Exploration of spin transport in heavy ion collisions from quantum kinetic theory

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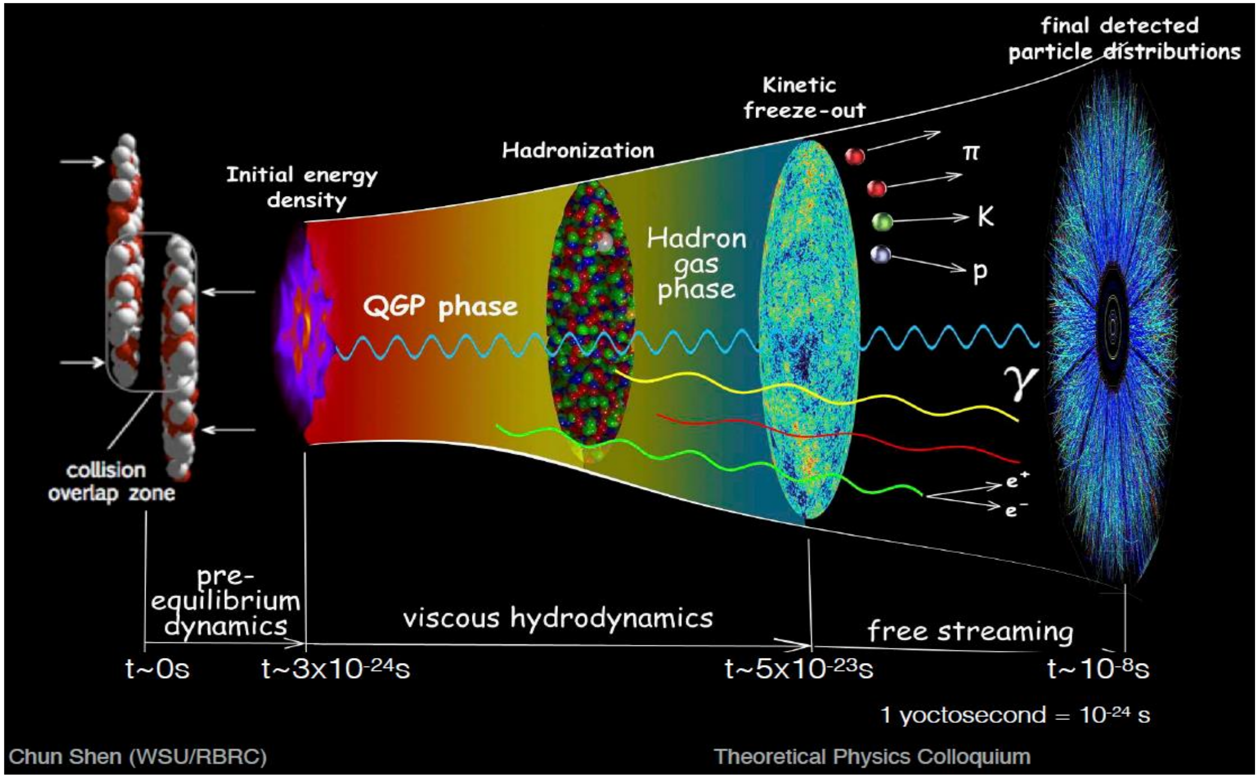
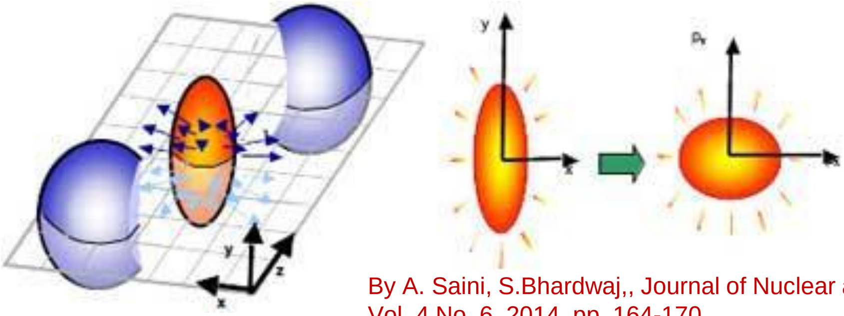
Relativistic heavy ion collisions

- Creating the quark gluon plasma (QGP) :



- Hydrodynamic evolution :



collective flow,
small viscosity,
strongly coupled

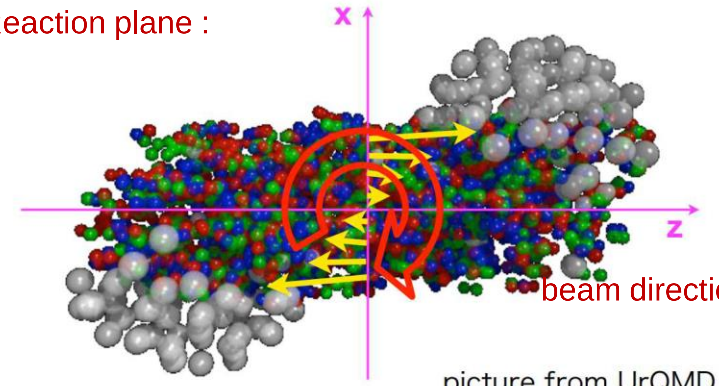
By A. Saini, S.Bhardwaj,, Journal of Nuclear and Particle Physics, Vol. 4 No. 6, 2014, pp. 164-170.

Subatomic swirls

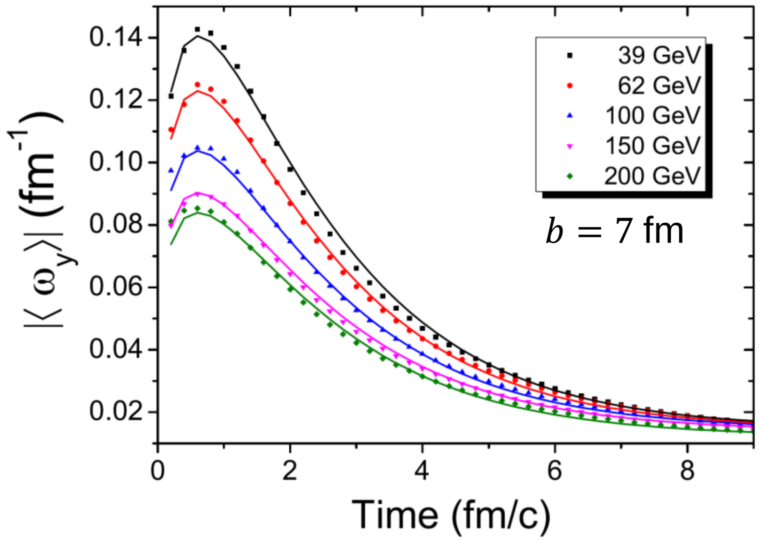
- Strong vortical fields in HIC :

Y. Jiang, Z.-W. Lin, J. Liao, PRC 94, 044910 (2016)
see also W.-T. Deng and X.-G. Huang, PRC 93, 064907 (2016)

Reaction plane :



impact parameter



❖ Angular momentum (AM) to vorticity :

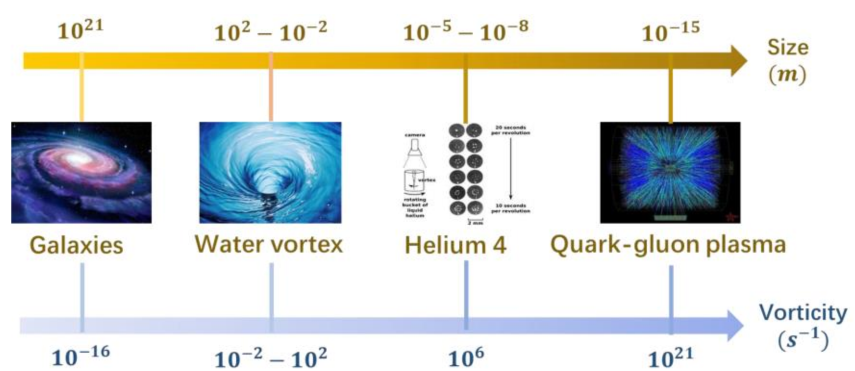
$$\mathbf{L} = \frac{1}{2} \int d^3\mathbf{r}\epsilon|\mathbf{r}|^2(1 - \hat{\boldsymbol{\omega}} \cdot \hat{\mathbf{r}})\boldsymbol{\omega},$$

$$\boldsymbol{\omega} = \nabla \times \mathbf{v} = \text{const.}$$

ϵ : energy density

❖ AM to spin polarization?

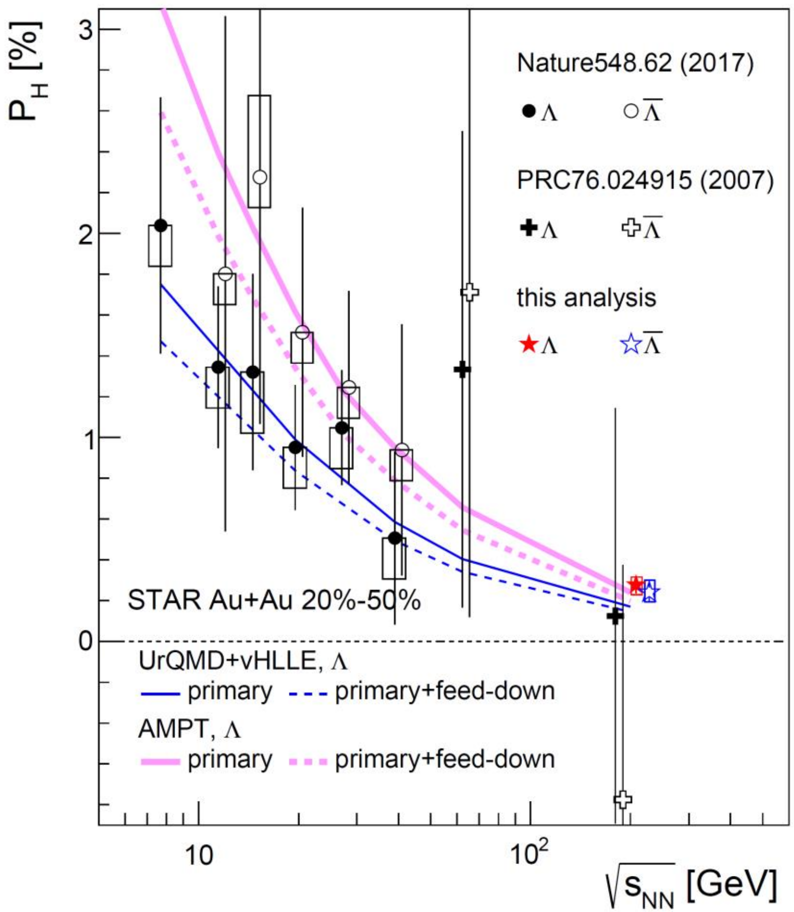
Z.-T. Liang and X.-N. Wang, PRL. 94, 102301 (2005)



X.-G. Huang, QM 19

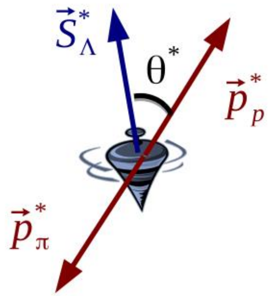
Λ polarization in HIC

- Global polarization of Λ hyperons :



L. Adamczyk et al. (STAR), Nature 548, 62 (2017)

❖ Self-analyzing via the weak decay :



T. Niida, QM18

❖ Statistical model/Wigner-function approach (in global equilibrium):

F. Becattini, et al., Ann. Phys. 338, 32 (2013)

R. Fang, et al., PRC 94, 024904 (2016)

$$\mathcal{P}^\mu(q) \approx \frac{1}{8m}\epsilon^{\sigma\mu\nu\rho}q_\sigma \frac{\int d\Sigma \cdot q\omega_{\nu\rho} f_q^{(0)}(1-f_q^{(0)})}{\int d\Sigma \cdot q f_q^{(0)}},$$

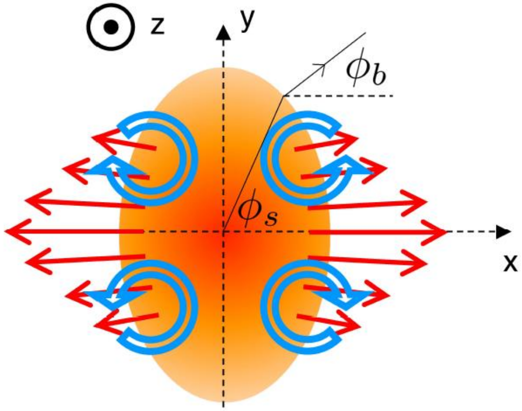
$$\omega_{\nu\rho} = \frac{1}{2}\left(\partial_\rho(u_\nu/T) - \partial_\nu(u_\rho/T)\right).$$

thermal vorticity $\xrightarrow[\text{T=const.}]{}$ $\omega_{\alpha\beta} = -\epsilon_{\alpha\beta\mu\nu}\omega^\mu u^\nu$

Local (longitudinal) polarization : a sign problem

- Local vorticity :

  transverse expansion :
  longitudinal vorticity & polarization



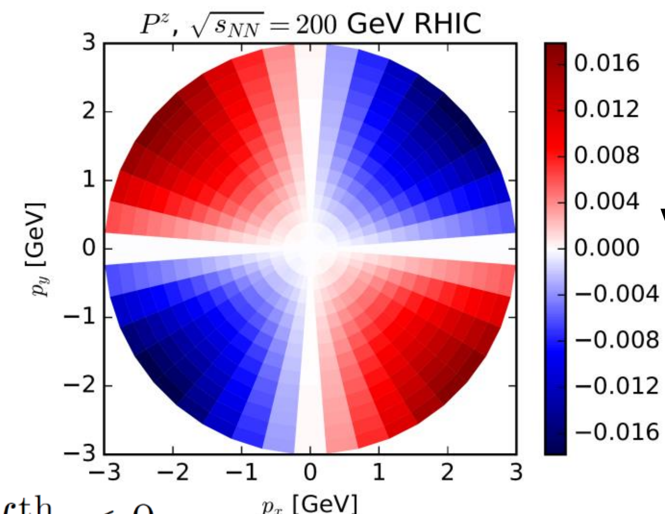
- A "sign problem" for longitudinal polarization

F. Becattini, I. Karpenko, PRL 120, 012302 (2018).

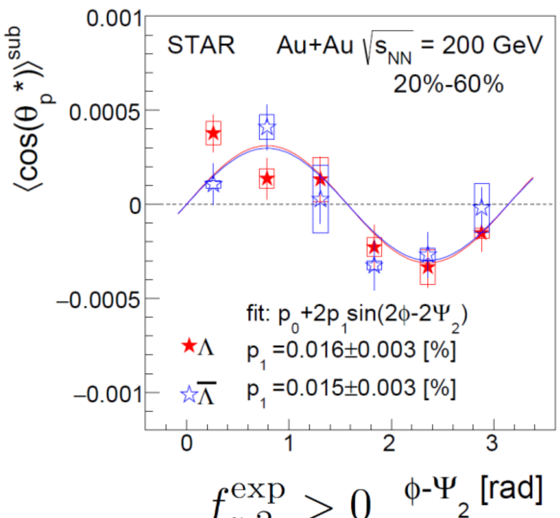
J. Adam et al. (STAR, PRL. 123, 132301 (2019)

Spin harmonics :

$$\frac{dP^z}{2\pi d\phi} = f_{z,0} + 2 f_{z,2} \sin(2\phi)$$



v.s.



$f_{z,2}^{\rm th} < 0$ $\qquad$ $f_{z,2}^{\rm exp} > 0$

(same structure, opposite signs!)

Go beyond global equilibrium

- The assumption for global equilibrium may be too naïve.

- To understand non-equilibrium effects and dynamical spin polarization :
  - Spin hydrodynamics (macroscopic)
  - Quantum kinetic theory (QKT) (microscopic)

  How a (strange) quark traversing QGP becomes polarized?

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

- The key ingredient to generate dynamical spin polarization : quantum corrections in collisions (spin-orbit int.).
- Tracking the non-equilibrium evolution in phase space is challenging : solving multi-dimensional differential equations.
- Near equilibrium : QKT ⇨ spin hydro.

Spin polarization in local equilibrium

- Spin polarization for massless fermions in local equilibrium can be obtained from the CKT with Coulomb scattering. Y. Hidaka, S. Pu, DY, PRD 97, 016004 (2018)

$$\mathcal{J}_5^\mu = \mathcal{J}^\mu_{\text{thermal}} + \mathcal{J}^\mu_{\text{shear}} + \mathcal{J}^\mu_{\text{accT}} + \mathcal{J}^\mu_{\text{chemical}} + \mathcal{J}^\mu_{\text{EB}},$$ (+ dissipative terms)

$$\mathcal{J}^\mu_{\text{thermal}} = a\frac{1}{2}\epsilon^{\mu\nu\alpha\beta}p_\nu\partial_\alpha\frac{u_\beta}{T}, \quad \Rightarrow \quad J_5^\mu = \sigma_{5\omega}\omega^\mu$$ (chiral vortical effect)

A. Vilenkin, PRD 20, 1807 (1979)

$$\mathcal{J}^\mu_{\text{shear}} = -a\frac{1}{(u\cdot p)T}\epsilon^{\mu\nu\alpha\beta}p_\alpha u_\beta p^\sigma\partial_{\langle\sigma}u_{\nu\rangle},$$

$$\mathcal{J}^\mu_{\text{accT}} = -a\frac{1}{2T}\epsilon^{\mu\nu\alpha\beta}p_\nu u_\alpha\left(Du_\beta - \frac{1}{T}\partial_\beta T\right),$$

$$a = 4\pi\hbar\,\text{sign}(u\cdot p)\delta(p^2)f_V^{(0)}(1-f_V^{(0)}).$$

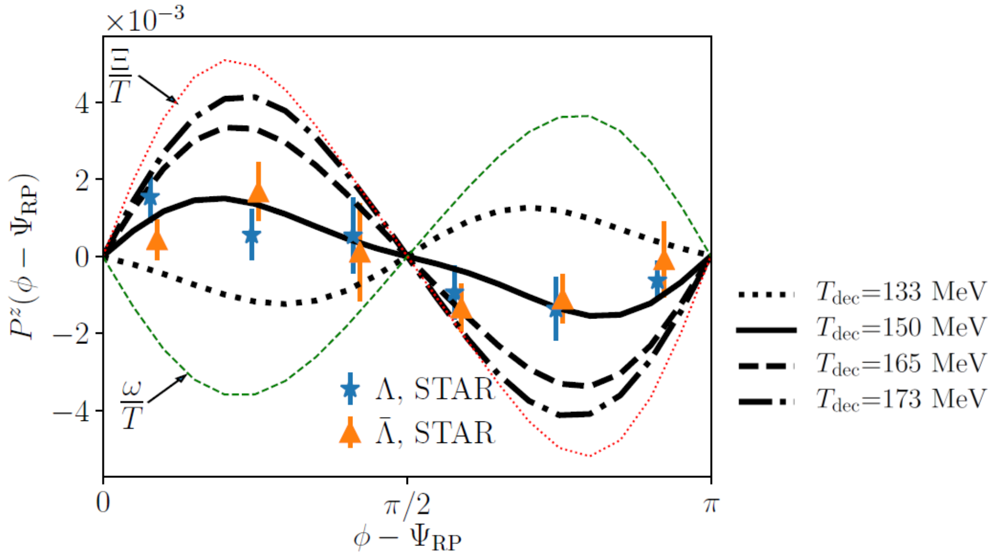
C. Yi, S. Pu, DY, PRC 104, 064901(2021)
("naïve" generalization to massive fermions)

- Generalization to the massive case was also derived from the linear response theory and statistical field theory. S. Y. F. Liu and Y. Yin, PRD 104, 054043 (2021)
S. Y. F. Liu, Y. Yin, JHEP 07, 188 (2021)
F. Becattini, M. Buzzegoli, A. Palermo, PLB 820,136519 (2021)

Shear corrections on longitudinal polarization

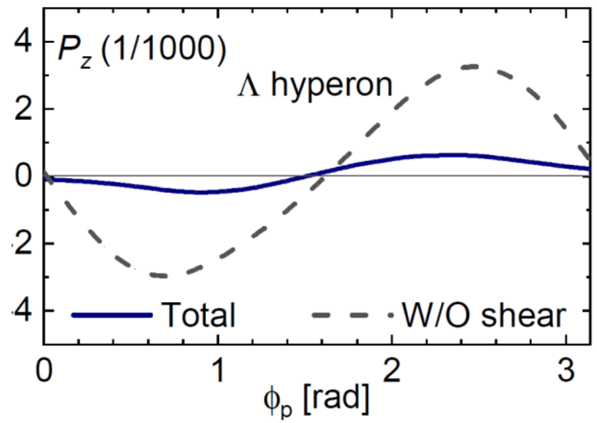
- Isothermal approximation :

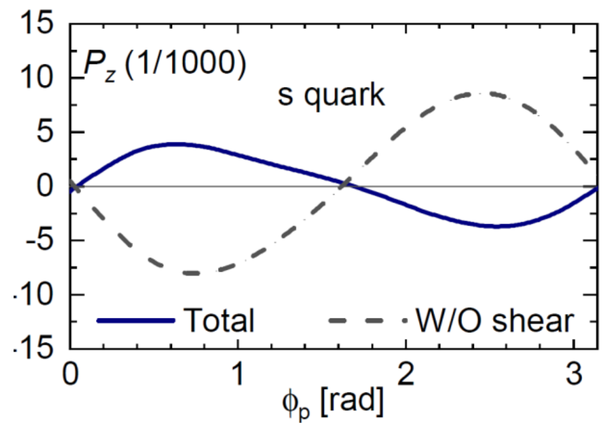
F. Becattini, M. Buzzegoli, A. Palermo, G. Inghirami, and I. Karpenko, PRL. 127 (2021) 27, 272302



- Λ and s equilibrium scenarios:

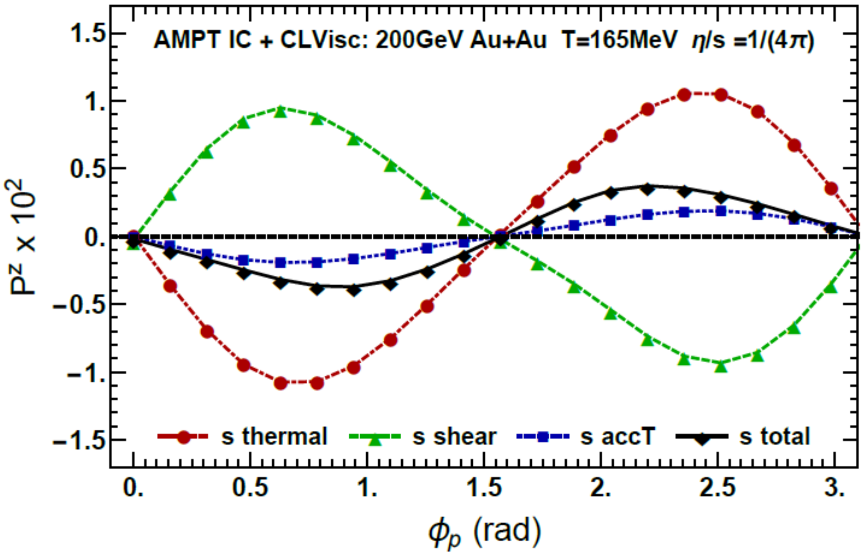
B. Fu, S. Y. F. Liu, L. Pang, H. Song, and Y. Yin, PRL 127, 142301 (2021)

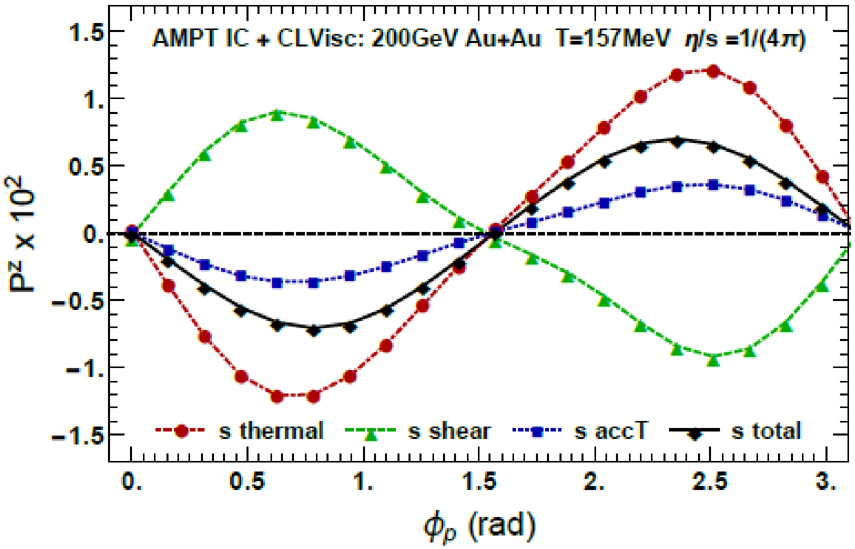




Is the spin sign problem solved?

- Sensitive to the equation of state and freeze-out T : out-off equilibrium corrections depending on interaction should be still considered.





C. Yi, S. Pu, DY, PRC 104 (2021) 6, 064901

Helicity polarization

- A better observable to probe the strength of local vorticity?
- Helicity polarization : $S^h = \widehat{\mathbf{p}}\cdot\boldsymbol{S}(\mathbf{p}) = \widehat{p}^x\mathcal{S}^x + \widehat{p}^y\mathcal{S}^y + \widehat{p}^z\mathcal{S}^z,$

F. Becattini et al., Phys.Lett.B 822 (2021) 136706
J.-H. Gao, Phys. Rev. D 104, 076016
C. Yi, S. Pu, DY, (2021) 2112.15531

$$S^h_{\mathrm{thermal}}(\mathbf{p}) = \int d\Sigma^\sigma F_\sigma p_0 \epsilon^{0ijk}\widehat{p}_i \nabla_j \left(\frac{u_k}{T}\right),$$

$$S^h_{\mathrm{shear}}(\mathbf{p}) = -\int d\Sigma^\sigma F_\sigma \frac{\epsilon^{0ijk}\widehat{p}^i p_0}{(u\cdot p)T}\{p^\sigma(\partial_\sigma u_j + \partial_j u_\sigma - u_\sigma D u_j)u_k\},$$

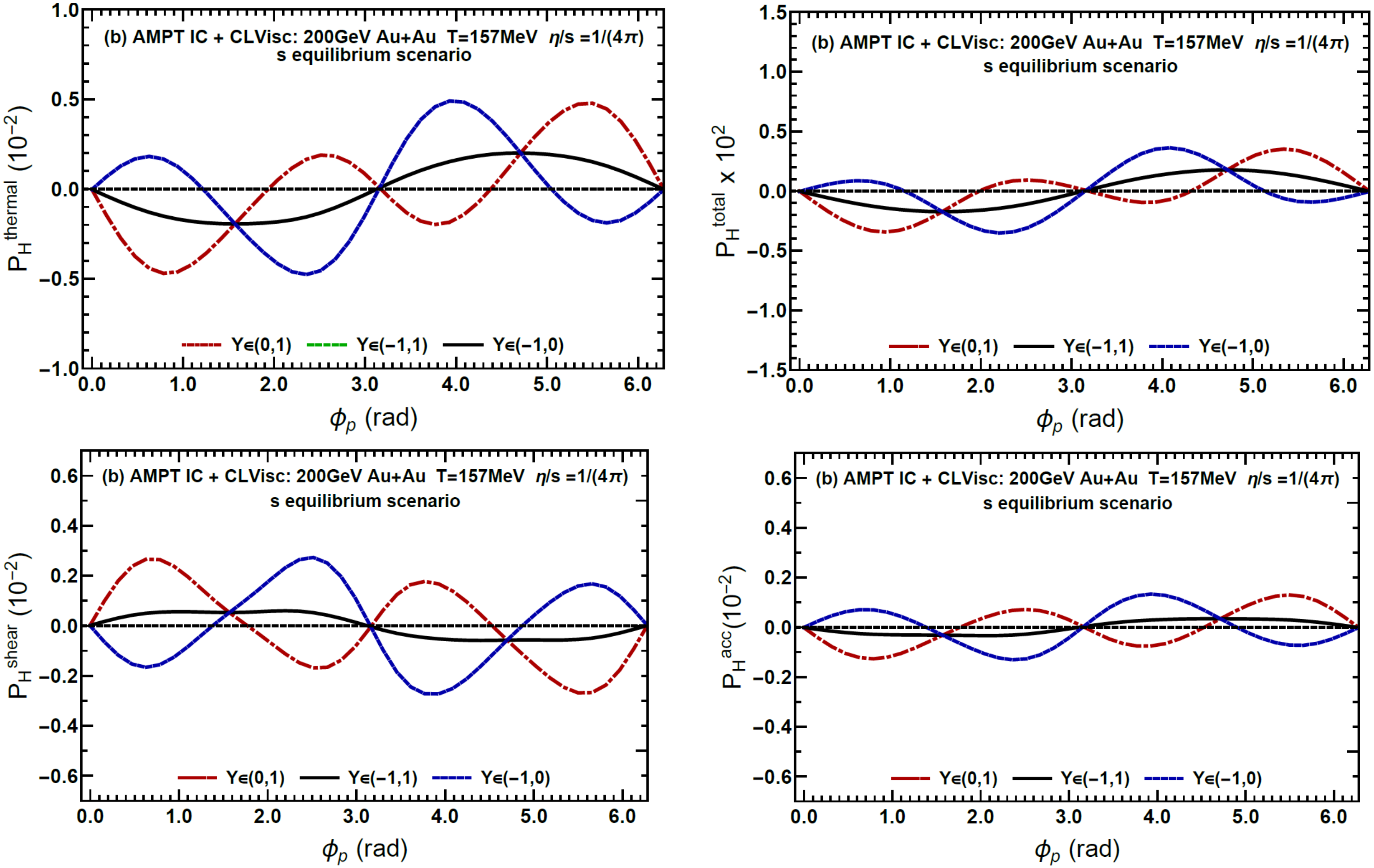
$$S^h_{\mathrm{accT}}(\mathbf{p}) = \int d\Sigma^\sigma F_\sigma \frac{1}{T}\epsilon^{0ijk}\widehat{p}^i p_0 u_j (D u_k - \frac{1}{T}\partial_k T),$$

$$F^\mu = \frac{\hbar}{8 m_\Lambda N} p^\mu f_V^{(0)}(1 - f_V^{(0)})$$

- When the fluid velocity is small, (fluid) vorticity contribution becomes dominant.

Hydrodynamic helicity polarization

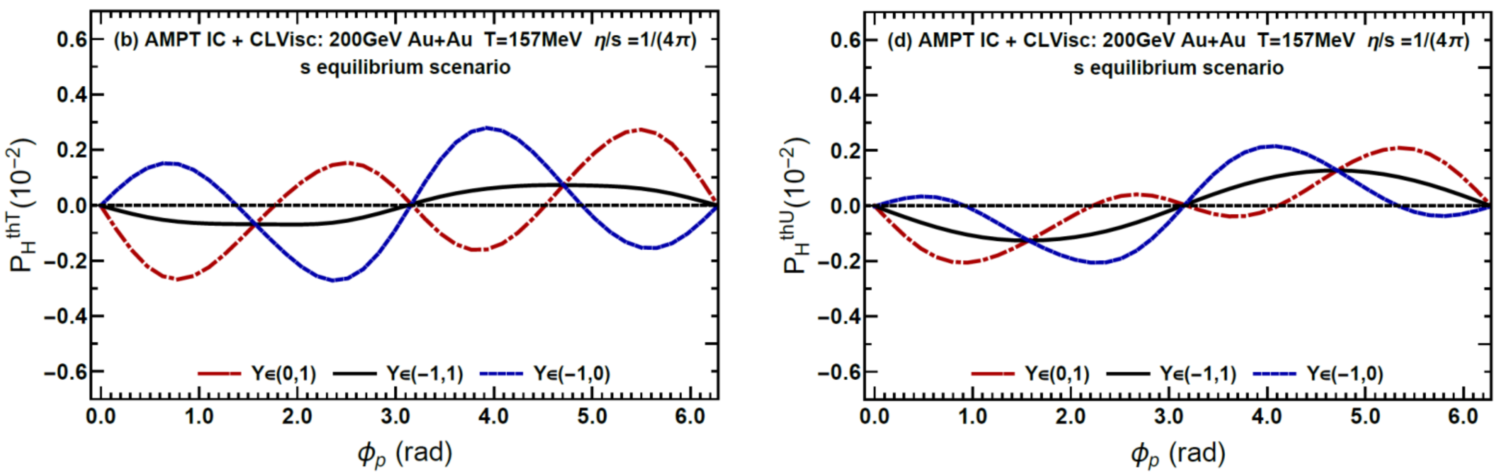
- The dominant contribution from thermal vorticity :



Helicity polarization from fluid vorticity

- Decomposition of the polarization from thermal vorticity:

$$S^h_{\rm thT}(\mathbf{p}) = \int d\Sigma^\sigma F_\sigma \frac{p_0}{T^2}\widehat{\mathbf{p}}\cdot(\mathbf{u}\times\nabla T), \qquad S^h_{\rm thU}(\mathbf{p}) = \int d\Sigma^\sigma F_\sigma \frac{p_0}{T}\widehat{\mathbf{p}}\cdot\boldsymbol{\omega}$$



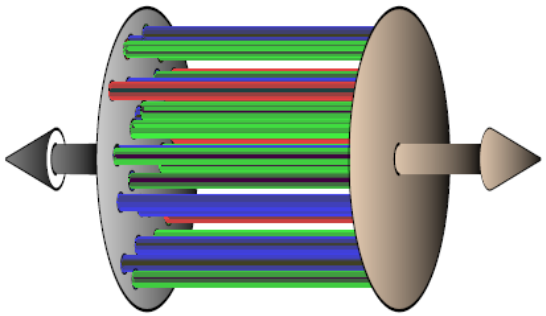
- For low-energy collisions, fluid vorticity increases and the velocity decreases.

  ⇨ Helicity polarization from fluid-vorticity becomes more dominant

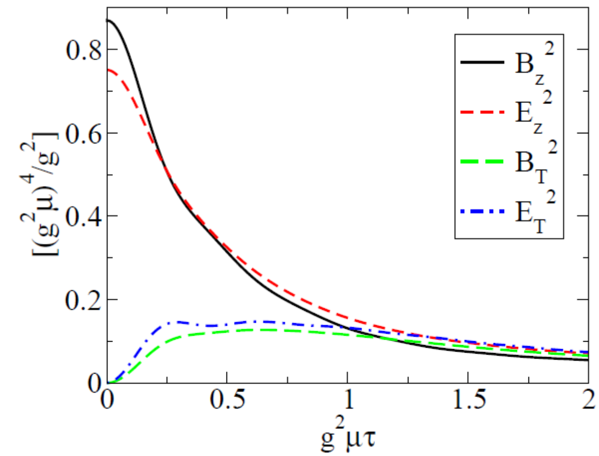
- Probing strongest local fluid vorticity from helicity polarization with the beam energy scan?

Chromo-electromagnetic fields in HIC

- Color flux tubes in the glasma phase : longitudinal chromo-EM fields in early times.



review: F. Gelis, E. Iancu, J. Jalilian-Marian, R. Venugopalan, Ann.Rev.Nucl.Part.Sci.60:463-489,2010



T. Lappi, Phys.Lett.B 643 (2006) 11-16

- Plasma instability could enhance the color fields.
- No local parity violation :

S. Mrowczynski, PLB 214, 587 (1988), PLB314,118 (1993)

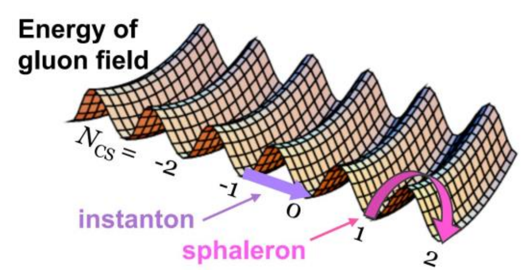
P. Romatschke and M. Strickland, PRD 68, 036004 (2003)

$$\langle B^a_\mu(X)B^a_\nu(X')\rangle \neq 0, \quad \langle E^a_\mu(X)E^a_\nu(X')\rangle \neq 0, \quad \langle B^a_\mu(X)E^a_\nu(X')\rangle = 0.$$

- Local-parity violation : $\langle B^a_\mu(X)E^a_\nu(X')\rangle \neq 0$

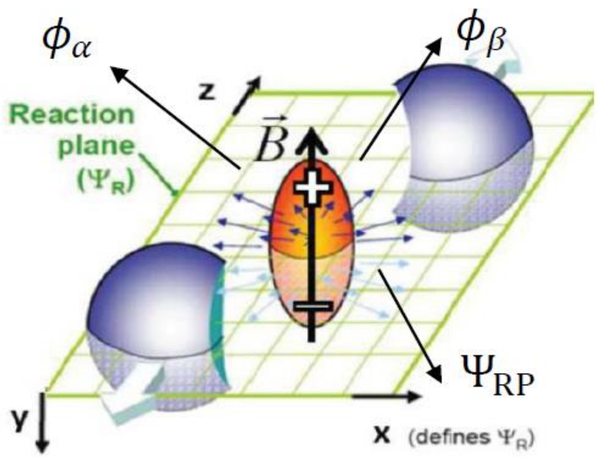
e.g. N. Tanji, N. Mueller, and J. Berges, PRD 93, 074507 (2016)

(Correlators in the QGP phase are unknown)



Probing local parity violation in QCD matter

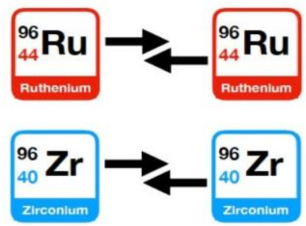
- Probing the local parity violation via the chiral magnetic effect (CME) :



$$\mathbf{J}_V = \frac{\mu_5}{2\pi^2}\mathbf{B}$$

D. E. Kharzeev et al., Prog. Part. Nucl. Phys. 88, 1 (2016)

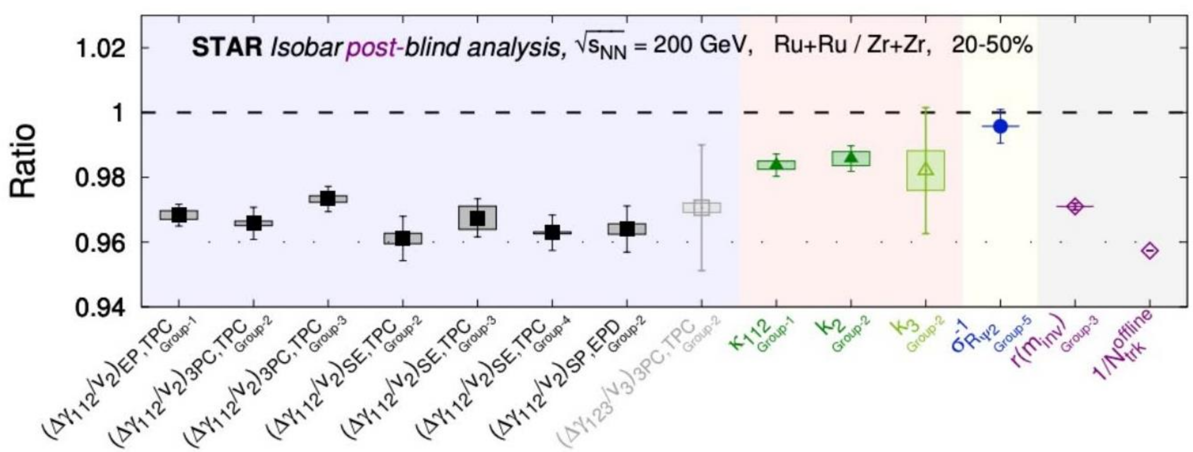
Isobar collisions :



(same shape=background?)

(diff. B fields=signal)

STAR, M. Abdallah et al., (2021), 2109.00131



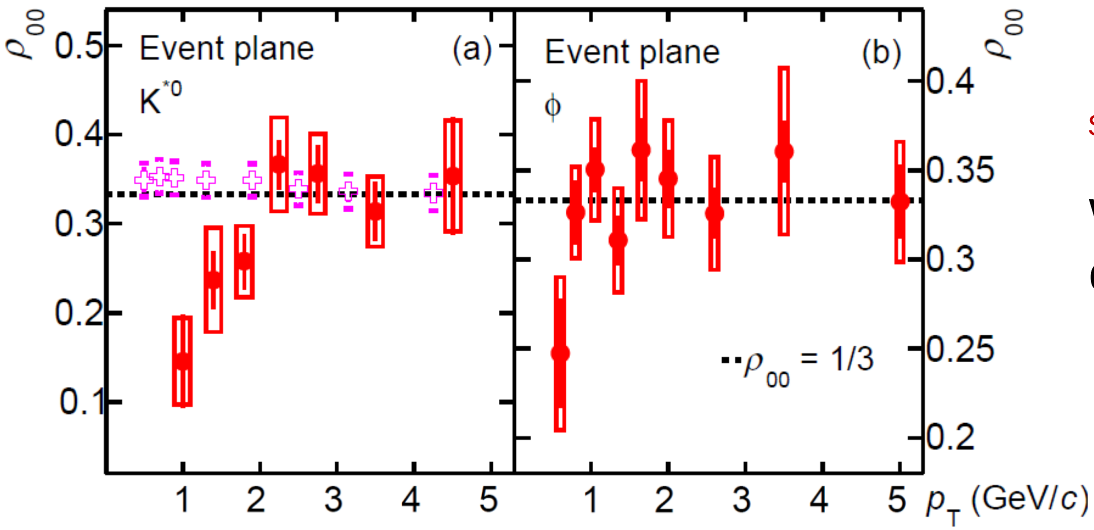
<1 no CME?

Spin alignments of vector mesons

- Decay daughter : $\frac{dN}{d\cos\theta^*} \propto [1-\rho_{00}+\cos^2\theta^*(3\rho_{00}-1)]$

$$\rho_{00} = \frac{1-\mathcal{P}_q^i\mathcal{P}_{\bar{q}}^i}{3+\mathcal{P}_q^i\mathcal{P}_{\bar{q}}^i}$$

Z.-T. Liang and X.-N. Wang, PLB 629, 20 (2005)



$\rho_{00} \neq 1/3$: spin polarization

S. Acharya et al. (ALICE), PRL.125, 012301 (2020)

What is the source for the large deviations ??

- From the QKT with background color fields :

B. Müller, DY, (2021), 2110.15630
DY, (2021), 2112.14392

$$\mathcal{P}^\mu(\mathbf{p}) \approx \frac{-\pi^{3/2}\tau_c\beta\int d\Sigma\cdot p\big(\langle E^a\cdot B^a\rangle u^\mu + \langle B^{a\mu}E^{a\nu}\rangle p_\nu\beta(1-2f_{\rm eq}(p\cdot u))\big)f_{\rm eq}(p\cdot u)\big(1-f_{\rm eq}(p\cdot u)\big)}{4mp\cdot u\int d\Sigma\cdot pf_{\rm eq}(p\cdot u)}$$

- Could spin alignments complement the CME study to probe the local parity violation?

Conclusions

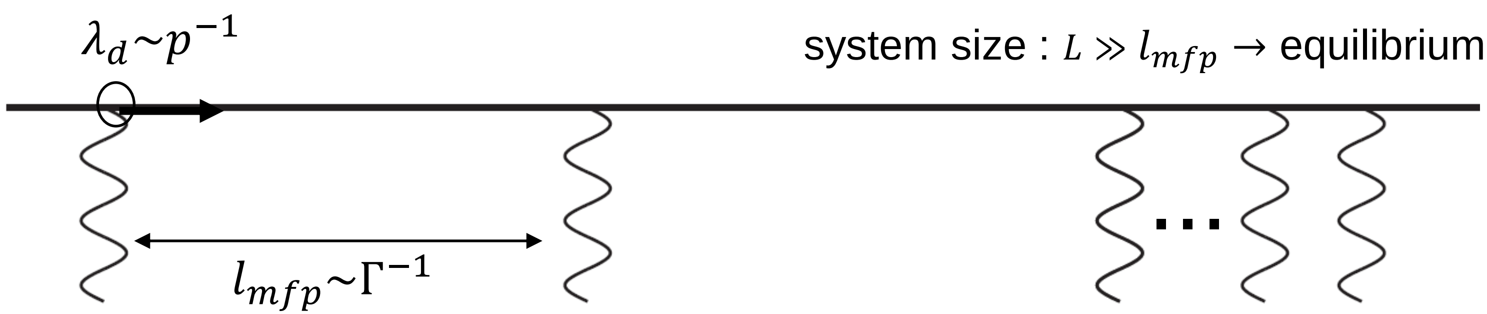
- ✓ QKT plays an essential role to understand dynamical spin polarization in HIC.
- ✓ Although local-equilibrium corrections (in particular the shear) yield substantial contributions to local spin polarization, non-equilibrium effects should be involved.
- ✓ Helicity polarization may be a better probe for local vorticity.
- ✓ Not only the collisions, but also dynamically generated color fields may affect the spin polarization of quarks in QGP.
- ✓ Anomalous spin polarization could be triggered by parity-odd correlators of color fields, which may possibly explain the spin alignments in high-energy nuclear collisions.

Refs: [1] Cong Yi, Shi Pu, Di-Lun Yang, PRC 104, 064901(2021).
[2] Cong Yi, Shi Pu, Di-Lun Yang, (2021), 2112.15531.
[3] Berndt Müller and Di-Lun Yang, (2021), 2110.15630.
[4] Di-Lun Yang, (2021), 2112.14392.
[5] Yoshimasa Hidaka, Shi Pu, Di-Lun Yang , Qun Wang, “Foundations and Applications of Quantum Kinetic Theory” (review), submitted to prog.part.nucl.phys.

Thank you!

Some properties of kinetic theory

- Kinetic theory : microscopic theory for quasi-particles in phase space
  - ❖ Boltzmann (Vlasov) Eq. : $q^\mu \Delta_\mu f(q,X) = q^\mu \mathcal{C}_\mu[f], \quad \Delta_\mu = \partial_\mu + F_{\nu\mu}\frac{\partial}{\partial q^\nu}.$
  - ❖ Physical quantities : $J^\mu(X) = \int \frac{d^3\boldsymbol{q}}{(2\pi)^3}\frac{q^\mu}{E_q}f(q,X), \quad T^{\mu\nu}(X) = \int \frac{d^3\boldsymbol{q}}{(2\pi)^3}\frac{q^\mu q^\nu}{E_q}f(q,X).$
  - ❖ Valid for weak coupling : mean free path ≫ de Broglie wavelength



  - ❖ Near equilibrium : kinetic theory ⇨ hydrodynamics

- Classical kinetic theory ⇨ $\partial_\mu J^\mu = 0, \quad \partial_\mu T^{\mu\nu} = F^{\nu\rho}J_\rho.$

- CKT: $(q\cdot\Delta + \hbar\tilde{\Delta})f_R = q\cdot C[f_R] + \hbar\tilde{C}[f_R]$ ⇨ $\partial_\mu J^\mu_R = -\frac{\hbar}{4\pi^2}E\cdot B$

  (for right-handed fermions) (chiral anomaly)

CKT with collisions

- WF up to $\mathcal{O}(\hbar)$: (for right-handed fermions) quantum corrections

$$\grave{S}^{<}(q,X)=\bar{\sigma}_\mu 2\pi\bar{\epsilon}(q\cdot n)\left(q^\mu\delta(q^2)f_q^{(n)}+\hbar\delta(q^2)S^{\mu\nu}_{(n)}\mathcal{D}_\nu f_q^{(n)}+\hbar\epsilon^{\mu\nu\alpha\beta}q_\nu F_{\alpha\beta}\frac{\partial\delta(q^2)}{2\partial q^2}f_q^{(n)}\right)$$

$$\mathcal{D}_\beta f_q^{(n)}=\Delta_\beta f_q^{(n)}-\mathcal{C}_\beta$$

- CKT with collisions $(\partial_\rho n^\mu=0)$:

Y. Hidaka, S. Pu, DY, PRD 95, 091901 (2017), PRD 97, 016004 (2018)

$$\delta\left(q^2-\hbar\frac{B\cdot q}{q\cdot n}\right)\left\{\left[q\cdot\Delta+\hbar\frac{S^{\mu\nu}_{(n)}E_\mu}{(q\cdot n)}\Delta_\nu+\hbar S^{\mu\nu}_{(n)}(\partial_\mu F_{\rho\nu})\partial_q^\rho\right]f_q^{(n)}-\tilde{\mathcal{C}}\right\}=0,$$

magnetic-moment coupling

spin tensor : $S^{\mu\nu}_{(n)}=\dfrac{\epsilon^{\mu\nu\alpha\beta}}{2(q\cdot n)}q_\alpha n_\beta$

($F^{\mu\nu}=0$: the quantum corrections only appear in collisions)

- Quantum corrections on the collision term :

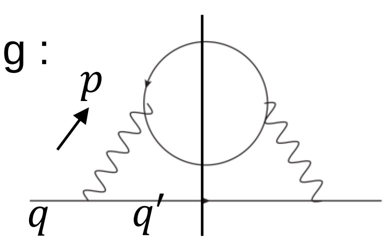
$$\tilde{\mathcal{C}}=q\cdot\mathcal{C}+\hbar\frac{S^{\mu\nu}_{(n)}E_\mu}{(q\cdot n)}\mathcal{C}_\nu+\hbar S^{\alpha\beta}_{(n)}\left((1-f_q^{(n)})\Delta_\alpha\Sigma^<_\beta-f_q^{(n)}\Delta_\alpha\Sigma^>_\beta\right),$$

induced by inhomogeneity of the medium

$$\mathcal{C}_\beta=\Sigma^<_\beta(1-f_q^{(n)})-\Sigma^>_\beta f_q^{(n)}.$$

also include hbar corrections

2-2 scattering :



Axial kinetic theory

- QKT for massive fermions :
- Wigner functions : $S^{<}(p,X)=\int d^4Y e^{ip\cdot Y/\hbar}\langle\bar{\psi}(y)U(y,x)\psi(x)\rangle$

  vector/axial-vector components : $\mathcal{V}^{\mu}(p,X)=\frac{1}{4}\mathrm{tr}\left(\gamma^{\mu}S^{<}(p,X)\right),\ \mathcal{A}^{\mu}(p,X)=\frac{1}{4}\mathrm{tr}\left(\gamma^{\mu}\gamma^{5}S^{<}(p,X)\right)$

- Dynamical variables in $\mathcal{V}^{\mu}/\mathcal{A}^{\mu}$: $f_{V/A}(q,X)$ & $a^{\mu}(q,X)$ spin 4-vector $(\tilde{a}^{\mu}=a^{\mu}f_A)$

  K. Hattori, Y. Hidaka, D.-L. Y, PRD100, 096011 (2019)

  $\xrightarrow{m=0}\ a^{\mu}=q^{\mu},\ f_V=(f_R+f_L)/2,\ f_A=f_R-f_L.$

- Axial kinetic theory : scalar/axial-vector kinetic eqs. (SKE/AKE) with quantum corrections
- Collisions for AKE : $\square^{(n)}\mathcal{A}^{\mu}=\hat{\mathcal{C}}^{\mu}_{\rm cl}+\hbar\hat{\mathcal{C}}^{(n)\mu}_{\rm Q}$

  D.-L. Y, K. Hattori, Y. Hidaka, JHEP 20, 070 (2020)

  spin diffusion $\propto L^{\mu\nu}\tilde{a}_{\nu}$

  spin polarization coupled to vector charge $\propto H^{\mu\nu}\partial_{\nu}f_V$

- E.g. diffusion for massive quarks in weakly coupled QGP : S. Li, H.-U. Yee, PRD100, 056022 (2019)
- The quantum correction is only studied for purely fermionic interactions.

  Z. Wang, X. Guo, P. Zhuang, Eur. Phys. J. C 81, 799 (2021)
  N. Weickgenannt, et al., PRL 127, 052301 (2021)
  ⇒ global-equilibrium sol. is reproduced from detailed balance (local equilibrium?)

- The role of gluons and color dof. for spin polarization is unknown.

WFs and AKE with source terms

- Incorporation of background color fields into WFs and kinetic theory.
- Color decomposition : $O = \boxed{O^s} I + O^a t^a$

U. W. Heinz, Phys. Rev. Lett. 51, 351 (1983)

-> physical observable

e.g. $J_5^\mu = 4\int \frac{d^4p}{(2\pi)^4} \mathrm{Tr}_c \mathcal{A}^\mu(p,X)$

$$O^s : \mathcal{O}(g^0),\ O^a : \mathcal{O}(g).$$

- SKE, AKE, WFs are decomposed into color-singlet & octet components.
- Perturbatively, we may rewrite $f_V^a,\ \tilde{a}^{a\mu}$ in terms of $f_V^s,\ \tilde{a}^{s\mu}$.
- Modified Cooper-Frye formula :

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

$$\mathcal{N}^\mu(p,X) = 4N_c(p^\mu f_V^s),$$
$$\mathcal{J}_5^\mu(p,X) = 4N_c\left(\tilde{a}^{s\mu} + \hbar \bar{C}_2 \mathcal{A}_Q^\mu\right),$$

- Source term in WFs : $\mathcal{A}_Q^\mu = \frac{\partial_{p\kappa}}{2} \int_{k,X'}^{p} p^\beta \langle \tilde{F}^{a\mu\kappa}(X) F^a_{\alpha\beta}(X') \rangle \partial_p^\alpha f_V^s(p,X')$

B. Müller and D.-L. Y, (2021), 2110.15630

M. Asakawa, S. A. Bass, B. Muller, PRL. 96, 252301 (2006)

- SKE & AKE :

$$0 = p\cdot\partial f_V^s(p,X) - \boxed{\partial_p^\kappa \mathscr{D}_\kappa[f_V^s]}$$

$\sim g^2 >$ collosions$\sim g^4$: anomalous viscosity

$$0 = p\cdot\partial\tilde{a}^{s\mu}(p,X) - \boxed{\partial_p^\kappa \mathscr{D}_\kappa[\tilde{a}^{s\mu}]} + \boxed{\hbar\partial_p^\kappa\left(\mathscr{A}_\kappa^\mu[f_V^s]\right)}$$

diffusion source

Spin polarization from color fields

- The real color- field correlators can only be obtained from real-time simulations.
- Physical assumptions : $\langle F^a_{\kappa\lambda}(X)F^a_{\alpha\rho}(X')\rangle = \langle F^a_{\kappa\lambda}F^a_{\alpha\rho}\rangle e^{-(t-t')^2/\tau_c^2}$

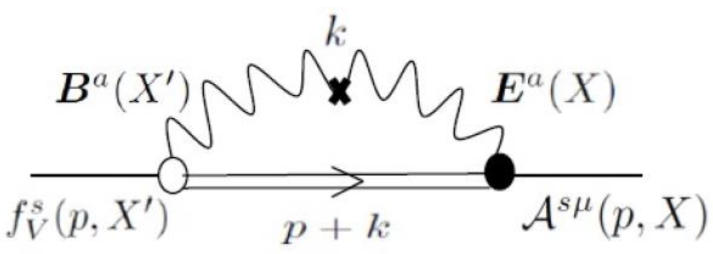
$$|\langle B^a_\mu B^a_\nu\rangle| \gg |\langle E^a_\mu B^a_\nu\rangle| \gg |\langle E^a_\mu E^a_\nu\rangle|$$

- f_V reaches thermal equilibrium : $\mathcal{J}^\mu_5(p,X) = 4N_c(\tilde{a}^{s\mu} + \hbar\bar{C}_2\mathcal{A}^\mu_Q)$,

$$\tilde{a}^\mu(t,p) = -\frac{\hbar\bar{C}_2(t-t_0)}{2p_0^2}(\partial_{p0}f_{\mathrm{eq}}(p_0))\left(\langle B^{a\mu}E^{a\nu}\rangle p_\nu - \langle B^a\cdot E^a\rangle p^\mu_\perp\right)$$

$$(\mathcal{A}^\mu_Q)_{\mathrm{eq}} = \frac{\pi^{3/2}\tau_c}{2p_0}\delta(p^2-m^2)\left(\langle E^a\cdot B^a\rangle u^\mu - \langle B^{a\mu}E^{a\beta}\rangle p_\beta\partial_{p0}\right)\partial_{p0}f_{\mathrm{eq}}(p_0)$$

- Origin of the source terms: correlation of the Lorentz force & anomalous force from quantum corrections



The axial charge currents and Ward identity

- A constant axial charge current (finite τ_c):

$$J_5^\mu = 4N_c \int \frac{d^4p}{(2\pi)^4}\mathrm{sign}(p_0)\mathcal{A}^{s\mu}(p,X) = -\frac{\hbar u^\mu}{8\pi^2}\sqrt{\pi}\tau_c\langle E^a\cdot B^a\rangle\mathcal{I} \qquad \mathcal{I}=1 \text{ for } m=0$$

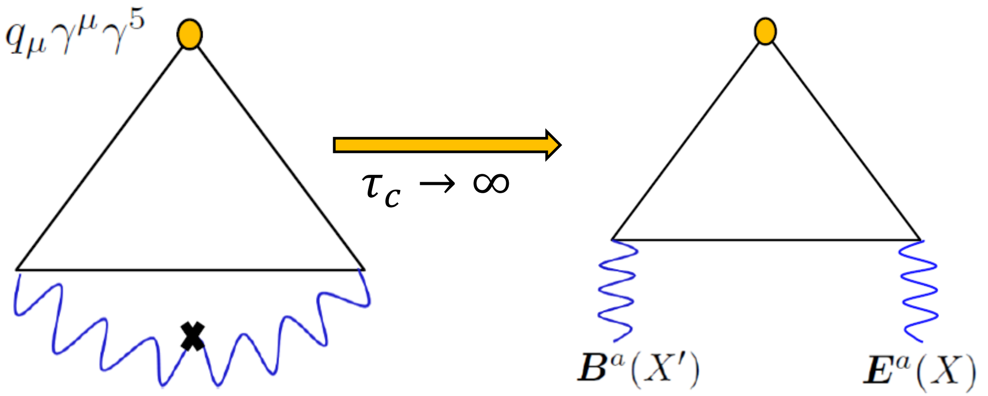
(similar to the steady state in Weyl semimetals $n_5 \sim \tau_R E\cdot B$)

- Vanishing axial-Ward identity : $\partial\cdot J_5 = 0$

- Constant-field limit ($\tau_c \to \infty$) : $\partial_\mu J_5^\mu(X) = -\hbar\frac{\langle B^a\cdot E^a\rangle}{4\pi^2} + 2m\langle\bar{\psi}i\gamma_5\psi\rangle,$

D.-L. Y, in preparation

$$\langle\bar{\psi}i\gamma_5\psi\rangle = -\frac{\hbar\langle B^a\cdot E^a\rangle}{8m\pi^2}\int_0^\infty d|\boldsymbol{p}|\left(1-\frac{|\boldsymbol{p}|}{\epsilon_{\boldsymbol{p}}}\right)\frac{d}{d|\boldsymbol{p}|}\left[f_{\rm eq}(\epsilon_{\boldsymbol{p}})-f_{\rm eq}(-\epsilon_{\boldsymbol{p}})\right]$$



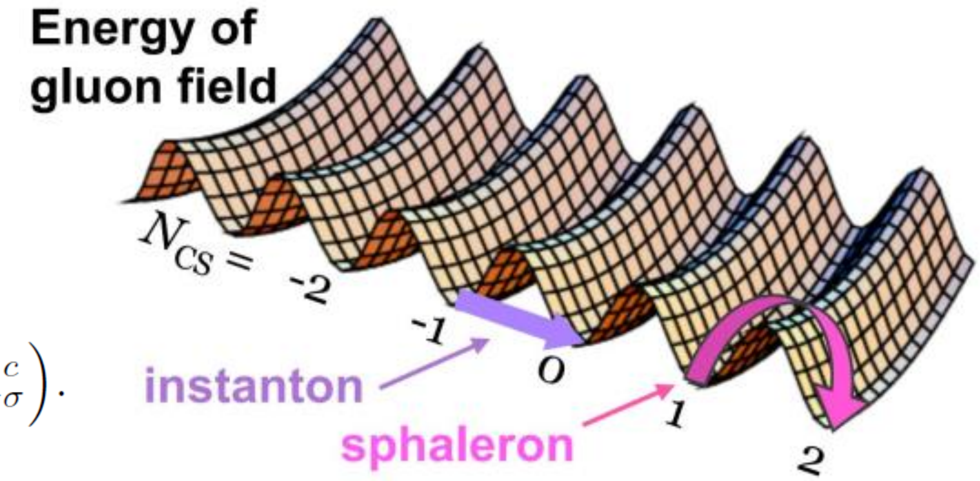
Probing local parity violation in QCD matter

- Transition between topological sectors in QCD vacuum yields parity violation and chirality production.

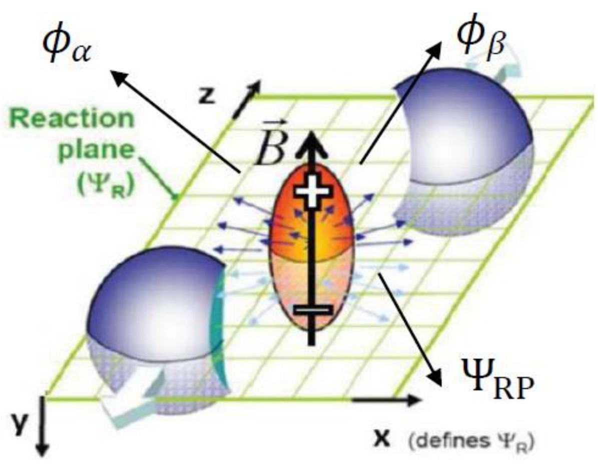
$$\partial_t(N_L - N_R) = 2g^2\partial_t N_{CS},$$

$$N_{CS} \equiv \int d^3x K_0,$$

$$K^\mu = \frac{\epsilon^{\mu\nu\rho\sigma}}{16\pi^2}\left(A^a_\nu \partial_\rho A^a_\sigma + \frac{1}{3}f^{abc}A^a_\nu A^b_\rho A^c_\sigma\right).$$



- Probing the local parity violation via the chiral magnetic effect (CME) :

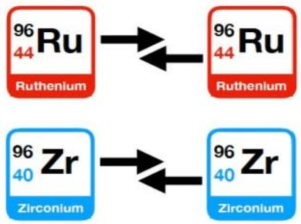


$$\mathbf{J}_V = \frac{\mu_5}{2\pi^2}\mathbf{B}$$

D. E. Kharzeev et al.,
Prog. Part. Nucl. Phys. 88, 1 (2016)

Isobar collisions : so far, negative

STAR, M. Abdallah et al., (2021), 2109.00131

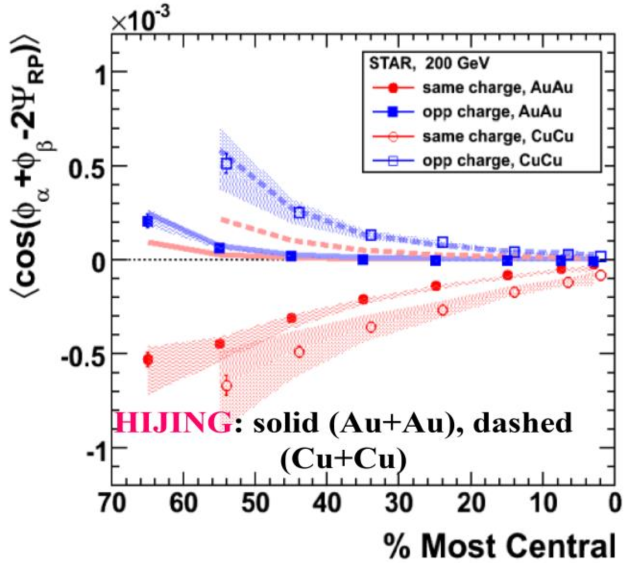


(observed in Weyl semimetals)

Qiang Li, et.al., Nature Phys. 12 (2016) 550-554

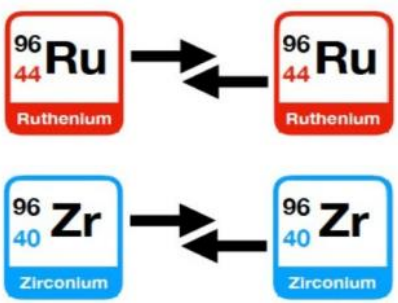
Searching for CME in heavy ion collisions

- CME : correlations of same & opposite charge particles



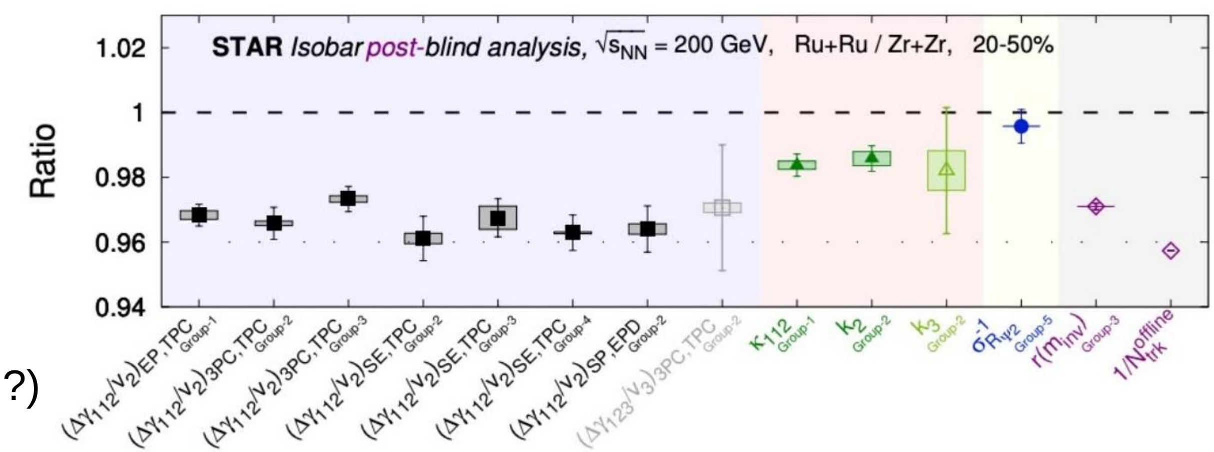
- Background >> signal

- Separating the signal from background : isobar collisions



(same shape=background?)

(diff. B fields=signal)



<1
no
CME?

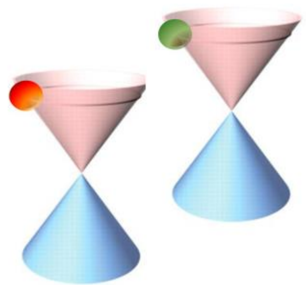
CME in Weyl Semimetals

- Chiral matter in the condensed matter system.

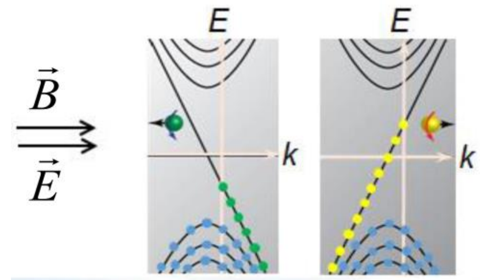
Weyl semimetals :

$$\partial_\mu J_5^\mu = \frac{\mathbf{E}\cdot\mathbf{B}}{2\pi^2} - \frac{n_5}{\tau_R}$$

τ_R → relaxation time



TaAs
NbAs
NbP
TaP



charge pumping via parallel E & B : generate $\mu_5 \sim n_5 \sim E\cdot B$

steady-state approxtion :

$$n_5 = \tau_R \frac{\mathbf{E}\cdot\mathbf{B}}{2\pi^2}$$

$$= \frac{4\mu_5^3}{3\pi^2 v_f^3} + \frac{\mu_5}{3v_f^3}\left(T^2 + \frac{4\mu_V^2}{\pi^2}\right)$$

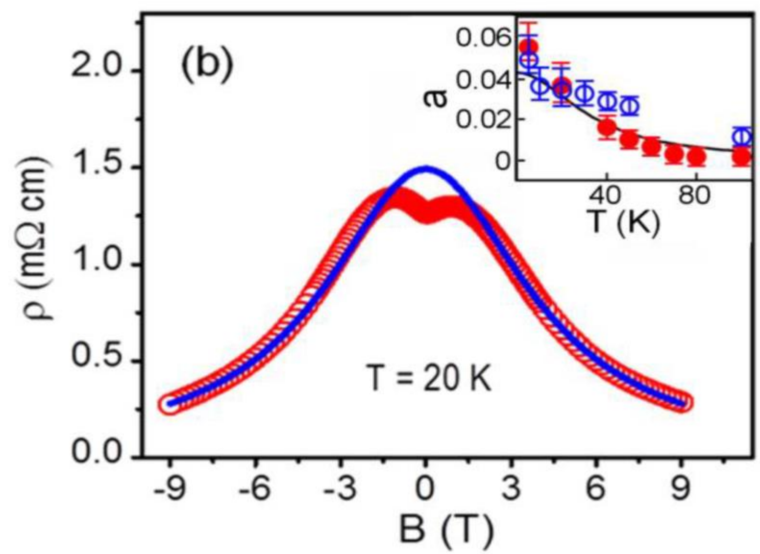
thermal equilibrium

$T \sim \mu_V \gg \mu_5$

$$\Longrightarrow \mathbf{J}_V = \frac{\mu_5}{2\pi^2}\mathbf{B} = \frac{3v_f^3\tau_R|\mathbf{B}|^2}{2(\pi^2T^2 + 4\mu_V^2)}\mathbf{E}$$

$$\rho = \frac{1}{\sigma} \sim \frac{1}{B^2}$$

"negative magnetoresistance"
(the signal of CME)



Qiang Li, et.al., Nature Phys. 12 (2016) 550-554