Measurements of the Chiral Magnetic Effect with Background Isolation in 200 GeV Au+Au Collisions at STAR

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Outline

- Chiral Magnetic Effect (CME)
- RHIC-STAR experiment
- Background issue
- Invariant mass dep. of the $\Delta \gamma$ correlator
- $\Delta \gamma$ with respect to $\Psi_{RP}$ (ZDC) and $\Psi_{PP}$ (TPC)
- Summary

$\Psi_{RP}$: reaction plane; $\Psi_{PP}$: participant plane

Another method, poster #593 by Niseem Magdy (for STAR)
Chiral Magnetic Effect (CME)

Voloshin, PRC 70, 057901 (2004)

Gluon configuration with non-zero topological charge \( Q_w \) converts left (right)-handed fermions to right (left)-handed fermions, generating electric current along B direction and leading to electric charge separation.

Experimentally, \( \gamma = \cos(\phi_\alpha + \phi_\beta - 2\psi_{RP}) \) used to search for the CME.
The STAR detector

- **Time Projection Chamber**  \((\phi=0-2\pi, |\eta|<1)\)
  - Tracking - momentum
  - Ionization energy loss - dE/dx (particle identification)

- **Time Of Flight detector**  \((\phi=0-2\pi, |\eta|<0.9)\)
  - Timing resolution <100ps - PID improvement

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Background issue

STAR, PRL 103,251601 (2009); PRC 81,54908 (2010); PRC 88,64911 (2013)

$\phi_\alpha$, $\phi_\beta$, $\phi_c$ are the azimuthal angles of the charged particles measure by STAR TPC

- $\Delta \gamma = \gamma_{\text{OS}} - \gamma_{\text{SS}}$ correlator consistent with CME expectation
- Recent measurements of charge correlations suggest dominant, if not all, background contribution
- What is the background?
Resonance decay background

- Resonance background: resonance decay + $v_2 \rightarrow$ CME-like $\Delta\gamma$
- Can we remove/isolate the background?
- Exploiting invariant mass dependence of $\Delta\gamma$
- $\Delta\gamma$ with respect to $\Psi_{RP}$ and $\Psi_{PP}$

\[ \langle \cos(\phi_\alpha + \phi_\beta - 2\psi_{RP}) \rangle \]
\[ = \langle \cos(\phi_\alpha + \phi_\beta - 2\phi_{reso.} + 2\phi_{reso.} - 2\psi_{RP}) \rangle \]
\[ \approx \langle \cos(\phi_\alpha + \phi_\beta - 2\phi_{reso.}) \rangle \times v_{2, reso} \]

**FIG. 1.** (a) Minimum Bias $p+p$ and (b) Peripheral $Au+Au$, $0.6 \leq p_T < 0.8$ GeV/c. 

**FIG. 2.** [(a), (b)] Simulation of $\Delta\gamma$ distribution and $v_2$ for $\pi^\pm$ from MC simulation and STAR $h^\pm$.
Identify resonance Bkg by $m_{\text{inv}}(\pi^+\pi^-)$

Full TPC acc. (|$\eta$|<1), pion PID by TOF

$\gamma = \cos(\phi_\alpha + \phi_\beta - 2\phi_c) / v_{2x}\{2\}$

- Systematic uncertainty currently estimated by run differences and different ways of combining runs (combine the $\Delta\gamma$ first or the fractions directly)

- Data show resonance structure in $\Delta\gamma$ as function of invariant mass ($m_{\text{inv}}$)
- At high $m_{\text{inv}} > 1.5$ GeV/c$^2$, $\Delta\gamma$ is $(5\pm2\pm4)$% of the inclusive $\Delta\gamma$ in 200 GeV Au+Au 20-50%

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Bkg shape by event shape engineering

STAR preliminary

run16 Au+Au $\sqrt{s_{NN}} = 200$ GeV

$\pi^\pm p_T$: 0.2-0.8 GeV/c

$r = (N_{OS} - N_{SS}) / N_{OS}$

20-50%

- A: large 50% $q_2$
- B: small 50% $q_2$

0-100% $q_2$

- A - B

$\Delta \gamma(m) = r(m) \cdot \cos(\alpha + \beta - 2\phi_{reso.}) \cdot v_{2,reso.} + \text{CME}$

Bkg $\Delta \gamma$ mass shape

ESE select events with diff. $v_2$ by $q_2$ class (A, B)

Bkg $\Delta \gamma$ mass shape: $\Delta \gamma_A - \Delta \gamma_B$

CME the same for events from different $q_2$ classes

Fit $\Delta \gamma = k \cdot (\Delta \gamma_A - \Delta \gamma_B) + \text{CME}$

Fit range $m_{inv}$ from 0.4 to 1.5 GeV/c$^2$

- TPC sub-event, one side for ESE (other side for ref.), pion PID by TPC dE/dx
- Obtain the Bkg $\Delta \gamma m_{inv}$ shape by event shape engineering (ESE)
Bkg shape by event shape engineering

\[ \gamma = \cos(\phi_\alpha + \phi_\beta - 2\phi_c) / \nu_{2,c} \{2\} \]

\[ \bar{q}_2 = \frac{1}{N} \sum (\cos 2\phi, \sin 2\phi) \]

Bkg \( \Delta \gamma \) mass shape: \( \Delta \gamma_A - \Delta \gamma_B \)

To properly handle errors, fit \( \Delta \gamma_A \) vs. \( \Delta \gamma_B \) with

\[ \Delta \gamma_A = b^* \Delta \gamma_B + (1-b)^* \text{CME} \]

- TPC sub-event, one side for ESE (other side for ref.), pion PID by TPC \( \text{dE/dx} \)
- Obtain the Bkg \( \Delta \gamma \) \( m_{\text{inv}} \) shape by event shape engineering (ESE)

\( \sum \) run16 Au+Au \( \sqrt{s_{\text{NN}}} = 200 \text{ GeV} \)

\( \pi^\pm p_T: 0.2-0.8 \text{ GeV/c} \)

\[ r = (N_{\text{os}} - N_{\text{ss}}) / N_{\text{os}} \]

\( 20-50\% \)

- A: large 50\% \( q_2 \)
- B: small 50\% \( q_2 \)

\( 0-100\% \) \( q_2 \)

- solid
- open

Fit range \( m_{\text{inv}} \) from 0.4 to 1.5 GeV/c^2
Bkg + CME fit at low invariant mass

\[ \Delta \gamma_A = b \Delta \gamma_B + (1-b) \times \text{CME} \]

Low mass ESE

\[ m_{\text{inv}} : 0.4-1.5 \text{ GeV/c}^2 \]

\[ \pi^\pm p^{-} : 0.2-0.8 \text{ GeV/c} \]

Bkg subtracted \( \Delta \gamma \) / inclusive \( \Delta \gamma \)

-30% -20% -10% 0% 10% 20% 30%

\( \Delta \gamma_B \)

\( \Delta \gamma_A \)

\[ A = 0[B + (1-0)][1] \]

- Bkg subtracted \( \Delta \gamma \) / inclusive \( \Delta \gamma \):

(2±4±6)% in 200 GeV 20-50% Au+Au
Use $\Psi_{PP}$ and $\Psi_{RP}$ to solve Bkg and CME

- $\Psi_{PP}$ maximizes flow, $\rightarrow$ flow background
- $\Psi_{RP}$ maximizes the magnetic field (B), $\rightarrow$ CME signal
- $\Psi_{PP}$ and $\Psi_{RP}$ are correlated, but not identical due to geometry fluctuations

$\Delta \gamma \text{ w.r.t. TPC } \Psi_{EP} \text{ (proxy of } \Psi_{PP} \text{) and } \Psi_{ZDC} \text{ (proxy of } \Psi_{RP} \text{)} \text{ contain different fractions of CME and Bkg}$

$\Delta \gamma \{\psi_{TPC}\} = \text{CME}\{\psi_{TPC}\} + \text{Bkg}\{\psi_{TPC}\}$

$\Delta \gamma \{\psi_{ZDC}\} = \text{CME}\{\psi_{ZDC}\} + \text{Bkg}\{\psi_{ZDC}\}$

$\text{CME}\{\psi_{TPC}\} = a \times \text{CME}\{\psi_{ZDC}\}, \text{Bkg}\{\psi_{ZDC}\} = a \times \text{Bkg}\{\psi_{TPC}\}$

$a = v_2\{\psi_{ZDC}\} / v_2\{\psi_{TPC}\}, A = \Delta \gamma \{\psi_{ZDC}\} / \Delta \gamma \{\psi_{TPC}\}$

Both are experimental measurements

$$r = \frac{\text{CME}\{\psi_{ZDC}\}}{\text{Bkg}\{\psi_{TPC}\}} = \frac{\left(\frac{a - 1}{a + 1} \frac{A - 1}{A + 1}\right)}{\left(\frac{a - 1}{a + 1} + \frac{A - 1}{A + 1}\right)} = \frac{A - a}{1 - Aa}$$

$$f_{EP}(\text{CME}) = \frac{\text{CME}\{\psi_{TPC}\}}{\Delta \gamma \{\psi_{TPC}\}} = r / (r + 1 / a) = (A / a - 1) / (1 / a^2 - 1)$$

H.-J. Xu, et al., arXiv:1710.07265
$\Delta \gamma$ with respect to $\Psi_{PP}$ and $\Psi_{RP}$

TPC sub-event (east and west) method to reduce non-flow effects

$\gamma = \cos(\phi_{a}+\phi_{b} - 2\psi)/R, \, v_2 = \cos(2\phi - 2\psi)/R$

$\Psi = \Psi_{PP}$ or $\Psi_{RP}$, $R$ the corresponding resolution

$\Psi_{PP}$ from TPC $\psi_{EP1}$ ($-1<\eta<-0.075$) or $\psi_{EP2}$ ($0.075<\eta<1$)

$\Psi_{RP}$ from combined ZDC $\psi_{ZDC1}$ and $\psi_{ZDC2}$

Poskanzer, Voloshin, PRC 58, 3 (1998); STAR, PRC 86, 054908 (2012)

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Δγ with respect to $\Psi_{PP}$ and $\Psi_{RP}$

nevertheless also look at full TPC acceptance

CME fractions are $(9\pm4\pm7)\%$ and $(12\pm4\pm11)\%$ from TPC sub-event and TPC full-event methods in 200 GeV 20-50% Au+Au collisions, respectively.
Identify resonance Bkg by $\pi\pi$ invariant mass. Observation of resonance structure in $\Delta\gamma$ at $m_{\text{inv}}<1.5$ GeV/c$^2$. Isolate the possible CME from Bkg by invariant mass + ESE. $\Delta\gamma$ with respect to $\Psi_{PP}$ and $\Psi_{RP}$, isolate possible CME from Bkg.

These data-driven estimates indicate that:
possible CME signal is small, within 1-2$\sigma$ from zero.

<table>
<thead>
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<th>Year</th>
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</tr>
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<tbody>
<tr>
<td>Run11</td>
<td>~0.5B</td>
</tr>
<tr>
<td>Run14</td>
<td>~0.8B</td>
</tr>
<tr>
<td>Run16</td>
<td>~1.2B</td>
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Identify resonance Bkg by $\pi\pi$ invariant mass.
Observation of resonance structure in $\Delta\gamma$ at $m_{\text{inv}} < 1.5$ GeV/$c^2$.
Isolate the possible CME from Bkg by invariant mass + ESE.

$\Delta\gamma$ with respect to $\Psi_{PP}$ and $\Psi_{RP}$, isolate possible CME from Bkg

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More Au+Au data (+isobar)
Consider ZDC upgrades for $\Psi_{RP}$

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