CMS results on CME and CMW in pPb and PbPb

Wei Li
Rice University

UCLA Chirality Workshop
March 27 – 30
Chiral Magnetic Effect in HI

Electric current induced by magnetic field

\[ \vec{j}_V = \frac{N_c e}{2\pi^2} \mu_A \vec{B} \] (analogous to Ohm’s law \( \vec{j} = \sigma \vec{E} \))

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

If discovered, evidence for

- Topological phase in nuclear matter
- Deconfinement, chiral symmetry restoration
Properties of correlations from the CME

\begin{equation}
\tau_O \leq \tau_{F.O.} \exp\left(-\frac{1}{2}|y_a - y_b|\right)
\end{equation}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure.png}
\caption{Properties of correlations from the CME}
\end{figure}

Short-range in rapidity!
Properties of correlations from the CME

Short-range in rapidity!

Is the CME long- or short- range?

→ formation time of chiral quarks
Properties of correlations from the CME

When chiral quarks are formed?

\[ \tau_O \leq \tau_{F.O.} \exp \left( -\frac{1}{2} |y_a - y_b| \right) \]

Is the CME long- or short-range?

→ formation time of chiral quarks
(My) status quo of the CME search in HI

No doubt about the fundamental physics of CME and its potential impact

However, many theoretical unknowns in HI:
• Lifetime of B field
• Formation time of quarks (long- vs short-range)
• Other charge-related (conservation, ordering) correlations at late time (a.k.a. BKGs) unconstrained
(My) status quo of the CME search in HI

No doubt about the fundamental physics of CME and its potential impact

However, many theoretical unknowns in HI:

• Lifetime of B field
• Formation time of quarks (long- vs short-range)
• Other charge-related (conservation, ordering) correlations at late time (a.k.a. BKGs) unconstrained

How to prove or rule out the presence of CME in HI in a simple, model-independent way?
Flow-like correlations (QGP?) in small system

Long-range, collective \(\rightarrow\) very little “background”

\[ v_n \text{ comparable for pPb and PbPb} \]
Flow-like correlations (QGP?) in small system

Can we learn about other exotic phenomena of QGP using small systems?

Long-range, collective → very little “background”
New insights to the CME from pA

\( B \neq 0 \)

\( B = 0 \)

**FIGURE 6.24**

Problem 6.16 (D. Griffiths)
New insights to the CME from pA

\[ B \neq 0 \]

\[ B = 0 \]

Problem 6.16 (D. Griffiths)

FIGURE 6.24
New insights to the CME from $pA$

Problem 6.16 (D. Griffiths)
New insights to the CME from $pA$

$B \neq 0$

$B = 0$

FIGURE 6.24

Problem 6.16 (D. Griffiths)
New insights to the CME from $pA$

Problem 6.16 (D. Griffiths)

$B \neq 0$

$B = 0$

**FIGURE 6.24**

$B \sim b\hat{z}$

$B \sim b\hat{\phi}$
New insights to the CME from pA

Charge separation signal: $\Delta \gamma = \langle B^2 \cos 2(\Psi_B - \Psi_{EP}) \rangle$

- B (PbPb) > B (pPb) in magnitude
New insights to the CME from pA

**Charge separation signal:** $\Delta \gamma = \left\langle B^2 \cos 2(\Psi_B - \Psi_{EP}) \right\rangle$

- $B (\text{PbPb}) > B (\text{pPb})$ in magnitude
- De-correlation of $\psi_B (\sim \psi_{RP})$ and $\psi_{EP} (\sim \psi_{PP})$

In pA, $\left\langle \cos 2(\Psi_B - \Psi_{EP}) \right\rangle \approx 0$ \quad $\Rightarrow$ \quad $\Delta \gamma^\text{CME} \approx 0$
New insights to the CME from pA

Charge separation signal: \( \Delta \gamma = \left< B^2 \cos 2(\Psi_B - \Psi_{EP}) \right> \)

- B (PbPb) > B (pPb) in magnitude
- De-correlation of \( \psi_B \) (\( \sim \psi_{RP} \)) and \( \psi_{EP} \) (\( \sim \psi_{PP} \))

\[
\ln pA, \left< \cos 2(\Psi_B - \Psi_{EP}) \right> \approx 0 \quad \Rightarrow \quad \Delta \gamma^{CME} \approx 0
\]
New insights to the CME from pA

Charge separation signal: \( \Delta \gamma = \left\langle B^2 \cos 2(\Psi_B - \Psi_{EP}) \right\rangle \)

- \( B (\text{PbPb}) > B (\text{pPb}) \) in magnitude
- De-correlation of \( \psi_B (\sim \psi_{RP}) \) and \( \psi_{EP} (\sim \psi_{PP}) \)

In pA, \( \left\langle \cos 2(\Psi_B - \Psi_{EP}) \right\rangle \approx 0 \) \( \Rightarrow \Delta \gamma^{\text{CME}} \approx 0 \)
New insights to the CME from pA

Charge separation signal: \( \Delta \gamma = \langle B^2 \cos 2(\Psi_B - \Psi_{EP}) \rangle \)

- \( B (\text{PbPb}) > B (\text{pPb}) \) in magnitude
- De-correlation of \( \psi_B (\sim \psi_{RP}) \) and \( \psi_{EP} (\sim \psi_{PP}) \)

In pA, \( \left\langle \cos 2(\Psi_B - \Psi_{EP}) \right\rangle \approx 0 \quad \rightarrow \quad \Delta \gamma^{\text{CME}} \approx 0 \)

A CME-free environment in HM pA

- \( \Delta \gamma^{\text{PbPb}} \gg \Delta \gamma^{\text{pPb}} \) \( \Rightarrow \) support CME in AA
- \( \Delta \gamma^{\text{PbPb}} \approx \Delta \gamma^{\text{pPb}} \) \( \Rightarrow \) challenge to CME
CME measurement at CMS

\[ \gamma = \left< \cos(\phi_\alpha + \phi_\beta - 2\Psi_{EP}) \right> \cong \frac{\left< \cos(\phi_\alpha + \phi_\beta - 2\phi_c) \right>}{\nu_{2,c}} \]

Particle \( c \) fixed at \( 4.4 < |\eta| < 5 \) (HF)
Particle \( \alpha, \beta \) sliced within \( |\eta| < 2.4 \) (Tracker)

\[ \nu_{2,c} = \sqrt{\frac{\left< Q_{2,\text{HF}+} Q_{2,\text{HF}+}^* \right> \left< Q_{2,\text{HF}+} Q_{2,\text{trk}}^* \right>}{\left< Q_{2,\text{HF}+} Q_{2,\text{trk}}^* \right>}} \quad (3\text{-subevent}) \]
CME measurement at CMS

\( \eta \text{ gap} > 2 \)

\[
\gamma = \left< \cos(\phi_\alpha + \phi_\beta - 2\Psi_{EP}) \right> \equiv \frac{\left< \cos(\phi_\alpha + \phi_\beta - 2\phi_c) \right>}{v_{2,c}}
\]

To ensure factorization (well defined EP)

- Particle \( c \) far removed from \( \alpha, \beta \) in \( \eta \)
- Multiplicity not too low

Otherwise, collective correlations not dominant and “obvious” BKGs present
$|\Delta \eta|$ dependence of $\gamma$

Clear splitting of SS and OS in pPb, similar to PbPb
→ NOT in favor of CME interpretation?
Clearly short-range (~ 1 unit in $\eta$)

Similar in pPb and PbPb

Same physical origin!? 

Is CME long- or short-range?
When are chiral quarks produced?
Large rapidity coverage is essential

Results stable with $|\eta_{\alpha,\beta} - \eta_c| > 1$ unit and beyond
Large rapidity coverage is essential

Results stable with $|\eta_{\alpha,\beta} - \eta_c| > 1$ unit and beyond
Centrality dependence of $\gamma$ in AA

Integrated over $|\eta_\alpha - \eta_\beta| < 1.6$

Little energy dependence from 0.2 to 5 TeV
Comparing $\Delta \gamma$ in pPb vs PbPb

Similarity between pPb and PbPb extends over a wide range of $N_{trk}$ or centrality
Comparing $\Delta \gamma$ in pPb vs PbPb

Almost all BKG in pPb and PbPb

OR

CME+BKG in PbPb ≈ BKG only in pPb
Some personal thoughts

Experimental facts: $\Delta \gamma$ (OS-SS) agrees well for pPb and PbPb at 5 TeV in both $\Delta \eta$ and multiplicity

→ As CME not expected in pPb, little room for CME in AA at 5 TeV?

Is expected as $B$ lifetime is too short at higher $\sqrt{s_{NN}}$?

![Graph showing $\Delta \gamma$ dependence on $\sqrt{s_{NN}}$](image)

No dramatic $\sqrt{s_{NN}}$ dependence of $\Delta \gamma$
Some personal thoughts

If all BKGs, what are they? Should they be same in pPb and PbPb?

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

\[ \sim \gamma_c + \langle \cos(\phi_\alpha - \phi_\beta) \rangle \langle \cos 2(\phi_\beta - \Psi_{RP}) \rangle \]

\[ \delta^* v_2 \]
Some personal thoughts

If all BKGs, what are they? Should they be same in pPb and PbPb?

\[
\gamma = \left\langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \right\rangle = \left\langle \cos(\phi_\alpha - \phi_\beta + 2\phi_\beta - 2\Psi_{RP}) \right\rangle \\
\sim \gamma_c + \left\langle \cos(\phi_\alpha - \phi_\beta) \right\rangle \left\langle \cos 2(\phi_\beta - \Psi_{RP}) \right\rangle \quad \Rightarrow \quad \delta^*v_2
\]

Can we find new observables insensitive to BKGs? Maybe not if CME is short-range and non-collective
Some personal thoughts

If all BKGs, what are they? Should they be same in pPb and PbPb?

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

\[ \sim \gamma_c + \langle \cos(\phi_\alpha - \phi_\beta) \rangle \langle \cos 2(\phi_\beta - \Psi_{RP}) \rangle \]

\[ \delta^* v_2 \]

Can we find new observables insensitive to BKGs? Maybe not if CME is short-range and non-collective

In general, pA is a litmus test for any effect related to

- B (CME, CMW)
- J (CVE, \Lambda polarization)

- A search in pA must yield zero signal
Chiral Magnetic Wave

\[ j_A = \frac{N_c e}{2\pi^2} \mu_v B \quad j_v = \frac{N_c e}{2\pi^2} \mu_A B \]

Coupling of electric and axial charge densities and currents

\[ \rightarrow (\partial_0 \mp \partial_1 v_\chi - D_L \partial_1^2) j^0_L, R = 0 \]
Chiral Magnetic Wave

\[
j_A = \frac{N_c e}{2\pi^2} \mu_V B \quad j_V = \frac{N_c e}{2\pi^2} \mu_A B
\]

Coupling of electric and axial charge densities and currents

\[
\rightarrow (\partial_0 \mp \partial_1 v_\chi - D_L \partial_1^2) j^0_{L,R} = 0
\]

\[A_{ch} = \frac{N^+ - N^-}{N^+ + N^-}\]

\[A_{ch} \uparrow \rightarrow v_2^+ \downarrow v_2^- \uparrow\]

\[v_2^- - v_2^+ = r \cdot A_{ch}\]
Chiral Magnetic Wave

Evidence of the CMW in AA

STAR PRL 114 (2015) 252302
Evidence of the CMW in AA

\[ v_2^-(\pi^-) - v_2^+ (\pi^+) = r \cdot A_{ch} \]
Chiral Magnetic Wave

- Does it stand the test of pA?
- How about higher-order harmonics, $v_3$?

$r(v_3)$ slope from CMW expected to be zero

$\Psi_3$ and $B$ direction uncorrelated
CMW results in pPb and PbPb

Significant nonzero slope in pPb: unexpected by CMW!
CMW results in pPb and PbPb

Significant nonzero slope in pPb: unexpected by CMW!
Significant nonzero slope in pPb: unexpected by CMW!
Local charge conservation in cluster decay

\[ \rightarrow \text{Correlation between } A_{ch} \text{ and } p_T \text{ of detected particles} \]

\[ A_{ch} \uparrow : <p_T>(h^+) \downarrow , <p_T>(h^-) \uparrow \]
Local charge conservation in cluster decay

\[ LCC + \text{finite detector acceptance} \]

\[ \Delta \langle p_T \rangle (h^- - h^+) \sim A_{ch} \]

\[ p_T\text{-averaged } \Delta v_2, \Delta v_3 \sim A_{ch} \]

\[ \Delta v_3 / \Delta v_2 \sim v_3 / v_2 \]

\[ v_n \sim p_T \text{ at low } p_T \]
Local charge conservation in cluster decay

\[ \Delta <p_T> \ (h^- - h^+) \sim A_{ch} \]

\[ p_T \text{-averaged } \Delta v_2, \Delta v_3 \sim A_{ch} \]

\[ \Delta v_3/\Delta v_2 \sim v_3/v_2 \]
<p_T> slopes in pPb and PbPb

Qualitatively in line with LCC mechanism
\(<p_T>\) slopes in pPb and PbPb

△ Similar normalized \(p_T\) slopes of pPb and PbPb
$v_3$ slopes in pPb and PbPb

$r_{\text{norm}}(v_2)$ and $r_{\text{norm}}(v_3)$ in PbPb are nearly identical
Unexpected by CMW but in line with LCC!
$v_3$ slopes in pPb and PbPb

CMS Preliminary

PbPb $\sqrt{s_{NN}} = 5.02$ TeV

$0.3 \leq p_T < 3.0$ GeV/c

$r_{\text{norm}}(v_2)$ and $r_{\text{norm}}(v_3)$ in PbPb are nearly identical

Unexpected by CMW but in line with LCC!
Summary and outlook

CMS “search” of CME and CMW in pPb at 5 TeV

- CME/CMW not expected in pPb
- Observed “signal” similar between pPb and PbPb, a challenge to the CME/CMW?
- CMW results in line with LCC mechanism
Summary and outlook

CMS “search” of CME and CMW in pPb at 5 TeV

- CME/CMW not expected in pPb
- Observed “signal” similar between pPb and PbPb, a challenge to the CME/CMW?
- CMW results in line with LCC mechanism

However, a key question still remains: **What are the backgrounds?** (is it $\delta^*v_2$?)

ESE, mixed harmonics
Summary and outlook

CMS “search” of CME and CMW in pPb at 5 TeV

- CME/CMW not expected in pPb
- Observed “signal” similar between pPb and PbPb, a challenge to the CME/CMW?
- CMW results in line with LCC mechanism

However, a key question still remains:

*What are the backgrounds?* (is it $\delta^*v_2$?)

ESE, mixed harmonics

With a large (CXX-free) pPb data sample in 2016, great opportunity to

- Nail down the nature of backgrounds
- Hopefully, a convincing hint of the signal in AA
Backups
(a) $|\Delta \eta| > 2$

CMS

pPb CGC

- $Q^2_{0}(\text{proton}) = 0.336 \text{ GeV}^2$
- $Q^2_{0}(\text{proton}) = 1.008 \text{ GeV}^2$
- $Q^2_{0}(\text{proton}) = 1.680 \text{ GeV}^2$

PbPb $\sqrt{s_{NN}} = 2.76 \text{ TeV}$

- $pPb \quad \sqrt{s_{NN}} = 5.02 \text{ TeV, 2013}$
- $pPb \quad \sqrt{s_{NN}} = 5.02 \text{ TeV, 2012}$
- $pp \quad \sqrt{s} = 7 \text{ TeV}$

(b) $|\Delta \eta| < 1$ minus $|\Delta \eta| > 2$

$1 < p^\text{trig}_T < 2 \text{ GeV/c}$

$1 < p^\text{assoc}_T < 2 \text{ GeV/c}$
The CMS experiment at the LHC

EM Calorimeter (ECAL)
Hadron Calorimeter (HCAL)
Beam Scintillator Counters (BSC)
Forward Calorimeter (HF)

Tracker (Pixels and Strips)
Muon System

Wide kinematic range and acceptance
Apple-to-apple comparison with ALICE

CMS Preliminary

Cent. 30-40%

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

$|\eta| < 0.8$

$\frac{V_n^- - V_n^+}{V_n^- + V_n^+}$

$r_{\text{norm}}(\text{ALICE}) = 0.137 \pm 0.013$

$r_{\text{norm}}(\text{CMS}) = 0.131 \pm 0.002$
$ \sqrt{s_{NN}} = 5.02 \text{ TeV}$

$|\eta_\alpha - \eta_\beta| < 1.6$

$|\eta_\beta| < 2.4, 4.4 < |\eta| < 5.0$

$\langle \cos(\phi_{\alpha,\beta} - 2\phi_c) \rangle/\sqrt{2c}$

$N_{\text{trk}}$

CMS

PbPb centrality (%)

SS  OS

pPb, $\phi_c$(Pb-going)
PbPb

ALICE $|\eta| < 2.0$

STAR $|\eta| < 1.6$

CMS $|\eta_\alpha - \eta_\beta| < 1.6$

ALICE $|\eta_\alpha - \eta_\beta| < 1.6$

STAR $|\eta_\alpha - \eta_\beta| < 2.0$
\[ S_{NN} = 5.02 \text{ TeV} \]

\[ \langle \cos(\phi_\alpha + \phi_\beta - 2\phi_c) \rangle / V_{2,c} \]

\[ N_{\text{trk}}^{\text{offline}} \]

PbPb centrality(%)
\[ \langle \cos(\phi_\alpha + \phi_\beta - 2\phi_c) \rangle / v_{2c} \]

CMS

PbPb \( \sqrt{s_{NN}} = 5.02 \) TeV

Cent. 60-70%

\[ l_\eta, l < 2.4, 4.4 < l_\eta l < 5.0 \]

\[ l_\eta, l < 0.8, l_\eta l < 0.8 \]