Event Plane Dependence of Jet-Hadron Correlations in Au–Au Collisions at $\sqrt{s_{NN}}$ = 200 GeV with the STAR Detector at RHIC †

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Abstract: The phenomenon of jet quenching indicates that partons lose energy as they traverse the hot dense medium. By restricting a trigger jet in azimuth relative to the event plane, we are given another tool, which allows us to study the path length dependence of medium modifications. Measurements of angular correlations relative to the event plane between reconstructed $R = 0.4$ full jets and charged hadrons are presented in mid-peripheral Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV with the STAR detector at RHIC. A robust and precise method, known as the Reaction Plane Fit (RPF) method is used to remove the complex, flow-dominated heavy-ion background from the correlation functions. Quantified through yield ratios, we study the event plane dependence of jet-correlated yields. The yield ratios are compared to prior measurements made by the ALICE Collaboration in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. With increased statistics and smaller uncertainties, the results from STAR show a similar conclusion to that of ALICE, that within uncertainties this measurement shows no significant path length dependence of medium modifications.

Keywords: STAR; jets; jet-hadron correlations; energy loss; path length dependence; background subtraction; RPF

1. Introduction

Jets are ideal probes of the Quark Gluon Plasma (QGP) because they originate from hard-scattered partons created early in the collision, prior to the formation of the medium. These partons are modified in the presence of a medium through collisional energy loss and induced gluon radiation. This modification is observed at both LHC and RHIC energies via the suppression of high-momentum particles, di-hadron correlations, and jets [1]. These proceedings will discuss the status of azimuthal correlations of fully reconstructed jets with charged and neutral constituents binned relative to the event plane with charged hadrons in STAR.

2. Jet-Hadron Correlations

The data used in this work comes from 20–50% central Au–Au collisions at nucleon-nucleon center of mass energy of $\sqrt{s_{NN}} = 200$ GeV. It was collected by the STAR experiment [2] at the Relativistic Heavy Ion Collider (RHIC) in 2014. Signal events were required to contain a high tower trigger (HT2) with $E_T > 4$–5 GeV in the Barrel Electromagnetic Calorimeter (BEMC) [3]; minimum bias (MB) events were used for the purpose of event mixing.

The primary detectors used in this work are the Time Projection Chamber (TPC) [4] and the BEMC which both cover the full azimuthal range and include a pseudorapidity window of $|\eta| < 1.0$. Events with a primary vertex within ± 24 cm of the TPC center are used. Charged hadrons tracks are reconstructed in the TPC and obey standard quality cuts. Events are removed from the analysis if they contain a track with $p_T > 35$ GeV/c to avoid contamination from cosmic rays. The same selections applied to the tracks and events that are used for jet-track constituents, event plane reconstruction, and the associated hadrons in the correlation analysis. Neutral energy deposited in the 0.05×0.05 ($\Delta\eta \times \Delta\phi$) BEMC towers is corrected for charged contributions with a 100% subtraction scheme to avoid potential double-counting.

The second-order harmonic event plane is reconstructed using charged hadrons in the transverse momentum range of $0.2 < p_T < 2.0$ GeV/c. Self-correlations are avoided by excluding particles from each p_T bin used in the correlation analysis, as described in [5]. To remove non-flow effects from intrajet correlations at high transverse momentum, particles within $|\Delta\eta| = |\eta - \eta_{trig}| < 0.4$ of the trigger jet axis are excluded from the EP determination. This approach is called the modified reaction-plane (MRP) method [6].

Jets are reconstructed from tracks and towers with $p_T > 2.0$ GeV/c and $E_T > 2.0$ GeV, respectively, using the anti-k_T sequential jet clustering algorithm from the FastJet package [7] with $R = 0.4$. Additionally, trigger jets are required to contain a constituent tower which fired the HT2 trigger in the event. These selections limit the influence of background on jet finding and eliminate the need to remove the underlying event contribution from the jet momenta.

We define the raw jet-hadron correlation function in heavy ion collisions by Equation (1).

$$\frac{1}{N_{trig}}\frac{d^2N_{assoc,jet}^{unc}}{d\Delta\phi d\Delta\eta} = \frac{1}{aN_{trig}}\frac{d^2N_{pairs}^{same,unc}}{d\Delta\phi d\Delta\eta} - b_0(1 + \sum v_n^{trig} v_n^{assoc}\cos(n\Delta\phi)) \tag{1}$$

Here the first term represents the same event pairs which are divided by an acceptance correction, a, provided by mixed events. Mixed events are used to correct for pair acceptance; single tracking efficiency correction has not yet been applied in this work. The second term of Equation (1) is the combinatorial heavy-ion background where b_0 is the background level and the v_n terms are the Fourier coefficients of the trigger jet and associated particles.

The trigger jets in this analysis are binned in angle relative to the event plane to explore the path length dependence of medium modifications. The orientations are defined such that in-plane is $0 < |\Delta\psi| < \frac{\pi}{6}$, mid-plane is $\frac{\pi}{6} < |\Delta\psi| < \frac{\pi}{3}$, and out-of-plane is $\frac{\pi}{3} < |\Delta\psi| < \frac{\pi}{2}$, where $\Delta\psi$ denotes the angular difference between the trigger jet and the second-order harmonic event plane.

When the trigger jet is restricted relative to the event plane, both the background level and effective v_n of the trigger are modified and will contain a dependence on the event plane resolution. The derivation of the event plane dependent background equations are given in [8] with more extensive descriptions given in [9]. The event plane resolution is used to correct for the difference between the reconstructed event plane and the underlying symmetry plane, ψ_n [10].

A background subtraction method known as the Reaction Plane Fit (RPF) method [10] is applied to the azimuthal correlation functions. The RPF method works under the assumption that the signal is negligible in the large $\Delta\eta$ and small $\Delta\phi$ region. It does not require independent measurements of v_n, and is able to extract the signal with smaller uncertainties while requiring fewer assumptions and less bias than prior background subtraction methods.

The background-dominated region is defined by $0.6 < |\Delta\eta| < 1.2$, while the signal+background region is defined by $|\Delta\eta| < 0.6$. The in-plane, mid-plane, and out-of-plane orientations are simultaneously fit, requiring the same fit parameters, to allow for more information to better constrain the shape and level of the background. The background-dominated region is fit over the region $|\Delta\phi| < \pi/2$ up to fourth order in v_n.

3. Results

The signal is extracted by removing the large correlated background from the correlation function. Figure 1 shows the signal for associated particles with transverse momenta 1.0–1.5 GeV/c. From left to right are the jet-hadron correlations from (**a**) in-plane, (**b**) mid-plane, (**c**) out-of-plane, and (**d**) all combined angles of the trigger jet relative to the second-harmonic event plane. At this low-p_T^{assoc} range, we are able to see an away-side peak emerging, in part due to the improved handling of the combinatorial background. The uncertainties are dominated by statistics, with the largest contribution coming from the shape uncertainty of the acceptance correction in $\Delta\eta$, which is correlated for different angles of the trigger jet relative to the event plane. With increased statistics, the uncertainties could be reduced to allow for a more precise measurement.
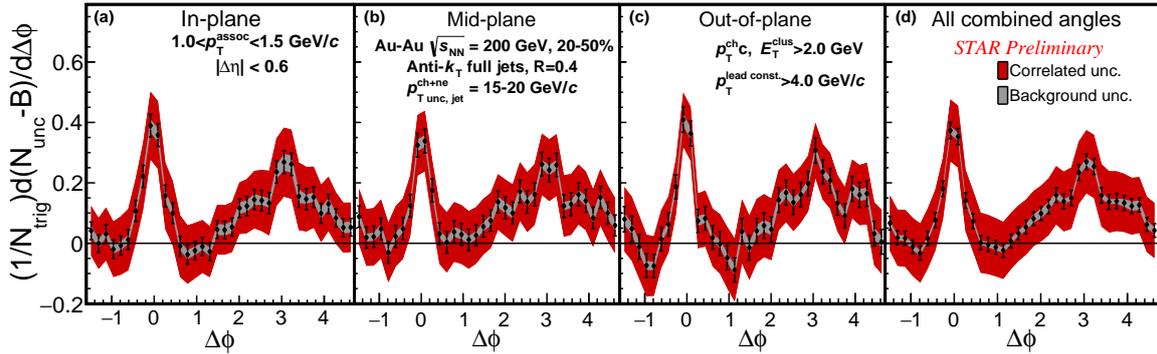

Figure 1. (**a**) In-plane, (**b**) mid-plane, (**c**) out-of-plane, and (**d**) all combined angles of trigger jets relative to the second-harmonic event plane for corrected $\Delta\phi$ correlation function for $1.0 < p_T < 1.5$ GeV/c associated hadrons for $R = 0.4$ full jets in Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV for the 20–50% most central events. The red band corresponds to the correlated uncertainty and the gray band corresponds to the RPF background [10] uncertainty which is non-trivially correlated point-to-point.

Associated yields are obtained as integrals over the background-subtracted correlations in $|\Delta\eta| < 0.6$ for the near-side $(-\pi/3 < \Delta\phi < +\pi/3)$ and away-side $(+2\pi/3 < \Delta\phi < +4\pi/3)$. The high-$p_T$ constituent cuts and HT requirement on the trigger jet are expected to bias the near-side strongly toward unmodified surface emission. The away-side jet and its associated hadrons, on the other hand, should experience a maximal path length before exiting the medium and reaching the detector. There are competing effects occurring at different magnitudes across different p_T ranges. Equilibration in the medium through elastic collisions will result in lower high-p_T out-of-plane yield, while induced gluon bremsstrahlung leads to softer, higher out-of-plane yield relative to other orientations. Additionally, fluctuations in medium density and the stochastic nature of energy loss on a jet-by-jet basis may cause individual jet energy loss to vary. Differences in associated hadron yields between correlations at different angles relative to the event plane are quantified by taking ratios of yields. While the yields do not have a single track reconstruction efficiency applied, it is expected to cancel out in the ratios. The ratios, calculated between mid/in-plane and out/in-plane, are shown in Figure 2. Within uncertainties, there are no clear signs of event plane dependence, and thus path length dependence, over the entire transverse momenta range. A comparable study in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with $R = 0.2$ jets [11] reached similar conclusions.
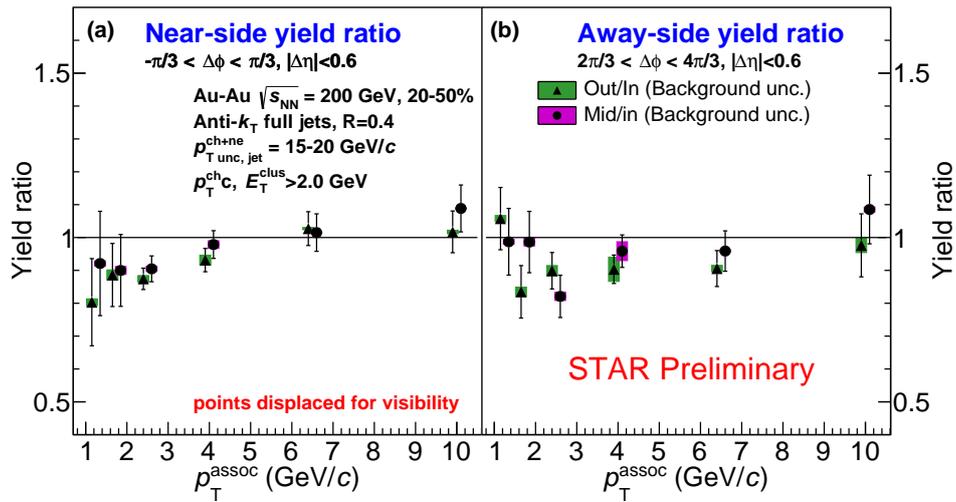
Figure 2. The (**a**) near-side and (**b**) away-side out/in and mid/in yield ratios for $R = 0.4$ full jets in Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV for the 20–50% centrality class. The colored bands correspond to the RPF background uncertainty which is non-trivially correlated point-to-point [10]. There is an additional 6% global scale uncertainty.

4. Discussion

The results shown in these proceedings detail a measurement carried out with the STAR detector of jet-hadron correlations relative to the event plane. They offer increased statistics compared to the study of ALICE and thus allow for a more precise measurement. Both analyses use a robust and precise background subtraction method known as the RPF method. With similar jet definitions and centrality selections as the ALICE analysis, no significant event plane dependence was seen within the current uncertainties by examining the associated yield ratios and widths. The current results are consistent with the ALICE results [11,12] and JEWEL studies performed at LHC energies [13]. These corroborative conclusions indicate that this measurement may not be sensitive enough to path length dependencies and that fluctuations to jet energy loss in the medium washes out the path length dependence.

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