Importance of non-flow background on the chiral magnetic wave search

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Abstract

An observable sensitive to the chiral magnetic wave (CMW) is the charge asymmetry dependence of the \(\pi^-\) and \(\pi^+\) anisotropic flow difference, \(\Delta v_n(A_{ch})\). We show that, due to non-flow correlations, the flow measurements by the Q-cumulant method using all charged particles as reference introduce a trivial linear term to \(\Delta v_n(A_{ch})\). The trivial slope contribution to the triangle flow difference \(\Delta v_3(A_{ch})\) can be negative if the non-flow is dominated by back-to-back pairs. This can explain the observed negative \(\Delta v_3(A_{ch})\) slope in the preliminary STAR data. We further find that the non-flow correlations give rise to additional backgrounds to the slope of \(\Delta v_2(A_{ch})\) from the competition among different pion sources and from the larger multiplicity dilution to \(\pi^+\) (\(\pi^-\)) at positive (negative) \(A_{ch}\).

Keywords: heavy ion collisions, chiral magnetic wave, anisotropic flow, non-flow background

1. Introduction

The interplay between the chiral magnetic effect and the chiral separation effect can lead to a gapless collective excitation, a phenomenon called the chiral magnetic wave (CMW) \cite{1, 2}. The CMW could introduce an electric quadrupole moment, giving opposite contributions to the \(\pi^+\) and \(\pi^-\) elliptic flow anisotropies \((v_2)\) dependent of the charge asymmetry \((A_{ch} = \frac{N^+ - N^-}{N^+ + N^-})\) \cite{2}

\[ v_2[\pi^\pm] = v_2^{base} \pm \frac{r[\pi^\pm]}{2} A_{ch}. \] (1)

The CMW-sensitive slope parameters \((r)\) measured by the STAR, ALICE and CMS collaborations qualitatively agree with the expectation from the CMW \cite{3, 4, 5}. The data can also be qualitatively explained by non-CMW mechanisms, such as the Local Charge Conservation (LCC) \cite{6} and the effect of isospin chemical potential \cite{7}. We will show in these proceedings that non-flow correlations can also cause \(A_{ch}\)-dependent \(\pi\) flows. We demonstrate \cite{8} that the non-flow correlations can give both trivial and non-trivial contributions to the slope parameters of \(\Delta v_n(A_{ch}) \equiv v_n^+(A_{ch}) - v_n^-(A_{ch})\), where \(n = 2\) (elliptic flow) and \(n = 3\) (triangle flow).
2. Trivial non-flow contributions to $v_2(A_{ch})$

Using the $Q_i$-vector $Q_i = \sum_{m=1,2} M_i^m w_i |q_i|^m$, the anisotropic flow of particles of interest (POI, $\pi^\pm$ in this study) can be calculated by $v_2^\mp[2] = \frac{d_n[2; \pi^\pm h]}{\sqrt{n_\pi[2]}}$ with $d_n[2] \equiv \langle \langle 2' \rangle \rangle = \sum_{m=1,2} w_i M_i^m |q_i|^m$, and $\sqrt{n_\pi[2]}$ is the flow of reference particles (REF). Here $w_i = m_i M_i^m$, $(m_i, q_{n,i})$ and $(M_i, Q_{n,i})$ are the (multiplicity, Q-vector) of POI and REF, respectively.

With all charged hadrons as REF, as typically done in data analysis, the two-particle cumulant can be rewritten into [8]

$$d_n[2; \pi^\pm h] = \frac{d_n[2; \pi^+ h^+] + d_n[2; \pi^- h^-]}{2} + \frac{d_n[2; \pi^+ h^-] - d_n[2; \pi^- h^+]}{2} A_{ch}. \quad (2)$$

The second term on r.h.s of Eq. (2) is proportional to $A_{ch}$ and opposite in sign for $\pi^+$ and $\pi^-$. This will directly give a trivial contribution to the CMW-sensitive slope parameter. It vanishes if the correlations are due to flow only because in this case $d_n[2; \pi^+ h^+] = d_n[2; \pi^- h^-]$. However, non-flow is present in experimental data and differs between like-sign and unlike-sign pairs, so the trivial term is finite.

The STAR preliminary results indicate a negative slope for $\Delta v_2(A_{ch})$ in central and peripheral collisions [9]. A negative trivial slope can easily arise from back-to-back pairs of particles. We illustrate this using a Monte Carlo model. We generate $\pi^+$ and $\pi^-$ with Poisson multiplicity fluctuations in each event. The $p_T$ spectra correspond to the measured data in the 30–40% centrality Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV [10,11]; The $\eta$ spectra are parameterized as in Ref. [12]. The mean multiplicity of charged hadrons is set to 380 in $|y| < 1$ with $p_T > 0.15$ GeV/c. To introduce a non-flow correlation difference between like-sign and unlike-sign pairs, we force, on average, 20% of the multiplicity in a given event to come from $\pi^+\pi^-$ pairs with back-to-back azimuthal angles for the two pions. A constant elliptic flow $v_2 = 4\%$ (triangle flow $v_3 = 4\%$) is used to generate the azimuth angle of those pairs as well as the rest 80% $\pi^+$ and $\pi^-$. The results are shown in Fig. [1] The slope of the trivial term, dubbed the trivial slope $r_{triv}$, is calculated by $r_{triv}(\pi^\pm) = \frac{d_n[2; \pi^+ h^+] - d_n[2; \pi^- h^-]}{2 (\Delta v_2)^2}$ (c.f. Eq. (2)). The slope parameter without removing the trivial term is denoted as $r_0$. The back-to-back pairs contribute a positive trivial slope to $\Delta v_2(A_{ch})$ shown in Fig. [1]a) and a negative trivial slope to $\Delta v_2(A_{ch})$ shown in Fig. [1]b).

Non-flow differences are present between like-sign and unlike-sign pairs in real collisions, and not much can be done to eliminate these non-flow differences. In order to eliminate the trivial linear $A_{ch}$ term, one can use hadrons of a single charge sign instead of all charged hadrons as REF. One may use positive and

Figure 1. (Color online) A Monte Carlo model demonstration of the trivial term, arising from back-to-back (B2B) unlike-sign pair non-flow correlations, due to the net effect of non-flow difference between like-sign and unlike-sign pairs and using all charged particles as REF: (a) $\Delta v_2(A_{ch})$, and (b) $\Delta v_2(A_{ch})$. Results before and after eliminating the trivial term are shown by open circles and filled stars, respectively.
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v
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r
non-zero slope. It is interesting to note, however, that the
and pions from resonance decays (denoted by ‘D’). We have
We now demonstrate this by using a two-component model, i.e., primordial pions (denoted by subscript ‘P’)
between two sources of pions, the paired pions and unpaired pions, to be discussed in the next section.
for back-to-back non-flow pairs, as shown in Fig. 1(b) by the red stars. The reason is due to a competition
slope following our methodology, the normalized

\[ \Delta v_n = 2\epsilon(1-\epsilon)(A_D - A_P)(v_{n,P} - v_{n,D}) \]

Here we have assumed the event-by-event distributions of \( A_P \) and \( A_D \) are both normal distributions, i.e.,
\( \mathcal{N}(\mu_P, \sigma_P^2) \) and \( \mathcal{N}(\mu_D, \sigma_D^2) \) in a charge-neutral system.
The slope $r^{2C}$ from the two-component (2C) model is clearly non-zero if $\sigma_P^2 \neq \sigma_D^2/(1 - \epsilon)$ and $v_{n,p} \neq v_{n,D}$. The root reason is that the relative fractions of pions from different sources depend on the event-by-event $A_{ch}$ value (because they contribute to $A_{ch}$ differently), therefore the average $v_2$ from multiple sources, which have different $v_2$’s, will depend on $A_{ch}$.

We have used two “flow” sources in the above derivation. However, this also applies to the competition between flow and non-flow contributions to the observed $\Delta v_2(A_{ch})$. This is the reason for the non-zero slope in Fig. 3(b) even after eliminating the trivial term, because the “$v_1$” from the back-to-back pairs is by definition zero, which differs from the single pion $v_1$, even though the back-to-back pairs are generated with the same $v_2$ modulation. Such a problem is not present for $v_2$. We have tested $v_2$ using two different input $v_2$’s for single and paired pions, and also found a non-zero slope parameter.

### 3.2. Like-sign non-flow correlations

The non-flow correlations from like-sign pairs can also introduce a non-zero slope parameter. We modify our non-flow Monte Carlo model to generate like-sign pairs by forcing 20% of $\pi^+$ and $\pi^-$ to be paired as $\pi^+\pi^+$ (and $\pi^-\pi^-$) with the same azimuth. All other parameters of the model are unchanged. The resulting $\Delta v_2(A_{ch})$ has a positive slope $r = 1.63\%$. This is due to the dilution effect: when more $\pi^+$ are counted resulting in a positive $A_{ch}$, the $\pi^+\pi^+$ non-flow correlation is more diluted while the $\pi^-\pi^-$ non-flow is less diluted, resulting in a large $v_2$ for $\pi^-$ than for $\pi^+$. This is different in the unlike-sign case, where the dilution effect is identical for $\pi^+$ and $\pi^-$. 

### 4. Summary

The charge asymmetry ($A_{ch}$) dependent pion elliptic flow difference $\Delta v_2(A_{ch})$ is a sensitive observable to the chiral magnetic wave (CMW). In these proceedings, we first demonstrate that the flow measurements can automatically introduce a trivial linear-$A_{ch}$ dependence if (1) there exists non-flow difference between like-sign and unlike-sign pairs and (2) hadrons or both charge sinds are used as reference particles in the two-particle cumulant flow measurements. Using a Monte Carlo model, we find that back-to-back unlike-sign pair non-flow correlations contribute a positive trivial slope to $\Delta v_2(A_{ch})$ and a negative trivial slope to $\Delta v_3(A_{ch})$. New data analysis indicates that the trivial contribution is the dominate reason for the large negative slope of $\Delta v_3(A_{ch})$ in the previous STAR preliminary results (see Fig. 2).

We further find that the competition among multiple $\pi$ sources can introduce a non-trivial linear-$A_{ch}$ term. This effect is sensitive to the differences in multiplicity fluctuations and anisotropic flows of those sources, and arises from the $A_{ch}$-dependent relative contributions of pions from those sources. We also find that the non-flow between like-sign pairs gives a positive slope to $\Delta v_2(A_{ch})$ because of the larger multiplicity dilution effect to $\pi^+$ ($\pi^-$) at positive (negative) $A_{ch}$.

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