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The role of jet quenching in the $\bar{p} \geq \pi^-$ anomaly at RHIC

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Abstract: Preliminary PHENIX data on $Au + Au$ reactions at $\sqrt{s} = 130$ AGeV suggest that $\bar{p}$ yields may exceed π^- at high $p_{\mathrm{T}} > 2$ GeV/c. We propose that jet quenching in central collisions suppresses the hard PQCD component of the spectra in central $A + A$ reactions, thereby exposing a novel non-perturbative component of baryon dynamics. We suggest that baryon junctions provide a possible explanation of the anomalous component. We predict that the $\bar{p} \geq \pi^-$ anomaly is limited to a finite p_{T} window and decreases with increasing impact parameter.

1. Introduction

Preliminary RHIC data on $\sqrt{s} = 130$ AGeV $Au + Au$ reactions have revealed a number of qualitatively new phenomena at moderate high $p_T \sim 2 - 6$ GeV/c.

1. The high p_{T} spectra of π^0 in the 10% central collisions were found by PHENIX to be suppressed by a factor 3-4 relative to PQCD predictions scaled by nuclear geometry ($T_{AB}(\mathbf{b})$, the number of binary collisions at impact parameter $\mathbf{b}$). In contrast, the inclusive charged particle spectrum was reported to be suppressed only by a factor of 2 [1].

2. Non-central collisions STAR measured elliptic flow consistent with hydro predictions in the soft p_{T} region. However, this asymmetry saturates at $v_2 \sim 0.15$ above $p_T > 2$ GeV/c [2, 3].

3. Even more surprisingly PHENIX reported [4] that the high $p_{\mathrm{T}} > 2$ GeV flavor composition of positive and negative hadron yield may actually be dominated by antiprotons and protons respectively!

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In addition to the results listed above, there are already global indications from preliminary STAR data [5] of novel baryon production dynamics in $A+A$. In central collisions the midrapdity $\bar{p}/p \sim 0.65$ and $dN^B/dy \simeq dN^p/dy - dN^{\bar{p}}/dy \sim 15$. Thus a very significant baryon number transport (stopping) five units of rapidity from the fragmentation regions and copious $B\bar{B}$ production seems to have been observed. This is consistent with expectations based on a non-perturbative baryon-junction mechanism for baryon number transport [6]. In this paper we propose that the baryon/meson anomaly together with the different degree of suppression of π^0 and inclusive charged hadrons in central collisions may be an unexpected new consequence of jet quenching which unveils a novel non-perturbative component of baryon production dynamics [7].

Our approach is to extend the two component hybrid model introduced in Ref. [3] considering an anomalously large contribution to $\bar{p}$ production at moderate $p_{\rm T}$ motivated by baryon junction dynamics [7]. The baryon junction picture implies a simple relation between the mean inverse slopes of pions and protons, $T_p \simeq \sqrt{3} T_\pi$ (in the hassles limit), for the soft to moderate $p_{\rm T}$ non-perturbative part of the spectrum. We compute jet quenching using the non-abelian energy loss from the Gyulassy-Levai-Vitev (GLV) formalism [8]. Our analysis suggests that the enhancement of $\bar{p}/\pi^-$ ratio is limited to a finite $p_{\rm T}$ range 2-5 GeV and to central and semi-central collisions. Beyond this range, the hadron ratios are predicted to converge to the jet quenched PQCD base.

2. Reference flavor composition in PQCD

The standard PQCD approach expresses the differential hadron cross section in $p+p \to h+X$ as a convolution of the measured structure functions $f(x_\alpha, Q^2_\alpha)_{\alpha/p}$ for the interacting partons ($\alpha = a, b$), with the parameterized fragmentation function $D_{h/c}(z, Q_c^2)$ for the leading rescattered parton c into a hadron of flavor h and the elementary parton-parton cross sections $d\sigma^{(ab\to cd)}/d\hat{t}$. The initial parton broadening can be accounted for by a normalized $k_{\rm T}$-smearing distribution. A simple functional form is the Gaussian smearing $f(k_{\rm T}) = e^{-k_{\rm T}^2/\langle k_{\rm T}^2\rangle}/\pi\langle k_{\rm T}^2\rangle$ where $\langle k_{\rm T}^2\rangle \simeq 0.6 - 1.0$ GeV^2 in pp collisions. The invariant hadron inclusive cross section is then given by

$$E_h \frac{d\sigma_h^{pp}}{d^3p} = K \sum_{abcd} \int dz_c dx_a dx_b \int d^2\mathbf{k}_{{\rm T}a} d^2\mathbf{k}_{{\rm T}b}\, f(\mathbf{k}_{{\rm T}a}) f(\mathbf{k}_{{\rm T}b}) f_{a/p}(x_a, Q_a^2) f_{b/p}(x_b, Q_b^2)$$

$$D_{h/c}(z_c, Q_c^2) \frac{\hat{s}}{\pi z_c^2} \frac{d\sigma^{(ab\to cd)}}{d\hat{t}} \delta(\hat{s}+\hat{u}+\hat{t}) \;, \qquad (2.1)$$

where x_a, x_b are the initial momentum fractions carried by the interacting partons, $z_c = p_h/p_c$ is the momentum fraction carried by the observed hadron.

Fig. 1a shows comparison between the PQCD calculation and the negative hadron multiplicities as measured by the UA1 experiment at $\sqrt{s} = 200$ GeV. For our first fit we used the Glück-Reya-Vogt structure functions (GRV 94) and Binnewies *et al.* (B) fragmentation functions. For our second fit we used the CETQ 5M structure functions and the Kniehl *et al.* (KKP) fragmentation functions [10]. Eq.(2.1) reproduces well the shape and norm of the data for $p_{\rm T} > 1$ GeV.

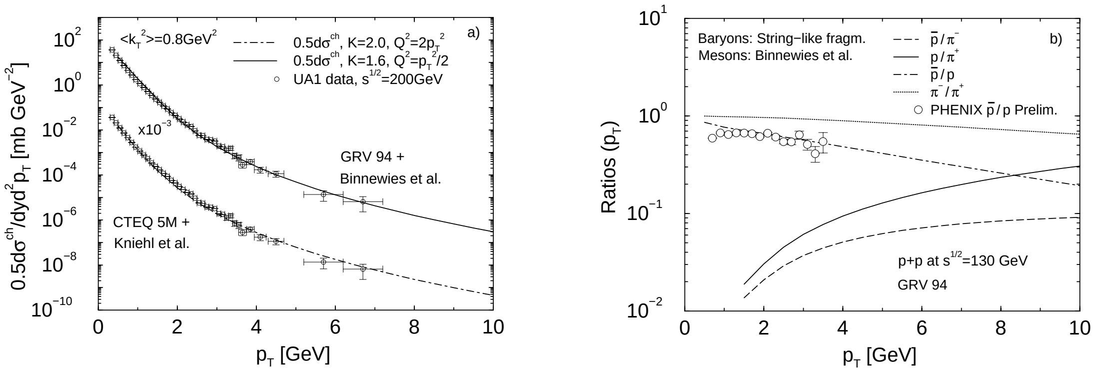

Figure 1: a) Negative hadron cross sections are shown as a function of $p_{\rm T}$. Experimental UA1 data at $\sqrt{s} = 200$ GeV is compared to PQCD calculations with GRV94 pdf + B fragmentation functions ($Q^2 = p_{\rm T}^2/2$) and CTEQ 5M pdf + KKP fragmentation function ($Q^2 = 2p_{\rm T}^2$) where $\langle k_{\rm T}^2 \rangle = 0.8$ GeV^2 in both cases. **b)** The PQCD predictions for the p/π^+, $\bar{p}/\pi^-$, π^-/π^+ and $\bar{p}/p$ ratios as a function of $p_{\rm T}$ are shown for $\sqrt{s} = 130$ GeV.

Fig. 1b, however, shows that although PQCD fragmentation can fit the π^-/π^+ and even get quantitatively correct $\bar{p}/p$ ratios for $p_{\rm T} > 3-4$ GeV the p/π^+ and $\bar{p}/\pi^-$ differ from the values suggested by data (~ 1) by an order of magnitude. Even large uncertainties in the gluon fragmentation functions (~ 3) [7] cannot account for such a discrepancy. The observed large (anti)proton enhancement in $Au+Au$ collisions in the region of $p_{\rm T} = 2-4$ GeV [4] signals of interesting interplay between competing possibly novel physical effects. We propose that the mechanism which accounts for the copious production of baryons and anti-baryons might be related to baryon junctions. Other possibilities include relativistic hydrodynamics and boosted thermal sources.

3. Medium effects and baryon junctions

We first discuss the medium effects on the high $p_{\rm T}$ particle spectra. The medium induced gluon radiation spectrum is calculated as in [8] and modifies the fragmentation function $D_{h/c}(z_c)$ in Eq.(2.1) as follows

$$D'_{h/c}(z_c) = \int_{x_{\min}}^{1} dx \; P(x) \left[\frac{1}{1-x} D_{h/c}\left(\frac{z}{1-x}\right) + \frac{1}{x} D_{h/g}\left(\frac{z}{x}\right) \right] \quad , \tag{3.1}$$

where $x = \omega/E_{\rm jet}$, $P(x)$ is the gluon radiative probability, and the second term in Eq.(3.1) accounts for the gluon feedback in the system. Transverse expansion was shown not to affect the *azimuthally averaged* quenching pattern [9]

The string and baryon junction description of the soft non-perturbative part of the spectrum is parametized in terms of the mean inverse slopes of hadrons T_0^α as in [3]. The baryon junction picture, however, suggest different T_0^π and T_0^p. Large T_0^p may arise from the small ($\delta r_\perp \sim 1/2T_0^{\bar{p}} \sim 1/4$ fm) intrinsic (non-perturbative) spatial structure of Junction-anti-Junction loops and the smaller junction trajectory slope $\alpha'_J \approx \alpha'_R/3$ [6]. The latter implies that the effective string tension is three times higher than $1/(2\pi\alpha'_R) \approx 1$ GeV/fm leading in the massless limit to

$$\langle p_{\rm T}^2 \rangle_J \approx 3 \langle p_{\rm T}^2 \rangle_R \, , \qquad T_0^p \simeq \sqrt{3} T_0^\pi \quad . \tag{3.2}$$

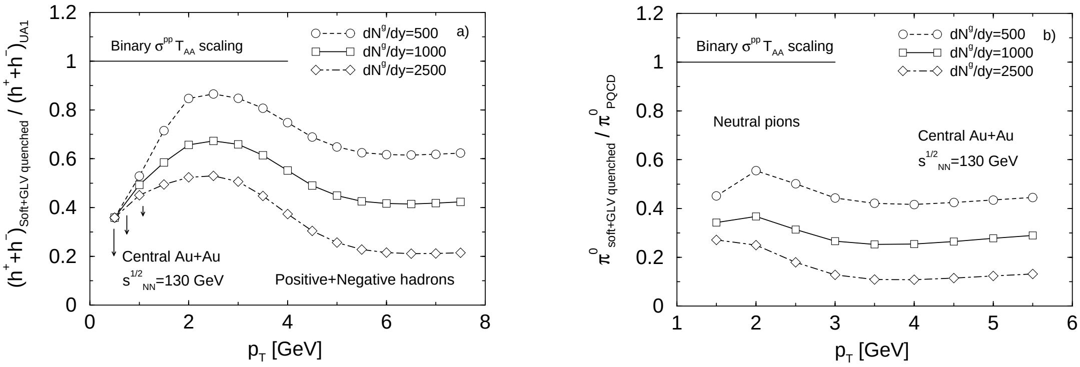

Figure 2: a) Inclusive charged hadrons and **b)** neutral pions are plotted versus p_{T} normalized by the corresponding scaled PQCD multiplicities. Curves reflecting the effect of non-abelian energy loss driven by $dN^g/dy = 500,\ 1000,\ 2500$ are shown.

Eq.(3.2) helps reduce the parameters that enter the phenomenological soft component to 2: $T_0^\pi \sim 210-220$ MeV and $dN^-_{ch}/dy \sim 600$ in central collisions at midrapidity. Assuming that similar string and baryon junction dynamics drives pp and AA collisions, we solve for the remaining parameters from the the existing data [11] ($\bar{p}/\pi^- \simeq 7-8\%,\ K^-/\pi^- \simeq 12-15\%$) or from charge and strangeness conservation ($\pi+/\pi^- \simeq 1,\ K^+/K^- \simeq 1-1.1$) and baryon transport [6] ($dN^B/dy \simeq \beta Z \cosh(1-\alpha_B(0)y)/\sinh(1-\alpha_B(0)Y_{\max}) \simeq 10-15$, given $Y_{\max} = 5.4,\ \beta \sim 1$).

4. Result and conclusions

In Figs. 2a and 2b we compute the quenching for inclusive charged hadrons and neutral pions. The ~ 2 difference in the suppression factors in the $p_{\mathrm{T}} = 1-4$ GeV window is largely due to the non-perturbative baryon component of dN_{ch}. The comparison of the quenching factors to data [1] suggest initial gluon rapidity density $dN^g/dy \sim 500-1000$. Fig. 3 presents the central result of this paper. The anomalous baryon/meson ratio exceeds unity in the $p_{\mathrm{T}} = 2-5$ GeV window in central collisions. It is here interpreted as a combined effect of non-perturbative baryon junction dynamics and jet quenching that suppresses the PQCD component of pions. Fig. 3 suggests that this result may be more readily observable in p/π^+ than in $\bar{p}/\pi^-$. The uncertainties in the mean inverse slope of pions and protons as well as the degree of quenching may affect $R_{B\,\max}$ by as much as $30-50\%$ (also seen in Fig. 3), without however qualitatively changing our predictions. Boosted thermal sources calculation with $v_T = \tanh\eta_r \sim 0.6$ and $T_f \simeq 160$ MeV

$$\frac{dN_s}{dyd^2\mathbf{p}_{\mathrm{T}}} \sim m_{\mathrm{T}}\, K_1\left(\frac{m_{\mathrm{T}}\cosh\eta_r}{T_f}\right) I_0\left(\frac{p_{\mathrm{T}}\sinh\eta_r}{T_f}\right) \tag{4.1}$$

may produce similar low p_{T} behavior but R_B is a monotone function p_{T} and saturates at $R_B = 2$ from spin counting. We predict that at high $p_{\mathrm{T}} > 5-6$ GeV R_B decreases again below unity to its PQCD dominated base. We also predict that in going from central to peripheral collisions the baryon/meson anomaly disappears since there is no jet quenching to suppress the perturbative pions and the R_B ratio resembles the pp measurement. Preliminary PHENIX data seems to support the suggested centrality dependence.

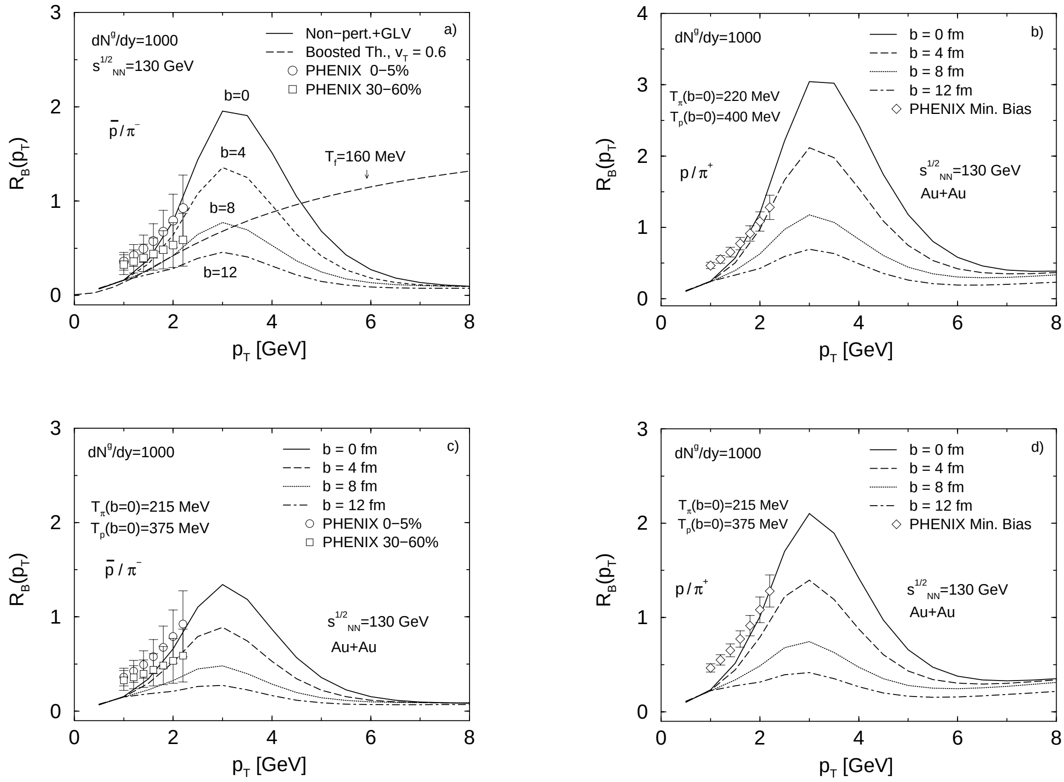

Figure 3: The $\bar{p}/\pi^-$ and p/π^+ ratios are plotted versus $p_{\rm T}$ for 4 different impact parameters $\mathbf{b} = 0,\ 4,\ 8,\ 12$ fm. The top and bottom row of figures illustrate plausible uncertainties in the mean inverse slope of π and p. The ratio of *our fits* to preliminary PHENIX data as well as boosted thermal source calculation are shown for comparison.

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