Spin-momentum correlation in QCD matter

1. Intro.

2. Spin-momentum correlation in hot and dense QCD matter

   - Shear-induced polarization (SIP).

   - Spin Hall effect by μ_B gradient (at BESII and forward rapidity).

3. Summary and outlook.

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Ref: Shuai Liu, YY, 2006.12421, PRD; 2103.09200, JHEP 21.

Baochi Fu, Shuai Liu, Longgang Pang, Huichao Song, YY, 2103.10403, PRL 21;

Hard Problems of Hadron Physics: Non-Perturbative QCD & Related Quests, Logunov Institute for High Energy Physics, Nov.12th, 2021

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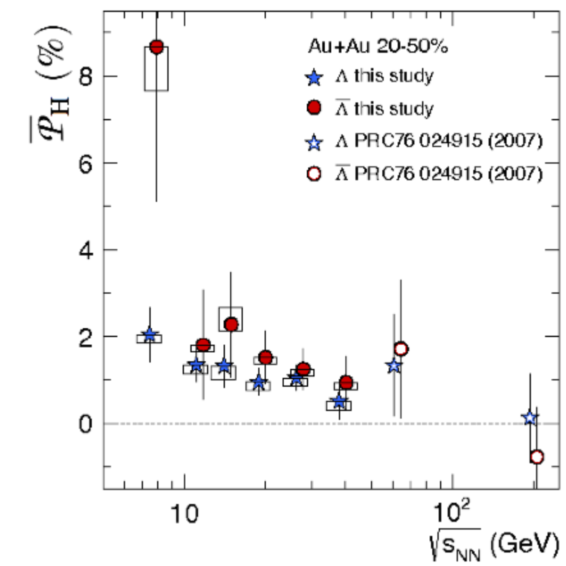
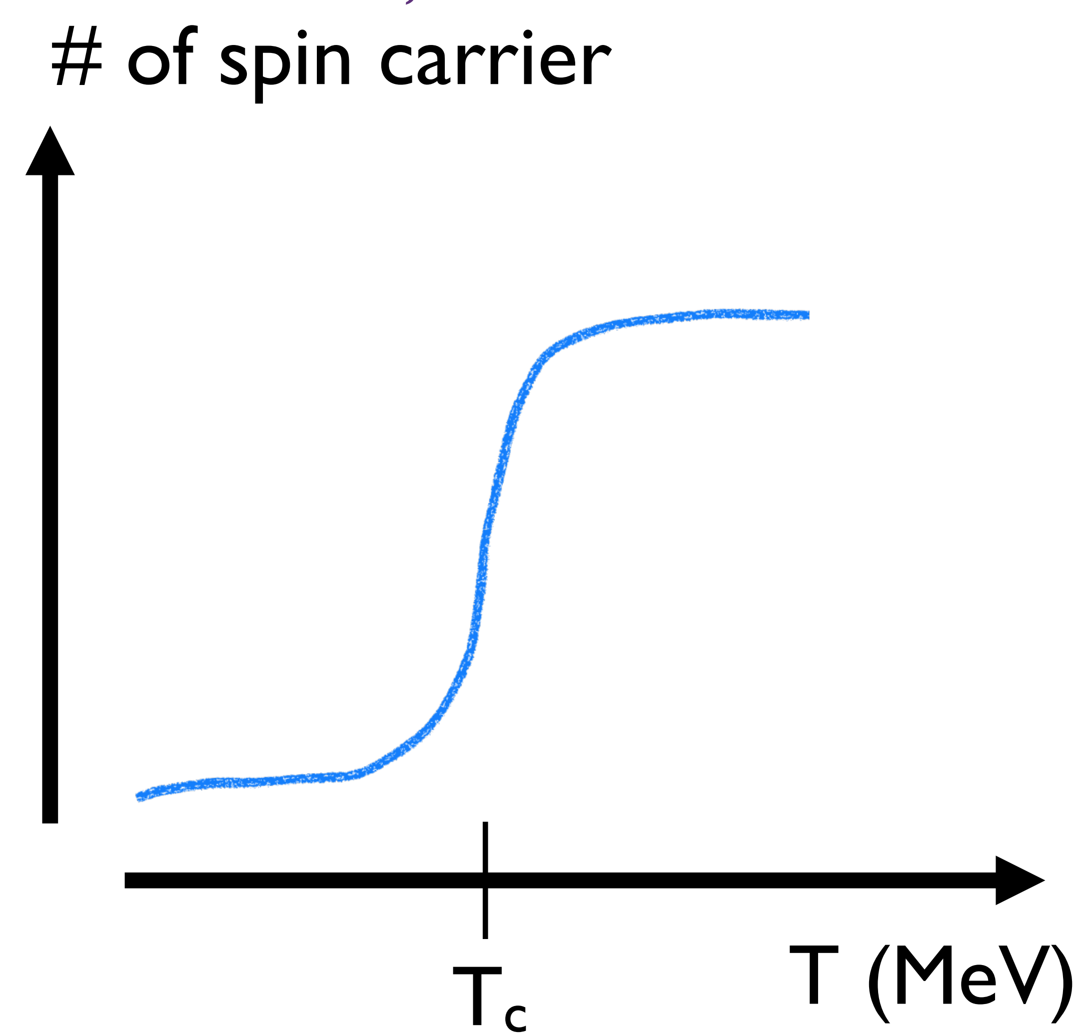
Background

- Polarization/spin alignment measurement in HIC: new arena to explore QCD matter.

Review: Becattini, Lisa, 2020



STAR, Nature 17'.



- Probing spin and phase structure of QCD matter.

Spin polarization generation

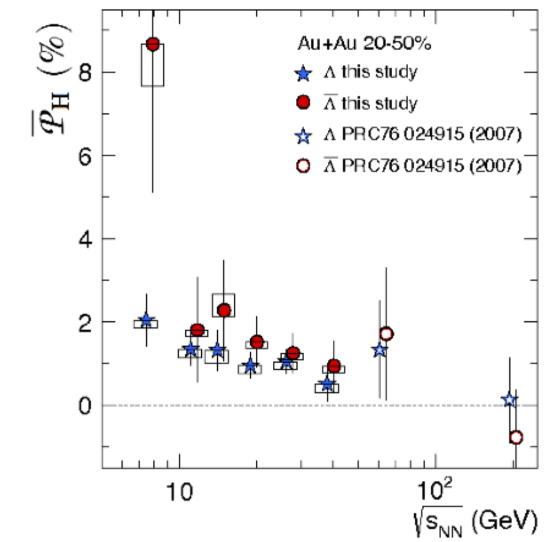
- Rotation (independent of the direction of $\vec{p}$):

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

Landau-Lifshitz volume 5

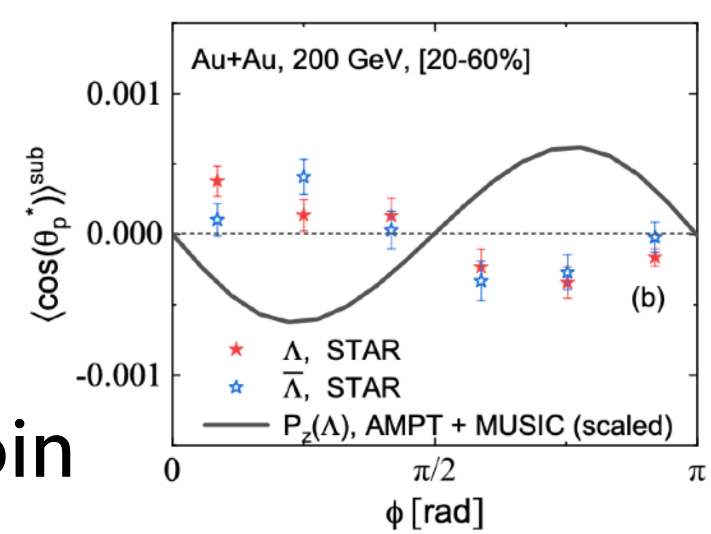
  - At macroscopic scale: vorticity-induced polarization.

- 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”).

But rotation is just one mechanism for spin polarization generation.

Baochi Fu et. al, PRC21'

Spin Hall effect

$$\vec{s} \propto \vec{v} \times \vec{E}$$

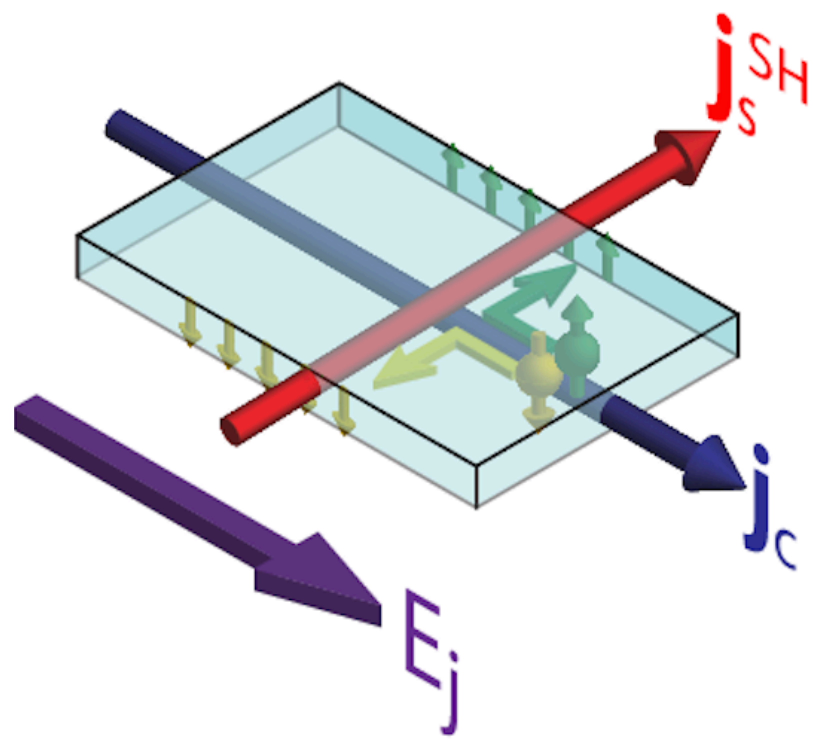


Fig. from Meyer et al, Nature material 17'

- Ubiquitous phenomenon: spin-momentum correlation. (c.f. TMD in nucleon structure.)

In global polarization, such a correlation has been largely washed out after momentum average.

Differential measurement probes the spin-momentum correlation (NB: differential spin polarization $\neq$ local vorticity).

Spin Hall effect and Berry curvature

Murakami, Nagaosa, Shou-Cheng Zhang, Science 2003'

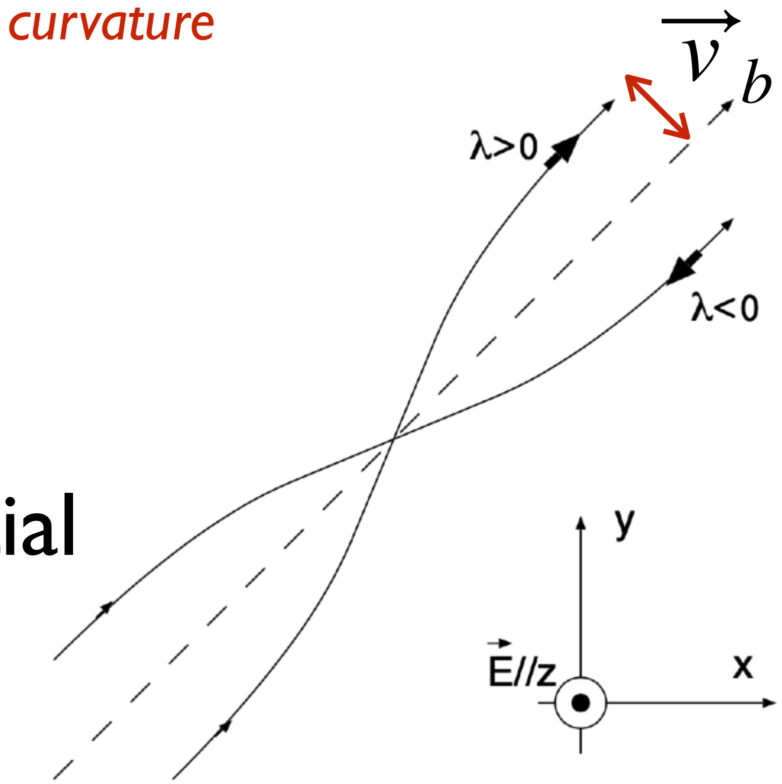
- Berry curvature modifies effective velocity⇒ SHE

$$\dot{\vec{x}} = \vec{v} + \lambda \vec{F} \times \vec{b}_k(\hat{p}) \qquad \vec{b} = \frac{\hat{p}}{2p^2}$$

helicity

Berry curvature

Shifted velocity $\vec{v}_b$



- Effective force $\vec{F}$ can be:
  - electric field $\vec{E}$ and chemical potential gradient $T\nabla(\mu/T)$(spin Hall effect).
  - T-gradient (spin Nernst effect);
  - and more ….
- A class of spin phenomena generated by Berry curvature effects.

Macroscopically, the gradient of hydro. field (e.g. flow and energy/charge density) leads to spin-momentum correlation.

Theory

- Chiral kinetic theory and its generalization, e.g., axial kinetic theory incorporate Berry curvature effects and can describe spin-momentum correlation.

- Another systematic approach is response theory:

  - expansion in gradient.

  - relating expansion coefficients to correlators $\langle O(x) T^{\mu\nu}(x') \rangle$.

- Consider 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, JHEP 21

- The most general expression for axial Wigner function $\mathscr{A}^\mu$ consistent with symmetries (for a 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 (SIP)

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

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

- Flow gradient and momentum quadrupole coupling have long been overlooked.

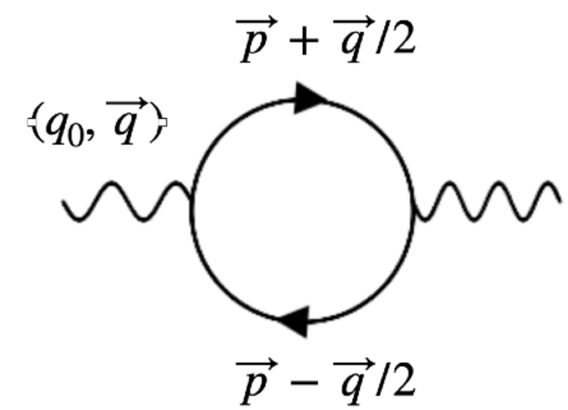
- All those effects are arguably non-dissipative (based on T-parity).

One-loop

Shuai Liu, YY, 2103.09200, JHEP 21

- The expansion coefficients can be computed systematically from microscopic theories.

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



- 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   SIP $\propto$(g-2)

- Chiral kinetic theory analysis is consistent with one loop calculations.

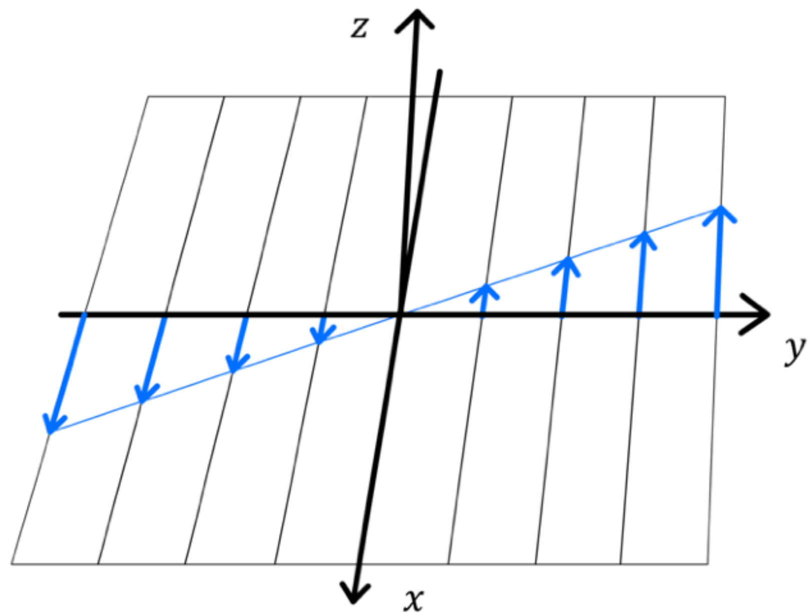
SIP has been derived almost simultaneously by Becattini et al, 2103.10917, PLB 21 via a different method

Shear-induced polarization (SIP)

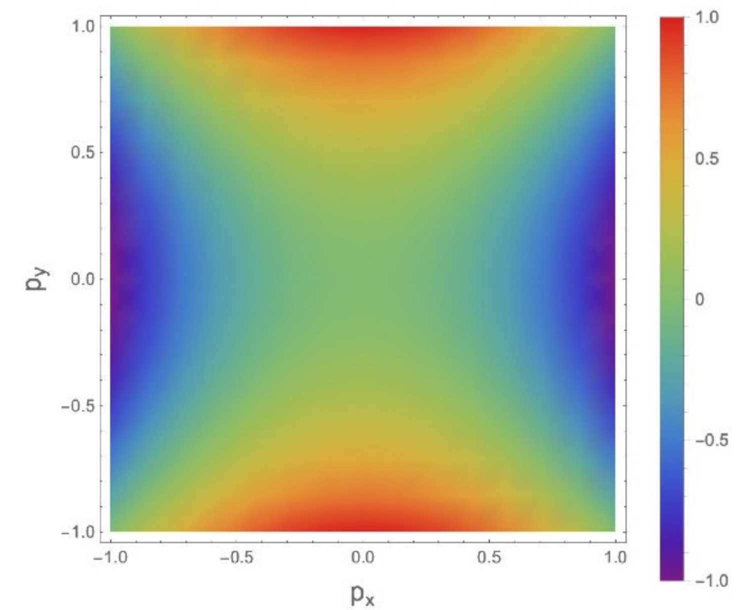
Spin polarization (of a neutral fluid)

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

Illustration



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

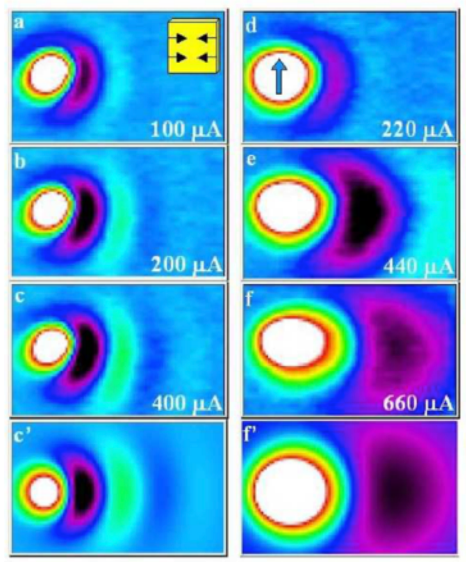


Spin polarization along z-direction in phase space from SIP.

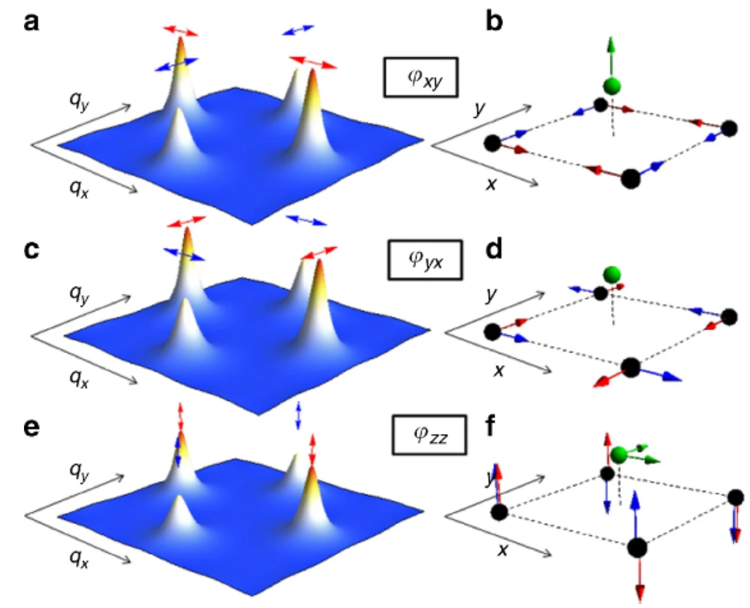
$$\mathscr{A}^i_{SIP} \propto \epsilon^{ikj} Q_{jl} \sigma^l{}_k\,, \qquad Q_{ij} = \hat{p}_i \hat{p}_j - \frac{1}{3}\delta_{ij}$$

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

Observation?



strain-induced polarization in n-type GaAs, Crooker and Smith, PRL, 04'

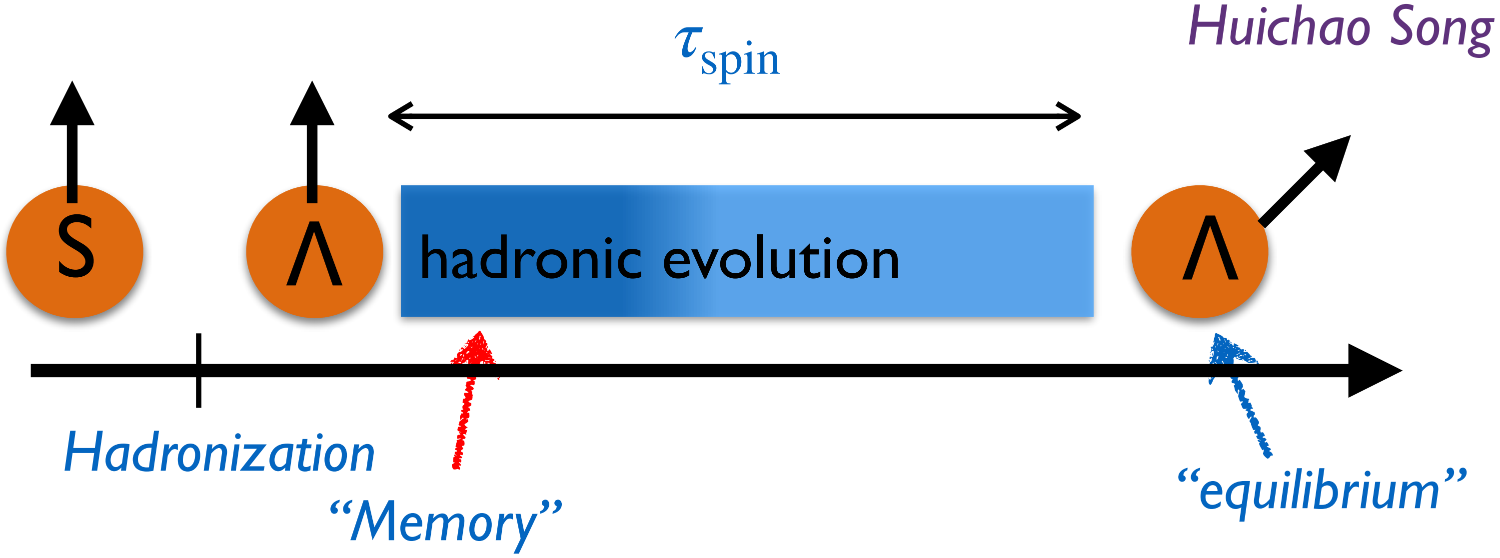


strain-induced polarization in BaFe2As2, Kissikov et al, Nature communication, 18'

- 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 ?

Phenomenology

Baochi Fu, Shuai Liu, Longgang Pang, Huichao Song and YY, PRL 21

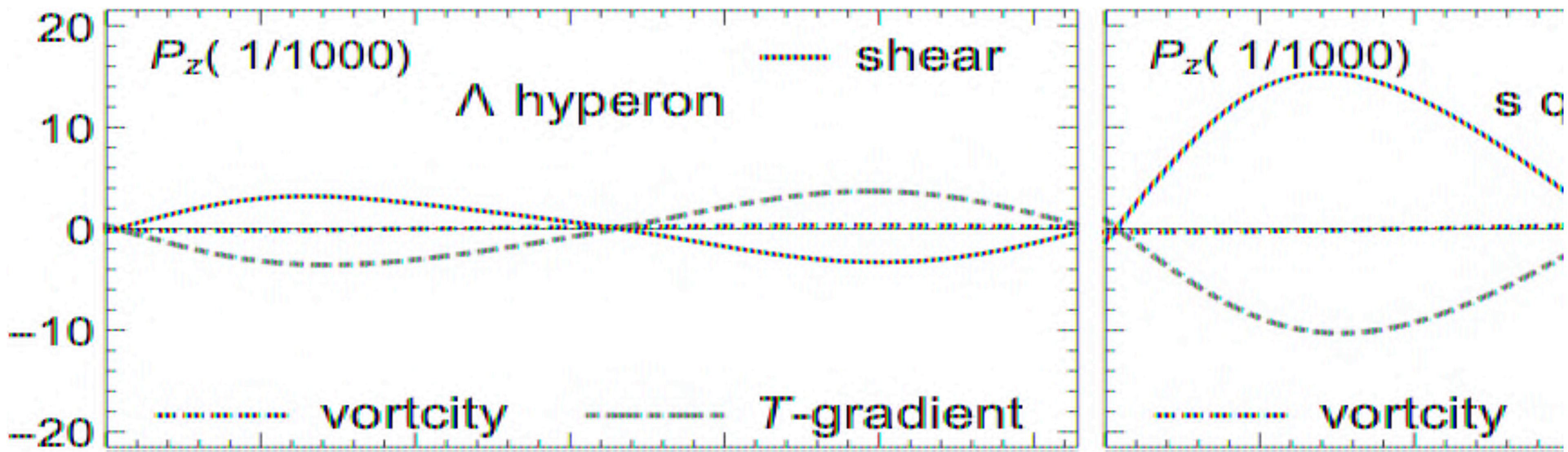


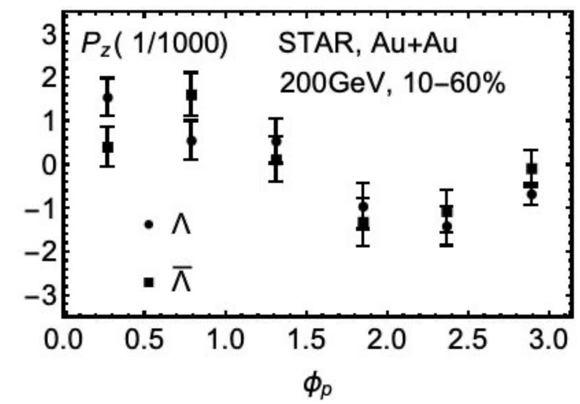
- Hydro. profile from AMPT (initial condition)+MUSIC.
- Two benchmark scenarios:
  - "Lambda equilibrium": Λ is born in equilibrium.
  - "Strange memory": Λ inherits the polarization of s-quarks

NB: spin-dependent d.o.f. might not be in equilibrium even if spin-independent ones are.

Differential longitudinal polarization (similar story for P_y)

Baochi Fu, Shuai Liu, Longgang Pang, Huichao Song and YY, PRL 21





vs transverse azimuthal angle ϕ_p

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

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

see also Becattini et al, 2103.14621; Cong Yi et al, 2106.00283.

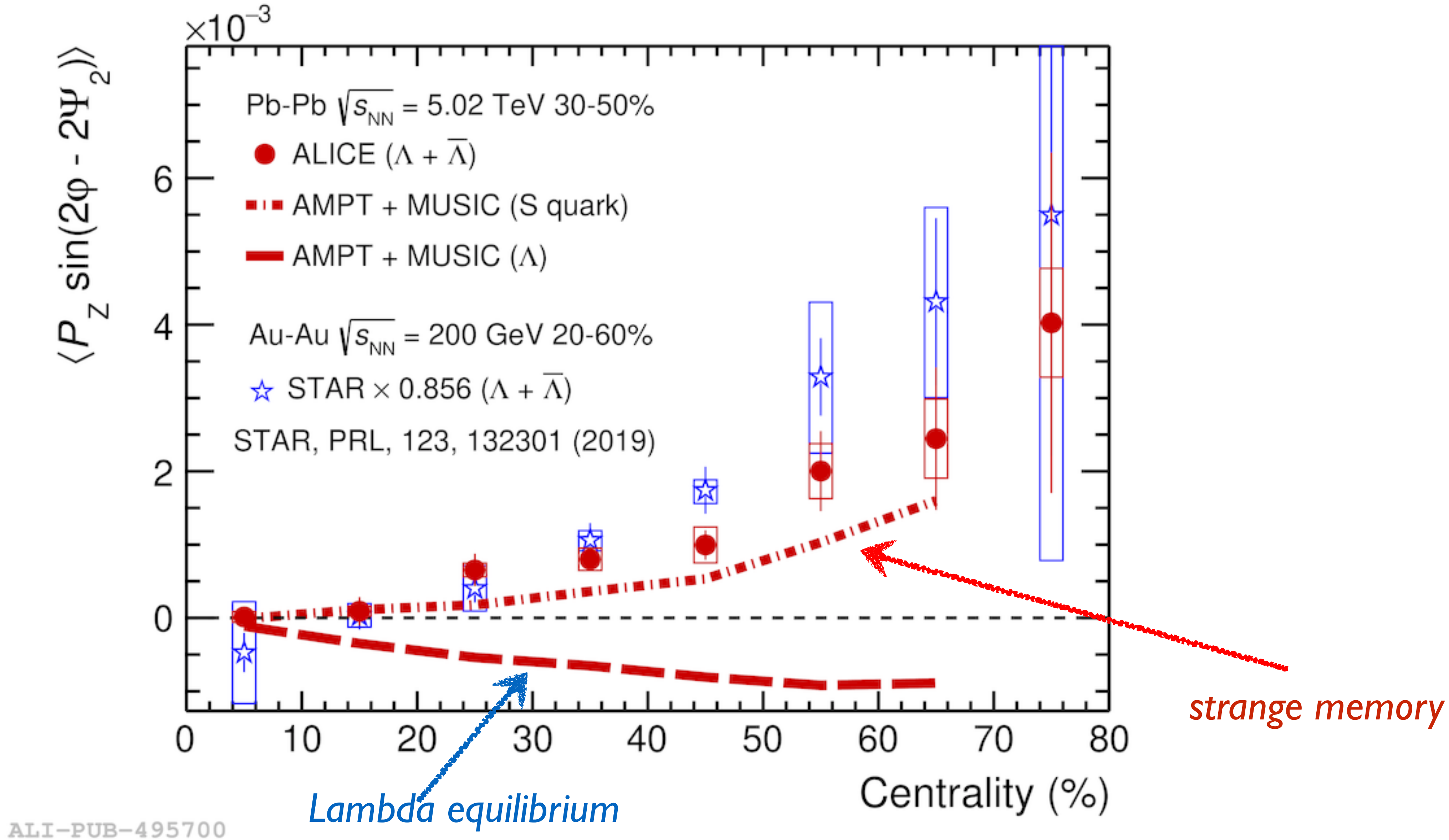
- "Strange memory" scenario: SIP determines the qualitative feature of differential polarization in

  - Macroscopic manifestation of Berry phase effects?

LHC

ALICE collaboration: 2107.11183;

benchmark calculations by Baochi Fu&Huicaho Song



- Tantalizing yet inconclusive evidence for SIP.
- The observation of SIP in QGP might be its first detection among all kinds of fluid!

Spin Hall effect induced by μ_B gradient

- SHE (induced by baryon density gradient) separates Lambda and anti-Lambda.

Theory: Son, Yamamoto, PRD 12; Di-Lung Yang, Hattori, Yoshimasa, PRD 19' … ; First phenomenological study: Liu-YY, 2006.12421, PRD21.

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

Shen et al, 2106.08125 on its effect on global spin polarization (splitting).

- Since its first detection in 2004, all known SHE materials (semi-conductors, metals, insulators) are not exceeding room temperature and are microscopically described by QED.

- Observation of SHE in HIC where QCD matter at trillion degrees is created with spin carriers interacting through strong interaction?

  - *Looking for SHE at difference in $\Lambda, \overline{\Lambda}$ differential polarization at lower beam energy (e.g. BESII) and forward rapidity; prediction is coming!*

Baochi Fu, Longgang Pang, Huichao Song, YY, to appear.

Summary and outlook

Summary

- Differential spin polarization: probes the spin-momentum correlation of QCD matter and is related to Berry curvature of spin carriers .

  - Response theory analyses the effects of hydro. gradient on spin polarization systematically.

- Shear-induced polarization (SIP): possible signature@RHIC and LHC.

- Spin Hall effect via gradient : new probe of baryon-rich QCD matter.

- Not covered: Berry curvature and topology in color superconducting phase.

Noriyuki Sogabe, YY, to appear.

Ultimate goal: spin and phase structure of QCD matter.

Back-up

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.