Search for Chiral Magnetic Effect in U+U, Au+Au and p+Au collisions

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Motivation: Separation of flow and CME

CME: QCD anomaly driven chirality imbalance leads to current along B-field.

Motivation: Separation of flow and CME

We observe from Fig. 1, that the CME ultimately leads to the formation of a chiral magnetic structure of the vector charge density at the edges of the sphaleron, resulting in a dipole-like current in coordinate space. Conservation of the vector current induces an axial current, at the same time the chiral magnetic imbalance of axial charge in Fig. 1.

The distribution of axial and vector charges at times over time electric charge accumulates with a similar profile. If not stated otherwise, we use a lattice spacing of \( 1 \) fm/c and the magnetic field strengths considered in this work is \( \mu_R \) corresponds to \( 64 \) lattice. The magnetic screening length (see e.g. [13, 43, 44]) a constant version to physical units can be achieved by assigning a cohesion constant \( (\mu_R^2 \Psi) \) with the sphaleron induced source term given as a function of the form \([2]\).

The dynamics of axial and vector charges is described in terms of anomalous hydrodynamics in a straightforward manner, which allows us to compare the results of our microscopic simulations with a macroscopic description within the framework of anomalous hydrodynamics. The emergence of such a collective excitation constant of the form \([18, 46]\)

\[ C_{112} = \langle \cos(\phi_1 + \phi_2 - 2\phi_3) \rangle \]

LPV correlator: \( \gamma^{a,b} \sim \langle \cos((\phi^a_1 + \phi^b_2 - 2\phi_3)) \rangle \), \( v_2\{2\} \), \( v_2\{2\}^2 = \langle \cos(2(\phi_1 - \phi_2)) \rangle \)

Goal: Search for signals of CME & suppress flow driven background

Observables:

Voloshin, PRC 70 (2004) 057901

Muller, Schlichting, Sharma, PRL 117 142301 (2016)
Mace, Mueller, Schlichting, Sharma PRD 95, 036023 (2017)
Why background removal is difficult?

\[ Y(Y)_{\text{max}} = \langle B^2 \cos(2(\Psi_B - \Psi_2)) \rangle \]

\[ Y = v_2\{2\} \]

\[ (\gamma^S_\text{OS} - \gamma^S_\text{SS})_{\text{Background}} \approx \frac{v_2\{2\}^2}{N} \]

\[ \gamma^{a,b} \sim \frac{\langle \cos((\phi_1^a + \phi_2^b - 2\phi_3)) \rangle}{v_2\{2\}} \]

The centrality dependence of B-field and flow is similar →

Attempts to reduce flow also reduces B-field

Disentangling the effects driven by B-field and flow is challenging
Signal & Backgrounds of charge separation

**Background**

- HBT, Coulomb
- Flowing resonance
- Charge conservation
- Momentum conservation

**Signal**

- Magnetic field

Possible strategy: look for $\Delta \gamma \rightarrow 0$, $v_2 \neq 0$

\[ \gamma^{a,b} = \langle \cos(\phi_1^a + \phi_2^b - 2\Psi_2) \rangle \]

Charge separation (central-events)


Jet-fragmentation

P.Tribedy, QCD chirality workshop, UCLA, 2017
STAR Detector

Time-Projection Chamber (used for this analysis)

Data Set:
- U+U 193 GeV (2012),
- Au+Au 200 GeV (2011),

Acceptance: \( 0 < \phi < 2\pi, \quad |\eta| < 1, \quad p_T > 0.2 \text{ GeV/c} \)

Centrality:
- Time Projection Chamber
- Zero Degree Calorimeter

Observables:

Three particle correlator:
\[ C_{112} = \langle \cos(\phi_1 + \phi_2 - 2\phi_3) \rangle \]

LPV correlator:
\[ \gamma^{a,b} \sim \frac{\langle \cos((\phi_1^a + \phi_2^b - 2\phi_3)) \rangle}{v_2\{2\}}, \quad v_2\{2\}^2 = \langle \cos(2(\phi_1 - \phi_2)) \rangle \]

Voloshin, PRC 70 (2004) 057901
Central and Ultra-central Collisions

Results shown at the last QCD chirality meeting

Projected B-field vs $\varepsilon_2$ can provide a natural explanation to the data

More theory inputs needed to see if a background model can explain data
A new approach to reduce background

Search of early time charge separation → should be long-range in $\Delta \eta$

Short-range limit: $\Delta \phi \to 0, \Delta \eta \to 0 : C_{112} = \langle \cos(\phi_1(\eta_1) + \phi_2(\eta_2) - 2\phi_3) \rangle \geq 0$

\[
C_{112}(\Delta \eta_{12}) = A_{SR}^+ e^{-\frac{(\Delta \eta)^2}{2\sigma_{SR}^2}} - A_{IR}^- e^{-\frac{(\Delta \eta)^2}{2\sigma_{IR}^2}} + A_{LR}^\text{Pedestal}
\]

Short-range-positive Residual Pedestal
Comparison between A+A centralities

Very different trend between central and peripheral events
Centrality dependence of charge separation

Charge separation: \( \gamma^{a,b} \sim \frac{\cos((\phi_1^a + \phi_2^b - 2\phi_3))}{v_2}\{2\} \) \( \rightarrow \Delta \gamma = \gamma^{OS} - \gamma^{SS} \)

After short-range-positive subtraction, \( \Delta \gamma \rightarrow 0 \) for small & large \( N_{\text{part}} \)

Separation of components
Strength: most efficient peripheral events
Limitations: partial removal in central events

Compare two systems/Isobars?
Comparison between A+A and p+A

Same-sign

Opposite-sign

STAR preliminary

p+Au data are consistent with peripheral U+U

P.Tribedy, QCD chirality workshop, UCLA, 2017
Comparison between U+U and p+Au

Short-range-positive

- 30-40% U+U 200 GeV
- 70-80% U+U 200 GeV
- 0-100% p+Au 200 GeV

Central
A+A

Peripheral
A+A

Min-bias
p+A

Residual

- 30-40% U+U 193 GeV
- 70-80% U+U 193 GeV
- 0-100% p+Au 200 GeV

p+A & peripheral A+A → dominated by short-range correlations
Summary of results in A+A and p+A

Data (short-range-positive subtracted)

Projecting B-field in A+A

Ultra-Central A+A

Short-range-positive component subtracted charge separation vanishes when projected B-field is zero but v_2 is still non-zero (Naive background model can’t explain this)
Summary of results in A+A and p+A

Data (short-range-positive subtracted)

<table>
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<tr>
<th>Δη_{12}</th>
<th>0-1% U+U 193 GeV</th>
<th>70-80% U+U 193 GeV</th>
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<td>0</td>
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<td>3.6</td>
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<tr>
<td>4</td>
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</table>

Projected B-field in A+A

\[ Y = \langle B^2 \cos(2(\Psi_B - \Psi_2)) \rangle \]

<table>
<thead>
<tr>
<th>N_{part}</th>
<th>0</th>
<th>100</th>
<th>200</th>
<th>300</th>
<th>400</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y/\langle Y \rangle_{\text{max}}</td>
<td>1.2</td>
<td>0.8</td>
<td>0.4</td>
<td>0.2</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Short-range-positive component subtracted charge separation vanishes when projected B-field is zero but \( v_2 \) is still non-zero (Naive background model can’t explain this)
Components of LPV correlator

\[(\gamma_{\text{OS}} - \gamma_{\text{SS}}) \times \text{N}_{\text{part}}\]

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Projected B-field in A+A

\[Y = \langle B^2 \cos(2(\Psi - \Psi_2)) \rangle\]

\[Y = v_2 \{2\}\]

U+U 193 GeV

Data (short-range-positive subtracted)

Short-range-positive component subtracted charge separation vanishes when projected B-field is zero but \(v_2\) is still non-zero (Naive background model can’t explain this)
Summary of results in A+A and p+A

Data (short-range-positive subtracted)

Projected B-field in A+A

Short-range-positive component subtracted charge separation vanishes when projected B-field is zero but $v_2$ is still non-zero (Naive background model can’t explain this)
Outlook for isobar collisions at RHIC

Idea is to change B-field without changing background

$$^{96}_{44}\text{Ru} + ^{96}_{44}\text{Ru} \quad \sqrt{s} = 200 \text{ GeV} \quad ^{96}_{40}\text{Zr} + ^{96}_{40}\text{Zr}$$

Different B-field with same flow background is expected

1.2 B events can provide about 5σ confidence of signal/bkg

Gang Wang, QCD Chirality workshop ‘2016,
Deng et al PRC 94, 041901 (2016),
Skokov et al, 1608.00982
What else can be done?

**Isobars**

Different B-field with same flow background is expected

- Zr\(^{96}\) + Zr\(^{96}\)
- Ru\(^{96}\) + Ru\(^{96}\)

**Au+Au, U+U**

Different B-field & different flow background is expected

- Au\(^{197}\) + Au\(^{197}\)
- U\(^{238}\) + U\(^{238}\)

Single (b=0) collision in IP-Glasma model,
Ru, Zr parameters: Deng et al PRC 94,041901 (2016)

**Change in Z by 13**

Precise flow data exists

\[
\Delta \gamma_{\text{Background}} = (\gamma^{OS} - \gamma^{SS})_{\text{Background}} 
\approx \frac{v_2\{2\}}{N}
\]

P.Tribedy, QCD chirality workshop, UCLA, 2017
At the same $N_{\text{part}}$ multiplicity $dN/d\eta$ per participant is similar $v_2\{2\}$ measurement with very small uncertainties available.

Background expectation is under control:

$$\Delta \gamma_{\text{Background}} \approx \frac{v_2\{2\}}{N}$$
Projected B-field differs in central collisions

One needs to take care of shape difference between Au+Au & U+U

At same \( N_{\text{part}} \) projected B-field differs when scaled by \( \varepsilon_2 \) or \( v_2 \)

Larger B-field per eccentricity in U+U than Au+Au at large \( N_{\text{part}} \)

Motivation: Qualitatively similar scenario as isobar collisions
Perform three component fit to remove fragmentation, HBT-like peak

\[ C_{112}(\Delta \eta_{12}) = A_{SR}^+ e^{-(\Delta \eta)^2/2\sigma_{SR}^2} - A_{IR}^- e^{-(\Delta \eta)^2/2\sigma_{IR}^2} + A_{LR} \]

- Short-range-positive
- Residual
- Pedestal
Residual components

\[ \langle \cos(\phi_1 + \phi_2 - 2\phi_3) \rangle \times N_{\text{part}} \]

Relative pseudo-rapidity dependence looks similar
Short range-positive component

No strong system dependence for short-range-positive component is observed.
Residual components in two systems

\[ \Delta \gamma \times N_{\text{part}} \]

*U+U 193 GeV*

- Au+Au (Residual)
- U+U (Residual)

**STAR preliminary**

\[ \Delta \gamma \times N_{\text{part}} / v_2 \]

- Au+Au (Residual)
- U+U (Residual)

**STAR preliminary**

**Au+Au is lower than U+U at large \( N_{\text{part}} \)**

\[ \Delta \gamma_{\text{Background}} \approx \frac{v_2 \{2\}}{N} \]

In a pure background scenario this plot should be flat & universal

System dependence \( \rightarrow \) not explained by naive background model
Summary

- Ultra-central U+U and Au+Au show $\Delta \gamma \sim 0$, $v_2 \neq 0$

  Short-range-positive component ($A_{SR}$)

  subtracted charge separation vanishes in central & peripheral A+A and in p+A collisions

- Comparison between Au+Au and U+U show difference in central events at same $N_{\text{part}}$

Several similarities of charge separation with projected B-field is observed in contrast to naive background ($\sim v_2/N$) expectation. Theoretical inputs needed to see if sophisticated background model calculations can explain these observations.

Future Isobar collisions at RHIC will provide more stringent test to disentangle background vs B-field driven charge separation.
Backup
Signal and background of CME

If B-field dominates

If Background dominates

Voloshin PRC 70 (2004) 057901,
Schlichting, Pratt, PRC 83 014913 (2011),
Wang PRC 81 064902 (2010),
Bzdak, Koch, Liao PRC 83 014905 (2011)

Chatterjee, Tribedy
PRC 92, 011902 (2015)