



# Spin alignment of vector mesons in relativistic heavy-ion collisions



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Date: 04<sup>th</sup> September 2025

Introduction

Physics Motivations

Results of spin-alignment observable

Light vector mesons ( $K^{*0}$ ,  $\phi$ ,  $\rho$ )

Heavy vector mesons ( $J/\psi$ ,  $\psi(2S)$ ,  $Y(1S)$ ,  $Y(2S)$ )

Conclusions

Based on:

1. B. Sahoo, C. R. Singh and R. Sahoo, Eur. Phys. J. C **85**, 580 (2025).
2. B. Sahoo, C. R. Singh and R. Sahoo, [arXiv:2506.09405].

# Spin-alignment: an Introduction

- Spin-alignment: observable measure the degree to which particle spin is aligned with respect to a chosen axis
- For a vector meson ( $\mathbf{V}$ ) the total angular momentum ( $\mathbf{J}, J_z$ ) state can be expressed as

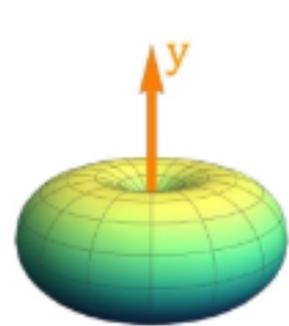
$$|V : J, J_z\rangle = \mathbf{b}_{+1}|1, +1\rangle + \mathbf{b}_0|1, 0\rangle + \mathbf{b}_{-1}|1, -1\rangle$$

Spin alignment  $\Leftrightarrow$  Decay daughter's angular distribution

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

- Spin-density matrix

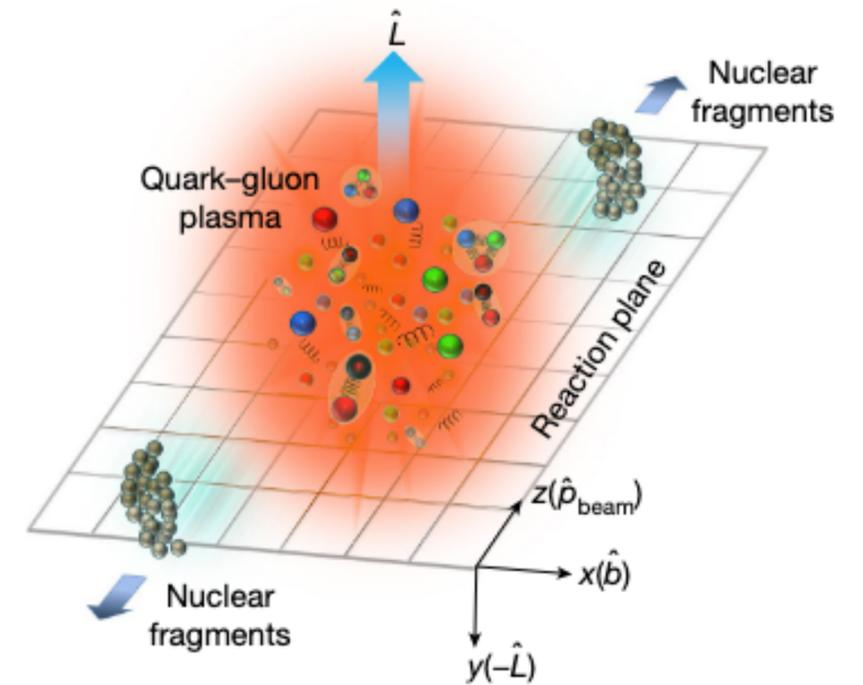
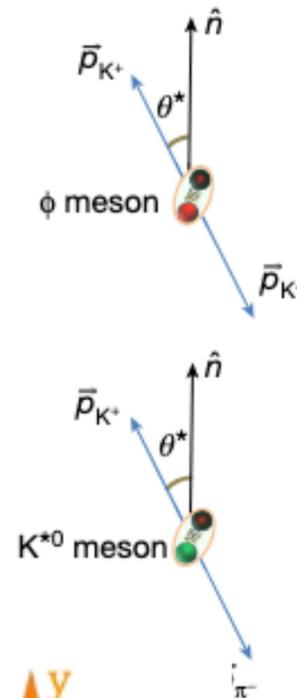
$$\rho = \begin{pmatrix} \rho_{11} & \rho_{1,0} & \rho_{1,-1} \\ \rho_{0,1}^* & \rho_{00} & \rho_{0,-1} \\ \rho_{-1,1}^* & \rho_{-1,0}^* & \rho_{-1,-1} \end{pmatrix}$$



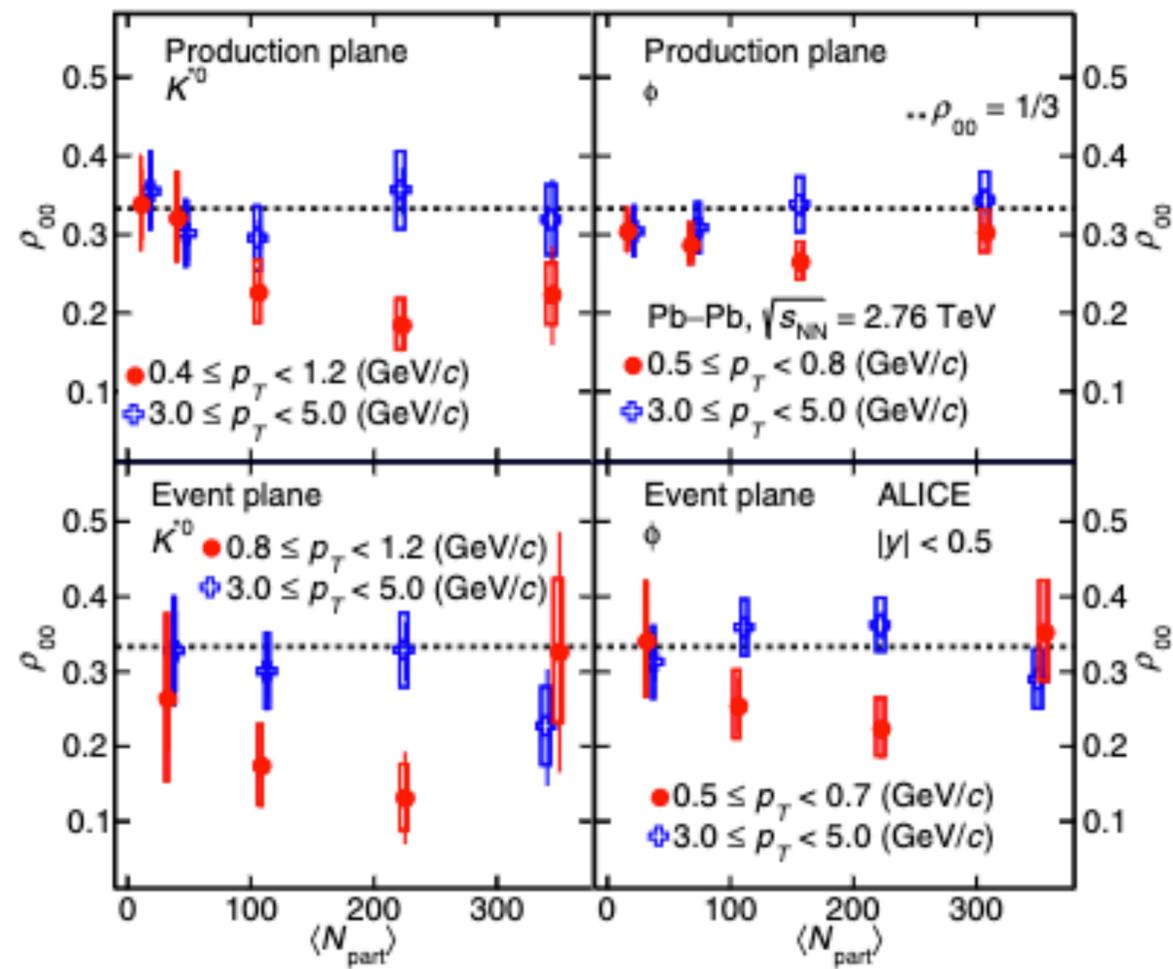
$\rho_{00} < 1/3$   
Transverse polarization



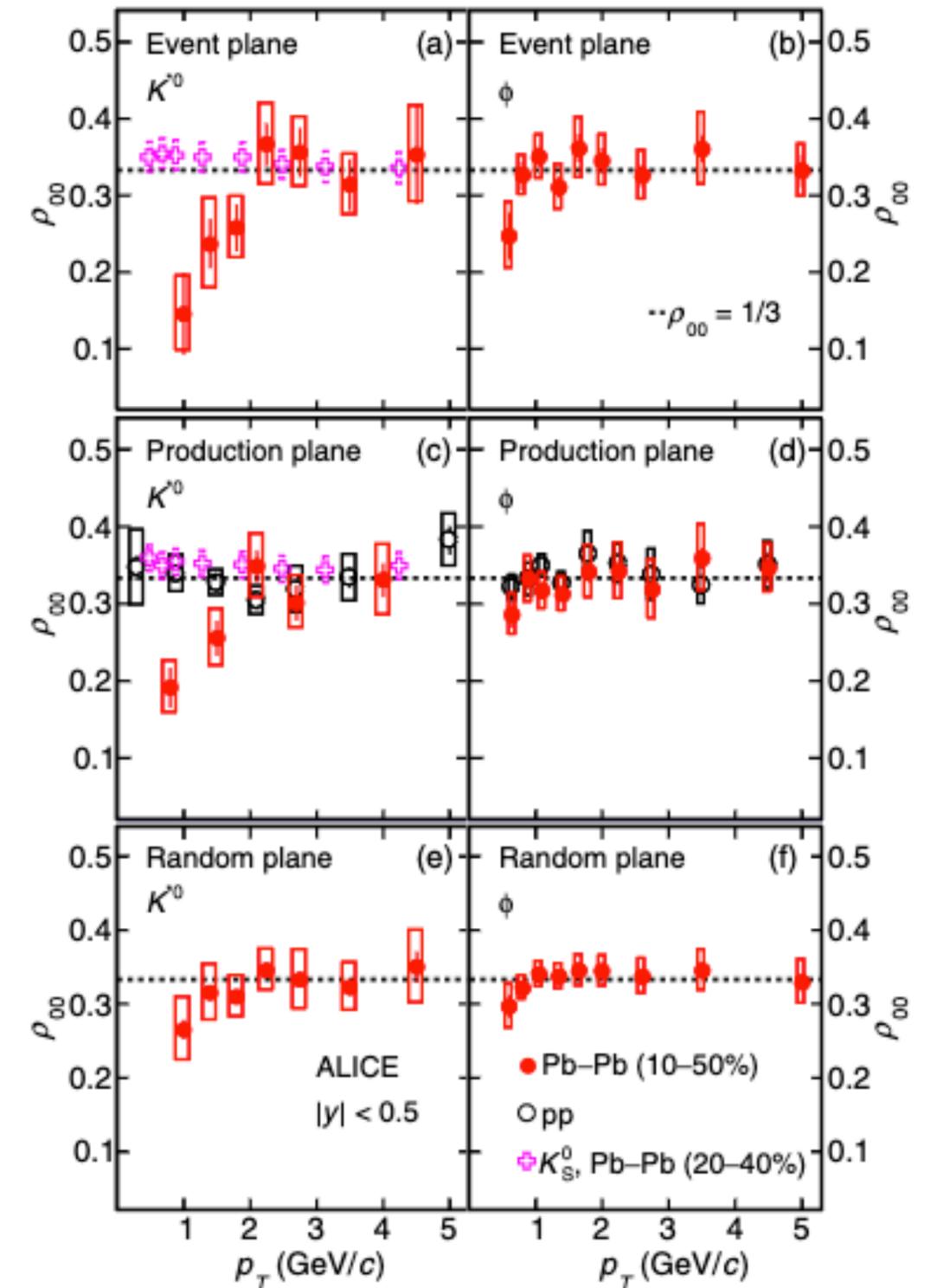
$\rho_{00} > 1/3$   
Longitudinal polarization



# Physics Motivation: Spin alignment of $K^{*0}$ , $\phi$ in Pb-Pb collisions at LHC energy

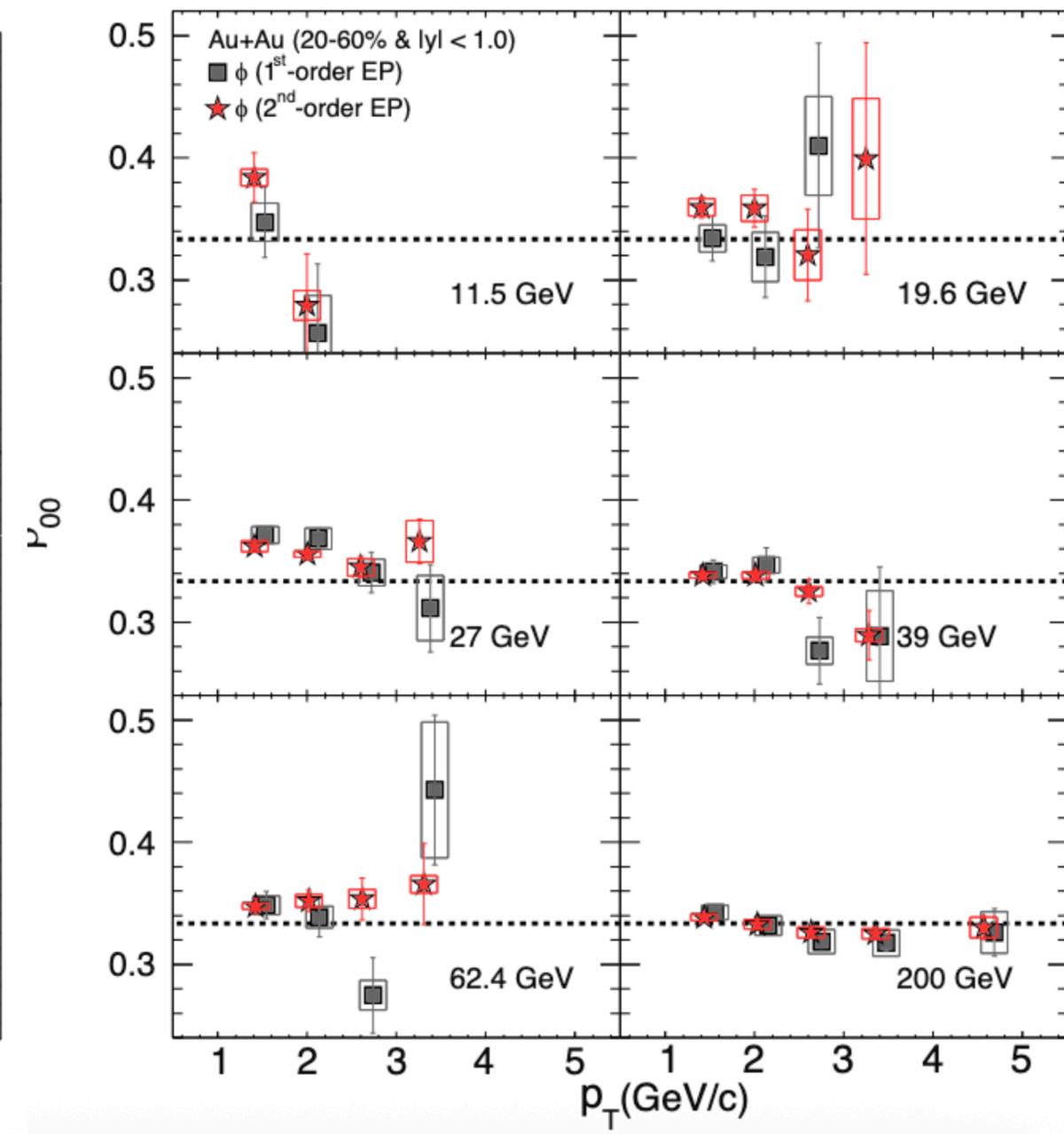
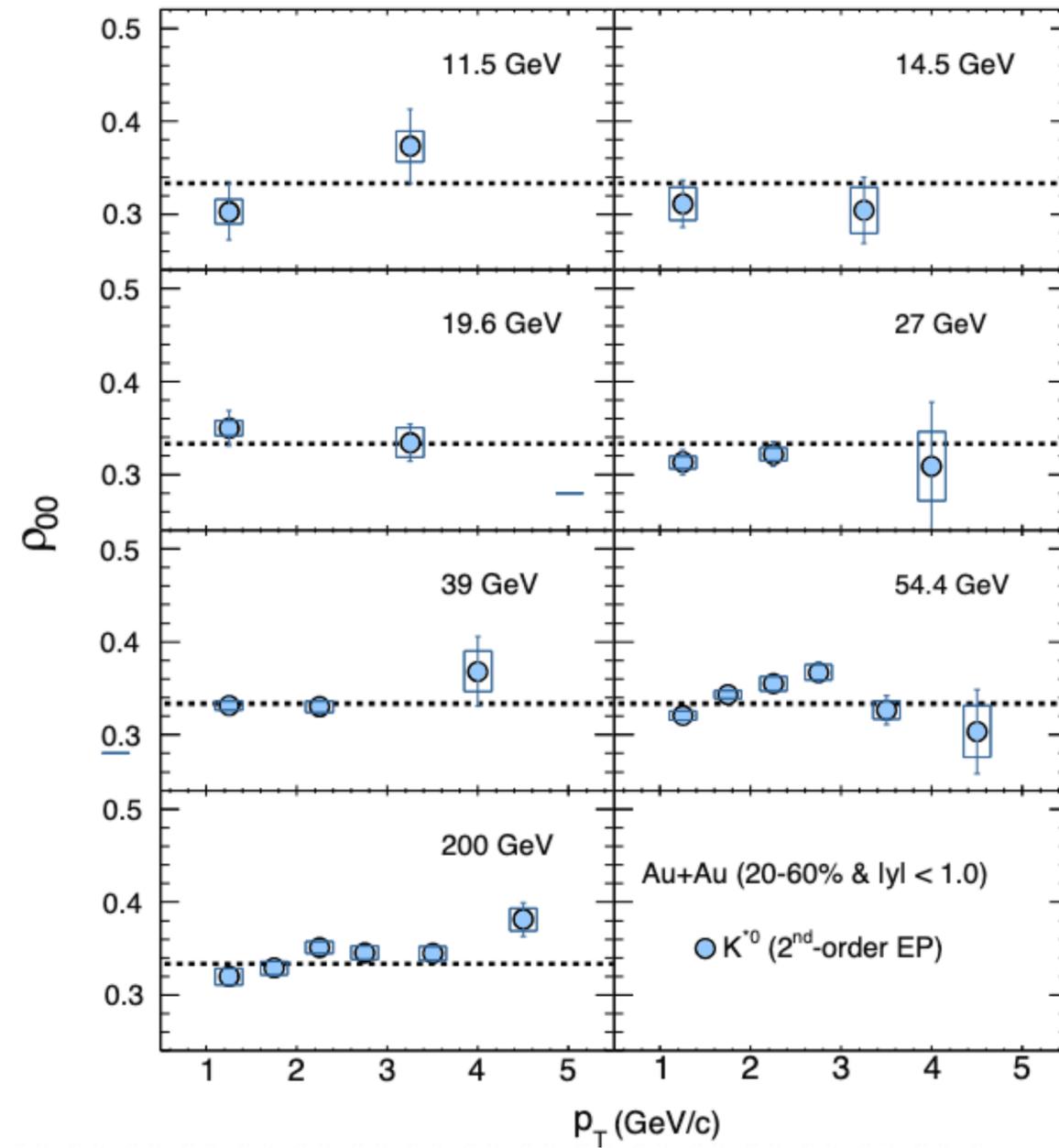
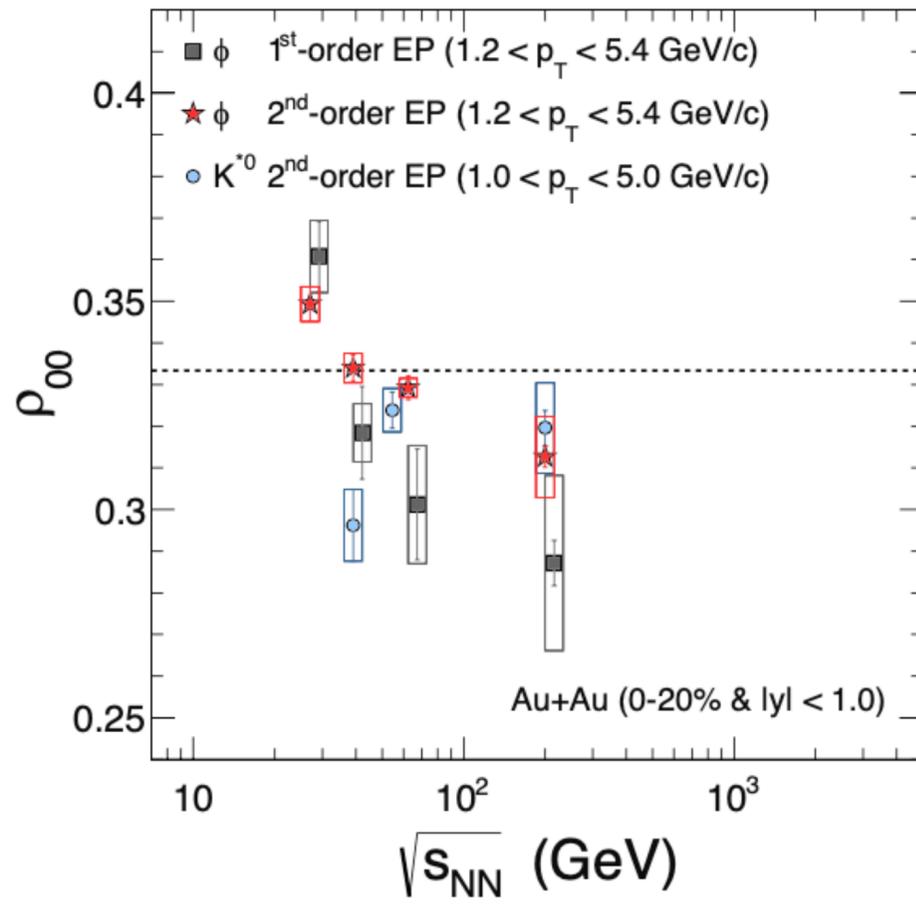


ALICE Collaboration, *Phys. Rev. Lett.* 125, 012301 (2020)



A significant spin alignment of  $K^{*0}$ ,  $\phi$  at low  $p_T$  for mid-central (10–50%) collisions

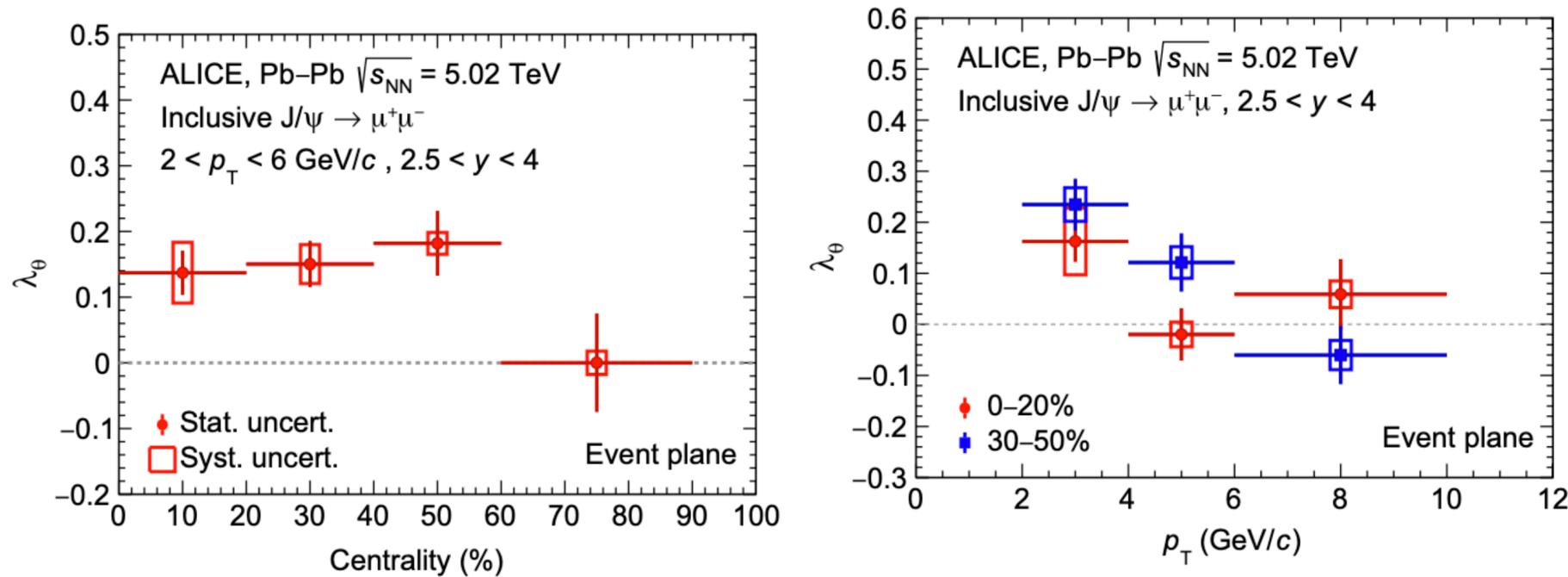
# Physics Motivation: Spin alignment of $K^{*0}$ , $\phi$ in Au+Au collisions RHIC energies



STAR Collaboration, [Nature 614, 244 \(2023\)](#)

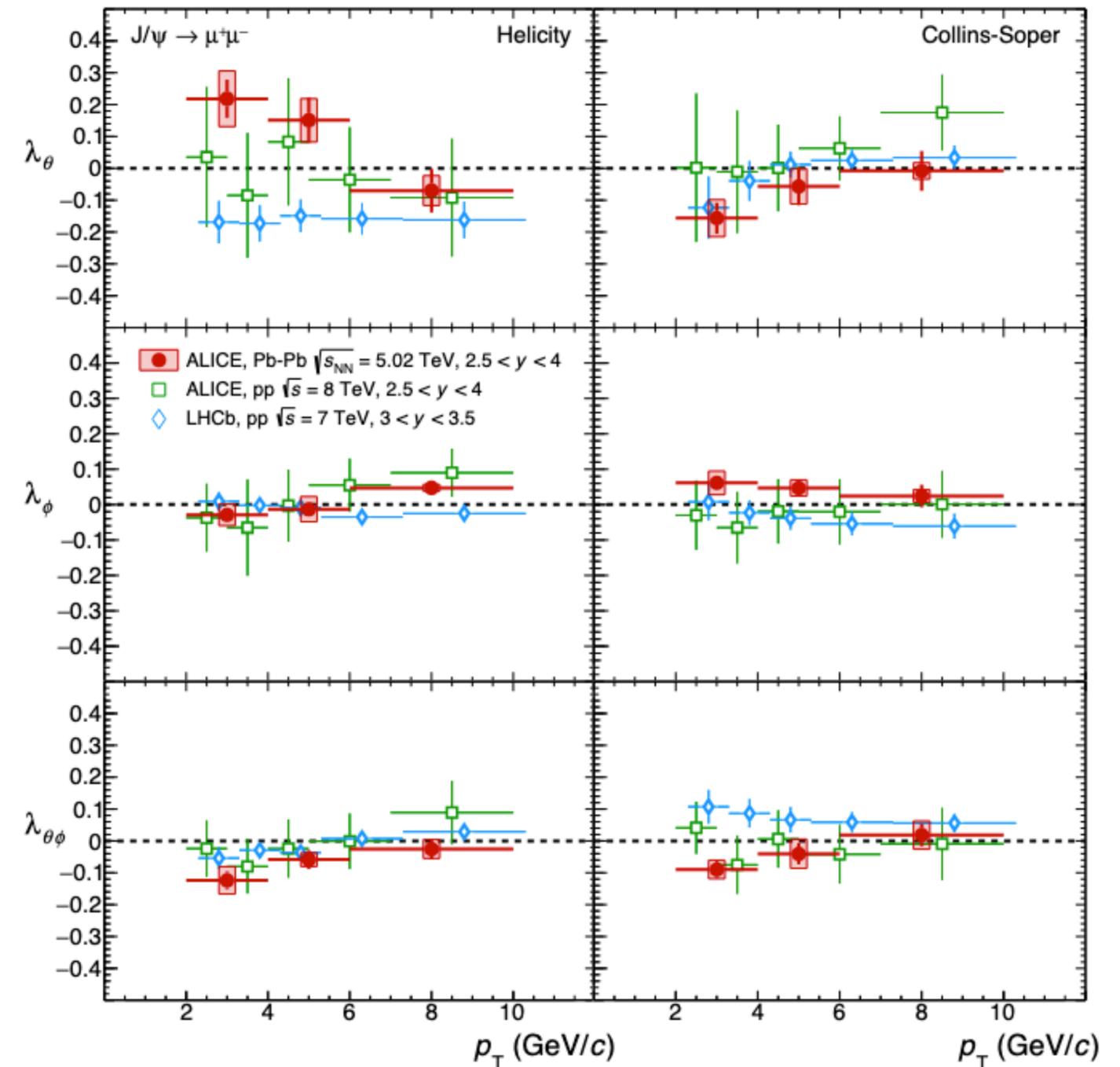
A significant spin alignment of  $K^{*0}$ ,  $\phi$  at low  $p_T$  for (20–60)% collisions at RHIC energies

# Physics Motivation: Spin alignment of $J/\psi$ in Pb-Pb collisions at LHC energy



ALICE Collaboration, *Phys. Rev. Lett.* 131, 042303 (2023)

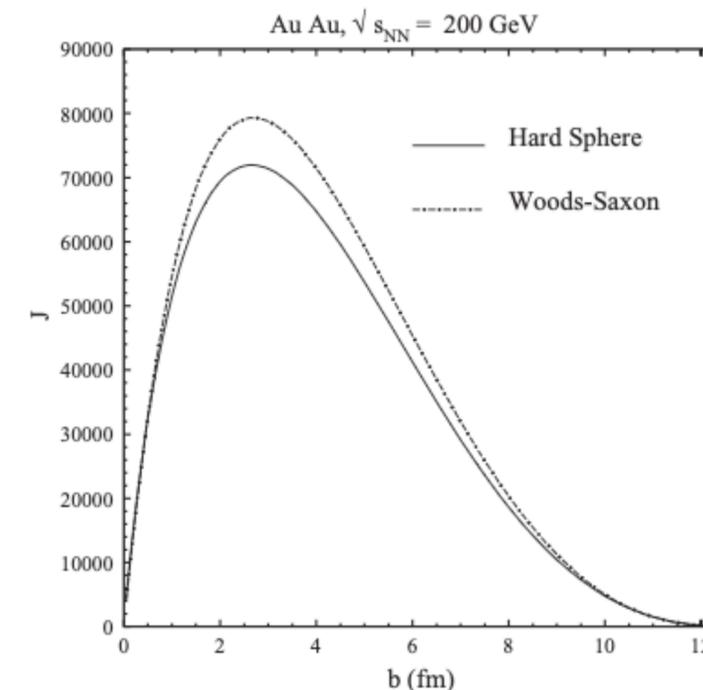
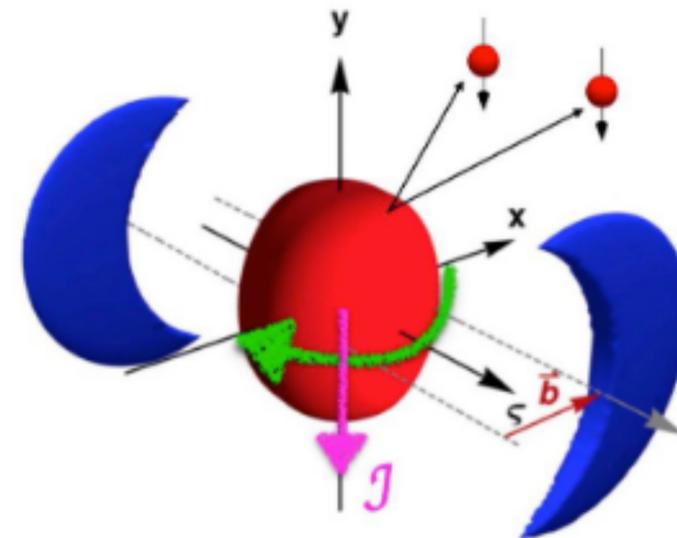
- Finite polarization ( $\sim 3.5\sigma$ ) of  $J/\psi$  is observed in Pb-Pb collisions for (40-60)% centrality class at  $\sqrt{s_{NN}} = 5.02$  TeV
- Significant deviation ( $\sim 3.9\sigma$ ) is observed for (30-50)% at low  $p_T$  ( $2 < p_T < 4$  GeV/c) for Pb-Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV
- A significant difference ( $3.3\sigma$ ) is found with respect to LHCb results at  $\sqrt{s} = 7$  TeV in the interval  $2 < p_T < 4$  GeV/c in HE frame
- What is the source of the finite polarization?



ALICE Collaboration, *Phys. Lett. B* 815, 136146 (2021)

# Source of global spin alignment in heavy-ion collisions: (1) Angular momentum

- Non-central heavy-ion collisions produces a large amount of **orbital angular momentum** (OAM) ( $L \sim 10^5 \hbar$ )
- A part of the OAM is transferred to QGP medium and create a **vorticity** in the system
- This vorticity field polarize the partons through **spin-orbit coupling** ( $\mathbf{L} \cdot \mathbf{S}$ )
- The global quark polarization obtained through the parton elastic scattering in a effective static potential model



Becattini et. al, *Phys. Rev. C* 77, 024906 (2008)

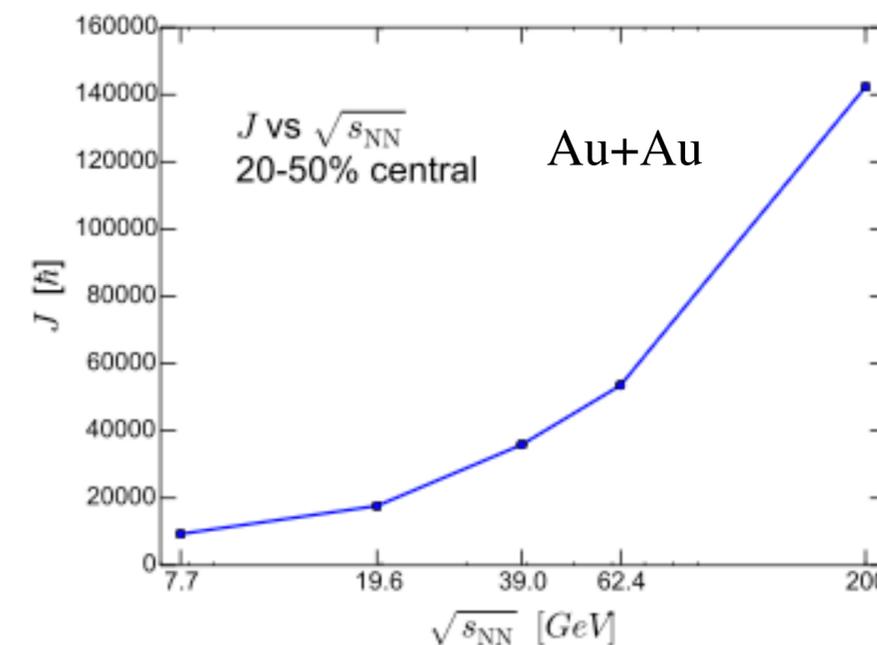
$$P_q = -\frac{\pi}{2} \frac{m_D \mathbf{p}}{E(E + m_q)}$$

Liang et. al, *Phys. Rev. Lett.* 94, 102301 (2005)

Liang et. al, *Phys. Lett. B* 629, 20 (2005)

Here,  $m_D$  is the Debye mass

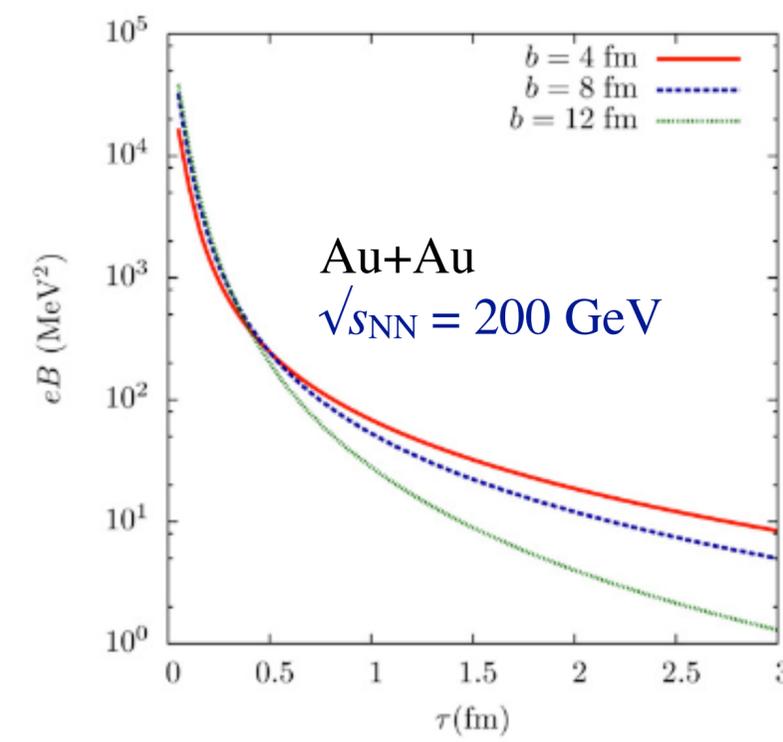
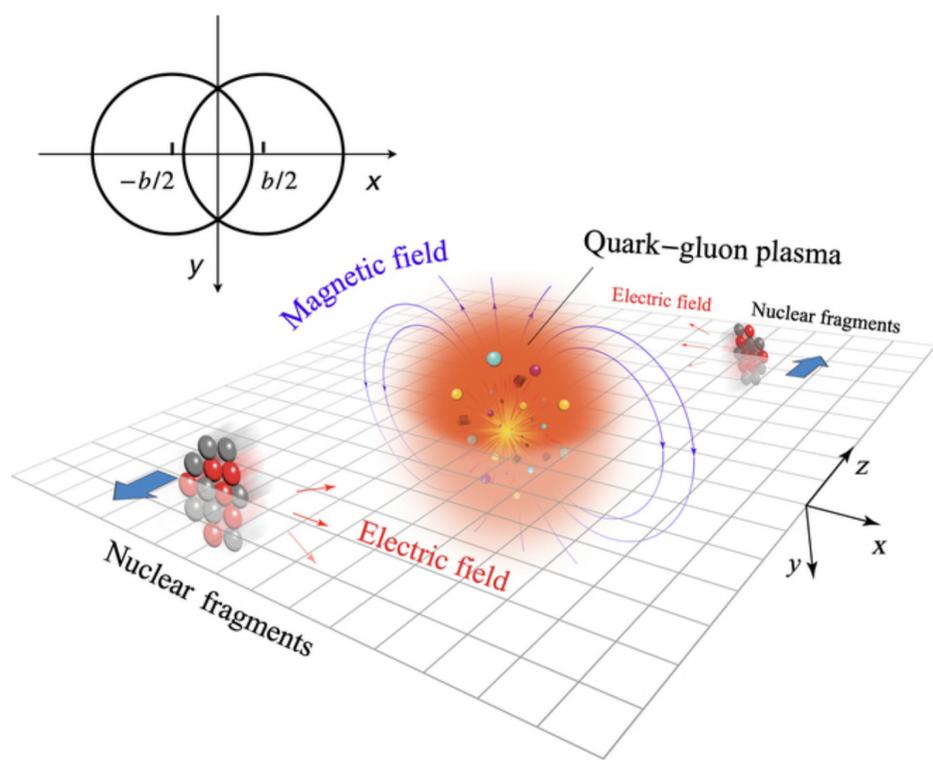
- Any change brought to the Debye mass will affect the polarization of quark



Karpenko et.al, *Eur. Phys. J. C* 77, 213 (2017)

# Source of spin alignment in heavy-ion collisions: (2) Magnetic field

- In addition to the OAM, a large amount of **magnetic field** is produced in non-central heavy-ion collisions ( $eB \sim 10^{14}$  T)
- This magnetic field polarize the quarks via **spin-magnetic coupling** ( $\boldsymbol{\mu} \cdot \mathbf{B}$ )
- The Debye mass due to strong magnetic field



$$m_D^2(T, eB) = 4\pi\alpha_s(\Lambda^2, |eB|) \left[ T^2 \frac{N_c}{3} + \sum_f \frac{|q_f eB|}{4\pi^2} \right]$$

$$\alpha_s(\Lambda^2, |eB|) = \frac{g_s^2}{4\pi} = \frac{\alpha_s(\Lambda^2)}{1 + b_1 \alpha_s(\Lambda^2) \ln \left( \frac{\Lambda^2}{\Lambda^2 + |eB|} \right)}$$

with

$$\alpha_s(\Lambda^2) = \frac{1}{b_1 \ln \left( \frac{\Lambda^2}{\Lambda_{MS}^2} \right)}$$

$$b_1 = \frac{11N_c - 2N_f}{12\pi}$$

STAR Collaboration, *Phys. Rev. X* 14, 011028 (2024)

Kharzeev et. al, *Nuclear Physics A* 803 227 (2008)

Karmakar et.al, *Eur. Phys. J. C* 79, 658 (2019)

# Source of spin alignment in heavy-ion collisions: (3) Medium anisotropy

- In non-central heavy-ion collisions a large amount of **momentum-space anisotropy** is produced
- This anisotropy will affect the polarization of the system
- The Debye mass in the presence of momentum anisotropy can be written as

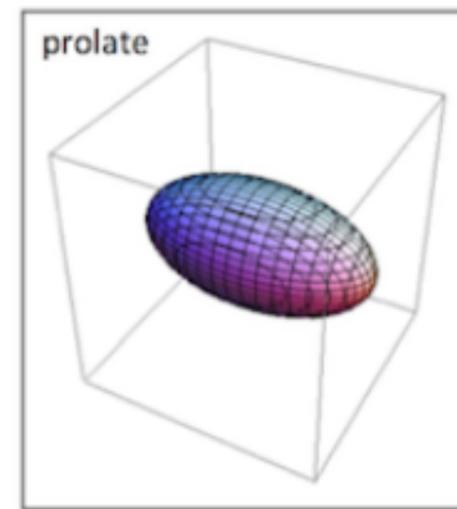
$$\xi = \frac{1}{2} \frac{\langle \mathbf{k}_\perp^2 \rangle}{\langle k_z^2 \rangle} - 1$$

$$m_D(T, \xi) = m_D(T) \left[ f_1(\xi) \cos^2 \theta + f_2(\xi) \right]^{-\frac{1}{4}}$$

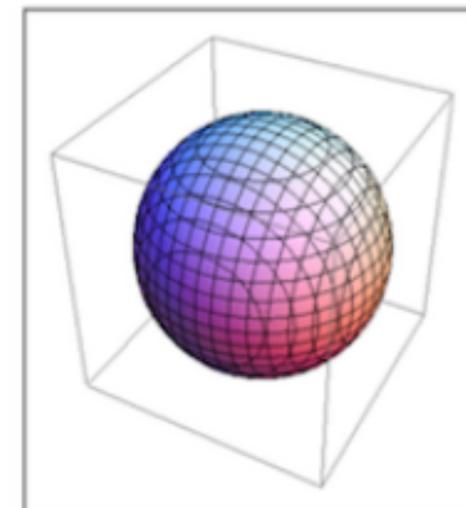
$$m_D(T) = \sqrt{4\pi\alpha_s(\Lambda^2)T^2 \left( \frac{N_c}{3} + \frac{N_f}{6} \right)}$$

$$f_1(\xi) = \frac{9\xi(1+\xi)^{\frac{3}{2}}}{2\sqrt{3+\xi}(3+\xi^2)} \frac{\pi^2(\sqrt{2} - (1+\xi)^{\frac{1}{8}}) + 16(\sqrt{3+\xi} - \sqrt{2})}{(\sqrt{6} - \sqrt{3})\pi^2 - 16(\sqrt{6} - 3)}$$

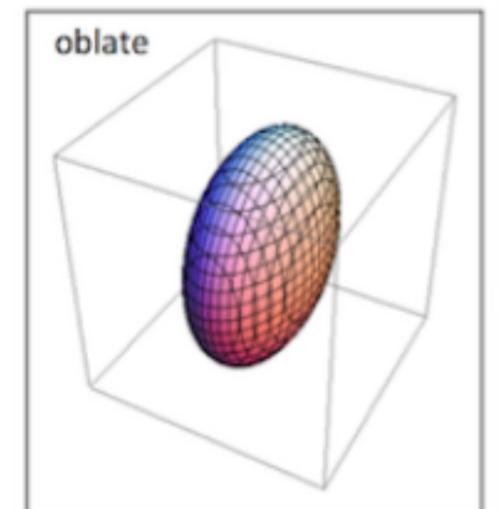
$$f_2(\xi) = \xi \left( \frac{16}{\pi^2} - \frac{\sqrt{2}(\frac{16}{\pi^2} - 1) + (1+\xi)^{\frac{1}{8}}}{\sqrt{3+\xi}} \right) \left( 1 - \frac{(1+\xi)^{\frac{3}{2}}}{1 + \frac{\xi^2}{3}} \right) + f_1(\xi) + 1$$



$$-1 < \xi < 0$$



$$\xi = 0$$



$$\xi > 0$$

Stikland (Lecture Note): [arxiv: 1410.5786](https://arxiv.org/abs/1410.5786)

The effect of these sources on spin-alignment of vector meson is investigated!!

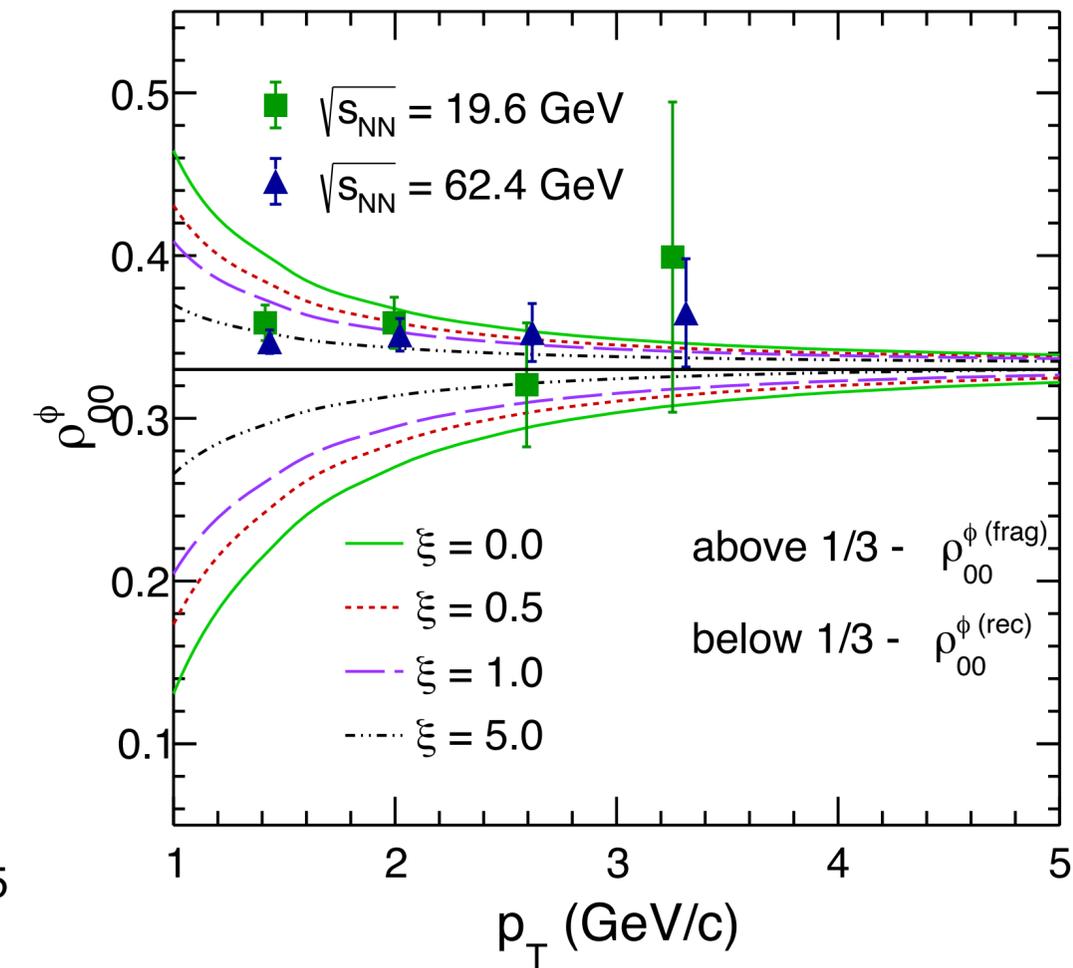
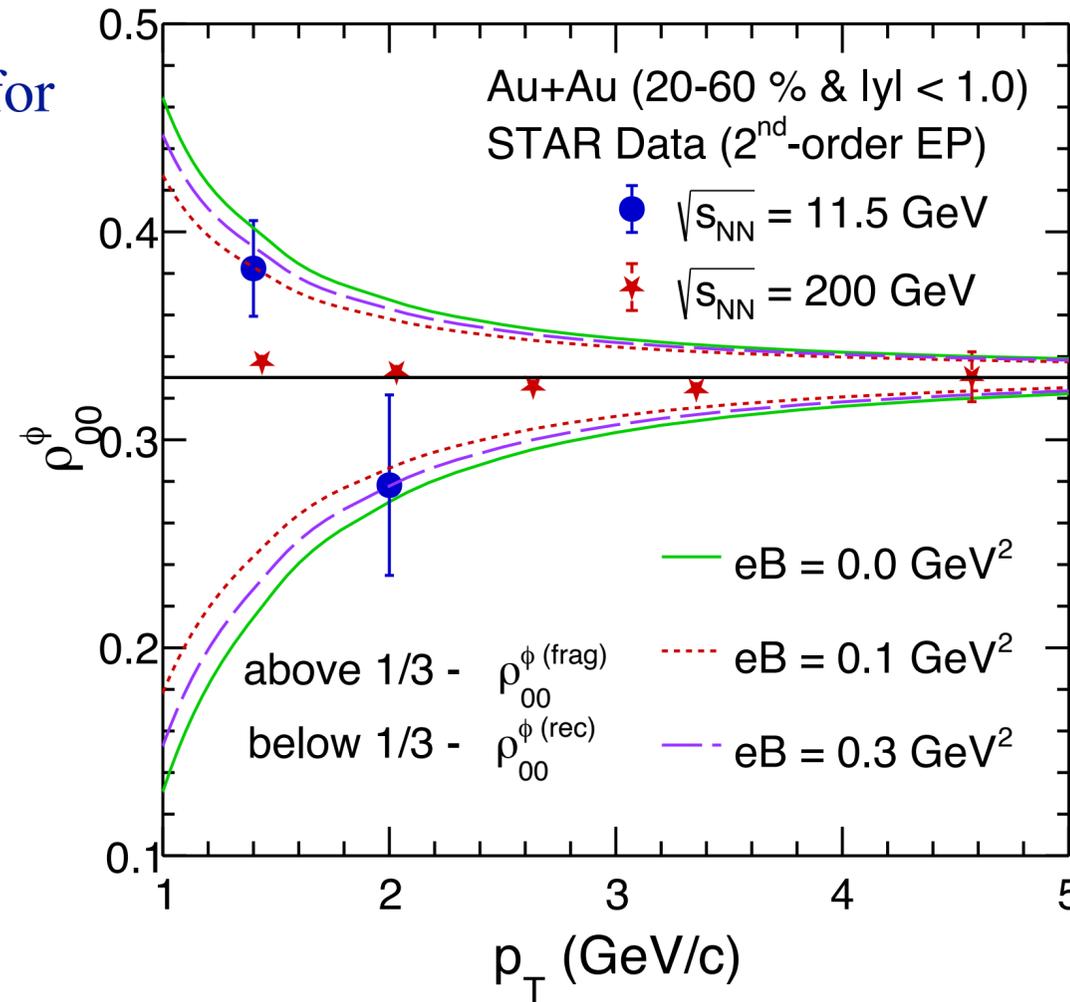
# Spin alignment of light vector mesons ( $\phi$ )

- The 00<sup>th</sup> element of the spin density matrix for  $\phi$  meson due to **recombination**

$$\rho_{00}^{\phi(rec)} = \frac{1 - P_s^2}{3 + P_s^2}$$

- The 00<sup>th</sup> element of the spin density matrix for  $\phi$  meson due to **fragmentation**

$$\rho_{00}^{\phi(frag)} = \frac{1 + \beta P_s^2}{3 - \beta P_s^2}$$



- Maximum spin-alignment is observed at **low  $p_T$**
- Spin-alignment observable depends on the hadronization mechanism (**Rec.** vs **Frag**)
- Magnetic field **enhance** the degree of spin alignment
- Medium anisotropy **reduces** the degree of spin alignment

B. Sahoo, C. R. Singh and R. Sahoo, *Eur. Phys. J. C* 85, 580 (2025).

# Spin alignment of light vector mesons ( $K^{*0}$ , $\rho$ , and $\phi$ )

- The 00<sup>th</sup> element of the spin density matrix for  $K^{*0}$  and  $\rho$  meson due to **recombination**

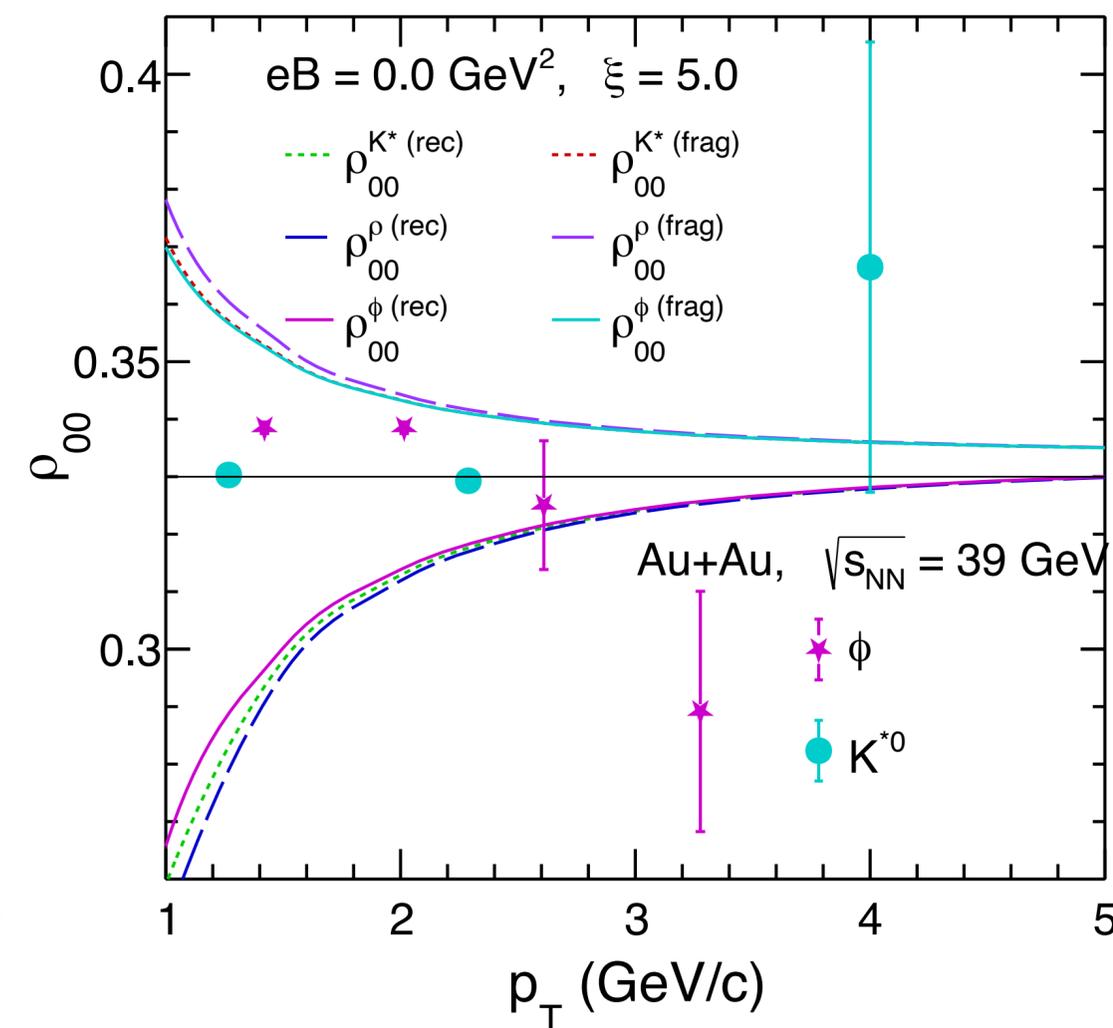
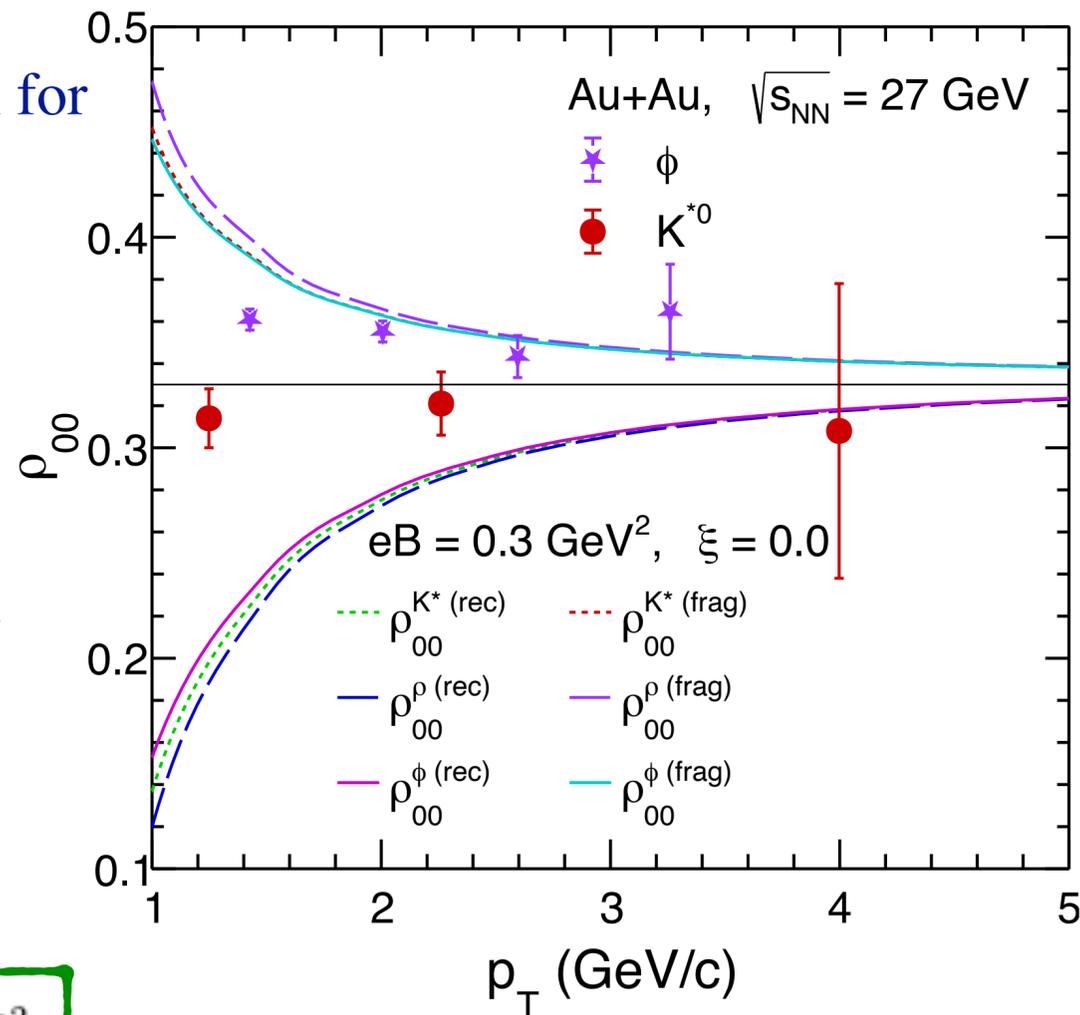
$$\rho_{00}^{K^{*0}(\text{rec})} = \frac{1 - P_q P_s}{3 + P_q P_s}$$

$$\rho_{00}^{\rho(\text{rec})} = \frac{1 - P_q^2}{3 + P_q^2}$$

- The 00<sup>th</sup> element of the spin density matrix for  $K^{*0}$  and  $\rho$  meson due to **fragmentation**

$$\rho_{00}^{\rho(\text{frag})} = \frac{1 + \beta P_q^2}{3 - \beta P_q^2}$$

$$\rho_{00}^{K^{*0}(\text{frag})} = \frac{f_s}{n_s + f_s} \frac{1 + \beta P_q^2}{3 - \beta P_q^2} + \frac{n_s}{n_s + f_s} \frac{1 + \beta P_s^2}{3 - \beta P_s^2}$$



B. Sahoo, C. R. Singh and R. Sahoo, *Eur. Phys. J. C* 85, 580 (2025).

- Degree of spin-alignment depends on particle species
- Mass ordering effect is observed in the spin alignment observable

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## Spin alignment of heavy vector mesons ( $J/\psi$ , $\psi(2S)$ , $Y(1S)$ , $Y(2S)$ )

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# Physics motivation and spin alignment of heavy vector mesons ( $J/\psi$ , $\psi(2S)$ , $Y(1S)$ , $Y(2S)$ )

- The **vorticity** and **magnetic field** are produced during the initial stage of the collision.
- So, **heavy quarks** are mostly expected to be affected due to the **vorticity** and **magnetic field** as compared to light quarks
- The Hamiltonian of a charged particle moving in a rotating medium with angular velocity and subjected to a magnetic field  $B$

$$\mathcal{H} = \frac{1}{2m} (\mathbf{p} - q\mathbf{A} - m\boldsymbol{\omega} \times \mathbf{r})^2 - \frac{m}{2} (\boldsymbol{\omega} \times \mathbf{r})^2 - \boldsymbol{\mu} \cdot \mathbf{B} - \boldsymbol{\omega} \cdot \mathbf{S} + V(r)$$

$\boldsymbol{\omega} \cdot \mathbf{S}$  denote spin-orbit coupling

$\boldsymbol{\mu} \cdot \mathbf{B}$  denote the spin-magnetic coupling

- The color singlet potential for heavy quark and anti-quark pair

$$V(r) = \frac{\sigma}{m_D} (1 - e^{-m_D r}) - \alpha_{\text{eff}} \left( m_D + \frac{e^{-m_D r}}{r} \right)$$

- The spin density matrix in a rotating frame:

$$\hat{\rho}^r(\theta_r, \phi_r) = U(\theta_r, \phi_r) \hat{\rho} U(\theta_r, \phi_r)^{-1}$$

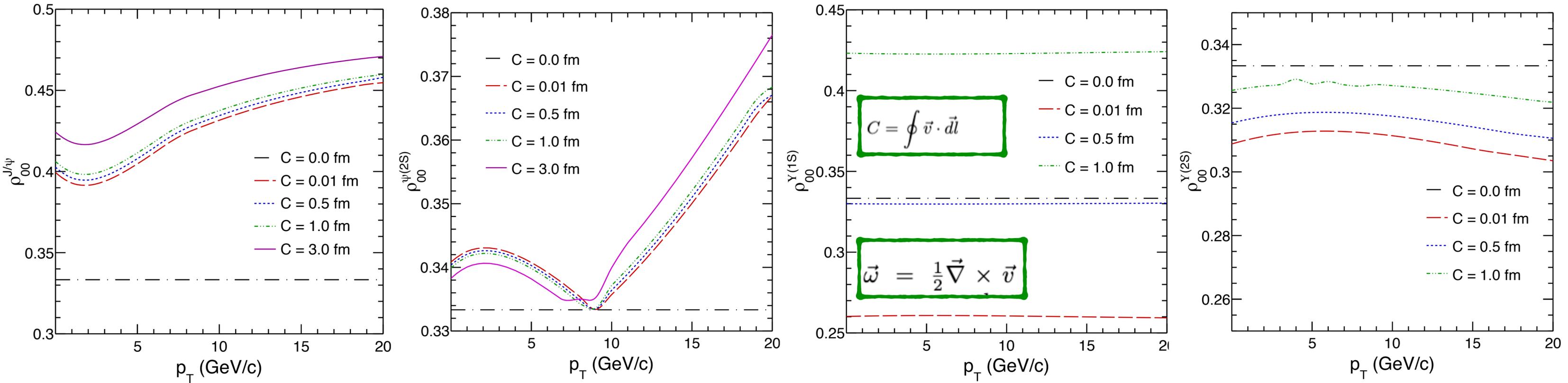
$$\hat{\rho} = e^{-\beta \hat{H}}, \quad \beta = \frac{1}{T}$$

$$U(\theta_r, \phi_r) = D(\alpha, \beta, \gamma) = \exp\left(\frac{-iJ_x \alpha}{\hbar}\right) \exp\left(\frac{-iJ_y \beta}{\hbar}\right) \exp\left(\frac{-iJ_z \gamma}{\hbar}\right)$$

B. Sahoo, C. R. Singh and R. Sahoo, [arXiv:2506.09405](https://arxiv.org/abs/2506.09405)

- The eigen energy is obtained by solving the time-independent Schrodinger equation using the medium modified potential

# Spin alignment of heavy vector mesons ( $J/\psi$ , $\psi(2S)$ , $Y(1S)$ , $Y(2S)$ ) due to rotation



The 00<sup>th</sup> element of the spin density matrix in a rotating frame

$$\rho_{00}^r = \frac{1}{Z} \left[ \cos^2 \theta_r e^{-\beta E_0} + \frac{1}{2} \sin^2 \theta_r (e^{-\beta E_1} + e^{-\beta E_{-1}}) \right]$$

The energy eigenvalues of the system depend on the medium temperature, rotation, magnetic field, and anisotropy

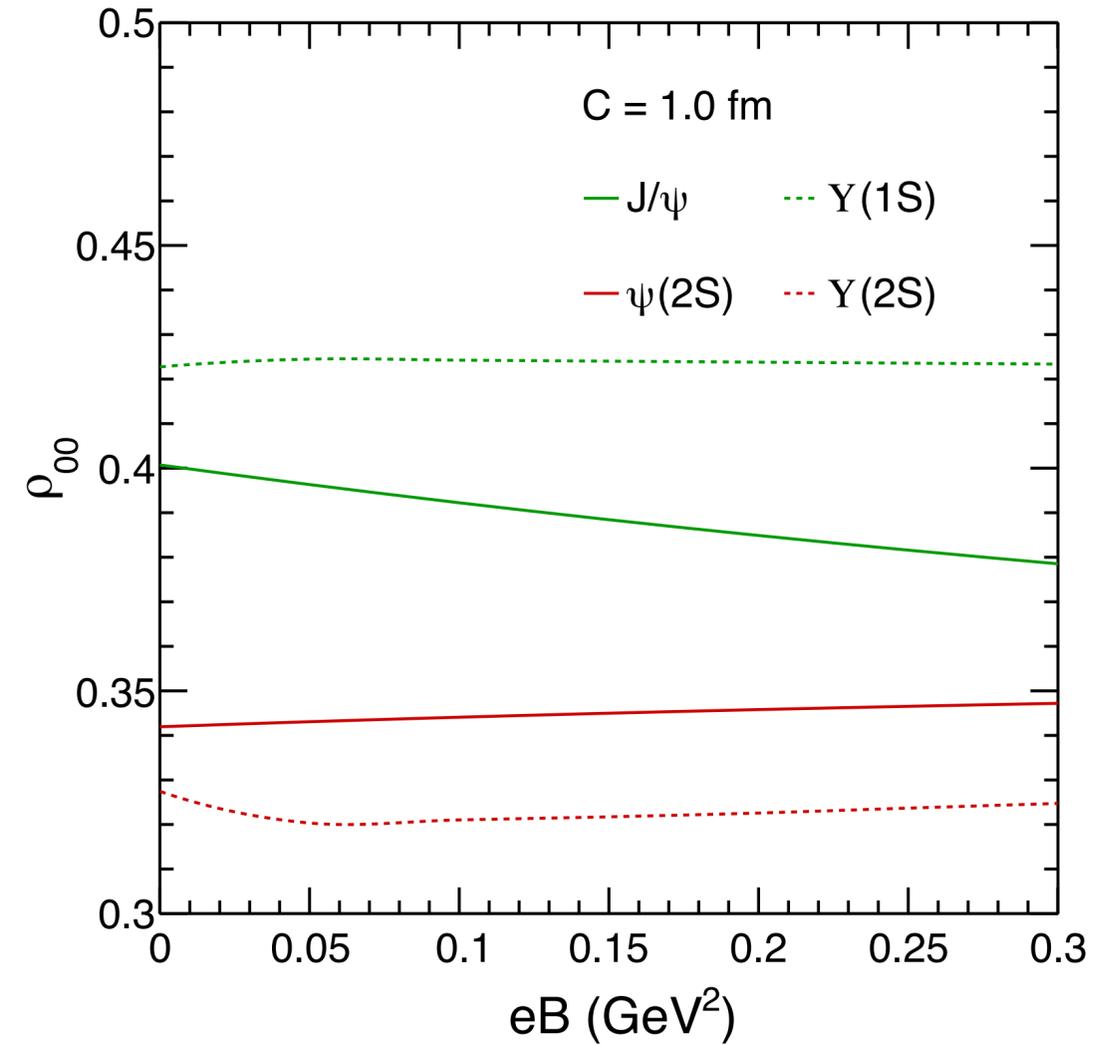
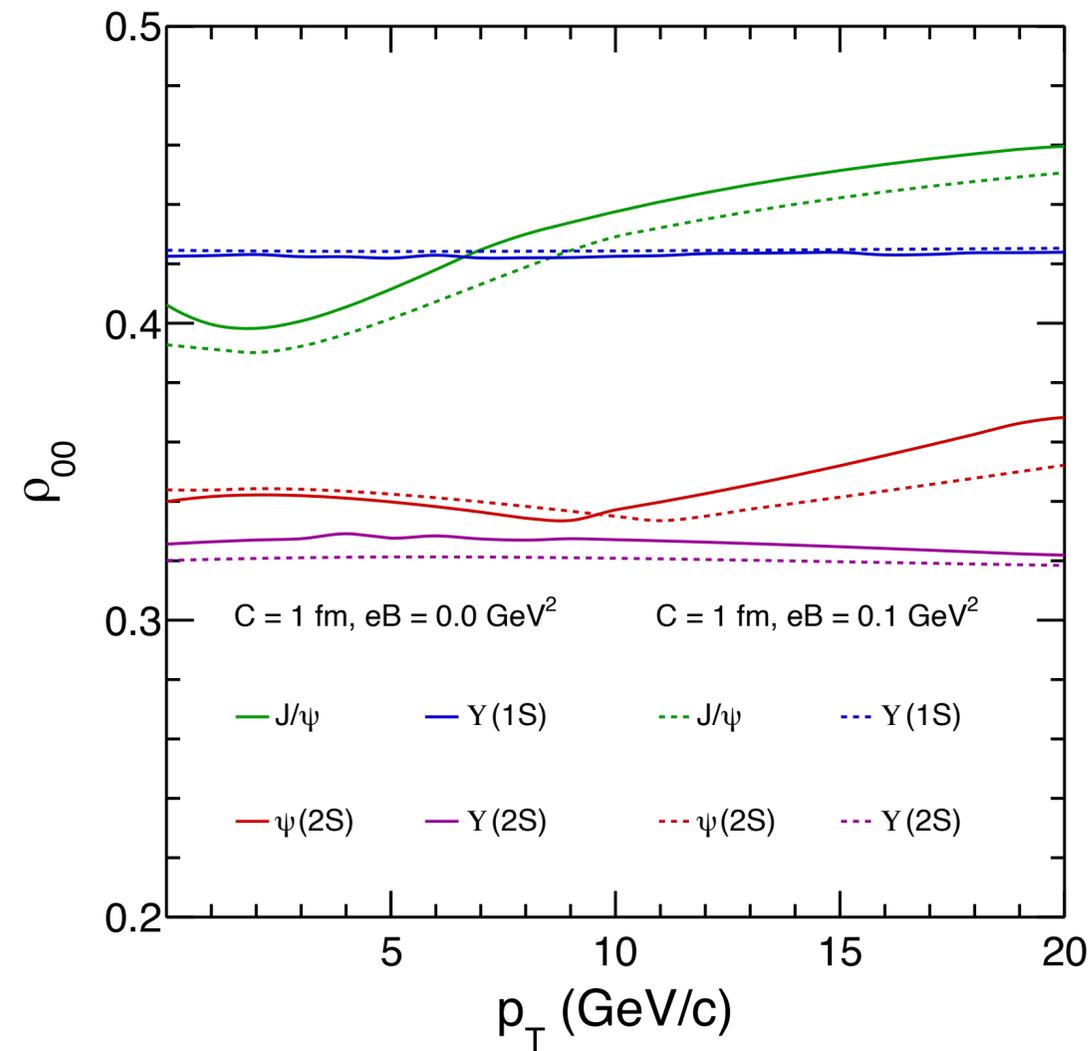
Quarkonium spin alignment is sensitive to rotation

The anisotropy due to rotation changes the shape of the angular distribution

The observable could be a potential signature of thermalization

B. Sahoo, C. R. Singh and R. Sahoo, [arXiv:2506.09405](https://arxiv.org/abs/2506.09405)

# Spin alignment of heavy vector mesons ( $J/\psi$ , $\psi(2S)$ , $Y(1S)$ , $Y(2S)$ ) due to magnetic field

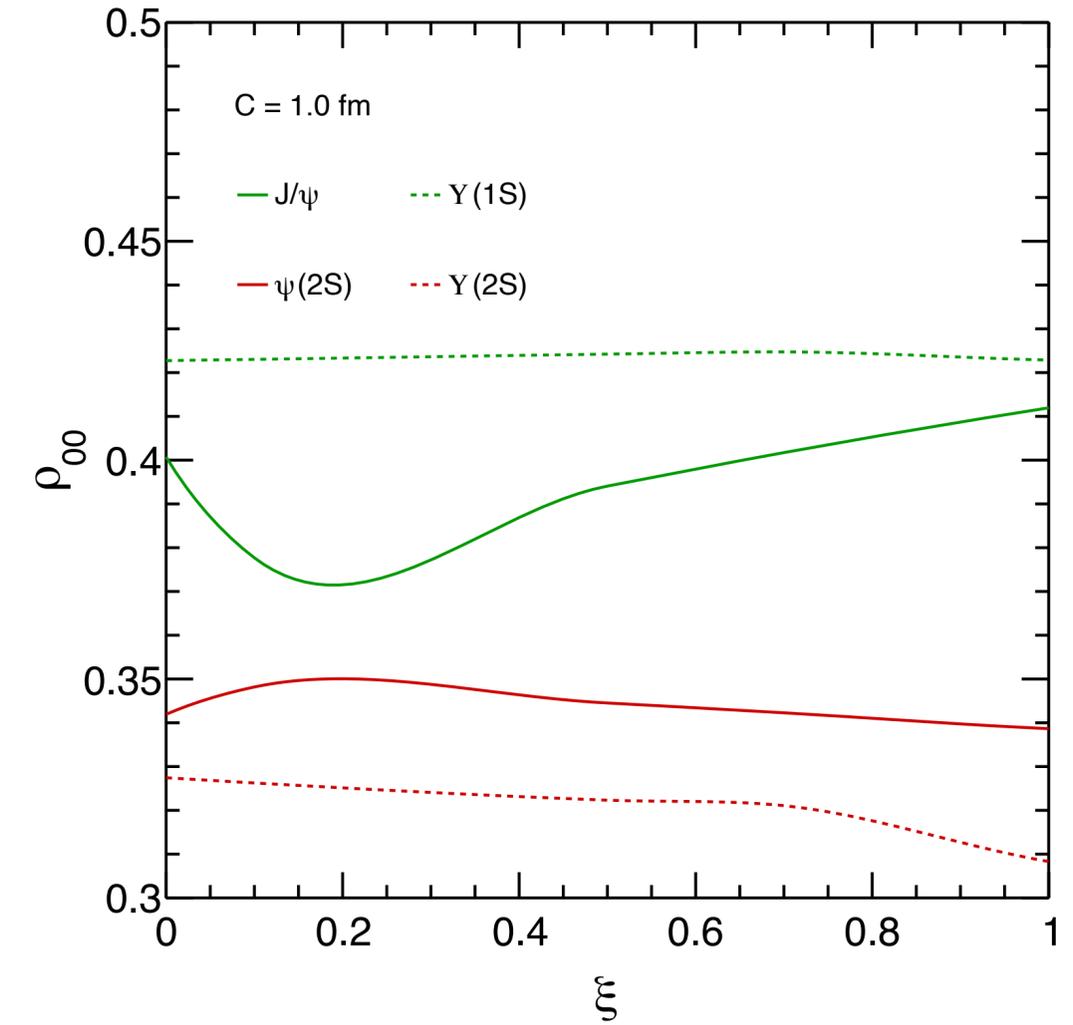
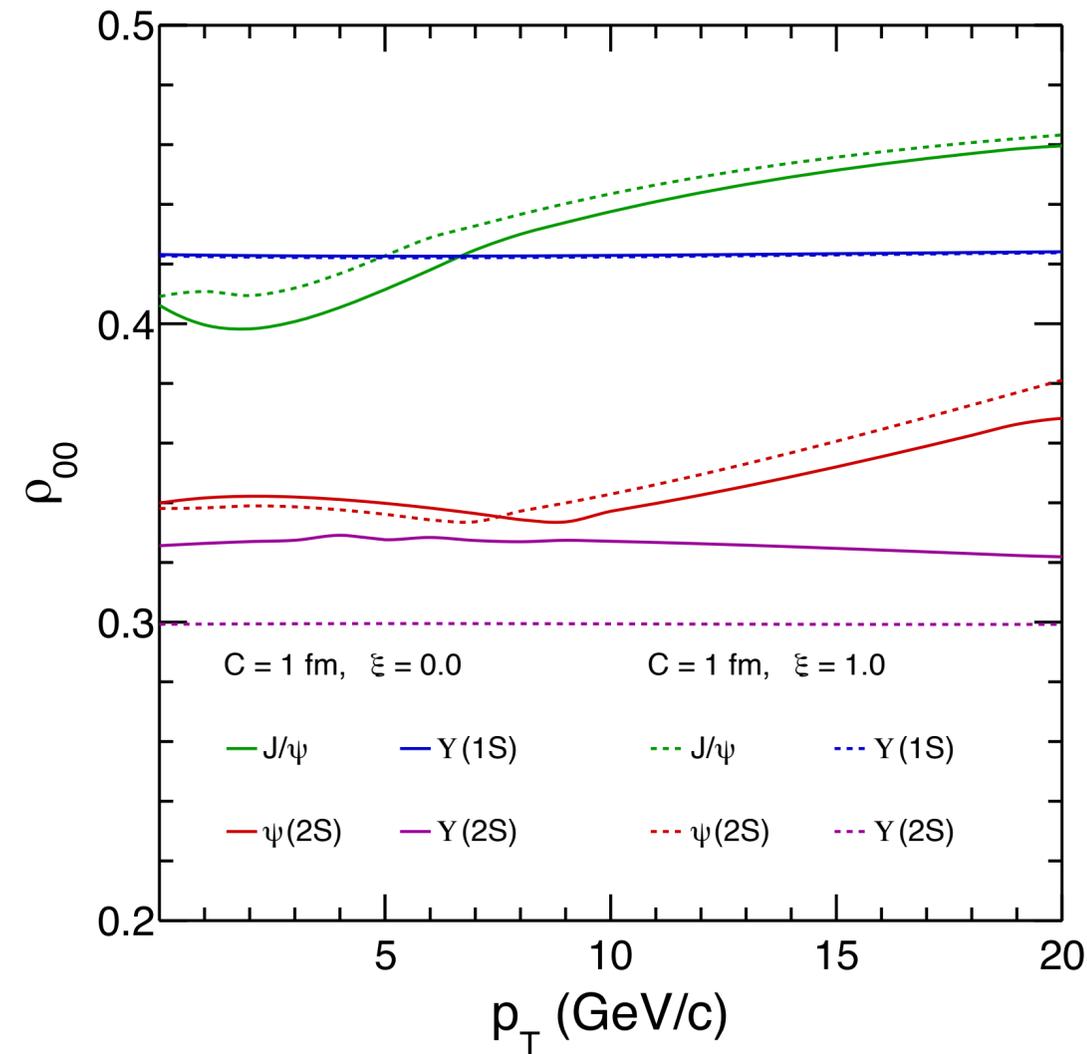


Sahoo, et. al, [arXiv:2506.09405](https://arxiv.org/abs/2506.09405)

- The magnetic field shifts the eigen energy through spin-magnetic coupling, which is reflected in spin-alignment
- However, the shift of depend on the particle momentum and mass
- The magnetic field affect the charmonia mostly as compared to bottomonia

# Spin alignment of heavy vector mesons ( $J/\psi$ , $\psi(2S)$ , $Y(1S)$ , $Y(2S)$ ) due to medium anisotropy

**Assumptions:** The direction of anisotropy is along the direction of particle momentum



Sahoo, et. al, [arXiv:2506.09405](https://arxiv.org/abs/2506.09405)

- The medium anisotropy modifies the Debye mass and changes the eigen energy
- $J/\psi$ , and  $\psi(2S)$  states are shows sensitive at smaller value of anisotropy
- $Y(1S)$  and  $Y(2S)$  states are found to be relatively unaffected due to anisotropy

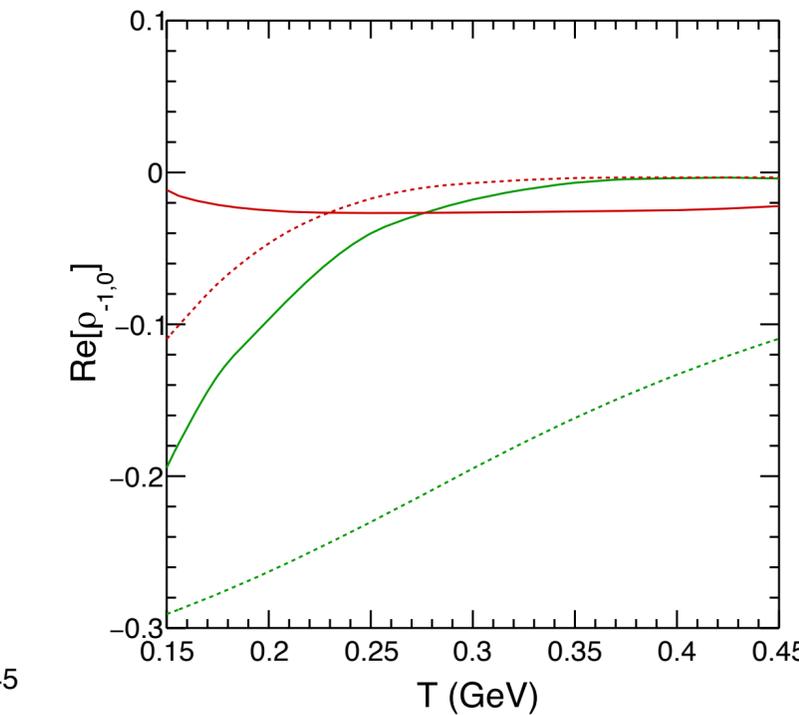
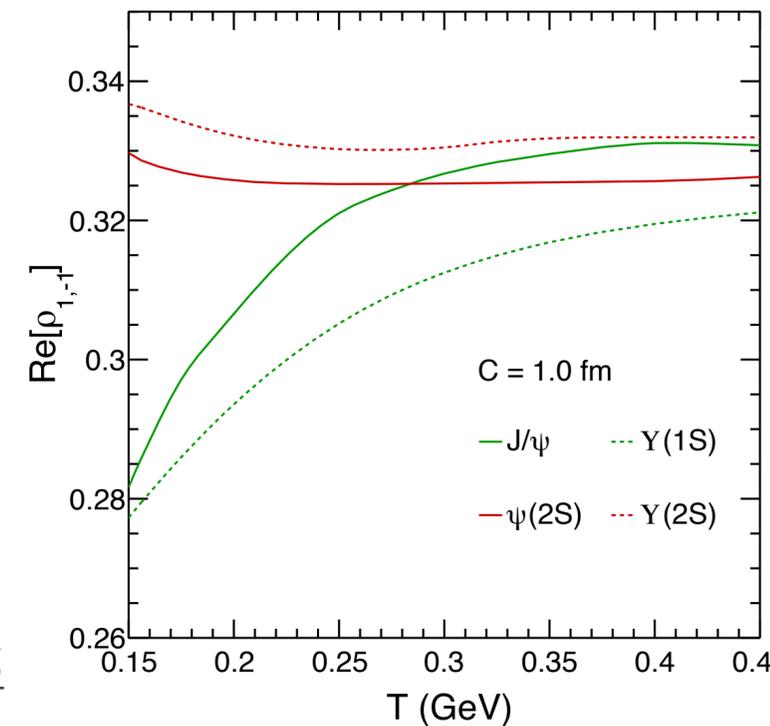
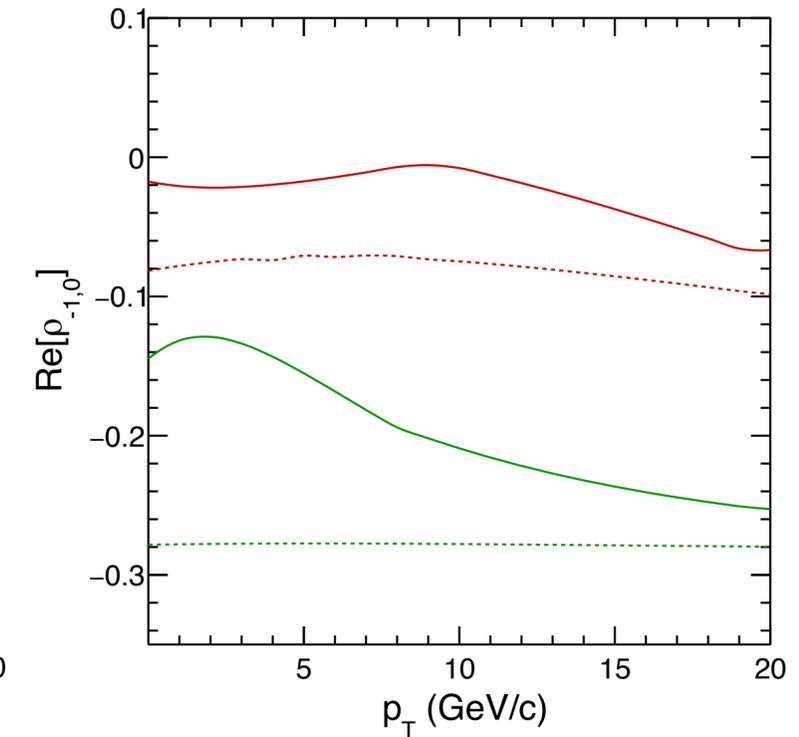
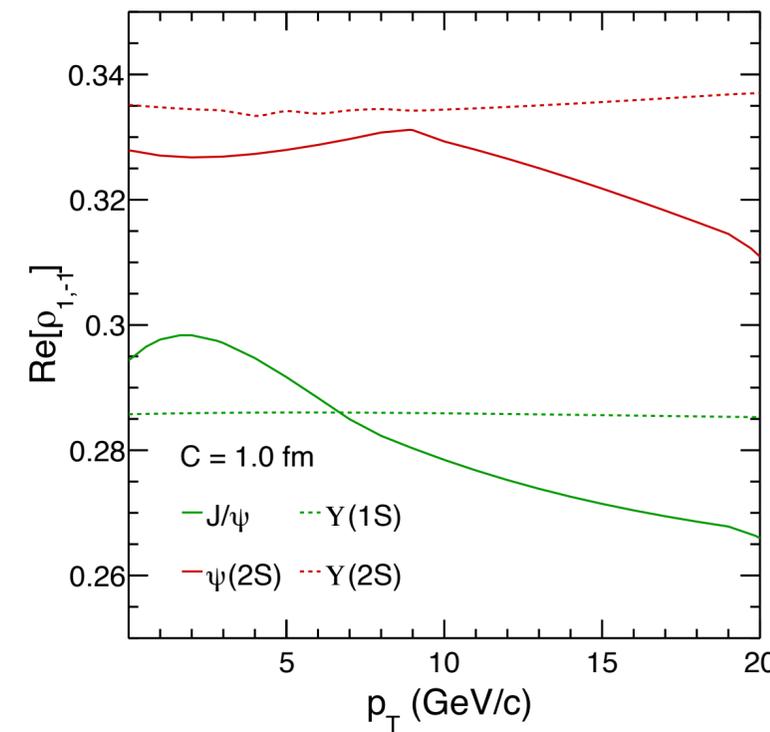
# Off-diagonal elements of the spin-density matrix

- Differentiate the local spin alignment of vector mesons from the global one.
- Provides insights about the spin hydrodynamic evolution in heavy-ion collision and the freeze-out dynamics, etc.
- These elements characterise the spin correlations, quantum coherence, the local spin structure, and non-equilibrium QCD dynamics
- The off-diagonal element of the spin density matrix in a rotating frames is given by

$$\text{Re}[\rho_{1,-1}^r] = \frac{\sin^2 \theta_r}{4Z} (1 + \rho_{0,0})$$

$$\text{Re}[\rho_{-1,0}^r] = \frac{\sin \theta_r}{Z 2\sqrt{2}} \left[ (1 - \cos \theta_r) \rho_{1,1} + 2 \cos \theta_r \rho_{0,0} - (1 + \cos \theta_r) \rho_{-1,-1} \right]$$

B. Sahoo, C. R. Singh and R. Sahoo, [arXiv:2506.09405](https://arxiv.org/abs/2506.09405)



# Summary

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## Light Vector Mesons

- **Hadronization** mechanism plays crucial role in the spin alignment of light vector meson
- The **magnetic** field and medium **anisotropy** influence the spin alignment observable
- Maximum spin-alignment is found at **low**  $p_T$

## Heavy Vector Mesons

- The role of **vorticity**, **magnetic field**, and **medium anisotropy** on the spin-alignment of  $J/\psi$ ,  $\psi(2S)$ ,  $Y(1S)$ ,  $Y(2S)$  states are investigated
- $Y(1S)$ ,  $Y(2S)$  states are more sensitive to **rotation**
- Off-diagonal elements shows the quantum **decoherence** between different spin states

Thank you very much for your attention!!