Selected Overview of Searches for Chiral Effects in Heavy Ion Collisions

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OUTLINE

1) CME and Charge Separation Across the RP
2) CMW and Background
3) Search for Chiral Vortical Effect
4) Future Perspective
QCD Domain Formation

Non-Abelian Gauge Theory
Dynamical by nature

The volume of the box is 2.4 by 2.4 by 3.6 fm.
The topological charge density
Animation by Derek Leinweber
Chiral Magnetic Effect (CME): finite chiral charge density induces an electric current along external magnetic field.

\[ j_V = \frac{N_c e}{2\pi^2 \mu_A} B \Rightarrow \text{electric charge separation along } B \text{ field} \]

\[ \gamma \text{ correlator} \]

A quantitative measure for extra charge fluctuation.

\[ \gamma_1^{12} \]

\[ \gamma = \left\langle \cos(\phi_\alpha + \phi_\beta - 2\psi_{RP}) \right\rangle \]

\[ = \langle \cos() \cos() \rangle - \langle \sin() \sin() \rangle \]

\[ \cong \left[ \left\langle v_{1,\alpha} v_{1,\beta} \right\rangle + B_{in} \right] - \left[ \left\langle a_\alpha a_\beta \right\rangle + B_{out} \right] \]

S. Voloshin, PRC 70 (2004) 057901

Directed flow

P-even quantity: sensitive to charge separation fluctuation

\[ \gamma_1^{123} = \langle \cos(\phi_\alpha + 2\phi_\beta - 3\psi_3) \rangle \]
pA Data Illuminating!

$\Delta \gamma$ correlator in pA – largely background
Many reasons $v_2$ related background in pA and AA may be different!

Little room for CME signal in $\Delta \gamma$ at 5.02 TeV from CMS!
CMS Quantitative Approach to CME

Pb+Pb at 5.02 TeV $v_2$ Independent
CME < 3.8%

P+Pb at 8.16 TeV
CME < 6.6%

All at 95% C.L. (See Wei Li’s talk) Event-Shape Selected Analysis
ALICE Quantitative Approach to CME

Event-Shape Selected Analysis

Background – linear dependence on $v_2$
CME – also dependent on $v_2$
Measurement – combination of background and CME
→ fraction of CME contributions
(10-50)% centrality region: at 2.76 TeV Pb+Pb collisions
CME fraction upper limit 26-33% at 95% C.L.
depending on models of initial state!
Charge Dependent $\gamma$ Measure

RHIC data

- Initial data publication on the topic
- We know better now about the residual background

H Measure

Against CME expectation, $\delta_{OS} > \delta_{SS}$

Indicate overwhelming background, larger than any possible CME effect.

Try combining information from $\gamma$ and $\delta$ to retrieve the CME contribution, $H$

\[ \gamma \equiv \langle \cos(\phi_1 + \phi_2 - 2\Psi_{RP}) \rangle = \kappa v_2 F - H \]
\[ \delta \equiv \langle \cos(\phi_1 - \phi_2) \rangle = F + H, \]

\[ 10^4 \times [\delta \equiv \langle \cos(\phi_1 - \phi_2) \rangle] \]


At lower beam energies, charge separation starts to diminish.

If $\Delta \gamma$ is largely background, the background cannot be proportional to $v_2$ alone as suggested!
Difficult to Remove Charge Separation

\[ H^\kappa = \frac{\kappa v_2 \delta - \gamma}{1 + \kappa v_2} \]

- \( \kappa \approx 2 - v_{2,F}/v_{2,\Omega} \approx 1.2 \):
  
  F and \( \Omega \) denote full phase space and finite detector acceptance, respectively.

- CME signal (\( \Delta H \)) decreases to 0 from 19.6 to 7.7 GeV and at LHC energies.

- The decomposition of \( \gamma \) into F and H is not unique.


Agree with CMS Statement!

the magnetic field is fixed. Using an event shape engineering technique, upper limits on the $v_2$-independent fraction of the three-particle correlator are estimated to be 6.6% for pPb and 3.8% for PbPb collisions at 95% confidence level. The results of this analysis, both the dominance of two-particle correlations as a source of the three-particle results and the similarities seen between PbPb and pPb, provide stringent constraints on the origin of charge-dependent three-particle azimuthal correlations and challenge their interpretation as arising from a chiral magnetic effect in heavy ion collisions.

To be precise, maybe useful to specify “at the 5.02 TeV LHC energy” in the CMS statement!

γ Correlator has major background contribution! CME contribution can be $v_2$ dependent as well! Background cannot be linear to $v_2$ solely if $\Delta \gamma$ is entirely due to background!
Is there a strong energy dependence in CME &
Is there a room for CME at 200 GeV and below?

Please see Gang Wang & Niseem Abdelrahman for STAR update!

Intriguing Observation from CMS:

\[ \gamma_{112} = \langle \cos(\varphi_\alpha + \varphi_\beta - 2\Psi_2) \rangle \]
\[ = \langle \cos(\varphi_\alpha - \Psi_2)\cos(\varphi_\beta - \Psi_2) \rangle - \langle \sin()\sin() \rangle \]
\[ = \langle \cos(\varphi_\alpha - \varphi_\beta)\cos^2(\varphi_\beta - \Psi_2) \rangle - \langle \sin()\sin() \rangle \]
\[ \rightarrow \kappa_2 < \cos(\varphi_\alpha - \varphi_\beta)\rangle<\cos^2(\varphi_\beta - \Psi_2)\rangle \]

\[ \gamma_{123} = \langle \cos(\varphi_\alpha + 2\varphi_\beta - 3\Psi_3) \rangle \]
\[ = \langle \cos(\varphi_\alpha - \Psi_3)\cos^2(\varphi_\beta - \Psi_3) \rangle - \langle \sin()\sin() \rangle \]
\[ = \langle \cos(\varphi_\alpha - \varphi_\beta)\cos^3(\varphi_\beta - \Psi_3) \rangle - \langle \sin()\sin() \rangle \]
\[ \rightarrow \kappa_3 < \cos(\varphi_\alpha - \varphi_\beta)\rangle<\cos^3(\varphi_\beta - \Psi_3)\rangle \]

Why are \( \kappa_2 \) and \( \kappa_3 \) almost the same?
No CME? Unknown Correlations?
Chiral Magnetic Wave

**CMW → Electric Quadrupole Moment**

\[ \nu_2^{\pm} = \nu_2 \mp rA_{ch} \quad A_{ch} = \frac{N^+ - N^-}{N^+ + N^-} \]
Local charge conservation may introduce $A_{\text{ch}}$ dependence of $\Delta v_2(\pi)$. Then one should see \textit{slope-for-$\Delta v_3$ / slope-for-$\Delta v_2$} $\sim$ $v_3/v_2$ (Bzak & Bozek PLB 726 239 (2013)). Our measurement for $\Delta v_3$ indicates that such mechanism alone cannot explain data.
ALICE Improved Approach for Slope

$\frac{dN_{ch}}{d\eta} v_2(2) - \langle A x v_2(2) \rangle$

$0.2 < p_T < 5.0 \text{ GeV/c}$

$-0.8 < \eta < 0.8$

Different centrality dependence from STAR data!
ALICE Slopes for $v_3$ and $v_4$

Not exactly the same magnitude as slopes for $v_2$
Room for CMW signal?
Need good background model!
STAR (0.20 TeV)-ALICE (2.76 TeV)-CMS (5.02 TeV)

Background levels are different!
Little room for CMW signal at 5.02 TeV
Chiral Vortical Effect

Chiral Magnetic Effect vs Chiral Vortical Effect

Chirality Imbalance ($\mu_A$)

Magnetic Field ($\omega \mu_e$) \hspace{1cm} Fluid Vorticity ($\omega \mu_B$)

↓ \hspace{1cm} ↓

Electric Charge ($j_e$) \hspace{1cm} Baryon Number ($j_B$)

D. Kharzeev, D. T. Son, PRL 106 (2011) 062301

\[ \langle \cos(\phi_A + \phi_P - 2\Psi_{RP}) \rangle \]

correlate $\Lambda$–p to search for the Chiral Vortical Effect
same baryon number: \( \Lambda p \) and \( \bar{\Lambda} \bar{p} \)

opposite baryon number: \( \Lambda \bar{p} \) and \( \bar{\Lambda} p \)

“same B” is systematically lower than “oppo B” in the mid-central and peripheral collisions, consistent with the CVE expectation.
Baryon-Baryon Correlation

Λ-p correlation – different from Λ-h and K_{S}p correlation! CVE?
STAR Measurement for Lambda Polarization WRT the Reaction Plane

1) Larger effect at lower beam energy!
2) Difference between Lambda and Anti-Lambda?

See STAR updates from Aihong Tang Takafumi Niida

and talks by Lisa and Voloshin

1) Larger effect at lower beam energy!
2) Difference between Lambda and Anti-Lambda?
Intriguing and Puzzling

Energy dependent intriguing observations!
There is a charge separation effect
  -- separate CME and background ?!
There is an extra-$v_2$ due to charge asymmetry
  -- electric quadrupole due to CMW or ?
There is a baryon-baryon separation effect
  -- CVE or ? Vortical Fluidity – Yes!

More insight and towards a definitive answer:
  -- establish B field and its consequence
  -- effect correlating CME/CVE/CMW
Isobar Collision Running 2018

$^{96}_{44}$Ruthenium and $^{96}_{40}$Zirconium:

Up to 10% variation in B field

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<thead>
<tr>
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<th>$^{96}<em>{44}$Ru+$^{96}</em>{44}$Ru vs $^{96}<em>{40}$Zr+$^{96}</em>{40}$Zr</th>
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<tbody>
<tr>
<td>Flow</td>
<td>$\leq$</td>
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<tr>
<td>CMW</td>
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<td>CME</td>
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Isobars: charge separation

- Projection from 1.2B events shows difference in $\Delta H$
- The ratio is $5\sigma$ above 1 ($3\sigma$ with 400M events)
- If it's $v_2$-driven, the ratio will follow eccentricity (be 1 or below 1)
Maybe a Better Beam Energy for Chirality Searches

Optimal Beam Energy: 15-50 GeV

Low beam energy A+A reduces short-range non-flow background!
Event Selection Technique Sensitive to By

\[ \frac{B_y}{m^2} \]

\[ \langle v_2 \rangle \]

\[ |y(p/\overline{p})| < 0.5 \]
\[ 0.5 < p_T^{p/\overline{p}} < 2.0 \text{ GeV/c} \]

Net-protons

Another handle for event selection

Subikash Choudhury
Fudan University

Au+Au @ 27 GeV
Experimental Window of Opportunity

1) Isobaric running to see B field effect @200 GeV in 2018
2) Au+Au data from low RHIC energies to observe B magnitude and life-time difference 2018 +
3) If promising, another run for isobaric system may be proposed

There must be some background – yet no satisfactory background model can explain all features in data – any room for CME/CMW? Definitive Answer?
THE END