重离子碰撞中的自旋极化现象

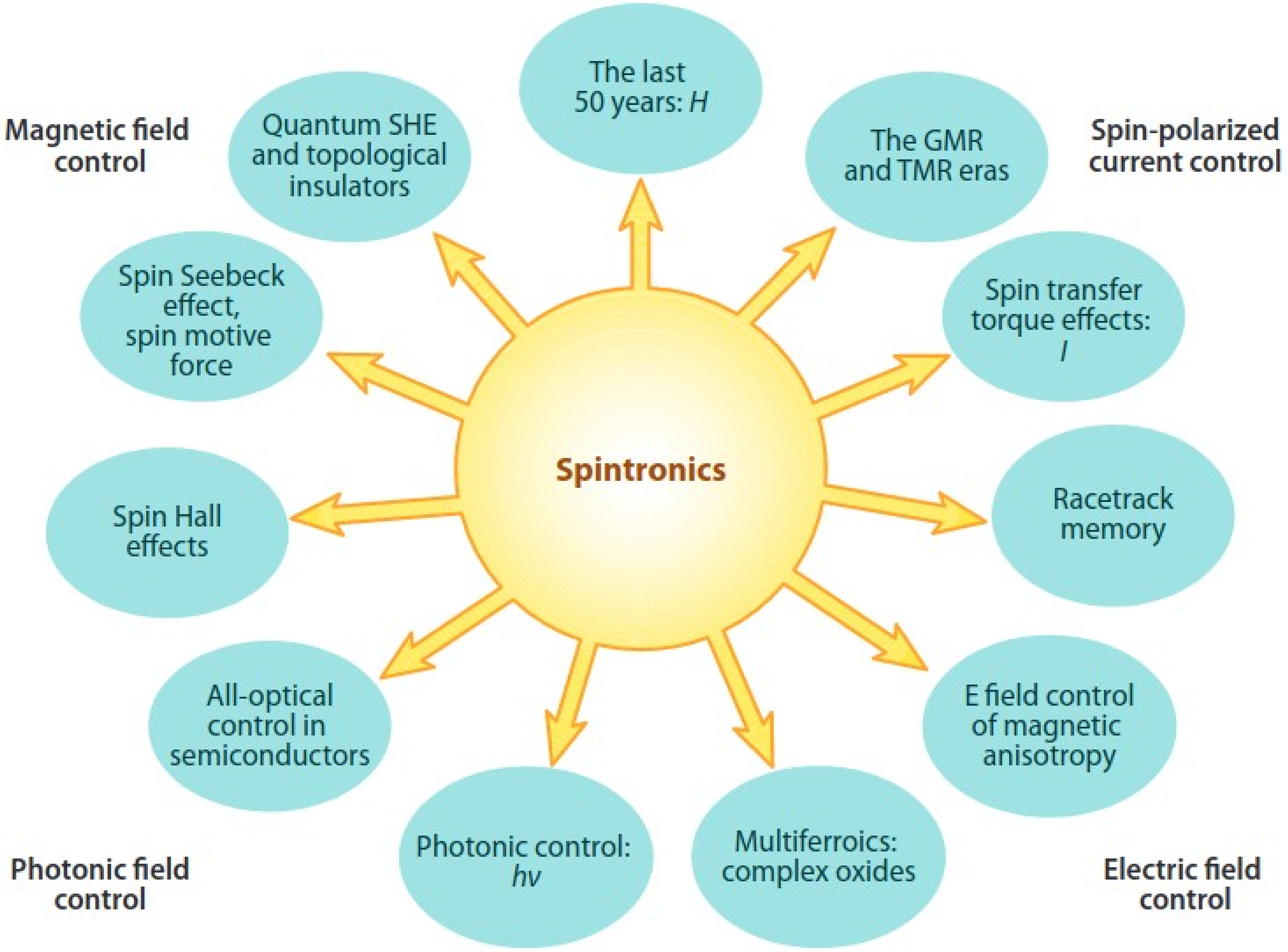
Shu Lin
Sun Yat-Sen University

第一届“粤港澳”核物理论坛，2022.7.2-6

Outline

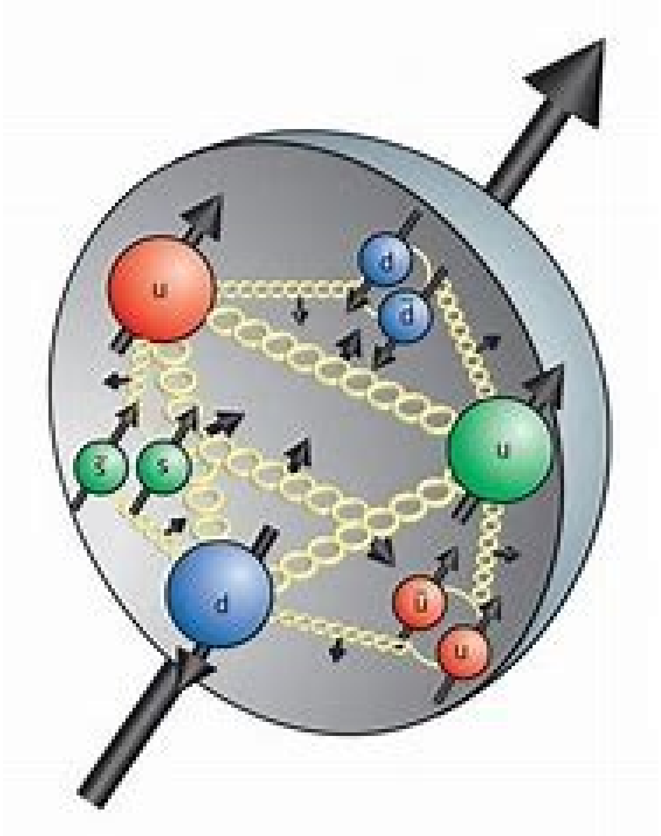
- Spin polarization in different physical systems
- Measurement of spin polarization in HIC
- Success in global polarization and puzzle in local polarization
- Collisional contributions to spin polarization
- Summary and Outlook

Spintronics in condensed matter physics



Bader+Parkin
ARCMP 2010

Spin in particle physics



Proton spin puzzle
(1988-now)

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

Spin in high energy nuclear physics

- Spin not conserved, spin angular momentum exchange with orbital angular momentum
- Spin coupling to external field such as magnetic, vorticity etc
- Offer a unique probe to polarized QCD medium

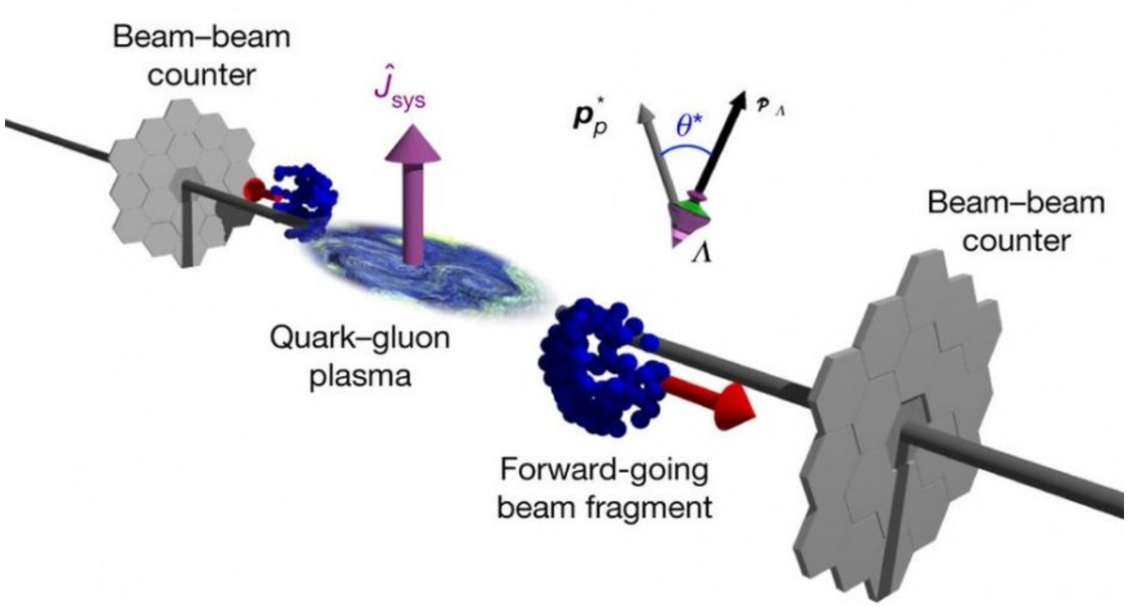
Explorations of spin polarization in HIC just begin!

Spin polarization measurement of J=1/2 particles

Baryon

$$\frac{dN}{d\cos\theta^*} = \frac{1}{2}[1 + \alpha_H P_H \cos\theta^*]$$

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



Spin polarization measurement of J=1 particles

Vecor meson

$$\frac{dN}{d\cos\theta^*} = N_0[1 - \rho_{00} + \cos^2\theta^*(3\rho_{00} - 1)]$$

$$\rho_{\lambda_1\lambda_2}, \quad \lambda_1, \lambda_2 = 1, 0, -1$$

spin density matrix

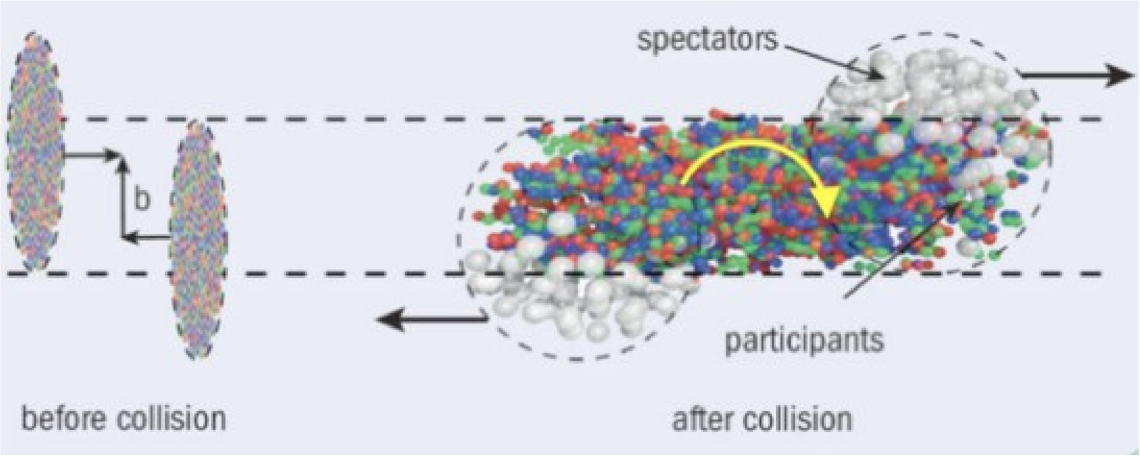
$$\rho_{00} < \frac{1}{3}$$

tend to be parallel to quantization axis

$$\rho_{00} > \frac{1}{3}$$

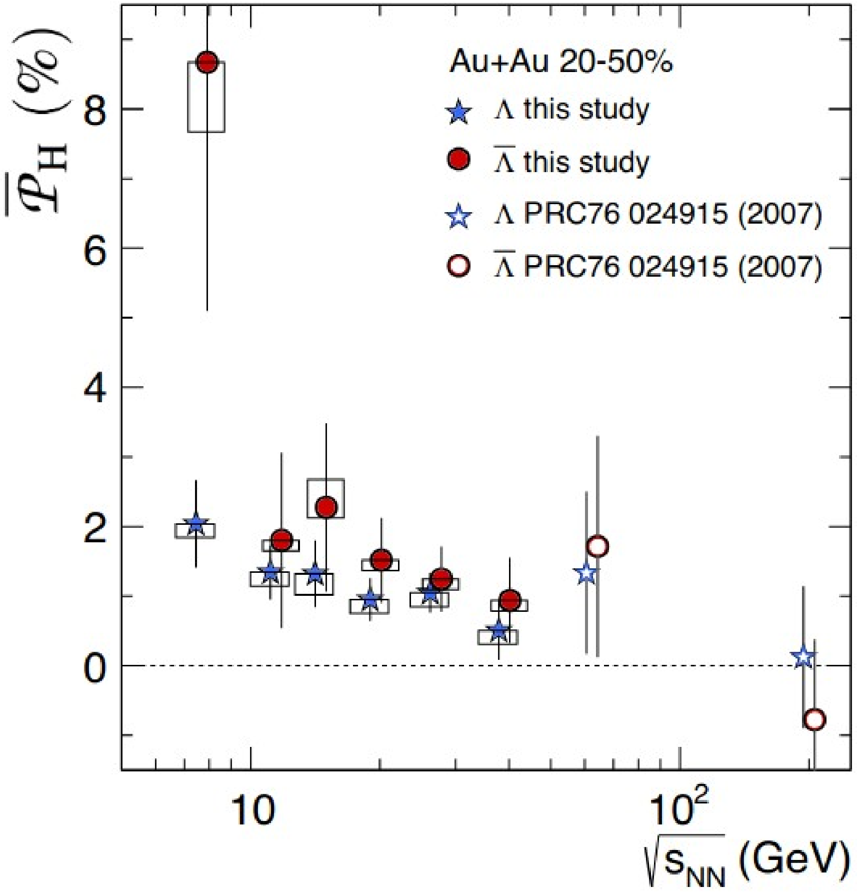
tend to be perpendicular to quantization axis

Λ Global Polarization at RHIC



$$L_{ini} \sim 10^5 \hbar \to S_{final}$$

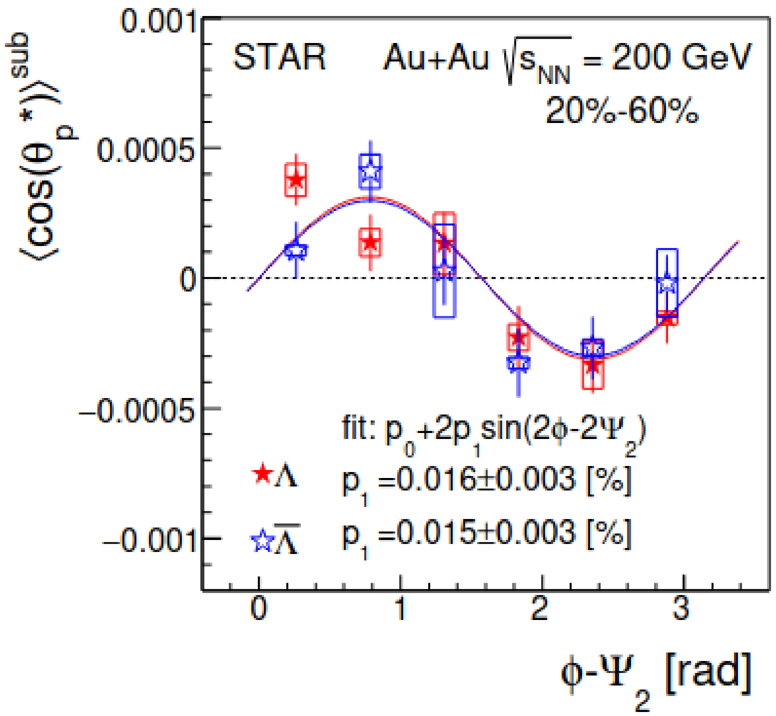
Liang, Wang, PRL 2005

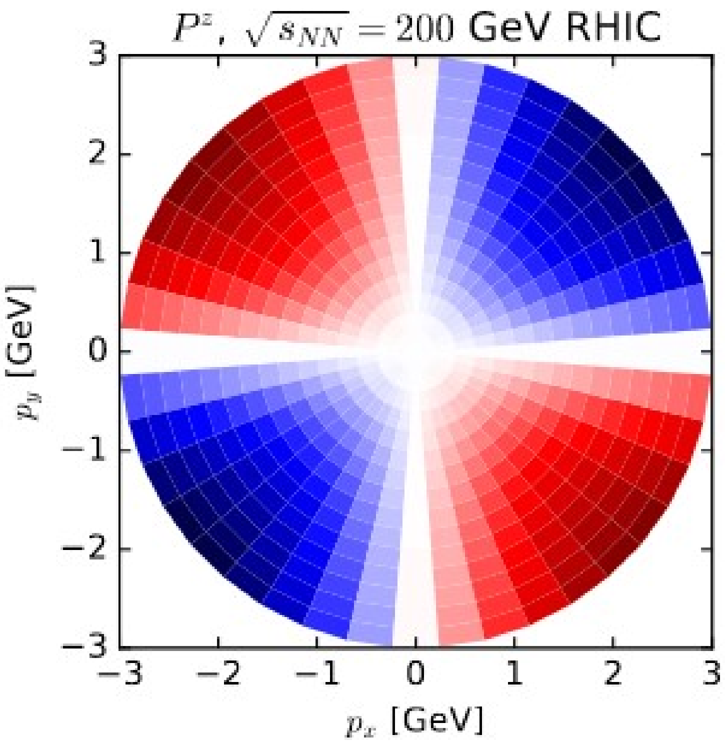


STAR collaboration, Nature 2017

$$e^{-\beta(H_0 - \mathbf{S}\cdot\omega)}$$

Λ Local polarization: sign puzzle



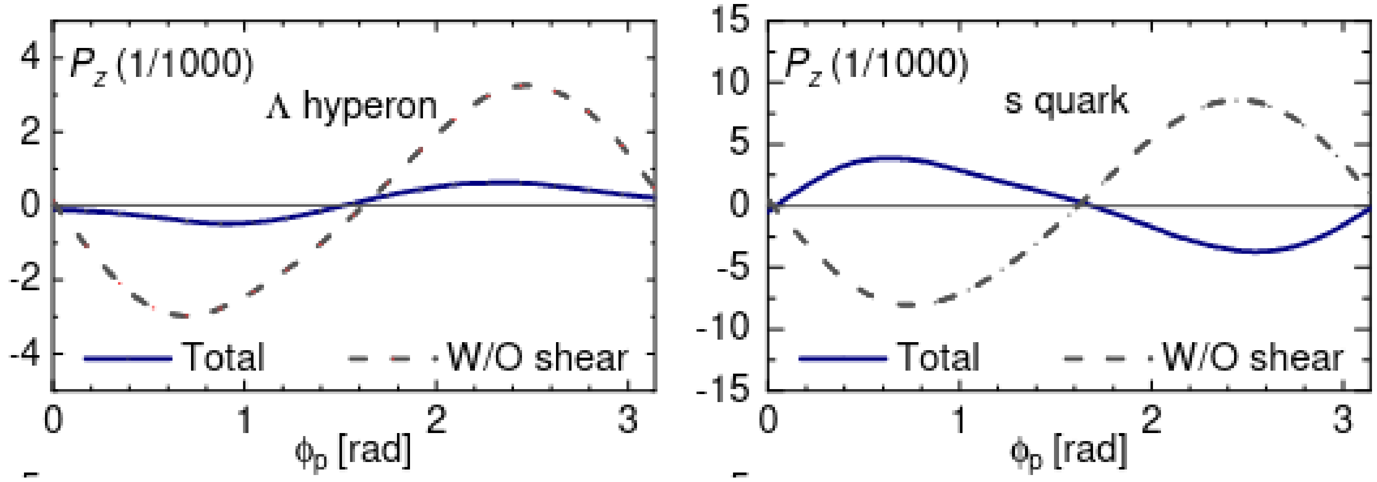


STAR collaboration, PRL 2019

Becattini, Karpenko, PRL 2018
Wei, Deng, Huang, PRC 2019
Wu, Pang, Huang, Wang, PRR 2019
Fu, Xu, Huang, Song, PRC 2021

$$e^{-\beta(H_0-\mathbf{S}\cdot\omega)}$$

Shear induced polarization



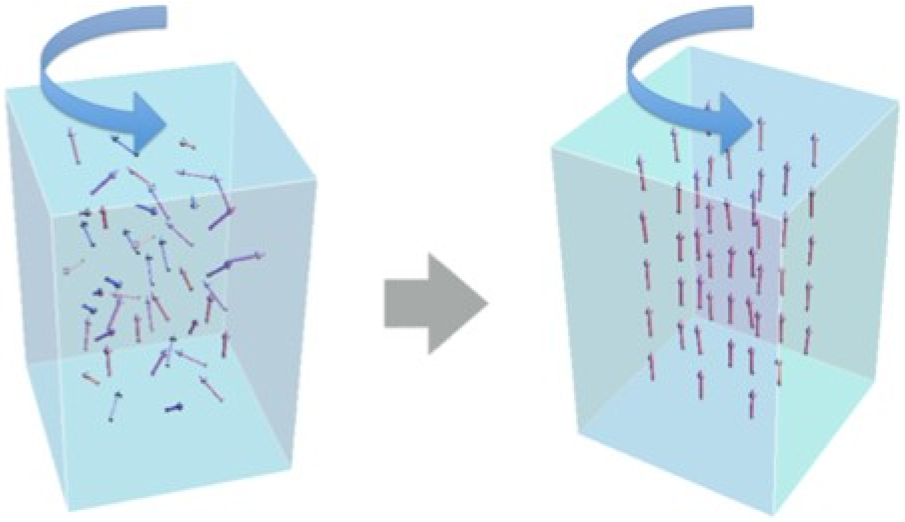
Liu, Yin JHEP 2021
Fu, Liu, Pang, Song, Yin, PRL 2021
Becattini, et al, PLB 2021, PRL 2021
Yi, Pu, Yang, PRC 2021

vorticity $\frac{1}{2}(\partial_x u_y - \partial_y u_x)$

shear $\frac{1}{2}(\partial_x u_y + \partial_y u_x)$

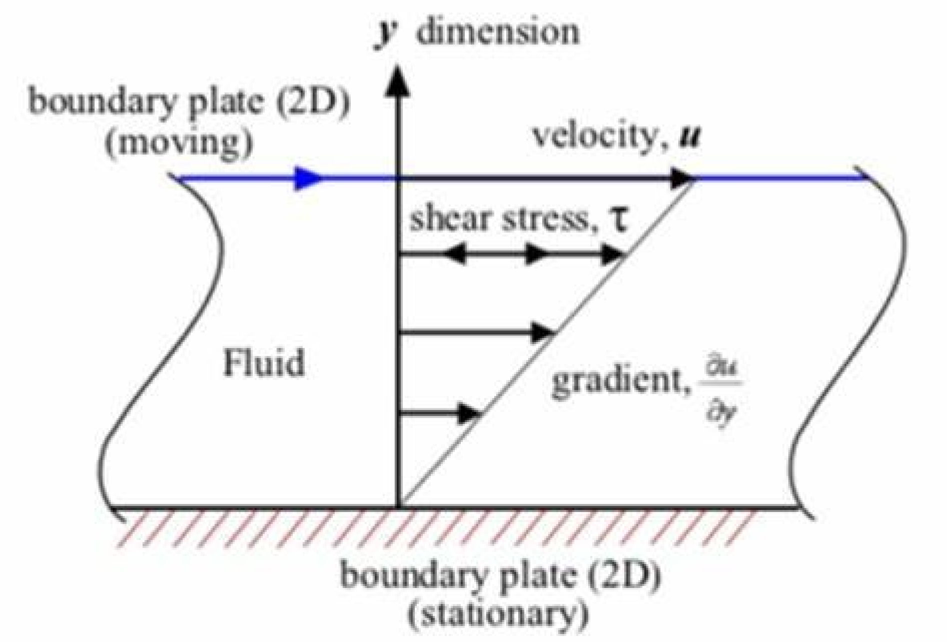
Caveat: shear induced polarization might not be sufficient

A fundamental difference between vorticity & shear



spin-vorticity coupling only (Barnett effect)

Equilbrium: collision vanishes
by detailed balance



spin-shear coupling + particle redistribution

Nonequilibrium:
Collision nonvanishing

Particle redistribution from spin-averaged kinetic theory

$$(\partial_t + \hat{\boldsymbol{p}} \cdot \boldsymbol{\nabla}_{\boldsymbol{x}})\, f_s(\boldsymbol{x}, \boldsymbol{p}, t) = -C_s^{2\leftrightarrow 2}[f] - C_s^{\text{“}1\leftrightarrow 2\text{”}}[f]$$

$f_s(\boldsymbol{x}, \boldsymbol{p}, t)$: distributions of quarks and transverse gluons

$C_s^{2\leftrightarrow 2}[f]$: elastic collisions

$C_s^{\text{“}1\leftrightarrow 2\text{”}}[f]$: inelastic collisions

Arnold, Moore and Yaffe, early 00s

shear induced particle redistribution → shear viscosity

$$\delta f \sim \partial f^{\mathrm{leq}}(p \cdot u)\, \tau \qquad \tau \sim \frac{1}{g^4 T}$$

Quantum kinetic theory (QKT)

- QKT in collisionless limit

sufficient for vorticity induced polarization

Hattori, Hidaka, Yang, PRD 2019
Weickgenannt, Sheng, Wang, Rishcke, PRD 2019
Gao, Liang, PRD 2019
Liu, Mameda, Huang, CPC 2020
Guo, CPC 2020

- Collisionful QKT

needed for shear induced polarization

Yang, Hattori, Hidaka JHEP 2020
Hattori, Hidaka, Yamamoto, Yang JHEP 2021
Weickgnnant et al, PRL 2021
Sheng et al, PRD 2021
Wang, Guo, Zhuang, EPJC 2021
Shi, Gale, Jeon, PRC 2021
SL, PRD 2022

Wigner function formalism

$$\tilde{S}^{<}(X=\frac{x+y}{2},P)=\int d^4(x-y)e^{iP\cdot(x-y)/\hbar}\langle S^{<}(x,y)\rangle$$

$$S^{<}=S^{<(0)}+\hbar S^{<(1)}$$

$$S^{<(0)}(X,P)=-2\pi\epsilon(P\cdot u)\delta(P^2-m^2)(\not{P}+m)f(X,P)$$

distribution function

$S^{<(1)}(X,P)$ encodes spin polarization

Composition of spin polarization

- Spin polarization ~ $\mathcal{A}^\mu = -2\pi\hbar\left[a^\mu f_A + \frac{\epsilon^{\mu\nu\rho\sigma}P_\rho u_\sigma \mathcal{D}_\nu f}{2(P\cdot u + m)}\right]\delta(P^2 - m^2)$

dynamical non-dynamical

a^μ dynamical spin vector

f_A parity violating distribution

$$\mathcal{D}_\nu = \partial_\nu - \Sigma_\nu^> - \Sigma_\nu^< \frac{1-f}{f}$$

green term: universal collision independent

blue term: collision dependent $-\Sigma_\nu^> - \Sigma_\nu^< \frac{1-f}{f} \sim \frac{\delta f}{\tau} \sim \partial f^{\rm leq}(p\cdot u)$

Parametrically the same as derivative term!

Example: kinetic theory for QED

$$(\partial_t + \hat{p}\cdot\nabla_x) f_p = -\frac{1}{2}\int_{p',k',k} (2\pi)^4\delta^4(P+K-P'-K')\frac{1}{16p_0k_0p_0'k_0'}\times$$
$$\Big[\ |\mathcal{M}|^2_{\mathrm{Coul},f}\left(f_pf_k(1-f_{p'})(1-f_{k'}) - f_{p'}f_{k'}(1-f_p)(1-f_k)\right)$$
$$+|\mathcal{M}|^2_{\mathrm{Comp},f}\left(f_p\tilde{f}_k(1+\tilde{f}_{p'})(1-f_{k'}) - \tilde{f}_{p'}f_{k'}(1-f_p)(1+\tilde{f}_k)\right)$$
$$+|\mathcal{M}|^2_{\mathrm{anni},f}\left(f_pf_k(1+\tilde{f}_{p'})(1+\tilde{f}_{k'}) - \tilde{f}_{p'}\tilde{f}_{k'}(1-f_p)(1-f_k)\right)\Big]$$

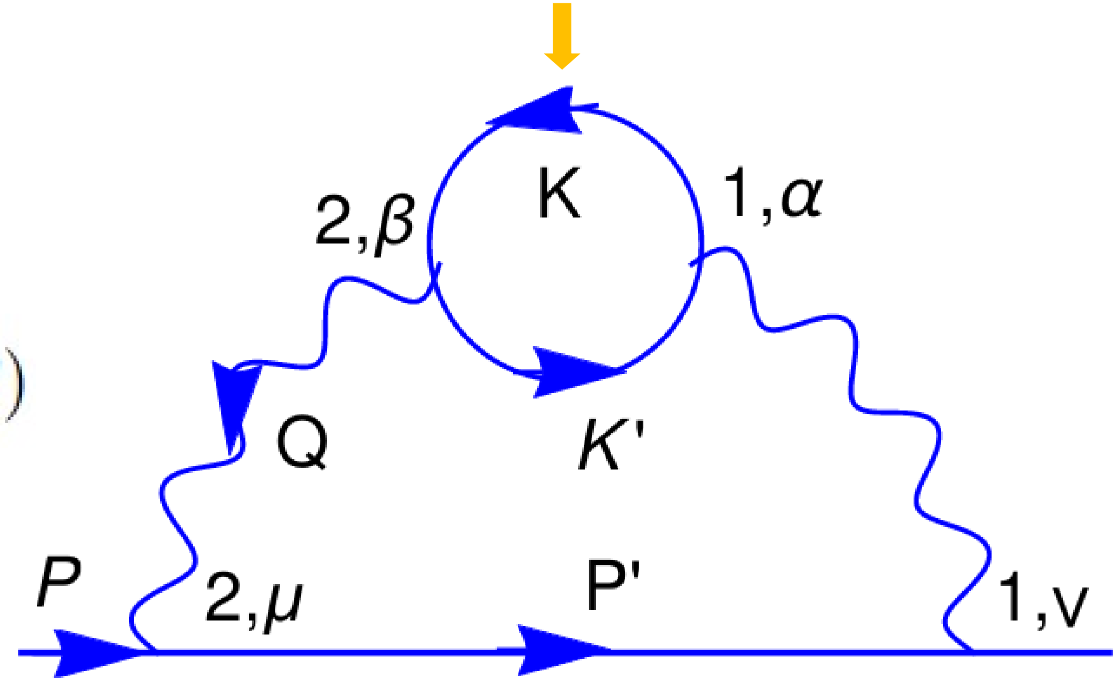
$$(\partial_t + \hat{p}\cdot\nabla_x) \tilde{f}_p = -\frac{1}{2}\int_{p',k',k} (2\pi)^4\delta^4(P+K-P'-K')\frac{1}{16p_0k_0p_0'k_0'}\times$$
$$\Big[\ |\mathcal{M}|^2_{\mathrm{Comp},\gamma}\left(\tilde{f}_pf_k(1-f_{p'})(1+\tilde{f}_{k'}) - f_{p'}\tilde{f}_{k'}(1+\tilde{f}_p)(1-f_k)\right)$$
$$+2N_f|\mathcal{M}|^2_{\mathrm{anni},\gamma}\left(\tilde{f}_p\tilde{f}_k(1-\tilde{f}_{p'})(1-\tilde{f}_{k'}) - f_{p'}f_{k'}(1+\tilde{f}_p)(1+\tilde{f}_k)\right)\Big]$$

Classical: Arnold, Moore and Yaffe, early 00s
Quantum generalization: SL, PRD 2022

Probe fermion in QED plasma with shear

shear induced medium
fermion redistribution

$\Sigma^{>}(P)$



probe massive fermion
m >> eT, Coulomb dominates, $\ln e^{-1}$
enhanced

SL, Wang, 2206.12573

Self-energy contribution to spin polarization

$$\mathcal{A}^i \simeq -\frac{1}{p_0+m}(I_2+I_3)\frac{\epsilon^{iml}p_n p_l S_{mn}}{p^5}\delta(P^2-m^2)C_f,$$

$$S_{ij} = \frac{1}{2}(\partial_i\beta_j + \partial_j\beta_i) - \frac{1}{3}\delta_{ij}\partial\cdot\beta$$ shear tensor

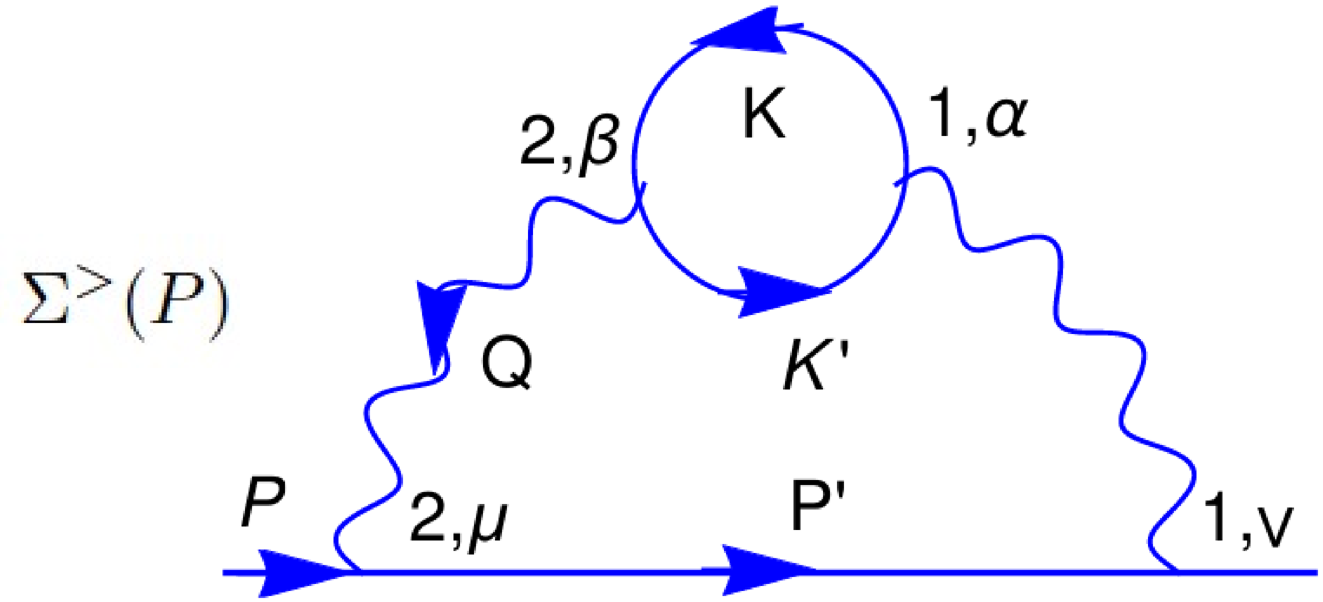
$$C_f = \frac{3N_f(1+2N_f)}{4\pi^2 N_f^2}$$ particle content dependent constant

$I_2,\ I_3$ functions of p, T

Parametrically the same as derivative term

SL, Wang, 2206.12573

Self-energy contribution gauge dependent!



Explicit results in Feynman and Coulomb gauges show difference

Self-energy gauge dependent in general, but spin polarization not

SL, Wang, 2206.12573

Gauge invariant propagator

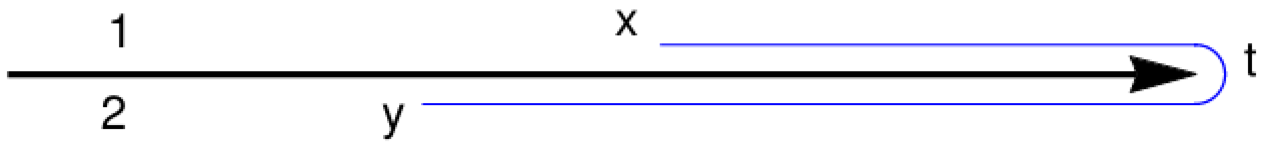
gauge transformation of propagator

$$S^<(x,y) \to e^{-ie\alpha_2(y)} S^<(x,y) e^{ie\alpha_1(x)}$$

gauge invariant propagator generalized to Schwinger-Keldysh contour

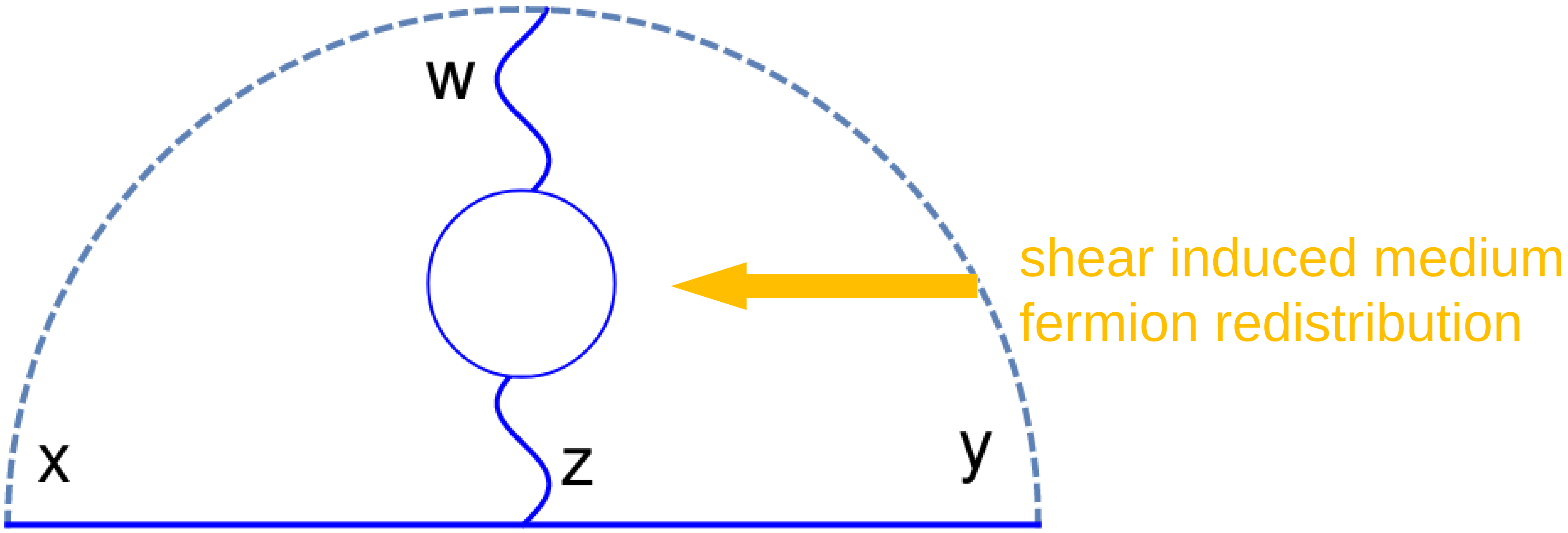
$$\bar{S}^<(x,y) = \psi_1(x)\bar{\psi}_2(y) U_2(y,\infty) U_1(\infty,x)$$

$$U_i(y,x) = \exp\left(-ie\int_y^x dw \cdot A_i(w)\right)$$



SL, Wang, 2206.12573

Gauge fields fluctuation



fermion propagates from x to y

gauge fields fluctuation A(z) from interaction, A(w) from gauge link

Gauge link contribution to spin polarization

$$\mathcal{A}^i = \frac{1}{(2\pi)} C_f \frac{9\zeta(3)}{2\beta^4} (J_1 + J_2 + J_3 + J_4) \frac{\epsilon^{iml} p_n p_l S_{mn}}{2p^5} f_p(1 - f_p)\delta(P^2 - m^2)$$

$$S_{ij} = \frac{1}{2}(\partial_i\beta_j + \partial_j\beta_i) - \frac{1}{3}\delta_{ij}\partial\cdot\beta$$ shear tensor

$$C_f = \frac{3N_f(1+2N_f)}{4\pi^2 N_f^2}$$ particle content dependent constant

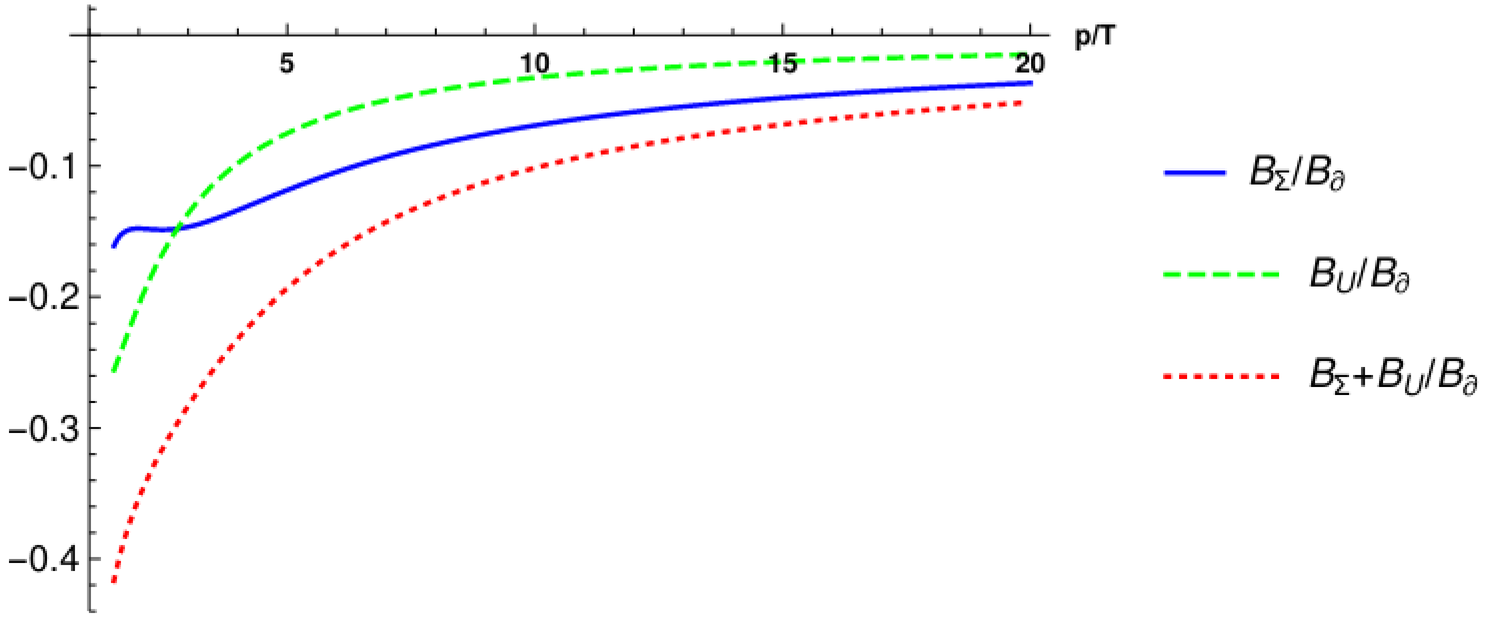
$J_1,\ J_2,\ J_3,\ J_4$ functions of p, T

Parametrically the same as derivative term

SL, Wang, 2206.12573

Suppression of spin polarization

$$\mathcal{A}^i_M = B_M \epsilon^{iml} p_n p_l S_{mn} \qquad M = \partial, \Sigma, U$$



Self-energy and gauge link contributions lead to modest suppression of derivative contribution to spin polarization

Summary

- Derived QKT for QED allows study of spin polarization with collisional effect
- Self-energy contribution+Gauge link contribution parametrically the same, lead to suppression of derivative contribution

Outlook

- Dynamical contribution to spin polarization
- Generalization to QKT for QCD
- Vector meson spin polarization

Thank you!

Angular distribution of vector meson

$$
\begin{aligned}
\frac{dN}{d\Omega} = \; & \frac{3}{8\pi}\Big[(1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta \\
& -2\mathrm{Re}\rho_{-1,1}\sin^2\theta\cos(2\phi) - 2\mathrm{Im}\rho_{-1,1}\sin^2\theta\sin(2\phi) \\
& +\sqrt{2}\mathrm{Re}(\rho_{-1,0}-\rho_{01})\sin(2\theta)\cos\phi \\
& +\sqrt{2}\mathrm{Im}(\rho_{-1,0}-\rho_{01})\sin(2\theta)\sin\phi\Big],
\end{aligned}
$$