HADRONIZATION AT RHIC: INTERPLAY OF RECOMBINATION AND FRAGMENTATION

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We discuss hadron production in heavy ion collisions at RHIC. We argue that hadrons at transverse momenta $P_T < 5$ GeV are formed by recombination of partons from the dense parton phase created in central collisions at RHIC. We provide a theoretical description of the recombination process for $P_T > 2$ GeV. Below $P_T = 2$ GeV our results smoothly match a purely statistical description. At high transverse momentum hadron production is well described in the language of perturbative QCD by the fragmentation of partons. We give numerical results for a variety of hadron spectra, ratios and nuclear suppression factors. We also discuss the anisotropic flow v_2 and give results based on a flow in the parton phase. Our results are consistent with the existence of a parton phase at RHIC hadronizing at a temperature of 175 MeV and a radial flow velocity of 0.55c.

1 Introduction

Recent data from the Relativistic Heavy Ion Collider (RHIC) have shown a strong nuclear suppression of the pion yield at transverse momenta larger than 2 GeV/c in central Au + Au collisions, compared to $p+p$ interactions [1]. This is widely seen as the experimental confirmation of jet quenching, the phenomenon that high energy partons lose energy when they travel through the hot medium created in a heavy ion collision [2,3,4], entailing a suppression of intermediate and high P_T hadrons.

However, the experiments at RHIC have provided new puzzles. The amount of suppression seems to depend on the hadron species. In fact, in the production of protons and antiprotons between 2 and 4 GeV/c the suppression seems to be completely absent. Generally, pions and kaons appear to suffer from a strong energy loss while baryons and antibaryons do not. Two stunning experimental facts exemplify this [5,6,7,8]. First, the ratio of protons over positively charged pions is equal or above one for $P_T > 1.5$GeV/c and is approximately constant up to 4 GeV/c. Second, the nuclear suppression factor R_{AA} below 4 GeV/c is close to one for protons and lambdas, while it is about 0.3 for pions.

There have been recent attempts to describe the different behavior of baryons and mesons through the existence of gluon junctions [9] or alternatively through recombination as the dominant mechanism of hadronization [10,11]. The recombination picture has attracted additional attention due to the observation that the elliptic flow pattern of different hadron species can be explained by a simple recombination mechanism [12,13,14,15]. The anisotropies v_2 for the different hadrons are compatible with a universal value of v_2 in the parton phase, related to the hadronic flow by factors of two and three depending on the number of valence quarks [16].

The competition between recombination and fragmentation delays the onset of the perturbative/fragmentation regime to relatively high transverse momentum of 4–6 GeV/c, depending on the hadron species, providing a natural explanation for the aforementioned phenomena.

2 Formalism

In the fragmentation process a parton with transverse momentum p_T is leaving the interaction zone while still being connected with other partons by a color string. The breaking of the string creates quark antiquark pairs which finally turn into hadrons. The distribution of one of these hadrons, which is bound to have less transverse momentum $P_T = zp_T$, is then described by a fragmentation function. The average value $\langle z \rangle$ is about 0.5 for pions in $p + p$ collisions. In other words the production of a, say, 5 GeV/c pion has to start with a 10 GeV/c parton in average, which are rare to find due to the steeply falling parton spectrum. Jet quenching even enhances the lack of high p_T partons. On the other hand, the 5 GeV/c pion could be produced by the recombination of a quark and an antiquark with about 2.5 GeV/c each in average. 2.5 GeV/c and 10 GeV/c are separated by orders of magnitude in the parton spectrum. The price to pay is of course that two of these partons have to be found close to each other in phase space. However we do have a densely populated phase space in central heavy ion collisions at RHIC where we even expect the existence of a thermalized quark gluon plasma.

Recombination of quarks has been considered before in hadron collisions [17] and was also applied to heavy ion collisions [18]. In QCD the leading particle effect in the forward region of a hadron collision is well known.

Since the hadron structure is best known in a light cone frame, we proceed in terms of light cone coordinates in a frame where the hadron has no transverse momentum but a large light cone component P^+. This can be achieved by a simple rotation from the lab frame. Introducing the momentum $k = P/2 - q$ of parton a in this frame we have $k^+ = xP^+$ with $0 < x < 1$. We make an ansatz for the Wigner function of the meson in terms of light cone wave functions $\phi_M(x)$. The final result can be written as [10]

$$E\frac{N_M}{d^3P} = C_M \int_\Sigma d\sigma \frac{P\cdot u(\sigma)}{(2\pi)^3} \int_0^1 dx\, |\phi_M(x)|^2 \times w_a\big(\sigma; xP^+\big)\, w_b\big(\sigma; (1-x)P^+\big)$$

For a baryon with valence partons a, b and c we obtain

$$E\frac{N_B}{d^3P} = C_B \int_\Sigma d\sigma \frac{P\cdot u(\sigma)}{(2\pi)^3} \int_0^1 dx_1\, dx_2\, dx_3 \times \delta(x_1+x_2+x_3-1)\, |\phi_B(x_1,x_2,x_3)|^2 \times w_a\big(\sigma; x_1P^+\big) w_b\big(\sigma; x_2P^+\big) w_c\big(\sigma; x_3P^+\big)$$

$\phi_B(x_1, x_2, x_3)$ is the effective wave function of the baryon in light cone coordinates.

It turns out that for a purely exponential spectrum the shape of the wave function does not matter. In that case the dependence on x drops out of the product of phase space densities

$$w_a\big(\sigma; xP^+\big) w_b\big(\sigma; (1-x)P^+\big) \sim e^{-xP^+/T} e^{-(1-x)P^+/T} = e^{-P^+/T}.$$

Fragmentation of partons is given by:

$$E\frac{d\sigma_h}{d^3P} = \sum_a \int_0^1 \frac{dz}{z^2} D_{a\to h}(z) E_a \frac{d\sigma_a}{d^3P_a}.$$

The sum runs over all parton species a and σ_a is the cross section for the production of parton a with momentum $P_a = P/z$. Energy loss of the partons is taken into account by a shift of the parton spectrum by

$$\Delta p_T = \sqrt{\lambda p_T}.$$

3 Selected Results

The upper frame of fig. 1 displays the scaled ratio $R_{\rm CP}$ for neutral pions and protons. The ratio of impact parameters 0 and 12 fm is used and compared to data from the PHENIX collaboration [21]. The data for protons shows $R_{\rm CP}$ to be between 0.8 and 1 below 4 GeV/c, which is quite surprising, considering the strong suppression suffered by the pions in that momentum domain. As already noticed above, recombination is more effective for protons than for pions. Therefore our calculation for the protons yields a similarly value of 0.8 as observed by the experiment. This implies that protons from recombination make up for the loss suffered from jet quenching at intermediate transverse momenta. Our calculations predicts sharp drops in R_{CP} and R_{AA} for protons and antiprotons beyond 4 GeV/c where fragmentation with jet quenching start to dominate.

In the lower frame of fig. 1 we compiled R_{CP} for K_s^0 and $\Lambda + \bar{\Lambda}$ together with data from STAR [22]. For the first time experimental data indicate that a steep decrease in R_{CP} for baryons will occur beyond 4 GeV/c. The data on $\Lambda + \bar{\Lambda}$ suggest a drop to the perturbative value even sharper than what our results show. This could be due to too less Λ baryons from fragmentation using this particular set of fragmentation functions [20].

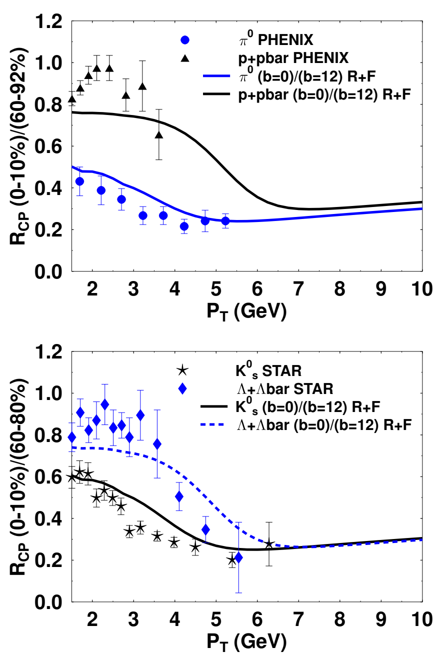

Figure 1. Upper frame: R_{CP} for neutral pions (bottom) and protons (top) given by the ratio of particle yields at impact parameters 0 and 12 fm compared to data from PHENIX. Lower frame: R_{CP} for K_s^0 (bottom) and $\Lambda + \bar{\Lambda}$ (top) given by the ratio of particle yields at impact parameters 0 and 12 fm compared to data from STAR.

The left panel of fig. 2 shows hadron ratios. The top frame displays the ratio of charged hadrons to neutral pions reported by PHENIX [23] in comparison with our results.

Preliminary results for the ratios $(\Lambda + \bar{\Lambda})/4K_s^0$ and were presented by the STAR collaboration [22]. Recombination predicts a large peak in the Λ/kaon ratio and a sharp decrease beyond 4 GeV/c similar to the p/π^0 ratio. First indications of such a sharp transition can be seen in the STAR data. The predicted decrease in the proton/pion ratio, if confirmed, and first observations of a similar drop in the Λ/kaon ratio will be strong arguments in favor of the recombination+fragmentation picture.

Anisotropic flow v_2 is defined as the second Fourier coefficient of the azimuthal hadron spectrum $v_2(P_T) = \langle \cos 2\Phi \rangle$. Such an asymmetry arises in heavy ion collisions with non-vanishing impact parameter $b > 0$.

Our results on the particle dependence of elliptic flow are summarized in fig. 3. One can see the different behavior of mesons and baryons by comparing protons with pions and kaons with Λs. v_2 for baryons saturates at a higher value than for mesons in the recombination domain. At higher P_T, when fragmentation takes over, the results rapidly approach each other. In our calculation, where we do not take into account the binding energies, we cannot resolve the splitting between protons and mesons coming from the mass difference. Nevertheless the agreement with data from PHENIX [24] and preliminary data from STAR [16] is good.

It can be shown that in the region where recombination of partons dominates the hadronization process (i.e. for $P_T < 4(6)$ GeV for mesons (baryons)) and mass effects are suppressed (i.e. $P_T > 1$ GeV), v_2 obeys a simple scaling law

$$v_2(P_T) \approx n v_2^q(P_T/n)$$

where n is the number of valence quarks of the hadron. Here it is assumed that strange quarks and light quarks have the same elliptic flow v_2^q. At higher transverse momentum, $P_T > 6$ GeV, where fragmentation of partons dominates, the v_2 of all hadrons lies on a universal curve since the effect of fragmentation functions largely cancels. We refer the reader to Refs. [25,26] for a more detailed discussion.

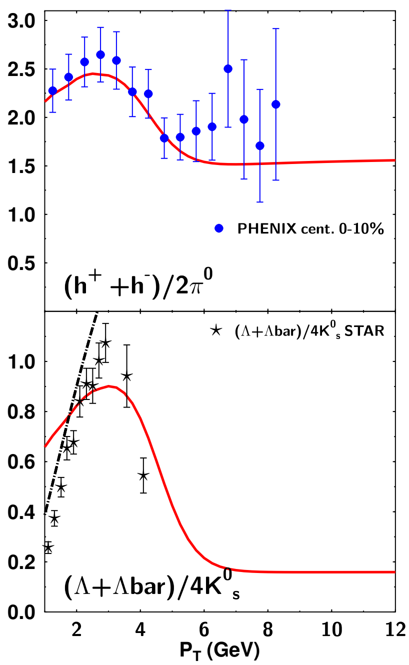

Figure 2. $(h^+ + h^-)/2\pi^0$ and $(\Lambda + \bar{\Lambda})/4K_s^0$ and $2(\Xi^- + \Xi^+)/(\Lambda + \bar{\Lambda})$ ratios as functions of transverse momentum P_T. We show data from STAR and PHENIX as well as results from the statistical model (dash dotted lines).

4 Conclusion

In summary, we propose a two component behavior of hadronic observables in heavy ion collisions at RHIC. These components include fragmentation from a high-p_T perturbative parton phase and recombination from a thermal parton phase. We have found that the competition between recombination and fragmentation of partons as hadronization mechanisms can simultaneously explain several of the surprising features of the published data. In particular, the proton excess at intermediate P_T, the different nuclear suppression observed in pion and proton spectra, and the different saturation thresholds in the elliptic flow, can be consistently explained. We predict that all baryon spectra will exhibit a rapid transition around 5 GeV/c to a region dominated by parton fragmentation. Finally, we emphasize that our scenario requires the assumption of a thermalized partonic phase characterized by an exponential momentum spectrum and without strong multi-parton correlations. Such a phase may be appropriately called a quark-gluon plasma.

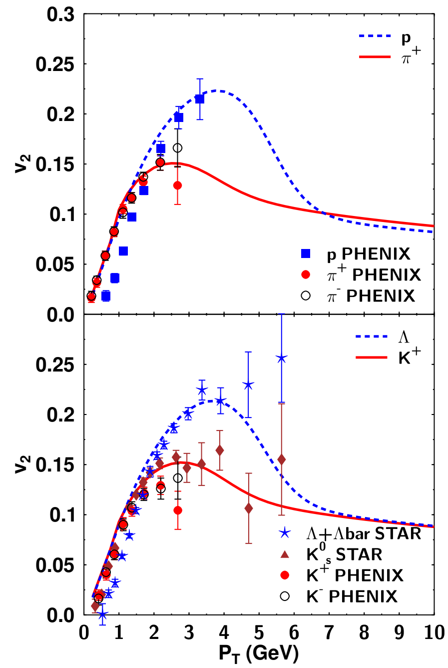

Figure 3. Anisotropic flow for p and π^+ compared to PHENIX data (top) and for K^+ and $\Lambda + \bar{\Lambda}$ compared to STAR and PHENIX data (bottom).

Acknowledgments

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References

1. K. Adcox *et al.* [PHENIX Collaboration], Phys. Rev. Lett. **88** (2002), 022301; C. Adler *et al.* [STAR Collaboration], Phys. Rev. Lett. **90** (2003), 082302.
2. J. D. Bjorken, FERMILAB-PUB-82-059-THY (1982); M. H. Thoma and M. Gyulassy, Nucl. Phys. B **351** (1991), 491; X. N. Wang and M. Gyulassy, Phys. Rev. Lett. **68** (1992), 1480; M. Gyulassy and X. Wang, Nucl. Phys. B **420** (1994), 583; R. Baier, Y. L. Dokshitzer, A. H. Mueller, S. Peigne and D. Schiff, Nucl. Phys. B **483** (1997), 291; B. G. Zakharov, JETP Lett. **65** (1997), 615; M. Gyulassy, P. Levai and I. Vitev, Phys. Rev. Lett. **85** (2000), 5535; U. A. Wiedemann, Nucl. Phys. B **588** (2000), 303.
3. R. Baier, Y. L. Dokshitzer, A. H. Mueller and D. Schiff, JHEP **0109** (2001), 033;
4. B. Muller, Phys. Rev. C **67** (2003), 061901.
5. K. Adcox *et al.* [PHENIX Collaboration], Phys. Rev. Lett. **88** (2002), 242301.
6. C. Adler *et al.* [STAR Collaboration], Phys. Rev. Lett. **86** (2001), 4778.
7. C. Adler *et al.* [STAR Collaboration], Phys. Rev. Lett. **89** (2002), 092301.
8. K. Adcox *et al.* [PHENIX Collaboration], Phys. Rev. Lett. **89** (2002), 092302.
9. I. Vitev and M. Gyulassy, Phys. Rev. C **65** (2002), 041902.
10. R. J. Fries, B. Müller, C. Nonaka and S. A. Bass, Phys. Rev. Lett. **90** (2003), 202303.
11. V. Greco, C. M. Ko and P. Levai, Phys. Rev. Lett. **90** (2003), 202302.
12. Z. W. Lin and C. M. Ko, Phys. Rev. Lett. **89** (2002), 202302.
13. S. A. Voloshin, Nucl. Phys. A **715** (2003), 379c.
14. D. Molnár and S. A. Voloshin, nucl-th/0302014;
15. Z. w. Lin and D. Molnar, Phys. Rev. C **68** (2003), 044901.
16. P. Sorensen for the STAR Collaboration, J. Phys. **G30** (2004) S217.
17. K. P. Das and R. C. Hwa, Phys. Lett. B **68** (1977), 459; Erratum *ibid.* **73** (1978), 504; R. G. Roberts, R. C. Hwa and S. Matsuda, J. Phys. G **5** (1979), 1043.
18. C. Gupt *et al.*, Nuovo Cim. A **75** (1983), 408; T. S. Biro, P. Levai and J. Zimanyi, Phys. Lett. B **347** (1995), 6; T. S. Biro, P. Levai and J. Zimanyi, J. Phys. G **28** (2002), 1561.
19. R. J. Fries, B. Müller, and D. K. Srivastava, Phys. Rev. Lett. **90** (2003), 132301; D. K. Srivastava, C. Gale and R. J. Fries, Phys. Rev. C **67** (2003), 034903.
20. D. de Florian, M. Stratmann and W. Vogelsang, Phys. Rev. D **57** (1998), 5811.
21. J. Velkovska for the PHENIX Collaboration, J. Phys. **G30** (2004) S151.
22. H. Long for the STAR Collaboration,J. Phys. **G30** (2004) S193.
23. S. S. Adler *et al.* [PHENIX Collaboration], Phys. Rev. Lett. **91** (2003), 172301.
24. . S. Adler *et al.* [PHENIX Collaboration], Phys. Rev. Lett. **91** (2003), 182301.
25. R. J. Fries, B. Muller, C. Nonaka and S. A. Bass, Phys. Rev. C **68** (2003), 044902.
26. C. Nonaka, R. J. Fries and S. A. Bass, Phys. Lett. **B583** (2004), 73.