Systematic study of the jet fragmentation function for inclusive jet-production in $p + p$ collisions at $\sqrt{s} = 200$ GeV in STAR

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Abstract Jet fragmentation functions measured in e^+e^- and $p + \bar{p}$ experiments are well-described on an inclusive hadron level by QCD-based calculations. Fragmentation is expected to be modified by the presence of a strongly interacting medium, but full theoretical description of this modification must still be developed. It has recently been suggested that particle-identified fragmentation functions may provide additional insight into the processes underlying jet quenching. To assess the applicability of QCD-based fragmentation calculations to RHIC data, and to provide a baseline with which to compare fragmentation function measurements in heavy ion collisions, we present the first measurements of charged hadron and particle-identified fragmentation functions of jets reconstructed via a midpoint-cone algorithm from $p + p$ collisions at 200 GeV in STAR. We study the dependence on jet cone-size and jet-energy, and compare the results to PYTHIA simulations based on the Modified Leading Log Approximation (MLLA).

1 Introduction

The measurement of jets in $p + p$ and $e^+ + e^-$ collisions provides a stringent test of perturbative QCD and factorization. In particular there have been recent efforts to theoretically describe the hadron multiplicity and its momentum distribution in jets in terms of fragmentation functions $dN/d\xi$, where $\xi = \ln(1/x) = \ln(E_{jet}/p_h)$. The modified leading logarithmic approximation (MLLA) describes the parton shower and has been successful at analytically computing the momentum and angular distributions

of partons in jets [1]. Assuming local parton hadron duality (LPDH) these distributions are converted to hadron fragmentation functions $dN/d\xi$ using a proportionality factor of order 1. Monte Carlo parton shower, such as implemented in PYTHIA, are also based on MLLA. Recent comparisons of the experimentally measured $dN/d\xi$ distribution of di-jets in $\sqrt{s} = 1.8$ TeV $p + \bar{p}$ collision at CDF to MLLA exhibit very good agreement [2].

The measurement at RHIC of the high-pt particle suppression in inclusive hadrons (R_{AA}) and the disappearance of back-to-back correlations in Au-Au collisions is commonly interpreted as medium induced jet-quenching [3, 4]. However both of these leading particle observables are from a biased sample of jets. Therefore in order to access jets in an unbiased way and to probe the underlying parton kinematics we need to perform full jet-reconstruction. A wide variety of jet-finding algorithms are now available and tested [5]. The jet fragmentation function, expressed in terms of ξ , also referred to as “hump-back plateau”, is a sensitive observable for the medium-modification of jets [7]. The $dN/d\xi$ distribution has the advantage over dN/dz of emphasizing the parton energy redistribution from harder to softer partons believed to be the predominant effect of gluon radiation. Some numerical results for $dN/d\xi$ for different jet-energies and jet-cone opening angles can be found here [8]. In that paper the authors also predict particle species dependent fragmentation functions and the change of particle ratios in jets as a function of jet-energy and p_T .

Thus the goal of the present analysis of STAR $p + p$ data at 200 GeV is threefold. First, we want to confirm that the MLLA framework also works at much lower jet-energies of the order of 15–50 GeV such as produced at RHIC. For this we compare $dN/d\xi$ distributions for charged hadrons in jets of various cone-sizes to predictions by MLLA as implemented in the PYTHIA Monte Carlo program (version 6.4).

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Second, we will present the first measurement of particle-identified $dN/d\xi$ distributions for Λ and K_S^0 particles in $p + p$ collisions. These will be useful to test and constrain the parameters in the Sapeta-Wiedemann model. And third, the $dN/d\xi$ distributions will be used as a baseline for future comparisons to medium modified $dN/d\xi$ from jets in heavy ion collisions at $\sqrt{s} = 200$ GeV. First progress towards this goal has been made recently [6].

2 Analysis technique

2.1 Event selection and online triggers

The data-sample presented here was taken during the 2005/2006 polarized pp running at RHIC. The total sampled luminosity was 6.2 pb^{-1} , which resulted in 8.3 million Jet-Patch triggered events. The two main online triggers used for the jet-analysis were the High-Tower (HT) and the Jet-Patch (JP) trigger. The tower granularity of the STAR barrel electromagnetic calorimeter (BEMC) is $\Delta\eta \times \Delta\phi = 0.05 \times 0.05$ and it has a coverage of $-1 < \eta < 1$ and $\Delta\phi = 2\pi$. The analysis presented here used the JP trigger, requiring the energy of an area of $\Delta\eta \times \Delta\phi = 1 \times 1$ to be above a threshold of 8 GeV. The reason for preferably using a JP trigger (instead of a HT) is that the trigger bias towards leading neutral particles (π^0) is less pronounced when integrating energy over a larger BEMC area, instead of a single tower. More details about the various BEMC triggers and their biases can be found in [11].

2.2 Jet-finding algorithm

For this study we used the midpoint-cone jet-finding algorithm commonly used in $p + \bar{p}$ collisions at CDF. This has also been used in previous STAR publications and the measured jet cross-section agrees well with NLO pQCD [12]. The main jet-reconstruction parameters were set to be

$R = 0.4\text{--}0.7$, $p_T^{\text{seed}} = 0.5 \text{ GeV}/c$ and $f_{\text{split}}^{\text{merge}} = 0.5$. In addition we only accepted jets whose Neutral Energy Fraction (NEF) was within $0.05 < \text{NEF} < 0.85$ to avoid a large trigger bias and to remove backgrounds with large NEF. Also the jet-axis was required to be within a given η range (dependent on R) to ensure full acceptance for the cone. For this analysis only the leading jet in each event was considered.

In order to compare our fragmentation function results to theory we used the PYTHIA Monte Carlo simulation (version 6.4) [14]. The PYTHIA output was further processed through our GEANT detector response simulator, and then analyzed in exactly the same way as the data. The PYTHIA sample was composed of several pt-hard bins which were weighted according to their cross-section. We applied the same jet-finding algorithm, with the same parameters to find jets and then extract $dN/d\xi$ distributions for charged hadrons.

In Fig. 1 (left) we studied the energy resolution by comparing the reconstructed jet-energy, after GEANT, tracking and jet-finding, with the energy obtained from applying the algorithm to the PYTHIA input. An approximately constant energy resolution of $\sim 25\%$ was obtained for all measurable jet-energies. On the right panel of Fig. 1 we show the measured jet-energy spectrum for the leading jets in each event. In this study the reconstructed energy was not corrected for the shift with respect to the input energies. The statistical reach allows to reconstruct about 500 jets in the 40–50 GeV energy range. In addition jet-energy was corrected for two effects. In jets with identified electrons, whose energy would be double-counted due to them being measured by both the Time Projection Chamber (TPC) and BEMC, only the track momentum was used. Second, for charged hadrons in jets which projected to an active BEMC tower (deposited energy above pedestal) the expected energy deposit of a minimum ionizing particle (MIP) was subtracted from the tower energy.

Fig. 1 (Left) Energy resolution as a function of PYTHIA jet-energy for the mid-point cone algorithm with radius $R = 0.4$. The y-axis is the reconstructed jet-energy after GEANT and track reconstruction. Horizontal error bars indicate bin-width, vertical error bars indicate RMS of reconstructed energy. (Right) Reconstructed leading jet-energy spectrum for the highest jet in the event. Differences in magnitude are due to the varying acceptance as a function of cone-radius

2.3 Particle identification

We used identified V0 particles, K_S^0 and Λ , via their dominant hadronic decay to charged particles. These were chosen because STAR has excellent efficiency and particle identification over a large kinematical range for reconstructing

these decays ($1 < p_T(\text{GeV}/c) < 8(\Lambda), 10(K_S^0)$). Using the methods described in [13] we reconstructed the invariant mass distributions of V0's and identify K_S^0 and Λ particles. These were then added to the particle pool and their charged daughters were removed before the jet-finding step. This resulted in a total of $\sim 100k$ jets with K_S^0 and $\sim 45k$ jets

Fig. 2 Charge particle $dN/d\xi$ distribution for reconstructed jet-energies 20–50 GeV (leading jets only) and cone-radii $R = 0.4$ (upper) and $R = 0.7$ (lower). Only statistical errors shown

Fig. 3 $dN/d\xi$ for identified strange particles in jets for three different jet-energies. Fits are Gaussian functions and are only used to obtain the peak value ξ_0 . The vertical (purple) line indicates the p_T -cutoff of

1 GeV/c for good identification of strange particles. Charged hadrons are shown for comparison. Only statistical errors shown

with Λ . The ξ distributions for Λ and K_S^0 were corrected for reconstruction efficiency using a sample of simulated jets. For p_T greater than 2.5 GeV/c the reconstruction efficiencies were independent of p_T and of the order of 30% and 15% for K_S^0 and Λ respectively.

3 Results and discussion

In Fig. 2 we compare the results of charged hadron $dN/d\xi$ distribution to results from PYTHIA, for two different cone-sizes and three jet-energy bins. The overall agreement between data and model is rather good although small deviations can be found, in particular for larger cone-sizes. The fact that the differences between experiment and model are small for $R = 0.4$ and more significant for $R = 0.7$, could be evidence of the importance of next-to-leading order corrections to PYTHIA since it is expected they are more important at larger angles with respect to the jet-axis.

In Fig. 3 we show the results for identified K_S^0 and Λ particles for different jet-energies, and as a reference the charged $dN/d\xi$ distribution. The jet-energy bins were chosen to optimize the available statistics of K_S^0 and Λ particles. $dN/d\xi$ distributions are expected to be Gaussian around their peak and therefore we used a Gaussian fit in order to extract the peak value ξ_0 . According to perturbative QCD ξ_0 is expected to be ordered with particle mass [9]. The result of extracting ξ_0 for different particle species and jet-energies is shown in Fig. 4. The data seem to indicate that the QCD predicted mass ordering is not obeyed since the peak value ξ_0 for Λ is equal or higher than ξ_0 for K_S^0 for all three energies. However the significance of this result needs to be confirmed once the systematic errors have been evaluated. A similar observation of violated mass ordering between pions, protons and kaons has been seen by a range of $e^+ + e^-$ experiments at $\sqrt{s} = 10\text{--}100$ GeV [10]. For comparison to this result, measurements in $e^+ + e^-$ collisions at

$\sqrt{s} = 10.54$ GeV from BABAR show the peak of the kaon and proton distribution to be equal at $\xi_0 \sim 1.6$.

In Fig. 5 we study the relative production of Λ vs K_S^0 in jets as a function of ξ . We can compare these results to previous measurements of inclusive strange particle production in $p + p$ collisions at $\sqrt{s} = 200$ (right panel) [13]. The values of the Λ/K_S^0 ratio at low ξ (left panel) are consistent with the measurements at high- p_T in the right panel. However the value of the ratio at high- ξ is much larger than the value at a comparable p_T in inclusive production. It grows significantly larger than 1 for $\xi > 2$ and does not exhibit the typical maximum as seen in the baryon-to-meson ratio in inclusive production. Such a large baryon-to-meson ratio in jets could be indicative of a different hadronization mechanism for low momentum baryons.

In summary, we have shown the first measurement of charged particle $dN/d\xi$ distributions in inclusive jets in $p + p$ collisions at $\sqrt{s} = 200$ at RHIC and concluded that they agree well with PYTHIA for small cone-radii. Furthermore we have measured identified particle $dN/d\xi$ and ob-

Fig. 4 Peak value ξ_0 of $dN/d\xi$ distribution for charged hadrons, K_S^0 and Λ for $R = 0.4$ and different jet-energy selections. The peak values were estimated from Gaussian fits within the range of $\xi > 1$ and $p_T > 1$ GeV/c as shown on Fig. 3

Fig. 5 (Left) Λ/K_S^0 ratio measured in jets as a function of ξ . Vertical lines allow easier reference to $p_T = 1, 2, 4$ GeV/c labeled in the figure. Statistical errors only. (Right) The Λ/K_S^0 ratio measured in inclusive $p + p$ collisions as a function of event multiplicity. From [13]

serve that the peak values do not follow a particle mass ordering scheme. In addition we observe a large strange baryon-to-meson ratio (> 1) at high ξ in jets. This apparent disconnect between theory and experiment points to a more fundamental lack of understanding of how baryons are produced. With the start of the LHC (Large Hadron Collider) further measurements of these fragmentation functions in vacuum and the medium should become available and may help resolve these issues.

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