High-$p_T$ Pion Quenching versus anti+Baryon Enhancement in Nucleus-Nucleus Collisions

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Jet quenching of quarks and gluons in central $A + A$ collisions suppresses the high-$p_T$ meson production and exposes novel baryon dynamics that we attribute to (gluonic) baryon junctions. This mechanism predicts baryon enhancement in a finite moderate-$p_T$ window that decreases with increasing impact parameter. We also extend recent calculations of the transverse momentum behavior of $p/\pi^+$ and $\bar{p}/\pi^-$ to other baryon species and show that a similar pattern is expected for the $K^-/\Lambda$ and $K^+/\bar{\Lambda}$ ratios. Within the framework of the model constant $\bar{p}/p$ and $\bar{\Lambda}/\Lambda$ ratios are found in central $Au + Au$ collisions at RHIC energies up to $p_T \simeq 4 - 5$ GeV.

1. INTRODUCTION

One of the unexpected results reported by PHENIX and STAR during the first year RHIC run at $\sqrt{s_{NN}} = 130$ GeV was that in contrast to the strong $\pi^0$ quenching for $2 \text{ GeV} < p_T < 5$ GeV, the corresponding charged hadrons were found to be suppressed by only a factor $\sim 2 - 2.5$. Even more surprisingly, the identified particle spectra analysis at PHENIX suggests that $R_B(p_T) = \bar{p}/\pi^- \hspace{0.1cm}, \hspace{0.1cm} p/\pi^+ > 1$ for $p_T > 2$ GeV. Thus, baryon and antibaryon production may in fact dominate the moderate- to high-$p_T$ hadron flavor yields [4].

These and other data point to novel baryon transport dynamics playing role in nucleus-nucleus reactions. An important indicator of this is the high valence proton rapidity density at midrapidity ($y = 0$). More recent results corroborate the non-perturbative baryon production hypothesis through equally abundant $\Lambda$ and $\bar{\Lambda}$ production [4]. It has also been observed that the mean transverse momentum $\langle p_T \rangle_B$ for various baryon and antibaryon species is approximately constant and deviates from the common hydrodynamic flow systematics of soft hadron production in $A + A$ collisions. This provides strong motivation to explore alternative physical mechanisms that may give insight into the anomalous anti+baryon behavior at RHIC.

Identified particle analyses from the recent $\sqrt{s_{NN}} = 200$ GeV RHIC run find similar puzzling features of moderate-$p_T$ baryon spectra that have to be understood in the context of even stronger quenching of neutral pions [2].

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2. BARYON PRODUCTION AND TRANSPORT MECHANISM

A topological non-perturbative baryon production and transport mechanism was originally proposed by Veneziano and Rossi in elementary nucleon-nucleon collisions \[3\]. It has recently been successfully generalized and implemented for the case of nucleus-nucleus collisions \[3\]. Its phenomenological applications are currently based on Regge theory, where a Regge trajectory \( J = \alpha(0) + \alpha'(0)M^2 \) is specified by its intercept \( \alpha(0) \) and slope \( \alpha'(0) \). It has been argued \[3\] that \( \alpha_J(0) \approx 0.5 \) and \( \alpha'_J(0) \approx 1/3 \alpha'_R(0) \). Regge theory gives exponential rapidity correlations, which in the presence of two sources (at \( \pm Y_{\text{max}} \)) lead to net baryon rapidity density in central \( A+A \) collisions of the form:

\[
\frac{dN_B^{\text{B}-\text{B}}}{dy} = (Z + N)(1 - \alpha_J(0)) \frac{\cosh(1 - \alpha_J(0))y}{\sinh(1 - \alpha_J(0))Y_{\text{max}}}.
\]

(1)

It is evident from Eq.(1) that the net baryon distribution integrates to \( 2A \) and in going to peripheral reactions scales as \( N_{\text{part}} \). At RHIC energies of \( \sqrt{s} = 130(200) \) GeV, corresponding to \( Y_{\text{max}} = 4.8(5.4) \), in central reactions \( dN_B^{\text{B}-\text{B}}/dy = d(p - \bar{p})/dy + d(n - \bar{n})/dy + d(\Lambda - \bar{\Lambda})/dy + \cdots \approx 18(13.5) \). The relative contribution of each baryon species can be evaluated from isospin symmetry and strangeness conservation (via comparison to midrapidity kaon production).

Hadronic transport in small-to-moderate \( p_T \) is effectively controlled by the slope of the Regge trajectory. This would suggest that the baryon/meson mean inverse slopes in a phenomenological \( p_T \)-exponential (\( \sim e^{-p_T/T} \)) soft particle production model are related as \( T_B : T_M \approx \sqrt{3} : \sqrt{2} \). Soft pion production, however, is largely dominated by resonance decays, where the cumulative effect from the random walk in \( p_T \) due to string braking is destroyed. This leads to the relation \( \langle p_T \rangle_{\pi} : \langle p_T \rangle_K : \langle p_T \rangle_B \approx 1 : (1 \div \sqrt{2}) : \sqrt{3} \) (220 MeV :
Figure 3. Same centrality classes as in Fig. 1 for $\bar{\Lambda}/K^+$ versus $p_T$. Au + Au reactions at $\sqrt{s_{NN}} = 130$ GeV.

Figure 4. Same as Fig. 2 for $\bar{\Lambda}/\Lambda$ in central Au + Au at $\sqrt{s_{NN}} = 130$ GeV. Minimum-bias data from PHENIX.

275 MeV : 380 MeV). One also notes that in the limit of pair production dominated by junction-antijunction loops (which we consider here) the transverse momentum distribution of antibaryons closely resembles that of baryons (with $\langle p_T \rangle_{\bar{B}} = \langle p_T \rangle_B$).

The high-$p_T$ part of the hadron spectra is computed from leading order PQCD augmented by the effects of initial multiple scattering (Cronin), nuclear shadowing, and parton energy loss. The most important modification to the perturbative scheme comes from the final state gluon bremsstrahlung computed here via the Gyulassy-Levai-Vitev (GLV) formalism. Its centrality dependence determines to a large extent (especially for pions) the centrality dependence of the baryon/meson ratios. Similar technique has been used to estimate the $A$-induced initial parton broadening.

3. RESULTS AND CONCLUSIONS

We have studied the interplay between a novel baryon production and transport mechanism (in rapidity $y$ and moderate $p_T$) and the suppression of particle spectra as a result of the medium induced non-Abelian energy loss of jets in Au + Au reactions at $\sqrt{s_{NN}} = 130$ GeV. We find an enhanced baryon/meson ratio $R_B(p_T) \gtrsim 1$ that decreases with centrality in a finite $p_T$ window as illustrated in Figs. 1 and 3. For $p_T > 5$ GeV the ratios reduce below unity and follow the perturbative calculation. We have extended recent studies of the $p_T$-differential $p/\pi^+, \bar{p}/\pi^-$ ratios (Fig. 1) to $K^-/\Lambda, K^+$/\bar{\Lambda} (Fig. 3). Similar enhancement pattern if found at moderate $2 \text{ GeV} \leq p_T \leq 5$ GeV. Its centrality dependence is predicted to be weak. Figs. 2 and 4 show that in central reactions the predicted $\bar{p}/p$ and $\bar{\Lambda}/\Lambda$ ratios are $p_T$-independent up to $p_T \approx 4 - 5$ GeV. At larger transverse momenta they decrease and approach perturbative estimates. We propose that the non-perturbative baryon dynamics may extend to $p_T \approx 5$ GeV.

The enhanced baryon and antibaryon production at moderate transverse momenta accounts for the difference in the suppression factor $R_{AA}(p_T)$ of inclusive charged hadrons and neutral pions (see Fig. 5). We have demonstrated that when the non-perturbative baryon
Figure 5. Suppression of neutral pions and inclusive charged hadrons relative to the binary collision scaled $p + p$ result. Central $Au + Au$ at $\sqrt{s_{NN}} = 130$ GeV.

Figure 6. Same as Fig. 5 extended to large transverse momenta. Note $R_{AA}(p_T \gtrsim 5 - 6$ GeV) $\approx$ const.

contribution becomes small $R_{AA}(p_T)$ is approximately equal for all hadron species. This is illustrated in Fig. 6 for $p_T \gtrsim 5$ GeV. For the first RHIC run at $\sqrt{s_{NN}} = 130$ GeV up to $p_T \sim 10$ GeV the suppression factor is found to have a value $R_{AA}(p_T) \approx 0.3$ and is almost independent of the transverse momentum [4].

We have performed PQCD calculations at the highest RHIC energy of $\sqrt{s_{NN}} = 200$ GeV that also predict a constant suppression factor $R_{AA}(p_T)$. The detailed $R_{AA}(p_T)$ behavior is shown to be a consequence of the combination of Cronin effect, shadowing, energy loss, and the computable shape of the underlying jet distributions.

REFERENCES

1. J. Velkovska, Nucl. Phys. A 698, 507 (2002); K. Adcox et al., Phys. Rev. Lett. 88, 242301 (2002); nucl-ex/0204007; N. Xu and M. Kaneta, Nucl. Phys. A 698, 306 (2002); C. Adler et al., Phys. Rev. Lett. 87, 262302 (2001); nucl-ex/0203016.
2. S. Mioduszewski, these proceedings; G. Kunde, these proceedings; D. d’Enterria, these proceedings; J. Jiangyong, these proceedings.
3. G.C. Rossi and G. Veneziano, Nucl. Phys. B 123, 507 (1977); Phys. Rept. 63, 153 (1980); D. Kharzeev, Phys. Lett. B 378, 238 (1996); S.E. Vance, M. Gyulassy, X.-N. Wang, Phys. Lett. B 443, 45 (1998); S.E. Vance and M. Gyulassy, Phys. Rev. Lett. 83, 1735 (1999).
4. I. Vitev and M. Gyulassy, Phys. Rev. C 65, 041902 (2002); hep-ph/0108043; I. Vitev, M. Gyulassy and P. Levai, hep-ph/0109198.
5. M. Gyulassy, P. Levai, and I. Vitev, Nucl. Phys. B 571, 197 (2000); Phys. Rev. Lett. 85, 5535 (2000); Nucl. Phys. B 594, 371 (2001); Phys. Lett. B 538, 282 (2002); Phys. Rev. D 66 014005 (2002).
6. X.-N. Wang, Phys. Rev. C 58, 2321 (1998); X.-F. Zhang, G. Fai, and P. Levai, hep-ph/0205008.