Searches for Chiral Effects and Prospects for Isobaric Collisions at STAR/RHIC

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Outline

• Physics motivation and observables

• Correlation measurements with the so-called $\gamma$ and $\kappa_K$:
  • $\gamma, \kappa_K$ for identified particles in Au+Au
  • $\gamma$ for charged hadrons in U+U, p+Au, d+Au
  • $\kappa_K$ projection in BES phase II

• Isobaric collisions (Ru+Ru and Zr+Zr) projection:
  • Charge separation signal difference
  • Significance vs background level
  • Other physics opportunities
Non-zero topological charge induces excess of right or left handed quarks. Under strong magnetic field (B), an electric current along B direction is generated and leads to electric charge separation.
Observable: $\gamma$ correlator

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 flow: Expected to be the same for “same sign” and “opposite sign”.

Background effects: Flow-related background may not be canceled out.

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

$$\gamma = \langle \cos(\phi_{\alpha} + \phi_{\beta} - 2\Psi_{RP}) \rangle$$

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

STAR, PRC 81 (2010). 054908

\[ \delta \equiv \cos(\phi_1 - \phi_2) = F + H \]

\[ \gamma \equiv \cos(\phi_1 + \phi_2 - 2\psi_{ep}) = \kappa v_2 F - H \]

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

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

F: Flow-related backgrounds  
H: Charge separation signal  
\( \Delta \): OS – SS
**Background!**


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

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

- **F**: Flow-related backgrounds
- **H**: Charge separation signal
- **Δ**: OS – SS

**Correlators:**

\[
\begin{align*}
\gamma_{ss} &= -1 \\
\delta_{ss} &= -1 \\
H^{\kappa=1}_{ss} &= 0 \\
\nu_2 &= 1 \\
\gamma_{os} &= 0 \\
\delta_{os} &= 0 \\
H^{\kappa=1}_{os} &= 0
\end{align*}
\]

Flow ✓
- Momentum Conservation ✓
- Local Charge Conservation ✓
- Decay ✓

**H** is more robust!
Background!


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

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

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

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

Correlators:

\[ \gamma_{ss} = -1 \]

\[ \delta_{ss} = -1 \quad H_{ss}^{K=1} = 0 \]

\[ v_2 = 1 \quad \kappa_K = 1 \]

\[ \gamma_{os} = 0 \quad H_{os}^{K=1} = 0 \]

\[ \delta_{os} = 0 \]

Flow

Momentum Conservation

Local Charge Conservation

Decay

H is more robust!

F: Flow-related backgrounds

H: Charge separation signal

\( \Delta \): OS – SS

\( v_p \) is a parameter near unity that can be estimated by background models.

Finite \( H_{ss} - H_{os} \) signal is observed in Au+Au collisions at \( \sqrt{s_{NN}} \geq 11.5 \) GeV for \( h^\pm h^\pm \).
\( \kappa_K: \) scaled background + signal

\[
\delta \equiv \cos(\phi_1 - \phi_2) = F + H \\
g \equiv \cos(\phi_1 + \phi_2 - 2\psi_{ep}) = \kappa v_2 F - H
\]

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

\[
\kappa = \frac{\Delta \gamma + \Delta H}{v_2 (\Delta \delta - \Delta H)} \quad \Delta H \approx 0
\]

\[
\kappa K = \frac{\Delta \gamma}{v_2 \Delta \delta}
\]
$\kappa K$: scaled background + signal

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

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

$H = \frac{\kappa v_2 \delta - \gamma}{1 + \kappa v_2}$

$\gamma = \frac{\Delta \gamma + \Delta H}{v_2(\Delta \delta - \Delta H)} \Rightarrow \Delta H = 0$

$k \kappa K = \frac{\Delta \gamma}{v_2 \Delta \delta}$

Assumption: $\kappa$ from background is beam-energy, centrality and particle independent and between 1 to 2!

Charge may not be conserved in this version of AMPT

Wen, Wen & Wang, arXiv: 1608.03205
**\( \kappa K \): scaled background + signal**

\[
\begin{align*}
\delta &\equiv \langle \cos(\phi_1 - \phi_2) \rangle = F + H \\
\gamma &\equiv \langle \cos(\phi_1 + \phi_2 - 2\psi_{ep}) \rangle = \kappa v_2 F - H \\
H &= \frac{\kappa v_2 \delta - \gamma}{1 + \kappa v_2} \\
\end{align*}
\]

- **Assumption:** \( \kappa \) from background is beam-energy, centrality and particle independent and between 1 to 2!

| STAR, Phys. Rev. Lett. 113 (2014), 052302, |
| Au + Au |
| 200 GeV Au+Au |
| \( \Omega: |\eta| < 1.5 \) |

\[
\begin{align*}
\kappa^\text{TMC} &= \frac{2v_{2,\Omega} - \bar{v}_{2,\Omega}}{v_{2,\Omega}} \quad \text{(PHOBOS)} \\
\kappa^\text{TMC} &= \frac{2v_{2,\Omega} - \bar{v}_{2,\Omega}}{v_{2,\Omega}} \quad \text{(AMPT)} \\
\kappa^\text{AVE} &= \frac{\Delta \gamma}{\langle v_{2,\delta} \rangle} \quad \text{(AMPT)} \\
\end{align*}
\]

- At the extreme, we introduce \( \kappa_K \) such that \( \Delta H = 0 \). If \( \kappa_K > \kappa (H_{\text{SS→0S}} > 0) \), there could be extra physics, like CME.

- \( \kappa_K \) at 7.7 GeV shows weak centrality dependence with values near 1-2.

- At energies \( \geq 19.6 \text{ GeV} \), \( \kappa_K \) shows higher values than 2 in mid-central and mid-peripheral collisions.

- \( \kappa_K \) is not applicable in peripheral collisions due to non-flow correlations.
\[ \Delta \gamma \] for \( \pi \pi \) in Au+Au 200 GeV shows similar values to charged hadrons.

- \( \kappa_K \) for mid-central and mid-peripheral collisions is much larger than the background level (1.0 to 2.0) estimated from AMPT.
$\pi\pi$ correlation, Au+Au 39 GeV

- Au+Au 39 GeV $\pi\pi$ pair $\Delta \gamma$ shows similar magnitude to charged hadron’s at the same energy.
- $\kappa_K$ is higher than 2 except in central collisions.
\(\pi K\) correlation

- \(\Delta \gamma\) for \(\pi K\) pair is finite in Au+Au at both 200 GeV and 39 GeV.
- \(\kappa_K\) values are close to or below 2, making it hard to distinguish from background.

\[\gamma_{cS}^\pi - \gamma_{cS}^K = K^0_\kappa \kappa_0 + K^+_\kappa (\pi^- K^+) - \pi^+ K^- (\pi^+ K^+)\]
• $\Delta \gamma$ for $p\pi$ pair is finite in Au+Au at both 200 GeV and 39 GeV.
• $\kappa_K$ values are close to or below 2, making it hard to distinguish from background.
**pp and pK correlation**

- *pp* pairs in Au+Au 200 GeV show large $\Delta \gamma$
- $\Delta \gamma$ for *pK* has smaller values, but still finite in peripheral and mid-central collisions.
- $\kappa_K$ for *pp* is lower than 2 or even 1 in some centrality bins.
- For *pK*, $\kappa_K$ fluctuates between 1 and 2.

![Graphs showing correlations](image-url)
PID Summary

• $\Delta \gamma$ for all PID pairs is finite in peripheral and mid-central Au+Au collisions at 200 GeV

• $\kappa_K$ for $\pi\pi$ is higher than estimated background in mid-central collisions. Other pairs are close to or within background range of 1.0 to 2.0

• pp shows large $\Delta \gamma$, but $\kappa_K$ is below 1.0, which is not fully understood yet.

% Most Central

$\delta = \frac{\Delta \gamma}{v \Delta \delta}$

Au+Au 200 GeV
STAR Preliminary

$\pi\pi$, $pK$, $\pi K$, pp, $p\pi$
Why we need U+U collisions?

- To disentangle the signal and the background by varying the background (trying to minimize flow background by selecting the most central collisions in UU)
- Similar pattern observed in $\Delta \gamma$ vs $v_2$ and projected B-field vs $\epsilon_2$ suggests magnetic field may be the driven force of observed $\Delta \gamma$ signal.
γ correlation in p+Au and d+Au

- Sizable $\Delta \gamma$ in p+Au and d+Au w.r.t 2nd–order event plane (EP) $\psi_2$ from TPC.
- $\Delta \gamma$ disappears in p+Au and d+Au when $\eta$ gap is introduced between EP and particles of interest: $\Delta \gamma$ in TPC EP results mostly from short range correlation (this can also be seen from difference between TPC and BBC $v_2$).

![Graphs showing γ correlation in p+Au, d+Au, and Au+Au at 200 GeV for TPC and BBC EP.]
The correlation in $p+Au$ and $d+Au$

- $\Delta \gamma \cdot N/v_2$ from AMPT (hadronic scattering is turned off) does not match data in central events, but accounts for $\sim 2/3$ of the observed signal from peripheral to mid-central $Au+Au$ w.r.t. TPC event plane.
- $\Delta \gamma \cdot N/v_2$ from AMPT accounts for $\sim 1/3$ of the observed signal in $d+Au$ w.r.t. TPC event plane.
Projection for BES II

<table>
<thead>
<tr>
<th>$\sqrt{s_{NN}}$ (GeV)</th>
<th>19.6</th>
<th>14.5</th>
<th>11.5</th>
<th>7.7</th>
</tr>
</thead>
<tbody>
<tr>
<td># of evts (M)</td>
<td>400</td>
<td>300</td>
<td>230</td>
<td>100</td>
</tr>
</tbody>
</table>

$K_K = \Delta y / (v_2^{\Delta})$

Au + Au $h^+ - h^-$

- 19.6 GeV
- 14.5 GeV
- 11.5 GeV
- 7.7 GeV

STAR preliminary

Error bars: BES I
Error bars: BES II projection
Isobars

• What are Isobars?
  • Isobars are nuclides of different chemical elements that have the same number of nucleons.
  • Examples: $^{96}_{44}Ru$ and $^{96}_{40}Zr$

• Why isobaric collisions?
  • Up to 10% variation in $B$ field
  • Flow (major source of background) magnitude will stay almost the same

<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>Similar</td>
</tr>
<tr>
<td>CME</td>
<td>Greater than</td>
</tr>
<tr>
<td>CMW</td>
<td>Greater than</td>
</tr>
<tr>
<td>CVE</td>
<td>Similar</td>
</tr>
</tbody>
</table>
\[
\rho(r, \theta) = \frac{\rho_0}{1 + \exp[(r - R_0 - \beta_2 R_0 Y_2^0(\theta))/a]}
\]

- \(\rho_0\): 0.16 \(fm^{-3}\), normal nuclear density
- \(R_0\): “radius” of the nucleus
- \(a\): surface diffuseness parameter
- \(\beta_2\): deformity of the nucleus

- **Case 1**: e-A scattering experiment. Atom. Data Nucl. Data Tabl. 78, 1 (2001); 107, 1 (2016)
- Uncertainty in \(\beta_2\) presents an opportunity or a by-product of the planned study.

<table>
<thead>
<tr>
<th></th>
<th>(R_0)</th>
<th>(a(d))</th>
<th>(\beta_2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zr96</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case 1</td>
<td>5.07</td>
<td>0.48</td>
<td>0.06</td>
</tr>
<tr>
<td>Case 2</td>
<td>5.05</td>
<td>0.45</td>
<td>0.18</td>
</tr>
<tr>
<td>Ru96</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case 1</td>
<td>5.14</td>
<td>0.46</td>
<td>0.13</td>
</tr>
<tr>
<td>Case 2</td>
<td>5.13</td>
<td>0.45</td>
<td>0.03</td>
</tr>
</tbody>
</table>
Charge Separation: $\gamma$ (2/3 background)

- Projection with 1.2B events from each collision type
- If it’s $v_2$-driven, relative difference follow eccentricity (~0 for 20-60%)
- If it’s 1/3 CME-driven, the difference in $\Delta \gamma$ is $8\sigma$ above $\epsilon_2$

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

\[ s_{NN} = 200 \text{ GeV} \]

1.2B MB events

- Ru+Ru (case 1)
- Zr+Zr (case 1)

(a)

(b)

\[ R_S (\text{case } 1) \]
\[ R_{\epsilon_2} (\text{case } 1) \]
\[ R_S (\text{case } 2) \]
\[ R_{\epsilon_2} (\text{case } 2) \]

Charge Separation: $\gamma$ (80% background)

- Projection with 1.2B events from each collision type
- If it’s $\nu_2$-driven, relative difference follow eccentricity ($\sim 0$ for 20-60%)
- If it’s 20% CME-driven, the difference in $\Delta \gamma$ is $5\sigma$ above $\epsilon_2$
Significance vs. Background

- Projection with 1.2B events from each collision type
- Significance of the difference in $\Delta \gamma$ depends on background level
- Case 2 is slightly better than case 1
- New EPD detector may help achieve $7.8\sigma$ significance with 1B events and 80% background level
**Zr and Ru, which is more deformed?**

<table>
<thead>
<tr>
<th></th>
<th>$R_0$ [fm]</th>
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<th>$\beta_2$</th>
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<tbody>
<tr>
<td>$^{96}$Zr</td>
<td>5.06</td>
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<td>0.06</td>
</tr>
<tr>
<td>$^{96}$Ru</td>
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<td>0.46</td>
<td>0.13</td>
</tr>
</tbody>
</table>

**case 1**

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<th>$\beta_2$</th>
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<tr>
<td>$^{96}$Ru</td>
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<td>0.46</td>
<td>0.03</td>
</tr>
</tbody>
</table>

**case 2**

$v_2$ measurements in central collisions will tell us which is more deformed.

Zr and Ru: di-lepton production mechanisms at very low $p_T$
Summary

- Search for Chiral Magnetic Effect in Au+Au:
  - $\kappa_K$ for $h^\pm h^\pm$ and $\pi\pi$ in mid-central Au+Au 200 GeV is larger than those from AMPT background.
  - $\kappa_K$ of other identified pairs, $\pi K, p\pi, pK$, is hard to distinguish from the background.
  - $\kappa_K$ for $pp$ needs further investigation.
  - BESII will significantly reduce statistical uncertainties.

- Search for Chiral Magnetic Effect in p+Au/d+Au:
  - $\Delta\gamma$ for $h^\pm h^\pm$ in p+Au and d+Au 200 GeV is significant when using TPC event plane.
  - $\Delta\gamma$ disappears when introducing $\eta$ gap (>2) between particles of interest and event plane in p+Au and d+Au 200 GeV.

- Isobaric Collisions:
  - With 1.2B MB events, significance of the difference in $\Delta\gamma$ between Ru+Ru and Zr+Zr can reach at least 5$\sigma$ if background level is as high as 80%. EPD may improve this to 7.8$\sigma$ with 1B events.
Back up slides
**B Field**

- B calculated at t=0, at one point (center of mass of participants)
- B field slightly affected by $\beta_2$
- Relative difference in $B^2$ is 15-18% for peripheral events
- Reduces to 13% for central collisions

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**Graphs**

(a) Ru+Ru

(b) $\sqrt{s_{\text{NN}}} = 200$ GeV

Collectivity vs. non-flow

What is collectivity? A working definition: multiple particles correlated across rapidity due to a common source.

Note 1: collectivity does not imply a specific physical interpretation (i.e. collectivity ≠ hydro).

Note 2: correlations between particles which do not have a "collective" origin (jets, resonance decays, momentum conservation) are commonly called "non-flow"...