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Search for the chiral magnetic effect at the LHC with the CMS experiment

Zhoudunming Tu, on behalf of the CMS Collaboration

Department of Physics and Astronomy, Rice University, Houston 77002, USA

Abstract

Searches for the chiral magnetic effect (CME) using charge-dependent azimuthal correlations with respect to event planes are presented in PbPb collisions at 5.02 TeV and pPb collisions at 5.02 and 8.16 TeV, with the CMS experiment at the LHC. The azimuthal correlations with respect to the second- and third-order event planes are explored as a function of pseudorapidity, transverse momentum, and event multiplicity, which provides new insights into the underlying background correlations. By employing an event-shape engineering technique, a linear dependence of charge-dependent correlations on the second-order anisotropy flow (v_2) is observed, and the upper limits on the v_2-independent fraction, which is directly related to the CME signal, are obtained at 95% confidence level for both pPb and PbPb collisions. These results provide strong constraints on the search for the chiral magnetic effect at LHC energies, and establish new guidelines for searches in future experiments.

Keywords: CME, Small Systems, Particle Correlation, Event Shape Engineering

1. Introduction

Metastable gluon fields with nontrivial topological fluctuations may cause parity and charge conjugation parity violating effects in local space and time [1, 2, 3]. In relativistic heavy ion collisions, these fluctuations are dominated by the sphaleron transition in the Quantum Chromodynamics (QCD) vacuum [1, 2, 3, 4]. The interaction between the chiral quarks and these gluon fields can lead to a chirality imbalance, μ_5, where number of left- and right-handed particles are not equal. Therefore, the extremely strong magnetic field produced at a early stage of a heavy ion collision, will induce an electric current along or opposite to the direction of the magnetic field, in which final-state charged-particles would be separated with respect to the reaction plane. This phenomenon is known as the “chiral magnetic effect” (CME).

The CME has been extensively studied both experimentally and theoretically. First results were reported by the STAR Collaboration and later by the ALICE Collaboration [5, 6, 7, 8, 9] using a charge-dependent three-particle azimuthal correlator with respect to the reaction plane. The results are found to be consistent with the CME expectations. However, non-negligible background related to elliptic flow, momentum conservation, local charge conservation, and other short-range correlations have been identified and have been found to be qualitatively consistent with the experimental data [10, 11, 12, 13, 14, 15]. One of the proposed background mechanisms is related to local charge conservation coupled with anisotropic flow at the freezeout surface [11, 14, 15]. For example, short-range correlation caused by jets or resonance decays

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that coupled with a strong elliptic flow can play an important role in the charge-dependent three-particle correlator, γ. However, this interpretation has never been directly confirmed using the experimental data.

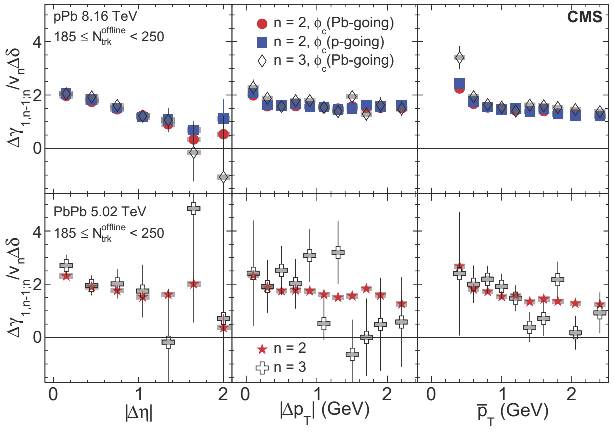

Fig. 1. The ratio of $\Delta\gamma_{112}$ and $\Delta\gamma_{123}$ to the product of v_n and δ, as functions of $|\Delta\eta|$ (left), $|\Delta p_T|$ (middle), and $\overline{p}_T$ (right) for $185 \leq N_{trk}^{offline} < 250$ in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV (upper) and PbPb collisions at 5.02 TeV (lower) [16]. Statistical and systematic uncertainties are indicated by the error bars and shaded regions, respectively.

Recently, the CMS experiment has published a new measurement of studying the γ-correlator in high-multiplicity pPb and peripheral PbPb collisions, where similar signal has been observed between pPb and PbPb systems [17, 16]. Because of the small magnetic field and its decorrelation to the second-order event plane in pA collisions [17], the CME is not expected to contribute in such small systems. This result has unambiguously shown the presence of large background in the experimental data. In order to quantitatively understand the background mechanism, a follow-up analysis of constraining the CME background has been carried out by the CMS Collaboration [16]. In this new analysis, CMS experiment has proposed to measure a new correlator, $\gamma_{123} \equiv \langle \cos(\phi_\alpha + 2\phi_\beta - 3\Psi_3) \rangle$, where the ϕ_α, ϕ_β are the azimuthal angles of the particle of interest with different charge sign and Ψ_3 is the third-order event plane. This correlator is expected to be a CME free correlator because of the decorrelation between the event planes Ψ_2 and Ψ_3 [18]. However, this can be extremely useful for testing whether the dominated source of background is related to 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 denotes the difference in the results between opposite- and same-sign pairs. The δ correlator, $\delta \equiv \langle \cos(\phi_\alpha - \phi_\beta) \rangle$, is a two-particle correlation between the α and β particles. The advantage of using the γ_{123} correlator, together with γ_{112} and δ correlators, is that they will provide an independent constrain on the background mechanism without involving any theoretical models.

Furthermore, using an event shape engineering (ESE) method (similar to Ref. [9]), upper limits on the v_2-independent component with respect to the γ_{112} correlator has been derived for both pPb and PbPb collisions, which is believed to be directly related to the CME signal. Instead of changing the centrality or multiplicity, the ESE method provides an independent handle on selecting events with very different v_2 values, so that the γ_{112} correlator can be explicitly studied as a function of v_2 without significantly changing the magnetic field [19, 16, 9]. This talk focused mainly on the new results that published from CMS Collaboration in Ref. [16], while details of the CMS detector can be found in Ref. [20].

2. Results

2.1. Higher-harmonic correlator

To test the hypothesis that the contributions from background effects to γ_{112} are dominant, the ratios of $\Delta\gamma_{112}/v_2\Delta\delta$ and $\Delta\gamma_{123}/v_3\Delta\delta$ are compared in Fig. 1 as a function of $|\Delta\eta|$ (left), $|\Delta p_T|$ (middle), and the average p_T, $\overline{p}_T$ (right), for $185 \leq N_{trk}^{offline} < 250$ in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV (upper) and PbPb collisions at 5.02 TeV (lower). These ratios are expected to be harmonic independent to first order as they are related to the particle productions and detector acceptance [16, 14]. In Fig. 1, these ratios are found to be the same within uncertainty for both harmonic order n=2 and 3, for both collision systems, and for all the measured differential observables. This indicates again a pure background scenario for the γ_{112} correlator. In addition, these ratios are almost invariant for different multiplicity ranges [16], which would have been different if the correlation is dominated by the event plane correlation between the second- and the third-order [18]. 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 provides 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 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. As a result, the charge-dependent correlator $\Delta\gamma_{112}$ can be studied explicitly as a function of v_2, and its intercept can be extracted when $v_2 = 0$.

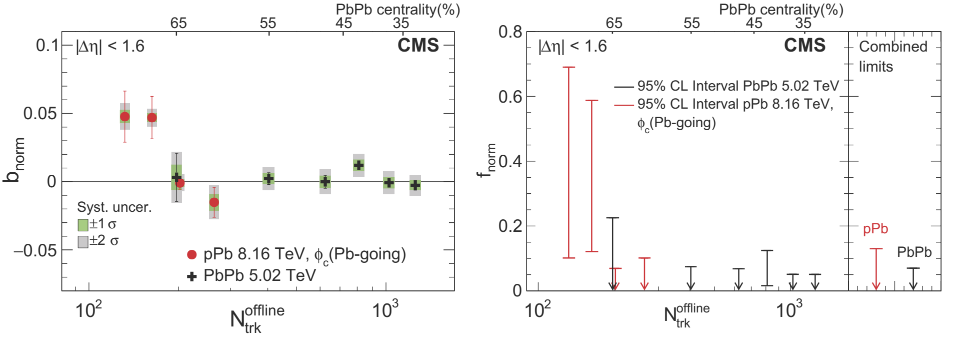

Fig. 2. Extracted intercept parameter b_{norm} (left) and corresponding upper limit of the fraction of v_2-independent γ_{112} correlator component (right), averaged over $|\Delta\eta| < 1.6$, as a function of $N_{trk}^{offline}$ in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV and PbPb collisions at 5.02 TeV [16]. Statistical and systematic uncertainties are indicated by the error bars and shaded regions in the top panel, respectively.

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 $\sqrt{s_{NN}} = 5.02$ TeV, are investigated [16]. 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 $1/\Delta\delta$). This ratio is found to be 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 [16].

In order to quantify the intercepts and the possible remaining CME fraction in terms of the $\Delta\gamma_{112}$ correlator, the intercepts, b_{norm} in Fig. 2 (left), and the upper limits at 95% confidence level (CL) on the v_2-independent fraction, f_{norm} in Fig. 2 (right), are shown as a function of multiplicity in pPb and PbPb collisions. After combining all the measured multiplicities and centralities, the upper limit at 95% CL is found to be 13% and 7% for pPb and PbPb collisions, respectively. Note that the systematic uncertainty dominates over the statistical uncertainty, so more data is not going to improve the precision of this measurement.

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 $\sqrt{s_{\rm NN}}$= 8.16 TeV and PbPb collisions at 5.02 TeV by the CMS experiment at the LHC. With an independent constrain from the charge-dependent three-particle correlator with respect to the third-order event plane, it has been quantitatively shown that the background mechanism is consistent with an interplay between the effect of local charge conservation and the anisotropic flow. 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 13% and 7% 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 for searching the CME in the future.

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