Collision-system Dependence of the Charge Separation Relative to the Event Plane: Implications for Chiral Magnetic Effect Search in STAR

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Outline

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➢ $R_{\psi m}(\Delta S)$ Correlator

➢ $\Delta \gamma$ vs $R_{\psi m}(\Delta S)$

➢ Data Analyses

➢ Results

➢ Conclusion
Introduction

✓ Chiral Magnetic Effect (CME)

- In non-central collisions, a strong magnetic field is created perpendicular to $\Psi_{RP}$

- Magnetic field acts on the chiral fermions with $\mu_5 \neq 0$ leading to an electric current along the magnetic field which leads to a charge separation

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

D.E. Kharzeev
Prog.Part.Nucl.Phys. 75 (2014) 133-151

D.E. Kharzeev et al.
Prog.Part.Nucl.Phys. 88 (2016) 1-28

Kharzeev hep-ph/0406125
Introduction

Chiral Magnetic Effect (CME)

CME-driven charge separation leads to a dipole term in the azimuthal distribution of the produced charged hadrons:

\[
\frac{dN^{ch}}{d\phi} \propto 1 \pm 2 a_1^{ch} \sin(\phi) + \ldots
\]

\[
a_1^{ch} \propto \mu_5 \vec{B}
\]

Can we identify & characterize this dipole moment?

What a good correlator should establish?

- Leverage Small systems
- Leverage \(\Psi_3\) measurements

B and \(\Psi_2\) \(\sim\) uncorrelated

B and \(\Psi_3\) \(\sim\) uncorrelated

✓ Excellent benchmark
The Gamma Correlator’s response is similar for signal and background

- Background-driven correlations complicate CME-driven signal extraction

- Can background account for a part, or all of the observed charge separation signal?

- CMS at QM-18
  - pPb consistent with 100% BKG
  - Same for PbPb
The correlator is constructed for a given event plane $\Psi_m$ via a ratio of two correlation functions:

$$R_{\Psi m}(\Delta S) = \frac{C_{\Psi m}(\Delta S)}{C_{\Psi m}(\Delta S)} , m = 2 \text{ and } 3$$

The $R_{\Psi 2}(\Delta S)$ correlator measures the magnitude of charge separation parallel to the B-field, relative to that for charge separation perpendicular to the B-field.

Note that both $C_{\Psi 3}(\Delta S)$ and $C_{\Psi 3}(\Delta S)$ are insensitive to the CME-driven charge separation (only background).
\( R_{\Psi m}(\Delta S) \) Correlator

N. Magdy, et al.
PRC 97, 061901 (2018)

\[
R_{\Psi m}(\Delta S) = \frac{C_{\Psi m}(\Delta S)}{C_{\Psi m}^\perp(\Delta S)}
\]

\[
C_{\Psi m}(\Delta S) = \frac{N(\Delta S)}{N(\Delta S_{sh})}
\]

\[
\Delta \varphi = \varphi - \Psi_m
\]

\[
C_{\Psi m}^\perp(\Delta S) = \frac{N(\Delta S^\perp)}{N(\Delta S_{sh}^\perp)}
\]

\[
\Delta S = \langle S_{\Psi m}^+ \rangle - \langle S_{\Psi m}^- \rangle
\]

Sensitive to charge separation (CME and Background)

\[
\langle S_{\Psi m}^+ \rangle = \frac{\sum_{1}^{p} w_p \sin\left(\frac{m}{2} \Delta \varphi\right)}{\sum_{1}^{p} w_p}
\]

\[
\langle S_{-\Psi m}^+ \rangle = \frac{\sum_{1}^{n} w_n \sin\left(\frac{m}{2} \Delta \varphi\right)}{\sum_{1}^{n} w_n}
\]

\( w_i \): charge dependent detector acceptance.

\[
\Delta S^\perp = \langle S_{\Psi m}^+ \rangle^\perp - \langle S_{\Psi m}^- \rangle^\perp
\]

Shuffling of charges within an event breaks the charge separation sensitivity

\[
\Delta S_{sh} = \langle S_{\Psi m}^+ \rangle_{sh} - \langle S_{\Psi m}^- \rangle_{sh}
\]

\[
\Delta S_{sh}^\perp = \langle S_{\Psi m}^+ \rangle_{sh}^\perp - \langle S_{\Psi m}^- \rangle_{sh}^\perp
\]

\[
N(\Delta S_{sh})
\]

\[
N(\Delta S_{sh}^\perp)
\]
- **$R_{\Psi m}(\Delta S)$ Correlator**

- Charge separation magnitude is reflected in the width of the $R_{\Psi m}(\Delta S)$ distribution which is affected by:
  - Number fluctuations
  - Empirical EP-resolution

- Number fluctuations:
  \[
  \Delta S' = \Delta S / \sigma_{\Delta S^{sh}}
  \]

- Empirical EP-resolution:
  \[
  \Delta S'' = \Delta S' / e^\left(\left(1 - \sqrt{\cos(2\Delta \Psi_2)}\right)\right)^2
  \]

- We can account for both number fluctuations and EP-resolution effect on the width of the $R_{\Psi m}(\Delta S)$
**$R_{\Psi_m}(\Delta S)$ Correlator**

- $R_{\Psi_m}(\Delta S)$ response in background models

![Graphs showing $R_{\Psi_m}(\Delta S)$ for different models and conditions.](image)

- Resonance suppression leads to flat $R_{\Psi_m}$

- The $R_{\Psi_2}$ and $R_{\Psi_3}$ give similar response to the background irrespective of the correlator shape

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*N. Magdy, et al.*

PRC 97, 061901 (2018)
• $R_{\Psi m}(\Delta S)$ Correlator

• $R_{\Psi m}(\Delta S)$ response in CME models

– Signal magnitude is reflected in the widths of the distributions
  ✓ Smaller widths for larger input signal

– Validation of the expected concave-shaped response of $R_{\Psi_2}(\Delta S)$ to the CME-driven charge separation input in CME-events.

[Graph showing $R_{\Psi_2}(\Delta S)$ vs. $\Delta S$ with different AVFD and $a_1$ values.]
**Δγ vs R_{Ψm}(ΔS)**

Chiral kinetic approach

Y. Sun et al.
PRC 98, 014911 (2018)

➢ $a_1 \sim 0$ for $τ_B < 0.6$ fm/c

✓ $Δγ$ shows non-zero value

✓ $R_{Ψm}(ΔS)$ shows a flat shape
Data Analysis

The STAR Detector at RHIC

- The TPC detector is used in the current analysis

- Charged hadrons with $0.2 < p_T < 2.0$ GeV/c used to construct $\Psi_2^{\eta>0.1}$ & $\Psi_2^{\eta<-0.1}$

- Particles with $0.35 < p_T < 2.0$ GeV/c and $\eta < 0$ analyzed using $\Psi_2^{\eta>0.1}$

- Particles with $0.35 < p_T < 2.0$ GeV/c and $\eta > 0$ analyzed using $\Psi_2^{\eta<-0.1}$
Data Analysis

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
Results
Results

- \( R_{\Psi m}(\Delta S) \) measurements at RHIC
  - Event plane dependence
  - Small systems dependence

- Measurements for \( R_{\Psi m} \) show:
  - Different response for \( R_{\Psi 2} \) and \( R_{\Psi 3} \)
  - Different response for small (p(d)+Au) and large (Au+Au) systems

- \( R_{\Psi m} \) results are consistent with the expectation for the CME-driven charge separation.
  - Note that these observations contrast with those from the \( \gamma \) correlator.

[CMS Collaboration arXiv:1610.00263]
Results

- Using acceptance correction ($w_i$) the charge dependent detector acceptance.

![Graphs showing data points and trends with acceptance correction and without.](STAR Preliminary)
Results

Event shape selection

Comparison of the $R_{\Psi_2}(\Delta S''')$ correlators for $q_2$ selected events for 30–50% central, Au+Au collisions at 200 GeV for (a) AMPT simulations and (b) experimental measurements.

- Different $q_2$ selections (right panel) suggests that $R_{\Psi_2}(\Delta S''')$ is not strongly influenced by the $v_2$ background-driven charge separation.
Results

- Different collision systems $R_{\Psi^2_m}(\Delta S'')$ and $R_{\Psi^3_m}(\Delta S'')$

$R_{\Psi^2_m}(\Delta S'')$ and $R_{\Psi^3_m}(\Delta S'')$ for 0-20% centrality selection in different collision systems.

- The $R_{\Psi^2_m}(\Delta S'')$ correlators for different collision systems is strikingly different from those for $R_{\Psi^3_m}(\Delta S'')$ correlators.

- $R_{\Psi^2_m}(\Delta S'')$ decidedly concave-shaped, as would be expected for CME-driven charge separation with limited influence from background-driven charge separation.
Results

- Au+Au collision system $R_{\Psi_2}(\Delta S)$

$R_{\Psi_2}(\Delta S)$ for different centrality selections in Au+Au at 200 GeV.

- $\sigma_{R_{\Psi_2}}^{-1}$ indicates a sizable centrality dependence, suggestive of the expected increase in the magnitude of the CME-driven charge separation when the $\vec{B}$-field increases as collisions become more peripheral.

All widths are normalized to the width of 0-20% (smallest $a_1$)
**Results**

- **U+U collision system $R_{\Psi_2}(\Delta S)$**

  $R_{\Psi_2}(\Delta S)$ for different centrality selections in U+U at 200 GeV.

- $\sigma_{R_{\Psi_2}}^{-1}$ indicates a sizable centrality dependence, suggestive of the expected increase in the magnitude of the CME-driven charge separation when the $B$-field increases as collisions become more peripheral.
Results

- **Cu+Au collision system $R_{Ψ_2}(ΔS)$**
  
  $R_{Ψ_2}(ΔS)$ for different centrality selections in Cu+Au at 200 GeV.

- $σ^{-1}_{R_{Ψ_2}}$ indicates a sizable centrality dependence, suggestive of the expected increase in the magnitude of the CME-driven charge separation when the $\vec{B}$-field increases as collisions become more peripheral.
Conclusions

Charge separation measurements performed with $R_{\Psi_m}$ (for $m = 2,3$) correlator, for U+U (193 GeV), p(d)+Au, Au+Au and Cu+Au at 200 GeV collisions with the STAR detector.

- $R_{\Psi_m}$ measurements show:
  - Difference in the response for $\Psi_2$ and $\Psi_3$ for different collision systems
  - Difference in the response for small (p(d)+Au) and large systems (Au+Au)

- $R_{\Psi_2}$ width:
  - Is $q_2$-independent (weak sensitivity to background)
  - Is centrality-dependent

- $R_{\Psi_m}$ results are consistent with the expectation for CME-driven charge separation.