The effects of self-energies in spin polarization and spin alignment

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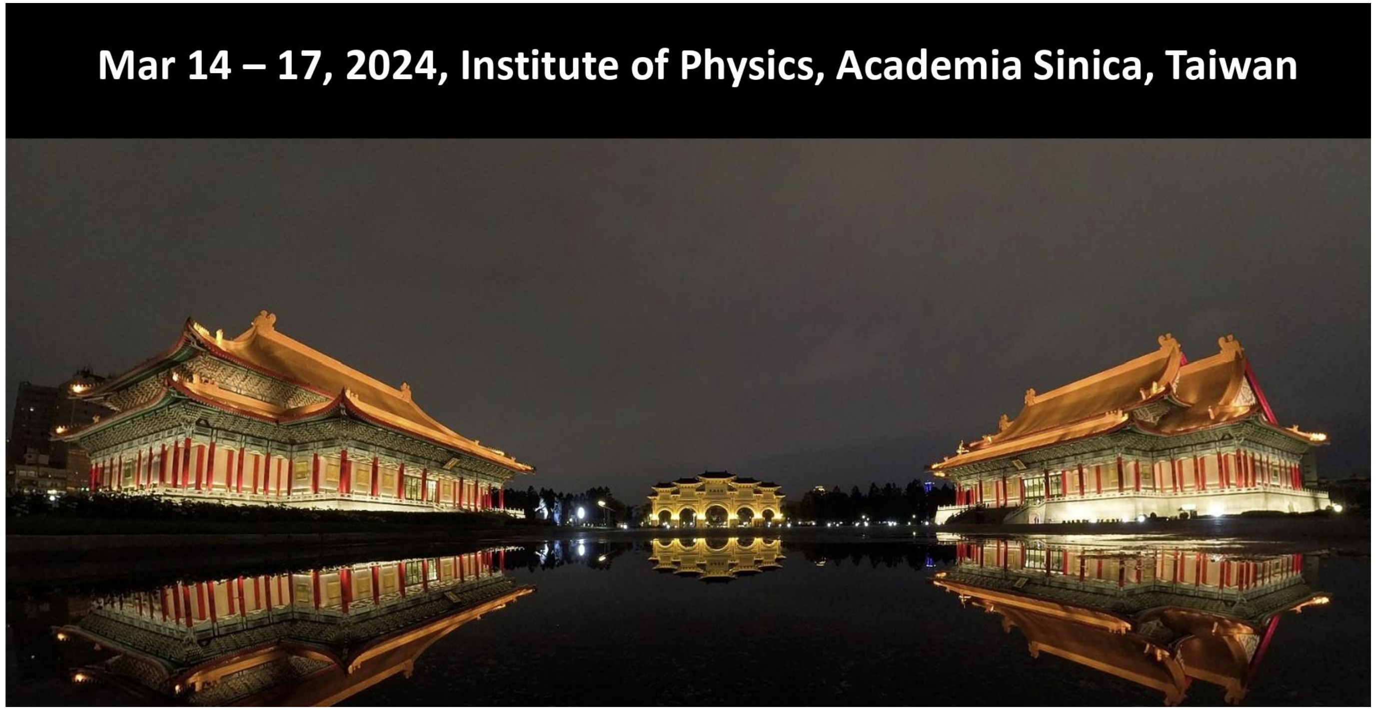

Outline

- Spin polarization and alignment in heavy ion collisions
- Quantum kinetic theory with collisions and self-energies
- Self-energy corrections to spin polarization and alignment
- Summary

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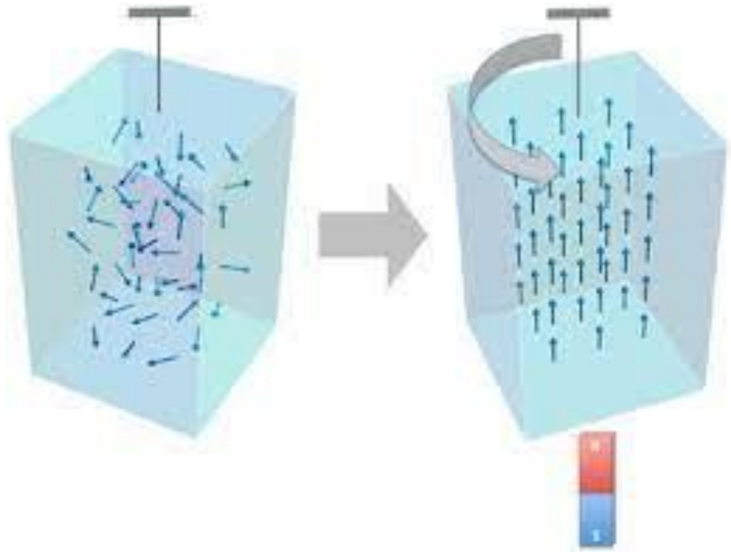
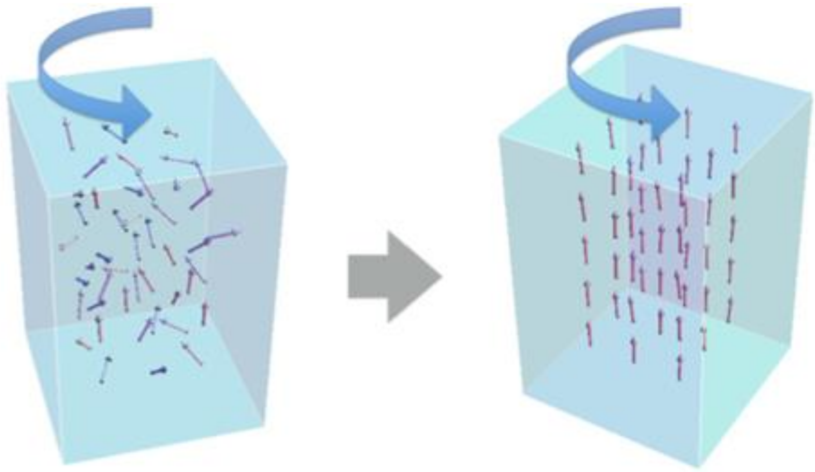
Spin-orbit coupling in many-body system



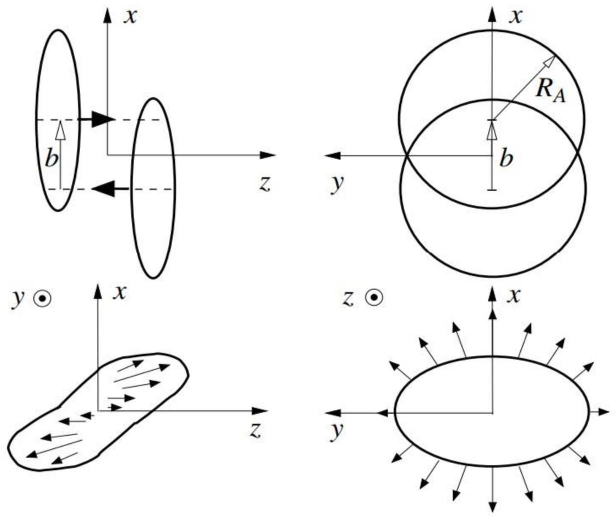
Einstein de-Haas effect
Polarization -> rotation



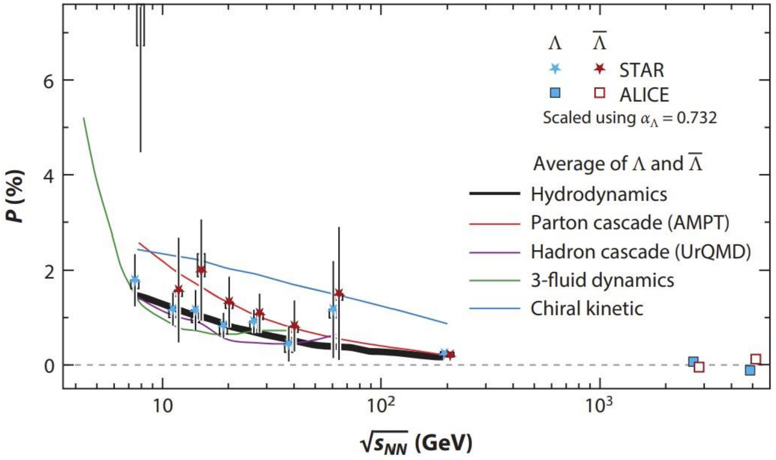
Barnett effect
Rotation -> Polarization

S. J. Barnett, Phys. Rev. 6, 239 (1915)
A. Einstein and W. J. de Haas, Verh. d. Deutsch. Phy. Ges. 17, 152 (1915)

Global polarization



- Large initial orbit angular momentum (OAM) of order of $10^5\hbar$ is produced in peripheral heavy ion collisions.
- The deconfined quarks can be polarized along the direction of the initial OAM via **spin-orbit coupling**, and the hadrons in final state can be further polarized from quark coalescence mechanism.
- QGP is **the most vortical matter in nature**, $\omega \sim 10^{22} s^{-1}$.



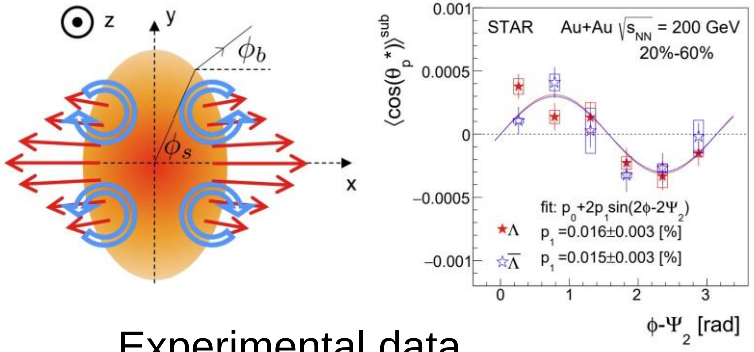
Z. T. Liang, X. N. Wang, PRL(2005)
B. Betz, M. Gyulassy, G. Torrieri, PRC (2007)
F. Becattini, F. Piccinini, J. Rizzo PRC (2008)
G.-H. Gao, S.-W. Chen, W.-T. Deng, Z.-T. Liang, Q. Wang PRC (2008)

L. Adamczyk et al. [STAR Collaboration], Nature 548, 62(2017)
F. Becattini, M. A. Lisa, ARNPS 70 (2020) 395-423

Recent review: Becattini, Buzzegoli, Niida, Pu, Tang, Wang, 2402.04540.

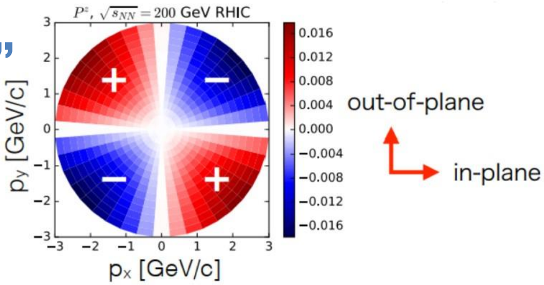
Sign puzzle in local polarization

- **Stronger in-plane expansion** of QGP due to **spacetime anisotropy** can induce **local polarization** along the beam line.
- In the past, the theories in the market **CANNOT** explain the local polarization well, even gives opposite results.
- The **shear effects** can be important to local polarization, and even quantitively explain the experiment by **proper choice of parameter**.



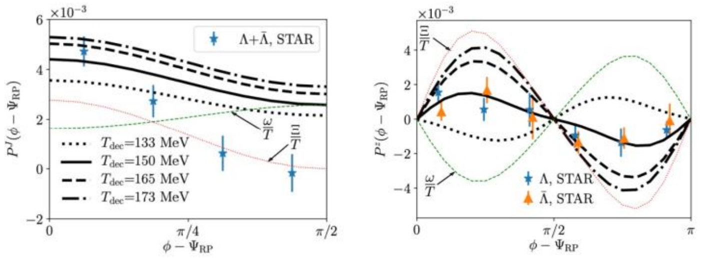
Experimental data
[STAR Collaboration], PRL(2019)

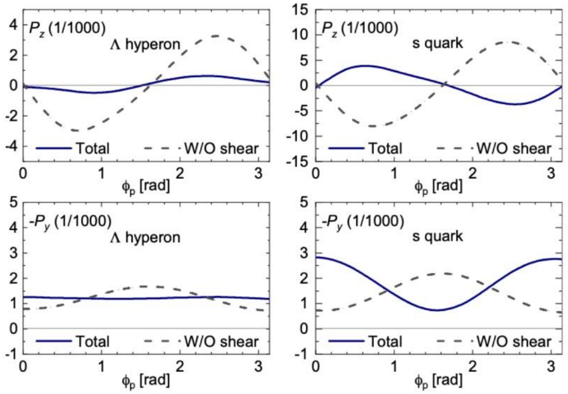
"sign puzzle"



Phenomenological model
Becattini , Karpenko, PRL(2018)

✓ Shear induced polarization:
An "**Intrinsic Hall effect**" in HIC

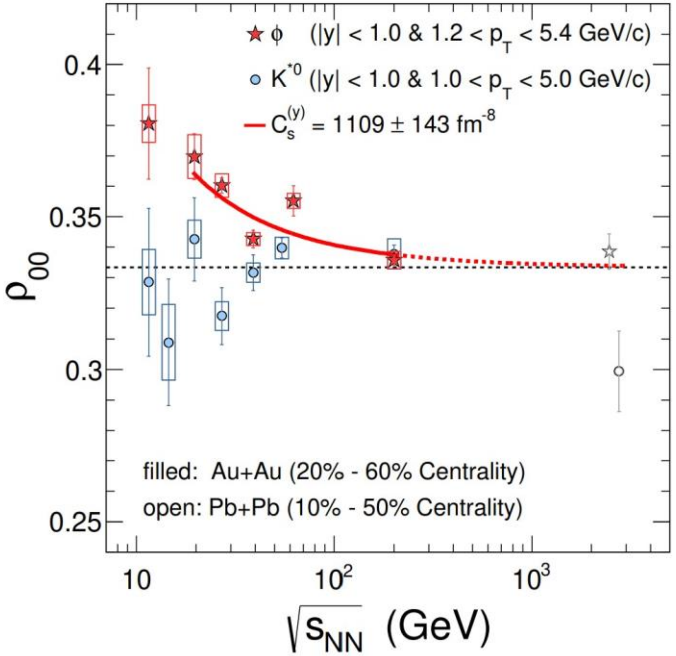


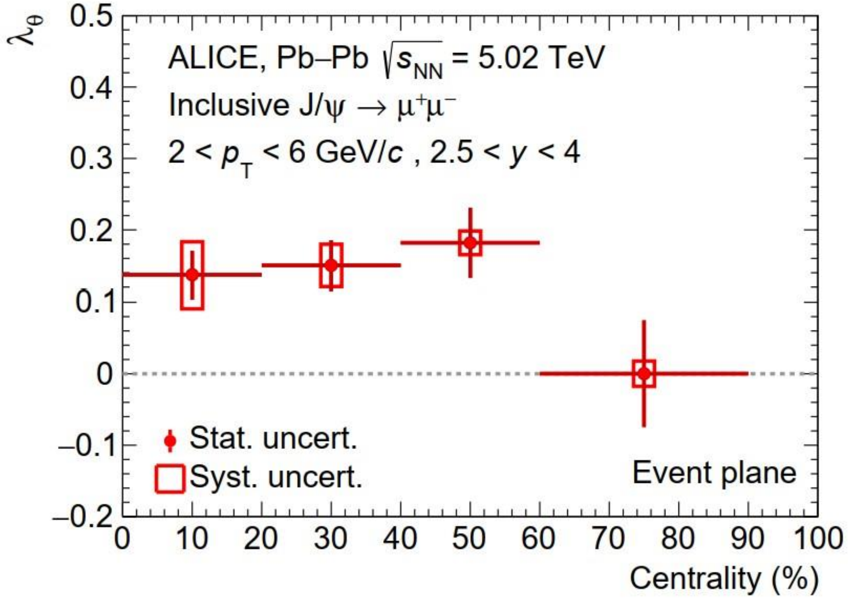


Fu, Liu, Pang et al, PRL. 127 (2021) 14, 142301
Becattini , Buzzegoli, Palermo, PRL. 127 (2021) 27, 272302
Yi , Pu, and Yang, PRC. 104 (2021) 6, 064901

Global spin alignment

Physics Mechanisms	(ρ_{00})
c_Λ: Quark coalescence vorticity & magnetic field[1]	< 1/3 (Negative ~ 10^{-5})
c_ε: E-comp. of Vorticity tensor[1]	< 1/3 (Negative ~ 10^{-4})
c_E: Electric field[2]	> 1/3 (Positive ~ 10^{-5})
c_F: Fragmentation[3]	> or, < 1/3 (~ 10^{-5})
c_L: Local spin alignments[4]	< 1/3
c_A: Turbulent color field[5]	< 1/3
c_ϕ: Vector meson strong force field[6]	> 1/3 (Can accommodate large positive signal)
c_g: Glasma fields + effective potential	could be significant





[STAR Collaboration], Nature (2023); [ALICE Collaboration], PRL (2023);
Sheng, Oliva, Wang PRD(2020); Sheng, Wang, Wang, PRD(2020)
Sheng, Oliva, Liang, Wang, Wang, PRL (2023); PRD(2024);
Kumar, Muller, Yang, 2212.13354; 2304,04181;
Muller, Yang, PRD(2022); Yang, JHEP(2022);
Wagner, Weickgenannt, Speranza, PRR(2023);
Li, Liu, 2206,11890; Dong, Yin, Sheng, Yang, Wang, 2311.18400;
……

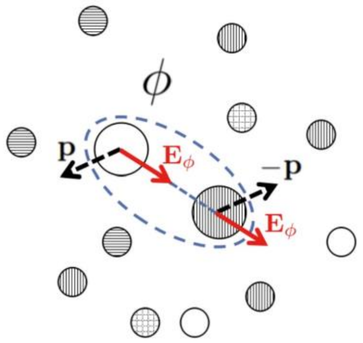
Table taken from Prof. **Ai-hong Tang**'s slides

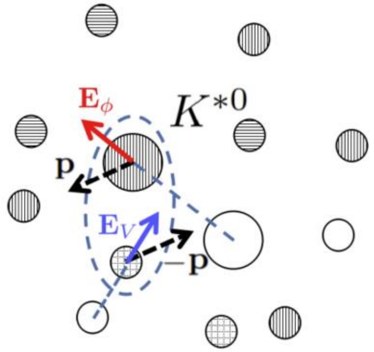
Question: how can we understand spin polarizations and alignments emerged in heavy ion collisions?

1. Roughly speaking, the **hyperon** spin polarization inherits from quarks, quantitatively describing the **spin polarization of quarks** in the **many-body system** needs a spin transport equation;

2. Spin transport equation of vector fields is also necessary to understand the spin properties of vector mesons;

3. **Vector meson** spin alignment also reflects the correlations of the polarization of quarks: also need the input from the spin transport of quarks.





Question: Microscopically, how to implement the **spin evolution** into the evolution of quarks and vector mesons?

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- Spin polarization and alignment in heavy ion collisions
- **Quantum kinetic theory with collisions and self-energies**
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Present efforts on quantum kinetic theory

Up to now there are plenty of investigations on relativistic quantum kinetic theory and spin transport equations of fermions:

See Prof. **Qun Wang**'s talk for a review

- Chiral kinetic theory:

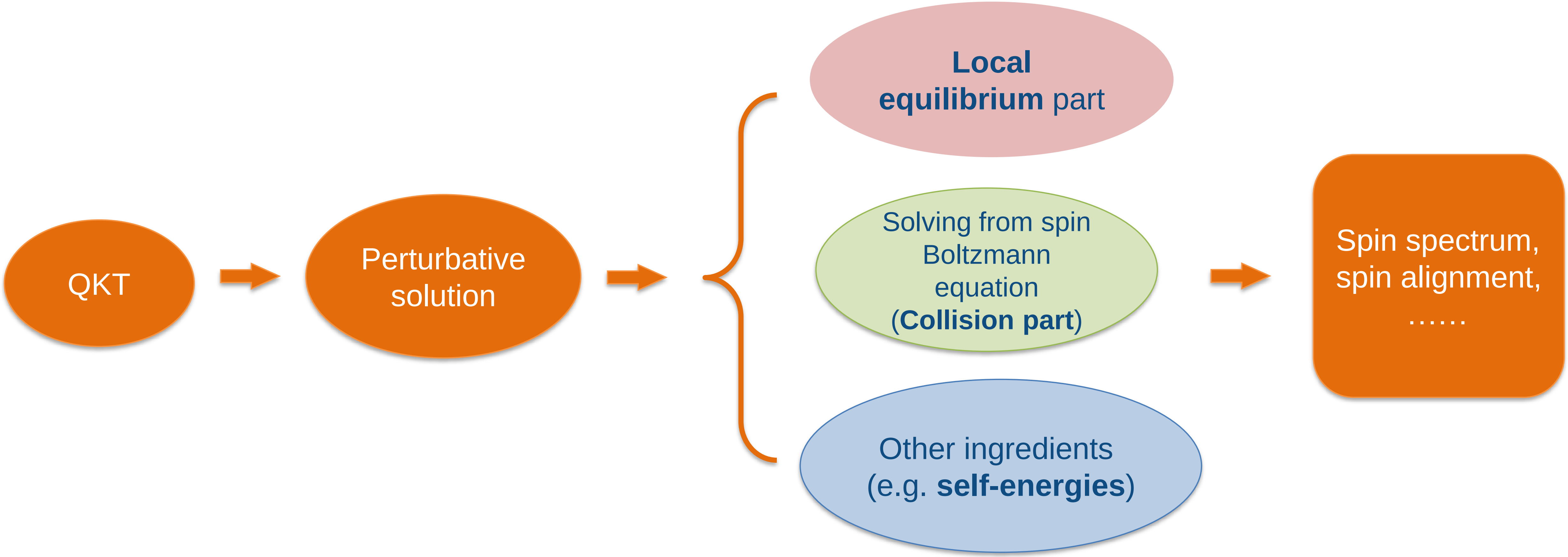
  D. T. Son, N. Yamamoto, PRL(2012); PRD(2013); S. Lin, A. Shukla, JHEP (2019) ; M.A. Stephanov, Y. Yin PRL (2012) ; J.-Y. Chen, D. T. Son, M. A. Stephanov, H.-U. Yee, Y. Yin, PRL (2014) ; J.-W. Chen, J.-Y. Pang, S. Pu, Q. Wang PRD (2014) ; J.-Y. Chen, D. T. Son, M. A. Stephanov, PRL (2015); J.-H. Gao, Z.-T. Liang, S. Pu, Q. Wang, X.-N. Wang PRL(2012);J.-W. Chen, S. Pu, Q. Wang, X.-N. Wang, PRL (2013) ; Y. Hidaka, S. Pu, D.-L. Yang, PRD (2017) ; A. Huang, S. Shi, Y. Jiang, J. Liao, P. Zhuang, PRD (2018) ; N. Mueller, R. Venugopalan, PRD(2018) ;PRD 96 (2017); Y.-C. Liu, L.-L. Gao, K. Mameda, X.-G. Huang, PRD(2019); S.-Z. Yang, J.-H. Gao, Z.T.-Liang, Q. Wang, PRD(2020); K. Mameda, PRD(2023); N. Yamamoto, D.-L. Yang, APJ(2020); PRD(2021),PRL(2023), 2308.08257;

- Quantum kinetic theory including quantum corrections:
  - Quantum kinetic theory without collisions: *J.-H. Gao. Z.-T. Liang, PRD(2019); N. Weickgenannt, X.-L. Sheng, E. Speranza, Q. Wang, D. H. Rischke PRD(2019); K. Hattori, Y. Hidaka, D.-L. Yang PRD(2019); Y.-C. Liu, K. Mameda, X.-G. Huang CPC (2021); Z. Wang, X. Guo, S. Shi, P. Zhuang PRD(2019); D.-L. Yang, JHEP(2022); S.-X. Ma, J.-H. Gao, 2209.10737;*
  - Spin transport theory with **collisions** based on QKT: *N. Weickgenannt, X.-L. Sheng, E. Speranza, Q. Wang, D. H. Rischke PRL(2021); PRD(2021); PRD(2021); D.-L. Yang, K. Hattori, Y. Hidaka, JHEP(2020); Z. Wang, X. Guo, P. Zhuang, EPJC(2021); Z. Wang, P. Zhuang, 2105.00915; N. Weickgenannt, D. Wagner, E. Speranza, D. H. Rischke, PRD(2022), PRDL(2022); SF, S. Pu, D.-L. Yang PRD(2022); Z. Wang, PRD(2022); S. Lin, PRD(2022); S. Lin, Z. Wang, JHEP(2022);*

Also see Y. Hidaka, S.Pu, Q. Wang, D.-L. Yang, **PPNP(2022)** for a recent **review on CKT&QKT**

Spin polarization from interactions

The **dynamical** evolution of spin DoFs incorporate the **effects of interactions** to spin polarization density S^{μ}, which further relates to the spin spectrum of quarks and spin density matrix of vector mesons.



Why QKT with self-energies?

An example in relativistic **classical** kinetic theory:

- In classical kinetic theory, the **leading order contribution** of interactions lies in the **mean field approximation**:

$$\Sigma(x,y)=\Sigma_{\rm MF}(x)\,\delta^{(4)}(x,y)+\Sigma^{>}(x,y)\,\Theta(x_0,y_0)+\Sigma^{<}(x,y)\,\Theta(y_0,x_0),$$
$$P(x,y)=P_{\rm MF}(x)\,\delta^{(4)}(x,y)+P^{>}(x,y)\,\Theta(x_0,y_0)+P^{<}(x,y)\,\Theta(y_0,x_0),$$
$$\Pi(x,y)=\Pi_{\rm MF}(x)\,\delta^{(4)}(x,y)+\Pi^{>}(x,y)\,\Theta(x_0,y_0)+\Pi^{<}(x,y)\,\Theta(y_0,x_0).$$

$$\left(\left[\left(p_\mu+\frac{i}{2}\partial_\mu\right)\gamma^\mu-M-\Sigma_{\rm MF}(X)+\frac{i}{2}\partial_\mu\Sigma_{\rm MF}(X)\,\partial_p^\mu\right]G^{\gtrless}(X,p)\right)_{\alpha\beta}$$
$$=\left(\Sigma^{\gtrless}(X,p)\,G^{-}(X,p)+\Sigma^{+}(X,p)\,G^{\gtrless}(X,p)\right)_{\alpha\beta},$$

A comprehensive paper on the Walecka model: *S. Mrowczynski, U. W. Heinz, Annals Phys. 229, 1(1994)*: In the pairing approximation, corrections of vacuum meson mass,

$$M^*(X)=M-g_s\langle\phi(X)\rangle.$$

And the *effective Lorentz force* induced by background mean mesonic field,

An effective Lorentz force

$$[p^\mu\partial_\mu-g_v p^\mu\langle F_{\mu\nu}(X)\rangle\,\partial_p^\nu-g_s M^*(X)\,\partial_\mu\langle\phi(X)\rangle\,\partial_p^\mu]\,G^{\gtrless}(X,p)$$
$$=-\tfrac{1}{2}g_s\,\partial_\mu\langle\phi(X)\rangle\{\gamma^\mu,G^{\gtrless}(X,p)\}-\tfrac{1}{2}g_v\langle F_{\mu\nu}(X)\rangle\{\gamma^\mu\gamma^\nu,G^{\gtrless}(X,p)\},$$

Similar applications in **high-temperature gauge theory**: *J. P. Blaizot & E. Iancu, NPB 557, 183(1999); Phys. Report. 359, 355(2002).*

Why QKT with collisions?

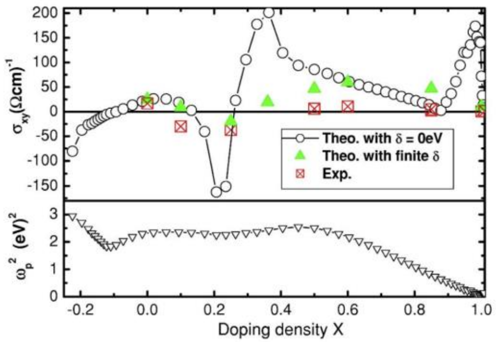
- Collision terms serve as **dynamical** sources of quark spin polarization with **higher order couplings**: the **collisions** between quarks bring **off-equilibrium effects**.

- Similar insights from condensed matter physics: the anomalous Hall effects, spin Hall effects etc from **electron scattering and impurity scattering**.

$$\mathcal{S}^{\mu}(\mathbf{p}) = \frac{\int d\Sigma \cdot p\mathcal{J}_5^{\mu}(p,X)}{2m_{\Lambda}\int d\Sigma \cdot \mathcal{N}(p,X)},$$

- Spin polarization phenomena: **momentum spectrum** of **spin Hall effects** for the hot dense matter. The **collisional effects** must play a role.

Extrinsic anomalous Hall effects from collisions in condensed matter physics



D. Xiao, M.-C. Chang, Q. Niu RMP 82, 1959
N. A. Sinitsyn 2008, J. Phys.: Condens. Matter 20,023201
Y. Yao, et al. PRB 75, 020401
Hirsch, J. E., 1999, PRL 83, 1834.

QKT with self-energies and collisions (I)

- We define the gauge invariant 2-point Wigner function for fermions,

$$S^{<}_{\alpha\beta}(x,p) = -\int d^4y\, e^{-ip\cdot y}\langle :\bar{\psi}_\beta(x+\frac{y}{2})\, e^{\frac{y}{2}\cdot\overleftarrow{D}(x)} \otimes e^{-\frac{y}{2}\cdot\overrightarrow{D}(x)}\psi_\alpha(x-\frac{y}{2}) :\rangle$$

- Along the Schwinger-Keldysh contour, one derives the Kadanoff-Baym equations up to O($\hbar$),

$$\Sigma(x,y) = -i\hbar^{-1}\Sigma^{\delta}(x)\delta^{(4)}_{C}(x,y) + \theta_C(x_0,y_0)\Sigma^{>}(x,y) + \theta_C(y_0,x_0)\Sigma^{<}(x,y),$$

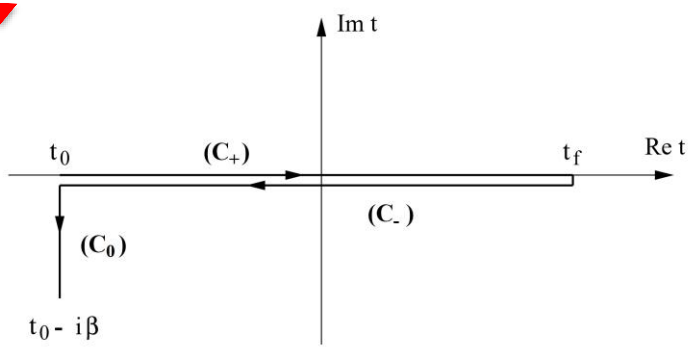
Retarded and advanced quantities

Tadpole self-energy

$$\left[\frac{i\hbar}{2}\gamma^\mu\nabla_\mu + \gamma^\mu\Pi_\mu - m + \Sigma^{\delta}(X)\star\right] S^{<}(q,X) = -\hbar\left[\Sigma^{\mathrm{r}}_{\mathrm{g}}\star S^{<} + \Sigma^{<}_{\mathrm{g}}\star S^{\mathrm{a}}\right],$$

$$S^{<}\left(-\frac{i\hbar}{2}\gamma^\mu\overleftarrow{\nabla}_\mu + \gamma^\mu\overleftarrow{\Pi}_\mu - m\right) + S^{<}\star\Sigma^{\delta}(X) = -\hbar\left[S^{\mathrm{r}}\star\Sigma^{<}_{\mathrm{g}} + S^{<}\star\Sigma^{\mathrm{a}}_{\mathrm{g}}\right],$$

Gauge-invariant Moyal product



- From the analytical properties of r/a quantities,

$$\mathcal{O}^{\mathrm{r}}(q,X) = \mathrm{Re}\mathcal{O}^{\mathrm{r}}(q,X) + i\frac{\mathcal{O}^{>}(q,X) - \mathcal{O}^{<}(q,X)}{2},$$

$$\mathcal{O}^{\mathrm{a}}(q,X) = \mathrm{Re}\mathcal{O}^{\mathrm{r}}(q,X) - i\frac{\mathcal{O}^{>}(q,X) - \mathcal{O}^{<}(q,X)}{2}.$$

√ $\mathrm{Re}S^{\mathrm{r}} = 0$, perfect quasi-particle $\Rightarrow \delta(p^2 - m^2)$

$\mathrm{Re}S^{\mathrm{r}} \neq 0$, nonzero-width

We will work on quasi-particle approximation but $\mathrm{Re}\Sigma^{\mathrm{r}} \neq 0$.

Blaizot, Iancu, Phys.Rept.(2002);
Hidaka, Pu, Yang, PRDL(2017);
Hattori, Hidaka, Yang, JHEP(2020);
Yamamoto, Yang, 2308.08257;
***SF**, Pu, Yang, 2311.15197.*

QKT with self-energies and collisions (II)

- Work in the Clifford basis,

$$\overline{\Sigma}_{\rm g}(q,X) = \Sigma^{\delta}(X) + {\rm Re}\Sigma^{\rm r}_{\rm g}$$

Self-energy with tadpole and retarded

$$S^{\lessgtr} = \mp\left[\mathcal{F}^{\lessgtr} + i\mathcal{P}^{\lessgtr}\gamma^5 + \gamma^{\mu}\mathcal{V}^{\lessgtr}_{\mu} + \gamma^5\gamma^{\mu}\mathcal{A}^{\lessgtr}_{\mu} + \frac{1}{2}\mathcal{S}^{\lessgtr}_{\mu\nu}\gamma^{\mu\nu}\right],$$

Collisional self-energy

$$\Sigma^{\lessgtr} = \mp\left[\Sigma^{\lessgtr}_{\rm F} + i\Sigma^{\lessgtr}_{\rm P}\gamma^5 + \gamma^{\mu}\Sigma^{\lessgtr}_{{\rm V},\mu} + \gamma^5\gamma^{\mu}\Sigma^{\lessgtr}_{{\rm A},\mu} + \frac{1}{2}\Sigma^{\lessgtr}_{{\rm T},\mu\nu}\gamma^{\mu\nu}\right]$$

- Based on the **quantum nature** of **spin polarization**, we adopt the power counting,

$$\mathcal{V}^{\mu} \sim \mathcal{O}(\hbar^0), \mathcal{A}^{\mu} \sim \mathcal{O}(\hbar^1),$$

$$\text{From EoMs}, \mathcal{P} \sim \mathcal{O}(\hbar^2), \mathcal{S}^{\mu\nu} \sim \mathcal{O}(\hbar^1), \mathcal{F} \sim \mathcal{O}(\hbar^0), \text{and similar for the self-energies}$$

- Then we obtain the master equations for the Clifford components of Wigner functions:
  - Kinetic equations for Wigner functions;
  - Constraint equations:

$$\widetilde{q}_{[\mu}\mathcal{V}^{<}_{\nu]} = \mathcal{O}(\hbar^2),$$

$$(\widetilde{q}^2 - \widetilde{m}^2)\mathcal{V}^{<}_{\mu} = \mathcal{O}(\hbar^2),$$

$$\widetilde{q}^{\mu}\mathcal{A}^{<}_{\mu} = \overline{\Sigma}^{\mu}_{\rm A}\mathcal{V}^{<}_{\mu} + \mathcal{O}(\hbar^3)$$

$$(\widetilde{q}^2 - \widetilde{m}^2)\mathcal{A}^{<}_{\mu} = \frac{\hbar}{2}\epsilon_{\mu\nu\alpha\beta}\widetilde{q}^{\nu}\widetilde{\mathcal{D}}^{\alpha}\mathcal{V}^{<,\beta} + \widetilde{m}\epsilon_{\mu\nu\alpha\beta}\mathcal{V}^{<,\nu}\overline{\Sigma}^{\alpha\beta}_{\rm T} + 2(\overline{\Sigma}_{\rm A}\cdot\widetilde{q})\mathcal{V}^{<}_{\mu} - 2\overline{\Sigma}_{{\rm A},\mu}(\widetilde{q}\cdot\mathcal{V}^{<}) + \mathcal{O}(\hbar^3)$$

$$\widetilde{\mathcal{D}}^{\mu}\mathcal{V}^{<}_{\mu} = -\frac{1}{\widetilde{m}}\widetilde{q}_{\mu}\widehat{\Sigma_{\rm F}\mathcal{V}^{\mu}} - \frac{1}{\widetilde{m}}\left[\Sigma_{\rm F}\left(\widetilde{q}_{\mu}\mathcal{V}^{<,\mu}\right)\right]^{F}_{\rm P.B.} + \mathcal{O}(\hbar^2),$$

K. Hattori, Y. Hidaka, D.-L. Yang, PRD 100, 096011 (2019)
D.-L. Yang, K. Hattori, Y. Hidaka, JHEP 07 (2020) 070
***SF**, S. Pu, D.-L. Yang, 2311.15197*

QKT with self-energies and collisions (III)

- From the master equations, we find the mass and momentum are modified by the self-energies,

$$\tilde{m} = m - \overline{\Sigma}_{\rm F}, \qquad \tilde{q}_\mu = q_\mu + \overline{\Sigma}_{{\rm V},\mu},$$

- The perturbative solutions are modified in dispersion relations, solution structure, etc,

Distribution of vector charge

Modified spin tensor

$$\mathcal{V}^<_\mu(q,X) = 2\pi\epsilon(q_0)\delta(\tilde{q}^2-\tilde{m}^2)\tilde{q}_\mu f^<_{\rm V}(q,X) + \mathcal{O}(\hbar^2),$$

$$\mathcal{A}^<_\mu(q,X) = \mathcal{A}^<_{({\rm dy})\mu}(q,X) + \mathcal{A}^<_{({\rm non})\mu}(q,X) + \mathcal{A}^<_{({\rm mag})\mu}(q,X)$$

$$= 2\pi\epsilon(q_0)\Big\{\delta(\tilde{q}^2-\tilde{m}^2)\left[a_\mu f^<_{\rm A} + \hbar S_{n,\mu\nu}(\tilde{q},\tilde{m})\tilde{D}^\nu f^<_{\rm V} - \overline{\Sigma}_{{\rm A},\mu} f^<_{\rm V}\right] - \delta'(\tilde{q}^2-\tilde{m}^2) f^<_{\rm V}$$

$$\times\left[\frac{\hbar}{2}\epsilon_{\mu\nu\alpha\beta}\tilde{q}^\nu(QeF^{\alpha\beta} + 2\nabla^{[\alpha}\overline{\Sigma}^{\beta]}_{\rm V}) + \tilde{m}\epsilon_{\mu\nu\alpha\beta}\tilde{q}^\nu\overline{\Sigma}^{\alpha\beta}_{\rm T} + 2(\overline{\Sigma}_{\rm A}\cdot\tilde{q})\tilde{q}_\mu - 2\tilde{m}^2\overline{\Sigma}_{{\rm A},\mu}\right]\Big\}$$

$$S^{\mu\nu}_n(\tilde{q},\tilde{m}) = \frac{\epsilon^{\mu\nu\rho\sigma}\tilde{q}_\rho n_\sigma}{2(\tilde{q}\cdot n+\tilde{m})},$$

Effective spin 4-vector in phase space

Effective field strength tensor

Other sources of spin polarizations from self-energies

- These new ingredients related to the **self-energies** and their **gradients** in the axial-vector Wigner function can serve as **new sources of quark spin polarization**.

*D.-L. Yang, K. Hattori, Y. Hidaka, JHEP 07 (2020) 070; **SF**, S. Pu, D.-L. Yang, 2311.15197*

QKT with self-energies and collisions (IV)

- We then obtain the scalar kinetic equation for fermion distributions (the **Boltzmann** equation),

$$0 = 2\pi\epsilon(q_0)\delta(\tilde{q}^2 - \tilde{m}^2)\Big\{\tilde{q}_\mu \tilde{\nabla}^\mu f_V^< + \tilde{q}_\mu \widehat{\Sigma_V^\mu f_V} + \tilde{m}\widehat{\Sigma_F f_V}$$
$$-\tilde{m}\left[(\nabla_\alpha \overline{\Sigma}_F)\partial_q^\alpha f_V^< - (\partial_{q,\alpha}\overline{\Sigma}_F)\partial_X^\alpha f_V^<\right]\Big\} + \mathcal{O}(\hbar^2),$$

And the axial kinetic equation for the quark effective **spin vector** with **modifications from self-energies**,

$$\Box_{a,\mu}^{(n)}\mathcal{A}^< + \tilde{q}_\mu \Box_q^{(n)}\mathcal{A}^< + \tilde{m}\Box_{m,\mu}^{(n)}\mathcal{A}^< = \mathcal{C}_{1,\mu}^{(n)} + \hbar(\tilde{q}_\mu \mathcal{C}_{2,\mu}^{(n),q} + \tilde{m}\mathcal{C}_{2,\mu}^{(n),m}).$$

with e.g.

$$\Box_{a,\mu}^{(n)}\mathcal{A}^< = \delta(\tilde{q}^2 - \tilde{m}^2)\Big\{\tilde{q}\cdot\tilde{\nabla}(a_\mu f_A^<) + Qe\overline{F}_{\mu\nu}(a^\nu f_A^<) + 2\epsilon_{\mu\nu\alpha\beta}\frac{\overline{\Sigma}_A^\nu}{\hbar}\tilde{q}^\alpha a^\beta f_A^<$$
$$+\frac{\tilde{q}\cdot\nabla\overline{\Sigma}_F}{\tilde{m}}(a_\mu f_A^<) - \tilde{q}_\mu\frac{\nabla^\nu\overline{\Sigma}_F}{\tilde{m}}(a_\nu f_A^<)\Big\},$$

- It is found that, there exists the terms similar to the **relaxation time** even **in the absence of collision kernel**; AKE serves as a **generalized BMT equation** with **effective "Lorentz forces"** originating from the spin tensor and self-energies.

*D.-L. Yang, K. Hattori, Y. Hidaka, JHEP 07 (2020) 070; **SF**, S. Pu, D.-L. Yang, 2311.15197*

Spin Boltzmann equation with collision terms (I)

- We firstly consider the **massless** fermions and **neglect the self-energies** for simplicity. The independent EoMs of the Wigner functions are simplified to,

$$\begin{aligned}\Delta\cdot\mathcal{V}^{<} &= \Sigma_V^{<}\cdot\mathcal{V}^{>}-\Sigma_V^{>}\cdot\mathcal{V}^{<},\\ \Delta\cdot\mathcal{A}^{<} &= \Sigma_V^{<}\cdot\mathcal{A}^{>}-\Sigma_V^{>}\cdot\mathcal{A}^{<}-\Sigma_A^{<}\cdot\mathcal{V}^{>}+\Sigma_A^{>}\cdot\mathcal{V}^{<}.\end{aligned}$$

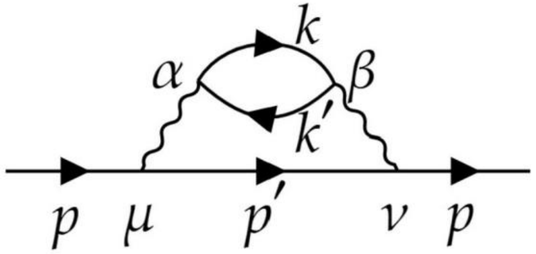
- For massless fermions, the **equilibrium conditions** are,

$$\begin{aligned}\text{global}\quad\text{equilibrium}\quad &:\quad \partial_{(\mu}(\beta u_{\nu)})=0,\omega_s^{\mu\nu}=-\Omega^{\mu\nu}=-\partial^{[\mu}(\beta u^{\nu]})\\ \text{local}\quad\text{equilibrium}\quad &:\quad \omega_s^{\mu\nu}=-\Omega^{\mu\nu}.\end{aligned}$$

Spin chemical potential ($\omega_s^{\mu\nu}$) — Thermal vorticity ($\Omega^{\mu\nu}$)

- We consider the evolution of a hard probe electron in a **thermalized QED plasma**, and evaluate the collision kernels for **a realistic gauge theory**.

$$e^-(p)+e^-_{eq}(k)\leftrightarrow e^-(p')+e^-_{eq}(k'),$$



Y. Hidaka, S. Pu, and D.-L. Yang, Phys.Rev.D 97 (2018) 1, 016004
***SF**,S. Pu, D.-L. Yang Phys.Rev.D 106 (2022) 1, 016002*

Spin Boltzmann equation with collision terms (II)

- A spin Boltzmann equation (SBE) with explicit collision kernel is derived using **HTL approximation**:

$$(p\cdot\partial)f_V^{<}(x,p)=\mathcal{C}_V^{\mathrm{HTL}}[f_V]+\mathcal{O}(\hbar^2),$$

$$(p\cdot\partial)f_A^{<}(x,p)+\hbar\partial_\mu S^{\mu\nu}_{(u)}\partial_\nu f_V^{<}(x,p)=\mathcal{C}_A^{\mathrm{HTL}}[f_V,f_A]+\mathcal{O}(\hbar^2),$$

$$\mathcal{C}_V[f_V]=\frac{e^4\delta(p^2)}{24\beta^2}\ln\frac{T}{m_D}\left[2f_V^{<}(p)f_V^{>}(p)+|\boldsymbol{p}|F(p)\hat{p}_{\perp,\alpha}\partial^\alpha_{p_\perp}f_V^{<}(p)-|\boldsymbol{p}|\frac{1}{\beta}(\partial_{p_\perp}\cdot\partial_{p_\perp})f_V^{<}(p)\right]$$

$$\begin{aligned}\mathcal{C}_A[f_V,f_A]=&-\frac{e^4\delta(p^2)}{8\pi^2|\boldsymbol{p}|}\ln\frac{T}{m_D}\left\{\frac{2\pi^2}{3\beta^2}|\boldsymbol{p}|F(p)f_A^{<}(p)+\frac{\pi^2}{3\beta^2}|\boldsymbol{p}|^2F(p)[(\hat{p}_\perp\cdot\partial_{p_\perp})-\frac{1}{\beta}(\partial_{p_\perp}\cdot\partial_{p_\perp})]f_A^{<}(p)\right.\\&-\frac{2\pi^2}{3\beta^2}|\boldsymbol{p}|^2f_A^{<}(p)(\hat{p}_\perp\cdot\partial_{p_\perp})f_V^{<}(p)+\hbar F(p)|\boldsymbol{p}|H_{3,\alpha}\partial^\alpha_{p_\perp}f_V^{<}(p)\\&-\hbar\frac{\pi^2}{12\beta^2}F(p)|\boldsymbol{p}|\epsilon^{\rho\alpha\nu\beta}\hat{p}_{\perp,\nu}u_\beta\partial_{p_\perp,\rho}\partial_\alpha f_V^{<}(p)+\hbar\frac{\pi^2}{6\beta^3}\epsilon^{\rho\alpha\nu\beta}\hat{p}_{\perp,\rho}u_\beta\partial_{p_\perp,\nu}\partial_\alpha f_V^{<}(p)\\&+\hbar\frac{\pi^2}{6\beta^2}\epsilon^{\mu\xi\lambda\kappa}p_\lambda u_\kappa\partial_\xi f_V^{<}(p)\partial_{p_\perp,\mu}f_V^{<}(p)\\&\left.-\hbar\frac{\pi^2}{12\beta^3}|\boldsymbol{p}|\epsilon^{\rho\alpha\nu\beta}\hat{p}_{\perp,\nu}u_\beta\hat{p}_{\perp,(\gamma}g_{\lambda)\rho}\hat{p}_{\perp,\lambda}\partial^\lambda_{p_\perp}\partial^\gamma_{p_\perp}\partial_\alpha f_V^{<}(p)\right\}+\mathcal{O}(\hbar^2).\end{aligned}$$

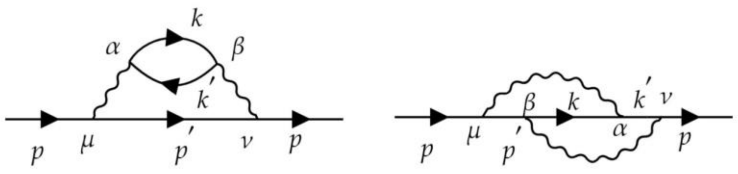
- It is found that, when the vector and axial **distribution functions of probes are in local equilibrium**, the **collision kernels are zero**: Detailed balance exists for **quantum modes**.

- For certain cases, we find the **spin relaxation rate can be much slower** than particle relaxation rate.

SF, *S. Pu, D.-L. Yang Phys.Rev.D 106 (2022) 1, 016002*

Solving SBE: Gradient expansion

- In the **Navier-Stokes limit**, we can derive the solution of SBE when the vector distribution $\boldsymbol{f_V}$ is in **local equilibrium** for the Moller scattering process,



$$
\begin{aligned}
&\delta f_{\rm A}^{<}(x,p)\\
=\ & -\frac{\hbar}{2} f_{V,\rm leq}^{<}(x,p) f_{V,\rm leq}^{>}(x,p) \frac{48\pi\beta^2}{e^4 \ln\frac{T}{m_{\rm D}}} \left\{ -(-\frac{27\zeta(3)}{\pi^2\beta} + E_{\mathbf{p}})\frac{2\ln 2}{3}(\omega_\rho \nabla^\rho \beta - \beta \nabla_\alpha \omega^\alpha) \right.\\
&+(-\frac{27\zeta(3)}{\pi^2\beta} + E_{\mathbf{p}})\left(\frac{5}{3} - \frac{360\zeta(3)}{7\pi^4}\ln 2\right)\beta\omega_\rho\nabla^\rho\alpha\\
&+\left[-\frac{45\zeta(3) - 7\pi^2\ln 2}{14\pi^2\ln 2}\epsilon^{\mu\nu\alpha\beta}u_\beta\nabla_\nu\alpha\nabla_\mu\beta - \frac{3\pi^2}{10\ln 2}\beta\sigma^{\mu\alpha}\omega_\mu\right]p_{\langle\alpha\rangle}\\
&+\left[-\frac{\beta}{4}\left(\omega^{\langle\alpha}\nabla^{\rho\rangle}\beta + \frac{1}{2}\beta\nabla^{\langle\rho}\omega^{\alpha\rangle} + \epsilon^{\mu\nu\sigma\langle\rho}\sigma_\mu^{\alpha\rangle}u_\sigma\nabla_\nu\beta\right) + \frac{3645\zeta^2(3) + 7\pi^6}{1512\pi^4\zeta(3)}\beta^2\epsilon^{\mu\nu\sigma\langle\rho}\sigma_\mu^{\alpha\rangle}u_\sigma\nabla_\nu\alpha\right.\\
&\left.\left.+\frac{10935\zeta^2(3) - 14\pi^6}{756\pi^4\zeta(3)}\beta^2\omega^{\langle\alpha}\nabla^{\rho\rangle}\alpha\right]p_{\langle\alpha}p_{\rho\rangle} + \frac{7\pi^4}{10125\zeta(5)}\beta^3\omega^{\langle\rho}\sigma^{\mu\lambda\rangle}p_{\langle\mu}p_\rho p_{\lambda\rangle}\right\},
\end{aligned}
$$

- We notice that, the corrections are proportional to combinations of hydrodynamic fluctuations and, therefore, lead to a **higher order corrections** to the spin polarization **if $\boldsymbol{f_V}$ is in local equilibrium**.

***SF**, S. Pu, et al in preparation*

Spin polarization with off-equilibrium corrections

- In terms of spin Cooper-Frye formula,

$$\delta\mathcal{P}^{\mu}(t;\mathbf{p}) = -\mathcal{P}^{\mu}_{\rm leq}(t;\mathbf{p})\frac{1}{N}\int_{\Sigma}\mathrm{d}\Sigma_{\alpha}p^{\alpha}\delta f^{<}_{\rm V}(x,p) + \frac{\hbar}{2N}\int_{\Sigma}\mathrm{d}\Sigma\cdot pp^{\mu}\delta f^{<}_{\rm A}(x,p)$$
$$= -\mathcal{P}^{\mu}_{\rm leq}\left(\mathcal{P}_{\rm V,shear}+\mathcal{P}_{\rm V,chem}\right)+\mathcal{P}^{\mu}_{\rm A,vort-\nabla T}+\mathcal{P}^{\mu}_{\rm A,\nabla vort}+\mathcal{P}^{\mu}_{\rm A,vort-chem}$$
$$+\mathcal{P}^{\mu}_{\rm A,vort-shear}+\mathcal{P}^{\mu}_{\rm A,chem-\nabla T}+\mathcal{P}^{\mu}_{\rm A,shear-\nabla T}+\mathcal{P}^{\mu}_{\rm A,shear-chem},$$

where we have, for example,

$$\mathcal{P}^{\mu}_{\rm A,vort-\nabla T} = -\frac{\hbar^2\beta_0^2}{4Ne^4\ln\frac{1}{e}}\int_{\Sigma}\mathrm{d}\Sigma\cdot p f^{<}_{\rm V,leq}(p)f^{>}_{\rm V,leq}(p)$$
$$\times p^{\mu}\left[d_2\left(E_{\mathbf{p}}-d_1\frac{1}{\beta_0}\right)\omega^{\alpha}\nabla_{\alpha}\beta_0 - d_6\beta_0 p_{\langle\alpha}p_{\rho\rangle}\omega^{\alpha}\nabla^{\rho}\beta_0\right],$$

$$\mathcal{P}^{\mu}_{\rm A,\nabla vort} = \frac{\hbar^2\beta_0^2}{4Ne^4\ln\frac{1}{e}}\int_{\Sigma}\mathrm{d}\Sigma\cdot p f^{<}_{\rm V,leq}(p)f^{>}_{\rm V,leq}(p)$$
$$\times p^{\mu}\left[\left(E_{\mathbf{p}}-d_1\frac{1}{\beta_0}\right)d_2\beta_0\nabla^{\alpha}\omega_{\alpha} + d_6\frac{1}{2}\beta_0^2\nabla^{\alpha}\omega^{\rho}p_{\langle\alpha}p_{\rho\rangle}\right],$$

Becattini, Chandra, Del Zanna, Grossi, Annals Phys (2013);
Fang, Pang, Wang. Wang, PRC(2016);
Yi, Pu, Yang, PRC(2021);
***SF**, Pu, et al in preparation*

Outline

- Spin polarization and alignment in heavy ion collisions
- Quantum kinetic theory with collisions and self-energies
- **Self-energy corrections to spin polarization and alignment**
- Summary

Self-energy: widely used in nuclear physics

The crucial role of self-energy has been realized in nuclear physics:

- The **mean field approximations** in low-energy nuclear physics: nuclear EoS, binding energy,…

See: *B. D. Serot, Rept. Prog. Phys. 55, 1855(1992); B. D. Serot and J. D. Walecka, Int. J. Mod. Phys. E 6, 515(1997).*

- The **mean field approximations** used in QCD phase transition: for example, in the use of NJL model,…

See: *S. P. Klevansky, RMP 64,649(1992); T. Hatsuda, T. Kunihiro, Phys. Rept. 247 (1994) 221-367.*

Actually, people use the contributions of self-energy widely when they deal with spin polarization phenomena……

- The **external electromagnetic** (EM) field induces the difference of spin polarization of $\Lambda/\bar{\Lambda}$: In the background field gauge, the EM field are the **classical fields (mean fields)**;
- Spin alignment of ϕ mesons from **spacetime dependent** mean ϕ fields

at freezeout:

$$g_\phi F_\phi^{\mu\nu} = g_\phi(\partial^\mu \langle \phi^\nu \rangle - \partial^\nu \langle \phi^\mu \rangle)$$

Muller, Schafer, PRD(2018);
Guo, Shi, Feng, Liao, PLB(2019);
Xu, Lin, Huang, Huang, PRDL(2022);
Peng, Wu, Wang, She, Pu, PRD(2023);

- Spin alignment of J/ψ from initial-stage **classical color fields**.

Sheng, Oliva, Liang, Wang, Wang, PRL (2023); PRD(2024); Muller, Yang, PRD(2022); Yang, JHEP(2022).

Spin polarization from one-point potential

- Consider a quark-meson interaction,

$$\mathcal{L}_{\rm int} = g_\phi \phi_\mu \overline{\psi}\gamma^\mu \psi,$$

Up to the leading order in coupling constant (with Hatree/tadpole diagram), we derive, $\overline{\Sigma}^\mu_{\rm V} = g_\phi \langle \phi_\mu \rangle,$
and the contribution to the axial vector Wigner function reads,

$$\delta \mathcal{A}_s^{<,\mu} = -2\pi \delta'(\widetilde{q}^2 - \widetilde{m}^2)\frac{\hbar}{2}\epsilon_{\mu\nu\alpha\beta}\widetilde{q}^\nu g_\phi F_\phi^{\alpha\beta} f_{\rm V}^<,$$

then up to the linear order in self-energy and working in the **global equilibrium** case, we obtain

$$\delta \mathcal{P}_s^\mu(\mathbf{q}, x) = \frac{\int \frac{dq_0}{2\pi}\delta \mathcal{A}_s^{<,\mu}(q,x)}{2\int \frac{dq_0}{2\pi}\mathcal{F}_s^<(q,x)} = -\frac{\hbar g_\phi}{4mT}B_\phi^\mu (1 - f_{\rm V}^<),$$

which induces the spin polarization of strange quarks.

- Similarly, one can obtain the quark polarization from other effective fields via a tadpole diagram.
- In our formalism, the **quantum part of gauge fields** and the **background color fields** are neglected in the **background field gauge**.

X.-L. Sheng, L. Oliva, Z.-T. Liang, Q. Wang, X.-N. Wang, 2206.5868; PRL 131, 042304(2023); ***SF****, S. Pu, D.-L. Yang, 2311.15197*

Spin polarization from a thermal QCD background (I)

- Omitting the external EM field and background color field, the **leading order contribution** from **gauge** fields to quark spin polarization comes from the **Fock diagram**.

- Due to a **lack** of knowledege the **quantum part of gluonic Wigner function** in $O(\hbar)$, we firstly neglect the corresponding corrections,

$$\delta\mathcal{A}^{<}_{\mu,\mathrm{SE}}(q,X) = 2\pi\epsilon(q_0)\partial^{\nu}_{q}\delta(q^2-m^2)f^{<}_{\mathrm{V}}\frac{\hbar}{2}\epsilon_{\mu\nu\beta\alpha}\partial^{\beta}_{X}\mathrm{Im}\Sigma^{++,\alpha}_{\mathrm{V}}$$

- For the weakly coupling QGP, we obtain,

$$\begin{cases} m_f^2 = C_{\mathrm{F}}\frac{g^2}{8}\left(\frac{\mu^2}{\pi^2}+T^2\right) \\ \mathcal{Q}_0(x) = \frac{1}{2}\ln\left|\frac{x+1}{x-1}\right|, \\ \mathcal{Q}_1(x) = x\mathcal{Q}_0(x)-1, \end{cases}$$

$$\begin{aligned} &\partial_\beta \mathrm{Im}\Sigma^{++}_{\mathrm{V},\alpha}(q,X) \\ &= C_{\mathrm{F}}\frac{g^2}{4}\left(\frac{\mu}{\pi^2}\partial_\beta\mu + T\partial_\beta T\right)\left[\frac{u_\alpha}{|q_\perp|}\mathcal{Q}_0\left(\frac{q_0}{|q_\perp|}\right)+\frac{q_{\perp,\alpha}}{|q_\perp|^2}\mathcal{Q}_1\left(\frac{q_0}{|q_\perp|}\right)\right] \\ &+m_f^2\left\{\frac{\partial_\beta u_\alpha}{|q_\perp|}\left[\mathcal{Q}_0\left(\frac{q_0}{|q_\perp|}\right)-\frac{q_0}{|q_\perp|}\mathcal{Q}_1\left(\frac{q_0}{|q_\perp|}\right)\right]-u_\alpha q^\gamma_\perp(\partial_\beta u_\gamma)\frac{2}{|q_\perp|^2}\mathcal{Q}_1\left(\frac{q_0}{|q_\perp|}\right)\right. \\ &\left.+q_{\perp,\alpha}q^\gamma_\perp(\partial_\beta u_\gamma)\frac{1}{|q_\perp|^3}\left[\mathcal{Q}_0\left(\frac{q_0}{|q_\perp|}\right)-3\frac{q_0}{|q_\perp|}\mathcal{Q}_1\left(\frac{q_0}{|q_\perp|}\right)\right]\right\}, \end{aligned}$$

M. L. Bellac, Thermal Field Theory (2011);
***SF**, S. Pu, D.-L. Yang, 2311.15197*

Spin polarization from a thermal QCD background (II)

- In the canonical pseudo-gauge, a modification to the spin Cooper-Frye formula reads,

$$\delta\mathcal{P}^{\mu}(t,\mathbf{q}) = \hbar\frac{\int_{\Sigma} q\cdot \mathrm{d}\sigma \int \frac{\mathrm{d}q_0}{2\pi}\delta\mathcal{A}^{<,\mu}(q,X)}{2\int_{\Sigma} q\cdot \mathrm{d}\sigma \int \frac{\mathrm{d}q_0}{2\pi}\mathcal{F}^{<}(q,X)}$$
$$= \delta\mathcal{P}^{\mu}_{\mathrm{therm}}(t,\mathbf{q}) + \delta\mathcal{P}^{\mu}_{\mathrm{shear}}(t,\mathbf{q}) + \delta\mathcal{P}^{\mu}_{\mathrm{chem}}(t,\mathbf{q}) + \delta\mathcal{P}^{\mu}_{\mathrm{acc}}(t,\mathbf{q}) + \delta\mathcal{P}^{\mu}_{\mathrm{vor}}(t,\mathbf{q}),$$

where
$$\delta\mathcal{P}^{\mu}_{\mathrm{therm}}(t,\mathbf{q}) = -\frac{\hbar^2}{2mN}\int_{\Sigma} q\cdot \mathrm{d}\sigma G_{\mathrm{T}}(E_q,\mathbf{q})\frac{m_f^2 T}{E_q^3}\epsilon^{\mu\nu\alpha\beta}q_\nu\partial_\alpha\left(\frac{u_\beta}{T}\right),$$
$$\delta\mathcal{P}^{\mu}_{\mathrm{shear}}(t,\mathbf{q}) = -\frac{\hbar^2}{4mN}\int_{\Sigma} q\cdot \mathrm{d}\sigma G_{\omega_1}(E_q,\mathbf{q})\frac{m_f^2}{E_q^3}\frac{\epsilon^{\mu\nu\rho\sigma}q_\rho u_\sigma}{E_q}q^\gamma\sigma_{\nu\gamma},$$
$$\delta\mathcal{P}^{\mu}_{\mathrm{chem}}(t,\mathbf{q}) = -\frac{\hbar^2}{4mN}\int_{\Sigma} q\cdot \mathrm{d}\sigma G_{\mathrm{T}}(E_q,\mathbf{q})\frac{C_{\mathrm{F}}g^2\mu T}{4\pi^2 E_q^2}\frac{\epsilon^{\mu\nu\rho\sigma}q_\rho u_\sigma}{E_q}\nabla_\nu\left(\frac{\mu}{T}\right),$$
$$\delta\mathcal{P}^{\mu}_{\mathrm{acc}}(t,\mathbf{q}) = \frac{\hbar^2}{4mN}\int_{\Sigma} q\cdot \mathrm{d}\sigma G_{\mathrm{T}}(E_q,\mathbf{q})\frac{3m_f^2}{E_q^3}\epsilon^{\mu\nu\rho\sigma}q_\rho u_\sigma D u_\nu,$$
$$\delta\mathcal{P}^{\mu}_{\mathrm{vor}}(t,\mathbf{q}) = \frac{\hbar^2}{4mN}\int_{\Sigma} q\cdot \mathrm{d}\sigma \frac{m_f^2}{E_q^2}\left[\omega^\mu\left(4G_{\mathrm{T}}(E_q,\mathbf{q}) - \frac{|q_\perp|^2}{E_q^2}G_{\omega_1}(E_q,\mathbf{q}) + 2G_{\omega_2}(E_q,\mathbf{q})\right) - \frac{(\omega\cdot q)}{E_q}\left(6u^\mu G_{\mathrm{T}}(E_q,\mathbf{q}) + \frac{q_\perp^\mu}{E_q}G_{\omega_1}(E_q,\mathbf{q})\right)\right],$$

Becattini, Chandra, Del Zanna, Grossi, Annals Phys (2013);
Fang, Pang, Wang. Wang, PRC(2016);
Yi, Pu, Yang, PRC(2021);
***SF**, Pu, Yang, 2311.15197*

Here,
$N \equiv \int_{\Sigma} q\cdot \mathrm{d}\sigma f_{\mathrm{V}}^{<}(E_q,X)$

Spin polarization from a thermal QCD background (III)

- Comments:
  - ✓ An additional term proportional to **kinetic vorticity appears** even **in global equilibrium**;
  - ✓ The distribution function f_V can be off-equilibrium in general;
  - ✓ Such **interaction-dependent contributions** of the first order in gradients may be **dissipationless** as they exists even when the collision terms are zero.

- An order-of-magnitude approximation with $g^2 = \frac{4\pi}{3}$, $N_c = 3$, $T = 0.165$ GeV, and $m_s = 0.3$ GeV, yields,

	$\lvert q_\perp \rvert = 0.5$ GeV	$\lvert q_\perp \rvert = 1.0$ GeV	$\lvert q_\perp \rvert = 2.0$ GeV
$\lvert \delta\mathcal{J}^{5,\mu}_{\text{therm}} / \mathcal{J}^{5,\mu}_{\text{therm,leq}} \rvert$	0.325	0.098	0.024
$\lvert \delta\mathcal{J}^{5,\mu}_{\text{shear}} / \mathcal{J}^{5,\mu}_{\text{shear,leq}} \rvert$	0.081	0.028	0.007
$\lvert \delta\mathcal{J}^{5,\mu}_{\text{vor}} / \mathcal{J}^{5,\mu}_{\text{therm,leq}} \rvert$	0.177	0.103	0.030

$$\mathcal{J}^{5,\mu}_{\text{therm,leq}}(\mathbf{q}, x) = \frac{\hbar}{8E_q} f^{<}_{\text{V,leq}} f^{>}_{\text{V,leq}} \epsilon^{\mu\nu\alpha\beta} q_\nu \partial_\alpha \left(\frac{u_\beta}{T}\right),$$

$$\mathcal{J}^{5,\mu}_{\text{shear,leq}}(\mathbf{q}, x) = -\hbar \frac{1}{4E_q^2 T} f^{<}_{\text{V,leq}} f^{>}_{\text{V,leq}} \epsilon^{\mu\nu\rho\sigma} q_\rho u_\sigma q^\alpha \sigma_{\nu\alpha},$$

M. L. Bellac, Thermal Field Theory (2011);
***SF**, S. Pu, D.-L. Yang, 2311.15197*

Spin alignment from quark self-energies

- Possible applications to vector meson spin alignment:

$$\rho_{00} \approx \frac{1-\hat{\Pi}^{yy}(\mathbf{q}=\mathbf{0})}{3-\sum_{i=x,y,z}\hat{\Pi}^{ii}(\mathbf{q}=\mathbf{0})},$$

where

$$\hat{\Pi}^{ii}(\mathbf{q}) = \frac{4\int_\Sigma d\sigma\cdot q\left[\mathcal{J}^i_{5q,\mathrm{a}}(\frac{\mathbf{q}}{2},x)+\delta\mathcal{J}^i_{5q,\mathrm{SE}}(\frac{\mathbf{q}}{2},x)\right]\left[\mathcal{J}^i_{5\bar{q},\mathrm{a}}(\frac{\mathbf{q}}{2},x)+\delta\mathcal{J}^i_{5\bar{q},\mathrm{SE}}(\frac{\mathbf{q}}{2},x)\right]}{\int_\Sigma d\sigma\cdot q f^<_{\mathrm{V}q}(E_{\mathbf{q}/\mathbf{2}},\frac{\mathbf{q}}{2}) f^<_{\mathrm{V}\bar{q}}(E_{\mathbf{q}/\mathbf{2}},\frac{\mathbf{q}}{2})}$$

- If one determine the $\delta J_{5,SE}$ from quark self-energies, a nontrivial contribution to spin alignment is obtained. One of the most important result is the **spin alignment of ϕ from an effective ϕ meson field**.

- In the framework of **chiral quark model**, the presence of **effective meson fields** can be used to explain the **spin alignment of** other mesons e.g. $K^{*,0}$.

Kumar, Muller, Yang, PRD(2023);
Sheng, Oliva, Liang, Wang, Wang, PRL (2023); PRD (2024)
***SF**, Pu, Yang, 2311.15197*

Outline

- Spin polarization and alignment in heavy ion collisions
- Quantum kinetic theory with collisions and self-energies
- Self-energy corrections to spin polarization and alignment
- Collisional effects on spin polarization
- **Summary**

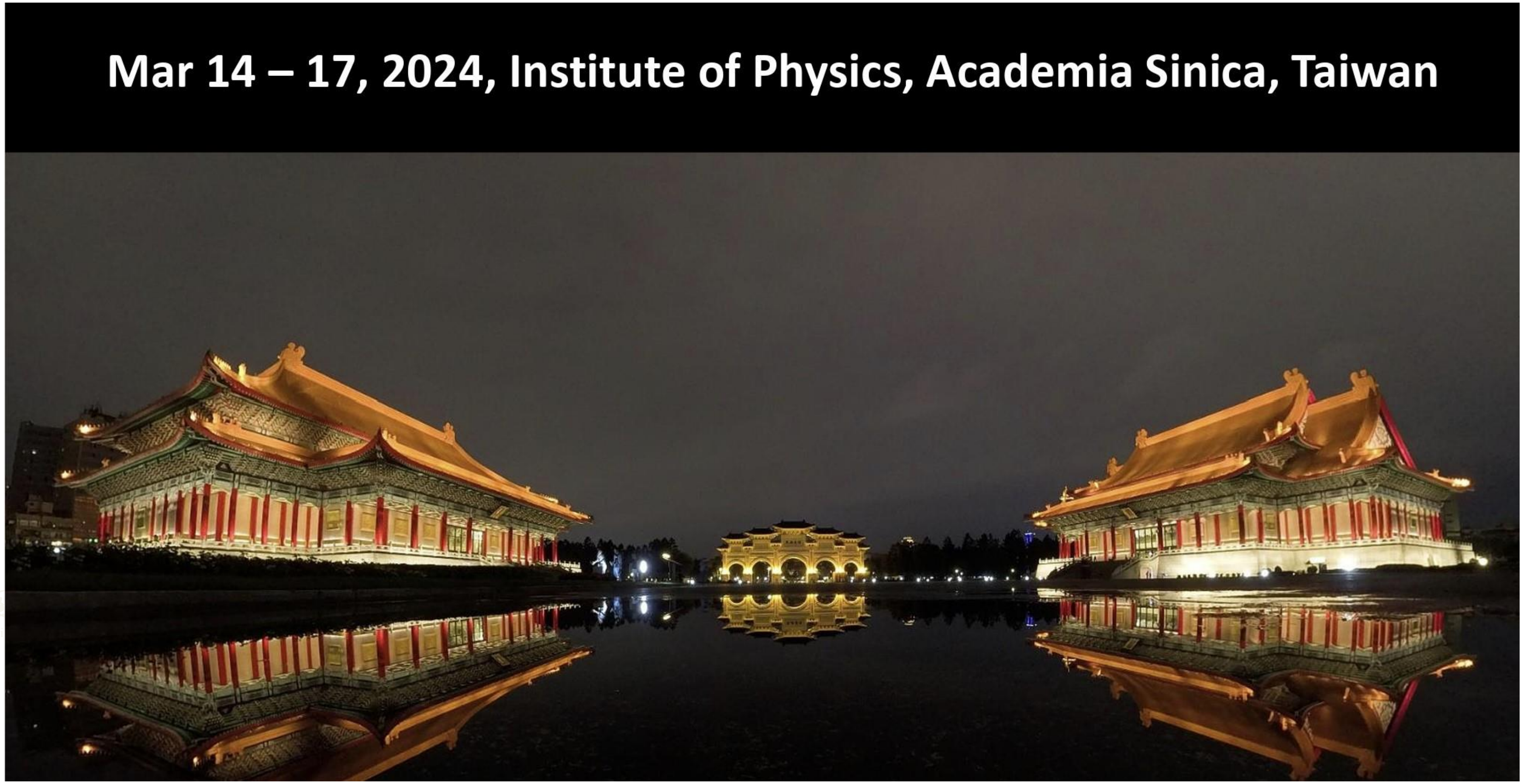
Summary

1. We have derived the **QKT with self-energies and collisions** for spin-half fermions. It is found that the dispersion relation, perturbative solutions, and kinetic equations are modified by self-energies.

2. The **spin polarization** of quarks from **self-energies** are **of leading order in couplings and gradients**. Our results provide a theoretical support to the s-quark polarization from effective meson fields; we also derive a **modification of the spin Cooper-Frye formula** from quark self-energies; it has important contributions to spin alignment.

3. **Collisional effects** is discussed from a spin Boltzmann equation based on HTL approximation; the **off-equilibrium corrections** are derived.

Thanks for your attention！



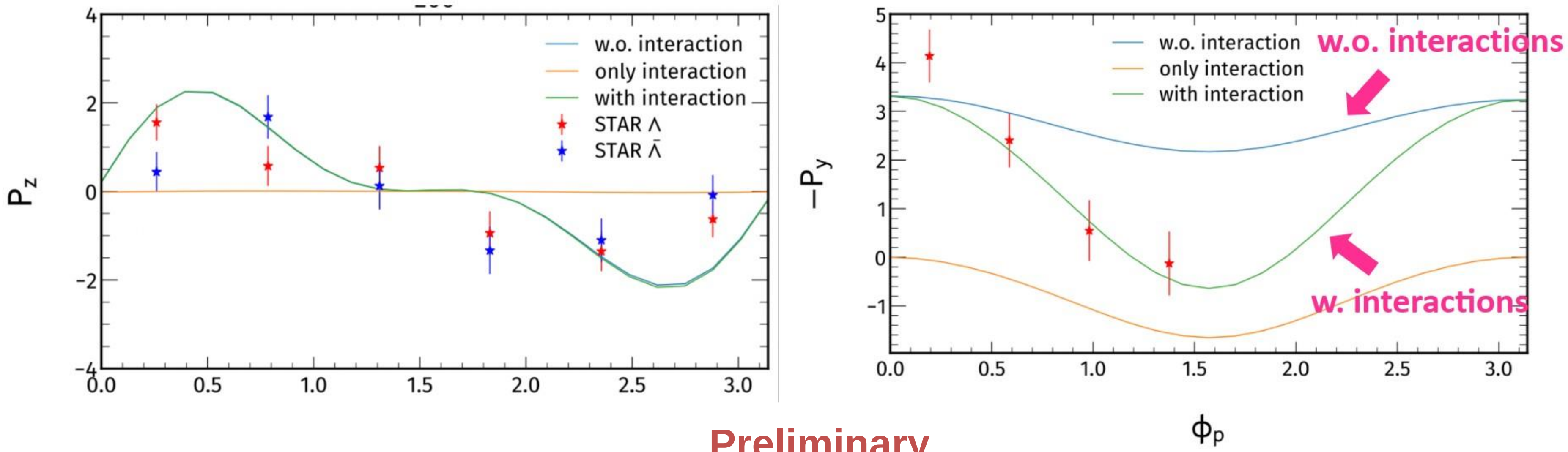
Backup slides

Numerical Estimation of off-equilibrium effects by solving SBE

- The off-equilibrium effect can be described using numerical simulation,

$$\mathcal{S}^{\mu}(\mathbf{p}) = \frac{\int d\Sigma \cdot p\mathcal{J}_5^{\mu}(p,X)}{2m_{\Lambda}\int d\Sigma \cdot \mathcal{N}(p,X)},$$

200GeV, CLVisc hydrodynamics + AMPT initial + EoS: NEOS-BQS



Preliminary

SF, S. Pu, et al in preparation
C. Yi, SF, S. Pu, et al. in preparation