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Event plane dependence of jet quenching studied via azimuthal correlations and differential jet shape in Au+Au collisions at $\sqrt{s_{\rm NN}} = 200$ GeV with the STAR detector at RHIC

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Jet quenching, which describes the energy lost by jets while interacting with the medium, can be studied using azimuthal correlations of associated hadrons with respect to a trigger jet, and by probing the jet substructure by measuring the differential jet shape. This work will present details of both analyses and explore the impact of a jet's orientation with respect to the event plane, defined by the beam direction and the vector of the impact parameter. This will allow for the study of the path length dependence of medium modifications to the jets and their associated hadrons. Both analyses will reconstruct full (charged + neutral) jets in mid-peripheral Au+Au collisions at $\sqrt{s_{\rm NN}} = 200$ GeV with the STAR detector at RHIC.

The analysis for the event plane dependent jet-hadron correlations uses a robust method, known as the Reaction Plane Fit (RPF) method to remove the complex, flow-dominated heavy-ion background from the correlation functions. The event plane dependence of jet-correlated yields is quantified through ratios of yields from different jet azimuthal angle with respect to the event plane. Compared to a similar measurement made by the ALICE Collaboration, STAR has increased statistics and smaller uncertainties. No significant path length dependence of jet modifications in the medium is seen within uncertainties, which is consistent with the previous conclusion at the LHC. A first study of the differential jet shape at RHIC energies is performed with an extension to also include the event plane dependence. The jet shape variable will be used to probe the internal jet structure by looking at the radial profile of transverse momentum inside the most energetic jet of each triggered event (leading jet). This work shows early hints of a possible event plane dependence of the differential jet shape and motivates further study.

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1. Introduction

Originating early in a collision from hard-scattered partons, jets make for an ideal probe of the Quark Gluon Plasma (QGP). They are created prior to the formation of the medium and consequently modified in the presence of a medium due to collisional energy loss and induced gluon radiation. This modification is observed at both LHC and RHIC energies through various observables, where each of them reveals particular aspects of jet quenching [1]. These proceedings will focus on two separate yet similar analyses in order to discuss the event plane dependence of jet quenching. Specifically, we will examine (**a**) azimuthal correlations of charged hadrons and jets with respect to the event plane, and (**b**) the differential jet shape relative to the event plane. The jet shape functions relative to the event plane are part of a new measurement and shown here for the first time. They will aim to further test the effects of the parton-medium interactions by using the energy flow inside the jet [2].

2. Analysis Setup

The data used in this work comes from Au+Au collisions collected in 2014 by the STAR experiment [3] at the Relativistc Heavy Ion Collider (RHIC) at nucleon-nucleon center of mass energy of $\sqrt{s_{\rm NN}} = 200$ GeV. Events referred to as signal (same) events are required to contain a high tower trigger (HT2) with $E_T > 4.3$ GeV in the Barrel Electromagnetic Calorimeter (BEMC) [4]. Event mixing, used for the acceptance correction and background correction, requires the use of minimum bias (MB) events [5].

In this work, the Time Project Chamber (TPC) [6] and the BEMC are the primary detectors used from the STAR experiment. Both of these detectors allow for the full azimuthal range to be used and both include a pseudorapidity window of $|\eta| < 1.0$. Only events with a primary vertex within ± 24 cm (± 28 cm for the jet shape analysis) of the TPC center are used. Events are rejected from the analysis if they contain a charged track with $p_T > 35$ GeV/c (30 GeV/c for the jet shape analysis) to avoid contamination from cosmic rays. Charged tracks are reconstructed in the TPC and required to obey standard quality cuts [7]. The same selections are applied to the tracks and events that are used for jet-track constituents, event plane reconstruction, and the associated hadrons in both presented analyses. Furthermore, a hadronic correction is applied to neutral energy deposited in the 0.05×0.05 ($\Delta\eta \times \Delta\phi$) BEMC towers to remove contributions from charged particles and avoid potential double-counting.

To reduce the background, jets are reconstructed from tracks and towers with $p_T > 2.0$ GeV/c and $E_T > 2.0$ GeV, respectively. The jets are defined using the anti-k_T sequential jet clustering algorithm from the FastJet package [8] with a radius parameter (in $\eta - \phi$ space) $R = 0.4$ ($R = 0.3$ for the jet shape analysis). Trigger jets used in the jet-hadron correlation analysis are required to contain a constituent tower which fired the HT2 trigger of 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.

The experimentally reconstructed second-order harmonic event plane is estimated with charged hadrons from a transverse momentum range of $0.2 < p_T < 2.0$ GeV/c. As described in [9], particles used in the estimation of the event plane are excluded from each associated p_T bin used in the azimuthal correlation and jet shape analyses to avoid auto-correlations. Particles within $|\Delta\eta| = |\eta - \eta_{trig}| < R$ of the trigger jet axis are excluded from the EP determination to help remove non-flow effects from intrajet correlations at high transverse momenta. This technique is referred to as the modified reaction plane (MRP) method [10].

The trigger jets in this work 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.

3. Jet-Hadron Correlations

The raw jet-hadron correlation function in heavy-ion collisions is defined by:

$$\frac{1}{N_{trig}}\frac{d^2N^{unc}_{assoc,jet}}{d\Delta\phi d\Delta\eta} = \frac{1}{aN_{trig}}\frac{d^2N^{same,unc}_{pairs}}{d\Delta\phi d\Delta\eta} - b_0(1+\sum v_n^{trig} v_n^{assoc}\cos(n\Delta\phi)). \tag{3.1}$$

In Eq. 3.1, the first term on the right hand side represents the same event pairs which are divided by a correction factor, a, provided by mixed events. The second term represents the combinatorial heavy-ion background where b_0 is the level of the background and the v_n terms represent the Fourier coefficents of the trigger jet and associated particles. N_{trig} refers to the number of trigger jets and is used for normalization. There has not yet been a single tracking efficiency correction applied to this work and thus the distributions are denoted by the superscript '*unc*'.

Handling of the combinatorial background in heavy-ion collisions must be done with care. When the trigger is restricted relative to the event plane, both the level of the background and the effective v_n of the trigger are modified and will contain a dependence on the resolution of the event plane. This new formalism is derived for two-particle correlations at different orientations to the reaction plane in [11, 12]. The resolutions of the event plane, $\mathfrak{R}$, are used to correct for the experimental difference between the reconstructed event plane and the underlying symmetry plane, ψ_n. The event plane resolution correction is incorporated into the background subtraction procedure described below.

A precise background subtraction method known as the Reaction Plane Fit (RPF) method was developed in [13] and is applied to the azimuthal correlation functions. The RPF method assumes that the signal is negligible in the large $\Delta\eta$ and small $\Delta\phi$ region. Independent measurements of v_n are not required for Fourier coefficents used in the RPF formulas. Compared to prior approaches such as ZYAM, this method is able to extract the signal with smaller uncertainties, while requiring less bias and having fewer assumptions. The region defined as 'background-dominated', is given by $0.6 < |\Delta\eta| < 1.2$, while the signal+background region is defined by $|\Delta\eta| < 0.6$, respectively. The in-plane, mid-plane, and out-of-plane orientations of the correlation function are simultaneously fit in the background-dominated region for $|\Delta\phi| < \pi/2$ up to fourth order in v_n. This helps the fit better constrain the shape and level of the background. The fit and associated uncertainties are extrapolated over the full azimuthal range. The uncertainty on the background fit is non-trivially correlated point-to-point. The signal is then extracted by removing the large correlated background, in the form of the RPF fit, from the signal+background correlation function. Uncertainties are propaged via the covariance matrix of the fit.

The data used in this azimuthal correlation analysis is from 20–50% central events. An example of the RPF background subtracted correlation function from this analysis can be found in [14]. There, we see a comparison of in-plane, mid-plane, out-of-plane, and all combined angles for 15–20 GeV/c trigger jets correlated with 1.0–1.5 GeV/c associated hadrons. At this low-p_T^{assoc}, there is a large contribution from the combinatorial background, but after removal, we can easily differentiate our near-side and away-side peaks. The uncertainties are dominated by statistics and we see that our background uncertainty is minimal. The largest source comes 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.

Once background is subtracted from the azimuthal correlation functions, associated yields are obtained by integrating over $|\Delta\eta| < 0.6$ for the near-side ($-\pi/3 < \Delta\phi < +\pi/3$) and away-side ($+2\pi/3 < \Delta\phi < +4\pi/3$). The trigger jet, which is on the near-side (defined by $\Delta\phi = 0$), is expected to be biased toward unmodified surface emission due to the high-p_T constituent cuts used in jet reconstruction and from the additional HT requirement on the jet. This allows, on average, for the away-side jet and its associated hadrons to traverse a maximal path length before exiting the medium and reaching the detector. Making comparisons between orientations is a useful form of understanding how the path length affects the modification of the away-side jet. It is of critical importance to understand the competing effects which occur across different p_T ranges and at varying magnitudes. Induced gluon bremsstrahlung can lead to softer, higher out-of-plane yield, while equilibration in the medium via elastic collisions is expected to result in lower high-p_T out-of-plane yield relative to other orientations. Additional considerations arise from fluctuations in both the medium density and the stochastic nature of energy loss on a jet-by-jet basis.

Event plane effects due to the angle of the trigger jet and thus the associated hadron yields are quantified by taking ratios of the yields between different event plane orientations. The yields do not currently have a single track reconstruction efficiency applied, but it is expected to cancel out in the ratios. In Fig. 1, ratios of the associated hadron yields are calculated and compared between mid/in-plane and out/in-plane for 15–20 GeV/c trigger jets of size $R = 0.4$. Across the transverse momentum range of 1.0–12.0 GeV/c, there are no clear signs of an event plane dependence and thus path length dependence within current uncertainties. The comparable study done in ALICE [15] reached similar conclusions.

4. Differential Jet Shape

The jet shape function, $\rho(r)$, provides information about the radial distribution of the momentum carried by the jet constituents (fragments). The differential jet shape function is expressed as:

$$\rho(\Delta r) = \frac{1}{\delta r}\frac{1}{N_{jet}}\sum_{jet}\frac{\sum_{tracks\in(r_a,r_b)} p_T^{trk}}{p_T^{jet}}, \tag{4.1}$$

where $r = \sqrt{(\eta_{trk} - \eta_{jet})^2 + (\phi_{trk} - \phi_{jet})^2}$, δr is the radial annulus bin size, with inner radius given by $r_a = r - \delta r/2$ and outer radius given by $r_b = r + \delta r/2$. Additionally, p_T^{trk} and p_T^{jet} are the

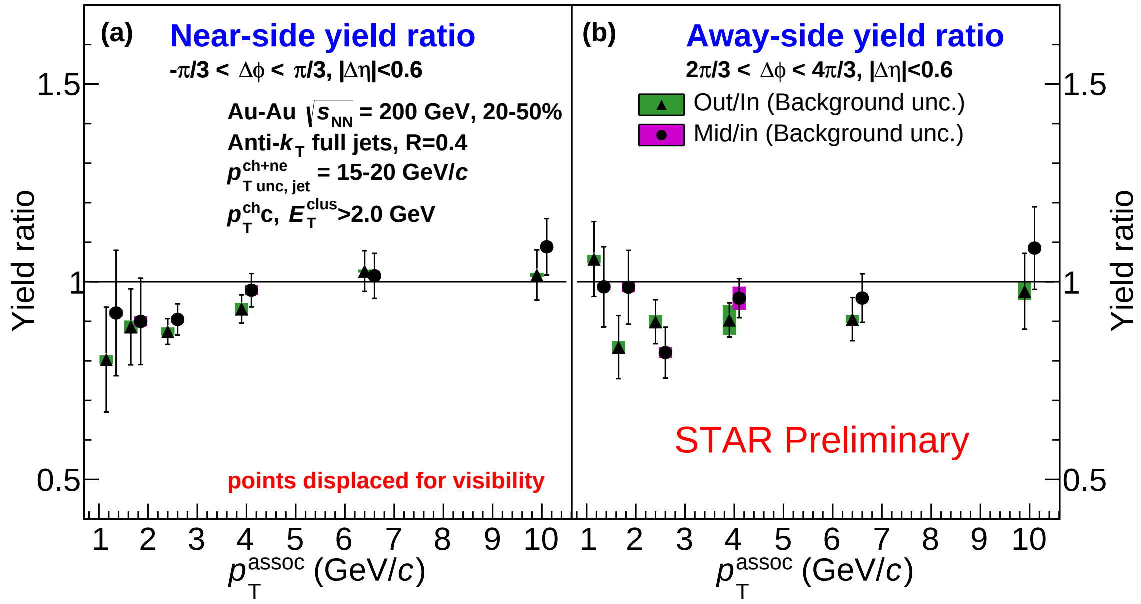

Figure 1: The (**a**) near-side and (**b**) away-side out/in and mid/in yield ratios for 15–20 GeV/c $R = 0.4$ full jets in Au+Au collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV for the 20–50% centrality class. The out/in-plane (mid/in-plane) ratios have a corresponding colored band which represents the RPF background uncertainty and is non-trivially correlated point-to-point [13]. There is an additional 6% global scale uncertainty.

transverse momentum of the track and jet, respectively, and N_{jets} is the number of trigger jets used. Summation is performed over all tracks for each annulus ring over a given jet cone and subsequently summed over all leading jets.

To represent the jet shape signal, one needs to construct $\rho(\Delta r)$ for both the signal+background and background jet cones (from mixed events) separately and then subtract the background as in $\rho_{sig}(\Delta r) = \rho_{sig+bgd}(\Delta r) - \rho_{bgd}(\Delta r)$. The mixed events for the jet shape analysis come from minimum bias events and are binned in 4 cm ranges for z-vertex, 26 multiplicity bins and 6 event plane angle bins (Ψ_2). The jet candidates are reconstructed with 2 GeV/c constituents and only include leading jets. All charged particles with transverse momenta greater than 0.5 GeV/c and less than 30 GeV/c are used in calculating the jet shape.

Measurements of the differential jet shape for 20–40 GeV/c leading jets as a function of Δr are shown for different angles of the trigger jet relative to the event plane in Fig. 2 to probe the modification of the jet structure in the medium for different path lengths due to parton energy loss. Figure 2 decomposes the transverse momentum contribution into p_T^{trk} bins, ranging from $0.5 < p_T^{trk} < 1.0$ GeV/c to $p_T^{trk} > 6.0$ GeV/c. High p_T hadrons are located close to the jet core, while lower momentum hadrons are more evenly distributed as a function of Δr. At low p_T^{trk}, the results are more sensitive to background within the jet cone. From Fig. 2, there are hints of an event plane dependence and thus path length dependence to the jet shape function at low p_T^{assoc}. These results have not yet been corrected for event plane resolution effects, but any differences between orientations would be magnified after correction.

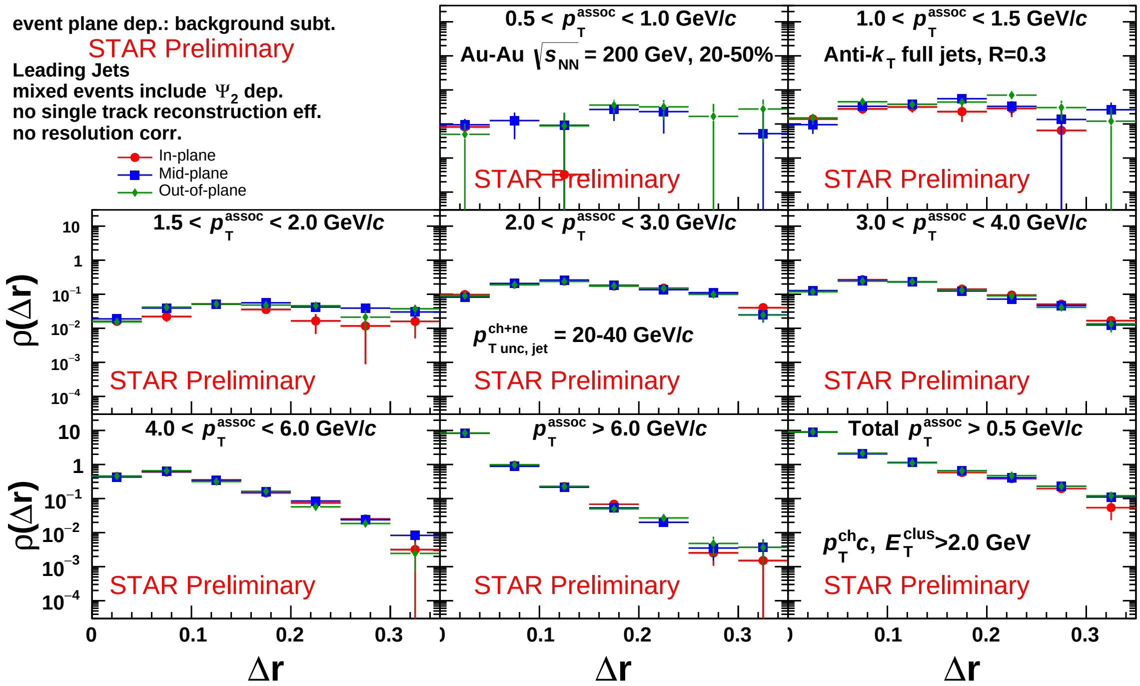

Figure 2: The differential jet shape as a function of Δr for leading 20–40 GeV/c $R = 0.3$ full jets in 20–50% central events from Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Comparisons are shown between jets which are located at different azimuthal angles relative to the event plane (in-, mid-, out-of-plane). These results are not yet corrected for event plane resolution effects.

5. Discussion

The results shown in this work highlight two jet measurements calculated relative to the event plane and carried out with the STAR detector, namely jet-hadron correlations and the first differential jet shape measurement at RHIC energies. The event plane dependence of jet shape is the first measurement of its kind.

The azimuthal correlation analysis can be compared to a similar study by the ALICE collaboration [15], but with increased statistics, allowing for a more precise measurement. Both measurements report no significant event plane dependence seen with the current uncertainties by examining the associated yield ratios. The STAR results are also consistent with JEWEL studies performed at LHC energies [16]. These conclusions are indicative that this particular observable may not be sensitive enough to path length dependencies and that fluctuations to jet energy loss in the medium wash out the path length dependence.

First differential jet shape results are shown in different constituent p_T ranges as a function of event plane orientation. While event plane resolution and single track reconstruction efficiency effects still need to be incorporated, hints of broadening for soft particles and event plane depedence of jet shapes are seen. Further studies are underway and plan to probe additional parameters such as transverse jet momentum, centrality, jet size R, dijet events, and to understand the medium-parton interactions by comparing with pp. This work will provide input for theoretical models that attempt to describe the patterns of energy loss by a highly-energetic probe passing through the QGP.

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