Identified Hadrons and Jet Chemistry for p+p and Au+Au Collisions at RHIC

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Abstract.

The study of hadron spectra at high $p_T$ in p+p collisions provides a good test of perturbative quantum chromo-dynamic calculations (pQCD) and a baseline for measurements of nuclear modification factors in Au+Au collisions. Using events triggered with electro-magnetic calorimetery, identified charged hadron transverse momentum ($p_T$) spectra are measured up to 15 GeV/c at mid-rapidity ($|y| < 0.5$) and neutral kaon $p_T$ spectra up to 12 GeV/c in p+p collisions at $\sqrt{s_{NN}} = 200$ GeV in the STAR Experiment [1]. The particle ratios of $p/\pi^+$, $\bar{p}/\pi^-$ and $K^{+0}/\pi^\pm$ in p+p collisions are shown and compared with next-to-leading order pQCD calculations. In central Au+Au collisions, we report nuclear modification factors ($R_{AA}$) for pion, kaon, proton and $\rho$ and discuss several model calculations: color-charge dependence of jet quenching and jet conversion. Finally, centrality dependence of $R_{AA}$ at high $p_T$ ($> 5.5$ GeV/c) for kaons are compared with that of pions in Au+Au collisions at 200 GeV.

1. Introduction:

Measurements of identified charged hadron ($\pi^\pm$, $K^\pm$, $p(\bar{p})$) transverse spectra at $p_T > 2$ GeV/c in elementary p+p collisions provide a good test of perturbative Quantum Chromodynamics (pQCD) [2]. In pQCD calculations, the inclusive production of single hadrons is described by the convolution of parton distribution functions (PDF), parton-parton interaction cross-sections, and fragmentation functions (FF). The FFs were parameterized according to experimental measurements in $e^+e^-$ collisions but are not well constrained. A more precise constraint on the quark and gluon FFs by comparing theory with experimental data is crucial to understand hadron production mechanisms. In addition, these measurements in p+p collisions at high $p_T$ provide an essential baseline for studying parton energy loss in heavy ion collisions. We use events triggered by an electro-magnetic calorimeter and extend the identified charged particle measurements up to 15 GeV/c, and neutral kaons up to 12 GeV/c in p+p collisions at $\sqrt{s_{NN}} = 200$ GeV. This significantly extends particle $p_T$ reach beyond previously published measurements of up to 10, 5, and 7 GeV/c respectively for pions, $K^0_S$, and protons in p+p collisions using events triggered with minimum bias [3 4]. The
relativistic ionization energy loss \( dE/dx \) in the Time Projection Chamber (TPC) was used for charged hadron identification. A new method to re-calibrate the TPC \( dE/dx \) was developed and applied \[5\], which significantly reduced the systematic uncertainties for protons compared to previous measurements \[3, 6\]. In these proceedings, identified particle \( p_T \) spectra, and the particle ratios \( (p/\pi^+, \bar{p}/p \) and \( K^{\pm,0}/\pi^\pm) \) are presented and compared with next-to-leading order (NLO) pQCD calculations, and with PYTHIA results. Nuclear modification factors \( R_{AA} \), the spectra in Au+Au collisions divided by spectra in p+p collisions scaled by the number of binary collisions, are presented and compared with theoretical calculations \[7\].

2. Experiment and Analysis

The p+p collision events with enhanced high-\( p_T \) charged particles we use in this analysis are obtained from an online trigger by the Barrel Electro-Magnetic Calorimeter (BEMC) with \( 0 < \eta < 1 \) and full \( (2\pi) \) azimuthal coverage in the year 2005 \[8\]. Charged particle tracking is performed with the Time Projection Chamber (TPC), spanning \( |\eta| < 1.8 \) and \( 2\pi \) in azimuth, which enables particle identification through measurements of momentum and \( dE/dx \) \[9\]. In p+p collisions, \( \sim 5.6 \) million events triggered by transverse energy \( E_T > 6.4 \) GeV in single BEMC towers (JP2 events), \( \sim 5.1 \) million events with \( E_T > 2.5 \) GeV (HT1 events), and \( \sim 3.4 \) million events with \( E_T > 3.6 \) GeV (HT2 events) are used for the analysis. Neutral kaons are reconstructed in the HT1 and HT2 triggered events through the \( K_S^0 \rightarrow \pi^+ + \pi^- \) decay mode, while JP2 triggered events are used to measure charged hadrons. These events also serve to check for a trigger bias by comparing \( K_S^0 \) on the near side of the trigger (in azimuth) with \( K^\pm \) on the away side using other triggered events. The charged kaon analysis involves \( \sim 21.2 \) million central Au+Au collisions.

The segment length \( x \) dependence of \( dE/dx \), gas multiplication gains, noise of TPC electronics, and pileup in high luminosity environment may cause the measured \( dE/dx \) of charge particles in the TPC to deviate from the expected values, as calculated from the Bichsel function \[10\]. In the relativistic rise region, the separation of \( dE/dx \) peaks among \( \pi^\pm, K^\pm \) and \( p(\bar{p}) \) are between approximately 1 to 3 \( \sigma \). Pions are the dominant particle species for inclusive and jet hadrons, and their \( dE/dx \) distributions overlap the smaller kaon and (even smaller) proton distributions within any given momentum slice, preventing clear peak separation. This results in large systematic errors in attributing yields to species due to the uncertainty of the reconstructed \( dE/dx \) peak positions. The re-calibration method is important to improve these systematics \[3, 11\]. With the Bichsel function, normalized \( dE/dx \) distributions for charged particles can be fit by an 8-Gaussian function to obtain identified particle yields at given momenta \[12\, 5\]. To correct for the trigger enhancement, PYTHIA is used to generate events which are then passed through GEANT, and the fraction of those events passing the trigger threshold is determined. The combined acceptance and efficiency correction is found to be 88\% from GEANT simulations. Final spectra for charged hadrons at \( |\eta| < 0.5 \) are shown in Fig. 1 and are consistent with previously published spectra in minimum bias events \[3\].
Figure 1. Charged hadrons and neutral kaon $p_T$ spectra in p+p collisions, compared with pQCD NLO calculations from DSS, AKK 2008. The shaded band on the right panel represents systematic uncertainties for $K^0_S$.

For the trigger bias cross check, near-side $K^0_S \to \pi^+ + \pi^-$ decays are reconstructed in HT1 and HT2 triggered events through identified displaced vertices (V0s) [4]. We require one of the daughter pions to have fired the BEMC tower energy trigger and compare the $p_T$ spectra of these pions to those from minimum bias events to determine trigger efficiency versus $p_T$. Simulations provide a combined efficiency of 55.6% for reconstructing the second daughter pion and identifying the V0. Final $K^0_S$ $p_T$ spectra are shown as stars on the right panel of Fig. 1. Within uncertainties, they are consistent with charged kaon spectra, indicating sufficient removal of trigger biases by our corrections. The NLO pQCD calculations (AKK 2008 [13] and DSS [14]) shown in Fig. 1 exhibit good agreement with charged pion spectra, but cannot describe our (anti-)proton and kaon spectra [11, 15]. Our data can be used to further constrain parameters of FFs in these calculations.

In addition, Fig. 2 shows several particle ratios ($p_\pi$, $p/\pi^-$, and $K^\pm/\pi^\pm$) [11, 15] as a function of $p_T$ at mid-rapidity in the BEMC triggered events from p+p collisions along with published results from minimum bias p+p collisions [3, 4] and predictions from pQCD calculations (DSS NLO calculations and PYTHIA simulations). The experimental data are consistent in regions of overlapping $p_T$ and show minor divergences from PYTHIA, but are well below the predictions of DSS at high $p_T$. This again show that our data can provide a good constraint to the NLO pQCD calculations.

Charged particles are identified in Au+Au collisions via the same re-calibrated dE/dx method [5]. The K/\pi ratios in Au+Au collisions are shown in Fig. 3 (left) compared with the ratios in p+p collisions. The enhancement of K/\pi in Au+Au collisions demonstrates less suppression for kaons than pions at high $p_T$. To further understand this phenomenon, $R_{AA}$ in central Au+Au collisions are shown in Fig. 3 (right) for kaon, pion, proton, and $\rho$ [16]. The study of detailed systematic uncertainties for kaons and protons is underway. We observe that $R_{AuAu}(K^\pm, K^0_S)$ is larger than
Figure 2. Experimental $\overline{p}/p, \overline{p}/\pi^-$ (left), and $K/\pi$ (right) ratios in $p+p$ collisions, compared with pQCD NLO calculations from DSS and PYTHIA. Vertical lines show statistical errors, while shading and boxes represent systematic uncertainties.

Figure 3. $K/\pi$ ratios and nuclear modification factors of $\pi$, $K$, $p$ and $\rho$ in Au+Au collisions as a function of $p_T$. The bars and boxes represent statistical and systematic uncertainties respectively.

$R_{AuAu}(\pi^{\pm})$, which is in contradiction to the prediction from a model based on parton energy loss through gluon radiation [17]. That $R_{AuAu}(\pi^{\pm})$ is similar to $R_{AuAu}(\rho)$ indicates that the difference is not a mass effect. The value of $R_{AuAu}(K^\pm, K^0_S)$ is consistent with the prediction from jet conversion in the hot dense medium (dashed line) [7]. The same factor, scaling the lowest-order QCD jet conversion rate, applied to calculate proton $R_{AA}$ [6, 18] is used in this prediction.

In order to understand more about the jet chemistry change in the medium, we also show the centrality dependence of $R_{AA}$ in Fig. 4. Due to limited statistics, we plot integrated $R_{AA}$ for $p_T > 5.5$ GeV/$c$ (with mean $<p_T> \sim 6.2$ GeV/$c$ in this range), where particle production may be dominated by hard processes.

Both kaon and pion production are suppressed in central collisions, and $R_{AA}(K)$ is about a factor of 2 larger than $R_{AA}(\pi)$, even in peripheral collisions. This raises the question whether parton flavor conversion is prevalent, even in the smaller systems, or...
if there is some other soft production mechanism than jet fragmentation contributing in this $p_T$ range for all centralities of A+A collisions.

3. Summary and discussion

Using the BEMC triggered events and a new $dE/dx$ re-calibration method, $\pi^\pm$, $K^\pm$ and $p(\bar{p})$ transverse momentum ($p_T$) spectra in p+p collisions at $\sqrt{s_{NN}} = 200$ GeV are extended up to 15 GeV/c at mid-rapidity ($|y| < 0.5$), and neutral kaon $p_T$ spectra up to 12 GeV/c. The ratios $p/\pi^+$, $\bar{p}/\pi^-$, and $K^{\pm,0}/\pi^\pm$ in p+p collisions are shown and compared with NLO pQCD calculations. These calculations cannot reproduce kaon and proton spectra at high $p_T$. In central Au+Au collisions, we observe $R_{AA}(p + \bar{p}) \geq R_{AA}(K_S^0, K^\pm) > R_{AA}(\pi^+ + \pi^-) \approx R_{AA}(\rho^0)$ at high $p_T$ (above 5.5 GeV/c). Jet conversion together with other mechanisms, such as parton splitting [19], might be able to explain these observations. Higher statistics from Run 10 may give us additional physics information from more precise measurements of the nuclear modification factors.

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