“Spin Puzzle” Spins Back

Outline

- Significant progress in understanding spin polarization generation: e.g. shear-induced polarization, baryonic spin Hall effect
- Puzzling recent BESII and pPb data
- Outlook

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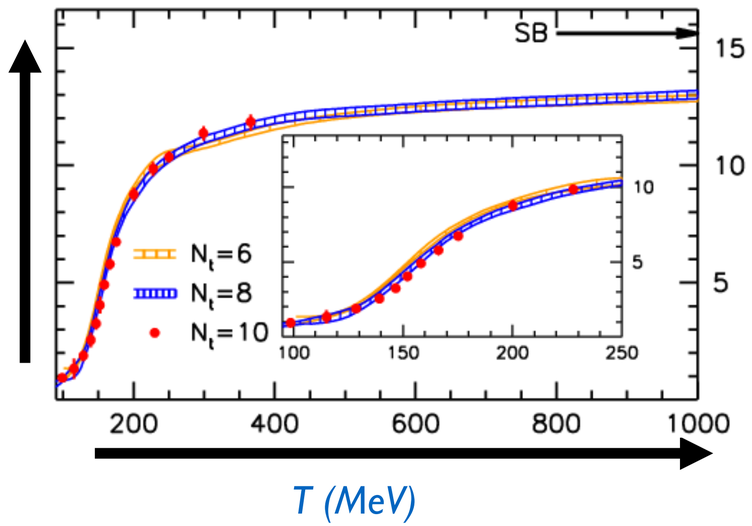
RHIC/AGS meeting, June. 11th, 2024

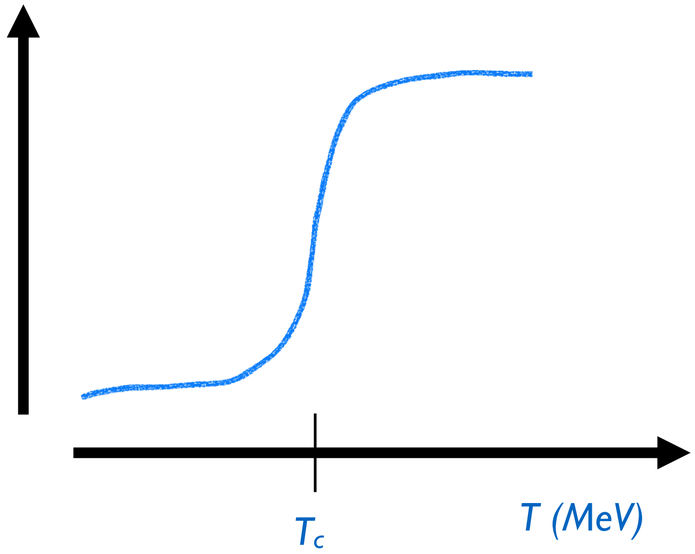
Spin and Phase Structure

ε/T^4~# of Degree of freedom



(Budapest-Marseille-Wuppertal Collaboration, JHEP'10)

# of spin carrier



- Spin carriers change dramatically near transition temperature
- Λ spin polarization/vector meson spin alignment measurement in heavy-ion collisions open a new frontier to investigate QCD matter

STAR Nature 2017, 2023

Polarization Generation in HIC

- Vorticity/rotation effect describes the trends of momentum-averaged (global) Λ polarization; was considered as the main mechanism for generating polarization

$$\hat{s} \parallel \overrightarrow{\Omega}$$

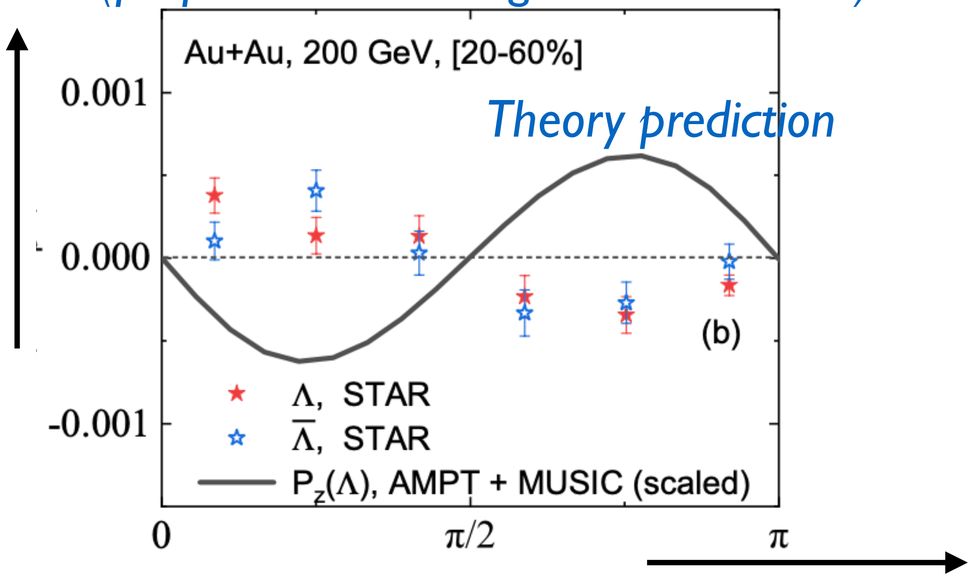
Xin-Nian Wang, Zuo-Tang Liang, PRL 05';
Becattini et al, Annals Phys 13'

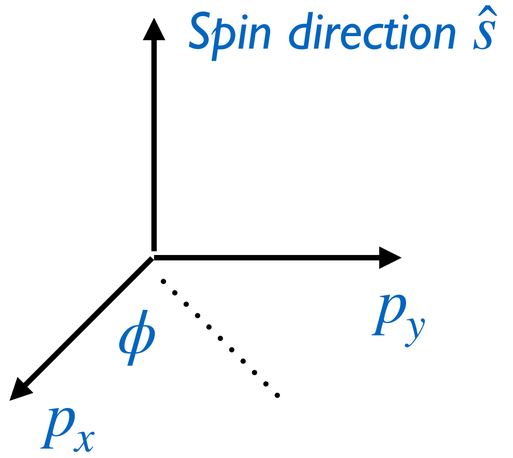
- Since 2021', significant progress reveals rich spin effects
- It is instructive to revisit spin "sign puzzle" for differential polarization

Differential Spin Polarization

STAR Collaboration PRL 19

Spin along beam direction (perpendicular to angular momentum)

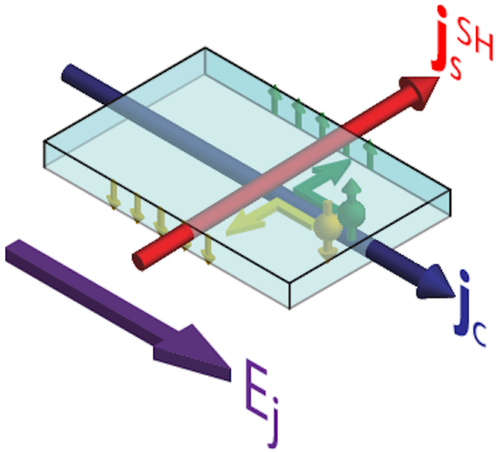




- Data indicates non-trivial spin-motion correlation, yet its origin is puzzling

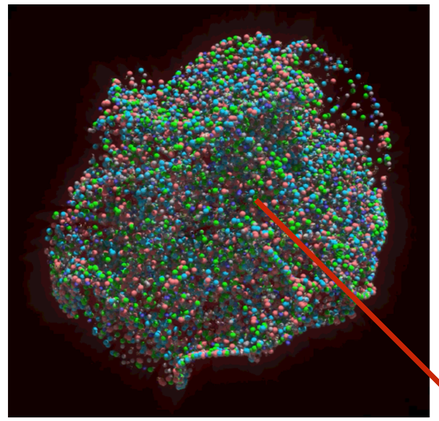
Hydro. simulations based on local vorticity effect predict qualitatively different behavior ("sign puzzle")

Spin Hall Effect



Meyer et al, Nature material 17

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



$$\hat{s} \propto \vec{v} \times \vec{\partial}$$

Direction of gradient

- Electric force generates spin-motion correlation
- The gradient of density (e.g. momentum, energy/charge density) in QGP acts as generalized force that correlates spin and motion;

can be analyzed systematically by extending usual gradient expansion to spin observables

Uncovering New Effects

Shuai Liu-YY JHEP 21
Also Becattini et al, PLB 21

Spin in phase space

$$s^i(t,\vec{x},\vec{p}) = c_\omega \omega^i + c_T \epsilon^{ijk} v_j \partial_k T + c_\sigma \epsilon^{ikj} \hat{v}_j \hat{v}_l \sigma^l{}_k$$

T-gradient *Shear-induced polarization*

$$\vec{\omega} = \nabla \times \vec{u}$$

$$\sigma_{ij} = (\partial_i u_j + \partial_j u_i)$$

Vorticity effect (dominating the global polarization)

Generating spin-motion correlation, dominating differential polarization

- Shear-induced polarization (SIP): allowed by symmetry, was never considered before
- One-loop calculation and quantum kinetic theory confirm the existence of SIP: $c_\omega \sim c_\sigma \propto$ density of spin carriers
- Baryon density gradient also polarizes spin (Baryonic Spin Hall effect)

Shuai Liu and YY, PRD 20; Fu et al, 2022

$$\vec{s} \propto \vec{v} \times \vec{\partial} \mu_B$$

Phenomenological Implications

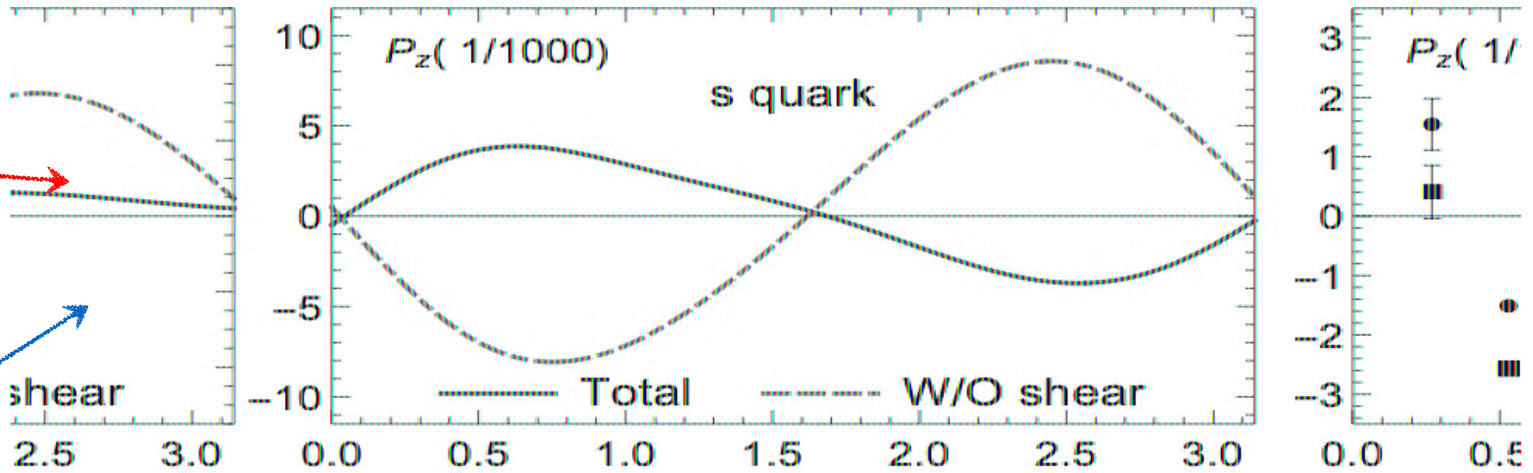
Particle distribution: ϵ, u^{μ} + gradient corrections

Spin distribution $\propto$ gradient; sensitive to initial condition, transport coefficients, etc

e.g. Palermo et al:, arXiv: 2404.14295

Differential Polarization and SIP

Baochi Fu, Shuai Liu, Longgang Pang, Huichao Song, YY, PRL 21
also confirmed in Becattini et al PRL 21

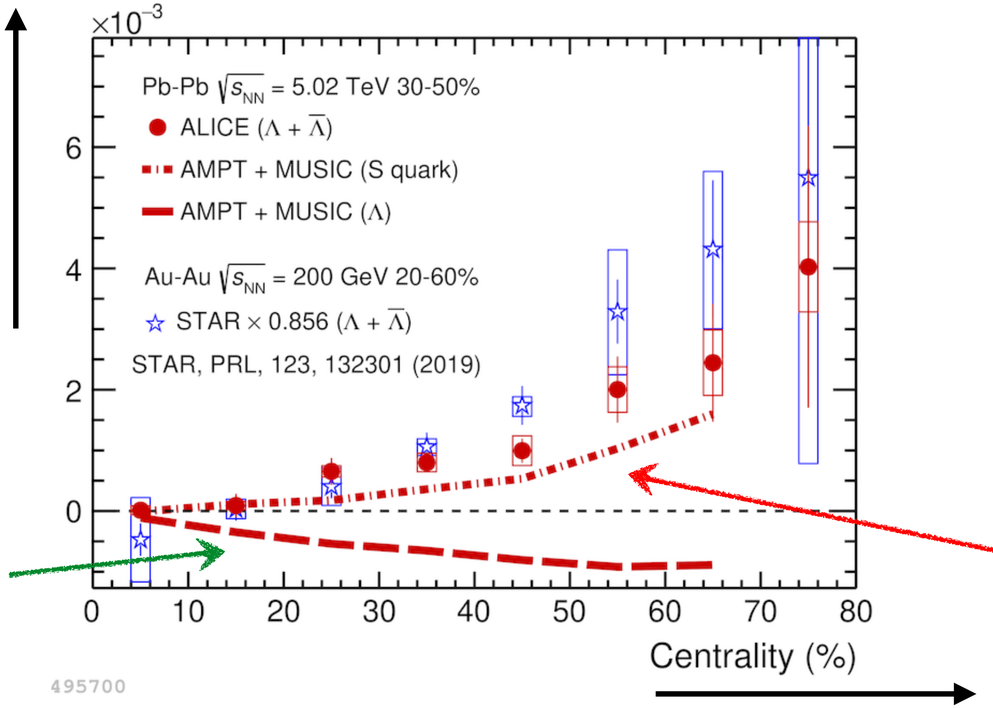


vs transverse azimuthal angle ϕ_p

- Shear-induced polarization (SIP) contribution qualitatively agrees with the data
- Theoretical uncertainty: freezeout prescription for spin; associated transport coefficients in strongly coupled QGP

$P_{2,z}$: *Coefficient of* $\sin(2\phi)$ *modulation*

LHC results from ALICE collaboration PRL 22



Suppressing shear effect

Including shear effect

Stronger shear stress

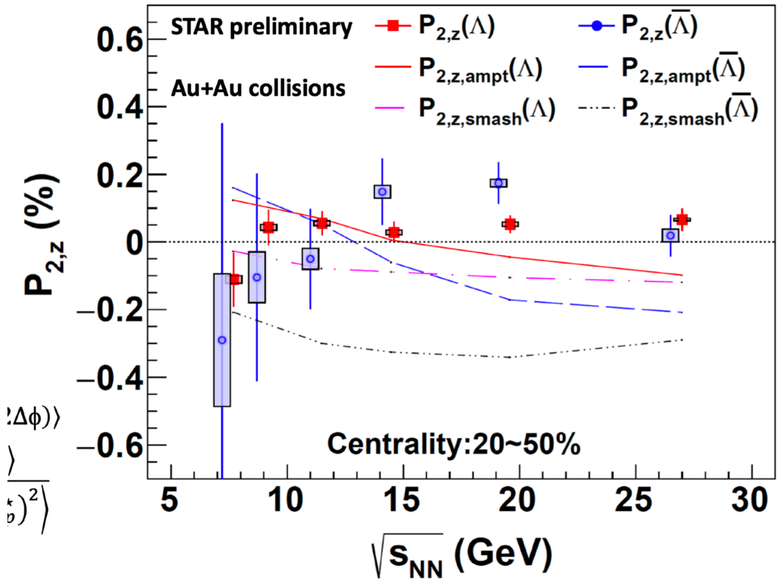
- Tantalizing evidence for SIP: data can no be understood without including shear effects. More efforts are needed to claim discovery

Shear effects on other spin observables: STAR PRL 23

Differential Polarization$\approx\partial T$ effect+Shear effect +$\partial\mu_B$ effect

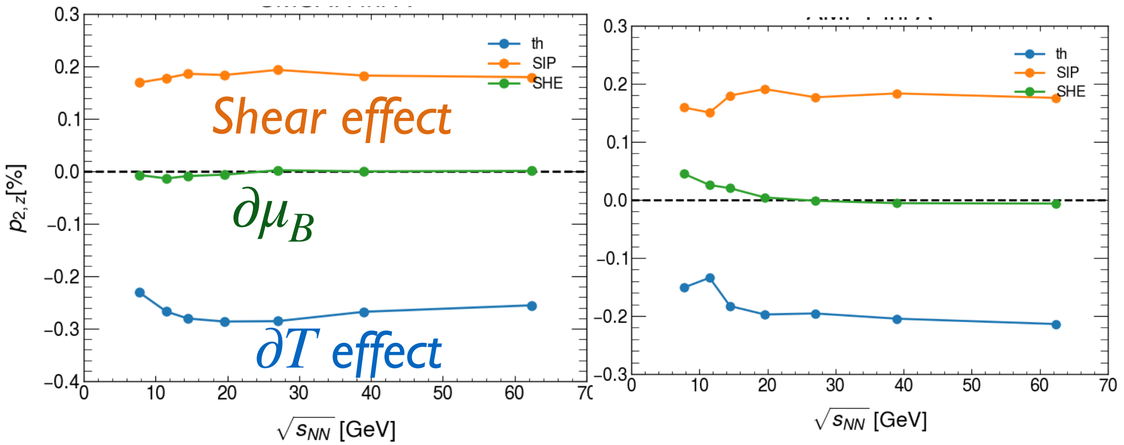
- Shear-induced polarization plays an important role in resolving differential longitudinal polarization puzzle
- Baryonic spin Hall effect might be measured at BES energies
- Nevertheless, recent pPb and BESII data bring new surprises

BESII Results of $P_{2,z}$



STAR talk at SQM 24'

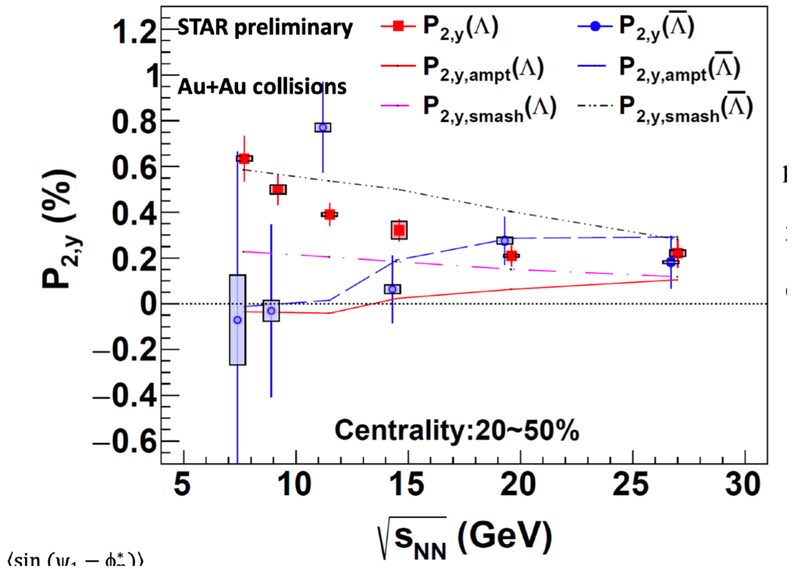
SMASH initial condition *AMPT initial condition*



Hydro. model calculations by Xiang-Yu Wu

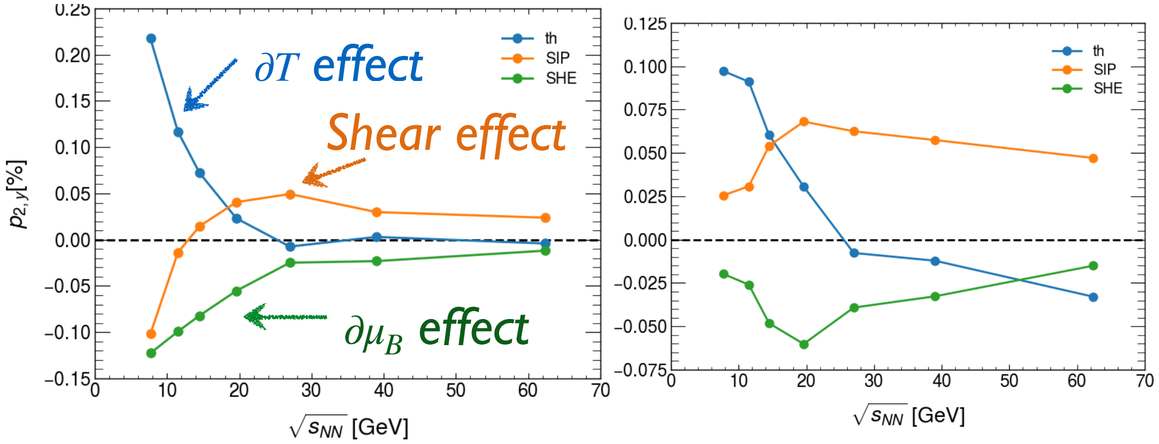
- Shear effect is almost cancelled by ∂T effect ; current model calculations fail to describe data quantitatively

BESII Results of $P_{2,y}$



STAR talk at SQM 24'

SMASH initial condition *AMPT initial condition*

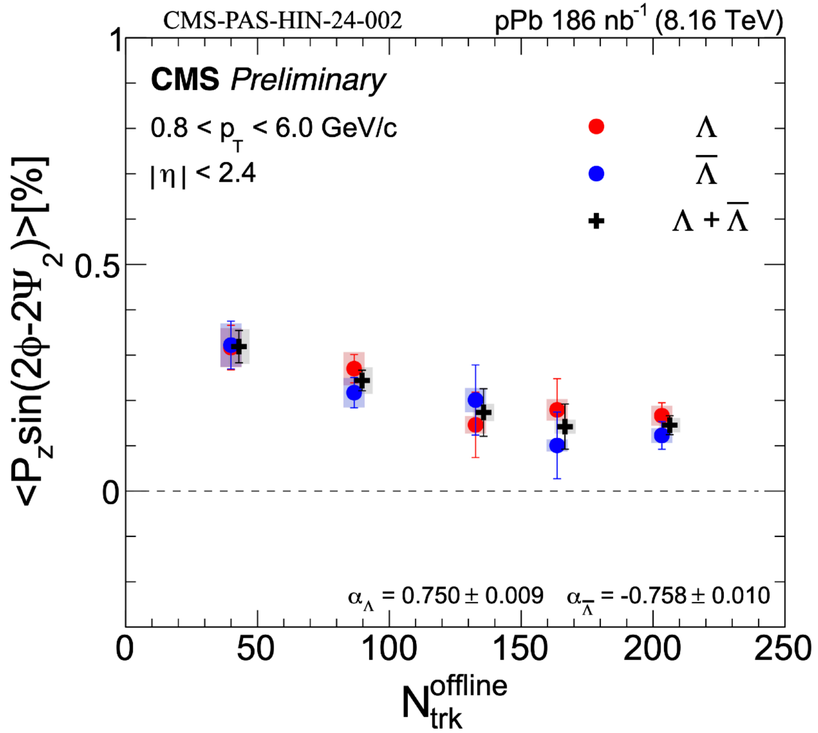


Hydro. model calculations by Xiang-Yu Wu

- $P_{2,y}$ increases with decreasing $\sqrt{s}$
- Different effects show non-monotonic dependence on $\sqrt{s}$
- Current model calculations fail to describe data quantitatively

Surprising p-Pb results

CMS at SQM 24'



- Differential polarization is present even without hydro. flow and increases with decreasing multiplicity
- New probe into the emergence of collectivity?

Spin Generation Far-from-equilibrium

$$\vec{s} \propto \vec{v} \times \vec{\partial} f$$

- By reformulating Quantum kinetic theory, we find momentum density gradient generates spin-motion correlation (the off-equilibrium generalization of spin Hall effect)

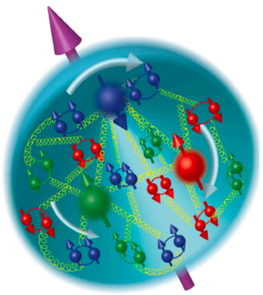
Zong-Lin Mo, YY in preparation

- Quantitative study is urgently needed

Summary

- Recent theoretical progress uncovers novel mechanism for spin polarization in QCD plasma
- Exciting new data, however, challenges current theoretical understanding; new puzzle, new opportunities

Outlook: QCD Spin Structure



$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L$$

Xiangdong Ji et al, Nature Review, 20

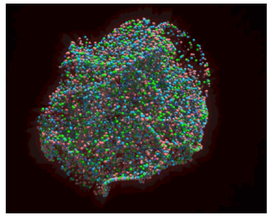
orbital ang. momen.

quark spin (only $\approx 20\,\%$ *)*

gluon spin (up to $50\,\%$ *)*

- Is the complex spin structure specific to confinement? Or a generic feature of non-perturbative quark-gluon interaction? EIC alone can not answer those questions

- Need to examine deconfined but strongly-coupled quark matter

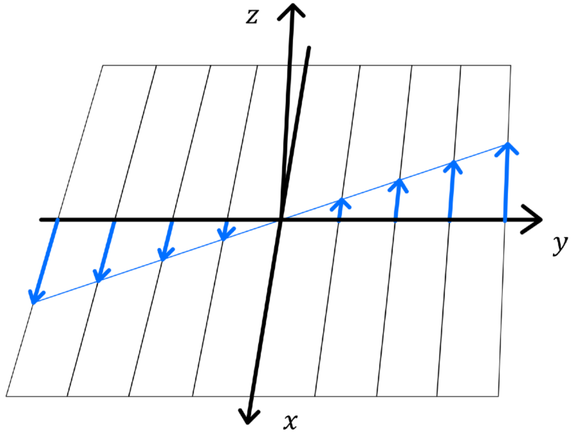


Total angular momentum $\hat{J} \neq 0$

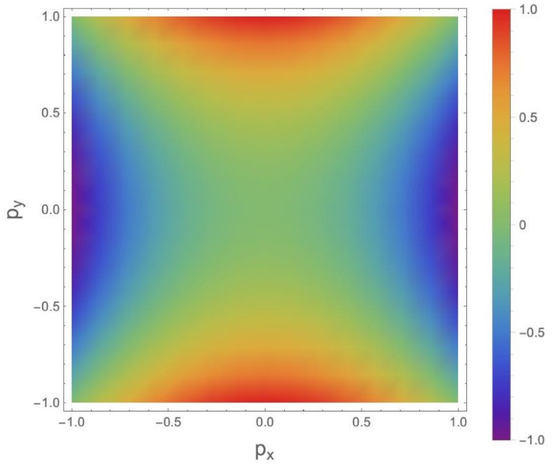
$$(J)_{\mathrm{QGP}} = \frac{1}{2}\Delta\Sigma + \Delta G + L$$

Back-up

How Shear Induces Polarization



$$s^i \propto \epsilon^{ikj}\hat{v}_j\hat{v}_l\sigma^l{}_k$$

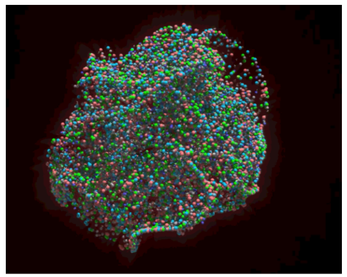


A standard shear flow profile:
$\omega^z \neq 0\,, \sigma^{xy} \neq 0$

Distribution of s^z *in* $v_x - v_y$ *plane due to shear force; vorticity does not induce any momentum distribution*

Spin Structure of Quark Matter

Total angular momentum
$\hat{J} \neq 0$



$$J = \frac{1}{2}\Delta\Sigma + \Delta G + L$$

gluon spin? *orbital ang. mom.?*

- Consider rotating hot/dense quark matter

Quark spin: $\frac{1}{2}\frac{\Delta\Sigma}{\Omega} = \frac{1}{12}T^2 + c_0 g^2$

Two-loop, De-fu Hou et al 2013

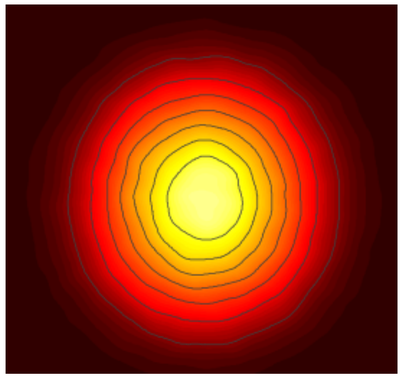
Related to Chiral Vortical Effect coefficients

$$\frac{\Delta G, L}{\Omega} = ?$$

Analyzing and comparing spin structure will deepen the understanding of confinement/deconfinement transition

Baryonic Spin Hall Effect

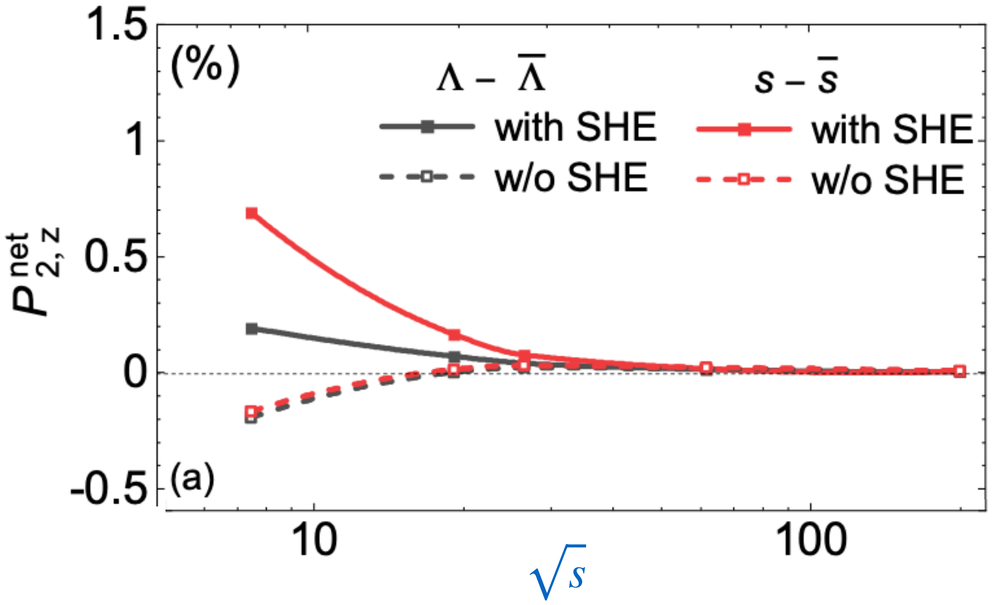
Baochi Fu, Longgang Pang, Huichao Song, YY, 2201.12970



Initial n_B profile at $\sqrt{s} = 7.7$ GeV from AMPT

$$\vec{s} \propto \vec{v} \times \vec{\partial}\mu_B$$

Coefficient of $\sin(2\phi)$ modulation: $\Lambda - \bar{\Lambda}$

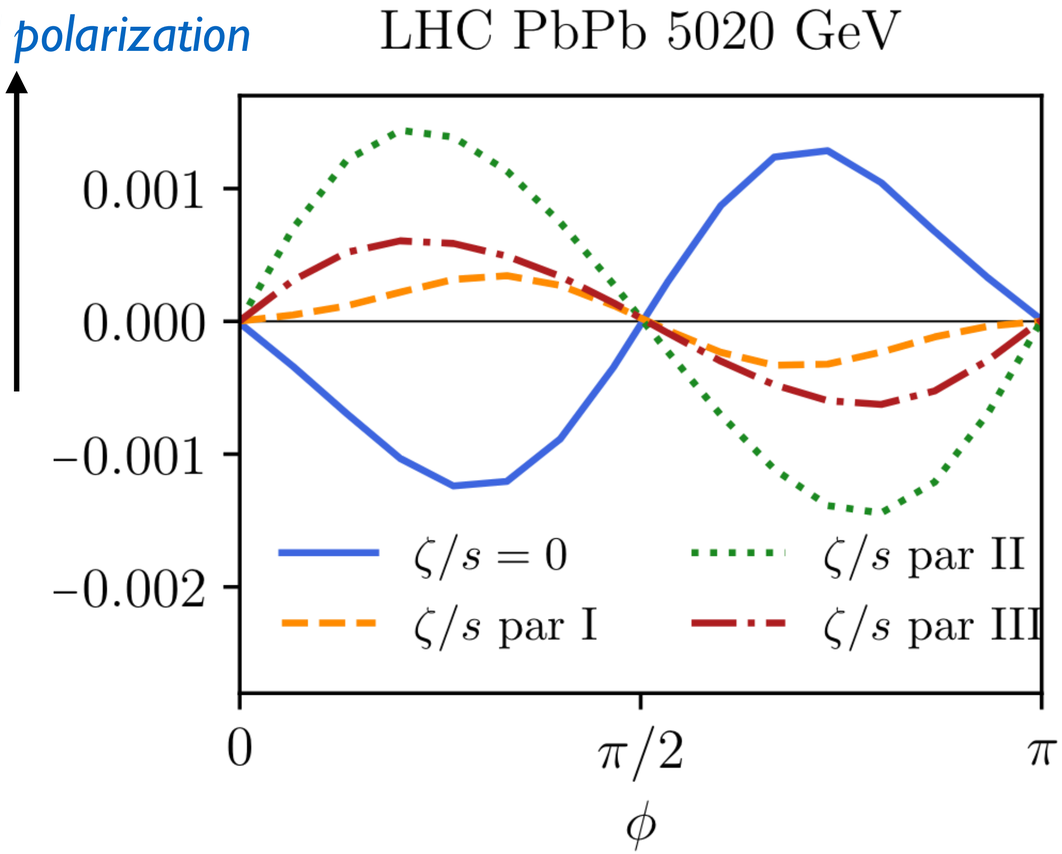


- Sensitive to EoS, diffusive constant and initial baryon stopping

A similarly effect induces neutrino current in supernovea *Di-Lun Yang, Naoki Yamamoto PRD 24*

Sensitivity to Transport Coefficient

Longitudinal polarization



Palermo et al:, arXiv: 2404.14295

- Extension to BESII data can help constraining transport properties of Baryon-rich QGP

An Emerging New Field

- Rapid progress in relativistic quantum kinetic theory, spin hydrodynamics

Works by many

- Dissipative or not: shear effect is typically dissipative but spin is inherently quantum.

Shear-induced polarization examplifies a new class of emergent phenomena that the system is off-equilibrium, yet the transport is non-dissipative

Becattini and YY, in preparation.

Spin, Quantum Matter and QCD

- Broad context: spin effects reveal quantum behavior of many-body systems
- QCD employs a sophisticated way to build up proton spin
- Λ spin polarization/vector meson spin alignment measurement in heavy-ion collisions open a new frontier to study the properties of QCD matter

STAR Nature 2017, 2023

(Modern view: quantum effects are important in characterizing and understanding phases)

Spin Dynamics

- Baryon density gradient also polarizes spin; the experimental investigation is under way

Shuai Liu and YY, PRD 20; Fu et al, 2022

A similarly effect induces neutrino current in supernovea

Di-Lun Yang, Naoki Yamamoto PRD 24

- Rapid progress in relativistic quantum kinetic theory, spin hydrodynamics

Works by many, e.g. Jianhua Gao, Xu-Guang Huang, Koichi Hattori, Defu Hou, Shu Lin, Shi Pu, Qun Wang, Pengfei Zhuang, Shuzhe Shi

- Dissipative or not: shear effect is typically dissipative but spin is inherently quantum. Calling for a deeper understanding

Becattini and YY, in progress.

Gradient Expansion

- Observables are expressible in terms of conserved densities, e.g., energy and momentum density (or flow velocity u^μ) for slow varying gradient $\partial \sim k,\ k\, l_{\text{mfp}} \ll 1$

In a collision, $kl_{\text{mfp}} \sim 0.1$

$$O = (\partial^0) + (\partial^1) + \dots$$

- All possible terms allowed by symmetry should be included with expansion coefficients computed from microscopic calculations

Reminiscent of effective field theory

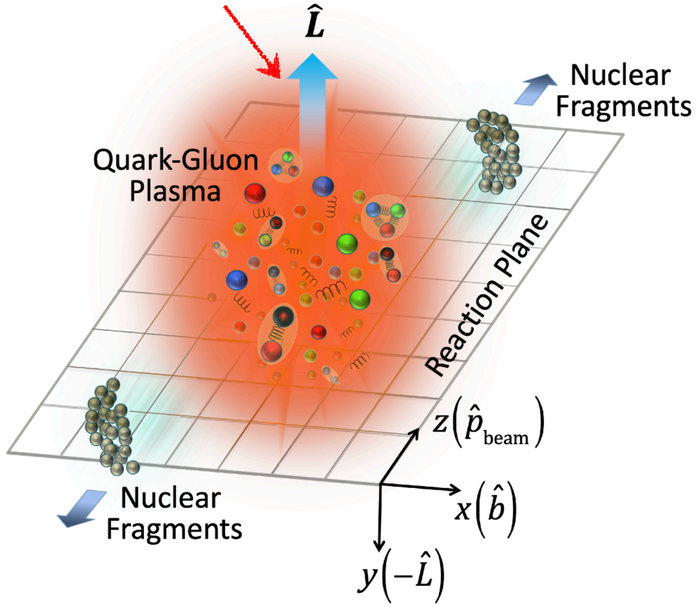
Constitutive relation in hydro: $T^{ij} = p\,\delta^{ij} + \eta\sigma^{ij} + \dots$

shear stress

- Applying the same method to spin observables

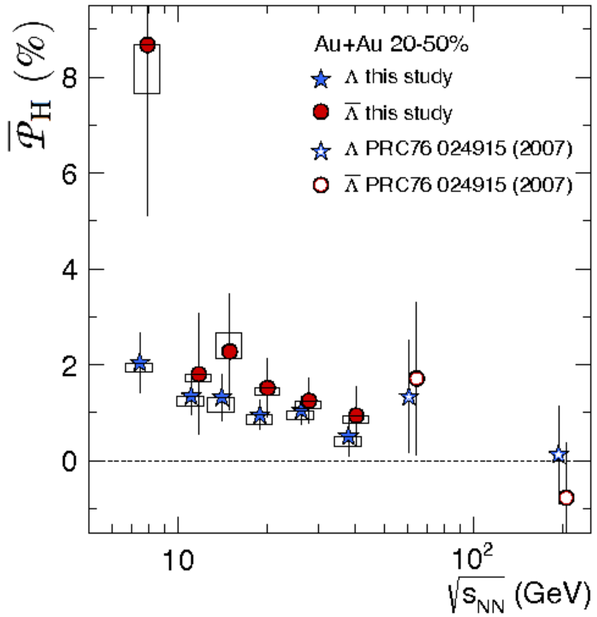
Λ Hyperon Polarization at RHIC

Direction of angular momentum



Rotating quark matter

STAR Collaboration Nature 17



Λ polarization (momentum-averaged) along the direction of angular momentum vs collision energy

Vorticity effect describes the trends of momentum-averaged Λ polarization (spin parallels to angular velocity)

Vector Meson Spin Alignment

- measures the difference between the occupation of transverse and longitudinal spin states

$$\delta\rho_{00} = \rho_{00}(\hat{n}) - \frac{1}{3} \propto \text{long. mode density - trans. mode density}$$

- shows non-trivial dependence on the species of mesons, centrality and $\sqrt{s}$ in both sign and magnitude; the underlying mechanism is under debate

e.g. Xin-Li Shen et al, PRL 23

- can be used to constrain in-medium properties of vector mesons

$$\delta\rho_{00}^{(0)} \propto E_L(p) - E_T(p)$$