Chiral magnetic effect and conductivity of quark-gluon plasma in external magnetic field

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ITEP Lattice

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Heavy ion collisions and nonzero chirality

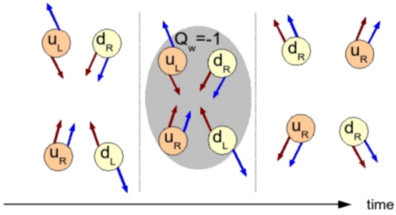
Nonzero chiral density in heavy ion collisions:

- Parallel (chromo) electric and magnetic fields
- Gluonic fluctuations (topological charge)
- Fermionic fluctuations

Axial anomaly:

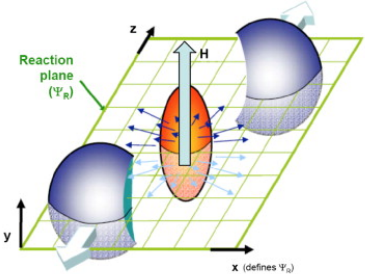
$$\partial^\mu j^5_\mu \sim F^a_{\mu\nu}\tilde{F}^{a\mu\nu}(\text{density of topological charge}) - 2im\bar{\psi}\gamma_5\psi$$

In chiral limit:
Right-handed particles u_R
have spin and momentum parallel
Left-handed particles u_L
have spin and momentum antiparallel



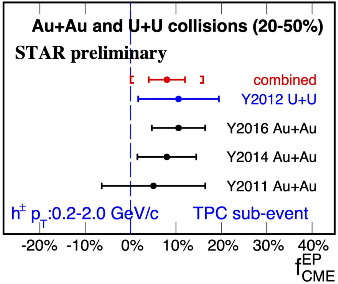
Chiral Magnetic Effect

"A system with a nonzero chirality responds to a magnetic field by inducing a current along the magnetic field. This is the Chiral Magnetic Effect."
[K. Fukushima, D. Kharzeev, H.J. Warringa, 2008]



$$\vec{J}_{CME} = \frac{e^2 \mu_5}{2\pi^2} \vec{B}$$

Chiral magnetic effect: current status



[Quark Matter, 2019]

Theory: subtleties with defining nonzero chiral density

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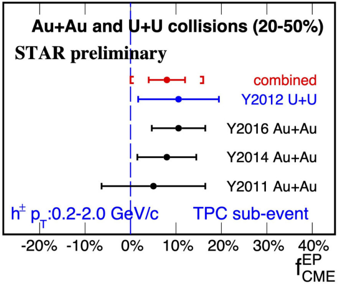

[Quark Matter, 2019]

Theory: subtleties with defining nonzero chiral density

Dynamical CME is manifested through electromagnetic conductivity

Conductivity of Quark-Gluon Plasma

$$\vec{J} = \sigma \vec{E}$$

- Large $E \sim m_\pi^2$ in HIC
- Large value of $\sigma \longrightarrow$ large relaxation time of eB

  [K. Tuchin, 2013]
- Asymmetric collision, like $Cu + Au \longrightarrow$ asymmetric flow

  [Y.Hirono, M.Hongo, T. Hirano, 2012]
- σ is related to emission rate of soft photons

  [S.Turbide, R.Rapp, C.Gale, 2004]

Conductivity in external magnetic field

- $\vec{E}, \vec{B}$
- $\frac{d\rho_5}{dt} = \frac{e^2}{4\pi^2}(\vec{E}, \vec{B}) - \frac{\rho_5}{\tau}$, τ - chirality-changing scattering time

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- $\rho_5(\mu_5)$?
  - Small B: $\rho_5 \sim \mu_5 T^2 \Rightarrow \mu_5 \sim \frac{e^2\tau}{4\pi^2 T^2}(\vec{E}, \vec{B})$
  - Large B: $\rho_5 \sim \mu_5 B \Rightarrow \mu_5 \sim \frac{e^2\tau}{4\pi^2}\frac{(\vec{E}, \vec{B})}{B}$

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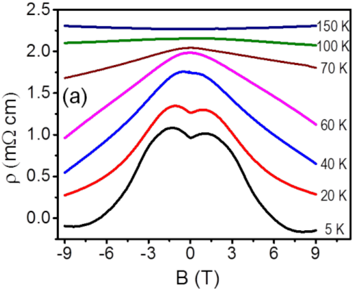
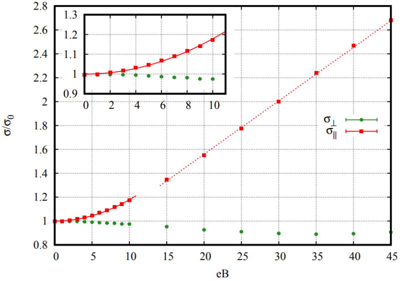
- $\vec{J} = \sigma\vec{E} + \frac{e^2}{2\pi^2}\vec{B}\mu_5$
- $\sigma_{\parallel}^{CME} \sim eB\tau$
- **Manifestation of CME: rise of the conductivity with B**
- Anomaly related quantum phenomenon (classically $\sigma_{\parallel}^{CME} = 0$)

CME observation: Dirac/Weyl semimetals

- Experimental: Q. Li et al., Nature Phys. 12 (2016) 550-554, H. Li et al., Nat. Comm. 7, 10301 (2016)
- QMC: D. Boyda, V. Braguta, M. Katsnelson, A. Kotov, Annals of Physics (2018), arXiv:1707.09810





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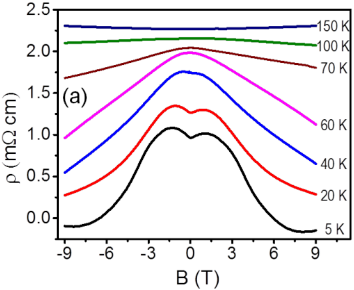
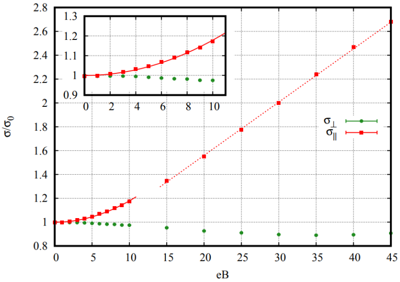




What happens in QCD?

Lattice simulation of QCD: details

- u,d,s – quarks
- Physical pion m_π and strange m_s quark masses
- $T \approx 200$, 250 MeV
- Lattice sizes and steps:

a, fm	L_s	N_t	T, MeV
0.988	48	10	200
0.0618	64	16	200
0.0493	64	16	250

Conductivity in lattice simulations

- $J_i = \sigma_{ij} E_j$

- Electromagnetic conductivity(Kubo formula)
  $\sigma_{ij} = \lim_{\omega \to 0} \frac{1}{\omega} \int_0^\infty dt \int d^3x \; e^{i\omega t} \langle [J_i(x), J_j(0)] \rangle$
  $\rho_{ij} = -\frac{1}{\pi} Im G_R^{ij}(\omega, \vec{k} = 0)$
  $\sigma_{ij} = \pi \lim_{\omega \to 0} \frac{1}{\omega} \rho_{ij}(\omega)$

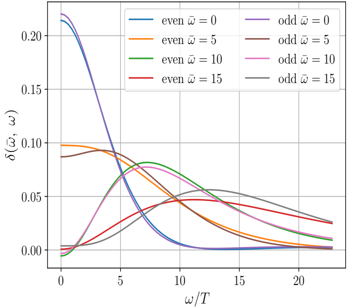
- Analytic continuation
  $G_E(\omega, \vec{p}) = -G_R(i\omega, \vec{p}), \quad \omega > 0$

- On lattice we measure
  $C_E(\tau) = \int d^3x \langle J_i(\tau, \vec{x}) J_j(0, \vec{0}) \rangle$
  $C_E(\tau) = \int_0^\infty d\omega \rho(\omega) \frac{ch\left(\frac{\omega}{2T} - \omega\tau\right)}{sh\left(\frac{\omega}{2T}\right)}, \quad \tau \in \left(0, \frac{1}{T}\right)$

Spectral function ρ

- Small ω: $\rho(\omega) \sim \sigma\omega$
- Large ω: $\rho(\omega) \sim \frac{3}{4\pi^2}\omega^2$
- Intermediate ω: ρ-meson peaks (confinement?)

Backus-Gilbert method for the spectral function



- Resolution function $\delta(\omega, \bar{\omega})$

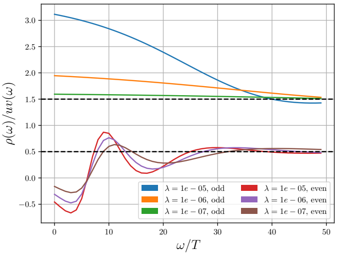
$$\bar{\rho}(\bar{\omega}) = \int d\omega \delta(\omega, \bar{\omega}) \rho(\omega)$$

- BG method average the spectral function over the width $\sim 4 \times T$

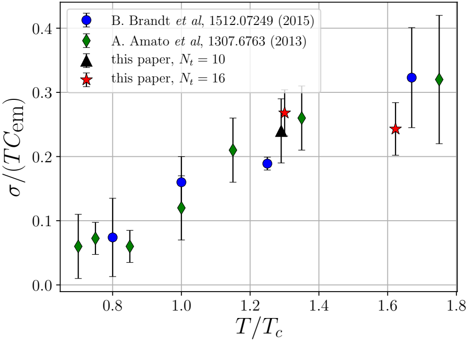
Estimation of *UV*-part of spectral function

$$\rho_{\mathrm{UV}}(\omega) \sim \frac{3}{4\pi^2}\omega^2$$

- It is hard to estimate it model independent
- $\rho(\omega) = B\omega\theta(\omega_0 - \omega) + A\rho_{\mathrm{UV}}(\omega)\theta(\omega - \omega_0)$
- Fit in B. Brandt et al. [1512.07249], A. Amato et al. [1307.6763]: $A \approx 1$, $\omega_0 \approx 7T$
- Additional reconstruction at $T = 0$, $N_t = 96$, $(eB = 0)$
- $A \approx 1$



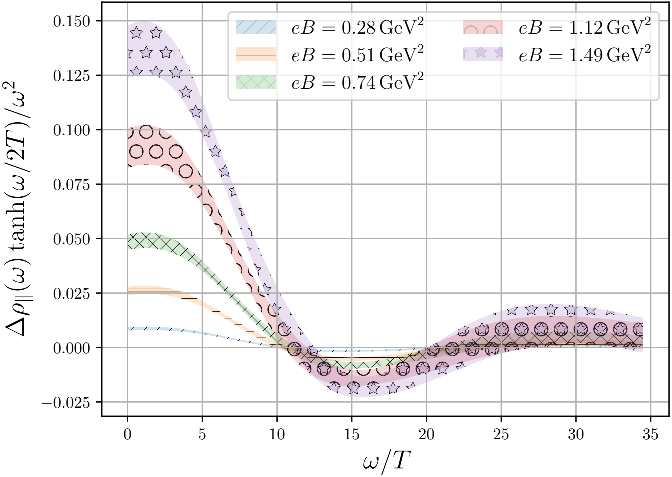
Conductivity at zero magnetic field $eB = 0$



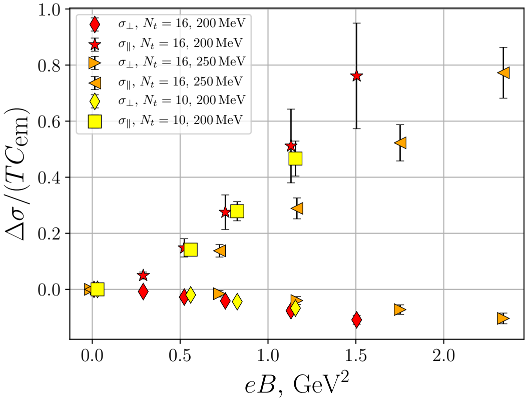
- **First calculation of the conductivity at physical pion mass**
- Agreement with previous papers ($C_{\mathrm{em}} = \sum_{f=u,d,s} q_f^2$)

Conductivity at nonzero magnetic field $eB \neq 0$

Idea: consider $\rho(\omega, eB) - \rho(\omega, eB = 0) \Leftrightarrow C(t, eB) - C(t, eB = 0)$

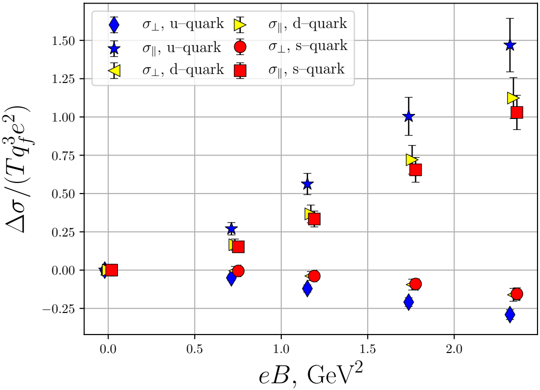


Conductivity at nonzero magnetic field $eB \neq 0$



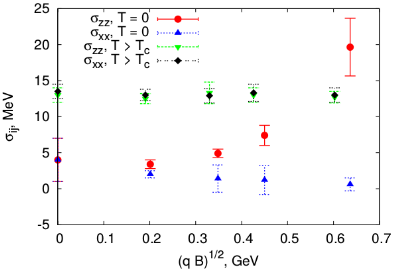
- We observe CME and magnetoresistance in QGP
- Estimation for relaxation time of the chiral charge:
  - $\tau = 0.26(5)$ fm/c at $T = 200$ MeV
  - $\tau = 0.24(3)$ fm/c at $T = 250$ MeV
  - $\tau \sim 0.1 - 1$ fm/c [M.Ruggieri, G.X. Peng, M. Chernodub, 2016]

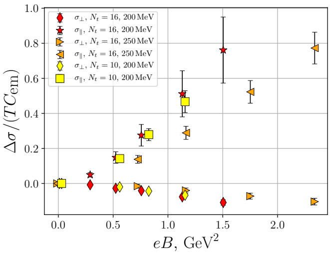
Contribution of different quarks ($T = 250$ MeV)



- The conductivity scale as q_f^3
- $\sigma_d/q_d^3 \simeq \sigma_s/q_s^3$, $\sigma_u/q_u^3 > \sigma_{d,s}/q_{d,s}^3$ ($|q_u| = \frac{2}{3}, |q_d| = |q_s| = \frac{1}{3}$)
- Large mass of s-quark does not influence the conductivity

Comparison with other studies





[P.V. Buividovich et al., Phys.Rev.Lett. 105 (2010) 132001]

- No CME in QGP and there is CME in the confinement phase
- Disagreement with our results (small magnetic fields? $eB < 0.36\,\text{GeV}^2$)

In confinement:

- Complicated structure of spectral density $\rho(\omega)$

Conclusion:

- The first calculation of the conductivity in QCD at physical pion mass
- Observe large magnetoconductivity ($\parallel B$) and magnetoresistance ($\perp B$) in QGP
- Results confirm (dynamical) CME