Review and Outlook of the Search for Chiral Effects at STAR

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for the STAR Collaboration
Outline

❖ Motivation

❖ STAR Results
  ❖ Chiral Magnetic Effect (CME)
  ❖ Chiral Magnetic Wave (CMW)
  ❖ Chiral Vortical Effect (CVE)

❖ Outlook
Vacuum transition may occur on a large scale or a small scale.

- **we can learn from the Little Bangs**
QCD vacuum transition

nonzero topological charge
chirality imbalance (local parity violation)

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

Local Parity Violation + CME

\[ \frac{dN^\pm}{d\phi} \propto 1 + 2a_\pm \cdot \sin(\phi^\pm - \Psi_{RP}) \]

A direct measurement of the \( P \)-odd quantity \( "a" \) should yield zero.

Visual evidence: fluctuation

There should be more out-of-plane charge fluctuation than in-plane. Indeed, we can visualize this effect, which is on percent level!

200 GeV Au+Au relative difference in RMS

A better way to quantify the extra charge fluctuation.

\[ \gamma = \left\langle \cos(\phi_\alpha + \phi_\beta - 2\psi_{RP}) \right\rangle \]

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

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

**Background effects:** largely cancel out

**P-even quantity:** still sensitive to charge separation

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S. Voloshin,
PRC 70 (2004) 057901
Charge separation signal

\[ \gamma_{os} > \gamma_{ss}, \text{ consistent with CME expectation} \]
- Consistent between different years (2004 and 2007)
- Confirmed with 1st-order EP (from spectator neutron \( v_1 \))
- Not explained by known event generators
Correlations of $K^0_S$-$h^-$ and $K^0_S$-$h^+$ consistent with each other: no charge-dependent separation
• Correlations of $\Lambda$-$h^{\pm}$ also show no charge-dependent separation (protons and antiprotons have been excluded from $h^{\pm}$)

• Separation observed for $h^{\pm}$-$h^{\pm}$ is due to electric charge

• $s$ quarks participate in the chiral dynamics in a similar way as $u/d$
At lower beam energies, charge separation starts to diminish.
Flow-related background


- Against CME expectation, $\delta_{OS} > \delta_{SS}$

- Indicate overwhelming background, larger than any possible CME effect.

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

$\gamma \equiv \langle \cos(\phi_1 + \phi_2 - 2\Psi_{RP}) \rangle = \kappa v_2 F - H$

$\delta \equiv \langle \cos(\phi_1 - \phi_2) \rangle = F + H$

CME contribution

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

- \( \kappa \approx 2 - \frac{v_{2,F}}{v_{2,\Omega}} \approx 1.2 \)
  - F and \( \Omega \) denote full phase space and finite detector acceptance, respectively
- CME signal (\( \Delta H \)) decreases to 0 from 19.6 to 7.7 GeV
- Probable domination of hadronic interactions over partonic ones
- Need better estimate of \( \kappa \) and more 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 \(~2.5\%\)

Extrapolate to intermediate centrality? Isobar collisions may work better.
Peak magnetic field $\sim 10^{15} \text{ Tesla}$!

(Kharzeev et al. NPA 803 (2008) 227)

$\vec{B}$

$\mu_V$

$\vec{j}_A$

$\vec{j}_V$

$(+)_A$

$(-)_A$

$\mu_A$

$N_c e$

$\frac{1}{2\pi^2}$

$B$

$\vec{j}_V$

$\vec{j}_A$

$\vec{j} = \frac{N_c e}{2\pi^2} \mu B$

$\vec{j} = \frac{N_c e}{2\pi^2} \mu A B$

Chiral Separation Effect

Chiral Magnetic Effect

CSE + CME $\rightarrow$ Chiral Magnetic Wave:

- collective excitation
- signature of chiral symmetry restoration
Formation of electric quadrupole: $v_2^\pm = v_2^{\text{base}} \mp \left( \frac{q_e}{\rho_e} \right) A_{\text{ch}}$, where charge asymmetry is defined as $A_{\text{ch}} = \frac{N^+ - N^-}{N^+ + N^-}$. Then $\pi^- v_2$ should have a positive slope as a function of $A_{\text{ch}}$, and $\pi^+ v_2$ should have a negative slope with the same magnitude.
• Clear $A_{ch}$ dependence of $v_2$\{2\}

• $v_2(A_{ch})$ slopes for $\pi^\pm$:
  • opposite sign
  • similar magnitude

• $v_2$ difference vs $A_{ch}$ may have a non-zero intercept: other physics?

\[ v_2^\pm = v_2^{\text{base}} \pm \left( \frac{q_e}{\rho_e} \right) A_{ch} \]
Similar trends between data and theoretical calculations with CMW. UrQMD can not reproduce the slopes.

arXiv:1504.02175, accepted by PRL
Similar trends are observed for different beam energies down to 19.6 GeV. Below 19.6 GeV, more statistics are needed.
Similar pattern and magnitude seen in U+U collisions.
With the same electric quadruple of QGP upon chemical freezeout, one expects to see a weaker effect for kaons (Y. Burnier, D. Kharzeev, J.g Liao, and H. Yee, PRL 107 052303)
Chiral Vortical Effect

Chiral Magnetic Effect vs Chiral Vortical Effect

Chirality Imbalance ($\mu_A$)

Magnetic Field ($\omega \mu_e$) \quad Fluid Vorticity ($\omega \mu_B$)

$\downarrow$ \quad $\downarrow$

Electric Charge ($j_e$) \quad Baryon Number ($j_B$)

$\langle \cos(\phi_A + \phi_p - 2\Psi_{RP}) \rangle$

correlate $\Lambda$–p to search for the Chiral Vortical Effect

D. Kharzeev, D. T. Son, PRL 106 (2011) 062301
Λ-proton correlation

- same baryon number: \( \Lambda p \) and \( \bar{\Lambda} \bar{p} \)
- opposite baryon number: \( \Lambda \bar{p} \) and \( \bar{\Lambda} p \)

“same B” is systematically lower than “oppo B” in the mid-central and peripheral collisions, consistent with the CVE expectation.
What we learned so far

- signal of charge separation w.r.t. RP
  - confirmed with different EP types (1st- and 2nd-order)
  - remain in Au+Au, Cu+Cu, Pb+Pb and U+U
  - persist from 19.6 GeV to 2.76 TeV
  - repeated with reduced correlators (not shown here)
  - robust when suppressing HBT+Coulomb (not shown here)

- signal seems to disappear when
  - one of h± is replaced with a neutral strange particle
  - the collision energy is down to ~7.7 GeV
  - B field from spectators is suppressed (v2 is still sizable)

- we also showed
  - CMW signal: finite Δv2(Ach) slopes
  - CVE signal: baryon-number separation w.r.t. RP
Isobars are atoms (nuclides) of different chemical elements that have the same number of nucleons.

For example, $^{96}_{44}$Ruthenium and $^{96}_{40}$Zirconium:

Up to 10% variation in B field

<table>
<thead>
<tr>
<th></th>
<th>$^{96}<em>{44}$Ru+$^{96}</em>{44}$Ru vs $^{96}<em>{40}$Zr+$^{96}</em>{40}$Zr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow</td>
<td>$\leq$</td>
</tr>
<tr>
<td>CMW</td>
<td>$&gt;$</td>
</tr>
<tr>
<td>CME</td>
<td>$&gt;$</td>
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<tr>
<td>CVE</td>
<td>$=$</td>
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Almost identical distributions of multiplicity (MC Glauber)
The ratio is close to 1 except for 0-10% most central events
Zr is a little deformed ($\beta_2 = 0.2$), and Ru is spherical ($\beta_2 = 0.05$)
- Clear difference in the B field for the same centrality
- The ratio is close to 1.1 for peripheral events
- Reduces to 1.07 for central events

Courtesy of Xu-Guang Huang and Wei-Tian Deng
Isobars: charge separation

- Projection from 1.2B events shows difference in $\Delta H$
- The ratio is $5\sigma$ above 1 ($3\sigma$ with 400M events)
- If it's $v_2$-driven, the ratio will follow eccentricity (be 1 or below 1)
The slope parameter is also expected to differ.

With 1.2B events, the ratio is 1σ above 1.

Need more statistics.
A possible direct evidence of the strong initial E field? (comparable to the strong initial B field).

Outlook: Cu+Au

Expect charge-dependence of directed flow due to a dipole deformation

Y. Hirono, M. Hongo and T. Hirano,
PRC 90, 021903(R)
Ohm's Law

<table>
<thead>
<tr>
<th></th>
<th>E</th>
<th>B</th>
</tr>
</thead>
<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>
</tr>
</tbody>
</table>

Chiral Magnetic Effect

Chiral Electric Separation Effect


Chiral Separation Effect

in-plane charge separation

Suppressed $\gamma$ signal of charge separation in Cu+Au collisions?
Backup slides
Which B quantity is sensitive to the charge separation?

The ratio is similar in term of $\sim B^2$ for 20-60% collisions.

$B \cdot \cos(2\Delta\phi)$ may be more realistic, with a bigger difference.

We use $B_y$ for simplicity.

Courtesy of Xu-Guang Huang and Wei-Tian Deng.
• \( \Delta H \cdot N_{\text{part}} \) is a roughly linear function of \( B^2 \) for \( \text{Au+Au 200 GeV} \).
• The 20-60\% isobar collisions covers [4, 10] in the x axis.
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

\[ \left\langle \cos(\varphi_\alpha + \varphi_\beta - 2\Psi_{RP}) \right\rangle = \left\langle \cos(\Delta\varphi_\alpha) \cos(\Delta\varphi_\beta) - \sin(\Delta\varphi_\alpha) \sin(\Delta\varphi_\beta) \right\rangle = \left\langle (M_\alpha M_\beta S_\alpha S_\beta)_{\text{IN}} \right\rangle - \left\langle (M_\alpha M_\beta S_\alpha S_\beta)_{\text{OUT}} \right\rangle \]

\[ \text{msc} \equiv \left( \frac{\pi}{4} \right)^2 \left( \left\langle S_\alpha S_\beta \right\rangle_{\text{IN}} - \left\langle S_\alpha S_\beta \right\rangle_{\text{OUT}} \right) \]

\[ \text{Phys. Rev. C 88 (2013) 64911} \]
A similarly reduced correlator, observes a similar charge separation.

Previously, when $v_2^{\text{obs}}=0$, the signal was consistent with zero!

Now, new measurements with higher statistics report non-zero signal!

Beam energy dependence also looks similar to that of $\gamma$.

\[ \nu_2^\Omega = 0.0504, \]
and
\[ \nu_2^F = 0.0397 \]

\[ \kappa \approx 2 - \frac{\nu_2^F}{\nu_2^\Omega} \approx 1.2 \]
Observed charge asymmetry

\[ A_{ch} = \frac{N^+ - N^-}{N^+ + N^-} \]

- \( N^+ \) (\( N^- \)) is the number of positive (negative) particles within \( |\eta| < 1 \).
- The distribution was divided into 5 bins, with roughly equal counts.
- Tracking efficiency was corrected with help of HIJING.
Local charge conservation may introduce $A_{ch}$ dependence of $\Delta v_2(\pi)$. Then one should see slope-for-$\Delta v_3$ / slope-for-$\Delta v_2 \sim v_3/v_2$ \cite{Bzak & Bozek PLB 726 239 (2013)}.

Our measurement for $\Delta v_3$ indicates that such mechanism alone cannot explain data.
$\Delta v_2@BES$

62.4 GeV Au+Au
30% - 40%

$\chi^2 / \text{ndf}$: 2.987 / 3
$p_0$: 0.03811 ± 0.01845
$p_1$: 2.002 ± 0.4615

27 GeV Au+Au
30% - 40%

$\chi^2 / \text{ndf}$: 2.66 / 3
$p_0$: 0.0818 ± 0.02179
$p_1$: 3.171 ± 0.7087

39 GeV Au+Au
30% - 40%

$\chi^2 / \text{ndf}$: 4.639 / 3
$p_0$: 0.07664 ± 0.0125
$p_1$: 2.409 ± 0.3579

19 GeV Au+Au
30% - 40%

$\chi^2 / \text{ndf}$: 2.971 / 3
$p_0$: 0.1123 ± 0.03856
$p_1$: 2.512 ± 1.138
Multi-component Coalescence (MCC) + Quark Transport

\[ X_{dT} - X_{uT} \text{ vs Charge Asymmetry} \]

only using charged hadrons

Pearson coefficient : -0.92 \quad \rightarrow \quad \text{Strong negative correlation}

\[ \Delta v_2^\pi \equiv v_2^{\pi^-} - v_2^{\pi^+} = (X_{dT} - X_{uT}) (v_2^T - v_2^P) \]

John Campbell's poster.