Event-plane dependent away-side jet-like correlation shape in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV from STAR

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We employ a data-driven method to subtract the flow background of all harmonics by calculating the difference of the two-particle correlations between the close-region and far-region, determined depending on the pseudo-rapidity ($\eta$) distance from the region where an enhanced recoil transverse momentum ($P_x$) from a high-$p_T$ trigger particle is selected. We analyze the correlation shape as a function of the trigger particle azimuthal angle relative to the event-plane (EP) reconstructed from the beam-beam counters (BBCs) which are displaced by several units in $\eta$ from the mid-rapidity region. The large $\eta$ gap can effectively eliminate the auto-correlation between trigger particles and EP. We correct for the relatively large resolution effect from the BBC EP determination via an unfolding procedure. The width of unfolded away-side jet-like correlation increases with longer path-length, which is an indication of jet-medium interactions.
1. Introduction

A strongly coupled quark gluon plasma (QGP) is believed to be created in relativistic heavy-ion collisions [1]. Jet-like correlations are a good probe of the energy loss mechanism of hard partons traversing the QGP medium [2, 3, 4]. They are often analyzed by calculating the azimuthal angle difference ($\Delta \phi$) between high transverse momentum ($p_T$) trigger particles and associated particles. While the near-side ($|\Delta \phi| < \pi/2$) correlations (in the trigger particle hemisphere) are not much modified, indicating surface bias of these correlations [2], the away-side ($|\Delta \phi - \pi| < \pi/2$) correlations recoiling from the trigger particles are significantly modified: suppressed at high $p_T$ and broadened at low $p_T$ [3, 4, 5]. For non-central Au+Au collisions, the in-medium path length that the recoil (away-side) parton traverses is expected to depend on its emission angle with respect to the reaction plane (RP) [6, 7], spanning by the impact parameter and beam directions and which is approximated by the final state event plane (EP). In these proceedings, we investigate the EP dependence of the away-side jet-like correlation shape.

2. Analysis Method

Measurements of jet-like correlations in heavy-ion collisions are complicated by the large underlying background [3]. A novel method to subtract all harmonic flow backgrounds without assumptions on their amplitude and shape [8] is used in this analysis. We first select events with a large recoil transverse momentum ($P_x$) to a high-$p_T$ trigger particle to enhance the away-side jet population for a specific forward or backward pseudo-rapidity ($\eta$) region ($-1 < \eta < -0.5$ or $0.5 < \eta < 1$). $P_x$ is given by

$$P_{x|\eta} = \sum_{\eta_1 < \eta < \eta_2, \phi - \phi_{\text{trig}} > \pi/2} p_T \cos(\phi - \phi_{\text{trig}}) \frac{1}{\epsilon},$$

where all charged particles ($0.15 < p_T < 10$ GeV/c) in the opposite hemisphere of the trigger particle within a given $\eta$ range are included. We use the inverse of single-particle tracking efficiency ($\epsilon$) to correct for particle detection efficiency. Then two $\eta$ regions ($-0.5 < \eta < 0$ and $0 < \eta < 0.5$) are defined as the close-region and far-region, respectively, depending on the distance to the $\eta$ region where $P_x$ is calculated. We analyze the two-particle correlations between the trigger and associated particles in the close-region and far-region separately. The anisotropic flow contributions to these two regions are nearly equal because these two regions are symmetric about mid-rapidity. Therefore, the flow contributions to the close-region and far-region are cancelled out in the correlation difference. The away-side jet contribution to the close-region should be significantly larger than that to the far-region because of the different $\eta$ distances. The difference between the close- and far-region two-particle correlations, therefore, contains predominantly the contribution from away-side jet-like correlations, hence is a good measure of the correlation shape.

The 2nd order harmonic EP [9] is reconstructed with the beam-beam counters (BBCs). The $\eta$ ranges of the BBCs are $3.3 < |\eta| < 5.2$. The trigger and associated particles are detected by the Time Projection Chamber (TPC) at mid-rapidity ($|\eta| < 1$). The large $\eta$ gap between the TPC and BBCs can effectively eliminate the auto-correlation between trigger particles and EP. The resolution of the reconstructed EP from the BBCs is calculated with the two sub-event method [9], and
3. Results

![Figure 1: Two-particle azimuthal correlations in the close-region (red solid circles) and far-region (blue open crosses) for different $\phi_s$ bins for $3 < p_T^{trig} < 10$ GeV/c and $1 < p_T^{assoc} < 2$ GeV/c in 20-60% Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV.](image)

![Figure 2: The differences between the close-region and far-region two-particle correlations in Fig. 1. Errors are statistical only. The blue curves are Gaussian fits with the mean value fixed at $\pi$.](image)

Figure 1 shows the close- and far-region two-particle correlations in eight different $\phi_s$ bins with the trigger and associated particle $p_T$ ranges of $3 < p_T^{trig} < 10$ GeV/c and $1 < p_T^{assoc} < 2$ GeV/c in 20-60% Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Here $\phi_s$ is the trigger particle azimuthal angle relative to the reconstructed EP. The near-side correlations are well consistent in all $\phi_s$ bins between the close- and far-region. The ratios of the far- to close-region on the near side are approximately unity, with deviations less than 0.5% (within 2$\sigma$ statistical uncertainty). This remaining deviation is normalized out before taking the correlation difference between the close-region and far-region, shown in Fig. 2. The away-side correlations are different presumably due to away-side jet-like contributions. We use a Gaussian function (with centroid fixed at $\pi$) to fit the differences in Fig. 2 to extract the correlation widths. The fits are superimposed as the blue curves. The Gaussian width ($\sigma$) increases modestly with $\phi_s$. 

is found to be $0.135 \pm 0.002$ (stat.) in 20-60% Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. This is a measure of its accuracy in representing the true EP, and is relatively poor. Future measurement by STAR’s recently installed Event Plane Detector will improve the EP resolution.
The away-side correlations in different $\phi_s$ bins are smeared significantly because of the poor EP resolution. We correct for this smearing effect by an unfolding procedure as follows. We take the measured trigger particle distribution in $\phi_s$ and the EP resolution as inputs. The true $\phi_s$ distribution is obtained by amplifying the Fourier modulation of the measured $\phi_s$ distribution by the inverse of the EP resolution factor [9]. Similarly, the distribution of azimuthal angle difference between the measured EP and true EP is evaluated by the EP resolution [9]. The probability matrix $(A)$ is determined using Monte Carlo simulations, where the element $A_{ij}$ is the probability for the measured $\phi_s$ in the $i^{th}$ bin to come from the true $\phi_s$ in the $j^{th}$ bin. For each $\Delta \phi$ bin, we take the eight amplitudes of the two-particle correlations in eight $\phi_s$ bins (as shown in Fig. 1) as the input in the unfolding procedure. We use a lest-squares method with Tikhonov regularization [10] as implemented in the TUnfold package [11]. The best value of the regularization strength ($\tau^2$) is obtained via implementing the L-curve scan in TUnfoldDensity. We set the number of unfolded bins to be half of the input in our analysis. We repeat the unfolding procedure for all $\Delta \phi$ bins and obtain the unfolded correlation results. Figure 3 shows the unfolded two-particle correlations in four $\phi_s$ bins. The $\Delta \phi$ bins are rebinned by two to reduce the point-to-point fluctuations. It is found that the unfolded correlation shape in the out-of-plane $(3\pi/8 < \phi_s < \pi/2)$ direction is significantly different from the measured correlation shape. This is a result of the poor EP resolution.

Figure 4 shows the differences between the unfolded close- and far-region two-particle correlations. The most in-plane and out-of-plane results have greater uncertainties after unfolding. We also use a Gaussian function to fit the data points to obtain the correlation width. The fits are superimposed as the pink curves.

**Figure 3:** The unfolded two-particle correlations in the close-region (red solid circles) and far-region (blue open crosses) from those in Fig. 1.

**Figure 4:** The differences between the unfolded close-region and far-region two-particle correlations in Fig. 3. Errors are statistical only. The pink curves are Gaussian fits with the mean value fixed at $\pi$.

Figure 5 shows the comparison between the raw and unfolded away-side correlation widths
as a functions of $\phi_s$. The black and red lines are linear fits to the widths. The slopes of the raw and unfolded results are $0.08 \pm 0.04$ (stat.) and $0.66 \pm 0.27$ (stat.) respectively. Because the errors on the widths of the unfolded correlations are correlated among the $\phi_s$ bins, we estimate the statistical error on the unfolded slope as follows: (1) we randomly vary the data points in Fig. 1 using Gaussian sampling according to their statistical errors; (2) we use the same procedure to unfold the varied data points and extract a new Gaussian width after unfolding; (3) we obtain the linear slope of the new Gaussian width as a function of $\phi_s$; and (4) we repeat step (1) - (3) many times to obtain a distribution of the slope and take the Gaussian width of the distribution as the statistical uncertainty on the slope. As seen from Fig 5, the unfolded away-side jet-like correlation width increases with $\phi_s$, providing a hint of jet-medium interactions.

**Figure 5:** The raw (black squares) and unfolded (red crosses) away-side correlation widths ($\sigma$) as a function of $\phi_s$. The black and red lines are corresponding linear fits.

### 4. Summary

We have applied a data-driven method to subtract flow backgrounds of all harmonics in jet-like correlations relative to high-$p_T$ trigger particles ($3 < p_T^{\text{trig}} < 10$ GeV/$c$) in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The event-plane dependence of the away-side jet-like correlation shape is reported. The 2$^{\text{nd}}$ order EP is reconstructed with BBCs and the EP resolution is corrected via an unfolding procedure. The Gaussian width of the away-side jet-like correlation is found to increase with $\phi_s$, providing a hint of jet-medium interactions.

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