# Hydrodynamic contributions to helicity polarization and spin alignment for $\phi$ mesons

Cong Yi

University of Science and Technology of China

**The 7th International Conference on Chirality, Vorticity and Magnetic Field in Heavy Ion Collisions Jul 15 – 19, 2023**

Based on
- CY , X.Y. Wu, D.-L. Yang, J.H. Gao, S. Pu, G.Y. Qin, 2304.08777.
- In preparation.

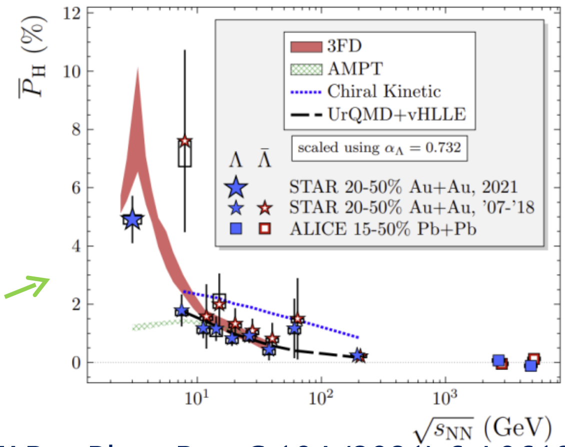
# Outline

- **Introduction**
- **Helicity Polarization**
- **Hydrodynamic contributions to the spin alignment**
- **Summary**

# Spin polarization

- **Global Polarization**

The global polarization contributed by the thermal vorticity is **quantitatively consistent** with experimental data ! Thermal vorticity is a good description of the global vortical properties of QGP.

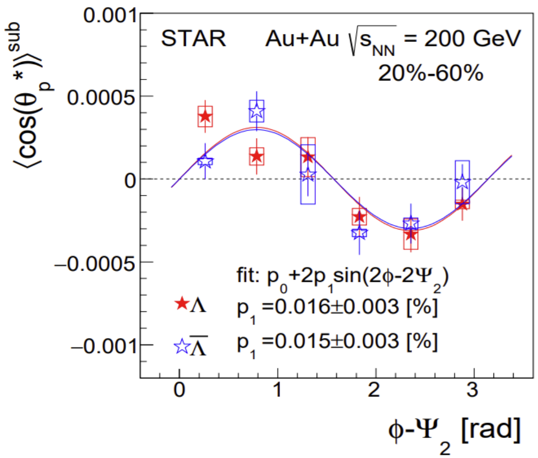



Thermal vorticity

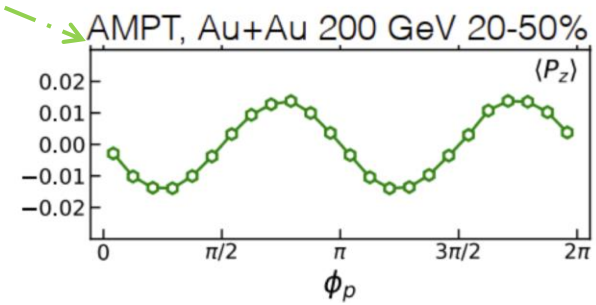
$$P^{\mu}_{\Lambda/\bar{\Lambda}}(x,\mathbf{p}) = \frac{1}{4m_{\Lambda/\bar{\Lambda}}}\epsilon^{\mu\nu\rho\sigma}\boxed{\omega^{\mathrm{th}}_{\rho\sigma}}p_{\nu}(1-f_{FD})$$

STAR, Phys. Rev. C 104 (2021) 6, L061901

- **Local Polarization**




STAR, J. Adam et al., Phys. Rev. Lett. 123, 132301




F. Becattini and I. Karpenko, Phys. Rev. Lett. 120, 012302
X.-L. Xia, H. Li, Z.-B. Tang, and Q. Wang, Phys. Rev. C 98, 024905

How about the out of global equilibrium effects ?

# Out of global equilibrium

- Recalling the original spin polarization distribution in phase space

$$\mathcal{S}^{\mu}(\mathbf{p}) = \frac{\int d\Sigma \cdot p \boxed{\mathcal{J}_5^{\mu}}(p,X)}{2m_{\Lambda}\int d\Sigma \cdot \mathcal{N}(p,X)},$$

Axial current

F. Becattini, V. Chandra, L. Del Zanna, and E. Grossi, Annals Phys. 338, 32 (2013).
R.-H. Fang, L.-G. Pang, Q. Wang, and X.-N. Wang, Phys. Rev. C94, 024904 (2016)

- The axial currents at the local equilibrium can be decomposed as

$$\begin{aligned}
\mathcal{J}^{\mu}_{\text{thermal}} &= a\frac{1}{2}\epsilon^{\mu\nu\alpha\beta}p_{\nu}\boxed{\partial_{\alpha}\frac{u_{\beta}}{T}}, \\
\mathcal{J}^{\mu}_{\text{shear}} &= -a\frac{1}{(u\cdot p)T}\epsilon^{\mu\nu\alpha\beta}p_{\alpha}u_{\beta}p^{\sigma}\boxed{\partial_{<\sigma}u_{\nu>}} \\
\mathcal{J}^{\mu}_{\text{accT}} &= -a\frac{1}{2T}\epsilon^{\mu\nu\alpha\beta}p_{\nu}u_{\alpha}\left(\boxed{Du_{\beta}-\frac{1}{T}\partial_{\beta}T}\right). \\
\mathcal{J}^{\mu}_{\text{chemical}} &= a\frac{1}{(u\cdot p)}\epsilon^{\mu\nu\alpha\beta}p_{\alpha}u_{\beta}\boxed{\partial_{\nu}\frac{\mu}{T}}, \\
\mathcal{J}^{\mu}_{\text{EB}} &= a\frac{1}{(u\cdot p)}\epsilon^{\mu\nu\alpha\beta}p_{\alpha}u_{\beta}\boxed{E_{\nu}},
\end{aligned}$$

Thermal vorticity

Shear viscous tensor
Shear Induced Polarization(**SIP**)

Fluid acceleration

Gradient of chemical potential
Spin Hall Effect (**SHE**)

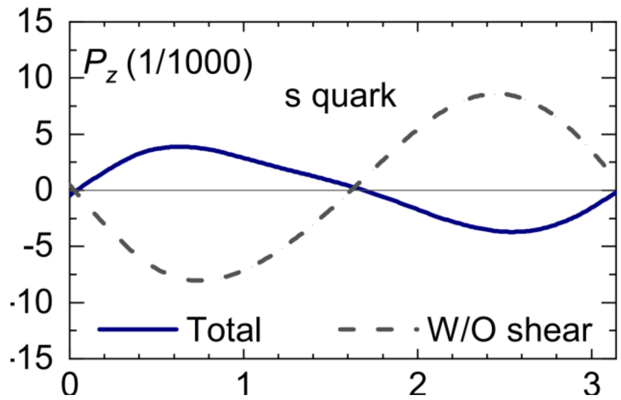
Electromagnetic fields

Y. Hidaka, S. Pu, and D.-L. Yang, Phys. Rev. D97, 016004 (2018)
S. Y. F. Liu, Y. Yin, PRD 104, 054043 (2021)
F. Becattini, M. Buzzegoli, A. Palermo, Phys. Lett. B 820 (2021) 136519
S. Y. F. Liu, Y. Yin, JHEP 07 (2021) 188.

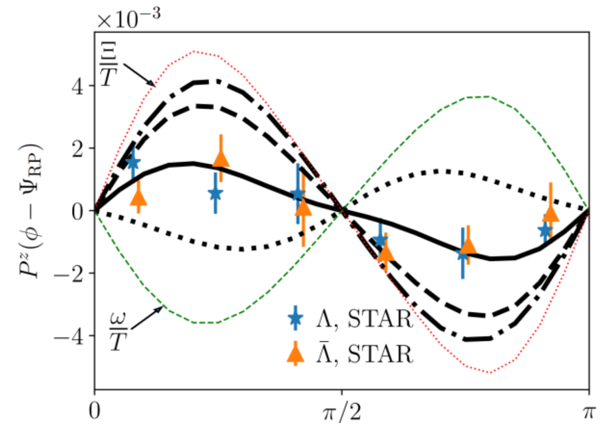
How about the interaction effects ?
Also see: Shuo Fang's talk at July 18th, Parallel Section A

# Local spin polarization

- Hydrodynamic contribution to the local spin polarization




B. Fu, et al. Phys. Rev. Lett. 127, 142301




F. Becattini et al, Phys. Rev. Lett. 127, 272302

**Also see:** CY, S. Pu, and D.-L. Yang, Phys. Rev. C 104, 064901.
S. Ryu, V. Jupic, and C. Shen, Phys. Rev. C 104, 054908
X.-Y. Wu, CY, G.-Y. Qin, and S. Pu, Phys. Rev .C 105 6, 064909
B. Fu, L. Pang, H. Song, and Y. Yin, (2022), 2201.12970.
……

The local spin polarization induced by these hydrodynamic effects has the same sign as the experimental data and have been studied by many works.

- **How about their contributions to spin alignment for vector mesons ?**

Due to these non-vorticity effects, local spin polarization will not accurately reflect the local vorticial structure of QGP.

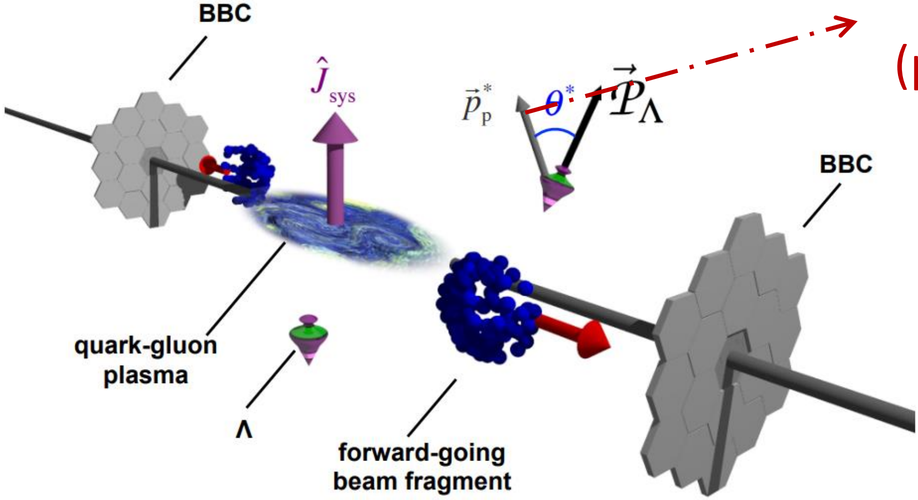
- **How to probe the fine vortical structure of QGP and distinguish these effects ?**

# Outline

- Introduction
- **Helicity Polarization**
- Hydrodynamic contributions to the spin alignment
- Summary

# Helicity polarization

- Helicity polarization is the projection of the spin polarization vector in the direction of momentum.




The original idea for helicity polarization is proposed to probe the initial chiral chemical potential.

$$S^h = \widehat{\mathbf{p}} \cdot \mathcal{S}(\mathbf{p}) \qquad\qquad S^h = S^h_{\text{hydro}} + S^h_{\chi}$$

F. Becattini, M. Buzzegoli, A. Palermo, and G. Prokhorov, Phys. Lett. B 826, 136909
J.-H. Gao, Phys. Rev. D 104, 076016

# Hydrodynamic helicity polarization

- Helicity polarization induced by thermal vorticity, shear viscous tensor, fluid acceleration and spin hall effect

$$
\begin{aligned}
S^h_{\text{thermal}}(\mathbf{p}) &= \int d\Sigma^\sigma F_\sigma p_0 \epsilon^{0ijk} \widehat{p}_i \partial_j \left(\frac{u_k}{T}\right), \\
S^h_{\text{shear}}(\mathbf{p}) &= -\int d\Sigma^\sigma F_\sigma \frac{\epsilon^{0ijk}\widehat{p}^i p_0}{(u\cdot p)T}(p^\sigma \pi_{\sigma j} u_k), \\
S^h_{\text{accT}}(\mathbf{p}) &= \int d\Sigma^\sigma F_\sigma \frac{\epsilon^{0ijk}\widehat{p}^i p_0 u_j}{T}\left[(u\cdot\partial)u_k + \frac{\partial_k T}{T}\right], \\
S^h_{\text{chemical}}(\mathbf{p}) &= -2\int d\Sigma^\sigma F_\sigma \frac{p_0 \epsilon^{0ijk}\widehat{p}_i}{(u\cdot p)} \partial_j \left(\frac{\mu}{T}\right) u_k, \qquad (4)
\end{aligned}
$$

- Kinetic vorticity

$$
\begin{aligned}
S^h_{\nabla T}(\mathbf{p}) &= \int d\Sigma^\sigma F_\sigma \frac{p_0}{T^2}\widehat{\mathbf{p}}\cdot(\mathbf{u}\times\nabla T), \\
S^h_{\omega}(\mathbf{p}) &= \int d\Sigma^\sigma F_\sigma \frac{p_0}{T}\widehat{\mathbf{p}}\,\boxed{\boldsymbol{\omega},} \dashrightarrow \nabla\times\mathbf{u}
\end{aligned}
$$

Kinetic vorticity

# Setup of simulation

- (3+1) dimensional viscous hydrodynamic framework CLVisc

Solve the Energy-momentum conservation and net baryon current Conservation equation:

$$\nabla_\mu T^{\mu\nu} = 0 \qquad T^{\mu\nu} = eU^\mu U^\nu - P\Delta^{\mu\nu} + \pi^{\mu\nu}$$

$$\nabla_\mu J^\mu = 0 \qquad J^\mu = nU^\mu + V^\mu$$

Equation of motion of dissipative current:

$$\Delta^{\mu\nu}_{\alpha\beta} D\pi^{\alpha\beta} = -\frac{1}{\tau_\pi}\left(\pi^{\mu\nu} - \eta\sigma^{\mu\nu}\right) - \frac{4}{3}\pi^{\mu\nu}\theta - \frac{5}{7}\pi^{\alpha\langle}\sigma^{\mu\nu\rangle}_{\alpha} + \frac{9}{70}\frac{4}{e+P}\pi^{\langle\mu}_{\alpha}\pi^{\nu\rangle\alpha}$$

$$\Delta^{\mu\nu} DV_\mu = -\frac{1}{\tau_V}\left(V^\mu - \kappa_B \nabla^\mu \frac{\mu}{T}\right) - V^\mu\theta - \frac{3}{10}V_\nu\sigma^{\mu\nu}$$

.

- **Setup**

initial condition: AMPT, SMASH

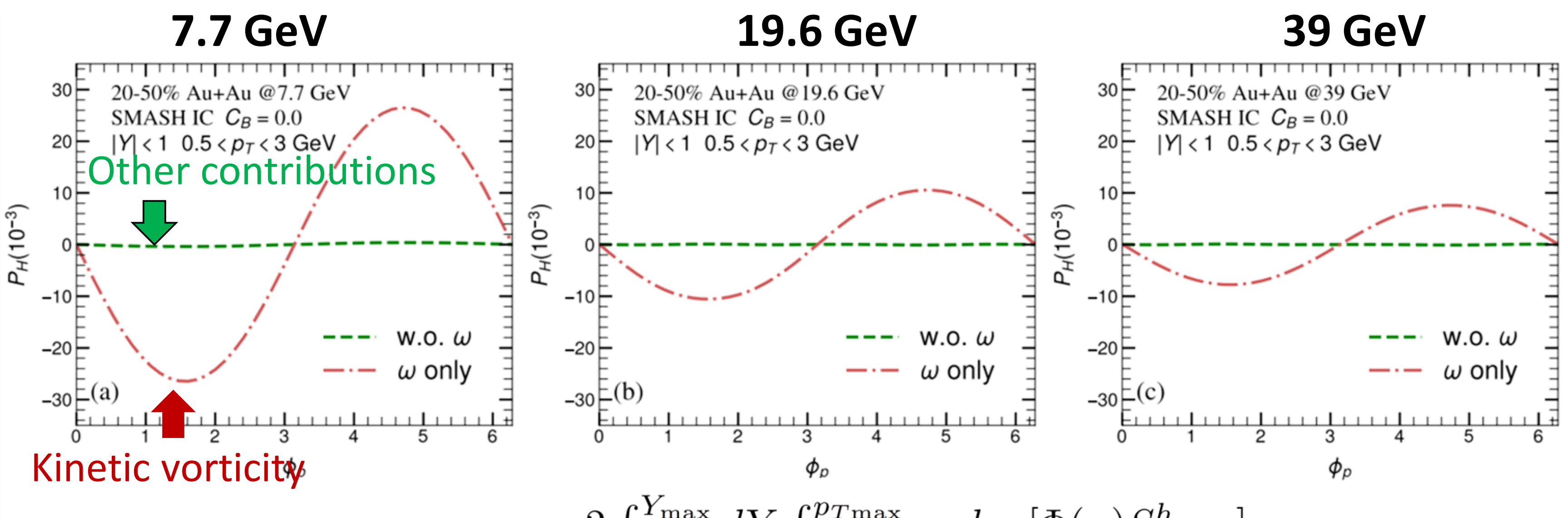
freeze out condition : e<0.4GeV/fm^3

Equation of State: NEOS BQS

L. Pang, Q. Wang, and X.-N. Wang, Phys. Rev. C 86, 024911
X.-Y. Wu, G.-Y. Qin, L.-G. Pang, and X.-N. Wang, Phys. Rev. C 105, 034909

# Numerical results

- **Helicity polarization across RHIC-BES energies**



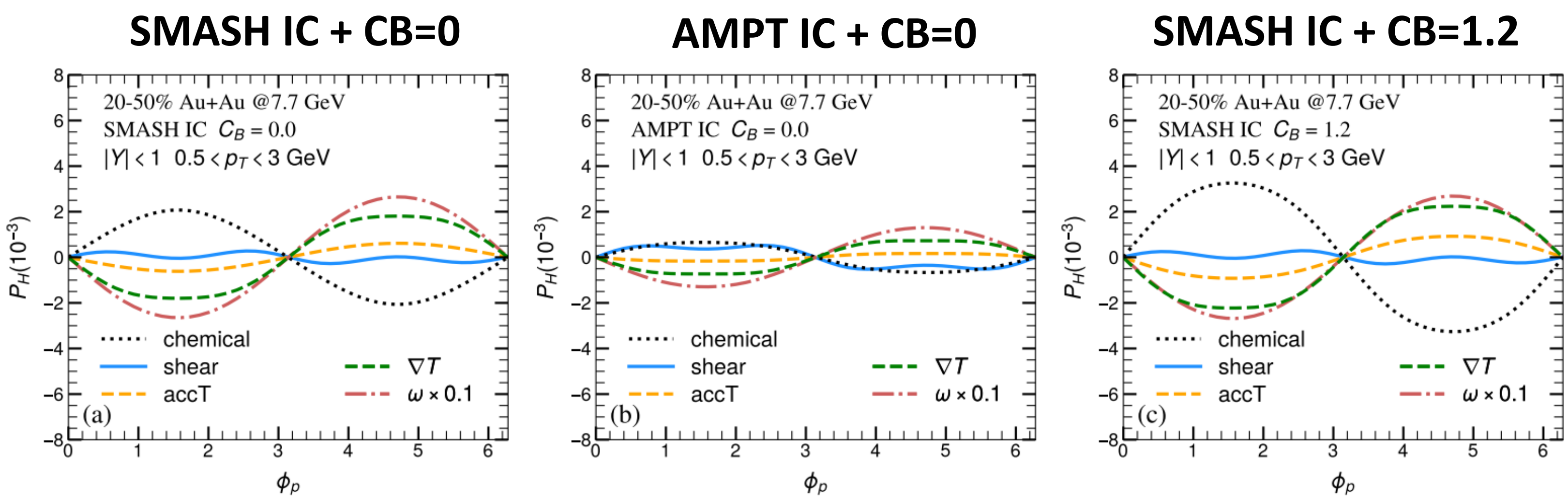

$$P_H(\phi_p) = \frac{2\int_{Y_{\min}}^{Y_{\max}} dY \int_{p_{T\min}}^{p_{T\max}} p_T dp_T [\Phi(\mathbf{p}) S^h_{\text{hydro}}]}{\int_{Y_{\min}}^{Y_{\max}} dY \int_{p_{T\min}}^{p_{T\max}} p_T dp_T \Phi(\mathbf{p})}$$

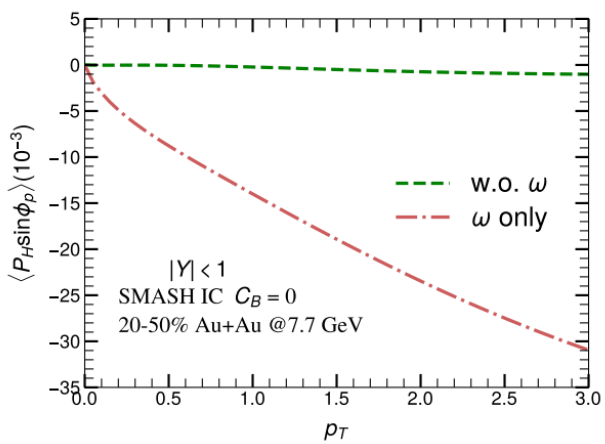
- Helicity polarization induced by kinetic vorticity dominates at BES energies
- Helicity polarization induced by kinetic vorticity increases as the collision energy decreases
- Helicity polarization induced by other contributions are almost vanishing

CY , X.Y. Wu, D.-L. Yang, J.H. Gao, S. Pu, G.Y. Qin, 2304.08777.

# Numerical results

- Different parameters




- Helicity polarization induced by kinetic vorticity is approximately 10 times larger than that induced by other sources, and this conclusion is not dependent on the initial condition and baryon diffusion.
- A possible way to probe the fine vorticity structure of the QGP by measuring helicity polarization.

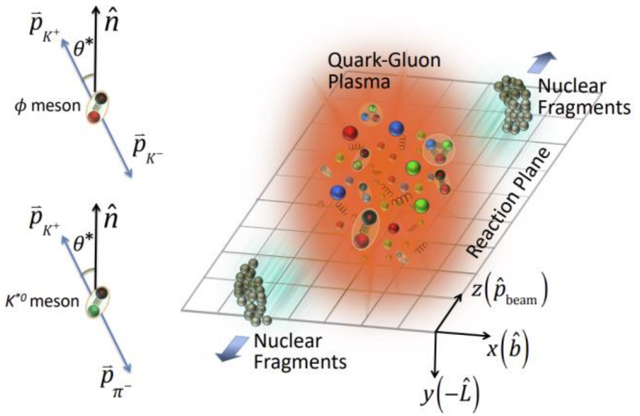
CY , X.Y. Wu, D.-L. Yang, J.H. Gao, S. Pu, G.Y. Qin, 2304.08777.

# Outline

- Introduction
- Helicity Polarization
- **Hydrodynamic contributions to the spin alignment**
- Summary

# Spin alignment

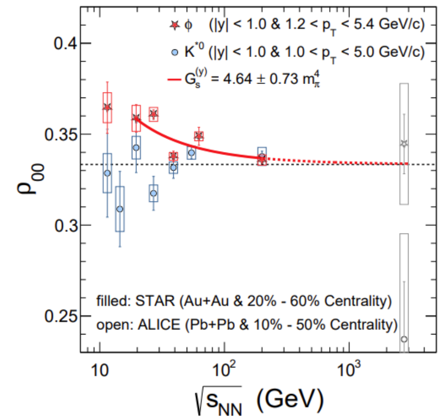
- **In experiments**




Spin density matrix

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

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




STAR, Nature 614, 244 (2023)

- **In theory**

Consistent with

$$\overline{\rho}_{00}^{\phi} = \frac{1}{3} + \boxed{c_{\text{hydro}}} + c_E + c_B + c_F + c_A + c_L + \boxed{c_\phi}$$

X.-L. Sheng, et al. 2205.15689

The contribution of hydrodynamic gradient such as, SIP and SHE to the spin alignment has not been studied systematically.

Liang and Wang, Phys. Lett. B629, 20 (2005)
Becattini, Csernai, Wang Phys. Rev. C 88 , 034905 (2013)
Yang, Fang, Wang, Wang, Phys. Rev. C97, 034917 (2018)
Sheng, Luica, Wang Phys. Rev. D 101 096005 (2020)
Xia, Li, Huang, Huang Phys. Lett. B 817, 136325 (2021)
Gao Phys. Rev. D 104, 076016 (2021)
Li, Liu 2206.11890. (2022);
Müller, Yang Phys. Rev. D 105 , L011901(2022)
Kumar, Müller, Yang, Phys. Rev. D 107, 076025 (2023)
Wager, et. al. Acta Phys. Polon. Supp. 16, 42 (2023)

# Spin alignment

- Spin density matrix (normalized MVSD) for $\phi$ mesons given by spin Boltzmann equation for the coalescence and dissociation process:

$$s+\bar{s}\rightleftharpoons\phi$$

$$\begin{aligned}\rho^{\phi}_{\lambda_1\lambda_2}(x,\mathbf{p})\propto&\frac{\Delta t}{32}\int\frac{d^3\mathbf{p}'}{(2\pi\hbar)^3}\frac{1}{E^{\bar{s}}_{p'}E^{s}_{\mathbf{p}-\mathbf{p}'}E^{\phi}_{p}}\boxed{f_{\bar{s}}(x,\mathbf{p}')f_s(x,\mathbf{p}-\mathbf{p}')}\\&\times2\pi\hbar\delta\left(E^{\phi}_p-E^{\bar{s}}_{p'}-E^{s}_{\mathbf{p}-\mathbf{p}'}\right)\epsilon^{*}_{\alpha}(\lambda_1,\mathbf{p})\epsilon_{\beta}(\lambda_2,\mathbf{p})\\&\times\mathrm{Tr}\left\{\Gamma^{\beta}(p'\cdot\gamma-m_{\bar{s}})\left[1+\gamma_5\gamma\cdot\boxed{P^{\bar{s}}}(x,\mathbf{p}')\right]\Gamma^{\alpha}\right.\\&\left.\times[(p-p')\cdot\gamma+m_s]\left[1+\gamma_5\gamma\cdot\boxed{P^{s}}(x,\mathbf{p}-\mathbf{p}')\right]\right\},\end{aligned}$$

Distribution function of $s$ and $\bar{s}$ quarks

Spin polarization of $s$ and $\bar{s}$ quarks

- Spin polarization vector for s quarks:

$$P^{\mu}_{s}(x,\mathbf{p})=\frac{1}{2m_s}\tilde{\omega}^{\mu\nu}_{s}p_{\nu},$$
$$P^{\mu}_{\bar{s}}(x,\mathbf{p})=\frac{1}{2m_s}\tilde{\omega}^{\mu\nu}_{\bar{s}}p_{\nu},$$

$$\begin{aligned}\overline{\rho}^{\phi}_{00}=&\frac{1}{3}+C_1\left[\frac{1}{3}\boldsymbol{\omega}'^2_x+\frac{1}{3}\boldsymbol{\omega}'^2_z-\frac{2}{3}\boldsymbol{\omega}'^2_y\right]\\&+C_2\left[\frac{1}{3}\boldsymbol{\varepsilon_x}'^2+\frac{1}{3}\boldsymbol{\varepsilon_z}'^2-\frac{2}{3}\boldsymbol{\varepsilon_y}'^2\right]\end{aligned}$$

$$<\overline{\rho}^{\phi}_{00}(\sqrt{s_{NN}})>=\frac{\int_{y_{\min}}^{y_{\max}}dy\int_{p_{T\min}}^{p_{T\max}}p_Tdp_T\int d\phi\int d\Sigma\cdot pf^{\phi}_{eq}\overline{\rho}^{\phi}_{00}(x,\mathbf{p})}{\int_{y_{\min}}^{y_{\max}}dy\int_{p_{T\min}}^{p_{T\max}}p_Tdp_T\int d\phi\int d\Sigma\cdot pf^{\phi}_{eq}},$$

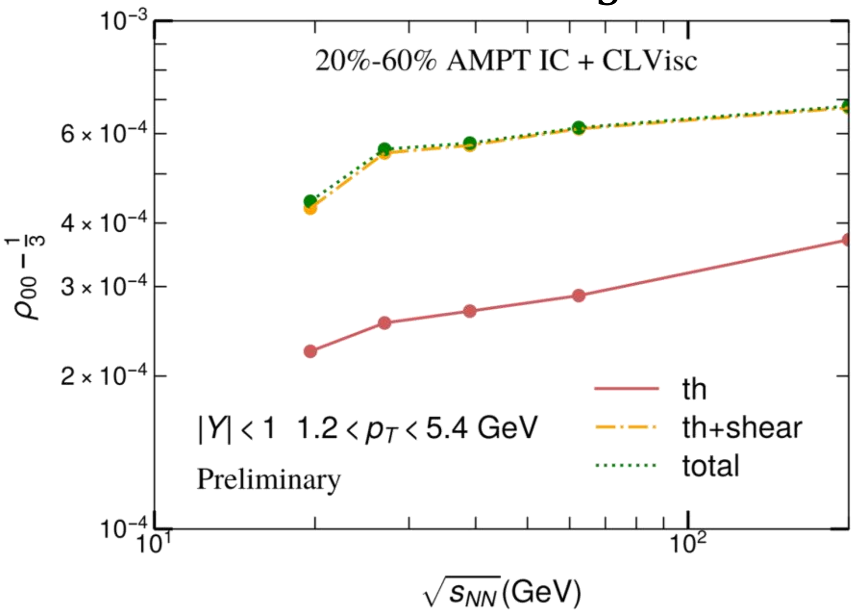
with

X.-L. Sheng, L. Oliva, Z.-T. Liang, Q. Wang, and X.-N. Wang, (2022), 2206.05868.
X.-L. Sheng, L. Oliva, Z.-T. Liang, Q. Wang, and X.-N. Wang, (2022), 2205.15689.

$$\omega^{s/\bar{s}}_{\alpha\beta}(x,p)=\omega^{\mathrm{th}}_{\alpha\beta}+\omega^{\mathrm{shear}}_{\alpha\beta}+\omega^{\mathrm{accT}}_{\alpha\beta}\pm\omega^{\mathrm{chemical}}_{\alpha\beta}$$

# Energy dependence

- Hydrodynamic contrition to $\rho_{00} - \frac{1}{3}$ as a function of collision energy

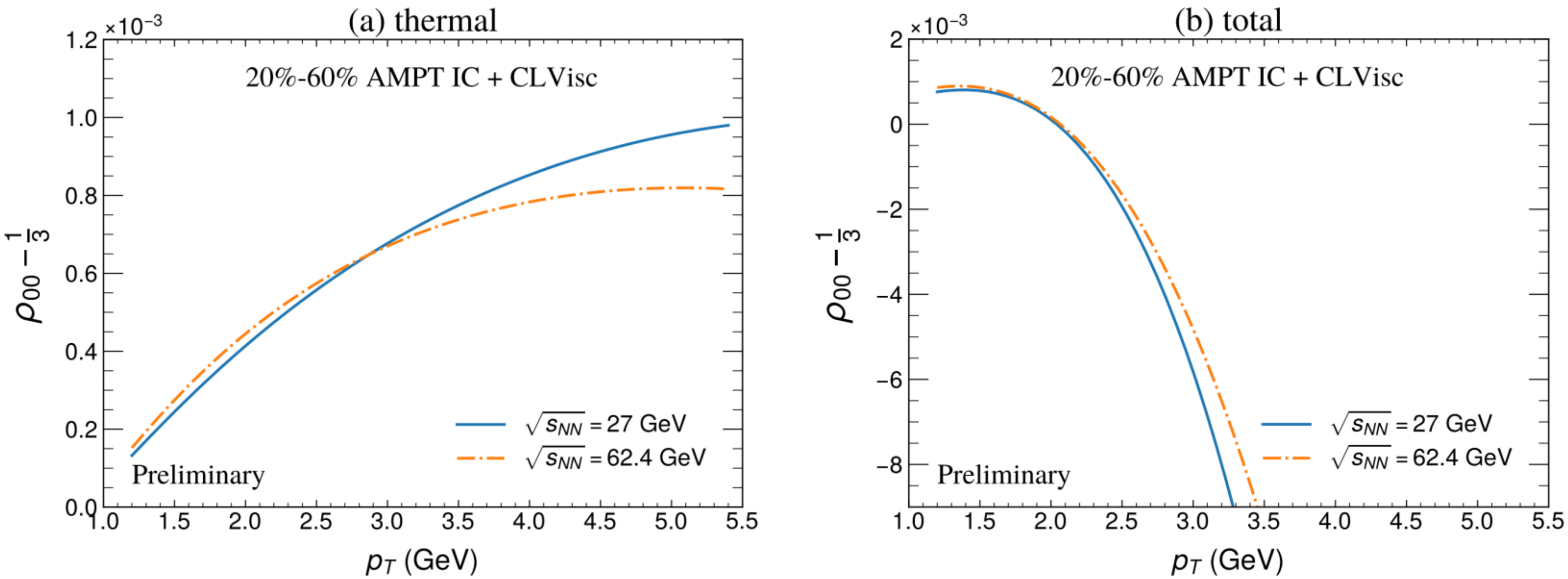



- ➢ The hydrodynamic contributions to $\boldsymbol{\rho_{00} - \frac{1}{3} > 0}$ at the order of $\mathbf{10^{-4}}$ and the magnitude increases with increasing collision energy

- ➢ The **shear induced polarization** have a **positive enhancement** to the contributions of thermal vorticity but do not change the orders of magnitude

# Pt dependence

- **Hydrodynamic contrition to $\rho_{00}-\frac{1}{3}$ as a function of $p_T$**



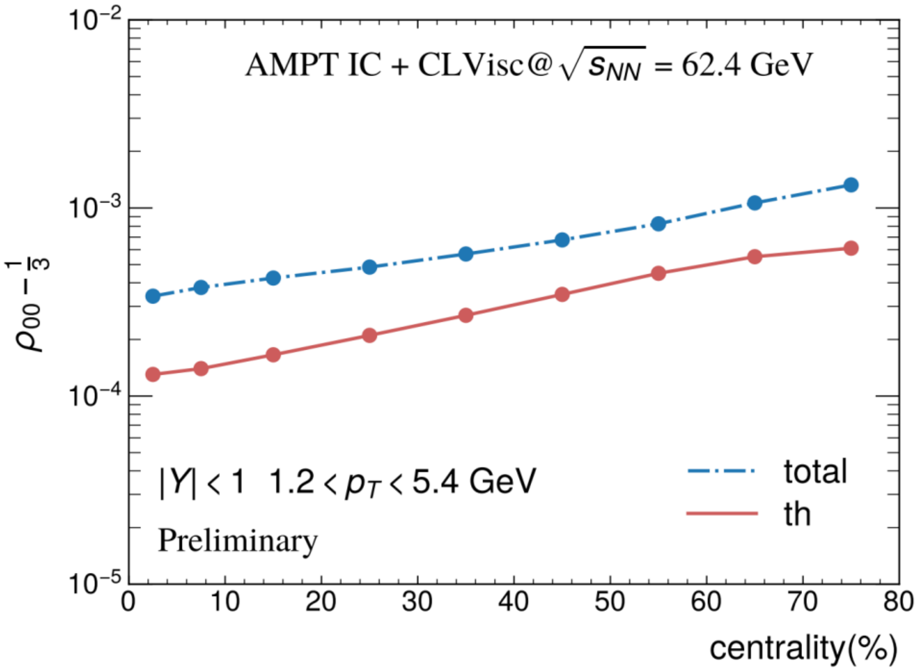

$$<\overline{\rho}_{00}^{\phi}(p_T)> \; = \frac{\int_{y_{\min}}^{y_{\max}} dy \int d\phi \int d\Sigma \cdot p f_{eq}^{\phi} \overline{\rho}_{00}^{\phi}(x,\mathbf{p})}{\int_{y_{\min}}^{y_{\max}} dy \int d\phi \int d\Sigma \cdot p f_{eq}^{\phi}}$$

- Shear induced polarization can reverse the $p_T$ dependence of spin alignment contributed by the hydrodynamic effects

In preparation.

# Centrality dependence

- Hydrodynamic contrition to $\rho_{00}-\frac{1}{3}$ as a function of centrality




➢ $\boldsymbol{\rho_{00}-\frac{1}{3}}$ becomes larger as the collision centrality increases. This is because the OAM will be larger at more peripheral collisions.

In preparation.

# Summary

- **Helicity Polarization**
  - Helicity polarization is mainly contributed by the kinetic vorticity at low energy collisions.
  - A possible way to probe the fine vortical structure of QGP by measuring helicity polarization.
- **Hydrodynamic contributions to the spin alignment of $\phi$ mesons**
  - The total hydrodynamic contributions to $\rho_{00}-\frac{1}{3}$ are positive and at the order of $10^{-4}$.
  - $\rho_{00}-\frac{1}{3}$ contributed by hydrodynamic effects increases with increasing collision energy.
  - The shear induced polarization have a positive enhancement on the contribution of thermal vorticity but do not change its orders of magnitude.

Thanks for your time !