Search for the Chiral Effect
using isobar collisions and BES-II data from STAR

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Topological transitions in the QCD plasma are allowed to change the chirality of the quarks. The electric dipole can be used to observe such chirality-changing transitions.

With the strongest magnetic field that can be produced in experiment, heavy ion collision, the chiral magnetic effect is one of the most attractive phenomena.
Experimental search with isobar collisions

Use $\Delta \gamma$ as an example:

$$\gamma^{\alpha, \beta} \equiv (\cos(\phi^\alpha + \phi^\beta - 2\psi_2))$$

$$\Delta \gamma = \gamma^{OS} - \gamma^{SS}$$

$\Delta \gamma^{Ru+Ru} = \Delta \gamma^{CME} + k \frac{v_2}{N} + \Delta \gamma^{non-flow}$

$\Delta \gamma^{Zr+Zr} = \Delta \gamma^{CME} + k \frac{v_2}{N} + \Delta \gamma^{non-flow}$

$B^2$ are $\approx 15\%$ different

Within $4\%$

The Solenoidal Tracker at RHIC (STAR):
Details of blind analysis

STEP-0: Mock Data challenge
- Test data structure (Au+Au data)
  - ~2 months

STEP-1: Isobar Mixed Analysis
- Code freezing (Each run is Ru+Ru & Zr+Zr)
  - ~1 year

STEP-2: Isobar Blind analysis
- QA with ~ 1% data (Each run is Ru+Ru or Zr+Zr)
  - ~1/2 year

STEP-3: Isobar Unblind analysis
- Final analysis (Ru+Ru & Zr+Zr separated)
  - ~2-3 months

Blind analyses (5 groups):
- $\Delta \gamma$, $\Delta \delta$ and $\kappa$
- $\Delta \gamma$, $\Delta \delta$, $\Delta \gamma (\Delta \eta)$
- $\Delta \gamma$ in PP/SP, $\Delta \gamma (M_{inv})$
- $\Delta \gamma$ in PP/SP
- $R (\Delta S)$ Correlator.

Connections between the methods are studied

Using the frozen code from STEP-1:
- Sensitivity of observables tested using AVFD simulation
- Similar sensitivities are found in all observables

A large, collective effort

M. S. Abdallah et al. (STAR) Phys. Rev. C, 105 (2022) 014901
J. Adam et al. (STAR) Nucl. Sci. Tech. 32 (2021) 48
The Glauber model including smaller size of Ru and larger size of Zr provides a good fit to the multiplicity distribution.

Mean raw multiplicity density is larger in Ru+Ru than in Zr+Zr in matching centrality.
Elliptic flow & triangular flow measurements

- Deviations depending on the rapidity gap remind us of the non-flow effects in this analysis.
- The $v_n$ ratios deviate from unity indicating differences in the shape, nuclear structure between two isobars.
1. $\gamma$ measurement with full TPC ($|\eta| < 1$)

$\gamma_{112}$

$\gamma_{123}$

$\delta$

$$\gamma_{112} \equiv \frac{\cos (\phi_1(\eta_1) + \phi_2(\eta_2) - 2\psi_2|\eta|<1)}{2}$$

$$\gamma_{123} \equiv \frac{\cos (\phi_1(\eta_1) + 2\phi_2(\eta_2) - 3\psi_3|\eta|<1)}{3}$$

$$\delta = \langle \cos (\phi_1 - \phi_2) \rangle$$

Pre-defined CME criteria:

$$\frac{(\Delta \gamma_{112}/v_2)_{Ru+Ru}}{(\Delta \gamma_{112}/v_2)_{Zr+Zr}} > 1$$

$$\frac{(\Delta \gamma_{112}/v_2)_{Ru+Ru}}{(\Delta \gamma_{112}/v_2)_{Zr+Zr}} > \frac{(\Delta \gamma_{123}/v_3)_{Ru+Ru}}{(\Delta \gamma_{123}/v_3)_{Zr+Zr}}$$

$$\frac{(\Delta \gamma_{112}/v_2)_{Ru+Ru}}{(\Delta \gamma_{112}/v_2)_{Zr+Zr}} > \frac{(\Delta \delta)_{Ru+Ru}}{(\Delta \delta)_{Zr+Zr}}$$

Data not compatible with pre-defined CME criteria
2. $\kappa_{112}$ measurement with full TPC ($|\eta| < 1$)

**Pre-defined CME criteria:**

$\frac{(\Delta \gamma_{112}/v_2)^{Ru+Ru}}{(\Delta \gamma_{112}/v_2)^{Zr+Zr}} > \frac{(\Delta \delta)^{Ru+Ru}}{(\Delta \delta)^{Zr+Zr}}$

The background contributions due to the local charge conservation (LCC) and transverse momentum conservation (TMC) have a similar characteristic structure that involves the coupling between $v_2$ and $\delta$. So, we studied the the normalized quantity:

$$\kappa_{112} \equiv \frac{\Delta \gamma_{112}}{v_2 \Delta \delta}.$$  

**Pre-defined CME criterion:**

$$\left(\frac{\kappa_{112}}{(\kappa_{112})^{Zr+Zr}} \right)^{Ru+Ru} > 1$$

![Graph showing data points and analysis](image-url)

Data not compatible with pre-defined CME criterion
3. Differential measurement vs. invariant mass

\[ \Delta \gamma_{\text{Ru}+\text{Ru}} - a' \Delta \gamma_{\text{Zr}+\text{Zr}} = \Delta \gamma_{\text{CME}} + a' \Delta \gamma_{\text{CME}} \]

Where:

\[ a' = \frac{v_2^{\text{Ru}+\text{Ru}}}{v_2^{\text{Zr}+\text{Zr}}} \]

Pre-defined CME criterion in the differential measurement:

\[ \Delta \gamma_{\text{Ru}+\text{Ru}} - a' \Delta \gamma_{\text{Zr}+\text{Zr}} > 0 \]

Do not see a significant difference between systems
4. Extraction of CME fraction: approach I

- TPC $\Psi_{EP} \rightarrow$ proxy of $\Psi_{PP}$
- ZDC $\Psi_1 \rightarrow$ proxy of $\Psi_{RP}$

$\Delta \gamma$ w.r.t. TPC $\Psi_{EP}$ and ZDC $\Psi_1$ contain different fractions of CME and Bkg.

Pre-defined CME criterion:

$$f_{CME}^{Ru+Ru} > f_{CME}^{Zr+Zr} > 0$$

Uncertainty dominated, no significant difference is observed between two isobar systems
4. Extraction of CME fraction: approach II

\[
\frac{\Delta \gamma / v_2^{\text{Ru+Ru}}}{\Delta \gamma / v_2^{\text{Zr+Zr}}} = 1 + f_{\text{CME}}^{\text{Zr+Zr}} \left( B_{\text{Ru+Ru}} / B_{\text{Zr+Zr}} \right)^2 - 1
\]

\[
\frac{\Delta \gamma / v_2^{\text{ZDC}}}{\Delta \gamma / v_2^{\text{TPC}}} = 1 + f_{\text{CME}}^{\text{TPC}} \left( \frac{v_2^{\text{TPC}}}{v_2^{\text{ZDC}}} - 1 \right)
\]

Pre-defined CME criterion:

\[ f_{\text{CME}}^{\text{TPC}} > 0 \]

Differences in the method of estimating \( v_2^{\text{ZDC}} \) and \( v_2^{\text{TPC}} \) compared with the approach-I

Uncertainty dominated, no significant difference is observed between two isobar systems
5. Charge separation measurement with $R_{\psi_2}$

Measurement of the in-plane and out-of-plane distribution of the dipole separation event-by-event

Pre-defined CME criterion:

$$1/\sigma_{\psi_2}^{\text{Ru+Ru}} > 1/\sigma_{\psi_2}^{\text{Zr+Zr}}$$

$$R_{\psi_2} (\Delta S) = C_{\psi_2} (\Delta S) / C_{\psi_2} (\Delta S)$$

$$C_{\psi_2} = \frac{N_{\text{real}} (\Delta S)}{N_{\text{shuffled}} (\Delta S)}$$

$$\Delta S = \frac{\sum_{i=1}^{n^+} w_i^+ \sin(\Delta \phi_i - \psi_2)}{\sum_{i=1}^{n^+} w_i^+} - \frac{\sum_{i=1}^{n^-} w_i^- \sin(\Delta \phi_i - \psi_2)}{\sum_{i=1}^{n^-} w_i^-}$$

$\sigma_{\psi_2}$ is the Gaussian width of the respective $R(\Delta S)$

No significant difference is observed between two isobar systems

$R_{\psi_2}$ and $\Delta \gamma$ have similar sensitivities to CME signal and background; $1/\sigma_{\psi_2} \approx N \Delta \gamma$

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Summary on the isobar blind analysis

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- No significant difference is observed for all the CME observables between two isobar systems.
- $\Delta \gamma / v_2$ ratios are below unity - mainly driven by the multiplicity difference between the two isobars.
Non-flow studies (new since isobar paper)

- No significant difference is observed for all the CME observables between two isobar systems
- $\Delta \gamma / v_2$ ratios are below unity - mainly driven by the multiplicity difference between the two isobars

From the blind analysis:

- Non-flow contribution will cause extra deviations
- The deviation can be understood by non-flow in the measured $v_2$ (estimated with data), the flow-induced CME background (estimated with data), and 3-particle non-flow contributions (estimated with HIJING)
- The isobar data are consistent with the current estimate of non-flow background within error
CME measurements at lower energies

The STAR collaboration has measured charge separation over a wide range of collision energies


A more definitive result may be obtained in the future if we can increase the statistics by a factor of ten for the low energies...


With the BES-II data

- New capabilities
  the new installed Event Plane Detectors
- ~10 times statistics
  the Event Shape Engineering technique
We measure charge-dependent azimuthal correlator using TPC and EPD
Approach-I: measurement with EPD @ 27 GeV

\[ \gamma_{\alpha\beta} = \cos(\Phi^\alpha + \Phi^\beta - 2\Psi) \]

\[ \Delta\gamma = \Delta\gamma^{BG} + \Delta\gamma^{CME} \]

If \[ \Delta\gamma^{BG} = b v_2 \]

\[ \left( \frac{\Delta\gamma}{v_2} \right) = \frac{\cos(\alpha + \beta - 2\Psi)}{\cos(2a - 2\Psi)} \]

Under the background scenario, all these ratios equal one to another. If two different measurements yield different ratios, this would indicate the CME signal.

In a short word, under the flow driven background scenario, we should have:

\[ \frac{\Delta\gamma}{v_2}(\Psi_A) = \frac{\Delta\gamma}{v_2}(\Psi_B) = \frac{\Delta\gamma}{v_2}(\Psi_C) = \cdots \]

Where the \( \Psi_A, \Psi_B, \Psi_C \ldots \) are different planes at same/similar rapidities.

We measure the elliptic flow and the charge separation, using \( \gamma \) correlator (\( \Delta\gamma = \gamma(\text{OS})-\gamma(\text{SS}) \)), w.r.t. TPC-EPD-inner first harmonic planes and the TPC-EPD-outer second harmonic plane.

The ratio of \( \Delta\gamma/v_2 \) between spectator proton rich EPD \( \Psi_1 \) plane and participant dominated \( \Psi_2 \) plane is presented — CME driven correlations will make this ratio >1.
Approach-II: Event Shape Engineering

\[ \Delta y = \Delta y^{BG} + \Delta y^{CME} \]

\[ \Delta y^{BG} = b \nu_2 \]

By looking at the events in different shapes with the flow vectors (corresponding to different \( \nu_2 \)). Then try to estimate the \( \Delta y^{CME} \) level.

\[ y^{\alpha, \beta} \equiv \{ \cos(\phi^\alpha + \phi^\beta - 2\psi_2) \} \]

We use \(|\eta| < 0.5\) to select the event shape;
Use the flow vector to control the event shape;
We use \(|\eta| < 0.5\) as \( \phi^\alpha \) and \( \phi^\beta \) sources;
We use the \( 0.55 < \eta < 1 \) and \(-1 < \eta < -0.55\) to determine our event plane \( \psi_2 \);

Approach-II: Event Shape Engineering technique @ 27 GeV

**Assumption:**
\[ \Delta \gamma = \Delta \gamma^{BG} + \Delta \gamma^{CME} \]

\[ \Delta \gamma^{BG} = b \nu_2 \]

- The measured \( \Delta \gamma_{112} \) decreases linearly with \( \nu_2 \)
- The intercept (\( \Delta \gamma_{112}^{ESE} \)) maximized the possible CME signal fraction

The measured \( \Delta \gamma_{112}^{ESE} \) in different centralities scaled by \( N_{\text{part}} \)

- A promising approach towards the CME signal
- The background is significantly reduced with this approach
- \( \Delta \gamma_{112}^{ESE} \) with finite numbers are observed in this approach. A quantitative investigation of the remaining background is needed for this measurement
Based on the assumption in the isobar blind analysis, a CME-related signal fraction which is larger than 20% is ruled out.

The going-on non-flow effects studies show the isobar data are consistent with the current estimate of non-flow background within the error.

Different techniques are used to search for the CME signal at 27 GeV. The BES-II data and EPDs bring a new opportunity for the CME search at lower energies in the future.
Thank you!
Backup
Backup-1: details in the isobar blind analysis

An automated Run-by-Run QA Algorithm!

How do we define the stable run period before we have the data?

Fully automated algorithm developed for blind QA
Backup-2: equations in the non-flow studies

\[
\frac{(N \Delta \gamma / v_2)_{Ru+Ru}}{(N \Delta \gamma / v_2)_{Ru+Ru}} \equiv \frac{(N C_3 / v_2)_{Ru+Ru}}{(N C_3 / v_2)_{Zr+Zr}}
\]

\[
\approx \frac{\varepsilon_{2}^{Ru+Ru}}{\varepsilon_{2}^{Zr+Zr}} \frac{(1 + \varepsilon_{\text{non-flow}})_{Ru+Ru}}{(1 + \varepsilon_{\text{non-flow}})_{Zr+Zr}} \left[ 1 + \frac{\varepsilon_{3}}{\varepsilon_{2}} / (N v_2^2 - \text{measured}) \right]_{Ru+Ru}
\]

\[
\approx 1 + \frac{\Delta \varepsilon_{2}}{\varepsilon_{2}} - \frac{\Delta \varepsilon_{\text{non-flow}}}{1 + \varepsilon_{\text{non-flow}}} + \frac{\varepsilon_{3}}{\varepsilon_{2}} / (N v_2^2 - \text{measured}) \left[ \frac{1 + \varepsilon_{3}}{\varepsilon_{2}} / (N v_2^2 - \text{measured}) \right]_{Zr+Zr}
\]