Abstract

We present an experimental study of full jet reconstruction in the high multiplicity environment of heavy ion collisions, utilizing $\sqrt{s_{NN}} = 200$ GeV $p + p$ and central Au + Au data measured by STAR. Inclusive differential jet production cross sections and ratios are reported, as well as high-$p_T$ hadron–jet coincidences.

1. Introduction

Measurements of jet quenching via single and di-hadron observables [1] have provided initial estimates of the energy density of the hot QCD medium generated in high energy nuclear collisions. However, such observables suffer from well-known biases and are limited in their sensitivity [2]. Fully reconstructed jets will enable an unbiased exploration of quenching, including new observables of energy flow within jets whose theoretical description is not dependent upon the modeling of hadronization.

Full jet reconstruction is difficult in the heavy-ion collision environment. Attempts to suppress background via seeded algorithms or the introduction of a modest cut on hadron $p_T$ in the jet reconstruction result in a jet population biased against quenched jets [3]. Our emphasis in this analysis is to minimize such biases. We apply the minimum cuts possible within the STAR acceptance ($p_T > 0.2$ GeV/$c$) and use seedless algorithms in both $p + p$ and Au + Au collisions.

We confront the challenging problem of high-density backgrounds by applying recently developed jet finding and background correction algorithms of the FastJet package [4]. We report inclusive jet cross-sections in $\sqrt{s_{NN}} = 200$ GeV $p + p$ and 10% most central Au + Au collision, using two resolution scales ($R = 0.2$ and $R = 0.4$). We report their ratios, jet $R_{AA}$, and hadron–jet correlations.

The results presented in these proceedings differ quantitatively in two respects from those presented at the conference, though all qualitative conclusions are unchanged. For $p + p$ collisions, full correction for the jet trigger bias has now been applied (whereas an approximation was used previously), resulting in an increase in the central value of the cross section for $p_T^{jet} < 30$ GeV/$c$ and corresponding decrease in $R_{AA}$. For Au + Au collisions, the study of simulated (Pythia) jets embedded in Au + Au background events resulted in a revision of the parameterization of background fluctuations. We correct the overall scaling error, which for narrow jets ($R = 0.2$) results in a corresponding increase of up to a factor of 3 in the inclusive cross section.
2. Data sets, algorithms, and procedures

For $p+p$ collisions, we use 12 pb$^{-1}$ recorded in Run 6 with a jet patch trigger, requiring a transverse energy deposition above 7.6 GeV in a fixed BEMC region of dimensions $\Delta \eta \times \Delta \phi = 1 \times 1$ rad. For central Au + Au collisions, we use the $7.6 \times 10^6$ most central events ($\sigma/\sigma_{\text{Geom}} = 10\%$) recorded in Run 7 with a minimum bias trigger. Jet reconstruction in both heavy-ion and $p+p$ collisions utilizes the $k_T$ [5] and anti-$k_T$ [6] sequential recombination algorithms provided by the FastJet package [4]. The two algorithms have different sensitivities to heavy-ion background. The energy recombination scheme is used for tracks and calorimeter towers, both of which are assigned zero mass. Jet candidates are found utilizing two resolution parameters $R = \sigma$ exceedings the correction factors extracted from embedded Pythia are predominantly responsible for the spectrum distortion. We therefore utilize in these proton background fluctuations; the Pythia embedding is more sensitive to the upwards fluctuations, which produces the spectrum distortion of Pythia jets embedded into central Au + Au the inclusive spectrum. The value of $\sigma$ is the measured jet area [4]. We define signal jets with $p_T^{\text{rec}} > 0$ and background jets with $p_T^{\text{rec}} \leq 0$. For central Au + Au collisions, $\rho \approx 75$ GeV/$c$ per unit area within $-0.6 < \eta < 0.6$. The term $\rho \cdot A$ is the most probable value of the background underlying the signal jet. Fluctuations around this value are approximated by a Gaussian distribution with width of $\sigma^{\text{bg}}$, which is applied in an unfolding procedure to correct the inclusive spectrum. The value of $\sigma^{\text{bg}}$ extracted from the distribution of background jets reproduces the spectrum distortion with width of $\sigma^{\text{bg}}$, which is applied in an unfolding procedure to correct the inclusive spectrum. We therefore utilize in these procedures the correction factors extracted from embedded Pythia using $\sigma^{\text{bg}}_{R=0.4} = 6.8$ GeV and $\sigma^{\text{bg}}_{R=0.2} = 3.7$ GeV. This choice results in an increase of a factor $\approx 3$ in the inclusive jet cross section for $R = 0.2$. Prior to the unfolding procedure, the signal jet spectrum is corrected for “false”-jet yield, defined as the signal in excess of the background model from random association of uncorrelated soft particles, estimated by running the jet finders on a randomized Au + Au event, with jet-leading particles removed.

The jet energy correction for tracking inefficiency, approximated in this analysis to be $p_T^{\text{track}}$, independent, is 8% in $p+p$ and 12% in Au + Au data, and correction for unobserved neutral energy (such as neutrons and K$^0_S$) is 5% in both systems. The total instrumental jet energy resolution ($\sigma^{\text{jet}}(E)/E \approx 20\%$ [7]) is corrected by unfolding. The systematic uncertainty on the jet energy scale, shown in all figures as the vertical shaded band, is dominated by the uncertainties on the BEMC calibration (5%), unobserved jet energy (3%), and charged component momentum resolution (2%). Solid lines represent systematic uncertainty on the jet yield in Au + Au due to background fluctuations.

3. Inclusive cross-sections and ratios

Figure 3 presents the differential cross sections for fully reconstructed inclusive jet production in $p+p$ and in 10% most central Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The reconstructed jet yields extend in $p_T^{\text{jet}}$ beyond 50 GeV/$c$. The $p+p$ measurement agrees within uncertainties with the published cross section (mid-point cone, $R = 0.4$) [8].

Figure 3 (left panel) shows $R_{AA}$, the ratio of the jet yield in Au + Au over the binary collision-scaled jet yield in $p+p$. For unbiased jet reconstruction, this ratio is expected to be close to
unity, with possible deviations due to initial state effects. We find $R_{AA}^{jet}$ for $R = 0.4$ compatible with unity, within the large uncertainties. The $R_{AA}^{jet}$ for $R = 0.4$ is significantly larger than $R_{AA}$ of hadrons for $p_T < 20 \text{ GeV}/c$ ($R_{AA}^{hadron} \approx 0.2$). The $R_{AA}^{jet}$ for $R = 0.2$ is markedly below that for $R = 0.4$. There are significant differences between $k_T$ and anti-$k_T$ algorithms, possibly arising from their different response to the heavy-ion background.

**Figure 1:** Cross sections for inclusive jet production in $p + p$ (left) and Au + Au collisions (right) at $\sqrt{s_{NN}} = 200 \text{ GeV}$ ($k_T$ and anti-$k_T$, $R = 0.2$ and 0.4). Error bands described in the text. Published $p+p$ data are from Ref. [8].

**Figure 2:** Ratios of inclusive jet cross sections in $p + p$ and Au + Au collisions at $\sqrt{s_{NN}} = 200 \text{ GeV}$ ($k_T$ and anti-$k_T$, $R = 0.2$ and 0.4). Left: Jet $R_{AA}$. Right: Ratio of cross sections $R = 0.2/R = 0.4$ for each system.

Figure 3 (right panel) shows the ratio of jet yield for $R = 0.2$ over that for $R = 0.4$, separately for $p + p$ and Au + Au collisions. Several jet energy scale systematic uncertainties cancel in this ratio. For $p + p$ collisions, the ratio increases with $p_T^{jet}$, consistent with a Pythia calculation but not with a recent NLO calculation [9]. The ratio is strongly suppressed for central Au + Au relative to $p + p$ collisions, indicating substantial broadening of the jets in heavy-ion collisions. A recent NLO calculation has been carried out that addressed these measurements directly [10].

**4. Hadron–jet coincidences**

We study the correlation of high-$p_T$ trigger particles (BEMC clusters with $p_T > 6 \text{ GeV}/c$) with a recoiling jet (matched in azimuth within $|\Delta \phi - \pi| < 0.4$), comparing central Au + Au and $p + p$ collisions. In Au + Au, this exploits the geometric bias of high-$p_T$ hadron production [2] due to quenching, which maximizes the path length of the recoiling jet in matter. Additional geometric bias can be introduced by applying the $p_T$ thresholds on the leading hadron in the
recoil jet. The recoil-jet spectra have been corrected for the “false”-jet contamination, described above. Additional uncorrected background due to multiple hard interactions in one Au+Au collision may be present. The yields are normalized to the number of trigger hadron pairs.

Figure 3 shows the ratio of conditional jet yields (Au+Au/p+p) vs. \( p_T \), for various recoil jet leading particle thresholds. The strongly exclusive requirement of two back-to-back high-\( p_T \) particles in Au+Au biases this measurement towards jets with little interaction, whereas a more relaxed condition permits more interacting jets. The ratio observed for the high-\( p_T \) selection is consistent with unity, indicating that in Au+Au collisions we reconstruct the same jet population per di-hadron trigger as in p+p collisions. For the low-\( p_T \) selection, on the contrary, the ratio is below unity and drops significantly with increasing \( p_T \), indicating substantial redistribution of jet energy in heavy-ion collisions. Related di-jet correlation studies are presented in Ref. [11].

5. Summary

We have presented the cross sections for fully reconstructed inclusive jet production in p+p and Au+Au collisions at \( \sqrt{s_{NN}} = 200 \) GeV, obtained with two different jet algorithms and with two different resolution parameters \( R = 0.2 \) and \( R = 0.4 \). While \( R_{AA}^{jet} \) for \( R = 0.4 \) is compatible with unity within large uncertainties, more discriminating measurements of the inclusive cross section as a function of resolution parameter and hadron–jet correlations indicate strong broadening of the jets in heavy-ion collisions.

References
[1] J. Adams et al. (STAR Collaboration) Phys. Rev. Lett. 91, 072304 (2003); J. Adams et al. (STAR Collaboration) ibid. 97, 162301 (2006); B. S. Adler et al. (PHENIX Collaboration) Phys. Rev. C69, 034910 (2004).
[2] T. Renk, Phys. Rev. C 78, 034904 (2008) [arXiv:0803.0218 (hep-ph)].
[3] S. Salur (STAR Collaboration), Eur. Phys. J. C 61, 761 (2009) [arXiv:0809.1699 (nucl-ex)].
[4] M. Cacciari, G. P. Salam, and G. Soyez, JHEP 0804 (2008) 005 [arXiv:0802.1188 (hep-ph)].
[5] S. Catani, Y. L. Dokshitzer, M. H. Seymour, and B. R. Webber, Nucl. Phys. B 406 (1993) 187 and refs. therein; S. D. Ellis and D. E. Soper, Phys. Rev. D 48 (1993) 3160 (hep-ph/9305266).
[6] M. Cacciari, G. P. Salam, and G. Soyez, JHEP 0804, 063 (2008) [arXiv:0802.1189 (hep-ph)].
[7] H. Caines (STAR Collaboration) arXiv:0903.4690 (nucl-ex), in these proceedings.
[8] B. I. Abelev et al. (STAR Collaboration) Phys. Rev. Lett. 97 (2006) 252001.
[9] W. Vogelsang, private communication (2009).
[10] I. Vitev and B. W. Zhang, arXiv:0910.1090 (hep-ph).
[11] E. Bruna (STAR Collaboration), arXiv:0907.4788 (nucl-ex), in these proceedings.

Figure 3: Ratios of hadron–jet conditional yields for three selections of the leading particle of the recoil jet, reconstructed in 10% most central Au+Au collisions and in p+p collisions. Jets were reconstructed with anti-kT algorithm with \( R = 0.4 \) and correlated at \( \Delta \phi \approx \pi \) with a leading high tower trigger cluster (dominated by \( \pi^0 \)).