Important take aways:

I. The scaling properties of background- and chiral-magnetically-driven charge separation provides a potent tool for characterizing the CME.

II. Current results indicate;
   ✓ a robust CME signal in Au+Au and isobar (Ru+Ru and Zr+Zr) collisions at $\sqrt{s_{NN}} = 200$ GeV.
   ✓ no CME signal in p+Au and d+Au collisions @ $\sqrt{s_{NN}} = 200$ GeV
   ✓ no CME signal in p+Pb (5.02 TeV) and Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV
Anomalous Transport in the QGP

Chiral Magnetic Effect (CME)

Electric Current  Chiral Magnetic Conductivity

Chiral Chemical potential

\[ \bar{J}_Q = \sigma_5 \bar{B} \]
\[ \sigma_5 = C_A \mu_5 \]
\[ C_A = Q^2 / (4\pi^2) \]

Kharzeev hep-ph/0406125

The CME results from anomalous transport of chiral fermions in the QGP, leading to the generation of an electric current along the B-field generated in the collision:

✓ Results in charge separation along the B-field

Why an interest in the CME?
CME detection & characterization could provide crucial insights on;

✓ Anomalous transport
✓ The interplay of chiral symmetry restoration, axial anomaly, and gluonic topology in the QGP
CME-induced charge separation leads to a dipole term in the azimuthal distribution of the produced charged hadrons:

\[ \frac{dN^{ch}}{d\phi} \propto [1 \pm 2a_{1}^{ch} \sin \phi + \ldots] \]

\[ a_{1}^{ch} \equiv \left\langle a_{1}^{2} \right\rangle^{1/2} \propto \mu_5 B \]

**Central objective:** identify & characterize this “dipole moment”

- This requires correlators that:
  - are sensitive to charge separation
  - can mitigate the influence of backgrounds
- Measurements designed to reduce the background influence
  - Isobars

Focus on two of the primary correlators

Roy A. Lacey, Stony Brook University, SQM22, June 13–17, 2022
Primary Correlators

\[ R_{\Psi_2}(\Delta S) = \frac{C_{\Psi_2}(\Delta S)}{C_{\Psi_2}(\Delta S)} \]

\[ C_{\Psi_2}(\Delta S) = \frac{N_{\text{real}}(\Delta S)}{N_{\text{Shuffled}}(\Delta S)} \]

Charge-dependent

\[ C_{\Psi_2}(\Delta S) \] quantifies charge separation along the B-field

\[ C_{\Psi_2}(\Delta S) \] quantifies charge separation perpendicular to the B-field (only background)

➢ The charge separation magnitude is reflected in the inverse variance \( \frac{1}{\sigma^2} \), of the \( R_{\Psi_2}(\Delta S) \) distribution which is corrected for:

✓ Number fluctuations

\[ \Delta S' = \Delta S / \sigma_{\Delta S^{sh}} \]

✓ Event plane resolution

\[ \Delta S'' = \Delta S' \delta_{\text{res}} \]

\[ \frac{1}{\sigma^2} \sim \frac{1}{\sigma_{\text{CME}}^2} + \frac{\kappa}{N_{\text{ch}}} \]

➢ The scaling property of both correlators can be leveraged to characterize the CME
Isobar collisions

✓ B-field difference
✓ Similar background

\[ \Delta \gamma \sim \Delta \gamma_{\text{CME}} + k \frac{v_2}{N_{\text{ch}}} \]
\[ \Delta \gamma_{\text{Ru+Ru}} > \Delta \gamma_{\text{Zr+Zr}} \]

\[ \frac{N_{\text{Ru+Ru}}}{N_{\text{Zr+Zr}}} \left( \frac{\Delta \gamma}{v_2} \right)_{\text{Ru+Ru}} > 1 \text{ (for CME)} \]

➢ Correction for \( N_{\text{ch}} \) difference necessary
➢ Correlator must be sensitive to a small signal difference


\[ a_1^{\text{ch}} \equiv \left( a_1^2 \right)^{1/2} \propto \mu_5 B \]

\[ \frac{1}{\sigma^2} \sim \frac{1}{\sigma_{\text{CME}}^2} + \frac{\kappa}{N_{\text{ch}}} \]
\[ \left( \sigma_{\text{CME}}^{-2} \right)_{\text{Ru+Ru}} > \left( \sigma_{\text{CME}}^{-2} \right)_{\text{Zr+Zr}} \]

\[ \frac{N_{\text{Ru+Ru}}}{N_{\text{Zr+Zr}}} \left( \sigma_{\text{CME}}^{-2} \right)_{\text{Ru+Ru}} > 1 \text{ (for CME)} \]
Scaling properties of the correlators

**Strategy**

Use the Anomalous Viscous Fluid Dynamics (AVFD) model to chart the scaling properties of background and signal + background.

AVFD features:
- ✓ Realistic representations of the experimentally measured particle yields, spectra, $v_n$, etc
- ✓ Includes CME signal (can be turned on/off)
- ✓ Realistic estimates of charge-independent and charge-dependent backgrounds
  - ✓ Resonance decays
  - ✓ Local charge conservation (LCC)
- ✓ Signal & background can be regulated

Comprehensive set of results generated to study scaling properties of both correlators:
- ✓ Centrality dependence for each system for
  - ✓ Background
  - ✓ Background + signal

➢ Tunable Glauber parameters to reproduce constraint measurements
  ✓ Multiplicity
  ✓ $V_n$
Scaling property of the Background

\[ \Delta \gamma \sim k \frac{v_2}{N_{ch}} \]

or

\[ \Delta \gamma \propto \frac{1}{v_2 N_{ch}} \]

\( N_{ch} \Delta \gamma \propto v_2 \)

\( \Delta \frac{\gamma}{v_2} \propto \frac{1}{N_{ch}} \]

This claim is incorrect

\[ R_{\psi^2}(\Delta S) = \frac{C_{\psi^2}(\Delta S)}{C_{\psi^2}^{\perp}(\Delta S)} \]

\[ C_{\psi^2}(\Delta S) = \frac{N_{\text{real}}(\Delta S)}{N_{\text{shuffled}}(\Delta S)} \]

\[ \frac{1}{\sigma^2} \sim \frac{\kappa}{N_{ch}} \]

\[ \frac{1}{\sigma^2} \propto \frac{1}{N_{ch}} \]

\[ \Delta \frac{\gamma}{v_2} \propto \frac{1}{N_{ch}} \]

The \( \frac{1}{N_{ch}} \) dependence of \( \frac{1}{\sigma^2} \) is well studied and well understood.
Scaling property of background and signal

\[ \frac{1}{\sigma^2} \sim \times + \frac{\kappa}{N_{\text{ch}}} \]

- **1/N_{\text{chg}}** scaling for background
  - ✓ Experimental observation of 1/N_{\text{chg}} scaling would be a clear indication for no CME

- Scaling violation for signal + background
  - ✓ f_{CME} benchmarks the signal

\[ f_{CME} = \frac{\sigma^{-2}_{R_{\psi_2}}(\text{Sig.} + \text{Bkg.}) - \sigma^{-2}_{R_{\psi_2}}(\text{Bkg.})}{\sigma^{-2}_{R_{\psi_2}}(\text{Sig.} + \text{Bkg.})} \]
Scaling property of background and signal

\[ \frac{1}{\sigma^2} \sim \frac{1}{\sigma_{\text{CME}}^2} + \frac{\kappa}{N_{\text{ch}}} \]

AVFD Au+Au 200 GeV

(a) LCC = 33%

Experimental observation of \( 1/N_{\text{ch}} \) scaling would be an indication for no CME

\[ f_{\text{CME}} = \frac{\sigma_{\text{CME}}^2 (\text{Sig.} + \text{Bkg.}) - \sigma_{\text{Bkg.}}^2 (\text{Bkg.})}{\sigma_{\text{Bkg.}}^2 (\text{Sig.} + \text{Bkg.})} \]

\( 1/N_{\text{ch}} \) scaling for background

Scaling violation for signal + background

✓ Insensitivity to signal in very central & peripheral collisions → Bkg. constraint

✓ Sensitivity difference

These scaling properties can be leveraged to characterize the CME in data

\[ \Delta \gamma \sim \Delta \gamma_{\text{CME}} + k \frac{v_2}{N_{\text{ch}}} \]

\[ f_{\text{CME}} = \frac{\Delta \gamma / v_2 (\text{Sig.} + \text{Bkg.}) - \Delta \gamma / v_2 (\text{Bkg.})}{\Delta \gamma / v_2 (\text{Sig.} + \text{Bkg.})} \]
Scaling property of the Data – $R_{\psi^2}(\Delta S)$ correlator

\[
\frac{N_{ch}^{-2}(\sigma_{Ru+Ru}^{-2})}{N_{ch}^{-2}(\sigma_{Zr+Zr}^{-2})} > 1 \quad \text{(for CME)}
\]

- **Small charge separation difference between the isobars**
  - Compatible with the CME
  - small signal difference

- **$q_2$–independent inverse variance validated for isobars**
  - This insensitivity spans a $v_2$ difference (between high and low $q_2$) that is much larger than the measured $v_2$ difference between the two isobars
Scaling property of the Data – $\Delta \gamma$ correlator

$\Delta \gamma \sim \Delta \gamma^{\text{CME}} + k \frac{V_2}{N_{\text{ch}}}$

- Experimental observation of $1/N_{\text{ch}}$ scaling would be an indication for no CME
- No indication for CME in p+Pb collisions @ 5.02 TeV
- No indication for CME in Pb+Pb collisions @ 5.02 TeV
Scaling property of the Data – $\Delta \gamma$ correlator

$\Delta \gamma \sim \Delta \gamma^{\text{CME}} + k \frac{V_2}{N_{\text{ch}}}$

- The experimental observation of $1/N_{\text{ch}}$ scaling would be an indication for no CME

- $1/N_{\text{ch}}$ scaling observed for $q_2$-selected Pb+Pb collisions @ 2.76 TeV
  - No indication for CME in Pb+Pb collisions @ 2.76 TeV
Scaling property of the Data – $\Delta \gamma$ correlator

$\Delta \gamma \sim \Delta \gamma^{\text{CME}} + k \frac{V_2}{N_{\text{ch}}}$

$\overrightarrow{B}$

$0 < \Psi_2 < 2\pi$ plane

$B$ and $\Psi_2$ ~ uncorrelated

CME not expected

$\gamma\gamma$

$\Delta \gamma$ + −

1/$N_{\text{ch}}$ scaling observed for d+Au (similar for p+Au) collisions @ 200 GeV

✓ No indication for CME

Scaling violations observed for Au+Au collisions @ 200 GeV

✓ Indication for the CME

✓ $f_{\text{CME}} \sim 27\%$ in mid-central collisions


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Scaling property of the Data – $\Delta \gamma$ correlator

$\Delta \gamma \sim \Delta \gamma^{\text{CME}} + k \frac{v_2}{N_{ch}}$

Scaling violations observed for Ru+Ru and Zr+Zr collisions @ 200 GeV

- $f_{\text{CME}} \sim 14\%$ in mid-central collisions
- Similar magnitudes for the two isobars (in sensitivity to signal difference?)
- Small signal difference implied from $f_{\text{CME}}$ magnitude

Data from Phys. Rev. C 105 (2022) 1, 014901
I. The scaling properties of background- and chiral-magnetically-driven charge separation give unique insight for characterizing the CME.

II. Ongoing analysis indicates

✓ a robust CME signal in Au+Au and isobar (Ru+Ru and Zr+Zr) collisions at $\sqrt{S_{NN}} = 200 \, \text{GeV}$.
✓ no CME signal in p+Au and d+Au collisions @ $\sqrt{S_{NN}} = 200 \, \text{GeV}$
✓ no CME signal in p+Pb and Pb+Pb collisions at $\sqrt{S_{NN}} = 2.76 \, \text{and} \, 5.02 \, \text{TeV}$

Thank You
Scaling property of the Background

AMPT, Au+Au 200 GeV 30-50%, CME = 10%
The predefined case for CME (Ratios > 1) are not observed!

Caveats:
- Ratios < 1.0, indicating background difference for isobars
- Implied ambiguity for presence/absence of CME
The blind background
The $R_{Ψ_m}(ΔS)$ Correlator

\[ R_{Ψ_2}(ΔS) = \frac{C_{Ψ_2}(ΔS)}{C_{Ψ_2}^⊥(ΔS)} \]

\[ C_{Ψ_2}(ΔS) = \frac{N(ΔS)}{N(ΔS_{sh})} \]

\[ Δφ = φ - Ψ_m \]

\[ N(ΔS) \]

\[ \langle S^+_{Ψ_2} \rangle = \frac{\sum_1^p w_p \sin(Δφ)}{\sum_1^p w_p} \]

\[ \langle S^-_{Ψ_2} \rangle = \frac{\sum_1^n w_n \sin(Δφ)}{\sum_1^n w_n} \]

\[ ΔS = \langle S^+_{Ψ_2} \rangle - \langle S^-_{Ψ_2} \rangle \]

\[ N(ΔS_{sh}) \]

\[ ΔS_{sh} = \langle S^+_{Ψ_2} \rangle_{sh} - \langle S^-_{Ψ_2} \rangle_{sh} \]

Sensitive to charge separation (CME and Background)

\[ w_i: \text{charge dependent detector acceptance.} \]

\[ N(ΔS^⊥) \]

\[ \langle S^+_⊥ \rangle = \frac{\sum_1^p w_p \cos(Δφ)}{\sum_1^p w_p} \]

\[ \langle S^-_⊥ \rangle = \frac{\sum_1^n w_n \cos(Δφ)}{\sum_1^n w_n} \]

\[ ΔS^⊥ = \langle S^+_⊥ \rangle - \langle S^-_⊥ \rangle \]

\[ N(ΔS_{sh}^⊥) \]

\[ ΔS_{sh}^⊥ = \langle S^+_⊥ \rangle_{sh} - \langle S^-_⊥ \rangle_{sh} \]

Charge shuffling within an event breaks the charge separation sensitivity

Shape-selected events

- Event-shape selections (Data)
  - Events are further subdivided into groups with different $q^2$ magnitude:

$$q_{2,x} = \sum_{i=1}^{M} \cos(2 \varphi_i) \quad q_{2,y} = \sum_{i=1}^{M} \sin(2 \varphi_i)$$

$$|q_2| = \sqrt{q_{2,x}^2 + q_{2,y}^2} \quad q_2 = \frac{|q_2|}{\sqrt{M}}$$

- The $q_2$ was created for each $N_{ch}$

- $v_2\{2\}$ increases linearly with $q_2$  
  - $q_2$ is good event-shape selector