山东大学
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Measurements of J/ψ polarization and spin alignment in Ru+Ru and Zr+Zr collisions at $\sqrt{s_{NN}}$= 200 GeV at STAR

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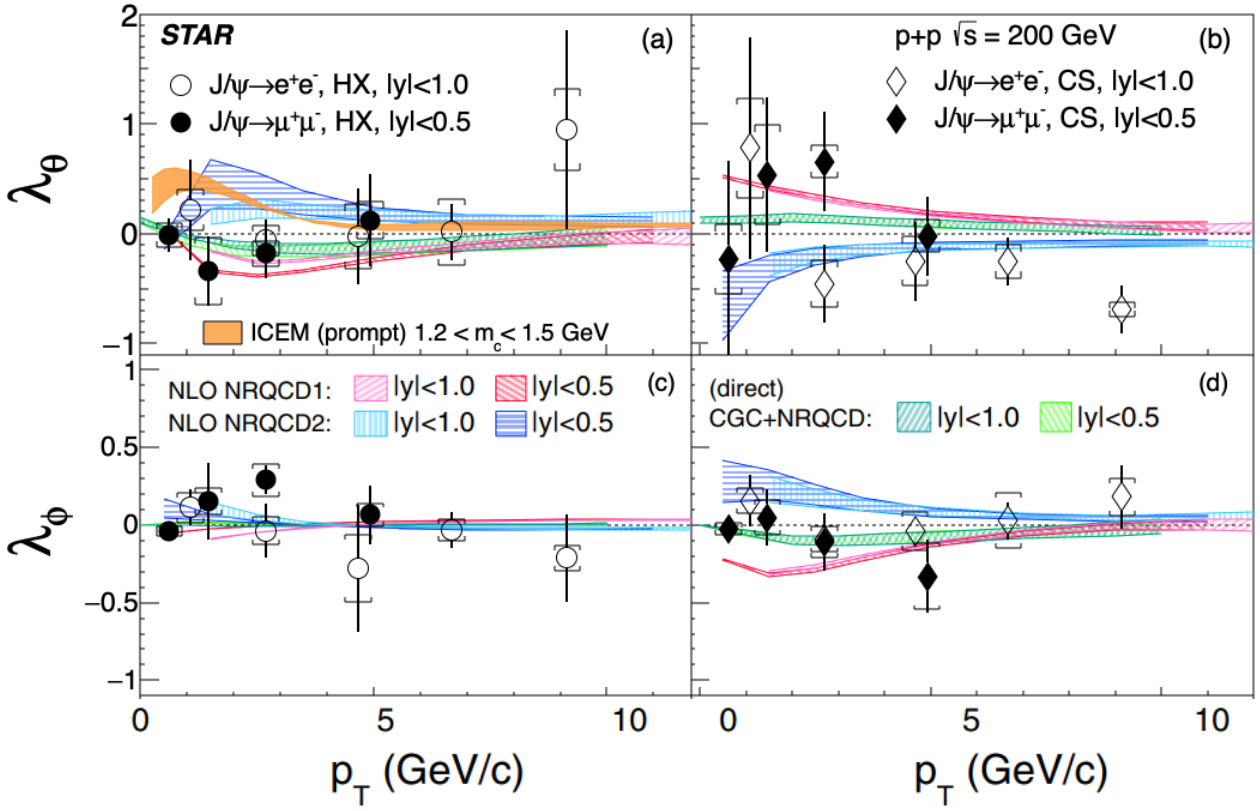
Outline

- Introduction and motivation
- J/ψ polarization in Helicity frame and Collins-Soper frame
- J/ψ global spin alignment
- Summary

Motivation: p+p Collisions

- **J/ψ polarization can be used to study production mechanism in p+p collisions**
  - colour-singlet vs colour-octet vs gluon fragmentation Faccioli et al, EPJC 69: 657–67 (2010)
- **Feed down also plays a role**
  - Prompt J/ψ = **Direct$^{60\%}$ + feed down$^{40\%}$**
  - Non-prompt: b-hadron decay



STAR PRD 102, 092009 (2020)

- No sizeable polarization for inclusive J/ψ in p+p collisions at $\sqrt{s} = 200$ GeV

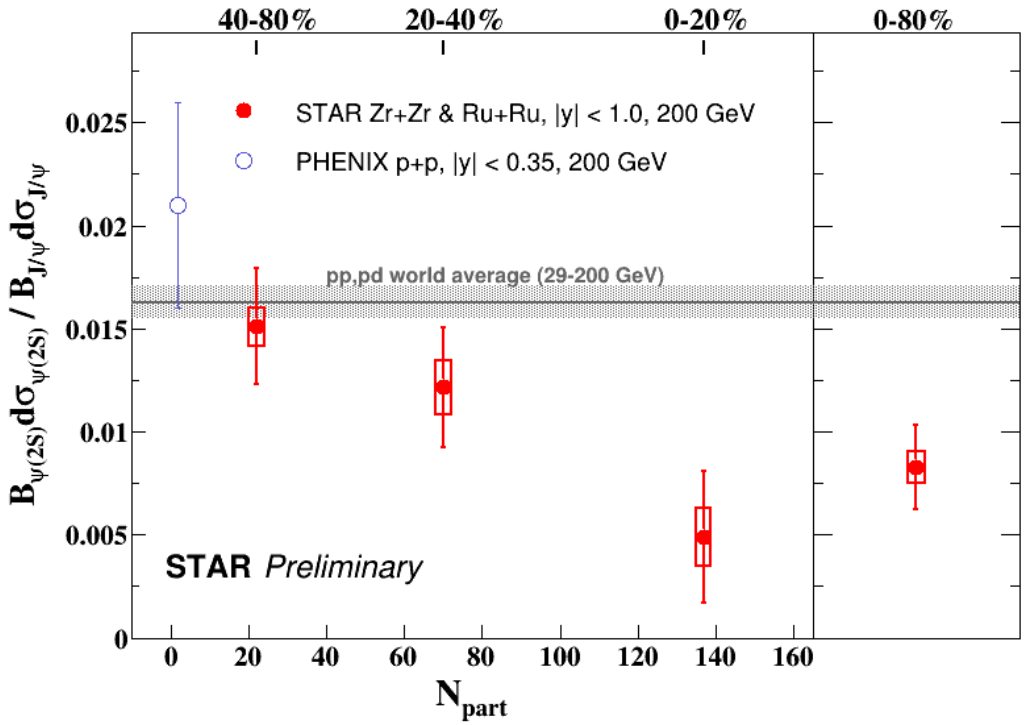
Could the inclusive J/ψ polarization be different in heavy-ion collisions?

Motivation: Heavy-Ion Collisions

- QGP affects the polarization of J/ψ ?

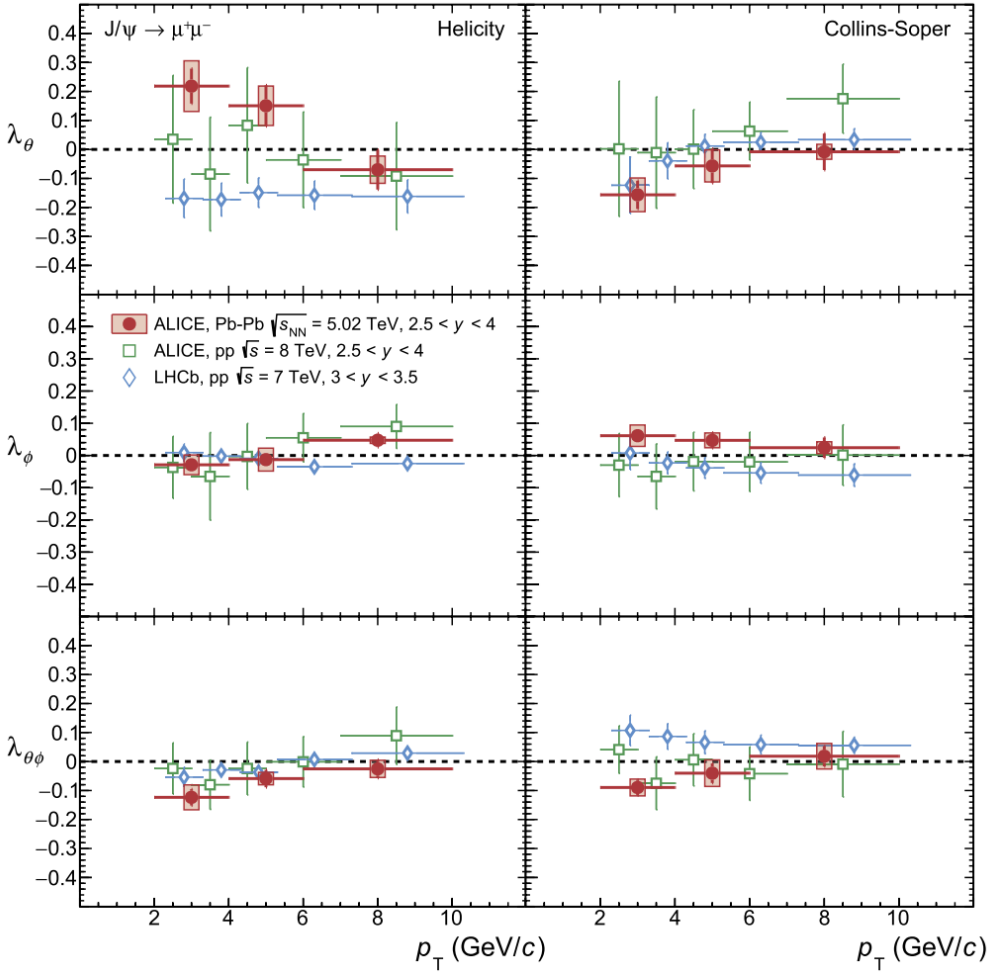
"Theoretical prediction: J/ψ polarization at small p_T, and find that it translates into the asymmetry of the $e^+e^-(\mu^+\mu^-)$ angular distribution $\boldsymbol{W(\theta) = 1 + \lambda_\theta \cos^2\theta}$, **with** $\boldsymbol{\lambda_\theta \cong 0.35 - 0.4}$."

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



- Modification of J/ψ feed-down fractions due to larger $\psi(2s)$ and χ_c suppression in the QGP

LHC Measurement



ALICE PLB 815 136146 (2021)

- **Hint of non-zero** J/ψ polarization at LHC
  - λ_θ shows a 2σ deviation w.r.t zero in HX for $2 < p_T < 4$ GeV/c

✓ Smaller regeneration contribution

✓ Different rapidity range

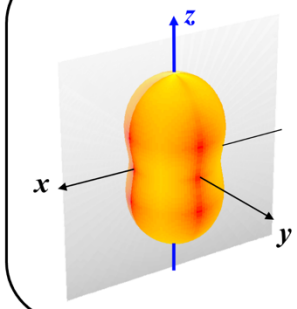
✓ …

- Is J/ψ polarized at the **RHIC energy**?

J/ψ Polarization

- ✓ J/ψ is a vector meson $(J^{PC} = 1^{--})$, Its spin can be described by the density matrix
- ✓ **Angular distribution of the decayed leptons:**

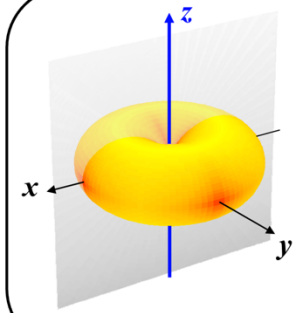
$$W(cos\theta, \phi) \propto 1 + \lambda_\theta \cos^2\theta + \lambda_\phi \sin^2\theta cos2\phi + \lambda_{\theta\phi} sin2\theta cos\phi$$



$\frac{dN}{d\Omega} \propto 1 + \cos^2\theta$

Transverse polarization

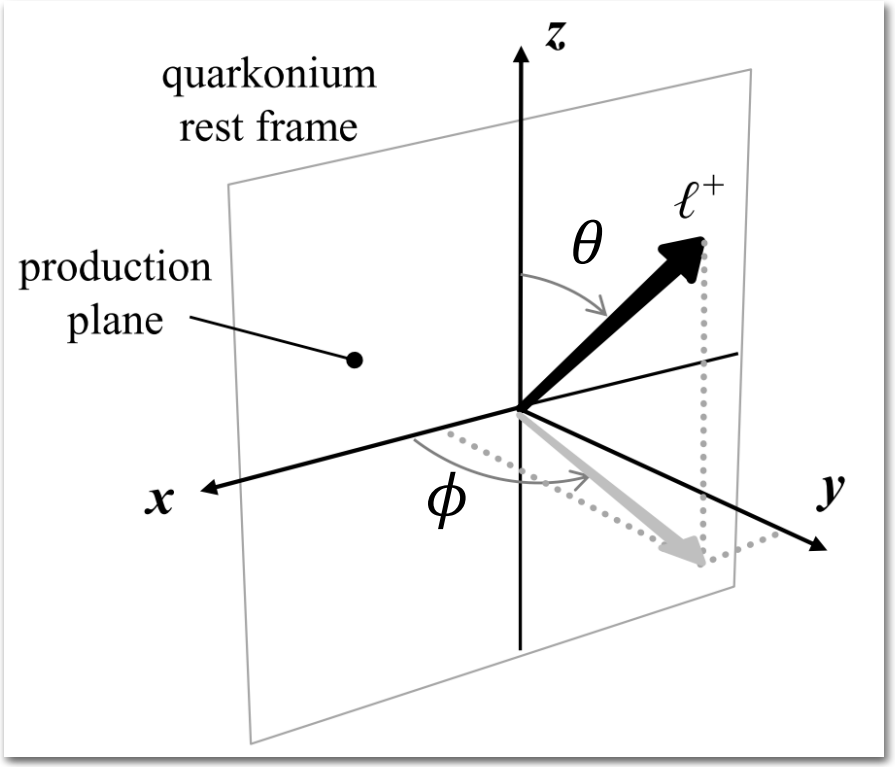
$(\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}) = (1,0,0)$



$\frac{dN}{d\Omega} \propto 1 - \cos^2\theta$

Longitudinal polarization

$(\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}) = (-1,0,0)$

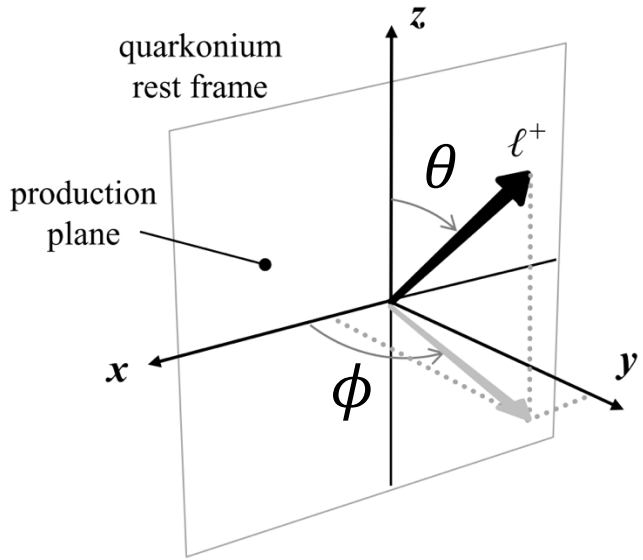


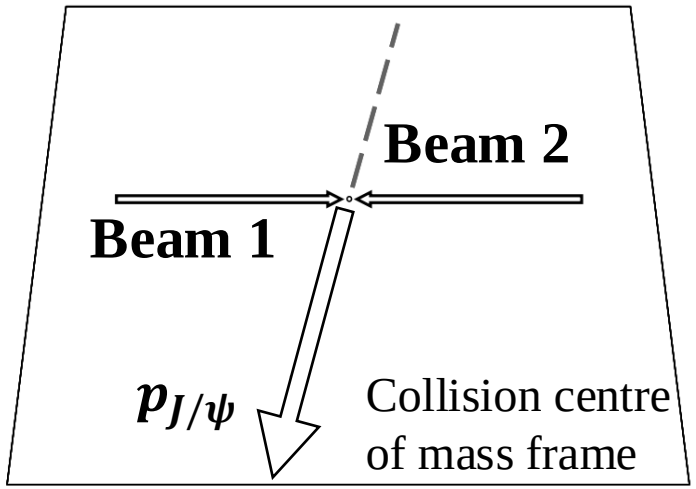
Faccioli et al, EPJC 69: 657-673 (2010)

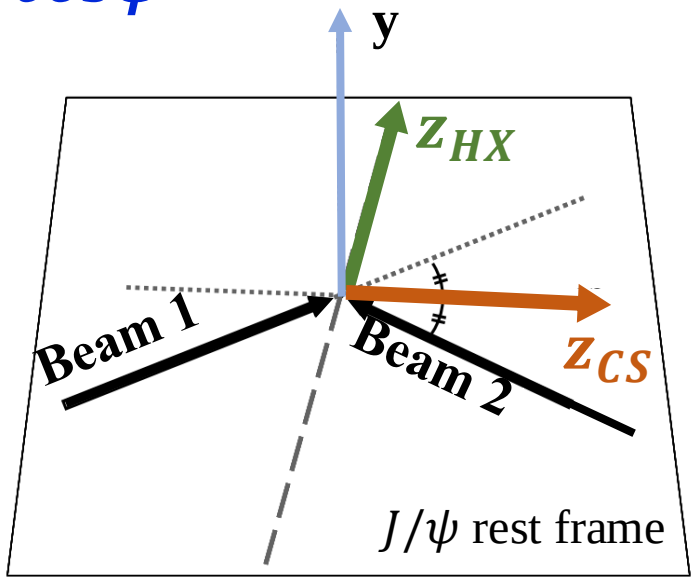
J/ψ Polarization

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

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







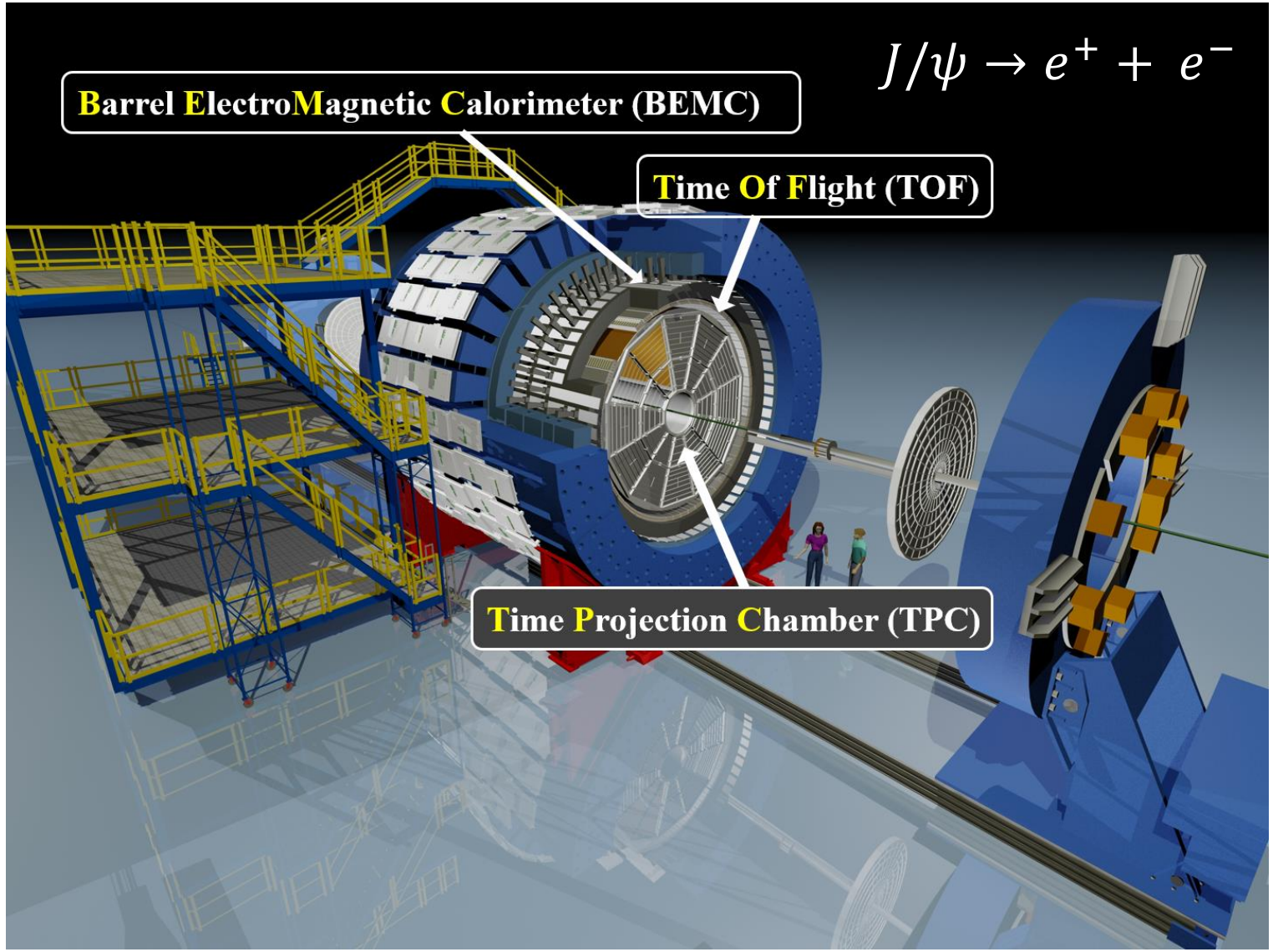
Production plane

➢ Definition of the z-axis in J/ψ rest frame:

Helicity frame (HX): along the J/ψ momentum direction

Collins-Soper frame (CS): bisector of angle between beams

The Solenoid Tracker At RHIC (STAR)



- TPC: -1< η <1

  Tracking, momentum and energy loss

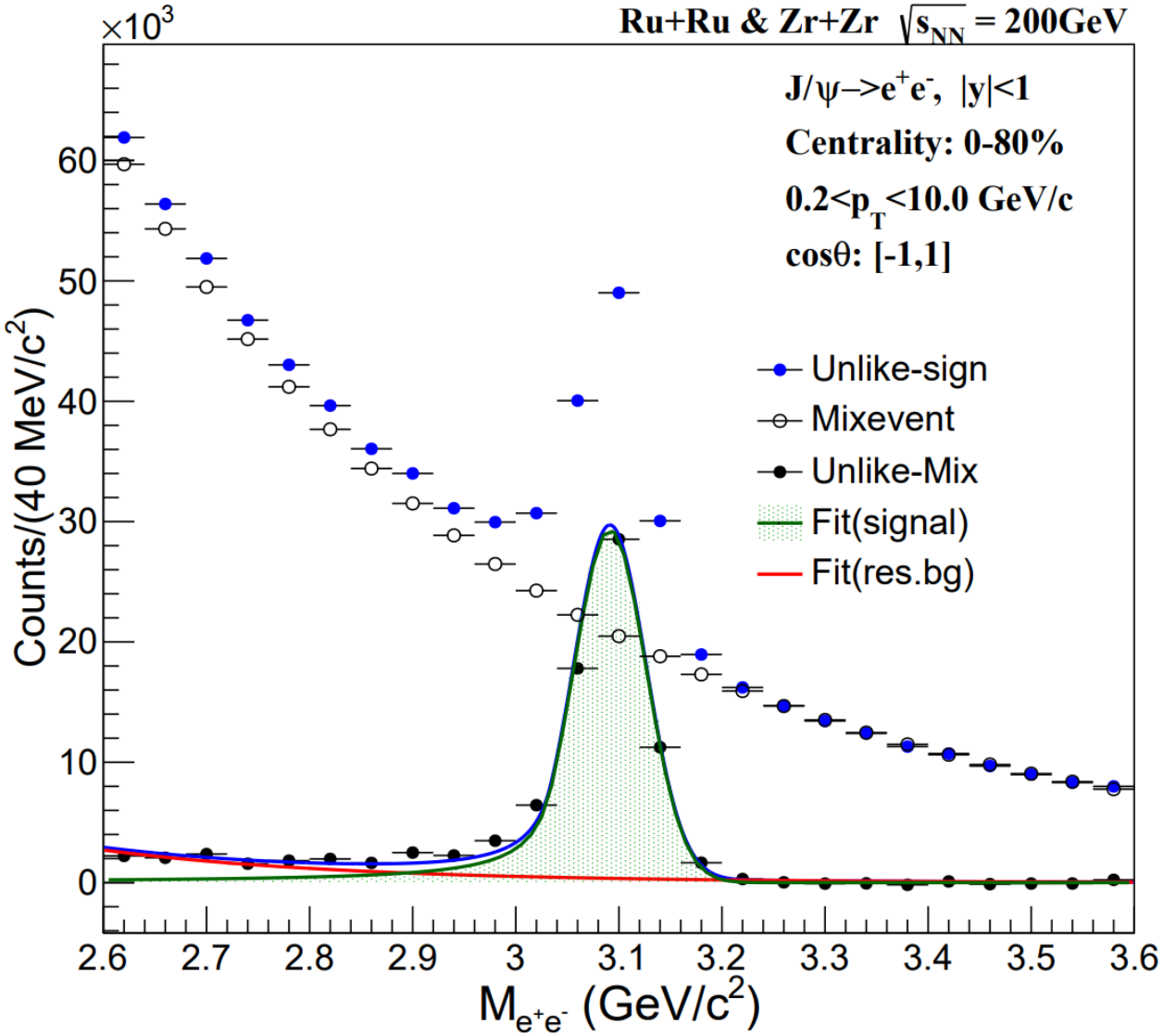
- TOF: -1< η <1

  Time of flight, particle identification

- BEMC: -1< η <1

  Identification of high-p_T electrons

Analysis Procedure: Signal Extraction



1. Signal extraction

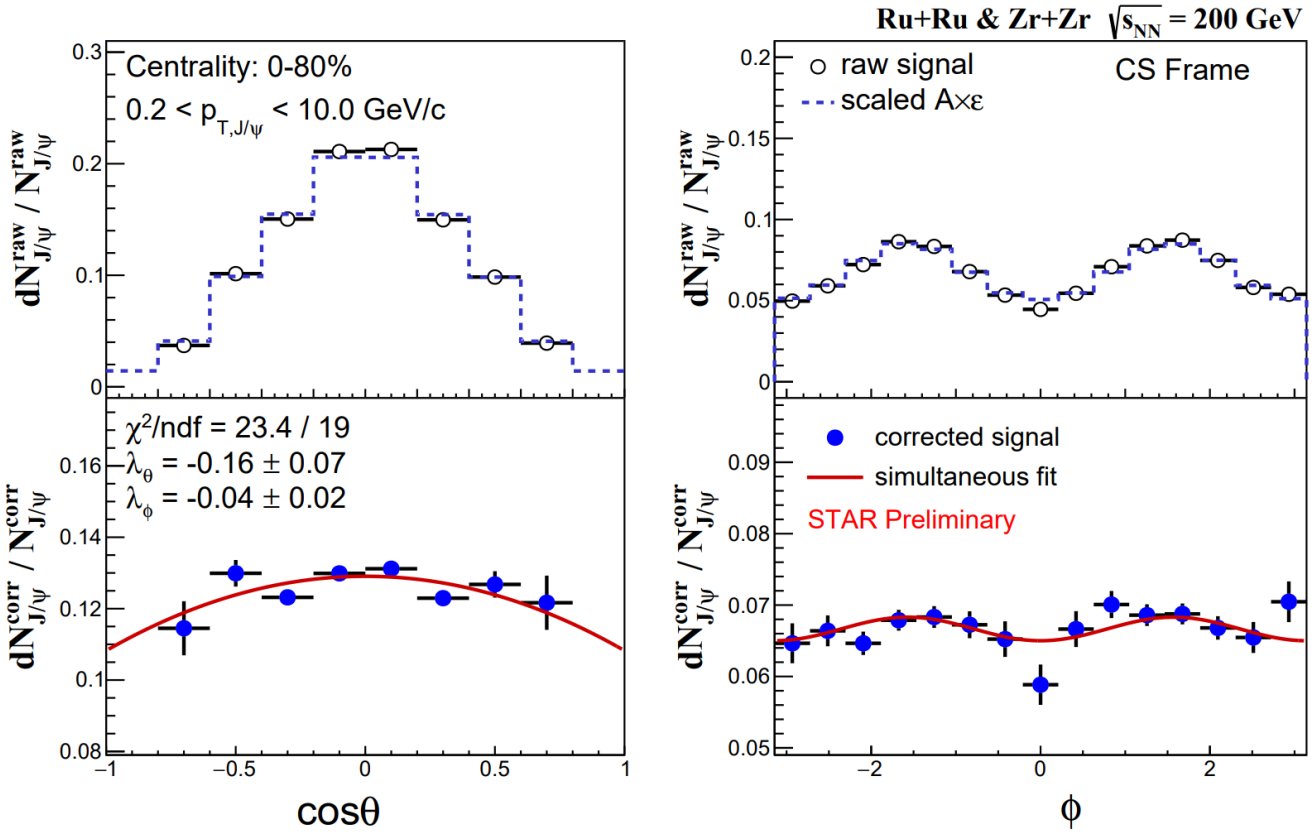
- Decay channel : $J/\psi \rightarrow e^+e^-$, |y|<1
- Combinatorial background: mixed-event technique
- Residual background: an exponential function
- J/ψ yields extracted as a function of cosθ and ϕ separately

Analysis Procedure: Extract Polarization

2. Acceptance × efficiency correction

- **Iterative procedure**: tuning of J/ψ polarization in simulation according to data

3. Polarization parameters extraction: simultaneously fit the corrected yield distributions

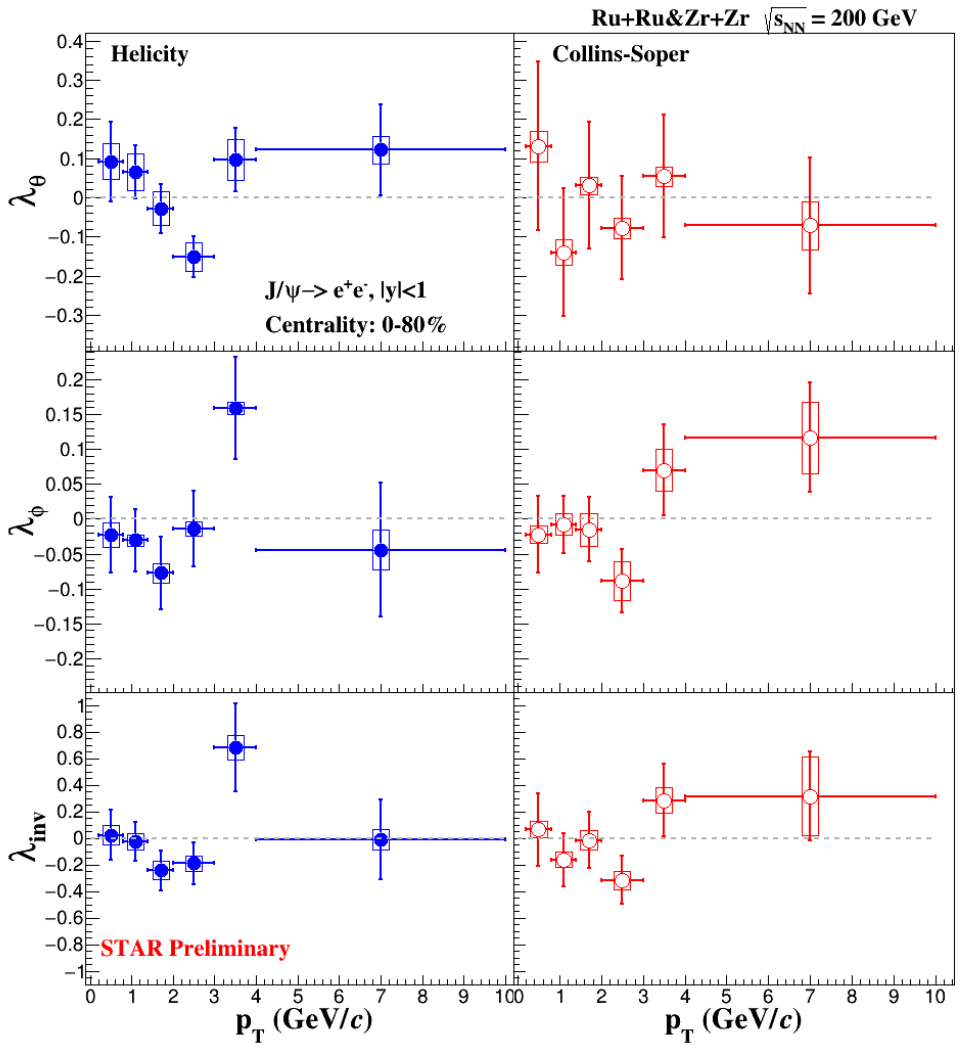


➢ **Simultaneously fit** angular distribution **and extract polarization parameters**

$$W(\theta) = 3 \times \frac{1+\lambda_\theta \cos^2\theta}{2\times(3+\lambda_\theta)}$$

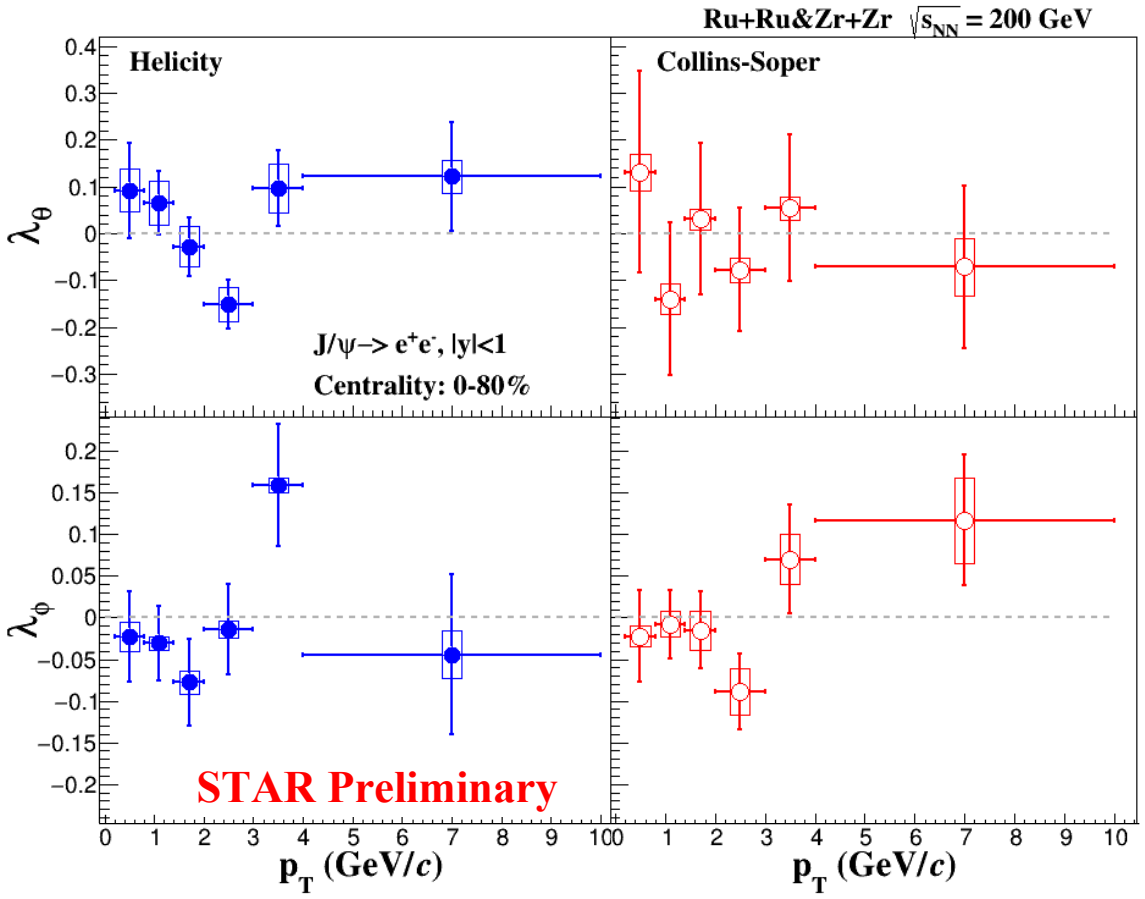
$$W(\phi) = \frac{2\times\lambda_\phi}{(3+\lambda_\theta)\times 2\pi} cos2\phi$$

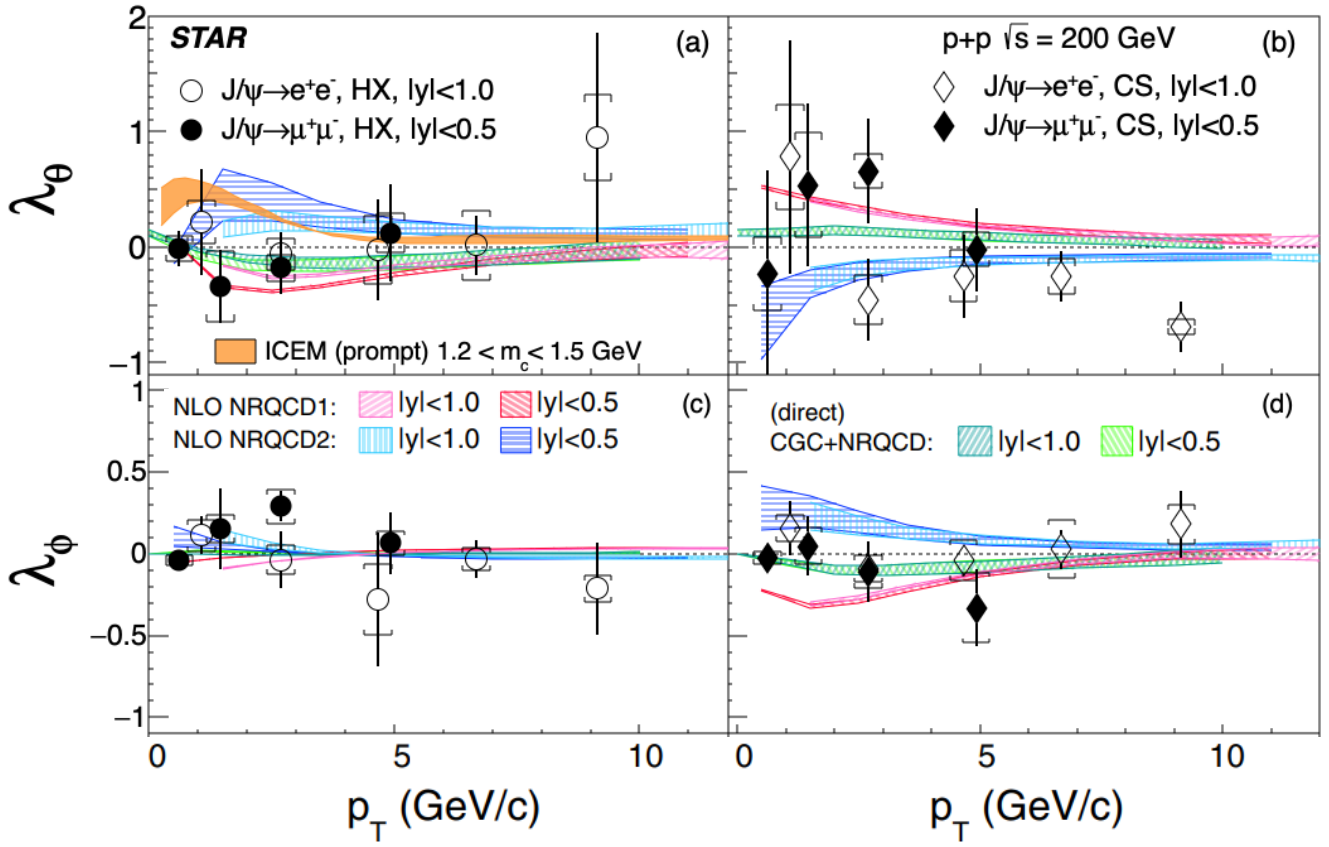
Transverse Momentum Dependence



- J/ψ polarization vs p_T:
  - $\lambda_\theta, \lambda_\phi$ are consistent with zero in HX and CS frames
  - no significant p_T dependence in either HX and CS
- Frame invariant quantity $\boldsymbol{\lambda_{inv}} = \frac{\boldsymbol{\lambda_\theta + 3\lambda_\phi}}{1-\lambda_\phi}$
- λ_{inv} are consistent between HX and CS frames

J/ψ polarization: Isobar vs p+p





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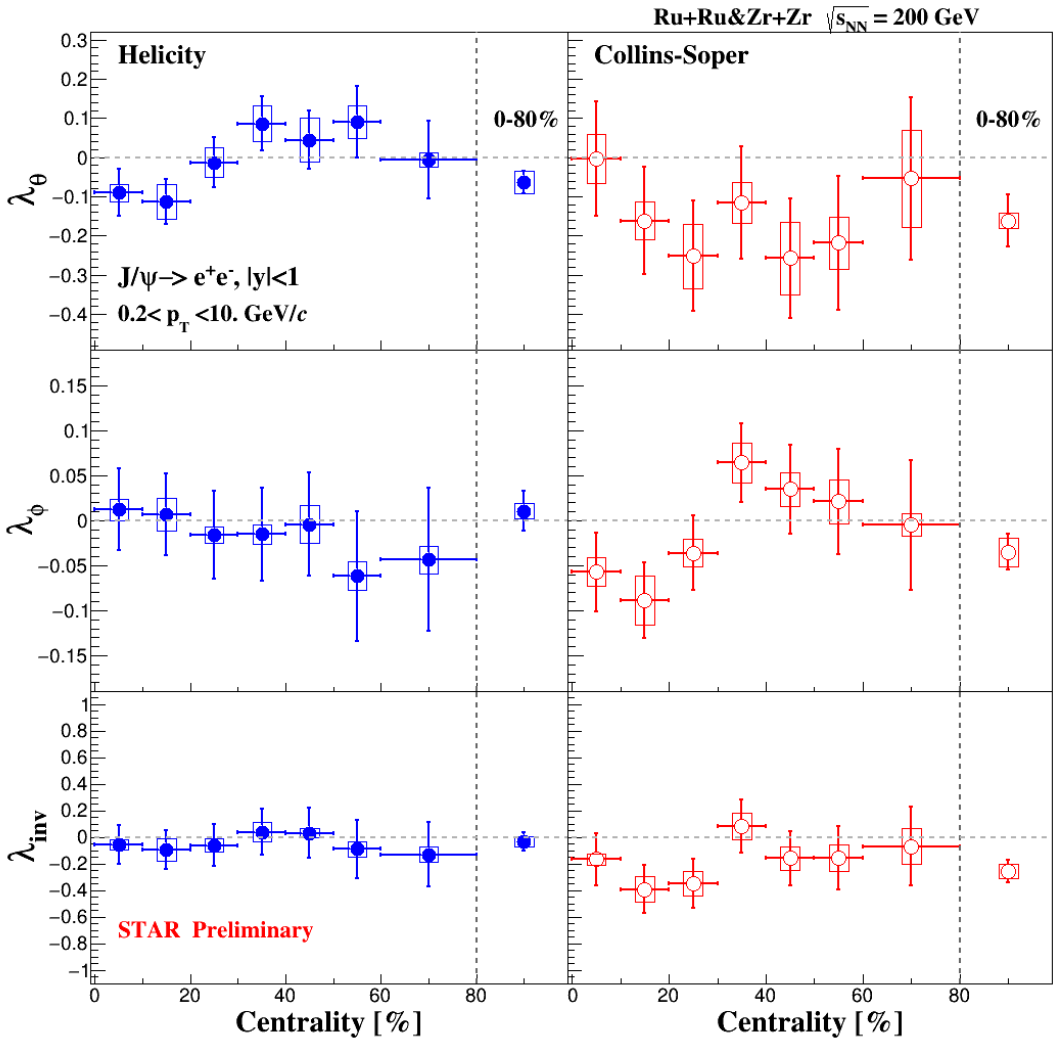
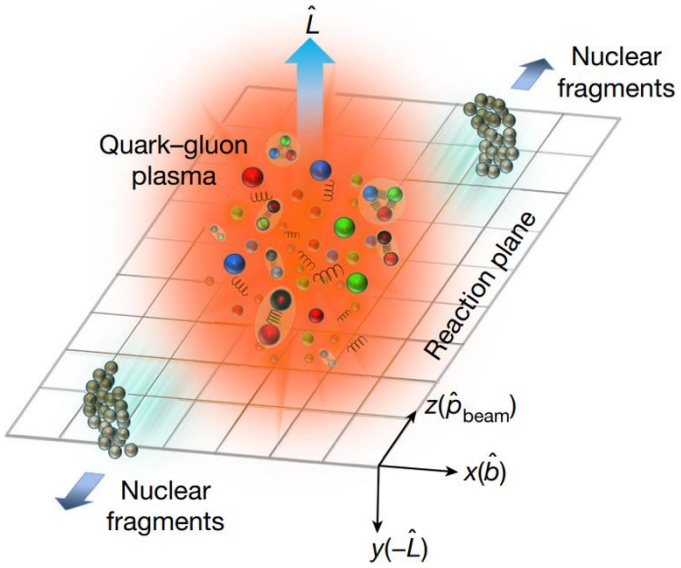
- λ_θ and λ_ϕ in isobar and p+p collisions are consistent with zero within uncertainties

Centrality Dependence



- No significant dependence of λ_θ, λ_ϕ from central to peripheral event
- λ_{inv} are consistent between HX and CS frames

J/ψ Global Spin Alignment Measurement



STAR, Nature 614, 244-248 (2023)

Angular momentum direction ⊥ reaction plane (lab frame)

~estimated by event plane (EP)

The relationship between polarization parameter and polarization density matrix element

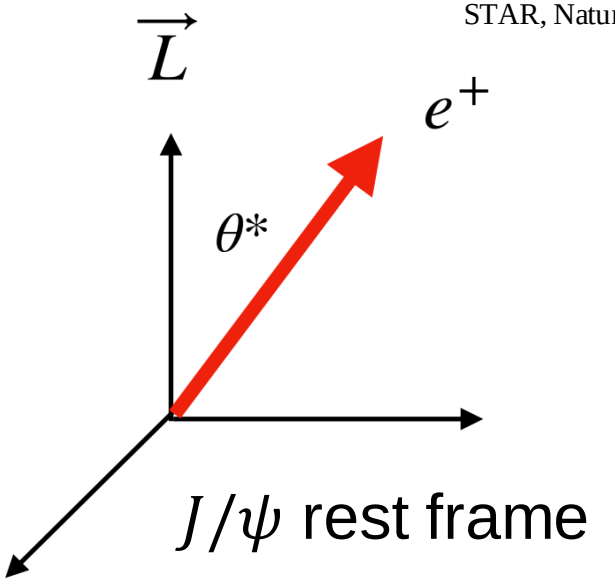
$$\lambda_\theta = \frac{1-3\rho_{00}}{1+\rho_{00}}$$

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

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

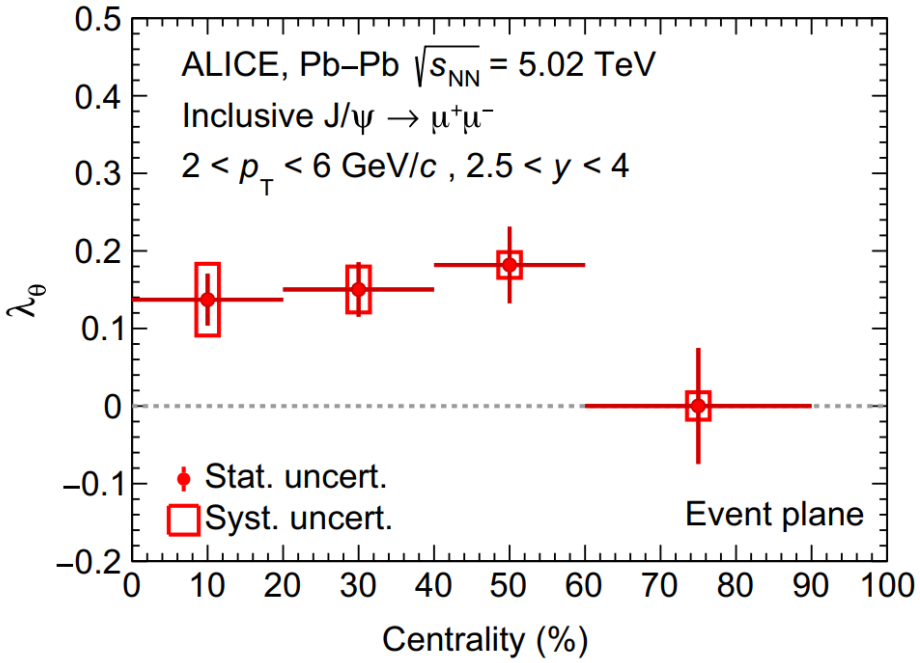
$\rho_{00} = 1/3$ → absence of spin alignment

$\rho_{00} \neq 1/3$ → spin alignment

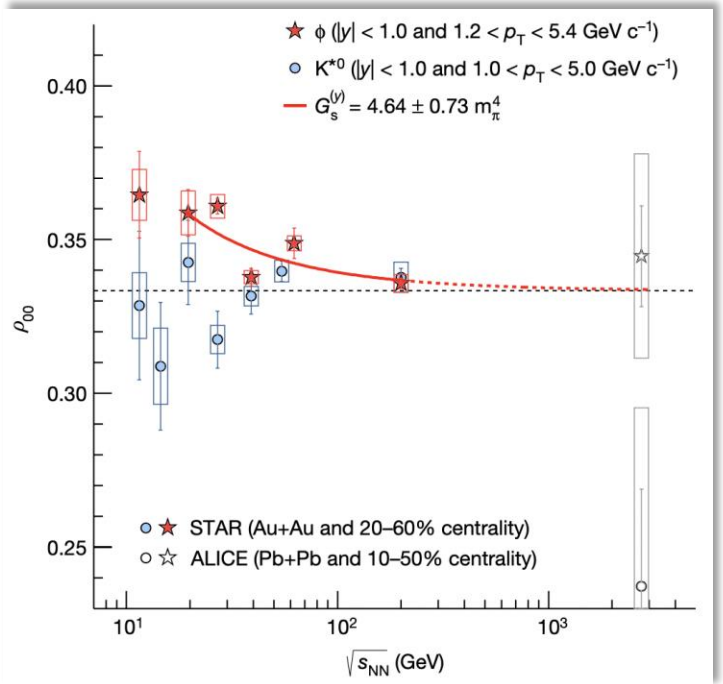


J/ψ Global Spin Alignment

- ϕ meson $\rho_{00} > 1/3$ at RHIC
- Might be caused by strange quark strong force field
- Similar effect expected for regenerated J/ψ



Alice PRL 131 4, 042303 (2023)



STAR, Nature 614, 244-248 (2023)

- J/ψ $\rho_{00} < 1/3$ at LHC forward rapidity
  - Spin alignment signal up to 60% centrality
- Consistent with regeneration of polarized charm quarks
  - Spin-orbital momentum coupling

Z.-T. Liang and X.-N. Wang, PLB 629, 20 (2005)

J/ψ Global Spin Alignment

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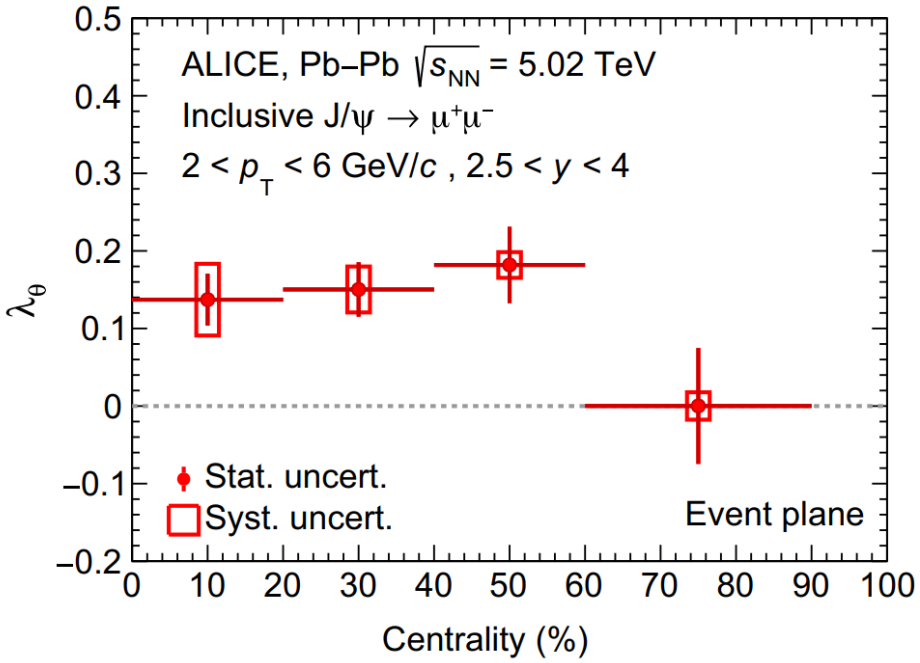

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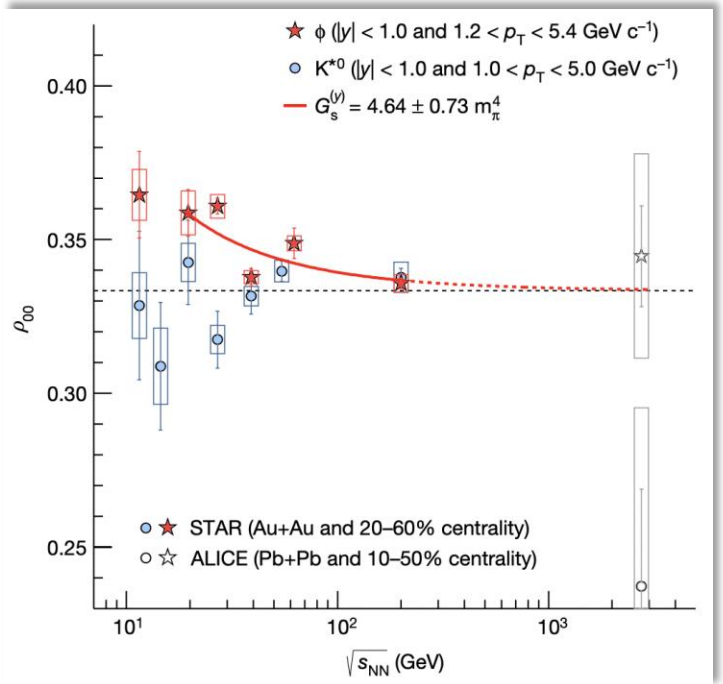
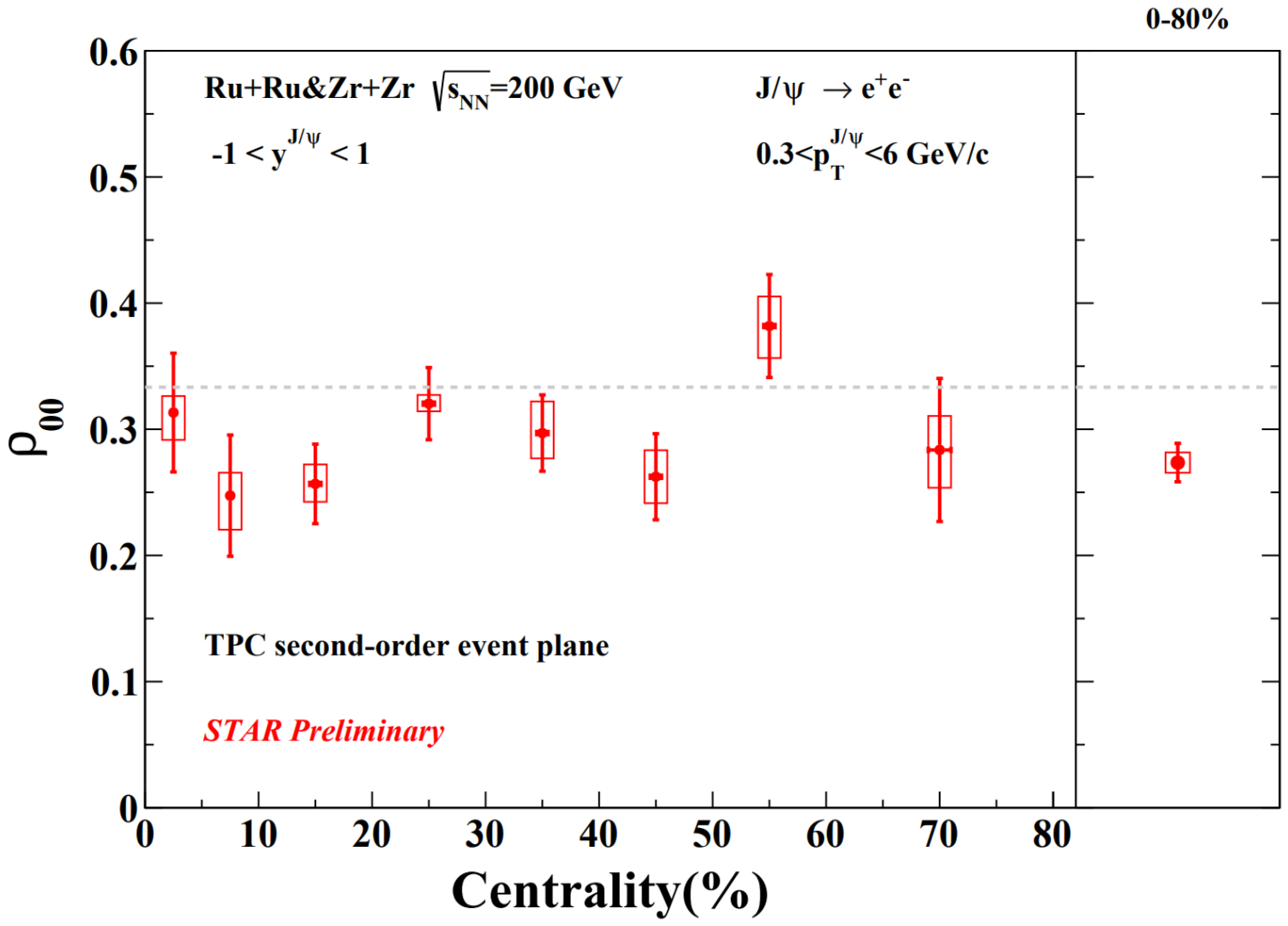


STAR, Nature 614, 244-248 (2023)

How about J/ψ spin alignment at RHIC energy?

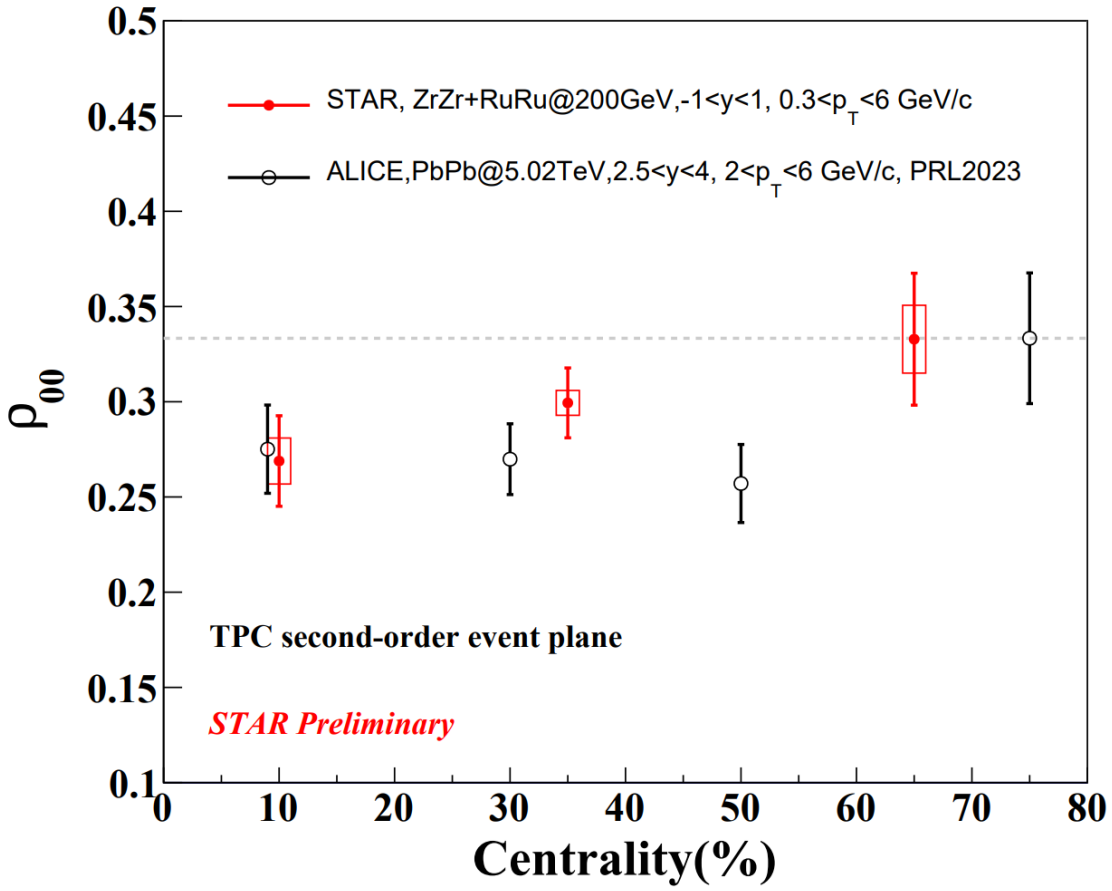
- **Smaller regeneration than LHC**

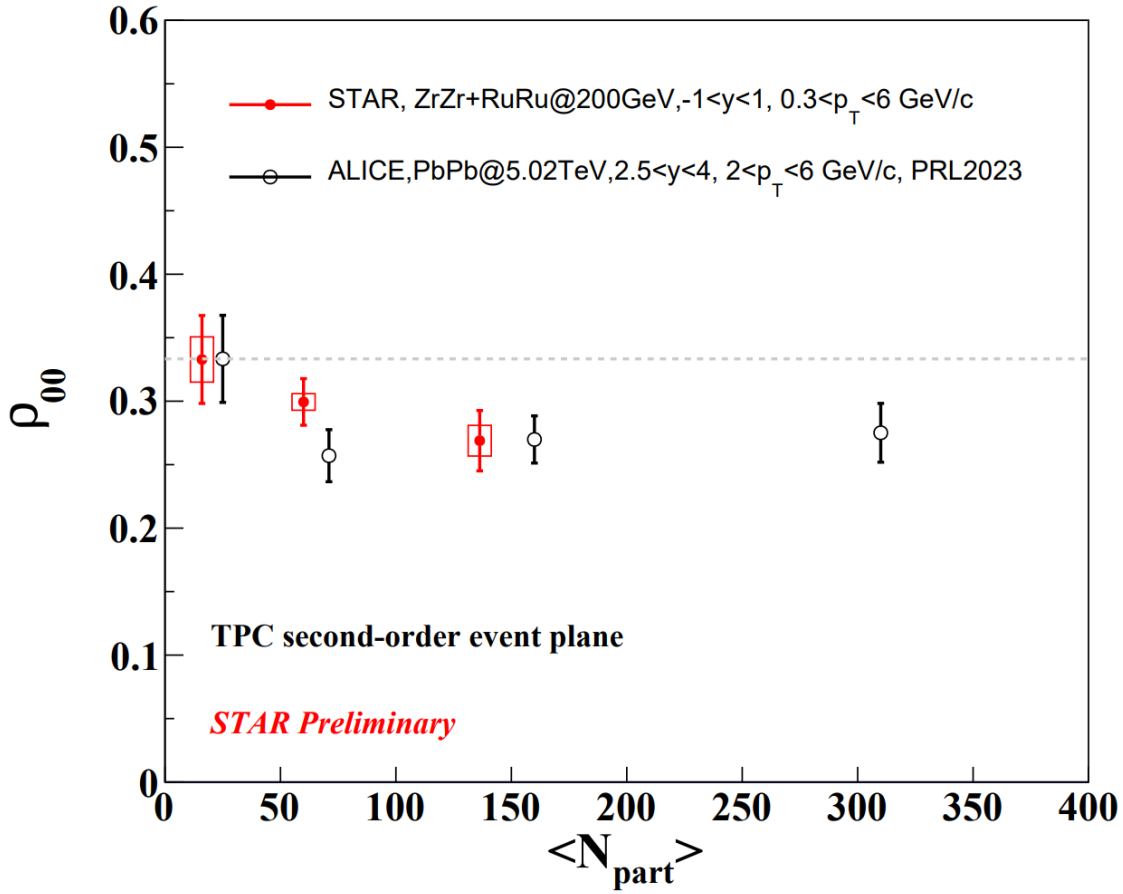
J/ψ Global Spin Alignment: Centrality Dependence



- First measurement of ρ_{00} using second-order event plane at RHIC
- ρ_{00} lower than 1/3 with a **significance of 3.5 σ** for p_T from 0.3 to 6 GeV/c and 0-80% centrality
- No significant centrality dependence within uncertainty.

J/ψ Global Spin Alignment: RHIC vs LHC





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

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**
  - $\lambda_\theta, \lambda_\phi$ consistent with zero in HX and CS frames
  - No significant centrality and p_T dependence
- **J/ψ global spin alignment**
  - ρ_{00} lower than 1/3 with a **significance of 3.5 σ** for p_T from 0.3 to 6 GeV/c and 0-80% centrality
  - Similar ρ_{00} values at RHIC and LHC, despite of very different collision energies, systems and rapidity

Summary

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

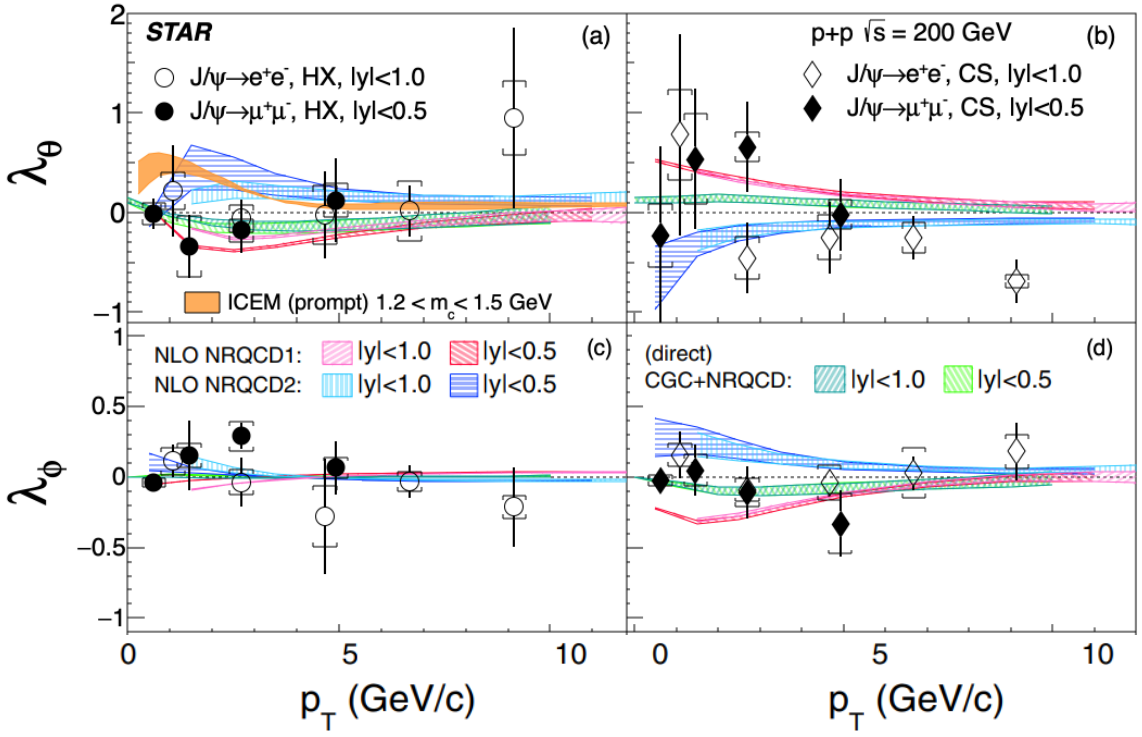
Thanks for your attention

- **J/ψ polarization**
  - $\lambda_\theta, \lambda_\phi$ consistent with zero in HX and CS frames
  - No significant centrality and p_T dependence
- **J/ψ global spin alignment**
  - ρ_{00} lower than 1/3 with a **significance of 3.5 σ** for p_T from 0.3 to 6 GeV/c and 0-80% centrality
  - Similar ρ_{00} values at RHIC and LHC, despite of very different collision energies, systems and rapidity

Back up

J/ψ Polarization-p+p collisions

proton+proton 1980



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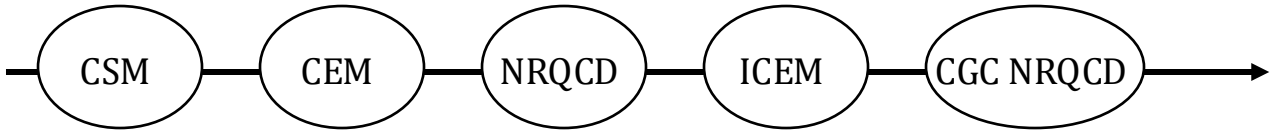
- ***J/ψ* polarization can be used to study production mechanism in p+p collisions**
  - colour-singlet vs colour-octet vs gluon fragmentation



CSM

- LO: transversal polarization
- NLO: a longitudinal polarization

COM:

- small p_T: small longitudinal polarization
- large p_T: a transverse polarization

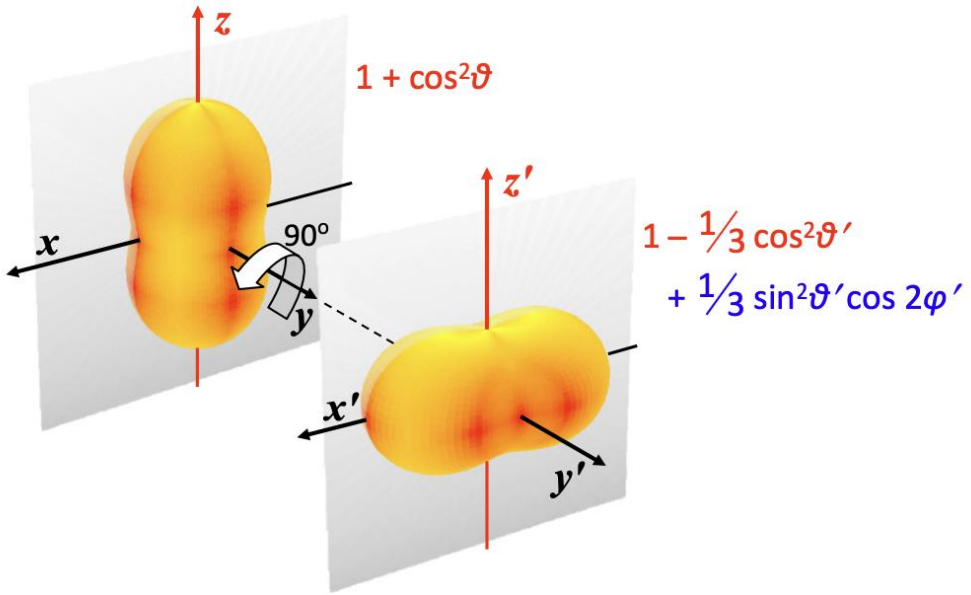
V. Cheung and R. Vogt P.R.C 105, 055202 (2022)

- No sizeable polarization for inclusive J/ψ in p+p collisions at $\sqrt{s} = 200$ GeV
- The current precision is not enough to distinguish between different models

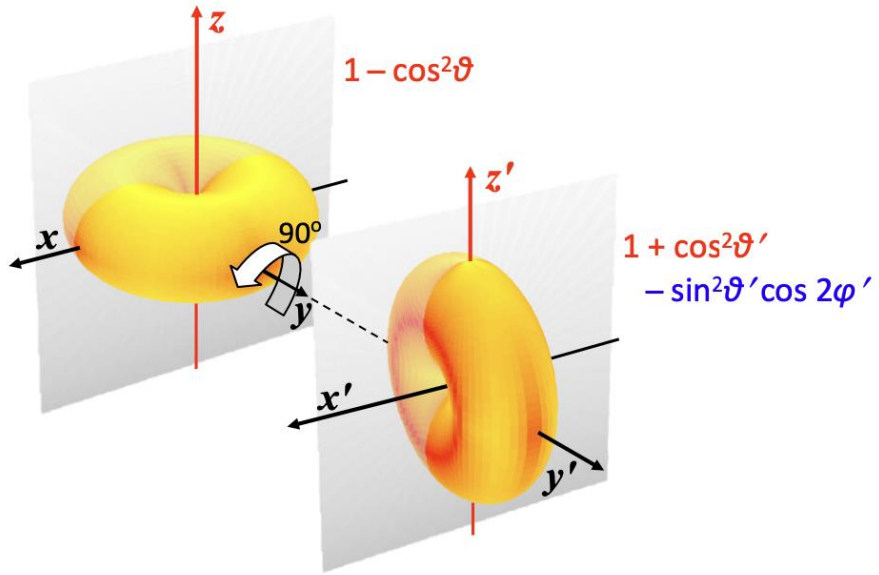
Other Polarization Parameters λ_{inv}

➢ Frame invariant quantity $\boldsymbol{\lambda_{inv} = \frac{\lambda_\theta + 3\lambda_\phi}{1-\lambda_\phi}}$

$\boldsymbol{\lambda_{inv} = 1}$



$\boldsymbol{\lambda_{inv} = -1}$



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

✓ Calculating invariant λ_{inv} removes frame-induced kinematic dependencies