Spin polarization in AA and pA collisions

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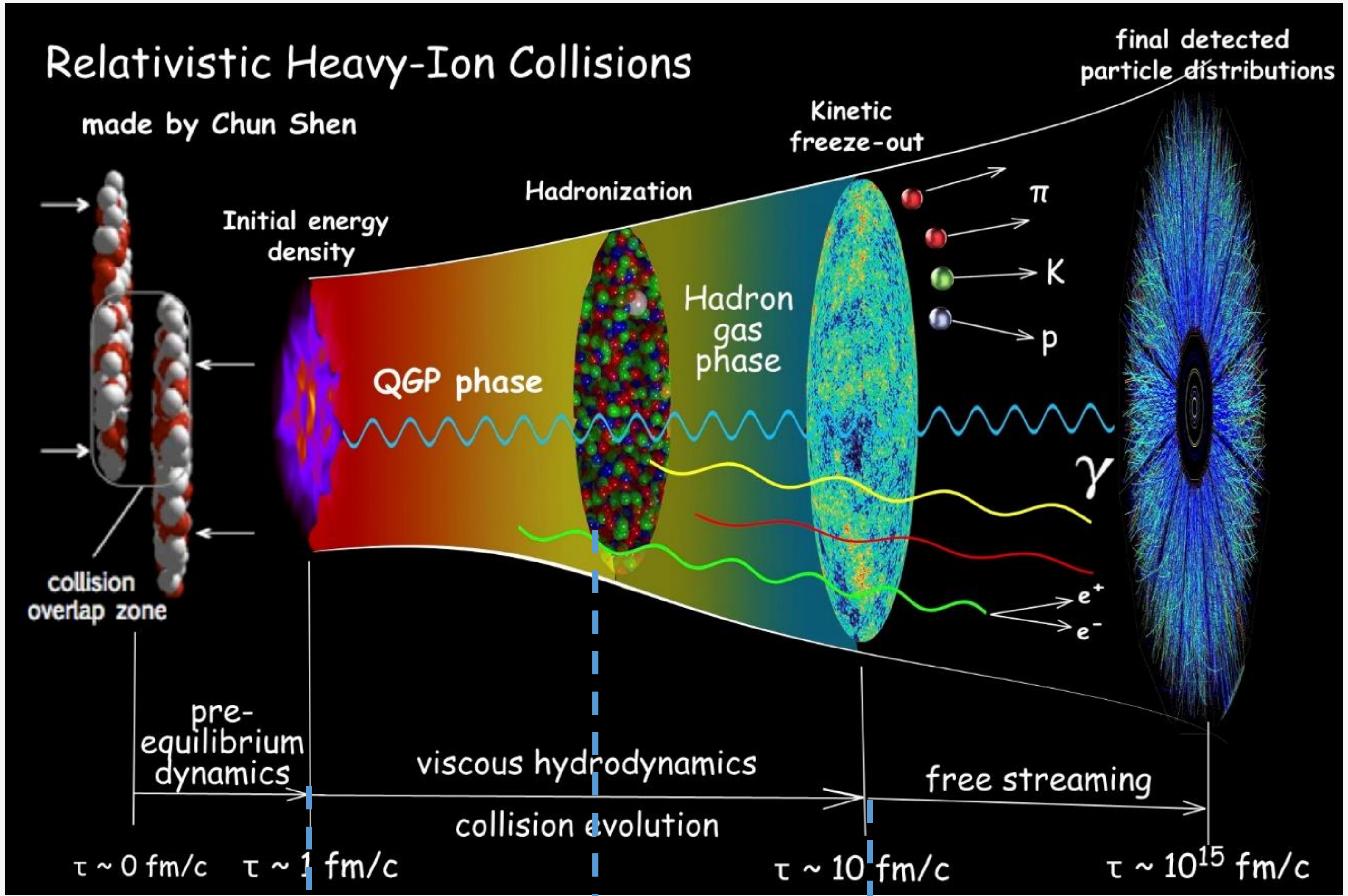
Based on:
- X.Y. Wu, CY , G.Y. Qin, S. Pu, Phys.Rev.C 105 (2022) 6, 064909
- CY , X.Y. Wu, J. Zhu, S. Pu, G.Y. Qin, 2408.04296
- CY , X.Y. Wu, D.-L. Yang, J.H. Gao, S. Pu, G.Y. Qin, Phys.Rev.C 109 (2024) 1, L011901

In collaboration with: Xiang-Yu Wu, Shi Pu, Guang-You Qin, Di-Lun Yang, Jian-Hua Gao

Outline

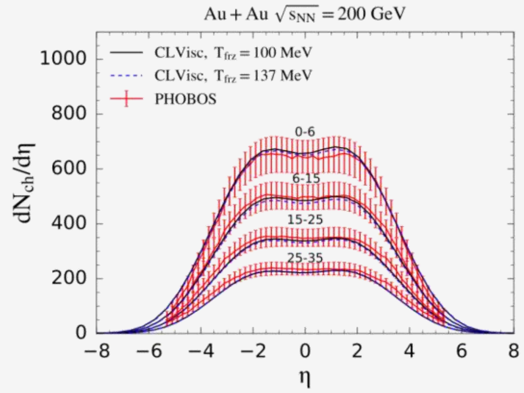
- Introduction
- Spin Polarization Vector
- Global and local polarization at AA systems
- Spin polarization at pA system
- Summary

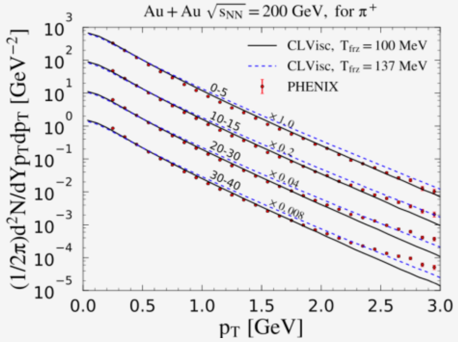
Relativistic heavy ion collision

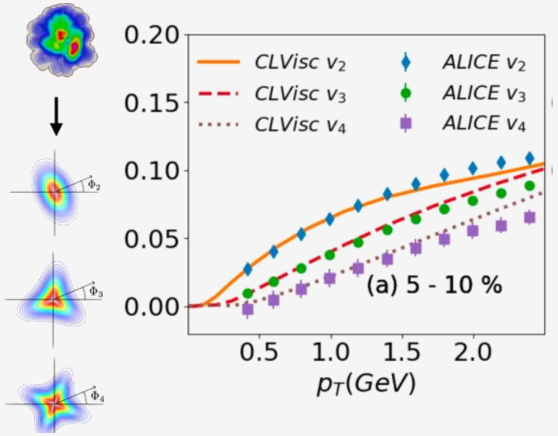


Initial Condition | Hydro-dynamics | Hadron cascade

Pang, Wang, and Wang, PRC 86, 024911
Wu, Qin, Pang, and Wang, PRC 105, 034909





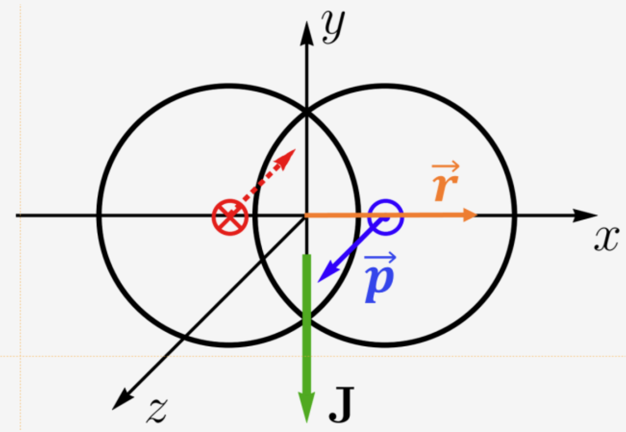


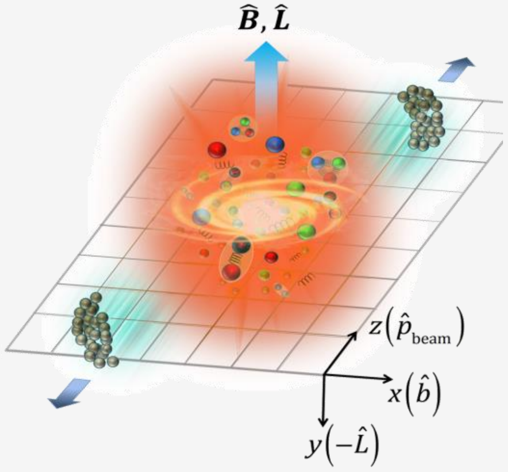
Observable
Vs. Simulation

hybrid model：hydrodynamics + hadron cascade

Orbital Angular Momentum (OAM)

➢Non-central heavy ion collision





b=7fm

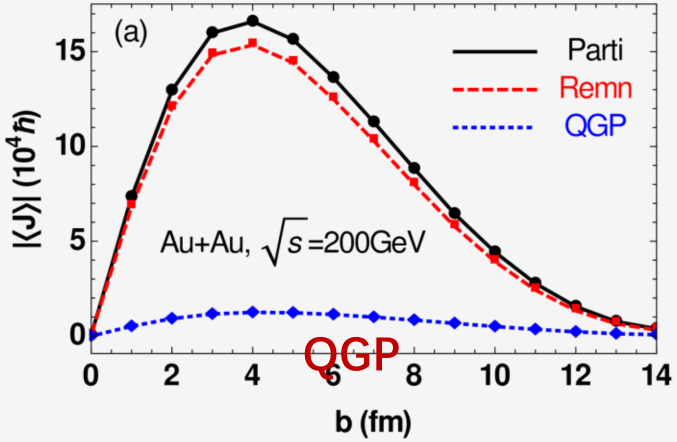
$$|J_y| = |\mathbf{r} \times \mathbf{p}| \approx \frac{b}{2} A \sqrt{s_{NN}}$$

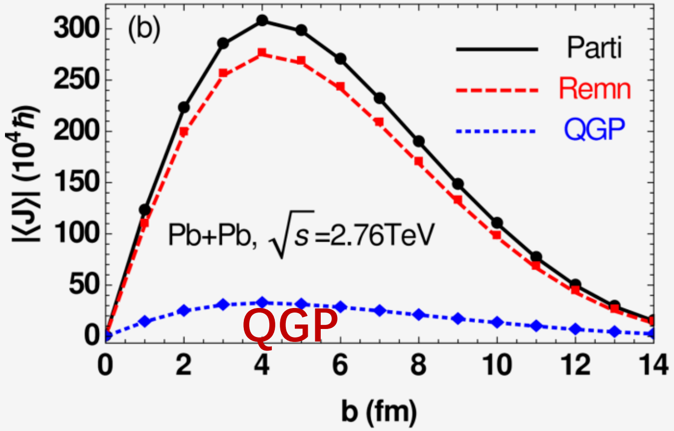
- **RHIC: Au+Au@200GeV:**

$$J_y \sim 7 \times 10^5 \hbar$$

- **LHC: Pb+Pb@2760GeV:**

$$J_y \sim 10^7 \hbar$$

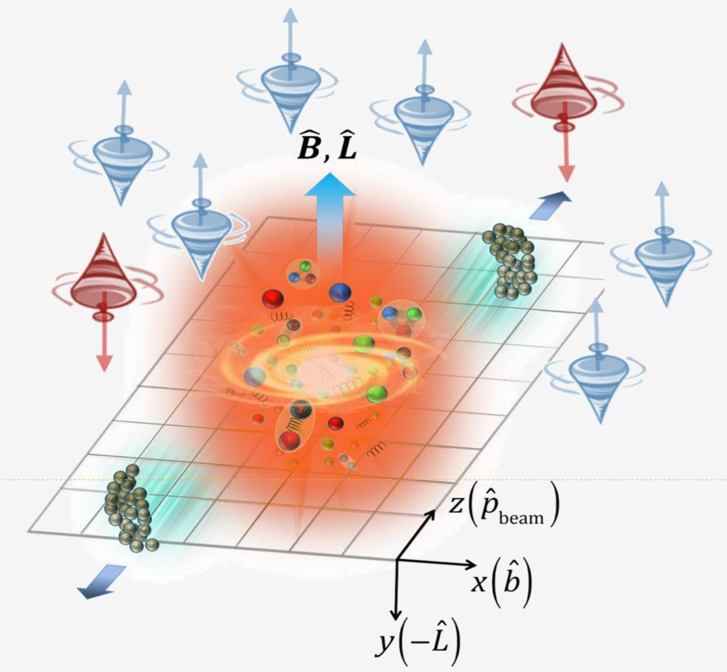




Deng and Huang, PRC 93, 064907.
Li, Pang, Wang, and Xia, PRC 96, 054908.

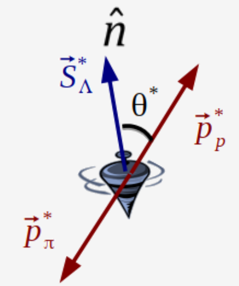
Spin-Orbital Coupling

➢Spin-Orbital Coupling



Hyperons

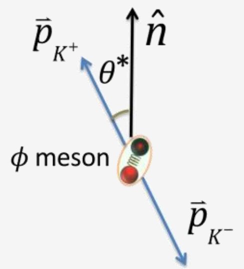
Spin Polarization $S = \frac{1}{2}$

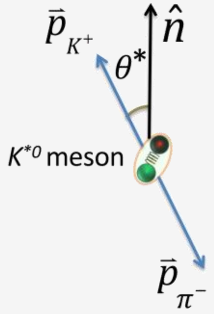


$\Lambda \to p + \pi^-$

Vector meson

Spin Alignment: S=1



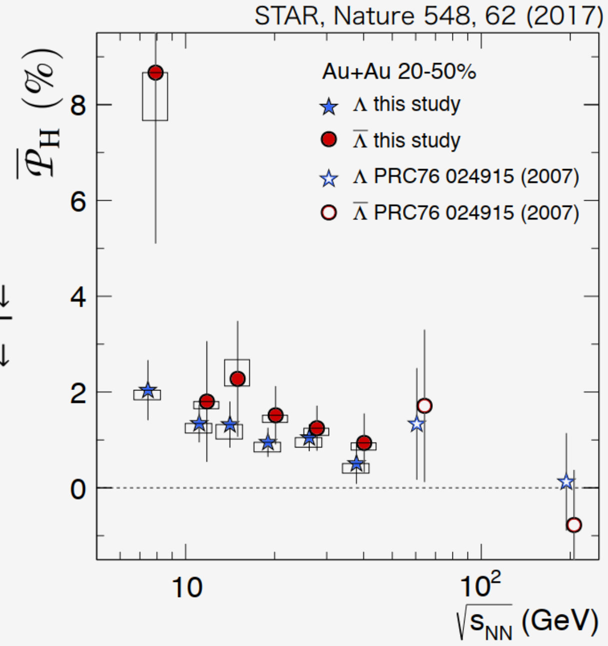


Z.-T. Liang and X.-N. Wang, Phys. Rev. Lett. 94, 102301 (2005)
Z.-T. Liang and X.-N. Wang, Phys. Lett. B 629, 20 (2005)

Global Polarization

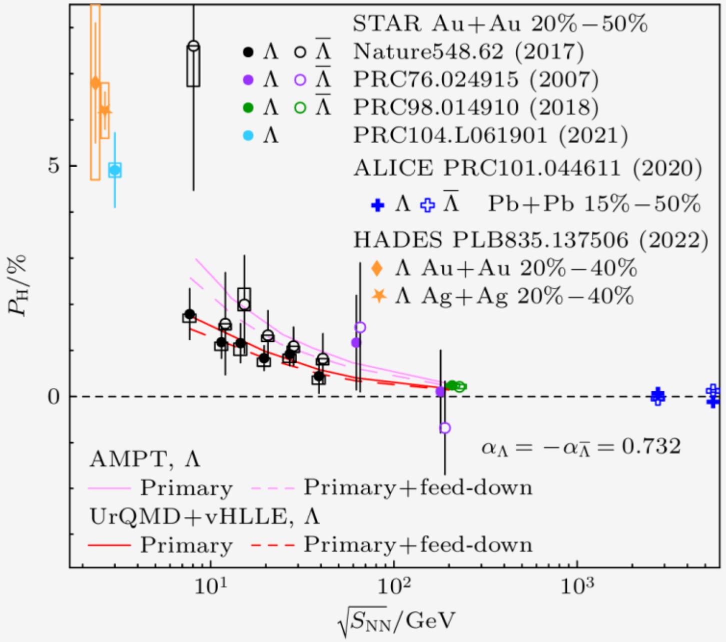
➢Global Spin Polarization of Λ Hyperons

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



STAR, Nature 548, 62 (2017).

Acta Phys. Sin. Vol. 72, No. 7(2023) 072401

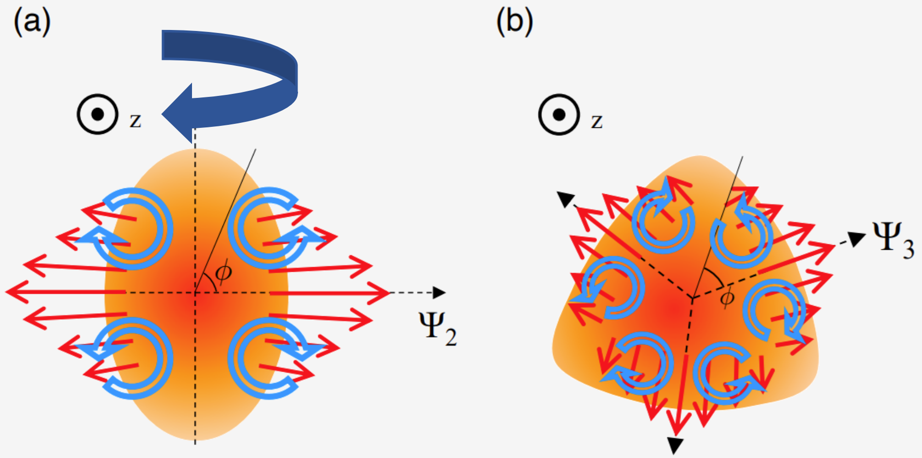


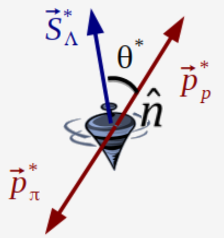
$$\omega = k_B T \left(\overline{P}_{\Lambda'} + \overline{P}_{\bar{\Lambda}'} \right) / \hbar \quad \sim \quad 10^{22} s^{-1}$$

Most vortical fluid !

Local Polarization

➢Local Vortical Structure



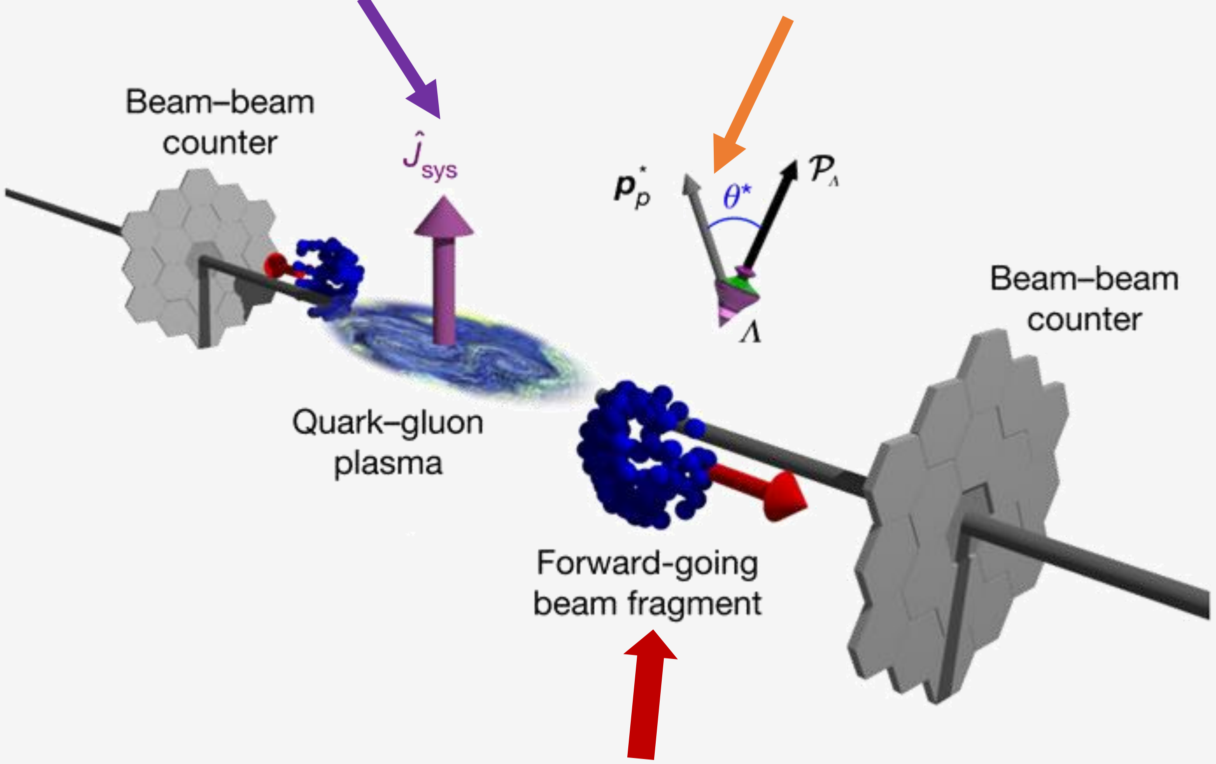


$\Lambda \to p + \pi^-$

STAR, J. Adam et al., Phys. Rev. Lett. 123, 132301.
STAR, Phys. Rev. Lett. 131 (2023) 20, 202301

Orbital Angular momentum
(Out-plane direction)

Helicity polarization
(particle's momentum)



Beam direction polarization

Outline

- Introduction
- **Spin Polarization Vector**
- Global and local polarization at AA systems
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Axial Current and Spin Density

➢Nöther's theorem:

Angular momentum density for the spin-half particles

$$\Psi_r(x) \quad \rightarrow \quad \Psi_r(x) - \frac{1}{2}\omega_{\mu\nu}(\Sigma^{\mu\nu})^r_s\Psi_r(x)$$
$$M^{\mu\nu\rho} \quad = \quad -i\frac{\partial\mathcal{L}}{\partial(\partial_\mu\Psi)}\Sigma^{\nu\rho}\Psi + x^\nu T^{\mu\rho} - x^\mu T^{\nu\rho}$$

➢Canonical decomposition:

$$M^{\mu\nu\rho} \quad = \quad L^{\mu\nu\rho} + S^{\mu\nu\rho}$$

Orbital density: $L^{\mu\nu\rho} \quad = \quad x^\nu T^{\mu\rho} - x^\mu T^{\nu\rho}$

Spin density: $S^{\mu\nu\rho} \quad = \quad -i\frac{\partial\mathcal{L}}{\partial(\partial_\mu\Psi)}\frac{1}{2}\sigma^{\nu\rho}\Psi = \frac{i}{8}\bar{\Psi}\left\{\gamma^\mu, [\gamma^\nu, \gamma^\rho]\right\}\Psi$

$$= \quad -\frac{1}{2}\epsilon^{\mu\nu\rho\sigma}J_{5,\sigma},$$

Axial Current: $J_5^\mu \quad = \quad \bar{\Psi}\gamma^\mu\gamma^5\Psi$

Spin Cooper-Frye Formula

➢Pauli–Lubanski pseudo-vector

Becattini, Chandra, Zanna, and Grossi, Annals Phys. (2013).
Fang, Pang, Wang, and Wang, PRC 94, 024904 (2016)

$$W^\mu = \frac{1}{2}\epsilon^{\mu\nu\alpha\beta}p_\nu M_{\alpha\beta} \xrightarrow[p_\nu=(m,0,0,0)]{\text{rest frame}} -mS^\mu$$

Just consider the spin part of the angular momentum:

$$S^\mu = \frac{-W^\mu}{m} = \frac{1}{2m}\epsilon^{\mu\nu\alpha\beta}p_\nu \int d\Sigma^\lambda S_{\lambda\alpha\beta}$$
$$= \frac{1}{2m}\int d\Sigma^\lambda p_\lambda J_5^\mu$$

➢Normalized Spin Polarization Vector

$$\mathcal{S}^\mu = \frac{1}{2m}\frac{\int d\Sigma_\lambda p^\lambda J_5^\mu}{\int d\Sigma_\lambda p^\lambda f_{eq}}$$

Axial Current is proportional to the spin polarization density .

Quantum Kinetic Theory

- **Classic Kinetic Theory**
- **Quantum Kinetic Theory**

Distribution function
$f(t, \mathbf{x}, \mathbf{p})$

Quantum version ⟹

Wigner function
$\mathcal{W}(x, p)$

$$p^\mu \partial_\mu f + mF^\mu \partial_{p_\mu}(f) = C(f)$$

Boltzmann Equation

⟹

$$\left[\gamma \cdot \left(p + i\frac{\hbar}{2}\partial\right) - m\right] W_{\alpha\beta} = \hbar \mathcal{C}_{\alpha\beta}$$

Wigner Equation

- **Wigner function for fermions:**

Gauge link $U(x_+, x_-) \equiv e^{-iQ\int_{x_-}^{x_+} dz^\mu A_\mu(z)},$

$$\hat{W}_{\alpha\beta} = \int \frac{d^4y}{(2\pi)^4} e^{-ip\cdot y} \bar{\psi}_\beta(x_+) U(x_+, x_-) \psi_\alpha(x_-), \quad W(x,p) = \langle : \hat{W}(x,p) : \rangle$$

Vasak, Gyulassy, Elze, Ann. Phys. (N.Y.) 173, 462 (1987); Zhuang, Heinz, PRD, 57,6525 (1998); Elze, Heinz,Phys.Rep.183,81(1989).

Wigner equation and axial currents

➢Wigner equations without interactions

$$\gamma_\mu \left(p^\mu + \frac{i}{2}\nabla^\mu - m \right) W(x,p) = 0, \quad \nabla^\mu \equiv \partial_x^\mu - Q F_\nu^\mu \partial_p^\nu$$

➢Clifford algebra

$$\left\{ 1_{4\times 4}, i\gamma^5, \gamma^\mu, \gamma^5\gamma^\mu, \frac{1}{2}\sigma^{\mu\nu} \right\}$$

$$W = \frac{1}{4}\left[\mathscr{F} + i\gamma^5 \mathscr{P} + \gamma^\mu \mathscr{V}_\mu + \gamma^5\gamma^\mu \mathscr{A}_\mu + \frac{1}{2}\sigma^{\mu\nu}\mathscr{S}_{\mu\nu} \right], \quad \mathcal{A}^\mu = \mathrm{Tr}\left[\gamma^\mu \gamma^5 W \right]$$

Charge Current:

$$\mathscr{V}^\mu = \int \frac{d^4y}{(2\pi)^4} e^{-ip\cdot y} <: \bar{\psi}_\beta \left(x + \frac{1}{2}y \right) \gamma^\mu U\left(x + \frac{1}{2}y, x - \frac{1}{2}y \right) \psi_\alpha \left(x - \frac{1}{2}y \right) :>$$

Axial Current:

$$\mathscr{A}_\mu = \int \frac{d^4y}{(2\pi)^4} e^{-ip\cdot y} <: \bar{\psi}_\beta \left(x + \frac{1}{2}y \right) \gamma^\mu \gamma^5 U\left(x + \frac{1}{2}y, x - \frac{1}{2}y \right) \psi_\alpha \left(x - \frac{1}{2}y \right) :>$$

Axial current at global equilibrium

➢Wigner equation for the chiral fermions

Hidaka, Pu, Wang, Yang, PPNP, 127,103989 (2022).

+:right -:left

$$\nabla \cdot \mathcal{J}^s = 0$$
$$p \cdot \mathcal{J}^s = 0$$
$$2s\left(p^\mu \mathcal{J}_s^\nu - p^\nu \mathcal{J}_s^\mu\right) = -\hbar \epsilon^{\mu\nu\rho\sigma} \nabla_\rho \mathcal{J}_\sigma^s$$

We consider the $\hbar$ (gradient) expansion,

$$\mathcal{J}_\mu^s(x,p) = \frac{1}{2}\left[\mathscr{V}_\mu(x,p) + s\mathscr{A}_\mu(x,p)\right]$$
$$\mathcal{J}_\mu^s(x,p) = \mathcal{J}_{\mu,(0)}^s(x,p) + \mathcal{J}_{\mu,(1)}^s(x,p) + \cdots,$$

➢Solutions up to $\hbar$ at global equilibrium

Global equilibrium conditions

$$\partial_\nu \beta_\sigma + \partial_\sigma \beta_\nu = 0$$
$$\partial_\nu \frac{\mu}{T} - eF_{\nu\gamma}\beta^\gamma = 0$$

$$\beta_\mu = \frac{u_\mu}{T}$$

$$\mathcal{J}_s^\mu = p^\mu f_{(0)} \delta(p^2) - \frac{s}{2}\hbar \widetilde{\omega}^{\mu\lambda} p_\lambda f'_{(0)} \delta\left(p^2\right) + s\hbar \widetilde{F}^{\mu\nu} p_\nu f_{(0)} \delta'\left(p^2\right) + \mathcal{O}(\hbar^2)$$

$$\mathcal{J}_5^\mu = \mathcal{J}_+^\mu - \mathcal{J}_-^\mu = \hbar \frac{1}{2} \epsilon^{\mu\nu\alpha\beta} \Omega_{\alpha\beta} p_\nu f_{(0)}\left(1 - f_{(0)}\right) \delta\left(p^2\right)$$

$$\Omega_{\mu\nu} = \frac{1}{2}\left(\partial_\mu \beta_\nu - \partial_\nu \beta_\mu\right)$$

Thermal vorticity

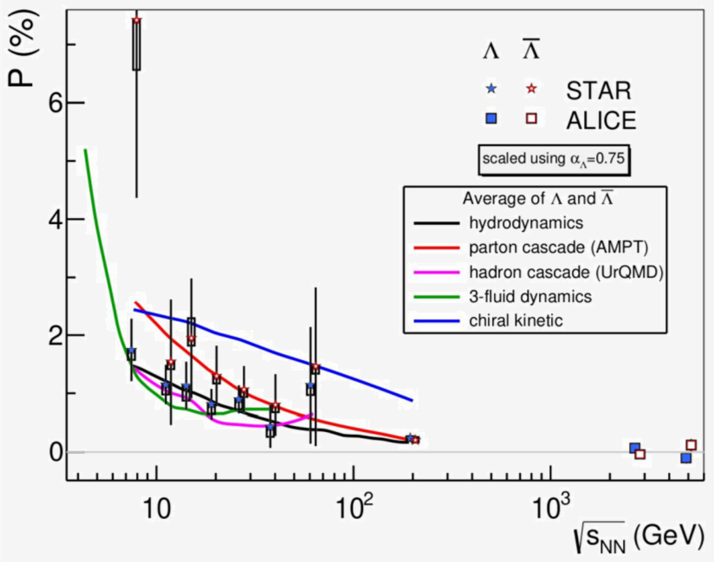
Spin Polarization at Global Equilibrium

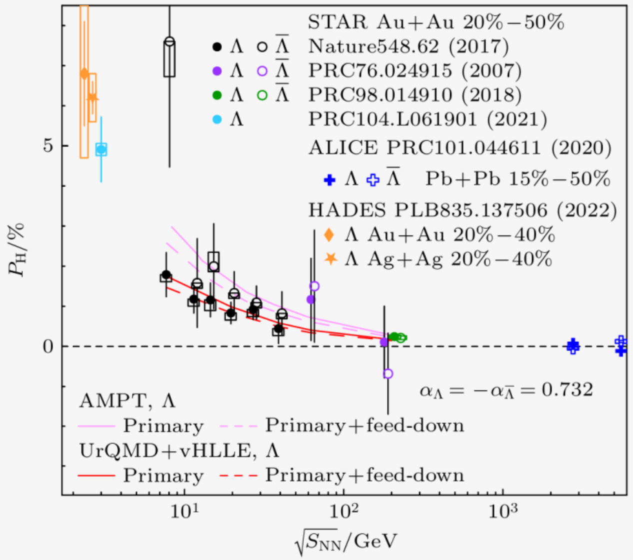
- **Thermal vorticity only**

Becattini, Chandra, Zanna, and Grossi, Annals Phys. (2013).
Fang, Pang, Wang, and Wang, PRC 94, 024904 (2016)

$$S^\mu(x,p) = -\frac{1}{8m}(1-n_F)\,\epsilon^{\mu\nu\rho\sigma}p_\nu\varpi_{\rho\sigma}(x).$$

$$\varpi_{\mu\nu} = \frac{1}{2}(\partial_\nu\beta_\mu - \partial_\mu\beta_\nu)$$





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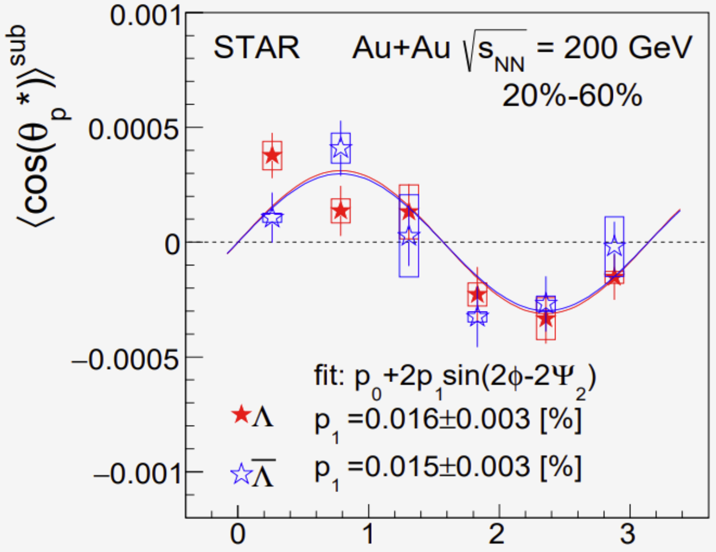
The theoretical calculations on the global equilibrium agree with the experimental data quantitatively.

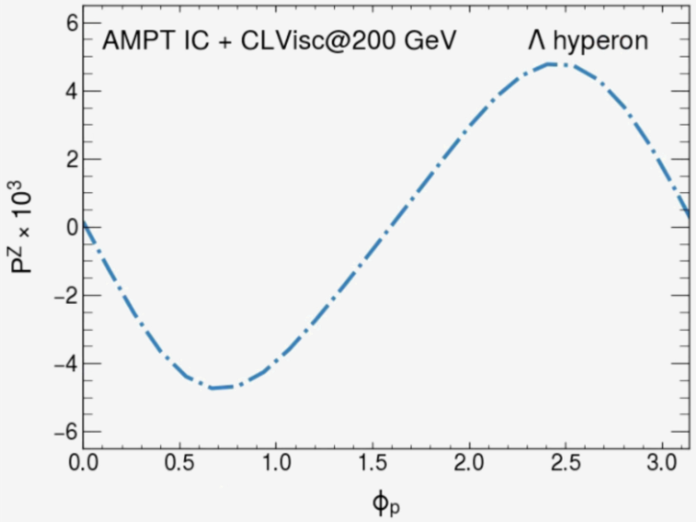
"Sign" Problem

➢ Experimental measurement

➢ Local spin polarization induced by thermal vorticity



Opposite Sign



Out of global equilibrium effects ?

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

Becattini and Karpenko, PRL 120, 012302
Xia, Li, Tang, and Wang, PRC 98, 024905

Axial Current at Local Equilibrium

At local equilibrium, the left and right handed currents read

$$\mathcal{J}^{\mu}_{\lambda}(p,X) = 2\pi\mathrm{sign}(u\cdot p)\left\{\delta(p^2)p^{\mu} + \lambda\frac{\hbar}{2}\delta(p^2)\left[u^{\mu}(p\cdot\omega) - \omega^{\mu}(u\cdot p) - 2S^{\mu\nu}_{(u)}\tilde{E}_{\nu}\right]\partial_{u\cdot p} + \lambda\frac{\hbar}{4}\epsilon^{\mu\nu\alpha\beta}F_{\alpha\beta}\partial^{p}_{\nu}\delta(p^2)\right\}f^{(0)}_{\lambda},$$

$$S^{\mu\nu}_{(u)} = \epsilon^{\mu\nu\alpha\beta}p_{\alpha}u_{\beta}/(2u\cdot p),$$

$$\tilde{E}_{\nu} = E_{\nu} + T\partial_{\nu}\frac{\mu_{\lambda}}{T} + \frac{(u\cdot p)}{T}\partial_{\nu}T - p^{\sigma}\left[\partial_{<\sigma}u_{\nu>} + \frac{1}{3}\Delta_{\sigma\nu}(\partial\cdot u) + u_{\nu}Du_{\sigma}\right].$$

$$f^{(0)}_{\lambda} = 1/(e^{(u\cdot p-\mu_{\lambda})/T}+1),$$

$$\partial_{\nu}\beta_{\sigma} + \partial_{\sigma}\beta_{\nu} = 0$$
$$\partial_{\nu}\frac{\mu}{T} - eF_{\nu\gamma}\beta^{\gamma} = 0$$

$\lambda = \pm$ **+:right -:left**

Recalling the original equations

$$\mathcal{S}^{\mu} = \frac{1}{2m}\frac{\int d\Sigma_{\lambda}p^{\lambda}J^{\mu}_{5}}{\int d\Sigma_{\lambda}p^{\lambda}f_{eq}}$$

Hidaka, Pu, and Yang, PRD, 97, 016004 (2018)

Polarization induced by different sources

➢Spin polarization at local equilibrium

$$\mathcal{S}^{\mu}(\mathbf{p}) = \mathcal{S}^{\mu}_{\text{thermal}} + \mathcal{S}^{\mu}_{\text{shear}} + \mathcal{S}^{\mu}_{\text{accT}} + \mathcal{S}^{\mu}_{\text{chemical}} + \mathcal{S}^{\mu}_{\text{EB}}$$

$$\mathcal{S}^{\mu}_{\text{thermal}}(\mathbf{p}) = \frac{\hbar}{8m_\Lambda N}\int d\Sigma^{\sigma} p_{\sigma} f_V^{(0)}(1-f_V^{(0)})\epsilon^{\mu\nu\alpha\beta}p_{\nu}\partial_{\alpha}\frac{u_{\beta}}{T},$$

Thermal vorticity

$$\mathcal{S}^{\mu}_{\text{shear}}(\mathbf{p}) = -\frac{\hbar}{4m_\Lambda N}\int d\Sigma\cdot p f_V^{(0)}(1-f_V^{(0)})\frac{\epsilon^{\mu\nu\alpha\beta}p_{\alpha}u_{\beta}}{(u\cdot p)T}\frac{1}{2}p^{\sigma}[(\partial_{\sigma}u_{\nu}+\partial_{\nu}u_{\sigma})-u_{\sigma}Du_{\nu}]$$

Shear Induced Polarization (SIP)

$$\mathcal{S}^{\mu}_{\text{accT}}(\mathbf{p}) = -\frac{\hbar}{8m_\Lambda N}\int d\Sigma\cdot p f_V^{(0)}(1-f_V^{(0)})\frac{1}{T}\epsilon^{\mu\nu\alpha\beta}p_{\nu}u_{\alpha}(Du_{\beta}-\frac{1}{T}\partial_{\beta}T),$$

Fluid Acceleration

$$\mathcal{S}^{\mu}_{\text{chemical}}(\mathbf{p}) = \frac{\hbar}{4m_\Lambda N}\int d\Sigma\cdot p f_V^{(0)}(1-f_V^{(0)})\frac{1}{(u\cdot p)}\epsilon^{\mu\nu\alpha\beta}p_{\alpha}u_{\beta}\partial_{\nu}\frac{\mu}{T},$$

Spin Hall Effect (SHE)

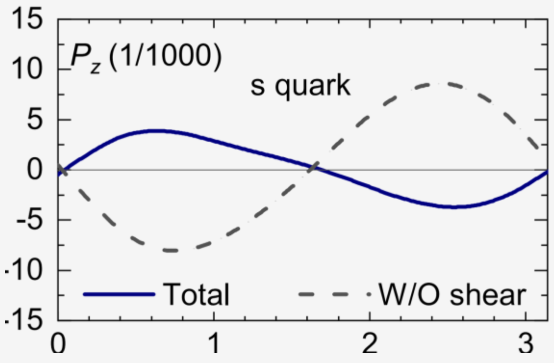
$$\mathcal{S}^{\mu}_{\text{EB}}(\mathbf{p}) = \frac{\hbar}{4m_\Lambda N}\int d\Sigma\cdot p f_V^{(0)}(1-f_V^{(0)})\left(\frac{1}{(u\cdot p)T}\epsilon^{\mu\nu\alpha\beta}p_{\alpha}u_{\beta}E_{\nu}+\frac{B^{\mu}}{T}\right),$$

EM Field

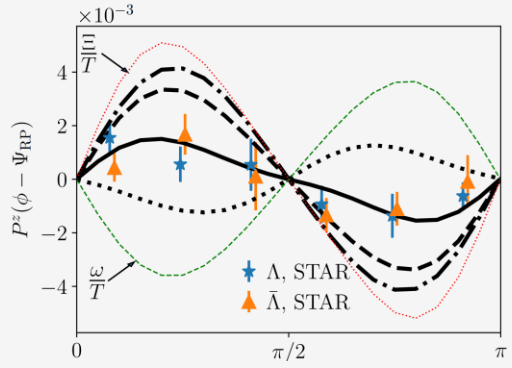
Hidaka, Pu, and Yang, PRD 97, 016004 (2018) ; Liu, Yin, PRD 104, 054043 (2021) ;Becattini, Buzzegoli, Palermo, PLB 820, 136519 (2021) ; Liu, Yin, JHEP 07,188 (2021); CY, Pu, and Yang, PRC 04, 064901(2021)

Shear induced polarization

➤ **Hydrodynamic contribution to the local spin polarization**

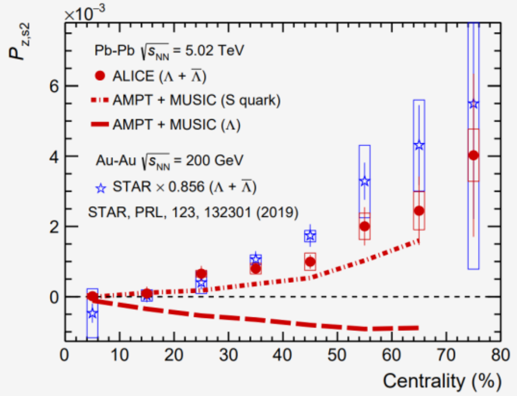


Fu, et al. PRL 127, 142301

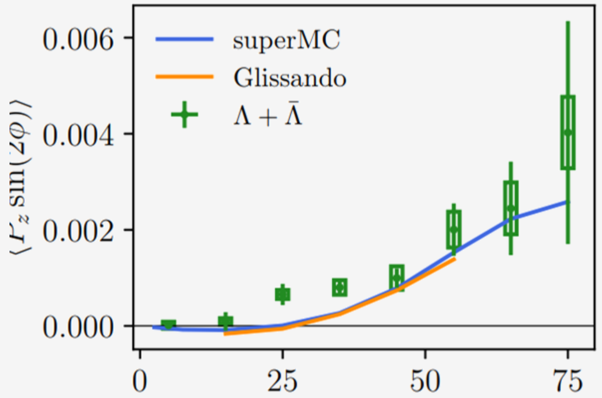


Becattini et al, PRL 127, 272302

Also see: CY, Pu, and Yang, PRC 104, 064901.
Ryu, Jupic, and Shen, PRC 104, 054908
Wu, CY, Qin, and Pu, PRC 105 6, 064909
Fu, Pang, Song, and Yin, (2022), 2201.12970.
……



ALICE, PRL 128, 172005(2022)



Palermo, et al. EPJC 84 9, 920 (2024)

Considering SIP under some assumptions, the theoretical calculations qualitatively/ quantitatively agree with the experimental data at RHIC top energy and 5.02 TeV Pb+Pb collision.

Outline

- Introduction
- Spin Polarization Vector
- **Global and local polarization at AA systems**
- Spin polarization at pA system
- Summary

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:

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

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

- **Setup**

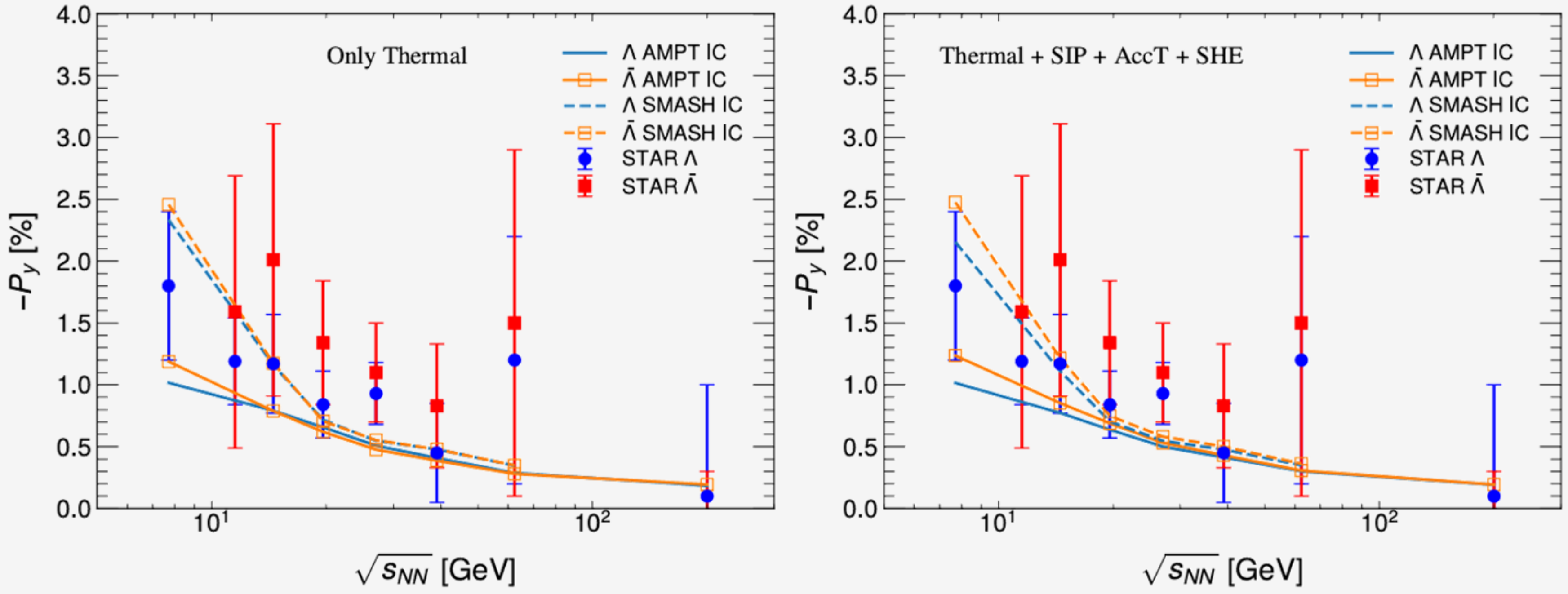
Initial condition: AMPT, SMASH
Freeze out condition : e<0.4GeV/fm^3
Equation of State: NEOS BQS

Pang, Wang, and Wang, PRC 86, 024911 .
Wu, Qin, Pang, and Wang, PRC 105, 034909.

Global Polarization

➢ Thermal vorticity only

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



Wu, CY, Qin, and Pu, PRC 105 6, 064909 (2022)

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

Local Polarization

➢ **RHIC Beam Energy Scan**

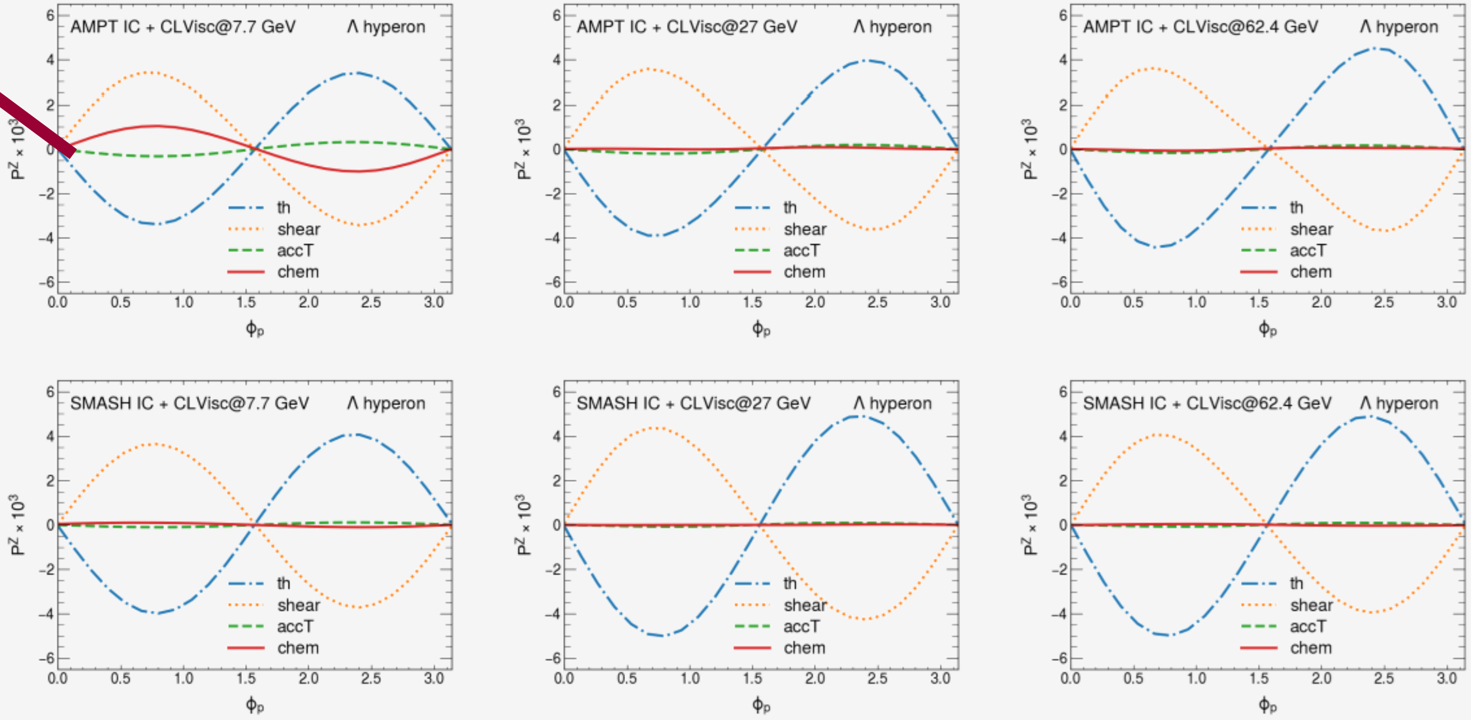
$$\mathcal{J}_5^{\mu} = \mathcal{J}^{\mu}_{\text{thermal}} + \mathcal{J}^{\mu}_{\text{shear}} + \mathcal{J}^{\mu}_{\text{accT}} + \mathcal{J}^{\mu}_{\text{chemical}}$$

7.7 GeV　　27 GeV　　62.4 GeV

Chemical Gradient

AMPT

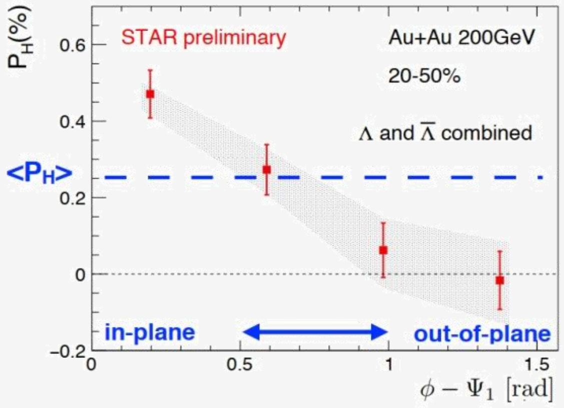
SMASH



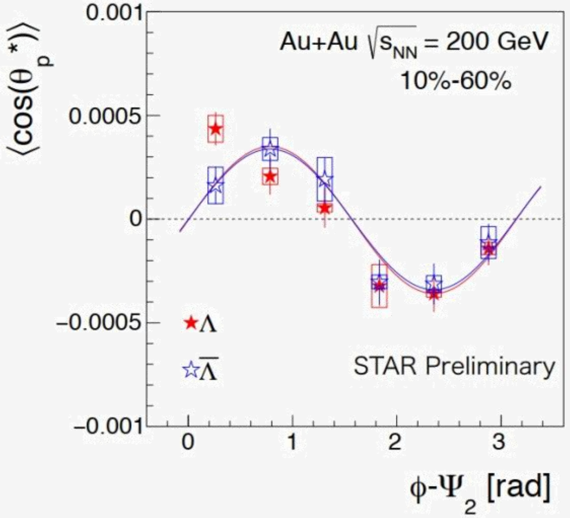
X.Y. Wu, CY, G.Y. Qin, S. Pu Phys. Rev. C 105, 064909

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

$P_{2,y}$ and $P_{2,z}$ across BES

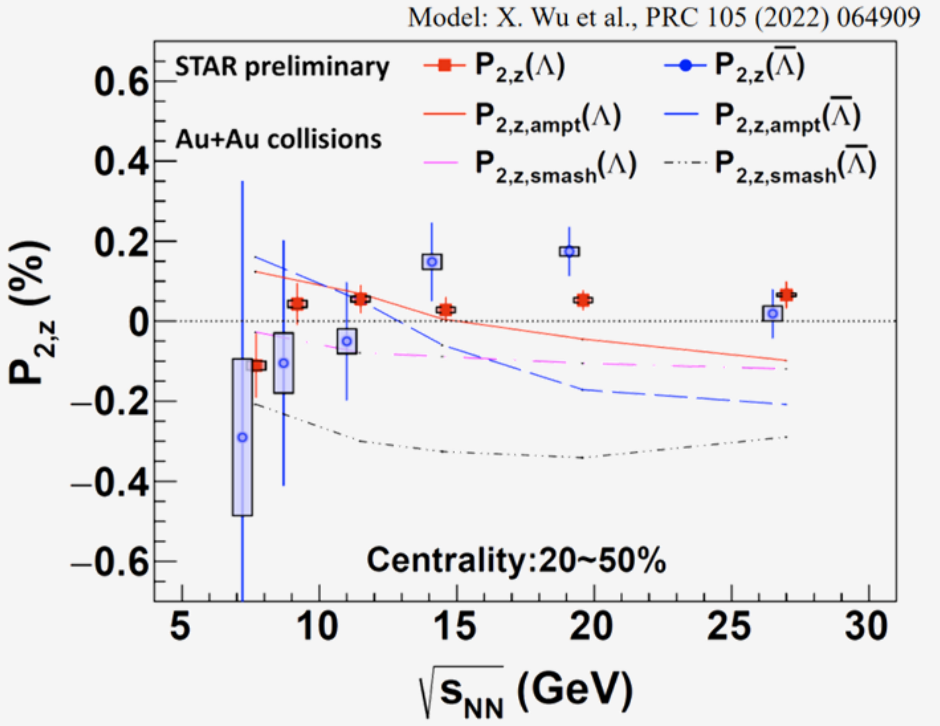


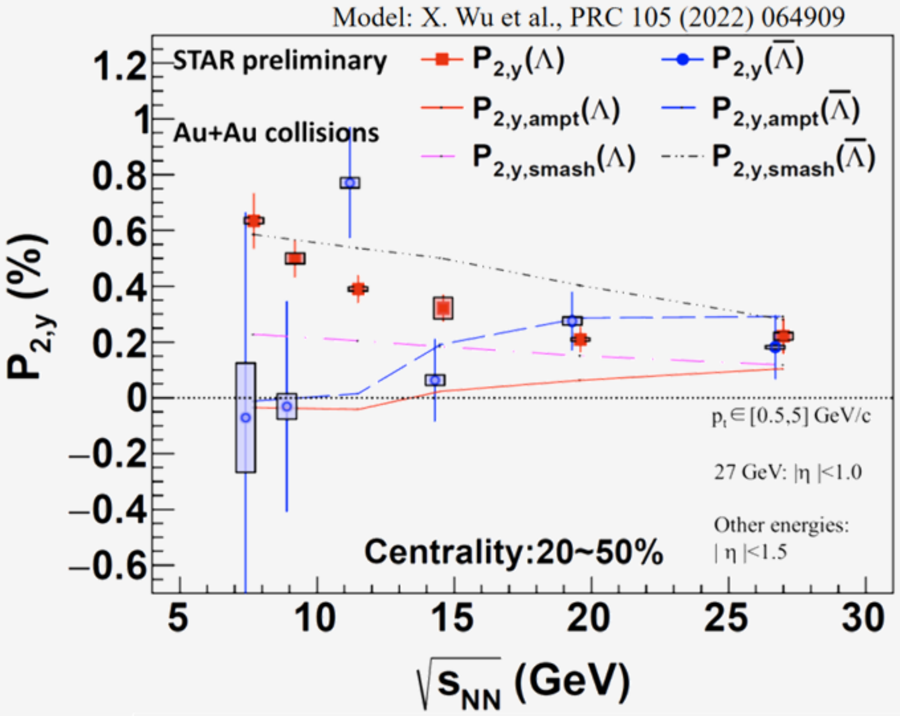
$$P_{2,y} \equiv \langle P_y \cos[2(\phi_\Lambda - \Psi_2)]\rangle$$



$$P_{2,z} \equiv \langle P_z \sin[2(\phi_\Lambda - \Psi_2)]\rangle$$

$P_{2,y}$ and $P_{2,z}$ across BES



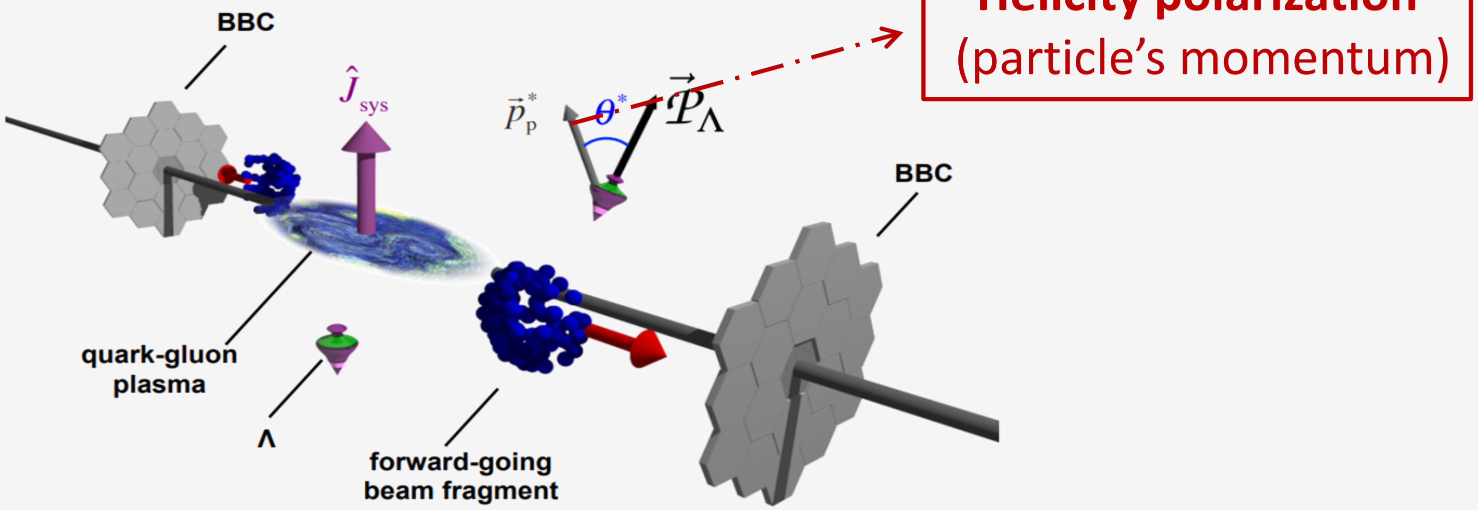


Qiang Hu, Talks on SQM 2024

- **The sign of the spin polarization will change at the lower collision energy**
- **P2,y of Λ increase with decreasing energy and current models cannot describe the results**

Local 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.

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

Becattini, Buzzegoli, Palermo, and Prokhorov, PLB 826, 136909 (2022)
Gao, PRD 104, 076016 (2022)

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.

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

➢ Kinetic vorticity

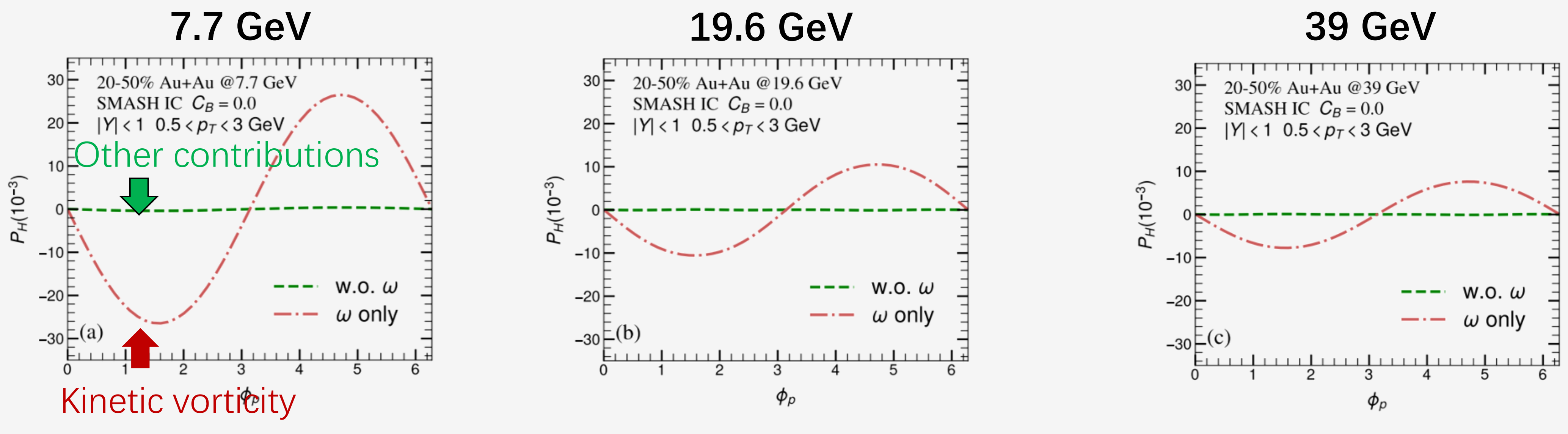
$$
\begin{aligned}
S^h_{\nabla T}(\mathbf{p}) &= \int d\Sigma^\sigma F_\sigma \frac{p_0}{T^2} \widehat{\mathbf{p}} \cdot (\mathbf{u} \times \nabla T), \\
S^h_{\omega}(\mathbf{p}) &= \int d\Sigma^\sigma F_\sigma \frac{p_0}{T} \widehat{\mathbf{p}} \cdot \boldsymbol{\omega},
\end{aligned}
$$

Kinetic vorticity

$\boldsymbol{\omega} \rightarrow \nabla \times \mathbf{u}$

Numerical results

➢ Helicity polarization across RHIC-BES energies



- ➢ **Helicity polarization induced by kinetic vorticity dominates at BES energies**
- ➢ **Helicity polarization induced by other contributions are almost vanishing**
- ➢ **A possible way to probe the fine vorticity structure of the QGP by measuring helicity polarization.**

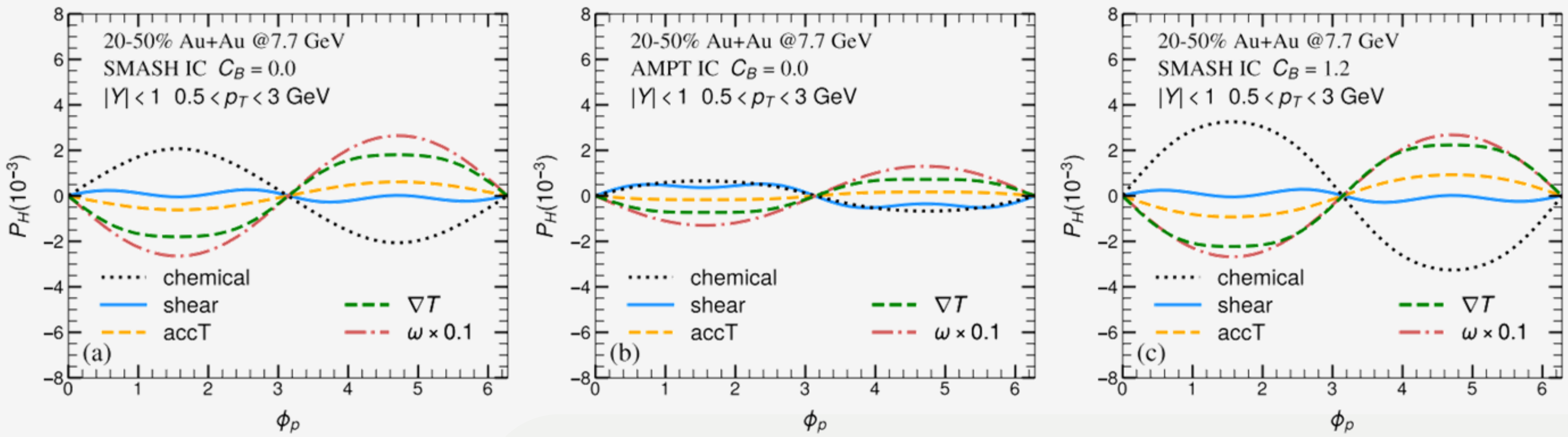
CY , X.Y. Wu, D.-L. Yang, J.H. Gao, S. Pu, G.Y. Qin, 2304.08777.

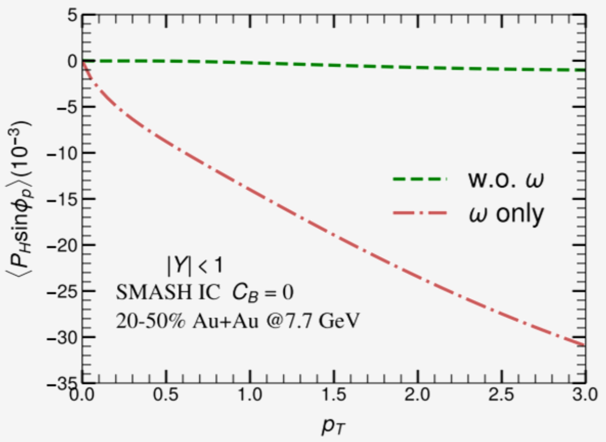
Numerical results

➢ 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.**

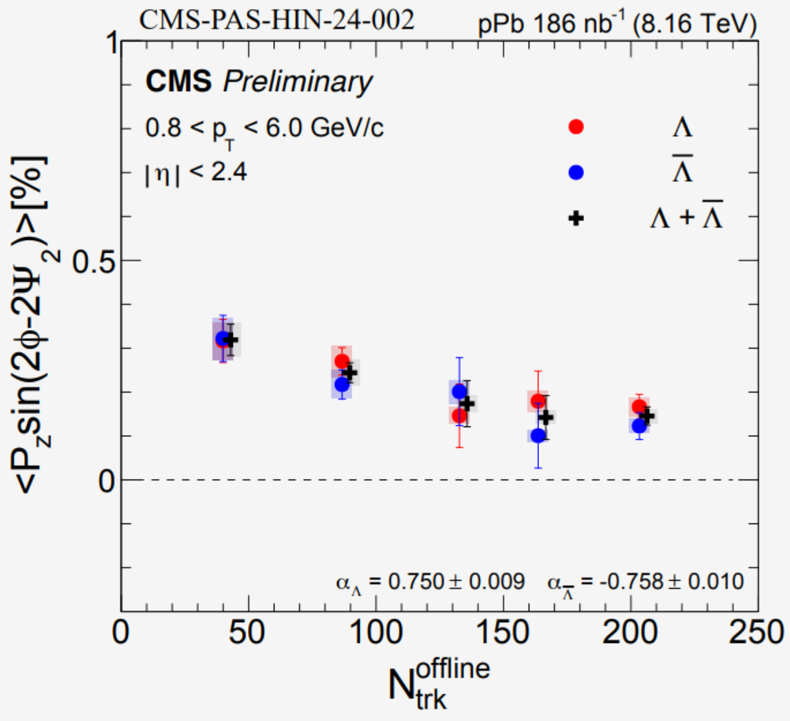
➢ **A possible way to probe the fine vorticity structure of the QGP by measuring helicity polarization.**

Outline

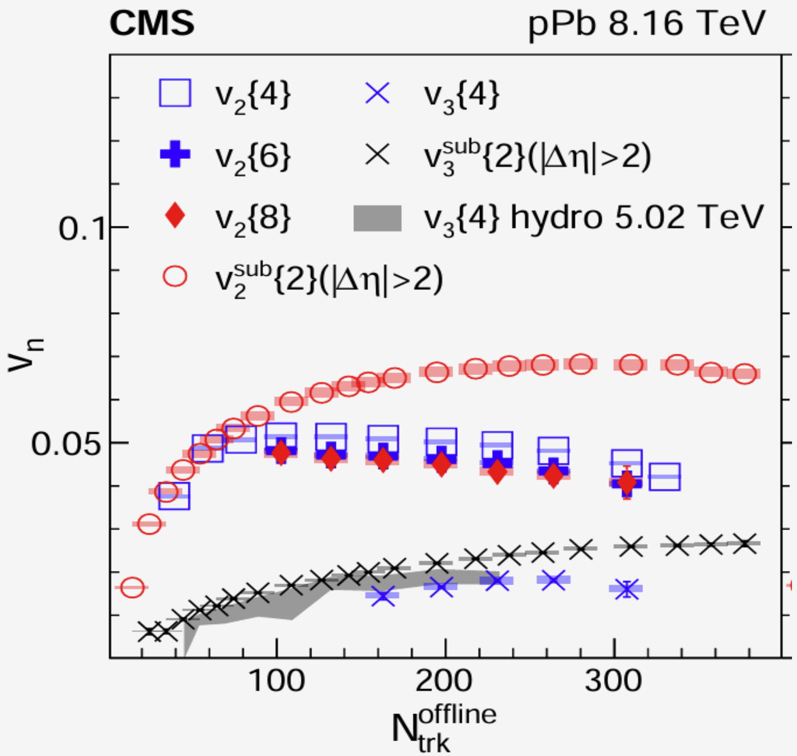
- Introduction
- Spin Polarization Vector
- Global and local polarization at AA systems
- **Spin polarization at pA system**
- Summary

CMS Results

- **Polarization along the beam direction in p+Pb collisions**



CMS, arXiv:2502.07898 (2025)

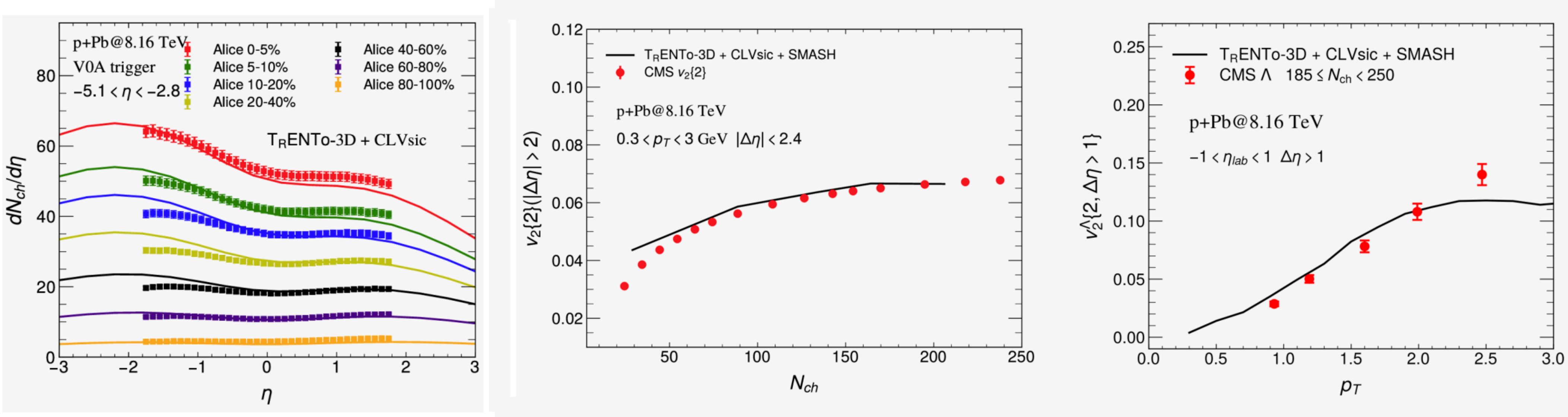


CMS,PRC,101, 014912 (2020)

- **The magnitude of polarization is the same order of magnitude as that in AA collisions**
- **Its dependence on multiplicity is inconsistent with that of v2**

Multiplicity and v2

➢Bulk properties



Multiplicity intervals	$\langle N_{ch}\rangle_{exp}$	$\langle N_{ch}\rangle_{CLVisc}$
[185,250)	203.3	204.2
[150,185)	163.6	164.5
[120,150)	132.7	133.57
[60,120)	86.7	87.7
[3,60)	40	29.3

- **Current parameters can have a good description of the multiplicity of charged particles and elliptic flow for Λ hyperons**

Spin Polarization Vector

We follow the modified Cooper-Frye formula to compute the polarization pseudo-vector including the contribution from thermal vorticity and thermal shear tensor and neglect the spin hall effect:

$$\mathcal{S}^{\mu}(\mathbf{p}) = \mathcal{S}^{\mu}_{\text{thermal}}(\mathbf{p}) + \mathcal{S}^{\mu}_{\text{th-shear}}(\mathbf{p}),$$

$$\mathcal{S}^{\mu}_{\text{thermal}}(\mathbf{p}) = \hbar \int d\Sigma \cdot \mathcal{N}_p \frac{1}{2} \epsilon^{\mu\nu\alpha\beta} p_\nu \varpi_{\alpha\beta},$$

$$\mathcal{S}^{\mu}_{\text{th-shear}}(\mathbf{p}) = \hbar \int d\Sigma \cdot \mathcal{N}_p \frac{\epsilon^{\mu\nu\alpha\beta} p_\nu n_\beta}{(n \cdot p)} p^\sigma \xi_{\sigma\alpha},$$

thermal vorticity: $$\varpi_{\alpha\beta} = \frac{1}{2}\left[\partial_\alpha\left(\frac{u_\beta}{T}\right) - \partial_\beta\left(\frac{u_\alpha}{T}\right)\right],$$

thermal shear tensor: $$\xi_{\alpha\beta} = \frac{1}{2}\left[\partial_\alpha\left(\frac{u_\beta}{T}\right) + \partial_\beta\left(\frac{u_\alpha}{T}\right)\right]$$

Different scenarios

We consider three different scenarios:

- **Λ equilibrium :**

  It is assumed that Λ hyperons reach the local (thermal) equilibrium at the freeze-out hyper-surface

- **s quark equilibrium:**

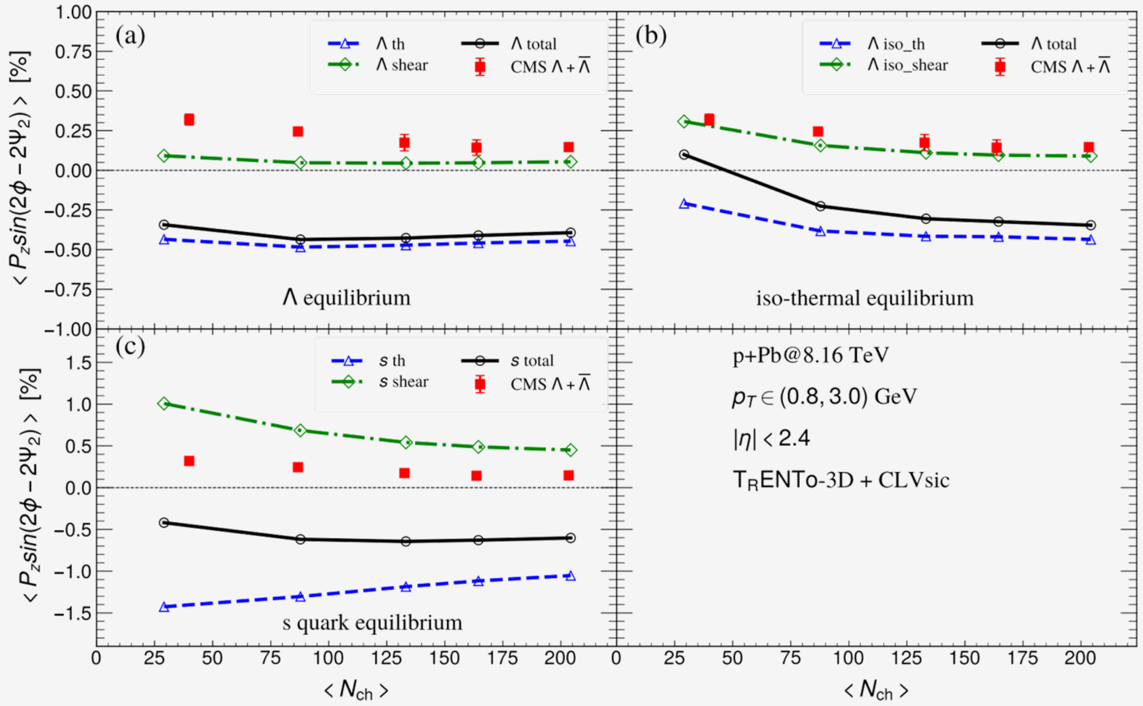
  The spin of Λ hyperons is assumed to be carried by the constituent s quark. We take the s quark's mass instead of Λ's mass in the simulation

- **Iso-thermal equilibrium:**

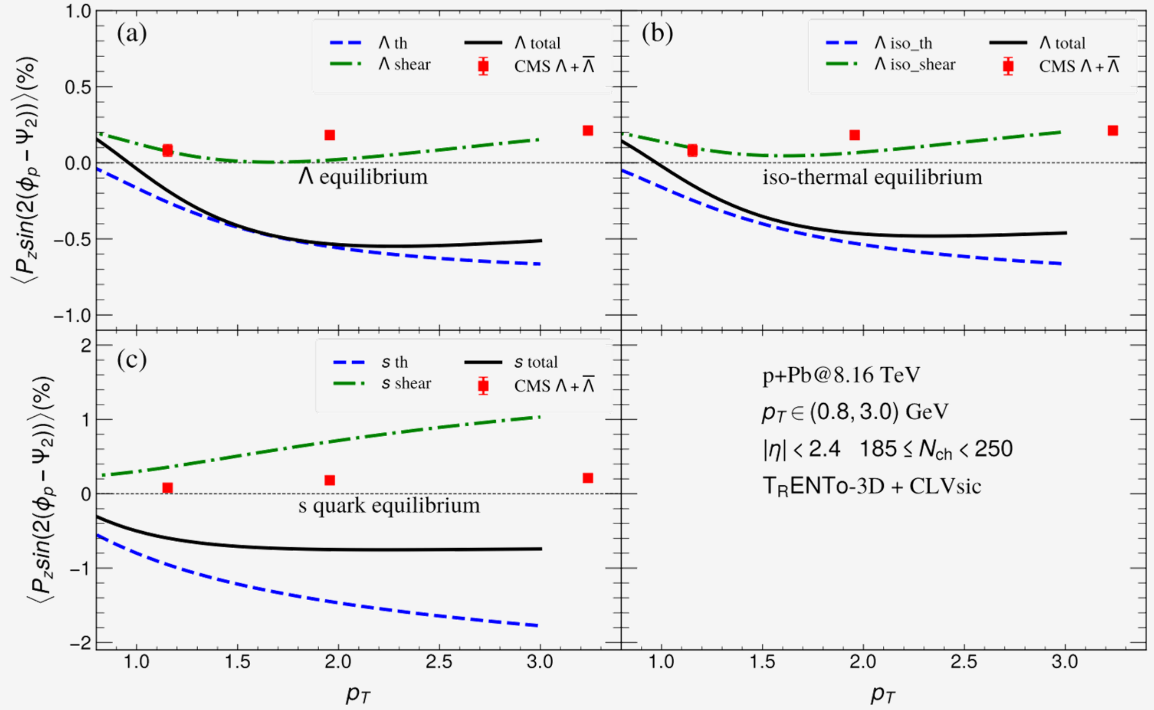
  The temperature of the system at the freeze-out hyper-surface is assumed to be constant. The time unit vector is taken as fluid velocity for simplicity.

$$\varpi_{\alpha\beta} \to (\partial_\alpha u_\beta - \partial_\beta u_\alpha)/(2T)$$
$$\xi_{\alpha\beta} \to (\partial_\sigma u_\alpha + \partial_\alpha u_\sigma)/(2T)$$

Multiplicity (centrality) dependence



Multiplicity dependence



p_T dependence

- Shear induced polarization always gives a positive contribution
- Polarization induced by the thermal vorticity is negative
- The results in the three scenarios are inconsistent with the data from the LHC-CMS experiments.

Outline

- Introduction
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Summary

➢ Spin Polarization in Au+Au collision

- ➢ The influence of these new effects on the global polarization is small.
- ➢ Shear induced polarization always give a positive contribution.
- ➢ The spin hall effect plays an important role in the low energy collisions.
- ➢ Helicity polarization is a possible way to probe the fine vortical structure of QGP.

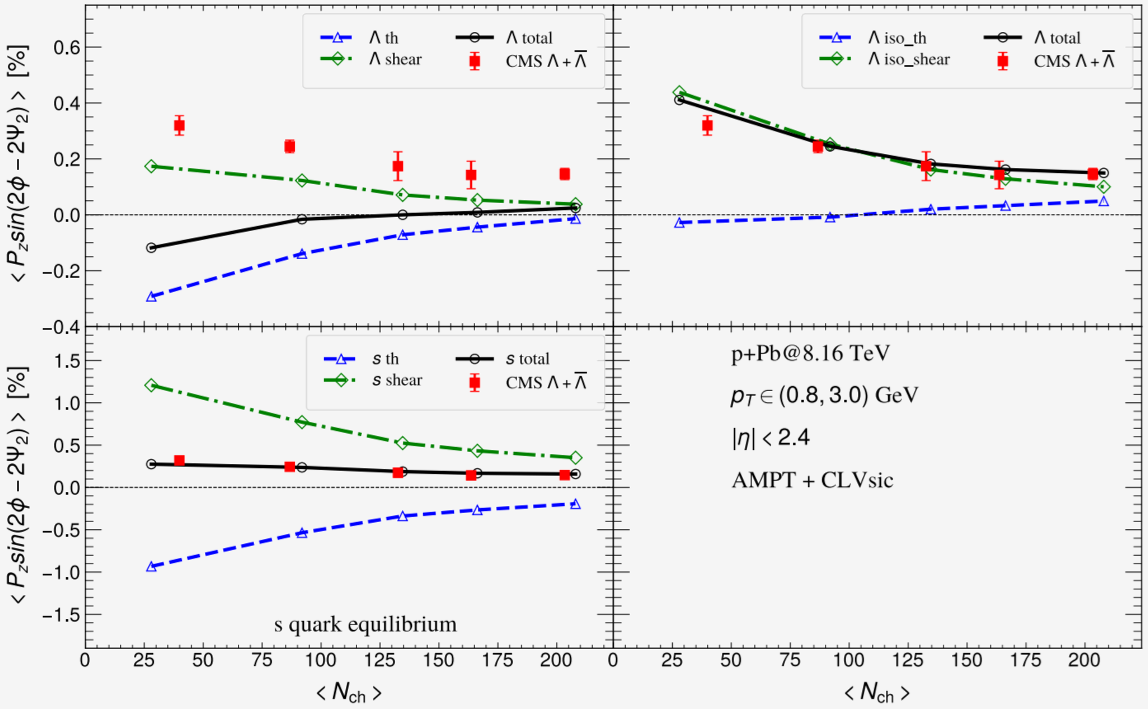
➢ Spin Polarization in p+Pb collision

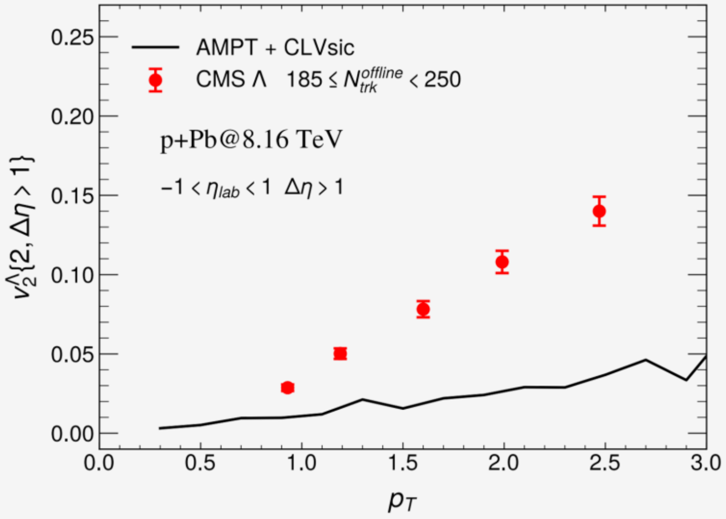
- ➢ Shear induced polarization always gives a positive contribution.
- ➢ Polarization induced by the thermal vorticity is negative.
- ➢ The results from hydrodynamics are inconsistent with the data from CMS.
- ➢ New effects need to be considered in the polarization at pPb collisions.

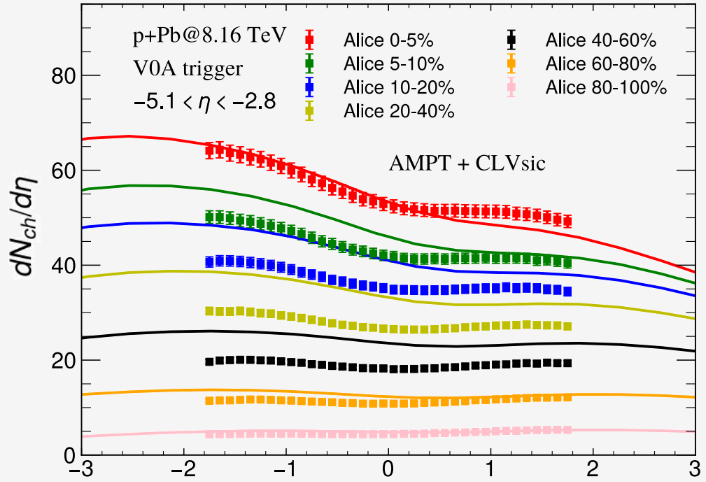
中国科学技术大学
University of Science and Technology of China

Thanks for your time !

Test for AMPT initial conditions

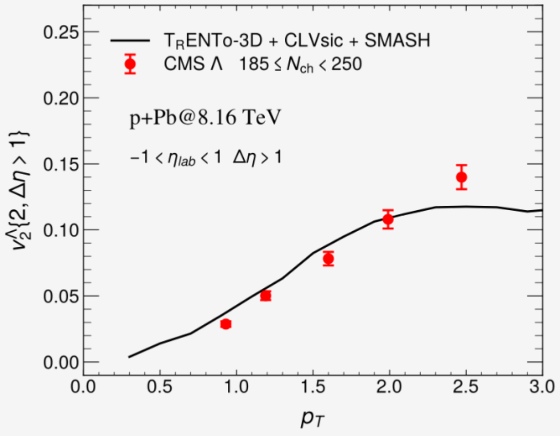


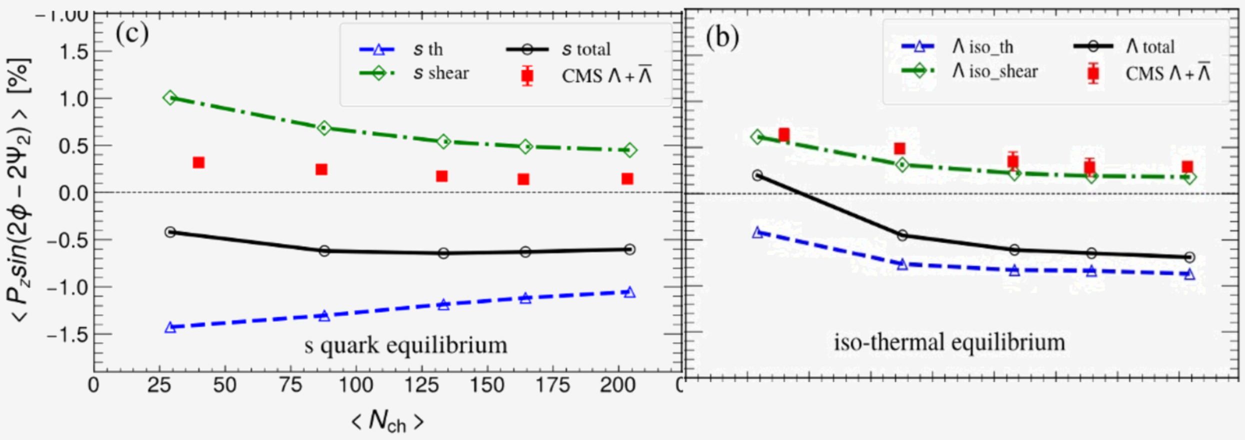




- **The parameters can describe spin polarization at the s quark equilibrium and iso-thermal equilibrium can not fit the multiplicity of charged particles and v2 of Λ.**

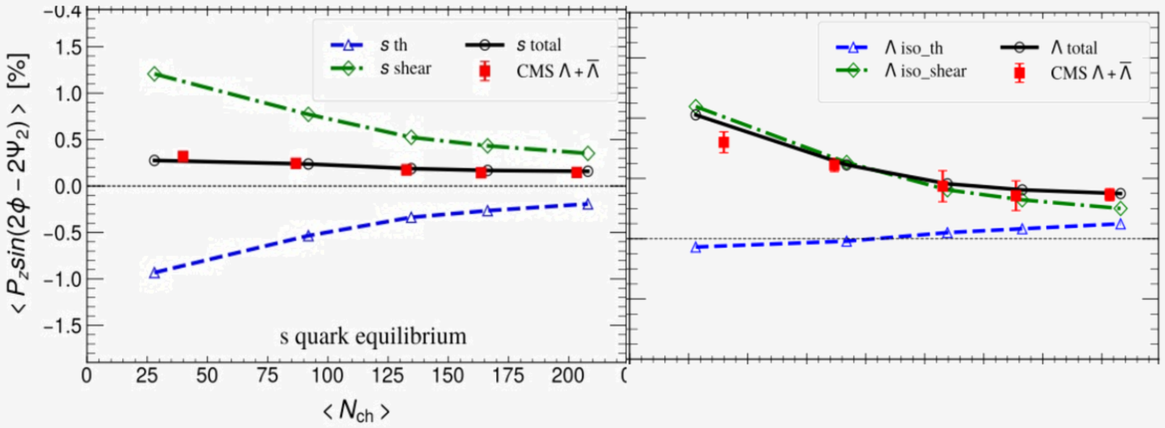
Different initial conditions

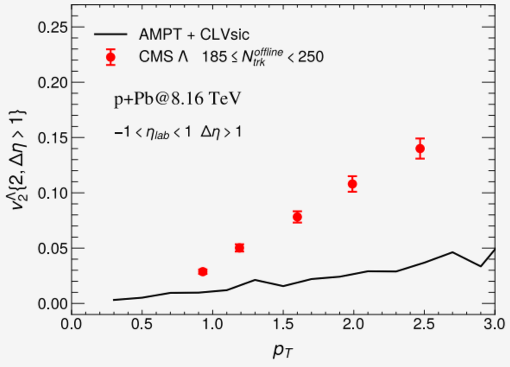




The P2z of Λ hyperons is not only induced by the v2 in the p+Pb collisions.

New effects need to be considered in the polarization at p+Pb collisions.





Questions

$$\mathcal{J}^\mu_{\text{thermal}} = a\frac{1}{2}\epsilon^{\mu\nu\alpha\beta}p_\nu\partial_\alpha\frac{u_\beta}{T},$$

$$\mathcal{J}^\mu_{\text{shear}} = -a\frac{1}{(u\cdot p)T}\epsilon^{\mu\nu\alpha\beta}p_\alpha u_\beta p^\sigma\partial_{<\sigma}u_{\nu>}$$

$$\mathcal{J}^\mu_{\text{accT}} = -a\frac{1}{2T}\epsilon^{\mu\nu\alpha\beta}p_\nu u_\alpha\left(Du_\beta-\frac{1}{T}\partial_\beta T\right).$$

$$\mathcal{J}^\mu_{\text{chemical}} = a\frac{1}{(u\cdot p)}\epsilon^{\mu\nu\alpha\beta}p_\alpha u_\beta\partial_\nu\frac{\mu}{T}$$

$$\mathcal{J}^\mu_{\text{EB}} = a\frac{1}{(u\cdot p)}\epsilon^{\mu\nu\alpha\beta}p_\alpha u_\beta E_\nu,$$

⇒ SIP

⇒ Fluid acceleration

⇒ SHE

- How about hydrodynamic contributions to spin polarization at RHIC-BES energies and p+Pb collisions?

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

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

Bulk Viscosity

- ## CLVisc Framework

The subsequent evolution of the system is simulated by the 3+1D CLVisc hydrodynamics model.
We just focus on the energy-momentum conservation equations

$$\partial_\mu T^{\mu\nu} = 0,$$

$$\tau_\Pi D\Pi + \Pi = -\zeta\theta - \delta_{\Pi\Pi}\Pi\theta + \lambda_{\Pi\pi}\pi^{\mu\nu}\sigma_{\mu\nu}$$

$$\tau_\pi \Delta^{\mu\nu}_{\alpha\beta} D\pi^{\alpha\beta} + \pi^{\mu\nu} = \eta_v\sigma^{\mu\nu} - \delta_{\pi\pi}\pi^{\mu\nu}\theta + \tau_{\pi\pi}\pi^{\lambda\langle\mu}\sigma^{\nu\rangle}_{\lambda} + \varphi_1\pi^{\langle\mu}_{\alpha}\pi^{\nu\rangle\alpha}.$$

We use the temperature dependent shear and bulk viscosity given by Bayesian parameter estimation in Phys. Rev. C 94, 024907 (2016) .
The equations of state are provided by the HotQCD collaboration and freeze-out temperature T_f = 154 MeV.