Investigation of the sensitivities of observables for CME search by the STAR experiment using AVFD framework

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arXiv:2105.06044
Outline

- Motivation
- CME observables and their Core-components
- Sensitivity Study with STAR’s frozen code in isobar blind-analysis, with EBE-AVFD events.
- Summary
The quark-gluon plasma (QGP) is created in heavy-ion collisions.

According to QCD, if the topological solutions of the SU(3) gauge group are chiral, they can transfer chirality to quarks via chiral anomaly, forming local chiral domains in QGP.
Chiral Magnetic Effects (CME)

In non-central collisions a strong magnetic field is produced \( \perp \) to \( \Psi_R \).

CME-induced charge separation shifts pos. and neg. particles in opposite directions (along \( B \)).

\[
\frac{dN_\alpha}{d\phi^*} \approx \frac{N_\alpha}{2\pi} [1 + 2v_{1,\alpha} \cos(\phi^*) + 2v_{2,\alpha} \cos(2\phi^*) + 2v_{3,\alpha} \cos(3\phi^*) + \ldots + 2a_{1,\alpha} \sin(\phi^*) + \ldots]
\]

The CME is present due to finite \( n_5/s \), measured as finite \( a_1 \) in experiment.

Experimental Observable: $\gamma$-correlator

$$\gamma_{112} \equiv \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle$$
$$= \langle \cos(\Delta \phi_\alpha) \cos(\Delta \phi_\beta) - \sin(\Delta \phi_\alpha) \sin(\Delta \phi_\beta) \rangle$$
$$= \left( \langle v_{1,\alpha} v_{1,\beta} \rangle + B_{IN} \right) - \left( \langle a_{1,\alpha} a_{1,\beta} \rangle + B_{OUT} \right).$$

**Directed flow**

**Fluctuations of $a_1$**

$$\Delta \gamma_{112} \equiv \gamma_{112}^{QS} - \gamma_{112}^{SS},$$

the $\langle v_{1,\alpha} v_{1,\beta} \rangle$ terms cancel out, as well as a large portion of $(B_{IN} - B_{OUT}).$

$$\delta \equiv \langle \cos(\phi_\alpha - \phi_\beta) \rangle$$
$$= \langle v_{1,\alpha} v_{1,\beta} \rangle + B_{IN} + \langle a_{1,\alpha} a_{1,\beta} \rangle + B_{OUT},$$

$$\kappa_{112} \equiv \frac{\Delta \gamma_{112}}{v_2 \cdot \Delta \delta}.$$
Experimental Observable: R-correlator

1) E-by-E $a_1$ difference between +/- charge $\Delta S$.

2) Removal of trivial contribution: 

$$C(\Delta S) = \frac{N_{\text{real}}(\Delta S)}{N_{\text{shuffled}}(\Delta S)}$$

3) Look for out-of-plane excess: 

$$R(\Delta S) = \frac{C(\Delta S)}{C(\Delta S)}$$

$$\Delta S = \frac{\sum_1^{n^+} w_i^+ \sin \left( \frac{m}{2} \Delta \varphi_m \right)}{\sum_i^{n^+} w_i^+} - \frac{\sum_1^{n^-} w_i^- \sin \left( \frac{m}{2} \Delta \varphi_m \right)}{\sum_i^{n^-} w_i^-}$$

- $R_{\psi^2}$ is concave with CME signal.
- $R_{\psi^2}$ is convex when backgrounds only.
- $R_{\psi^2}$ getting more concave when the signal is larger.

However, the interpretation of the shape of $R_{\psi^2}$ is complicated by other effects.

Experimental Observable: Signed Balance Function

1) Count pair’s momentum ordering in $p_y$:
$$B_{p_y}(S_y) = \frac{N_{+-}(S_y) - N_{++}(S_y)}{N_+},$$
$$B_{p_y}(S_y) = \frac{N_{-+}(S_y) - N_{--}(S_y)}{N_-}$$

2) Count net-ordering (e.g. excess of pos. leading neg. ) for each event:
$$\delta B_y(\pm 1) = B_{p,y}(\pm 1) - B_{p,y}(\pm 1),$$
$$\Delta B_y(\pm 1) = \delta B_y(\pm 1) - \delta B_y(\pm 1)$$
$$= \frac{N_{+-} + N_{-+}}{N_+ N_-} [N_y(+-) - N_y(-+)]$$

3) Look for enhanced event-by-event fluctuation of net ordering in $y$ direction.
$$r = \frac{\sigma \Delta B_y}{\sigma \Delta B_x} (>1 \text{ with CME})$$
$$R_B = \frac{r_{rest}}{r_{lab}} (>1 \text{ with CME})$$

- Not participated in isobar blind-analysis, but included here for completeness.
Isobaric Collision and Blind-analysis at STAR

- The two isobaric systems: **Difference** in the CME signal but **same** flow backgrounds.

  - Phase-I Blinding
    - Mock data challenge
    - Test data Structure (27 GeV files)
    - Isobar-Mixed Analysis QA, physics & code freezing (One run is Ru+Zr)

  - Phase-II Blinding
    - Isobar-Blind Analysis Run-by-run QA, Full analysis (One run is Ru/Zr)
    - Mass Data production Originally ~3 months
    - Isobar-Unblind Analysis Full analysis (Ru and Zr Separated)

Establish all procedures

- Act "blindly" on all procedures

  - The STAR has implemented a blind-analysis procedure in data analyses, and all the analysis codes have been frozen as part of the blinding procedure (Five institutional groups, with various observables).

  - **Desirable** to study the connection and difference between various observables, and their sensitivities to the CME signals.

\[
\frac{O_{Ru+Ru}^{Ru+Ru}}{O_{Zr+Zr}^{Zr+Zr}} > 1 \text{ (with CME)}
\]

EBE-AVFD: event-by-event anomalous-viscous fluid dynamics,

\( a_1 \) is obtained with RP

<table>
<thead>
<tr>
<th>( n_5/s )</th>
<th>( a_{1,+} ) (%)</th>
<th>( a_{1,-} ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ru+Ru Zr+Zr</td>
<td>Ru+Ru Zr+Zr</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.05</td>
<td>0.37 0.35</td>
<td>0.35 0.33</td>
</tr>
<tr>
<td>0.10</td>
<td>0.74 0.69</td>
<td>0.71 0.66</td>
</tr>
<tr>
<td>0.20</td>
<td>1.48 1.38</td>
<td>1.42 1.32</td>
</tr>
</tbody>
</table>

- \( a_1 \) (Ru) > \( a_1 \) (Zr)
- The major background (\( v_2 \)) is identical.
Connection of CME methods

The relation between experimental observables via analytical derivation:

SBF:
\[ \Delta_{SBF} \equiv \sigma^2(\Delta B_y) - \sigma^2(\Delta B_x) \approx \frac{128M^2}{\pi^4}(\Delta \gamma_{112} - \frac{4}{3} v_2 \Delta \delta). \]

R-correlator:
\[ \Delta_{R2} \approx 2(1 - \frac{1}{M}) \Delta \gamma_{112} \]
\[ \frac{S_{\text{concavity}}}{\sigma_{R2}^2} = \frac{S_{\text{concavity}}}{\sigma_{R2}^2} \langle (\Delta S_{2,\text{shuffled}})^2 \rangle \approx -M \Delta \gamma_{112}. \]

In next slides, we will study core-components \( \Delta \gamma_{112}, \Delta_{SBF} \) and \( \Delta_{R2} \)

All three observables have very similar responses to the signal and background.
\( \gamma \) Correlator with Frozen code

\[ 0.2 < p_T < 2.0 \]
\[ |\eta| < 1.0 \]

\( \Delta \gamma_{112} \) and \( \kappa_{112} \) are both increase with the CME signal.

The ratio (Ru/Zr) is increases with \( n_5/s \).

The dotted lines are polynomial fit.

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R(ΔS) - correlator with Frozen code

0.35 < p_T < 2.0  
|η| < 1.0

- As n_5/s increases, the $R_{\psi_2}$ distribution becomes more concave.
- The $\sigma_{R_{\psi_2}}^{-1}$ value are increasing with n_5/s.
- $R_{\psi_2}$(Ru/Zr) shows no visible response to signal increase.

(However, if studied with true RP and same kinematic cuts, it shows similar sensitivity as $\Delta\gamma_{112}$).

AVFD 30-40%

(a) $R_{\psi_2}^{Ru+Ru}$

- n_5/s = 0.
- n_5/s = 0.05

(b) $R_{\psi_2}^{Zr+Zr}$

- n_5/s = 0.10
- n_5/s = 0.20

(c) AVFD 30-40%

- $R_{\psi_2}^{Ru+Ru}$
- $R_{\psi_2}^{Zr+Zr}$

(d) $\sigma_{R_{\psi_2}}^{-1}$

- $\sigma_{R_{\psi_2}}^{Ru+Ru}$
- $\sigma_{R_{\psi_2}}^{Zr+Zr}$

- $\sigma_{R_{\psi_2}}^{Ru+Ru}/\sigma_{R_{\psi_2}}^{Zr+Zr}$

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Signed Balance Function

\[ 0.2 < p_T < 2.0 \]

\[ |\eta| < 0.5 \]

- \( r_{\text{lab}} \) shows compatible sensitivity to \( \Delta y \).
- \( R_B \) (Ru/Zr) shows little sensitivity,
- due to worsen EP resolution and lower multiplicity (relative to AuAu).

No hope using \( R_B \) for isobar collisions due to its nature of statistics hungry.
Significance Study for Isobaric Collisions

\[ \frac{O^{Ru+Ru}_{\gamma}}{O^{Zr+Zr}_{\gamma}} - 1 \]

<table>
<thead>
<tr>
<th>( n_5/s )</th>
<th>( N_{\text{event}} )</th>
<th>( \Delta\gamma_{112} )</th>
<th>( \kappa_{112} )</th>
<th>( r_{\text{lab}} )</th>
<th>( \sigma_{R2}^{-1} )</th>
<th>( \Delta\gamma_{112}{\text{RP}} )</th>
<th>( \sigma_{R2}^{-1}{\text{RP}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>( 2 \times 10^8 )</td>
<td>-1.50</td>
<td>-1.21</td>
<td>-0.77</td>
<td>1.33</td>
<td>0.67</td>
<td>0.56</td>
</tr>
<tr>
<td>0.05</td>
<td>( 4 \times 10^8 )</td>
<td>0.62</td>
<td>1.37</td>
<td>0.47</td>
<td>0.29</td>
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<td>3.33</td>
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<td>0.10</td>
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<td>3.43</td>
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<tr>
<td>0.20</td>
<td>( 2 \times 10^8 )</td>
<td>7.73</td>
<td>14.07</td>
<td>5.96</td>
<td>1.84</td>
<td>37.48</td>
<td>27.90</td>
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The \( O_{\text{RP}} \): True RP and same kinematic cuts.

- The ratios of two isobars, \( \Delta\gamma \) and \( r_{\text{lab}} \) show compatible and decent sensitivity
- \( R_{\psi 2} \) and \( R_B \) show flat response to signal increase.
Summary

- The relations among experimental observables have been established via analytical derivation, and the equivalence between the core-components of these observables have been verified.

- With EBE-AVFD events and STAR’s frozen codes, we have studied $\Delta \gamma$, $R_{\psi n}$-correlator, and SBF’s (not in frozen codes) response to same $n_5/s$ for two isobars separately.
  - The results show that all three methods are sensitive to CME signal for each individual isobar species.
  - When studied as the ratio of two isobars, $\Delta \gamma$ and $r_{\text{lab}}$ show compatible and decent sensitivity, while $R_{\psi 2}$ and $R_B$ shows flat response to signal increase.

- This study provides a reference point to gauge the STAR isobaric-collision data.
## BackUp: Model Descriptions

<table>
<thead>
<tr>
<th>Model</th>
<th>Conditions</th>
<th>references</th>
</tr>
</thead>
</table>
| Toy model   | A simplified Monte Carlo calculations, in which the signals and backgrounds can be controlled.                                              | STAR, PRC 79 034909 (2009)  
STAR, PRL 92, 092301 (2004)  
F.Q. Wang, PRC 95, 051901 (2017) |
and private communication with Z.W. Lin and G.L. Ma                                                      |
| EBE-AVFD    | Signals and backgrounds are both taken into account in more realistic way.                                                                     | Y. Jiang, S. Shi, Y. Yin and J. Liao, Chin. Phys. C 42 No. 1 011001 (2018)  
BackUp: $\gamma$ Correlator with Frozen code

$0.2 < p_T < 2.0$  
$|n| < 1.0$

<table>
<thead>
<tr>
<th>$n_5/s$</th>
<th>$N_{event}$</th>
<th>$\Delta \gamma_{112}$</th>
<th>$\Delta \delta$</th>
<th>$\kappa_{112}$</th>
<th>$n_{lab}$</th>
<th>$\sigma^{-1}_{R2}$</th>
<th>$\Delta \gamma_{112}{RP}$</th>
<th>$\sigma^{-1}_{R2}{RP}$</th>
</tr>
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Core-Component Comparisons of CME Observables

\[ 2\Delta \gamma_{112}, \Delta_{R2} \text{ and } \Delta'_{SBF} \equiv \left( \frac{\pi^4}{64M^2} \Delta_{SBF} + \frac{8}{3}v_2\Delta\delta \right). \]

\[ O(n_5/s) - O(0) = a_{1,+}^2 + a_{1,-}^2 - 2a_{1,+}a_{1,-}. \]
# BackUp: Study Related the R-correlator

<table>
<thead>
<tr>
<th>Studies</th>
<th>$R_{\psi 2}$ Shape</th>
<th>Shape Similarity in $R_{\psi 2}$ and $R_{\psi 3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roy/Niseem’s PRC, PLB AMPT with resonance decay, No LCC</td>
<td>Convex. 30-50% centrality</td>
<td>$R_{\psi 2}$ and $R_{\psi 3}$ Shape similar. Both convex</td>
</tr>
<tr>
<td>Huang/Nie/Ma. PRC 101, 024916 (2020) AMPT</td>
<td>Flat. 30-50% centrality</td>
<td>$R_{\psi 3}$ is slightly concave (may also consistent with being depending on viewing range)</td>
</tr>
<tr>
<td>P. Bozek, PRC 97 034907(2018)</td>
<td>Concave. All centralities</td>
<td>Both concave (after EO resolusion correction, based on private comm. Between Roy/Niseem and Bozek)</td>
</tr>
<tr>
<td>Aihong Tang, STAR Collab. Mtg AVFD version beta1.0</td>
<td>Concave. 30-40% centrality</td>
<td>n/a</td>
</tr>
<tr>
<td>Yicheng Feng PRC 103, 034912 (2021) AMPT</td>
<td>Concave in 30-50% centrality. Other centrality may be flat or convex depending on viewing range</td>
<td>$R_{\psi 2}$ and $R_{\psi 3}$ Shape not similar, although both are concave.</td>
</tr>
<tr>
<td>Gang Wang, CME focus group Mtg 09/20/19 AMPT</td>
<td>Concave in 30-50% centrality. Other centrality may be flat or convex depending on viewing range</td>
<td>$R_{\psi 2}$ and $R_{\psi 3}$ Shape similar flat.</td>
</tr>
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</table>

No clear conclusion about the Shape of R’s observables.