Polarization Dynamics in Charged Magnetized Quark-Gluon Plasma

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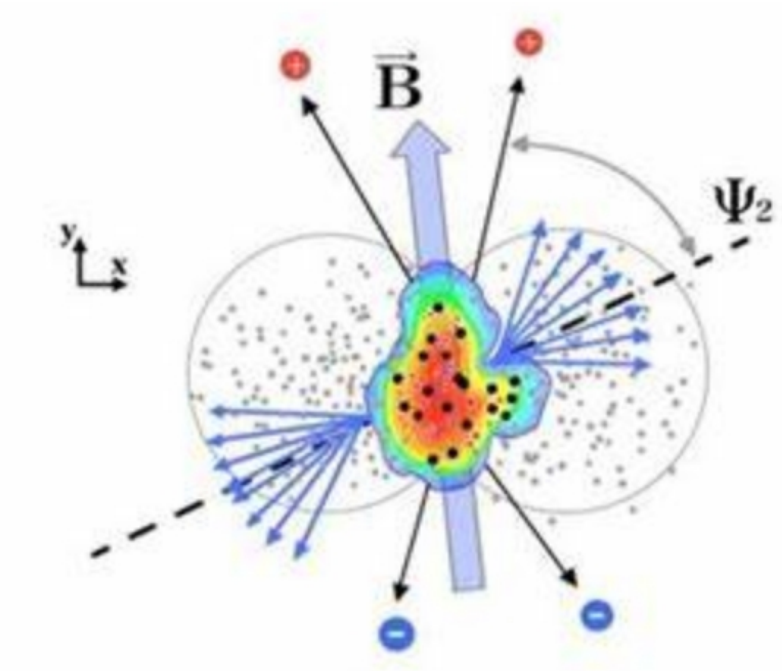
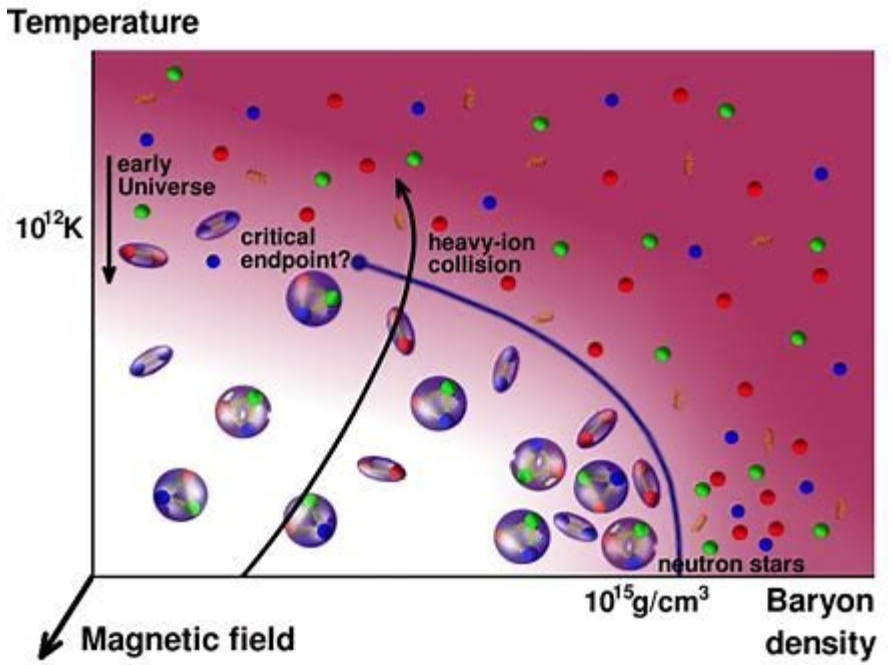
L. Dong, SL, 2403.12615

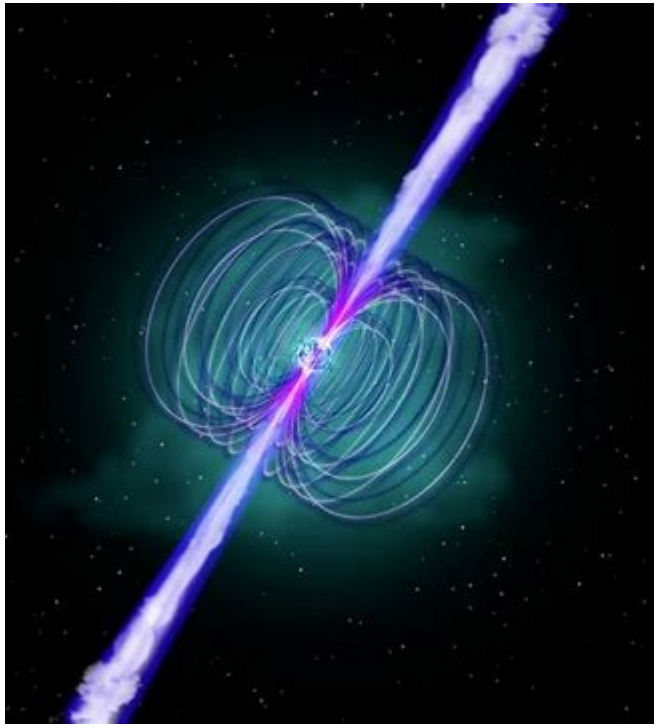
Outline

- 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

Novel magnetic induced phenomena in QCD

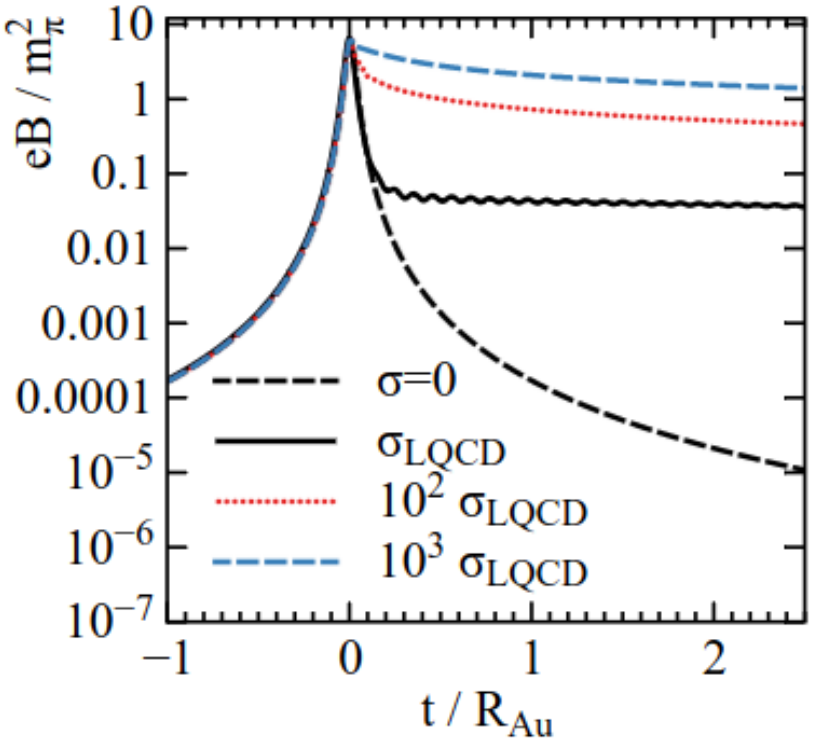


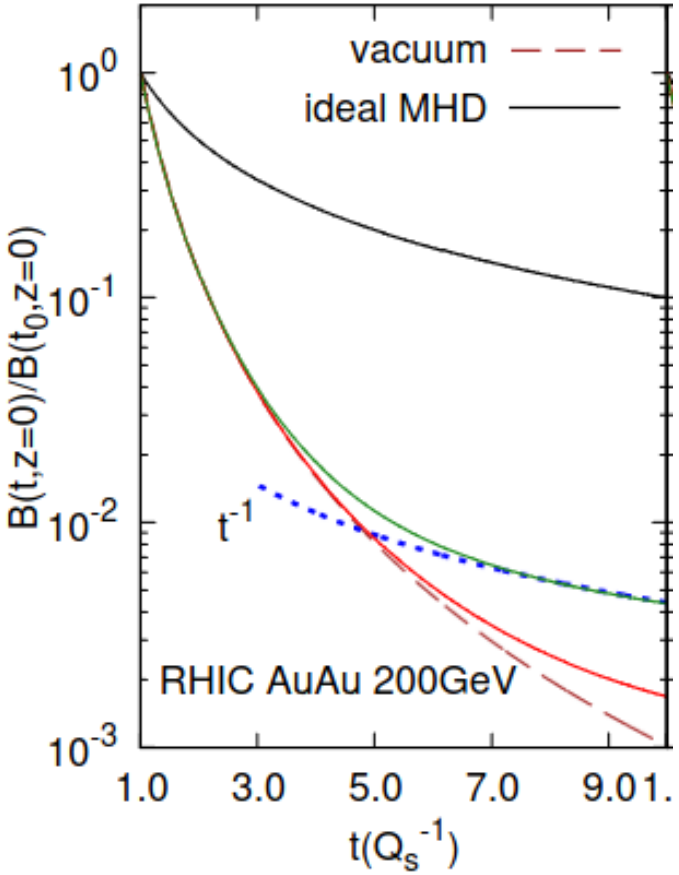




talks by D.f. Hou,
H.-T. Ding, G.-L. Ma

Magnetic field in Heavy ion Collisions



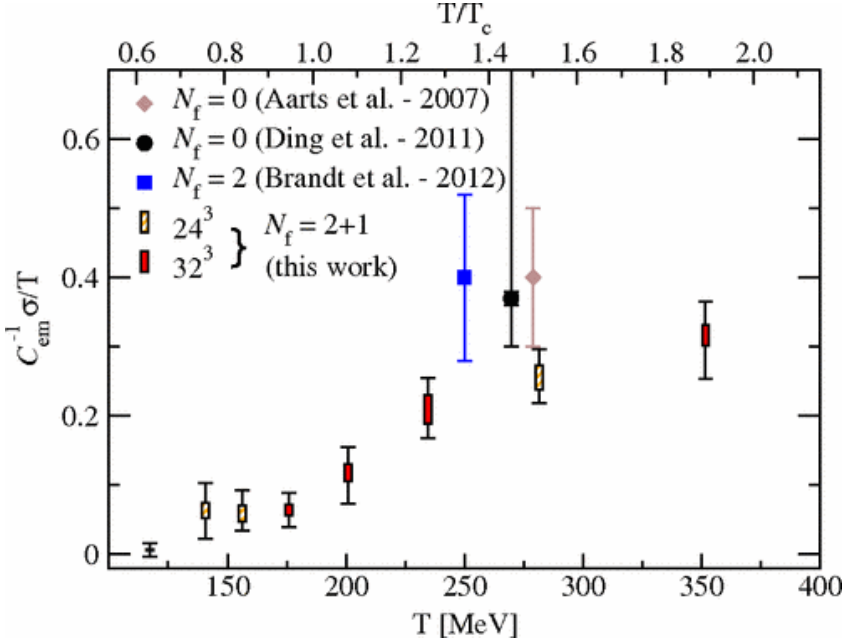


Skokov, McLerran, NPA 2014
Yan, Huang, PRD 2023

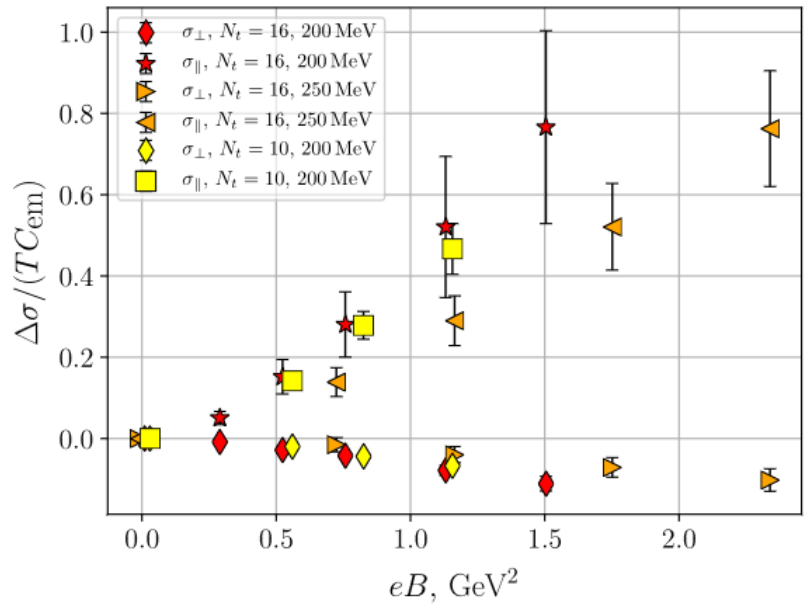
talks by X.-G. Huang, L. Yan

Expect short life time of B

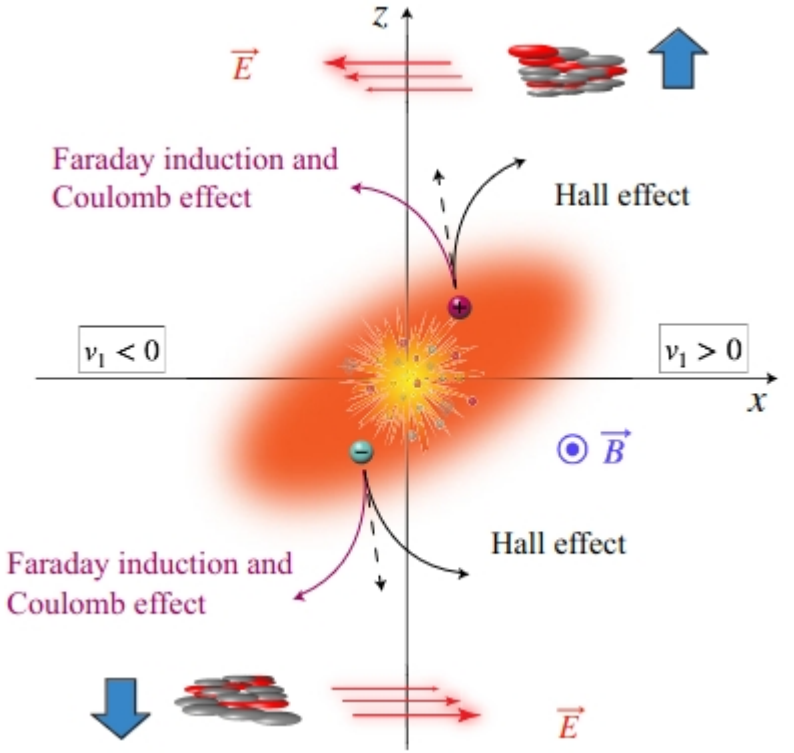
Electric conductivity from Lattice & Experiment



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



Kotov et al, PRD, 2020



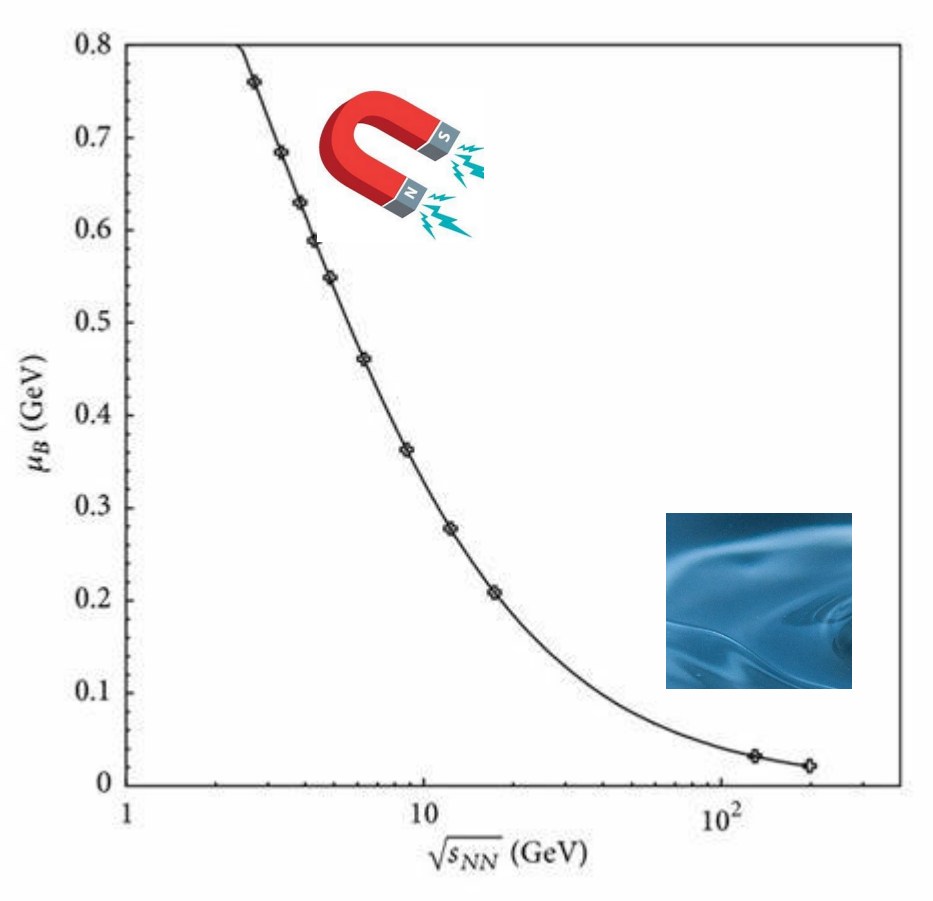
STAR, PRX, 2024

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, polarizable by B-field, like magnet



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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

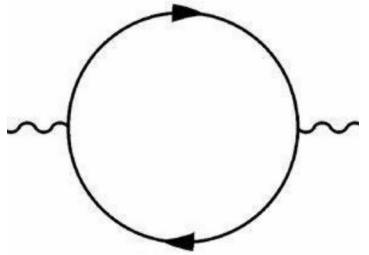
$$q_0^2=\frac{1}{2}\left(\tilde{\mu}^2+q_\perp^2+2q_3^2-\sqrt{4\tilde{\mu}^2q_3^2+\left(q_\perp^2+\tilde{\mu}^2\right)^2}\right)\equiv x_1^2,$$

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

$\mu=0$

$q_0^2=q_3^2$

CMW



$q_0^2=q^2$ free

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

medium Fermi liquid-like rather than fluid-like

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Photon polarization in massless QED under strong B

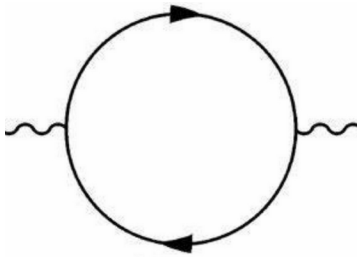
Hall dynamics requires

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

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

simple interpretation at $q_3 \gg q_\perp$ $\quad \frac{A_1}{A_2} \simeq -i$

CMW



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

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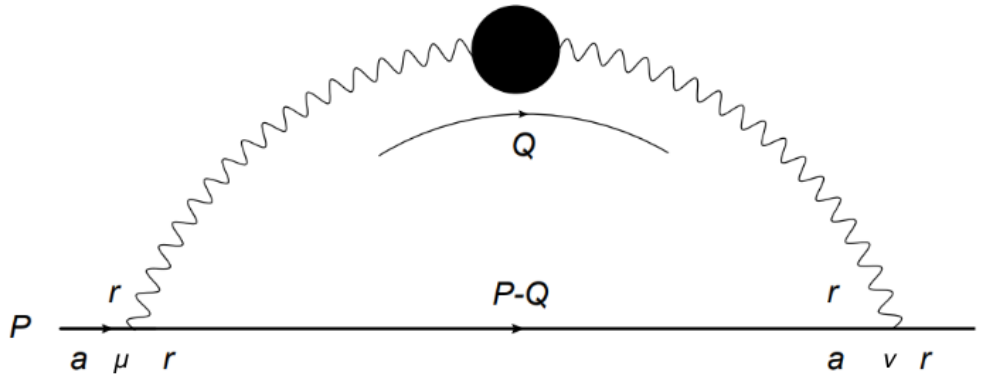
Self-energy of unpolarized massless probe fermion



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

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

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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

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

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

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

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

temperature dominate $\quad \bar{\mu}^2 \ll \Pi_{T/L}$ $\quad$ 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

damping from scattering with CMW states

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

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

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

charged magnetized QGP in density dominated limit behaves like paramagnet

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Temperature dominated limit

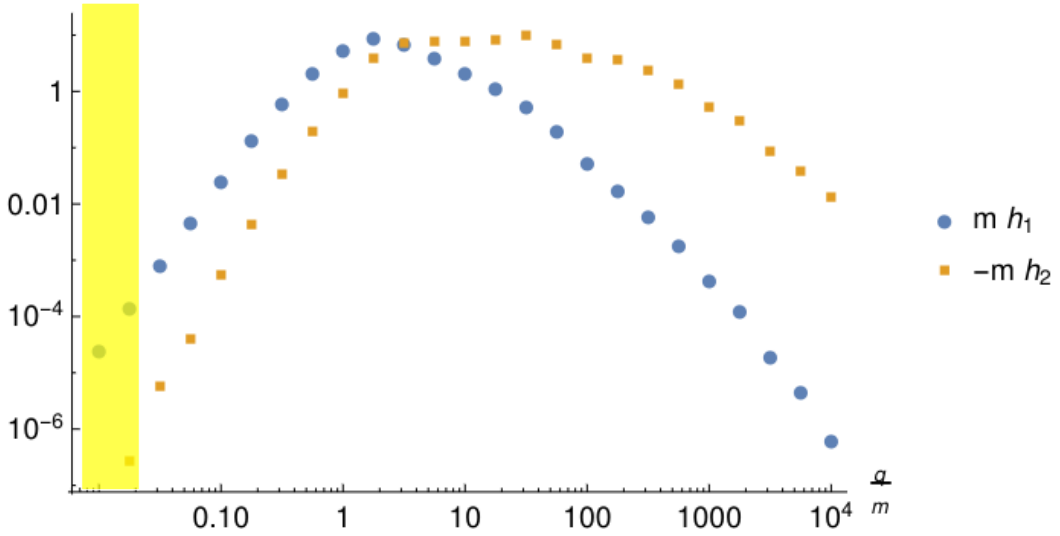
$$D^{rr,A}_{\mu\nu}(Q) = 2i\mathrm{Im}\left[\frac{Q^2q^2}{(Q^2-\Pi_T)\left(q^2Q^2(q_0^3-q_3^2)-Q^2q_3^2\Pi_T-q_0^2q_\perp^2\Pi_L\right)}\right]\left(\frac{1}{2}+f_g(q_0)\right)A_{\mu\nu}\bar{\mu}.$$

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

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

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

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



charged magnetized QGP in temperature dominated limit behaves like paramagnet

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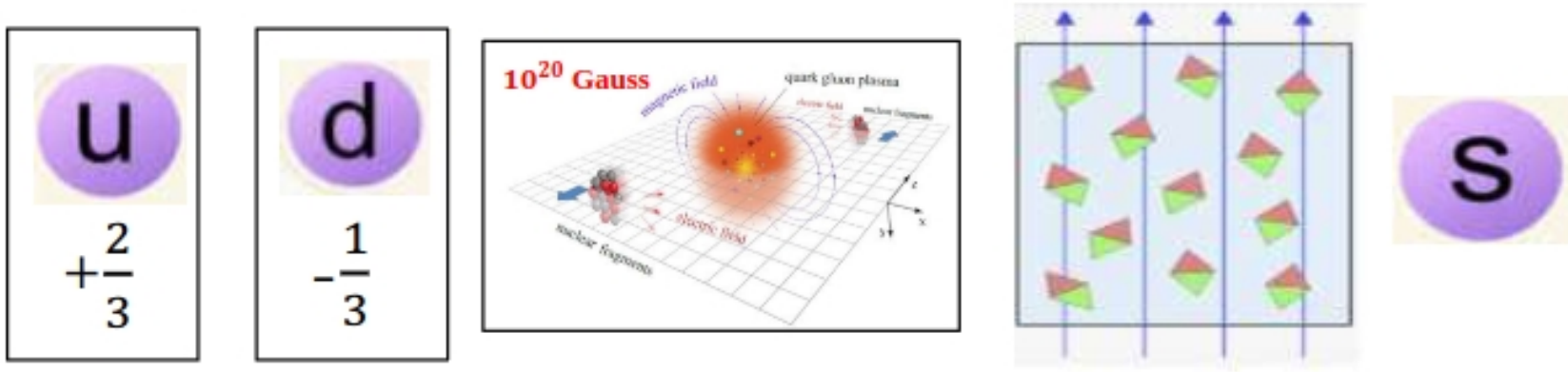
Implication for polarization dynamics in HIC



- 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

- Hall effect and polarized photon in charged magnetized QED matter
- Splitting of damping rate of spin component of probe fermion
- Chromo-Hall effect + gluon self interaction and polarized gluon in charged magnetized QCD matter
- Splitting of damping rate of spin component of probe quark
- QGP can behaves as a paramagnet

Outlook

- Beyond strong B field limit
- Analogy in vorticity

Thank you!