Blind analysis of isobar data for the CME search by the STAR collaboration

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Based on: https://arxiv.org/abs/2109.00131
The versatility of RHIC and the unique capabilities of the STAR detector were crucial to the success of the isobar program.
Chirality

1. Deconfined medium of massless quark (chiral symmetry restored)
   - Right-handed quark: $u_R$
   - Right-handed anti-quark: $\bar{u}_R$
   - Left-handed quark: $u_L$
   - Left-handed anti-quark: $\bar{u}_L$

   Kharzeev, McLerran, Warringa 0711.0950

2. Mechanism to create imbalance of left & right handed quarks
   - Initial chirality imbalance, $n_R \neq n_L$
   - Non-conservation of chirality
   - Topological transitions

   Kharzeev et al, hep-ph/0109253, Mace et al, 1601.07342,
   Muller et al, 1606.00342, Lappi et al, 1708.08625

3. Presence of a strong magnetic-field
   - $z=0$

   Kharzeev et al 0711.0950, Skokov et al 0907.1396, McLerran et al 1305.0774

4. Chiral Magnetic Effect ($J \parallel B$)


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P. Tribedy, RBRC seminar, Sept 2, 2021
How do we detect it: find B-field direction

Elliptic anisotropy is measured by correlation between two particles

\[ v_2\{EP\} = \langle \cos(2\phi_1 - 2\Psi_2) \rangle \]

\[ v_2\{2\}^2 = \langle \cos(2\phi_1 - 2\phi_2) \rangle \]

The plane of elliptic anisotropy \( \Psi_2 \) is correlated to B-field direction
How do we detect it: measure charge separation

Measure charge separation across $\Psi_2$ using the correlator:

$$\gamma^{\alpha,\beta} = \langle \cos(\phi_1^\alpha + \phi_2^\beta - 2\Psi_2) \rangle$$

CME case:

$$\gamma^{ss} \neq \gamma^{os}$$

- $\gamma^{+-} = \cos(\pi/2 - \pi/2 + 0) = 1$
- $\gamma^{++,-,-} = \cos(\pi/2 + \pi/2 + 0) = -1$

Quantity of interest:

$$\Rightarrow \Delta\gamma^{CME} = \gamma^{os} - \gamma^{ss} > 0$$

CME causes difference in opposite-sign & same-sign correlation

Voloshin, hep-ph/0406311
How do we detect it: measure charge separation

Measure charge separation across $\Psi_2$ using the correlator:

$$\gamma^{\alpha,\beta} = \langle \cos(\phi_1^\alpha + \phi_2^\beta - 2\Psi_2) \rangle$$

Flowing resonance decay: $\gamma^{ss} \neq \gamma^{os}$

$$\gamma^{+-} = \cos(0 + 0 + 0) = 1$$
$$\gamma^{++,-} = \cos(0 + \pi + 0) = -1$$

Non-CME effect such as flowing resonance decay can lead to difference

$$\Delta \gamma^{reso} = \gamma^{os} - \gamma^{ss} \propto \frac{v_2^{reso}}{\langle N \rangle}$$

Voloshin, hep-ph/0406311
The first measurements at RHIC

STAR collaboration, PRL 103, 251601 (2009)
The first measurements at RHIC

Significant charge separation observed, consistent with CME+ Background

\[ \Delta \gamma = \Delta \gamma^{CME} + k \times \frac{v_2}{N} + \Delta \gamma^{non-flow} \]

Measurement  | Signal  | Background-1  | Background-2
Small system collisions to test CME

Two systems of very different sizes → limited control over background
(This naturally leads to the idea of using two systems of similar sizes)

\[
\Delta \gamma^{A+A} = \Delta \gamma^{CME} + k \times \frac{v_2}{N} + \Delta \gamma^{non-flow}
\]

\[
\Delta \gamma^{p+A} = \Delta \gamma^{CME} + k \times \frac{v_2}{N} + \Delta \gamma^{non-flow}
\]


Only two equations & more unknowns
difficult to prove if

\[\Delta \gamma^{CME} = 0\]
Isobar collisions

Isobar collisions provide the best possible control of signal and background compared to all previous experiments.

$Larger$ signal in $Ru$: $1.2\ B$ events can give $5\sigma$ significance for $20\%$ signal level.
Details Of The Data Taking Of The Isobar Run

**Goal:** minimize the systematics in observable ratios, similar run conditions for both species

**Two important steps:**
1) Fill-by-fill switching
2) Level luminosity

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G. Marr et al., in 10th International Particle Accelerator Conference (2019) pp. 28–32.
Blind analysis of the isobar data
Steps of Isobar blind analysis

NPP PAC recommended a blind analysis of isobar data
Blinding committee decides the procedure

Five independent groups will perform analysis

No access to species-specific information before last step
Everything documented (not written → not allowed)
Case for CME & interpretation must be pre-defined
All codes must be frozen and run by another person
Centrality determination

Blind analysis: we decided to compare observables at same centralities between isobars

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<th>Nucleus</th>
<th>Case-1 [83]</th>
<th>R (fm)</th>
<th>a (fm)</th>
<th>$\beta_2$</th>
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See references in:

MC-Glauber with two-component model used to describe uncorrected multiplicity distribution. WS parameters with no deformation (thinker neutron skin in Zr) provides the best description of the multiplicity distributions.
Multiplicity difference between the isobars

Mean efficiency uncorrected multiplicity density is larger in Ru than in Zr in a matching centrality, this can affects signal and background difference between isobars.
Elliptic flow difference between the isobars

\[ v_2 \{EP\} = \langle \cos(2\phi_1 - 2\Psi_2) \rangle \]
\[ v_2 \{2\}^2 = \langle \cos(2\phi_1 - 2\phi_2) \rangle \]

\( v_2 \) studied \( \eta \)-gap (including EPDs), ratio deviates from unity indicating difference in the shape, nuclear structure between two isobars (larger quadruple deformation in Ru+Ru)
Elliptic flow difference between isobars

\[ v_2\{EP\} = \langle \cos(2\phi_1 - 2\Psi_2) \rangle \]
\[ v_2\{2\}^2 = \langle \cos(2\phi_1 - 2\phi_2) \rangle \]

\( v_2 \) studied η-gap (including EPDs), ratio deviates from unity indicating difference in the shape, nuclear structure between two isobars (larger quadruple deformation in Ru+Ru)
Triangular flow difference between isobars

\[ v_3\{2\}^2 = \langle \cos(3\phi_1 - 3\phi_2) \rangle \]

Strong rapidity dependence, ratio below unity in central collisions, not fully understood
$v_n$ ratio deviates from unity indicating difference in the shape, nuclear structure between two isobars. $v_n$ drives flow-driven background:

$$\Delta \gamma^{bg} = \gamma^{OS} - \gamma^{SS} \propto \frac{v_2^{reso}}{N}$$
Results on CME sensitive variables
Charge separation across elliptic flow plane

\[ \gamma_{112}\{\text{EP}\} = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_2^{\text{TPC}}) \rangle \]

\[ \Delta \gamma = \gamma_{112}(\text{OS}) - \gamma_{112}(\text{SS}) \]

Ratio of charge separation correlated to elliptic flow plane is below unity, however only this quantity is not decisive.
Charge separation scaled by elliptic flow

\[ \gamma_{12}\{\text{EP}\} = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_2^{\text{TPC}}) \rangle \]

\[ \Delta \gamma = \gamma_{12}(\text{OS}) - \gamma_{12}(\text{SS}) \]

\[ \Delta \gamma^\text{bkg} = \gamma_\text{OS} - \gamma_\text{SS} \propto \frac{v_2^{\text{reso}}}{N} \]

\[ \frac{\Delta \gamma}{v_2} \]

Pre-defined criteria for CME

\[ \frac{(\Delta \gamma/v_2)_{\text{RuRu}}}{(\Delta \gamma/v_2)_{\text{ZrZr}}} > 1 \]

NOT seen
Two-particle correlator of charge separation

\[ \delta \equiv \langle \cos(\phi_\alpha - \phi_\beta) \rangle \]

\[ \Delta \delta = \delta(\text{OS}) - \delta(\text{SS}) \]

Two particle-charge separation observable \( \delta \)-correlator — measures charge separation that may or may not be correlated to event plane.
Charge separation across elliptic flow plane

Charge separation correlated to event plane

Charge dependent two-particle correlation

\[
\gamma_{112}\{\text{EP}\} = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_2^{\text{TPC}}) \rangle \\
= \langle \cos(\phi_\alpha - \phi_\beta + 2\phi_\beta - 2\Psi_2) \rangle \\
\approx \langle \cos(\phi_\alpha - \phi_\beta) \cos(2\phi_\beta - 2\Psi_2) \rangle \\
= \kappa_{112} \langle \cos(\phi_\alpha - \phi_\beta) \rangle \langle \cos(2\phi_\beta - 2\Psi_2) \rangle
\]

\[
\delta = \langle \cos(\phi_\alpha - \phi_\beta) \rangle \\
v_2 = \langle \cos(2\phi - \Psi_2) \rangle
\]

\[
\gamma_{112} \equiv \kappa_{112} \delta v_2
\]

This factorization breaking coefficient should be >1 and can help test CME
Ratio of factorization breaking

\[ \gamma_{112}\{EP\} = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_T^{\text{TPC}}) \rangle \]

\[ \Delta \gamma = \gamma_{112}(OS) - \gamma_{112}(SS) \]

\[ \delta \equiv \langle \cos(\phi_\alpha - \phi_\beta) \rangle \]

\[ \Delta \delta = \delta(OS) - \delta(SS) \]

Factorization breaking:

\[ \kappa_{112} \equiv \frac{\Delta \gamma_{112}}{\nu_2 \cdot \Delta \delta} \]

Pre-defined CME criteria:

\[ \frac{\kappa_{112}^{\text{Ru+Ru}}}{\kappa_{112}^{\text{Zr+Zr}}} > 1 \]

This pre-defined CME signature is NOT seen
Charge separation across triangular flow plane

**B-field is corrected to $\Psi_2$ plane**

$\gamma_{112} = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_2) \rangle$

Signal (B-field) + Background ($\propto v_2$)

**B-field is not-corrected to $\Psi_3$ plane**

$\gamma_{123} = \langle \cos(\phi_\alpha + 2\phi_\beta - 3\Psi_2) \rangle$

Background only ($\propto v_3$)

Charge separation across third harmonic plane can serve as data-driven baseline
Charge separation across $\Psi_2$ and $\Psi_3$ planes

$\gamma_{12} = \langle \cos(\phi_1^\alpha + \phi_2^\beta + 2\Psi_2) \rangle$

signal + background

$\gamma_{13} = \langle \cos(\phi_1^\alpha + 2\phi_2^\beta - 3\Psi_3) \rangle$

100% background

Pre-defined CME criteria:

$$\frac{(\Delta \gamma_{112}/v_2)^{RuRu}}{(\Delta \gamma_{112}/v_2)^{ZrZr}} > \frac{(\Delta \gamma_{123}/v_3)^{RuRu}}{(\Delta \gamma_{123}/v_3)^{ZrZr}}$$

This pre-defined CME signature is NOT seen
Measurement using STAR EPD (for the first time)

Pre-defined CME criteria:

\[
\frac{(\Delta \gamma_{112}/v_2)^{RuRu}}{(\Delta \gamma_{112}/v_2)^{ZrZr}} > \frac{(\Delta \gamma_{123}/v_3)^{RuRu}}{(\Delta \gamma_{123}/v_3)^{ZrZr}}
\]

This pre-defined CME signature is NOT seen
Relative pseudorapidity dependence of $\gamma_{112}$

Causality precludes late-time correlations to spread over large $\eta$ (wide acceptance $\rightarrow$ strength)

B-field driven charge separation: large $\Delta\eta > 1$
Resonance decay: smaller $\Delta\eta < 1$

The relative pseudorapidity dependence is similar between the two species
Invariant mass dependence of $\gamma_{112}$

Pre-defined CME criteria:

$$\Delta \gamma^{\text{Ru}+\text{Ru}} - a' \Delta \gamma^{\text{Zr}+\text{Zr}} > 0$$

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

Resonances are identifiable as peaks in invariant mass distribution

This pre-defined signature is NOT seen
Alternate charge separation measure: R-variable

R-variable is a ratio of distribution (of event-by-event charged-dependent dipole anisotropy)

$$R_{\psi_2}(\Delta S) = \frac{C_{\psi_2}(\Delta S)}{C_{\psi_2}^{\perp}(\Delta S)} ,$$

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

$$\Delta S = \frac{\sum_{i=1}^{n^+} w_i^+ \sin(\Delta \varphi_2) - \sum_{i=1}^{n^-} w_i^- \sin(\Delta \varphi_2)}{\sum_{i=1}^{n^+} w_i^+ - \sum_{i=1}^{n^-} w_i^-}$$

The width of R-variable is sensitive to signal + Background

The case for CME is: $1/\sigma_{R_{\psi_2}}(Ru + Ru) > 1/\sigma_{R_{\psi_2}}(Zr + Zr)$
Alternate charge separation measure: R-variable

Pre-defined CME criteria: $1/\sigma_{R_{\psi_2}}(\text{Ru} + \text{Ru}) > 1/\sigma_{R_{\psi_2}}(\text{Zr} + \text{Zr})$

This pre-defined signature is NOT seen
Compilation of all the results

Good consistency between results from different groups.
Predefined CME signatures: Ratios involving $\Psi_2 >$ those involving $\Psi_3$, and $> 1$
None of the predefined signatures have been observed in the blind analysis
Postblinding

Why ratios of $\Delta y/v^2$ are below unity?

Inverse of multiplicities, or as an alternative $r$ maybe better baselines compared to unity used in the pre-defined blind analysis documentation

Alternate baselines also do not present a clear case for CME
Conclusion

Experimental test of CME in isobar collisions performed using a blind analysis

Multiplicity distributions and mean multiplicity are different between isobars

\( v_2 \) (2.5\%) & \( v_3 \) (7\%) difference between the isobars seen in central events

A precision down to 0.4\% achieved in the primary CME variable

All criteria to observe CME were pre-defined and none observed

CME observables \( \Delta y/v_2 \) baseline are affected by the multiplicity difference (4\% in 20-50\%), post-blind analysis compared two possibilities, no clear case for CME

The observed multiplicity difference between the isobars requires future CME analyses to better understand the baselines in order to best utilize the precision demonstrated in this analysis. Better understanding of the non-flow may be another goal.