Search for the Chiral Magnetic Effect at STAR

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for the STAR Collaboration
Outline

- Motivation
- STAR Experiment
- Chiral Magnetic Effect (CME)
- Summary
- Outlook
What if the vacuum/domain we live in is not a true ground state?

- "false" vacua will topple into lower states
- we may learn from the Micro-Bangs
QCD vacuum transition

- nonzero topological charge
- chirality imbalance (local parity violation)

\[ N_L^f - N_R^f = 2Q_W, \quad Q_W \neq 0 \rightarrow \mu_A \neq 0 \]
Chiral Magnetic Effect (CME): finite chiral charge density induces an electric current along external magnetic field.

\[ j_V = \frac{N_c e}{2\pi^2} \mu_A B \]  \Rightarrow  electric charge separation along \( B \) field

charge separation effect beyond conventional physics background

\[
\frac{dN_{\pm}}{d\phi} \propto 1 + 2a_{\pm} \cdot \sin\left(\phi_{\pm} - \Psi_{RP}\right)
\]

S. Voloshin, PRC 70 (2004) 057901,
A direct measurement of the $P$-odd quantity \( a \) should yield zero.
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\[ \gamma = \left\langle \cos(\phi_\alpha + \phi_\beta - 2\psi_{RP}) \right\rangle \]

\[ = \left[ \langle v_{1,\alpha} v_{1,\beta} \rangle + B_{in} \right] - \left[ \langle a_\alpha a_\beta \rangle + B_{out} \right] \]

Directed flow: expected to be the same for SS and OS

P-even quantity: still sensitive to charge separation
STAR experiment

Relativistic Heavy Ion Collider (RHIC)

Solenoidal Tracker at RHIC (STAR)
Azimuthal anisotropy

\[ E \frac{d^3 N}{d^3 p} = \frac{1}{2\pi} \frac{d^2 N}{p_t dp_t dy} \left( 1 + \sum_{n=1}^{\infty} 2v_n \cos[ n(\varphi - \Psi_{RP})] \right) \]

\[ v_n = \langle \cos[ n(\varphi - \Psi_{RP})] \rangle \]

The estimated reaction plane is called the event plane.

\[ Q_n \cos(n\Psi_n) = Q_x = \sum_i w_i \cos(n\phi_i) \]

\[ Q_n \sin(n\Psi_n) = Q_y = \sum_i w_i \sin(n\phi_i) \]

\[ \Psi_n = \left( \tan^{-1} \frac{Q_y}{Q_x} \right) / n \]
\( \gamma \) at 200 GeV

- \( \gamma_{os} \gtrsim \gamma_{ss} \), consistent with CME expectation: both AuAu and CuCu
- Not explained by known event generators


HIJING: solid (Au+Au), dashed (Cu+Cu)
1st-order EP

- Consistent between different years (2004 and 2007)
- Confirmed with 1st-order EP (from spectator neutron $v_1$)

200 GeV Au+Au

\[ \langle\cos(\phi_{\alpha} + \phi_{\beta} - 2\Psi_{RP})\rangle \]
• Prominent correlations exist at small $\Delta p_T$ and $\Delta \eta$
• Probably due to HBT+Coulomb
Modulated sign correlator (msc)

- robust after removing HBT+Coulomb effects with kinematic cuts ($\Delta\eta$ and $\Delta p_T$)
- $\gamma$ weights different azimuthal regions of charge separation differently
- Modify $\gamma$ such that all azimuthal regions are weighted equally
- $\gamma$ is reduced to modulated sign correlator (msc)
- The charge separation signal is confirmed with msc

$$
\langle \cos(\varphi_\alpha + \varphi_\beta - 2\Psi_{RP}) \rangle \\
= \langle \cos(\Delta\varphi_\alpha) \cos(\Delta\varphi_\beta) - \sin(\Delta\varphi_\alpha) \sin(\Delta\varphi_\beta) \rangle \\
= \langle (M_\alpha M_\beta S_\alpha S_\beta)_{IN} \rangle - \langle (M_\alpha M_\beta S_\alpha S_\beta)_{OUT} \rangle \\
msc \equiv \left( \frac{\pi}{4} \right)^2 \left( \langle S_\alpha S_\beta \rangle_{IN} - \langle S_\alpha S_\beta \rangle_{OUT} \right)
$$

Charge-independent background ($\Delta msc$)

\[ msc = \Delta msc + \Delta N \]

\[ \Delta msc = \frac{1}{N_E} \sum_{\Delta Q} \langle N(\Delta Q) \rangle \left[ msc_{IN}(\Delta Q) - msc_{OUT}(\Delta Q) \right] \]

\[ \Delta N = \frac{1}{N_E} \sum_{\Delta Q} \langle msc(\Delta Q) \rangle \left[ N_{IN}(\Delta Q) - N_{OUT}(\Delta Q) \right] \]

- $msc$ was split to study background
- $N_{IN}(\Delta Q)$ stands for the number of events with $\Delta Q$ units of in-plane charge separation, and $msc_{IN}(\Delta Q)$ stands for the $<msc>$ in those events.
- MEVSIM and $-v_2/N$ tell us that the CI bg is likely due to momentum conservation + $v_2$
Correlations of $K^0_S$-hadron correlation consistent with each other: no charge-dependent separation
• Correlations between \(\Lambda\) and \(h^\pm\) also show no charge-dependent separation

• Separation observed for \(h^\pm-h^\pm\) is sensitive to electric charge

• Strange quarks participate in the chiral dynamics in a similar way as \(u/d\)
Beam Energy Scan

At lower beam energies, charge separation starts to diminish.


At lower beam energies, charge separation starts to diminish.
Flow-related background

Against CME expectation, $\delta_{\text{OS}}$ is above $\delta_{\text{SS}}$.

Indicate overwhelming background larger than any possible CME effect.

Try combining information from $\gamma$ and $\delta$ to retrieve the CME contribution, $H$.

\begin{align*}
\gamma & \equiv \langle \cos(\phi_1 + \phi_2 - 2\Psi_{\text{RP}}) \rangle = \kappa v_2 F - H \\
\delta & \equiv \langle \cos(\phi_1 - \phi_2) \rangle = F + H,
\end{align*}
CME contribution

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


- \( \kappa \approx 2 - \frac{v_{2,F}}{v_{2,\Omega}} \): \( F \) and \( \Omega \) denote the full phase space and the finite detector acceptance, respectively.

- CME signal via \( H \) decreases to zero from 19.6 GeV to 7.7 GeV.

- Probable domination of hadronic interactions over partonic ones.

- Need better estimate of \( \kappa \) and better statistics.
A dedicated trigger for events with 0-1% spectator neutrons

With magnetic field suppressed, the charge separation signal (mostly background) disappears, while $v_2$ is still $\sim 2.5\%$

Deformed nuclei: U+U

- Similar signals in U+U
- Use $\gamma_{OS}-\gamma_{SS}$ to quantify the signal
- $N_{part}$ accounts for dilution effects

- A dedicated trigger for events with 0-1% spectator neutrons
- With magnetic field suppressed, the charge separation signal (mostly background) disappears, while $v_2$ is still $\sim 2.5\%$
Summary

• three-point correlator $\gamma$ shows charge separation w.r.t RP
  - signal robust with different EPs (1st- and 2nd-order)
  - robust when suppressing HBT+Coulomb
  - robust with a reduced correlator, msc
  - robust in Au+Au, Cu+Cu, Pb+Pb and U+U
  - robust from 19.6 GeV to 2.76 TeV

• signal of charge separation seems to disappear when
  - one charged particle is replaced with a neutral strange particle
  - the collision energy is down to $\sim$7.7 GeV
  - the magnetic field from spectators is supressed ($v_2$ is still sizable)

• we also learn
  - CI bg mostly comes from momentum conservation+$v_2$
  - flow-related bg could be subtracted via $H$ correlator
Isobars are atoms (nuclides) of different chemical elements that have the same number of nucleons.

For example, $^{96}_{44}$Ruthenium and $^{96}_{40}$Zirconium:
10% difference in B field $\rightarrow$ 20% difference in $\gamma$

<table>
<thead>
<tr>
<th></th>
<th>$^{96}<em>{44}$Ru+$^{96}</em>{44}$Ru</th>
<th>vs</th>
<th>$^{96}<em>{40}$Zr+$^{96}</em>{40}$Zr</th>
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<tbody>
<tr>
<td>Flow</td>
<td>=</td>
<td>vs</td>
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<td>CMW</td>
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<td>CVE</td>
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**Outlook: Cu+Au**

<table>
<thead>
<tr>
<th></th>
<th>( E )</th>
<th>( B )</th>
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<tbody>
<tr>
<td>( J_V )</td>
<td>( \sigma )</td>
<td>( (e/2\pi^2)\mu_A )</td>
</tr>
<tr>
<td>( J_A )</td>
<td>( \propto \sigma \mu_V \mu_A / T^2 )</td>
<td>( (e/2\pi^2)\mu_V )</td>
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**Ohm's Law**

**Chiral Magnetic Effect**

**Chiral Electric Separation Effect**


**Chiral Separation Effect**

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**Suppressed \( \gamma \) signal of charge separation in Cu+Au collisions?**

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**in-plane charge separation**
Backup slides
Particle identification

**TPC** $\sqrt{s_{NN}} = 39$ GeV Au + Au Collisions **TPC+ToF**

\[
\frac{dE}{dx} \text{ (keV/cm)}
\]

\[
p^*q \text{ (GeV/c)}
\]

\[
\pi^-, K^-, p
\]

\[
\frac{1}{\beta}
\]

\[
p^*q \text{ (GeV/c)}
\]

\[
\pi^-, K^-, p
\]

\[
z = \log \left( \frac{(dE/dx)_{\text{meas.}}}{(dE/dx)_{\text{theory}}} \right)
\]

H. Bichsel, NIM A. 562 (2006) 154

\[
m^2 = p^2 \left( \frac{c^2 t^2}{L^2} - 1 \right)
\]

c=velocity of light, 
L= path length

\[
m^2 \text{ (GeV}^2/c^4)
\]

Counts

\[
z_{\pi^-}
\]

\[
z_{K^-}
\]

\[
z_{p^-}
\]

\[
z_{e^-}
\]

\[
z_{K^+}
\]

\[
z_{p^+}
\]

Counts

\[
n^2 \text{ (GeV}^2/c^4)
\]

\[
\text{pbar}
\]
Excellent tracking

The azimuthal angle resolution at STAR is better than 99.9%.
Dilution effect

What do we know about the position $R_n$ after $n$ steps?

$R_n$ follows a Gaussian distribution: mean $= 0$, and \( \text{rms} = \sqrt{n} \)

Our measurement of PV is like $R_n^2$, expected to be $n$.

Compared with going in one fixed direction, where $R_n^2 = n^2$,
the "random-walk" measurement is diluted by a factor \(~ n \sim N_{\text{part}}\).
More on flow-related background

charge conservation/cluster + $v_2$  


In RHIC run2012, STAR took 350M minbias events and 14M central trigger events.

Seemingly correlated!
Can we disentangle the relationship with U+U?
Possible physics background

charge conservation/cluster + $v_2$

\[
\langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle \\
= \langle \cos((\phi_\alpha + \phi_\beta - 2\phi_{res}) + 2(\phi_{res} - \Psi_{RP})) \rangle \\
\approx f_{res} \langle \cos(\phi_\alpha + \phi_\beta - 2\phi_{res}) \rangle \frac{v_{2, res}}{N_{ch}}
\]
Balance function

MC simulation (no radial flow)
- $a_1 = 0, \ n_2 = 5\%, M = 200$
- $a_1 = 2\%, n_2 = 5\%, M = 200$