Identified Baryon and Meson Distributions at Large Transverse Momenta from Au + Au Collisions at √s_{NN} = 200 GeV


Identified Baryon and Meson Distributions at Large Transverse Momenta from Au + Au Collisions at √s_{NN} = 200 GeV


0031-9007/06/97(15)/152301(6) 152301-1 © 2006 The American Physical Society
Au Transverse momentum spectra of +Au collisions at \( \sqrt{s_{NN}} = 200 \) GeV are presented. In central Au +Au collisions, both \( \pi^\pm \) and \( p(\bar{p}) \) --
Ultrarelativistic heavy ion collisions provide a unique environment to study properties of strongly interacting matter at high temperature and energy density. When hard partons traverse the hot and dense medium created in the collision, they lose energy by gluon radiation and/or hard partons traverse the hot and dense medium created at high temperature and energy density. When the environment to study properties of strongly interacting matter at high temperature and energy density.

In this Letter, we present the $p_T$ distributions of pions ($\pi^\pm$), protons ($p$), and antiprotons ($\bar{p}$), their nuclear modification factors, and particle ratios in 200 GeV $Au + Au$ collisions at $0.3 < p_T < 2$ GeV/c. This explores the full range of particle production mechanisms, with emphasis on the intermediate $p_T$ range ($0.3 < p_T < 6$ GeV/c), where coalescence may play a role in hadronization, and high $p_T$ ($p_T > 6$ GeV/c), where particle production is dominated by jet fragmentation. Identified particles at high $p_T$ provide direct sensitivity to differences between quark and gluon fragmentation. For example, proton and pion production at high $p_T$ is expected to have significant contributions from quark fragmentation, while antiprotons are mostly from gluon fragmentation [4,15]. Therefore, $\bar{p} / p$ and $\bar{p} / \pi$ ratios in different systems are sensitive to the possible color charge dependence of energy loss [4]. We discuss the possible transition between jet fragmentation and quark coalescence at hadronization, the color charge dependence of the energy loss, and the fragmentation functions at high $p_T$.

The data used for this analysis were taken in 2004 by the STAR experiment [16]. A total of $15 \times 10^8$ central triggered events for the most central bin (0%-12% total cross section) and $14 \times 10^8$ minimum-bias (MB) triggered events for the other centrality classes are used [17]. Measurements of the ionization energy loss ($dE/dx$) of charged tracks in the time projection chamber (TPC) gas are used to identify pions (protons) in the region $p_T < 0.75(\leq 1.1)$ GeV/c and $2.5 \leq p_T \leq 12$ GeV/c [19,20].
For each centrality, the ratio \( R_{CP} \) is constant over the range 1.5 < \( p_T \phi < 4.5 \text{ GeV/c} \), and the extended \( p_T \phi \) reach shows that \( R_{CP} \) for protons decreases again at higher \( p_T \phi \).

The results in Fig. 2 clearly show different \( R_{CP} \) for protons and pions at intermediate \( p_T \). A similar effect has been observed for \( K^0_S \) and \( \Lambda \) [9], with \( K^0_S/\Lambda \) \( R_{CP} \) similar to pion (proton) \( R_{CP} \). The grouping of particle production according to the number of constituent quarks has been attributed to quark coalescence at hadronization from a collective partonic medium [11–14]. Our high statistics measurements show that these effects disappear at high \( p_T \), where baryons and mesons show a common degree of suppression. This is consistent with the general expectation that collective and coalescence effects have a finite \( p_T \phi \) reach.

Figure 3 shows the ratio \( \pi^-/\pi^+\) and \( \bar{p}/p \) ratios in 0%–12%, MB \( Au + Au \), and \( d + Au \) [21,22] collisions. We observe that the \( \pi^-/\pi^+ \) ratios are consistent with unity in \( d + Au \), MB, and central \( Au + Au \) collisions. Predictions from a pQCD based model with and without partonic energy loss are consistent with our data [4]. The same calculation shows a significant effect from energy loss on the \( \bar{p}/p \) ratio (Fig. 3(b)), due to the large energy loss of gluons in the medium. Our measurements, in contrast, show little centrality dependence of the \( \bar{p}/p \) ratio at \( p_T \phi \leq 6 \text{ GeV/c} \phi \) and a possible increase of the \( \bar{p}/p \) ratio at higher \( p_T \phi \) in central \( Au + Au \) collisions compared to \( d + Au \) collisions.

Figure 4 shows the ratio \( \pi^+/\pi^- \) for 0%–12%, 60%–80% \( Au + Au \), and \( d + Au \) [21,22] collisions. The

![Figure 1](https://example.com/figure1.png)  
**FIG. 1** (color online). Centrality dependence of midrapidity (|y| ≤ 0.5) \( \pi^+/-\pi^- \), and \( p/\bar{p} \) invariant yields versus \( p_T \phi \) from 200 GeV \( Au + Au \) collisions. The error bars are the quadrature sum of statistical and systematic errors. The solid lines depict our best estimates of the proton yields corrected for the hyperon (\( \Lambda \) and \( \Sigma^- \)) feed-down [25]. The shaded bands on the lines represent the uncertainties. The order of the spectra in different centralities is the same for both panels.

![Figure 2](https://example.com/figure2.png)  
**FIG. 2** (color online). Nuclear modification factors \( R_{CP} \) for \( \pi^+/-\pi^- \) and \( p/\bar{p} \) for 200 GeV \( Au + Au \) collisions. The point-to-point systematic uncertainties are shown as the shaded boxes around the data points. The dark shaded bands show the normalization systematic uncertainty in the number of binary collisions. The solid lines show jet quenching predictions for pions [27].

For \( Au + Au \) collisions, the pion yield shows strong suppression with \( R_{CP} \) between 0.2 and 0.4 at \( p_T \phi \geq 3 \text{ GeV/c} \). This is consistent with the jet quenching calculation shown in Fig. 2(a) [27].

For each centrality, the \( R_{CP} \) values for protons peak at \( p_T \phi \) = 2–3 GeV/c. At intermediate \( p_T \), \( p/\bar{p} \) are less suppressed, with respect to binary scaling, than \( \pi^\pm \), but a significant suppression is still observed in central \( Au + Au \) collisions. This is in contrast to nuclear modification factors in \( d + Au \) collisions, where a significant enhancement is seen for protons [22]. Previous measurements at lower transverse momentum [10] showed that \( R_{CP} \) for protons is close to 1 for 1.5 < \( p_T \phi < 4.5 \text{ GeV/c} \), and the extended \( p_T \phi \) reach shows that \( R_{CP} \) for protons decreases again at higher \( p_T \).

Nuclear effects on hadron production in \( Au + Au \) collisions are quantified through comparison of the spectrum in central \( Au + Au \) collisions to 40%–80% or 60%–80% peripheral \( Au + Au \) collisions, scaled by the number of underlying binary nucleon-nucleon inelastic collisions \( N_{bin} \) calculated from a Glauber model [2], using the ratio

\[
R_{CP} = \frac{d^2N/(2\pi p_T dp_T dy)_{(central)}}{N_{bin}(central)} \frac{d^2N/(2\pi p_T dp_T dy)_{(peripheral)}}{N_{bin}(peripheral)}
\]

Figure 2 shows pion \( (\pi^+/-\pi^-) \) and proton \( (p/\bar{p}) \) \( R_{CP} \) for \( Au + Au \) collisions. In 0%–12% central \( Au + Au \) collisions, the ratio shows strong suppression with \( R_{CP} \) between 0.2 and 0.4 at \( p_T \phi \geq 3 \text{ GeV/c} \). This is consistent with the jet quenching calculation shown in Fig. 2(a) [27].
FIG. 3 (color online). The $\pi^-/\pi^+$ and $p/\pi^+$ ratios in 12% central, MB Au + Au and $d + Au$ [21,22] collisions at $\sqrt{s_{NN}} = 200$ GeV. The shaded boxes represent the systematic uncertainties in the top 12% central Au + Au collisions. The systematic uncertainties for MB Au + Au collisions are similar. Curves are the corresponding predictions from a jet quenching model [4].

ratios in Au + Au collisions are observed to be strongly centrality dependent at intermediate $p_T$. In central Au + Au collisions, the $p/\pi^+$ and $p/\pi^-$ ratios peak at $p_T \sim 2$–3 GeV/c with values close to unity, decrease with increasing $p_T$, and approach the ratios in $d + Au$, $p + p$ and peripheral Au + Au collisions at $p_T \approx 5$ GeV/c. The dotted and dashed lines are predictions for central Au + Au collisions from recombination [12] and coalescence with jet quenching and KKP fragmentation functions [13,28], respectively. These models can qualitatively describe the $p(\bar{p})/\pi$ ratio at intermediate $p_T$, but, in general, underpredict the results at high $p_T$.

At high $p_T$, the $p/\pi^+$ ratios can be directly compared to results from quark jet fragmentation as measured in $e^+e^- \rightarrow e\bar{\psi}$ collisions by DELPHI [29], indicated by the dotted-dashed line in Fig. 4(a). The $p/\pi^+$ ratio measurements in $d + Au$ and Au + Au collisions are higher than in quark jet fragmentation. This is likely due to a significant contribution from gluon jets to the proton production, which have a $(p + p)/(\pi^+ + \pi^-)$ ratio up to 2 times larger than quark jets [30]. A similar comparison cannot be made for $\bar{p}\psi$ production [Fig. 4(b)], because there is a significant imbalance between quark (q) and antiquark ($\bar{q}$) production at high $p_T$ in $d + Au$ and Au + Au collisions, and the fragmentation function of $q + \bar{q}$ is not well described by the STAR data in $p + p$ collisions [22], showing that gluon fragmentation contributes to 40% of pion production at $p_T = 10$ GeV/c while more than 80% of $p + p$ are from gluon fragmentation.

At high $p_T$, the nuclear modification factor of protons is similar to that of pions (Fig. 2) and the $p/\pi^+$ ratios in central Au + Au collisions are similar to those in $p + p$ and $d + Au$ collisions [22]. These observations indicate that, at sufficiently high $p_T$, fragmentation in central Au + Au and $p + p$ events is similar and that there is no evidence of different energy loss for quarks and gluons in the medium. The theoretical calculations in Fig. 3 show that differences in radiative energy loss are expected to result in measurable changes in the $p(p)/\pi$ and $\bar{p}(\bar{p})/\pi$ ratios. Those calculations, however, do not reproduce the measured $p(\bar{p})$ and $\bar{p}(\bar{p})$ spectra in $p + p$ collisions [22], indicating that the fragmentation functions for baryon production are not well known. The determination of baryon fragmentation functions from elementary collisions and the expected range of validity of factorization for baryon production are areas of ongoing investigation [15,22]. In addition, there is some uncertainty in the mechanism of energy loss. It has been postulated that the addition of collisional energy loss to radiative energy loss may explain the large suppression of leptons from heavy flavor decays in Au + Au collisions [32,33]. The latest calculations [34,35] including collisional energy loss and path length fluctuations [36] show that the nuclear modification factor of gluons is still expected to be a factor of 3 lower than that of light quarks.

We have reported the transverse momentum spectra of pions and protons at midrapidity from 200 GeV Au + Au collisions up to 12 GeV/c. Protons and antiprotons are less suppressed than pions at intermediate $p_T$. At $p_T \approx 6$ GeV/c, both mesons and baryons are strongly suppressed. However, the relative particle abundances show no system dependence among $p(\bar{p})$, $d + Au$, and Au + Au collisions. These results indicate that the partonic
sources of \( \pi^+; \pi^-; p \), and \( \bar{p}d \) have similar energy loss when traversing the nuclear medium. Particle identification at high \( p_T \) provides crucial information and new challenges to the understanding of energy loss and modified parton fragmentation in strongly interacting matter.

We thank Dr. M. Djordjevic, R.J. Fries, R.C. Hwa, I. Vitev, and X.N. Wang for valuable discussions and for providing the theory calculations. We thank the RHIC Operations Group and RCF at BNL and the NERSC Center at LBNL for their support. This work was supported in part by the Offices of NP and HEP within the U.S. DOE Office of Science; the U.S. NSF; the BMBF of Germany; CNRS/IN2P3, RA, RPL, and EMN of France; EPSRC of the U.K.; FOM of the Netherlands; DAE, DST, and CSIR of the Government of India; Swiss NSF; the Czech Republic; FOM of the Netherlands; DAE, DST, and CSIR of the Government of India; Swiss NSF; the Polish State Committee for Scientific Research; SRDA of Slovakia; and the Korea Science and Engineering Foundation.

[17] Centrality tagging follows Ref. [18]. The central trigger selected the most central 12% of the total hadronic cross section based on an on-line cut of energy deposited in the zero-degree calorimeters. The pion spectra from 0%–10% MB events and 0%–12% central events had a 5% difference in overall scale due to the different centrality selections.
[25] The feed-down corrections were estimated using the \( \Lambda \) spectra from Ref. [9] with a full simulation of decay, detection efficiency, and momentum resolution. The measured \( \Lambda \) spectra were extrapolated to high \( p_T \), assuming \( \Lambda/p\bar{p} = 0.2 \) at \( p_{T\text{lab}} = 120 \text{ GeV}/c \). The \( \Lambda/\Lambda^+ \) ratio was assumed to be 0.35 [24], independent of \( p_T \). The systematic uncertainty on the correction was calculated from the statistical and systematic uncertainties on the inclusive proton and \( \Lambda \) measurements, with a 30% uncertainty assigned to the extrapolated \( \Lambda \) spectra. An additional 20% uncertainty was assigned to account for the uncertainty in the \( \Lambda^+ \) yields.
[27] I. Vitev, hep-ph/0603010; curves are calculations with initial gluon rapidity density 1150 in 0%–10% MB events and 0%–12% central events had a 5% difference in overall scale due to the different centrality selections.
[33] B.I. Abelev et al., nucl-ex/0607012.