Strong color field baryonic remnants in nucleus-nucleus collisions at 200*A* GeV

V. Topor Pop,[1] M. Gyulassy,[2] J. Barrette,[1] and C. Gale[1]
[1]*McGill University, Montreal, PQ, H3A 2T8 Canada*
[2]*Physics Department, Columbia University, New York, NY 10027, USA*
(Received 2 June 2005; published 16 November 2005)

The effects of strong-color electric fields on the baryon production at RHIC are studied in the framework of the HIJING/B$\bar{\text{B}}$ (v2.0) model. The particle species dependence of nuclear modification factors are analyzed for Au+Au collisions at 200*A* GeV. A doubling of the string tension leading to a modification of the strangeness suppression according to the Schwinger mechanism is shown to provide an alternative explanation to coalescence models for the interpretation of the observed baryon and meson production at moderate p_T and results in a predicted enhancement in the (multi)strange (anti)hyperon production.

DOI: 10.1103/PhysRevC.72.054901 PACS number(s): 25.75.Dw, 24.10.Lx

I. INTRODUCTION

Although the phase transition from a hadronic degree of freedom to a partonic degrees of freedom (quarks and gluons) in ultrarelativistic nuclear collisions is a central focus of recent experiments at the Relativistic Heavy Ion Collider (RHIC), data on baryon and hyperon production have revealed interesting and unexpected features at RHIC that may be of novel dynamical origin instead. The so-called *baryon/meson anomaly* [1–4] is observed as a large enhancement of the baryon-to-meson ratio and a large difference of the nuclear modification factor (NMF) between total charged [5] and neutral pions (π^0) [6] at moderate transverse momenta ($2 < p_T < 5$ GeV/c).

In a previous paper [7] we studied the possible role of topological baryon junctions [8] in nucleus-nucleus collisions. We have shown in the framework of the HIJING/B$\bar{\text{B}}$ v2.0 model that junction-antijunction ($J\bar{J}$) loops with an enhanced *intrinsic transverse momentum*$k_T \approx 1$ GeV/c, a default string tension $\kappa_0 = 1$ GeV/fm, and a diquark suppression factor [PARJ(1) $= \gamma_{qq} = 0.07$] provide a partial explanation of the baryon/meson anomaly [7]. That model therefore provides an alternative dynamical explanation of the data to recombination models [9]. Within HIJING/B$\bar{\text{B}}$ v2.0 [7] one of the main assumptions is this: The strings could survive and fragment [10,11], and in particular populate the mid- to low-p_T range. In contrast, in the recombination picture [9] or in a hydrodynamical approach [12], all coherent strings are assumed to become rapidly incoherent, resulting in rapid thermalization.

In this paper we explore further dynamical effects associated with long-range coherent fields [i.e, strong-color fields (SCF)] including baryon junctions [8] and loops [13] that may arise in nuclear reactions. Our emphasis here is on the novel baryon observables measured at RHIC. In nucleus-nucleus collisions the color charge excitations may be considerably greater than in nucleon-nucleon collisions due to the almost simultaneous interaction of several participating nucleons in a row [10,14]. Molecular dynamics models [15–17] have been used to study the effects of color ropes as an effective description of the nonperturbative, soft gluonic part of QCD [18–20]. Strangeness enhancement [21–29], strong baryon transport [30], and increase of intrinsic k_T [19] are all expected consequences of the SCF. This can be modeled in microscopic models as an increase of the effective string tension that controls the $q\bar{q}$ and $qq\overline{qq}$ pair creation rates and strangeness suppression factors [14].

For a uniform chromoelectric flux tube with field E the probability of creating a pair of quarks with mass m, effective charge e, and transverse momentum p_T per unit time per unit volume is given by [31]

$$P(p_T)\, d^2p_T = -\frac{|eE|}{4\pi^3} \ln\left\{1 - \exp\left[-\frac{\pi\left(m^2 + p_T^2\right)}{|eE|}\right]\right\} d^2p_T. \tag{1}$$

The integrated probability (P_m) reproduces the classical Schwinger results [32], derived in spinor quantum electrodynamics for e^+e^- production rate, when the leading term in Eq. (2) is taken into account, i.e.,

$$P_m = \frac{(eE)^2}{4\pi^3} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left(-\frac{\pi\, m^2 n}{|eE|}\right). \tag{2}$$

In general in microscopic string models the heavier flavors (and diquark) are suppressed according to Schwinger formula [32]:

$$\gamma_Q = \frac{P(Q\bar{Q})}{P(q\bar{q})} = \exp\left[-\frac{\pi\left(m_Q^2 - m_q^2\right)}{\kappa}\right], \tag{3}$$

where $\kappa = |eE|$ is the *string tension*, m_Q is the effective quark mass ($Q = s$ for a strange quark; $Q = qq$ for a diquark), and $q = u, d$ are the light nonstrange quarks.

In the case of quark-gluon plasma (QGP) creation it is necessary to modify the dynamics of particle vacuum production at short time scales, and the abundance of a newly produced particle may deviate considerably from the values obtained for the constant field [33]. Two possible processes that may lead to an increase of strangeness production within the framework of the Schwinger mechanism are (i) increasing the field strength by a modified string tension (κ) [14,19,25,26,34], or (ii) dropping the quark masses that are due to chiral symmetry restoration [34–37]. A specific chiral symmetry restoration could be induced by a rapid deceleration of the colliding nuclei [38].

Present estimates [39] of the *current quark masses* are in the following ranges: m_u =1.5–5 MeV, $m_d = 3$–9 MeV, and $m_s = 80$–190 MeV. For a diquark we consider $m_{qq} = 450$ MeV [40]. Taking for constituent quark masses of light nonstrange quark $M_{u,d} = 230$ MeV, strange quark $M_s = 350$ MeV [41], and diquark mass $M_{qq} = 550 \pm 50$ MeV as in Ref. [40], it is obvious that the masses of (di)quark and strange quark will be substantially reduced at the chiral phase transition. If the QGP is a chirally restored phase of strongly interacting matter, in this picture the production of strange hadrons will be enhanced [37]. In this case a possible decrease of the strange quark mass would lead to a similar enhancement of the suppression factors, obtained (in microscopic models) by an increase of string tension [18,19,33,34,36]. Moreover, if we consider that Schwinger tunneling could explain the thermal character of hadron spectra and that, because of the SCF effects, the string tension value κ fluctuates, we can define an apparent temperature $T = \sqrt{\langle\kappa\rangle/2\pi}$ [42].

II. OUTLINE OF THE HIJING/B$\bar{\text{B}}$ V2.0 MODEL

Our analyses are performed in the framework of the HIJING/B$\bar{\text{B}}$ v2.0 model [7] that is based on HIJING/B$\bar{\text{B}}$ v1.10 [43]. Multiple hard and soft interactions proceed as in HIJING v1.37 [44]. In HIJING/B$\bar{\text{B}}$ v2.0 we introduced [7] a possible topology with two junctions [45] and a new algorithm in which $J\bar{J}$ loops are modeled by an enhancing diquark p_T kick characterized by a Gaussian width of $\sigma'_{qq} = f\sigma_{qq} = 1.08$ GeV/c, with $\sigma_{qq} = 0.360$ GeV/c (consistent with PYTHIA [46] default value), i.e., $f = 3$, which we fit to best reproduce the observed p_T spectrum of the baryons.

Following the equations above, we take into account the SCF in our model by an *in-medium effective string tension* $\kappa > \kappa_0$, which leads to new values for the suppression factors, as well as the new effective intrinsic transverse momentum k_T [18–20]. This includes (i) the ratio of production rates of diquark-to-quark pairs (diquark suppression factor), $\gamma_{qq} = P(qq\overline{qq})/P(q\bar{q})$, (ii) the ratio of production rates of strange-to-nonstrange quark pairs (strangeness suppression factor), $\gamma_s = P(s\bar{s})/P(q\bar{q})$, (iii) the extra suppression associated with a diquark containing a strange quark compared with the normal suppression of a strange quark (γ_s), $\gamma_{us} = [P(u\bar{u}s\bar{s})/P(u\bar{u}d\bar{d})]/(\gamma_s)$, (iv) the suppression of spin 1 diquarks relative to spin 0 ones (apart from the factor of 3 enhancement of the former based on counting the number of spin states), γ_{10}, and (v) the (anti)quark ($\sigma''_q = \sqrt{\kappa/\kappa_0}\sigma_q$) and (anti)diquark ($\sigma''_{qq} = \sqrt{\kappa/\kappa_0}f\sigma_{qq}$) Gaussian width. These parameters correspond to $\gamma_{qq} =$ PARJ(1), $\gamma_s =$ PARJ(2), $\gamma_{us} =$ PARJ(3), $\gamma_{10} =$ PARJ(4), and $\sigma_{qq} =$ PARJ(21) of the JETSET 7.3 subroutines [46]. Our calculations are based on the assumption that the effective enhanced string tension (κ) in both basic ropes ($q^n - \bar{q}^n$) and junction ropes ($q^n - q^n - q^n$) are the same. For elementary n strings and junctions this ansatz is supported by baryon studies [47]. A different approach to baryon production without baryon junctions has been proposed in [25] in which the SCF from the string fusion process can lead to $(qq)_6 - (\bar{q}\bar{q})_{\bar{6}}$ with about double the string tension. Both types of SCF configurations may arise but predict different rapidity dependences of the valence baryons. We consider in v2.0 of HIJING/B$\bar{\text{B}}$ only baryon junction rope loops.

There is a debate on the study of a qqq system on the shape of Δ-like geometry and Y-like geometry [45,48], and on the stability of these configurations for the color electric fields [49]. In both topologies we expect a higher string tension than in an ordinary $q\bar{q}$ string [$\kappa_Y = \sqrt{3}\,\kappa_0$ and $\kappa_\Delta = (3/2)\,\kappa_0$]. It was shown [49] that the total string tension has neither the Y- nor the Δ-like value, but lies rather in between the two pictures. However, the Y configuration appears to be a better representation of the baryons. If two of these quarks stay close together, they behave as a diquark [48]. In dual-superconductor models of color confinement for the Y geometry, the flux tubes converge first toward the center of the triangle, and there is also another component that runs in the opposite direction. They attract each other, and this lowers the energy of the Y configuration [45].

Phenomenological applications are currently based on a Regge trajectory, which gives the appropriate relationship between the mass M of the hadrons and its spin J_s: $J_s = \alpha + \alpha_s\, M^2$, where $\alpha \simeq 0.5$ is the Regge intercept and α_s is the Regge slope. The value of the Regge slope for baryons is $\alpha_s \simeq 1$ GeV^{-2} [43] that yields a string tension (related to the Regge slope, $\kappa_0 = 1/2\pi\alpha_s$ [50]) $\kappa_0 \approx 1$ GeV/fm. This value is taken in our calculations within HIJING/B$\bar{\text{B}}$ v2.0 toghether with the following values for the suppression factors correponding to the constituent quark masses given above: $\gamma_{qq} = 0.02$, $\gamma_s = 0.30$, $\gamma_{us} = 0.40$, $\gamma_{10} = 0.05$. A broadening in k_T is chosen as $\sigma_q = 0.360$ GeV/c and $\sigma'_{qq} = 1.08$ GeV/c (i.e $f = 3$). HIJING/B$\bar{\text{B}}$ v2.0 predictions made with this set of parameters are labeled here by w/o SCF, i.e. without a strong color field, or by κ_0 =1 GeV/fm.

The multigluon exchange processes dominated by Pomeron exchange in high-energy nucleus-nucleus collisions could be described by a Regge trajectory with a smaller slope $\alpha'_s \approx 0.45$ GeV^{-2} [51], leading to an increase in string tension to $\kappa \approx 2\,\kappa_0$ [19], corresponding to increasing values for the suppression factors, $\gamma'_{qq} = 0.12$, $\gamma'_s = 0.55$, $\gamma'_{us} = 0.63$, and $\gamma'_{10} = 0.12$ as well as in a broadening in k_T, $\sigma''_q = 0.500$ GeV/c and $\sigma''_{qq} = 1.5$ GeV/c. The results obtained with this set of parameters are labeled here w/SCF, i.e., with a strong color field or by κ=2 GeV/fm. We note that the increase of "intrinsic k_T" (the Gaussian width σ''_{qq}) is strongly supported by recent experimental values reported by PHENIX [52], which show an increase from $p + p$ (k'_{Ty}=1.08 $\pm$ 0.05 GeV/c) to d+Au collisions (k''_{Ty}=1.36 $\pm$ 0.07 $\pm$ 0.12 GeV/c) at $\sqrt{s_{NN}} =$ 200 GeV.

III. NUCLEAR MODIFICATION FACTORS

Here we concentrate our analysis on the species dependence of the NMFs R_{AA} and R_{cp} in Au+Au collisions at $\sqrt{s_{NN}} =$ 200 GeV. R_{AA} is the ratio of the heavy-ion yield to the pp cross section normalized by the number of binary collisions, and R_{cp} is the ratio of scaled central-to-peripheral particle

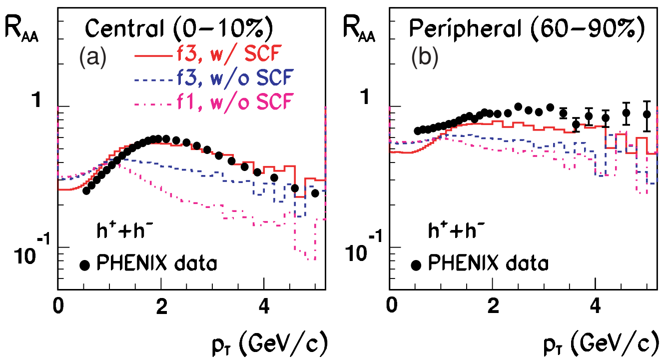

FIG. 1. (Color online) Comparison of HIJING/B$\bar{\text{B}}$ v2.0 predictions for R_{AA} of total inclusive charged hadrons, in (a) central (0%–10%) and (b) peripheral (60%–90%) Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The results are with (solid histograms) and without a SCF (dashed histograms). The label f3 stands for model calculations assuming $f = 3$. Dash-dotted histograms are the results without SCF and $f = 1$ (label f1). The data are from PHENIX [53]. Only statistical error bars are shown.

yield and are defined as in Ref. [7]. For the $p + p$ interactions we used in our calculations, the set of optimized parameters which is taken from PYTHIA [46] or HIJING [44].

Figure 1 shows the predicted NMF R_{AA} for the sum of hadrons for two centralities. The results are compared with the data obtained by the PHENIX Collaboration [53]. The data at both centralities could not be described with the assumption of a broadening of only the *intrinsic* k_T from its standard value (dotted histograms) to $\sigma'_{qq} = 1.08$ GeV/c (i.e., $f = 3$, dashed histograms). The introduction of the SCF has an effect on the predicted NMF, of the total inclusive hadrons and results in a better agreement with data (solid histograms). The data indicate at most a small variation with centrality of the factor f, consistent with the broadening originating at the parton level.

To better quantify possible effects of the SCF on particle production, we investigate species dependence of NMFs $R_{AA}(p_T)$ for central collisons [Figs. 2(a)–2(d)], where higher sensitivity to a SCF is expected. Because of their dominance, the production of pions is only moderately modified when we consider an increase in the string tension value, since the total energy is conserved. Taking into account SCF effects (solid histograms) results in changes at moderate p_T of less than $\approx$20% for the pion yield [Fig. 2(a)]. The scaling behavior in $R_{AA}(p_T)$ of the pions is different from those of the sum of protons and antiprotons [Fig. 2(c)]. The pions, yield in central events is strongly suppressed compared with that of binary collision scaling [$R_{AA}(p_T) = 1$]. The hadron production in HIJING/B$\bar{\text{B}}$ v2.0 is mainly from the fragmentation of energetic partons. Thus the observed suppression of pions in central collisions may be a signature of the energy loss of partons during their propagation through the hot and dense matter (possibly QGP) created in the collisions, i.e., *jet quenching*. On the contrary, strange particles are highly sensitive to the presence of a SCF. Kaons [Fig. 2(b)] and Λ [Fig. 2(d)], show an increase by a factor of 2 and 10, respectively. Such an increase results in a predicted enhancement of the Λ yield relative to

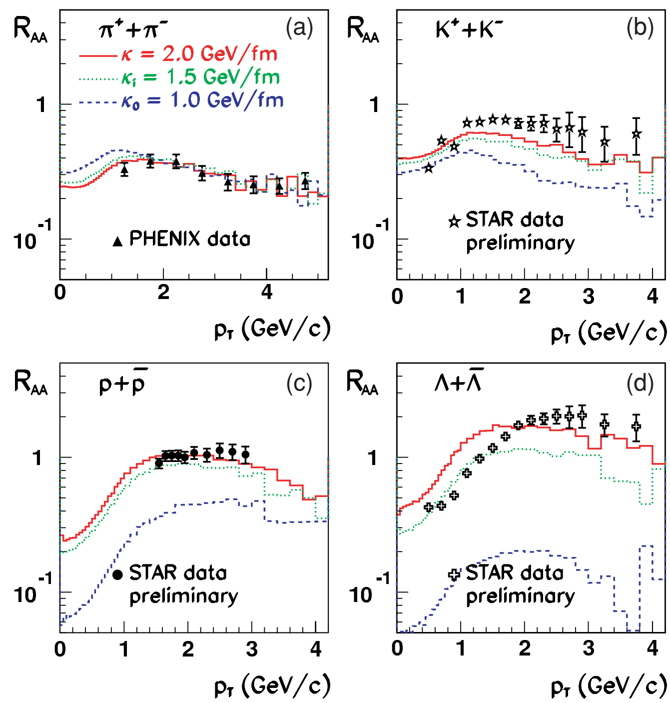

FIG. 2. (Color online) HIJING/B$\bar{\text{B}}$ v2.0 predictions for species dependence of NMF (R_{AA}) in central (0%–10%) Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV for (a) charged pions, (b) kaons, (c) inclusive $p + \bar{p}$, (d) inclusive $\Lambda + \bar{\Lambda}$. The results are with (solid histograms) and without SCF (dashed histograms). The dotted histograms are the predictions assuming $\kappa_i = 1.5$ GeV/fm. The data are from PHENIX [54] and STAR [55,56] collaborations. Only statistical error bars are shown.

scaled binary collisions as opposed to the strong suppression predicted (and observed) for pions. These results are consistent with the PHENIX data [54] and preliminary STAR data [55,56]. To study the sensitivity to string tension values we also present the results corresponding to an intermediate value of the string tension i.e., $\kappa_i = 1.5$ GeV/fm (dotted histograms). The discrepancy seen at low $p_T < 1.2$ GeV/c (solid histograms) comes from a sizable contribution from radial flow, not included in our model. The low-p_T region at the RHIC seems to be better described within a hydrodynamical approach [12].

The predicted particle dependence is due to the interplay between nuclear effects such as jet quenching and shadowing and fluctuations of the chromoelectric field in the early phase of the reaction. Insight into the source of the particle dependence is obtained from Figs. 3 and 4. The comparison of the NMFs $R_{cp}(p_T)$ for protons and pions [Fig. 3(a)] as well as for kaons [Fig. 3(c)] presents a behavior similar to $R_{AA}(p_T)$, i.e., shows a meson/baryon anomaly that is well described and was interpreted in Ref. [7] as due to a possible exotic gluonic mechanism ($J\bar{J}$ loops). In Ref. [9] it is suggested that the behavior of $R_{cp}(p_T)$ may be interpreted as due to the competition between recombination and parton fragmentation. The results obtained for $R_{cp}(p_T)$ for the strange [Fig. 3(b)] and multistrange particles [Fig. 3(d)] show a small suppression relative to binary scaling, consistent with

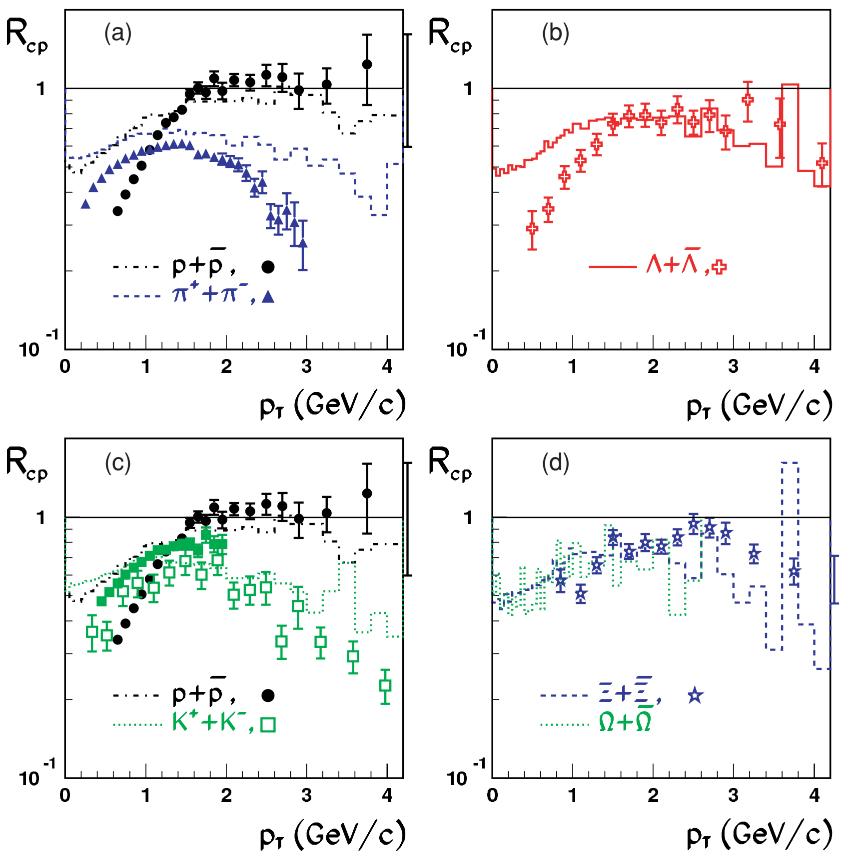

FIG. 3. (Color online) HIJING/B$\bar{\text{B}}$ v2.0 w/SCF ($\kappa = 2$ GeV/fm) predictions for species dependence of NMFs $R_{cp}(p_T)$ in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The results are for scaled (0%–10%)/(60%–90%). The data are from PHENIX (filled symbols) and from STAR (open symbols). PHENIX data are scaled (0%–10%)/(60%–90%) [2]. STAR data are at slightly different centralities: scaled (0%–5%)/(60%–80%) for kaons and $\Lambda's$ [57], and scaled (0%–5%)/(40%–60%) for Ξ (preliminary data) [55]. Only statistical error bars are shown.

the experimental results for Λ [2,57], and preliminary data for Ξ [55].

In contrast, the equivalent predictions of $R_{AA}(p_T)$ for protons and (multi)strange particles (Fig. 4) show a predicted strong enhancement of the NMF that is due to SCF effects that are dependent on the mass and strangeness content of the produced particles. In particular, the model predicts a dramatic enhancement in the multistrange (anti)hyperon production at moderate p_T, up to a factor of roughly 2 (relative to binary scaling) for Ξ's and up to a factor of more than 10 for Ω's [Fig. 4(b)]. The striking difference between R_{AA} and R_{cp} could be explained in our model as a consequence of the SCF that is manifest in both central and peripheral collisions. This shows that there is a clear difference between using peripheral Au+Au yields (as in R_{cp}), or p+p yields (as in R_{AA}) as a baseline for comparison with binary collision scaling ($R_{AA} = R_{cp} = 1$).

IV. SUMMARY AND CONCLUSIONS

In summary, we studied the influence of possible strong longitudinal color fields in particle production in heavy-ion collisions. We modeled SCF effects within HIJING/B$\bar{\text{B}}$ v2.0 by varying the effective string tension that controls the $q\bar{q}$ and $qq\overline{qq}$ pair creation rates and strangeness suppression factors. We show that junction-(anti)junction loops and a higher string

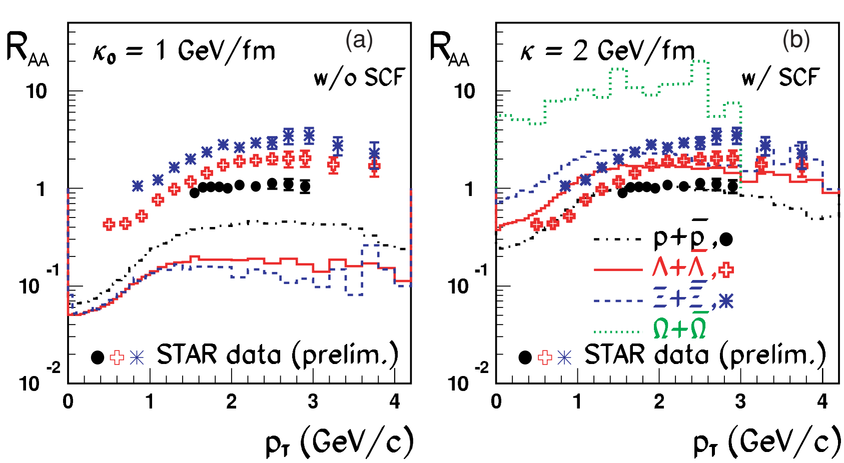

FIG. 4. (Color online) HIJING/B$\bar{\text{B}}$ v2.0 predictions (a) with SCF and (b) without SCF for species dependence of $R_{AA}(p_T)$ in central (0%–5%) Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The preliminary STAR data are from [55,56]. Only statistical error bars are shown.

tension $\kappa = 2\,\kappa_0$ ($\kappa_0 \approx 1$ GeV/fm) could be important dynamical mechanisms in the solution of the observed baryon/meson anomaly. Our approach has the advantage of correlating many observables in the same dynamical model including pion, kaon, and baryon productions and of predicting species dependence of the NMFs $R_{AA}(p_T)$ and $R_{cp}(p_T)$, and the transverse momenta over a large p_T range. A greater sensitivity to SCF effects is predicted for the NMFs of (multi)strange hyperons. In particular, the measurement of Ω and $\bar{\Omega}$ yields would provide an important test of the consistency of SCF and baryon junction mechanisms at RHIC.

ACKNOWLEDGMENTS

We thank N. Xu and R. Bellwied for helpful discussions and suggestions throughout this project. This work was partly supported by the Natural Science and Engineering Research Council of Canada and the Fonds Nature et Technologies of Quebec. This work was supported also by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Division of Nuclear Physics, and by the Office of Basic Energy Science, Division of Nuclear Science, of the U.S. Department of Energy under contract nos. DE-AC03-76SF00098 and DE-FG-02-93ER-40764.

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