

New experimental constraints on chiral magnetic effect using charge-dependent azimuthal correlation in pPb and PbPb collisions at the LHC

On behalf of the CMS Collaboration

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Abstract. Studies of charge-dependent azimuthal correlations for the same- and opposite-sign particle pairs are presented in PbPb collisions at 5 TeV and pPb collisions at 5 and 8.16 TeV, with the CMS experiment at the LHC. The azimuthal correlations are evaluated with respect to the second- and also higher-order event planes, as a function of particle pseudorapidity and transverse momentum, and event multiplicity. By employing an event-shape engineering technique, the dependence of correlations on azimuthal anisotropy flow is investigated. Results presented provide new insights to the origin of observed charge-dependent azimuthal correlations, and have important implications to the search for the chiral magnetic effect in heavy ion collisions.

1 Introduction

In relativistic heavy ion collisions, the metastable gluon field with nontrivial topological configurations may form, which can cause parity and charge conjugation parity violating effects [1–4]. The interactions between chiral quarks and these gluon field can lead to a chirality imbalance, where the number of left- and right-handed particles are not the same. Given the extremely strong magnetic field that can be produced by noncentral heavy ion collisions, charged-particles would tend to move along or opposite to the direction of the magnetic field. This phenomenon is known as the “chiral magnetic effect” (CME).

The CME has been extensively studied both experimentally and theoretically. The measurement was firstly done by the STAR Collaboration and later ALICE Collaboration [5–9] using a charge-dependent azimuthal correlation with respect to the reaction plane. The results are found to be consistent with the CME expectations. However, not long after this observation, it has been realized that there is non negligible flow-related background contaminated in this correlator. One of the proposed background mechanisms is related to the local charge conservation coupled with an anisotropic flow at the freezeout surface, where short-range correlation caused by jets or resonance decays that coupled with a strong elliptic flow can play an important role in the charge-dependent three-particle correlator, γ [10–12]. However, this speculation has never been directly confirmed using the experimental data.

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Recently, the CMS experiment reported a new measurement of studying the CME with γ -correlator in high-multiplicity pPb and peripheral PbPb collisions, where similar signal has been observed between pPb and PbPb systems [13, 14]. Because of the small magnetic field and its decorrelation to the second-order event plane in pA collisions [13], the CME is not expected to be observed in such small systems. Therefore, this data poses a challenge to the interpretation of the CME in AA collisions. It has been suggested that the lifetime of the strong magnetic field will not survive long enough at LHC energies in order to have CME to be present even in AA collisions. However, assuming there is no CME present at LHC energies, the CMS data still cannot be explained from a pure background model if the background is dominated by a flow only scenario, $\sim v_2/N$, where N is charged-particle multiplicity. Therefore, understanding the background related to this γ -correlator is also extremely important for searching the CME.

The very recent analysis done by the CMS Collaboration has developed a new experimental approach to study the background correlation, together with an upper limit for the CME signal using an event shape engineering (ESE) technique at LHC energies. This analysis introduces a new correlator, $\gamma_{123} \equiv \langle \cos(\phi_\alpha + 2\phi_\beta - 3\Psi_3) \rangle$, which is expected to be a CME free correlator because of the decorrelation between the event planes Ψ_2 and Ψ_3 [15]. However, this can be extremely useful for testing whether the dominated source of background is related to the local charge conservation and anisotropic flow, because one would expect, $\Delta\gamma_{112}/v_2\Delta\delta \approx \Delta\gamma_{123}/v_3\Delta\delta$, where Δ represents the difference between same and opposite sign pairs, $\delta \equiv \langle \cos(\phi_\alpha - \phi_\beta) \rangle$ is a two-particle correlation between the α and β particles and γ_{112} is the same as the conventional γ -correlator (hereafter γ_{112} - and γ -correlator are used intermittently). The advantage of using this correlator is that it provides an independent constrain on the background mechanism without involving any theoretical models. Furthermore, not only the background mechanism has been explored, an upper limit on the v_2 -independent component fraction with respect to the γ_{112} correlator that is directly related to the CME, has been set for both pPb and PbPb collisions using an ESE method. Instead of changing the centrality or multiplicity, the ESE method provides an independent handle on the initial geometry of the collisions, which is proportional to the elliptic flow, so that the γ_{112} correlator can be explicitly studied as a function of v_2 without changing the magnetic field [9, 14, 16]. This talk focused mainly on the new results that published from CMS Collaboration in Ref. [14], while details of the CMS detector can be found in Ref. [17].

2 Results

2.1 Higher-harmonic correlator

In Fig. 1, the same sign (SS) and opposite sign (OS) three-particle correlators γ_{112} (upper) and γ_{123} (middle), and two-particle correlator, δ (lower) are shown as a function of $|\Delta\eta|$ for multiplicity range $185 \leq N_{\text{trk}}^{\text{offline}} < 250$ in pPb collisions at $\sqrt{s_{\text{NN}}} = 8.16$ TeV (left) and PbPb collisions at 5.02 TeV (right). For pPb collisions, the solid markers denote the results that are obtained with particle c from the Pb-going direction, and the open markers are for the p-going direction. It is shown that the γ_{123} and δ correlator are both charge dependent at similar $|\Delta\eta|$ range as it is found in γ_{112} , where no charge separation is expected for the γ_{123} correlator. Furthermore, both the OS and SS two-particle correlator, δ , in pPb collisions are found to have a larger magnitude than that in PbPb collisions.

In order to explore the multiplicity dependence of the charge-dependent correlators, the SS and OS three-particle correlators, γ_{112} (upper) and γ_{123} (middle), and two-particle correlator, δ (lower), averaged over $|\Delta\eta| < 1.6$ as a function of $N_{\text{trk}}^{\text{offline}}$ in pPb collisions at $\sqrt{s_{\text{NN}}} = 8.16$ TeV and PbPb collisions at 5.02 TeV, are shown in Fig. 2. The published results from pPb collisions at 5.02 TeV are also shown [13]. In pPb collisions, the particle c for three-particle correlators is taken from the

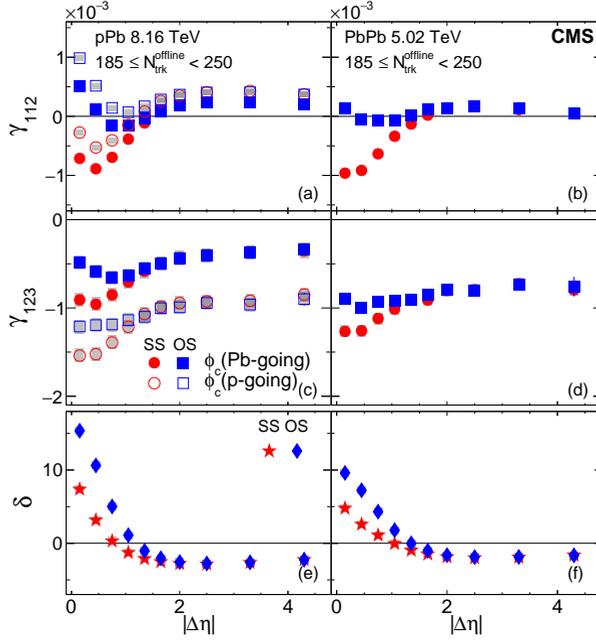


Figure 1. The same sign (SS) and opposite sign (OS) three-particle correlators, γ_{112} (upper) and γ_{123} (middle), and two-particle correlator, δ (lower), as a function of $|\Delta\eta|$ for $185 \leq N_{\text{trk}}^{\text{offline}} < 250$ in pPb collisions at $\sqrt{s_{\text{NN}}} = 8.16$ TeV (left) and PbPb collisions at 5.02 TeV (right) [14]. The pPb results obtained with particle c in Pb-going (solid markers) and p-going (open markers) sides are shown separately. The SS and OS two-particle correlators are denoted by different markers for both pPb and PbPb collisions. Statistical and systematic uncertainties are indicated by the error bars and shaded regions, respectively.

Pb-going direction of the HF detectors. The average over $|\Delta\eta| < 1.6$ is weighted by the density of particle pairs in $|\Delta\eta|$. Hereafter, all figures that averaged over $|\Delta\eta| < 1.6$ are weighted similarly.

From 5.02 TeV to 8.16 TeV, the SS and OS three-particle correlator, γ_{112} , in pPb collisions have been found to be the same within uncertainties and both agree with results from PbPb collisions, which indicates the γ_{112} correlator is mostly dominated by background correlation at both collision energies and systems. On the other hand, both OS and SS of γ_{123} in pPb collisions are different than that in PbPb collisions. For two-particle correlator, δ , the SS shows similar magnitude between pPb and PbPb collisions, while OS shows different values.

However, the individual SS and OS correlators also have charge-independent correlations (e.g., momentum conservation) and the difference in OS and SS should largely cancel out those effects. In Fig. 3, the difference between OS and SS three-particle correlators, γ_{112} (upper) and γ_{123} (middle), and two-particle correlators, δ (lower), averaged over $|\Delta\eta| < 1.6$ as a function of $N_{\text{trk}}^{\text{offline}}$ in pPb collisions at $\sqrt{s_{\text{NN}}} = 8.16$ TeV and PbPb collisions at 5.02 TeV, are shown. The results in terms of γ_{112} from 5.02 TeV pPb collisions are also shown for comparison [13]. Note that the $\Delta\delta$ is shown very differently between pPb and PbPb collisions, with pPb collisions a larger magnitude. Given the v_2 , however, is larger in PbPb than in pPb collisions at the same multiplicity, a similar value between pPb and PbPb collisions in terms of the $\Delta\gamma_{112}$ can be explained by the difference in v_2 and $\Delta\delta$ correlator, which is expected from the background mechanism of local charge conservation coupled with the anisotropy flow.

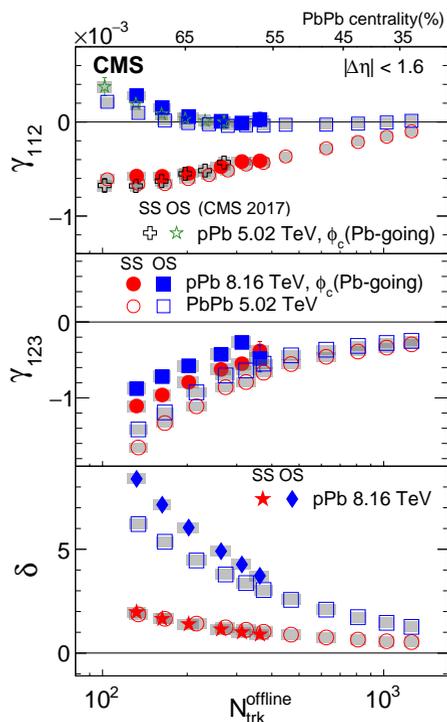


Figure 2. The SS and OS three-particle correlators, γ_{112} (upper) and γ_{123} (middle), and two-particle correlator, δ (lower), averaged over $|\Delta\eta| < 1.6$ as a function of $N_{\text{trk}}^{\text{offline}}$ in pPb collisions at $\sqrt{s_{\text{NN}}} = 8.16$ TeV and PbPb collisions at 5.02 TeV [14]. The SS and OS two-particle correlators are denoted by different markers for pPb collisions. The results of γ_{112} for pPb collisions at 5.02 TeV from CMS Collaboration (CMS 2017 [13]), are also shown for comparison. Statistical and systematic uncertainties are indicated by the error bars and shaded regions, respectively.

To test if the γ_{112} is entirely from background, the ratios of $\Delta\gamma_{112}/v_2\Delta\delta$ and $\Delta\gamma_{123}/v_3\Delta\delta$ are compared in Fig. 4 as a function of multiplicity, where these ratios are expected to be harmonic independent to the first order as they are related to the particle productions and detector acceptance [11, 14]. These ratios are found to be the same for both harmonic order $n=2$ and 3, and for both collision systems, which indicates again a pure background scenario for the γ_{112} correlator. In addition, these ratios are almost invariant for different multiplicity ranges, which would have been different if the correlation is dominated by the event plane correlation between the second- and the third-order [15]. The measurement of this ratio, usually regarded as κ , has been constrained for the background only scenario in a data-driven way. For future CME searches, this has provided a new experimental approach to constrain the κ parameter, which can be used to estimate the background contribution together with a measurement of v_2 and δ correlator.

2.2 Event shape engineering (ESE)

It has been shown in the previous section that the γ_{112} is consistent with a pure background scenario, where the background has been found to be an interplay between local charge conservation and the

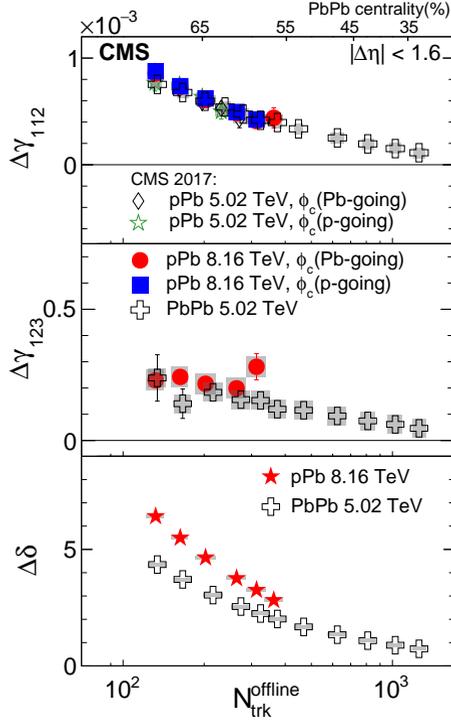


Figure 3. The difference of the OS and SS three-particle correlators, γ_{112} (upper) and γ_{123} (middle), and two-particle correlator, δ (lower), averaged over $|\Delta\eta| < 1.6$ as a function of $N_{\text{trk}}^{\text{offline}}$ in pPb collisions at $\sqrt{s_{\text{NN}}} = 8.16$ TeV and PbPb collisions at 5.02 TeV [14]. The pPb results are obtained with particle c from Pb- and p-going sides separately. The $\Delta\delta$ correlator is denoted by a different marker for pPb collisions. The results of γ_{112} for pPb collisions at 5.02 TeV from CMS Collaboration (CMS 2017 [13]), are also shown for comparison. Statistical and systematic uncertainties are indicated by the error bars and shaded regions, respectively.

anisotropy flow. However, the v_2 -independent component, which is believed to be related to the CME, still remains unknown. Using an ESE technique, events in the same multiplicity or centrality range with different average v_2 values can be selected without changing the magnetic field, a consequence of the initial-state fluctuation. As a result, the charge-dependent correlator $\Delta\gamma_{112}$ can be studied explicitly as a function of v_2 , and its intercept when $v_2 = 0$.

In Fig. 6, the ratios between $\Delta\gamma_{112}$ and $\Delta\delta$ correlators, averaged over $|\Delta\eta| < 1.6$ as a function of v_2 (evaluated as the average v_2 in each q_2 event class), for different centrality classes in PbPb collisions at $\sqrt{s_{\text{NN}}}=5.02$ TeV, are shown. The $\Delta\gamma_{112}$ and $\Delta\delta$ as a function of v_2 separately can be found in Ref. [14]. After taking the ratio, the v_2 dependence of the $\Delta\delta$ correlator is expected to be removed, and the intercepts can be interpreted as the v_2 -independent component that is related to the CME (scaled by $1/\Delta\delta$). As one can see from Fig. 6, this ratio is linear as a function of v_2 and the intercepts are found to be consistent with zero, which is expected from a pure background scenario without any CME signal. Similar results have been found in pPb collisions [14].

In order to quantify the intercepts and the possible remaining CME fraction in terms of the $\Delta\gamma_{112}$ correlator, the intercepts, b_{norm} , from Fig. 6 (left) and the upper limits at 95% confidence level (CL) on the v_2 -independent fraction, f_{norm} (right), are shown as a function of multiplicity in pPb and PbPb

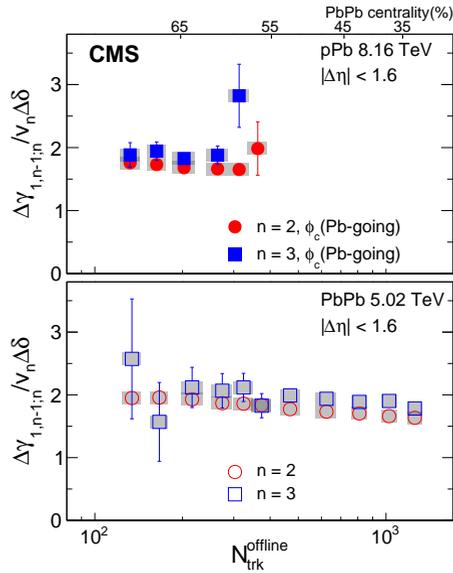


Figure 4. The ratio of $\Delta\gamma_{112}$ and $\Delta\gamma_{123}$ to the product of v_n and δ , averaged over $|\Delta\eta| < 1.6$, in pPb collisions for the Pb-going direction at $\sqrt{s_{NN}} = 8.16$ TeV (upper) and PbPb collisions at 5.02 TeV (lower) [14]. Statistical and systematic uncertainties are indicated by the error bars and shaded regions, respectively.

collisions. After combining all the measured multiplicities and centralities, the upper limit at 95% CL is found to be 6.6% and 3.8% for pPb and PbPb collisions, respectively. Note that the dominant uncertainty comes from the systematics instead of statistics, where more data is not going to improve the precision of this measurement.

A similar study has been recently done by the ALICE Collaboration [9], where details of extracting the v_2 -independent component are slightly different. Because of the finite resolution of the v_2 measurement, the expected CME signal that can be experimentally measured also depends on the value of v_2 . However, this correlation is only accessible via model-dependent simulations, and the upper limits that extracted from CMS Collaboration [14] may increase by $\sim 20\%$ depending on specific models with different initial-state fluctuations, which would still be at a few % level. Therefore, the precision measurement of the charge-dependent three-particle azimuthal correlations in pPb and PbPb collisions are consistent with a pure background scenario, posing a constrain to the possible CME signal at LHC energies.

3 Summary

Charge-dependent azimuthal correlations of same- and opposite-sign (SS and OS) pairs with respect to the second- and third-order event planes have been studied in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV and PbPb collisions at 5.02 TeV by the CMS experiment at the LHC. With the independent constrain from the charge-dependent three-particle correlator with respect to the third-order event plane, it has been found that the background mechanism is consistent with local charge conservation coupled with the anisotropy flow. In addition, the ratio, divided the OS and SS difference of the three-particle correlator by the product of v_n harmonic of the corresponding order and the difference of the two-particle correlator, is experimentally constrained at the value around 2 at LHC energies, which provides a

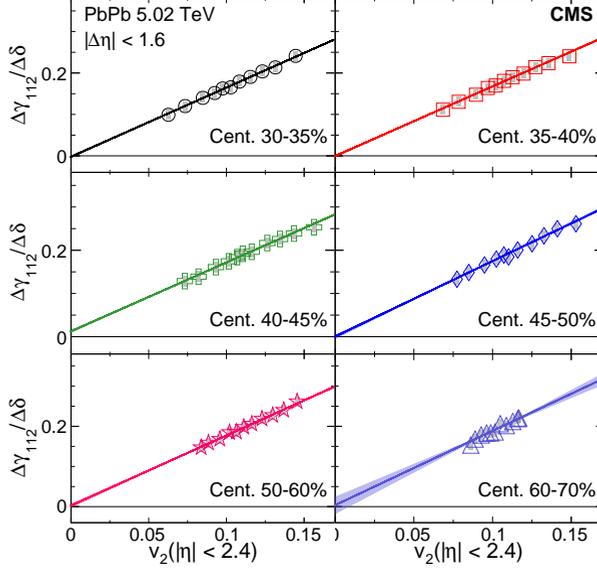


Figure 5. The ratio between the difference of the OS and SS three-particle correlators and the difference of OS and SS in δ correlators, $\Delta\gamma_{112}/\Delta\delta$, averaged over $|\Delta\eta| < 1.6$ as a function of v_2 evaluated in each q_2 class, for different centrality classes in PbPb collisions at $\sqrt{s_{NN}}=5.02$ TeV [14]. Statistical and systematic uncertainties are indicated by the error bars and shaded regions, respectively. A one standard deviation uncertainty from the fit is also shown.

new experimental approach to the understanding of background contribution in terms of the charge-dependent correlators. Moreover, using an event shape engineering technique, the upper limit on the v_2 -independent fraction that is related to the CME, has been found to be 6.6% and 3.8% for pPb and PbPb collisions, respectively, at 95% confidence level after combining all the measured multiplicity and centrality ranges. Therefore, this measurement not only provides a constrain on the magnitude of the possible CME signal at LHC energies, but also a new baseline and experimental approach of searching the CME signal for future attempts.

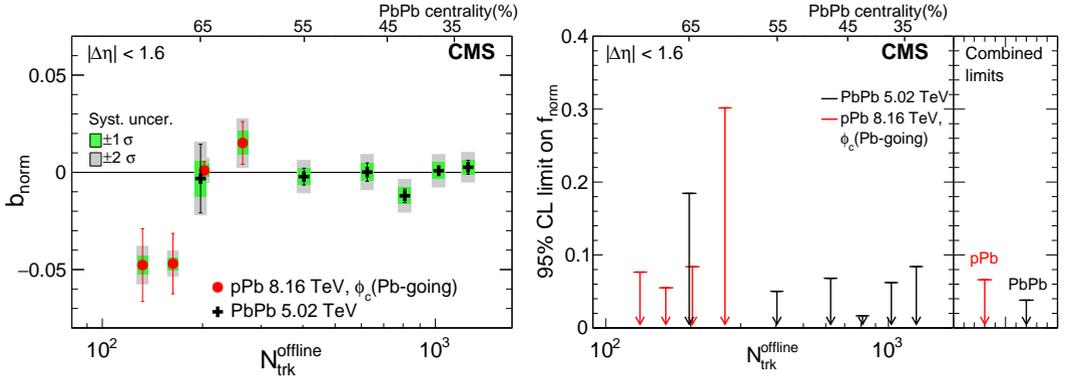


Figure 6. Extracted intercept parameter b_{norm} (left) and corresponding upper limit of the fraction of v_2 -independent γ_{112} correlator component (right), averaged over $|\Delta\eta| < 1.6$, as a function of $N_{\text{trk}}^{\text{offline}}$ in pPb collisions at $\sqrt{s_{\text{NN}}} = 8.16$ TeV and PbPb collisions at 5.02 TeV [14]. Statistical and systematic uncertainties are indicated by the error bars and shaded regions in the top panel, respectively.

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