Shear-induced polarization in heavy-ion collisions

1. Introduction: spin polarization and spin-momentum correlation
2. Response theory and shear-induce spin polarization (SIP).
3. Opportunities at BES program.

Yi Yin

Institute of Modern Physics (IMP), Lanzhou, Chinese academy of sciences

Shuai Liu, YY, 2103.09200

Baochi Fu, Shuai Liu, Longgang Pang, Huichao Song, YY, 2103.10403;

Shuai Liu, postdoc@IMP

Baochi Fu, graduate@Peking U.

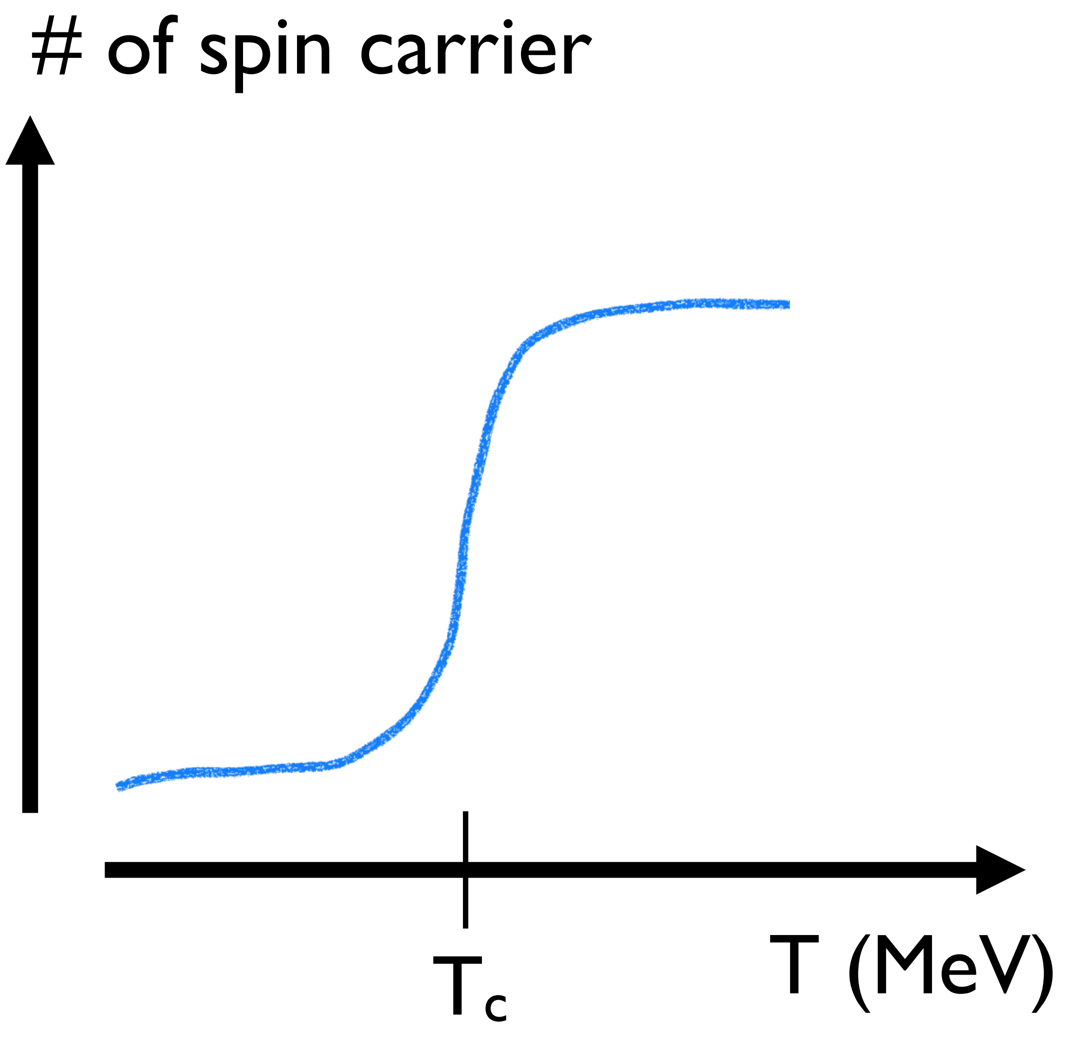
RHIC/AGS Annual User's Meeting, June. 8th, 2021

Motivation

- Polarization/spin alignment measurement: new degrees of freedom to study QCD matter.

  - probing spin structure of QCD matter.

  - sensitive to phase transition.



Challenges and open issues

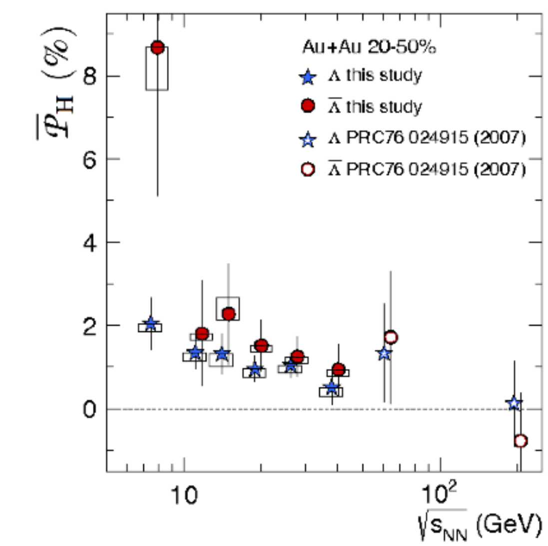
Review: Becattini, Lisa, 2020

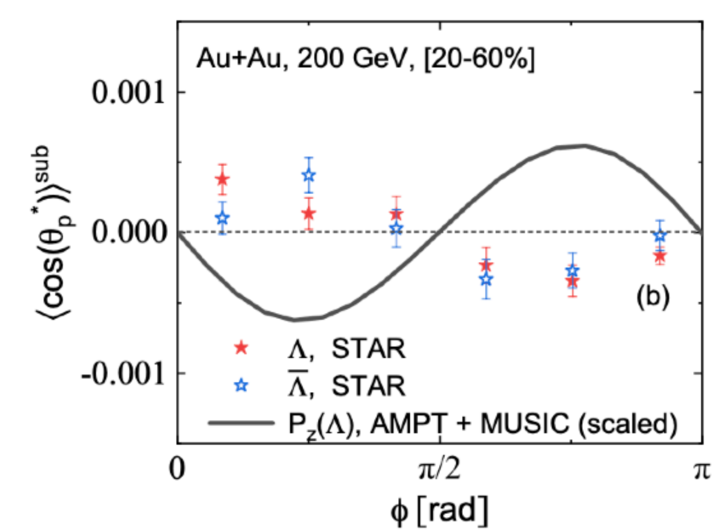
- Vorticity effects in heavy-ion collisions:
  - describe the trends of global (phase-space averaged) Λ polarization.

    Xin-Nian Wang, Zuo-Tang Liang, PRL 05'; Becattini et al, Annals Phys 13'

  - predict qualitatively different behavior in differential measurements. ("sign puzzle")

    STAR PRL 19'; hydro. simulations by many





Baochi Fu et. al, PRC21'

This talk: recent theoretical progress on spin polarization generation.

Spin polarization generation

- Rotation (independent of the direction of $\overrightarrow{p}$):

Landau-Lifshitz volume 5

$$\Delta\epsilon = -\vec{s}\cdot\overrightarrow{\Omega} \rightarrow \vec{s} \parallel \overrightarrow{\Omega}$$

- Spin Hall effect:

$$\vec{s} \propto \overrightarrow{p} \times \overrightarrow{E}$$

NB: hydro. force plays the role of analogue electric field

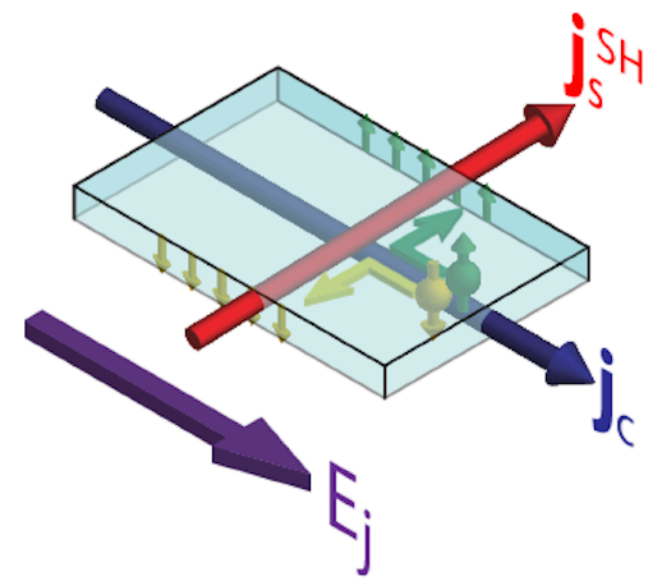


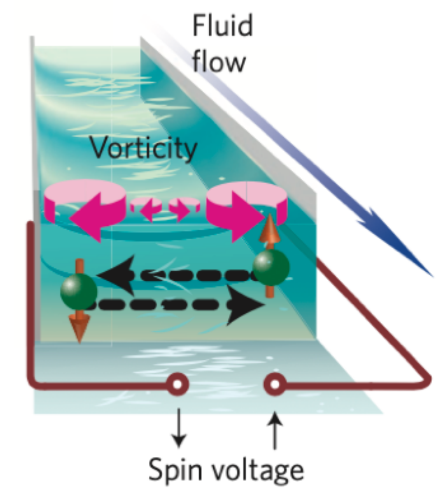
Illustration of spin Hall effect, Meyer et al, Nature material 17'

- General phenomenon: spin-momentum correlation.

In heavy-ion collisions, differential spin polarizations probe the spin-momentum correlation in the medium. (NB: differential spin polarization $\neq$ local vorticity)

Hydro. gradient generates spin polarization

- The gradient of hydro. field (e.g. flow and energy/ charge density) leads to spin polarization of fermions in a fluid.



Nature phys., Takahashi et al, 16'

  - A familiar example: vorticity-induced polarization.

- Nevertheless, vorticity is just one example of hydro. gradients. Can we systematically analyze all possible effects of hydro. gradients?

The answer is yes from response theory

Response theory

Response theory

- Response to hydro. gradients:
  - expansion in gradient.
  - relating expansion coefficients to correlators $\langle O(x) T^{\mu\nu}(x') \rangle$.
- E.g.: viscous stress-tensor and viscosities.

$$(T^{\mu\nu})_{\rm vis} \propto \eta \sigma^{\mu\nu} \qquad q^{\mu}_{\rm heat} \propto \kappa \partial^{\mu}_{\perp} T$$

- Applying similar procedure to spin polarization (axial Wigner function).

$$\mathscr{A}^{\mu}(t, \overrightarrow{x}, \overrightarrow{p}) = \int d^3\overrightarrow{y}\, e^{-i\overrightarrow{y}\cdot\overrightarrow{p}} \langle \bar{\psi}(t, \overrightarrow{x} - \frac{1}{2}\overrightarrow{y})\, \gamma^{\mu}\gamma^{5} \psi(t, \overrightarrow{x} + \frac{1}{2}\overrightarrow{y}) \rangle$$

The derivative expansion

Shuai Liu, YY, 2103.09200

- The most general expression consistent with symmetries (for the neutral fluid):

$$u \cdot \mathscr{A} = \tilde{c}_\omega p \cdot \omega \,,$$

$$\mathscr{A}^\mu_\perp = c_\omega \omega^\mu - c_T \epsilon^{\mu\nu\alpha\lambda} u_\nu p_\alpha \partial_\lambda \log T + g_\sigma \epsilon^{\mu\nu\alpha\lambda} u_\nu Q_{\alpha\rho} \sigma^\rho{}_\lambda + g_\omega Q^{\mu\nu}\omega_\nu$$

vorticity effects — spin Nernst effect — shear-induced polarization

$$\vec{s} \propto \hat{p} \times \nabla \log T$$

Spin-momentum correlation

$$\omega^\mu = \frac{1}{2}\epsilon^{\mu\nu\alpha\beta} u_\nu \partial_\alpha u_\beta$$

vorticity

$$\sigma_{\mu\nu} = \frac{1}{2}\left(\partial_\mu u_\nu + \partial_\mu u_\nu - \text{trace}\right)$$

shear

$$Q^{\mu\nu} = -\frac{p^\mu_\perp p^\nu_\perp}{p^2_\perp} - \frac{1}{3}\Delta^{\mu\nu}, \ldots$$

quadrupole

- Although allowed by symmetry, flow gradient and momentum quadrupole coupling, has never been discussed before.

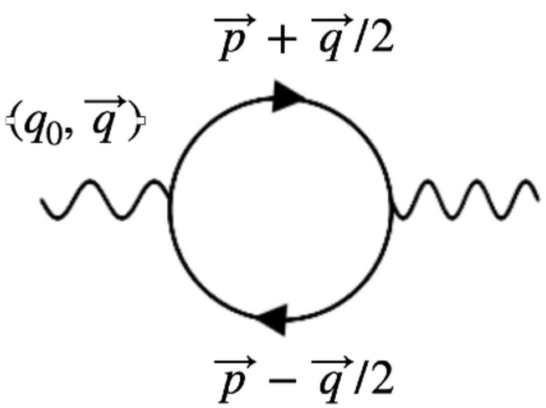
One-loop

Shuai Liu,YY, 2103.09200

- The expansion coefficients can be determined from microscopic theories.

- evaluating retarded correlators:

$$\int_{\vec{y}} e^{i\vec{y}\cdot\vec{p}}\langle\bar{\psi}(t,\vec{x}-\frac{1}{2}\vec{y})\,\gamma^{\mu}\gamma^{5}\psi(t,\vec{x}+\frac{1}{2}\vec{y})\,T^{\alpha\beta}(0,0)\rangle$$



- For general fermion mass at one-loop:

$$\mathscr{A}^{\mu}_{\perp} = (-n'_{FD})\left[\omega^{\mu} + \epsilon^{\mu\nu\alpha\lambda}u_{\nu}p_{\alpha}\partial_{\lambda}\log\beta + \frac{-p_{\perp}^{2}}{(p\cdot u)}\epsilon^{\mu\nu\alpha\lambda}u_{\nu}Q_{\alpha\rho}\sigma^{\rho}{}_{\lambda}\right] + \#\times Q^{\mu\nu}\omega_{\nu}$$

vorticity effects — spin Nernst effect — shear-induced polarization — $\propto$(g-2)

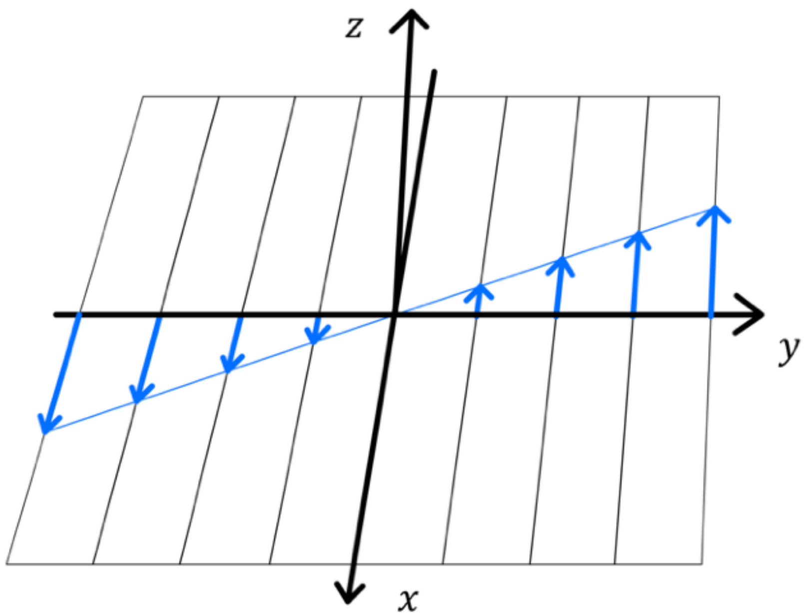
- Chiral kinetic theory analysis agrees with one loop calculations in the same setting.

SIP has been derived via alternative method by Becattini et al, 2103.10917

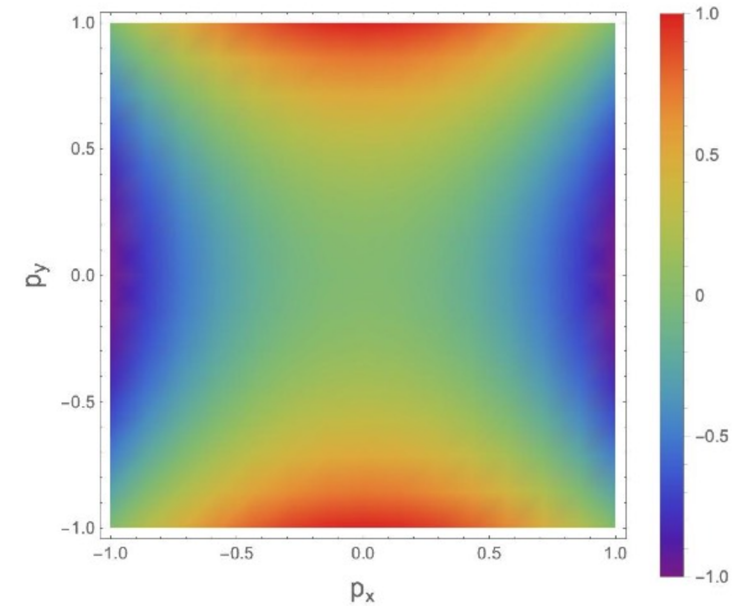
Shear-induced polarization

Spin polarization=[Vorticity]+[T-gradient]+[Shear]

Illustration



A standard shear flow profile:
$\omega^z \neq 0\,, \sigma^{xy} \neq 0$

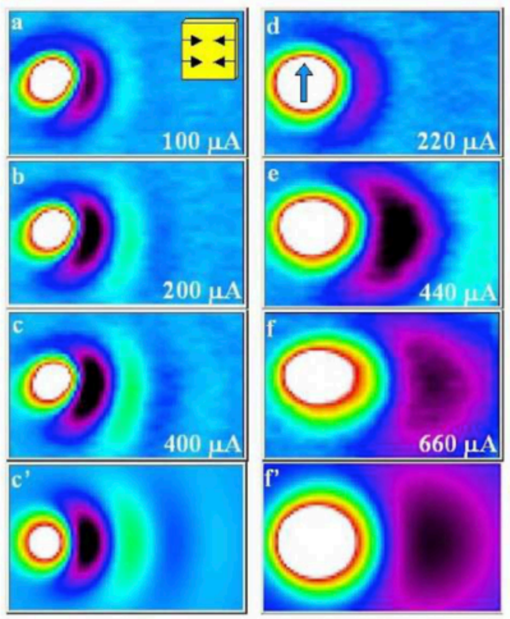


Spin polarization along z-direction in phase space from SIP.

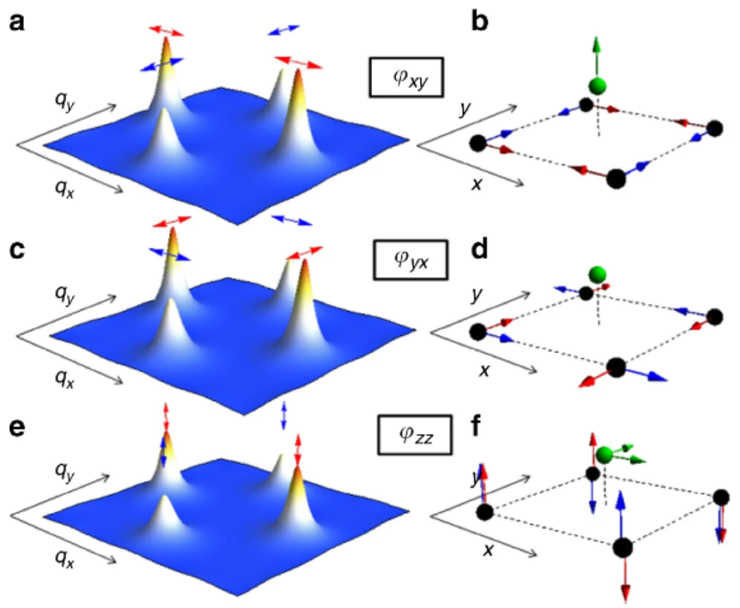
$$\mathscr{A}^i_{SIP} \propto \epsilon^{ikj} Q_{jl} \sigma^l{}_k\,, \qquad Q_{ij} = \hat{p}_i \hat{p}_j - \frac{1}{3}\delta_{ij}$$

Shear-induced polarization (SIP): imaging anisotropy in a fluid into anisotropy in spin space.

Observation?



n-type GaAs, Crooker and Smith, PRL, 04'



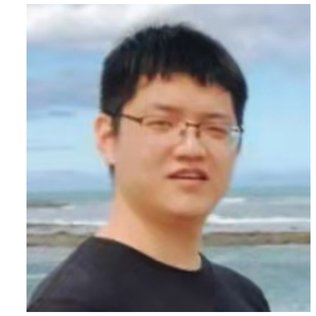
BaFe2As2, Kissikov et al, Nature communication, 18'

- The cousin effect, strain-induced polarization has been observed in crystals and liquid crystals.
- Shear-induced polarization (SIP): generic in fluids.
  - Can we/did we see SIP in heavy-ion collisions?
  - What can we learn ?

Heavy-ion collisions

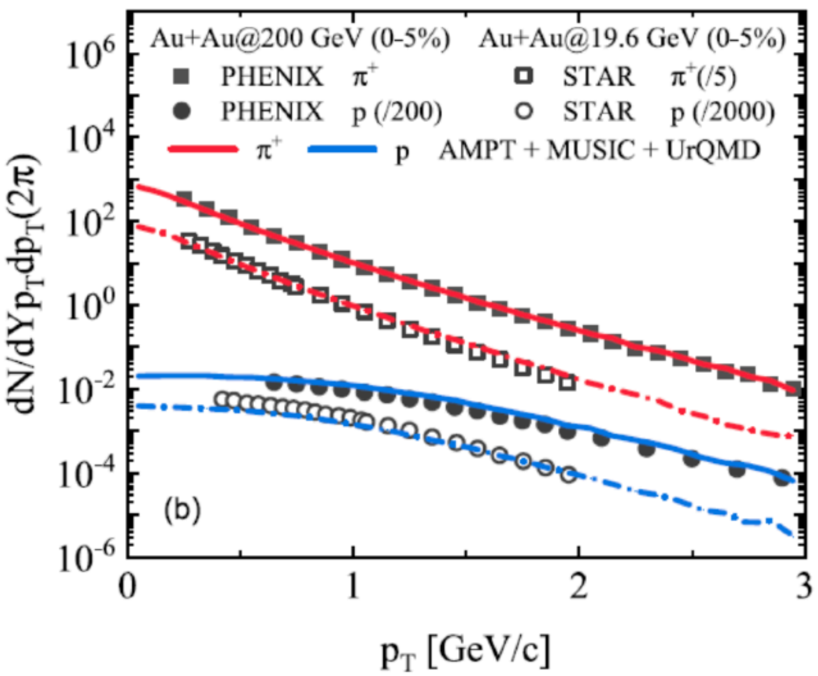
Hydro. Model

Baochi Fu, K. Xu, XuGuang Huang, Huichao, PRC 21'

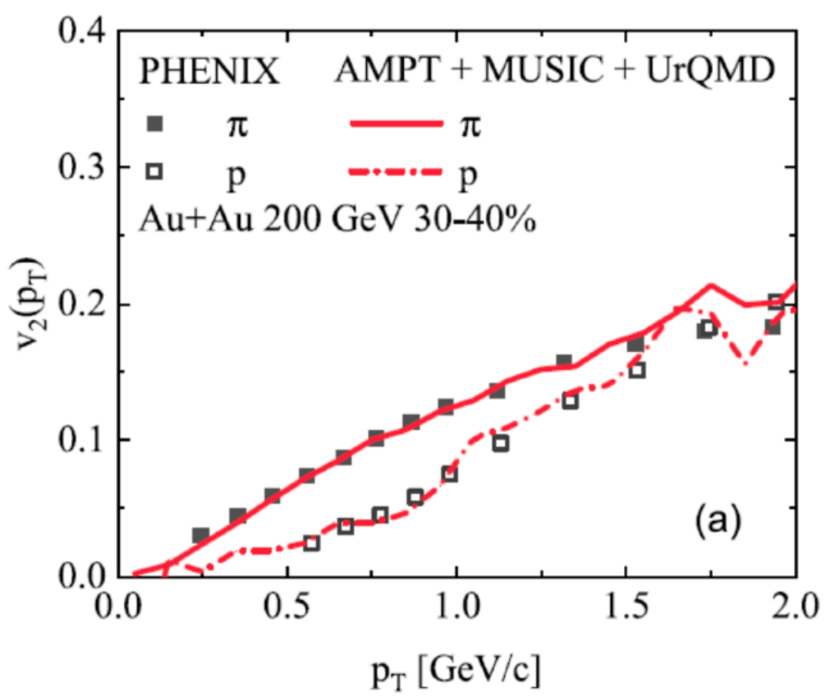


Baochi Fu, graduate@Peking U.

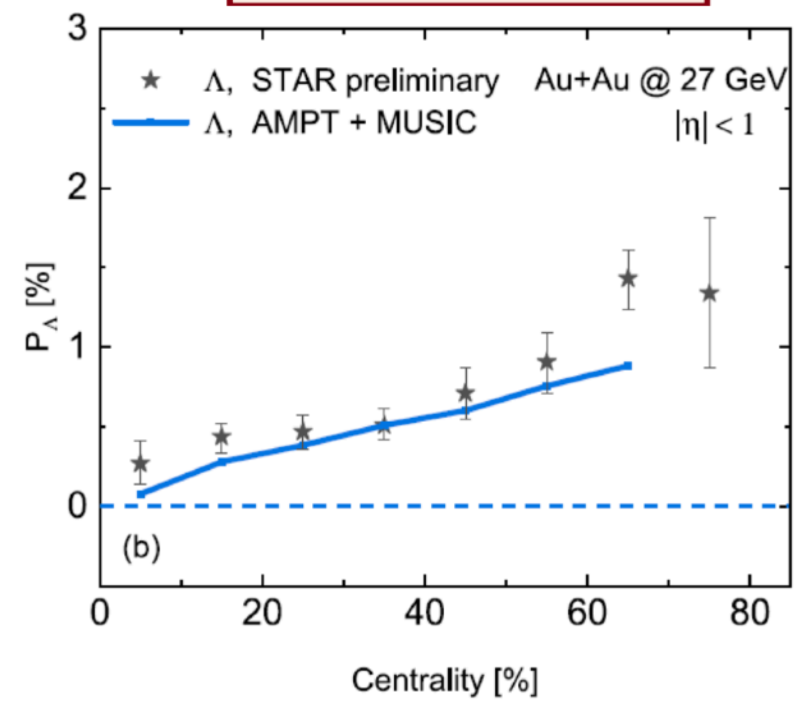
Transverse momentum spectra



$v_2(p_T)$



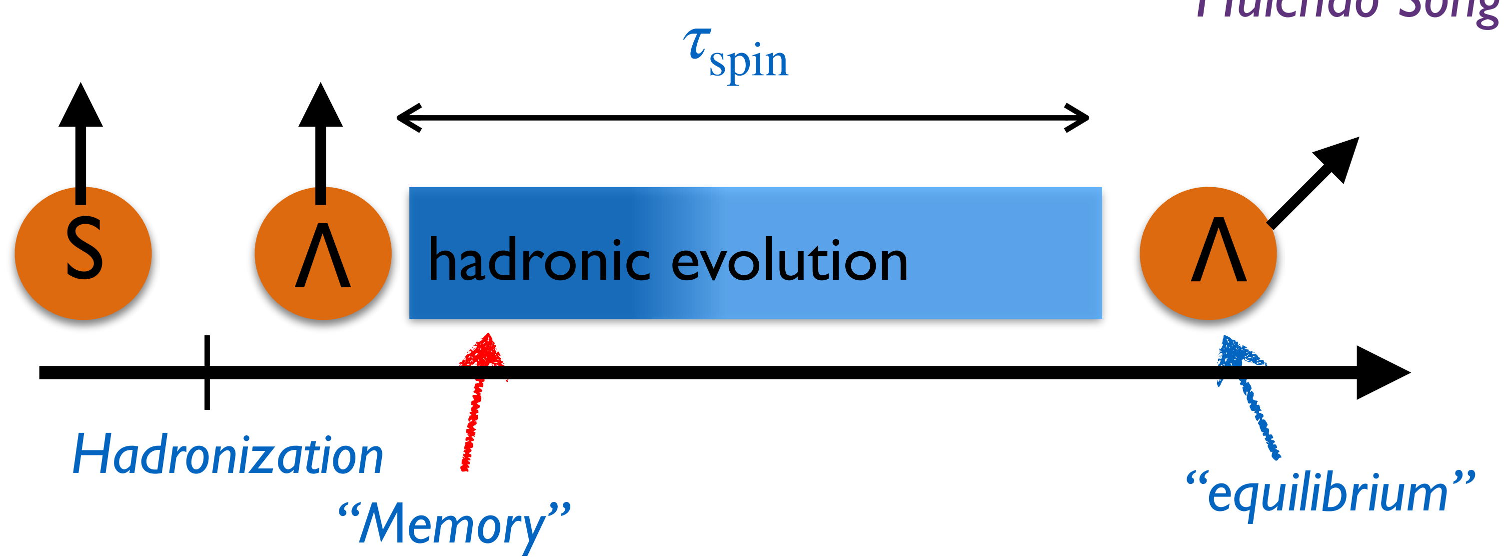
Global Polarization from thermal vorticity



- Hydro. profile from the data-calibrated hydro. modeling (AMPT+MUSIC).

Limiting scenarios

Baochi Fu, Shuai Liu, Longgang Pang, Huichao Song and YY, 2103.10403

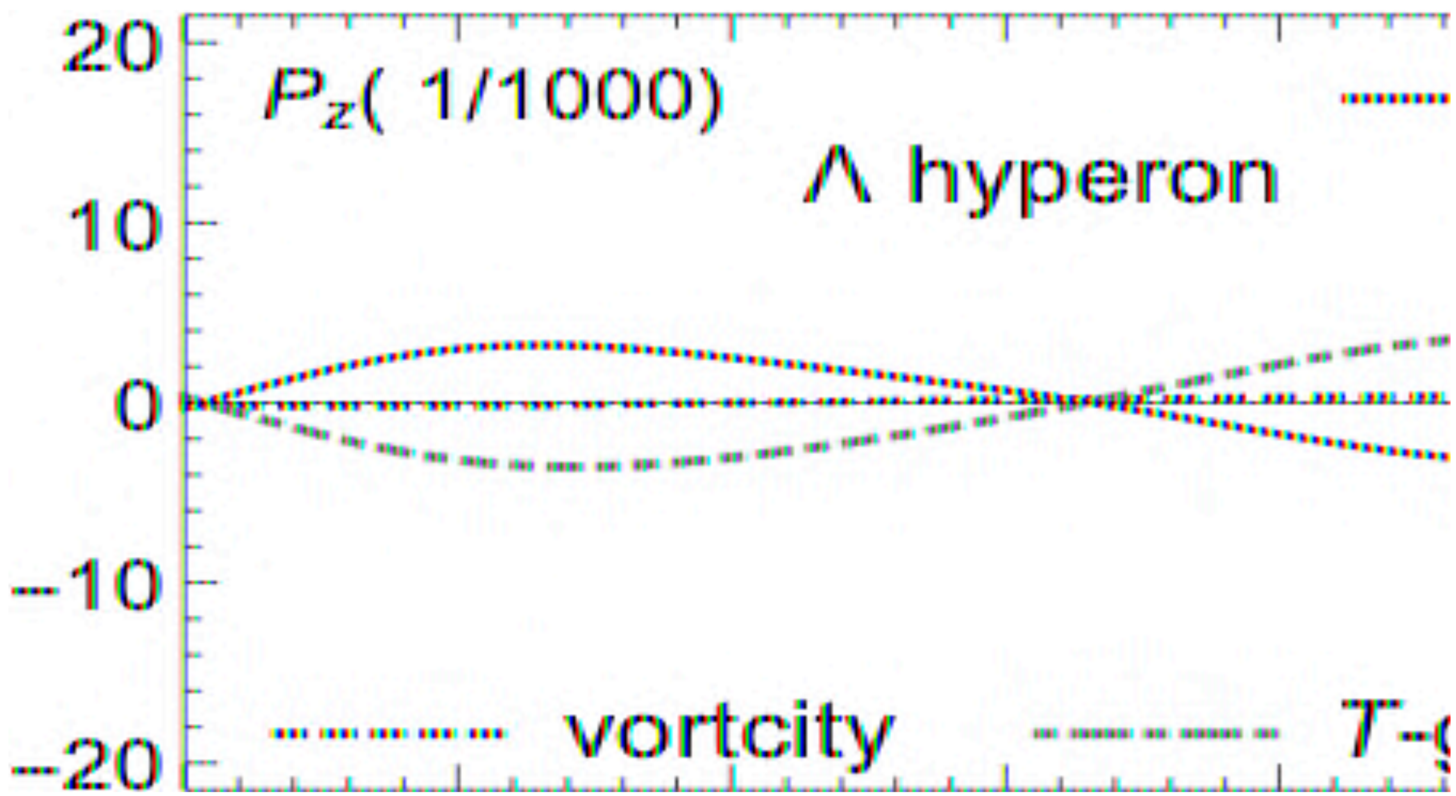


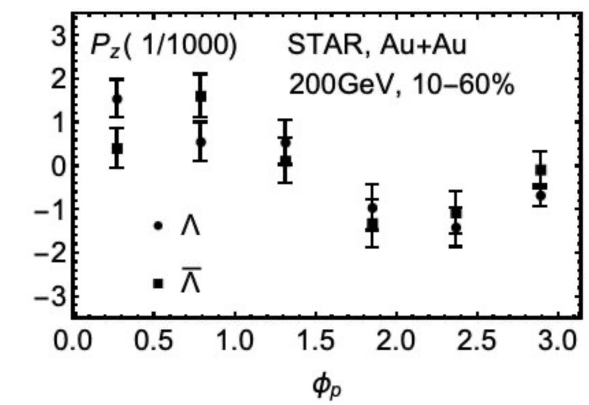
- Two benchmark scenarios:
  - "Lambda equilibrium": Λ is born (shortly after hadronization) in equilibrium.
  - "strange memory": Λ memorizes the polarization of strange quarks

NB: spin-dependent d.o.f. can be off-equilibriums even if spin-independent ones are in equilibrium.

- Focus on the qualitative feature.

Lambda spin polarization along longitudinal direction





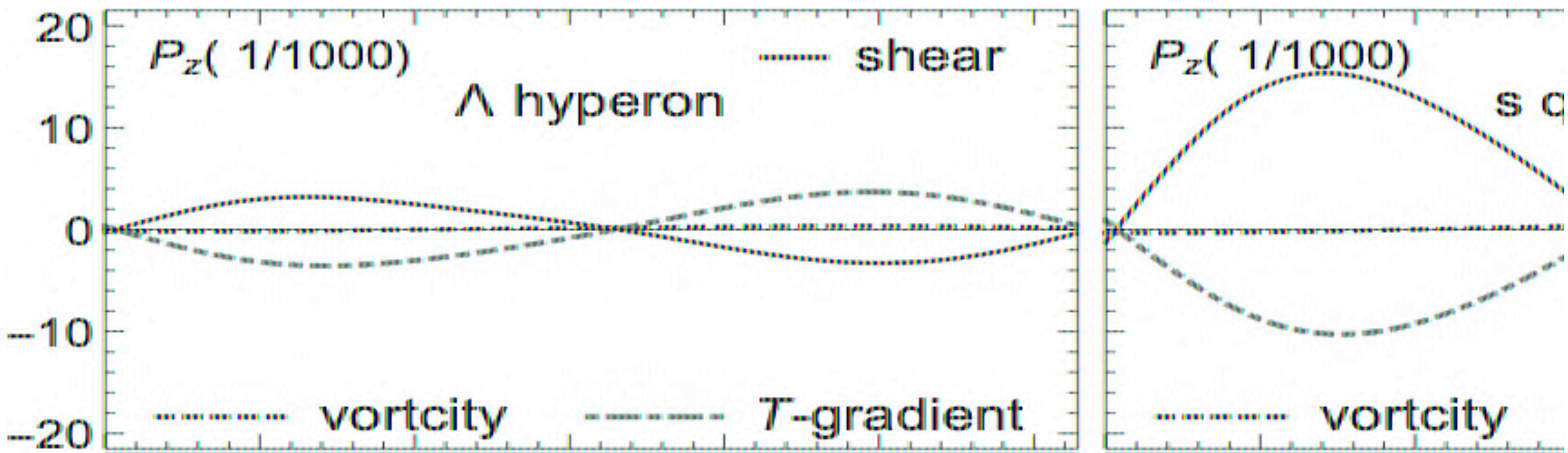
vs transverse azimuthal angle ϕ_p

Spin polarization=[vorticity]+[T-gradient]+[Shear]

- SIP gives a "right sign" while the effect of T-gradient leads to "wrong sign".

also confirmed independently in 2103.14621 by Becattini et al

"Lambda equilibrium" vs "strange memory"

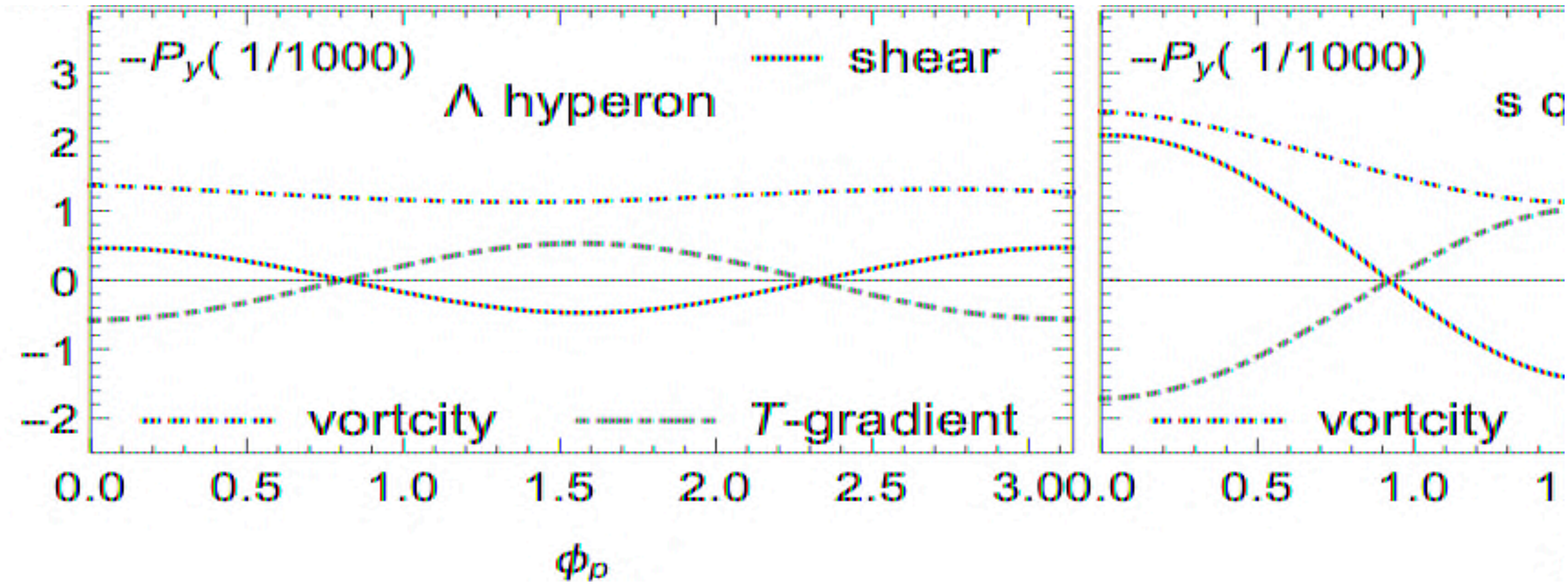


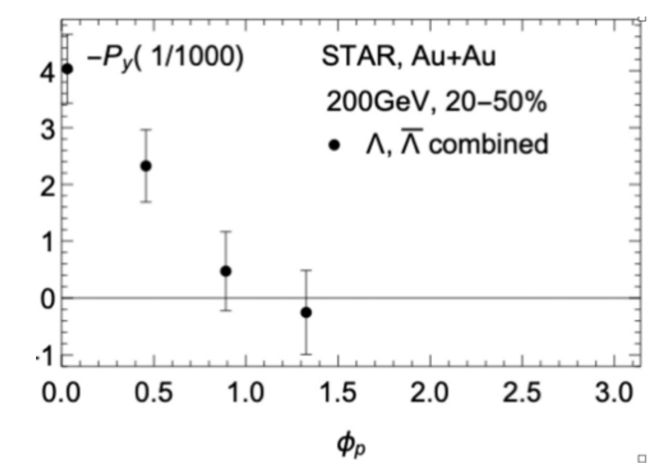
vs transverse azimuthal angle ϕ_p

Spin polarization=[Vorticity]+[T-gradient]+[Shear]

- SIP: sensitive to the mass of spin carrier.

Similar story for Py

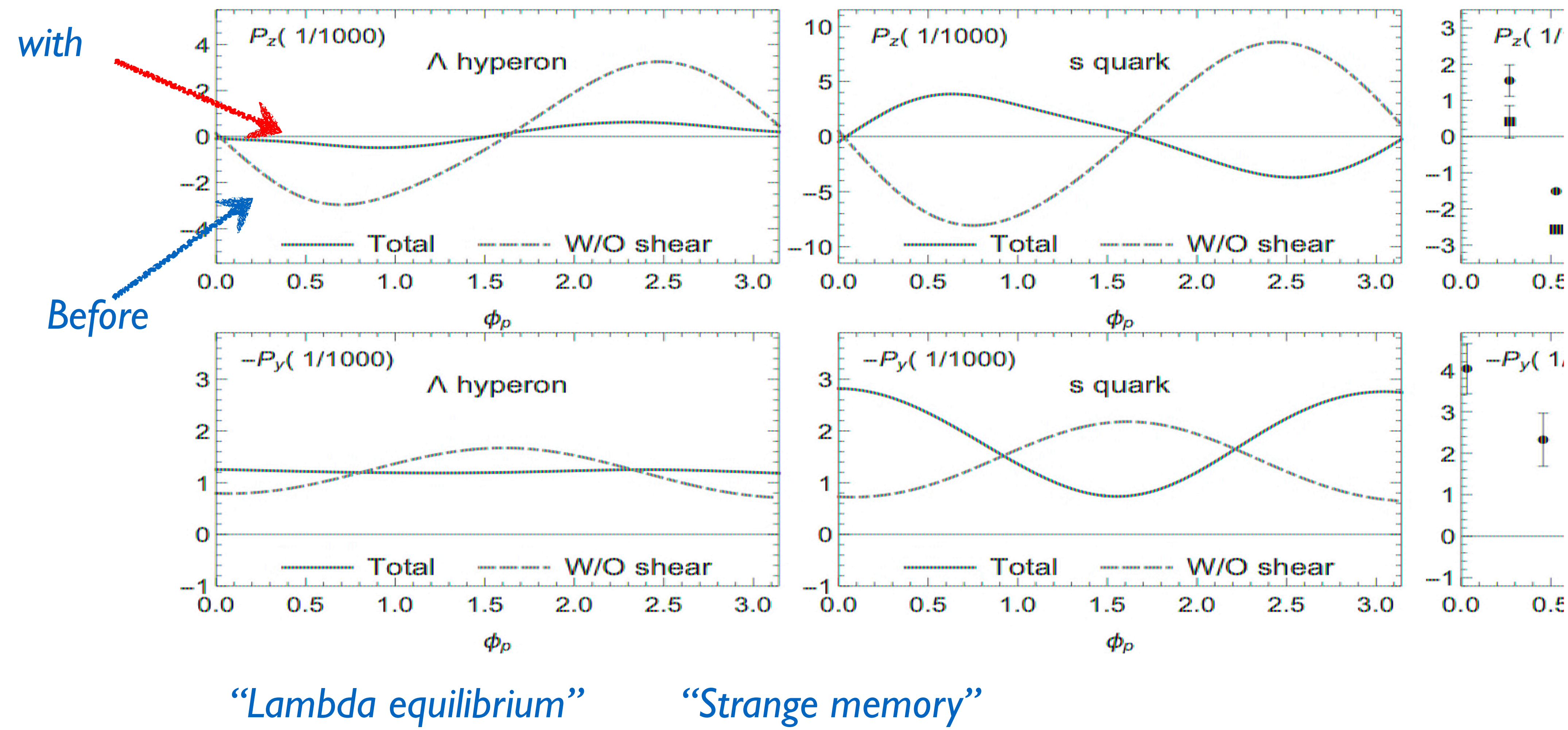




STAR preliminary results

Total spin polarization

Baochi Fu, Shuai Liu, Longgang Pang, Huichao Song and YY, 2103.10403



- Shear-induced polarization (SIP) effects are in-dispensable.
- SIP determines the qualitative feature of differential polarization in the "strange memory" scenario .
  - Λ polarization may probe the properties of QGP.

Discovery?

nature communications

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Uniaxial strain control of spin-polarization in multicomponent nematic order of $BaFe_2As_2$

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Published: 11 September 2017

Observation of the spin Nernst effect

- Road map towards claiming the discovery of shear-induced polarization (SIP) and spin Nernst effect (from T-gradient)?

Summary and outlook

Summary

- Differential spin polarization: probes the spin-momentum correlation of QCD matter
- Response theory analyses the effects of hydro. gradient on spin polarization systematically.
- New! Shear-induced (SIP): shear stress tensor generates spin momentum correlation.
- SIP and Lambda's memory of strange quark polarization: key to understand qualitative behavior of heavy-ion collisions data.
  - For quantitative study, a comprehensive transport theory with spin is crucially needed.

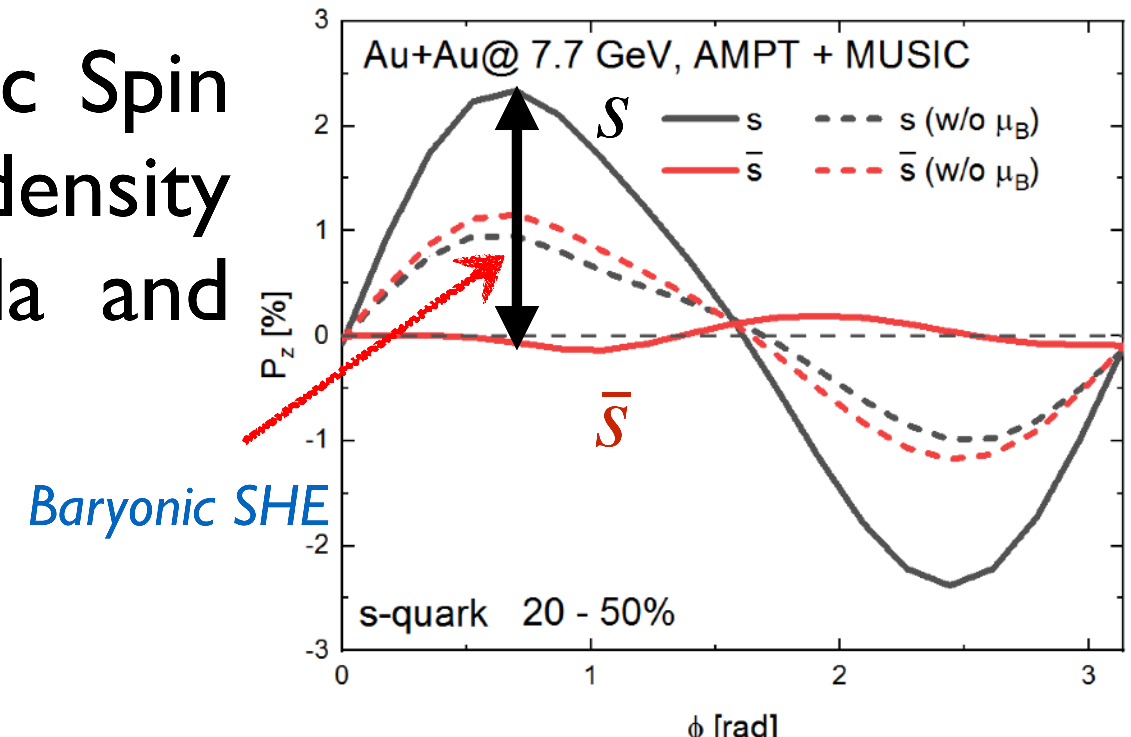
Opportunities at BES

- Beam energy dependence of local spin polarization (probing EoS, transport coefficients etc).

- New players in the game: baryonic Spin Hall effect (induced by baryon density gradient) which separates Lambda and anti-Lambda.

$$\overrightarrow{P}_{\pm} \propto \pm \hat{p} \times \nabla \mu_B$$

First phenomenological study: Liu-YY, 2020.12421. Theory: Son, Yamamoto, PRD 12; Di-Lung Yang, Hattori, Yoshimasa, PRD 19' … .



Preliminary results for 7.7 GeV; Baochi Fu, Shuai Liu, Longgang Pang, Huichao Song, YY, in preparation.

NB: μ_B gradient is sensitive to beam energy, baryon stoping mechanism and diffusive constant.

Ultimate goal: spin structure and phase structure of QCD matter.

Back-up

Interpretation

- In spatial components

$$(s^i)_{\text{SIP}} \propto \epsilon^{ikj} Q_{jl} \sigma^l{}_k = \epsilon^{ikj} \hat{p}_j \hat{p}_l \sigma^l{}_k \,, \qquad Q_{ij} = \hat{p}_i \hat{p}_j - \frac{1}{3}\delta_{ij}$$

- c.f. Spin Hall effect:

$$\vec{s} \propto \hat{p} \times (\overrightarrow{\ \sigma \odot p\ })$$

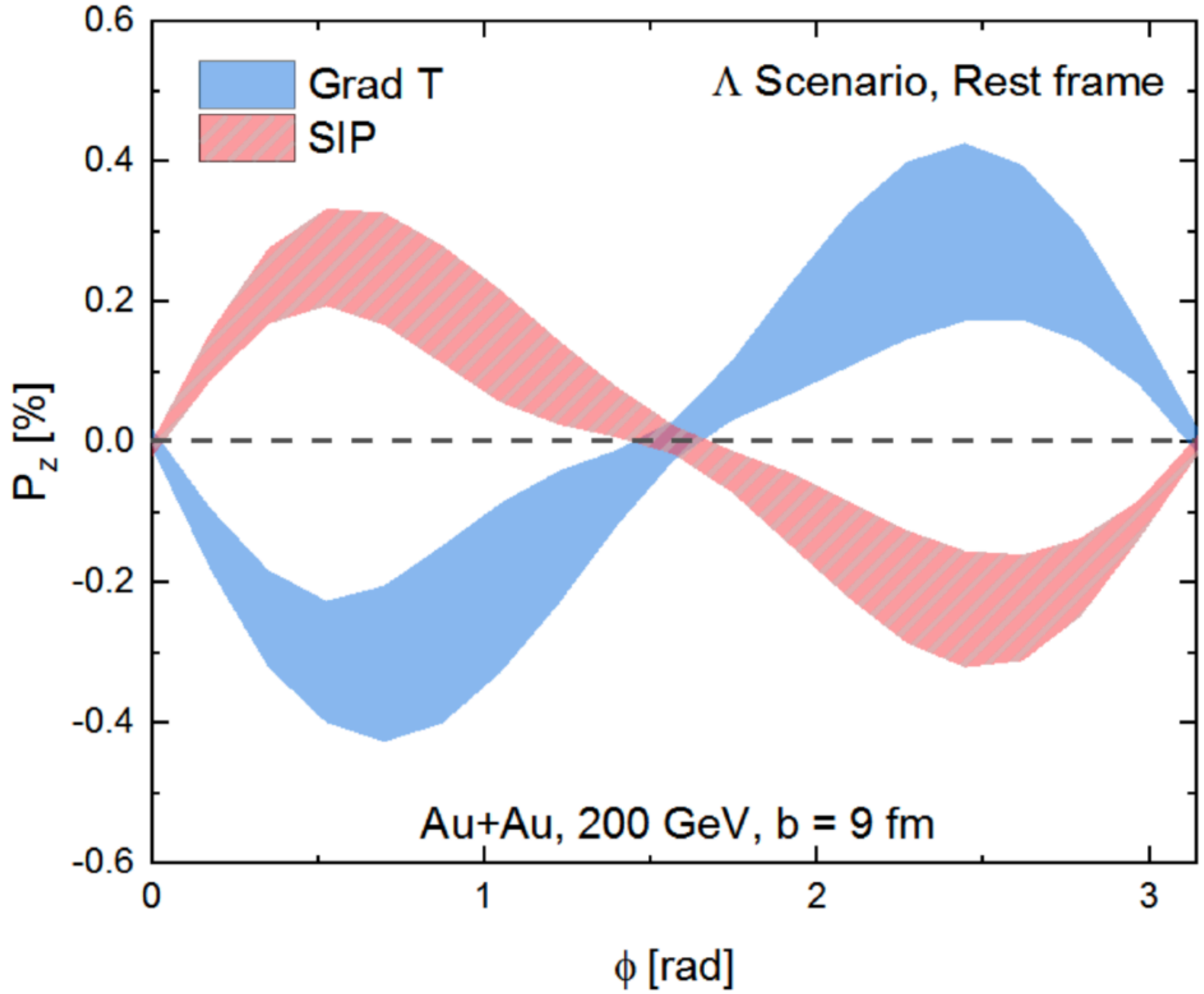
hydro. force

- $\sigma^{\mu\nu} \to T^{\mu\nu} \to M^{\mu\nu\alpha} \to$ spin polarization

$$(M^{\mu\nu\alpha} = x^\nu T^{\mu\alpha} - x^\mu T^{\nu\alpha}\ )$$

Belinfante, 1940

Sensitivity to the inputs of hydro.



Band: possible flexibility of [Grad T] and [SIP]

- Initial flow: on → off
- Initial condition: AMPT → Glauber
- Shear viscosity: 0.08 → off
- Bulk viscosity: $\zeta/s(T)$ → off
- Freeze-out temperature:

  167 MeV → 157 MeV

Comparison

- Summary of one-loop results:

see also Becattini et al, 2103.10917

Spin polarization=[Vorticity]+[T-gradient]+[Shear]

- Popular approach: spin distribution in a specific hydro. configuration (no entropy production)

Becattini et al,Annals Phys. 323:2452 (08) Annals Phys. 338:32 (13) and follow-ups;

$$\partial_\mu(\beta u_\nu) + \partial_\nu(\beta u_\mu) = 0 \leftrightarrow \partial_\mu s^\mu = 0$$

$$\to \mathscr{A}^\mu \propto \epsilon^{\mu\nu\alpha\beta}\left[\partial_\alpha(\beta u_\beta) - \partial_\beta(\beta u_\alpha)\right] p_\nu$$

  - Without shear, agrees with one-loop calculations.

- Response theory applies to general hydro. profile and can be improved systematically through higher-loop/non-perturbative calculations.

Can Λ spin flipping rate be small?

Quark model+vector meson dominance➡ nucleon (N)-hyperon interaction is mediated by ω meson which only couples with constituent u and d quark.

Jennings, PLB1990; Cohen-Weber PRC 1991

However, spin of Λ is carried by s quark. So

(spin-dependent) N-Λ interaction<<(spin-dependent) N-N interaction.

This picture explains the puzzling experimental results

$$\text{N-}\Lambda \approx \frac{1}{40}\,\text{N-N}$$

S. Ajimura et al. PRL 2001

Under this picture, Λ spin flip rate could be (much) smaller than its equilibration rate => worthy checking in future.