Chiral Magnetic Effect and Relativistic Heavy-Ion Collisions

Lecture in the student day
Strangeness in Quark Matter 2022
Busan, South Korea
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Suggested Reviews

- Kharzeev -1312.3348 - introduction and history of CME
- Fukushima - 1209.5064 - early anecdotes and conceptual issues
- Kharzeev-Liao-Voloshin-Wang -1511.04050 - comprehensive
- CME Task Force Report -1608.00982 - concise summary
- Kharzeev-Liao -2102.06623 - review in Nature Physics
- Hattori-Huang -1609.00747 - broad topics
- Li-Wang - 2002.10397 - review of experiments

The lecture will be focused on the basics, aiming to motivate you to search deeper in literature.
Plan

• Chiral Symmetry of QCD and Chiral Anomaly
• Chiral Magnetic Effect (CME) - Theory
• CME in Heavy-Ion Collisions - Experiments
• Chiral Magnetic Wave (CMW)
• Questions and Discussions
Relativistic Massless Fermions: Helicity

\[ \mathbf{S} \, \uparrow \circlearrowright \mathbf{p} \]

- **Helicity**: \( h = \mathbf{S} \cdot \mathbf{p} = \pm \frac{\hbar}{2} \) : 
  \( h = + \hbar/2 \) (Right-Handed) 
  \( h = - \hbar/2 \) (Left-Handed)

- Under the parity \( \mathbf{x} \rightarrow - \mathbf{x} \) transformation (P),
  \( \mathbf{S} \rightarrow -\mathbf{S} \) and \( \mathbf{p} \rightarrow -\mathbf{p} \), and \( h \) is P-odd

- Any observable that correlates \( \mathbf{S} \) and \( \mathbf{p} \) breaks P
QCD Quark Field: \( \Psi = (\Psi_R, \Psi_L) \) (Dirac)

<table>
<thead>
<tr>
<th>( \Psi_R )</th>
<th>( \Psi_L )</th>
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<tr>
<td>R-handed Weyl field</td>
<td>L-handed Weyl field</td>
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Quark: \( Q = +1 \)

Anti-quark: \( Q = -1 \)

\( h = + \)

\( h = - \)

\( P \)

\( C \)
Chiral Symmetry of QCD

$$U(1)_R \times U(1)_L$$

$$\Psi_R \rightarrow \Psi_Re^{i\alpha}$$

$$\Psi_L \rightarrow \Psi_Le^{i\alpha}$$

$$N_R = N_R^+ - N_R^-$$ conservation

$$N_L = N_L^+ - N_L^-$$ conservation

$$U(1)_V = U(1)_R + U(1)_L, \quad U(1)_A = U(1)_R - U(1)_L$$

Vector charge $$N_V = N_R + N_L$$: Net quark number
Axial $U(1)_A$ Symmetry

\[ N_A = N_R - N_L = N_R^+ + N_L^- - (N_L^+ + N_R^-) \]

Total number of Helicity $h = +$ fermions

Total number of Helicity $h = -$ fermions

Axial charge is Parity-odd, but C-even (CP-odd)
(it doesn't care whether quarks or anti-quarks)

It is simply the Net Helicity
For $N_F$ flavors, we have an extended symmetry

$$U(N_F)_R \times U(N_F)_L$$

We usually extract $U(1)_V \times U(1)_A$ part:

$$SU(N_F)_R \times SU(N_F)_L \times U(1)_V \times U(1)_A$$

since $U(1)_A$ part is violated quantum mechanically, called Chiral Anomaly (we will come back to this later)
Quark Mass Breaks Chiral Symmetry

\[ m_q \bar{\Psi} \Psi = m_q (\bar{\Psi}_L \Psi_R + \text{h.c.}) \]

This is invariant only under \( U(N_F)_R = U(N_F)_L \)

\[ U(N_F)_R \times U(N_F)_L \longrightarrow U(N_F)_V \]

QCD Chiral Symmetry is an \textbf{Approximate Symmetry} since \( m_q \approx 5 \text{ MeV} \ll \Lambda_{QCD} \sim 1 \text{ GeV} \)
Even in the absence of quark mass and chiral anomaly, the QCD vacuum breaks chiral symmetry dynamically,

\[ \langle \bar{\Psi} \Psi \rangle = \langle \bar{\Psi}_L \Psi_R \rangle + \text{h.c.} \approx (1 \text{ GeV})^3 \]

(Chiral Condensate)

\[ U(N_F)_R \times U(N_F)_L \rightarrow U(N_F)_V \]

Why does this have to be non-perturbative?
Let's look at the operator more explicitly in \( p \)-space

\[
\Psi_R = \int \mathbf{p} \ u_R(\mathbf{p}) a_R(\mathbf{p}) e^{i \mathbf{p} \cdot \mathbf{x}} + v_L(\mathbf{p}) b_L^\dagger(\mathbf{p}) e^{-i \mathbf{p} \cdot \mathbf{x}}
\]

\[
\Psi_L = \int \mathbf{p} \ u_L(\mathbf{p}) a_L(\mathbf{p}) e^{i \mathbf{p} \cdot \mathbf{x}} + v_R(\mathbf{p}) b_R^\dagger(\mathbf{p}) e^{-i \mathbf{p} \cdot \mathbf{x}}
\]

\( u_{R/L}, v_{R/L} \) = Spinor Wave Functions

\( a_{L/R}^\dagger, b_{L/R}^\dagger \) = Quark, Anti-Quark Creation Operators
\[ \bar{\Psi}_L \Psi_R = \int \bar{u}_L(p) u_R(p) a_L^\dagger(p) a_R(p) + \bar{v}_R(p) v_L(p) b_R^\dagger(p) b_L(p) \]

\[ + \bar{u}_L(p) v_L(-p) a_L^\dagger(p) b_L^\dagger(-p) + \bar{v}_R(p) u_R(-p) b_R(p) a_R(-p) \]

Spin flip is forbidden by angular momentum conservation.

Creation of L-handed fermion and anti-fermion pair back-to-back.
\[ \langle \bar{\Psi}_L \Psi_R \rangle = \langle a_L^\dagger(p) b_L^\dagger(-p) \rangle + \langle a_R(p) b_R(-p) \rangle \]

Similar to Cooper Pair \( \Delta = \langle a^\dagger a^\dagger \rangle \) in Superconductivity, but with Quark-Antiquark Pair

Possible only Non-Perturbatively
Chirality Flipping by Quark Mass

A simple "mass insertion" cannot flip helicity, due to angular momentum conservation.

We need QCD interactions and $m_q$ to flip chirality.

(Grabowska-Kaplan-Reddy, 1409.3602)
Chirality Anomaly of $U(1)_A$

\[ \partial_\mu J^\mu_A \]

Triangle Diagram

\[ \frac{dN_A}{dt} = \frac{e^2}{2\pi^2} \mathbf{E} \cdot \mathbf{B} + \frac{g^2}{4\pi^2} \mathbf{E}_g \cdot \mathbf{B}_g \]

QCD Gluons
Topological Fluctuations, e.g.
Instantons in vacuum
Sphalerons in high T

$U(1)_A$ is strongly broken in QCD vacuum

\[ m_{\eta'} \approx 950 \text{ MeV}, \ m_{\pi^0,\pi^\pm} \approx 140 \text{ MeV} \]

Note

\[ m_u \approx 2 \text{ MeV}, \ m_d \approx 5 \text{ MeV} \]

Why $m_{\pi^0} \approx m_{\pi^\pm}$?
Subtle Aspects of Chiral Anomaly

Topological

\[ \frac{1}{4\pi^2} \int d^4x \, \mathbf{E}_g \cdot \mathbf{B}_g = \text{Integer} \]
Gribov's Picture of Anomaly

R-Handed Weyl Fermion $\Psi_R$ in magnetic field

Landau Levels with 2D density of states

$\frac{eB}{2\pi}$

$n = 0$ Chiral Zero Mode
UV-IR Connection

\[ E(p_z) \]

\[ \frac{dp_z}{dt} = eE \]

\[ \frac{dn_R}{dt} = \left( \frac{eB}{2\pi} \right) \frac{dp_z}{dt} = e^2 \frac{E \cdot B}{4\pi^2} \]

Anomaly happens here (IR)

Infinite "Dirac Sea" is needed (UV)
Axial Chemical Potential

In high T deconfined quark-gluon plasma, chiral symmetry $U(1)_A$ is approximately restored

(We will come back to this later)

$N_R$ and $N_L$ approximately conserved

Chiral chemical potentials

$\mu_R$ and $\mu_L$

or, axial $\mu_A = (\mu_R - \mu_L)/2$
Chiral Magnetic Effect

\[ \mathbf{J} = \frac{e^2}{2\pi^2} \mu A \mathbf{B} \]

- P-odd
- C-odd
- T-odd
- Chiral Anomaly Coefficient
- P-odd
- C-even
- T-even
- Axial Charge
- Non-Dissipative

(Fukushima-Kharzeev-Warranga, 0808.3382, Vilenkin '79)
Chiral Version of CME

There is also the Chiral Separation Effect (CSE)

\[ \vec{J}_A = \frac{e^2}{2\pi^2} \mu_V \vec{B} \]

where \( \mu_V = (\mu_R + \mu_L)/2 \)

Spin Polarization \( \vec{S} \)
for Dirac fermions
(Xu-Guang Huang's Lecture)

CME + CSE

\[ \vec{J}_R = \frac{e^2}{4\pi^2} \mu_R \vec{B} \]

\[ \vec{J}_L = -\frac{e^2}{4\pi^2} \mu_L \vec{B} \]
Derivation of CME (I) - Nielsen-Ninomiya

Poynting's Theorem: \[ \frac{\partial u}{\partial t} + \nabla \cdot S = - \mathbf{E} \cdot \mathbf{J} \]

Power to the chiral matter:

\[ P = \mathbf{E} \cdot \mathbf{J} = \frac{dn_A}{dt} \mu_A = \frac{e^2}{2\pi^2} \mathbf{E} \cdot \mathbf{B} \mu_A \]

\[ \implies \mathbf{J} = \frac{e^2}{2\pi^2} \mu_A \mathbf{B} \]

Same Coefficients
Derivation of CME (II) - Chiral Kinetic Theory

\[ \Psi_R \] quark \( Q = +1 \) anti-quark \( Q = -1 \)

\[ \vec{B} \]

Magnetic Moment Interaction

\[ \Delta H = - \vec{\mu}_M \cdot \vec{B} = - \frac{eQ}{|\vec{p}|} \vec{S} \cdot \vec{B} = - \frac{eh}{2|\vec{p}|^2} \vec{p} \cdot \vec{B} \]

(Son-Yamamoto '12, Stephanov-Yin '12, Chen-Pu-Wang-Wang '13)
\[ \mathbf{J}_R = \int \frac{d^3 p}{(2\pi)^3} \left( \mathbf{v}_+ f_+(p) - \mathbf{v}_- f_-(p) \right) \]

Classical Velocity: \( \mathbf{v}_+ = \mathbf{v}_- = \frac{p}{|p|} \equiv \hat{p} \)

Equilibrium: \( f^{\text{eq}}_\pm = \frac{1}{e^{\beta(|p|+\mu_R)} + 1} , \quad (\beta = 1/kT) \)

Both of them are modified at \( \mathcal{O}(\hbar) \) with \( \mathbf{B} \)
Magnetic moment interaction

\[ \Delta H = - \frac{e\hbar}{2|\vec{p}|^2} \vec{p} \cdot \vec{B} \]

\[ f_\pm = f_{\pm}^{eq}(|p| + \Delta H) = f_{\pm}^{eq}(|p|) + \frac{\beta e\hbar(p \cdot B)}{2|p|^2} f_{\pm}^{eq}(1 - f_{\pm}^{eq}) \]

\[ \mathcal{O}(\hbar) - \text{correction} \]

This accounts for 1/3 of total CME

\[ \Delta J_R = \frac{\beta \hbar(eB)}{6} \int_p \frac{1}{|p|} \left( f_+^{eq}(1 - f_+^{eq}) - f_-^{eq}(1 - f_-^{eq}) \right) = \frac{1}{3} \cdot \frac{\mu_R}{4\pi^2}(eB) \]
The rest 2/3 comes from quantum correction to the classical velocity $\Delta \vec{v}_{\pm}$, due to the Berry's Phase of spinor wave functions in $p$-space

$$\mathcal{A}_p = (i\hbar) u_R^\dagger(p) \nabla_p u_R(p)$$

(Son-Yamamoto '12, Stephanov-Yin '12, Chen-Pu-Wang-Wang '13)
Quantum correction to velocity

\[ \Delta v_\pm = \frac{\hbar \hat{p} (\hat{p} \cdot (eB))}{|\mathbf{p}|^2} \]

This accounts for \( \frac{2}{3} \) of total CME

\[ \Delta J_R = \frac{\hbar (eB)}{3} \int |\mathbf{p}|^2 (f^{eq}_+ - f^{eq}_-) = \frac{2}{3} \cdot \frac{\mu_R}{4\pi^2} (eB) \]

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<tr>
<th>( \Delta f_\pm )</th>
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<td>( \Delta v_\pm )</td>
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</tr>
<tr>
<td>Total</td>
<td>1</td>
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Out-of Equilibrium CME: \( \mathbf{J}(\omega) = \sigma_5(\omega) \mathbf{B}(\omega) \)

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<th>( \omega \ll \tau_R^{-1} )</th>
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</tr>
<tr>
<td>( \mathbf{J}_M )</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
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**Magnetization Current** \( \mathbf{J}_M = \nabla \times \mathbf{M} \),

\[
\mathbf{M} = \int_p \frac{e\hbar}{2|\mathbf{p}|^2} \mathbf{p} \left( f_+(\mathbf{p}) + f_-(\mathbf{p}) \right)
\]

(Kharzeev-Stephanov-Yee, 1612.01674)
Chiral Vortical Effect (CVE)

\[ \vec{J} = \frac{e^2}{2\pi^2} \mu \mu_A \vec{\omega} \]

\[ \vec{\omega} = \nabla \times \vec{v} \]

P-odd
C-odd
T-odd

P-odd
C-odd
T-even

P-even
C-even
T-odd

Axial Charge

Non-Dissipative
Relativistic Heavy-Ion Collisions (RHIC)
Heavy-Ion Collisions: Basics

- Linear superposition
- Collinear forward radiation

QED

- Non-linear YM eqns
- Gluon production in wide rapidity

QCD

Gluon production in wide rapidity

Gunion-Bertsch '82
Fluctuating Color Charges (Color Glass Condensate) [McLerran-Venugopalan '93]

Au-Au $\sqrt{s_{NN}} = 200$ GeV (RHIC)
Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV (LHC)

Gluon fields $\rightarrow$ Quark-Gluon Plasma (QGP)

Lifetime $\sim 10$ fm/c, Initial temperature $T \sim 300 - 400$ MeV

120 neutrons and 80 protons
Hydrodynamics: Elliptic Flow $v_2$

Elliptic Flow:
\[
\frac{dN}{d\phi} = N_0 \left( 1 + 2v_2 \cos(2(\phi - \Psi_{EP})) + \cdots \right)
\]

Typical value $v_2 \sim 0.01 - 0.1$
The initial gluon fields have random topological fluctuations of $\mathbf{E}^g \cdot \mathbf{B}^g \neq 0$

How long does $\mu_A$ last in QGP?

- Relaxation rate due to Sphaleron transitions $\sim \alpha_s^5 T$
- Relaxation rate due to quark mass $\sim m_q^2 \alpha_s^2 / T$

$\mu_A$ lasts up to $\sim 10 \text{ fm}/c$

(Kharzeev-Krasnitz-Venugopalan, hep-ph/0109253)
(Kapusta-Rrapaj-Rudaz, 2012.13784, Lin-Yee, 1305.3949)
CME in Heavy-Ion Collisions (II) : Magnetic Field

\[ \vec{B} \sim \alpha_{EM} Z \gamma \]

Initial Magnetic Field

\[ eB \sim \frac{\alpha_{EM} Z \gamma}{b^2} \sim (100 \text{ MeV})^2 \]

(Kharzeev-McLerran-Warringa, 0711.0950)

\[ Z \sim 100, \gamma \sim 100, b \sim 10 \text{ fm} \]

\[ eB \sim (100 \text{ MeV})^2 \sim 10^{18} \text{ G} \]

is comparable to initial T

Magnetars

\[ eB \sim 10^{16} \text{ G} \]
Magnetic Field Diffusion

How long does $B$ last in QGP?

Maxwell's eqns in a conducting plasma

$$\nabla \times E = -\frac{\partial B}{\partial t}, \quad \nabla \times B = J + \frac{\partial E}{\partial t} = \sigma E + \frac{\partial E}{\partial t}$$

$$\nabla \times (\nabla \times B) = -\nabla^2 B = -\sigma \frac{\partial B}{\partial t} - \frac{\partial^2 B}{\partial t^2} \approx -\sigma \frac{\partial B}{\partial t}$$

Conductivity from Lattice QCD: $\sigma_{\text{Lattice}} \approx 0.1 e^2 T \sim 0.01 / \text{fm}$

Magnetic field diffusion time $\tau_D = \sigma L^2 \approx 1 \text{ fm/c}$: Not long nor too short
Experimental Observables of CME

\[ \mu_A > 0 \]

\[ \mu_A < 0 \]

Event Plane

Event-by-Event Fluctuating Charge Dipoles

\[ \frac{dN_\pm}{d\phi} = N_0 \left( 1 + 2v_2 \cos(2(\phi - \Psi_{EP})) \pm 2a_1 \sin(\phi - \Psi_{EP}) + \cdots \right) \]

(D. Kharzeev, hep-ph/0406125)
\[ \langle a_1^{\text{CME}} \rangle_{\text{events}} = 0 \rightarrow \langle (a_1)^2 \rangle \neq 0, \text{ but it is now } P\text{-even} \]

(We will come back to this later)

Event-by-Event \( dN/d\phi \) is a large \( N \) approximation

Each event gives \((\phi_1, \phi_2, \ldots, \phi_N)\)

Averaging over events gives Probability Dist. : \( P(\phi_1, \phi_2, \ldots, \phi_N) \)

Measured in experiments

E.g., 2-Particle Distribution

\[
\frac{d^2N}{d\phi_1d\phi_2} = \mathcal{N} \int_{\phi_3,\phi_4,\ldots,\phi_N} P(\phi_1, \phi_2, \phi_3, \ldots, \phi_N)
\]
\[ \gamma = \langle \cos(\phi_1 + \phi_2 - 2\Psi_{EP}) \rangle = \frac{1}{\mathcal{N}} \int_{\phi_1, \phi_2} \cos(\phi_1 + \phi_2 - 2\Psi_{EP}) \frac{d^2N}{d\phi_1 d\phi_2} \]

\[ \Delta \gamma = \gamma_{+-} - \gamma_{++} \approx a_1^2 \left( \cos \left( \frac{\pi}{2} + \left( -\frac{\pi}{2} \right) \right) - \cos \left( \frac{\pi}{2} + \frac{\pi}{2} \right) \right) = 2 \langle a_1^2 \rangle \]

(S. Voloshin, hep-ph/0406311)
\[ \gamma_{++/-} = \langle \cos \phi_1 \cos \phi_2 \rangle - \langle \sin \phi_1 \sin \phi_2 \rangle \approx v_1^2 + a_1^2 + (B_{\text{IN}} - B_{\text{OUT}}) \]

The key idea is the cancellation of angle-independent backgrounds, e.g., resonance decays: \( B_{\text{IN}} - B_{\text{OUT}} \)

(Directed flow \( v_1 \) can be eliminated experimentally)

This reduces the backgrounds to only those correlated with global azimuthal asymmetry, i.e., the elliptic flow:

\[ B_{\text{IN}} - B_{\text{OUT}} \sim v_2/N \sim \mathcal{O}(10^{-3}) \]
\[ \Delta \gamma = \gamma_{\text{OS}} - \gamma_{\text{SS}} > 0 \]
and \( \gamma \to 0 \) for \( |\Delta \eta| > 1 \)

But, \( \gamma_{\text{OS}} \approx 0 \)
and \( \Delta \gamma \sim \mathcal{O}(10^{-3}) \)
\[ \delta - \text{Correlator} \]
\[ \delta = \langle \cos(\phi_1 - \phi_2) \rangle = \langle \cos \phi_1 \cos \phi_2 \rangle + \langle \sin \phi_1 \sin \phi_2 \rangle \]

CME: \[ \Delta \delta = \delta_{OS} - \delta_{SS} \approx -2 \langle (a_1)^2 \rangle < 0 \]

Experiments: \[ \Delta \delta^{\text{exp}} > 0 \]

In-Plane and Out-Plane can be separated
\[ \langle \cos \phi_1 \cos \phi_2 \rangle = \frac{1}{2} (\gamma + \delta), \quad \langle \sin \phi_1 \sin \phi_2 \rangle = \frac{1}{2} (-\gamma + \delta) \]

(Bzdak-Koch-Liao, 0912.5050)

Very Tricky and Interesting to Explain Theoretically
LHC '12 (1207.0900) Pb + Pb at $\sqrt{s} = 2.76$ TeV

Similar Pattern is Observed
Non-CME Backgrounds is large

Magnetic Field is Much Smaller in $P + Pb$ than in $Pb + Pb$
A finite multiplicity of particles, $M = N_+ + N_- = 2N$, have self-correlations of $1/N$.

If one particle is selected, it is no longer available in the second selection experimentally, which affects $rac{d^2N}{d\phi_1d\phi_2}$.

In addition, $rac{d^2N}{d\phi_1d\phi_2}$ in general has genuine charge-dependent 2-particle correlations.

These effects combined is described by the Balance Function of "Local Charge Conservation" (Pratt-Schlichting, 1005.5341).
A Toy Example of Local Charge Conservation

Neutral pairs of $\pi^{\pm}$ at $\phi = 0, \pi/2, \pi, 3\pi/2$ with elliptic flow $v_2$

\[
\langle \cos(2\phi) \rangle = \frac{M}{4}(1 + v_2)/(M/2) - \frac{M}{4}(1 - v_2)/(M/2) = v_2
\]

\[
\gamma_{++} = \frac{M}{4}(1 + v_2)/(M/2)(-1/(M/2 - 1)) + \frac{M}{4}(1 - v_2)/(M/2)(1/(M/2 - 1)) = -\frac{2v_2}{M}
\]

\[
\gamma_{+-} = 0
\]

\[
\Delta \gamma = \frac{2v_2}{M}
\]
Sum Rules

\[ \Delta \gamma = \frac{2v_2}{M} + \frac{1}{2} \langle d_y^2 - d_x^2 \rangle, \quad \Delta \delta = \frac{2}{M} - \frac{1}{2} \langle d_y^2 + d_x^2 \rangle \]

From Self-Correlations

From CME and Finite size of the 2-particle Balance Function

\[ d_y = \frac{1}{N} \left( \sum_{i=1}^{N} \sin \phi_i^+ - \sum_{i=1}^{N} \sin \phi_i^- \right), \quad d_x = \frac{1}{N} \left( \sum_{i=1}^{N} \cos \phi_i^+ - \sum_{i=1}^{N} \cos \phi_i^- \right) \]

Event-by-Event Mean Charge Dipole
The Balance Function

\[ \frac{d^2N}{d\phi^+ d\phi^-} - \frac{d^2N}{d\phi^+ d\phi^+} = \frac{dN}{d\phi} \cdot B(\phi, \Delta \phi) \]

\(\Delta \gamma^{\text{exp}}\) may be explained by Local Charge Conservation
The $H$ - Observable

(Bzdak-Koch-Liao, 1207.7327)

This motivates $\Delta \gamma = \kappa v_2 B - H$, \hspace{0.5cm} $\Delta \delta = B + H$, with the backgrounds $B \sim 1/N$

\[
H = \frac{\kappa v_2 \Delta \delta - \Delta \gamma}{1 + \kappa v_2}
\]

$\kappa \sim 1$
Experimental Efforts

Beam Energy Scan in RHIC - S. Voloshin, G. Wang, 0907.2213, 1210.5498
Event Shape Eng. U+U in RHIC - Chatterjee-P. Tribedy, 1412.5103
Pb+Pb in LHC - 1207.0900, 2005.14640
pA vs AA in LHC - W. Li, 1610.00263
New Observables, e.g., Pair-Invariant Mass - F. Wang et al., 1705.05410
R-correlator - R. Lacey, et al. 1710.01717
Signed Balance Function - A. Tang, 1903.04622
Isobar collisions of Zr and Ru in RHIC (2018) (New Result !) - 2109.00131

Theoretical Efforts

Chiral Magneto-Hydrodynamics - Y. Yin, Gursoy-Kharzeev-Rajagopal
Beam Energy Scan Theory Collaboration (BEST) - 2108.13867
Isobar Collisions: $^{96}_{40}\text{Zr}$ and $^{96}_{44}\text{Ru}$

(S. Voloshin, 0907.2213)

CME signal scales with $(eB)^2$: $R = \frac{\text{CME(Ru)}}{\text{CME(Zr)}} \sim \left(\frac{44}{40}\right)^2 \approx 1.2$
STAR '21 Result : Predefined Observables

Predefined observables, assuming identical backgrounds for Zr and Ru

\[ R^{\text{exp}} < 1 \]

Baseline for the backgrounds \( \sim v_2/N \)

\[ R^{\text{base}} = \frac{N_{\text{Zr}}}{N_{\text{Ru}}} < 1 \quad \text{and} \quad \frac{R^{\text{exp}}}{R^{\text{base}}} > 1 \]

CME signal may exist !

(Kharzeev-Liao-Shi, 2205.00120)
Chiral Magnetic Wave (CMW)

\( \partial_t n_{R/L} + \nabla \cdot \mathbf{J}_{R/L} = \partial_t n_{R/L} \pm \frac{e}{4\pi^2\chi} \mathbf{B} \cdot \nabla n_{R/L} = (\partial_t + \mathbf{v}_\chi \cdot \nabla)n_{R/L} = 0 \)

\( \mathbf{J}_{R/L} = \pm \frac{e^2}{4\pi^2 \mu_{R/L}} \mathbf{B} \approx \pm \frac{e}{4\pi^2\chi} n_{R/L} \mathbf{B} \quad \chi = \text{charge susceptibility} \)

Hydrodynamic propagating modes of chiral charges with velocity

\( \mathbf{v}_\chi = \pm \frac{1}{4\pi^2\chi} \mathbf{B} \)

Similar to sound waves
Experimental Signature of CMW

\[ n_{ch} > 0 \]
\[ n_L > 0 \]
\[ n_R > 0 \]

\[ \vec{B} \]

Quadrupole Moment of Charges

(Gorbar-Miransky-Shovkovy, 1101.4954
Burnier-Kharzeev-Liao-Yee, 1103.1307)

Charge Dependent Elliptic Flows

\[ v_2(\pi^-) - v_2(\pi^+) = rA_{ch} , \quad A_{ch} \equiv \left( \frac{N_{\pi^+} - N_{\pi^-}}{N_{\pi^+} + N_{\pi^-}} \right) \]

Slope Parameter \( r > 0 \)
Slope Parameter in RHIC and LHC

Agrees with the CMW Predictions
(but, there are backgrounds effects, too)

STAR, 1504.02175
LHC, 1512.05739
What we did not discuss

- Chiral Hydrodynamics - D. Son-P. Surowka, 0906.5044
- Collective Modes - I. Shovkovy, 1807.07608, 2111.11416
- Chiral Plasma Instability and Chiral Turbulence - N. Yamamoto, 1302.2125, 1603.08864
- CME in Dirac/Weyl semi-metals - D.Kharzeev, Q. Li, et al., 1412.6543, K. Landsteiner, 1306.4932, 1610.04413
Related Presentations

Tuesday, June 14

• Parallel 1, 4:30 pm, by Wenya Wu
• Parallel 4, 4:00 pm, by Roy Lacey
• Parallel 4, 4:20 pm, by Yicheng Feng

Thursday, June 16

• Plenary, 9:05 am, by Evan Finch