Spin polarization and spin alignment from hydrodynamic studies

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Outline

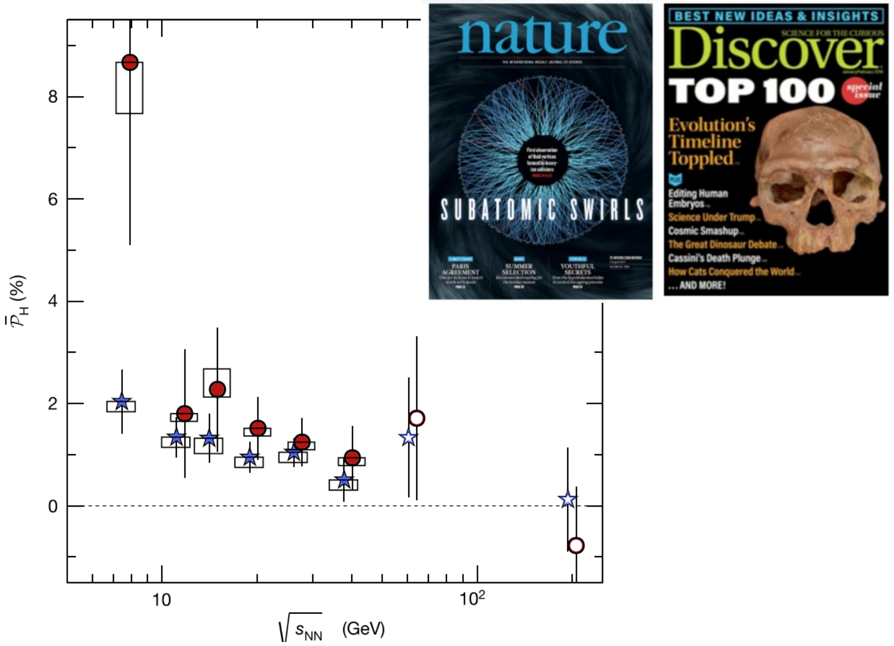
- Introduction
- Hydrodynamic contributions to the spin polarization of Λ hyperons
- Hydrodynamic contributions to the spin alignment of ϕ mesons
- Summary

Global Polarization

- **Global Spin Polarization of Λ Hyperons**

Experiments

$$P = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$$

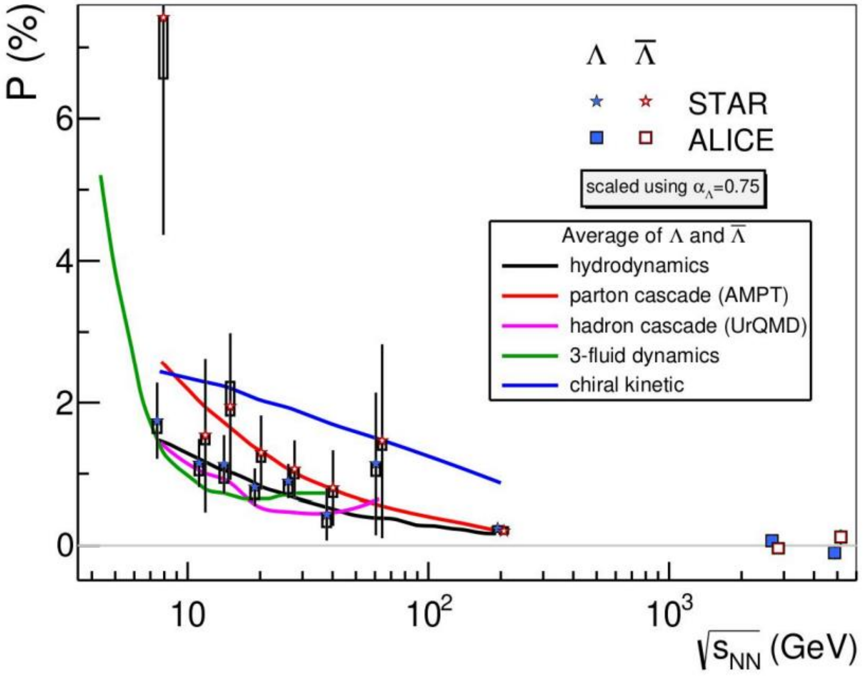


$$\omega = k_B T \left(\overline{P}_{\Lambda'} + \overline{P}_{\bar{\Lambda}'}\right)/\hbar \quad \sim \quad 10^{22} s^{-1}$$

Most vortical fluid so far !

Z.-T. Liang and X.-N. Wang, Phys. Rev. Lett. a94, 102301 (2005)
STAR, L. Adamczyk et al., Nature (London) 548, 62 (2017).

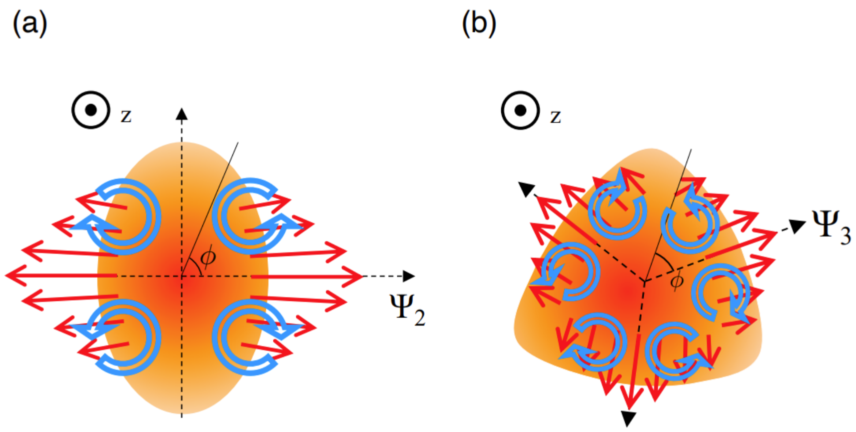
Theory

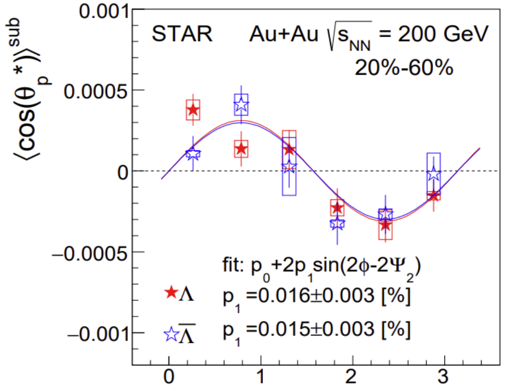


I. Karpenko and F. Becattini, Eur. Phys. J. C 77, 213 (2017).
H. Li, L.-G. Pang, Q. Wang, and X.-L. Xia, Phys. Rev. C 96, 054908 (2017).
Y. Xie, D. Wang, and L. P. Csernai, Phys. Rev. C 95, 031901(R) (2017).
Y. Sun and C. M. Ko, Phys. Rev. C 96, 024906 (2017)
S. Shi, K. Li, and J. Liao, Phys. Lett. B 788, 409 (2019).

Local Polarization

- **Local Vortical Structure**

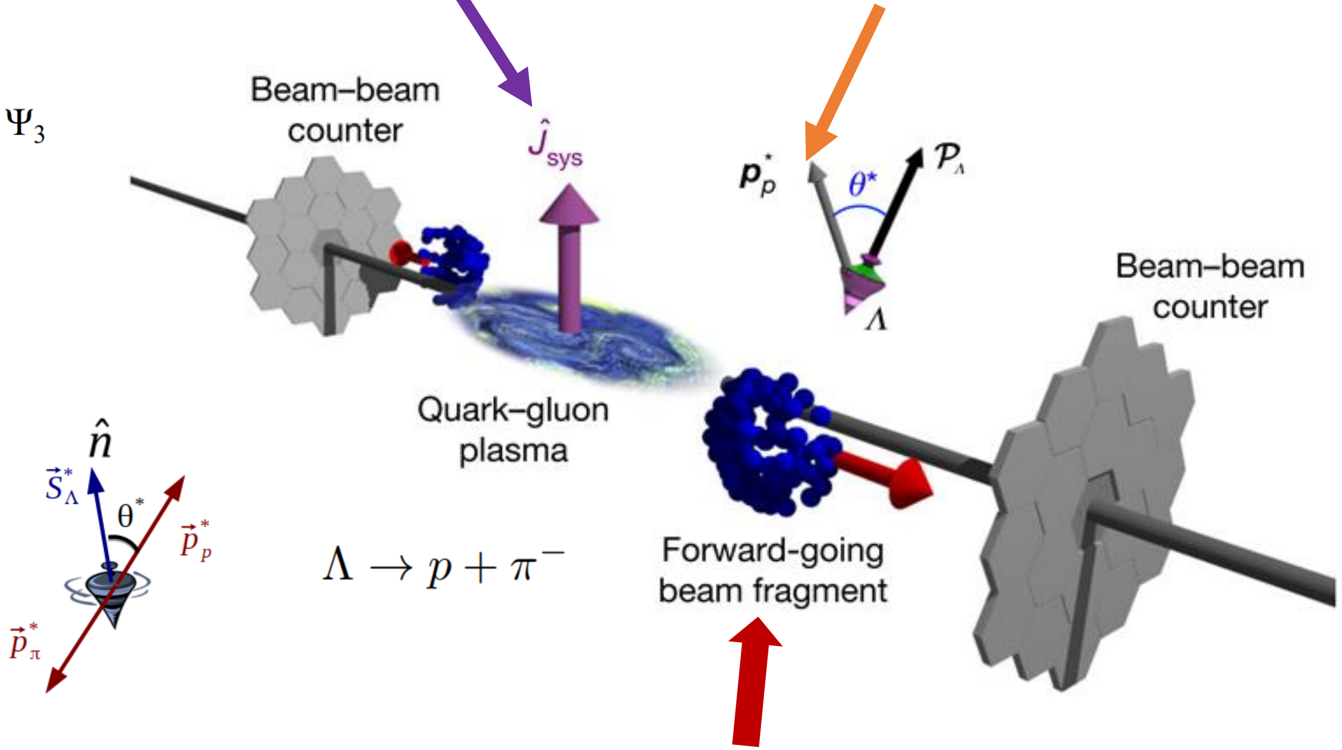




STAR, L. Adamczyk et al., Nature (London) 548, 62.
STAR, J. Adam et al., Phys. Rev. Lett. 123, 132301.

Transverse polarization
(Out-plane direction)

Helicity polarization
(particle's momentum)



Longitudinal polarization
(Beam direction)

Hydrodynamic Effects

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

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

Thermal vorticity

Shear viscous tensor
Shear Induced Polarization(SIP)

Fluid acceleration

Gradient of chemical potential
Spin Hall Effect (SHE)

New effects!

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.

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- Hydrodynamic contributions to the spin alignment of ϕ mesons
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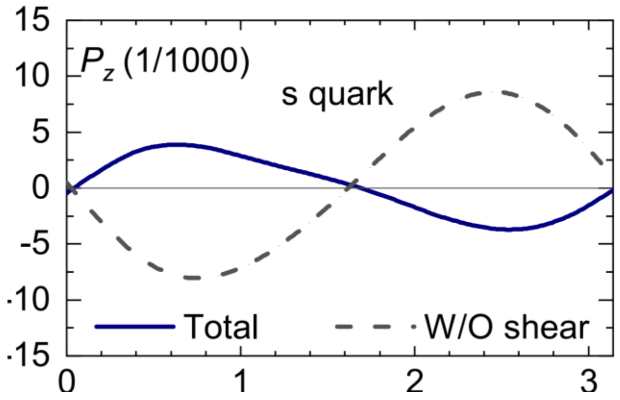
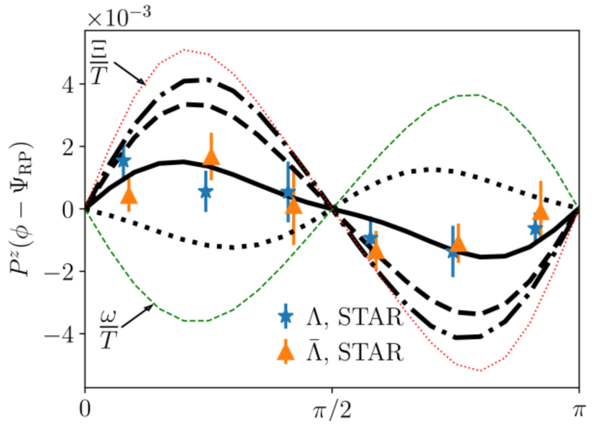
Hydrodynamic Effect

- **Hydrodynamic contributions to the local spin polarization**



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



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

$$\mathcal{S}^\mu_{\rm shear}(\mathbf{p}) = \int d\Sigma^\sigma F_\sigma \frac{\epsilon^{\mu\nu\alpha\beta} p_\nu u_\beta}{\boxed{(u\cdot p)}T} \times p^\rho(\partial_\rho u_\alpha + \partial_\alpha u_\rho - u_\rho D u_\alpha)$$

$$(u\cdot p) \sim m$$

$$\beta_\mu = \frac{u_\mu}{T} \qquad \varpi_{\mu\nu} = -\frac{1}{2}(\partial_\mu \beta_\nu - \partial_\nu \beta_\mu)\,.$$

s-quark memory

Iso-thermal equilibrium

$$m_\Lambda \to m_s \qquad m_s \simeq 0.3\mathrm{GeV} \qquad m_\Lambda \simeq 1.116\mathrm{GeV}$$

$$\omega_{\rho\sigma} = \frac{1}{2}(\partial_\sigma u_\rho - \partial_\rho u_\sigma)$$

Considering shear induced polarization under some assumptions, the theoretical calculations agree with the experimental data qualitatively/quantitatively.

Setup of Simulation

- **(3+1) dimensional viscous hydrodynamic framework CLVisc**

Solve the Energy-momentum conservation and net baryon current:

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

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

Equation of motion of dissipative current:

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

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

- **Setup**

Initial condition: AMPT, SMASH
Freeze out condition : e<0.4GeV/fm^3
Equation of State: NEOS BQS, sp95-pce

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

Simulation

- **Spin Polarization Vector**

$$
\begin{aligned}
\mathcal{S}^{\mu}_{\text{thermal}}(\mathbf{p}) &= \int d\Sigma^{\sigma} F_{\sigma} \epsilon^{\mu\nu\alpha\beta} p_{\nu} \partial_{\alpha} \frac{u_{\beta}}{T}, \\
\mathcal{S}^{\mu}_{\text{shear}}(\mathbf{p}) &= \int d\Sigma^{\sigma} F_{\sigma} \frac{\epsilon^{\mu\nu\alpha\beta} p_{\nu} u_{\beta}}{(u \cdot p)T} \\
&\quad \times p^{\rho}(\partial_{\rho} u_{\alpha} + \partial_{\alpha} u_{\rho} - u_{\rho} D u_{\alpha}) \\
\mathcal{S}^{\mu}_{\text{accT}}(\mathbf{p}) &= -\int d\Sigma^{\sigma} F_{\sigma} \frac{\epsilon^{\mu\nu\alpha\beta} p_{\nu} u_{\alpha}}{T} \left(D u_{\beta} - \frac{\partial_{\beta} T}{T} \right), \\
\mathcal{S}^{\mu}_{\text{chemical}}(\mathbf{p}) &= 2 \int d\Sigma^{\sigma} F_{\sigma} \frac{1}{(u \cdot p)} \epsilon^{\mu\nu\alpha\beta} p_{\alpha} u_{\beta} \partial_{\nu} \frac{\mu}{T},
\end{aligned}
$$

$$
\begin{aligned}
F^{\mu} &= \frac{\hbar}{8 m_{\Lambda} \Phi(\mathbf{p})} p^{\mu} f_{eq}(1 - f_{eq}), \\
\Phi(\mathbf{p}) &= \int d\Sigma^{\mu} p_{\mu} f_{eq}.
\end{aligned}
$$

- **Global Polarization**

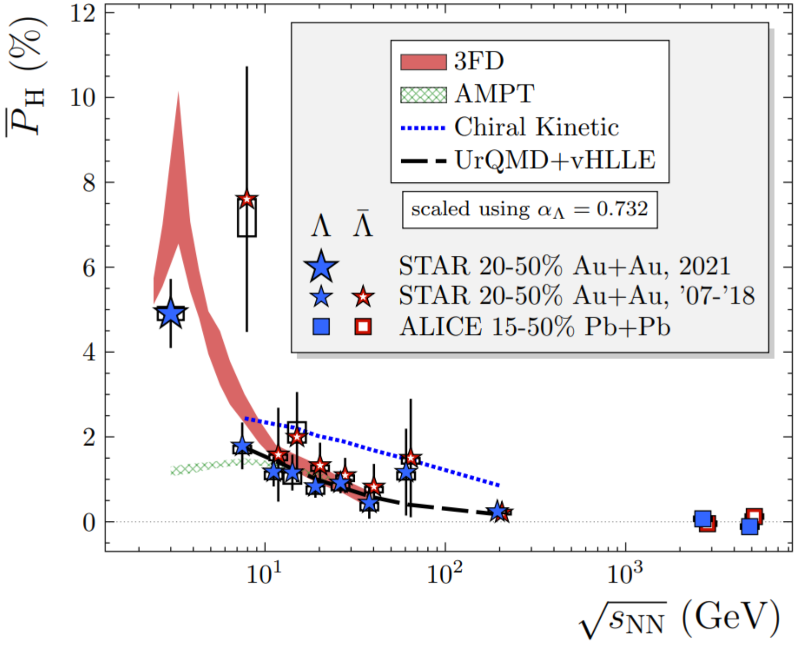
$$
\langle \vec{P} \rangle = \frac{\int_0^{2\pi} d\phi \int_{y_{\min}}^{y_{\max}} dy \int_{p_{T\min}}^{p_{T\max}} p_T dp_T [\Phi(\mathbf{p}) \vec{P}^{*}(\mathbf{p})]}{\int_0^{2\pi} d\phi \int_{y_{\min}}^{y_{\max}} dy \int_{p_{T\min}}^{p_{T\max}} p_T dp_T \Phi(\mathbf{p})}
$$

- **Local Polarization**

$$
\langle \vec{P}(\phi_p) \rangle = \frac{\int_{y_{\min}}^{y_{\max}} dy \int_{p_{T\min}}^{p_{T\max}} p_T dp_T [\Phi(\mathbf{p}) \vec{P}^{*}(\mathbf{p})]}{\int_{y_{\min}}^{y_{\max}} dy \int_{p_{T\min}}^{p_{T\max}} p_T dp_T \Phi(\mathbf{p})}
$$

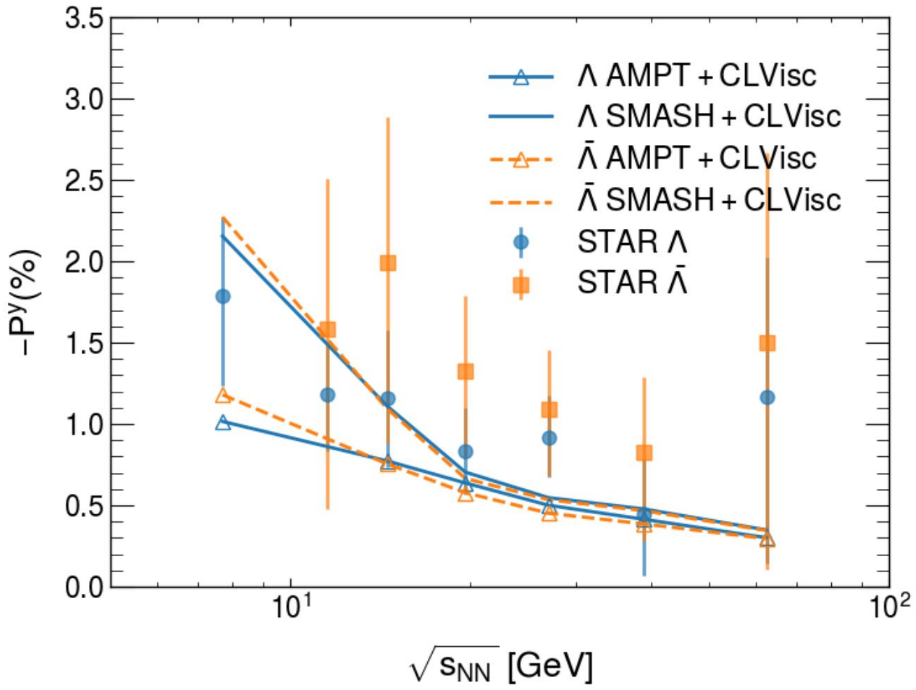
Global Polarization

Thermal vorticity only



STAR, M. S. Abdallah et al., Phys. Rev. C 104, L061901.

$$\mathcal{J}_5^\mu = \mathcal{J}^\mu_{\rm thermal} + \mathcal{J}^\mu_{\rm shear} + \mathcal{J}^\mu_{\rm accT} + \mathcal{J}^\mu_{\rm chemical}$$



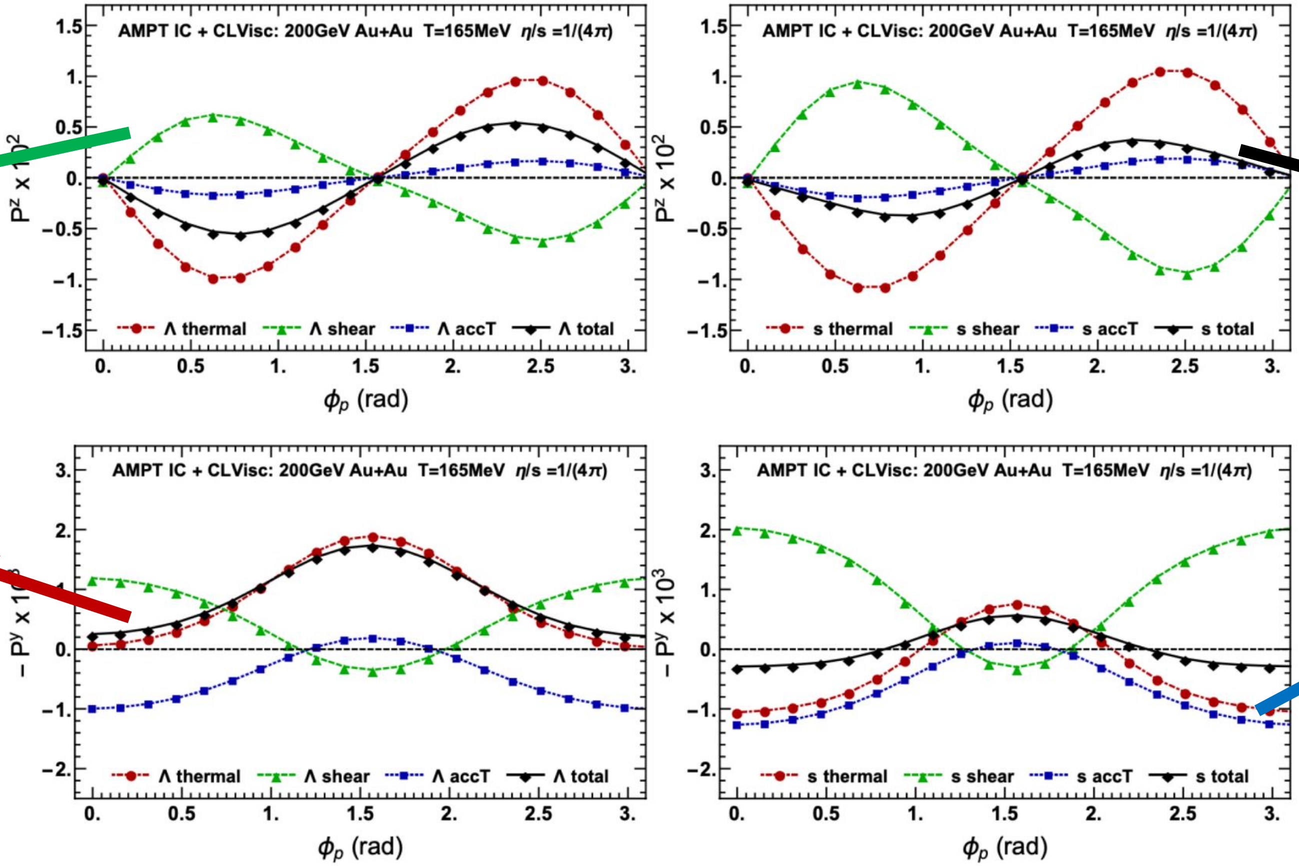
X.-Y. Wu, CY, G.-Y. Qin, and S. Pu, Phys. Rev .C 105 6, 064909

- **The influence of these new effects on the global polarization is small. The theoretical calculations are consistent with the experimental results in both two cases.**

Local Polarization

- RHIC Top Energy

$$\mathcal{J}_5^\mu = \mathcal{J}^\mu_{\rm thermal} + \mathcal{J}^\mu_{\rm shear} + \mathcal{J}^\mu_{\rm accT} + \mathcal{J}^\mu_{\rm chemical}\,.$$



Shear Induced Polarization

Total Polarization

Thermal Vorticity

Fluid Acceleration

CY, S. Pu, and D.-L. Yang, Phys. Rev. C 104, 064901.

- ➢ **Shear induced polarization always gives a “correct” sign**
- ➢ **The local spin polarization has not been fully understood.**

Local Polarization

- **RHIC Beam Energy Scan**

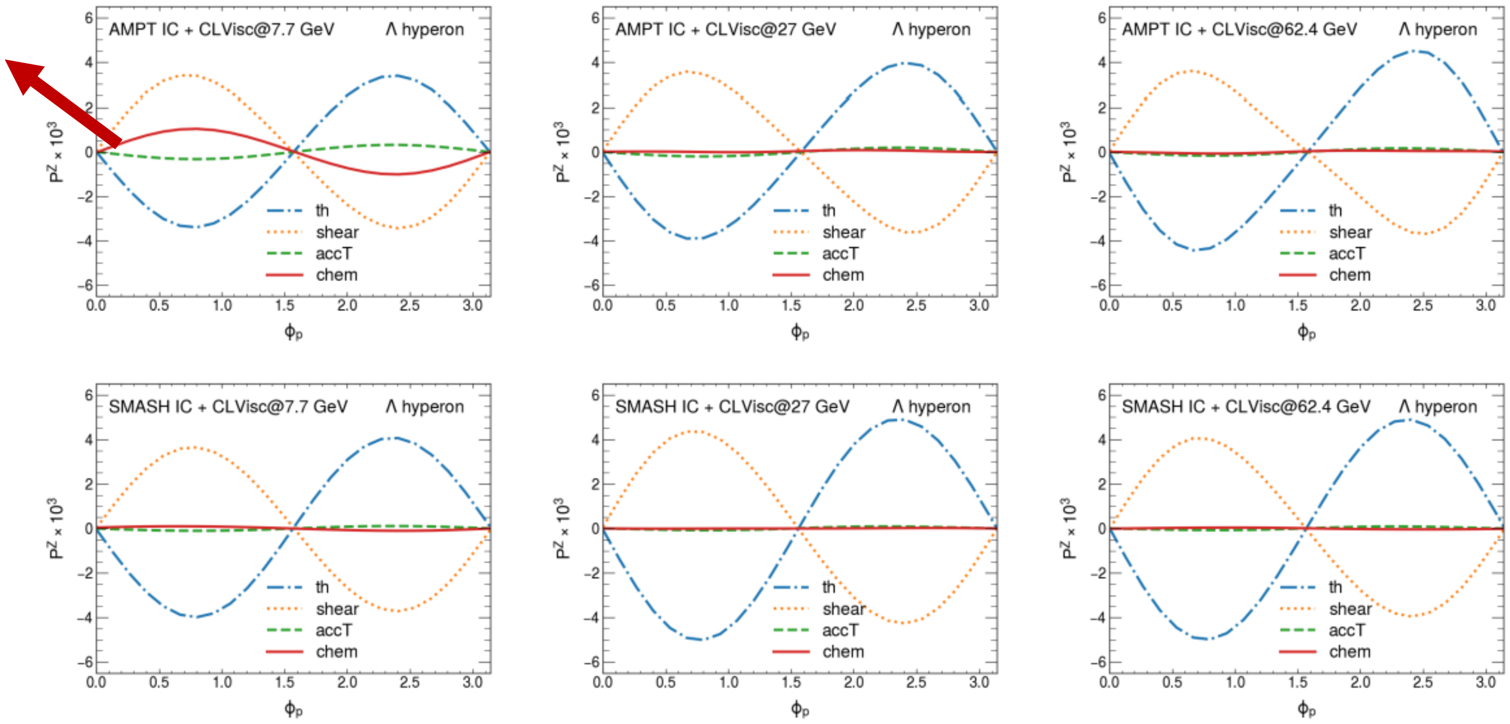
$$\mathcal{J}_5^\mu = \mathcal{J}^\mu_{\mathrm{thermal}} + \mathcal{J}^\mu_{\mathrm{shear}} + \mathcal{J}^\mu_{\mathrm{accT}} + \boxed{\mathcal{J}^\mu_{\mathrm{chemical}}}$$

7.7 GeV **27 GeV** **62.4 GeV**

Chemical Gradient

AMPT

SMASH

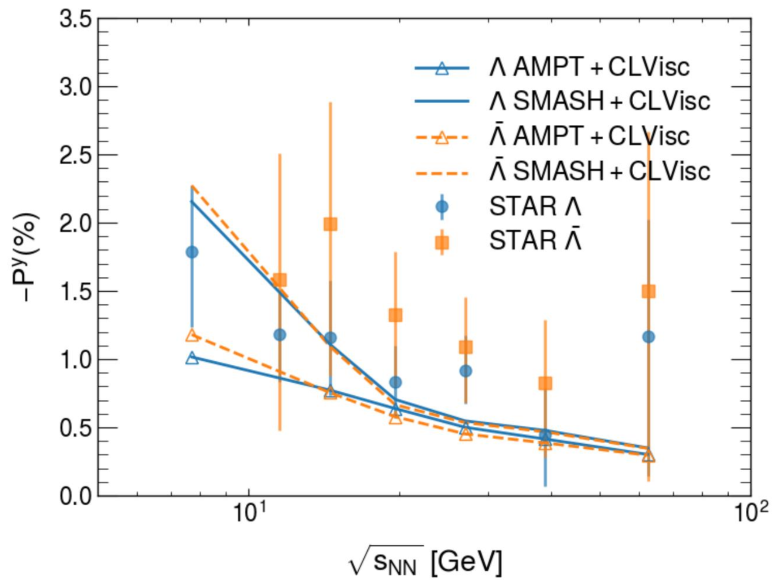


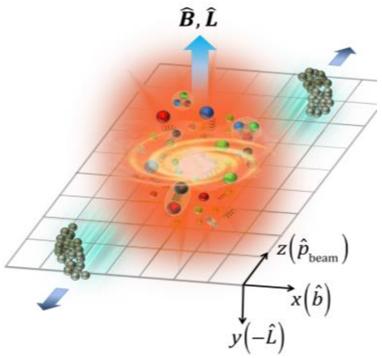
X.Y. Wu, CY, G.Y. Qin, S. Pu Phys. Rev. C 105, 064909

➢ **The local longitudinal polarization contributed by chemical gradient depends on initial conditions strongly**

Vortical Structure

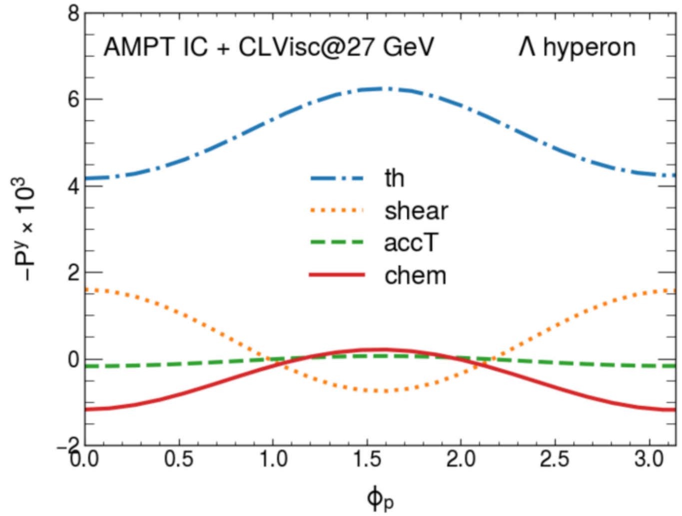
- **Global Vorticity**





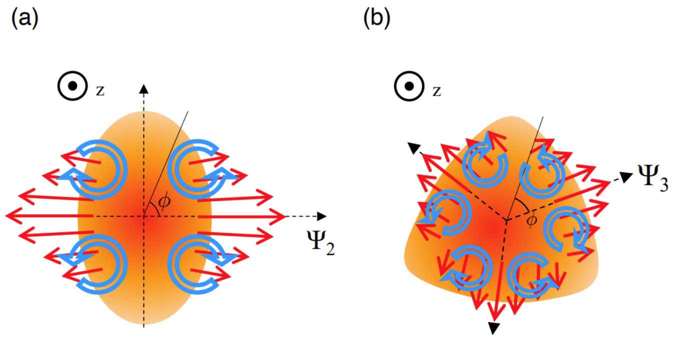
√

- **Local Vorticity**



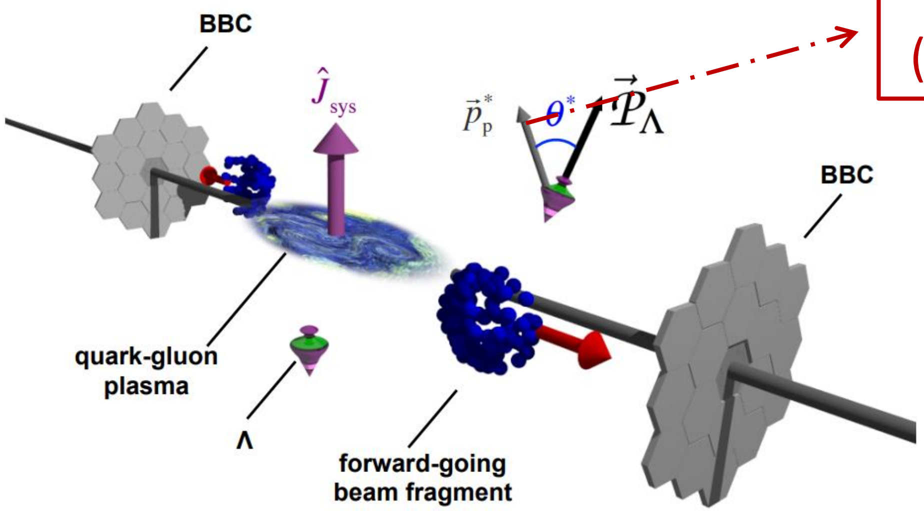
✗

Helicity Polarization?



Local Helicity polarization

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



Helicity polarization
(particle’s momentum)

$$\begin{aligned}\langle h_1 h_2(\Delta\phi)\rangle &\simeq \frac{1}{2\pi}\int_0^{2\pi} \mathrm{d}\phi\,\left(\bar{S}_0^2 + \bar{P}_0^2 \sin^2\phi\cos\Delta\phi\right)\\ &= \bar{S}_0^2 + \frac{1}{2}\bar{P}_0^2\cos\Delta\phi,\end{aligned}$$

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

$$S^h = \widehat{\mathbf{p}}\cdot\boldsymbol{S}(\mathbf{p}) = \widehat{p}^x\mathcal{S}^x + \widehat{p}^y\mathcal{S}^y + \widehat{p}^z\mathcal{S}^z$$

$$S^h = S^h_{\text{hydro}} + S^h_\chi$$

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

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

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

- **Kinetic vorticity**

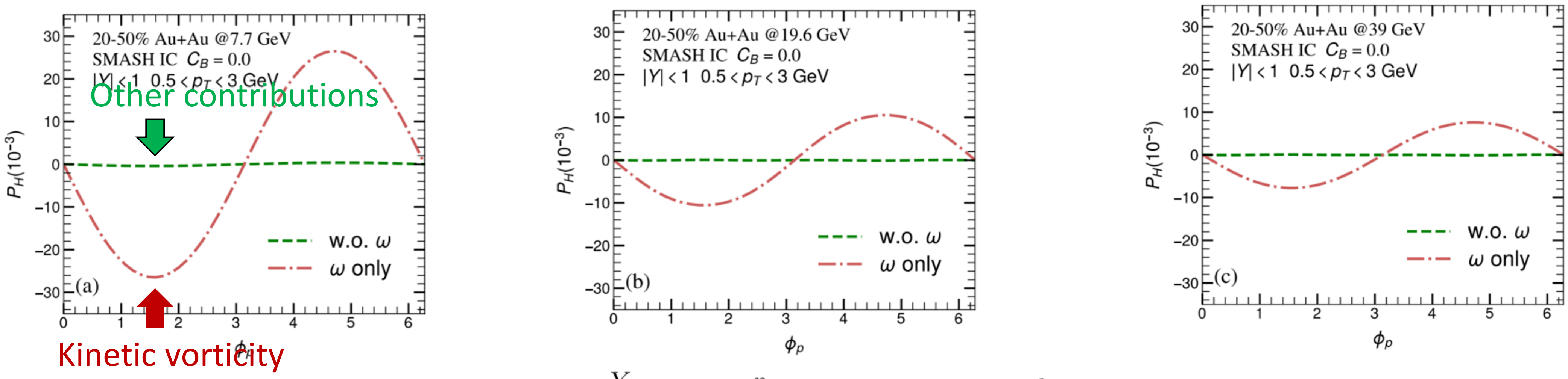
$$
\begin{aligned}
S^h_{\nabla T}(\mathbf{p}) &= \int d\Sigma^\sigma F_\sigma \frac{p_0}{T^2}\widehat{\mathbf{p}}\cdot(\mathbf{u}\times\nabla T), \\
S^h_{\omega}(\mathbf{p}) &= \int d\Sigma^\sigma F_\sigma \frac{p_0}{T}\widehat{\mathbf{p}}\cdot \boxed{\boldsymbol{\omega},} \dashrightarrow \nabla\times\mathbf{u}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

Kinetic vorticity

Numerical results

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

7.7 GeV **19.6 GeV** **39 GeV**



Other contributions

Kinetic vorticity

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

- **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 is almost vanishing**

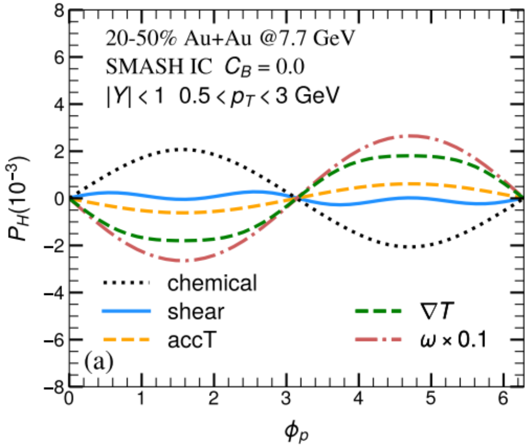
CY , X.Y. Wu, D.-L. Yang, J.H. Gao, S. Pu, G.Y. Qin, 2304.08777.

Numerical results

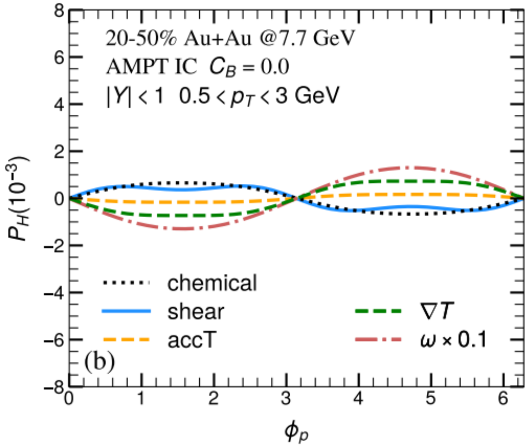
- **Different parameters**

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

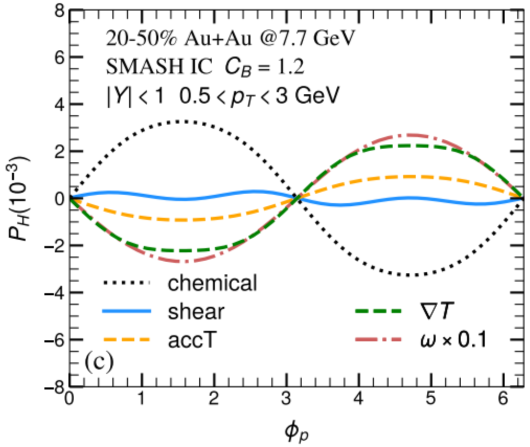
SMASH IC + CB=0

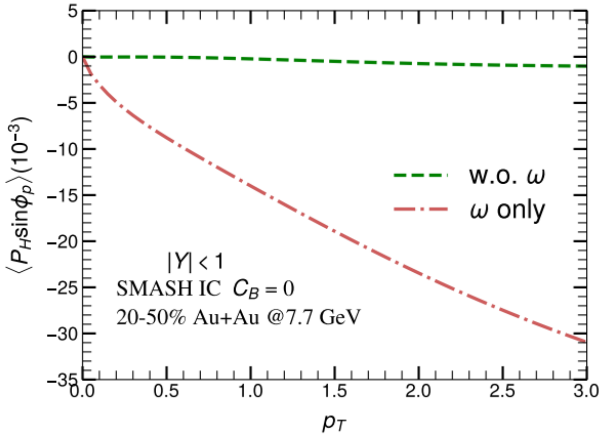


AMPT IC + CB=0



SMASH IC + CB=1.2





- **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.**

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Various Sources

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

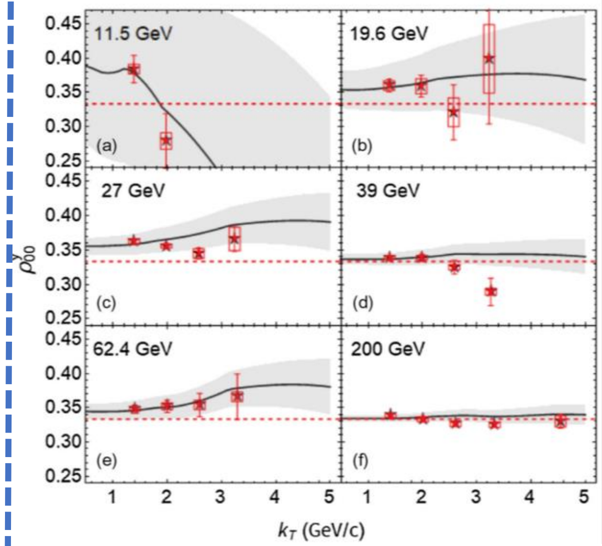
The contribution of hydrodynamic gradient such as, SIP and SHE to the spin alignment have not been studied systematically.

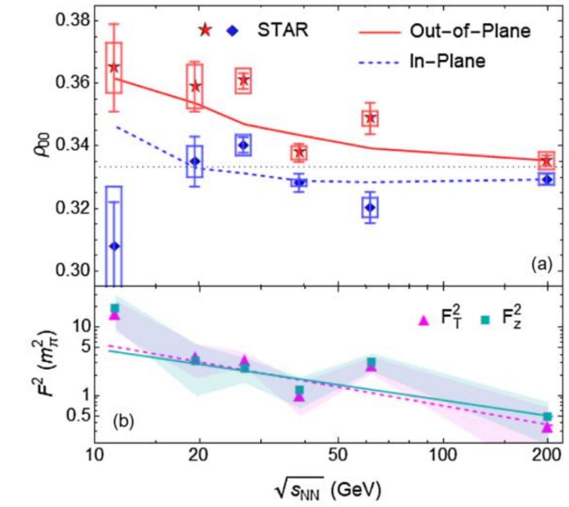
$$\rho_{00}^{y} = \frac{1 - \langle P_q^y P_{\bar{q}}^y \rangle + \langle P_q^x P_{\bar{q}}^x \rangle + \langle P_q^z P_{\bar{q}}^z \rangle}{3 + \langle P_q^y P_{\bar{q}}^y \rangle + \langle P_q^x P_{\bar{q}}^x \rangle + \langle P_q^z P_{\bar{q}}^z \rangle}$$

X.-L. Xia, H. Li, X.-G. Huang, H.-Z. Huang, PLB 817, 136325 (2021)

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)
X.-L. Sheng,, L. Oliva, Q.Wang, PRD 101, 096005 (2020)

Contributions from effective ϕ meson field can reproduce the most of experimental data for spin alignment of ϕ meson





STAR, Nature 614, 244 (2023)
X.-L. Sheng, et al. Phys. Rev. Lett. 131, 042304 (2023)
X.-L. Sheng, S. Pu, and Q. Wang, 2308.14038. (2023).

Formalism

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

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

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

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

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

- **Spin polarization vector for s quarks:**

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

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

with

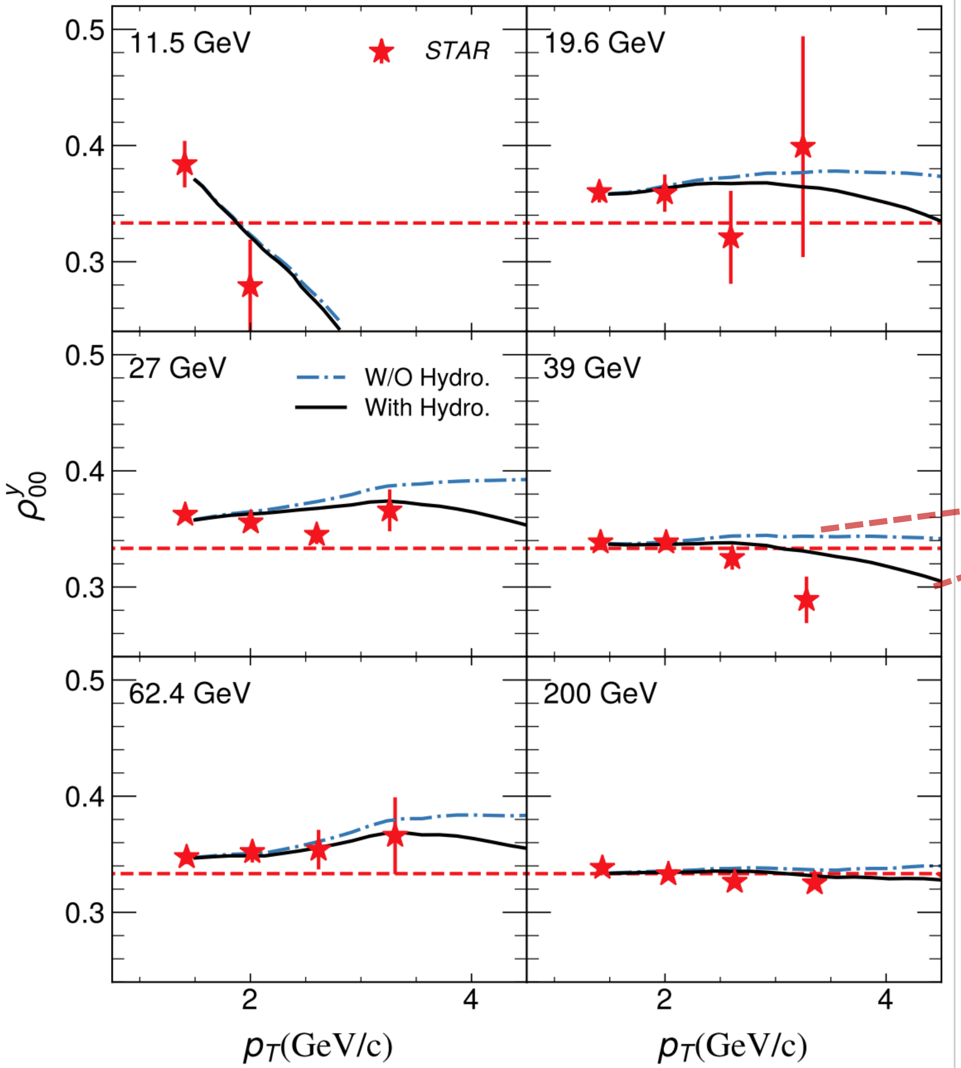
$$\omega^{s/\bar{s}}_{\alpha\beta}\ (x,p) = \omega^{\mathrm{th}}_{\alpha\beta} + \omega^{\mathrm{shear}}_{\alpha\beta} + \omega^{\mathrm{accT}}_{\alpha\beta} \pm \omega^{\mathrm{chemical}}_{\alpha\beta}$$

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

X.-L. Sheng, L. Oliva, Z.-T. Liang, Q. Wang, and X.-N. Wang, Phys. Rev. Lett. 131, 042304 (2023).
X.-L. Sheng, L. Oliva, Z.-T. Liang, Q. Wang, and X.-N. Wang, 2206.05868, (2022).

Hydrodynamic contribution (I)

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



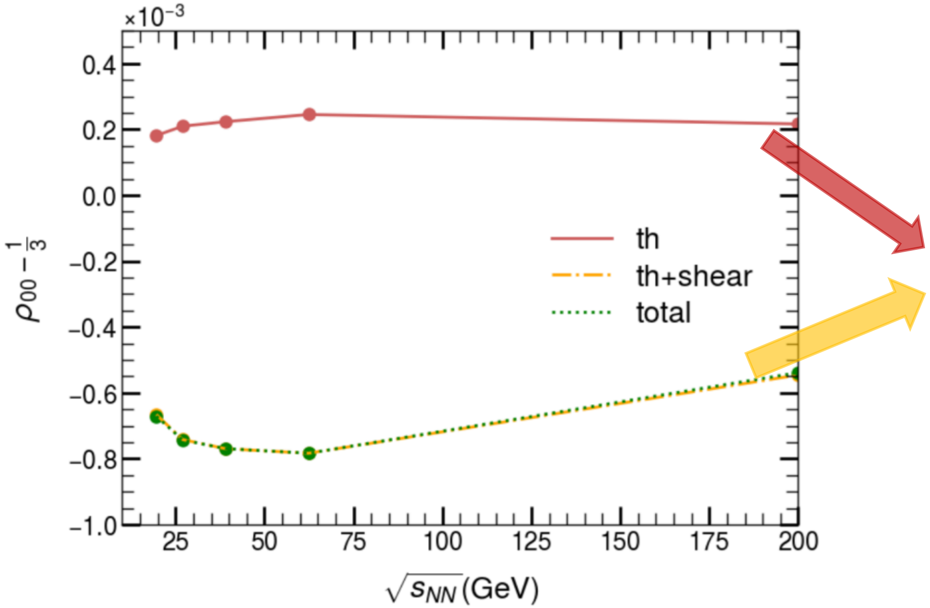
$$<\overline{\rho}_{00}^{\phi}(p_T)> \; = \; \frac{\int_{y_{\min}}^{y_{\max}} dy \int d\phi \int d\Sigma \cdot p f_{eq}^{\phi} \overline{\rho}_{00}^{\phi}(x,\mathbf{p})}{\int_{y_{\min}}^{y_{\max}} dy \int d\phi \int d\Sigma \cdot p f_{eq}^{\phi}}$$

Differences caused by the hydrodynamic contributions

- **The contribution of hydrodynamic effect is at order of -10^{-2} in large transverse momentum.**
- **The theoretical calculations included the hydrodynamic contributions are consistent with the experimental data better.**

Hydrodynamic contribution (II)

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



Differences mainly caused by the shear viscous tensor

$\omega^{\mathrm{shear}}_{\alpha\beta}$

- ➢ **The thermal vorticity contributes to $\rho_{00}-\frac{1}{3}>0$ at the order of 10^{-4} and the magnitude increases with increasing collision energy.**
- ➢ **The total hydrodynamic contributions to the $\rho_{00}-\frac{1}{3}$ is negative.**

Outline

- Introduction
- Hydrodynamic contributions to the spin polarization of Λ hyperons
- Hydrodynamic contributions to the spin alignment for ϕ mesons
- Summary

Summary

- **Spin Polarization of Λ hyperons**
  - Shear induced polarization always gives a “correct” sign.
  - The local spin polarization has not been fully understood.
  - The spin hall effect plays an important role in the low energy collisions.
  - Helicity polarization is mainly contributed by the kinetic vorticity at low energy collisions.
  - Helicity polarization is a possible way to probe the fine vortical structure of QGP.

- **Spin Alignment of ϕ mesons**
  - The theoretical calculations included the hydrodynamic contributions are consistent with the experimental data better in $\boldsymbol{p_T}$ dependence.
  - Global $\rho_{00}-\frac{1}{3}$ contributed by hydrodynamic effects is at the order of -10^{-4}.

Thanks for your time !