The charged-hadron/pion ratio at the Relativistic Heavy Ion Collider

Xiaofei Zhang and George Fai

Center for Nuclear Research, Department of Physics, Kent State University
Kent, Ohio 44242, USA

Abstract

The hadron/pion ratio is calculated in 200 GeV AuAu collisions at midrapid-
ity, applying pQCD and non-universal transverse-momentum broadening. Ar-
guments are presented for such non-universality, and the idea is implemented
in a model, which reproduces the main features of the centrality dependence
of the hadron/pion ratio in AuAu collisions. The model also reasonably de-
scribes the qualitative difference between the recently-measured dAu nuclear
enhancement factors for pions and charged hadrons.

PACS Numbers: 25.75.-q, 25.75.Dw, 25.75.Nq, 13.85.-t
Nuclear collisions are studied at unprecedented energies at the Relativistic Heavy Ion Collider (RHIC), revealing several new phenomena embedded in a large amount of high-quality data, most aspects of which are consistent with general expectations [1]. A lot of attention is centered on final-state particles (secondaries) with high transverse momenta ($p_T$), where perturbative quantum chromodynamics (pQCD) should have good predictive power. In this regime, a suppression of total charged hadron and pion production has been observed relative to a nucleon-nucleon ($NN$) reference in $AuAu$ collisions [2,3]. The suppression can be described by pQCD calculations after incorporating final-state partonic energy loss in dense matter [4–6], or using a model of initial-state gluon saturation [7]. The most recent $dAu$ data [8] provide important information for understanding RHIC physics.

Furthermore, the PHENIX collaboration reports an anomalous enhancement of the high-$p_T$ proton-to-pion ($p/\pi$) ratio in $AuAu$ collisions at $\sqrt{s} = 130$ GeV [9] and $\sqrt{s} = 200$ GeV [10]. At 200 GeV, PHENIX also measured the ratio of charged hadrons ($h^\pm = (h^+ + h^-)/2$) to neutral pions, and found it enhanced in central collisions, presumably due to the enhancement of proton production. Different versions of coalescence (recombination) of partons from the Quark-Gluon Plasma were proposed to understand the enhanced $p/\pi$ ratios [11]. Nevertheless, the measured azimuthal correlations for high-$p_T$ charged particles [12] and the binary-collision scaling of proton production gleaned from comparing different centralities [10] indicate that the production from hard scattering remains important. Enhanced proton/pion and kaon/pion ratios have also been observed in lower-energy pA collisions [13]. Therefore, other effects could also contribute to the enhanced particle ratio at RHIC. In this paper, we will try to provide an alternative explanation for the particle ratio data at RHIC based on pQCD.

Another experimentally favored quantity, where differences between $h^\pm$ and $\pi$ secondaries manifest themselves, is the “nuclear modification factor”, $R_{AB}$. This ratio is designed to display the effects arising in an actual $AB$ nuclear collision, relative to a hypothetical collection of independent $NN$ collisions. Earlier experimental information on $R_{AB}$ for $AuAu$ has recently been augmented by data obtained in the $dAu$ run to provide a crucial reference
[8], and the nuclear modification factor was also addressed theoretically [14–16].

Here we concentrate on the transverse-momentum and impact-parameter dependence of hadron/pion ratios at midrapidity and on the nuclear modification factor in dAu at √s = 200 GeV, using leading-order pQCD. We observe that while pQCD is quite successful for charged hadron and pion production at large \( p_T \) in proton-proton (pp) collisions, proton production in pp is not well understood using the language of pQCD. In fact, pQCD underestimates the \( p/\pi^+ \) ratio by a factor of 3-10 in pp collisions. This can be attributed to the limited information about a nonperturbative ingredient, the fragmentation function (FF), in the usual factorization-theorem based treatment of particle production in pQCD (see \( D(z,Q^2) \) in eq. (1)). Most of the FF-s are extracted from \( e^+e^- \) data, where the most relevant large-z part of the FF-s is not well constrained [17], and the information on proton FF-s is very limited, especially for gluon fragmentation functions. We are aware of only one set of proton FF-s from global fitting to date [18]. Compared to proton FF-s, FF-s for charged hadron and pion production are better studied, supported by more experimental information [19,20]. At the same time, the RHIC data for the \( p/\pi \) ratio are only available for \( p_T \leq 5 \) GeV, while \( h^+/\pi \) ratios are available for \( p_T \) to about 10 GeV. Therefore, in this paper we focus on the \( h^+/\pi^0 \) ratio. Any insight gained is expected to also help in understanding the \( p/\pi \) ratios.

In an attempt to provide a more satisfactory description of available data and to mimic higher-twist contributions (of order \( Q^2_v/p_T^2 \), where \( Q_v \) is the appropriate virtuality [21]), many pQCD calculations take direct account of the transverse momentum of partons ("intrinsic \( k_T \)"). This can be accomplished via unintegrated parton distribution functions or, more phenomenologically, via a product assumption and a Gaussian transverse momentum distribution \( g(k_T) \) (characterized by the width \( \langle k_T^2 \rangle \)) [22,23]. We apply the latter procedure in the present paper. Then, for pp collisions, the usual convolution of the standard parton distribution functions (PDF-s) \( f_a \), transverse momentum distributions \( g(k_T) \), partonic cross sections \( d\sigma/d\hat{t} \), and fragmentation functions (FF) \( D_{h/c} \) takes the form
where the partonic subprocesses $a + b \rightarrow c + d$ are summed over, $x_a, x_b$ and $z_c$ are momentum fractions, and $\hat{s}, \hat{t}$ and $\hat{u}$ denote the parton level Mandelstam variables. In this paper, we use CTEQ5L [24] PDF-s and a set of FF-s [19] which were determined relying also on semi-inclusive data.

Figure 1 shows our results for $pp$ collisions. We apply fixed scales, $Q = \hat{Q} = p_T/2$, for both charged hadron and neutral pion production. The top portions of the Figure compare the calculated charged hadron and pion spectra to RHIC data [2,25] for $p_T \geq 2$ GeV, where the pQCD calculation can be used. The data are well described with $\langle k_T^2 \rangle = 1.8 \pm 0.3$ GeV$^2$. The $h^\pm/\pi^0$ ratio is displayed in the bottom panel of Fig. 1. The ratio depends very weakly on $p_T$, and its value is close to the peripheral $AuAu$ result ($\approx 1.6$) [10]. The dependence of the cross sections on the scale is not weak, limiting the predictive power of leading order pQCD. Therefore we do not expect to fit the data in detail and concentrate on the main features. One advantage of calculating ratios is that the hadron-to-pion ratio is not sensitive to the scale chosen. The width $\langle k_T^2 \rangle$ has a weak effect on the hadron to pion ratio as long as the same $\langle k_T^2 \rangle$ value is used for charged hadrons and for pions. (Later on in this paper we will introduce different values of $\langle k_T^2 \rangle$ for different particle species, but such differences should be small without medium enhancement, with small effects on the $h^\pm/\pi^0$ ratio in $pp$ collisions.)

It was observed in lower-energy proton-nucleus ($pA$) collisions that the production of hard particles ($p_T \geq 2 - 3$ GeV) is enhanced more strongly than the naively expected scaling with $A$. This so-called Cronin effect [13] has been explained as initial state scattering or $k_T$ broadening [26]. The observed Cronin effect is not universal for different particle species. In $pA$ collisions at $\sqrt{s} = 38.8$ GeV, a stronger nuclear enhancement was seen in proton production than for pions [13]. We argue that the non-universality of the Cronin effect may
be explained by the non-universality of the $k_T$ smearing. The latter can be understood in part by the large difference between pion and proton masses. While the incoming parton does not “know” whether it will produce a pion or a proton, it requires a larger $s$ to produce a proton than a pion at the same transverse momentum. This correlation connects initial-state broadening and final-state fragmentation. Furthermore, as mentioned earlier, $k_T$ effects partly account for higher-twist contributions of order $Q^2_v/p_T^2$. Assuming larger $Q^2_v$ leads to larger power corrections for protons or charged hadrons than for pions.

We make this observation the centerpiece of our description of the differences between the production of different hadrons in the present study. Our strategy is to keep the other features of the model as simple as possible. We therefore write

$$\langle k_T^2 \rangle_{h}^{AB} = \langle k_T^2 \rangle + c_h L_{AB}(b),$$

$$\langle k_T^2 \rangle_{\pi}^{AB} = \langle k_T^2 \rangle + c_\pi L_{AB}(b),$$

where $\langle k_T^2 \rangle$ is the width of the transverse-momentum distribution in $pp$ collisions (here 1.8 GeV$^2$), and we only distinguish between an average value for charged hadron production, $\langle k_T^2 \rangle_{h}$, and a value for pions $\langle k_T^2 \rangle_{\pi}$, corresponding to the data we wish to consider. In both cases, we wrote the $k_T$-broadening as proportional to the effective length of the medium along the path of the parton before the hard collisions, $L(b)$, which depends on the impact parameter, $b$. In $pA$ collisions, $L_{pA}(b)$ is the average of the effective length,

$$L_{pA}(b) = \int_{-\infty}^{z_A} dz' \rho_A(z', b)/\rho_0,$$

with $(z_A, b)$ representing the point of the hard collision and $\rho_0$ the average density of the target, over the Glauber nuclear thickness function of the nucleus. The quantity (3) integrated over $b$ is proportional to $A^{1/3}$. In $AB$ collisions, the effective length for a hard parton from nucleus $A$ passing through nucleus $B$, $L_{AB}(b)$, is the average of $L(z_B, s_B)$ over the nuclear thickness function for the collision of nuclei $A$ and $B$, at the given value of $b$, which is proportional to the probability of hard collisions at a certain vector impact parameter $b$. In this paper we use Woods-Saxon nuclear density profiles, with the parameter values for
Au taken from Ref. [28]. The effective length can also be written in terms of the number of collisions suffered by the incoming nucleon, $\nu(b)$ [23]. For our schematic average purposes we find it more appropriate to use the effective length $L(b)$.

Here we focus on the difference between the coefficients $c_h$ and $c_\pi$. If the proton contribution to charged hadrons varied with impact parameter, then the composition-dependent $c_h$ should also be expected to depend on $b$ or $p_T$. However, we will show that the data can be fitted well by $b$ and $p_T$ independent coefficients. This may be understood in terms of a $p_T$-integrated proton contribution to the charged hadron yield, which does not strongly depend on $b$ or $p_T$. Thus, we neglect any potential $b$ and $p_T$ dependence of $c_h$. We expect $c_h$ to be larger than $c_\pi$. To calculate hadron and pion cross sections separately, one needs to account for additional nuclear effects like e.g. shadowing and the suppression mentioned in the introduction. Testing various shadowing parameterizations, we found that the shadowing effects are not important to the $h^\pm/\pi^0$ ratio. Similarly, if the suppression factors are not too different, we expect an approximate cancellation in cross section ratios. We make this assumption in the following calculation.

Figure 2 shows the hadron-to-neutral-pion ratio for different centralities in AuAu collisions at $\sqrt{s} = 200$ GeV with $c_\pi = 0.13 \pm 0.04$ GeV$^2$/fm and $c_h = 0.45 \pm 0.08$ GeV$^2$/fm. The agreement appears to be satisfactory, and is similarly good for other centrality bins (not shown). As we expected $c_h > c_\pi$. In other words, the effective $\hat{s}$ (the energy involved in the partonic cross section) is larger at the same $p_T$ for the average hadrons than for pions. Larger $\hat{s}$ leads to more room for a dynamical intrinsic $k_T$, just like in the Drell-Yan case, where the larger $Q^2_v$ of the lepton pair leads to a larger $k^2_T$ [27]. Therefore we find $c_h > c_\pi$ natural, while we do not have a quantitative understanding of the fact that $c_h \approx 3.5c_\pi$. We noticed that the trend of the $h^\pm/\pi$ ratio at large $p_T$ for the 60 – 70% bin is somewhat different from the trend of other bins. We hope future data with smaller error bars will clarify this point.

As the collisions become more central, the effective length increases, and the average transverse momentum associated with charged hadrons will broaden more than that of
pions. This leads to the enhancement of the charged-hadron-to-pion ratio. More study is needed to further understand the origin of the difference between the coefficients $c_h$ and $c_\pi$.

Now, let us apply the above parameters to calculate the $R_{dAu}$ nuclear enhancement factors for charged hadron and neutral pion production. It is believed that final state effects are much less important in $dAu$ than in $AuAu$, and initial $k_T$-broadening may play a key role. We carry out the calculation with both unmodified PDF-s [24] and nuclear PDF-s which incorporate “shadowing”. Here we use the EKS parameterization [29]. The results are displayed in Fig. 3, together with the recently released PHENIX data [8]. One important feature at $2 \text{ GeV} \leq p_T < 6 \text{ GeV}$ is that the $R_{dAu}$ nuclear modification factors for charge hadrons (solid line: without shadowing; dashed: with EKS shadowing) and neutral pions (dotted: without shadowing; dot-dashed: with EKS shadowing) are different. The EKS shadowing increases $R_{dAu}$ somewhat, since we are in the anti-shadowing region. The nuclear modification factors for pions are generally much smaller than the ones for $h^\pm$, in agreement with the data [8]. This is because, as observed e.g. in Ref. [14], the proton-proton $\langle k_T^2 \rangle$ determines the position of the Cronin peak, while the coefficient $c$ in eq. (2) regulates the height of the peak. The non-universal $k_T$-broadening may further contribute to the different behavior of the nuclear modification factor for $h^\pm$ and for pions in $AuAu$ collisions. It will however be interesting to carry out a less schematic calculation to understand the different shapes of $R_{AB}$ for charged hadrons and neutral pions, respectively. In addition, data for the nuclear modification factors are becoming available species by species. A less schematic calculation should also address them to distinguish mass effects and effects of particle species [30].

In summary, we explored the consequences of different Cronin enhancement coefficients in the widths of the transverse-momentum distributions of different secondaries in this paper. We argued for this non-universality on the basis of lower-energy observations and on theoretical grounds, related to the higher-twist structure of pQCD calculations. It was found that the main features of the transverse-momentum and impact-parameter dependence of hadron/pion ratios at $\sqrt{s} = 200 \text{ GeV}$ can be obtained in a simplistic model if the non-
universality is incorporated. The different nuclear modification factors recently measured in $dAu$ collisions are also displayed by the model. Enhancement of the charged-hadron/pion ratio in $dAu$ compared to $pp$ collisions is a direct prediction of this model, which could be tested in the near future. The understanding of further intriguing features of nuclear modification factors in $AuAu$ collisions is left for future work.

We are grateful to D. D’Enterria, J. Jia, D. Keane, and J. W. Qiu for stimulating discussions. X. F. Zhang acknowledges the hospitality of the Institute for Nuclear Theory, where part of this work was carried out. This work was partially supported by the U.S. DOE under DE-FG02-86ER-40251.
REFERENCES

[1] Proceedings of the 16\textsuperscript{th} International Conference on Ultra-Relativistic Nucleus-Nucleus Collisions, Nantes, France, 18-24 July, 2002, eds. H. Gutbrod, J. Aichelin, and K. Werner, Elsevier (2003); Proceedings of the 17\textsuperscript{th} International Conference on Ultra-Relativistic Nucleus-Nucleus Collisions, Oakland, California, 11-17 January, 2004, to be published, J. Phys. G.

[2] J. Adams \textit{et al.} [STAR Collaboration], Phys. Rev. Lett. \textbf{91}, 172302 (2003) [arXiv:nucl-ex/0305015].

[3] S. S. Adler \textit{et al.} [PHENIX Collaboration], Phys. Rev. Lett. \textbf{91}, 072301 (2003) [arXiv:nucl-ex/0304022].

[4] M. Gyulassy, P. Levai and I. Vitev, Phys. Rev. Lett. \textbf{85}, 5535 (2000) [arXiv:nucl-th/0005032].

[5] X. N. Wang, arXiv:nucl-th/0305010.

[6] R. Baier, Y. L. Dokshitzer, A. H. Mueller and D. Schiff, Phys. Rev. C \textbf{58}, 1706 (1998) [arXiv:hep-ph/9803473].

[7] D. Kharzeev, E. Levin and L. McLerran, Phys. Lett. B \textbf{561}, 93 (2003) [arXiv:hep-ph/0210332].

[8] S. S. Adler \textit{et al} [PHENIX Collaboration], Phys. Rev. Lett. \textbf{91}, 072303 (2003) [arXiv:nucl-ex/0306021]; J. Adams \textit{et al}. [STAR Collaboration], Phys. Rev. Lett. \textbf{91}, 072304 (2003) [arXiv:nucl-ex/0306024]; B. B. Back \textit{et al}. [PHOBOS Collaboration], Phys. Rev. Lett. \textbf{91}, 072302 (2003) [arXiv:nucl-ex/0306025].

[9] K. Adcox \textit{et al}., Phys. Rev. Lett. \textbf{88}, 242301 (2002).

[10] S. S. Adler \textit{et al.} [PHENIX Collaboration], Phys. Rev. Lett. \textbf{91}, 172301 (2003) [arXiv:nucl-ex/0305036]; Phys. Rev. C \textbf{69}, 034910 (2004) [arXiv:nucl-ex/0308006].
[11] V. Greco, C. M. Ko and P. Levai, Phys. Rev. Lett. 90, 202302 (2003) [arXiv:nucl-th/0305024]; R. J. Fries, B. Muller, C. Nonaka and S. A. Bass, Phys. Rev. Lett. 90, 202303 (2003) [arXiv:nucl-th/0301087]; R. J. Fries, B. Muller, C. Nonaka and S. A. Bass, Phys. Rev. C 68, 044902 (2003).

[12] C. Adler et al. [STAR Collaboration], Phys. Rev. Lett. 90, 082302 (2003) [arXiv:nucl-ex/0210033].

[13] J. W. Cronin, H. J. Frisch, M. J. Shochet, J. P. Boymond, R. Mermod, P. A. Piroue and R. L. Sumner, Phys. Rev. D 11, 3105 (1975).

[14] P. Levai, G. Papp, G.G. Barnafoldi, and G. Fai, nucl-th/0306019 (2003).

[15] I. Vitev, Phys. Lett. B 562, 36 (2003) [arXiv:nucl-th/0302002].

[16] X. N. Wang, Phys. Lett. B 565, 116 (2003) [arXiv:nucl-th/0303004].

[17] X. f. Zhang, G. Fai and P. Levai, Phys. Rev. Lett. 89, 272301 (2002) [arXiv:hep-ph/0205008].

[18] B.A. Kniehl, G. Kramer, and B. Pötter, Nucl. Phys. B 597, 337 (2001).

[19] S. Kretzer, E. Leader, and E. Christova, Eur. Phys. J. C 22, 269, (2001).

[20] L. Bourhis, M. Fontannaz, J.P. Guillet, and M. Werlen, Eur.Phys.J. C 19, 89 (2001).

[21] M. Luo, J. Qiu and G. Sterman, Phys. Lett. B 279, 377 (1992).

[22] J. F. Owens, Rev. Mod. Phys. 59, 465 (1987).

[23] Y. Zhang, G. Fai, G. Papp, G. G. Barnafoldi and P. Levai, Phys. Rev. C 65, 034903 (2002) [arXiv:hep-ph/0109233].

[24] H. L. Lai et al. [CTEQ Collaboration], Eur. Phys. J. C 12, 375 (2000) [arXiv:hep-ph/9903282].

[25] S. S. Adler et al. [PHENIX Collaboration], Phys. Rev. Lett. 91, 241803 (2003)
[26] M. Lev and B. Petersson, Z. Phys. C 21, 155 (1983).

[27] J.W. Qiu and X.F. Zhang, Phys. Rev. Lett. 86, 2724 (2001); Phys. Rev. D 63, 114011 (2001).

[28] Atomic Data and Nuclear Data tables, Vol. 14, No. 5 (1974).

[29] K. J. Eskola, V. J. Kolhinen and C. A. Salgado, Eur. Phys. J. C 9, 61 (1999) [arXiv:hep-ph/9807297].

[30] J. Adams et al. [STAR Collaboration], arXiv:nucl-ex/0406003.
FIG. 1. Invariant cross section of charged hadron (top) and pion (middle) production in $pp$ collisions at $\sqrt{s} = 200$ GeV. The data points are from STAR [2] and PHENIX [25]; the solid lines represent the leading-order pQCD calculation with $\langle k_T^2 \rangle = 1.8$ GeV$^2$. Bottom: hadron/pion ratio calculated with $\langle k_T^2 \rangle = 1.8$ GeV$^2$ for both, pion and charged hadron production.
FIG. 2. Hadron-to-pion ratios at different centralities. From top to bottom: 0-10%; 20-30% ... (solid lines); data are from PHENIX(normalization errors are not included) [10].
FIG. 3. The nuclear modification factor $R_{dAu}$ for $h^\pm$ (solid line: without shadowing; dashed: with EKS shadowing) and $\pi^0$ (dotted: without shadowing; dot-dashed: with EKS shadowing. Data points are from PHENIX $dAu$ data [8].