Overview of Chiral Magnetic Effect from RHIC Beam Energy Scan program

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Thanks to the STAR CME focus group and many collaborators for discussions and insights!
Chiral Magnetic Effect

- QCD vacuum transition leads to nonzero topological charge.
- Chirality imbalance of quarks coupled with strong magnetic field induces an electric charge separation along the B field direction (violates local Parity Symmetry and CP Symmetry!)

\[ \vec{J} = \frac{e^2}{2\pi^2} \mu_5 \vec{B} \]

Kharzeev, Pisarski, Tytgat, PRL 81(1998) 512
Voloshin, PRC 70 (2004) 057901
CME Observables

- Common observables:
  - $\gamma_{112}$ correlator
  - R correlator
  - Signed balance functions

Core components of them are equivalent. Here we focus on:

$\gamma_{112} = \langle \cos(\phi_1 + \phi_2 - 2\psi_{RP}) \rangle = \langle v_1v_1 \rangle - \langle a_1a_1 \rangle + \text{BG}(v_2^c)$

CME signal: $\Delta \gamma^\text{CME} = \gamma^\text{OS} - \gamma^\text{SS} > 0$

Parity Odd, can not directly observe

Parity Even, sensitive to charge separation

Variants of $\gamma_{112}$: To suppress $\kappa_{112}$ correlator

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

$H^k = (k v_2 \delta - \gamma) / (1 + k v_2) \quad k = 1, 1.5 \ldots$

Non-CME

Flowing resonance decay

More Methods:
- Participant Plane vs Spectator Plane,
  Covariance between variables,
  Event Shape Selection (Engineering), $M_{inv}$ …
Why search CME in Beam Energy Scan?

- At LHC energies, $\Delta y^{112}$ could be explained by $v_2$ related BKG.
- ESE based on variables excluding POI is unstable.
- We should focus on lower energy. Advantage: longer lasting B.
- Possible to see the turn-off effect near 7.7 GeV (where QGP is about to vanish!)
Beam Energy Scan at RHIC

**BES-I**

<table>
<thead>
<tr>
<th>√sNN (GeV)</th>
<th>Events (10^6)</th>
<th>Year</th>
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<tr>
<td>62.4</td>
<td>46</td>
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</tr>
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<td>7.7</td>
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Statistics:
- 20 times higher

**BES-II**

<table>
<thead>
<tr>
<th>√sNN (GeV)</th>
<th>Events (10^6)</th>
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<tr>
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<td>9.2</td>
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<td>2020</td>
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<tr>
<td>7.7</td>
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Publication on CME
- BES-I: STAR, PRL 113 (2014) 052302
- BES-II: STAR, PLB 839 (2023) 137779

Detector Upgrades:
- 2018 EPD: high EP resolution into spectator region (2.1<η<5.1)
- 2019 iTPC: wider acceptance
Beam Energy Scan I

- Common BKG in $\gamma^{OS}$ and $\gamma^{SS}$ could be subtracted by $\Delta \gamma$
- In mid-central collisions, a finite charge separation is observed.
- However, $\Delta \gamma^{112}$ contains BKG contribution related to flow and nonflow.
Beam Energy Scan I

$H^k = (k v^2 \delta - \gamma) / (1 + k v^2)$  \( k = 1, 1.5 \ldots \)

- $\Delta H$ disappears at the lowest and highest energies.
- The vanishing $\Delta H$ at 7.7 GeV indicates the domination of hadronic interactions over partonic ones.
- The $B$ field may decay too fast at 2.76 TeV.

- Mid-central collisions are preferred.
  - $B$ field stronger than central events
  - More robust against nonflow $\sim 1/N$
Normalized observable $\kappa^{112}$ allows better comparison between data and pure BKG model.

- $\kappa^{112}$ at highest and lowest energies are consistent with BKG prediction from AMPT.
- Nonflow in peripheral region may cause the enhancement of $\kappa^{112}$. 
The Lesson and Challenge from BES-I

In BES-I, we learned:

- Using participant plane (TPC) entails large nonflow BKG (can be avoided with $\Psi_1$)
- Much Larger statistics needed!
- The large $v_2$-BKG requires better methods.

Lesson from Recent Isobar Data:

Fraction of CME signal is not as large as expected in smaller system: larger nuclei fluctuation and smaller B field; in higher energy: shorter B life time.

BES-II provides unique opportunity to search for the CME!

In BES-II

- ✔ EPD (2.1<\eta<5.1) covers spectator range
- ✔ x20 statistics
- ✔ New methods being developed

<table>
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<th>Beam rapidity</th>
<th>Year</th>
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<td>2.11</td>
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Beam Energy Scan II - P.P. vs S.P.

Assumption: In a pure-BKG scenario driven by flow

$$\frac{\Delta \gamma (\Psi_{1,SP})}{v_2} = \frac{\Delta \gamma (\Psi_{2,pp})}{v_2} = \frac{\Delta \gamma (\Psi_{2,|\eta|<1})}{v_2}$$

$$R(\Psi_n) = \frac{\Delta \gamma (\Psi_n)}{v_2(\Psi_n)} \times N_{\text{part}}$$

would be unity

Double ratio is consistent with unity for 10-50%.

Flow decorrelation is a significant uncertainty yet to be understood in this approach.
Assumption: Λ and $\bar{\Lambda}$ hyperon global polarization is split by strong B field

$$P(\Lambda) \approx \frac{\omega}{2T} + \frac{\mu_\Lambda}{T} B$$

$$P(\bar{\Lambda}) \approx \frac{\omega}{2T} - \frac{\mu_\bar{\Lambda}}{T} B$$

$$\Rightarrow \Delta P \propto B$$

Parity-even

$$\text{Cov}(\Delta P, \Delta \gamma^{112})$$ sensitive to B field, should be < 0

Limited by statistics, we are unable to use covariance to reach the required sensitivity.

At the hyperon formation time, the magnetic field may be much smaller than expected.
Assumption: Event by Event chirality (handness) fluctuation impacts the following covariance:

\[
\Delta n = \frac{n_L - n_R}{n_L + n_R} \quad ; \quad \Delta a_1 = a_1^+ - a_1^- \quad \text{parity-odd}
\]

\[
\operatorname{Cov}(X, Y) = \langle XY \rangle - \langle X \rangle \langle Y \rangle
\]

\[
\operatorname{Cov} (\Delta n, \Delta a_1) \text{ sensitive to chirality fluctuations } < 0
\]

Both covariance method, even if they entail true signal, can not reach the statistical precision needed for observation.
Beam Energy Scan II - Event Shape Selection

Assumption:

$$\Delta \gamma^{112} = \Delta \gamma^\text{CME} + k \frac{v_2}{N} + \Delta \gamma^\text{non-flow}$$

Measured Signal

Backgrounds

Flow vector $$q_2^2 = \frac{(\sum \sin 2\phi)^2 + (\sum \cos 2\phi)^2}{N(1 + Nv_2^2)}$$ (event binning) or $$v_2$$ (BKG control) has contributions from:

- participant shape distribution – likely long range and correlated over large $$\eta$$ gaps
- emission pattern fluctuations – short range, uncorrelated for different $$\eta$$ regions

Geometric Variation

Emission pattern fluctuation

Flow vector has contributions from:

- single $$q_2$$
- pair $$q_2$$
- single $$v_2$$
- pair $$v_2$$

Pair information used

27 GeV Au+Au (run18)

STAR preliminary

Centrality: 30 - 40%

Intercept = $$(1.8 \pm 0.3) \times 10^{-4}$$
Beam Energy Scan II - Event Shape Selection

More coming soon:

- Event shape variables
  - single $q^2$
  - pair $q^2$
- Elliptic flow variables
  - single $v_2$
  - pair $v_2$

○ From AVFD study, we settled the optimal ESS recipe (c) that can accurately match the input true CME signal.
○ ESS recipe (a) and (b) under-subtract the BKG.
○ Recipe (d) over-subtracts the BKG.

c - arXiv:2307.14997
Beam Energy Scan II - Event Shape Selection

- Spectator plane $\Psi_1$ is more correlated to the magnetic field direction.
- ESS (a) and (b) present finite $\Delta \gamma_{ESS}^{112}$ in mid central events with effectively more than 70% of $v_2$ BKG removed.
- The precision of STAR measurement after ESS is controlled to be 5.4% (3.6%) of ensembled average $\Delta \gamma^{112}$ at BES-II 27 (19.6) GeV.
- We will report the new findings of BES-II result (7.7 to 27 GeV) in the upcoming QM2023.
Summary

- The search for the CME addresses an intrinsic topological property of QCD.
- We have learned many new insight for the $v_2$-related BKG in the CME observables
  - H-correlator, $\kappa^{112}$, double ratio of S.P./P.P, and inter-observable covariance.
- We have developed new Event Shape Selection utilizing pair information to select events, and single $v_2$ to control BKG.
- New BES-II $\Delta y$ measurements will be presented in QM2023.
Thank you!