Search for Chiral Effects with Identified Particles in Heavy Ion Collisions

Liwen Wen (for the STAR Collaboration)
University of California, Los Angeles
Strangeness in Quark Matter 2016, Berkeley, CA

6/28/16
Outline

‣ Physics Motivation

‣ STAR Experiment

‣ Two Case Studies on Search for Chiral Effects @ STAR

‣ Background Study

‣ Summary
QCD vacuum transition:

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

\[ N_L - N_R = 2Q_W, \quad Q_W \neq 0 \rightarrow \mu_A \neq 0 \]
Configuration with non-zero topological charge converts left(right)-handed fermions to right(left)-handed fermions, generating electromagnetic current along B direction and leading to electric charge separation.
**Chiral Vortical Effect (CVE)**

Chiral Magnetic Effect vs Chiral Vortical Effect

- **Chirality Imbalance ($\mu_A$)**
- **Magnetic Field ($\omega \mu_e$)**
- **Electric Charge ($j_e$)**

Vorticity

- **Chirality Imbalance ($\mu_A$)**
- **Fluid Vorticity ($\omega \mu_B$)**
- **Baryon Number ($j_B$)**

Electric charge separation

Baryonic charge separation

$\Lambda - p$ correlation measurement ($\gamma = \langle \cos(\varphi_{\Lambda} + \varphi_p - 2\Phi_{RP}) \rangle$)
can be used to search for the Chiral Vortical Effect

D. Kharzeev, D. T. Son, PRL 106 (2011) 062301
Solenoidal Tracker At RHIC (STAR)
STAR Particle Identification

\[ TPC \quad \sqrt{s_{NN}} = 39 \text{ GeV Au + Au Collisions} \quad TPC+ToF (|\eta| < 1) \]

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

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

\( \eta \quad \pi \quad K \quad p \)

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

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

\( K \quad \pi \quad p \)

\( \pi \quad e \quad K \quad p \)

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

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

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

\[ \pi \quad K \quad \bar{p} \]

\[ \text{Counts} \quad \text{Z}_\pi \quad \text{Z}_{\pi} \]

\[ \text{Counts} \quad m^2 \]

6/28/2016

Strangeness in Quark Matter 2016
The estimated reaction plane is called the event plane.
Lambda/Ks0 and Event Plane Resolution

\[ K^0_s \]
\[ \Lambda(\bar{\Lambda}) \]

Event Plane Resolution v.s. Centrality

EP Resolution

STAR preliminary

200 GeV Au+Au
We investigate the charge dependent two-particle correlations with respect to the reaction plane:

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

Direct measurement of “a” would yield zero value. So we need “three-point-correlator”— observable “gamma”!

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

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

Directed flow: expected to be same for “same sign” and “opposite sign”

Background effects: largely cancel out, but flow-related background may still exist.

P-even quantity: still sensitive to separation effect, i.e., different for “same sign” and “opposite sign”

Same & opposite sign: correlated particles ($\alpha, \beta$) have same (opposite)electric/baryonic charge.

Significant baryonic charge separation signal is observed. The magnitude is larger than electric charge separation signal of h-h correlations. CVE predicts qualitatively the same order of hierarchy.
As a systematic check of h-h correlation, proton-pion correlation shows similar separation signal as h-h, suggesting similar underlying physics (CME) as expected.
Identified particle correlation case studies show hierarchical structure of chiral effects. From Npart scaling plot, we can observe within error bars, separation signals are consistent with zero in the most central collisions.
Background!

Against CME expectation, \( \delta_{OS} > \delta_{SS} \)

Overwhelming bg, larger than any CME effect.

Combine information from \( \gamma \) and \( \delta \), and retrieve the CME contribution, \( H \)

\[
\begin{align*}
\gamma & \equiv \langle \cos(\phi_1 + \phi_2 - 2\psi_{ep}) \rangle = \kappa v_2 F - H \\
\delta & \equiv \langle \cos(\phi_1 - \phi_2) \rangle = F + H
\end{align*}
\]

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

Two simple examples: why $H$ is better?

$\nu^2$ + momentum conservation

$\gamma_{SS} = 1$ \hspace{1cm} $H_{SS}^{\kappa=1}=0$

$\delta_{SS} = 1$

$\nu_2 = 1$

$\gamma_{OS} = -1$ \hspace{1cm} $H_{OS}^{\kappa=1}=0$

$\delta_{OS} = -1$

$\gamma \equiv \langle \cos(\phi_1 + \phi_2 - 2\psi_{ep}) \rangle = \kappa \nu_2 F - H$

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

$\Rightarrow H = (\kappa \nu_2 \delta - \gamma)/(1 + \kappa \nu_2)$

$\nu^2$ + momentum conservation + local charge conservation + decay

$\gamma_{SS} = -1$ \hspace{1cm} $H_{SS}^{\kappa=1}=0$

$\delta_{SS} = -1$

$\nu_2 = 1$

$\gamma_{OS} = 0$ \hspace{1cm} $H_{OS}^{\kappa=1}=0$

$\delta_{OS} = 0$

$\gamma \equiv \langle \cos(\phi_1 + \phi_2 - 2\psi_{ep}) \rangle = \kappa \nu_2 F - H$

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

$\Rightarrow H = (\kappa \nu_2 \delta - \gamma)/(1 + \kappa \nu_2)$

$H$ is more robust.

F: Flow-related background
H: Charge separation signal

\[ \gamma \equiv \langle \cos(\phi_1 + \phi_2 - 2\psi_{ep}) \rangle = \kappa v_2 F - H \]
\[ \delta \equiv \langle \cos(\phi_1 - \phi_2) \rangle = F + H \]
\[ \Rightarrow H = (\kappa v_2 \delta - \gamma)/(1 + \kappa v_2) \]

\( \kappa \) could deviate from 1 due to a finite detector acceptance and theoretical uncertainties

\( \triangleright \) The CME signal decreases to zero in the interval between 19.6 and 7.7 GeV

\( \triangleright \) Need better theoretical estimate of \( \kappa \) and better statistics

\[ \kappa = ? \quad \text{Transverse Momentum Conservation} \]

\[ \gamma = - \frac{1}{N_{\text{tot}}} \frac{\langle p_t \rangle_{\Omega}^2}{\langle p_t^2 \rangle_{F}} \frac{2\bar{v}_{2,\Omega} - \bar{v}_{2,F} - \bar{v}_{2,F}(\bar{v}_{2,\Omega})^2}{1 - (\bar{v}_{2,F})^2}, \]

\[ \delta = - \frac{1}{N_{\text{tot}}} \frac{\langle p_t \rangle_{\Omega}^2}{\langle p_t^2 \rangle_{F}} \frac{1 + (\bar{v}_{2,\Omega})^2 - 2\bar{v}_{2,F}\bar{v}_{2,\Omega}}{1 - (\bar{v}_{2,F})^2}, \]

we have introduced certain weighted moments of \( v_2 \):

\[ \bar{v}_2 = \frac{\langle v_2(p_t, \eta)p_t \rangle}{\langle p_t \rangle}, \quad \bar{v}_2^2 = \frac{\langle v_2(p_t, \eta)p_t^2 \rangle}{\langle p_t^2 \rangle}. \]

If our measurements are dominated by this type of background,

\[ \gamma / \delta \approx 2\bar{v}_{2,\Omega} - \bar{v}_{2,F} \]

where \( F \) and \( \Omega \) denote particle averages in the full phase-space and the detector acceptance, respectively.

The ratios of the pt-weighted $v_2$ over conventional $v_2$ are almost constant across centralities. This result enables us to use $v_2$ to estimate pt or pt squared weighted $v_2$. 
Data driven estimation of $\kappa$ (II): $v_{2,\Omega}$ and $v_{2,F}$

<table>
<thead>
<tr>
<th>Centrality</th>
<th>$v_{2,\Omega}$ (%)</th>
<th>$v_{2,F}$ (%)</th>
<th>$v_{2,F}/v_{2,\Omega}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-15%</td>
<td>3.17</td>
<td>2.66</td>
<td>0.84</td>
</tr>
<tr>
<td>15-25%</td>
<td>5.04</td>
<td>3.97</td>
<td>0.79</td>
</tr>
<tr>
<td>25-50%</td>
<td>6.21</td>
<td>4.87</td>
<td>0.78</td>
</tr>
</tbody>
</table>

PHOBOS, PRC 72 014904 (2005); PRC 83 024913 (2001)
• $\kappa$ is almost constant across different centrality bins. But this is for TMC effect only.

• Other background effects (Local Charge Conservation, resonance decay…) may be different and the final $\kappa$ will be the average of all these effects (estimated to be $\sim 1-2$, but still need more investigations).
\[ \kappa_{\text{signal killer}} = \frac{\Delta \gamma}{|v_2 \Delta \delta|} \]

1. \( \kappa_{\text{signal killer}} \) is value required to make \( H \) zero.

2. From 200 to 19.6 GeV, \( \kappa_{\text{signal killer}} \) has centrality dependence and is always above the estimation of estimated \( \kappa \) (i.e., our signals are safe).

• Two identified particle correlation studies are presented, which show different strength levels of (baryonic/electric) charge separation signal ($\rho - \Lambda > p - \pi$). This measurement may suggest the possible hierarchical structure of chiral effects (CVE > CME).

• A data-driven study of flow-related background is presented and shows our charge separation signal is robust with H correlator.
backup slides
As a background check of proton-pion correlation, proton-$K^0_S$ shows zero separation signal. But more statistics are needed to make strong conclusion.