J/ψ polarization in Ru+Ru and Zr+Zr collisions at $\sqrt{s_{NN}}$ = 200 GeV from STAR experiment
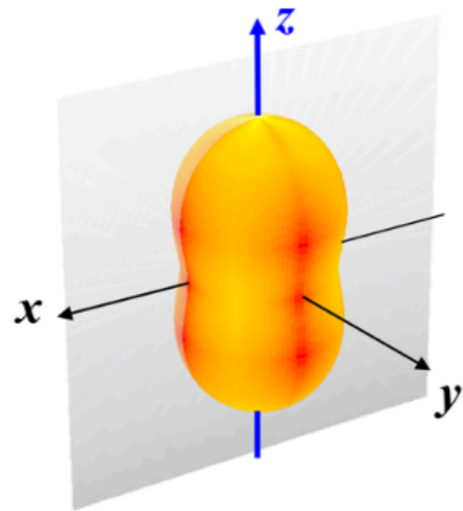
Qian Yang （杨 钱）

Shandong University (山东大学)

J/ψ polarization

The spin state of J/ψ meson ($J^{PC} = 1^{--}$) can be described by a 3×3 spin density matrix

- $\rho_{11} + \textcolor{red}{\rho_{00}} + \rho_{-1-1} = 1$ **(normalization requirement)**
- ρ_{11} **and** ρ_{-1-1} **cannot be measured separately due to parity conservation**
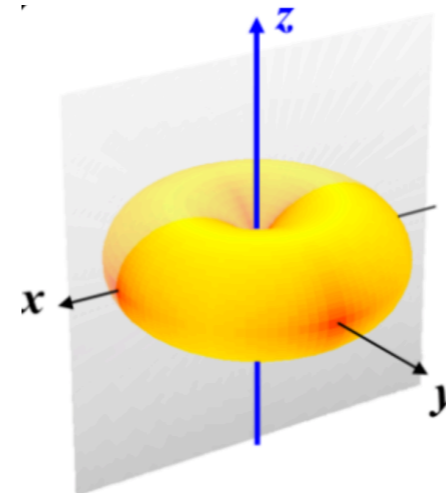
Transverse polarization

$$\rho_{00} < \frac{1}{3}$$

$$|J/\psi\rangle = |1, +1\rangle \text{ or } |1, -1\rangle$$
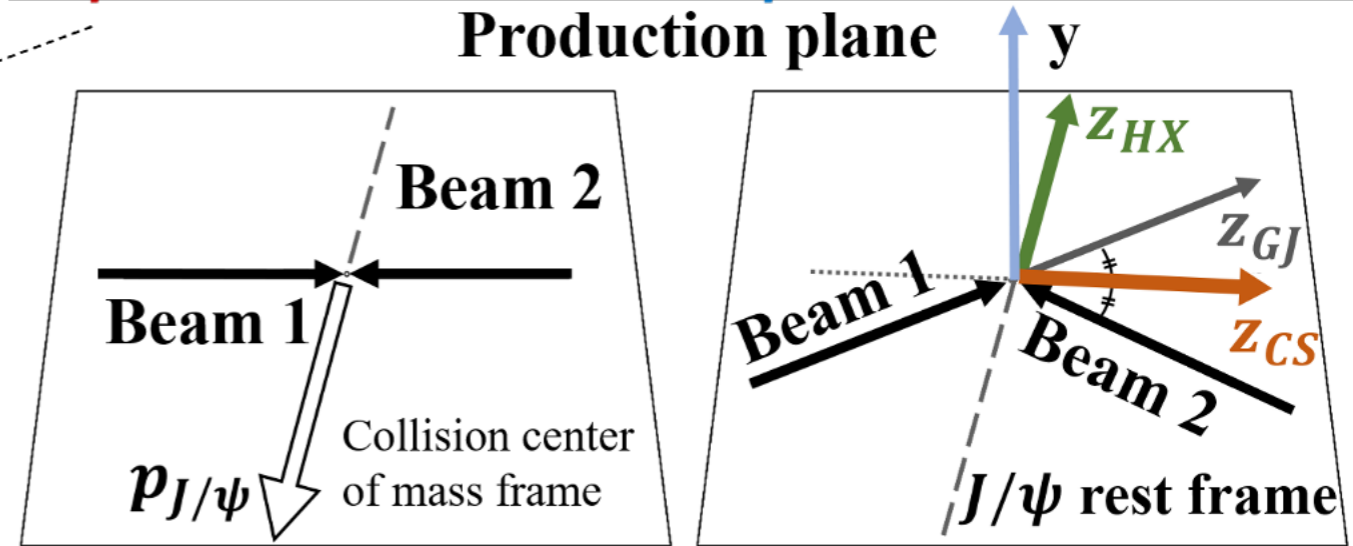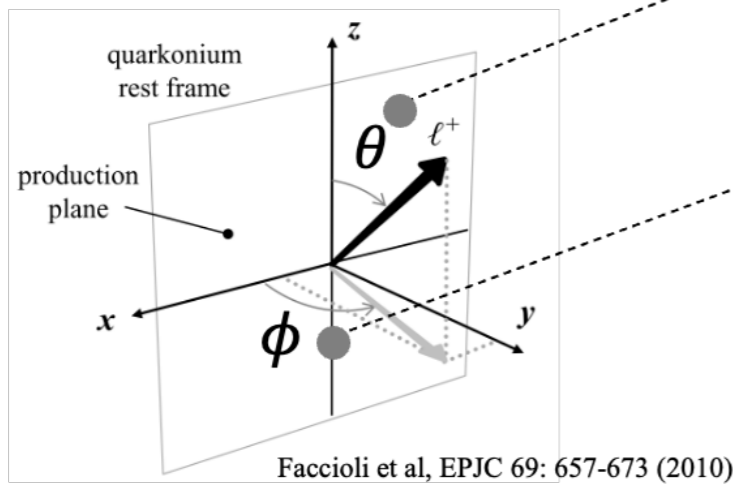
Longitudinal polarization

$$\rho_{00} > \frac{1}{3}$$

$$|J/\psi\rangle = |1, 0\rangle$$

J/ψ polarization measurement

✓ **Angular distribution of the decayed leptons:**

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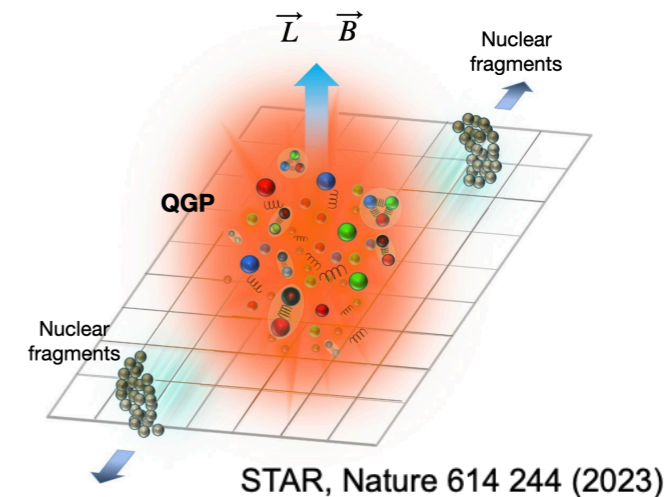

Faccioli et al, EPJC 69: 657-673 (2010)

➤ Definition of the z-axis:

Helicity frame (HX): J/ψ momentum direction

Collins-Soper frame (CS): bisector of angle between beams
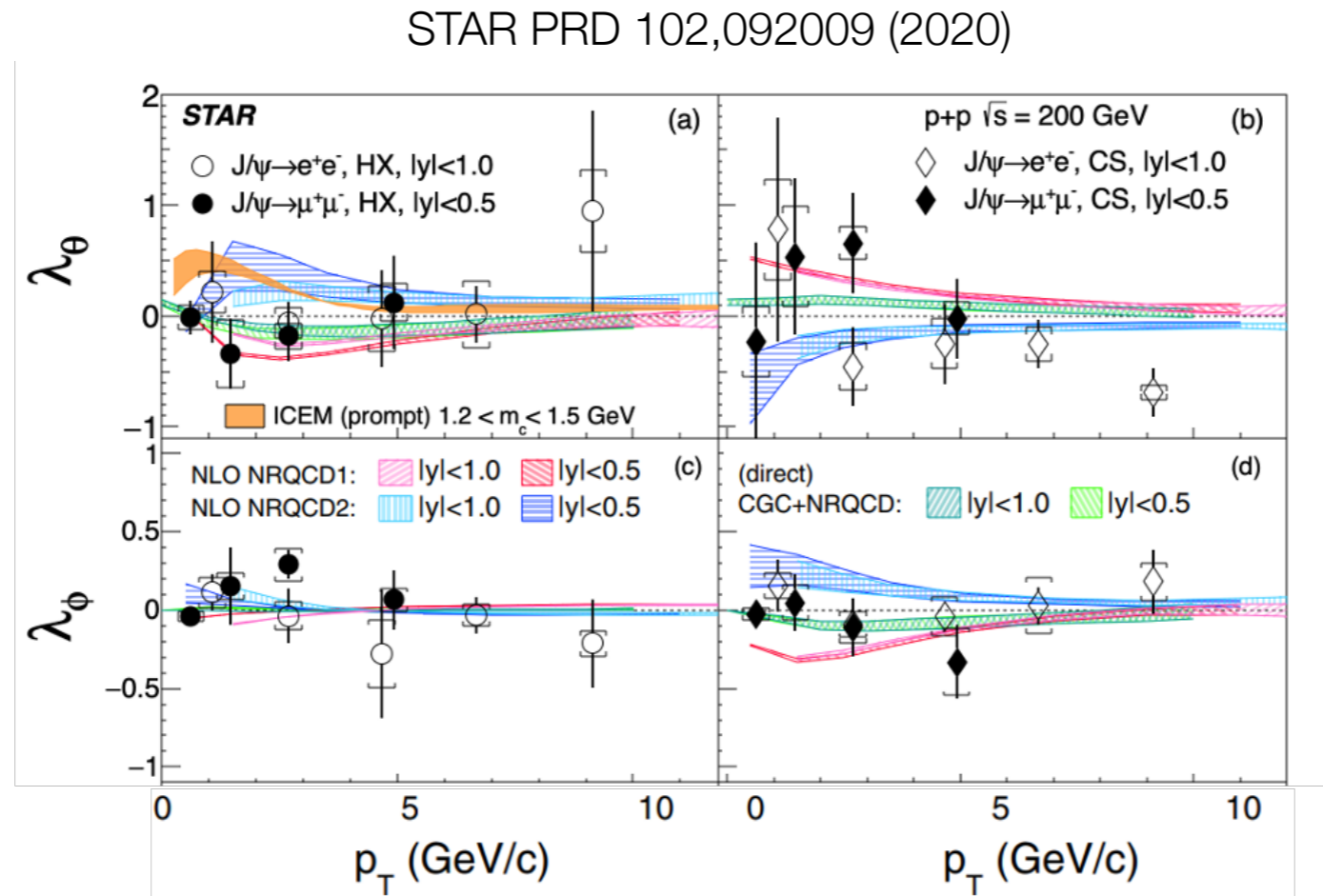
Event plane: axis orthogonal to reaction plane

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

STAR, Nature 614 244 (2023)

Probing production mechanism

J/ψ polarization: **one of the key observables** for J/ψ production mechanism study in p+p collisions
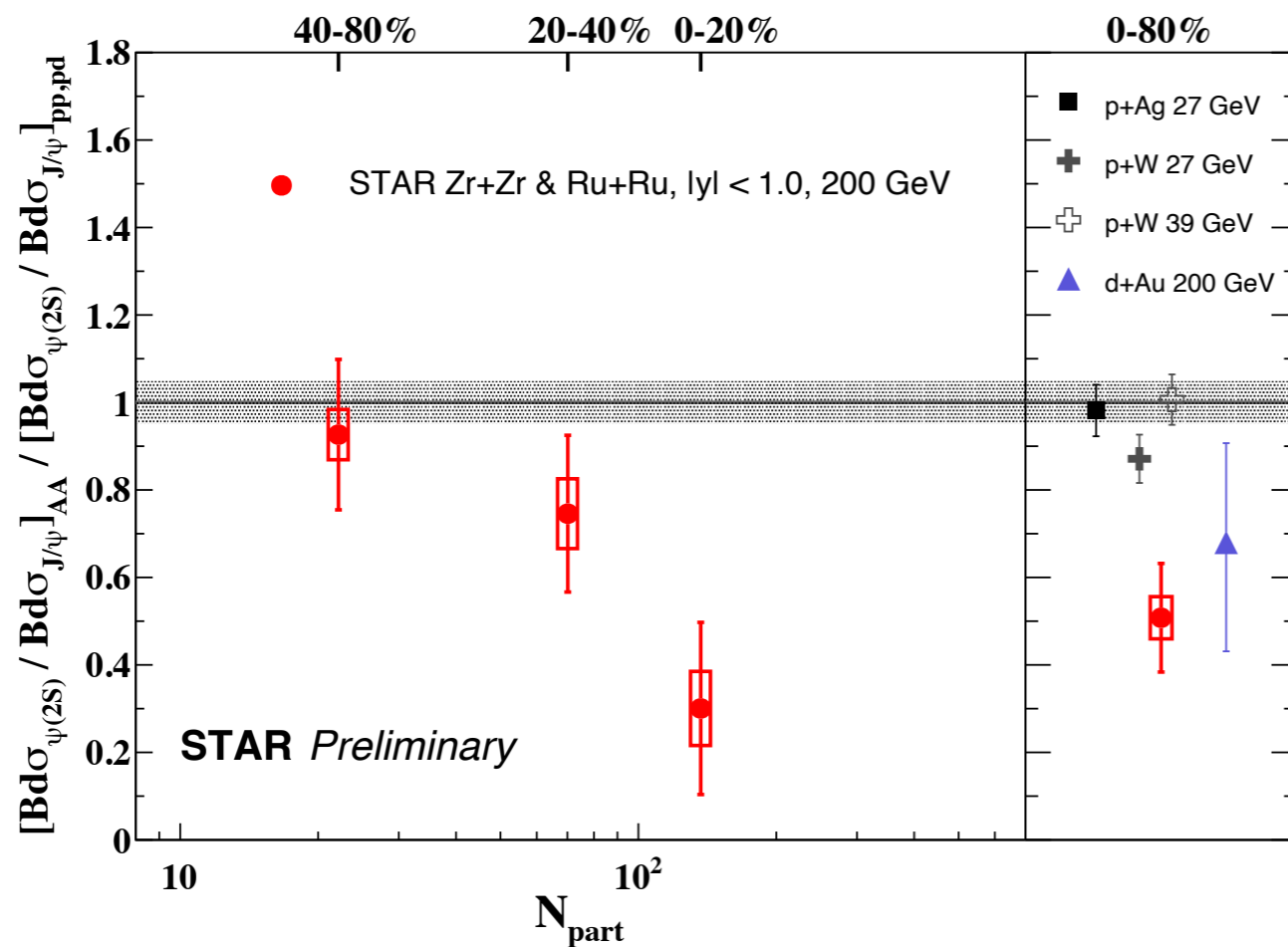
- Color-singlet vs. color-octet vs. gluon fragmentation

STAR PRD 102,092009 (2020)

Inclusive J/ψ in experiment： **Prompt J/ψ = Direct[60%] + feed down[40%]**

Non-prompt: B-hadron decay

No sizable polarization for inclusive J/ψ in p+p collisions at RHIC energy

Probing medium effect in A+A

Inclusive J/ψ in p+p: **Prompt J/ψ = Direct⁶⁰% + feed down⁴⁰%**
Non-prompt: B-hadron decay

"Theoretical prediction without regeneration contribution:
J/ψ polarization at small p_T, and find that it translates into the asymmetry of e^+e^- angular distribution $W(\theta) = 1 + \lambda_\theta \cos^2\theta$, with $\lambda_\theta \simeq 0.35 - 0.4$ "

B. L. Ioffe and D. E. Kharzeev, PRC 68, 061902(R) (2003)

Modification of J/ψ feed-down fractions due to charmonium sequential melting in QGP
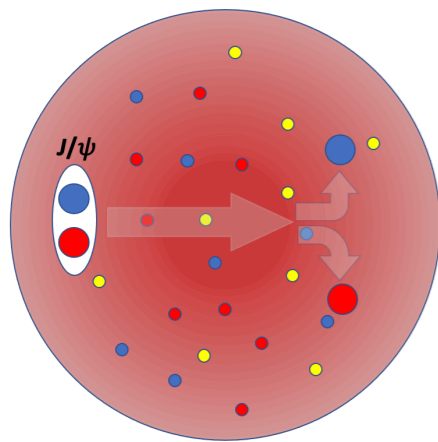
A different picture in A+A system

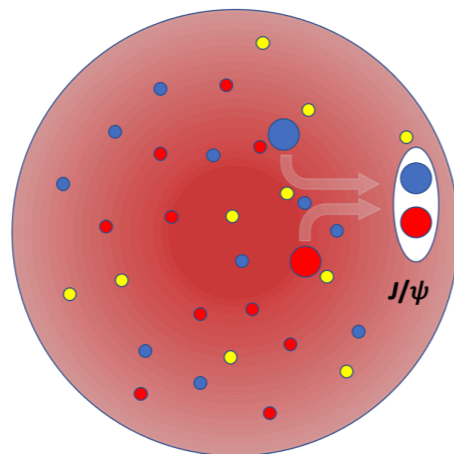More complex process related to J/ψ in heavy-ion collisions:
1) primordial production; 2) dissociation; 3) regeneration; 4) CNM effect

Additional source

Dissociation   Coalescence

STAR, PLB 771(2017)13-20
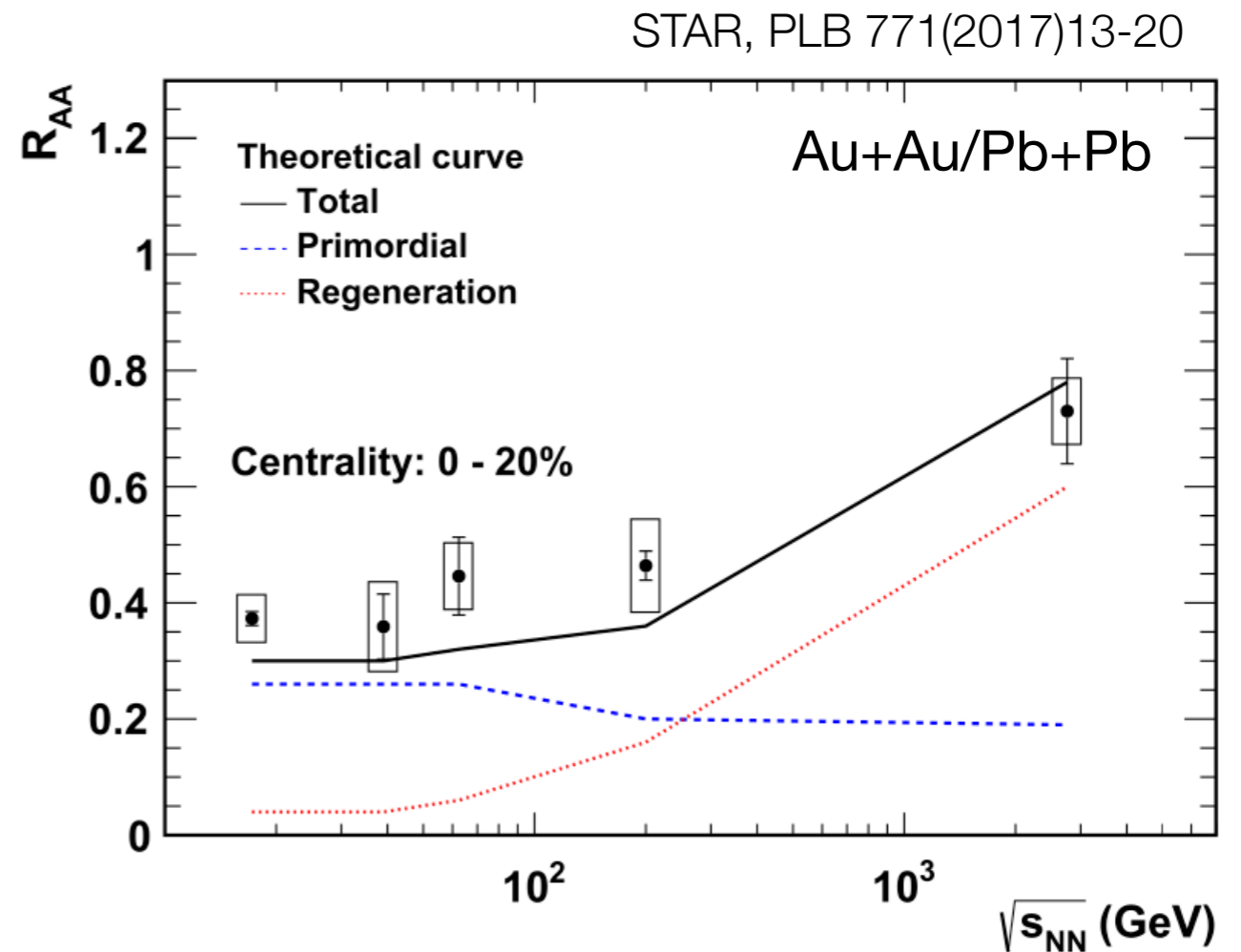

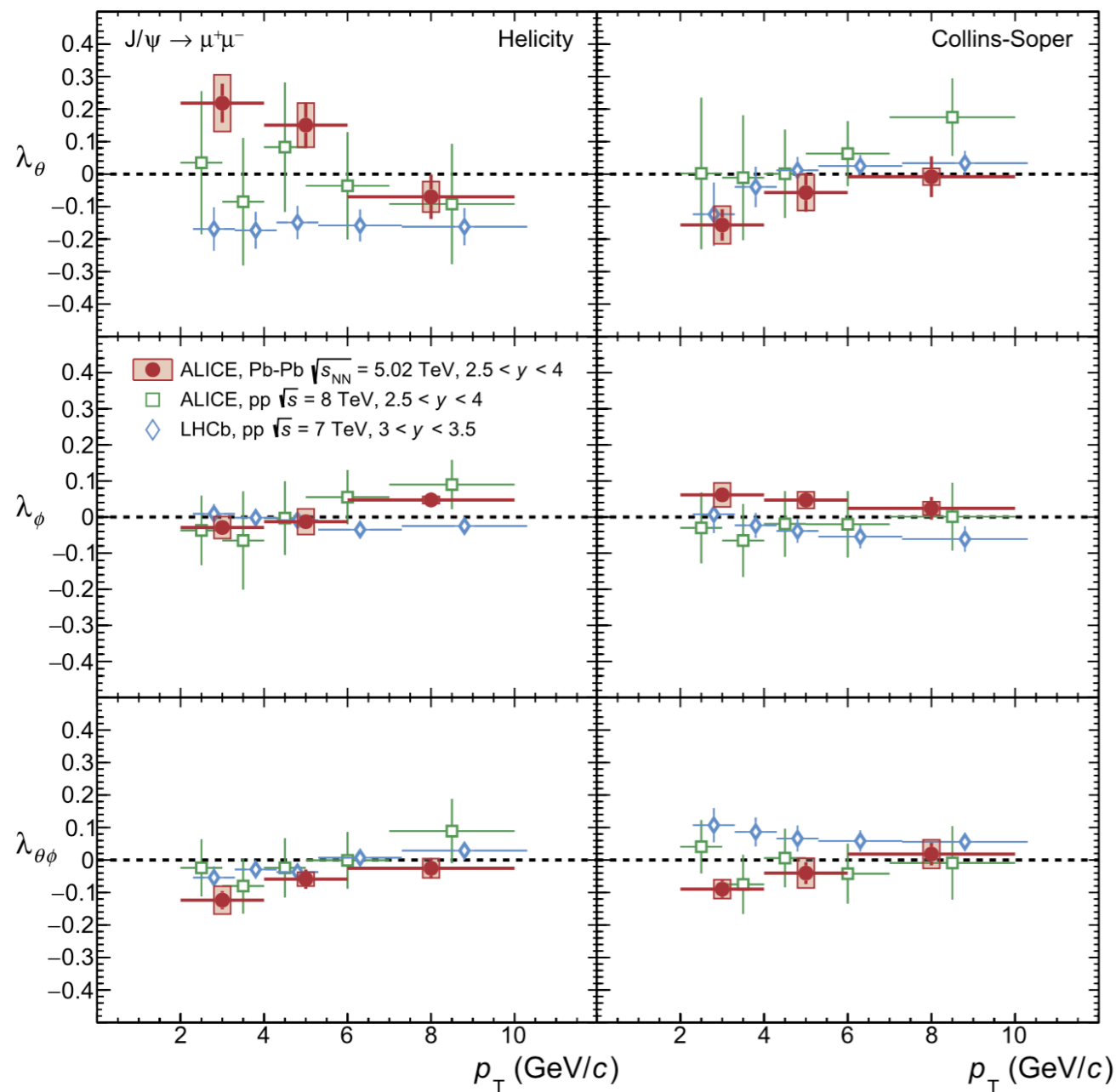Charm quark multiplicity in central A+A collisions:
> 100 at LHC
~ 10 at RHIC top-energy

- Significant coalescence contribution at LHC energy
- Coalescence only plays a partial role at RHIC energy

Measurement at LHC

Hint of non-zero J/ψ polarization in HX at low-p_T range

- 2σ deviation from zero in λ_θ
- Regeneration dominates J/ψ production at LHC energy → dilute polarization signal

What is the case at RHIC energy?

The Solenoidal Tracker at RHIC

TOF
Identification of low-p_T electrons
($|\eta| < 1$, $0 < \varphi < 2\pi$)

J/ψ → e$^+$ + e$^-$

EPD
Event-plane reconstruction
($2.1 < |\eta| < 5.1$, $0 < \varphi < 2\pi$)
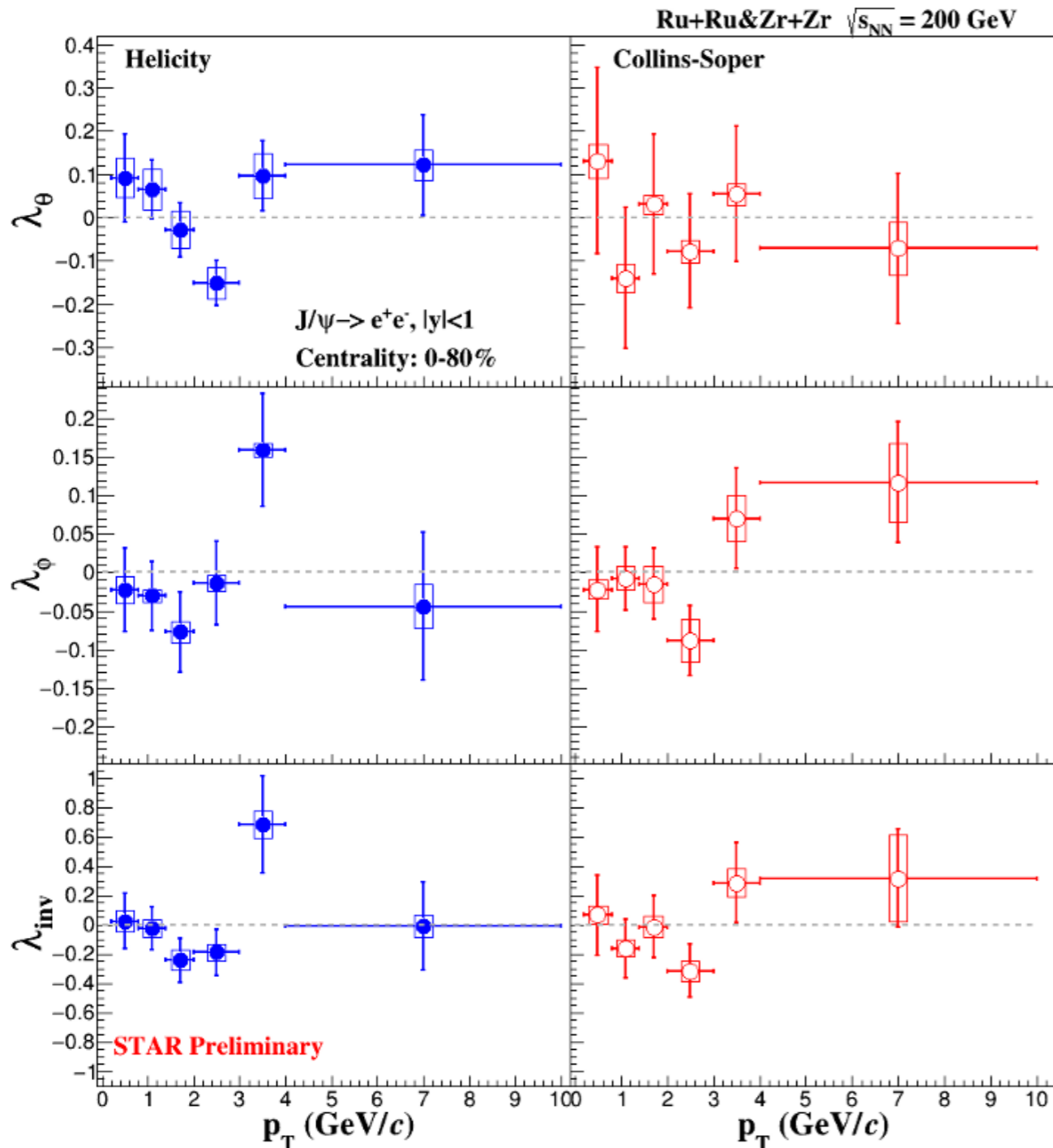
TPC
Tracking (momentum measurement, particle identification)
($|\eta| < 1$, $0 < \varphi < 2\pi$)

BEMC
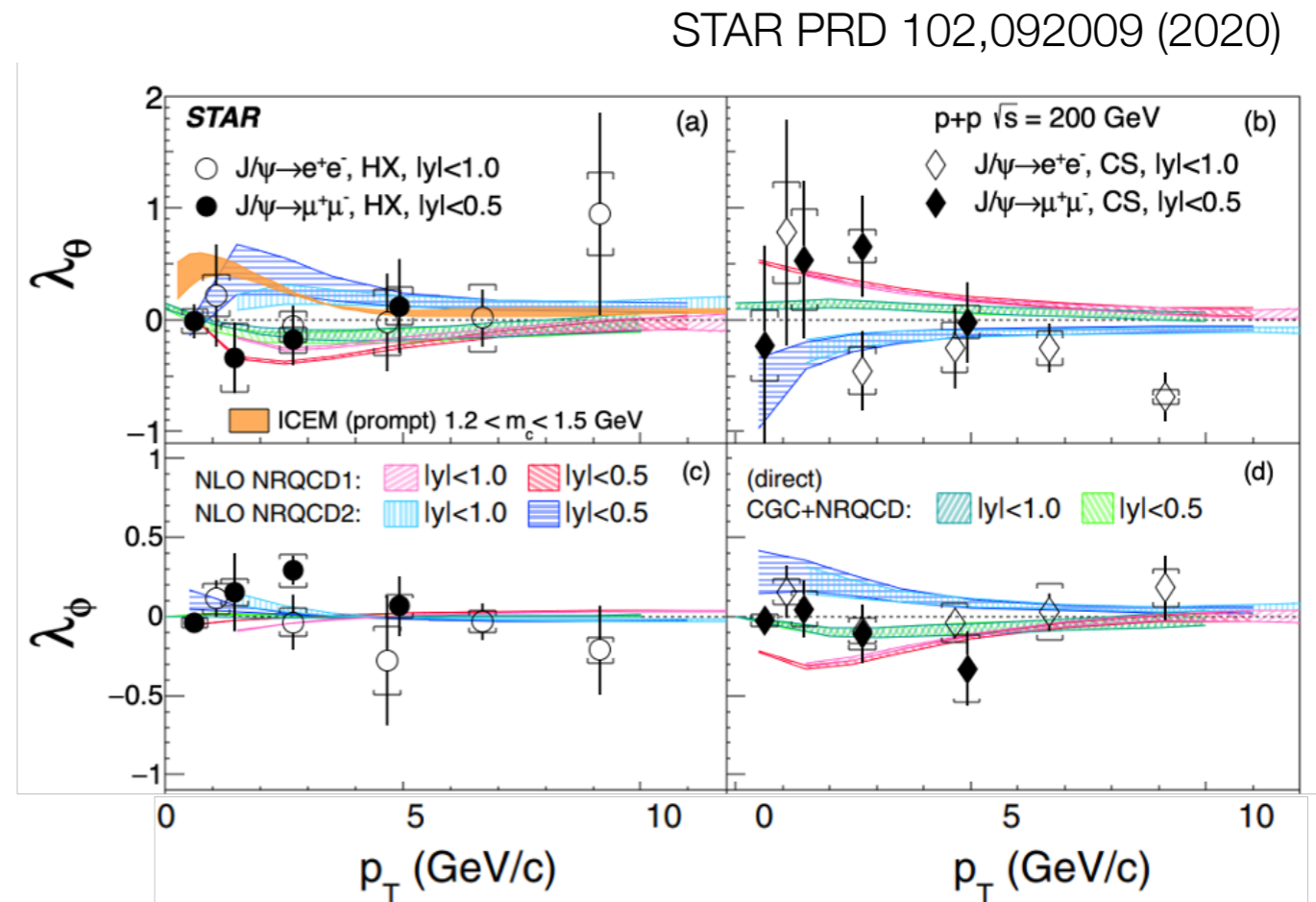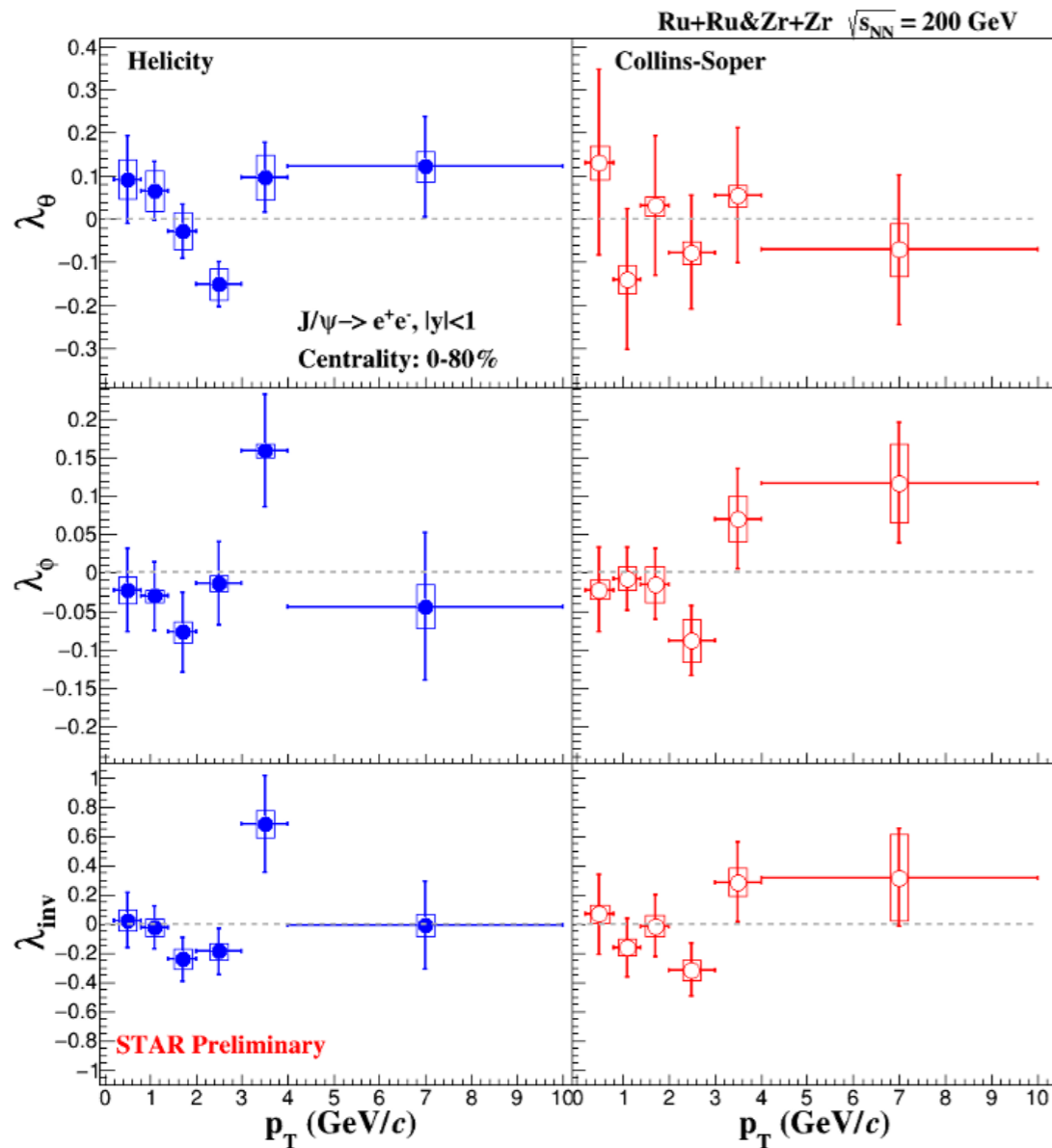Identification of high-p_T electrons
($|\eta| < 1$, $0 < \varphi < 2\pi$)

Transverse momentmun dependence

- J/ψ polarization vs p_T in isobar

  - λ_θ and λ_ϕ are consistent with zero in HX and CS frames

  - Hint of a non-trivial p_T dependence at low-p_T range in the HX frame
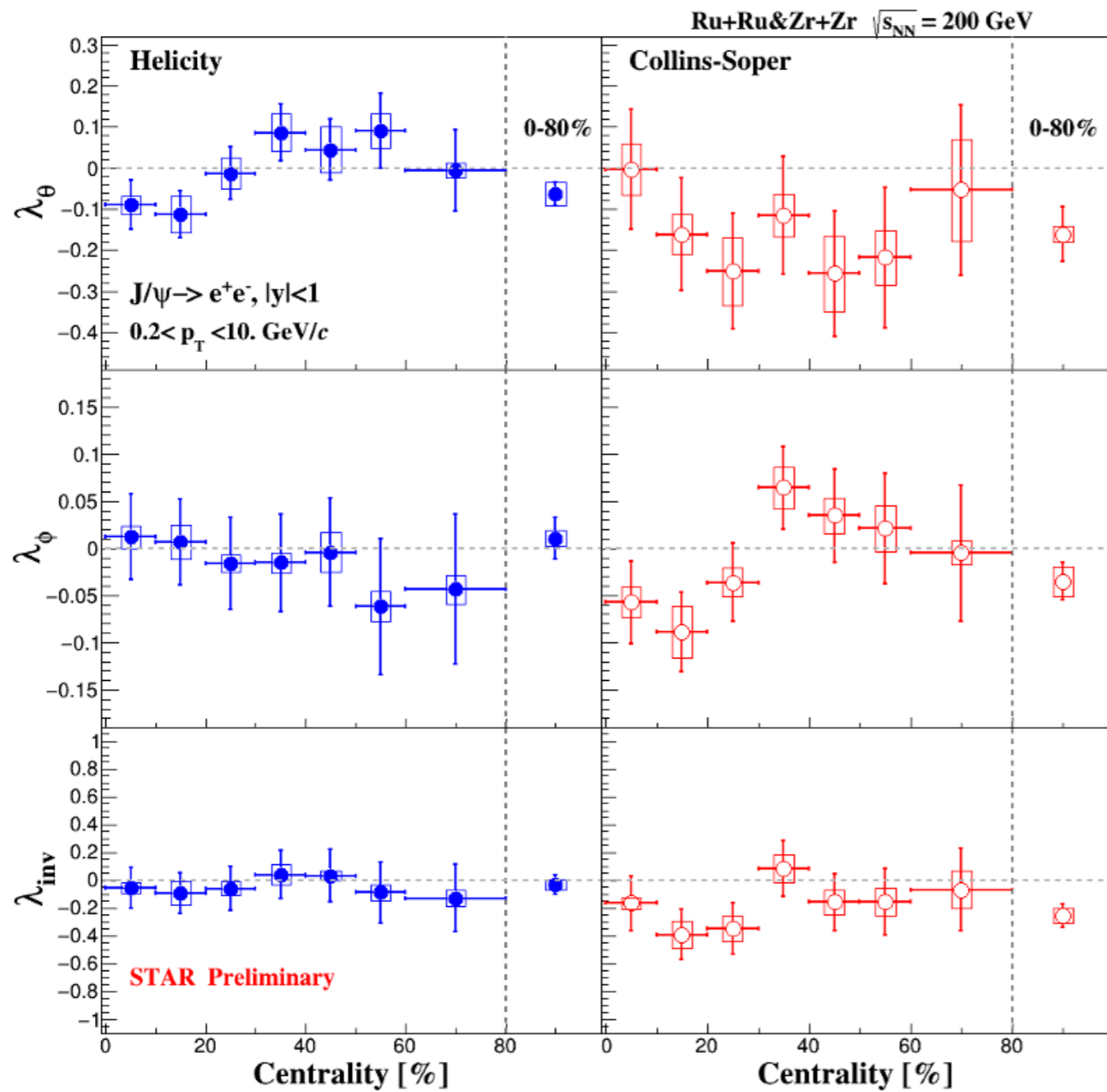
- Frame invariant quantity

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

Transverse momentmun dependence

STAR PRD 102,092009 (2020)

- λ_θ and λ_ϕ in isobar and p+p collisions are consistent with zero within uncertainties
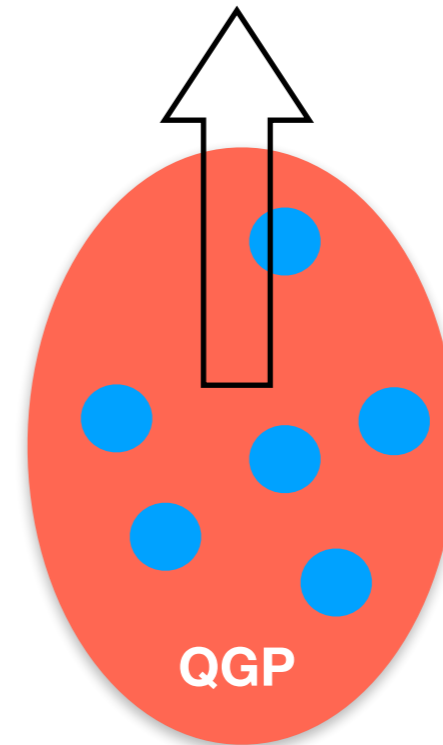 - Theory inputs are needed!

Centrality dependence

- No significant dependence of λ_θ and λ_ϕ from central to peripheral event

J/ψ global spin alignment

J/ψ momentum depend reference axis:
HX and CS frame

$p^{J/\psi}$

$p^{J/\psi}$

$p^{J/\psi}$

$p^{J/\psi}$

$p^{J/\psi}$

QGP
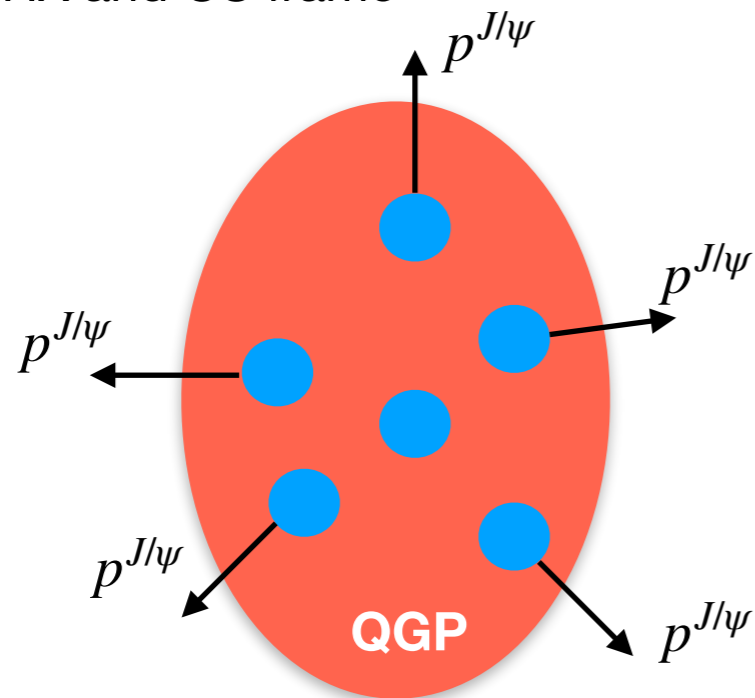
Global angular momentum direction

QGP

Angular momentum direction $\perp$ reaction plane (lab frame) $\sim$ estimated by event plane(EP)

$$\frac{dN}{dcos\theta*} \propto (1 - \rho_{00}) + (3\rho_{00} - 1)cos^2\theta*$$

Uniform distribution ➔ $\rho_{00} = 1/3$ ➔ absence of spin alignment

Non-uniform distribution➔ $\rho_{00} \neq 1/3$ ➔ spin alignment

Probing gluon field fluctuation in QGP?

ϕ (|y| < 1.0 & 1.2 < p_T < 5.4 GeV/c)
K^{*0} (|y| < 1.0 & 1.0 < p_T < 5.0 GeV/c)
$G_s^{(y)}$ = 4.64 ± 0.73 m_π^4

$\phi(s\bar{s})$

filled: STAR (Au+Au & 20% - 60% Centrality)
open: ALICE (Pb+Pb & 10% - 50% Centrality)

STAR, Nature 614 244 (2023)

$\sqrt{s_{NN}}$ (GeV)

We could expect similar picture for J/ψ from coalescence process!

What is the case at RHIC with small coalescence contribution?

$\phi(s\bar{s})$ mainly from s and $\bar{s}$ quark coalescence

STAR measurement show: $|\rho_{00}^\phi - \frac{1}{3}| \gg P_s^2$

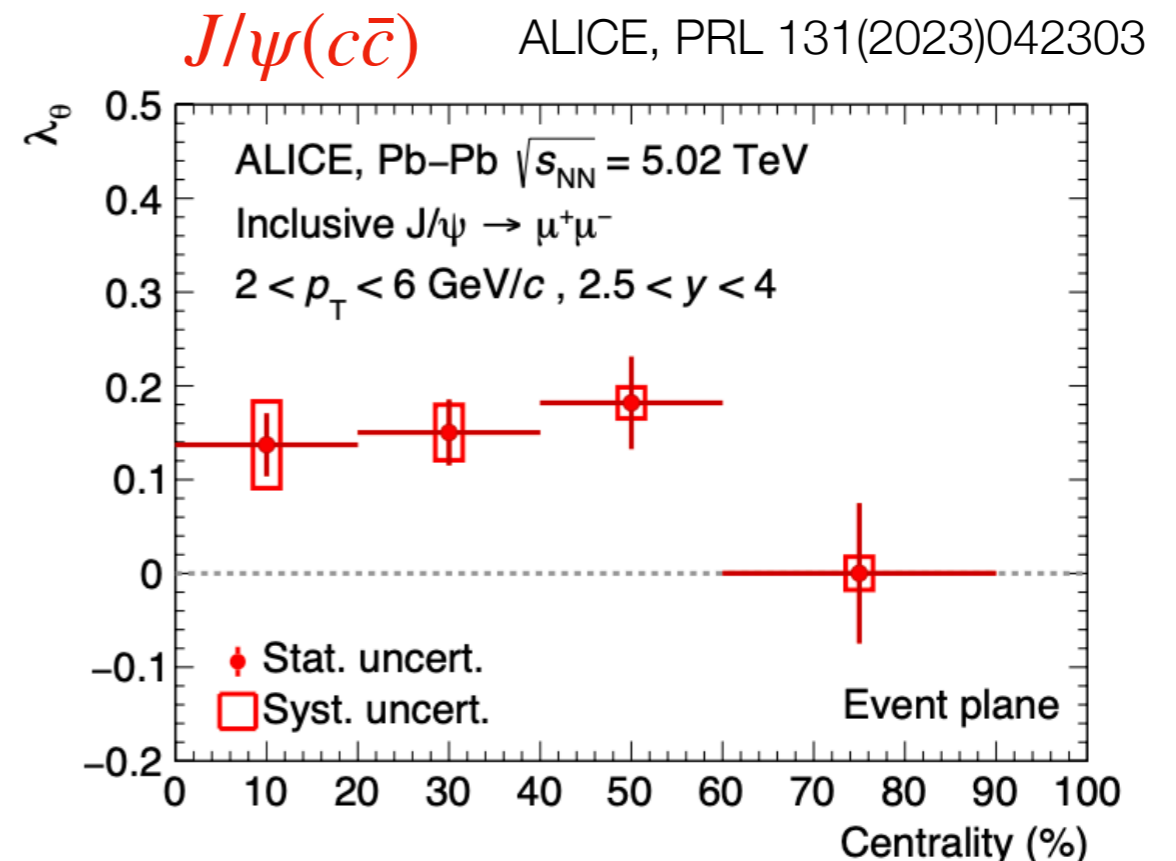The polarization of s and $\bar{s}$ are correlated
- Local field fluctuations induced global spin alignment — the only model matches data
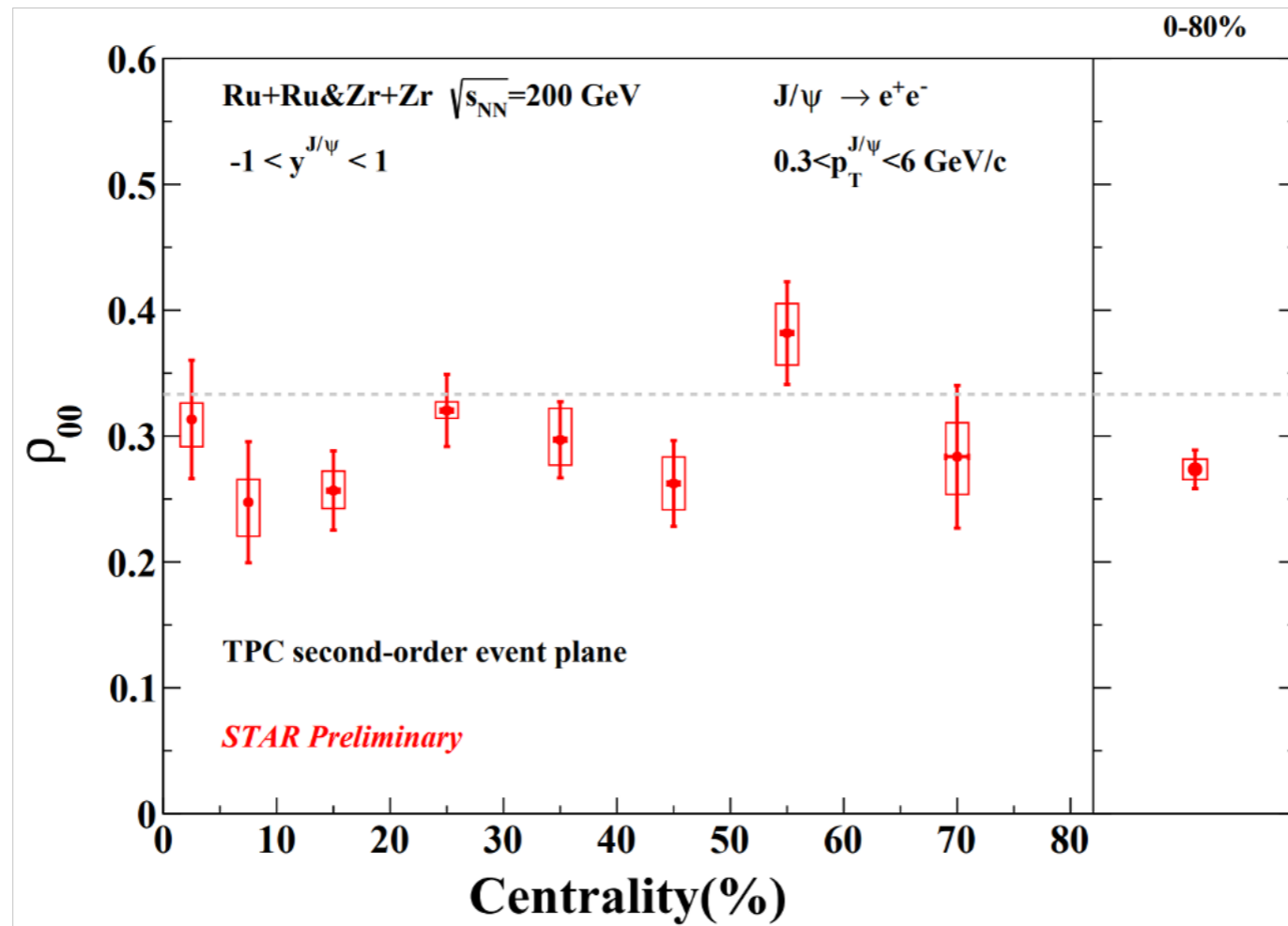
$J/\psi(c\bar{c})$ ALICE, PRL 131(2023)042303

ALICE, Pb–Pb $\sqrt{s_{NN}}$ = 5.02 TeV
Inclusive J/ψ → $\mu^+\mu^-$
2 < p_T < 6 GeV/c , 2.5 < y < 4

Stat. uncert.
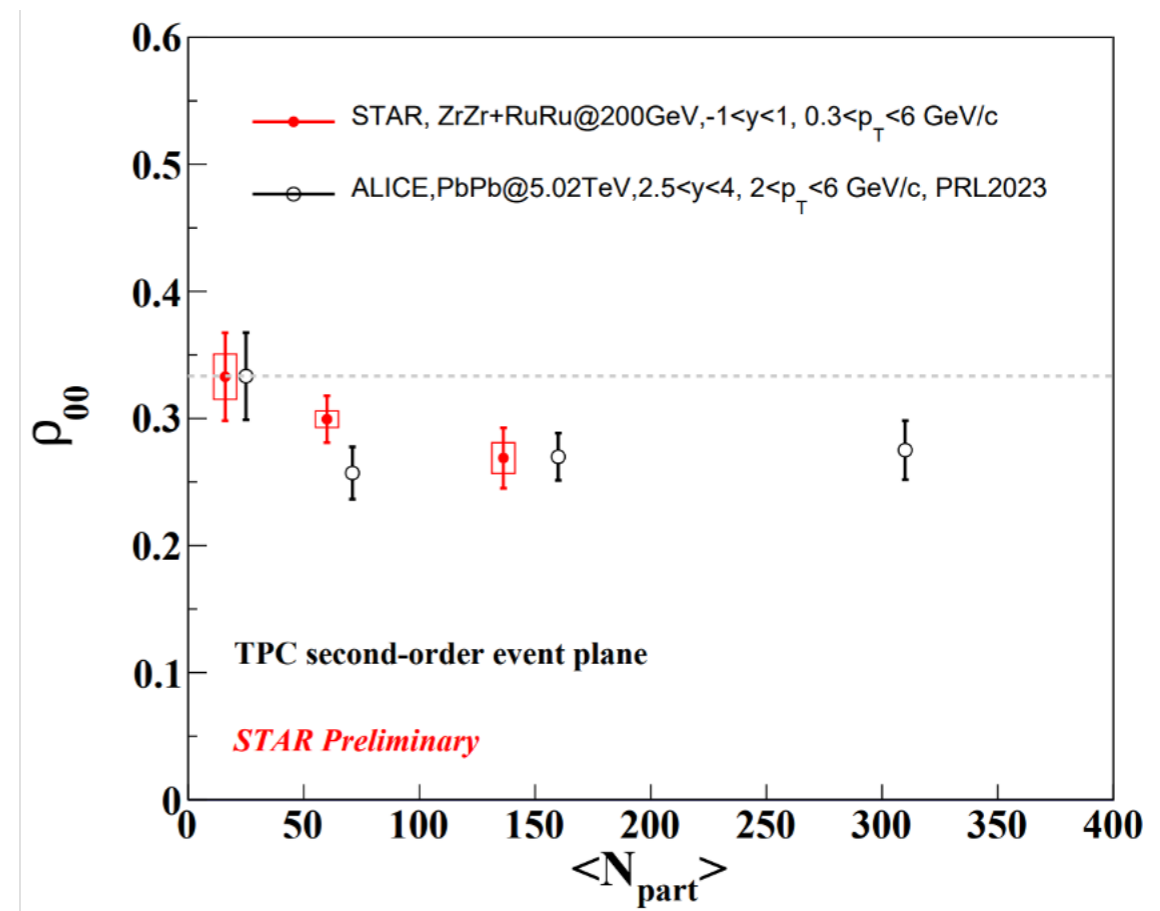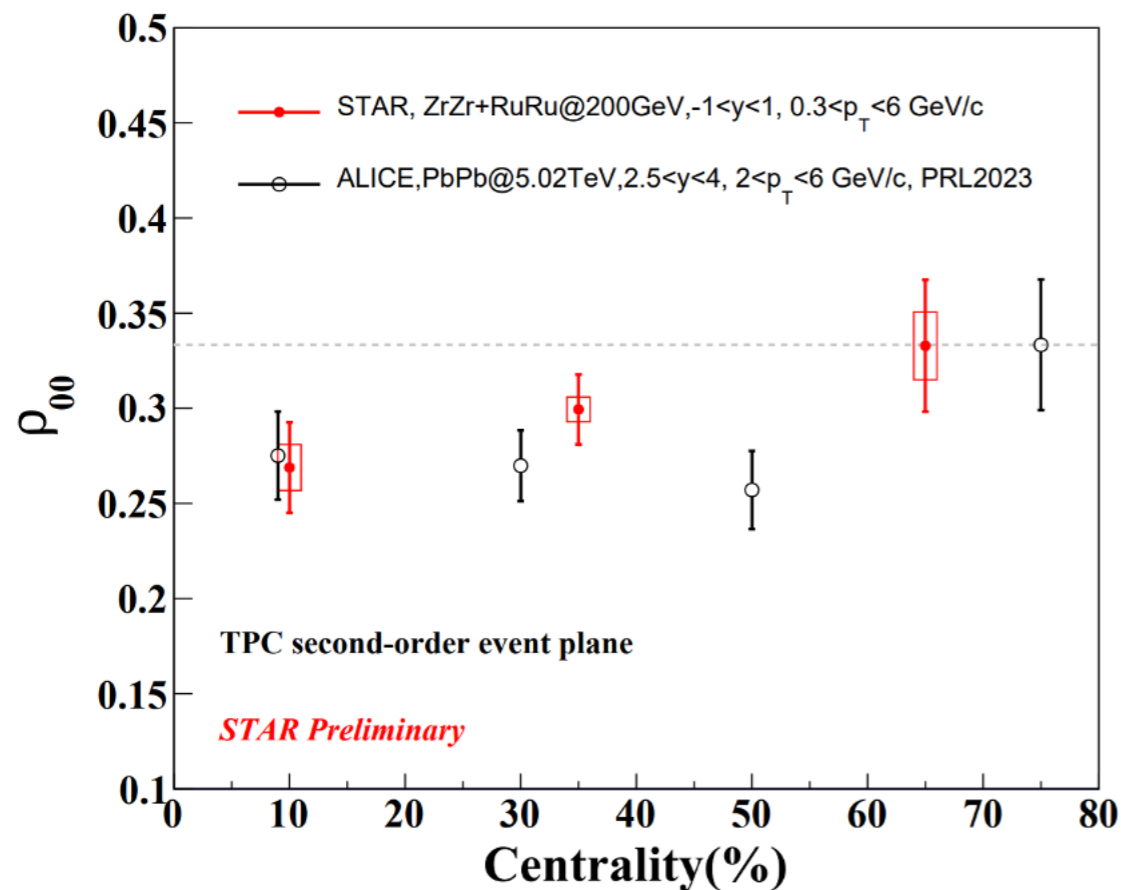Syst. uncert.

Event plane

Centrality (%)

J/ψ global spin alignment at RHIC

- ρ_{00} lower than 1/3 with a significance of 3.5σ for p_T from 0.3 to 6 GeV/c and 0-80% centrality

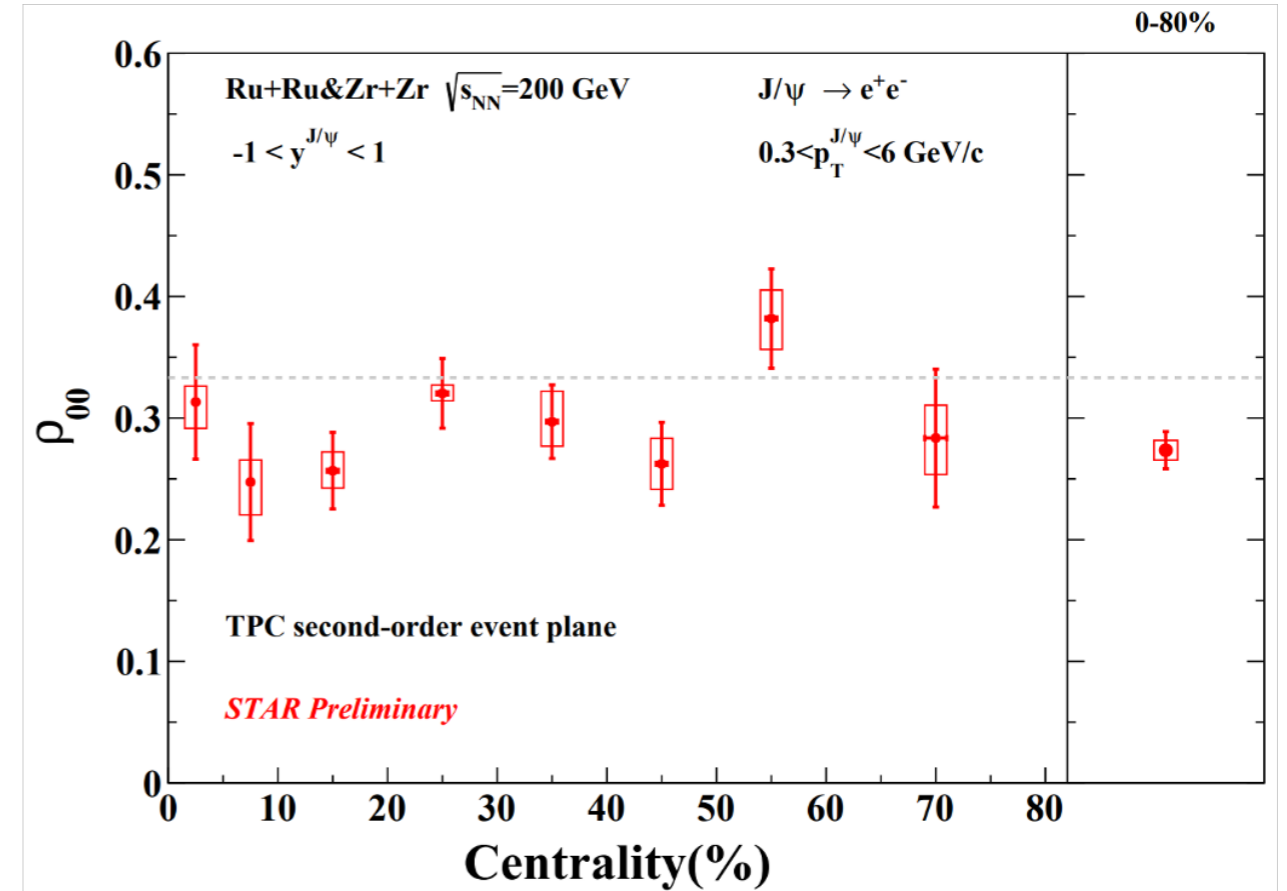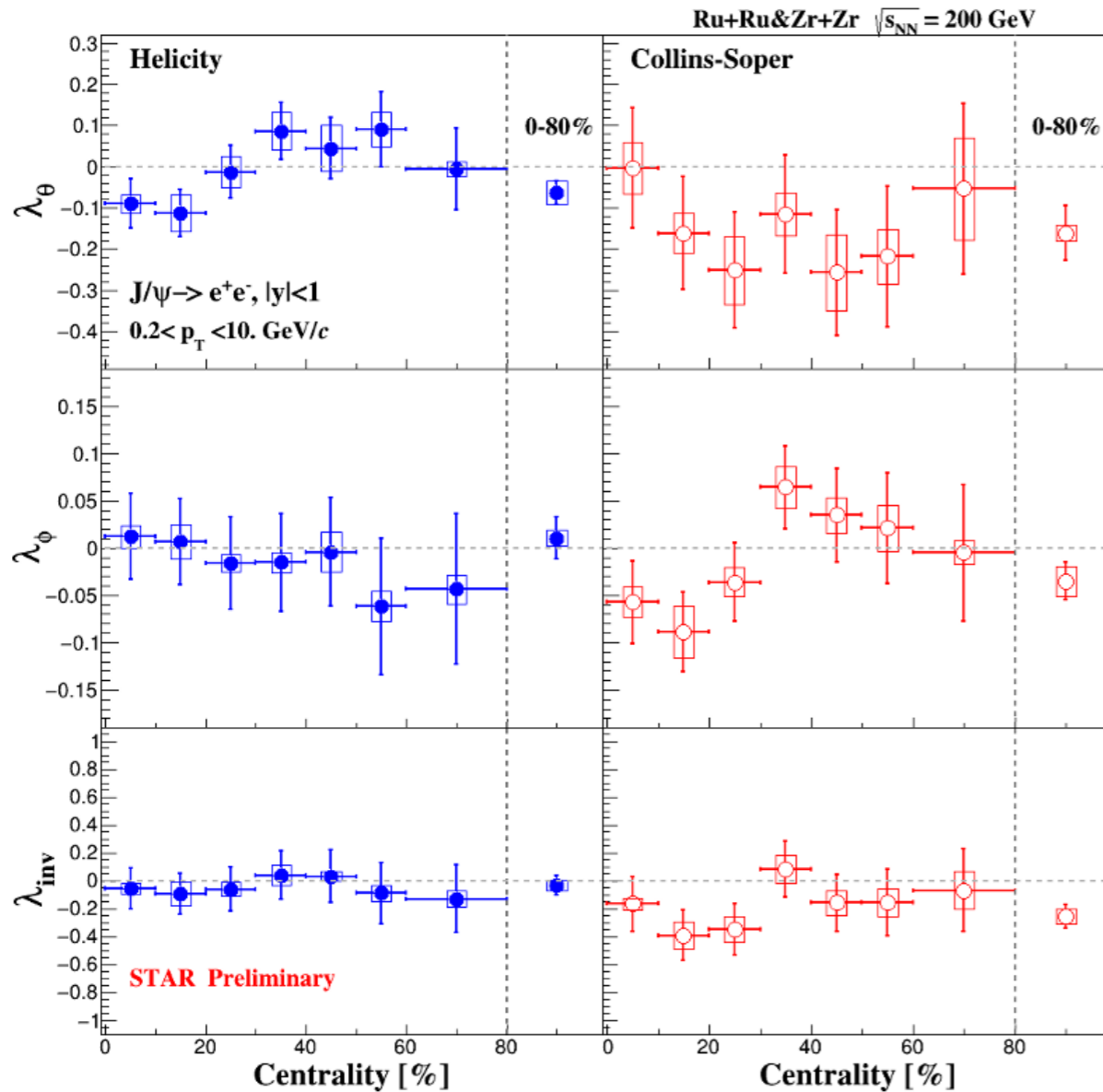- No significant centrality dependence within uncertainty

J/ψ spin alignment :RHIC vs LHC

- The ρ_{00} at RHIC energy is comparable to LHC results, despite of very different coalescence effect contribution and different rapidity

Theory inputs are needed!!

J/ψ polarization in different frame

Measurement of J/ψ polarization in HX, CS frame and w.r.t Event-plane can give a comprehensive constrain on J/ψ production in heavy-ion collisions
Primordial production v.s. regeneration ? Theory inputs are welcome!!

Summary

- First measurement of J/ψ polarization and spin alignment with respect to TPC event-plane in heavy-ion collisions at RHIC

  - J/ψ polarization consistent with zero in both HX and CS frames, no significant centrality and a hit of non-trivial p_T dependence at low-p_T range in HX frame

  - J/ψ global spin alignment ρ_{00} is found to be less than 1/3, and is comparable to the LHC result, despite of very different collision energy, systems and rapidity
- Theory inputs to both J/ψ polarization and global spin alignment are very welcome and crucial to understand the physics

Thanks!

J/ψ in Isobar collisions
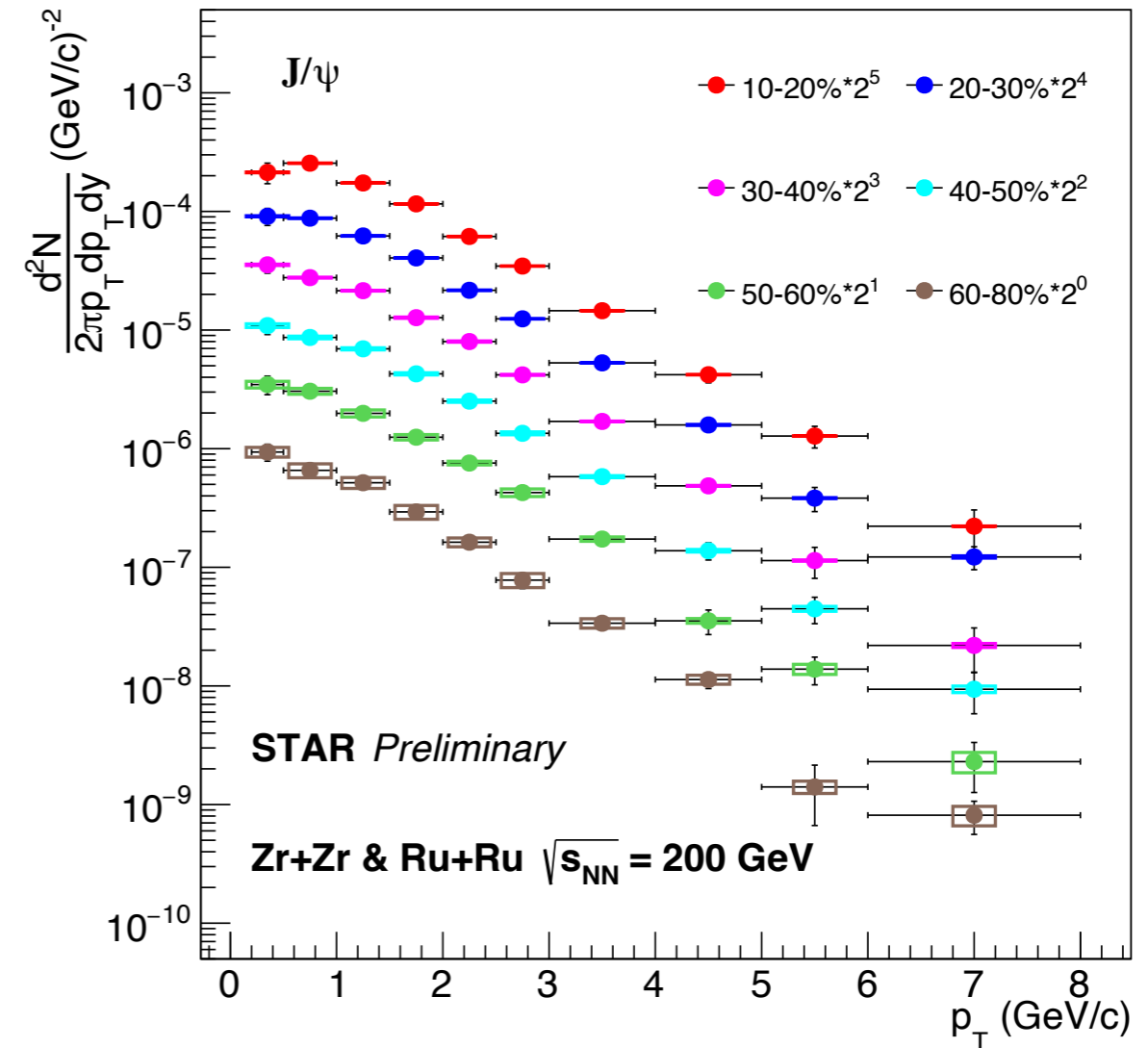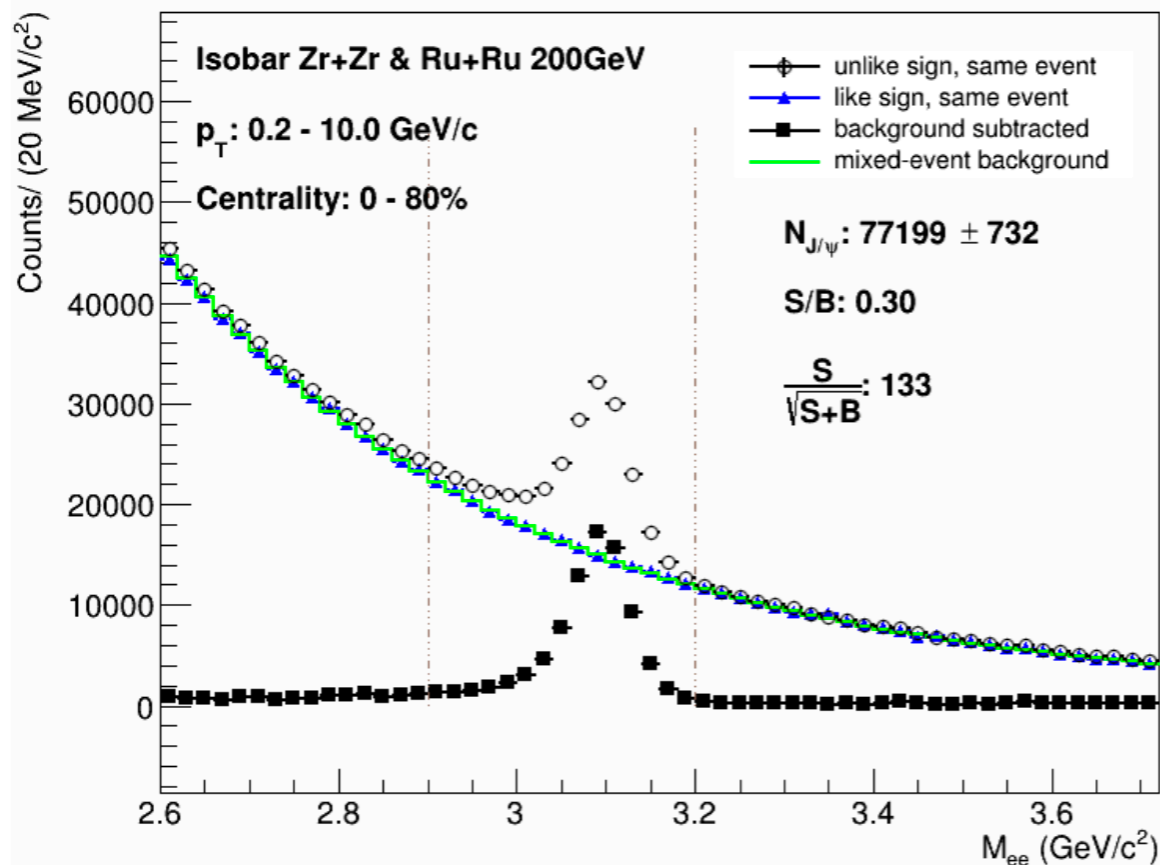
- Largest J/ψ sample at RHIC to date
  - High precision measurement
  - More differential measurement