Back-to-back relative-excess observable in search for the chiral magnetic effect

Yicheng Feng,† Jie Zhao,‡ and Fuqiang Wang†,‡

1Department of Physics and Astronomy, Purdue University, West Lafayette, IN 47907, USA
2School of Science, Huzhou University, Huzhou, Zhejiang 313000, China

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Background: The chiral magnetic effect (CME) is extensively studied in heavy-ion collisions at RHIC and LHC. In the commonly used reaction plane (RP) dependent, charge dependent azimuthal correlator ($\Delta\gamma$), both the close and back-to-back pairs are included. Many backgrounds contribute to the close pairs (e.g. resonance decays, jet correlations), whereas the back-to-back pairs are relatively free of those backgrounds.

Purpose: In order to reduce those backgrounds, we propose a new observable which only focuses on the back-to-back pairs, namely, the relative back-to-back opposite-sign (OS) over same-sign (SS) pair excess ($r_{BB}$) as a function of the pair azimuthal orientation with respect to the RP ($\varphi_{BB}$).

Methods: We use analytical calculations and toy model simulations to demonstrate the sensitivity of $r_{BB}(\varphi_{BB})$ to the CME and its insensitivity to backgrounds.

Results: With finite CME, the $\varphi_{BB}$ distribution of $r_{BB}$ shows a clear characteristic modulation. Its sensitivity to background is significantly reduced compared to the previous $\Delta\gamma$ observable. The simulation results are consistent with our analytical calculations.

Conclusions: Our studies demonstrate that the $r_{BB}(\varphi_{BB})$ observable is sensitive to the CME signal and rather insensitive to the resonance backgrounds.

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1. INTRODUCTION

In quantum chromodynamics (QCD), vacuum fluctuations can produce nontrivial topological gluon fields in local domains [1]. The chirality of quarks, under the approximate chiral symmetry, is imbalanced in those gluon fields [2–4]. This violates the $CP$ symmetry in QCD in local domains. In a strong magnetic field, the single-handed quarks will polarize along or opposite to the magnetic field depending on the quark charge. This produces an electric current along the magnetic field, resulting in an observable charge separation in the final state [3, 4]. This phenomenon is called the chiral magnetic effect (CME) [3, 4].

In non-central heavy-ion collisions, the spectator protons can produce an intense, transient magnetic field, approximately perpendicular to the reaction plane (RP) (spanned by the beam direction and the impact parameter) [4]. The high energy density region created in these collisions, where the approximate chiral symmetry may be restored, provides a suitable environment to search for the CME [4]. The observation of CME-induced charge separation in heavy-ion collisions would provide a strong evidence for QCD vacuum fluctuations and local $CP$ violation.

The CME is extensively studied in heavy-ion experiments at the Relativistic Heavy Ion Collider (RHIC) [5–12] and the Large Hadron Collider (LHC) [13–16].

To probe the CME signal, the RP-dependent, charge-dependent $\Delta\gamma$ observable was proposed [17] and widely used. Positive CME-like signals in $\Delta\gamma$ have been observed in both heavy ion collisions (Au+Au at RHIC [5–8] and Pb+Pb at the LHC [14]) and small systems collisions (p+Au and d+Au at RHIC [9, 10] and p+Pb at the LHC [13]), where the latter is believed to come only from backgrounds. In fact, it has been pointed out previously that the $\Delta\gamma$ in heavy-ion collisions was contaminated by major backgrounds [18–20]. Various methods have been developed to suppress the backgrounds, such as event shape engineering [15, 16], invariant mass dependence [9], and the comparative $\Delta\gamma$ measurements with respect to the reaction and participant planes [21, 22]. The current results with those methods show a CME signal consistent with zero.

In this paper, we propose a new method. In the original definition of $\Delta\gamma$, both the close pairs and the back-to-back pairs are included. Many backgrounds contribute to the close pairs (e.g. resonance decays, jet correlations) [18–20, 23–30], whereas the back-to-back pairs are relatively free of those backgrounds. Thus, we propose a new observable which only focuses on the back-to-back pairs, namely, the relative back-to-back opposite-sign (OS) over same-sign (SS) pair excess as a function of the pair azimuthal orientation with respect to the RP.

We use simulations by a toy model (previously used in Ref. [31, 32]) to demonstrate the sensitivity of this observable to the CME signal and insensitivity to the backgrounds. The relationship between this new observable and the $\Delta\gamma$ observable is also discussed.

The paper is organized as follows. Section 2 describes the methodology of this study. Section 3 shows our toy-model simulation results using the new method. Sec-
expansion of this quantity is a measure of the CME signal.

If we expand this ratio by Fourier series, as we will show in Sec. 2.2, the second-order coefficient of the Fourier expansion of this quantity is a measure of the CME signal.

2. METHODOLOGY

2.1. New back-to-back relative-excess observable, $r_{BB}$

We divide a heavy-ion collision event into three subevents according to the $\eta$ range, the east ($-1 < \eta < -0.5$), middle ($-0.5 \leq \eta < 0.5$), and west ($0.5 \leq \eta < 1$) subevent. The middle subevent is used to reconstruct the second-order event plane azimuthal angle ($\Psi_2$) as a proxy for that of the RP ($\Psi_{RP}$). We form pairs of two charges, one from the west subevent and the other from the east subevent. The middle subevent provides an $\eta$ gap between the pair of charges. The opening angle between the two charges are required to be larger than a certain value (e.g. 150°) to define as “back-to-back” pairs. According to their charges, we classify those back-to-back pairs as either OS or SS pairs. The azimuthal orientation of the back-to-back pairs is defined to be

$$\varphi_{BB} = (\varphi_1 + \varphi_2 - \pi)/2,$$

(1)

where $\varphi_1$, $\varphi_2$ are the azimuthal angles of the two charges relative to $\Psi_{RP}$ (see Fig. 1 for the various azimuthal angle definitions). We count the numbers of the OS (SS) pairs, $n_{OS}$ ($n_{SS}$), as a function of $\varphi_{BB}$. We define our new observable as

$$r_{BB}(\varphi_{BB}) = \frac{n_{OS}(\varphi_{BB}) - n_{SS}(\varphi_{BB})}{n_{OS}(\varphi_{BB}) + n_{SS}(\varphi_{BB})}. \quad (2)$$

If we expand this ratio by Fourier series, as we will show in Sec. 2.2, the second-order coefficient of the Fourier expansion of this quantity is a measure of the CME signal.

2.2. CME signal extraction from $r_{BB}$

We first clarify analytically how $r_{BB}(\varphi_{BB})$ is sensitive to the CME signal. The azimuthal distribution for the primordial pions can be written as

$$n^\pm(\varphi) \equiv \frac{dN^\pm(\varphi)}{d\varphi} = \frac{N^\pm}{2\pi} (1 \pm 2a_1 \sin \varphi + 2v_{2,\mp} \cos 2\varphi), \quad (3)$$

where the superscript $\pm$ means the charge sign, and $N^\pm$ is the total number of primordial $\pi^\pm$ of the event. The CME signal is described by the term $\pm2a_1 \sin \varphi$. A rough estimation is $\langle a_1^2 \rangle \sim 10^{-4}$ in typical heavy ion collisions \[.\]

Without loss of generality, we use $\varphi_1$ to denote a $\pi^+$ from the east subevent and $\varphi_2$ to denote a $\pi^-$ from the west subevent. Transferring to pair variables $\varphi_{BB}$ and $\delta$, noting the Jacob determinant $|\partial(\varphi_1, \varphi_2)/\partial(\varphi_{BB}, \delta)| = 2$, we obtain the pair distribution

$$n_{W}(\varphi_{BB} - \delta)n_{E}(\varphi_{BB} + \pi + \delta)2d\varphi_{BB}d\delta. \quad (4)$$

Including the other case, we have the OS pair density distribution

$$n_{OS}(\varphi_{BB}, \delta) = 2n_{W}(\varphi_{BB} - \delta)n_{E}(\varphi_{BB} + \pi + \delta) + 2n_{W}(\varphi_{BB} - \delta)n_{E}(\varphi_{BB} + \pi + \delta)

= \frac{N_{W}N_{E}}{2\pi^2} \left[ 1 + 4a_1^2 \sin(\varphi_{BB} - \delta) \sin(\varphi_{BB} - \delta) + 4v_{2,\mp}\cos(2\varphi_{BB} + \delta) \cos(2\varphi_{BB} - \delta) + \cos(2\varphi_{BB} - \delta) \times (v_{2,\mp} + v_{2,\pi} - 2a_1(v_{2,\mp} - v_{2,\pi}) \sin(\varphi_{BB} - \pi)) + \cos(2\varphi_{BB} - \delta) \times (v_{2,\mp} + v_{2,\pi} - 2a_1(v_{2,\mp} - v_{2,\pi}) \sin(\varphi_{BB} + \pi)) \right]. \quad (5)$$

Assuming the event averages

$$\langle N_{W}^+ N_{E}^- \rangle = \langle N_{W}^- N_{E}^+ \rangle = \langle N_{W}^+ N_{E}^+ \rangle = \langle N_{W}^- N_{E}^- \rangle = \langle N^2 \rangle, \quad (6)$$

and integrating over $\delta$ from $-\Delta$ to $\Delta$, we have

$$n_{OS}(\varphi_{BB}) = \int_{\Delta-\Delta}^{\Delta} n_{OS}(\varphi_{BB}, \delta)d\delta \quad \text{and} \quad n_{SS}(\varphi_{BB}, \delta)$$

$$= \frac{2\langle N^2 \rangle \Delta}{\pi^2} \left[ 1 + 2v_{2,\pi} + v_{2,\pi} - \Delta \cos 4\varphi_{BB} + a_1^2 \sin 2\Delta + \cos 2\varphi_{BB}(-2a_1^2 + v_{2,\mp} + v_{2,\pi}) \sin 2\Delta \right] + \frac{1}{2}v_{2,\pi} + v_{2,\pi} - \sin 4\Delta. \quad (7)$$

Similarly, we obtain the SS pair density distribution

$$n_{SS}(\varphi_{BB}, \delta) = 2n_{W}(\varphi_{BB} - \delta)n_{E}(\varphi_{BB} + \pi + \delta) + 2n_{W}(\varphi_{BB} - \delta)n_{E}(\varphi_{BB} + \pi + \delta), \quad (8)$$

FIG. 1. A sketch of “back-to-back” pair on the transverse plane.
Our new observable is the ratio and we expand it into effects in \(-v\) first order of (\(v\)). Noticing that (11), up to the difference and sum are, respectively,

\[
\begin{align*}
n_{\text{OS}}(\phi_{\text{BB}}) - n_{\text{SS}}(\phi_{\text{BB}}) &= \frac{2\langle N^2 \rangle}{\pi^2} \left[ 2\Delta + 2a_1^2 \cos(2\phi_{\text{BB}}) \cos 4\phi_{\text{BB}} \right. \\
&\left. + (v_{2,\pi^+} + v_{2,\pi^-}) \sin 4\Delta \right], \quad (10)
\end{align*}
\]

Our new observable is the ratio and we expand it into Fourier series

\[
r_{\text{BB}}(\phi_{\text{BB}}) = \frac{n_{\text{OS}}(\phi_{\text{BB}}) - n_{\text{SS}}(\phi_{\text{BB}})}{n_{\text{OS}}(\phi_{\text{BB}}) + n_{\text{SS}}(\phi_{\text{BB}})} = \sum_{k=0}^{+\infty} c_k \cos(k\phi_{\text{BB}}).
\]

Noticing that \((v_{2,\pi^+} + v_{2,\pi^-})\) is small \((\sim 0.1)\), up to the first order of \((v_{2,\pi^+} + v_{2,\pi^-})\), the coefficient of \(\cos 2\phi_{\text{BB}}\) is

\[
c_2 \approx a_1^2 \left( -2 - (v_{2,\pi^+} + v_{2,\pi^-}) \frac{\sin^2 2\Delta}{\Delta^2} \right) + (v_{2,\pi^+} + v_{2,\pi^-}) (v_{2,\pi^+} - v_{2,\pi^-}) \frac{2(2\Delta + \sin 4\Delta) \sin 2\Delta}{8\Delta^2}.
\]

If we require the opening angle to be larger than \(150^\circ\) for the back-to-back pairs, then \(\Delta = 15^\circ\),

\[
c_2 \approx a_1^2 \left( -2 - 3.648(v_{2,\pi^+} + v_{2,\pi^-}) \right) + 1.267(v_{2,\pi^+} + v_{2,\pi^-})(v_{2,\pi^+} - v_{2,\pi^-})^2.
\]

The second term is not related to the CME; taking \(|v_{2,\pi^+} - v_{2,\pi^-}| \sim 10^{-3}\), \((v_{2,\pi^+} + v_{2,\pi^-}) \sim 10^{-1}\), its magnitude is on the order of \(10^{-7}\). For a CME signal of \(a_1 \geq 10^{-3}\), \(a_1^2\) dominates over the primordial flow effects in \(c_2\), indicating that \(c_2\) is a good measure of the CME.

Similarly, the coefficient of the constant term \((k = 0)\) is

\[
c_0 = \frac{\sin 2\Delta}{4\Delta} \left( 4a_1^2 (1 + v_{2,\pi^+} + v_{2,\pi^-}) \right.
\]

\[
- \left( v_{2,\pi^+} - v_{2,\pi^-} \right)^2 \cos 2\Delta),
\]

and for \(\Delta = 15^\circ\),

\[
c_0 \approx 1.910a_1^2 (1 + v_{2,\pi^+} + v_{2,\pi^-}) - 1.654(v_{2,\pi^+} - v_{2,\pi^-})^2.\]

Note that \(c_2\) and \(c_0\) are both sensitive to the CME, with similar sensitivities. It will be shown later, however, that \(c_0\) is also sensitive to the backgrounds. Those backgrounds are mainly from the low \(p_T\) resonance decays whose decay daughters are back-to-back. The \(c_2\) is less sensitive to those backgrounds because their \(v_2\) at low \(p_T\) is small.

### 2.3. Comparison to the back-to-back \(\Delta\gamma\) observable, \(\Delta\gamma_{\text{BB}}\)

The \(\Delta\gamma\) observable is frequently used in heavy-ion collisions to search for the CME,

\[
\Delta\gamma = \gamma_{\text{OS}} - \gamma_{\text{SS}},
\]

\[
\gamma = (\cos(\phi_1 + \phi_2)).
\]

To see the relationship between \(r_{\text{BB}}\) and \(\Delta\gamma\), we will apply the same “back-to-back” requirement to the pairs in \(\Delta\gamma\), denoted as \(\Delta\gamma_{\text{BB}}\). For back-to-back pairs, \(\cos(\phi_1 + \phi_2) = -\cos(2\phi_{\text{BB}})\). The correlators \(\gamma_{\text{OS}}\) and \(\gamma_{\text{SS}}\) can be simplified into

\[
\begin{align*}
\gamma_{\text{OS}} &= -\int \cos(2\phi_{\text{BB}}) n_{\text{OS}}(\phi_{\text{BB}}) d\phi_{\text{BB}} \\
&= \frac{2a_1^2 \Delta - (v_{2,\pi^+} + v_{2,\pi^-}) \sin 2\Delta}{2\Delta + 2a_1^2 \sin 2\Delta + v_{2,\pi^+} + v_{2,\pi^-} \sin 4\Delta}, \quad (18)
\end{align*}
\]

\[
\begin{align*}
\gamma_{\text{SS}} &= -\int \cos(2\phi_{\text{BB}}) n_{\text{SS}}(\phi_{\text{BB}}) d\phi_{\text{BB}} \\
&= \frac{-2a_1^2 \Delta - (v_{2,\pi^+} + v_{2,\pi^-}) \sin 2\Delta}{2\Delta - 2a_1^2 \sin 2\Delta + \frac{1}{2}(v_{2,\pi^+} + v_{2,\pi^-}) \sin 4\Delta}.
\end{align*}
\]

The difference to the first order of \((v_{2,\pi^+} + v_{2,\pi^-})\) is therefore

\[
\Delta\gamma_{\text{BB}} = \gamma_{\text{OS}} - \gamma_{\text{SS}}
\]

\[
\begin{align*}
&\approx a_1^2 \left( 2 + (v_{2,\pi^+} + v_{2,\pi^-}) \frac{\sin^2 2\Delta}{\Delta^2} \right) \\
&\quad \quad - (v_{2,\pi^+} + v_{2,\pi^-})(v_{2,\pi^+} - v_{2,\pi^-}) \frac{2\sin 2\Delta \sin 4\Delta}{8\Delta^2}.
\end{align*}
\]

With \(\Delta = 15^\circ\), it becomes

\[
\begin{align*}
\Delta\gamma_{\text{BB}} &= \gamma_{\text{OS}} - \gamma_{\text{SS}} \\
&\approx a_1^2 \left( 2 + 3.648(v_{2,\pi^+} + v_{2,\pi^-}) \right) \\
&\quad \quad - 0.790(v_{2,\pi^+} + v_{2,\pi^-})(v_{2,\pi^+} - v_{2,\pi^-})^2.
\end{align*}
\]
Comparing Eqs. [19] and [20] to Eqs. [13] and [14], it is clear that \( \Delta_{\gamma_{BB}} \) and \( r_{BB} \) have similar sensitivity to the CME. The \( r_{BB} \) observable is directly related to \( \Delta_{\gamma_{BB}} \). Only the back-to-back pairs are used in these two observables, so the backgrounds among the close pairs are reduced.

3. RESULTS

In this section, we show the back-to-back \( r_{BB}(\phi_{BB}) \) and back-to-back \( \Delta_{\gamma_{BB}} \) observables calculated from a toy model (with/without input CME) simulations.

3.1. Toy-model simulation

We use a toy model including the primordial pions and the \( \rho \) meson decays to study the sensitivities of \( r_{BB} \) to CME signal and resonance backgrounds. This toy model has been used for CME background studies in Ref. [31, 32]. Both the resonance decays and primordial pions have the \( p_T \) distributions and \( v_2(p_T) \) obtained from Au+Au measurements corresponding to centrality 40%~50% [31, 33, 34].

To simulate the CME signal in the toy model, we input the coefficient \( a_1 \) when generating the primordial pions from the azimuthal distribution (Eq. [3]). Two cases are studied, one without CME input \((a_1 = 0)\), and the other with 1% CME input \((a_1 = 0.01)\). Each case has 2 \times 10^9 events. The tracks are selected with transverse momentum 0.2 GeV < \( p_T \) < 2.0 GeV and pseudorapidity \(-1.0 < \eta < 1.0\). Figure 2 shows the \( r_{BB}(\phi_{BB}) \) distributions for the two cases. The case with finite CME shows larger amplitude and modulation than the case without, indicating the sensitivity of the \( r_{BB}(\phi_{BB}) \) observable to the CME. The case without CME shows some finite amplitude and modulation, at low \( m_{inv} \), indicating that the observable still has some background contamination. In order to further suppress resonance backgrounds, we also show the \( r_{BB} \) distributions with the invariant mass range 1.5 GeV < \( m_{inv} \) < 3.0 GeV. The result is consistent with zero as expected.

We fit the \( r_{BB}(\phi_{BB}) \) distributions to Eq. [12]. Figure 3 shows the fitted Fourier coefficients \( c_0 \) and \(-c_2\), respectively, as a function of \( m_{inv} \). The \( c_0 \) has strong sensitivity to both signal and background. Although still affected by the residual resonance backgrounds, the \(-c_2\) has better sensitivity to CME than \( c_0 \) and less sensitivity to background. To illustrate our results more quantitatively, we list the fitted coefficients \( c_0 \) and \(-c_2\) in Table I. Also listed are the \( a_1 \) values extracted from \( c_0 \) and \(-c_2\), via Eqs. [19] and [14], respectively, ignoring the presence of
backs. Due to resonance backgrounds in the low
\( m_{\text{inv}} \) range, the extracted \( a_1 \) are large with 0.0 GeV < 
\( m_{\text{inv}} < 3.0 \) GeV, no matter whether the input \( a_1 \) are zero
or not. In the range 1.5 GeV < \( m_{\text{inv}} < 3.0 \) GeV, with
zero input \( a_1 \), the extracted \( a_1 \) values are also close
to zero; the small deviations from zero are due to residual
resonance backgrounds. With input \( a_1 = 0.01 \), the ex-
tracted \( a_1 \) values are close to 0, the differences are due to residual res-
onance backgrounds. However, under this condition, the
extracted \( a_1 \) values are smaller than the inputs. This is
because there are pairs composed of pions from uncor-
related sources (one primordial pion and one resonance
pion, or two pions from two different resonance decays),
whose zero contributions are averaged in \( c_0 \), \( -c_2 \). The
dilution from those uncorrelated pairs reduces the ex-
tracted \( a_1 \) values.

3.2. Comparison among \( \Delta_\gamma \), \( \Delta_\gamma^{\text{BB}} \), and \( -c_2 \)

We also calculate the inclusive \( \Delta_\gamma \) and back-to-back
\( \Delta_\gamma^{\text{BB}} \) observables in our model studies. Figure 4 com-
pares the results of those three observables. It is found
that \( \Delta_\gamma^{\text{BB}} \) and \( -c_2 \) are very close to each other. This
indicates that the \( r_{\text{BB}} \) and \( \Delta_\gamma^{\text{BB}} \) observables are nearly
the same, as expected from Eqs. 14 and 20. With zero CME
input \( (a_1 = 0) \) in the toy model simulation (Fig. 4a), the
inclusive \( \Delta_\gamma \) is further away from zero than the other two
observables in the invariant mass range 0.6 \( \sim \) 1.5 GeV
where resonance contributions are large. This shows that
the inclusive \( \Delta_\gamma \) is more significantly affected by the res-
onance backgrounds. In the high mass region where res-
onance contributions are small, all three observables ap-
proach to zero as expected. With nonzero CME input
\( (a_1 = 0.01) \) in the toy model simulation (Fig. 4b), the
three observables are all away from zero. The inclusive
\( \Delta_\gamma \) is lower than the other two in the mass range
1.5 GeV \( \sim \) 3.0 GeV where there is not much resonance
contribution. This is because the back-to-back CME sig-

\begin{table}[]
\centering
\begin{tabular}{|c|c|c|c|}
\hline
\textbf{\( m_{\text{inv}} \) range (GeV)} & \textbf{input \( a_1 \)} & \textbf{Fourier coefficients \((x \times 10^{-4})\)} & \textbf{extracted \( a_1 \) \((x \times 10^{-2})\)} \\
\hline
0.0 \( \sim \) 3.0 & 0 & \( c_0 \): 1.57 \( \pm \) 0.01 & 0.87 \( \pm \) 0.01 \\
 & & \( -c_2 \): 0.37 \( \pm \) 0.02 & 0.39 \( \pm \) 0.02 \\
 & 0.01 & \( c_0 \): 3.07 \( \pm \) 0.01 & 1.21 \( \pm \) 0.01 \\
 & & \( -c_2 \): 2.04 \( \pm \) 0.02 & 0.93 \( \pm \) 0.01 \\
1.5 \( \sim \) 3.0 & 0 & \( c_0 \): 0.88 \( \pm \) 0.03 & 0.20 \( \pm \) 0.07 \\
 & & \( -c_2 \): 0.07 \( \pm \) 0.04 & 0.17 \( \pm \) 0.10 \\
 & 0.01 & \( c_0 \): 1.45 \( \pm \) 0.03 & 0.83 \( \pm \) 0.02 \\
 & & \( -c_2 \): 1.69 \( \pm \) 0.04 & 0.85 \( \pm \) 0.02 \\
\hline
\end{tabular}
\caption{The fitted Fourier coefficients \( c_0 \) and \( -c_2 \) are shown for the \( r_{\text{BB}}(\varphi_{\text{BB}}) \) distributions from the toy-model simulations
with/without CME signal input. Two invariant mass ranges are shown. If we set \( (v_2^{+} + v_2^{-}) \approx 0.1 \), ignore the \( (v_2^{+} - v_2^{-})^2 \) terms in Eqs. 14 and 16 and assume zero resonance background in the toy-model simulations, the \( a_1 \) can be extracted from \( c_0 \)
and \( c_2 \), respectively. These extracted \( a_1 \) values are also listed, to be compared to the input \( a_1 \).}
\end{table}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig4}
\caption{Comparison among the inclusive \( \Delta_\gamma \), the back-to-
back \( \Delta_\gamma^{\text{BB}} \), and the Fourier coefficient \( -c_2 \) of the \( r_{\text{BB}}(\varphi_{\text{BB}}) \) distribution in different simulations.}
\end{figure}

pairs from backgrounds. This can also be explained by
the analytical calculations in Eq. 19 by assigning \( \Delta = 90^\circ \)
for the inclusive \( \Delta_\gamma \) and \( \Delta = 15^\circ \) for \( \Delta_\gamma^{\text{BB}} \).

4. SUMMARY

In this paper, we propose a new observable to search
for the CME, called the back-to-back relative-excess ob-
 observable of OS to SS pairs \( (r_{\text{BB}}) \), as a function of the
pair azimuthal orientation \( (\varphi_{\text{BB}}) \). The charge pairs used
in this observable are required to be back-to-back: opening angle larger than 150° on the transverse plane; they are taken from different \( \eta \) ranges with a \( \Delta \eta \) gap to further reduce backgrounds. As a result, the backgrounds (such as resonance decays) contributing mostly to the close pairs can be reduced. A modulation of the form \( \cos 2\gamma_{BB} \) in the observable can indicate a CME signal, which is described by the second-order coefficient \( c_2 \) in Fourier expansion.

We use a toy model simulation without input CME \((a_1 = 0)\) and with 1% input CME \((a = 0.01)\), and calculate the observable from the simulated data. The coefficient \( c_2 \) is close to zero when there is no input CME, whereas it is far from zero with 1% input CME.

To relate the new observable to the previous \( \Delta \gamma \) observable, we apply the same back-to-back pair requirement to the definition of \( \Delta \gamma \) to obtain \( \Delta \gamma_{BB} \). We use analytical calculations and toy-model simulations to show that \( \Delta \gamma_{BB} \) is nearly identical to \( -c_2 \). Both are more sensitive to the CME and less sensitive to resonance backgrounds than the inclusive \( \Delta \gamma \) observable.

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