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Jet shapes and fragmentation functions in Au+Au collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV in STAR

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This work reports new measurements on differential jet shapes and semi-inclusive jet fragmentation functions from Au+Au collisions at $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV with the STAR detector at RHIC. The jet shape variable is used to probe the internal jet structure by looking at the radial profile of the most energetic jet (leading jet) of each triggered event. A first study of the differential jet shape at RHIC energies is performed and extended to further include a dependence of the azimuthal angle between the jet and the second-order event plane. This work shows early hints of a possible event-plane dependence of the differential jet shape and motivates further studies. Jet fragmentation functions for 40-60% peripheral Au+Au events are examined via a semi-inclusive approach whereby recoil jets from a high transverse momentum trigger tower are measured and compared to PYTHIA 8 simulations as a vacuum reference. A ratio of the fragmentation functions in Au+Au to PYTHIA 8 shows little to no modification (ratio $\sim$ 1.0) within uncertainties across three separate jet transverse momentum bins.

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1. Introduction

Jet are created from hard-scattered partons early in high energy collisions of nuclei, prior to the formation of the medium, known as the Quark Gluon Plasma (QGP). Jets are modified in the presence of this medium due to collisional energy loss and induced gluon radiation, making them ideal probes for studying detailed properties of the QGP [1]. This modification has been observed at both LHC and RHIC energies through various observables, each revealing varied aspects of jet quenching [2]. These proceedings will focus on two separate jet structure measurements to study how the parton shower is modified in the presence of the medium: (**a**) the differential jet shape measured relative to the event plane and (**b**) semi-inclusive jet fragmentation functions.

Both measurements utilize data collected in 2014 for Au+Au collisions at nucleon-nucleon center of mass energy of $\sqrt{s_{\rm NN}}$ = 200 GeV by the STAR experiment [3] at the Relativistc Heavy Ion Collider (RHIC). Events referred to as signal (same) events are required to contain a high tower trigger (HT2) with transverse energy ($E_{\rm T}$) above 4.5 GeV in the Barrel Electromagnetic Calorimeter (BEMC) [4]. Minimum-bias (MB) events are used in both analyses to estimate the effects of background via a mixed-event (ME) technique [5]. The mixed events are sorted into event classes based on their multiplicity, primary vertex position along the beam direction, and the second-order event-plane angle ($\Psi_{\rm EP}$).

The Time Projection Chamber (TPC) [6] and the BEMC are the primary detectors used in this work. Both provide full azimuthal coverage (0 to 2π) within a pseudorapidity window of $|\eta| < 1.0$. Only events with a primary vertex within ± 30 cm of the TPC center along the beam direction are used. Events are rejected if they contain a charged track with transverse momentum ($p_{\rm T}$) bove 30 GeV/c to avoid both contamination from cosmic rays and tracks with poor momentum resolution. Charged tracks are reconstructed in the TPC and required to pass standard quality cuts [7]. The same selections are applied to both presented analyses.

Jets are reconstructeed with only charged tracks in the fragmentation function study and both charged tracks and BEMC towers in the differential jet shape measurement. The jets are defined using the anti-$k_{\rm T}$ sequential jet clustering algorithm from the FastJet package [8] with a radius parameter (in $\eta - \phi$ space) $R = 0.4$. Furthermore, hadronic correction is applied to neutral energy deposited in the BEMC towers to remove contributions from charged particles and avoid potential double-counting.

2. 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 defined by:

$$\rho(r) = \frac{1}{\delta r}\frac{1}{N_{\rm jet}}\sum_{\rm jet}\frac{\sum_{{\rm tracks}\in(r_a,r_b)} p_{\rm T}^{\rm trk}}{p_{\rm T}^{\rm jet}}, \qquad (2.1)$$

where $r = \sqrt{(\eta_{\rm trk} - \eta_{\rm jet})^2 + (\phi_{\rm trk} - \phi_{\rm jet})^2}$, δr is the radial annulus bin size, with inner radius $r_a = r - \delta r/2$ and outer radius $r_b = r + \delta r/2$. Additionally, $p_{\rm T}^{\rm trk}$ and $p_{\rm T}^{\rm jet}$ are the transverse momenta of the track and jet, respectively, and $N_{\rm jet}$ is the number of jets. All charged tracks between $1.0 < p_{\rm T}^{\rm trk}$ < 30.0 GeV/c are summed over in annulus rings for given jets when calculating the jet shape.

The most energetic jet in each event, i.e. "leading jet", is selected for the analysis. To reduce the background effects from fluctuations and combinatorial jets, jets are reconstructed from tracks and towers with $p_T > 2.0$ GeV/c and $E_T > 2.0$ GeV, respectively. These jets are referred to as "hard-core" jets and their selection criteria limit the influence of background on jet finding and eliminate the need to remove the underlying event contribution from the jet momenta [7]. Jet shape background is estimated via a mixed-event technique [5].

Figure 1 shows distributions of the background subtracted total jet shapes for all charged particles with $p_T^{\rm trk}$ greater than 1.0 GeV/c in the 0-10% most central events. The STAR measurement (left) is compared to that of the CMS Collaboration (right) [9]. Systematic uncertainties are denoted by the light blue band. Statistical uncertainties are smaller than the marker itself. $\rho(r)$ at 200 GeV, shown in Fig. 1, are observed to be less steep than those at LHC energies (with variations in kinematics and jet selection).

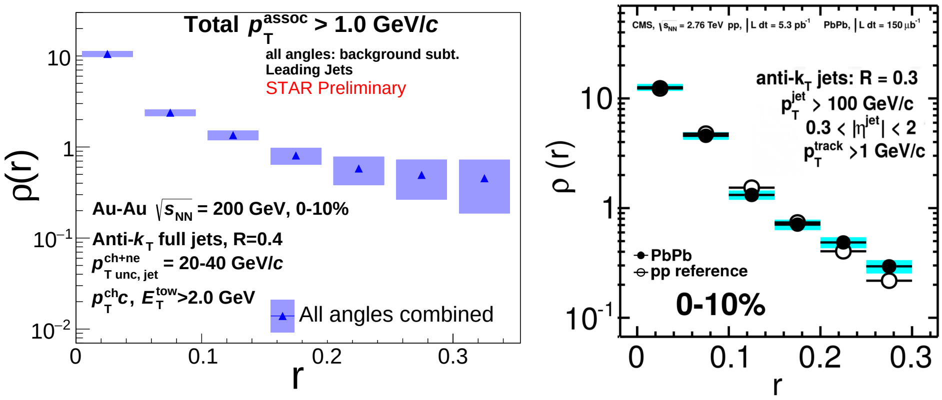

Figure 1: The total differential jet shape (greater than 1.0 GeV/c) for leading anti-k_T full jets with $20 < p_T^{\rm jet} < 40$ GeV/c of size $R = 0.4$ in the 0-10% most central Au+Au events at 200 GeV (left) and a similar measurement by the CMS Collaboration at $\sqrt{s_{NN}}$ = 2.76 TeV (right).

The experimentally reconstructed second-order event plane is estimated from charged particles with $0.2 < p_T < 2.0$ GeV/c using the TPC to ensure good event plane resolutions. To avoid self-correlations, particles from the p_T bin used in the jet shape analysis (e.g., $1 < p_T^{\rm assoc} < 1.5$ GeV/c) are excluded from event-plane reconstruction [10]. Particles within $|\Delta\eta| = |\eta_{\rm trk} - \eta_{\rm jet}| < R$ of the trigger jet axis are also excluded from the event-plane determination to help suppress non-flow effects from intrajet correlations. This technique is referred to as the modified reaction plane (MRP) method [10]. The resolutions of the event plane, $\mathfrak{R}$, are used to quantify the difference between experimentally reconstructed event plane and the underlying symmetry plane, ψ_2. Results are corrected for the event plane resolution by unfolding $N_{\rm jet}$ and $\rho(r)$ separately with Bayesian unfolding [11].

In order to probe the modification of the jet structure in the medium for different path lengths due to parton energy loss, measurements of the differential jet shape for 20-40 GeV/c leading jets as a function of r are shown for different angles of the jet axis relative to the event plane in Fig. 2. The leading jets are labeled depending on their azimuthal angle relative to the event plane such that in-plane is defined by $0 < |\Delta\psi| < \frac{\pi}{6}$, mid-plane by $\frac{\pi}{6} < |\Delta\psi| < \frac{\pi}{3}$, and out-of-plane by $\frac{\pi}{3} < |\Delta\psi| < \frac{\pi}{2}$, where $\Delta\psi$ denotes the azimuthal difference between the jet axis and the event plane. $\rho(r)$ is decomposed into different transverse momentum contributions in Fig. 2. It can be seen that

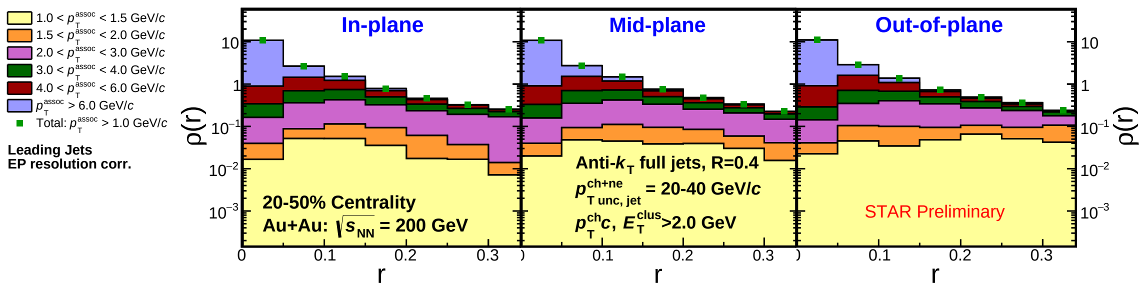

Figure 2: The p_{T}-dependence of the jet constituents for the jet shape of leading anti-k_{T} full jets with $20 < p_{\mathrm{T}}^{\mathrm{jet}} < 40$ GeV/c of size $R = 0.4$ in 20-50% semi-central Au+Au events. Comparisons are shown for in-plane, mid-plane, and out-of-plane jets. Results are background subtracted and corrected for event plane resolution.

high-p_{T} hadrons are located close to the jet core, while lower momentum hadrons are more evenly distributed as a function of r. At low-$p_{\mathrm{T}}^{\mathrm{trk}}$, the results are more sensitive to background within the jet cone. From Fig. 2, there are subtle hints of an event-plane dependence and thus path-length dependence to the jet shape function as low-$p_{\mathrm{T}}^{\mathrm{assoc}}$ hadrons in out-of-plane jets are found at farther distances away from the jet axis, and in greater abundances than in-plane jets.

3. Semi-inclusive jet fragmentation functions

The jet fragmentation function, defined by $1/N_{\mathrm{jet}} dN_{\mathrm{ch}}/dz$, and normalized per jet, provides information of the longitudinal momentum fraction of charged constituent particles with respect to the jet. Fragmentation functions have been previously reported at LHC energies [12, 13]. This work utilizes a semi-inclusive approach following [5] to remove combinatorial jets. Charged jets in the recoil region of a high energy BEMC tower ($9.0 < E_{\mathrm{T}} < 30.0$) are studied. The trigger tower and jet are required to be separated by $\Delta\phi > 3\pi/4$. Charged tracks falling within $r < R$ with $0.2 < p_{\mathrm{T}}^{\mathrm{trk}} < 30.0$ GeV/c are associated with the corresponding jet and used to calculate the fragmentation variable: $z \equiv p_{\mathrm{T}}^{\mathrm{trk}} \cos(r)/p_{\mathrm{T}}^{\mathrm{jet}}$.

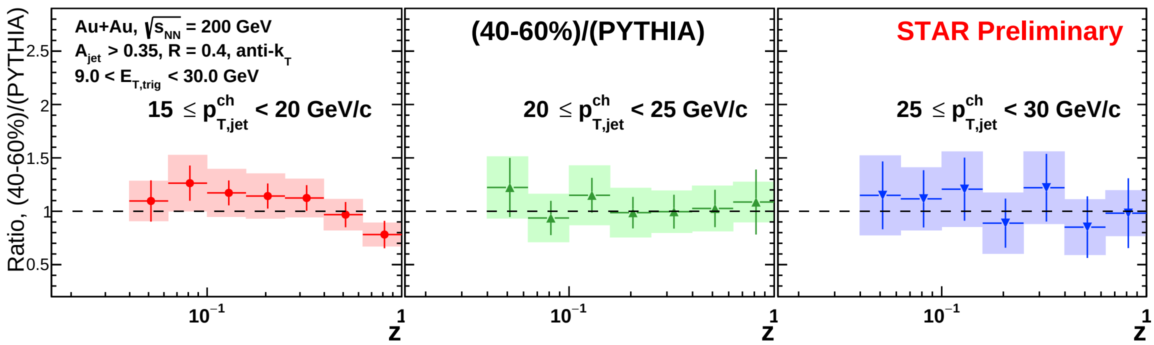

Figure 3: Jet fragmentation function ratios between 40-60% peripheral Au+Au collisions and PYTHIA 8 calculations for pp collisions in three $p_{\mathrm{T,jet}}^{\mathrm{ch}}$ ranges.

For additional analysis details, please see [14] and references therein. Figure 3 shows the jet fragmentation function ratios between 40-60% peripheral Au+Au events and PYTHIA 8 pp estimations [15] for three $p_{\mathrm{T}}^{\mathrm{jet}}$ ranges. These results correspond to no significant modifications of jet fragmentation functions in 40-60% peripheral Au+Au events at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV. Potential explanations of the current findings include: 1) no significant jet-medium interactions in 40-60% peripheral Au+Au events at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV, or 2) the possibility that PYTHIA 8 results may not accurately represent the pp events at $\sqrt{s} = 200$ GeV, as the Monash 2013 tune is based on LHC data. Additional work is needed to differentiate amongst them.

4. Discussion

This work highlights two preliminary differential jet structure measurements by the STAR Collaboration. The differential jet shape for $p_{\mathrm{T}}^{\mathrm{assoc}} > 1.0$ GeV/c is shown for 0-10% central Au+Au events and reveals a broader jet shape at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV than LHC energies. The event-plane dependence shows a hint of a larger abundance of low-p_{T} tracks farther from the jet axis for out-of-plane jets relative to in-plane jets suggesting possible path length dependence of jet quenching. Further work on the jet shape includes variations in jet selection, centrality, and comparison to a *pp* reference. The semi-inclusive jet fragmentation functions are shown for 40-60% peripheral Au+Au events and compared to PYTHIA 8 pp calculations for charged jets. The fragmentation function measurements in Au+Au appears unchanged compared to PYTHIA 8 for 15-30 GeV/c charged jets. Further studies are needed to elucidate medium-induced modification of the jet structure at RHIC energies.

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