Constraining the Chiral Magnetic Effect with charge-dependent azimuthal correlations in ALICE

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Introduction: Chiral Magnetic Effect (CME)

- Strong (& short-lived) magnetic field ($\vec{B} \sim 10^{18}$ Gauss).
- Spins (& momentum) of the quarks are aligned along $\vec{B}$.
- Net current in QGP is non-zero i.e., charge separation in Final State! $\rightarrow$ +Ve and −Ve charges follow opposite direction ($\perp$ Reaction plane $\Psi_{RP}$).

Azimuthal distribution of produced particles can be described by a Fourier series,
\[
\frac{dN}{d\phi} \sim 1 + 2\sum (v_n \cos [n(\phi - \Psi_n)] + a_n \sin [n(\phi - \Psi_n)])
\]
where CME contribution is quantified by the sine terms with coefficients \(a_n\) \[^{[2]}\].

**CME Observable:** \[^{[2]}\]
\[
\gamma_{112} = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle \approx \langle \text{BG}_{\text{in}} - \text{BG}_{\text{out}} - a_1a_1\rangle,
\]
where, \(\alpha, \beta\) = particle pair with same (\(+ +\) or \(- -\)) or opposite (\(+ -\) or \(- +\)) charge and \(\Psi_{RP}\) is the Reaction plane angle. The terms \(\text{BG}_{\text{in}}\) and \(\text{BG}_{\text{out}}\) corresponds to in- and out-of plane backgrounds.

\(\gamma_{112}\) is free from correlations independent of symmetry plane, however is sensitive to symmetry plane dependent backgrounds\[^{[2]}\] (such as \(v_1\) fluctuations, flowing clusters, \(v_2\)).

To remove charge independent correlations (\(e.g. v_2\)), we take difference of OS and SS, \(i.e., \Delta \gamma_{112} = \gamma_{112}(\text{OS}) - \gamma_{112}(\text{SS})\).

\(\Delta \gamma_{112}\) is sensitive to charge separation due to CME and Local Charge conservation (LCC).

Introduction

Previous ALICE Measurements

- ALICE and STAR: Magnitude of $\gamma_{112}$ is of the same order at RHIC and LHC$^3$.
- ALICE has used Event Shape Engineering (ESE) technique to constrain the CME signal$^4$.
- CME fraction ($f_{\text{CME}}$) in $\Delta\gamma_{112}$ correlator for Pb–Pb collisions is found to be 26% to 33% (with 95% CL) for 10-50% centrality$^4$. 

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$^3$ALICE Collaboration, PRL 110, 012301 (2013), $^4$PLB 777, 151, (2018); Md Rihan Haque (for the ALICE collaboration)
CMS has measured $\Delta \gamma_{112}$ correlator in p–Pb and Pb–Pb utilizing ESE method\textsuperscript{[5]}.

STAR has measured $\Delta \gamma_{112}$ vs $m_{\text{inv}} \to$ resonances are large contributor in CME background\textsuperscript{[6]}.

CME fraction ($f_{\text{CME}}$) Limits

$\to$ by CMS = 13\% and 7\% (95\% CL) for p–Pb and Pb–Pb respectively\textsuperscript{[5]}.

$\to$ by STAR = 0 (within 2\sigma)\textsuperscript{[6]}.

Methods followed in this analysis

- Generalized 3-particle correlator: $\gamma_{m,n} = \cos[m\phi_\alpha + n\phi_\beta - (m+n)\Psi_{m+n}]$.
  - The $\gamma_{1,1}$ (or $\gamma_{112}$) is the only 3-particle correlator sensitive to CME.
  - Mixed harmonic correlators ($\gamma_{1,2}, \gamma_{2,2}$) are only sensitive to background.

- Approximations:
  \[
  \begin{align*}
  \gamma_{1,1} &= \cos[(\phi_\alpha - \phi_\beta) + 2(\phi_\beta - \Psi_2)] \propto \delta_1 v_2 \\
  \gamma_{1,2} &= \cos[(\phi_\alpha - \phi_\beta) + 3(\phi_\beta - \Psi_3)] \propto \delta_1 v_3
  \end{align*}
  \]
  where $\delta_n$ is two particle correlator defined as, $\delta_n = \langle \cos(n\phi_\alpha - n\phi_\beta) \rangle$

- By taking the difference of OS and SS correlators, we have
  \[
  \Delta \gamma_{1,1} \approx \kappa_2 \Delta \delta_1 v_2 \\
  \Delta \gamma_{1,2} \approx \kappa_3 \Delta \delta_1 v_3
  \]

- Therefore background in $\gamma_{1,1}$ can be expressed as
  \[
  \Delta \gamma_{1,1,\text{Bkg}} \approx \frac{\kappa_2 v_2}{\kappa_3 v_3} \Delta \gamma_{1,2}
  \]

- $\kappa_n$ depends on kinematic selection for the analysis and should be of similar magnitude.
  - can be tested using models which do not contain CME.

- We also estimated background using Blast-wave+LCC model.
The charge-dependent two-particle correlators are primarily dominated by background effects.

The first harmonic correlator, $\delta_1$ exhibits a significant charge-dependent difference. → contains contributions from local charge conservation.

For higher harmonics, the charge-dependent differences become progressively smaller and zero (for centrality $\leq 60\%$).
Measurement of $\gamma_{m,n}$ correlators in ALICE

- Significant charge-dependent difference is observed for $\gamma_{1,1}$ → Sensitive to 1st order parity term $\sim \langle a_1,\alpha a_1,\beta \rangle$.
- The correlator $\gamma_{1,-3}$ is also sensitive to CME however, it probes 1st and 3rd order parity term $\sim \langle a_1,\alpha a_3,\beta \rangle$.
- The $\gamma_{1,2}$ and $\gamma_{2,2}$ correlators are not sensitive to CME however they contain background from LCC.
- We can use $\gamma_{1,2}$ (and $\gamma_{2,2}$) to estimate background in $\gamma_{1,1}$.
- The resolution power of $\gamma_{2,2}$ is poor as $\Delta \gamma_{2,2} \approx$ zero.

\[^7\text{ALICE Collaboration, JHEP 2020, 160 (2020);}\]
3-particle correlations in Models

\[ \Delta \gamma_{1,1}/v_2 \] is measured in AMPT and BW-LCC model \( \rightarrow \) no CME.

From fit we observe \( \Delta \gamma_{1,1}/v_2 \approx \Delta \gamma_{1,2}/v_3 \) \( \rightarrow \) \( \kappa_2/\kappa_3 \approx 1 \).

Therefore background \( \Delta \gamma_{1,1,Bkg} \approx \frac{v_2}{v_3} \Delta \gamma_{1,2} \)

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ALICE Collaboration, JHEP 2020, 160 (2020);
CME fraction is defined as, $f_{\text{CME}} = \frac{\Delta \gamma_{1,1} - \Delta \gamma_{1,1Bkg}}{\Delta \gamma_{1,1}}$.

The $f_{\text{CME}}$ is consistent with zero (for centrality up to 40%).

The upper limit on $f_{\text{CME}}$ is 15–18% for Pb–Pb at $\sqrt{s_{\text{NN}}} = 2.76$ and 5.02 TeV.
Elliptic flow ($v_2$) and $p_T$ spectra are used to get Blast-wave parameters.

- BW-LCC model is tuned to reproduce the background in $\Delta \delta_1$.
- The tuned model then predicts the background for $\Delta \gamma_{1,1}$.
- BW-LCC fails to reproduce the background as measured by $\Delta \gamma_{1,2}$.

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7 ALICE Collaboration, JHEP 2020, 160 (2020);
\( \gamma_{112} \) with one identified hadron in Pb-Pb at \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \)

- \( \gamma_{112} \) with one identified pion at \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \) is found to be similar to that for inclusive charge particles, while results for protons indicate a particle type dependence for these correlations.

- Increased statistics expected for LHC RUN-3 will allow to significantly reduce statistical/systematic uncertainty for \( \gamma_{112} \) correlations with one and two identified hardons.
Summary and Outlook

Summary:
- Background in CME sensitive $\gamma_{1,1}$ correlator is estimated using mixed harmonic $\gamma_{1,2}$.
- Comparison of the results for $f_{\text{CME}}$ at $\sqrt{s_{\text{NN}}} = 2.76$ and 5.02 TeV shows no significant difference (up to centrality 40%).
- Upper limit for the CME fraction (for 0–40% centrality) is 15-18% (95% CL) for Pb–Pb $\sqrt{s_{\text{NN}}} = 2.76$ and 5.02 TeV.
- BW-LCC model fails to reproduce the background estimated in data.
- $\gamma_{112}$ measured with one identified particle at $\sqrt{s_{\text{NN}}} = 2.76$ TeV indicates mass dependence of the correlator.

Outlook:
- Measurement of $\gamma_{112}$ with one/two identified hadrons in high statistics Pb–Pb 5.02 TeV data
- Fine tune or improve theoretical model to reproduce 3-particle correlators.