Spin polarization in strongly coupled QGP

Shu Lin

Sun Yat-Sen University

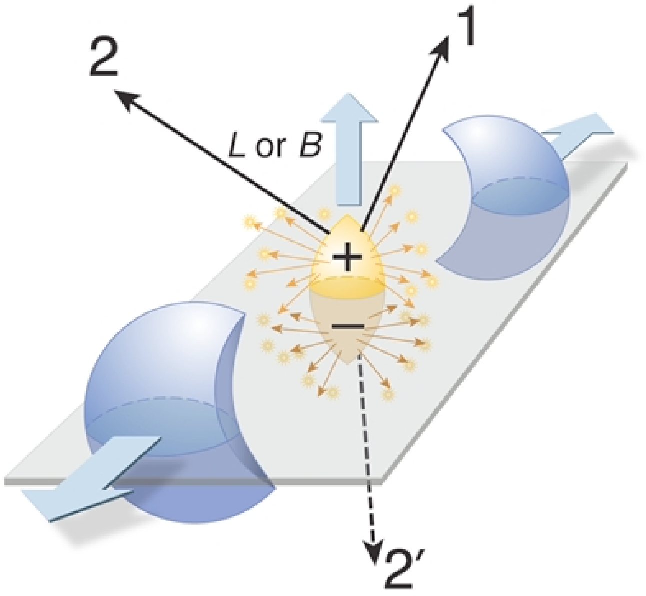
第二十届全国中高能核物理大会，上海， 2025.4.24-28

S.-W. Li, SL, to appear
SL, Tian, 2410.22935

Outline

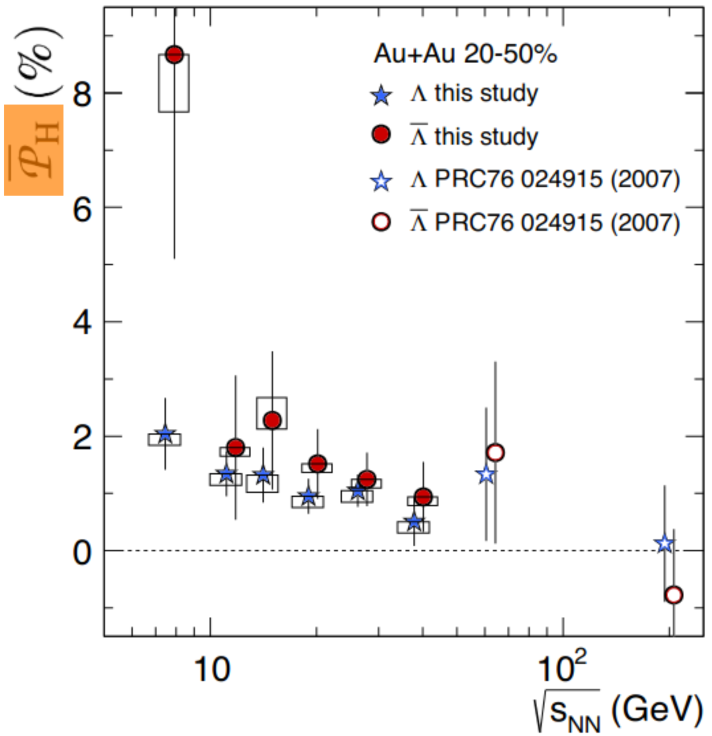
- Spin polarization in HIC: sensitivity on baryon structure
- Lessons and limitations of quantum kinetic theory (QKT)
- Holographic model for spin polarization
- Spectral function and polarized excitations in off-equilibrium holographic QGP
- Conclusion and outlook

HIC: global polarization from vorticity



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

Liang, Wang, PRL 2005, PLB 2005

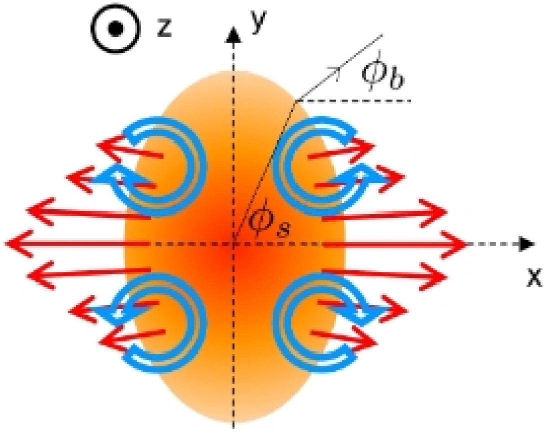


STAR collaboration, Nature 2017

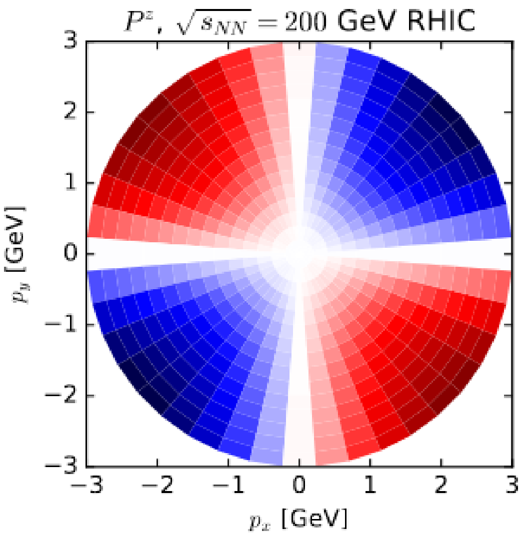
$$e^{-\beta(H_0 - \mathbf{S}\cdot\omega)}$$

talk by Z.-T. Liang

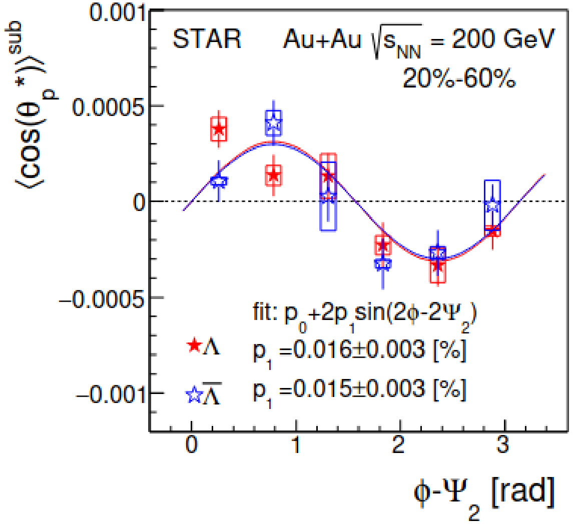
HIC: local polarization from vorticity



$$S^i \sim \omega^i$$



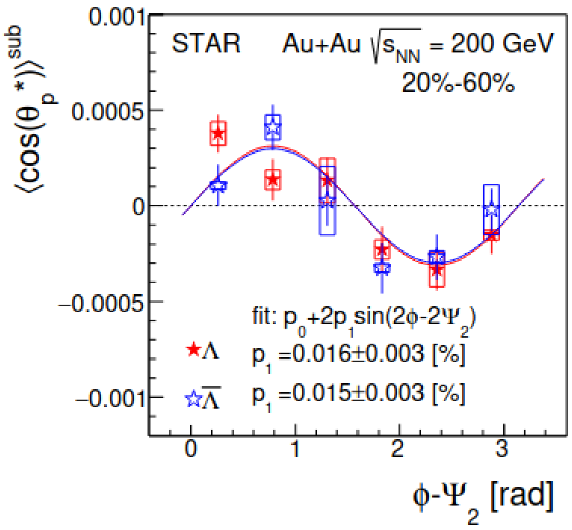
Becattini, Karpenko, PRL 2018
Wei, Deng, Huang, PRC 2019
Wu, Pang, Huang, Wang, PRR 2019
Fu, Xu, Huang, Song, PRC 2021



STAR collaboration, PRL 2019

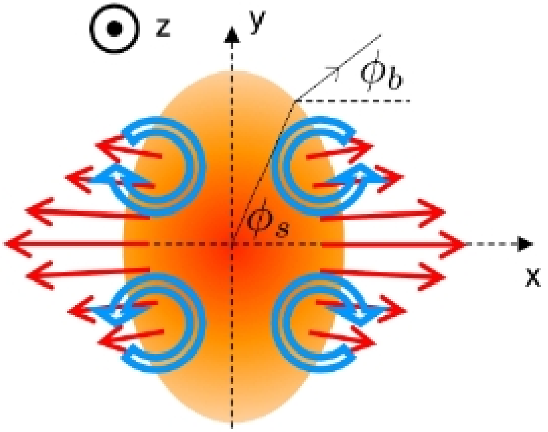
wrong sign

HIC: local polarization from vorticity + shear



STAR collaboration, PRL 2019

vorticity



$$S^i \sim \omega^i$$

wrong sign

shear

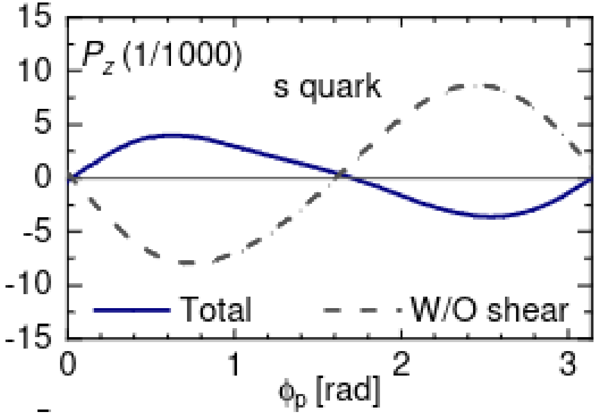
$$S^i \sim \epsilon^{ijk}\hat{p}_k\hat{p}_l\sigma_{jl}$$

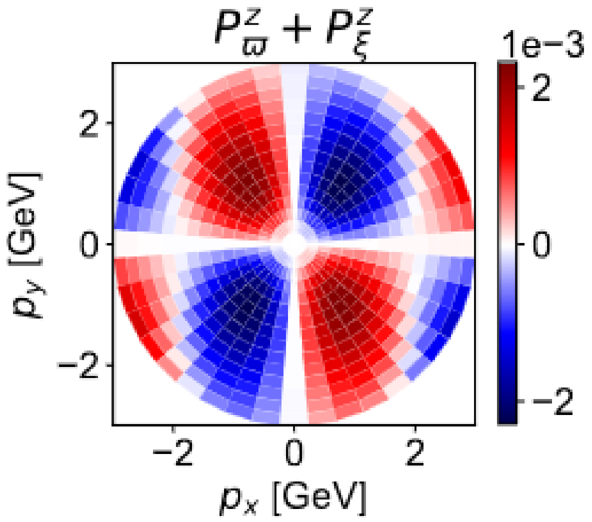
$$S^z \sim \left(\langle p_y^2\rangle - \langle p_x^2\rangle\right)\partial_y u_x$$

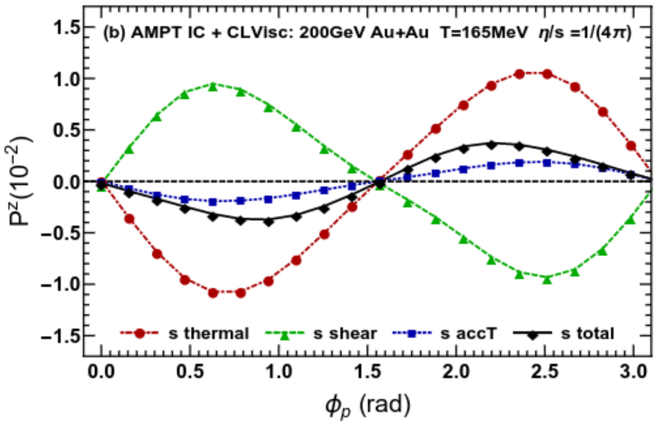
right sign

Hidaka, Pu, Yang, PRD 2018
Liu, Yin, JHEP 2021
Becattini, et al, PLB 2021

Uncertainty in spin response to shear







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

two scenarios
Λ: point particle
Λ: quark model

talk by Z.-T. Liang

$$S^\mu(p^\alpha) = \frac{1}{4m} \frac{\int d\Sigma \cdot p\, n_0 (1 - n_0) \mathcal{A}^\mu}{\int d\Sigma \cdot p\, n_0},$$

Polarization for quark from QKT

free theory
point particle

$$S^i \sim \left(\omega^i + \epsilon^{ijk}\hat{p}_j\hat{p}_l\sigma_{kl} + \frac{\partial_i T}{T}\right)\delta(P^2 - m^2)$$

spectral function ρ

- collisional correction

example: shear

$$S^i \sim \left((1 + O(1))\epsilon^{ijk}\hat{p}_j\hat{p}_l\sigma_{kl}\right)\delta(P^2 - m^2)$$

SL, Wang, JHEP 2022, PRD 2025
Fang, Pu, Yang, PRD 2024
Fang, Pu, PRD 2025

- spectral correction

example: shear/vorticity

SL, Tian, 2410.22935
Fang, Pu, Yang, 2503.13320

$$\delta S^i \sim \int dp_0 \delta\rho \sim g^2\gamma^i\gamma^5\left(\#\omega^i + \#\epsilon^{ijk}\hat{p}_j\hat{p}_l\sigma_{kl} + \#\epsilon^{ijk}\hat{p}_j\frac{\partial_k\beta}{\beta}\right)$$

Polarization for Λ from QKT

s quark polarization w/ perturbative collisional & spectral corrections

→ Λ polarization

quark model also subject to correction!

structure of Λ encoded in non-perturbative correction to spectral function

More complete Λ spectral function? Holographic model

Spectral function and density matrix

$$\rho_{\alpha\beta}(\omega,\vec{p}) = \int d^4x e^{ip\cdot x} \left\langle \Psi_\alpha(x)\Psi^\dagger_\beta(0) + \Psi^\dagger_\beta(0)\Psi_\alpha(x) \right\rangle$$

$\langle\cdots\rangle = \mathrm{Tr}[D\cdots]$ D: density matrix for generic state

reduces to distribution in quasi-particle picture

$\omega,\, p \gg \partial_X$ Excitation localized in fluid element

Probe baryon in off-equilibrium fluid $D = D_{\mathrm{baryon}} \otimes D_{\mathrm{fluid}}.$

S.-W. Li, SL, to appear

Holographic model for baryon

$$S = i \int d^{D+1}x \sqrt{-g}\bar{\psi}\left(\Gamma^M \nabla_M - m\right)\psi,$$

Iqbal, Liu 2009

5D Dirac fermion ⟷ 4D Weyl fermion

$$\psi = \begin{pmatrix} \psi_R \\ \psi_L \end{pmatrix}$$

“lump of quark/gluon”

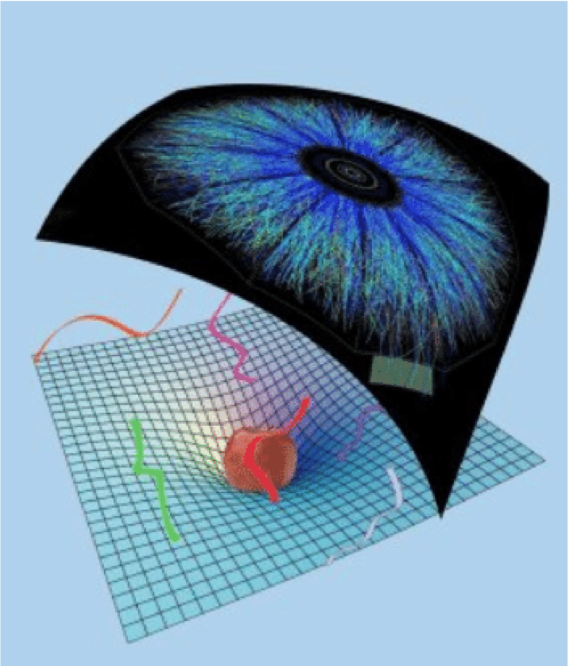
One baryon = R/L Weyl fermions

focus on spectral function in off-equilibrium QGP

Holographic model for QGP

$$ds^2 = -2u_\mu(x)dx^\mu dr - r^2 f(b(x)r)u_\mu u_\nu dx^\mu dx^\nu + r^2 P_{\mu\nu}dx^\mu dx^\nu$$ local equilibrium

$$+ 2r^2 bF(br)\sigma_{\mu\nu}dx^\mu dx^\nu + \frac{2}{3} r u_\mu u_\nu \partial_\lambda u^\lambda dx^\mu dx^\nu - r u^\lambda \partial_\lambda(u_\mu u_\nu)dx^\mu dx^\nu$$ steady state



Bhattacharyya et al,
JHEP 2008

$O(\partial^0)$ $O(\partial)$

$$T^{\mu\nu} = (\pi T)^4 (\eta^{\mu\nu} + 4u^\mu u^\nu) - 2(\pi T)^3 \sigma^{\mu\nu}$$

local equilibrium

η

steady state

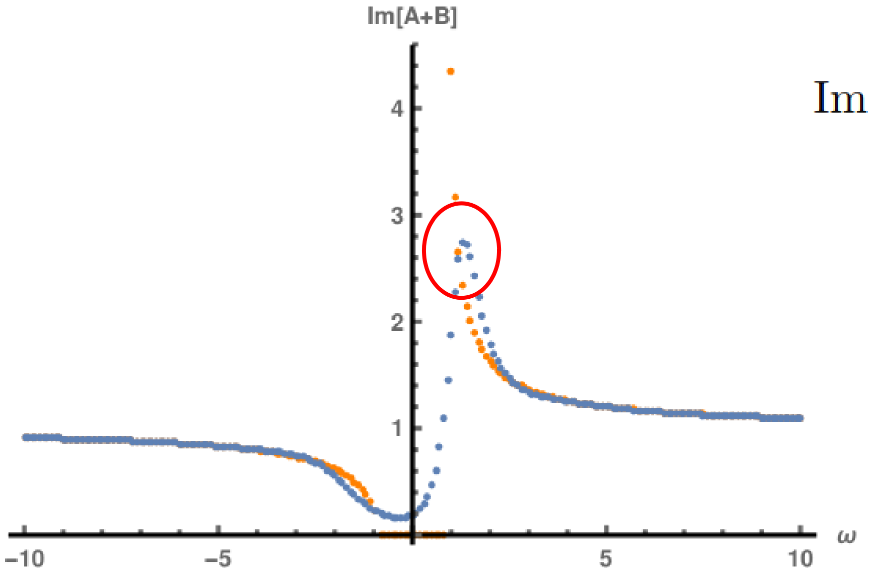
σ_{ij} ~~$\partial_0 b = \frac{1}{3}\partial_i u_i$~~ $\partial_i b = \partial_0 u_i$

T-grad = acceleration

Holography: equilibrium spectral function

$$G_R = A + B\hat{p}\cdot\vec{\sigma}$$

$$\rho = 2\mathrm{Im}G_R = \mathrm{Im}[A+B]\left(1-\hat{p}\cdot\vec{\sigma}\right) + \mathrm{Im}[A-B]\left(1+\hat{p}\cdot\vec{\sigma}\right)$$



orange: vacuum

Iqbal, Liu 2009

$$\mathrm{Im}[A+B] = \mathrm{sgn}(\omega)\theta(\omega^2 - p^2)\left(\frac{\omega+p}{\omega-p}\right)^{1/2}$$

no spacelike spectral

blue: equilibrium QGP
soften the singularity
develop spacelike spectral

focus on timelike spectral for baryon

Gradient corrections

$$(\Gamma^M \nabla_M - m)\psi = 0$$

gradient correction to Dirac field ➡ gradient correction to baryon

$$D^{(0)}_{\text{fluid}} \otimes D^{(1)}_{\text{baryon}}$$

$$(\Gamma^M \nabla_M - m)\psi = 0$$

gradient correction to Dirac operator ➡ gradient correction to QGP

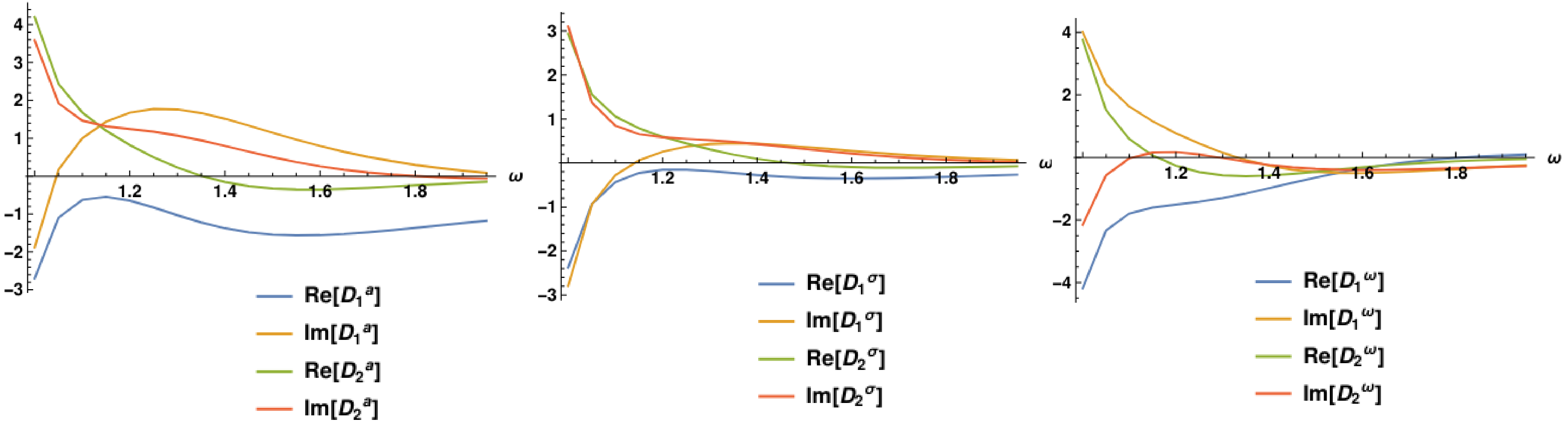
$$D^{(1)}_{\text{fluid}} \otimes D^{(0)}_{\text{baryon}}$$

S.-W. Li, SL, to appear

Gradient correction to baryon

$$S^k \sim \mathrm{tr}[\delta\rho\sigma_k] \sim \left(\mathrm{Im}[D_1^a]\partial_0 u_k - \mathrm{Re}[D_2^a]\epsilon^{ijk}\hat{p}_j\partial_0 u_i\right)$$

$$+\left(\mathrm{Im}[D_1^\omega]\omega_k - \mathrm{Re}[D_2^\omega]\epsilon^{ijk}\hat{p}_j\omega_i\right) + \left(\mathrm{Im}[D_1^\sigma]\hat{p}_j\sigma_{kj} - \mathrm{Re}[D_2^\sigma]\epsilon^{ijk}\hat{p}_j\hat{p}_l\sigma_{il}\right)$$

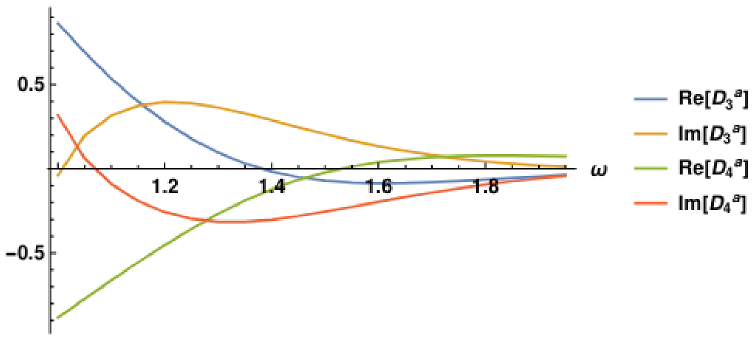


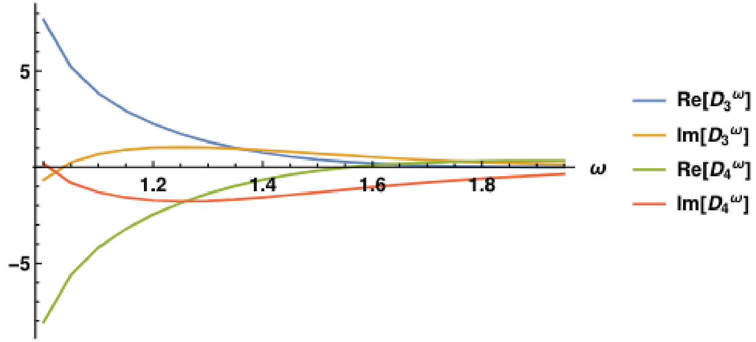
S.-W. Li, SL, to appear

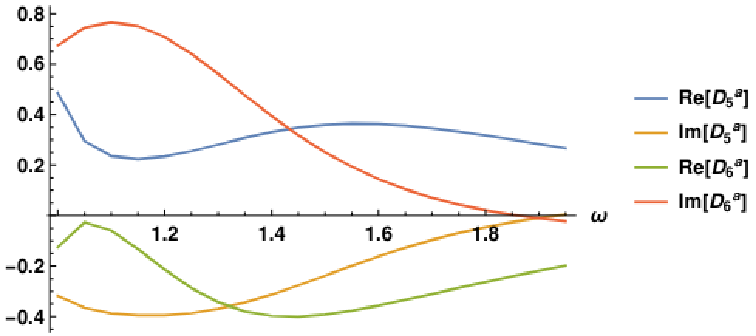
Gradient correction to QGP

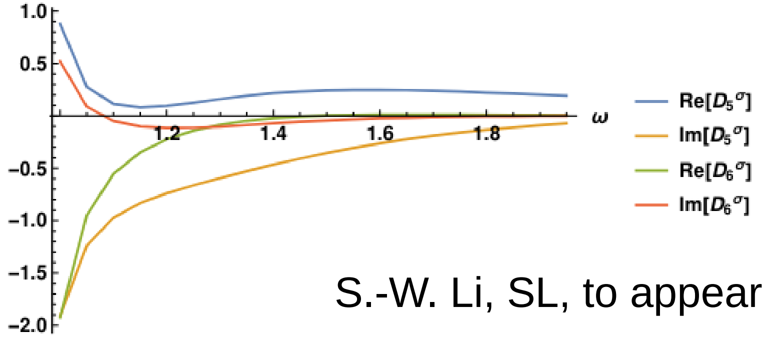
$$S^k \sim \mathrm{tr}[\delta\rho\sigma_k] \sim \left(\mathrm{Im}[D_3^a + D_5^a]\partial_0 u_k - \mathrm{Re}[D_4^a + D_6^a]\right)\epsilon^{ijk}\hat{p}_j\partial_0 u_i$$

$$+ \left(\mathrm{Im}[D_3^\omega]\omega_k - \mathrm{Re}[D_4^\omega]\epsilon^{ijk}\hat{p}_j\omega_i\right) + \left(\mathrm{Im}[D_5^\sigma]\hat{p}_j\sigma_{kj} - \mathrm{Re}[D_6^\sigma]\epsilon^{ijk}\hat{p}_j\hat{p}_l\sigma_{il}\right)$$









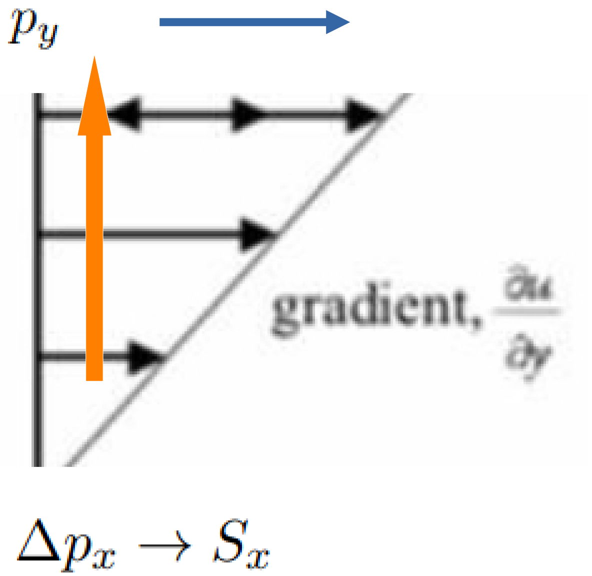
S.-W. Li, SL, to appear

Steady state effect: shear example

$$\delta G^R = F_1 \hat{p}_j \sigma_{ij} \sigma_i + iF_2 \epsilon^{ijk} \hat{p}_j \hat{p}_l \sigma_{kl} \sigma_i$$

steady state effect of baryon, not contribute to polarization

acceleration balanced by collision



contribute to polarization of Weyl fermion, cancels in axial component (polarization)

baryon = R-Weyl + L-Weyl

do modify vector component of spectral function!

Expected contribution at $O(\partial^2)$

Expect mixed contributions to polarization

$$S^i \sim \quad \epsilon^{ijk}\partial_j b\hat{p}_l\sigma_{kl} \qquad \Delta p_k$$

steady state effect

$$\mathrm{tr}\left[\gamma^\mu\gamma^5 W_{\mathrm{quad}}(x,p)\right] = \frac{\delta(p^2-m^2)\mathrm{sgn}(p^0)}{(2\pi)^3(p^0)^2} n_F(p)[1-n_F(p)][1-2n_F(p)](y_\Sigma^0 - x^0)$$

to be added to

$$\times p^{\lambda'}\partial_{\lambda'}\left[p^{\tau'}\beta_{\tau'}(x) - \zeta(x)\right]$$

$$\times\left\{2\epsilon^{\mu\nu\rho\lambda}p_\nu\hat{t}_\rho\partial_\lambda\left[p^\tau\beta_\tau(x)-\zeta(x)\right] + (p^\mu p_\tau - g^\mu_\tau m^2)\hat{t}_\rho\epsilon^{\rho\nu\lambda\tau}\Omega_{\nu\lambda}(x)\right\}$$

$$\xi_{ij} \sim \sigma_{ij} \qquad \epsilon^{ijk}\varpi_{jk} \sim \omega_i$$

Sheng, Becattini, Huang, Zhang, PRC 2024

Conclusion

- Sensitivity of local polarization to Λ structure
- Holographic model for probe baryon in strongly coupled QGP
- Gardient corrections to baryon spectral function
- Expect mixed contribution to polarization at second order

Outlook

- Schwinger-Keldysh extended holographic model for complete gradient correction to polarization

Thank you!