Search for CME with STAR experiment

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For the STAR Collaboration

Supported in part by
OUTLINE

• Physics motivation and observables
• Brief historical review of STAR (and other) measurements
• Recent CME measurements from STAR
  o Invariant mass
  o EPD measurements
  o Other observables/approaches
  o Spectator/participant planes in Au+Au collisions
  o Isobar collisions
• Summary and outlook
CHIRAL MAGNETIC EFFECT (CME)

The strong interaction

\[ \mathcal{L}_{QCD} = \sum_q ( \bar{\psi}_q i \gamma^\mu \left[ \partial_\mu, \partial_\nu \right] + i g \left( G_\mu^a t^a \right)_i) \psi_q - m_q \bar{\psi}_q \psi_q - \frac{1}{4} G_\mu^a G^{\mu\nu}_a \]

\[ \alpha^2 \left( E^2 - B^2 \right) \]

\[ + \frac{\theta}{2\pi} \left( \alpha^a \tilde{E}_a \cdot \tilde{B}_a \right) \]

\('t Hooft vacuum\]

\[ \text{to solve the } U(1)_A \text{ problem (1976)} \]

E: C-odd, P-odd, T-even
B: C-odd, P-even, T-odd

Explicitly breaks CP

Early universe ultraviolet \( \theta \approx 1 \gg \text{current infrared } \theta \approx 0 \)

QCD vacuum fluctuation, chiral anomaly, topological gluon field

Discovery of the CME would imply: Chiral symmetry restoration (current-quark DOF & deconfinement);
Local P/CP violation that may solve the strong CP problem (matter-antimatter asymmetry)
THE COMMON $\gamma$ VARIABLE

$\gamma_{\alpha\beta} = \langle \cos(\varphi_\alpha + \varphi_\beta - 2\varphi_{RP}) \rangle$

$\gamma_{+-,-} > 0, \quad \gamma_{++,-} < 0$

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

$\Delta \gamma > 0$

$$
\gamma_{\alpha\beta} = \left[ \langle \cos(\varphi_\alpha - \psi_{RP}) \cos(\varphi_\beta - \psi_{RP}) \rangle - \langle \sin(\varphi_\alpha - \psi_{RP}) \sin(\varphi_\beta - \psi_{RP}) \rangle \right] + \frac{N_{\text{cluster}}}{N_\alpha N_\beta} \left( \cos(\varphi_\alpha + \varphi_\beta - 2\varphi_{\text{cluster}}) \cos(2\varphi_{\text{cluster}} - 2\varphi_{RP}) \right)
$$

$$
= \left[ \langle v_{1,\alpha} v_{1,\beta} \rangle - \langle a_\alpha a_\beta \rangle \right] + \text{[charge-independent Bkg (e.g. mom. conservation)]} + \frac{N_{\text{cluster}}}{N_\alpha N_\beta} \left( \cos(\varphi_\alpha + \varphi_\beta - 2\varphi_{\text{cluster}}) \right) v_{2,\text{cluster}}
$$

$\Delta \gamma = 2 \langle a_1^2 \rangle + \frac{N_{\text{cluster}}}{N_\alpha N_\beta} \left( \cos(\varphi_\alpha + \varphi_\beta - 2\varphi_{\text{cluster}}) \right) v_{2,\text{cluster}}$
Established analytical relationship between $\Delta \gamma$ and $R_{\psi_2}(\Delta S)$

"Equivalence" verified by MC simulations and the EBE-AVFD model

$\Delta \gamma$ and $R_{\psi_2}(\Delta S)$ have similar sensitivities to CME signal and background
STAR (and ALICE, CMS) MEASUREMENTS

STAR, PRL 103 (2019) 251601; PRC 81, 054908 (2010)

Measurement wrt ZDC $\psi_1$; Similar result wrt TPC $\psi_2$

STAR, PRC 88 (2013) 064911

Small system; signal as large as heavy ion; large bkg contributions

STAR, PRL 113 (2014) 052302

ESE projection to $v_2=0$; bkg significantly reduced, but not eliminated

STAR, PRC 89 (2014) 044908

First measurement; Large signal

STAR, PRL 103 (2019) 251601; PRC 81, 054908 (2010)

ALICE, PRL 110 (2013) 012301

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• Explicit demonstration of “resonance” background

• Exploit “ESE” to extract CME, assuming CME is mass independent

• Upper limit 15% at 95% CL
MORE RECENT LOW ENERGY (27 GeV) DATA

- Higher statistics, new detector (EPD)
- New approach: inner EPD -> first-order harmonic plane; Outer EPD -> second-order harmonic plane.
- Current data consistent with background contributions

Covers both spectator and Participant regions @27 GeV

Yu Hu (STAR), arXiv:2110.15937, SQM 2021
NEW OBSERVALES/APPROACHES

Signed balance function (SPF)
Tang, CPC 44 (2020) 054101
Yufu Lin (STAR), NPA 1005 (2021) 121828, QM 2019

CME-helicity correlation
Du, Finch, Sandweiss, PRC 78 (2008) 044908
Finch, Murray, PRC 96 (2017) 044911
Yicheng Feng (STAR), DNP 2020

Sliding Dumbbell
Jagbir Singh (STAR) QM 2019

Yufu Lin’s talk this afternoon
• r is out-of-plane to in-plane ratio of the SPF momentum-ordering difference
• Both $r_{rest}$ and $R_B=r_{rest}/r_{lab}$ are larger than unity, above model calculations without CME.

• Positive correlation btw CME $\Delta a_1$ and $\Lambda$ net-helicity from chirality anomaly
• Current signal consistent with zero within uncertainties

• Select CME enriched sample
• Perform $\Delta \gamma$ measurement with background subtraction in separate event classes

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INTRA-EVENT “CME-v2 FILTER”

\[ \Delta \gamma_{(SP)} = a \Delta \gamma_{Bkg \{PP\}} + \Delta \gamma_{CME \{PP\}} / a \]
\[ \Delta \gamma_{(PP)} = \Delta \gamma_{Bkg \{PP\}} + \Delta \gamma_{CME \{PP\}} \]
\[ A = \Delta \gamma_{(SP)} / \Delta \gamma_{(PP)} \]
\[ a = v_{2 \{SP\}} / v_{2 \{PP\}} \]
\[ \Delta \gamma_{(SP)} / a - \Delta \gamma_{(PP)} = (1 / a^2 - 1) \Delta \gamma_{CME \{PP\}} \]
\[ f_{CME} = \frac{\Delta \gamma_{CME \{PP\}}}{\Delta \gamma_{(PP)}} = \frac{A}{a - 1} \]

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• Consistent-with-zero signal in peripheral 50-80% collisions with relatively large errors
• Indications of finite signal in mid-central 20-50% collisions, with 1-3σ significance
• Possible remaining nonflow effects
REMAINING NONFLOW EFFECTS

Feng et al., arXiv:2106.15595

\[ f_{CME} = \frac{\Delta \gamma_{CME} \{PP\}}{\Delta \gamma \{PP\}} = \frac{A/a - 1}{1/a^2 - 1} \]

\[ A = \frac{\Delta \gamma \{SP\} / v_2 \{SP\}}{\Delta \gamma \{PP\}^* / v_2 \{PP\}^*} = \frac{C_3 \{SP\} / v_2^2 \{SP\}}{C_3 \{PP\}^* / v_2^2 \{PP\}^*} = \frac{1 + \epsilon_{nf}}{1 + \epsilon_3 / \epsilon_2} \]

Cv

Nonflow in $\Delta \gamma$ → negative $f_{CME}$

Nonflow in $v_2$ → positive $f_{CME}$

\[ C_3 \{SP\} = \frac{C_{2p} N_{2p} v_{2,2p} \{SP\} v_2 \{SP\}}{N^2} \]

\[ C_3^* \{EP\} = \frac{C_{2p} N_{2p} v_{2,2p} \{EP\} v_2 \{EP\}}{N^2} + \frac{C_{3p} N_{3p}}{2N^3} \]

\[ \epsilon_2 \equiv \frac{C_{2p} N_{2p} v_{2,2p}}{N v_2} \quad \epsilon_3 \equiv \frac{C_{3p} N_{3p}}{2N} \]

\[ \Delta \gamma_{bkgd} = \frac{N_{2p}}{N^2} \langle \cos(\phi_\alpha + \phi_\beta - 2\phi_{2p}) \rangle v_{2,2p} \]

\[ C_{2p} = \langle \cos(\phi_\alpha + \phi_\beta - 2\phi_{2p}) \rangle \]

\[ C_{3p} = \langle \cos(\phi_\alpha + \phi_\beta - 2\phi_e) \rangle_{3p} \]

\[ v_2^* \{EP\} = \sqrt{v_2^2 \{EP\} + v_{2,nf}^2} \]

\[ \epsilon_{nf} \equiv \frac{v_{2,nf}^2}{v_2^2} \]

\[ f_{CME}^* \approx \frac{\epsilon_{nf} - \frac{\epsilon_3 / \epsilon_2}{N v_2^2 \{EP\}}}{\frac{1 + \epsilon_{nf}}{a^2} - 1} \]

\[ f_{CME}^* = \left( \frac{1 + \epsilon_{nf}}{1 + \frac{\epsilon_3 / \epsilon_2}{N v_2^2 \{EP\}} - 1} \right) \left( \frac{1 + \epsilon_{nf}}{a^2} - 1 \right) \]

\[ = \left( \frac{1 + \epsilon_{nf}}{1 + \frac{(1+\epsilon_{nf}) \epsilon_3 / \epsilon_2}{N v_2^2 \{EP\}} - 1} \right) \left( \frac{1}{a^*^2} - 1 \right) \]

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MODEL ESTIMATES OF NONFLOW

Feng et al., arXiv:2106.15595

\[ f_{\text{CME}}^* \approx \left( \frac{\epsilon_{\text{nf}} - \frac{\epsilon_3}{N v_2^2} \{\Delta P}\}}{1 + \epsilon_{\text{nf}} - 1} \right) \]

- 2-particle nonflow estimates from AMPT
- 3-particle nonflow estimates from HIJING
- Net effect on \( f_{\text{CME}}^* \) can possibly be negative (model dependent)
- Further, additional model studies
Search for the Chiral Magnetic Effect with Isobar Collisions at $\sqrt{s_{NN}} = 200$ GeV by the STAR Collaboration at RHIC

**ISOBAR COLLISIONS**

Deng et al. PRC **94** (2016) 041901(R)

Same A → same background
Different Z → different signal

Voloshin, PRL **105** (2010) 172301

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**Figure:**

- **Projection with 400M events**
  - Case 1
  - Case 2

- **Significance**
  - 11σ
  - 5σ
  - 2σ

- **Background level (%)**
  - 20 - 60%

- **R_s - R_{B_{eq}} = (1-bg)(R_{B_{eq}})\sqrt{s_{NN}} = 200 GeV**

- **Background ∝ 1/N → isobar/AuAu ~ 2**
- **Mag. field B ∝ A^{1/3} → Signal: AuAu/isobar ~ 1.5**
- Could be x3 reduction in f_{CME} at the same n/s
- If AuAu f_{CME}=10%, then isobar 3% (1σ effect)

- **Caveats:** Axial charge densities and sphaleron transition probabilities could be different between Au+Au and isobar, e.g. AVFD-glasma \(\mu_s/s\): isobar/AuAu ~ 1.5

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**Voloshin, PRL 105 (2010) 172301**

**Yicheng Feng, Yufu Lin, Jie Zhao, FW, arXiv:2103.10378**

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**Formula:**

- **Ru/Zr = 1 + 15%*10% = 1.015 \pm 0.004**

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**Text:**

- **3.3σ effect if isobar ≈ AuAu (f_{CME}=10%)**

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**ISOBAR SYSTEMS ARE NOT IDENTICAL: MULTIPLICITY**

- **Ru**
- **Zr**

Larger charge radius
Little neutron skin

Smaller charge radius
Much thicker neutron skin

Overall size: Ru < Zr

→ Larger energy density in Ru > Zr
→ Larger multiplicity in Ru > Zr

Predicted by DFT:
Hanlin Li et al. PRC 98 (2018) 054907

Isobar data:
arXiv: 2109.00131
**ISOBAR SYSTEMS ARE NOT IDENTICAL: \( v_2 \)**

Larger charge radius
Little neutron skin

Smaller charge radius
Much thicker neutron skin

**Halo-type**

Predicted by DFT:
Haojie Xu et al. PRL 121 (2018) 022301

Nuclear deformity:
Deng et al. PRC 94 (2016) 041901(R)

\[
\Delta \gamma_{\text{bkgd}} = \frac{4N_2p}{N^2} \left\langle \cos(\phi_\alpha + \phi_\beta - 2\phi_{2p}) \right\rangle v_{2,2p}
\]

Normalize by \( v_2 \) and \( N \rightarrow N\Delta \gamma/v_2 \)

**Isobar data:**
arXiv: 2109.00131

Note centrality axis flip

\( v_2 \) differs by 2-3%

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$\Delta \gamma / v_2$ RESULTS FROM MULTIPLE GROUPS

\[ \Delta \gamma_{\text{bgd}} = \frac{4N_{2p}}{N^2} \left\langle \cos(\phi_\alpha + \phi_\beta - 2\phi_{2p}) \right\rangle v_{2,2p} \]

- Trivial multiplicity dilution effect
- Not included in the predefined observable
- $N \Delta \gamma / v_2$ would be better

Under the assumption of flowing clusters, scales with overall multiplicity, then $\Delta \gamma$ is diluted by $1/N$

All groups are consistent. $\Delta \gamma / v_2$ follows closely with $N_{\text{ch}}$

4.4% different

Flipped: 1/N ratio
\[ \Delta \gamma, \Delta \gamma/v_2, \kappa = \Delta \gamma/(\Delta \delta*v_2) \] MEASUREMENTS

Indeed a precision of 0.4% is achieved!

Ru+Ru/Zr+Zr ratios all below unity, naively unexpected; main reason is the 4.4% Nch difference
MONEY PLOTS

Nonflow difference is important!

Nonflow: \[
\frac{(N\Delta\delta)^{\text{Ru+Ru}}}{(N\Delta\delta)^{\text{Zr+Zr}}} \approx 1.03
\]
REMAINING NONFLOW EFFECTS

Feng et al., arXiv:2106.15595

\[ f_{CME} = \frac{\Delta \gamma_{CME} \{PP\}}{\Delta \gamma \{PP\}} = \frac{A/a - 1}{1/a^2 - 1} \]

\[ A = \frac{\Delta \gamma \{SP\} / v_2^2 \{SP\}}{\Delta \gamma \{PP\}^* / v_2^2 \{PP\}^*} = \frac{C_3 \{SP\} / v_2^2 \{SP\}}{C_3 \{PP\}^* / v_2^2 \{PP\}^*} = \frac{1 + \varepsilon_{nf}}{1 + \frac{\varepsilon_3 / \varepsilon_2}{N v_2^2 \{PP\}}} \]

Nonflow in \( \Delta \gamma \) \( \Rightarrow \) negative \( f_{CME} \)

\[
\left( \frac{N \Delta \gamma / v_2^2 \{SP\}^*}{N \Delta \gamma / v_2^2 \{PP\}^*} \right)^{Ru} \left( \frac{NC_3 / v_2^2 \{SP\}^*}{NC_3 / v_2^2 \{PP\}^*} \right)^{Zr} = \left( \frac{C_{2p} N_{2p} v_{2,2p} \{SP\}^*}{C_{2p} N v_2 \{PP\}^*} \right)^{Ru} \left( \frac{C_{2p} N_{2p} v_{2,2p} \{SP\}^*}{C_{2p} N v_2 \{PP\}^*} \right)^{Zr} \left( \frac{1 + \varepsilon_{nf}}{1 + \varepsilon_{nf}} \right)^{Ru} \left( \frac{1 + \varepsilon_{nf}}{1 + \varepsilon_{nf}} \right)^{Zr} \]

- Depending on the relative Ru+Ru/Zr+Zr difference of various nonflow effects, the baseline can be above, equal, or below unity
- Final isobar conclusion will require detailed nonflow studies

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SUMMARY AND OUTLOOK

• CME is very important physics. Significant efforts in theory and experiments.

• STAR has pioneered and played significant role in the CME search. Primary efforts in understanding and removing backgrounds.

• The possible CME is a small fraction of the measured $\Delta\gamma$ signal. Most recent STAR data indicate a finite CME signal with 1-3$\sigma$ significance; nonflow effects under investigation.

• Isobar blind analysis is a tour de force. Anticipated precision down to 0.4% is achieved. No CME signal is observed in the blind analysis; not inconsistent with Au+Au data. Further (nonflow) investigations needed to quantify significance.

• Current data 2.4B MB Au+Au, 3.8B isobar events. Expect 20B Au+Au from 2023+25 runs, together with large BES-II data samples.