Search for the Chiral Magnetic Effect at the LHC with CMS

Wei Li (Rice University) for the CMS collaboration

- PRL 118, 122301 (2017)
- arXiv:1708.01602 (submitted to PRC)
Search for the CME in AA

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

PRL 110 (2013) 012301
Search for the CME in AA

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\gamma \equiv \langle \cos(\alpha + \beta - 2\psi) \rangle = \langle \cos(\Delta \alpha) \cos(\Delta \beta) \rangle - \langle \sin(\Delta \alpha) \sin(\Delta \beta) \rangle - \langle a_\alpha a_\beta \rangle
\]

Data consistent with charge separation from CME
Extraordinary Discovery Requires Extraordinary Evidence

\[ \Delta \gamma (\gamma^{\text{os}} - \gamma^{\text{ss}}) = \text{SIGNAL} + \text{BKG} \]

Largely unconstrained
Extraordinary Discovery Requires Extraordinary Evidence

\[ \Delta \gamma \ (\gamma^{\text{OS}} - \gamma^{\text{SS}}) = \ \text{SIGNAL} + \ \text{BKG} \]

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Must rule out the hypothesis of data being consistent with 100% (known) BKG in a data-driven way!
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i. What’s the exact origin of BKG in \( \Delta \gamma \)?

ii. Any CME signal, if BKG is removed?
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i. What’s the exact origin of BKG in \( \Delta \gamma \)?

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✓ New systems and new strategies!
Small system (pPb) strikes again!

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

In pA, \( \langle \cos 2(\Psi_B - \Psi_{EP}) \rangle \approx 0 \)

\[ \Delta \gamma_{\text{CME}} \approx 0 \]

A litmus test of the CME (any \( B \) related observable)
Small system (pPb) strikes again!

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

- **Modeling proton size fluc.**
  \[
  R_{\text{proton}} \sim \sqrt{N_{\text{trk}}}
  \]
  \[
  \Delta \gamma_{PbPb}^{CME} > 4 \Delta \gamma_{pPb}^{CME}
  \]

D. Kharzeev, Z. Tu, W. Li
PRC 97, 024905 (2018)

**A litmus test of the CME (any \( B \) related observable)**
$\Delta \gamma$ in pPb vs PbPb

Nearly **identical** in pPb and PbPb

✧ *A challenge to the CME for $\Delta \gamma$ in AA at the LHC!*?
Δγ in pPb vs PbPb

Nearly identical in pPb and PbPb

✡ A challenge to the CME for Δγ in AA at the LHC!?

But why BKGs are identical? – A new challenge?!
Questions/Requests from Huan Zhong
– experimental summary @ QCD chirality 2017

CMS $\gamma(\text{OS-SS})/v_{2c}(\text{pPb}) \sim (\text{PbPb})$ peripheral
Coincidental or not?

We urge CMS to publish
detailed centrality
dependence of OS and SS
$\gamma$ Correlators!

What does it take for ALICE to
constrain CME fraction
to the level of 10%?
Two major questions yet to be answered:

i. What’s the exact origin of BKG in $\Delta \gamma$?

ii. Any CME signal, if BKG is removed?

CMS collaboration
arXiv:1708.01602
Measurement of γ correlator at CMS

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

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

\[ |\eta_c - \eta_{\alpha,\beta}| > 2 \] to minimize \( \Psi_2\)-indep. BKG or “nonflow”
Origin of background in $\Delta \gamma$?

$$\gamma = \left\langle \cos\left(\phi_\alpha + \phi_\beta - 2\Psi_{EP}\right) \right\rangle \cong \left\langle \cos\left(\phi_\alpha + \phi_\beta - 2\phi_c\right) \right\rangle \over v_{2,c}$$

- **$\Psi_{EP}$-independent**
  - between $\alpha$ ($\beta$) and $c$
  - short-range correlations (jets, clusters etc.)
  - “Nonflow”

- **$\Psi_{EP}$-dependent**
  - between $\alpha$ and $\beta$
  - (jet, clusters etc.)
  - both correlate to $\Psi_{EP}$
  - (elliptic flow)

Charge-dep. due to charge conservation, ordering etc.
\( \Psi_{EP}\)-independent BKG

\[
\langle \cos 2(\phi_{\alpha} - \Psi_{EP}) \rangle \approx \frac{\langle \cos 2(\phi_{\alpha} - \phi_{c}) \rangle}{v_{2,c}}
\]

CMS

\[ V_{n}^{\text{sub}} \]

<table>
<thead>
<tr>
<th>( n )</th>
<th>Data Points</th>
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PRL 120, 092301 (2018)
$\Psi_{EP}$-independent BKG

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\langle \cos 2(\phi_\alpha - \Psi_{EP}) \rangle \approx \frac{\langle \cos 2(\phi_\alpha - \phi_c) \rangle}{v_{2,c}}
\]

CMS

- $pPb$ 8.16 TeV
- $pPb$ 5.02 TeV
- $pPb$ 5.02 TeV

$V_n^{\text{sub}}$ $V_n$

- $n=2$ (red circles)
- $n=3$ (blue squares)
- $n=4$ (black crosses)

$N_{\text{trk}}^{\text{offline}}$

PRL 120, 092301 (2018)
Negligible with (1) large $|\Delta \eta|$ and (2) high multiplicities
$\Delta \gamma^{BKG} = K \cdot v_2 \cdot \Delta \delta$

where $\delta \equiv \langle \cos (\phi_\alpha - \phi_\beta) \rangle$

(two-particle corr.)

$\Psi_{EP}$-dependent BKG

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\[ \Delta \gamma^{BKG} = \kappa \cdot v_2 \cdot \Delta \delta \]

where \( \delta \equiv \left\langle \cos(\phi - \phi) \right\rangle \)

(two-particle corr.)


**i.** Constant \( \kappa \) undetermined

**ii.** Linearity in \( v_2 \) hard to observe (without varying \( B \))
\[ \Delta \gamma^{BKG} = \kappa \cdot v_2 \cdot \Delta \delta \]

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✓ New systems and new strategies!

(pPb)
New strategy (I): higher-order correlator

3rd-order harmonic correlator

\[ \gamma_{123} \equiv \left\langle \cos \left( \phi_\alpha + 2\phi_\beta - 3\Psi_3 \right) \right\rangle \]

- CME signal free: no charge separation w.r.t. \( \Psi_3 \)
- For \( \Psi_3 \)-dep. BKG:

\[ \Delta \gamma_{123} = \kappa \cdot \nu_3 \cdot \Delta \delta \]
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\[
\Delta \gamma_{123} = \kappa \cdot v_3 \cdot \Delta \delta
\]

Generalize to all orders

\[
\gamma_{1,n-1;n} = \left\langle \cos \left( \phi_\alpha + (n - 1)\phi_\beta - n\Psi_n \right) \right\rangle
\]

\[
\Delta \gamma_{1,n-1;n} = \kappa \cdot v_n \cdot \Delta \delta
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- For \( \Psi_3 \)-dep. BKG:

\[ \Delta \gamma_{123} = \kappa \cdot v_3 \cdot \Delta \delta \]

If BKG dominant (i.e., for pPb)

\[ \frac{\Delta \gamma_{112}}{v_2 \delta} \approx \frac{\Delta \gamma_{123}}{v_3 \delta} \quad \ldots \]

\( \kappa \) constrained!
Differential data in $\Delta \eta$, $\Delta p_T$ and $\bar{p}_T$ for all centrality/$N_{\text{trk}}$ in arXiv:1708.01602.
Differential data in $\Delta \eta$, $\Delta p_T$ and $\bar{p}_T$ for all centrality/$N_{\text{trk}}$ in arXiv:1708.01602

$\Delta \delta_{pPb} > \Delta \delta_{PbPb}$

($\nu_2^{pPb} < \nu_2^{PbPb}$)

$\Delta \gamma^{pPb} \approx \Delta \gamma^{PbPb}$
\[ \frac{\Delta \gamma_{112}}{\nu_2 \Delta \delta} \approx \frac{\Delta \gamma_{123}}{\nu_3 \Delta \delta} \]

\[ n = 2, n = 3 \]

\[ pPb \text{ consistent with } 100\% \text{ BKG} \quad \text{benchmark!} \]

\[ 100\% \text{ BKG} - \text{benchmark!} \]

\[ \text{CMS} \]

\[ pPb 8.16 \text{ TeV} \]

\[ 185 \leq N_{\text{trk}}^{\text{offline}} < 250 \]

\[ \sum_{i=0}^{3} \Delta \gamma_{i1} \approx \sum_{i=0}^{3} \Delta \gamma_{i2} \]

\[ \Delta \gamma_{112} \approx \Delta \gamma_{123} \]

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Testing

\[ \frac{\Delta\gamma_{112}}{v_2\Delta\delta} \approx \frac{\Delta\gamma_{123}}{v_3\Delta\delta} \]

\[ \text{CMS} \]

\[ \text{pPb} \]

\[ \text{PbPb} \]

\[ \text{YES!} \]

✓ pPb consistent with 100% BKG – benchmark!

✓ Same for PbPb!

arXiv:1708.01602

CMS

pPb 8.16 TeV

185 \leq N_{\text{trk}}^{\text{offline}} < 250

CMS

pPb 8.16 TeV

|\Delta\eta| < 1.6

CMS

PbPb 5.02 TeV

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CMS

PbPb 5.02 TeV

|\Delta\eta| < 1.6

YES!

\[ n = 2, \phi_c (\text{Pb-going}) \]

\[ n = 2, \phi_c (\text{p-going}) \]

\[ n = 3, \phi_c (\text{Pb-going}) \]

\[ n = 2 \]

\[ n = 3 \]

\[ \text{YES!} \]

\[ 100\% \text{ BKG} – \text{benchmark!} \]
New strategy (II): Event-Shape Engineering

Can we directly see the linearity: $\Delta \gamma^{BKG} \sim v_2$?

$q_2 = \left\| \frac{\sum_i w_i e^{2i\phi_i}}{\sum_i w_i} \right\|$
New strategy (II): Event-Shape Engineering

Can we directly see the linearity: $\Delta \gamma^{\text{BKG}} \sim v_2$?

Vary event Ellipticity within a centrality/$N_{\text{trk}}$ class
New strategy (II): Event-Shape Engineering

PbPb vs pPb

CMS

Benchmark!

Linear, intercepting nearly zero
New strategy (II): Event-Shape Engineering

PbPb, various centralities

Linear, intercepting nearly zero
New strategy (II): Event-Shape Engineering

\[ \Delta y = \kappa \cdot \Delta \delta \cdot v_2 + \Delta y^{\text{CME}} \]

\[ \Delta \delta \text{ indep. of } q_2/v_2? \]

\[ \Delta \delta \text{ deviates from constant at high } q_2/v_2 \]
Taking a ratio: \[
\frac{\Delta \gamma}{\Delta \delta} = \kappa \cdot v_2 + \frac{\Delta \gamma^\text{CME}}{\Delta \delta}
\]
Taking a ratio: $\frac{\Delta \gamma}{\Delta \delta} = \kappa \cdot v_2 + \frac{\Delta \gamma_{\text{CME}}}{\Delta \delta}$

![Graph showing comparisons for different centrality ranges.](image)
Upper limits on the $\Delta \gamma^{\text{CME}}$ at the LHC

- PbPb 5.02 TeV
- pPb 8.16 TeV, $\phi_c$ (Pb-going)

Combined Limits
Upper limits on the $\Delta \gamma^{\text{CME}}$ at the LHC

\[
\frac{\Delta \gamma^{\text{CME}}}{\Delta \gamma} < 6.6\% \text{ (pPb)} \text{ and } 3.8\% \text{ (PbPb)}
\]

(systematic limited!)
Summary

Small system applied in the search for the CME

- Challenged the CME as a main source of $\Delta \gamma$ in PbPb at the LHC
- Served as a benchmark for $\Delta \gamma^{BKG}$ studies
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Key questions addressed by data-driven approaches

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$$\Delta \gamma_{1,n-1; n}^{BKG} = \kappa \cdot \nu \cdot \Delta \delta, \quad \kappa \approx 2$$

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$$\frac{\Delta \gamma^{CME}}{\Delta \gamma} < \text{a few \% (systematic limited)}$$
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New approaches also provide insights to future RHIC RHIC program (NOT 100\% compatible with BKG?)
Outlook at the CMS/LHC

3 Million → 6 Billion + ZDC $\Psi_1$

Tracker upgrade:
$|\eta| < 2.4 \rightarrow 4$

2015 → 2018 → 2027 (run 4)

**CME:** higher precision with full centrality scan

**Magnetic field:** $D_0$ directed flow

**CVE:** baryon number separation ($\Lambda$-$\Lambda$, $\Lambda$-$p$)

**Vorticity:** $\Lambda$ polarization (transverse and longitudinal)
Outlook at the CMS/LHC

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+ ZDC $\Psi_1$

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2015 2018 2027 (run 4)

Highly rapidity differential!

**CME:** higher precision with full centrality scan

**Magnetic field:** $D_0$ directed flow

**CVE:** baryon number separation ($\Lambda-\Lambda$, $\Lambda-p$)

**Vorticity:** $\Lambda$ polarization (transverse and longitudinal)
Backups
PHOBOS $p+p@200\text{GeV}$

Cluster model
$(K=3)$

Collective phenomena observed in pPb

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

<table>
<thead>
<tr>
<th>Energy</th>
<th>Condition</th>
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<td>pPb 8.16 TeV</td>
<td>(185 \leq N_{\text{trk}} &lt; 250)</td>
<td>(n = 2, \phi (\text{Pb-going})), (n = 2, \phi_c (\text{p-going})), (n = 3, \phi_c (\text{Pb-going}))</td>
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- \(\Delta \gamma_{1,n-1,n} / N_r \Delta \delta\)
- \(|\Delta \eta|\)
- \(|\Delta p_T| (\text{GeV})\)
- \(p_T (\text{GeV})\)
CMS

pPb 8.16 TeV
|Δη| < 1.6

\[ v_2 (|η| < 2.4) \]

- 120 ≤ \( N_{\text{trk \ offline}} \) < 150
- 150 ≤ \( N_{\text{trk \ offline}} \) < 185
- 185 ≤ \( N_{\text{trk \ offline}} \) < 250
- 250 ≤ \( N_{\text{trk \ offline}} \) < 300
- 300 ≤ \( N_{\text{trk \ offline}} \) < 400
Higher-order $\gamma$ correlator

\[ \gamma_{123} \equiv \left\langle \cos\left(\phi_\alpha + 2\phi_\beta - 3\Psi_3\right) \right\rangle \]

\[ = \left\langle \cos(\phi_\alpha - \phi_\beta)\cos(3\phi_\beta - 3\Psi_3) \right\rangle - \left\langle \sin(\phi_\alpha - \phi_\beta)\sin(3\phi_\beta - 3\Psi_3) \right\rangle \]

\[ \langle ab \rangle = \langle a \rangle \langle b \rangle \Rightarrow a \text{ and } b \text{ are independent of each other.} \]

Factorization if two-particle correlations are EP independent

This is the case in flow-driven BKG scenario, where clusters are first produced and then decay isotropically in their rest frame

Namely, two-particle p.d.f.

\[ p(\phi_\alpha, \phi_\beta, \Psi_n) = p(\phi_\alpha, \Psi_n)p(\phi_\beta, \Psi_n)\left[1 + C(\phi_\alpha - \phi_\beta)\right] \]

where

\[ p(\phi, \Psi_n) = 1 + 2v_n \cos n(\phi - \Psi_n) \]

\[ C(\phi_\alpha - \phi_\beta) = c_1 \cos \Delta\phi + ... \]
Higher-order $\gamma$ correlator

$$\gamma_{1,-3,-2} = \left< \cos \left( \phi_\alpha - 3\phi_\beta + 2\Psi_2 \right) \right>$$

Do not call it, $\gamma_{132}$ please!

$$= \left< \cos \left( \phi_\alpha - \phi_\beta - 2(\phi_\beta - \Psi_2) \right) \right>$$

$$= \left< \cos \left( \phi_\alpha - \phi_\beta \right) \cos \left( 2(\phi_\beta - \Psi_2) \right) \right> + \left< \sin \left( \phi_\alpha - \phi_\beta \right) \sin \left( 2(\phi_\beta - \Psi_2) \right) \right>$$

$$= \delta \quad \nu_2 \quad 0$$

$\Rightarrow \quad \gamma_{1,-3,-2} = \gamma_{1,1,2}$ for flow BKG only scenario

The CME contribution to this correlator should be $<a_1^*a_3>$, much smaller than for gamma112.

It could have been tested by pPb data but I have not thought about it before so it’s not done in CMS paper.