Geometrical Effect on Conical Emission of Correlated Hadrons

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Abstract. Dihadron correlations at intermediate $p_T$ revealed novel structures on the away side of high $p_T$ trigger particles at RHIC. The away-side correlations in central Au+Au collisions are significantly broader than in pp and d+Au collisions and in restricted kinematic range, double-peaked away from $\Delta \phi = \pi$. Three-particle correlations indicate conical emission of the away-side correlated hadrons at angles independent of associated particle $p_T$, consistent with formation of Mach-cone shock waves. In this talk we further investigate the conical emission phenomenon exploiting dihadron correlations as a function of the trigger particle azimuth from the reaction plane. Such correlations are sensitive to the collision geometry. We study these geometrical effects and discuss how they might be used to further our understanding of the medium created in heavy-ion collisions.

1. Introduction

Dihadron jet-like correlations with a high transverse momentum ($p_T$) trigger particle provide a unique tool to study the hot and dense medium created in relativistic heavy-ion collisions, owing to the fact that the away-side partner jet has to traverse the entire medium due to the surface bias of the production points of high-$p_T$ particles. Dihadron correlations of intermediate $p_T$ associated particles revealed novel structures on the away side of the high $p_T$ trigger particle. The away-side correlations in central Au+Au collisions are significantly broader than in pp and d+Au collisions and in restricted kinematic range, double-peaked away from $\Delta \phi = \pi$ \cite{1, 2, 3}. This observation has motivated many theoretical investigations of its physics origin \cite{4, 5, 6, 7}. Three-particle correlations showed evidence of conical emission of away-side correlated hadrons \cite{8}. The conical emission angle is found to be independent of the associated particle $p_T$, suggesting the underlying physics mechanism may be Mach-cone shock waves. Three-particle cumulant in azimuth relative to the reaction plane \cite{8} confirms this finding. Recent study \cite{9} suggests that fluctuations in initial conditions may also create an away-side double-hump structure in dihadron correlations. Such mechanisms, however, would not generate conical emission structures in three-particle correlations \cite{10}.

The conical emission angle is measured to be $\theta = 1.37 \pm 0.02$ (stat.) $\pm 0.06$ (syst.) \cite{8}. If Mach cones are indeed the underlying mechanism, one may obtain, ideally, the
medium’s speed of sound via \( c_s = \cos(\theta) \). However, model studies [7] indicate that the Mach cone angle would be strongly affected by the medium expansion. The effects depend on the relative configurations of the Mach cones and the collision geometry. We attempt to study these effects by exploiting dihadron correlations as a function of the trigger particle azimuth relative to the reaction plane (RP). Such correlations are sensitive to the collision geometry as well as the orientation of the possible Mach cones.

2. Dihadron correlation analysis relative to the reaction plane

We use the second Fourier harmonic to determine the event plane (EP) azimuth \( \psi_{\text{EP}} \) [11], using particles below \( p_T = 2 \text{ GeV/c} \). To avoid self-correlation, particles from the \( p_T \) bin used for our correlation analysis are excluded from the EP construction. Non-flow correlations, such as dijets, can influence the EP determination. To reduce this effect, we use the modified reaction plane (MRP) method [12], excluding particles within \( |\Delta \eta| < 0.5 \) of the highest \( p_T \) particle in the event from the EP construction.

We divide our data into six slices in \( \phi_s \), the trigger particle azimuth relative to the EP, and analyze azimuthal correlations separately in each slice. The correlation background has a flow modulation that depends on the trigger and associated particle’s second and fourth harmonic anisotropies, \( v_2 \) and \( v_4 \), and the EP resolutions [13]. We obtain the EP resolutions by the sub-event method [11]. There are several measurements of elliptic flow anisotropies. The two-particle and the MRP methods give similar results and significantly overestimate elliptic flow due to non-flow [12]. The major component of non-flow is the measured small-angle minijet correlation [14]. Since away-side pairs contain much less non-flow and the elliptic flow effect is symmetric between near- and away-side, we use \( v_2\{2,\text{AS}\} = \sqrt{\langle \cos 2\Delta \phi \rangle} \), computed from untriggered two-particle azimuthal correlations in inclusive events for our centrality and \( p_T \) bins, as our upper limit of systematic uncertainty. The four particle method \((v_2\{4\}) [15]\) gives the smallest anisotropy parameter for the centrality range 20-60% used in the present study [16].

The \( v_2\{4\} \) is likely an underestimate of elliptic flow because the flow fluctuation effect is negative in \( v_2\{4\} \). We note that \( v_2\{4\} \) may still contain some non-flow effects, however the agreement between \( v_2\{4\} \) and the Lee-Yang-Zero method suggests that such non-flow effects are small. We take \( v_2 = (v_2\{2,\text{AS}\} + v_2\{4\})/2 \) and the range between \( v_2\{2,\text{AS}\} \) and \( v_2\{4\} \) as our uncertainty. We parameterized the \( v_4 \) measurement [12] by \( v_4 = 1.15v_2^2 \).

The background level \( B \) is normalized using the Zero-Yield-At-Minimum (ZYAM) method. The background levels can be different for the different \( \phi_s \) slices because of the net effect of the variations in jet-quenching with \( \phi_s \) and the centrality cuts on particle multiplicity in \( |\eta| < 0.5 \). In our correlation analysis \( B \) is treated independently in individual \( \phi_s \) slices. The systematic uncertainty of \( B \) due to ZYAM itself is assessed by varying the size of the \( \Delta \phi \) normalization range between \( \pi/12 \) and \( \pi/6 \). The systematic uncertainty due to deviation of \( B \) from ZYAM is assessed by Gaussian fits to the ZYAM-subtracted correlation functions, similar to those in Fig. 1 but with a free pedestal, as well as by comparing \( B \) to those obtained from asymmetric correlation functions (see
The effect of the $B$ uncertainty is an approximate constant shift to the baseline of the correlation functions, without significant change to their shapes. The systematic uncertainty on $B$ is not included in the results reported in these proceedings.

When assessing the systematic uncertainty due to elliptic flow on our correlation results, we use ZYAM to adjust background normalization. Due to the interplay between flow modulation and ZYAM normalization, the uncertainty on our correlation functions due to flow is larger for in-plane than out-of-plane trigger particles (see Figs. 1 and 3).

Further details of the analysis can be found in Ref. [17].

3. Dihadron correlation results relative to the reaction plane

In this work we focus on the away-side dihadron correlations. We avoid the near-side jet-like component by analyzing azimuthal correlations at large $|\Delta \eta| > 0.7$. Figure 1 shows the azimuthal correlations in six slices of $|\phi_s|$ from in- to out-of-plane [17]. The positive and negative $\phi_s$ slices are combined. The near-side peak is mainly due to the ridge which decreases from in-plane to out-of-plane. The away-side structure changes dramatically, from singly peaked in-plane to distinctively double-peaked out-of-plane. It appears that whenever there is a large ridge on the near side, there is a comparable component at $\Delta \phi = \pi$ on the away side.

Many experimental observations suggest that the ridge and the jet-like component are unrelated [18, 19, 20]. If they are indeed unrelated, then due to symmetry there ought to be an identical excess of momentum on the away-side to balance the ridge. This momentum balance is different from statistical momentum balance to an extra, fluctuating high-$p_T$ particle. In other words, there is no criterion to determine which is near-side and which is away-side if the ridge and the jet are unrelated; the two sides have to be considered equally. It is thus attempting to fit the large $\Delta \eta$ azimuthal correlation with two away-side Gaussians symmetric about $\Delta \phi = \pi$ and two ridge Gaussians back-to-back at $\Delta \phi = 0$ and $\pi$. We keep identical width for the ridge Gaussians but allow their magnitudes to vary independently. The fit results are superimposed in Fig. 1.
Figure 2(a) shows the fit double-peak angle as a function of $\phi_s$ for three associated $p_T^{(a)}$ bins [17]. The peak angle is approximately constant for $|\phi_s| < 45^\circ$. For $|\phi_s| > 45^\circ$ it increases with $\phi_s$, and becomes different for low and high $p_T^{(a)}$. The larger angle for out-of-plane trigger particles may be due to a more significant influence from medium flow. For in-plane orientation, the conical emission hadrons on the away side are likely aligned with the medium flow direction, receiving insignificant deflection to their $p_T$. The conical emission angle may even be shrunk if it forms after passing the center of the medium. Moreover, the overlap collision zone is thinner in-plane, so the away-side correlated hadrons can escape the collision zone more easily. For out-of-plane orientation, on the other hand, the conical emission hadrons move more or less perpendicularly to the medium flow direction because of the long path length they have to traverse. They receive a large side-kick from the medium flow, broadening their final emission angle.

![Figure 2. Away-side double-peak fit position (relative to $\pi$) as a function of (a) $\phi_s$ and (b) $p_T^{(a)}$. Error bars are statistical only. The systematic uncertainties due to elliptic flow are indicated by the dashed lines. Data are from 20-60% Au+Au collisions, and the trigger particle $p_T^{(t)}$ range is $3 < p_T^{(t)} < 4$ GeV/c [17].](image)

Figure 2(b) shows the conical emission peak angle as a function of $p_T^{(a)}$ for in- and out-of-plane trigger particle orientations [17]. The peak angle is relatively independent of associated $p_T^{(a)}$ for in-plane trigger particles. The peak angle for the out-of-plane orientation is larger, consistent with a larger broadening effect from medium flow. However, the angle position increases with $p_T^{(a)}$, which is naively not expected if those particles are pushed by the same medium flow velocity. It is, however, possible that the higher $p_T^{(a)}$ hadrons are emitted earlier by the away-side parton while traversing the medium, thereby receiving a larger flow effect in the outer region of the bulk medium than the low $p_T^{(a)}$ hadrons [21].

It is worthwhile to note that the peak positions reported here are from fits to dihadron correlations. They are different from those obtained from three-particle correlations [8] where the conical emission angle was found to be independent of associated particle $p_T^{(a)}$. The angle from the three-particle correlation fit is cleaner because the peaks are more cleanly separated in the two-dimensional azimuth space, while the fit to dihadron correlations is more affected by other physics effects. One such effect is jet deflection, which was found to be present in three-particle correlation where the diagonal peaks are stronger than the off-diagonal conical emission peaks [8].
The results reported above combine the trigger particles above and below the EP. We can study the correlations of those trigger particles separately and learn more about the interplay between jet-correlation and the collision geometry. Those results are shown in Fig. 3 where the correlation for a positive $\phi_s$ bin is flipped via $\Delta \phi \rightarrow -\Delta \phi$ and properly shifted before combined with that in the symmetric negative $\phi_s$ bin. The background normalization is done by the ZYAM method; the subtracted background is lower than in Fig. 1 because the minimum now appears at only one side, $\Delta \phi \approx -1$ instead of both sides ($\Delta \phi \approx \pm 1$) in Fig. 1. This difference is used as an assessment of the ZYAM uncertainty as aforementioned. Again we fit the correlation functions with four Gaussians: two for the back-to-back ridges and two for the away-side conical emission peaks. We fix the back-to-back ridges to be identical including their amplitudes. We also allowed their magnitudes to vary independently, and obtained consistent fit results.

![Figure 3](image_url)

**Figure 3.** Same as Fig. 1 except that the correlation in a positive $\phi_s$ bin is flipped and properly shifted before combined with that in the symmetric negative $\phi_s$ bin. The away-side peaks are now not symmetric about $\Delta \phi = \pi$. The associated $p_T^{(a)}$ range is $1 < p_T^{(a)} < 1.5$ GeV/c.

![Figure 4](image_url)

**Figure 4.** The away-side double-peak (a) positions, (b) areas, and (c) widths from the fits in Fig. 3 (d) Illustration of away-side conical emission angles. The triangles (circles) in (a-c) correspond to the first (second) conical emission peak in (d).

Figure 4(a) shows the away-side peak positions versus $\phi_s$. The cartoon aids to the visualization. As discussed above, the conical emission angle is not significantly affected by medium flow when the trigger particle is aligned in the RP. As the trigger particle moves away from the RP, the angle of the second peak (circles) does not seem to change, indicating insignificant effect from medium flow. In contrary, the other conical emission peak changes its location significantly. The largest change appears at $\phi_s \sim 45^\circ$. If the away-side partner parton is deflected by the medium flow and then lose energy

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generating conical emission at a fixed angle, then the relative distance between the peaks would be the same. The data seem to indicate otherwise, suggesting that it is the conical emission particles that are pushed by flow, not the away-side partner parton.

It was suggested that asymmetric away-side peaks may arise from absorption of particles traversing different amount of medium [22]. To investigate such effect, we show in Fig. 4(b,c) the Gaussian areas and widths of the away-side peaks. The peak areas are similar, without evidence of medium absorption, whereas the peak widths are broadened, consistent with broadening due to the medium flow.

4. Summary

We have studied dihadron correlations with high \( p_T \) trigger particles at \( |\Delta \eta| > 0.7 \) as a function of the trigger azimuth (\( \phi_s \)) relative to the event plane. We combine the correlations from the two symmetric \( \phi_s > 0 \) and \( \phi_s < 0 \) bins straightforwardly as well as after flipping the former in \( \Delta \phi \). We argue the near-side ridge is accompanied by a similar ridge on the away side. We fit the correlation function with four Gaussians, two for the back-to-back ridges and two for the away-side conical emission peaks. We investigate the fit parameters as a function of \( \phi_s \). We found significant variations in the peak positions, areas, widths with \( \phi_s \), suggesting geometrical effects on conical emission. These effects are likely due to the medium flow. We found no evidence of medium absorption. Our study should help disentangle medium flow effects in the conical emission signal and may further our understanding of the medium created in heavy-ion collisions, such as its speed of sound and equation of state.

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