NSFC National Natural Science Foundation of China

SHANDONG UNIVERSITY 1901

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STAR

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STAR Heavy Flavor Overview

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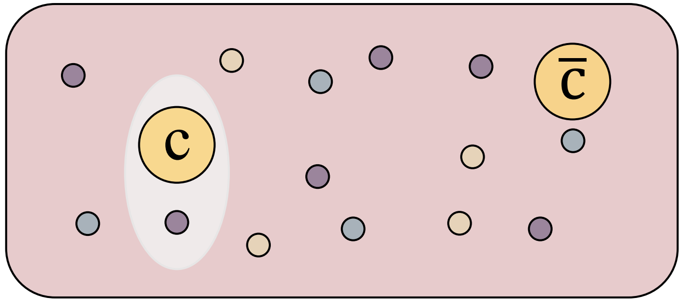
Shandong University (山东大学)

The 9th International Symposium on Heavy Flavor Production in Hadron and Nuclear Collisions

Why heavy flavor?

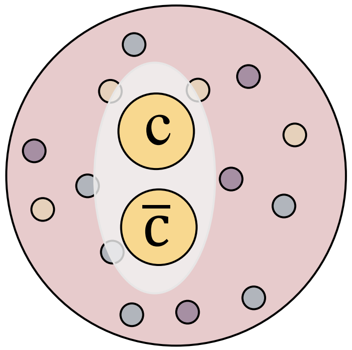
- **Heavy quarks (c and b) are produced in early hard scatterings**
- **Test QCD Predictions**
  - Explore perturbative and non-perturbative QCD
- **Probe Quark-gluon plasma (QGP) Properties**
  - QGP dynamics and spin related effect

Open heavy flavor



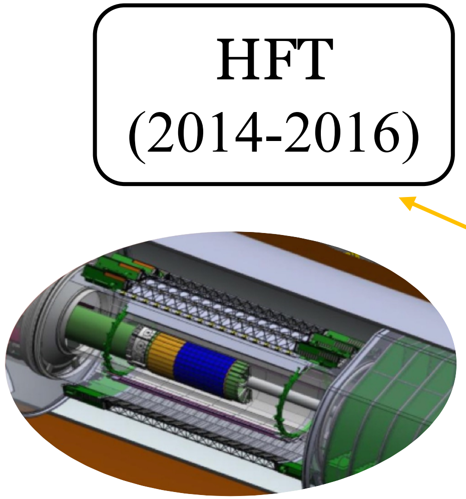
D mesons, etc

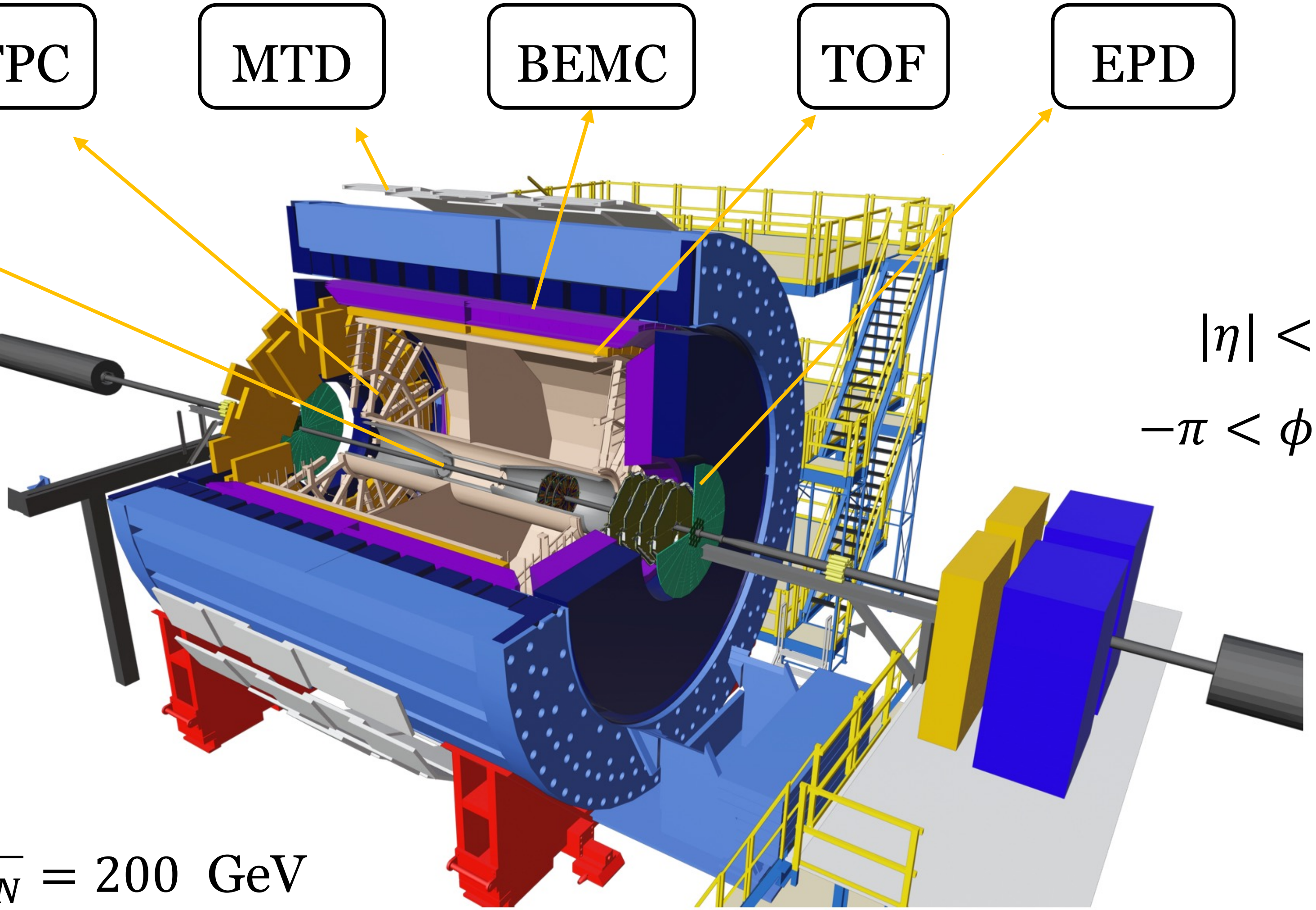
Quarkonium



J/ψ, $\psi(2s)$, etc

The STAR detector





$|\eta| < 1$

$-\pi < \phi < \pi$

Presented here collision species:

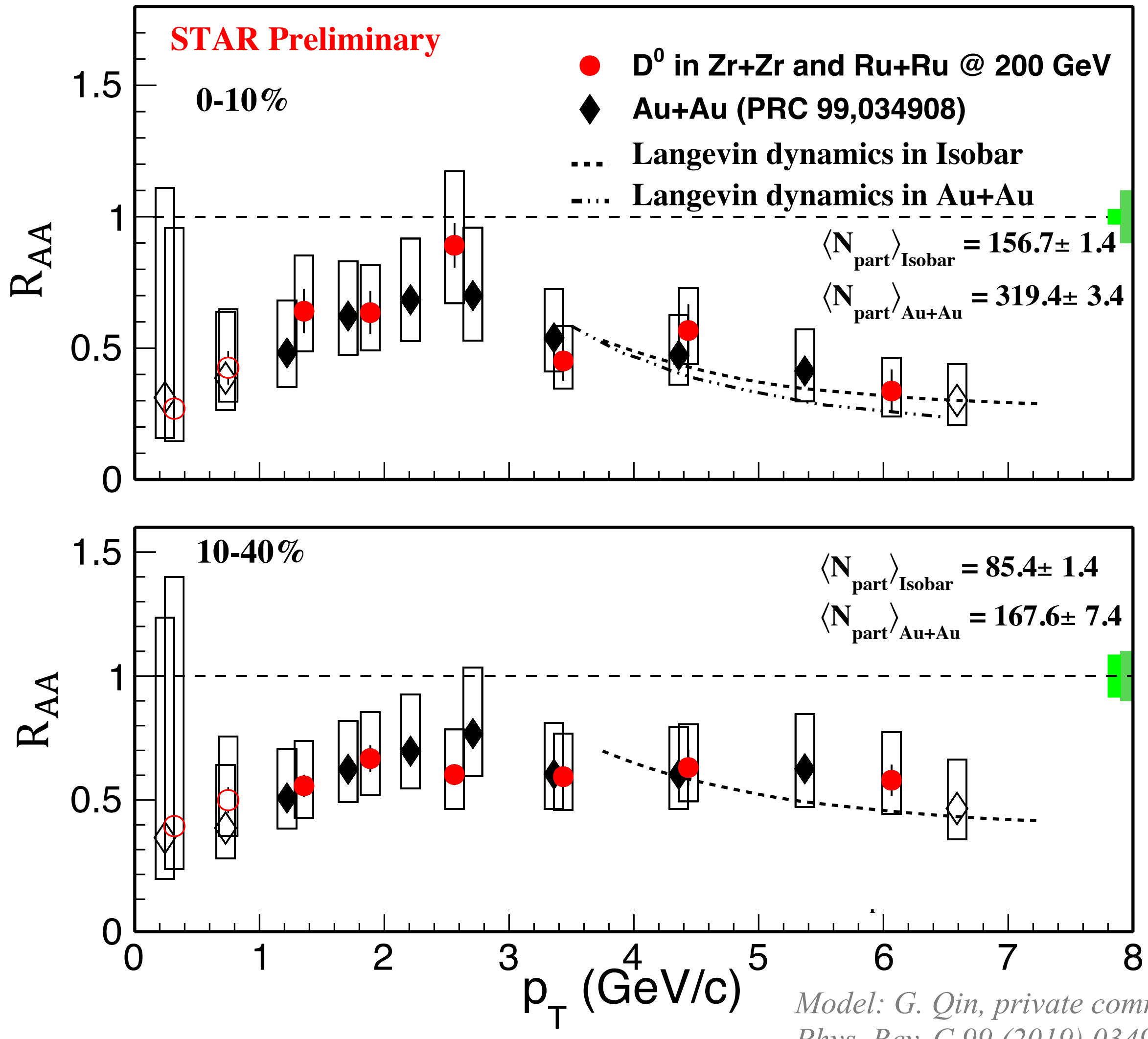
- p+p: $\sqrt{s} = 500$ GeV
- Heavy-ion collisions:
  - Isobar (Ru+Ru, Zr+Zr): $\sqrt{s_{NN}} = 200$ GeV
  - Au+Au: BES-II($\sqrt{s_{NN}} = 14.6 - 27$ GeV), $\sqrt{s_{NN}} = 200$ GeV

Open Heavy Flavor

D^0 suppression

Zr(Ru)+Zr(Ru) 200 GeV

✓ Energy loss in medium



Model: G. Qin, private communication
Phys. Rev. C 99 (2019) 034908

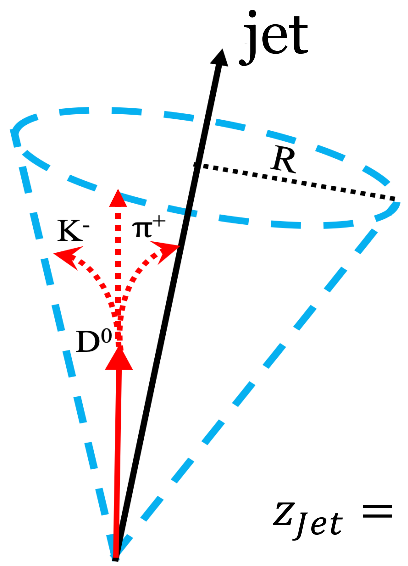
$$R_{AA} = \frac{\sigma_{inel}^{NN} d^2 N_{AA}^{D^0} / dp_T dy}{< N_{coll} > d^2 \sigma_{pp}^{D^0} / dp_T dy}$$

- Similar level of suppression in Isobar and Au+Au at same centrality
- Qualitatively reproduced by energy loss model calculations

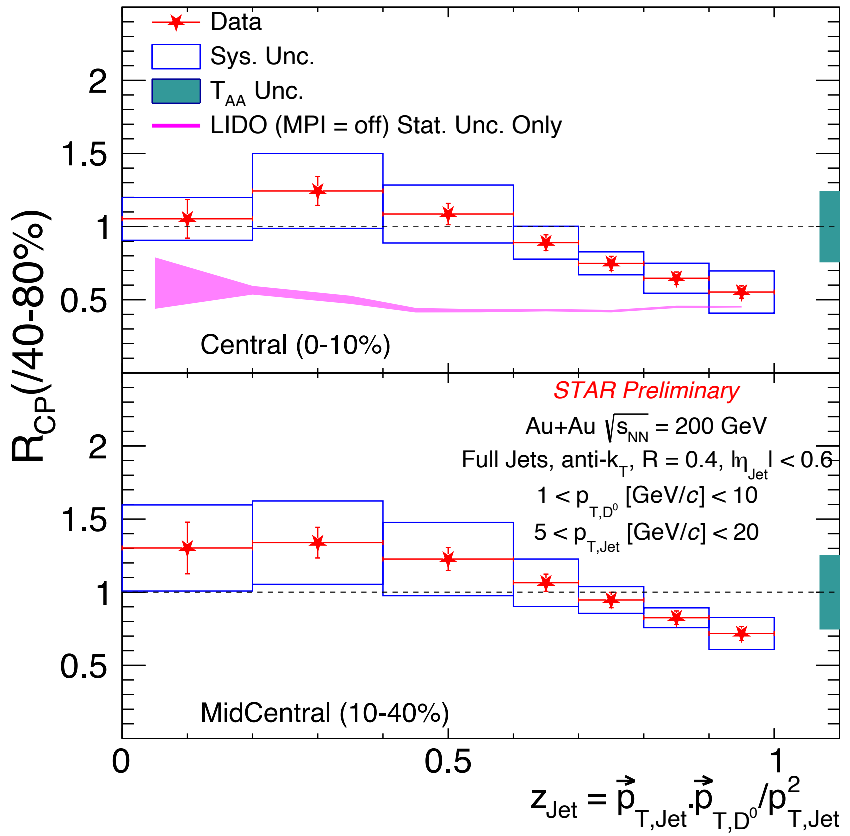
D^0-tagged jet yield and fragmentation

Au+Au 200 GeV

✓ Charm quark fragmentation function in medium



$$z_{Jet} = \frac{\vec{p}_{T,Jet} \cdot \vec{p}_{T,D^0}}{p^2_{T,Jet}}$$



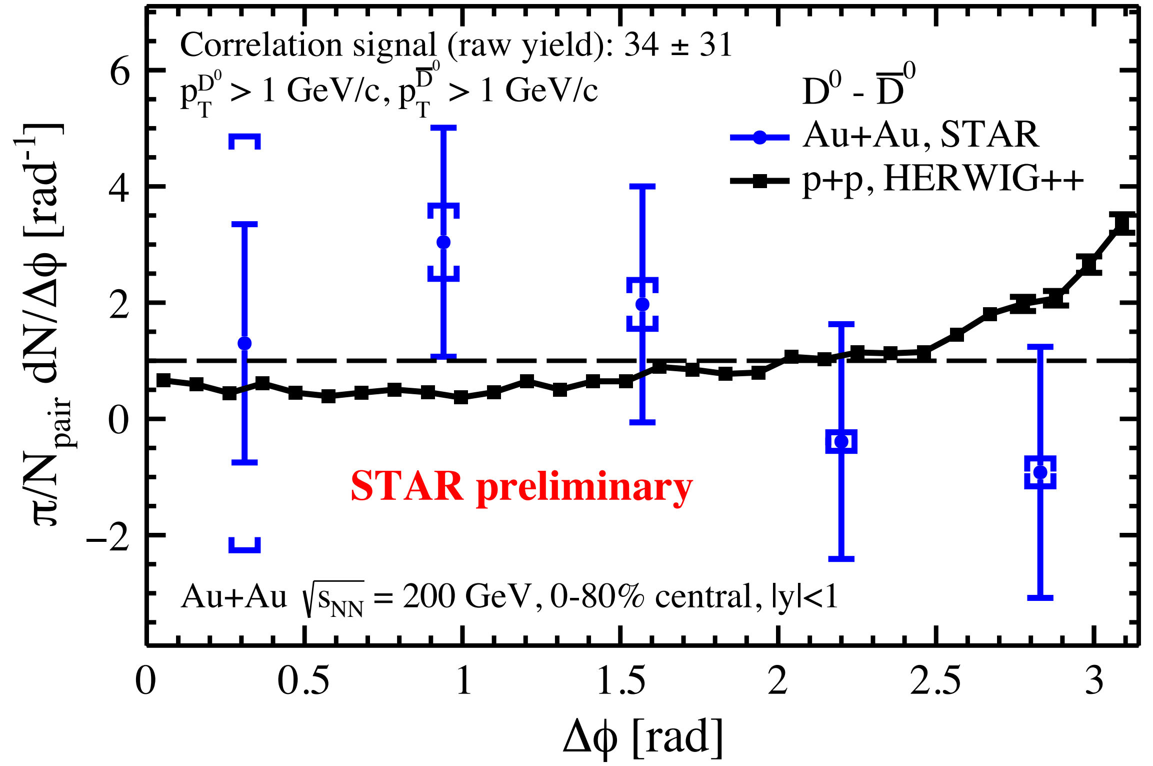
➢ Hard-fragmented jets (large z) are more suppressed than soft-fragmented ones (small z)

D^0-$\overline{D}^0$ azimuthal correlations

Au+Au 200 GeV

✓ Energy loss and thermalization in medium → weaker correlation at $\Delta\varphi \approx \pi$ in HIC

Phys. Lett. B 647 (2007) 366–370

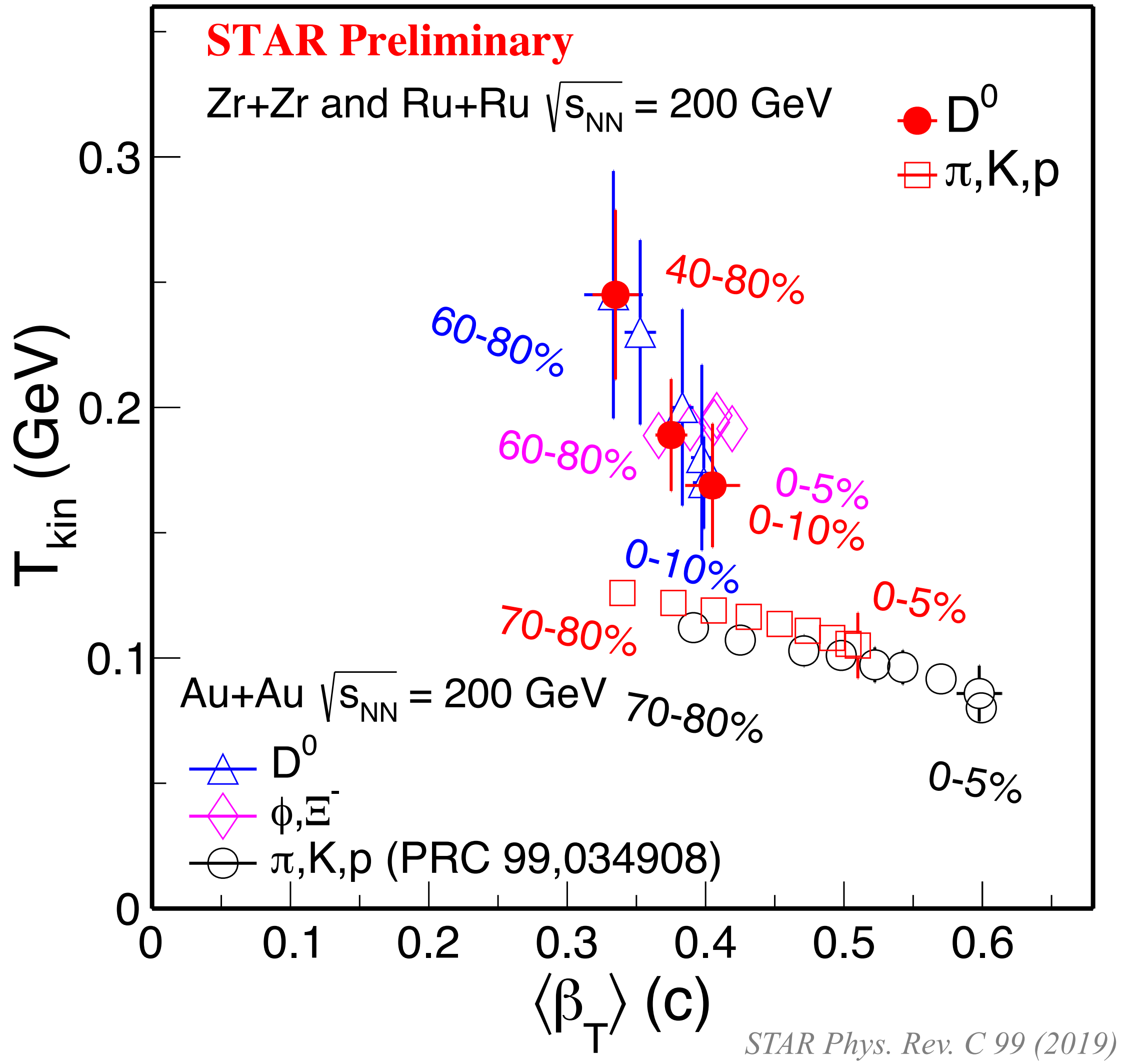


➢ No azimuthal correlation is seen for D^0-$\overline{D}^0$ pairs within large uncertainties

➢ Need better precision

D^0 freeze-out property

Zr(Ru)+Zr(Ru) 200 GeV



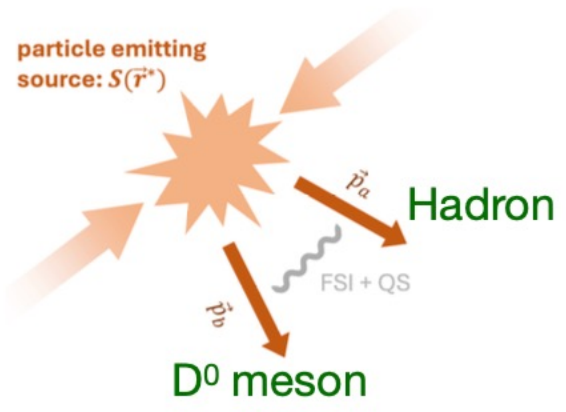
STAR Phys. Rev. C 99 (2019) 034908

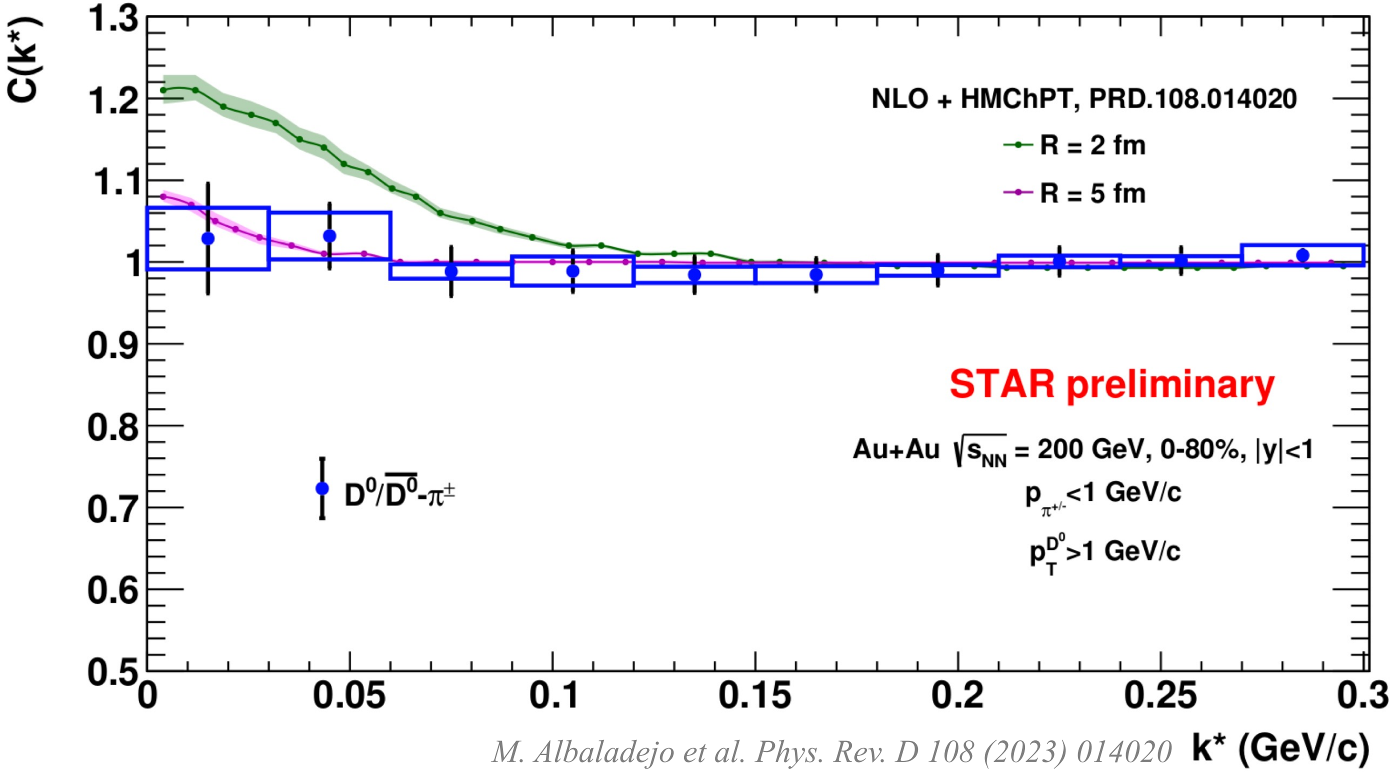
- D^0 freezes out earlier than light hadrons
- No significant collision system dependence in isobar and Au+Au collisions

D^0-$\pi^{\pm}$ femtoscopic correlations

Au+Au 200 GeV

✓ Freeze-out dynamics and final state interaction





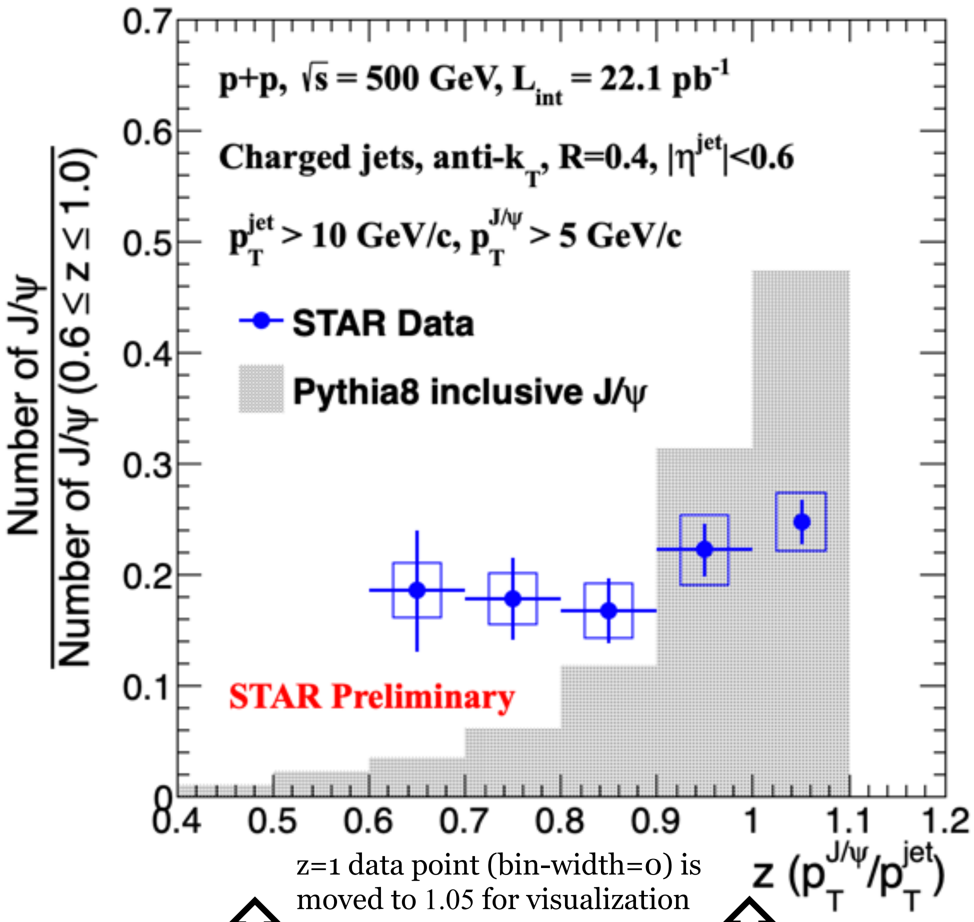
M. Albaladejo et al. Phys. Rev. D 108 (2023) 014020

➢ No significant correlations, but also consistent with theoretical predictions with emission source size of 5 fm or larger within uncertainty

Quarkonium

J/ψ production mechanism

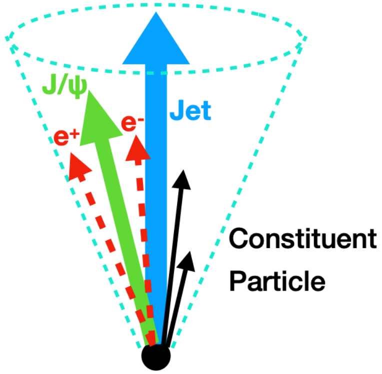
p+p 500 GeV



z=1 data point (bin-width=0) is moved to 1.05 for visualization

J/ψ + many charged jet activity

J/ψ + little charged jet activity



Model with different LDMEs describe the J/ψ p_T spectrum well, but differ in J/ψ fragmentation predictions.

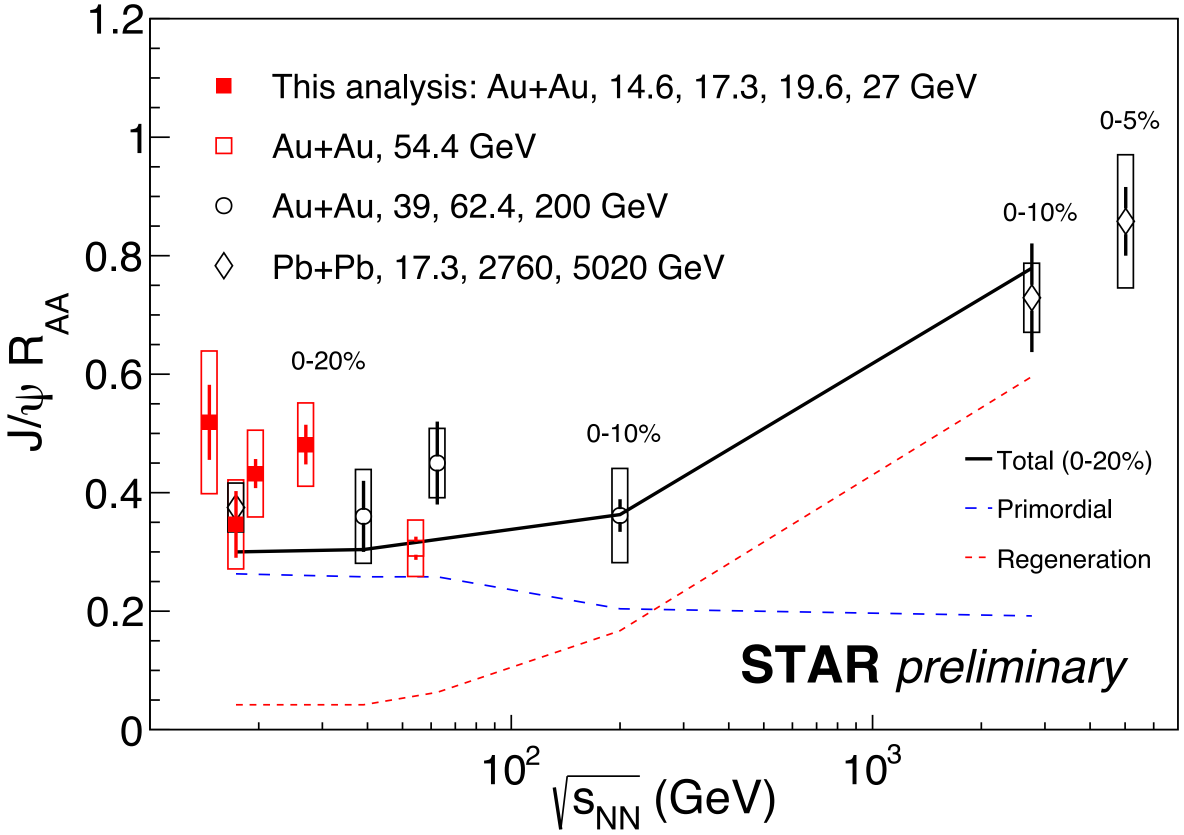
Phys.Rev. Lett. 119 (2017) 032001

- No significant z dependence observed in data within uncertainties for z <1
- Data show less isolated production than PYTHIA8

J/ψ R_{AA} vs. collision energy

Au +Au BES-II (14.6-27) GeV

✓ Hot and cold nuclear matter effect



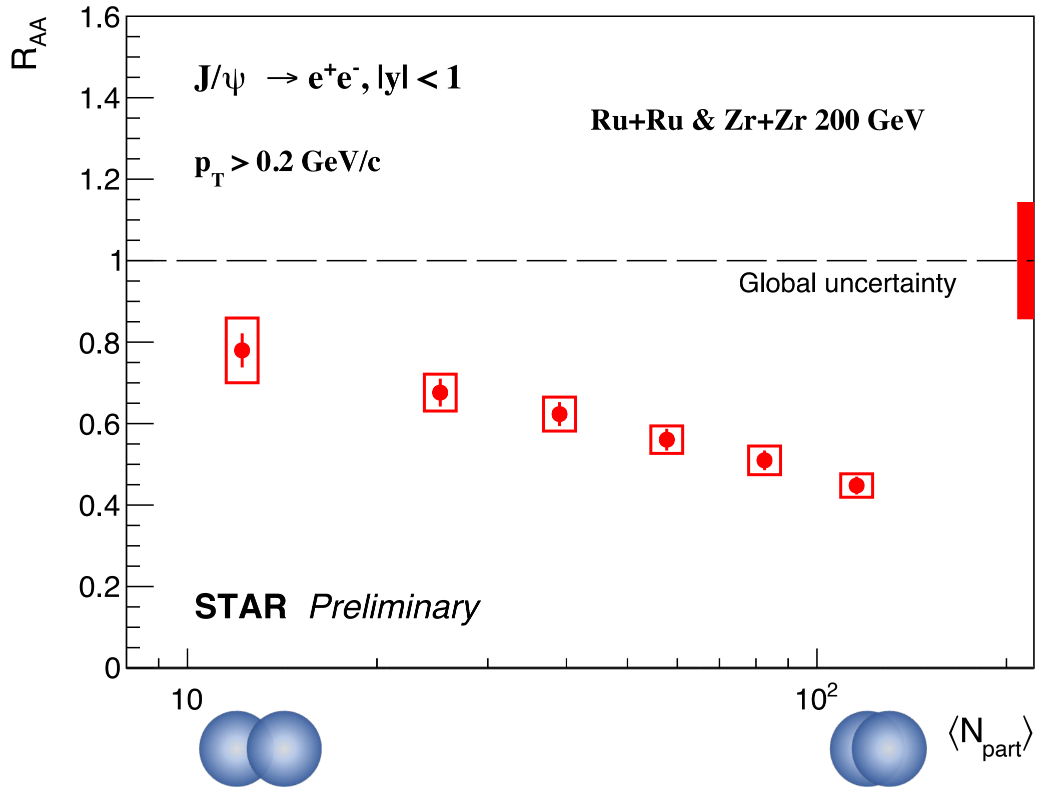
X. Zhao, R. Rapp, Phys. Rev. C 82 (2010) 064905 (private communication).
L. Kluberg, Eur. Phys. J. C 43 (2005) 145.

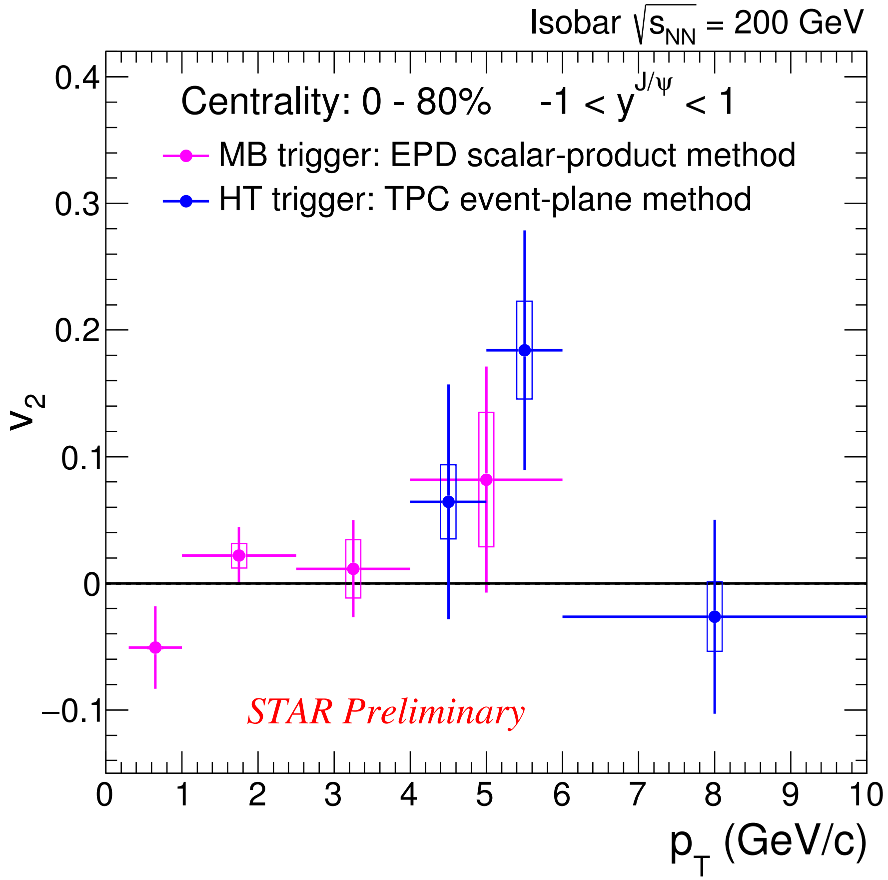
- No significant energy dependence of J/ψ R_{AA} below 200 GeV
- The observed energy dependence is qualitatively described by the transport model

J/ψ R_{AA} and v_2 in isobar collisions

Zr(Ru)+Zr(Ru) 200 GeV

✓ J/ψ suppression and regeneration in HIC



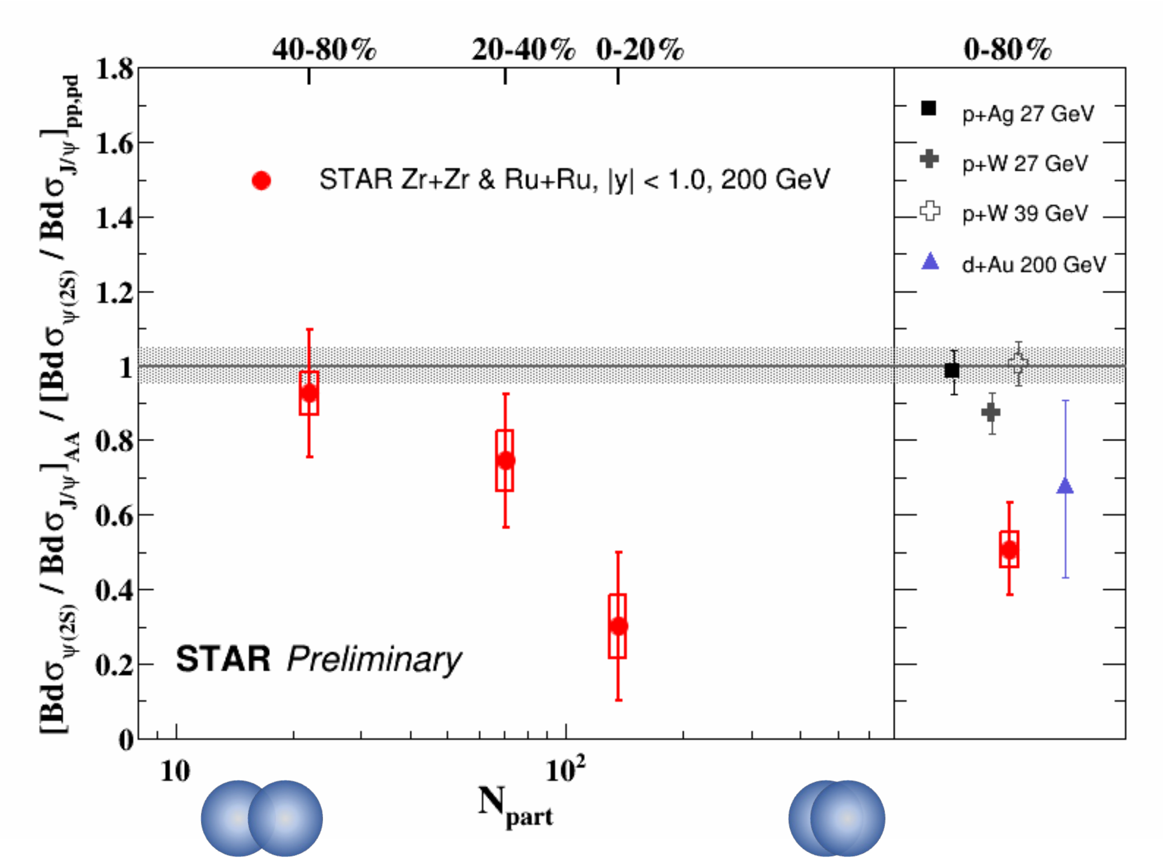


- ➢ Indication of small regeneration effect in isobar collisions?
- ➢ Clear J/ψ suppression with little v_2

Charmonium sequential suppression

Zr(Ru)+Zr(Ru) 200 GeV

✓ QGP thermal properties at RHIC



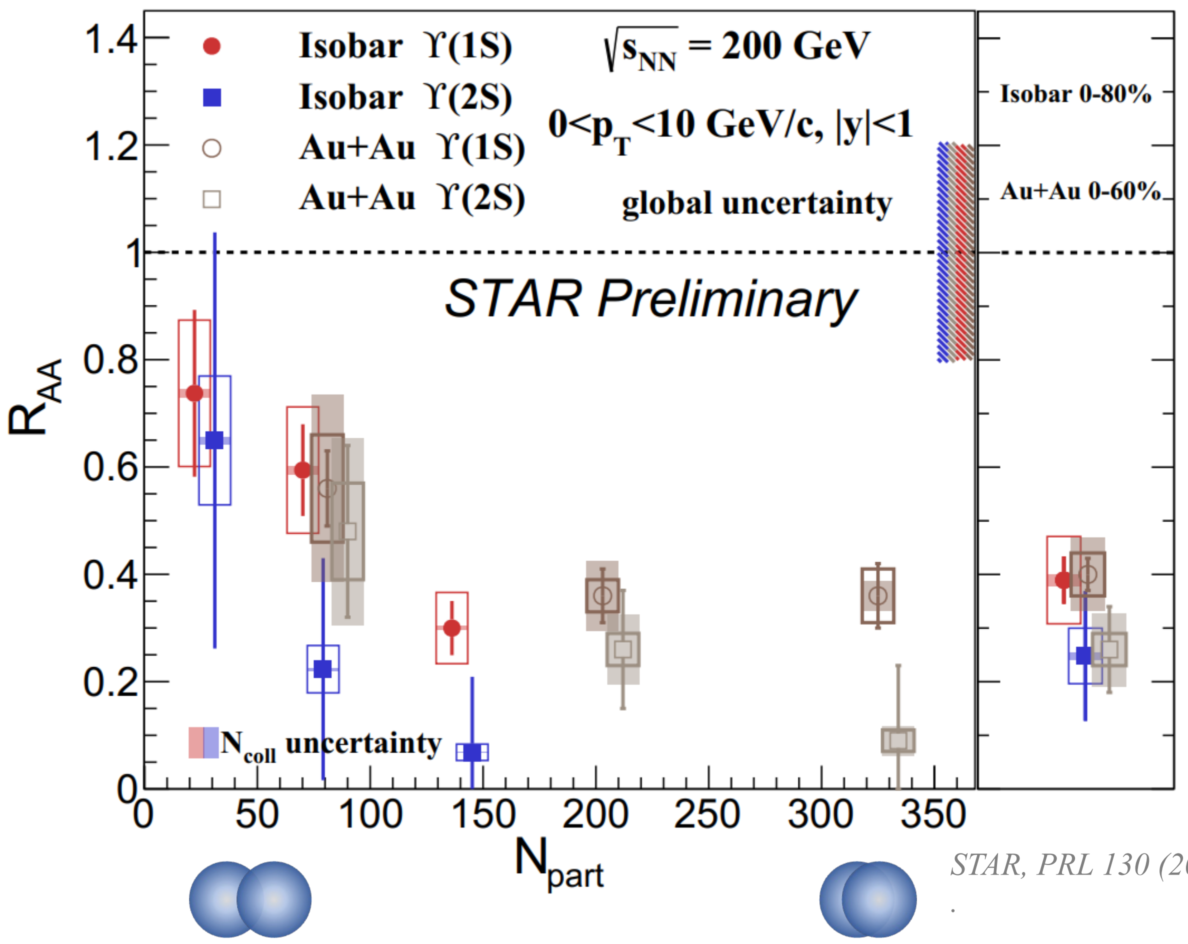
- $\psi(2S)$ over J/ψ double ratio is smaller than that in p+A collisions
- First observation of charmonium sequential suppression in HIC at RHIC (3.5σ, 0-80%)

PHENIX, Phys.Rev.D, 85,092004 (2012)
NA51, Phys.Lett.B 438 (1998) 35-40
ISR, Nucl.Phys.B 142 (1978) 29

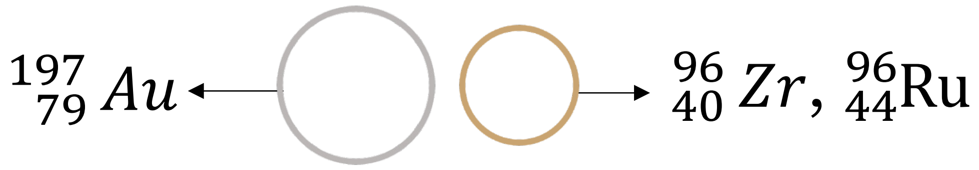
Bottomonium suppression

Zr(Ru)+Zr(Ru) 200 GeV

✓ Smaller regeneration contribution compared to charmonium



STAR, PRL 130 (2023) 112301

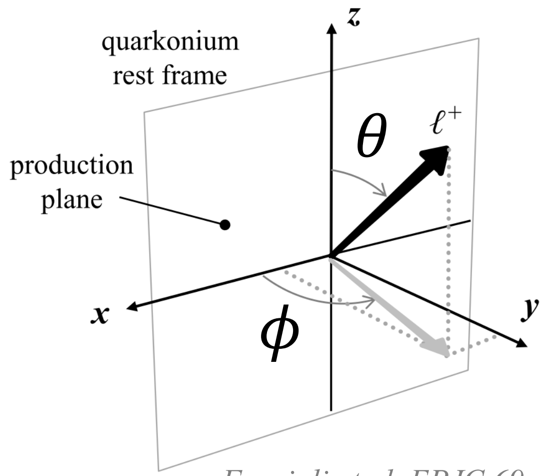


- Clear suppression is observed for $\Upsilon(1s)$ and $\Upsilon(2s)$
- Consistent results in isobar and Au+Au at 200 GeV collisions at similar $\langle N_{part} \rangle$

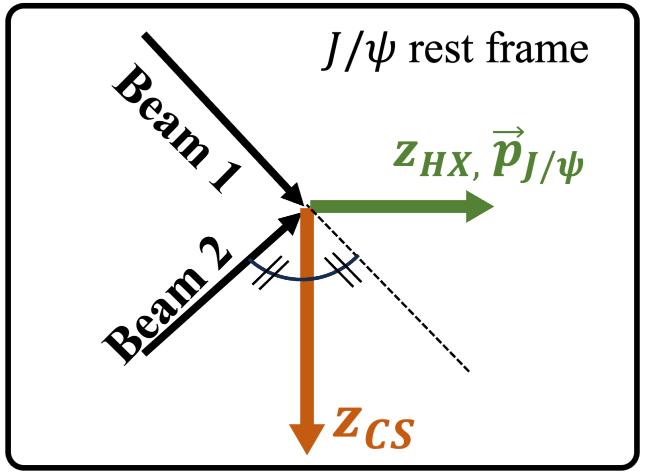
J/ψ polarization

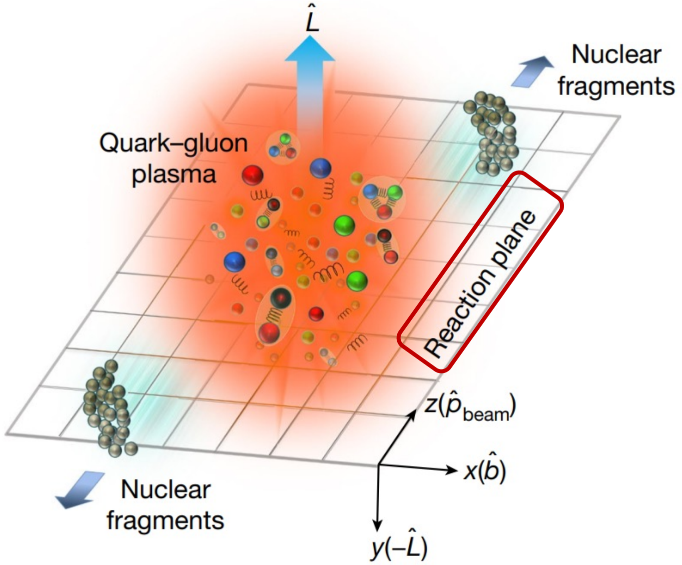
✓ Angular distribution of the decayed leptons:

$$W(\cos\theta,\phi) \propto 1 + \lambda_\theta \cos^2\theta + \lambda_\phi \sin^2\theta\cos2\phi + \lambda_{\theta\phi}\sin2\theta\cos\phi$$



Faccioli et al, EPJC 69: 657-673 (2010)





STAR, Nature 614, 244-248 (2023)

✓ Definition of the axes

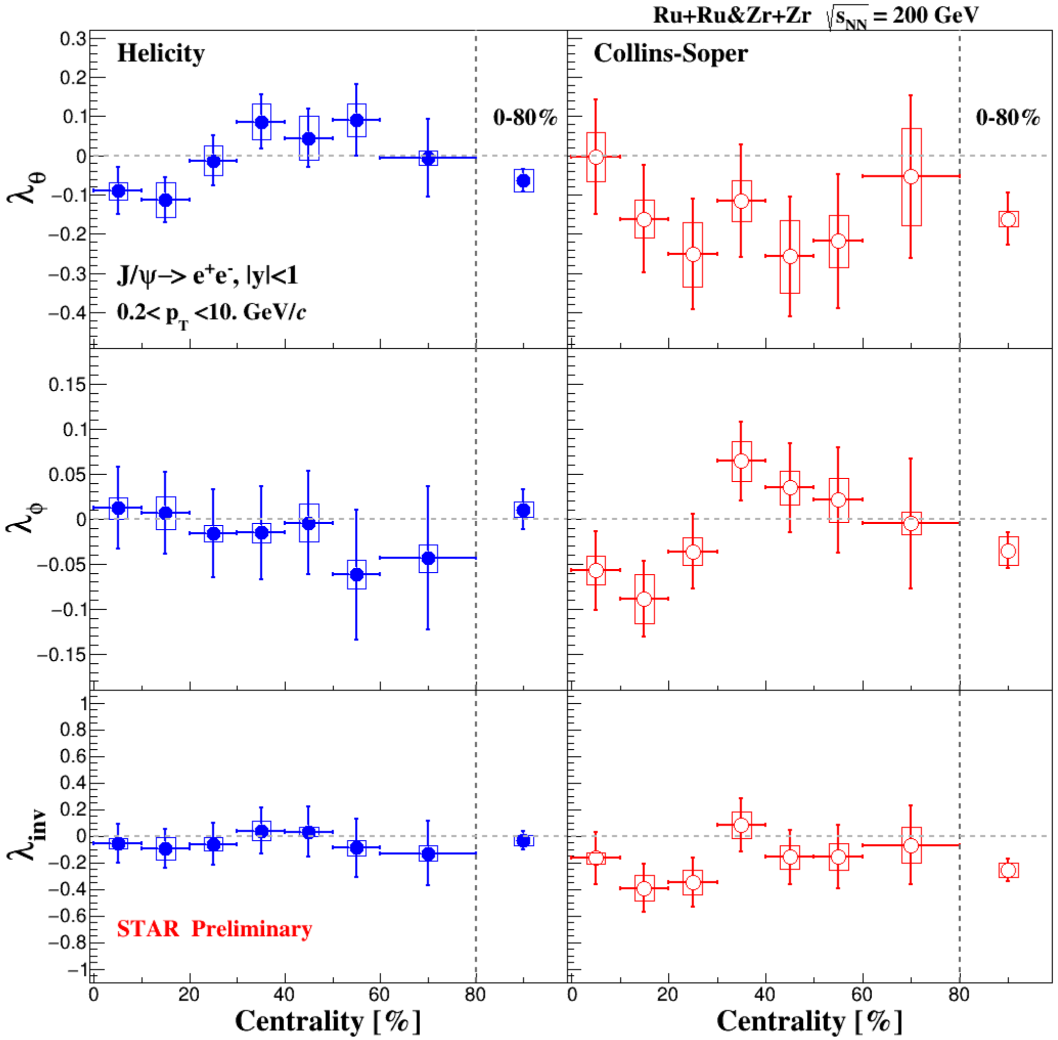
- **Helicity frame (HX)**: J/ψ momentum direction
- **Collins-Soper frame (CS)**: bisector of angle between beams
- **"Event plane"**: axis orthogonal to reaction plane

$$\lambda_\theta = \frac{1-3\rho_{00}}{1+\rho_{00}}$$

J/ψ polarization vs. centrality

Zr(Ru)+Zr(Ru) 200 GeV

✓ Sequential melting of charmonium suppresses feed-down contribution($\psi(2s), \chi_{cJ}$)



- No significant centrality dependence
- $\lambda_\theta, \lambda_\phi$ are consistent with zero
- Consistent λ_{inv} for the two frames, as expected

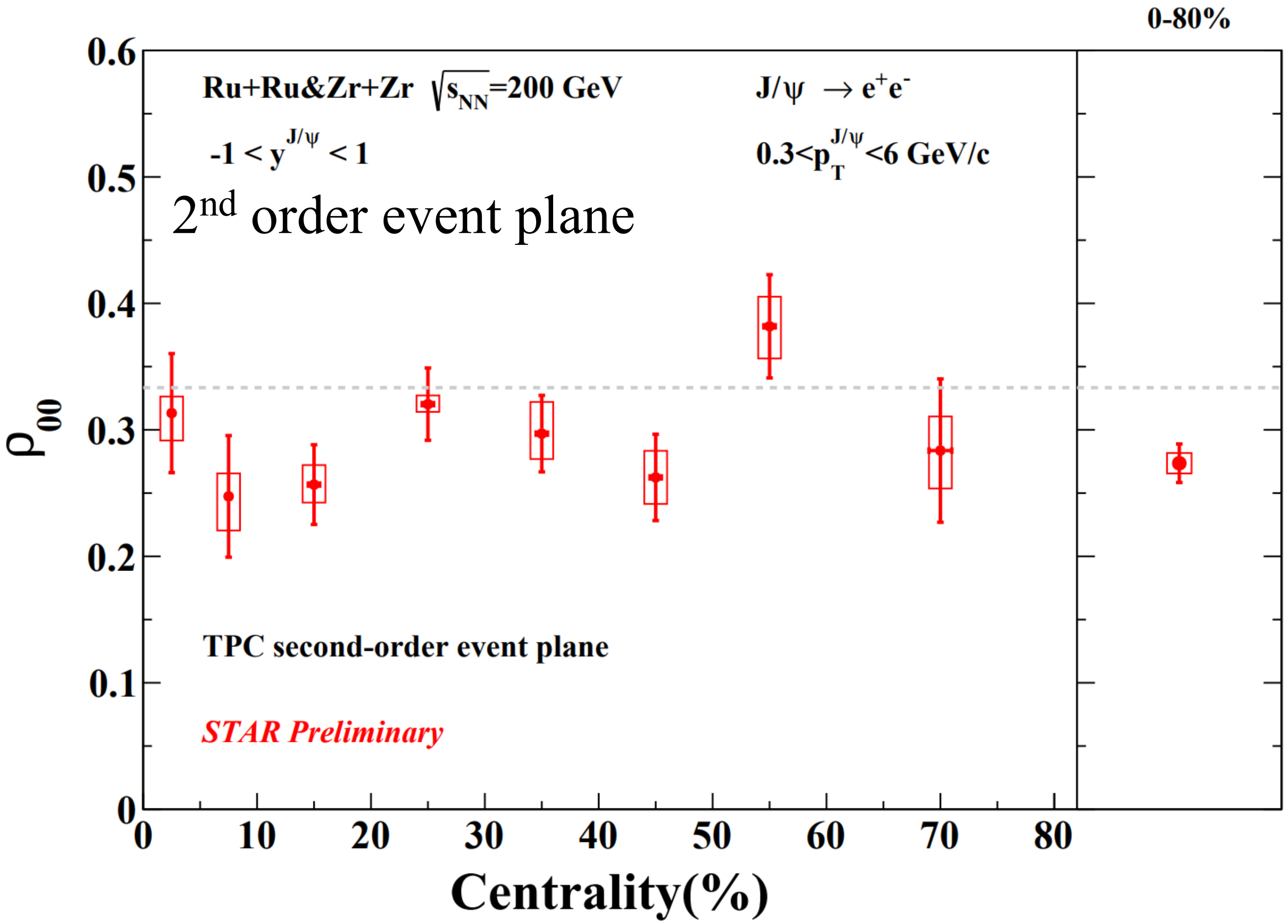
$$\lambda_{inv} = \frac{\lambda_\theta + 3\lambda_\phi}{1 - \lambda_\phi}$$

J/ψ global spin alignment at RHIC

Zr(Ru)+Zr(Ru) 200 GeV

- ✓ ϕ meson $\rho_{00} > 1/3$ at RHIC
- ✓ J/ψ $\rho_{00} < 1/3$ at LHC forward rapidity

How about J/ψ ρ_{00} at RHIC energy?

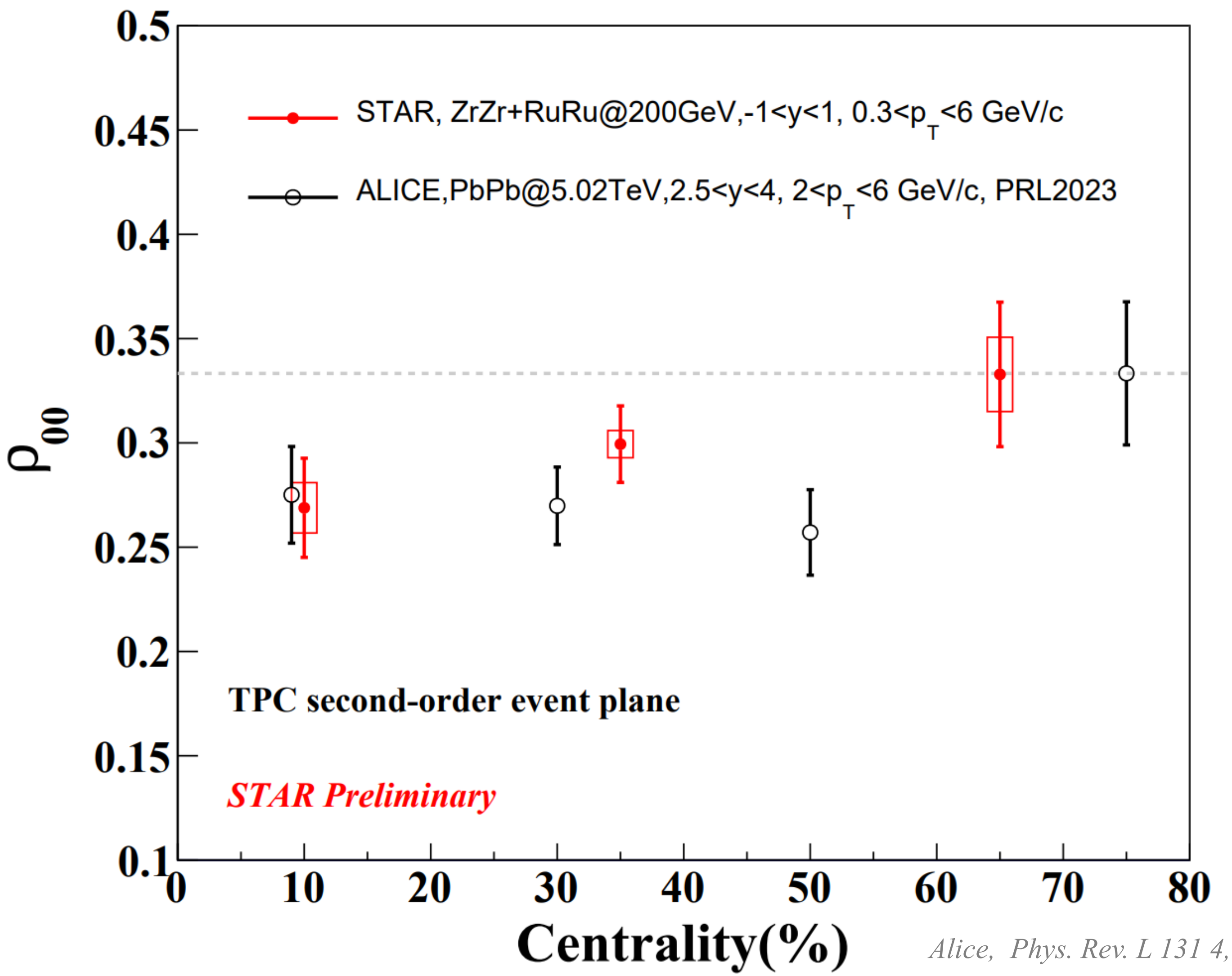


- ➢ ρ_{00} lower than 1/3 with a significance of 3.5 σ using 2nd order event plane

STAR, Nature 614, 244-248 (2023)
Alice, Phys. Rev. L 131 4, 042303 (2023)

J/ψ global spin alignment: RHIC vs. LHC

Zr(Ru)+Zr(Ru) 200 GeV



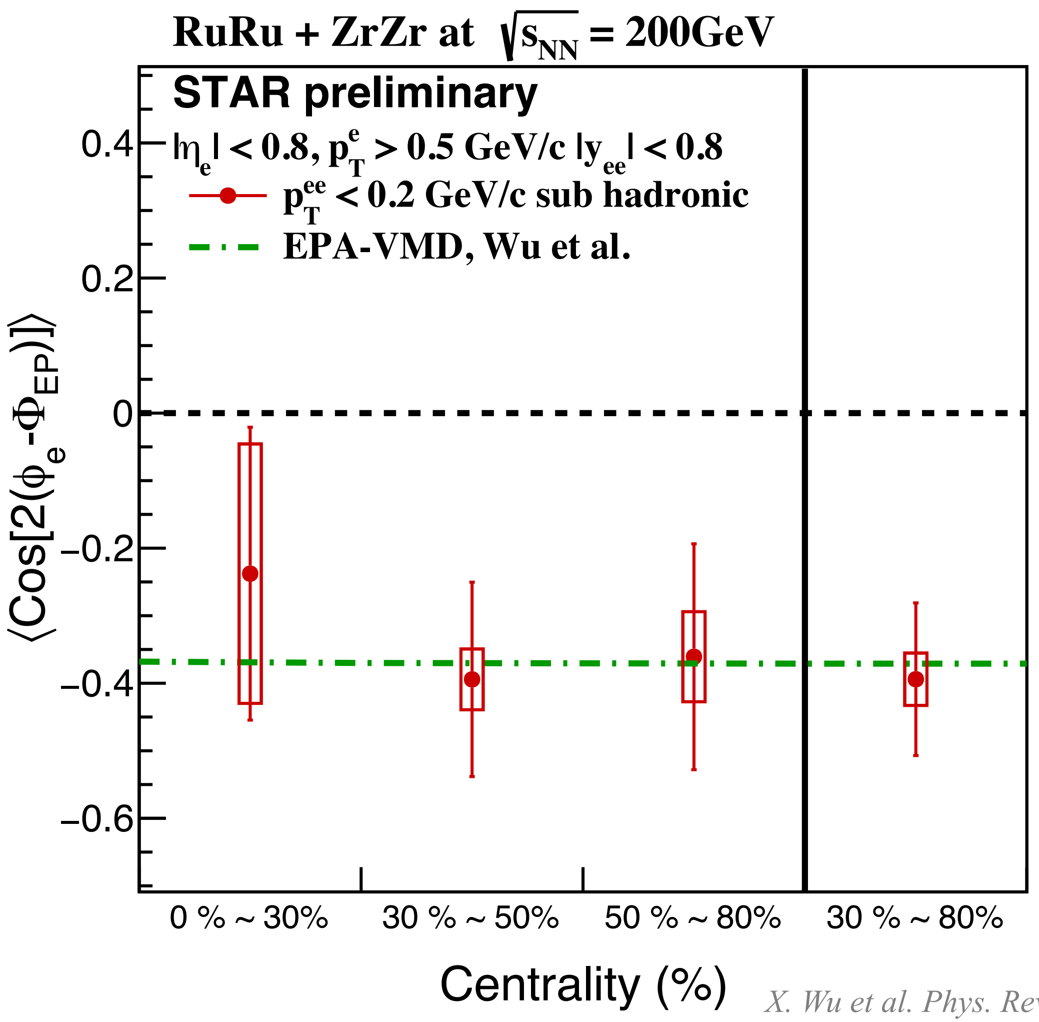
Alice, Phys. Rev. L 131 4, 042303 (2023)

- The ρ_{00} at RHIC energy is comparable to LHC results, with different collision energies, systems and rapidities

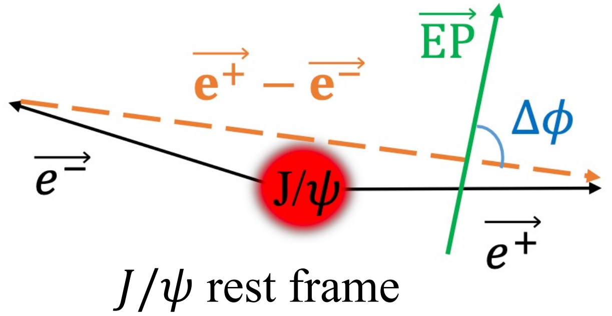
Photon-induced J/ψ decay anisotropy

Zr(Ru)+Zr(Ru) 200 GeV

✓ Photon-induced J/ψ decay anisotropy expected due to linearly polarized photon



X. Wu et al. Phys. Rev. Res. 4, L042048 (2022)



$\Delta\phi[e^+ - e^-, \Psi_{EP}^{2nd}]$

Ψ_{EP}^{2nd}: second order TPC event plane

➢ Photon-induced $\cos(2\Delta\phi)$ modulation with a significance of ~3.3 σ

➢ Measured modulation consistent with EPA-VMD model prediction

Summary and outlook

✓ Open heavy flavor

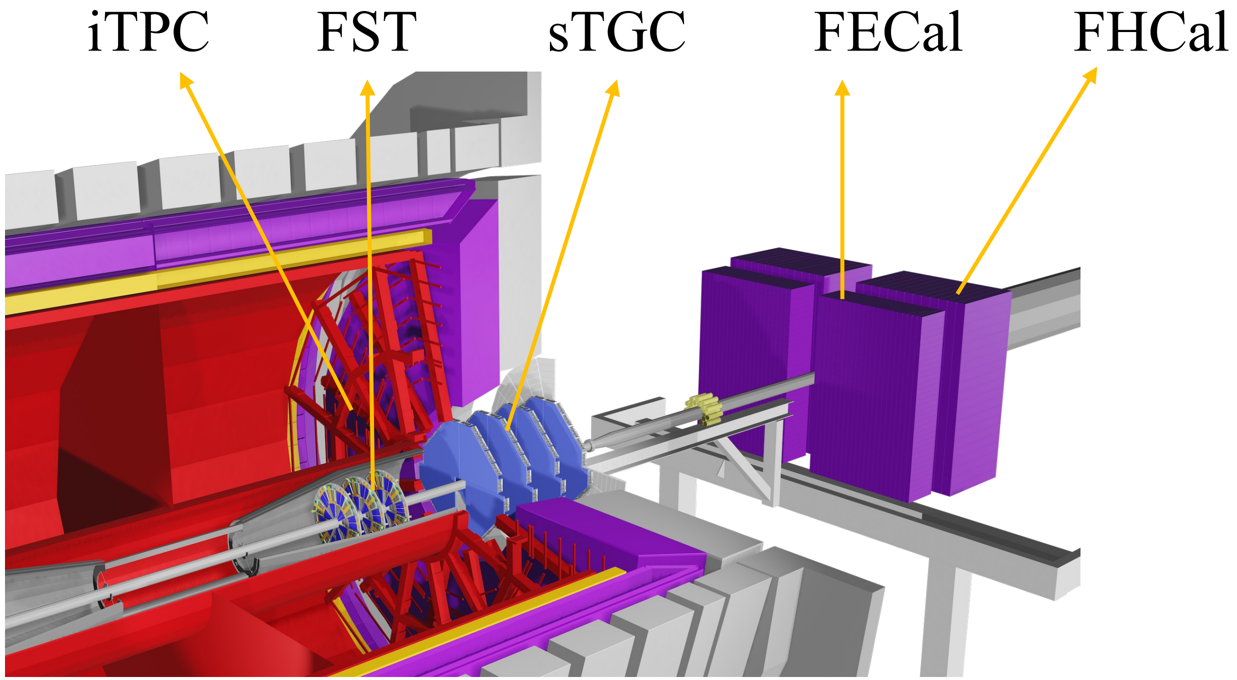
- Energy loss: similar level of D^0 suppression in Isobar and Au+Au 200 GeV; larger suppression of hard-fragmented D^0 jets in Au+Au
- Freeze-out and final state interaction: D^0 freezes out earlier than light hadrons; D^0-hadron femtoscopy correlations suggest source size of 5 fm or larger

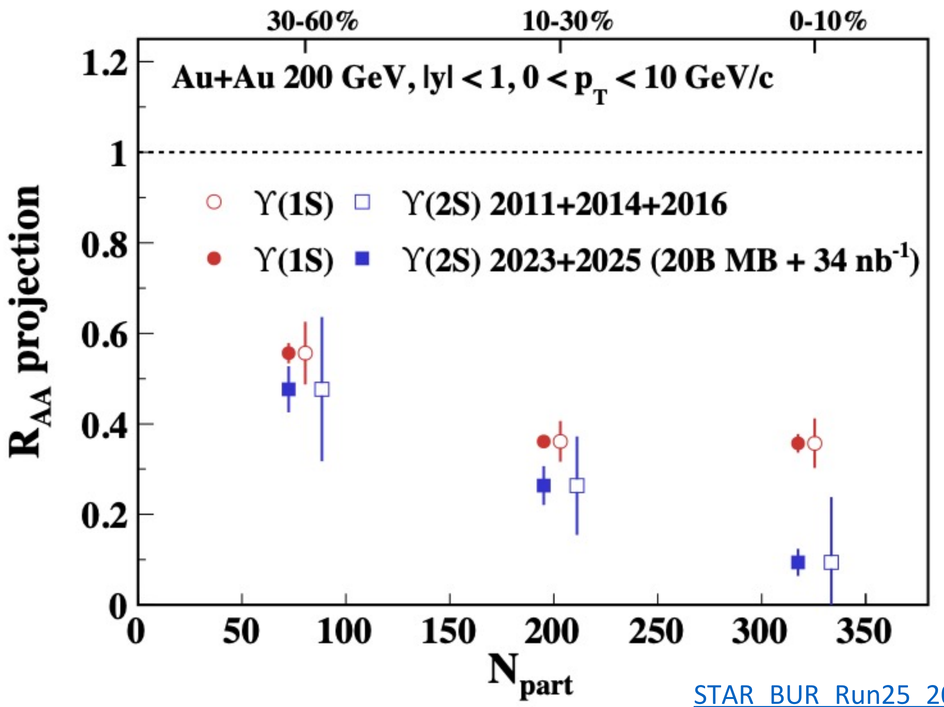
✓ Quarkonia

- Production mechanism: no significant z dependence of J/ψ in charged jet for z <1 in p+p 500 GeV
- Dissociation and regeneration: charmonium sequential suppression and limited J/ψ v_2 in isobar collisions; no significant energy dependence of J/ψ R_{AA} in Au+Au collisions @14.6-200 GeV
- Polarization and spin alignment: J/ψ polarization is consistent with zero in HX and CS frames; J/ψ spin alignment and photon-induced J/ψ decay anisotropy are observed in isobar

Summary and outlook

- Run23-25: high statistics p+p(Au), Au+Au collisions
- STAR detector with enhanced capabilities
  - Higher DAQ rate; extended coverage (iTPC+ forward upgrade)





STAR_BUR_Run25_2024

Summary and outlook

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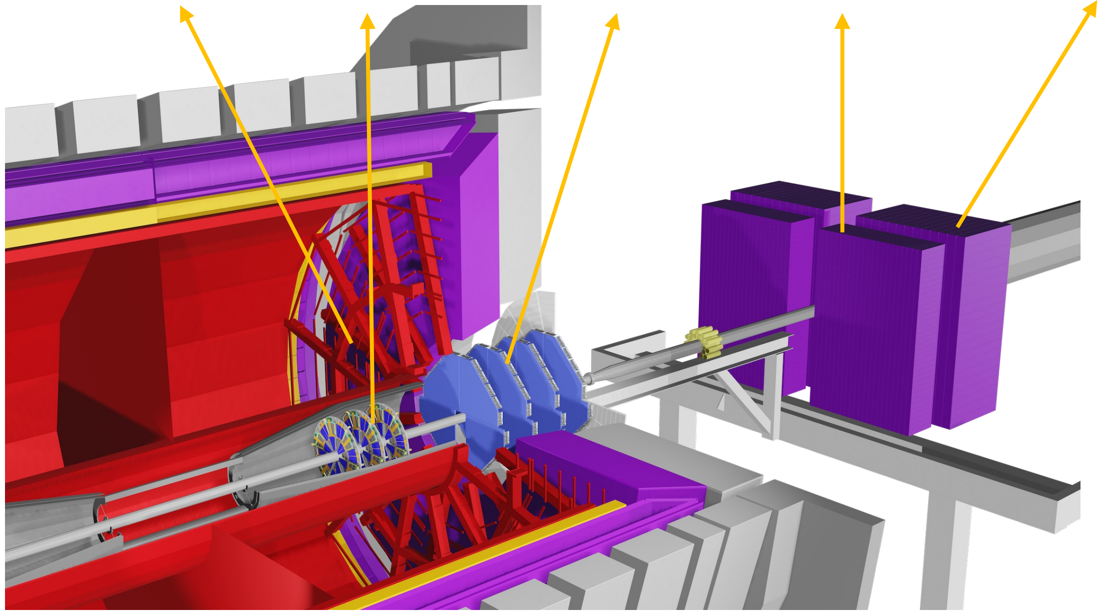
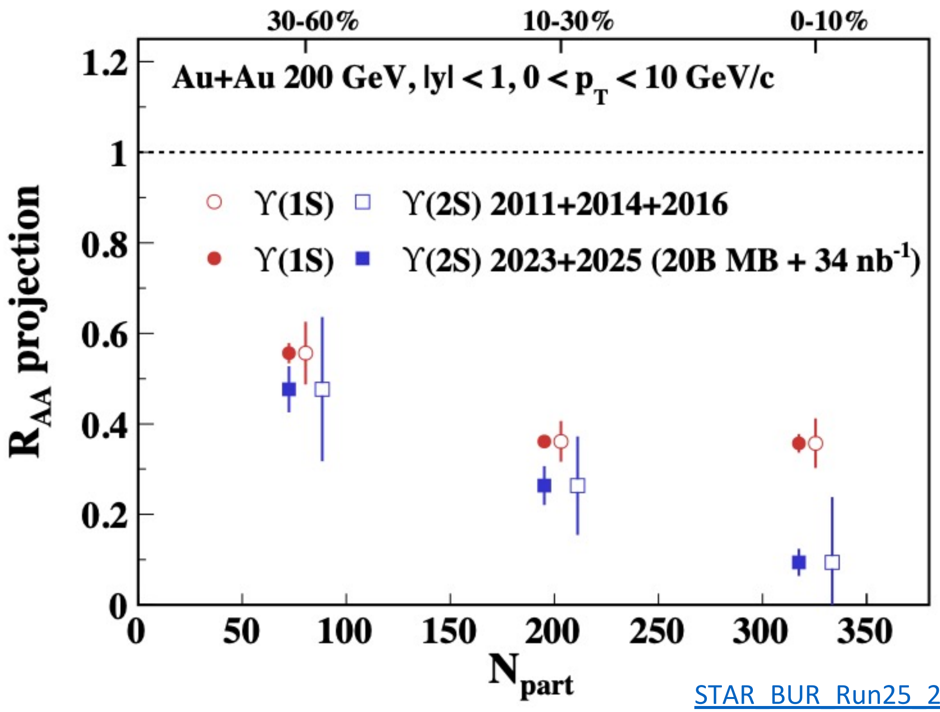
Thank you !



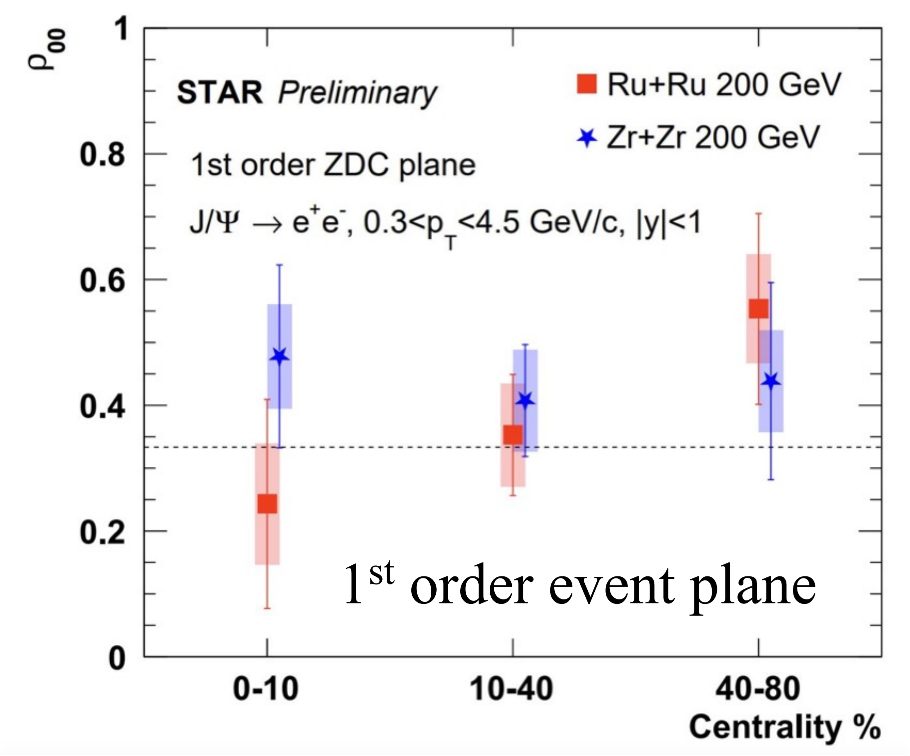


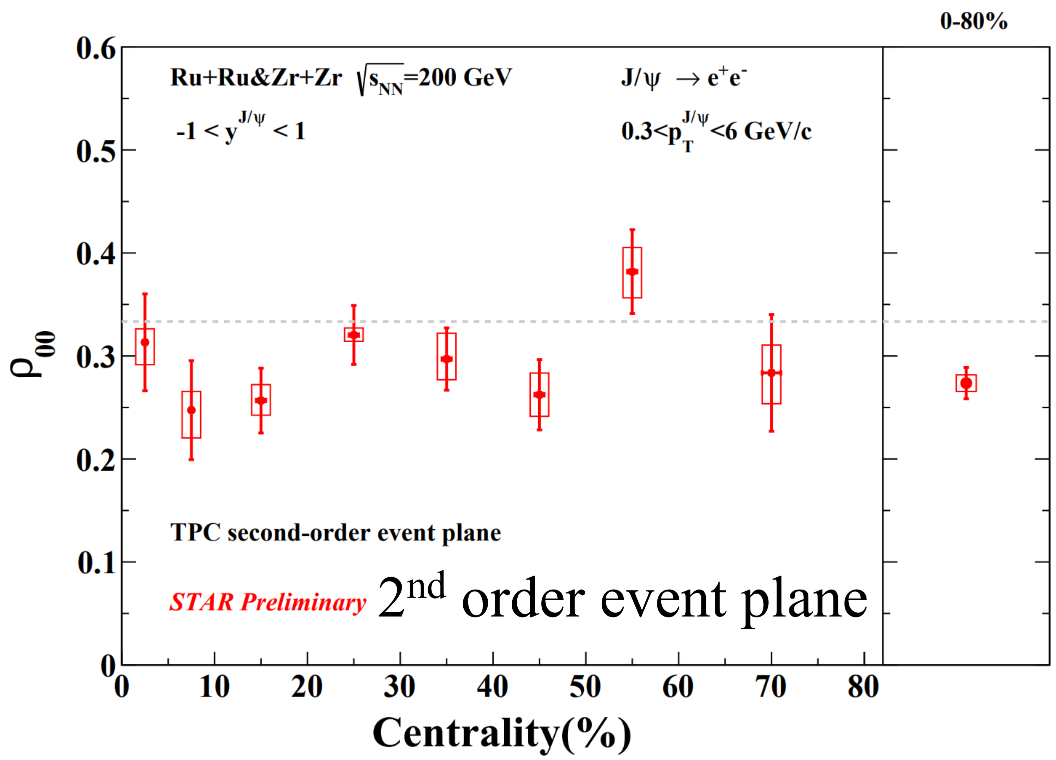
STAR_BUR_Run25_2024

Back up

J/ψ global spin alignment at RHIC

Zr(Ru)+Zr(Ru) 200 GeV





- ρ_{00} consistent with 1/3 with large uncertainty using 1st order event plane
- ρ_{00} lower than 1/3 with a significance of 3.5 σ using 2nd order event plane

Photon-induced J/ψ decay anisotropy

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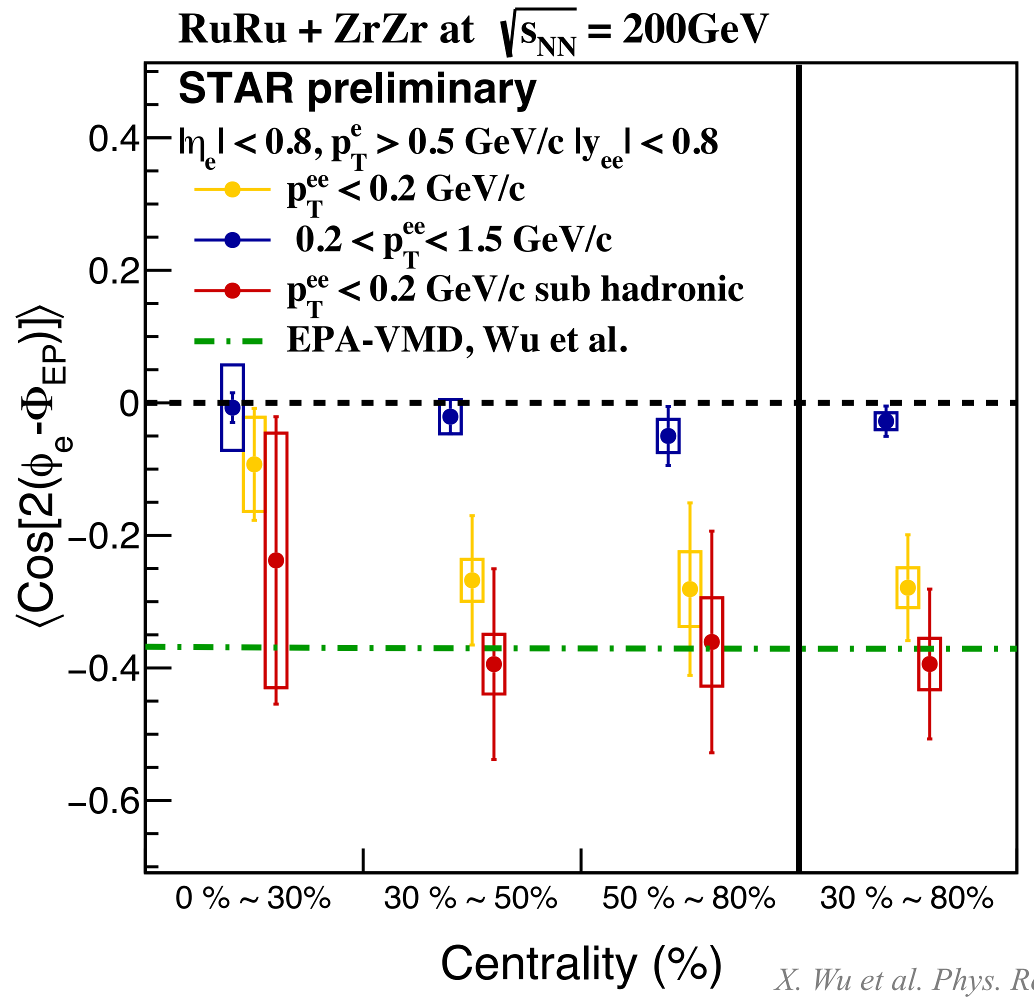
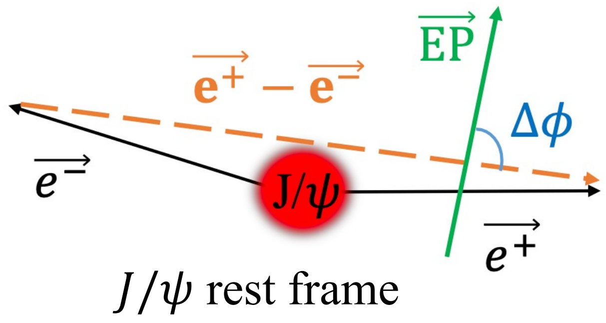
✓ Photon-induced J/ψ decay anisotropy expected due to linearly polarized photon



X. Wu et al. Phys. Rev. Res. 4, L042048 (2022)



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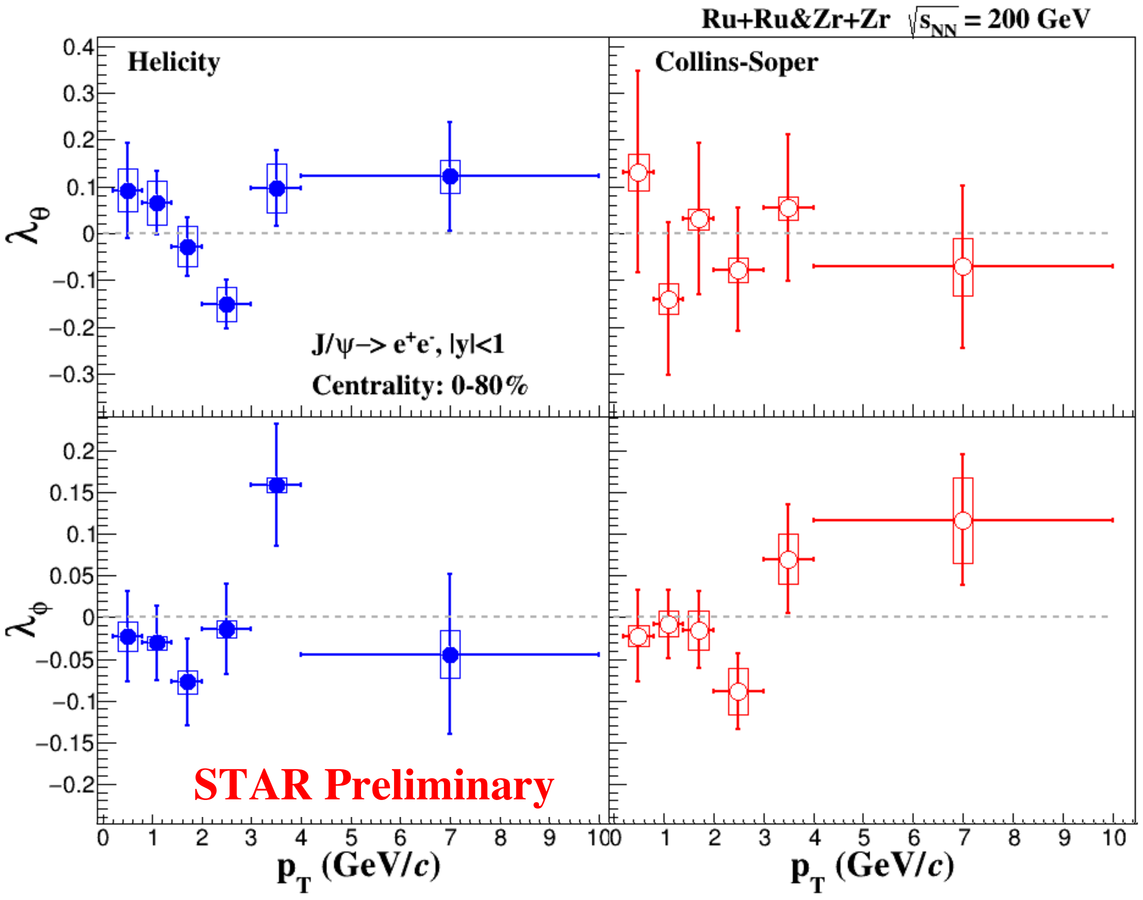
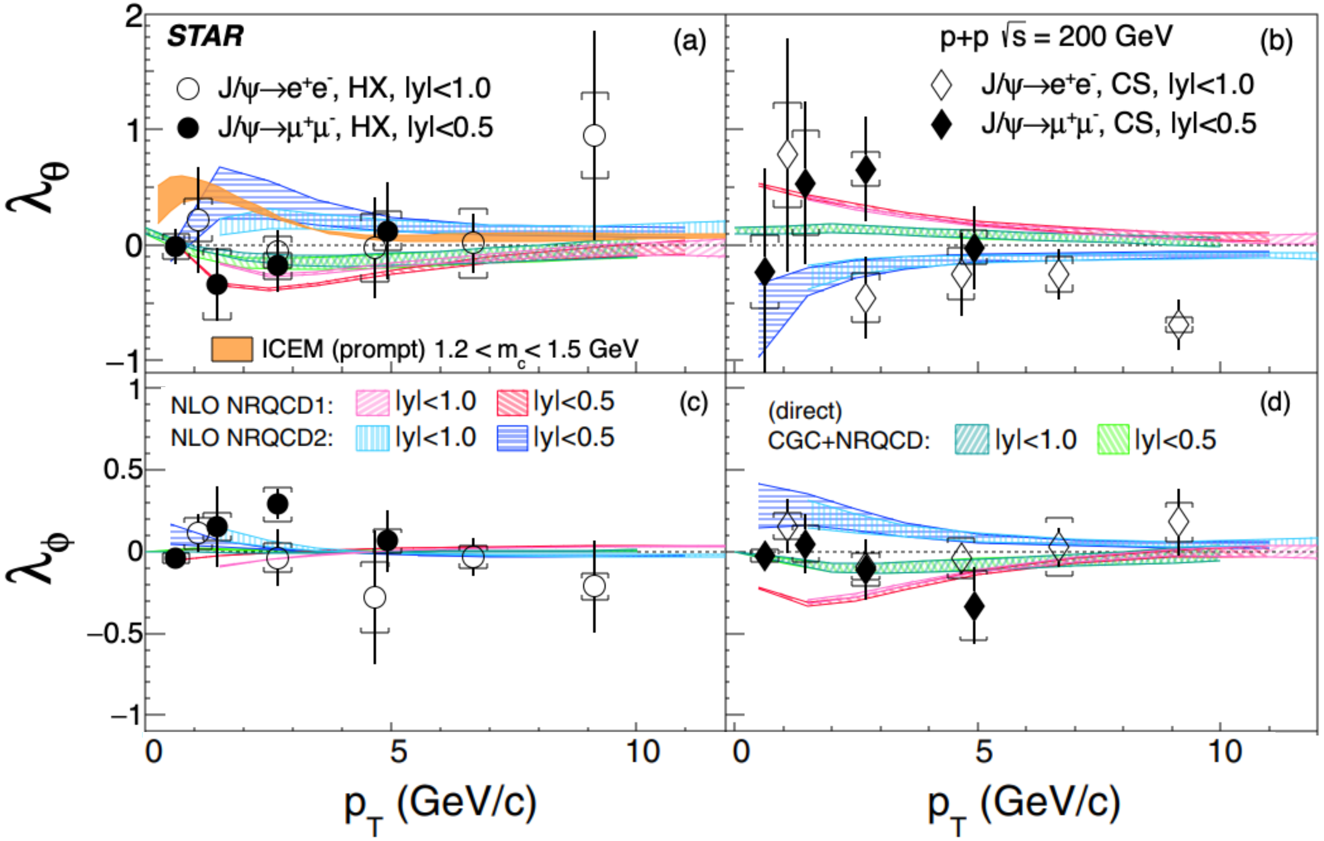
➢ Measured modulation consistent with EPA-VMD model prediction

J/ψ polarization: Isobar vs pp





STAR PRD 102, 092009 (2020)

- λ_θ and λ_ϕ in isobar and pp collisions are consistent with zero within uncertainties

Femtoscopic correlation

- Femtoscopic correlations are observed between pair of particles with low relative momentum
- Correlations are measured as a function of the reduced momentum difference (k^*) of the pair of particles in rest frame

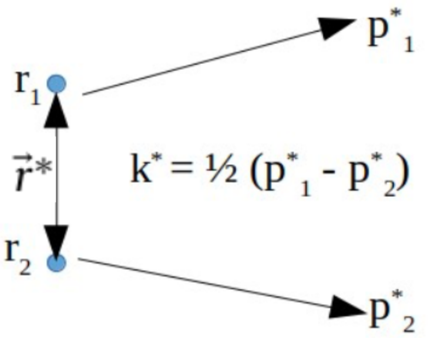
$$C(\vec{k}^*) = \int S(\vec{r}^*) \left|\Psi(\vec{k}^*, \vec{r}^*)\right|^2 d^3r^*, \quad (1)$$

where, $S(\vec{r}^*)$ → source emission function

$\vec{r}^*$ → relative separation vector

$\Psi(\vec{k}^*, \vec{r}^*)$ → pair wave function

- Femtoscopic Correlation ⟶ QS + FSI
  - Quantum Statistics [QS]: Bose-Einstein / Fermi-Dirac
  - Final-State-Interaction [FSI]: Strong & Coulomb interaction
  - **Only strong interaction contributes to $D^0/\overline{D^0}$-$h^\pm$ femtoscopy**



Femtoscopic correlation & k^*

Femtoscopic and interaction parameters

The Lednicky–Lyuboshitz analytical model connects the correlation function with final-state strong interaction parameters

$$C(k^*) = 1 + \sum_S \rho_s \left[\frac{1}{2}\left|\frac{f^S(k^*)}{r_0}\right|^2 \left(1-\frac{d_0^S}{2\sqrt{\pi}r_0}\right)+\frac{2\Re(f^S)(k^*)}{\sqrt{2}r_0}F_1(Qr_0)-\frac{\Im(f^S k^*)}{r_0}F_2(Qr_0)\right] \quad (2)$$

where , $f^s(k^*)$ is the scattering amplitude for singlet (s = 0) or triplet (s = 1) state

ρ_s is fraction of pairs with a given spin s (ρ_0 = ¼ and ρ_1 = ¾)

$$Q=2k^*,\quad F_1(z)=\int_0^z dx\, e^{x^2-z^2}/z,\quad F_2(z)=(1-e^{-z^2})/z$$

This model assumes, average separation vector $(\vec{r}^*)$ from eq. (1), follows Gaussian distribution

$$dN^3/d^3r^* \quad e^{-r^{*2}/4r_0^2} \quad (3)$$

where, r_0 is the effective radius of the correlated source

Correction of raw correlation function

- Correlation function $C(k^*)$ for $D^0/\overline{D}^0$ - $h^{+/-}$ pairs: $$C(\vec{k}^*) = \mathcal{N}\frac{A(\vec{k}^*)}{B(\vec{k}^*)}. \quad (4)$$

  $A(\vec{k}^*)$ and $B(\vec{k}^*) \rightarrow k^*$ distribution for correlated and uncorrelated pairs; $\mathcal{N} \rightarrow$ normalization factor

- Pair-purity corrected correlation function: $$C^{corr}_{measured}(k^*) = \frac{C_{measured}(k^*) - 1}{PairPurity} + 1, \quad (5)$$

  where PairPurity = **D^0 purity** * **hadron purity**

- $C_{measured}(k^*)$ is the raw correlation function calculated using Eq. (4)
- D^0-hadron pair purity correction is required to remove the contribution from combinatorial background (D^0 candidates reconstructed from like-sign $K\pi$ pairs within selected mass range)
- Average D^0 purity ~ 37%, 1 GeV/c < p_T < 10 GeV/c
- Kaon purity ~ (97 ± 3 (syst.))%, p_K < 1 GeV/c
- Pion purity ~ (99.5 ± 0.5 (syst.))%, p_π < 1 GeV/c
- Proton purity ~ (99.5 ± 0.5 (syst.))%, p_p < 1.2 GeV/c