New Physical Phenomena Associated with Chiral Fermions/Chirality in Heavy-Ion Collisions

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Outline

• Chirality, anomalies, and chiral magnetic effect (CME)

• The isobar collisions for CME search

• Realistic evolution of magnetic field

• Deep-learning assisted CME search

• Summary
Chirality

- A common concept

- For massless fermions

\[ J_\mu^L = \bar{\psi}_L \gamma^\mu \psi_L \]
\[ J_\mu^R = \bar{\psi}_R \gamma^\mu \psi_R \]

- Classically

\[ \partial_\mu J_\nu^\mu = 0 = \partial_\mu J_\sigma^\mu \quad \text{with} \quad J_\nu^\mu = J_\nu^R \pm J_\nu^L \]
Chiral anomalies

- Quantumly, in external $U(1)$ gauge field and background geometry

$$\nabla_\mu J_A^\mu = -\frac{e^2}{8\pi^2} F_{\mu\nu} \tilde{F}^{\mu\nu} - \frac{1}{192\pi^2} R^\alpha_{\beta\mu\nu} \tilde{R}_\alpha^{\beta\mu\nu} + \frac{\Lambda^2}{16\pi^2} (2\tilde{R}_{\mu\nu}^{\mu\nu} - T_\lambda^{\mu\nu} \tilde{T}_\mu^{\lambda\nu})$$

ABJ anomaly  Gravitational anomaly  Nieh-Yan anomaly
Chiral anomalies

- Quantumly, in external $U(1)$ gauge field and background geometry

$$\nabla_\mu J^\mu_A = -\frac{e^2}{8\pi^2} F_{\mu \nu} \tilde{F}^{\mu \nu} - \frac{1}{192\pi^2} R^\alpha_{\beta \mu \nu} \tilde{R}^{\beta \mu \nu} + \frac{\Lambda^2}{16\pi^2} \left( 2 \tilde{R}^{\mu \nu} - T_\lambda^{\mu \nu} \tilde{T}_\lambda^{\mu \nu} \right)$$

ABJ anomaly  Gravitational anomaly  Nieh-Yan anomaly

- Macroscopic anomalous chiral transport phenomena

  - Chiral magnetic effect (CME): Axial imbalance + B field = vector current (Kharzeev 2004; Kharzeev-Fukushima-McLerran-Warringa 2007; ...)
  - Chiral separation effect (CSE): vector imbalance + B field = axial current (Son-Zhitnitsky 2004; ...)
  - Chiral vortical effect (CVE): Temperature + vorticity = vector/axial current (Erdmenger et al 2008; Banerjee et al 2008; Torabian-Yee 2009; ...)
  - Chiral torsional effect (CTE): Temperature + torsion = vector/axial current (Khaidukov-Zubkov 2018; Imaki-Yamamoto 2019; Nissinen-Volovik 2019; ...)
  - ... ...
Chiral anomalies

- Quantumly, in external $U(1)$ gauge field and background geometry

\[ \nabla_\mu J_A^\mu = -\frac{e^2}{8\pi^2} F_{\mu\nu} \tilde{F}^{\mu\nu} - \frac{1}{192\pi^2} R^\alpha_{\beta\mu\nu} \tilde{R}_\alpha^{\beta\mu\nu} + \frac{\Lambda^2}{16\pi^2} \left( 2 \tilde{R}_{\mu\nu}^{\mu\nu} - T_\lambda^{\mu\nu} \tilde{T}_\mu^{\nu\lambda} \right) \]

- ABJ anomaly
- Gravitational anomaly
- Nieh-Yan anomaly

- Macroscopic anomalous chiral transport phenomena

\[ 10^{-10} K \quad 1 - 10^2 K \quad 10^{10} K \quad 10^{12} K \]

Temperature

- Cold atomic gases
- Supernovae
- Weyl/Dirac semimetals
- Heavy-ion collisions
Probe QCD topological sector

QCD chiral anomaly

QED chiral anomaly

Chiral magnetic/vortical effects

Observable: e.g. $\gamma$-correlator

(Voloshin 2004)

Initial state topological fluctuations

(STAR 2009, 2014)
Difficulties in observing CME

- Small signal versus big elliptic-flow related backgrounds

- Isobar collisions: fix $v_2$ but vary B field

Averaged CME fraction = $(8 \pm 4 \pm 8)\%$

Exp. talk by Abdelrahman 10:30AM

One eccentric geometry gives two outcomes, B field and $v_2$. Difficult to disentangle them.
Difficulties in observing CME

- Isobar collisions: fix $v_2$ but vary B field

Relative difference $R = 2(R_u - Z_r)/(R_u + Z_r)$

Sizable $R$ for $B$: $R_{BSq} \sim 10 - 20\%$

Small $R$ for eccentricity: $R_{\epsilon_2} < 2\%$

- Signal versus background level

If background level = 67\%, 400M events give 5\$ signal

RHIC first run 2018 produces 3B events.

If bg level = 88\%, signal significance = 5\$

If bg level = 93\%, signal significance = 3\$

(Deng-XGH-Ma-Wang 2016, 2018)
Evolution of B field
Difficulties in quantifying CME

• Quantifying CME in theory: hydrodynamic and transport models

(AVFD: Liao et al. 2018, 2019)

• Main theoretical uncertainties:
  Initial axial charges

(AMPT: Ma-Zhang 2011; Deng-XGH-Ma-Wang 2018)

Realistic evolution of B field

(Early attempt: Muller-Schlichting-Sharma 2016)

In vacuum: moving charges
In conductor: Faraday effect
Realistic evolution of B field

- If quark-gluon matter is insulating (Deng-XGH 2012; XGH 2015; and many others)

Well fitted by

\[
\langle eB_y(t) \rangle \approx \frac{\langle eB_y(0) \rangle}{(1 + t^2/t_B^2)^{3/2}}
\]

Life time of B field

\[
t_B \approx R_A/(\gamma v_z) \approx \frac{2m_N}{\sqrt{s}} R_A
\]

- In hydro stage: couple Maxwell with hydro equations

\[\text{ECHO-QGP} \quad \text{(Inghirami et al. 2016)} \quad \text{AVFD} \quad \text{(Huang-Kharzeev-Liao-Shi-She 2020)}\]
Realistic evolution of B field

• But what is the pre-hydro evolution and the IC for hydro?

• We study the pre-hydro evolution for $t \sim Q_s^{-1} - \tau_0$ by solving coupled Maxwell and Boltzmann equations

$$\begin{align*}
[p^\mu \partial_\mu + e Q_a p_\mu F^{\mu \nu} \partial_\nu] f_a(t, x, p) &= \mathcal{C}[f_a] & a = q, \bar{q}, g \\
\partial_\mu F^{\mu \nu} &= j^\nu \\
j^\mu &= e \sum_F Q_F S_F \int \frac{d^3p}{(2\pi)^3 E_p} p^\mu \left( f^F_q - f^F_{\bar{q}} \right)
\end{align*}$$

Initial condition for EM field: moving colliding nuclei in vacuum

Initial condition for q and g: CGC inspired distribution (Blaizot-Wu-Yan 2014)
Realistic evolution of B field

- For the collision kernel: 2-2 processes

\[ C[f^a_p] = \frac{1}{2E_p\nu_a} \sum_{b,c,d} s_{cd} \int \frac{d^3p'}{(2\pi)^3 2E_{p'}} \frac{d^3k}{(2\pi)^3 2E_k} \frac{d^3k'}{(2\pi)^3 2E_{k'}} \times (2\pi)^4 \delta^{(4)}(P + P' - K - K') |M_{cd}^{ab}|^2 \times [f^c_k f^d_{k'} (1 + \epsilon_a f^a_p) (1 + \epsilon_b f^b_{p'}) - f^a_p f^b_{p'} (1 + \epsilon_c f^c_k) (1 + \epsilon_d f^d_{k'})] \]

\[ |M|^2 \ni gg \leftrightarrow q\bar{q}, \ gq \leftrightarrow qg, \ g\bar{q} \leftrightarrow g\bar{q}, \ gg \leftrightarrow gg \]

Under 2-2 scattering, the system evolves towards hydrodynamization

(Yan-XGH to appear)
Realistic evolution of B field

• The B field (In case of Bjorken longitudinal expansion)

• Longitudinal distribution of B field

Background = B field by moving nucleus

(Roy-Pu-Rezzola-Rischke 2015)
(Inghirami et al. 2016)
(Yan-XGH to appear)
Deep-learning and CME search
Deep-learning assisted CME search

- Recall the main challenge of CME search: Find a way to disentangle signal and elliptic-flow backgrounds
- Any designed observable is based on hadron distribution in momentum space.

Why don’t we just look at the distribution itself?

Cat

Dog

CME?

1, yes

0, no
Deep-learning assisted CME search

• We train a machine to recognize initial charge separation (mimicking CME): Supervised learning
• We use Convolutional Neural Network (CNN): good at pattern recognition of figures.

In our case: input = $\pi^\pm$ with $|Y| < 1$ projected on $(p_x, p_y)$-plane generated by AMPT

AMPT simulation (with or without initial charge separation)
Deep-learning assisted CME search

- We use 50000 events for training for blue each box

<table>
<thead>
<tr>
<th>$f$</th>
<th>$\sqrt{s_{NN}}$ (GeV)</th>
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<tbody>
<tr>
<td></td>
<td>11.5</td>
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<tr>
<td>0-10</td>
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<td>10-20</td>
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$f = 0$: No CME, Label ‘0’

$f = 5\%$ and $10\%$: With CME, Label ‘1’
Deep-learning assisted CME search

• **Test:** very robust. The machine learns key feature of charge separation. Insensitive to centrality and energy.

<table>
<thead>
<tr>
<th>CNN</th>
<th>0+5%</th>
<th>0+10%</th>
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<tbody>
<tr>
<td>Accuracy (Under training cond.)</td>
<td>78.47%</td>
<td>93.38%</td>
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(Zhao-Zhou-XGH to appear)
Deep-learning assisted CME search

- **Test:** very robust. The machine learns key feature of charge separation. Insensitive to centrality and energy.

- **Output:** accuracy $P_1$
- $P_1$=the possibility of having CS, indicating robustness

![Graph showing Test Accuracy vs Charge Separation rate](image)

$\sqrt{S_{NN}} = 39\text{GeV}$

(Zhao-Zhou-XGH to appear)
Deep-learning assisted CME search

- Test: Comparing to $\gamma$-correlator with 10% CS

$\gamma_{same} = \left\{ \cos \left( \phi_{\alpha}^{(\pm)} + \phi_{\beta}^{(\pm)} - 2\Phi_R \right) \right\}$

$\gamma_{opp} = \left\{ \cos \left( \phi_{\alpha}^{(\pm)} + \phi_{\beta}^{(\pm)} - 2\Phi_R \right) \right\}$

$\Delta \gamma = \gamma_{opp} - \gamma_{same}$

$R_\gamma = \frac{|\Delta \gamma(1) - \Delta \gamma(0)|}{|\Delta \gamma(1)| + |\Delta \gamma(0)|}$

(Zhao-Zhou-XGH to appear)
Deep-learning assisted CME search

- Using the machine trained by AuAu data to test isobar collisions

\[ {}^{96}_{44}\text{Ru} + {}^{96}_{44}\text{Ru} \text{ with CS } f = 11\% \text{ and } \]
\[ {}^{96}_{40}\text{Zr} + {}^{96}_{40}\text{Zr} \text{ with CS } f = 10\% \]

(Zhao-Zhou-XGH to appear)
Summary
Summary

• We study the pre-hydro evolution of B field, see the Faraday retaining effect for B field. This result may used as initial condition of hydro computation of B field.

• We train a CNN that can recognize the initial charge separation pattern (mimicking CME). The machine behaves robust against centrality, energy, and colliding systems.

Thank you!
Deep-learning assisted CME search

- Recall the main challenge of CME search: Find a way to disentangle signal and elliptic-flow backgrounds.
- Any designed observable is based on hadron distribution in momentum space.

Why don’t we just look at the distribution itself?