Jets and high-$p_T$ probes measured in the STAR experiment

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Hard probes created through large momentum transfers are used to study the properties of QCD matter created in heavy-ion collisions, by comparing the measurements to those in p+p collisions. Jets, and the “quenching” or suppression of jets in the medium created in heavy-ion collisions, are studied through various different observables. We present the most recent measurements from $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions, with p+p collisions as the reference, by the STAR Collaboration. The observables are semi-inclusive charged jets and di-jet transverse momentum imbalance. Additionally, correlation measurements of direct photon-hadron and neutral pion-hadron are presented and discussed.
1. Introduction

Jets and high-$p_T$ particles are produced on very short time scales ($\sim 0.1\text{fm}/c$) in collisions with large momentum transfer ($p_T > Q_0 \gg \Lambda_{\text{QCD}}$). Hence they are considered good tomographic probes of the hot and dense QCD medium created in heavy-ion collisions. Over the last decade or so, many compelling measurements, such as the disappearance of away-side jets and high-$p_T$ suppression [1], di-jet suppression [2] and high-$p_T$ suppression balanced by low $p_T$ enhancement in jet-hadron correlation [3] etc., contributed to our understanding of jet quenching in the medium created at RHIC. In these proceedings, I discuss three recent measurements in the STAR experiment: (i) Jet-like direct photon-hadron and $\pi^0$-hadron correlations, (ii) di-jet transverse momentum imbalance, and (iii) semi-inclusive recoil charged jets.

2. Jet-like direct photon-hadron and $\pi^0$-hadron correlation

The motivation for jet-like direct photon-hadron and $\pi^0$-hadron correlation studies is to understand the flavor and path length dependence of parton energy loss in the hot and dense medium [4]. In this analysis, the triggered $\gamma_{\text{dir}}$ and $\pi^0$ are selected with $12 < p_T^{\text{trig}} < 20$ GeV/c and charged tracks with $1.2$ GeV/c $< p_T^{\text{assoc}}$ in order to attain low $z_T$ ($p_T^{\text{assoc}} / p_T^{\text{trig}}$) values down to 0.1. A detailed discussion and analysis techniques can be found in the Ref. [4]. The suppression of these jet-like yields in central Au+Au collisions is then quantified by comparing to the per-trigger yields measured in p+p collisions, denoting the ratio of integrated yields $I_{AA}$. The away-side medium modification for $\gamma_{\text{dir}}$ ($I_{AA}^{\gamma_{\text{dir}}}$) and $\pi^0$ ($I_{AA}^{\pi^0}$) triggers are shown as a function of $z_T$ in Fig. 1. The away side $I_{AA}$ for both triggers has a systematic trend to lower values with increasing $z_T$ though not significant within uncertainties. This observation is somewhat more significant when $I_{AA}$ is plotted as a function of $p_T^{\text{assoc}}$ in Fig. 2 (right panel). The expected difference between $I_{AA}^{\gamma_{\text{dir}}}$ and $I_{AA}^{\pi^0}$ triggers as in models [5, 6] at low $z_T$ is difficult to observe because of large uncertainties in the data. $I_{AA}^{\gamma_{\text{dir}}}$ is plotted for three $p_T^{\text{trig}}$ bins ranging from 8 to 20 GeV/c for $0.3 < z_T < 0.4$ in Fig 2 (left panel). It is found that $I_{AA}^{\gamma_{\text{dir}}}$ is insensitive to the $\gamma_{\text{dir}}$-trigger energy in this range at RHIC energy. Further understanding on the redistribution of lost energy in heavy-ion collisions can be explored by measuring the distribution of fully reconstructed recoil jets with respect to a $\gamma_{\text{dir}}$-trigger. Such a measurement of charged and full jets is underway in the STAR experiment.

![Figure 1](https://example.com/fig1.png)

Figure 1: (Color online.) The $I_{AA}$ for $\gamma_{\text{dir}}$ (red squares) and $\pi^0$ (blue circles) triggers are plotted as a function of $z_T$. The points for $I_{AA}$ for $\gamma_{\text{dir}}$ are shifted by +0.03 in $z_T$ for visibility. The vertical line and shaded boxes represent statistical and systematic errors, respectively [4]. The curves represent theoretical model predictions [5, 6, 7, 8].
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**Figure 2:** (Color online.) \(dN_{AA}^\gamma\) are plotted as a function of \(p_T^{\text{trig}}\) (left panel) and \(p_T^{\text{assoc}}\) (right panel). The vertical line and shaded boxes represent statistical and systematic errors, respectively. The curves represent theoretical model predictions [5, 6, 7].

3. Semi-inclusive recoil charged jets

**Figure 3:** (Color online.) Upper panels: Corrected charged recoil jet \(p_T^{\text{ch}}\) distributions for peripheral and central Au+Au collisions for R=0.3 (left) and R=0.5 (right). Arrow represents level of horizontal shift in \(p_T^{\text{ch}}\) spectra (guide to eyes) [11]. Lower panels: \(I_{CP}\) for R=0.3 (left) and R=0.5 (right).

A new jet measurement performed in the STAR experiment is the semi-inclusive charged jet spectrum on the recoil side of a high-\(p_T\) charged-hadron trigger. The reconstructed charged recoil jets are termed as semi-inclusive, since the triggered hadron \(p_T\) is not inclusive (within \(9 < p_T^{\text{trig}} < 30\) GeV/c). This type of measurement is very challenging owing to the high-multiplicity environment and underlying background fluctuations in heavy-ion collisions. A novel mixed-event...
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The technique was used for correcting uncorrelated jet background from the reconstructed jets by a statistical subtraction method [10, 11]. One trigger hadron is selected randomly in the above \(p_T\) range and charged jets (consisting of charged tracks with \(p_T > 0.2\) GeV/c) are reconstructed using the anti-\(k_T\) algorithm for a given resolution parameter (R = 0.3 and 0.5 for these results). The recoil jet acceptance is in \(|\pi - \Delta \phi| < \pi/4\). The estimated background energy density (\(\rho\)) scaled by jet area (\(A\)) is subtracted from each reconstructed jet raw transverse momentum (\(p_{T,\text{raw}}^{\text{jet}}\)), \(p_{T,\text{jet}}^{\text{reco}} = p_{T,\text{jet}}^{\text{raw}} - \rho A\). This reconstructed jet \(p_{T,\text{jet}}^{\text{reco}}\) spectrum is then corrected by subtracting that of mixed-events. This raw correlated distribution is finally corrected by an unfolding procedure for instrumental effects and \(p_T\)-smearing due to the background. The upper panels of Fig. 3 show the semi-inclusive corrected and recoil charged jet transverse momentum (\(p_{T,\text{ch}}^{\text{jet}}\)) spectra for peripheral and central Au+Au collisions for R=0.3 and 0.5. Significant suppression in central vs. peripheral, via the medium modification, \(I_{CP}\), is observed for \(p_{T,\text{ch}}^{\text{jet}} > 10\) GeV/c in case of R=0.3 and R=0.5. The horizontal shift in \(p_{T,\text{ch}}^{\text{jet}}\) spectra in central compared with peripheral for R=0.3 indicates that the jet energy is transported out of the cone due to the jet-quenching effect. This horizontal shift is \(-2.3 \pm 0.2\) GeV/c for R=0.5 and \(-5.0 \pm 0.5\) GeV/c for R=0.3 with \(p_{T,\text{ch}}^{\text{jet}} > 10\).

![Figure 4](https://example.com/figure4.png)

**Figure 4:** (Color online.) Normalized \(A_J\) distributions for Au+Au HT data (filled symbols) and p + p HT \(\oplus\) Au+Au MB (open symbols). The red circles points are for jets found using only constituents with \(p_{T,\text{Cut}} > 2\) GeV/c and the black squares for matched jets found using constituents with \(p_{T,\text{Cut}} > 0.2\) GeV/c [14, 15]. Upper panel: for R = 0.4. Lower panel: for R = 0.2.
4. Di-jet transverse momentum imbalance

Di-jet measurement has been performed in the STAR experiment to understand the emission of soft particles with respect to the di-jet axis by measuring the di-jet transverse momentum ($p_T$) imbalance. The di-jet $p_T$ imbalance observable is defined as $A_J = (p_{T, lead} - p_{T, sublead})/(p_{T, lead} + p_{T, sublead})$. Where $p_{T, lead}$ and $p_{T, sublead}$ are the $p_T$ of the leading and sub-leading jets, respectively. Events were required to have a high tower trigger (HT) with an uncorrected transverse energy of $E_T > 5.4$ GeV in the barrel electromagnetic calorimeter (BEMC) towers. In these HT events, $A_J$ is calculated using $p_{T, lead} > 20$ GeV/c and $p_{T, sublead} > 10$ GeV/c with $|\phi_{lead} - \phi_{sublead} - \pi| < 0.4$. Full jets are reconstructed using charged tracks measured in the TPC and neutral tracks information recored in the BEMC using the anti-$k_T$ algorithm [12, 13]. Details of the technique used in this analysis can be found in Ref. [14, 15].

The upper panel of Fig. 4 shows the normalized distributions of $A_J$ for $R=0.4$ in Au+Au HT events compared with p+p HT $\oplus$ Au+Au MB events (events of p+p HT embedded into Au+Au 0-20% central events of minimum bias data sample) for constituents $p_T > 2$ GeV/c. It is observed that di-jets in Au+Au HT are significantly imbalanced compared with p+p HT $\oplus$ Au+Au MB events. This behavior is further studied by including soft particles $p_T > 0.2$ GeV/c in jet reconstruction and then performing a geometrical matching ($\Delta R = \sqrt{\Delta \phi^2 + \Delta \eta^2} < R$) with the initial hardcore di-jets. The di-jet imbalance is restored by including soft particles for jet cone parameter $R=0.4$. A similar study is also performed using $R=0.2$, and the $A_J$ distributions are shown in the lower panel of Fig. 4. It shows that the di-jet $p_T$ imbalance can not be restored including soft particles for $R=0.2$. The above observations indicate that the studied selection of "hard core" di-jets clearly experiences medium modification, but in contrast to corresponding LHC measurements, the redistributed energy is still contained within the original $R = 0.4$ cone. With a smaller cone size, balance cannot be recovered, suggestive of broadening of the jet structure compared with p+p collisions.

5. Summary

The STAR experiment recently measured the following three jet observable to study the hot and dense matter created at RHIC.

- Jet-like direct photon-hadron and $\pi^0$-hadron correlations: Both $I_{AA}^{\gamma}$ and $I_{AA}^{\pi^0}$ show similar levels of suppression. The expected differences due to the color factor and path length dependence are not observed within current experimental uncertainties. At top RHIC energy, no $\gamma_{dir}$-trigger energy dependence is observed on the suppression of away-side yields in the range of $8 < p_T^{\text{trigger}} < 20$ GeV/c. The lost energy reappears predominantly at low $p_T$ ($p_T < 2$ GeV/c), regardless of the trigger $p_T$ of $\gamma_{dir}$.

- Semi-inclusive recoil charged jets: A novel mixed-event method was developed to correct the uncorrelated fake jets contribution in heavy-ion collisions in the STAR experiment. After this correction, the semi-inclusive recoil charged-jets spectra of a high-$p_T$ hadron trigger show $\sim$80% suppression in recoil jet $p_T$ in central collisions with respect to peripheral collisions with $R=0.3$. A significant horizontal shift in the recoil jet $p_T$ spectra in central collisions with respect to peripheral collisions at $R=0.3$ compared with that at $R=0.5$ indicates that a comparatively wider jet cone is the consequence of jet-quenching in heavy-ion collisions.
Di-jet transverse momentum imbalance: A significant di-jet imbalance is observed in Au+Au collisions in comparison with the p+p reference for the jet resolution parameter R=0.4 including constituent particles with $p_T > 2$ GeV/c. When including softer particles (with $p_T > 0.2$ GeV/c), the balance is restored to the level of the embedded p+p reference, indicating that redistributed energy is still contained within the original R = 0.4 cone, though not within a smaller jet resolution parameter of R=0.2. It indicates that the energy loss in di-jet events can not be recovered within a narrow jet cone in heavy-ion collisions at $\sqrt{s_{NN}} = 200$ GeV for this particular selection of di-jets.

Beside these measurements, new jet measurements like neutral triggered jets, soft drop grooming in jet etc., are ongoing in the STAR experiments to study the QCD medium.

References