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Helicity polarization in heavy ion collisions at RHIC-BES energies

Di-Lun Yang

Institute of Physics, Academia Sinica

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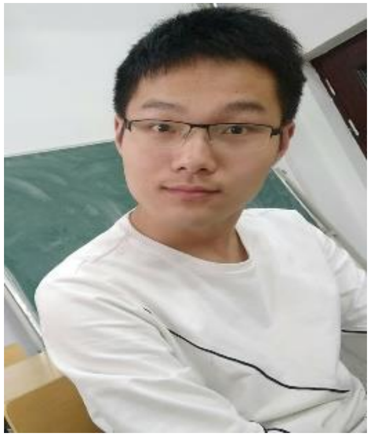
References

- Local spin polarization and helicity polarization :

Cong Yi, Shi Pu, DY, PRC 104, 064901(2021), arXiv:2106.00238

Cong Yi, Shi Pu, Jian-Hua Gao, DY, PRC 105, 044911 (2022), arXiv:2112.15531

Cong Yi, Xiang-Yu Wu, DY, Jian-Hua Gao, Shi Pu, Guang-You Qin, PRC 109, L011901 (2024), arXiv:2304.08777



Cong Yi
(USTC)

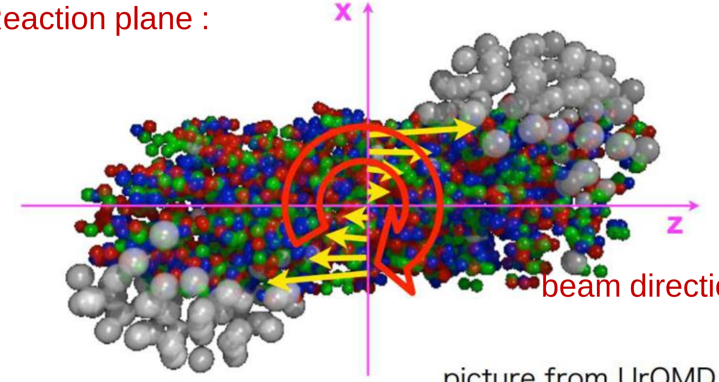
Shi Pu
(USTC)

Jian-Hua Gao
(Shandong Univ.)

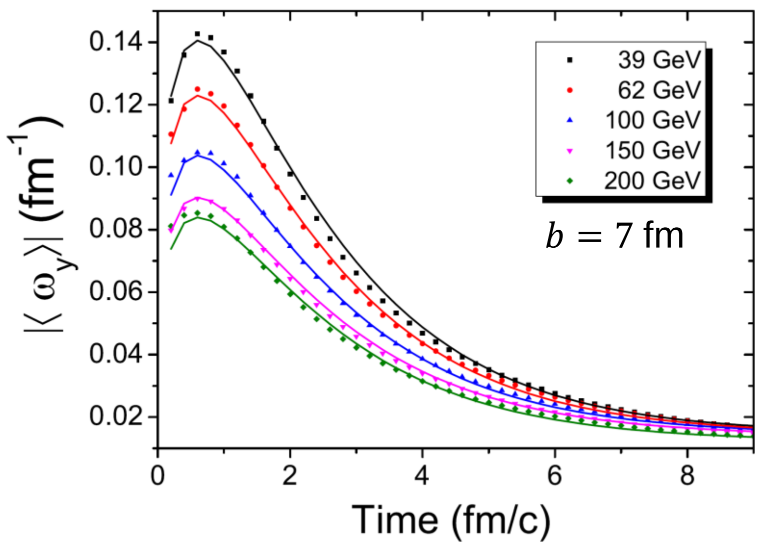
Subatomic swirls

- Strong vortical fields in HIC :

Reaction plane :



Y. Jiang, Z.-W. Lin, J. Liao, PRC 94, 044910 (2016)
see also W.-T. Deng and X.-G. Huang, PRC 93, 064907 (2016)



❖ Angular momentum (AM) to vorticity :

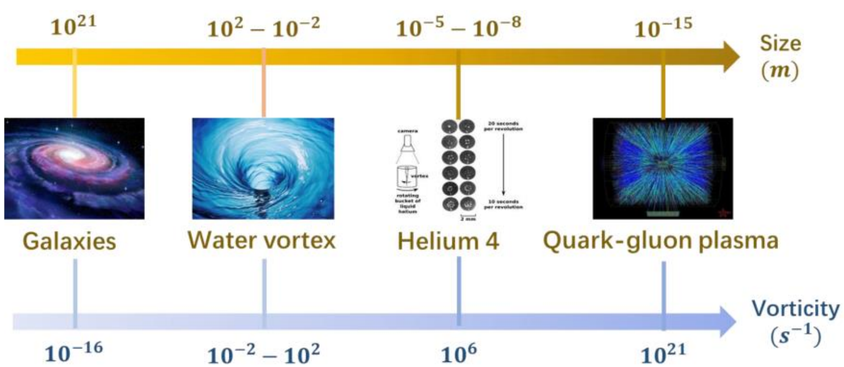
$$\mathbf{L} = \frac{1}{2}\int d^3\mathbf{r}\epsilon|\mathbf{r}|^2(1-\hat{\boldsymbol{\omega}}\cdot\hat{\mathbf{r}})\boldsymbol{\omega},$$

$$\boldsymbol{\omega} = \nabla \times \mathbf{v} = \text{const.}$$ kinetic vorticity

ϵ : energy density

❖ AM to spin polarization?

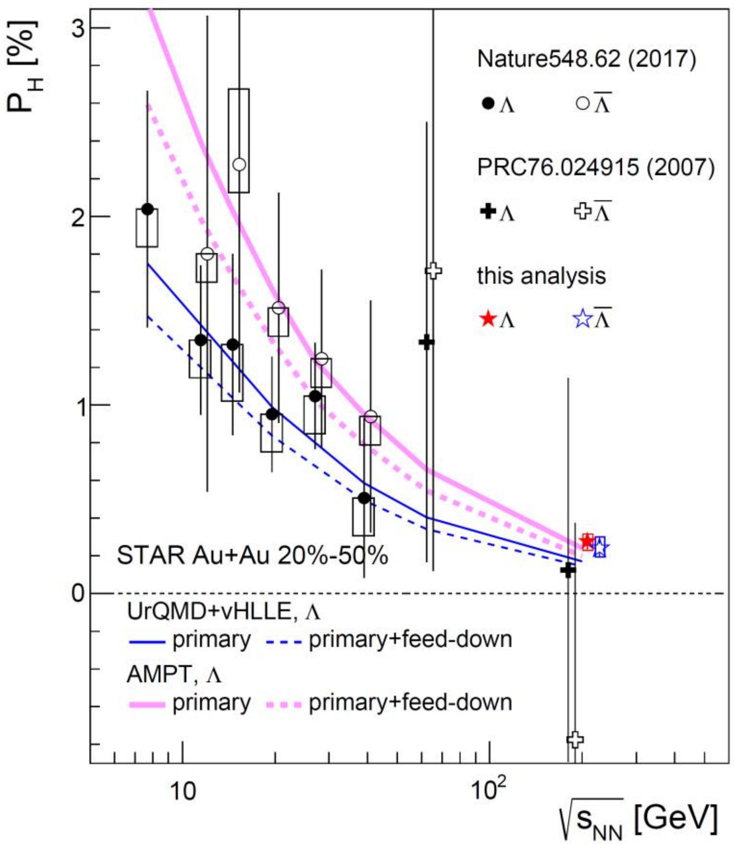
Z.-T. Liang and X.-N. Wang, PRL. 94, 102301 (2005)



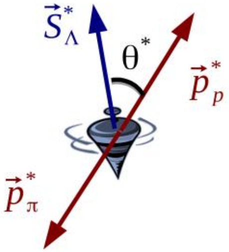
X.-G. Huang, QM 19

Global Λ polarization in HIC

- Spin polarization of Λ hyperons can be measured through the weak decay.
- Global polarization of Λ hyperons :



L. Adamczyk et al. (STAR), Nature 548, 62 (2017)



Killing condition

❖ In global equilibrium : $\partial_\mu \beta_\nu + \partial_\nu \beta_\mu = 0$

$$\mathcal{P}^\mu(\boldsymbol{p}) = \frac{1}{8m} \epsilon^{\mu\nu\rho\sigma} p_\nu \frac{\int d\Sigma \cdot p\,\omega_{\rho\sigma} f_{\text{eq}}(1 - f_{\text{eq}})}{\int d\Sigma \cdot p f_{\text{eq}}},$$

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

thermal vorticity $(\beta^\mu \equiv u^\mu / T)$

F. Becattini, V. Chandra, L. Del Zanna, E. Grossi, Ann. Phys. 338, 32 (2013)

R. Fang, L.-G. Pang, Q. Wang, X.-N. Wang, PRC 94, 024904 (2016)

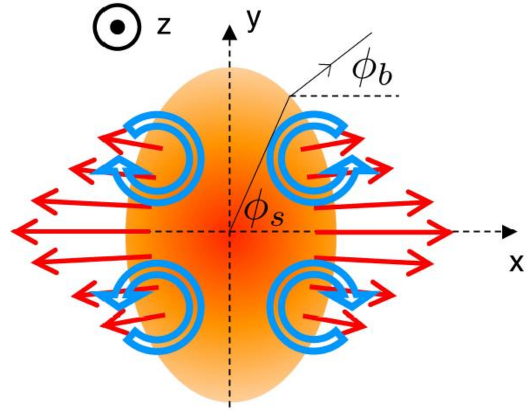
❖ Indication of strong (kinetic) vorticity :

$$P_{\Lambda(\bar{\Lambda})} \simeq \frac{1}{2}\frac{\omega}{T} \pm \frac{\mu_\Lambda B}{T} \Longrightarrow \omega \sim 10^{22}\,\text{s}^{-1}$$

F. Becattini et al., PRC95, 054902 (2017)

Local (longitudinal) polarization : a sign problem

- Local vorticity from transverse expansion
  - ⇨ longitudinal vorticity & polarization



- A "sign problem" for longitudinal polarization

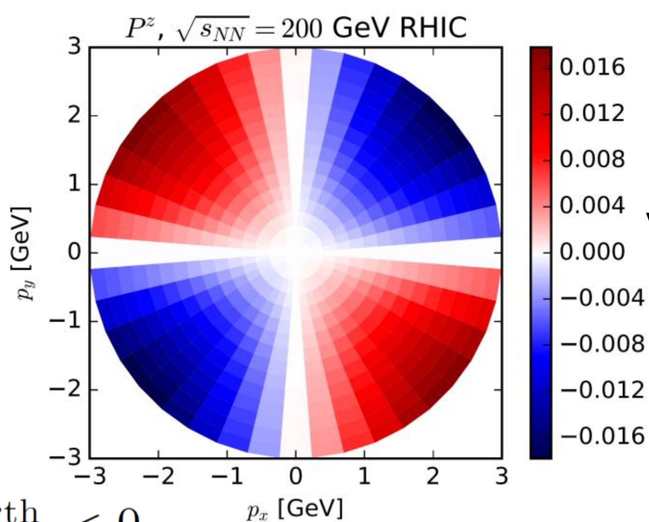
F. Becattini, I. Karpenko, PRL 120, 012302 (2018).

J. Adam et al. (STAR, PRL. 123, 132301 (2019)

Spin harmonics :

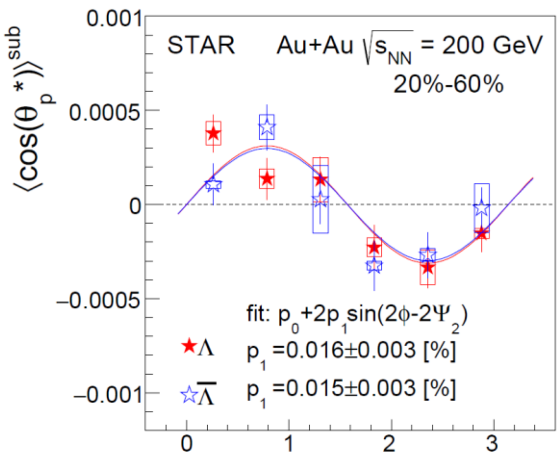
$$\frac{dP^z}{2\pi d\phi} = f_{z,0} + 2 f_{z,2} \sin(2\phi)$$

⇨



$f^{\text{th}}_{z,2} < 0$

v.s.



$f^{\text{exp}}_{z,2} > 0$

(same structure, opposite signs!)

Go beyond global equilibrium

- The assumption for global equilibrium may be too naïve.
  Killing cond. needs not be satisfied : $"\partial_\nu(u_\rho/T)+\partial_\rho(u_\nu/T)\neq 0"$
- A more general form for the spin polarization spectrum?
- Relativistic angular momentum (canonical pseudogauge) :

$$M_C^{\lambda\mu\nu}=M_S^{\lambda\mu\nu}+M_O^{\lambda\mu\nu},$$
$$M_S^{\lambda\mu\nu}=-\frac{1}{2}\epsilon^{\lambda\mu\nu\rho}\bar{\psi}\gamma_\rho\gamma_5\psi=-\frac{1}{2}\epsilon^{\lambda\mu\nu\rho}J_{5\rho},$$
$$M_O^{\lambda\mu\nu}=\frac{i}{2}\bar{\psi}\gamma^\lambda\left(x^\mu\overleftrightarrow{\partial}^\nu-x^\nu\overleftrightarrow{\partial}^\mu\right)\psi=x^\mu T_C^{\lambda\nu}-x^\nu T_C^{\lambda\mu}$$

spin-orbit int.

spin ⇒ $-\frac{\hbar}{2}\epsilon^{\lambda\mu\nu\rho}\partial_\lambda J_{5\rho}+2T_A^{\mu\nu}=0$ orbit

- Experimental observables are spectra :

e.g., from Wigner functions (with ambiguity)

DY, PRD 98, 076019 (2018)

particle number spectrum : $E_p\frac{dN}{d^3p}=\int d\Sigma_\lambda\mathcal{N}^\lambda(p,x)$

extension to phase space : $J_5^\mu\to\mathcal{J}_5^\mu(p,X),\ T_C^{\mu\nu}\to\mathcal{T}_C^{\mu\nu}(p,X).$

Pauli–Lubanski pseudovector : $W^\mu(p)=-\frac{1}{2m}\epsilon^{\mu\nu\alpha\beta}p_\nu\int d\Sigma_\lambda M^{\lambda\alpha\beta}(p,x)$

⇒ polarization spectrum : $\mathcal{P}^\mu(p)=\frac{W^\mu(p)}{E_p\frac{dN}{d^3p}}=\frac{\int d\Sigma\cdot p\mathcal{J}_5^\mu(p,x)}{2m\int d\Sigma\cdot\mathcal{N}(p,x)}$

Spin polarization near local equilibrium

- Dynamical spin polarization from spin transport theories
- Simplified strategy : studying “near equilibrium” spin polarization spectra

➢ Polarization : (from chiral kinetic theory for massless fermions)

$$\mathcal{J}^{\mu}_{5} = \boxed{\mathcal{J}^{\mu}_{\rm thermal} + \mathcal{J}^{\mu}_{\rm shear} + \mathcal{J}^{\mu}_{\rm accT} + \mathcal{J}^{\mu}_{\rm chemical} + \mathcal{J}^{\mu}_{\rm EB},}$$

(+ nonequilibrium corrections, int. dep.)

local equilibrium, indep. of int.

Y. Hidaka, S. Pu, DY, PRD 97, 016004 (2018)

S. Fang, S. Pu, DY, PRD 106, 016002 (2022)

$$\mathcal{J}^{\mu}_{\rm thermal} = a\frac{1}{2}\epsilon^{\mu\nu\alpha\beta}p_{\nu}\omega_{\alpha\beta}, \quad \Rightarrow \quad J^{\mu}_{5} = \sigma_{5\omega}\omega^{\mu}$$

see the talks by S. Lin & S. Fang

$$\mathcal{J}^{\mu}_{\rm shear} = -a\frac{1}{(u\cdot p)T}\epsilon^{\mu\nu\alpha\beta}p_{\alpha}u_{\beta}p^{\sigma}\pi_{\sigma\nu},$$

$$\mathcal{J}^{\mu}_{\rm accT} = -a\frac{1}{2T}\epsilon^{\mu\nu\alpha\beta}p_{\nu}u_{\alpha}\left(u\cdot\partial u_{\beta} - \frac{1}{T}\partial_{\beta}T\right),$$

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

$$\pi_{\mu\nu} = \partial_{\mu}u_{\nu} + \partial_{\nu}u_{\mu} - u_{\mu}(u\cdot\partial)u_{\nu},$$

$$\propto \epsilon^{\mu\nu\alpha\beta}p_{\alpha}u_{\beta}\xi_{\nu} \rightarrow \epsilon^{ijk}p_{j}\xi_{k}$$

(typical structure from magnetization currents or the spin Hall effect)

$$\mathcal{J}^{\mu}_{\rm EB} = a\frac{B^{\mu}}{T} + \boxed{a\frac{1}{(u\cdot p)T}\epsilon^{\mu\nu\alpha\beta}p_{\alpha}u_{\beta}E_{\nu}}, \quad \Rightarrow \quad J^{\mu}_{5} = \sigma_{5B}B^{\mu}$$

(“naïve” extension to massive fermions : $\delta(p^2) \rightarrow \delta(p^2 - m^2)$)

C. Yi, S. Pu, DY, PRC 104, 064901(2021)

$$a = f_{\rm eq}(1 - f_{\rm eq})/4.$$

global pol. : $\mathcal{P}^{\mu} \sim \int_{Vp} d^3p\,\mathcal{P}^{\mu}(p) \sim J^{\mu}_{5}$

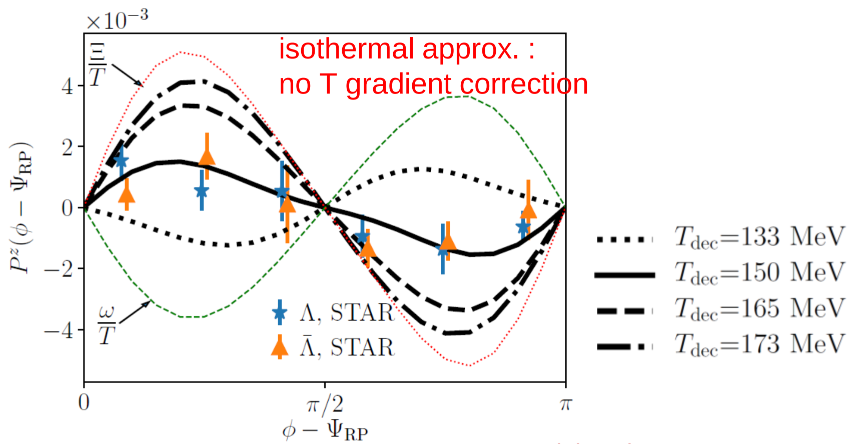
Local polarization from shear corrections

- Generalization to the massive case was also derived from the linear response theory and statistical field theory. $u^{\mu} \leftrightarrow \hat{t}^{\mu}$

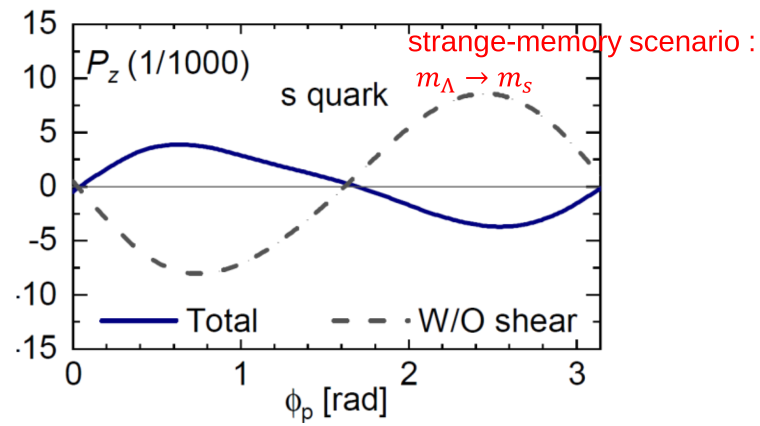
  (The same and similar results are found for arbitrary mass)

  S. Liu and Y. Yin, PRD 104, 054043 (2021)
  S. Liu, Y. Yin, JHEP 07, 188 (2021)
  F. Becattini, et al., PLB 820,136519 (2021)

- Shear corrections on the longitudinal polarization :



F. Becattini et al., PRL. 127, 272302 (2021)



B. Fu et al., PRL 127, 142301 (2021)

- Sensitive to the adopted approximations and numerical parameters

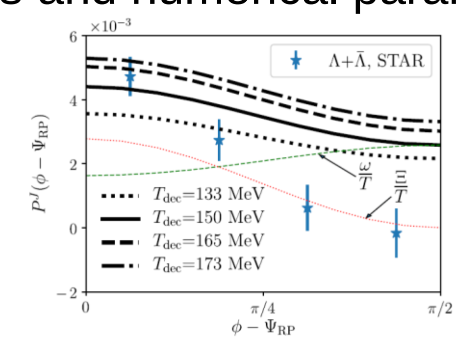
C. Yi, S. Pu, DY, PRC 104, 064901 (2021)

W. Florkowski et al., PRC 105, 064901 (2022)

S. Alzharani, S. Ryu, C. Shen, PRC 106, 014905 (2022)

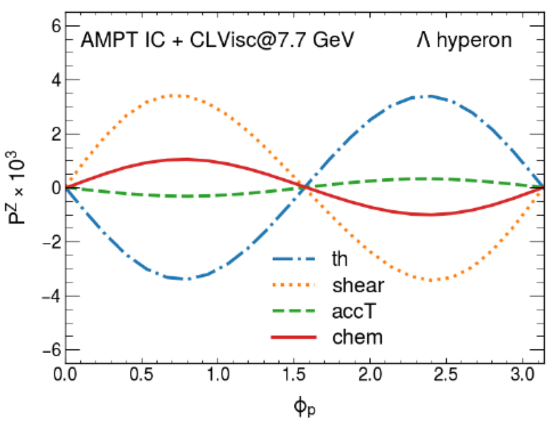
spin polarization review : F. Becattini, Rept. Prog. Phys. 85, 122301 (2022)

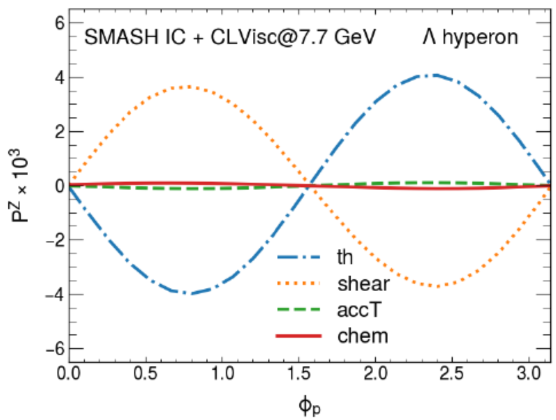
S. Liu, Y. Sun, C. M. Ko, PRL. 125, 062301 (2020)



Spin Hall effect

- Spin Hall effect on local polarization : $\mathcal{P}^{\mu}(p) \propto \epsilon^{\mu\nu\alpha\beta} p_{\alpha} u_{\beta} \partial_{\nu}(\mu/T)$
- prominent at low energy collisions but sensitive to initial conditions.





X.-Y. Wu, C. Yi, G.-Y. Qin, S. Pu, PRC 105, 064909 (2022)

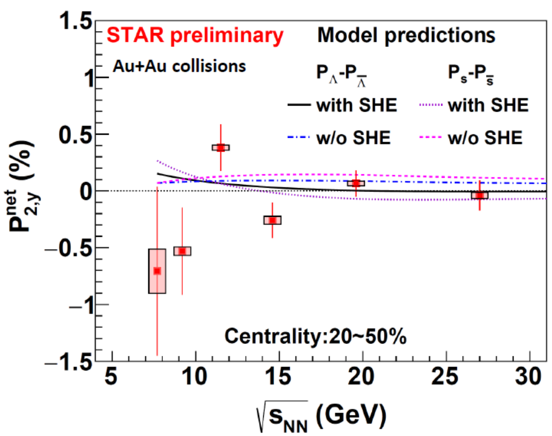
see also

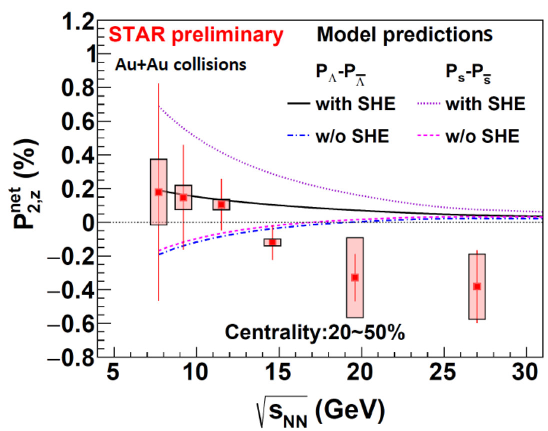
S. Ryu, V. Jupic, C. Shen, PRC 104, 054908 (2021)

B. Fu et al., arXiv:2201.12970

- Tension with experimental observations :

Q. Hu (STAR), SQM2024





Helicity polarization

- A better observable to probe the strength of local vorticity?
- Helicity polarization : $S^h = \widehat{\mathbf{p}}\cdot\mathcal{S}(\mathbf{p})$

F. Becattini et al., PLB 822 (2021) 136706
J.-H. Gao, PRD 104, 076016
C. Yi, S. Pu, J.-H. Gao, DY, PRC 105, 044911 (2022)

Local eq : $S^h_{\mathrm{hydro}}(\mathbf{p}) = S^h_{\mathrm{thermal}}(\mathbf{p}) + S^h_{\mathrm{shear}}(\mathbf{p}) + S^h_{\mathrm{accT}}(\mathbf{p}) + S^h_{\mathrm{chemical}}(\mathbf{p}),$

$$S^h_{\mathrm{thermal}}(\mathbf{p}) = \int d\Sigma^\sigma F_\sigma p_0 \epsilon^{0ijk}\widehat{p}_i\partial_j\left(\frac{u_k}{T}\right) = S^h_{\nabla T}(\mathbf{p}) + S^h_\omega(\mathbf{p}),$$

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

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

kinetic vorticity

$$S^h_{\mathrm{shear}}(\mathbf{p}) = -\int d\Sigma^\sigma F_\sigma \frac{\epsilon^{0ijk}\widehat{p}^i p_0}{(u\cdot p)T}(p^\sigma \pi_{\sigma j} u_k),$$

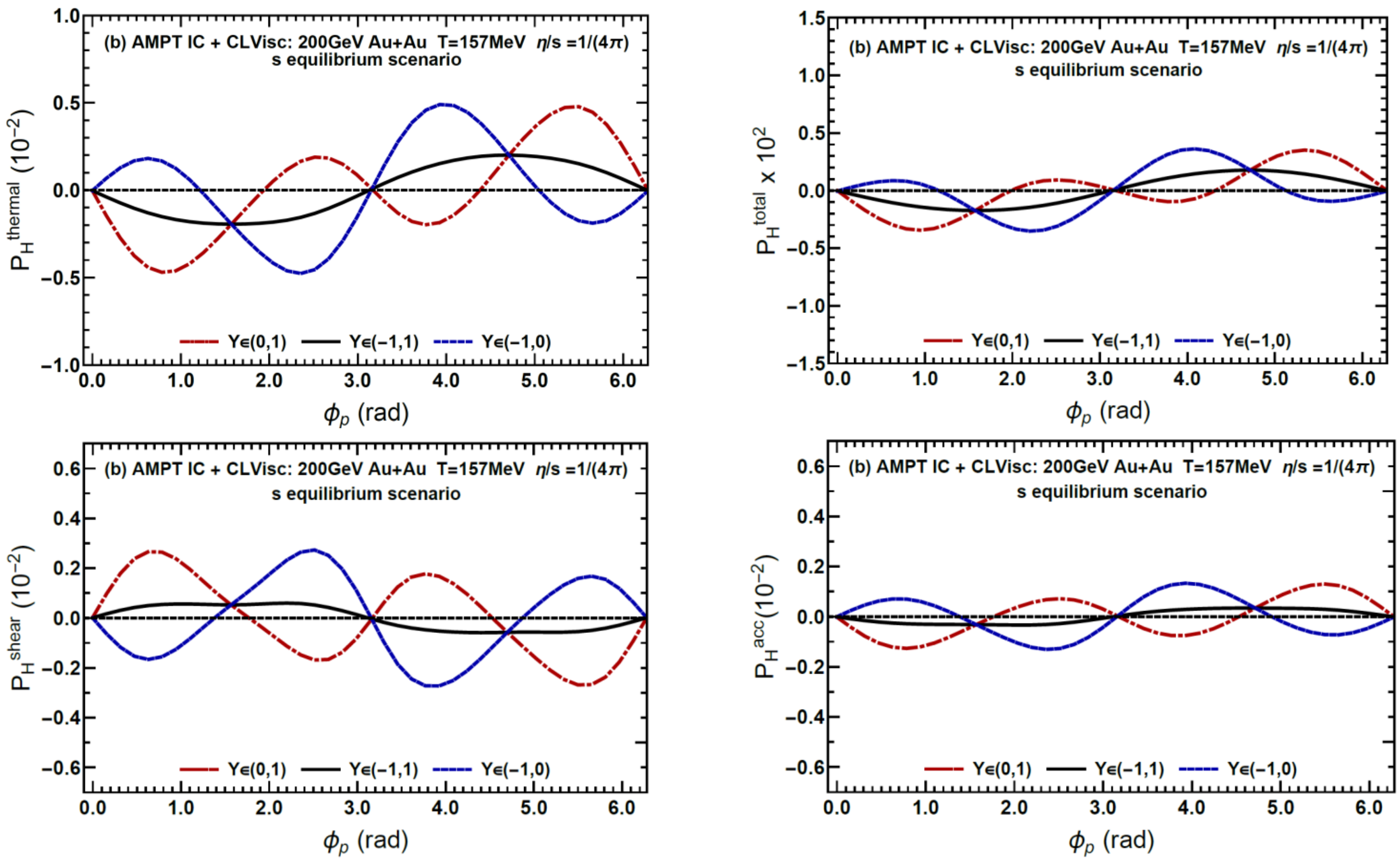
$$S^h_{\mathrm{accT}}(\mathbf{p}) = \int d\Sigma^\sigma F_\sigma \frac{\epsilon^{0ijk}\widehat{p}^i p_0 u_j}{T}\left[(u\cdot\partial)u_k + \frac{\partial_k T}{T}\right],$$

$$S^h_{\mathrm{chemical}}(\mathbf{p}) = -2\int d\Sigma^\sigma F_\sigma \frac{p_0\epsilon^{0ijk}\widehat{p}_i}{(u\cdot p)}\partial_j\left(\frac{\mu}{T}\right)u_k, \qquad F^\mu = \frac{p^\mu f_{\mathrm{eq}}(1-f_{\mathrm{eq}})}{8m\int d\Sigma\cdot p f_{\mathrm{eq}}}.$$

- When the fluid velocity is small, kinetic-vorticity contribution becomes dominant.

Hydrodynamic helicity polarization

- Hydro simulations : AMPT IC+ CLVisc at the top RHIC energy
  - Weighted helicity polarization : $P_H(\phi_p) = \frac{2\int_{Y_{\min}}^{Y_{\max}} dY \int_{p_{T\min}}^{p_{T\max}} p_T dp_T [S^h_{\mathrm{hydro}} \int d\Sigma \cdot p f_{\mathrm{eq}}]}{\int_{Y_{\min}}^{Y_{\max}} dY \int_{p_{T\min}}^{p_{T\max}} p_T dp_T \int d\Sigma \cdot p f_{\mathrm{eq}}}$

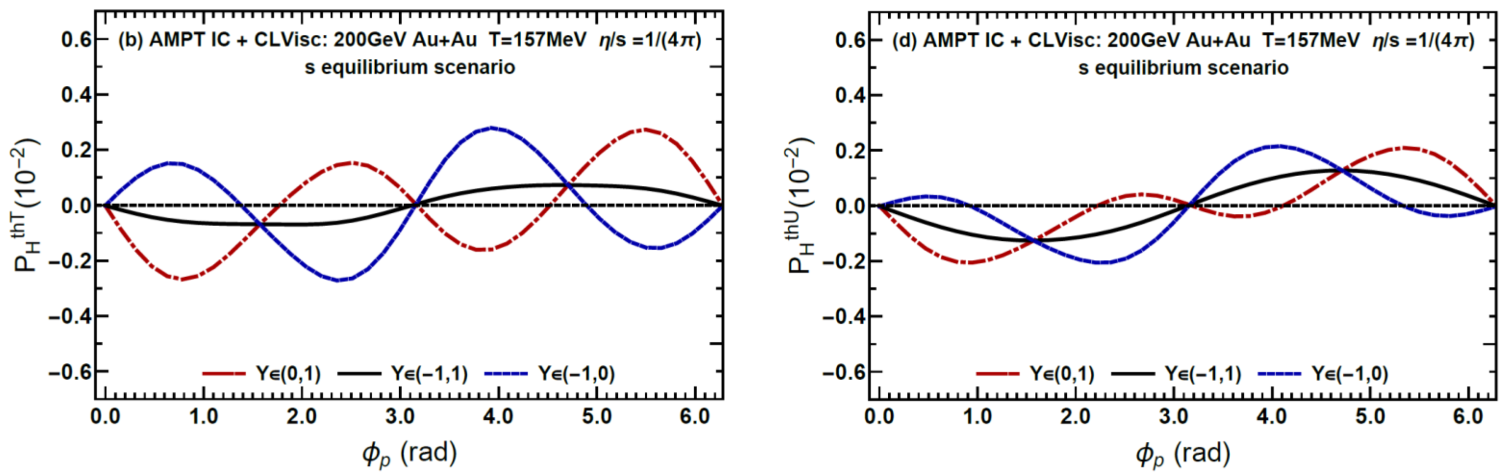


C. Yi, S. Pu, J.-H. Gao, DY, PRC 105, 044911 (2022)

Helicity polarization from fluid vorticity

- Decomposition of the polarization from thermal vorticity:

$$S^h_{\mathrm{thT}}(\mathbf{p}) = \int d\Sigma^\sigma F_\sigma \frac{p_0}{T^2} \widehat{\mathbf{p}} \cdot (\mathbf{u} \times \nabla T), \qquad S^h_{\mathrm{thU}}(\mathbf{p}) = \int d\Sigma^\sigma F_\sigma \frac{p_0}{T} \widehat{\mathbf{p}} \cdot \boldsymbol{\omega}$$



➢ Onset of the dominant contribution from kinetic vorticity

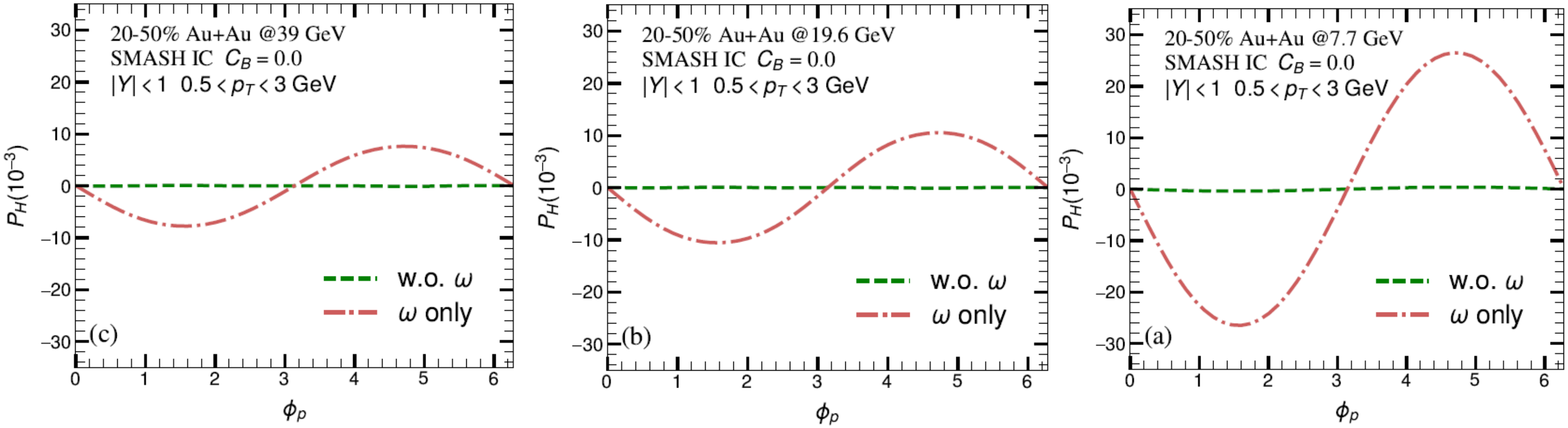
- Collision energy (fluid velocity) is still not low enough.
- Probing the strongest local fluid vorticity from helicity polarization with the beam energy scan (BES)?

RHIC-BES energies

- Hydro simulations at BES energies : SMASH IC+ CLVisc

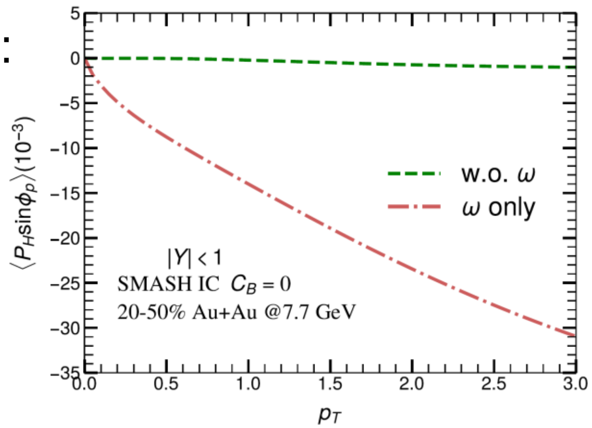
⇨ Helicity polarization from kinetic vorticity becomes more dominant

- Helicity polarization :



❖ Fourier sine coefficient :

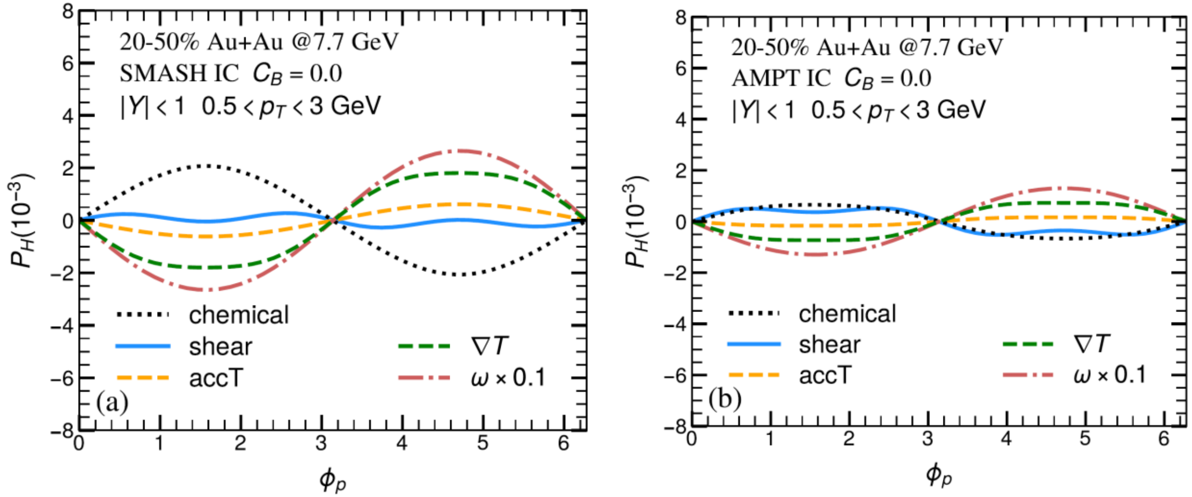
(with pT dep.)



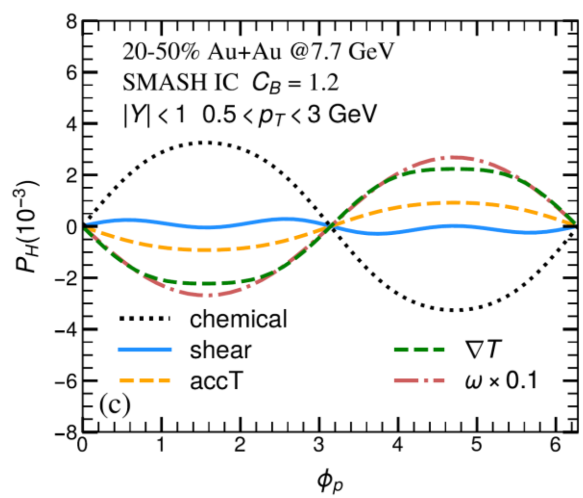
C. Yi, X.-Y. Wu, DY, J.-H. Gao, S. Pu, G.-Y. Qin, PRC 109, L011901 (2024)

Model dependence

- Different initial conditions : SMASH v.s. AMPT



- Nonzero baryon diffusion :



Overall features are similar : Dominance of ω

Summary & concluding remarks

- Local spin polarization spectra contain different contributions from vorticity, shear corrections, spin Hall effect, and potentially non-equilibrium corrections depending on interactions.

- For helicity polarization at low collisional energies, the kinetic-vorticity contribution dominates over other interaction-independent corrections in local equilibrium.

- A useful baseline to understand spin transport in HIC:

  comparison with the future experimental analysis

  ⇨ { match : probing strong local (kinetic) vorticity

  mismatch : probing non-equilibrium corrections sensitive to the details of interactions }

Thank you!