Polarization Dynamics in Charged Magnetized Quark-Gluon Plasma

热烈祝贺安徽理工大学基础物理研究中心成立！

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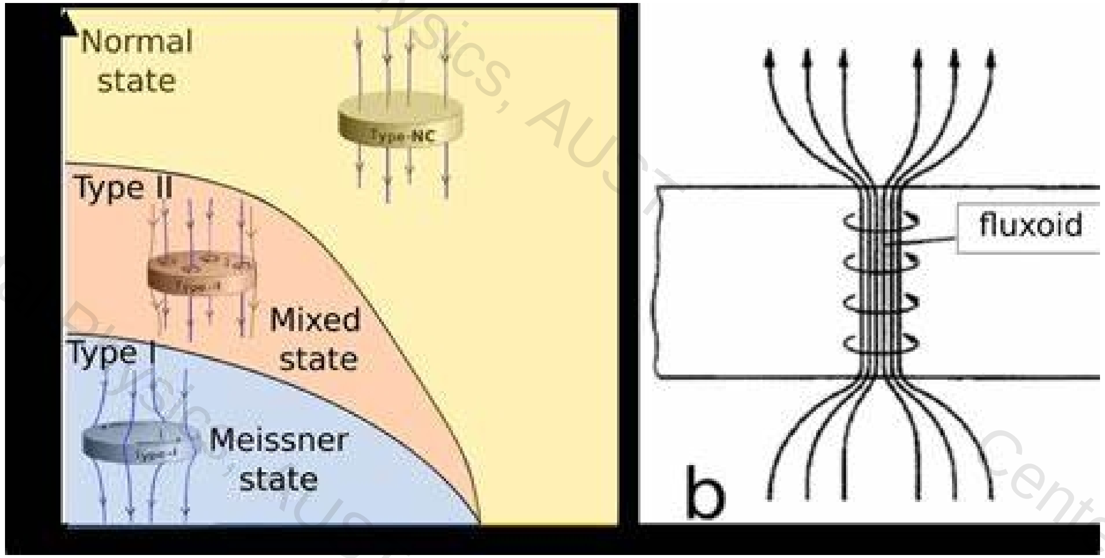
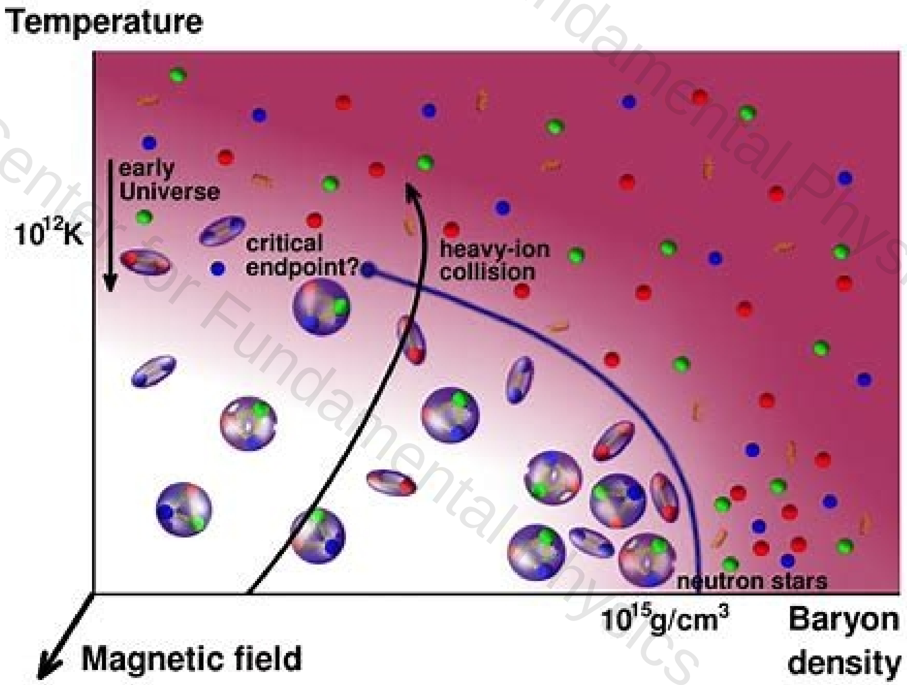
Outline

- Magnetic field induced phases and transports
- Uncertainty in magnetic field in heavy ion collisions
- Magnetized QGP in HIC: a spinless fluid or a magnet?
- Dense magnetized QED matter: paramagnet
- Dense & hot magnetized QCD matter: paramagnet
- Polarization dynamics in HIC
- Conclusion and outlook

Phases under magnetic field



Superconductor under B

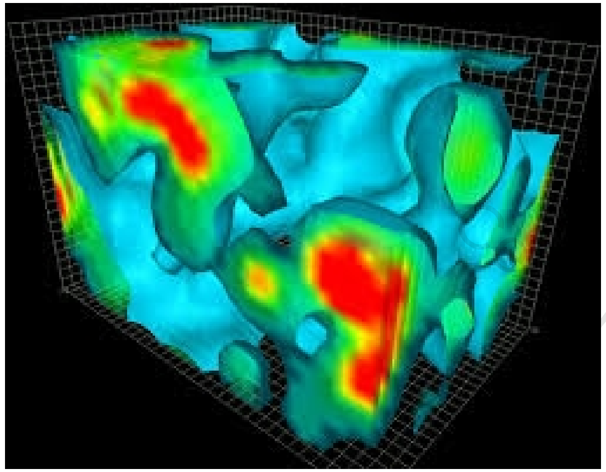


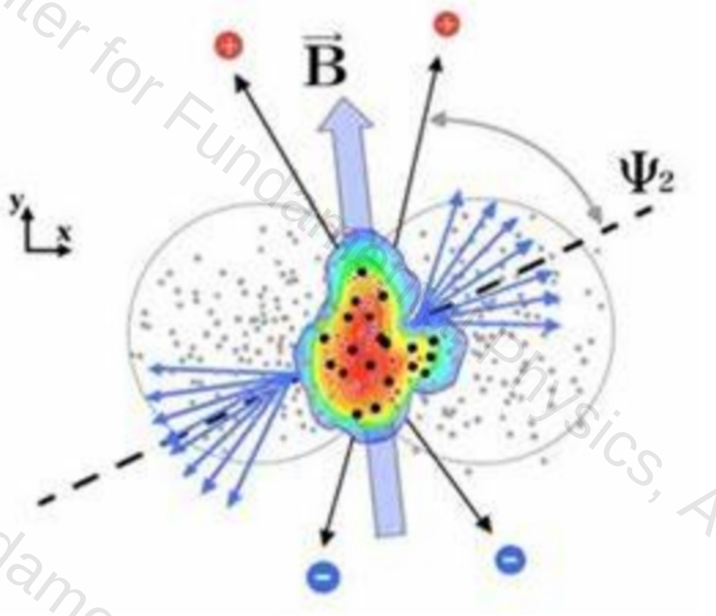
QCD phases under B

Transport under magnetic field: chiral magnetic effect

Chiral magnetic effect $\mathbf{J}_{\rm CME} = \frac{e^2}{2\pi^2}\mu_5 \mathbf{B}$

Kharzeev, McLerran, Warringa, NPA 2008





$$\partial_\mu J_5^\mu = -\frac{g^2 N_f}{16\pi^2}\mathrm{Tr}\left[\epsilon^{\mu\nu\rho\sigma}G_{\mu\nu}G_{\rho\sigma}\right]$$

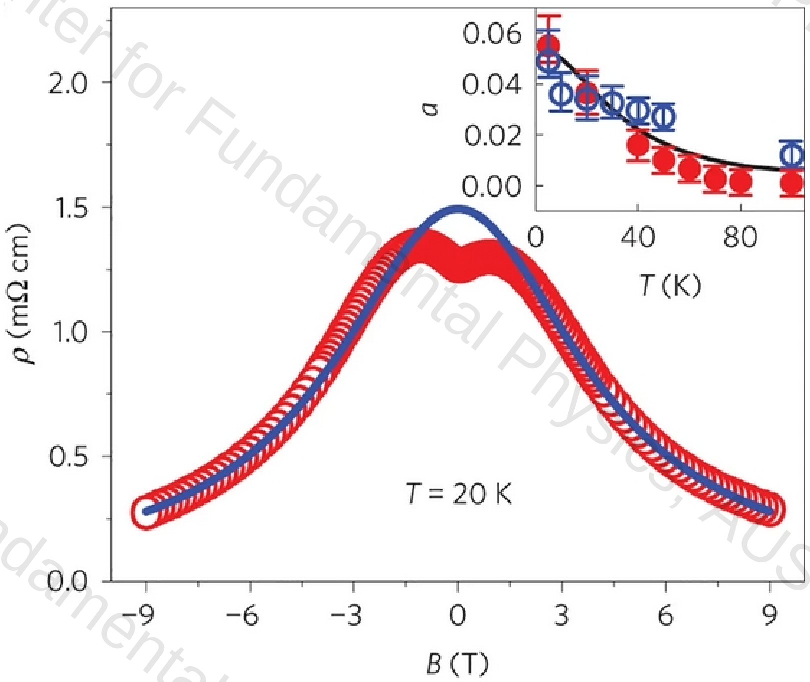
CME measures topological fluctuation in quark-gluon plasma

Transport under magnetic field: chiral magnetic effect

Chiral magnetic effect $\mathbf{J}_{\rm CME} = \frac{e^2}{2\pi^2}\mu_5 \mathbf{B}$

Li, Kharzeev, et al, Nature physics 2016

$$\partial_\mu J_5^\mu = -\frac{e^2}{16\pi^2}\epsilon^{\mu\nu\rho\sigma}F_{\mu\nu}F_{\rho\sigma} \sim \mathbf{E}\cdot\mathbf{B}$$



$$\sigma_{\rm CME} = \sigma_0 + a(T)B^2,$$

Negative magnetoresistance in ZrTe5

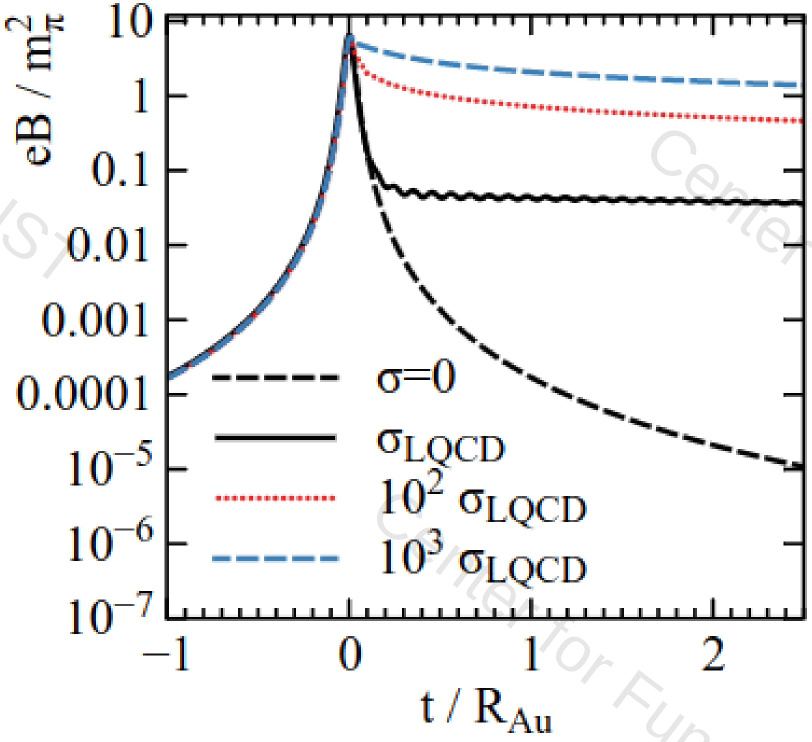
Magnetic field in Heavy ion Collisions

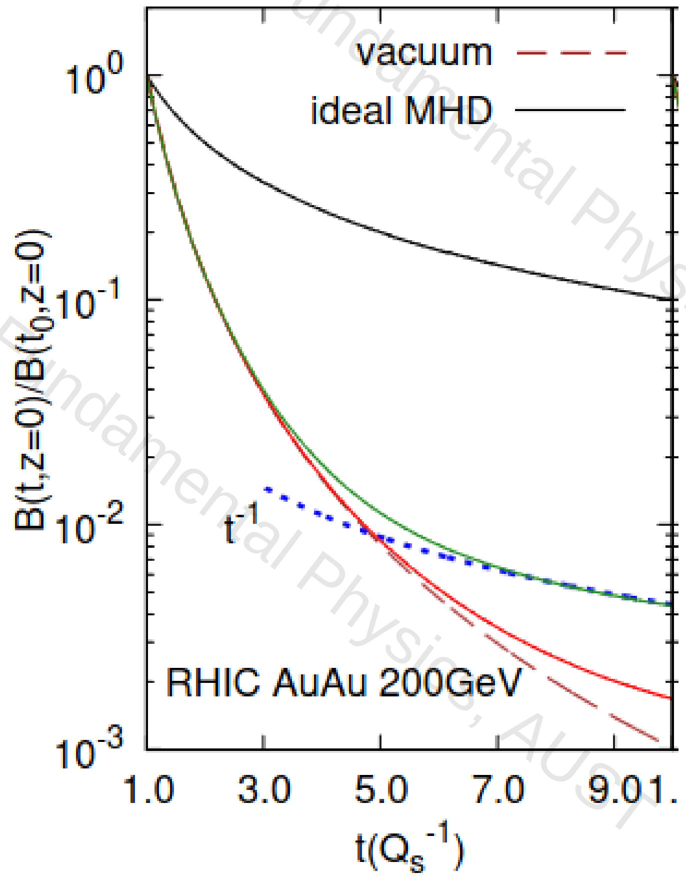
$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{j} + \frac{1}{c^2}\frac{\partial \mathbf{E}}{\partial t}$$

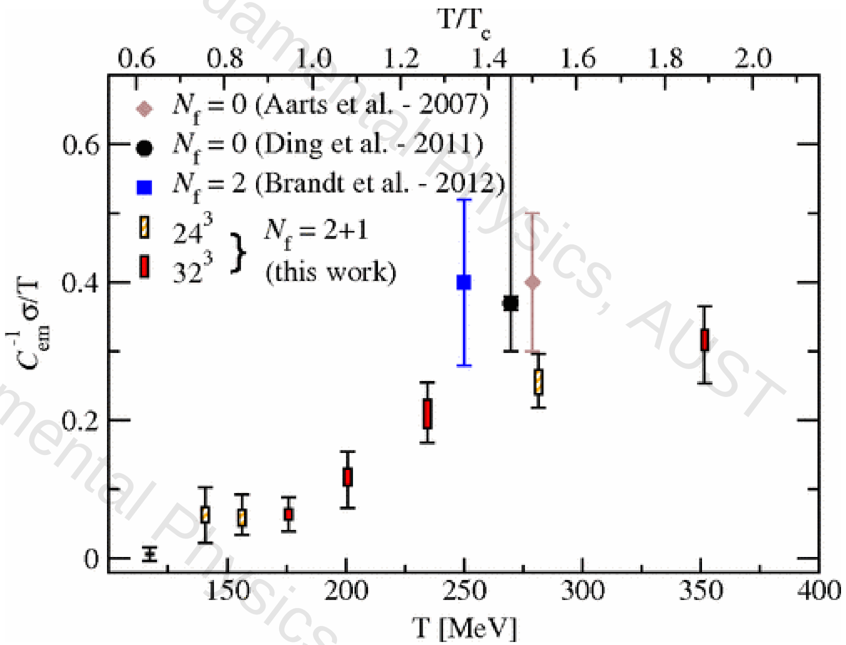




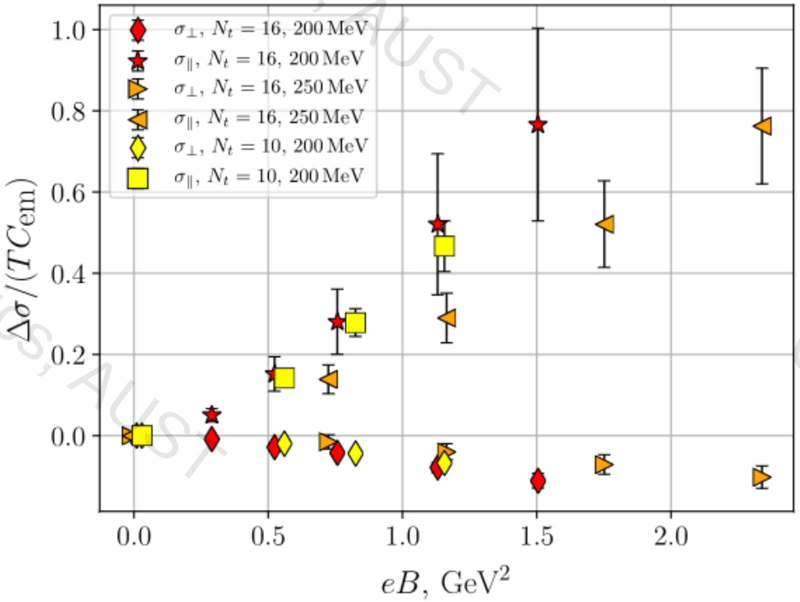
Expect short life time of B

Skokov, McLerran, NPA 2014
Yan, Huang, PRD 2023

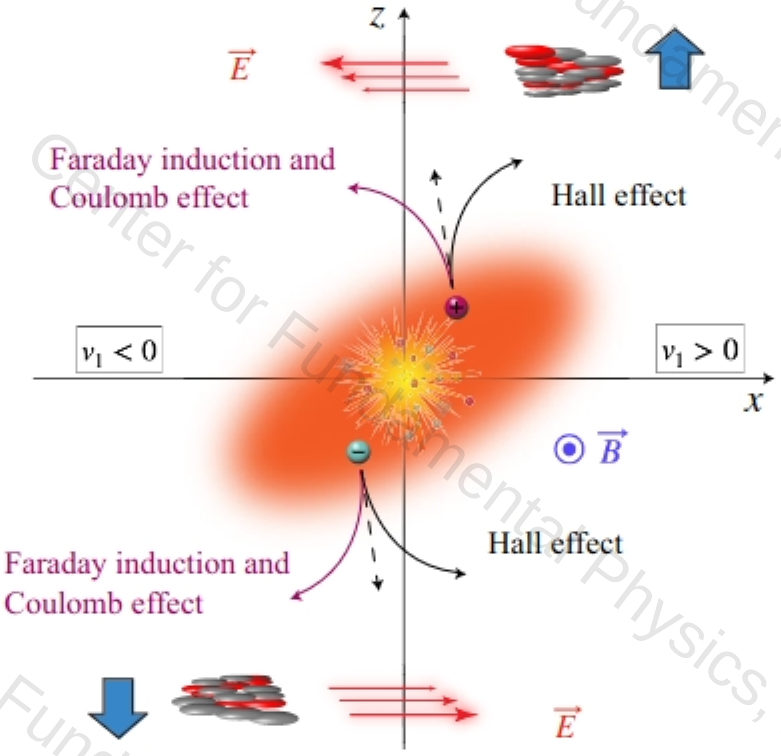
Electric conductivity from Lattice & Experiment



Aarts et al, 2007, 2013
Ding et al, 2011, 2014



Kotov et al, PRD, 2020

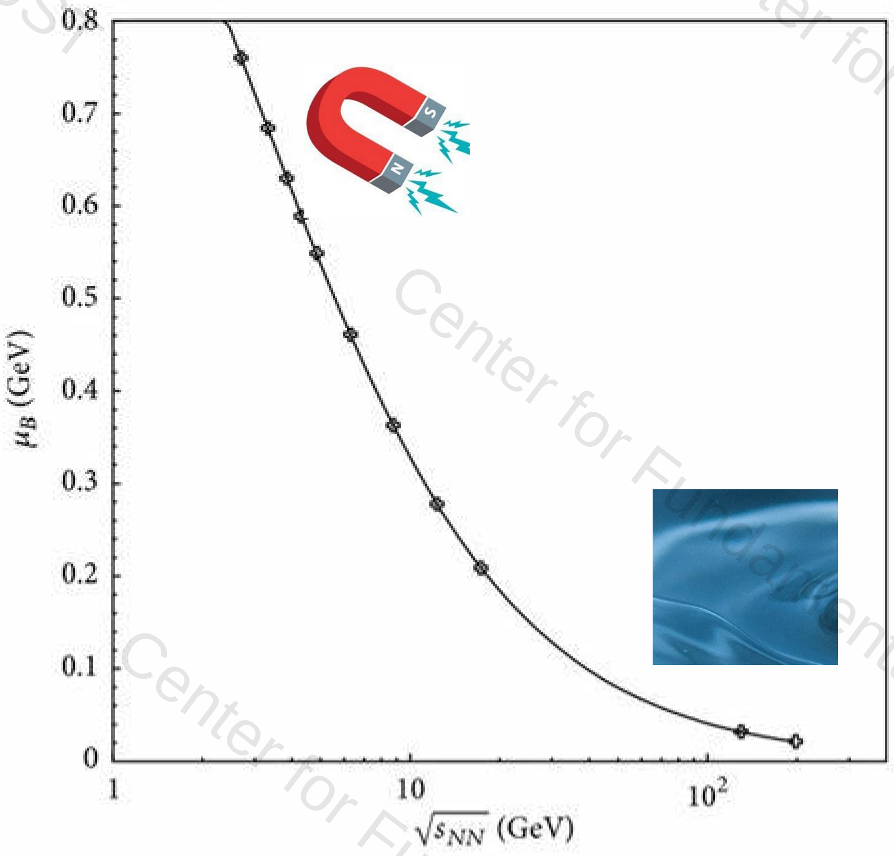


STAR, PRX, 2024

Lattice disfavors large conductivity
Experiment measurement of v1 consistent with lattice

What can QGP be other than conducting medium?

0^{th} approx: spinless conducting fluid
1^{st} approx: consisting of spinning particles, magnetized by B-field, like magnet



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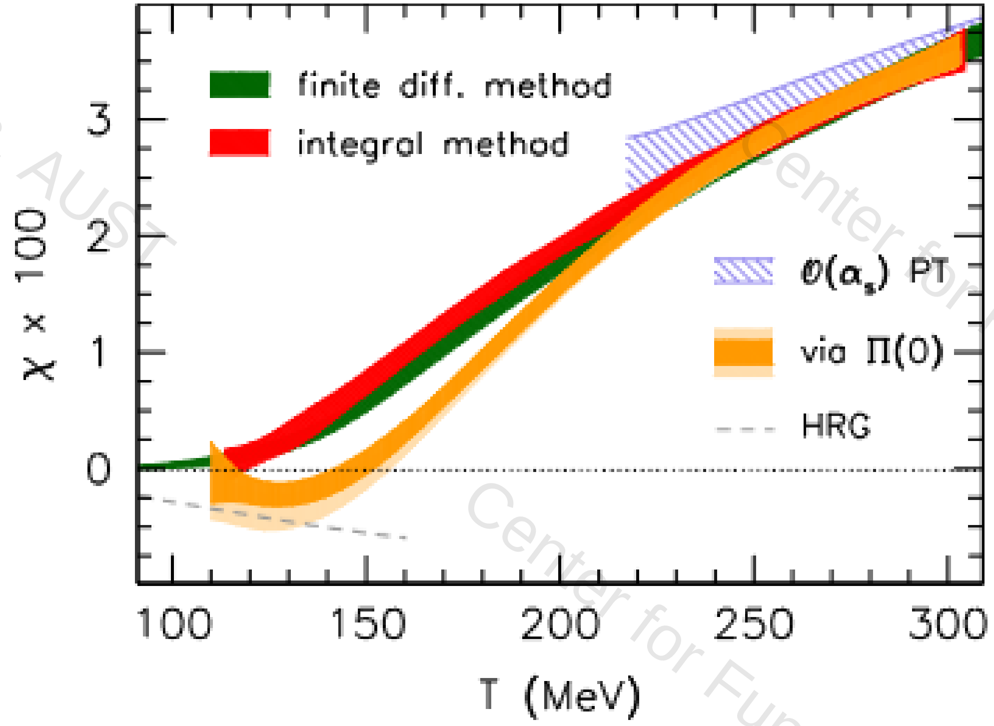
QGP as a paramagnet (weak B)



Bali, Endrodi, Piemonte, JHEP 2020

$$\chi^{\text{OAM}} = -\frac{1}{3}\chi^{\text{spin}}$$

QGP as a paramagnet (strong B)

$$E = \sqrt{m^2 + p_3^2 + 2neB}$$

$n = 0$ lowest Landau level dominated

positive charge $s_z = 1/2$

negative charge $s_z = -1/2$

magnetization from spin of LLL states

Sheng, Rischke, Vasak, Wang, EPJA 2017
Gorbar, Miransky, Sovkovy, Sukhachov, JHEP 2017
SL, Yang, JHEP 2021

What if B turned off (strong B)?

turned off adiabaticaly: LLL states demagnetized $\tau_B \gg \tau_{rel}$

turned off suddenly: free relaxation of LLL states $\tau_B \ll \tau_{rel}$

momentum isotropization $$\tau_{rel} \sim \frac{1}{g^4 T}$$

It is likely QGP remains a LLL state after rapid decay of B

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Photon self-energy in massless QED under strong B

soft photon

symmetric | anti-symmetric

$$\Pi_R^{\mu\nu} = -\frac{e^3 B}{2\pi^2}\frac{q_3^2 u^\mu u^\nu + q_0^2 b^\mu b^\nu + q_0 q_3 u^{\{\mu}b^{\nu\}}}{(q_0+i\epsilon)^2 - q_3^2} + \frac{ie^2\mu}{2\pi^2}\left(q_0\epsilon^{\mu\nu\rho\sigma} + u^{[\mu}\epsilon^{\nu]\lambda\rho\sigma} q_\lambda^T\right)u_\rho b_\sigma$$

Chiral Magnetic Wave in lowest Landau level approx

Kharzeev, Yee, PRD 2011
Fukushima PRD, 2011
Gao, Mo, SL, PRD 2020

Hall effect: drift velocity + charge density → current

Hidaka, Fukushima, JHEP 2020
SL, Yang, JHEP 2021
Yang, PRD 2022

$u^\mu = (1,0,0,0)$ fluid

$b^\mu = (0,0,0,1)$ B-field

q^μ photon momentum

Photon dispersions in massless QED under strong B

$$\left(\partial^2\eta^{\mu\nu} - \partial^\mu\partial^\nu\right) A_{\nu,r} = j_r^\mu = -i\int d^4y\,\Pi_{ar}^{\mu\nu}(x,y)A_{\nu,}$$

$q_0^2 = \tilde{B} + q^2$ gapped mode $eB \gg \mu q$

low-energy modes

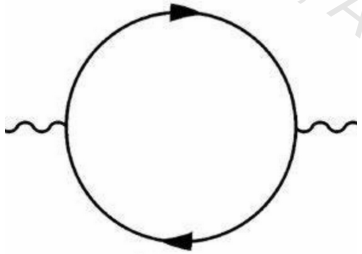
$$q_0^2 = \frac{1}{2}\left(\tilde{\mu}^2 + q_\perp^2 + 2q_3^2 - \sqrt{4\tilde{\mu}^2 q_3^2 + \left(q_\perp^2 + \tilde{\mu}^2\right)^2}\right) \equiv x_1^2,$$

$$q_0^2 = \frac{1}{2}\left(\tilde{\mu}^2 + q_\perp^2 + 2q_3^2 + \sqrt{4\tilde{\mu}^2 q_3^2 + \left(q_\perp^2 + \tilde{\mu}^2\right)^2}\right) \equiv x_2^2.$$

$\mu = 0$ →

$q_0^2 = q_3^2$

LLL



$q_0^2 = q^2$ free

$\tilde{\mu} = e^2\mu/2\pi^2$ $\tilde{B} = e^3 B/2\pi^2$ $q_\perp^2 = q_1^2 + q_2^2$

medium Fermi liquid-like rather than fluid-like

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Photon polarization in massless QED under strong B

Hall dynamics requires

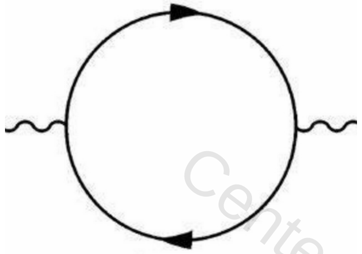
$q_0,\, q \sim \tau_R^{-1} \sim e^4\mu$ → $\tilde{\mu} \sim e^2\mu \gg q$

$$q_0^2 = x_1^2 : \quad \frac{A_1}{A_0} = \frac{i(q_2 q + i q_1 |q_3|)}{q_\perp^2 q}\tilde{\mu}, \qquad \frac{A_2}{A_0} = -\frac{i(q_1 q - i q_2 |q_3|)}{q_\perp^2 q}\tilde{\mu}, \qquad \frac{A_3}{A_0} = \frac{q_3}{|q_3| q}\tilde{\mu}.$$

simple interpretation at $q_3 \gg q_\perp$

$$\frac{A_1}{A_2} \simeq -i$$

LLL



One photon polarization favored due to interaction with spin polarized CMW in charged magnetized medium

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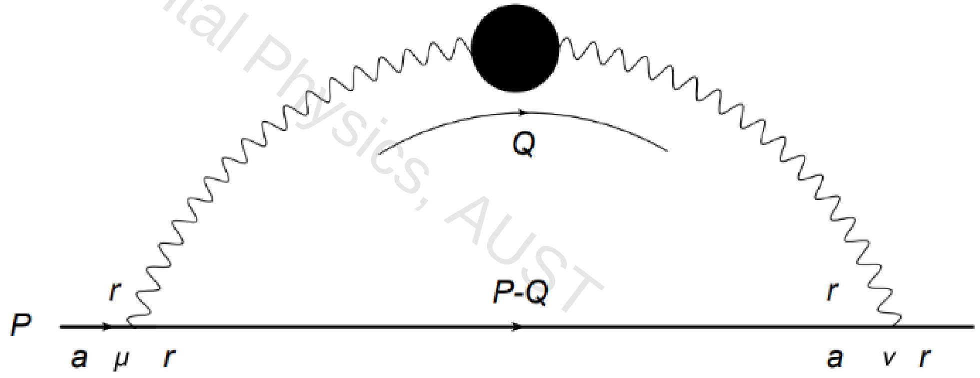
Self-energy of unpolarized massless probe fermion



$$D^{rr}_{\mu\nu}(Q) = -2i\pi\ \epsilon(q_0)\,(S_{\mu\nu}(Q) + A_{\mu\nu}(Q)\tilde{\mu})\left(\frac{1}{2} + f_\gamma(q_0)\right)\left(\frac{\delta(q_0^2 - x_1^2)}{q_0^2 - x_2^2} + \frac{\delta(q_0^2 - x_2^2)}{q_0^2 - x_1^2}\right)$$

symmetric   anti-symmetric

$$S_{ra(0)}(P) = \frac{i\not{P}}{(p_0 + i\epsilon)^2 - p^2}$$

$$\Gamma_L \simeq \frac{c_3 p_3}{p} = \frac{e^2 T q_{\rm UV}^2}{8\pi\tilde{\mu}p}\epsilon(p_3),$$

$$\Gamma_R \simeq -\frac{c_3 p_3}{p} = -\frac{e^2 T q_{\rm UV}^2}{8\pi\tilde{\mu}p}\epsilon(p_3).$$

anti-symmetric component leads to splitting in damping rate

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Implication for polarization dynamics

$$\Gamma_L \simeq \frac{c_3 p_3}{p} = \frac{e^2 T q_{\rm UV}^2}{8\pi\tilde{\mu}p}\epsilon(p_3),$$
$$\Gamma_R \simeq -\frac{c_3 p_3}{p} = -\frac{e^2 T q_{\rm UV}^2}{8\pi\tilde{\mu}p}\epsilon(p_3).$$

amplified modes:
right-handed $p_3 > 0$
left-handed $p_3 < 0$.

Positive spin polarization along B

charged magnetized QED medium behaves like paramagnet
in dynamical sense

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Gluon self-energy in massless QCD under strong B

soft gluon

CMW in LLL approx

$$\Pi_R^{\mu\nu,AB} = \Bigg[-\frac{g^2 eB}{2\pi^2} \frac{q_3^2 u^\mu u^\nu + q_0^2 b^\mu b^\nu + q_0 q_3 u^{\{\mu} b^{\nu\}}}{(q_0 + i\epsilon)^2 - q_3^2} + \frac{ig^2}{2\pi^2}\frac{\mu}{2}\left(q_0 \epsilon^{\mu\nu\rho\sigma} + u^{[\mu}\epsilon^{\nu]\lambda\rho\sigma} q_\lambda^T \right) u_\rho b_\sigma$$

$$- P_T^{\mu\nu}\Pi_T - P_L^{\mu\nu}\Pi_L \Bigg]\delta^{AB},$$

chromo-Hall effect: balance between chrome-electric force and Lorentz force

gluon self-interaction

$u^\mu = (1,0,0,0)$ fluid

$b^\mu = (0,0,0,1)$ B-field

q^μ gluon momentum

$$\Pi_T = m^2 \left(x^2 + (1 - x^2) x Q_0(x) \right),$$

$$\Pi_L = -2m^2 (x^2 - 1)\left(1 - xQ_0(x)\right),$$

$$m^2 = \tfrac{1}{6} N_c g^2 T^2$$

Two limits of QGP medium

$$\Pi_R^{\mu\nu,AB} = \Bigg[-\frac{g^2 eB}{2\pi^2} \frac{q_3^2 u^\mu u^\nu + q_0^2 b^\mu b^\nu + q_0 q_3 u^{\{\mu} b^{\nu\}}}{(q_0 + i\epsilon)^2 - q_3^2} + \frac{ig^2}{2\pi^2} \frac{\mu}{2} \left(q_0 \epsilon^{\mu\nu\rho\sigma} + u^{[\mu} \epsilon^{\nu]\lambda\rho\sigma} q_\lambda^T \right) u_\rho b_\sigma$$
$$- P_T^{\mu\nu} \Pi_T - P_L^{\mu\nu} \Pi_L \Bigg] \delta^{AB},$$

density dominate $\bar{\mu}^2 \gg \Pi_{T/L}$ medium like Fermi-liquid

temperature dominate $\bar{\mu}^2 \ll \Pi_{T/L}$. medium like fluid

$$\bar{\mu} \sim g^2 \mu, \quad \Pi_{T/L} \sim g^2 T^2$$

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Density dominated limit

$$D^{rr,A}_{\mu\nu}(Q) = -2i\pi\ \epsilon(q_0)\left(\frac{1}{2}+f_g(q_0)\right)\left(\frac{\delta(q_0^2-\bar{x}_1^2)}{q_0^2-\bar{x}_2^2}+\frac{\delta(q_0^2-\bar{x}_2^2)}{q_0^2-\bar{x}_1^2}\right)A_{\mu\nu}(Q)\bar{\mu}.$$

similar to QED case

$$q_0,\ q \sim \tau_R^{-1} \sim g^4\mu \ll \bar{\mu}.$$

damping from scattering
with CMW states

$$\Gamma_L \simeq \frac{N_c^2-1}{2N_c}\frac{g^2Tq_{\rm UV}^2}{8\pi\bar{\mu}p}\epsilon(p_3),$$

$$\Gamma_R \simeq -\frac{N_c^2-1}{2N_c}\frac{g^2Tq_{\rm UV}^2}{8\pi\bar{\mu}p}\epsilon(p_3).$$

charged magnetized QGP in density
dominated limit behaves like paramagnet
in dynamical sense

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Temperature dominated limit

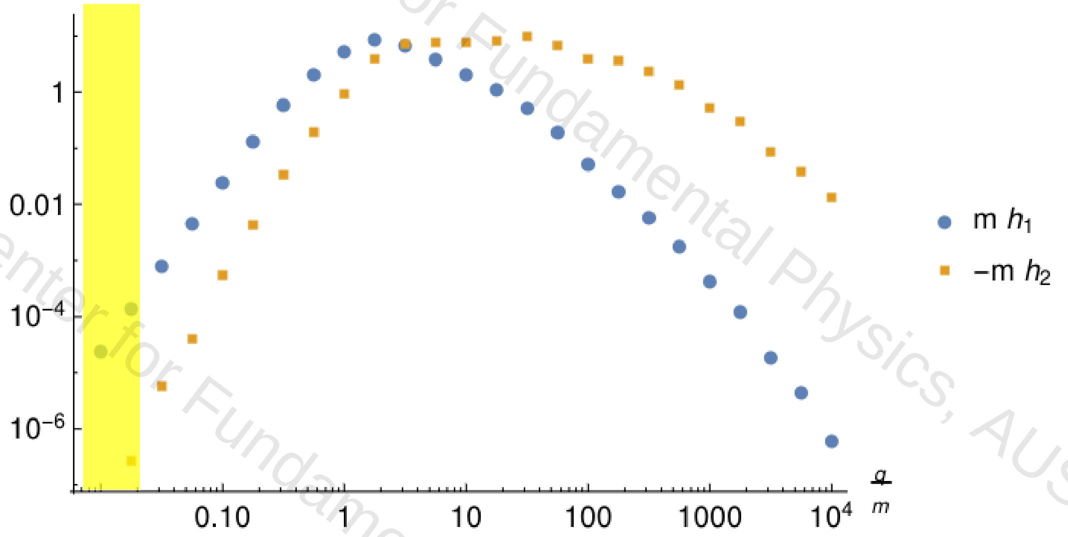
$$D^{rr,A}_{\mu\nu}(Q) = 2i\mathrm{Im}\left[\frac{Q^2q^2}{(Q^2-\Pi_T)\left(q^2Q^2(q_0^3-q_3^2)-Q^2q_3^2\Pi_T-q_0^2q_\perp^2\Pi_L\right)}\right]\left(\frac{1}{2}+f_g(q_0)\right)A_{\mu\nu}\bar{\mu}.$$

$q_0,\ q \sim \tau_R^{-1} \sim g^4T.$ damping from scattering with gluons

$$\Gamma_L \simeq -\epsilon(p_3)\left(H_2-\frac{|p_3|H_1}{p}\right),$$

$$\Gamma_R \simeq \epsilon(p_3)\left(H_2-\frac{|p_3|H_1}{p}\right).$$

$H_i \sim \int dq h_i$ → $H_1 \gg H_2$



charged magnetized QGP in temperature dominated limit behaves like paramagnet
in dynamical sense

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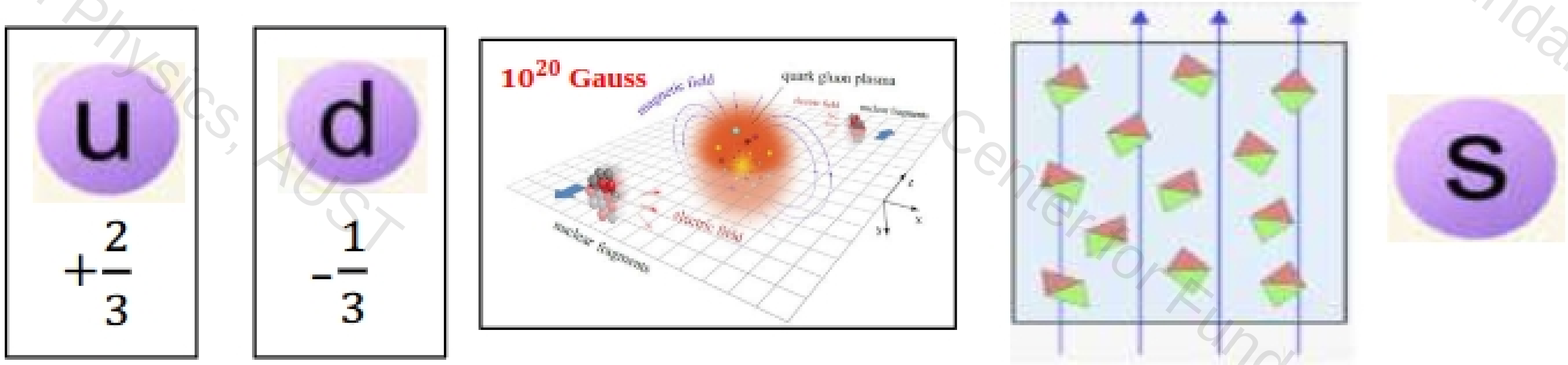
Implication for polarization dynamics in HIC



- Low energy HIC produces medium with baryonic and electric charge
- Initial magnetic field decays quickly and magnetizes QGP
- Magnetized QGP continues to polarize quarks produced at later stage like strange quark, effectively extend life time of B

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Conclusion

- Splitting of damping rate of spin component of probe fermion in charged magnetized QED matter
- Splitting of damping rate of spin component of probe quark in charged magnetized QCD matter
- Paramagnet charged QGP can polarize probe quark

Outlook

- Beyond strong B field limit
- Beyond probe limit, backreaction to paramagnet

Thank you!