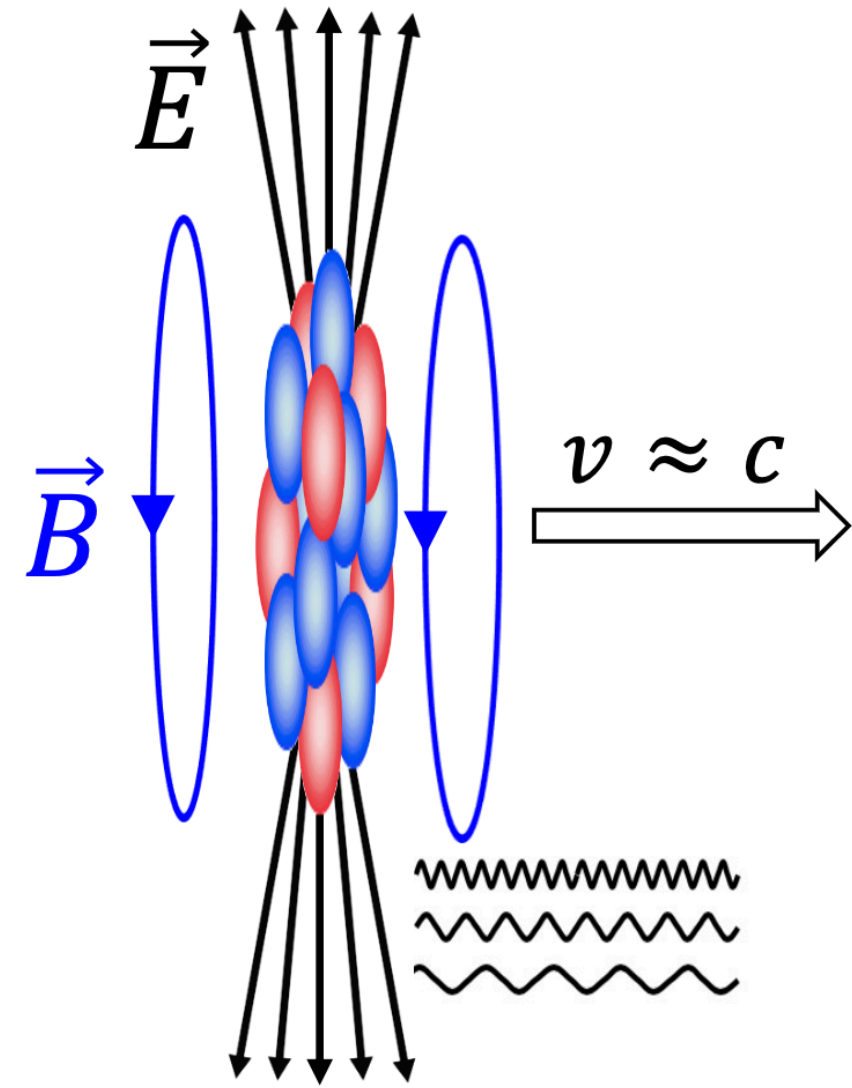
华南师范大学



极端核物质前沿研讨会

Workshop on extreme nuclear matter frontiers

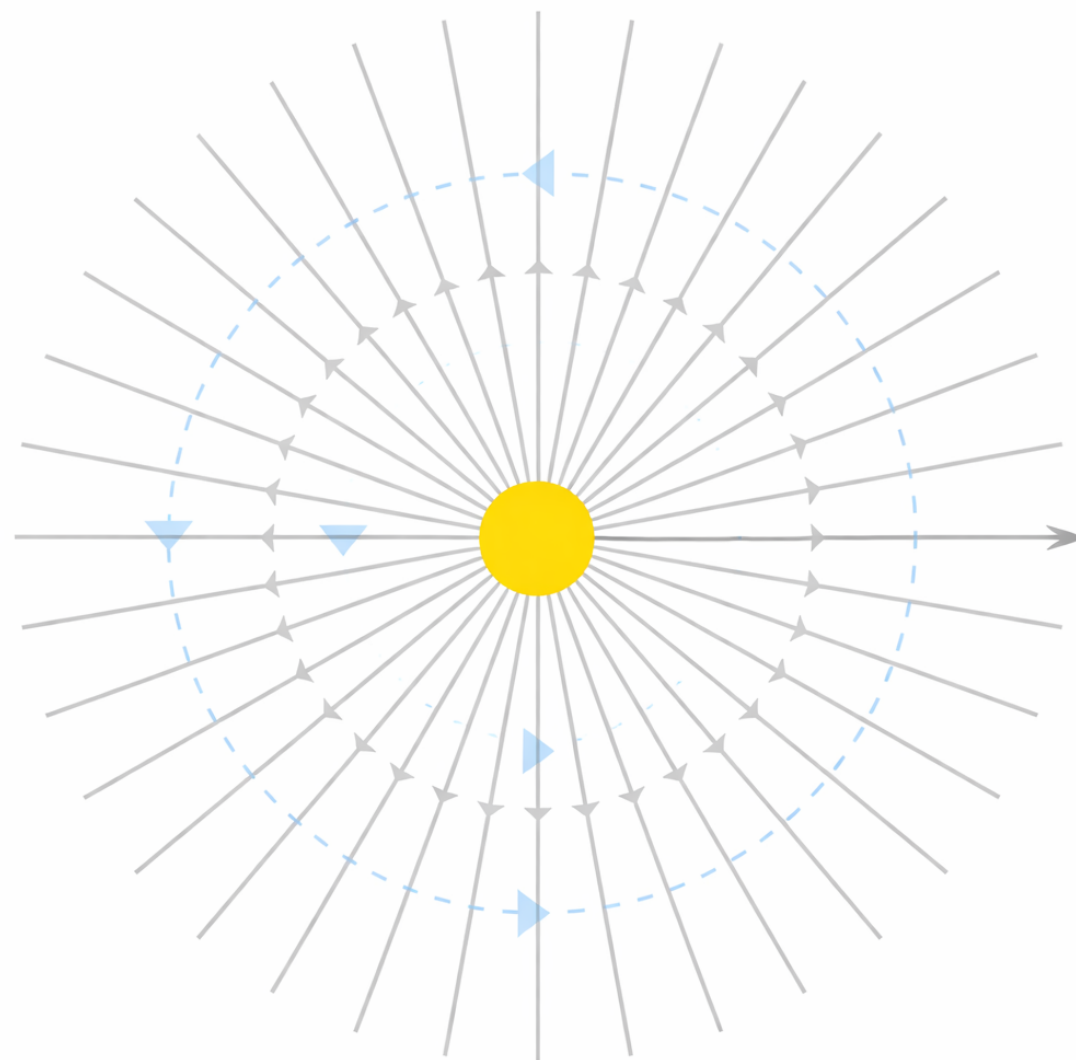
# Linearly polarized photon



## ● 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*

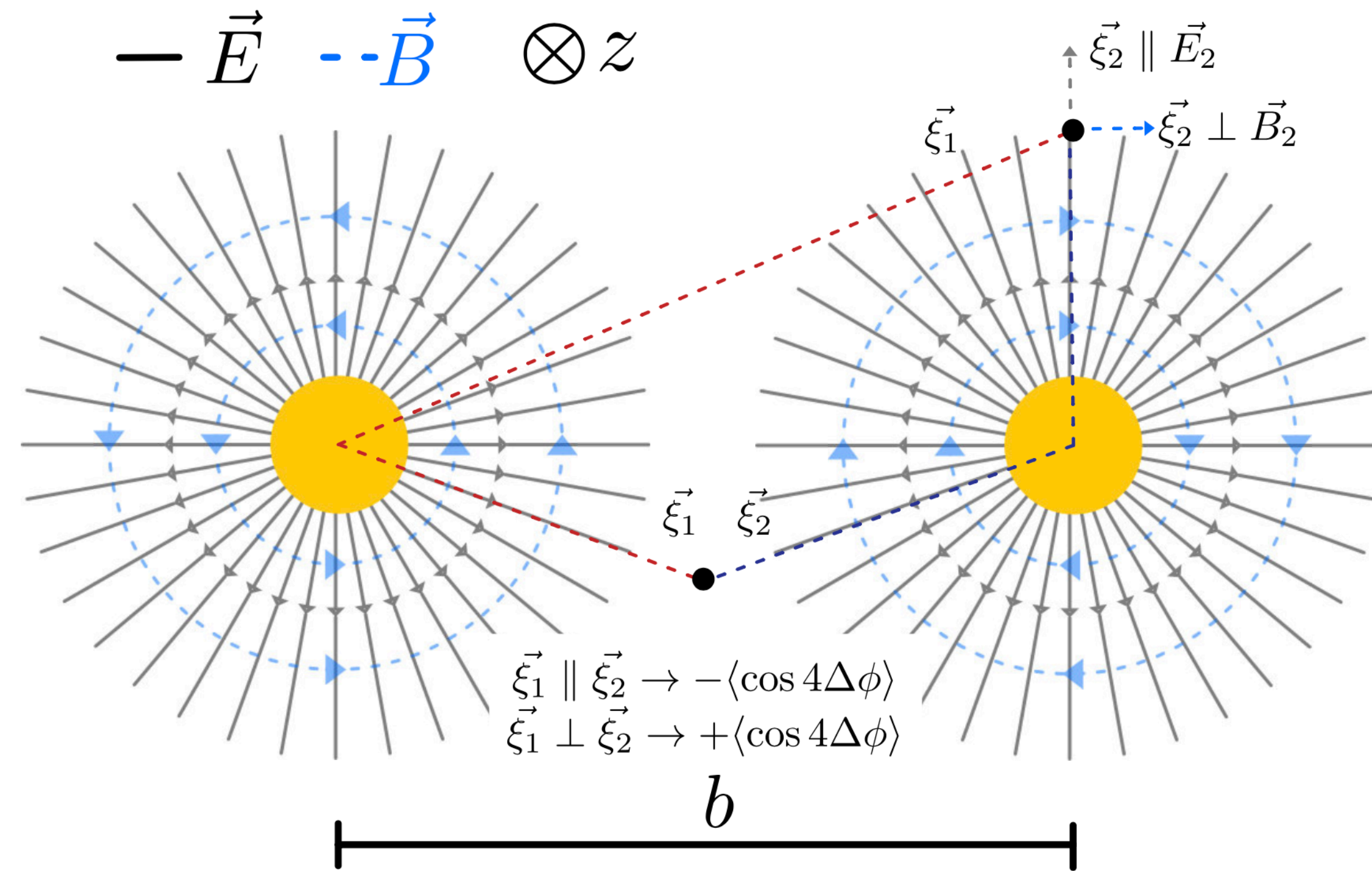


## ● The photon is linearly polarized

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

*Zhou et al., PLB 88 (2019) 576*

# Linearly polarized photon



◉ Linearly polarized photons lead a  $\cos(4\Delta\phi)$  modulation in

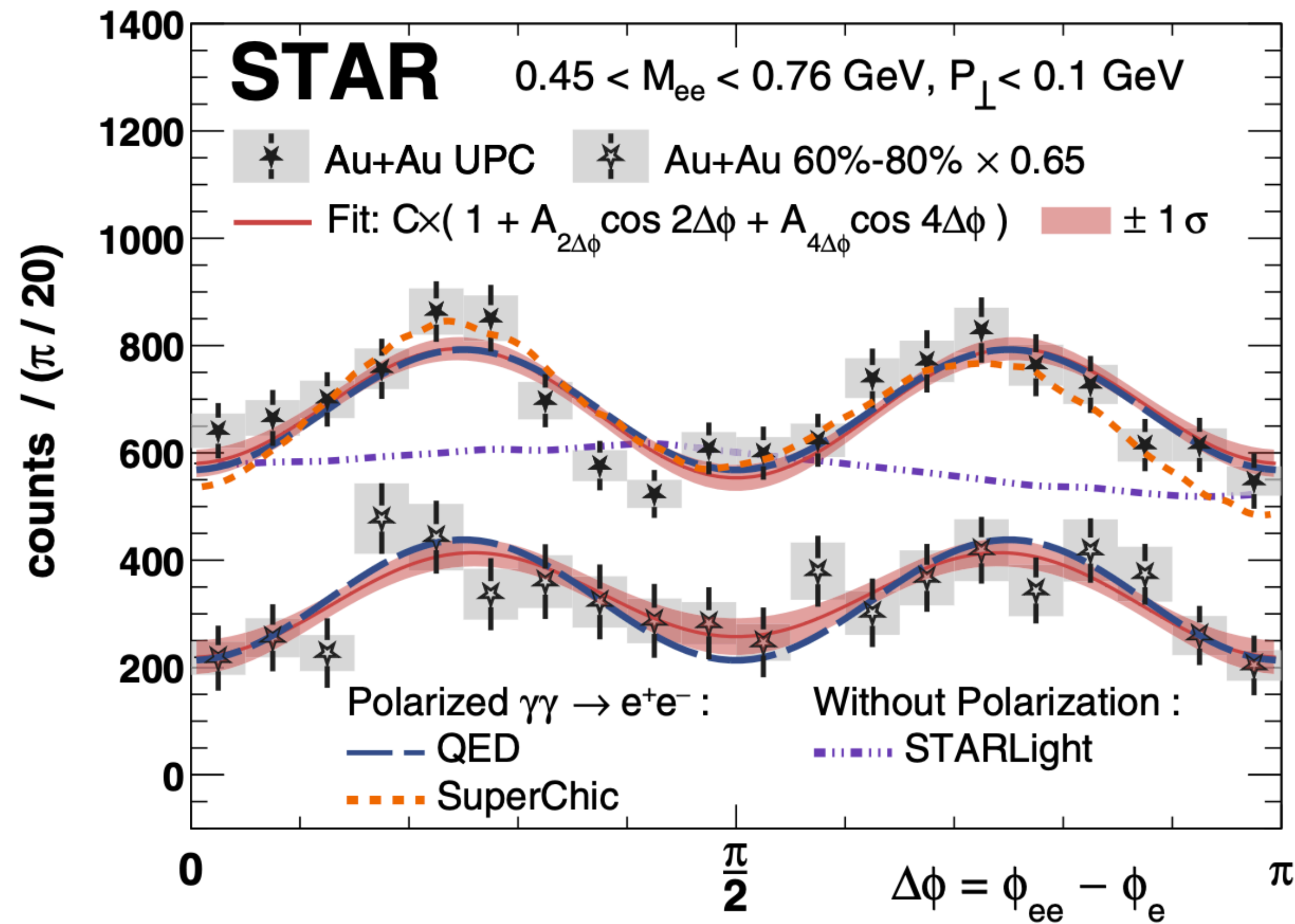
$$\gamma\gamma \rightarrow l^+l^-$$

$$\bullet \Delta\phi = \Delta\phi[(l^+ + l^-), (l^+ - l^-)] \approx \Delta\phi[(l^+ + l^-), l^+]$$

Zhou et al., PLB 88 (2019) 576

# Linearly polarized photon

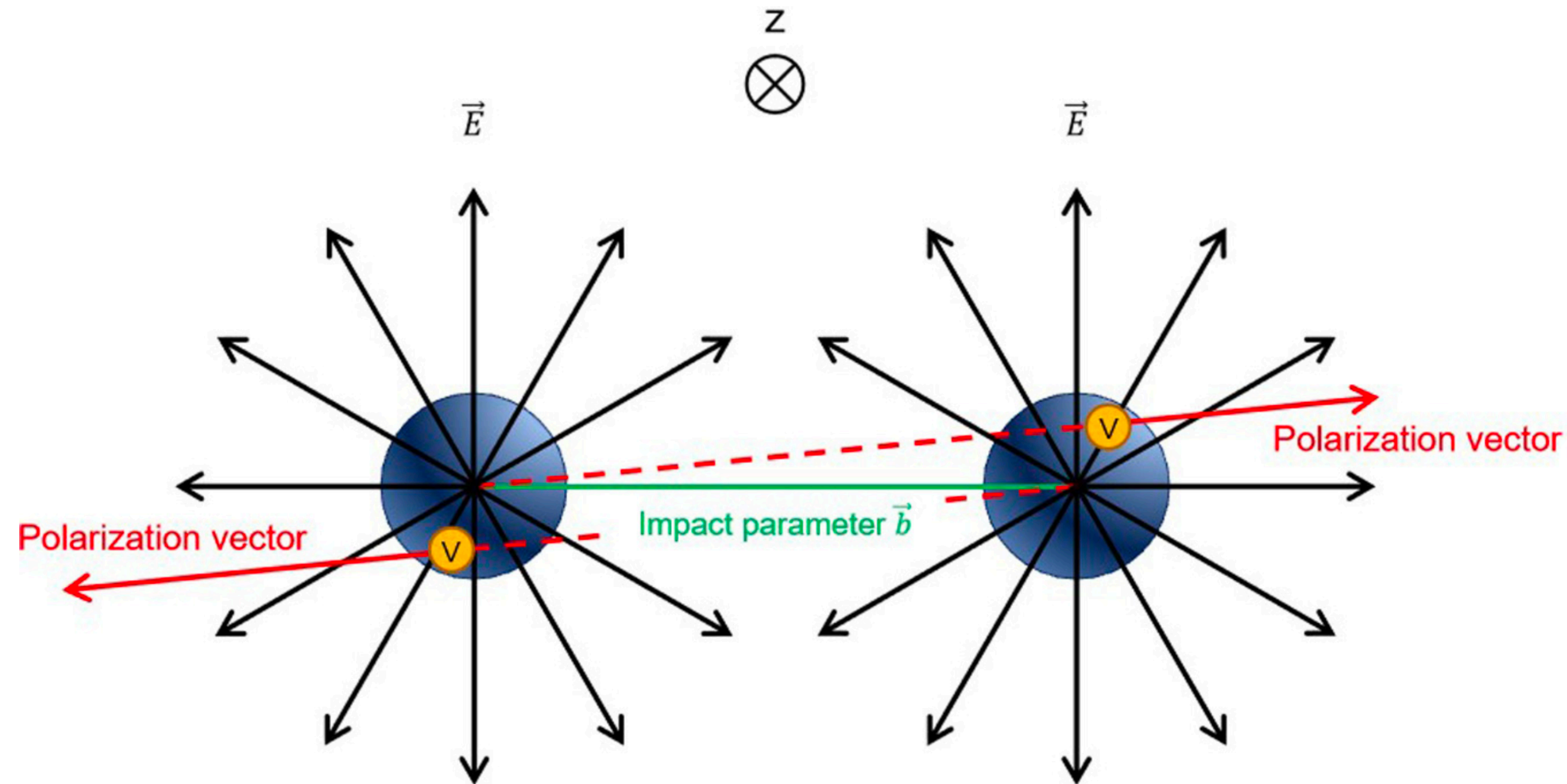
STAR, PRL 127 (2021) 122001



- Experimentally observed the linear polarization of equivalent photons
  - $\sim 6.7\sigma$  in UPC and  $\sim 4.5\sigma$  in non-UPC

# Modulation of photoproduced vector meson

Wu et al., PRR 4 (2022) L042048

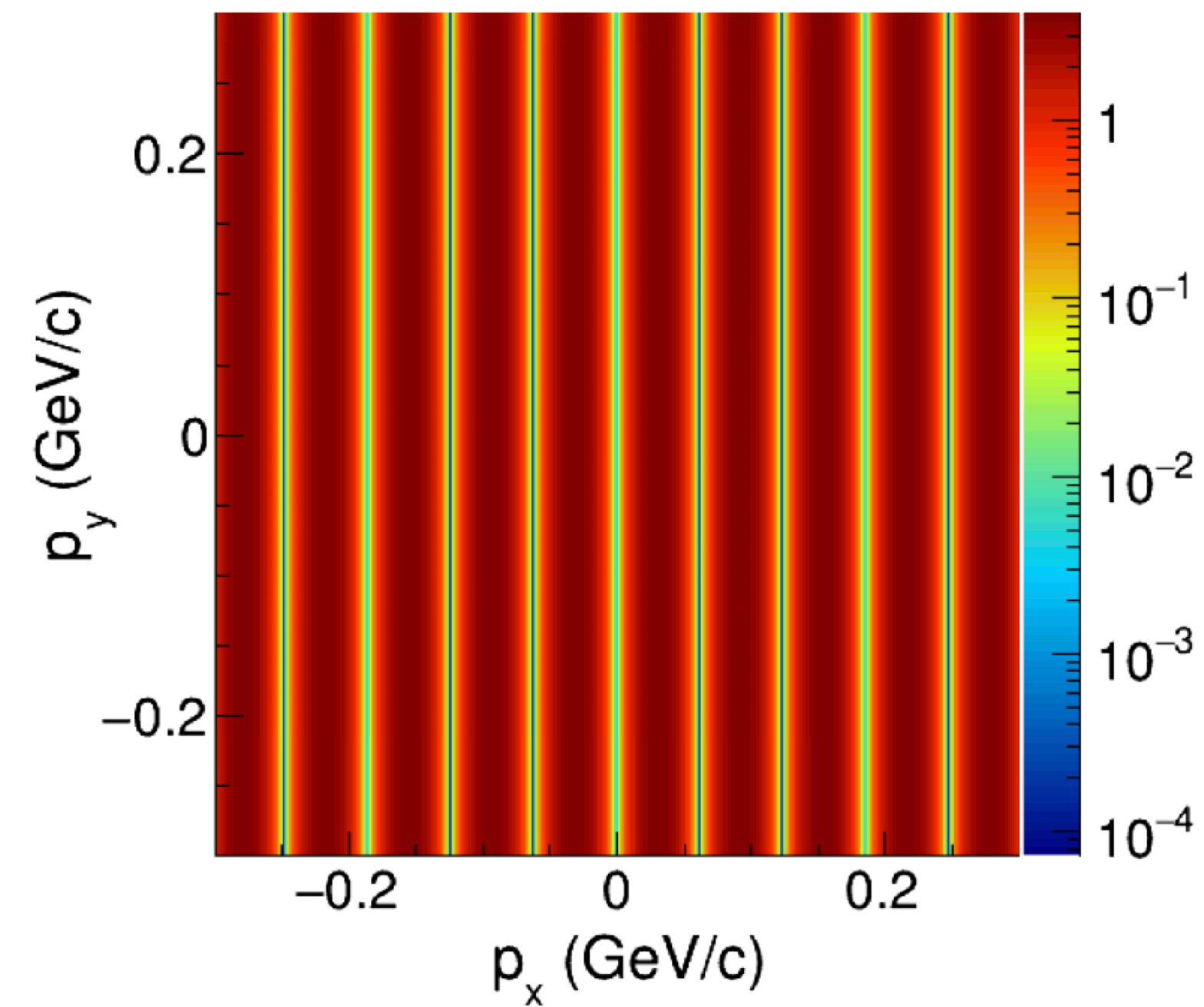
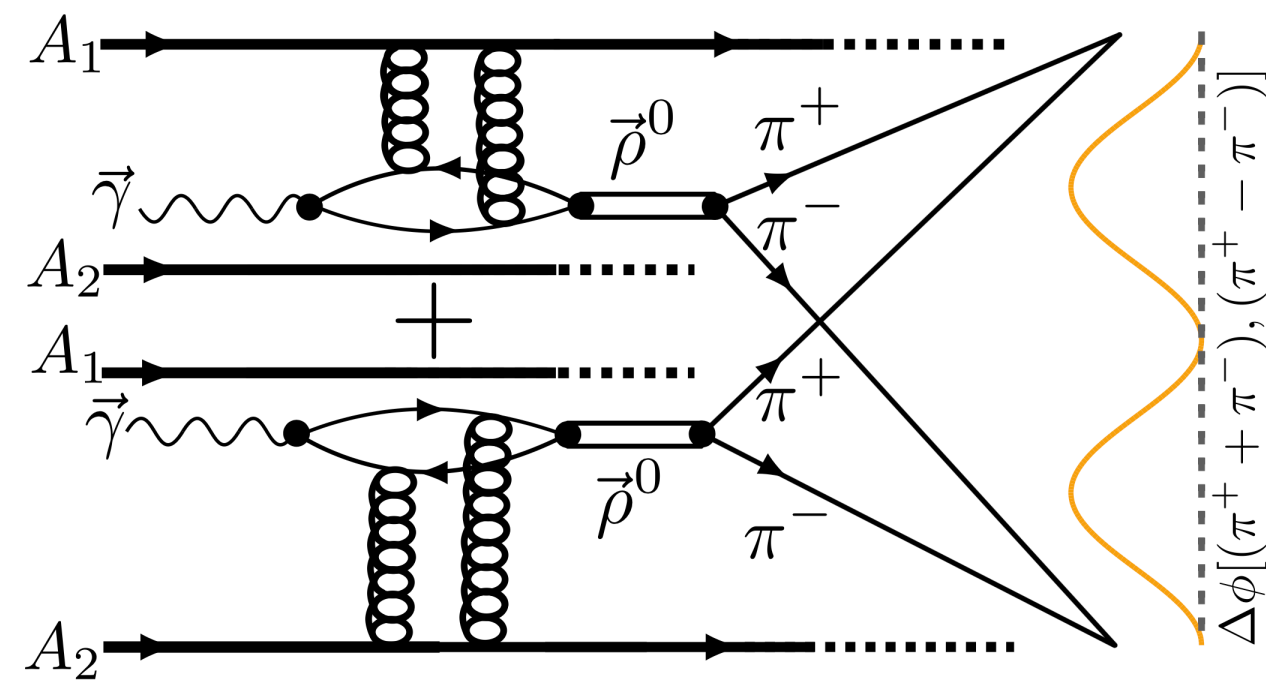


- VM inherits the polarization because of s-channel helicity conservation
- $\cos(2\Delta\phi)$  azimuthal modulation of decayed daughter **w.r.t. the polarization direction**

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

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

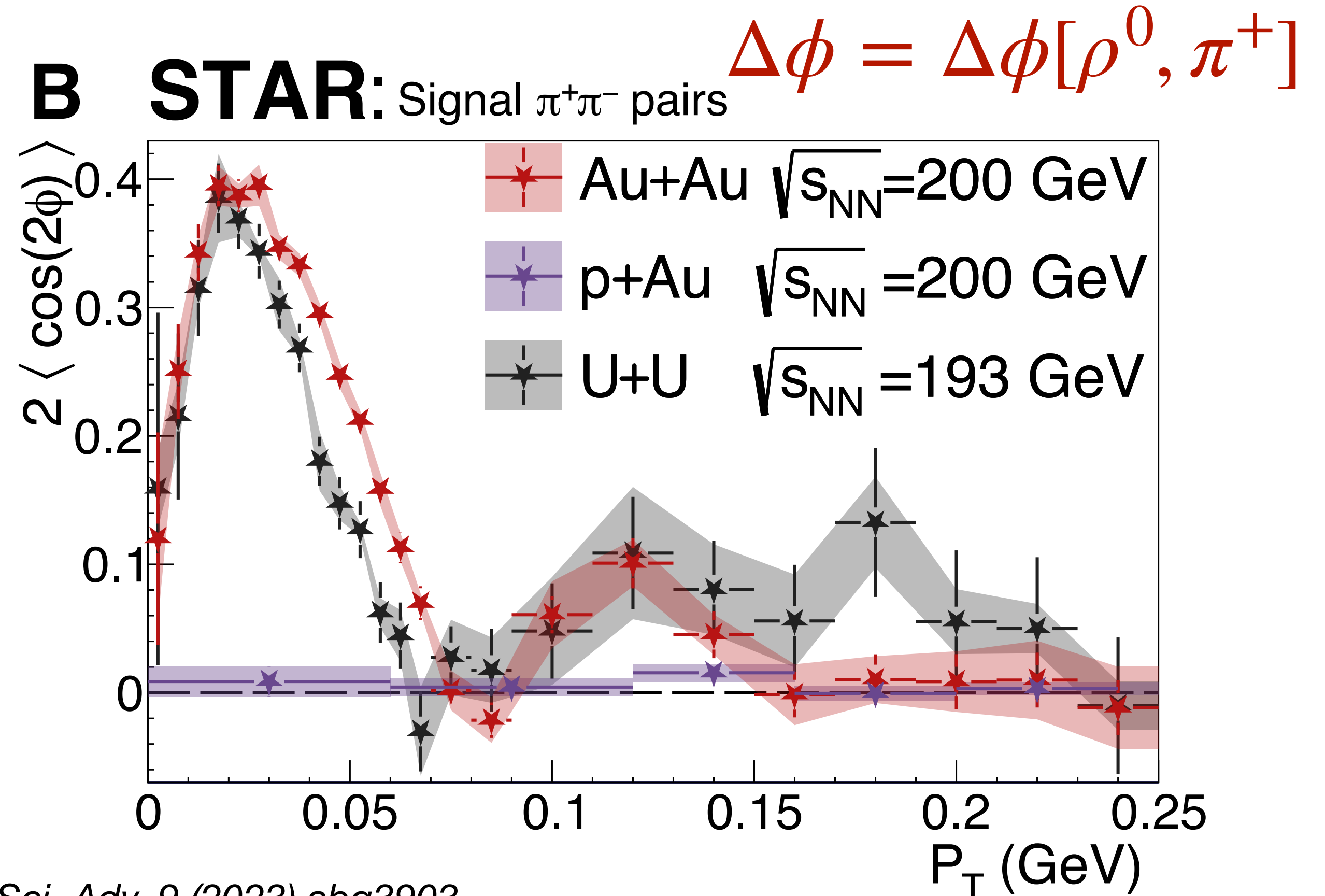
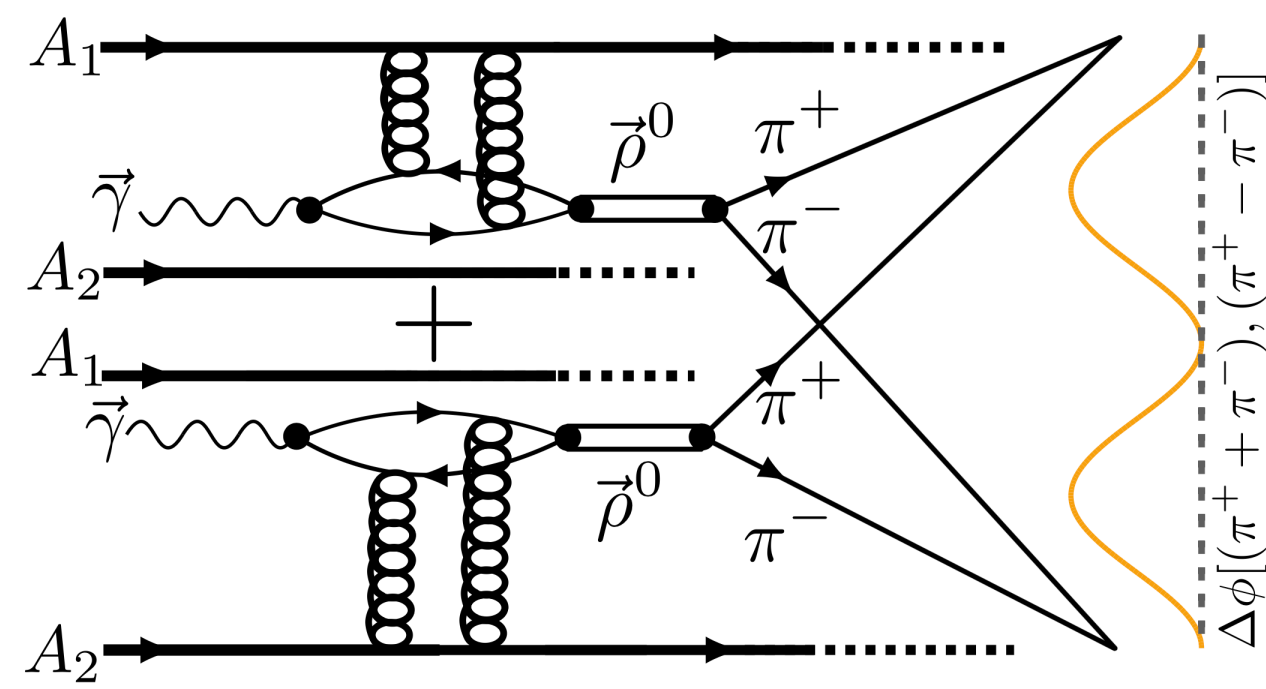
- ◎ **Symmetric A+A collisions:** **Strong correlation** between the  $p_T$  and polarization directions



STAR, Sci. Adv. 9 (2023) abq3903

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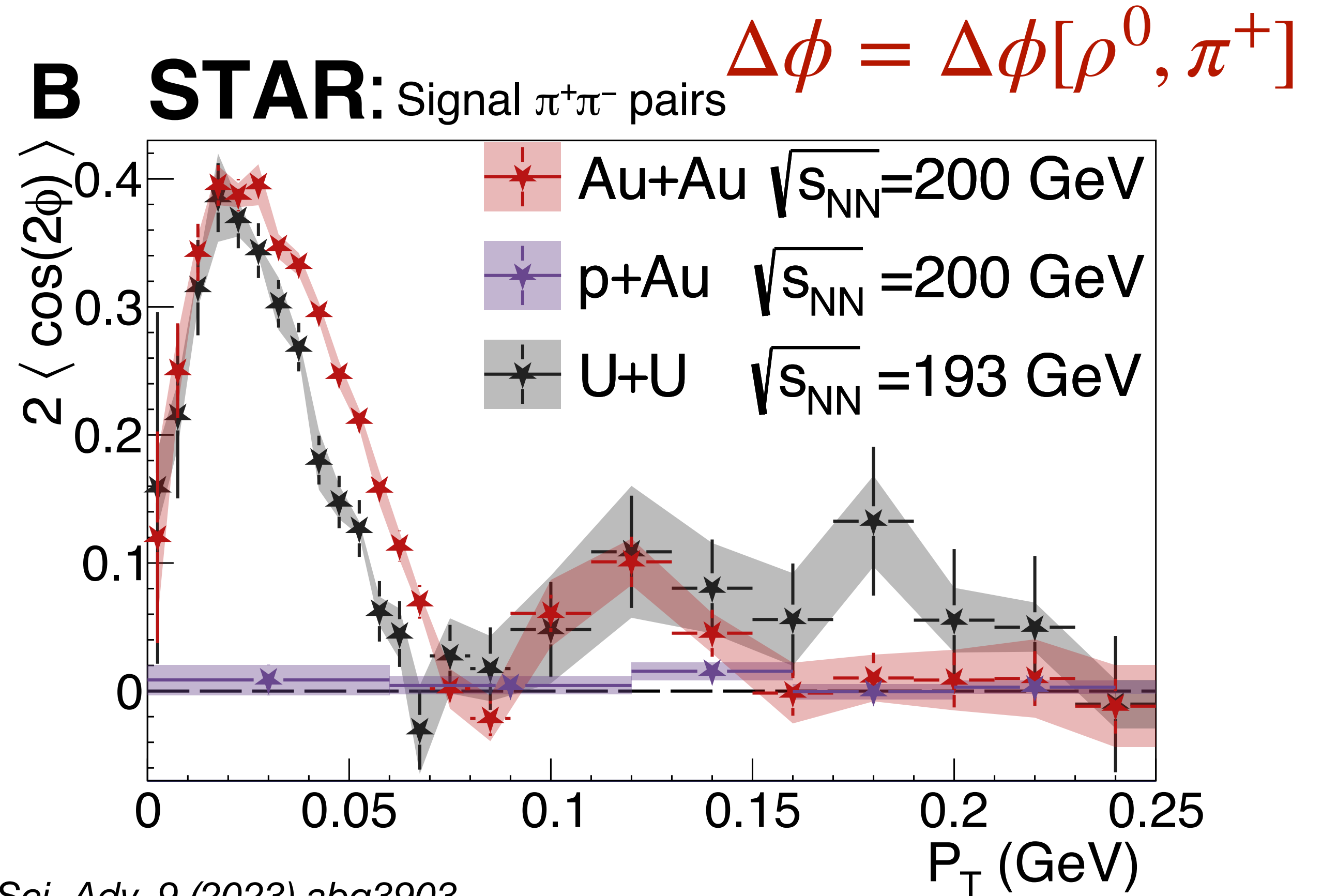
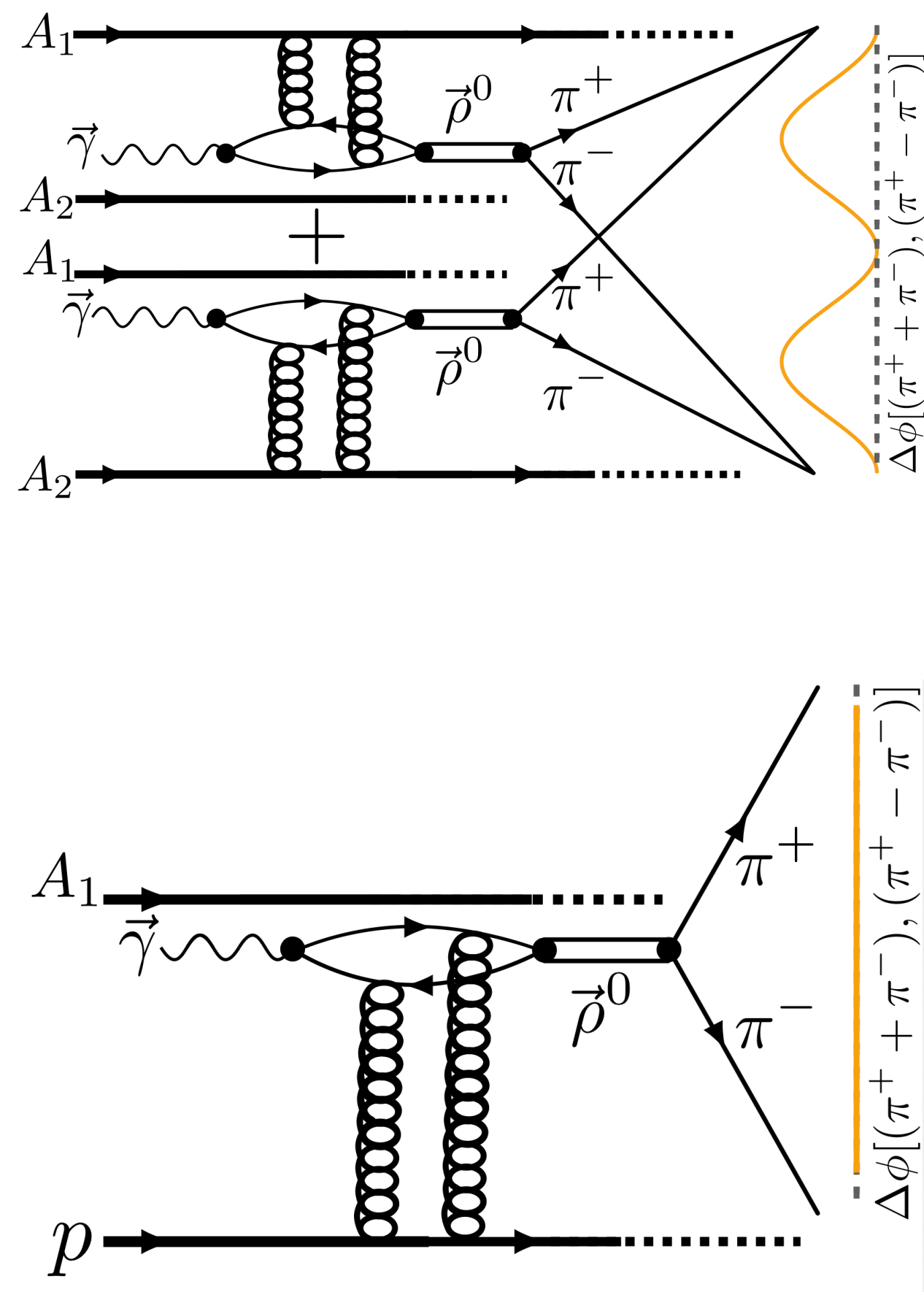
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STAR, Sci. Adv. 9 (2023) abq3903

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

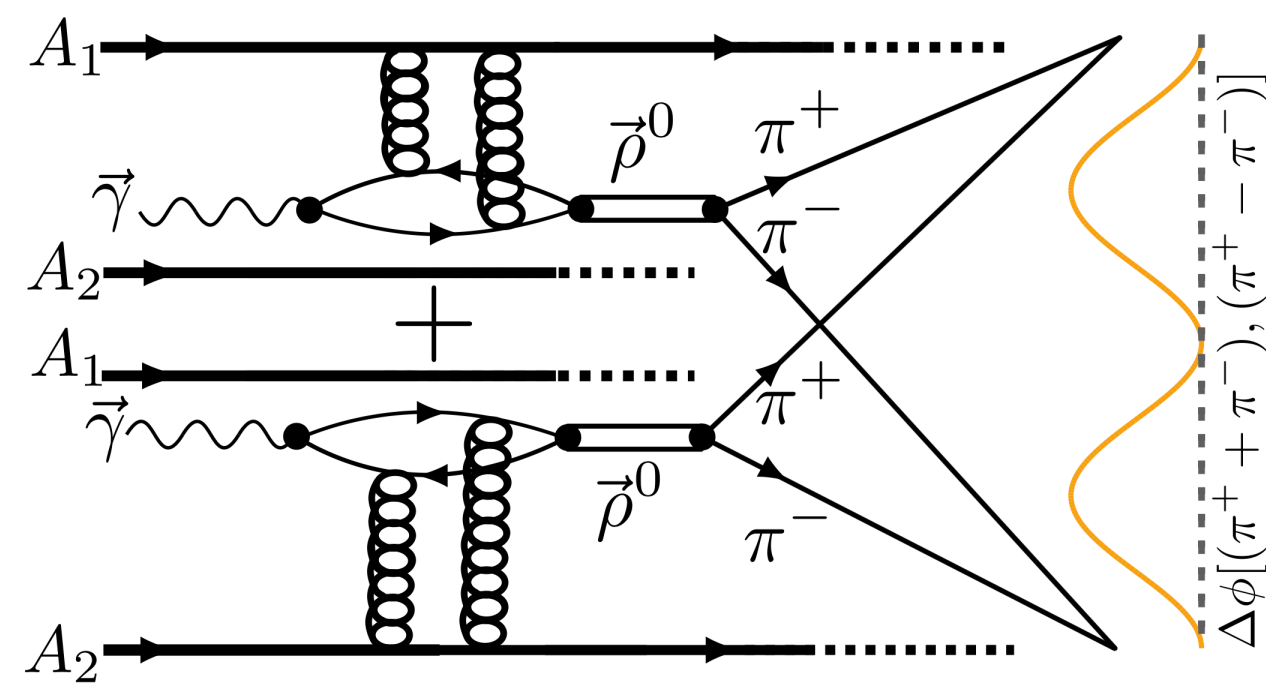


STAR, Sci. Adv. 9 (2023) abq3903

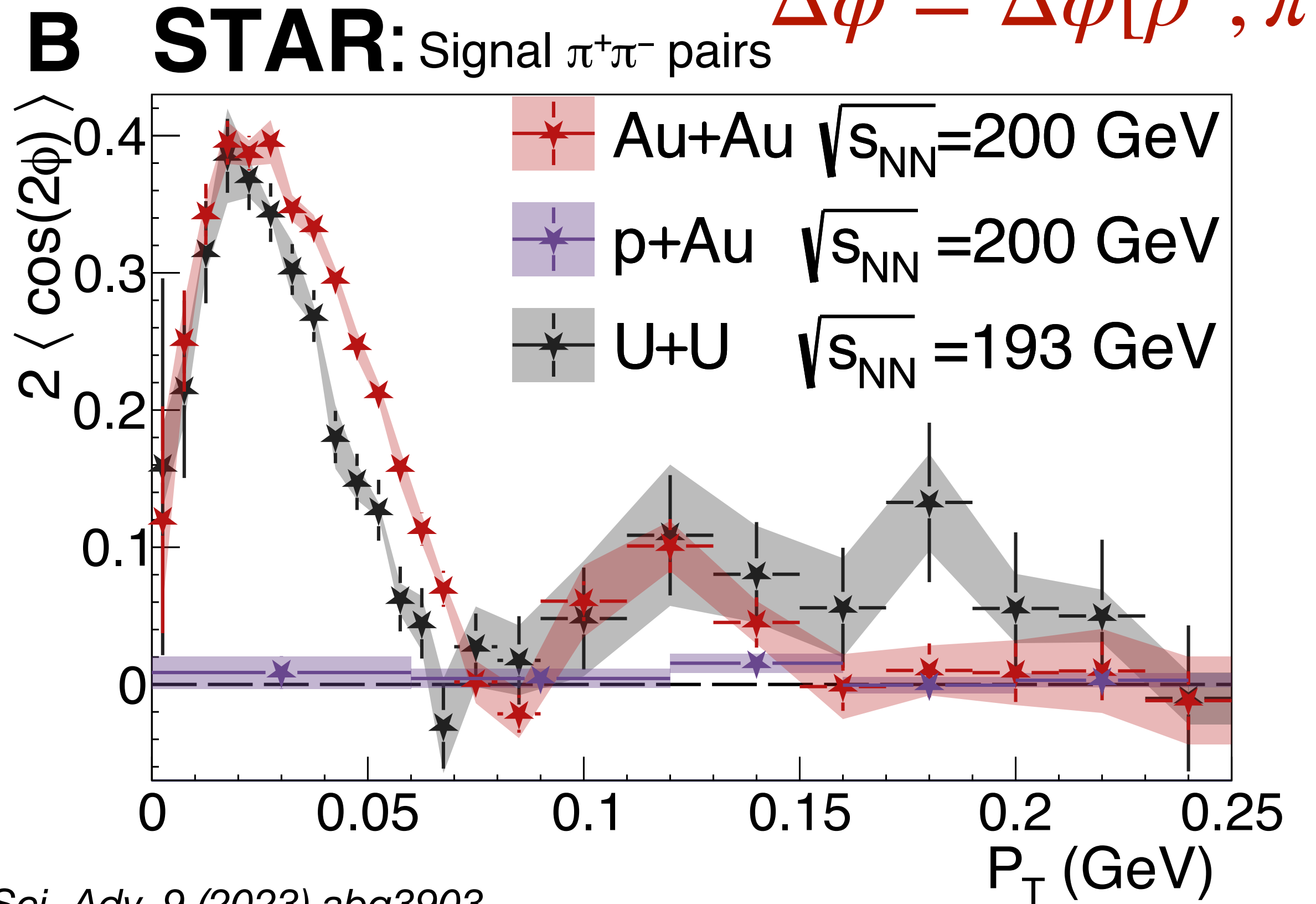
- ◎ **Asymmetric collisions:** **No/weak correlation** between the  $p_T$  and polarization direction

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

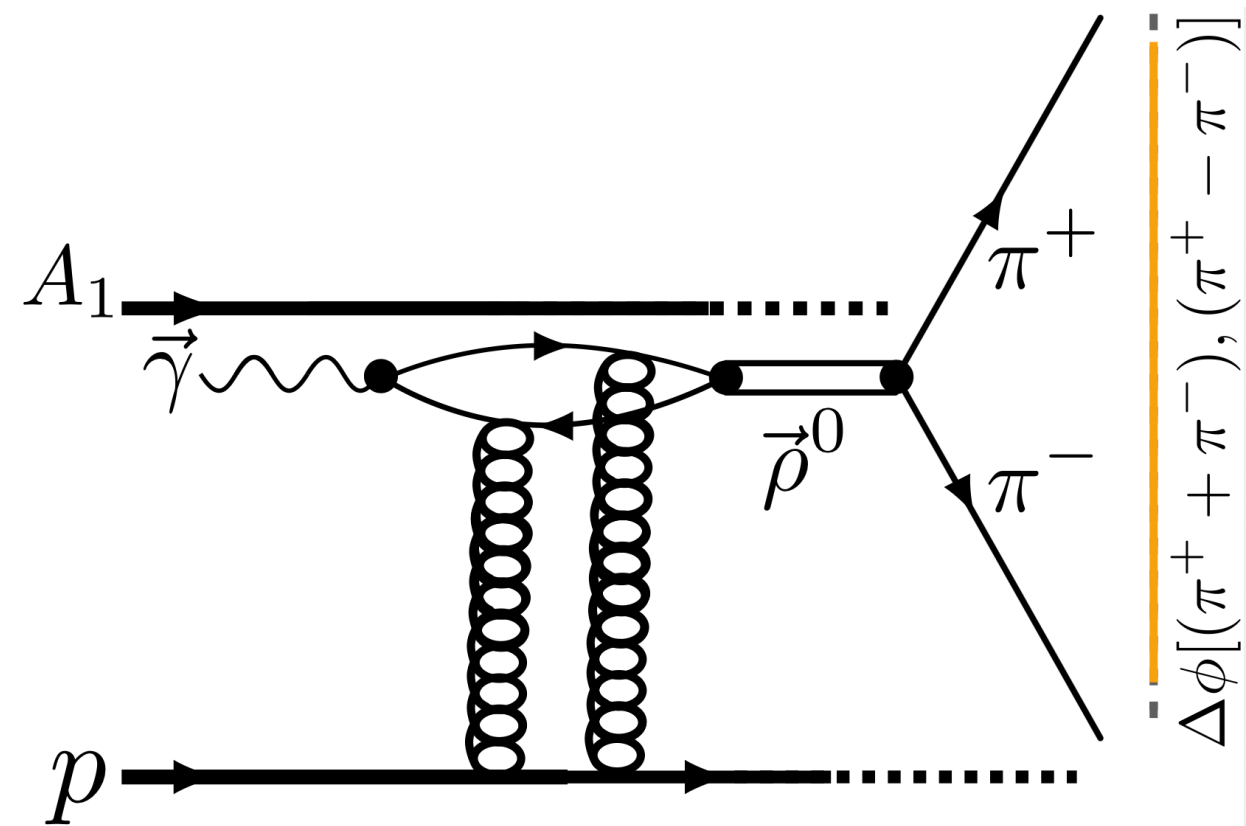


$$\Delta\phi = \Delta\phi[\rho^0, \pi^+]$$



STAR, Sci. Adv. 9 (2023) abq3903

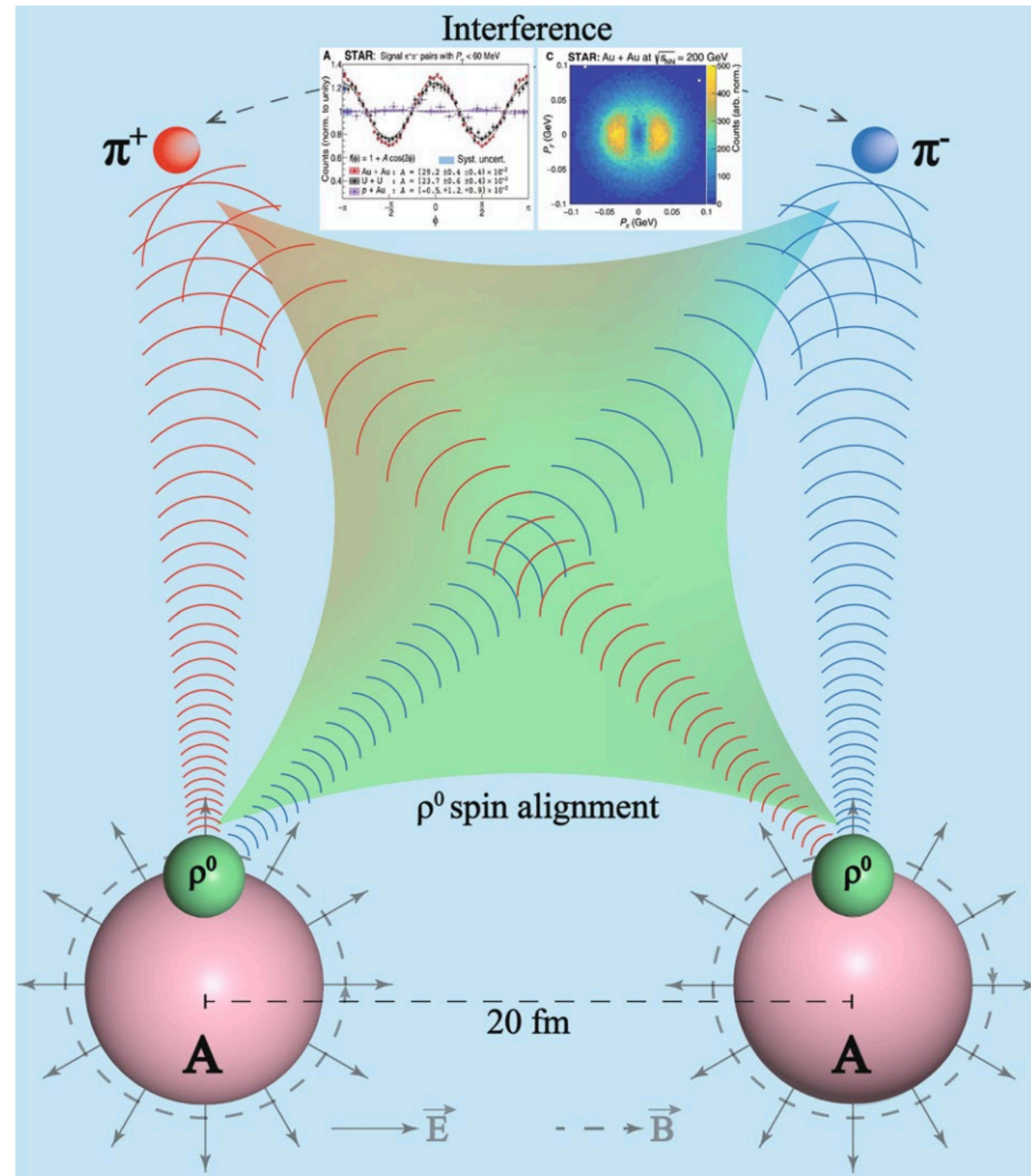
**Interference matters for  $p_T$  proxy!**



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

# Impact of the observed modulation

Ma, NST 34 (2023) 16

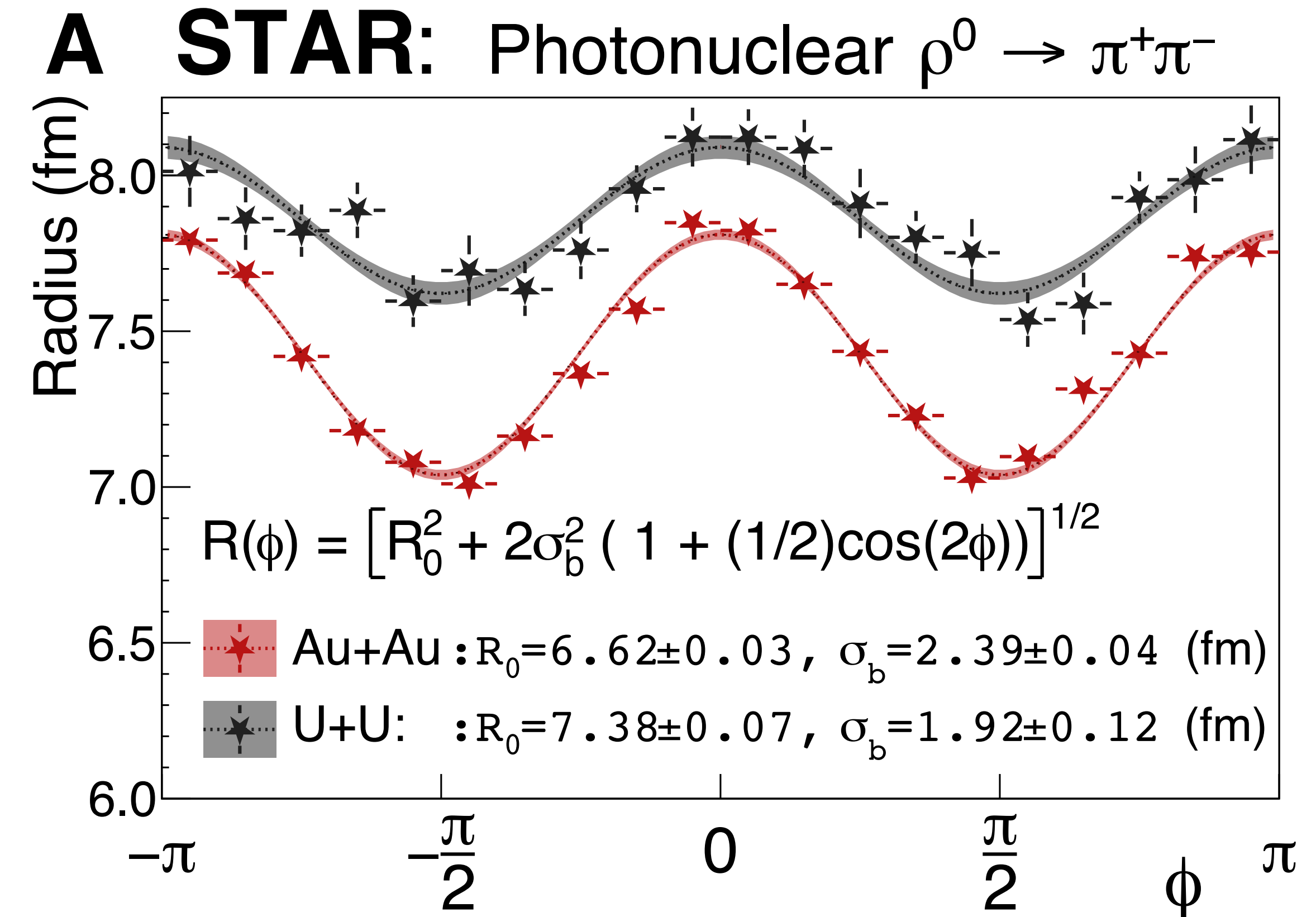
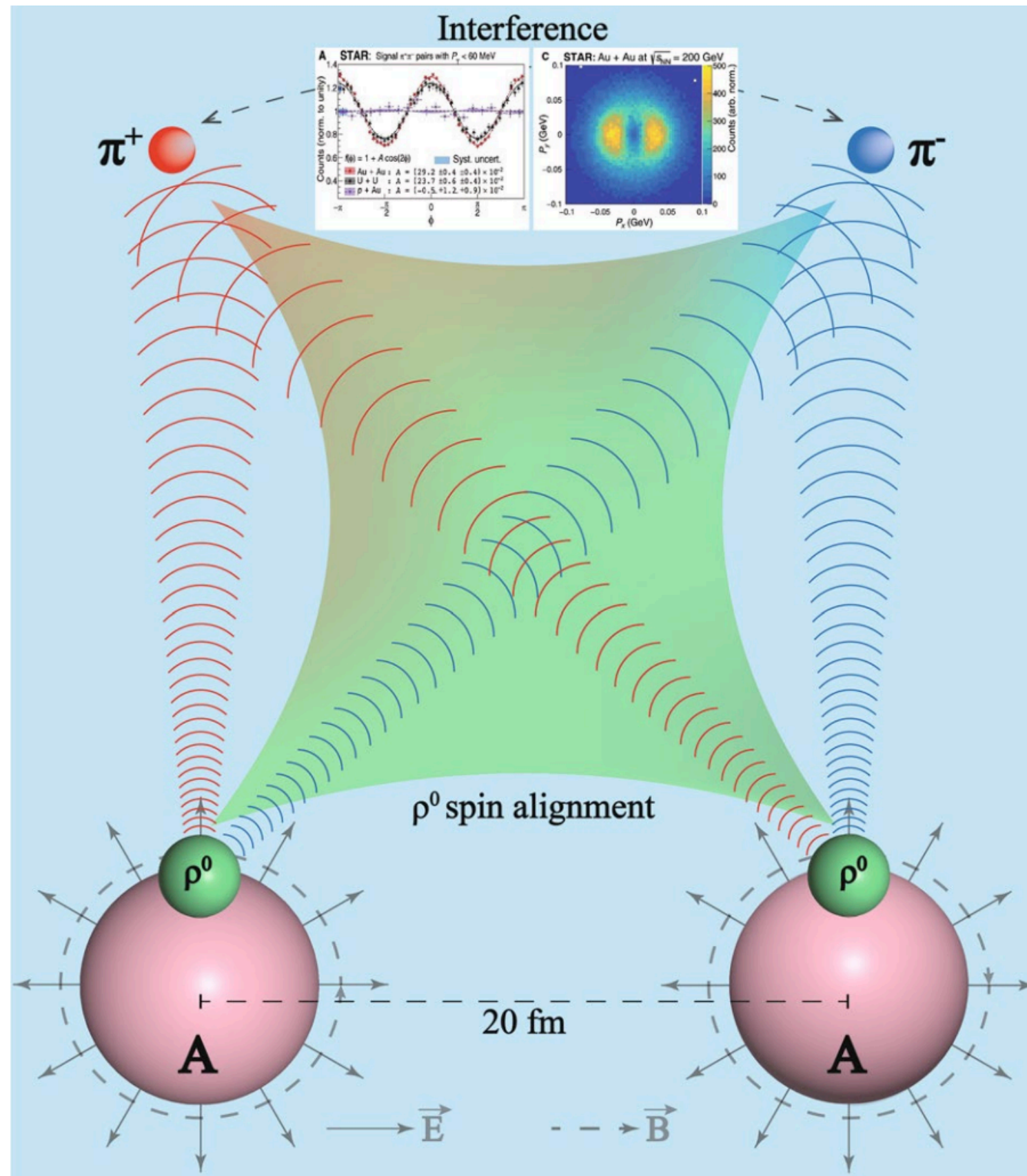


◎ Interference must happen between two daughters

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Ma, NST 34 (2023) 16

STAR, Sci. Adv. 9 (2023) abq3903

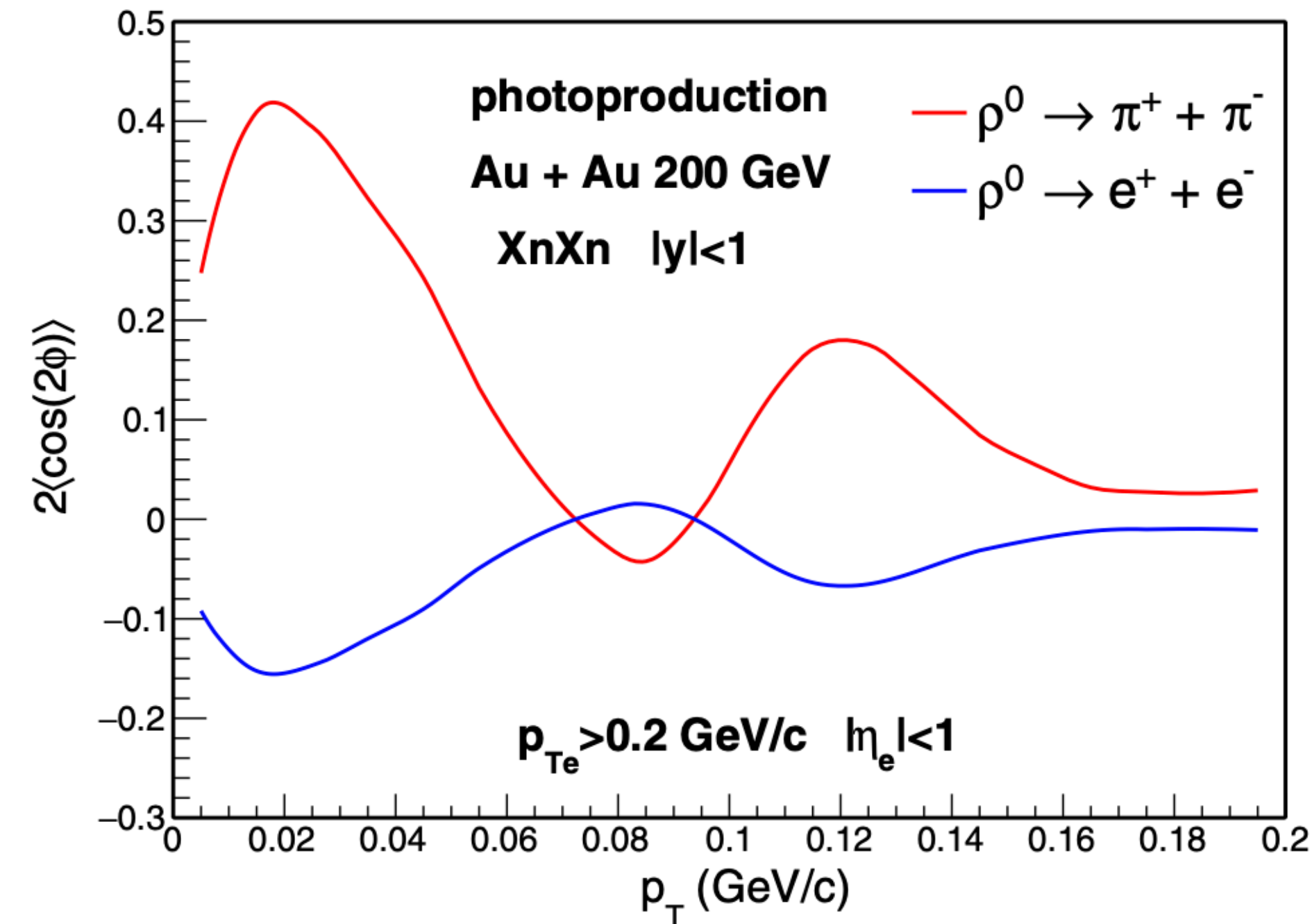


◎ Interference must happen between two daughters

◎ Interference affects the extraction of the nuclear radius

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

Zha et al., PRD 103 (2021) 033007



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

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

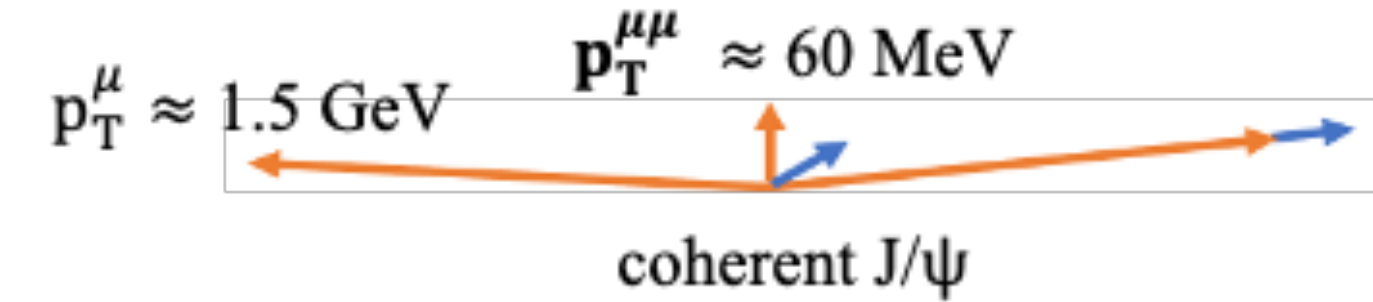
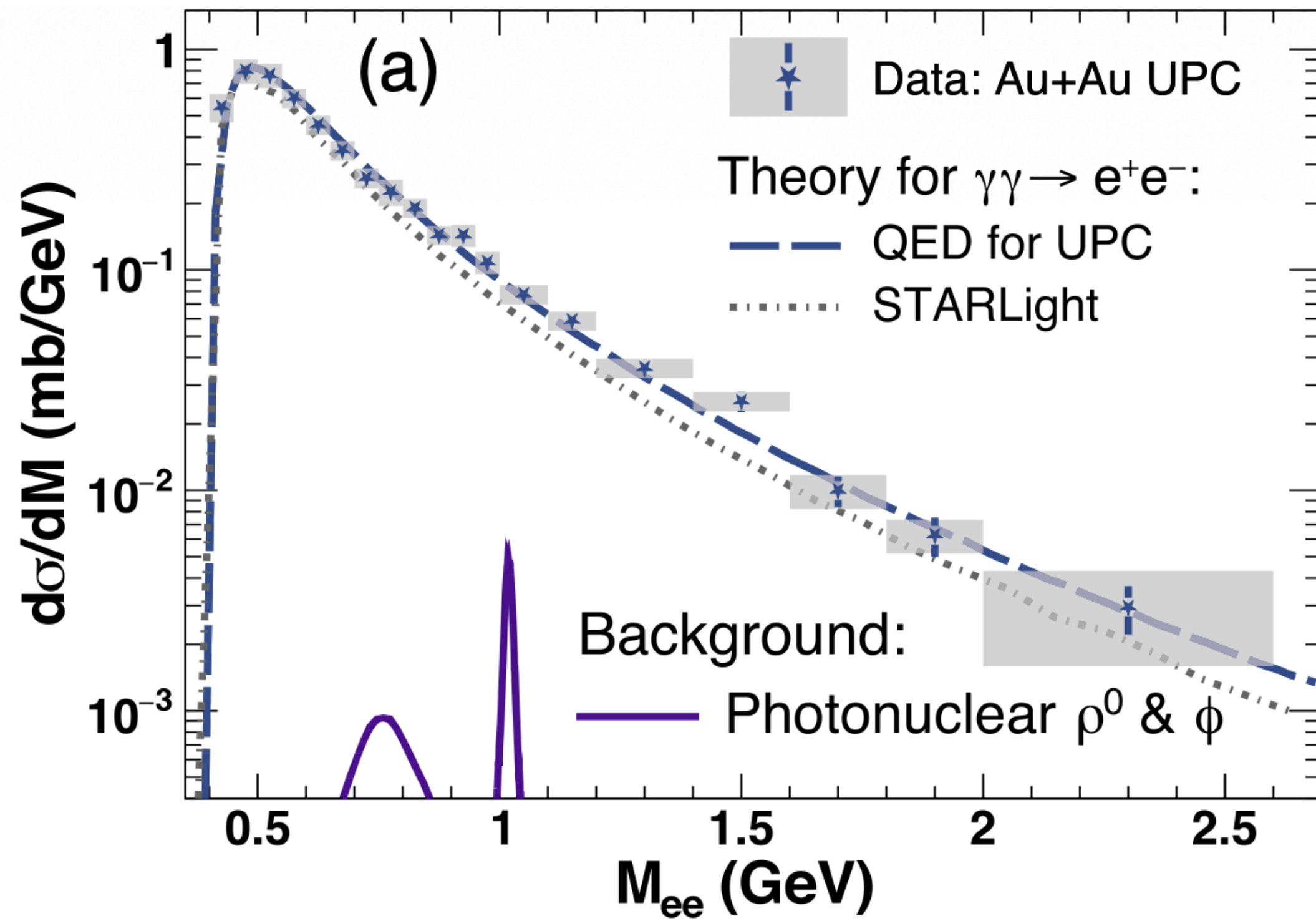
● Spin-1/2 final states ( $J/\psi/\rho^0 \rightarrow l^+ l^-$ )

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

# Challenge of spin-1/2 measurement

Zha et al., PRD 103 (2021) 033007

STAR, arXiv: 2512.02865 (accepted by PRL)

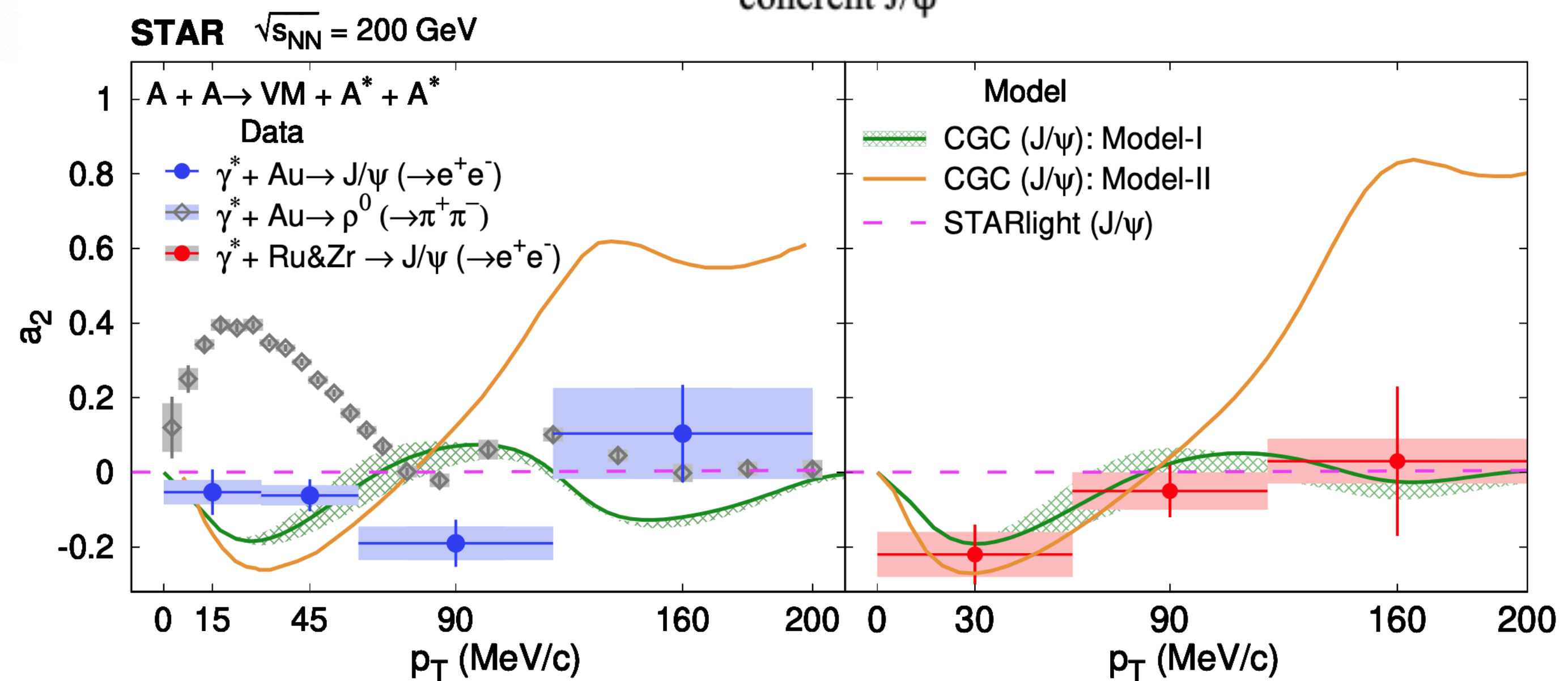
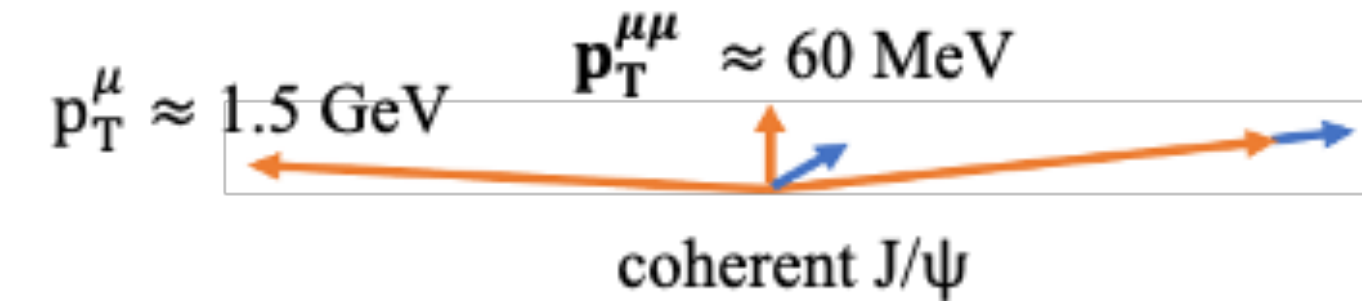
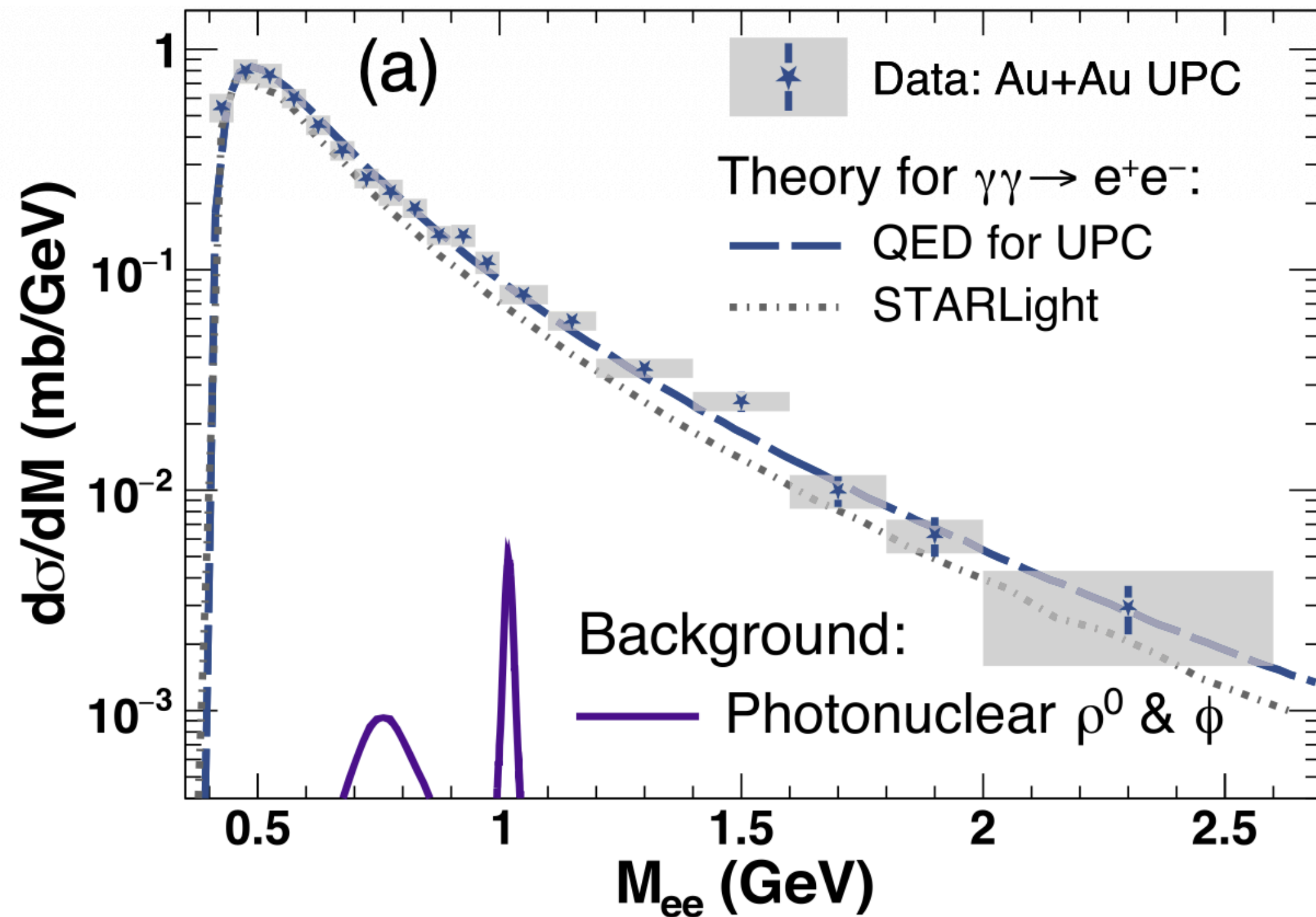


⊙  $\rho^0/\phi \rightarrow e^+e^-$  is overwhelmed by two-photon interactions

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Zha et al., PRD 103 (2021) 033007

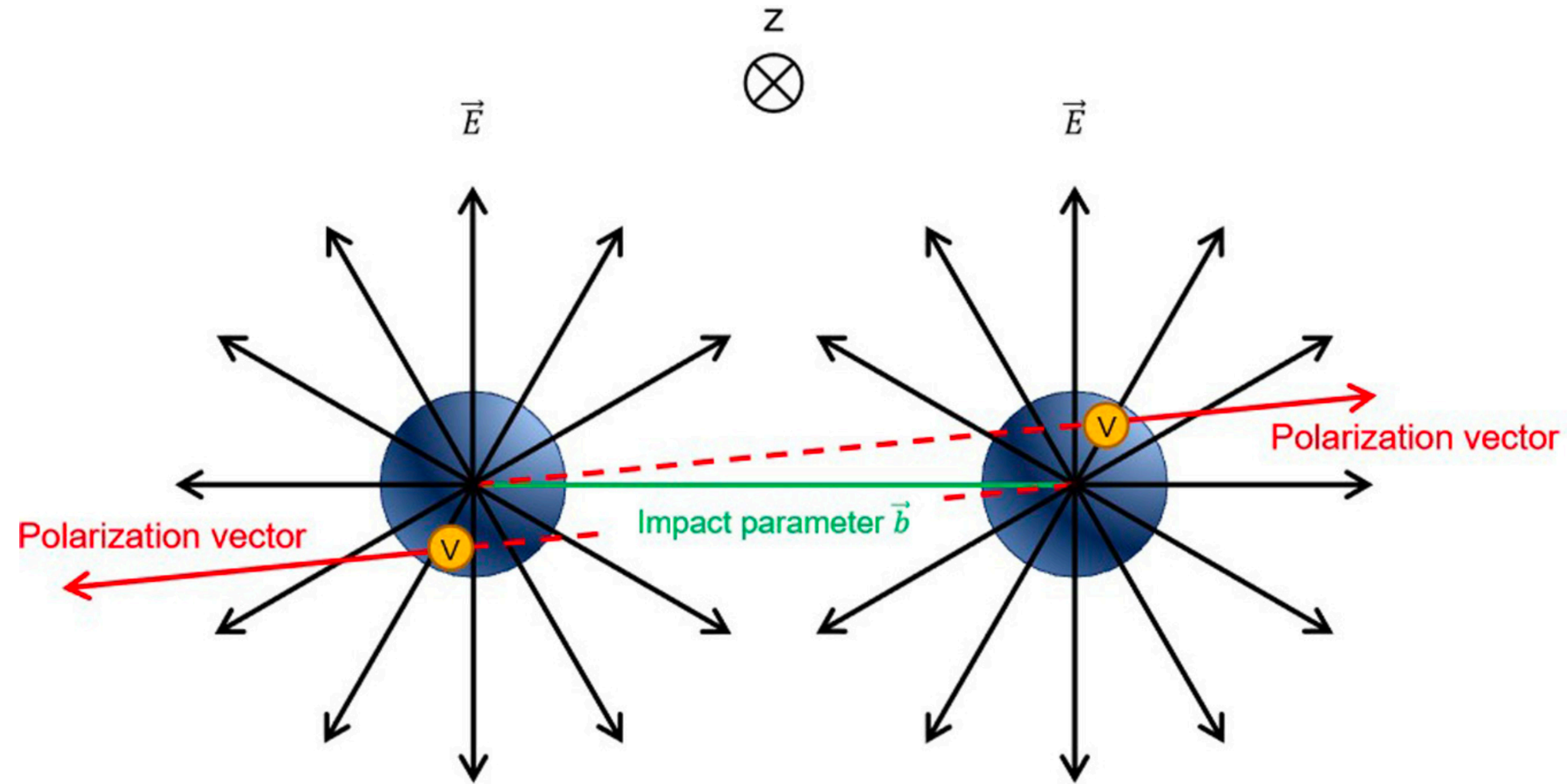
STAR, arXiv: 2512.02865 (accepted by PRL)



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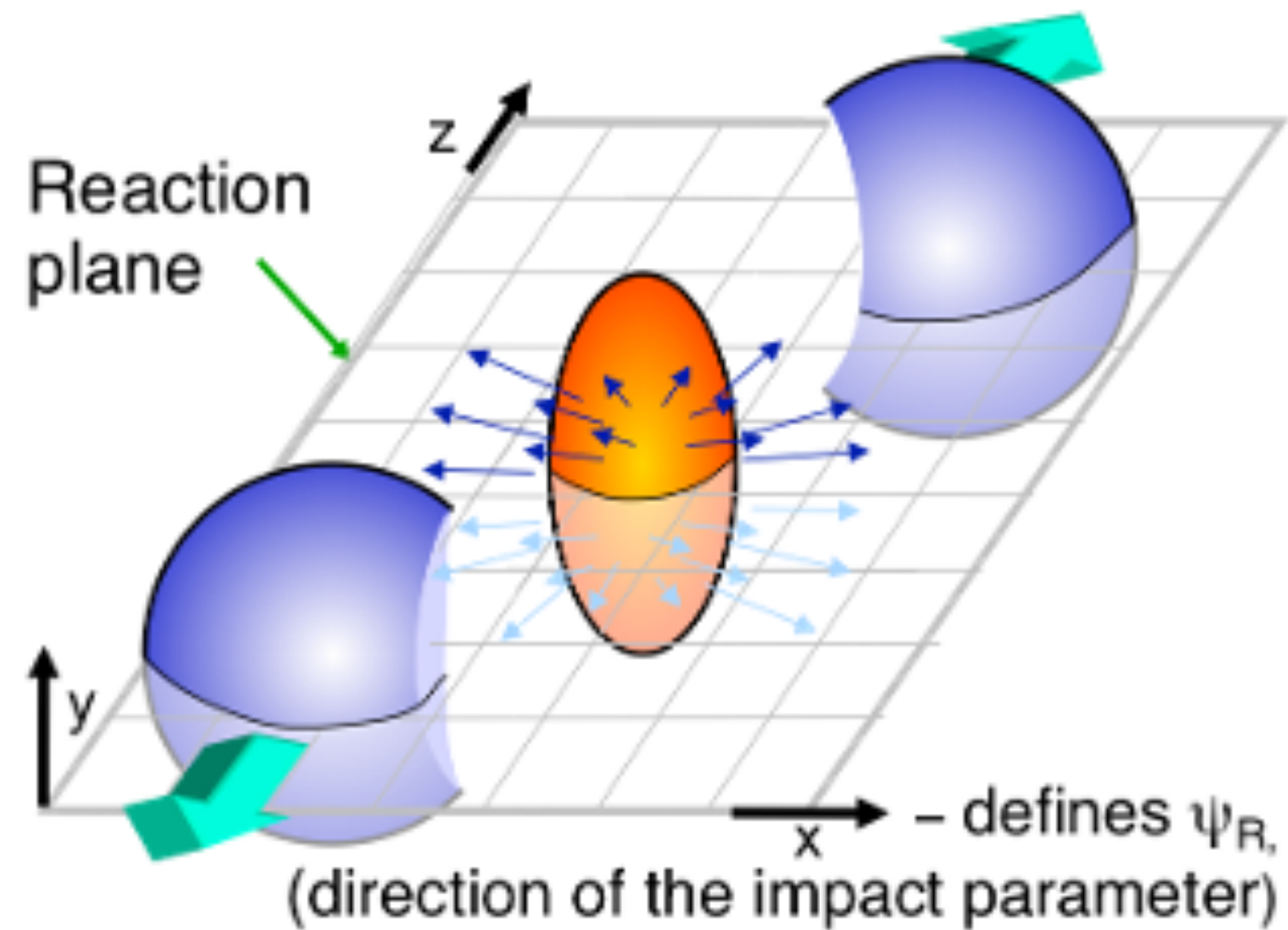
⊙  $J/\psi \rightarrow e^+e^-$  is suffered by the detector resolution and soft photon radiation

# What else can we do?



- ◎ Impact parameter ( $\mathbf{b}$ ): a robust estimator of polarization direction
  - Valid in any collision system and rapidity range

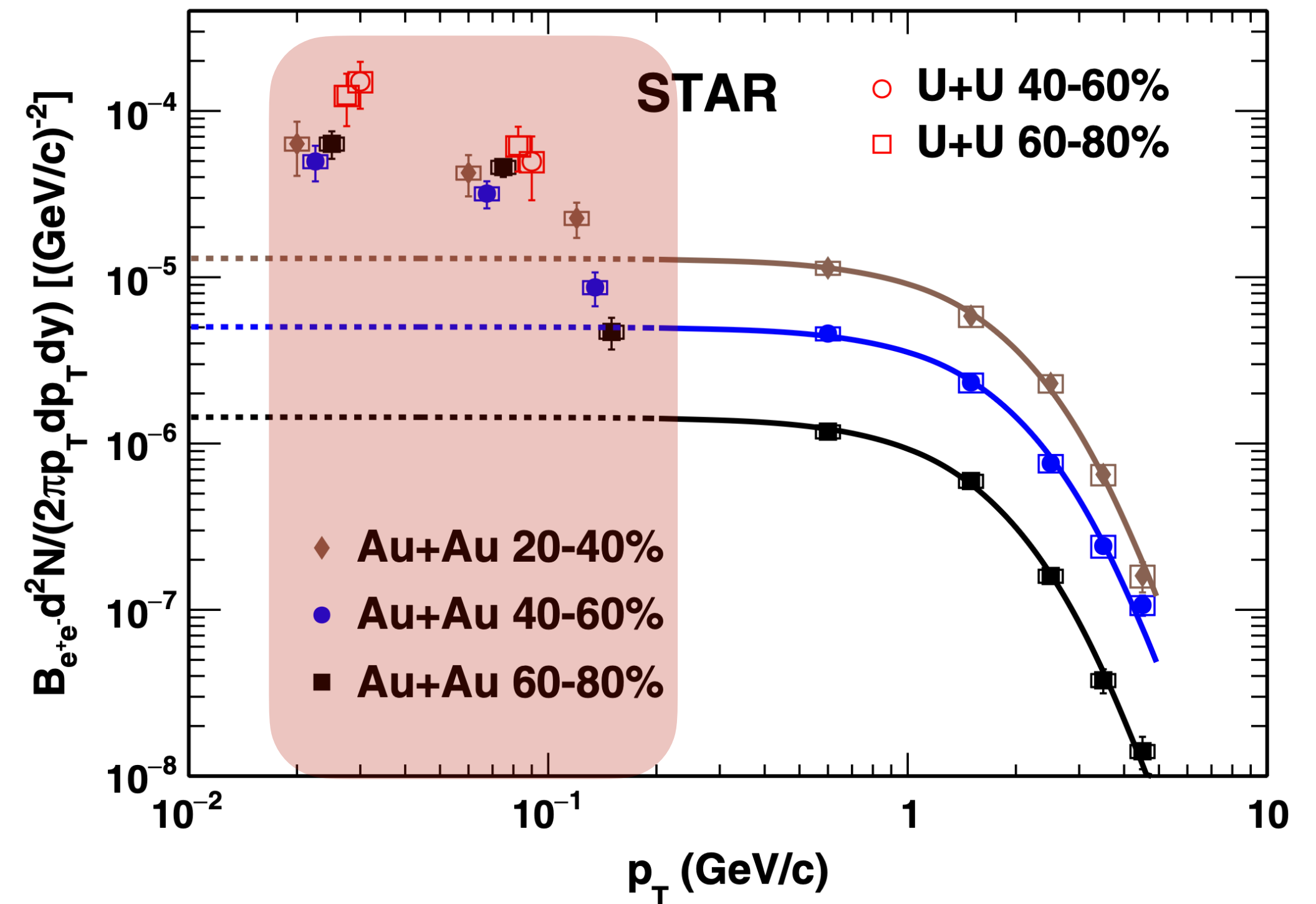
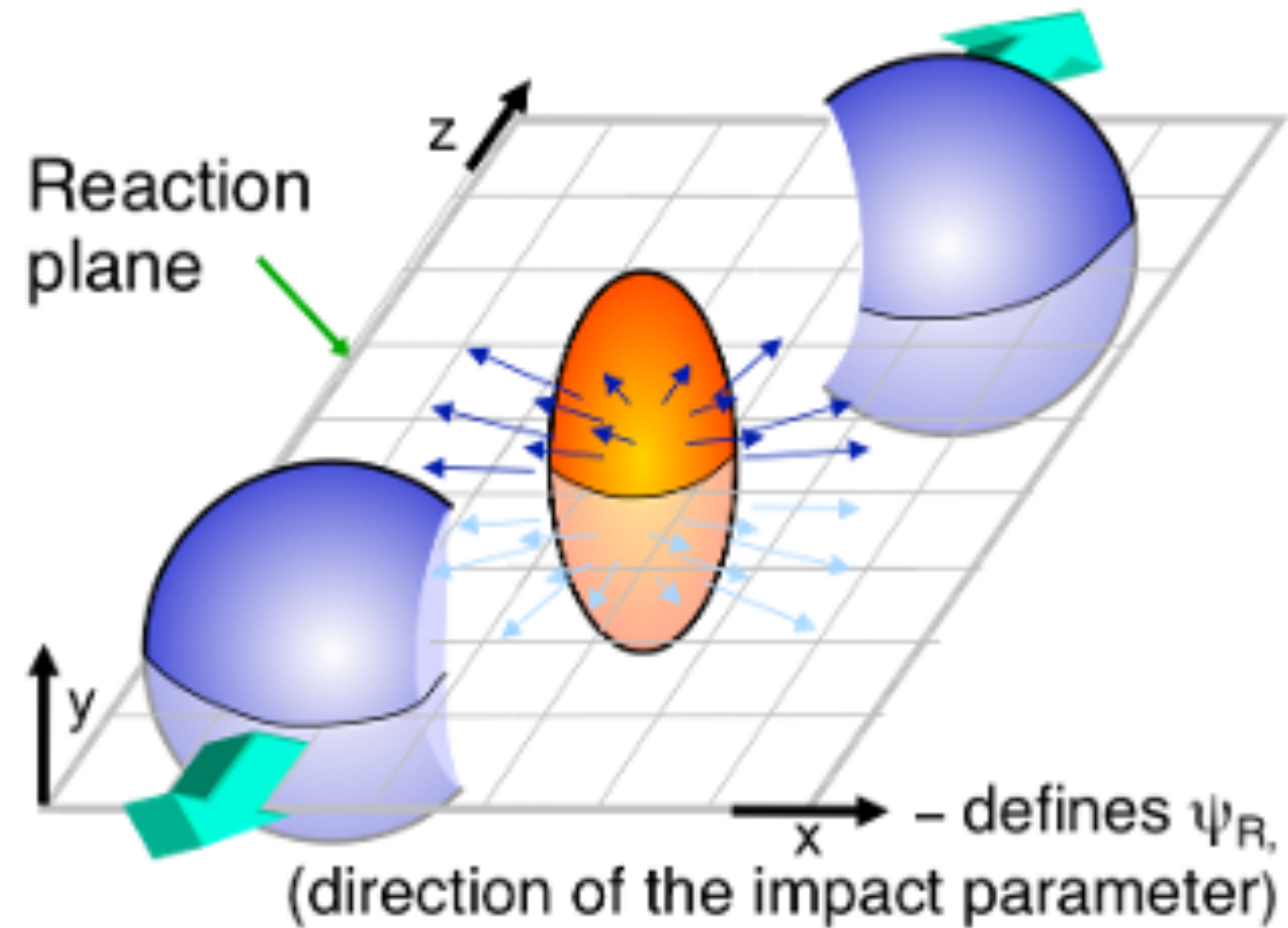
# What else can we do?



- $b$  is estimated by the second order event plane technique

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



- $b$  is estimated by the second order event plane technique

[STAR, QM 2025](#)

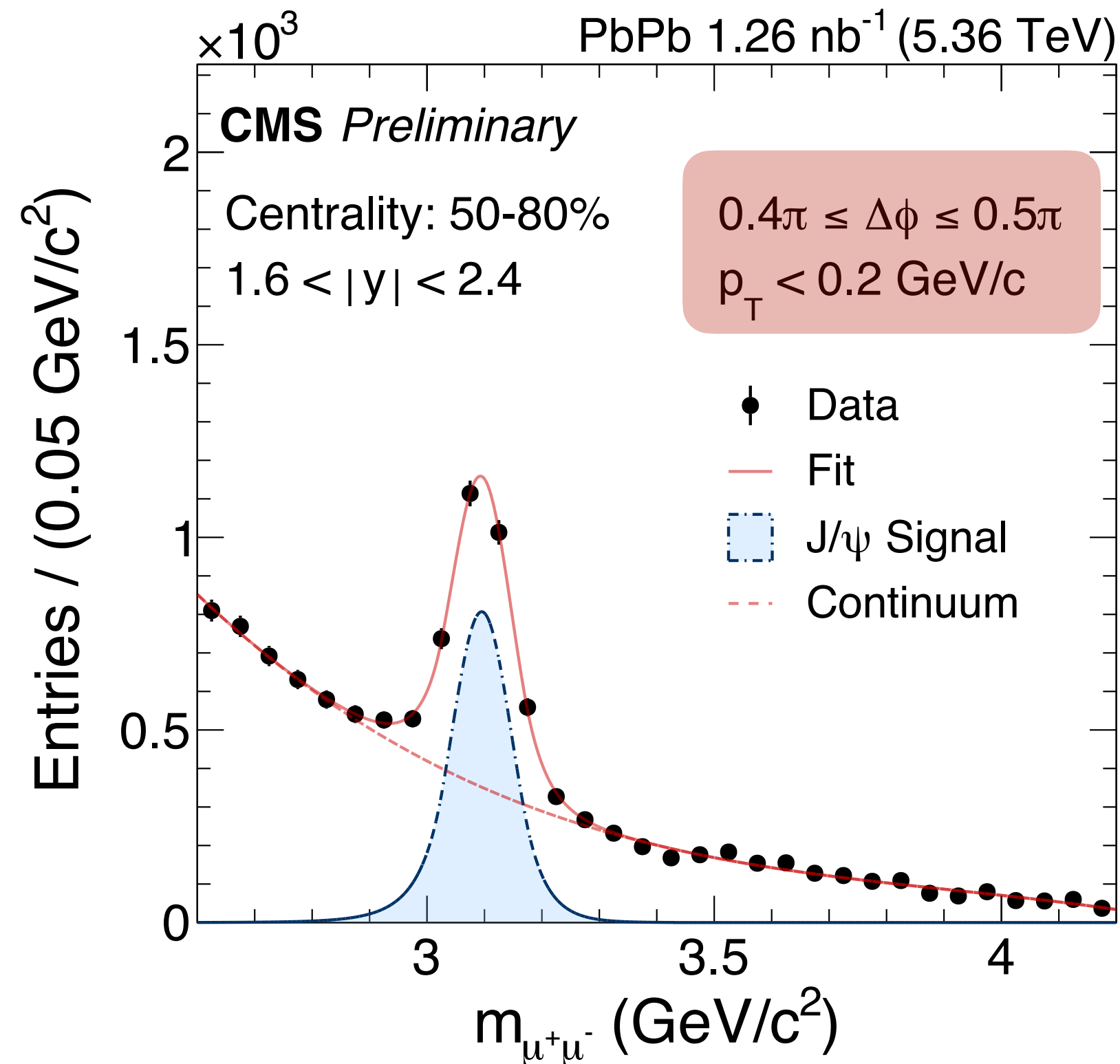
- Coherent  $J/\psi$  was observed in hadronic collisions

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

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

CMS-PAS-HIN-25-006

$J/\psi$  signal extraction in  
each  $\Delta\phi = \phi_\mu - \Psi_2$  bin



## • $J/\psi$ signal

- Coherent  $J/\psi \rightarrow \mu^+\mu^-$
- Incoherent  $J/\psi \rightarrow \mu^+\mu^-$
- Hadronic  $J/\psi \rightarrow \mu^+\mu^-$

## • Continuum background

- QED  $\gamma\gamma \rightarrow \mu^+\mu^-$
- Drell-Yan contribution
- Heavy-flavor decay
- Combinatorial background

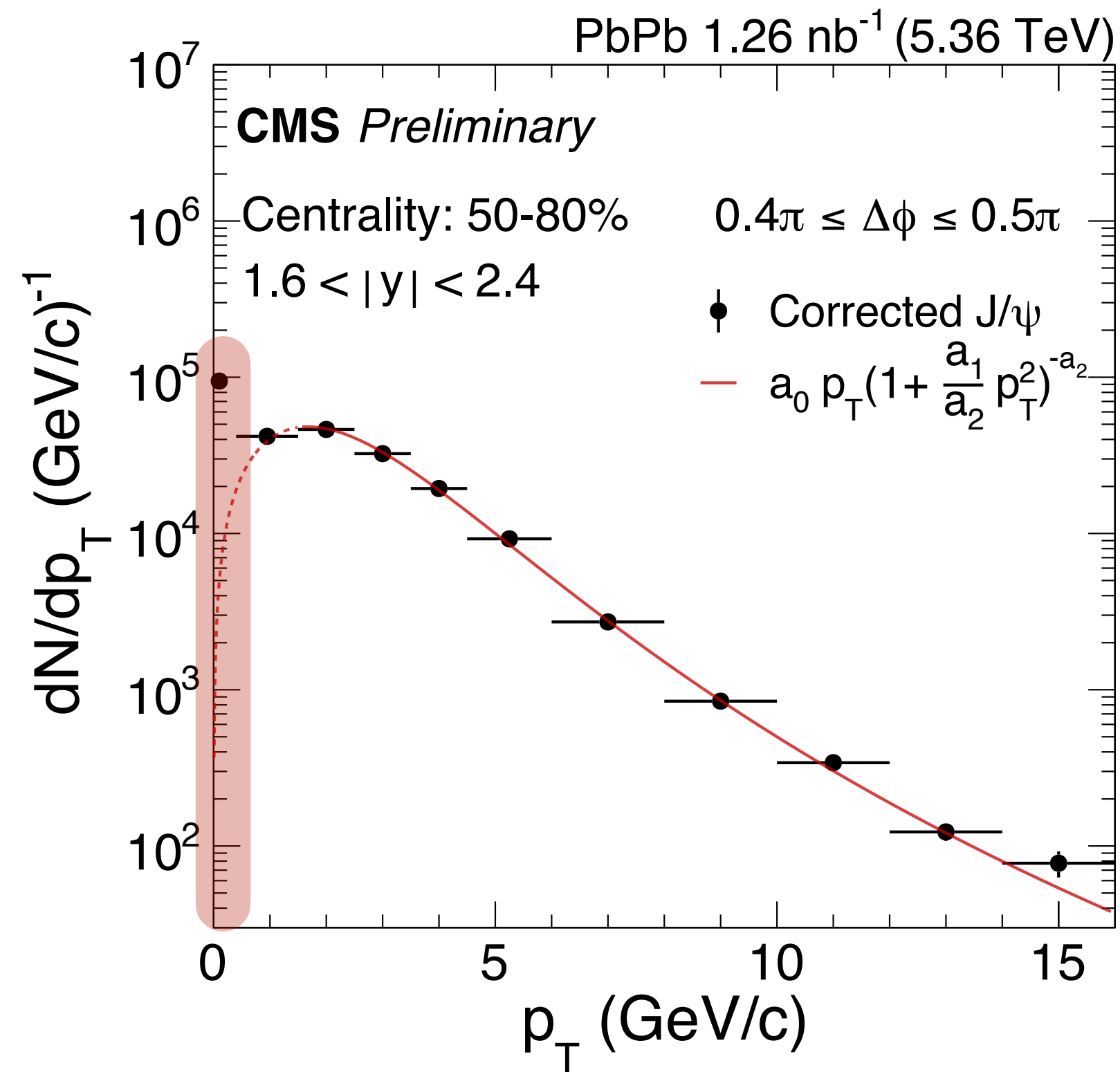
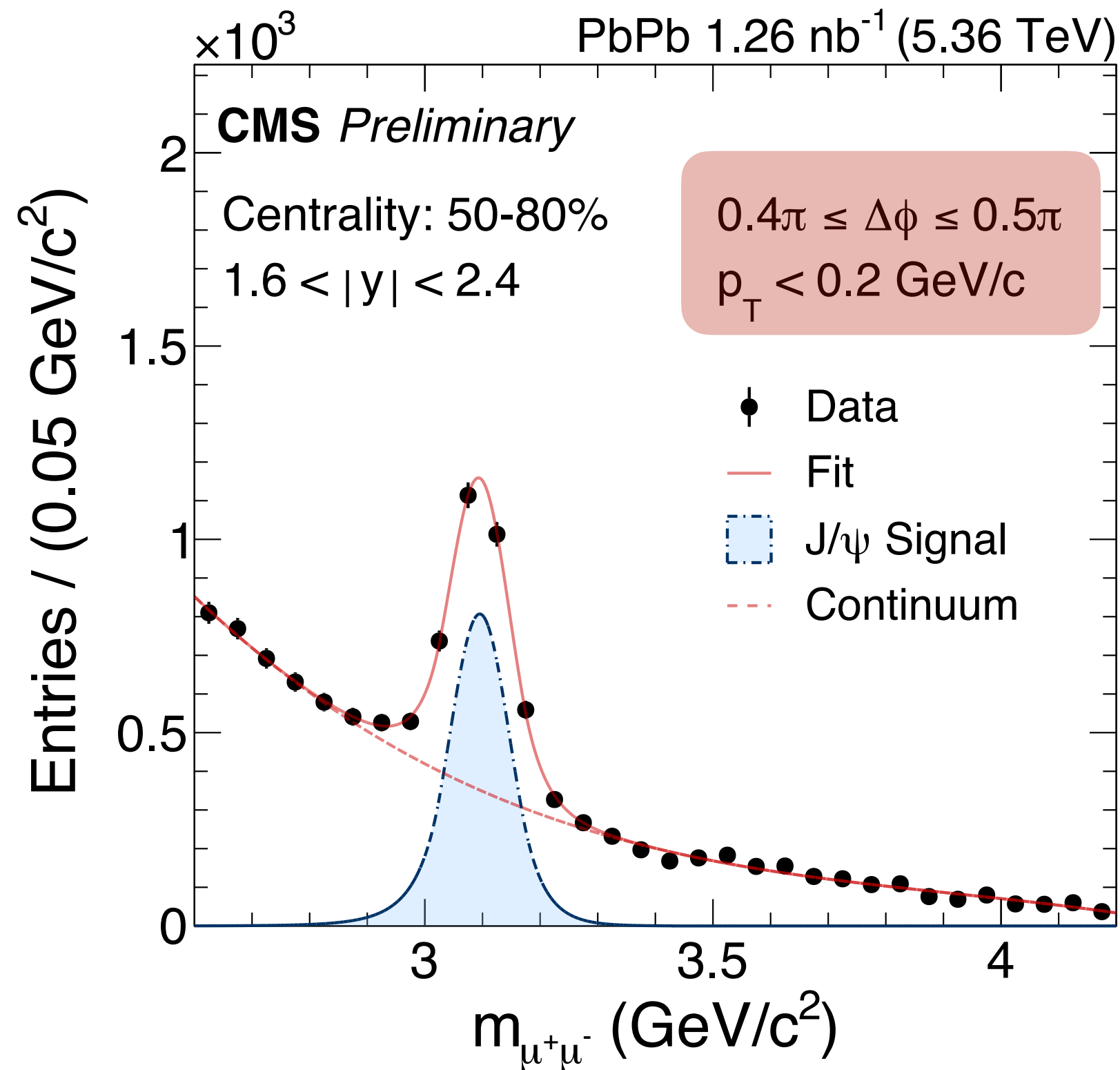
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CMS-PAS-HIN-25-006

J/ $\psi$  signal extraction in each  $\Delta\phi = \phi_\mu - \Psi_2$  bin



Hadronic subtraction in each  $\Delta\phi$  bin



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

CMS-PAS-HIN-25-006

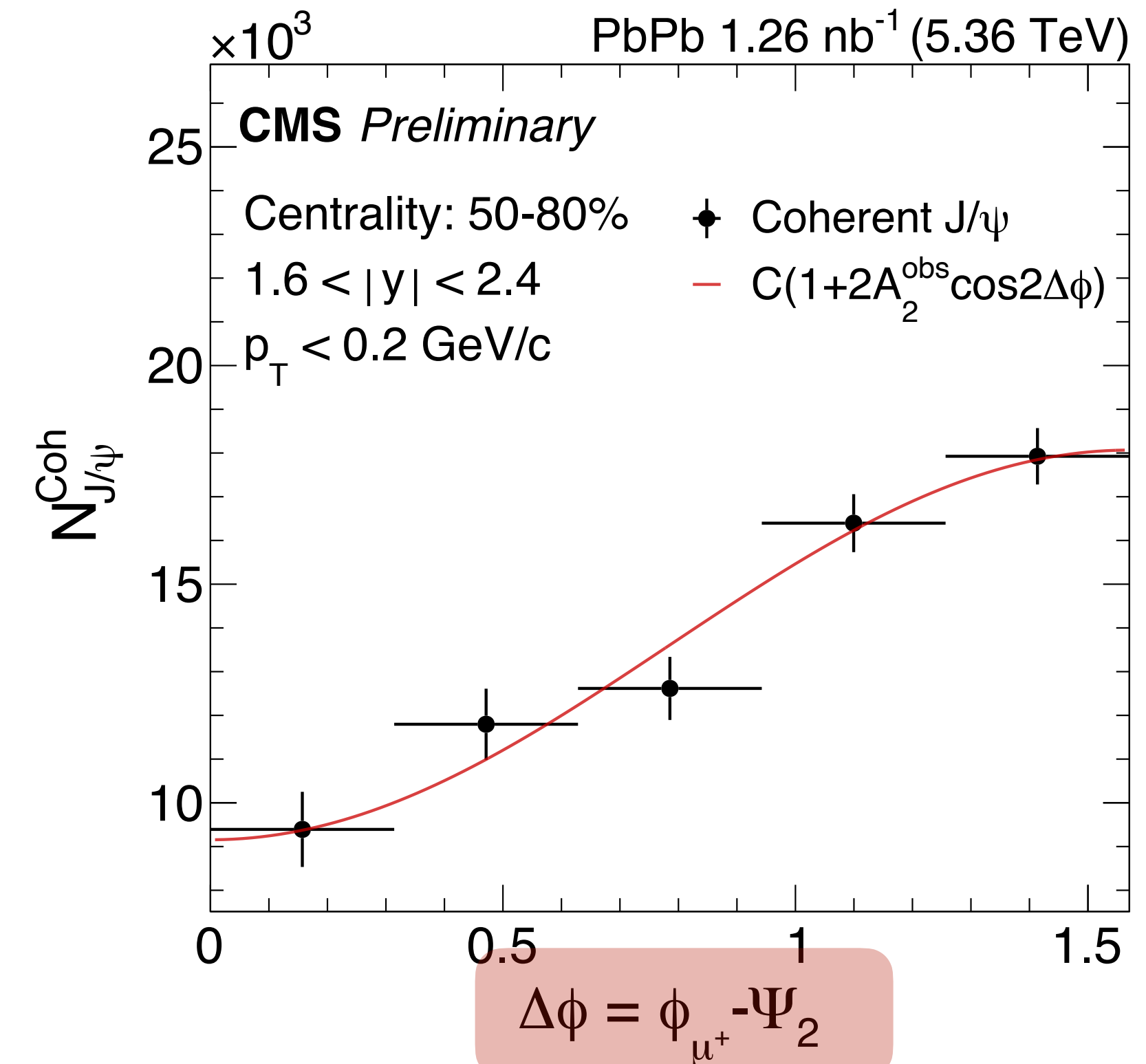
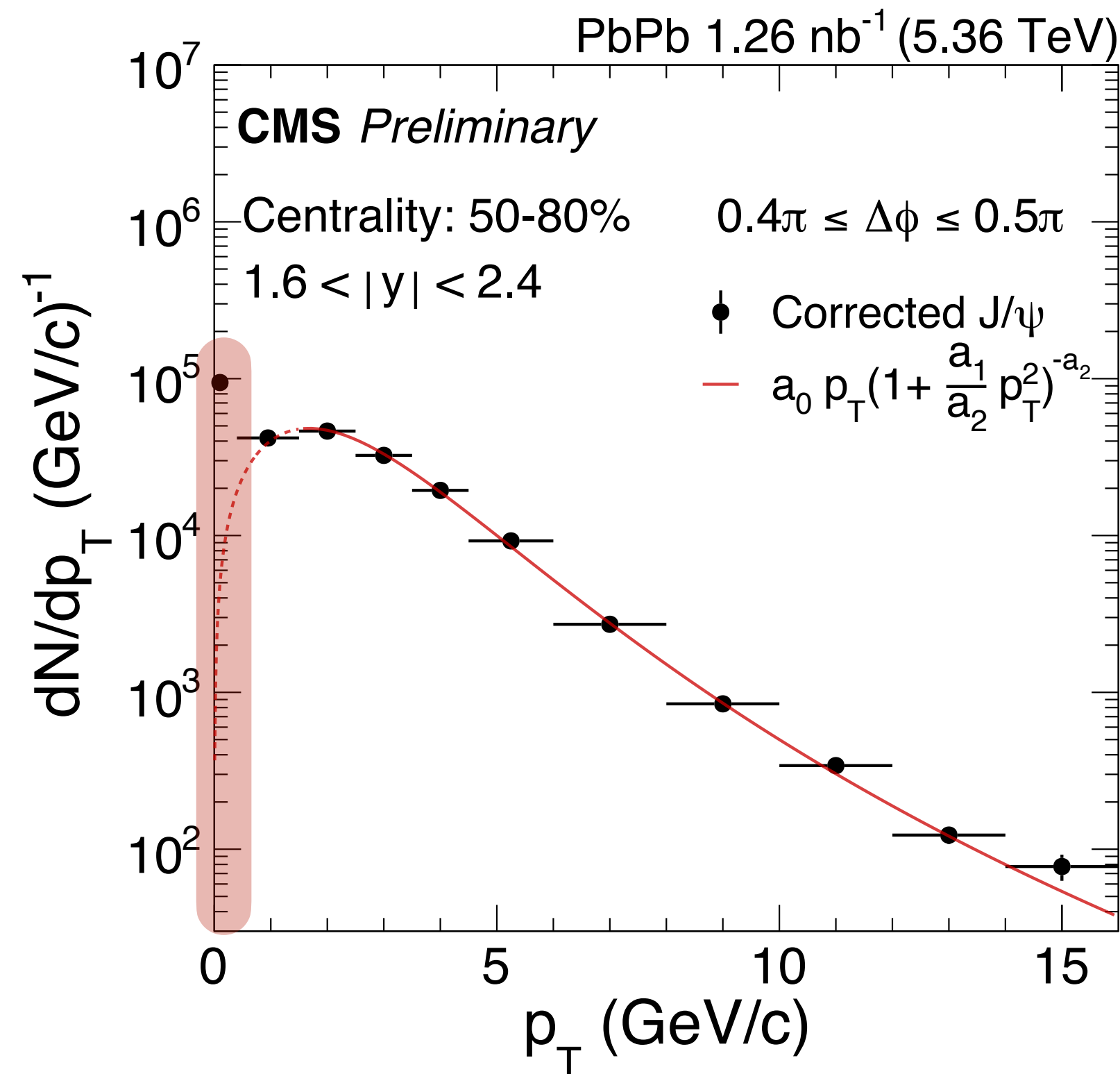
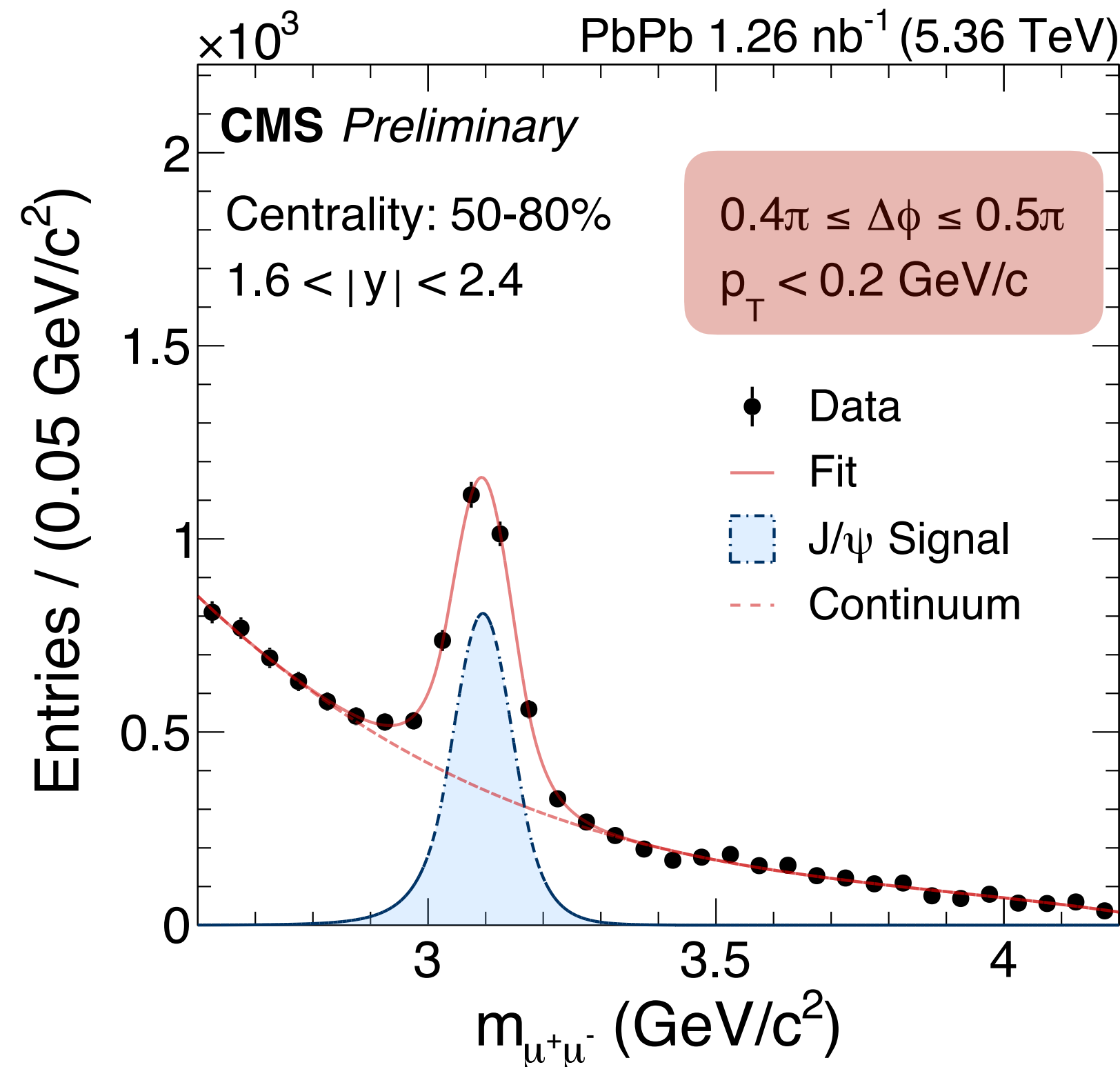
J/ $\psi$  signal extraction in each  $\Delta\phi = \phi_{\mu^+} - \Psi_2$  bin



Hadronic subtraction in each  $\Delta\phi$  bin

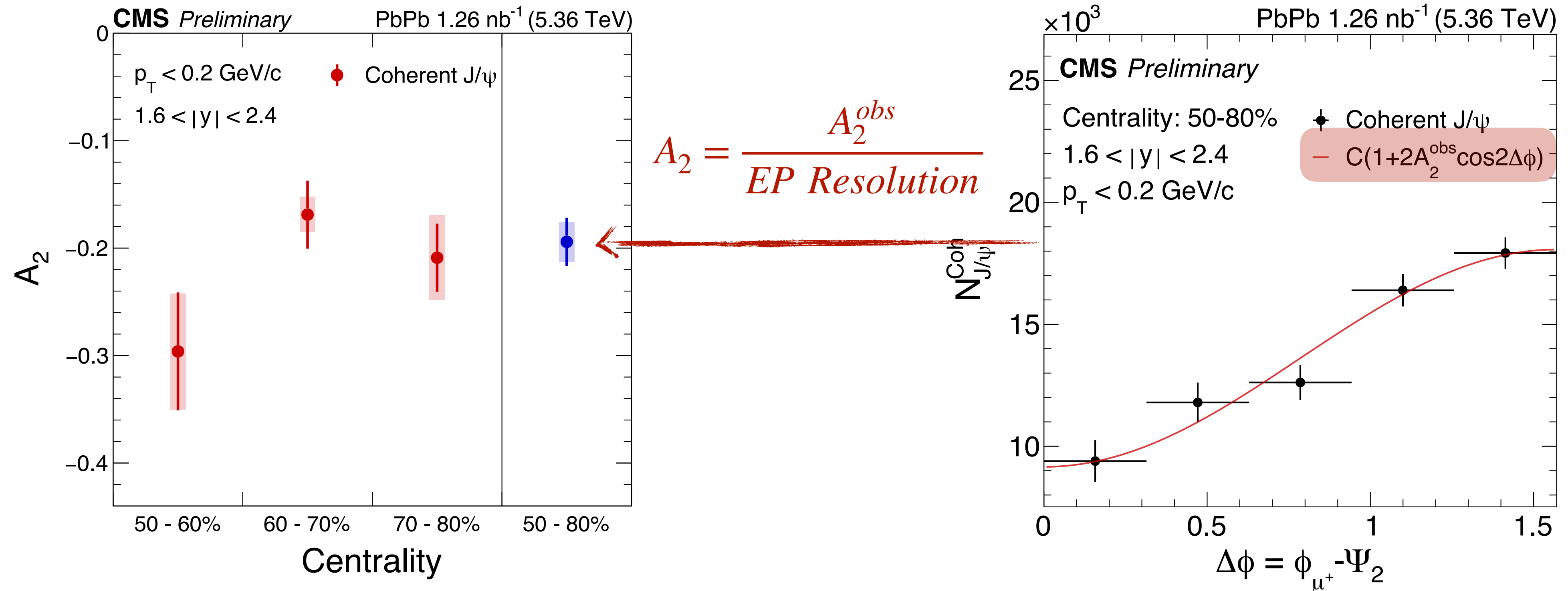


$\cos(2\Delta\phi)$  amplitude  $A_2^{obs}$  extraction



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

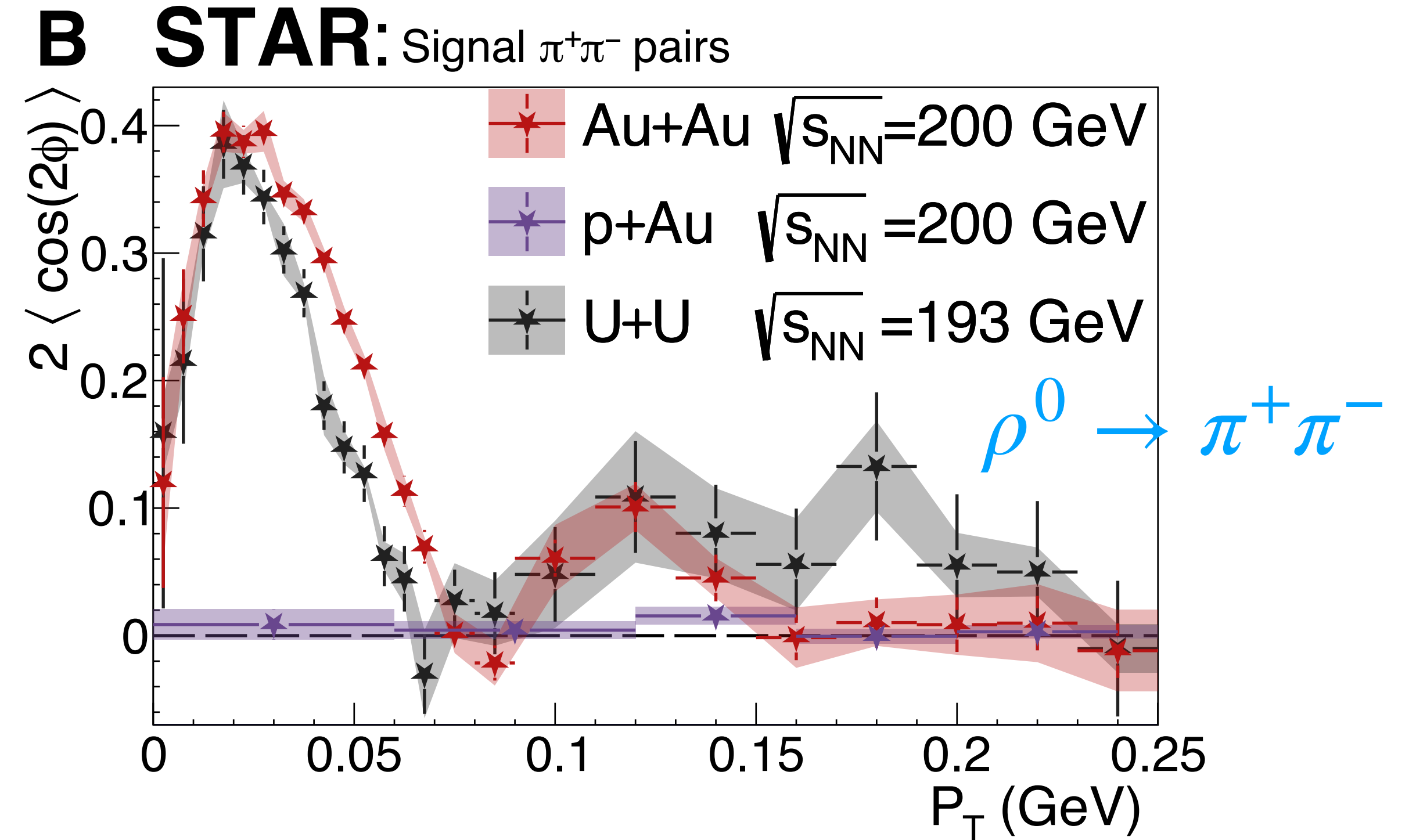
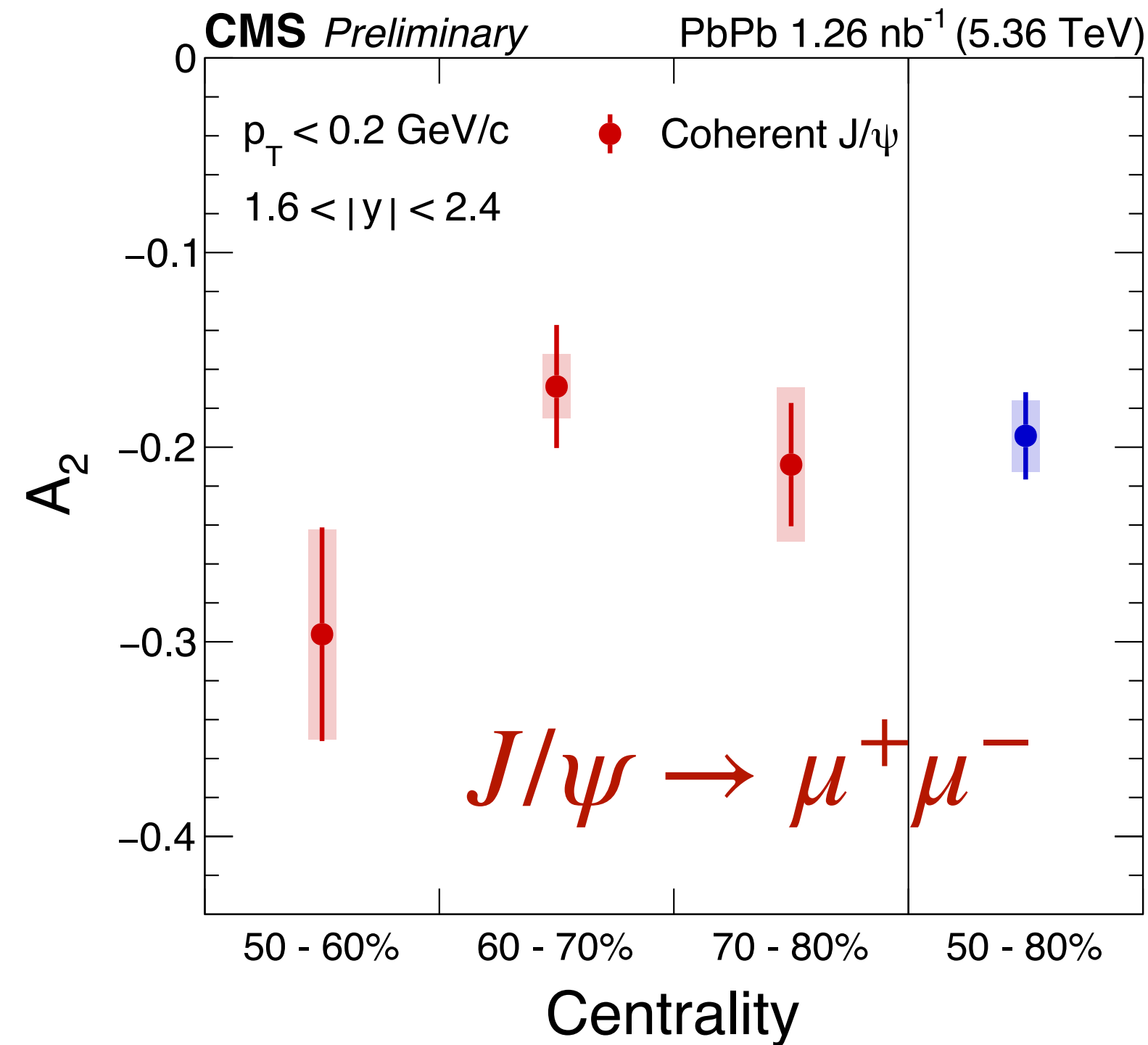
CMS-PAS-HIN-25-006



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

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

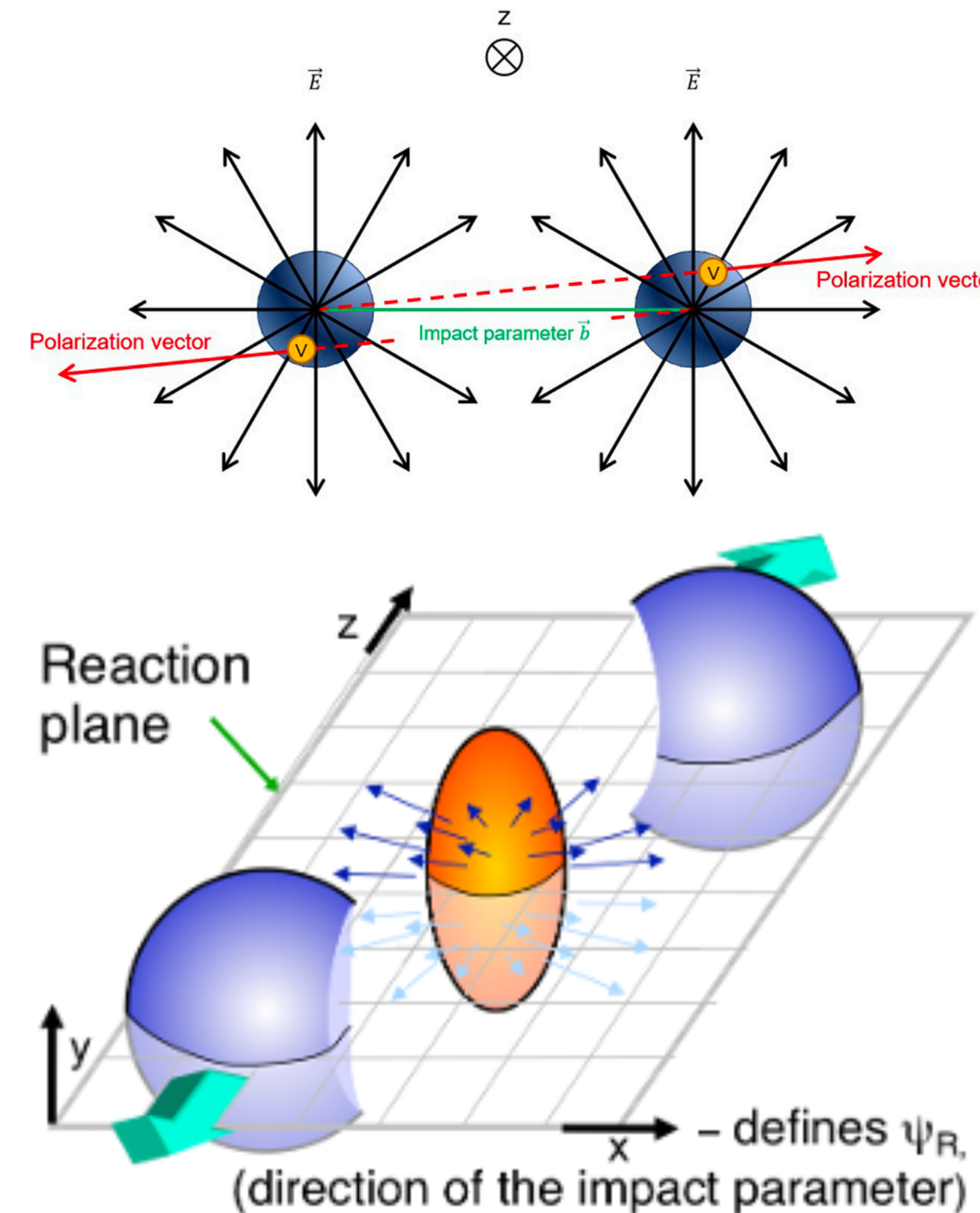
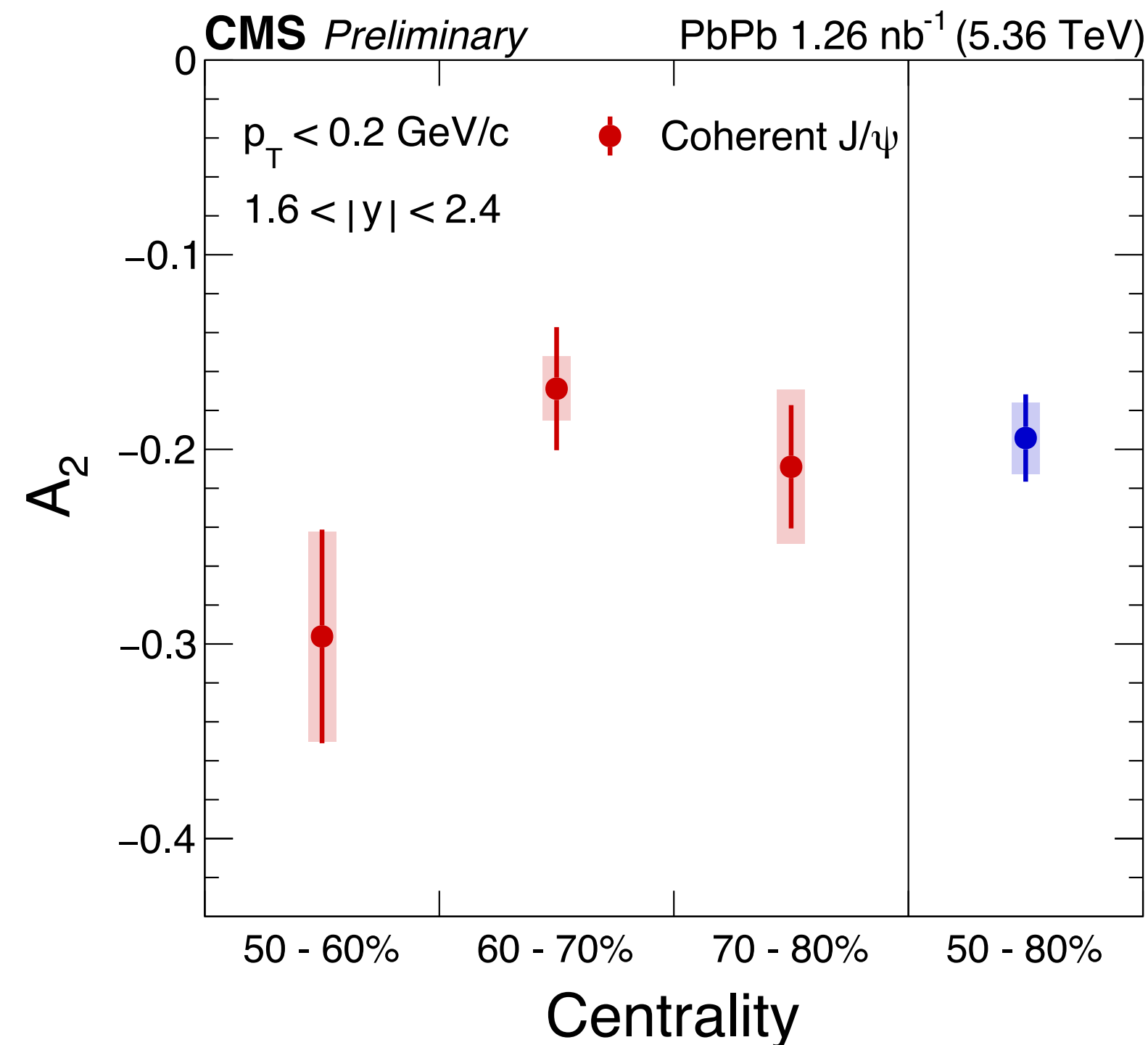
CMS-PAS-HIN-25-006



- 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

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

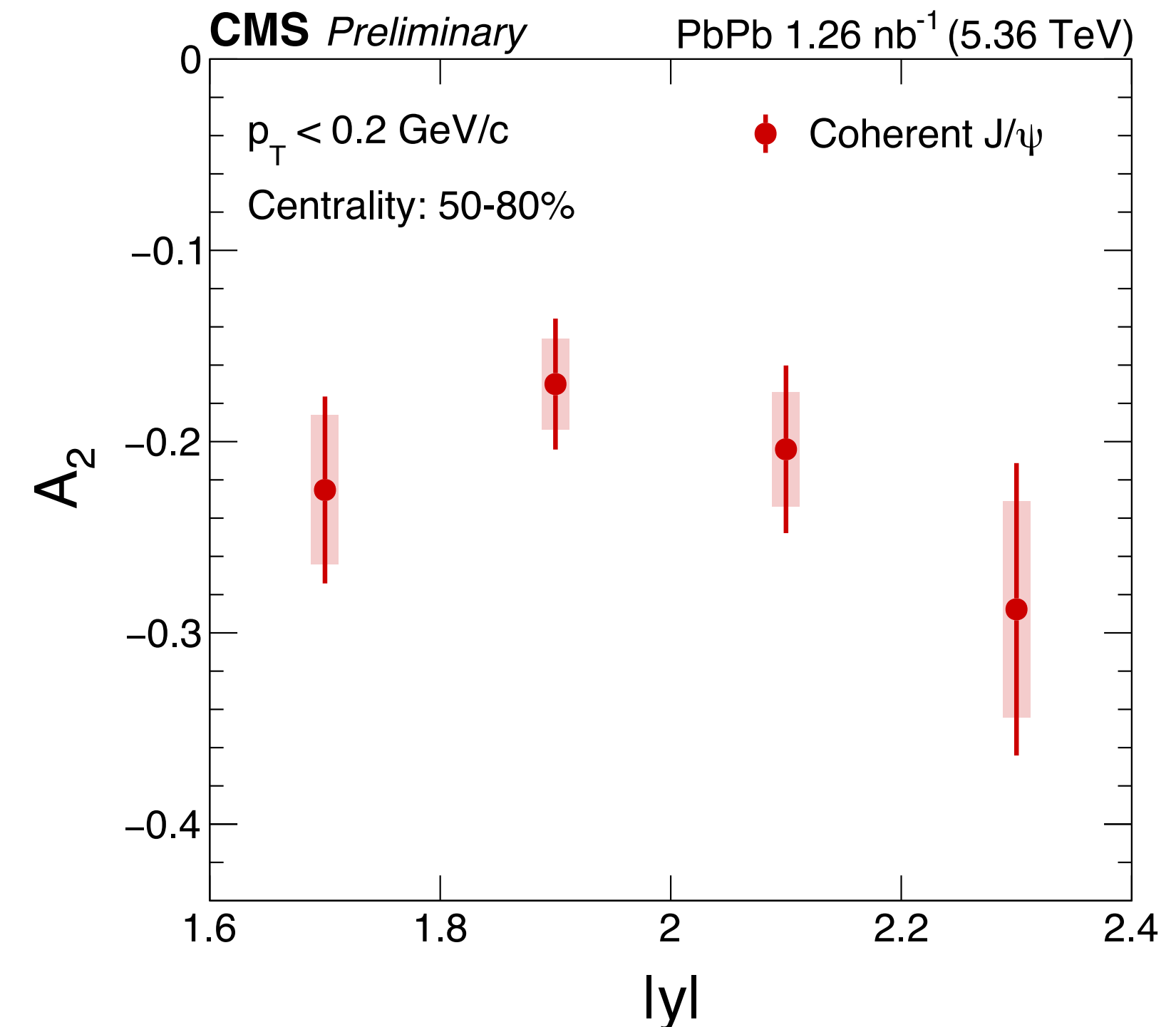
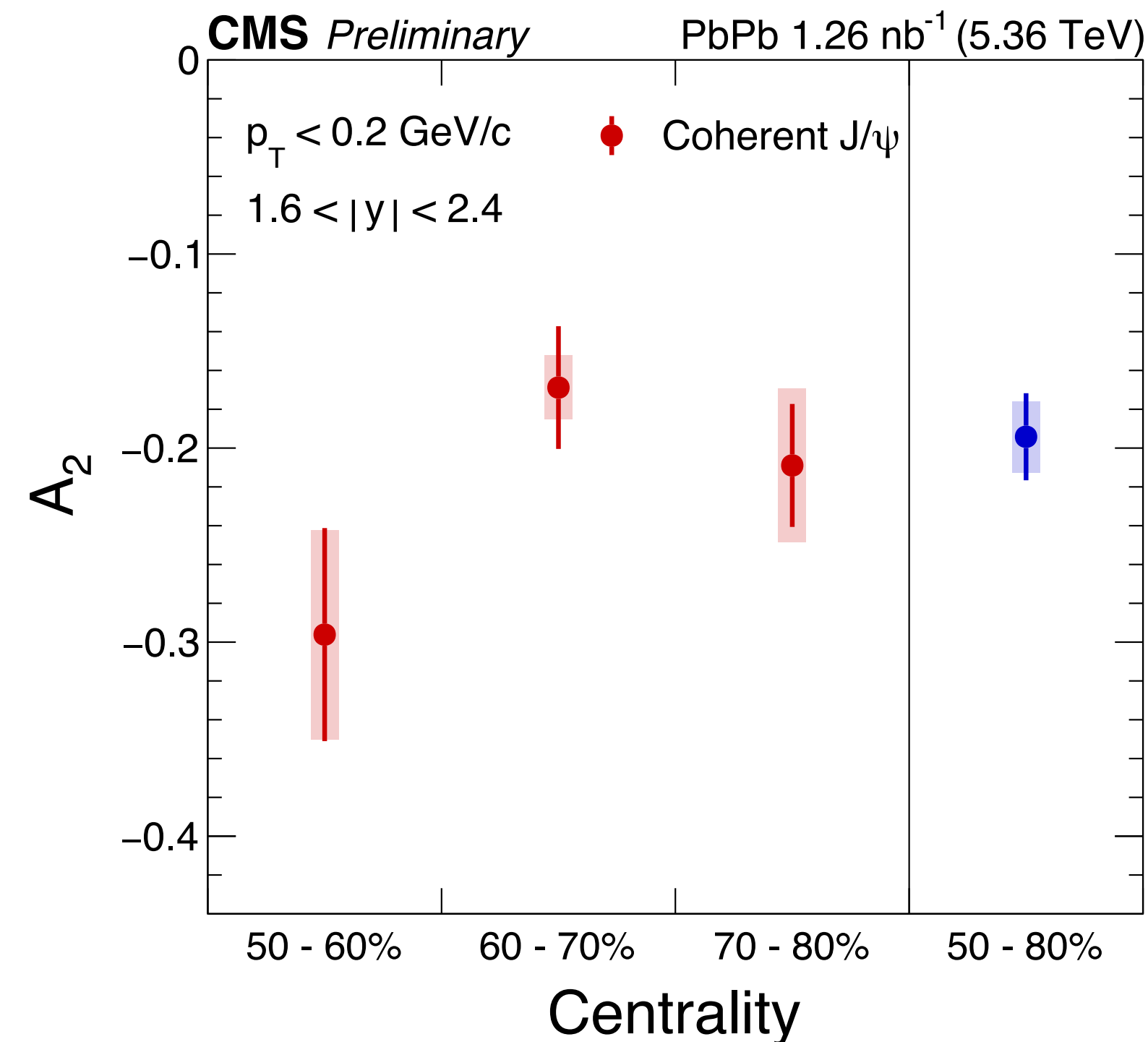
CMS-PAS-HIN-25-006



- 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 $J/\psi \rightarrow \mu^+\mu^-$

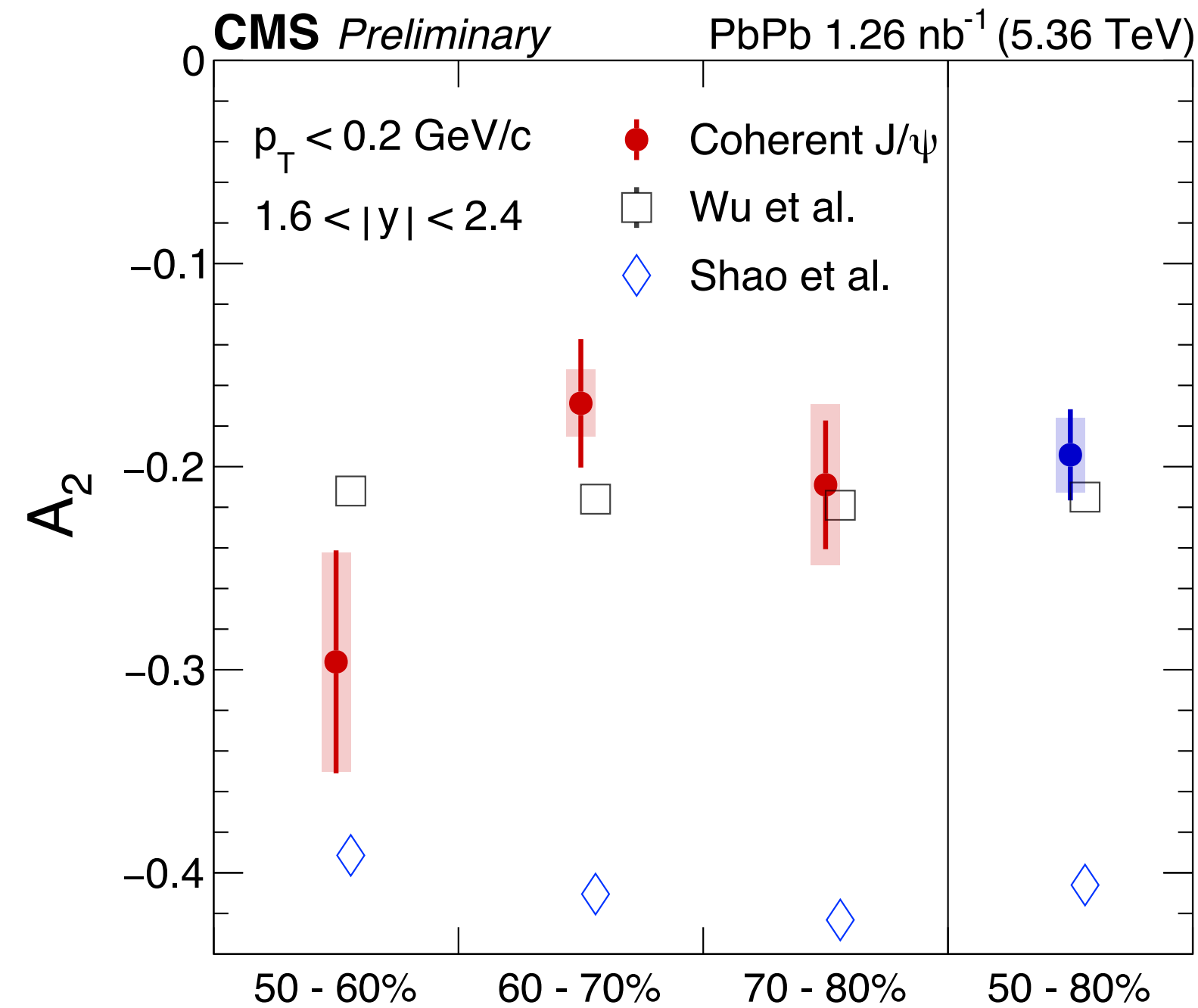
CMS-PAS-HIN-25-006



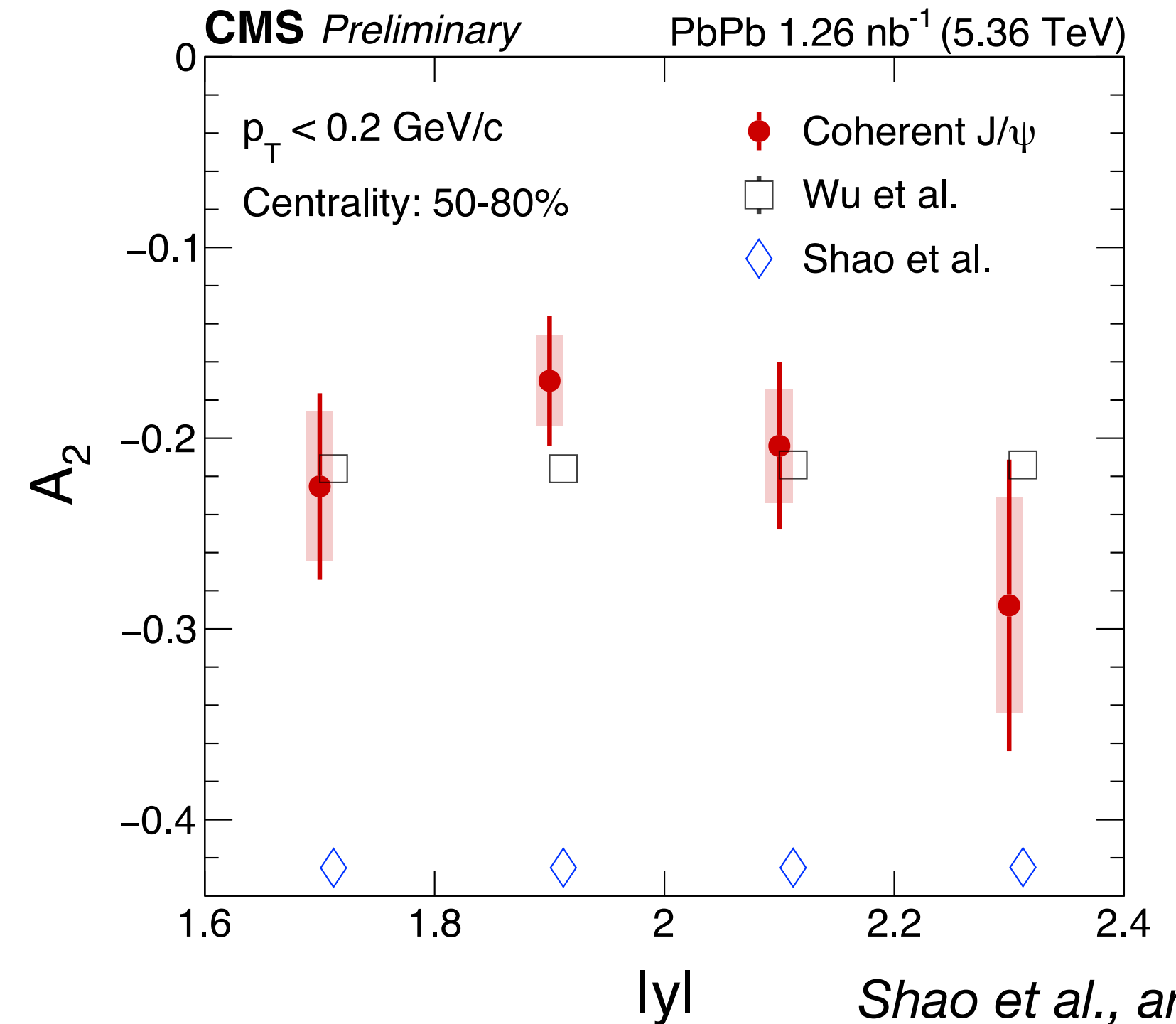
- A negative modulation is observed in coherent  $J/\psi \rightarrow \mu^+\mu^-$  (spin-1/2)
- Provide the first observation of spin-state dependence in azimuthal asymmetry
- Demonstrate the feasibility of a complementary reaction plane probe
- **No significant rapidity dependence in  $1.6 < |y| < 2.4$**

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

CMS-PAS-HIN-25-006



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

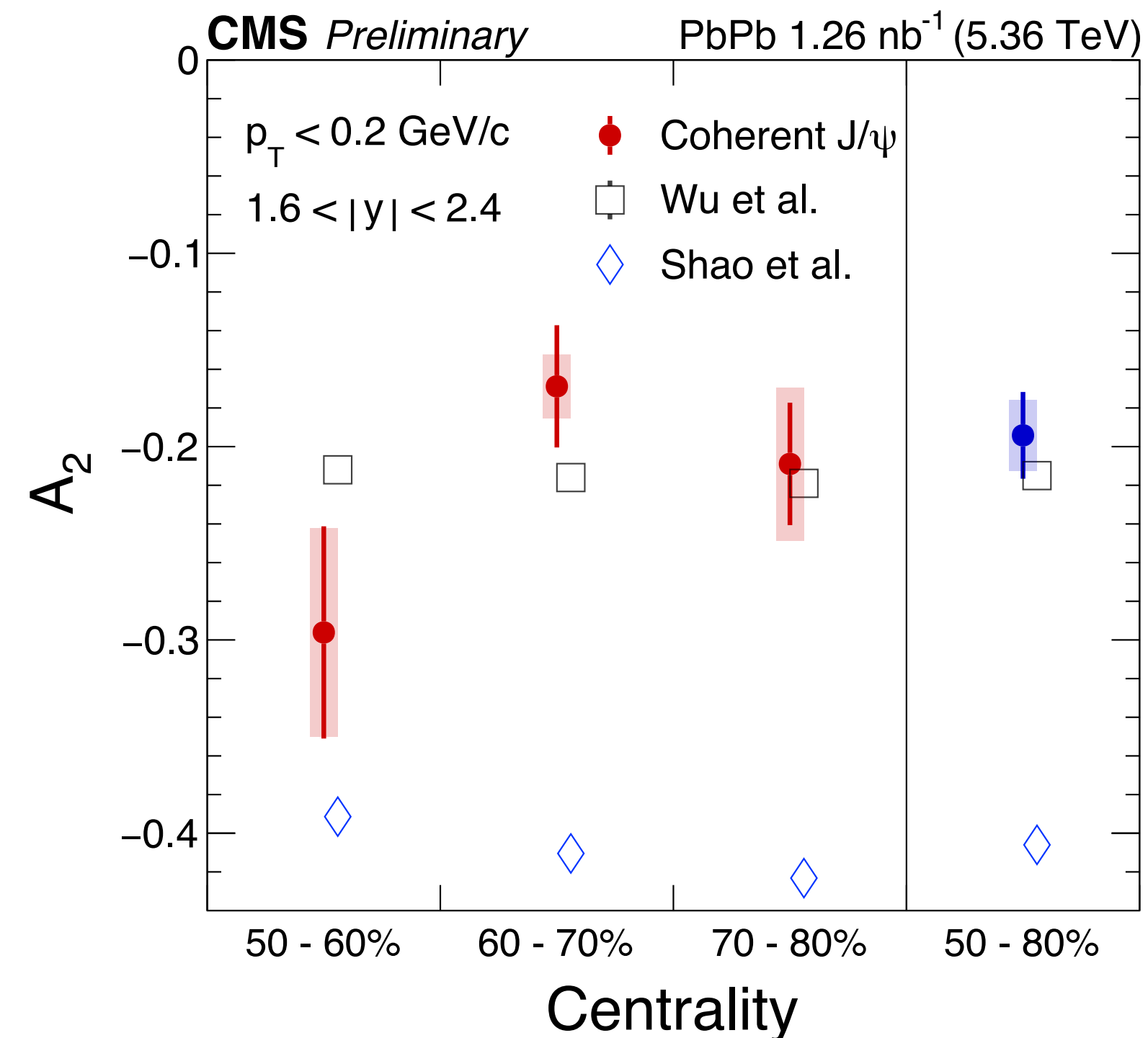
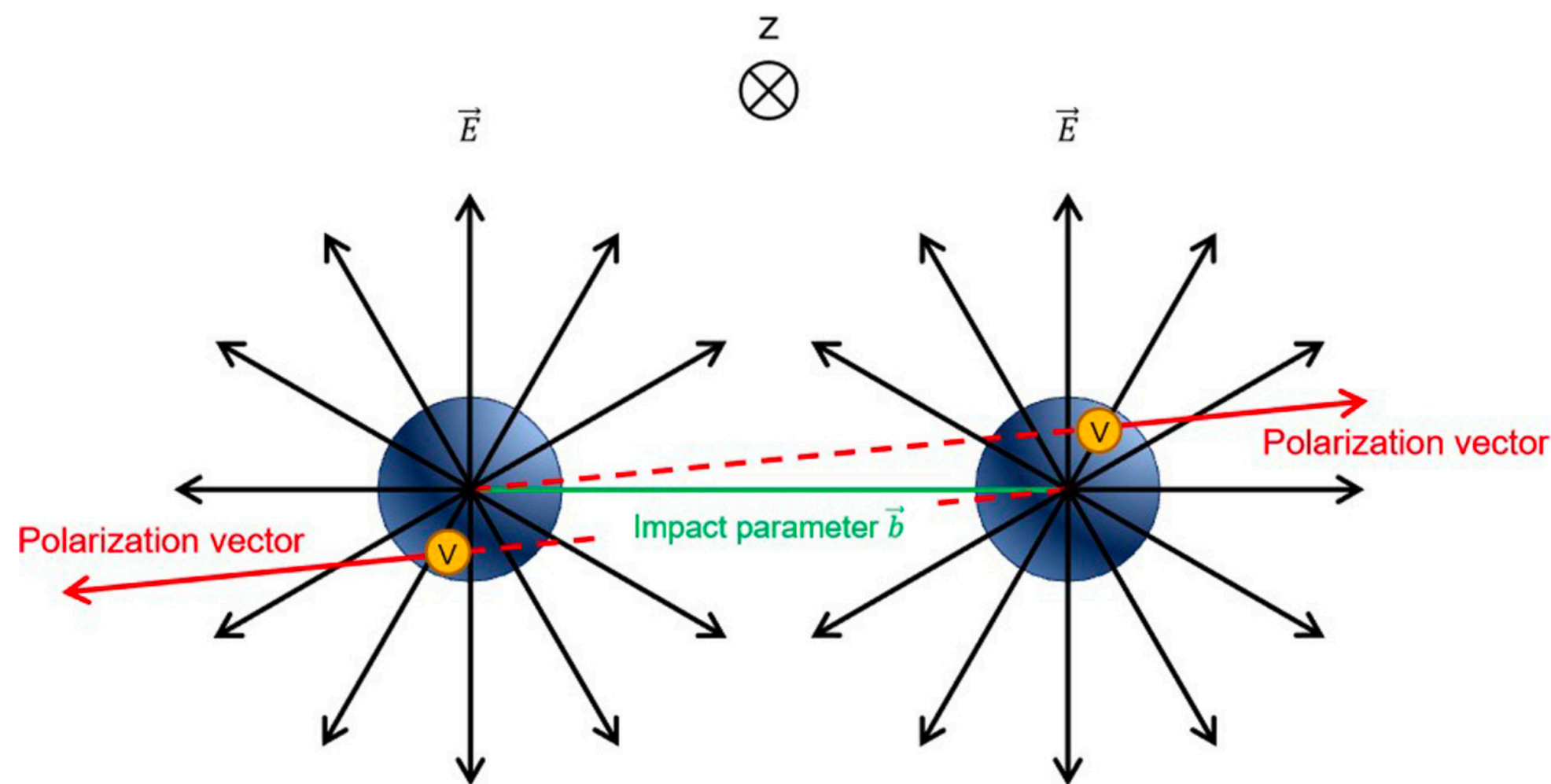


Shao et al., arXiv:2511.17670

- 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

- A negative  $A_2$  of coherent  $J/\psi \rightarrow \mu^+\mu^-$  is observed in hadronic collisions with significance of  $> 5\sigma$
- Provide the direct observation of the spin-state dependence of  $A_2$
- Demonstrate the feasibility of a complimentary reaction plane



# Backups

# Coordinate system

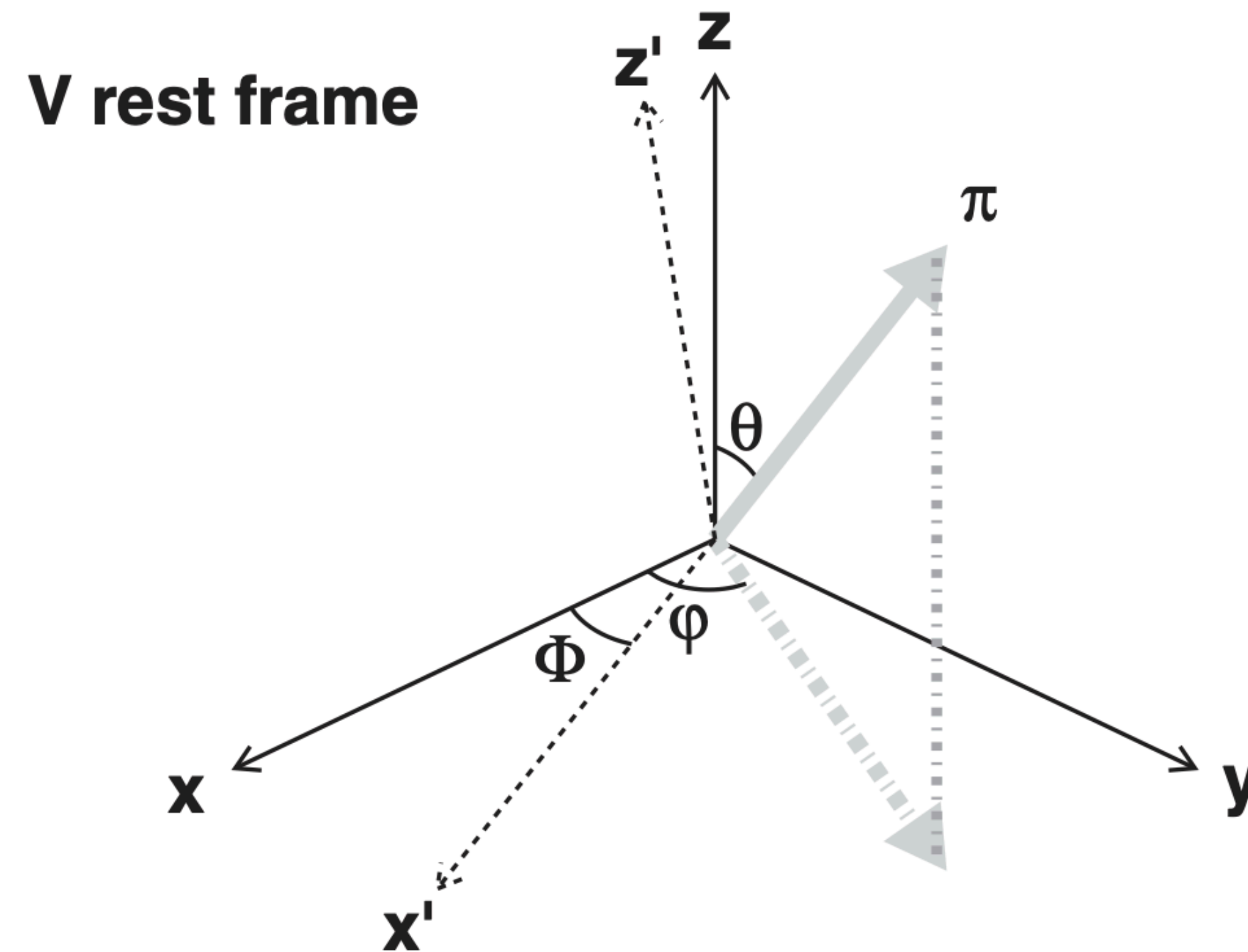


FIG. 1. The coordinate system for the measurement of a two-body decay angular distribution in the vector meson rest frame. The definition of the  $x$ ,  $y$ , and  $z$  axes is described in the text. The  $z'$  axis denotes the beam direction, and the  $x'$  axis represents the linear polarization vector.