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PUZZLES AT HIGH p_{T} AT RHIC AND THEIR RESOLUTION*

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Several puzzles about the data at high p_{T} in heavy-ion collisions are listed. The resolution of them all is given in the framework of parton recombination. More specifically, it is the recombination of the soft and semi-hard shower partons that enhances the region $3 < p_{\mathrm{T}} < 9$ GeV/c, and gives rise to the large p/π ratio in Au Au collisions. The Cronin effect can be explained in terms of final-state interaction for both π and p. The structure of jets produced in Au Au is different from that in pp collisions. The suppression of R_{CP} in forward production can also be understood by extending the same hadronization scheme at $\eta = 0$ to $\eta > 0$ without the introduction of any new physics.

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In the past two years several features of the high-p_{T} data obtained by various experiments at RHIC are puzzling, and may be regarded as anomalies according to the "standard model." By standard model I mean that which has been standard in the treatment of hadron production at high p_{T}, namely: a hard scattering of partons, followed by a fragmentation process that leads to the detected hadron. What I plan to show in this talk are evidences that all those anomalies can be resolved when the process of hard parton fragmentation is replaced by the recombination of soft and shower partons. The basic reason why the fragmentation model has worked so well for high-p_{T} processes in leptonic and hadronic collisions, but poorly for heavy-ion collisions, is that there is a large body of soft partons in the latter case, but absent in the former. The hadronization of those soft partons by recombination with the semi-hard partons results in a significant enhancement in the intermediate-p_{T} region that is missing in the fragmentation model.

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If hard partons fragment in vacuum, whether or not they have lost energy while in transit in the dense medium, the fragmentation products should be independent of the medium. Thus the ratio of produced hadrons, when all else are the same, should depend only on the ratio of the fragmentation functions (FF), $D(z)$. Given a parton, whether a quark or a gluon, its FF for the production of a proton $D^p(z)$ is much smaller than that for a pion $D^\pi(z)$. The observed data reveal several anomalies according to that picture.

Anomaly 1. The ratio of proton to pion, $R_{p/\pi}$, in Au+Au collisions is approximately 1 at $p_{\rm T} \approx 3$ GeV/c.

Anomaly 2. The nuclear modification factor, $R_{\rm CP}$, in d+Au collisions is greater for p than for π at $p_{\rm T} \approx 3$ GeV/c.

Anomaly 3. The jet structure, *i.e.*, the distribution of particles associated with a trigger, is different for jets produced in Au+Au collisions compared to that for $p+p$ collisions.

Anomaly 4. The azimuthal anisotropy parameter v_2 is larger for baryons than for mesons for $p_{\rm T} \geq 2$ GeV/c.

Another irregularity. Forward–backward asymmetry.

Time and space do not permit all the topics above to be addressed adequately. I give only a sketch here.

How can recombination solve the puzzles? First of all, let it be understood on general grounds that when a multi-parton state is to hadronize, it is far more efficient for a q and $\bar{q}$ to recombine than for a higher momentum q to fragment, assuming that the parton distribution is falling rapidly in momentum. That is simply because recombination involves the addition of two lower momenta of q and $\bar{q}$, where the densities are higher, whereas fragmentation involves first the creation of a parton at higher momentum (at a cost in yield), and then the production of a hadron at some momentum fraction at the cost of another factor of suppression. The comparison is meaningful only when there are many soft partons moving collinearly with a hard parton, which is the case for heavy-ion collisions, but not for leptonic and hadronic collisions.

The fragmentation process makes use of a phenomenological FF because it describes the non-perturbative process of hadronization that cannot be calculated in pQCD. Thus $D(z)$ represents a black box, in which there are gluon radiation, quark pair creation, *etc.*, that generate a shower of partons before hadronization. Although the density of shower partons cannot be calculated from first principles, those partons are nevertheless there, and their momentum distributions can possibly be determined phenomenologically. That is what we have done in the framework of recombination [1], in which we write

$$xD(x) = \int \frac{dx_1}{x_1}\frac{dx_2}{x_2} F_{q\bar{q}'}(x_1,x_2) R_M(x_1,x_2,x)\,, \tag{1}$$

where $F_{q\bar{q}'}$ is the joint distribution of a shower quark q and a shower antiquark $\bar{q}'$ that recombine to form a meson M. R_M is the corresponding recombination function. The FF on the LHS is known from phenomenological analysis of leptonic and hadronic processes. R_M is known from previous work on the recombination model. So $F_{q\bar{q}'}$ can be determined. If we assume that $F_{q\bar{q}'}$ has the factorizable form $S_i^q S_i^{\bar{q}'}$, where i labels the hard parton that initiates the shower, then there are 5 types of S_i^j to be determined from 5 types of D_i, where i takes on the species: u, d, s, g, and j is allowed to be u, d, s, but not g, on the grounds that gluon conversion to $q\bar{q}$ relieves the burden of considering direct hadronization of gluons. The distributions $S_i^j(x)$ of the shower partons have been determined in [1] at a fixed $Q = 10$ GeV$/c$. The Q^2 evolution of $S_i^j(x)$ was not considered, although it constitutes an interesting project in its own right. On the basis that hadron production in the intermediate $p_{\rm T}$ region at RHIC depends crucially on the recombination of soft and shower partons, but not sensitively on the virtuality of $S_i^j(x)$ we have proceeded to the study of the consequences of considering the shower partons in heavy-ion collisions [2], and found some remarkable results.

For pion production at large $p_{\rm T}$ the inclusive distribution is

$$p\frac{dN_\pi}{dp} = \int \frac{dp_1}{p_1}\frac{dp_2}{p_2} F_{q\bar{q}'}(p_1, p_2) R_\pi(p_1, p_2, p), \tag{2}$$

where

$$R_\pi(p_1, p_2, p) = \frac{p_1 p_2}{p}\delta(p_1 + p_2 - p). \tag{3}$$

Similar equations can be written for proton production [2]. The essence of recombination is then in what one should include for $F_{u\bar{d}}$ in case of π^+, say, and for F_{uud} for p. If we denote thermal parton distribution by $\mathcal{T}$ and shower parton distributions by $\mathcal{S}$, then they ought to be

$$F_{u\bar{d}} = \mathcal{T}\mathcal{T} + \mathcal{T}\mathcal{S} + \mathcal{S}\mathcal{S}\,, \tag{4}$$

$$F_{uud} = \mathcal{T}\mathcal{T}\mathcal{T} + \mathcal{T}\mathcal{T}\mathcal{S} + \mathcal{T}\mathcal{S}\mathcal{S} + \mathcal{S}\mathcal{S}\mathcal{S}\,, \tag{5}$$

where the pure $\mathcal{T}$ terms give the soft component, and the pure $\mathcal{S}$ terms recover the fragmentation component. It is the mixed terms involving both $\mathcal{T}$ and $\mathcal{S}$ that are new and dominate the intermediate-$p_{\rm T}$ region, as we shall show below.

To proceed, we need to specify $\mathcal{T}$ and $\mathcal{S}$. For $\mathcal{T}$ we do not rely on any low-$p_{\rm T}$ model, but determine it phenomenologically from the low-$p_{\rm T}$ data of pion production, using the $\mathcal{T}\mathcal{T}$ term of (4) in (2). In that way we can attribute the enhancement at higher $p_{\rm T}$ directly to the $\mathcal{TS}$ term without raising any question on the reliability of the low-$p_{\rm T}$ model. For $\mathcal{S}$ we shall use the distributions S_i^j determined in [1], convoluted with the distribution of hard parton i in Au+Au collisions, and then sum over i. More specifically, we write

$$\mathcal{T}(p_1) = C\, p_1 e^{-p_1/T}, \tag{6}$$

$$\mathcal{S}(p_2) = \xi \sum_i \int dk\, k f_i(k)\, S_i^j(p_2/k)\ , \tag{7}$$

where $f_i(k)$ is the hard-parton distribution. C and T are parameters to be varied to fit $dN_\pi/p_{\rm T}dp_{\rm T}$ for $p_{\rm T} < 2$ GeV/c. ξ is the average fraction of hard partons that can get out of the dense medium to produce showers. Without discussing the details that can be found in [2], let me just show the results.

Fig. 1 shows the pion distribution that exhibits the dominance of the $\mathcal{TS}$ component in the $p_{\rm T}$ region between 3 and 9 GeV/c. The sum of all components agrees well with data [3]. Similarly, the $\mathcal{TTS}$ and $\mathcal{TSS}$ components dominate over other components of the proton spectrum in the same $p_{\rm T}$ region. The p/π ratio is shown in Fig. 2; indeed, it reaches the level of 1 at around $p_{\rm T} \sim 3$ GeV/c, as observed [4]. Without the thermal-shower recombination, the proton spectrum would be too low in the intermediate-$p_{\rm T}$ region, so the first anomaly in the fragmentation picture is now satisfactorily resolved. It should be mentioned that the large p/π ratio has also be obtained in other recombination/coalescence models using slightly different schemes to implement the hadronization process [5, 6].

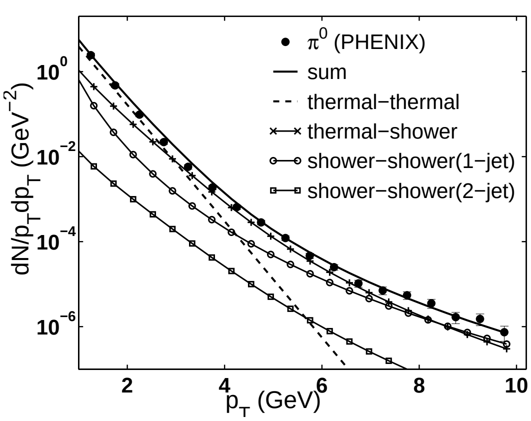

Fig. 1. Transverse momentum distribution of π^0 in Au+Au collisions. Data are from [3].

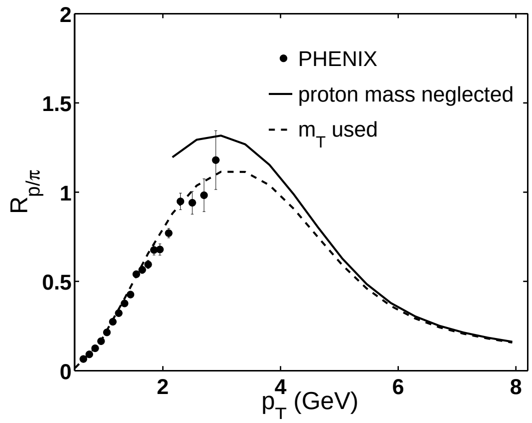

Fig. 2. Comparison of calculated p/π ratio with data from [4].

The second anomaly concerns the Cronin effect in d+Au collisions. The traditional explanation of the effect is that multiple scattering of partons in the initial state leads to the broadening of the p_T distribution of hadrons at high p_T in the final state. If those hadrons are produced by the fragmentation of high-p_T partons, then R_{CP} for protons should be much lower than that for pions. However, the data at RHIC reveal $R^p_{CP} > R^\pi_{CP}$ for $1 < p_T < 3$ GeV/c [7]. This anomaly can be well explained in the recombination model when the consideration given above for Au+Au collisions is extended to d+Au collisions [8,9], as shown in Fig. 3. Although the soft partons in d+Au are not thermal in the sense of Au+Au, the soft component nevertheless plays a similar role and the recombination of soft and shower partons gives

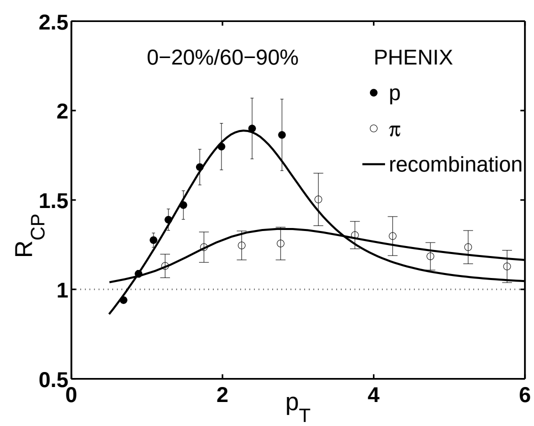

Fig. 3. Comparison of calculated ratios for R_{CP} for π and p with data from [7].

rise to components that can reproduce the π and p spectra in $p_{\rm T}$ without any initial parton broadening. Thus it is the final state rather than the initial state interaction that is mainly responsible for the Cronin effect. The reason is simply that the formation of proton by the recombination of 3 quarks, some soft some semi-hard, is far more effective than the fragmentation of a hard parton.

The third anomaly according to the fragmentation picture is that the jet structure in Au+Au collisions is different from that in $p+p$ collisions. Data from STAR show that the charge multiplicity and total scalar $p_{\rm T}$ in the near-side jets are significantly higher for Au+Au than for $p+p$, even when the trigger (that is the same for both) is included [10]. If the trigger were not included, one would expect the associated particle distributions to be drastically different for the two cases. Such behaviors cannot follow from the fragmentation of hard partons, once the trigger momentum is fixed to be the same. This problem has been studied in the framework of the recombination model, in which at least two shower partons in a jet must be considered, one for the trigger, the other for the associated particle. Specifically, for π^+ (trigger) and π^+ (associated) in a jet the 4-parton distribution has the structure

$$F_4^{\pi^+\pi^+} = (\mathcal{TS})(\mathcal{TS}) + (\mathcal{TS})(\mathcal{SS}) + (\mathcal{SS})(\mathcal{TS}) \ , \qquad (8)$$

where the first pair of parentheses in each term correspond to the trigger, the second pair the associated particle. We have omitted the term $(\mathcal{SS})(\mathcal{SS})$ in that equation because it is negligible in Au+Au collisions; however, it is the only term that is important in *pp* collisions. This point clearly reveals the difference between jets produced in heavy-ion and hadronic collisions. The difference becomes even greater when other types of associated particles are included, since the thermal environment in heavy-ion collisions helps the formation of other mesons and baryons in conjunction with shower partons. In Fig. 4 we show the distribution associated with a π^+ trigger when π^+, π^- and p in the jets are all included [11]. The data [10] are for all charged hadrons in both the trigger and the associated particles and are, therefore, not exactly what we have calculated. Nevertheless, the agreement is remarkably good.

The fourth anomaly concerns elliptic flow where v_2 for baryon exceeds that for meson. This phenomenon has nicely been explained by the coalescence model [12], and the scaling of v_2 with the number of constituent quarks remarkably verified by the STAR data [13].

The final issue to be mentioned here is about the production of intermediate $p_{\rm T}$ hadrons at large forward rapidity in d+Au collisions. It is the region where high hopes have been raised for the verification of a signature of color glass condensate. As with pQCD, the hadronization mechanism is

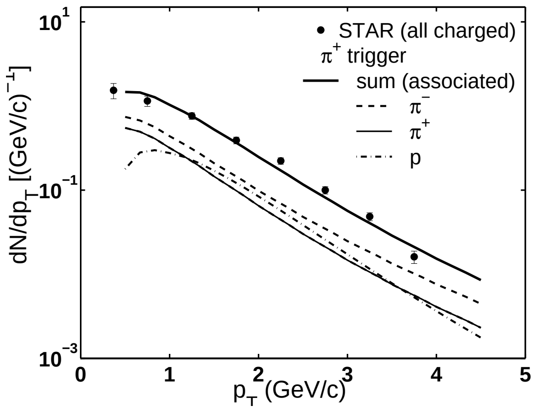

Fig. 4. Transverse momentum distribution of π^+, π^- and p associated with a π^+ trigger in central Au+Au collisions. Data are from [10] for all charged hadrons.

fragmentation. BRAHMS data already show that $R_{\rm CP}$ at $\eta = 3.2$ rises no higher than 0.5 at $p_{\rm T} \sim 3$ GeV/c [14]. This suppression is regarded as evidence for gluon saturation [15]. However, before novel physics is invoked, it is reasonable to ask whether the phenomenon can be understood in the conventional way, *i.e.*, by extrapolating what is known to work at midrapidity to the forward region. We have preliminary results that show a general agreement between the data and the expectation from parton recombination at all η and $p_{\rm T}$. The spectra at forward rapidities are suppressed because there are less soft partons as η is increased, resulting in less hadrons formed that rely on soft partons recombining with shower partons. At $\eta = 3.2$ there are so few hard partons that most hadrons are the result of soft–soft recombination. We have also studied the backward–forward asymmetry and found that there is no need for a transition of basic physics from multiple scattering in the initial-state interaction on the $\eta < 0$ side to gluon saturation on the $\eta > 0$ side.

Our emphasis on the hadronization process in the final state provides a universal framework for the description of particle production at all η and $p_{\rm T}$, at all centralities. In that framework of interpreting the existing high-$p_{\rm T}$ data from RHIC there are no features that are puzzling. In a sense that may be disappointing, since exciting new physics usually comes with anomalies. However, it is far better to have no puzzles than to be misled by false anomalies.

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