Eur. Phys. J. C 43, 233–237 (2005)
Digital Object Identifier (DOI) 10.1140/epjc/s2005-02271-4

THE EUROPEAN PHYSICAL JOURNAL C

Parton recombination at all p_{T}

R.C. Hwa[a]

Institute of Theoretical Science and Department of Physics, University of Oregon, Eugene, OR 97403-5203, USA

Received: 24 January 2005 /
Published online: 31 May 2005 –

Abstract. Hadron production at all p_{T} in heavy-ion collisions in the framework of parton recombination is reviewed. It is shown that the recombination of thermal and shower partons dominates the hadron spectra in the intermediate p_{T} region. In $d+\mathrm{Au}$ collisions, the physics of particle production at any η is basically the same as at $\eta = 0$. The Cronin effect is described as a result of the final-state instead of the initial-state interaction. The suppression of R_{CP} at high η is due to the reduction of the soft parton density on the deuteron side, thus resulting in less pions being produced by recombination, an explanation that requires no new physics. In $\mathrm{Au}+\mathrm{Au}$ collisions a large p/π ratio is obtained because the thermal partons can contribute to the formation of a proton more than they do to the pion.

PACS. 25.75.-q, 25.75.Dw

The conventional approach to hadronization at high p_{T} is by use of the fragmentation model, which has been highly successful in leptonic and hadronic collision processes. However, the application of such a hadronization scheme to heavy-ion collisions has encountered a number of difficulties. There are at least five areas where the predictions disagree badly with the data. The problems can all be resolved if fragmentation is replaced by recombination. The reason is simple. When a hard parton at large p_{T} is in the environment of collinear soft partons that are abundant in heavy-ion collisions, then the recombination of a semi-hard shower parton in the parton jet with a soft parton cannot be ignored. Those processes turn out to dominate in the intermediate p_{T} region and contribute to the anomalies that cannot be understood in the fragmentation picture. Even at very high p_{T} where fragmentation is valid, such a process can be interpreted as the recombination of shower partons in the same jet. Thus it is possible to frame all hadronization processes in terms of parton recombination – hence the title of this talk.

The five areas that can be listed at this point as puzzles in the fragmentation picture are the following.
(1) The proton-to-pion ratio in central $\mathrm{Au}+\mathrm{Au}$ collisions is greater than 1 at $2 < p_{\mathrm{T}} < 4\,\mathrm{GeV}/c$.
(2) In $d+\mathrm{Au}$ collisions R_{CP} for the proton is greater than that for the pion in a p_{T} region even wider than that above.
(3) Azimuthal anisotropy as measured by v_2 is greater for baryons than for mesons for $p_{\mathrm{T}} > 2\,\mathrm{GeV}/c$.
(4) The structure of jets produced in $\mathrm{Au}+\mathrm{Au}$ collisions is different from that in $p+p$ collisions.
(5) Forward production in $d+\mathrm{Au}$ collisions is more suppressed in central than in peripheral collisions at nearly all p_{T}, contrary to a naive interpretation of the Cronin effect.

Space does not permit adequate discussion of all of these problems here, although they were all summarized in the talk presented. We describe in this written report only items (1), (2) and (5). A summary of the others can be found in [1], which contains the basic references on each topic.

Starting with the latest phenomenon in item (5), BRAHMS data from $d+\mathrm{Au}$ collisions at RHIC at 200 GeV indicate that the central-to-peripheral ratio, R_{CP}, in the $1 < p_{\mathrm{T}} < 3\,\mathrm{GeV}/c$ region decreases monotonically from a value ~ 1.8 at pseudorapidity $\eta \sim -2$ to a value ~ 0.5 at $\eta \sim 3.2$ [2]. This has led to the interpretation of a change of the physics responsible for the phenomena from the gold side $\eta < 0$ to the deuteron side ($\eta > 0$) [3]. For $\eta \leq 0$ the enhancement of the particle yield that has been referred to as the Cronin effect is generally regarded as the result of multiple scattering in initial-state interaction. For $\eta > 0$ saturation physics has been considered to be dominant, especially at large η, so that there is suppression, instead of enhancement, in particle production [4]. Neither explanation takes into account any details about hadronization in the final state. The use of the fragmentation model is inappropriate because of the known failure to explain the p/π ratio. We discuss below how the Cronin effect can be understood in terms of parton recombination without any multiple scattering in the initial state [5]. Then we present an extension of that consideration to $\eta > 0$ and show that the suppression in forward production can be well reproduced without the explicit introduction of any new physics [6].

[a] e-mail: hwa@oregon.uoregon.edu

Following the formalism developed in [5,7] for parton recombination at $p_T > 0.5\,\mathrm{GeV}/c$, we have for the inclusive distribution of pions in a 1D description

$$p\frac{\mathrm{d}N_\pi}{\mathrm{d}p\mathrm{d}\eta} = \int \frac{\mathrm{d}p_1}{p_1}\frac{\mathrm{d}p_2}{p_2} F_{q\bar{q}'}(p_1,p_2,\eta) R_\pi(p_1,p_2,p), \quad (1)$$

where the recombination function for forming a pion at p is $R_\pi(p_1,p_2,p) = (p_1,p_2/p)\delta(p_1+p_2-p)$. For p in the transverse plane so that $p_T = p$, the distribution $\mathrm{d}N_\pi/\mathrm{d}^2p\mathrm{d}\eta$, averaged over all ϕ, is

$$\frac{\mathrm{d}N_\pi}{p\mathrm{d}p\mathrm{d}\eta} = \frac{1}{p^3}\int_0^p \mathrm{d}p_1 F_{q\bar{q}'}(p_1,p-p_1,\eta). \quad (2)$$

The joint parton distribution $F_{q\bar{q}'}$ has three components:

$$F_{q\bar{q}'} = \mathcal{TT} + \mathcal{TS} + \mathcal{SS}, \quad (3)$$

where $\mathcal{T}$ stands for soft parton distribution and $\mathcal{S}$ for shower parton distribution. At low p_T the observed pion distribution is exponential, which suggests the form

$$\begin{aligned}\mathcal{T}(p_1,\eta) &= p_1\frac{\mathrm{d}N_q^{\mathcal{T}}}{\mathrm{d}p_1\mathrm{d}\eta} \quad (4)\\ &= C(\beta,\eta)p_1\exp\left[-p_1/T(\beta,\eta)\right],\end{aligned}$$

where $C(\beta,\eta)$ and $T(\beta,\eta)$ are to be determined phenomenologically. Here, we use β to denote the centrality, e.g., $\beta = 0.1$ for 0–20% centrality. We do not rely on any model to derive the properties of the soft partons, but determine $T(\beta,\eta)$ from the data on soft pions. Our prediction is on the behavior in the intermediate p_T region where hard partons can cause a measurable effect.

The distribution $\mathcal{S}$ is a convolution of the hard parton distribution $f_i(k,\eta)$ with transverse momentum k and the shower parton distribution (SPD) $\mathcal{S}_i^j(z)$ from hard parton i to semi-hard parton j

$$\mathcal{S}_j(p_1,\eta) = \sum_i \int_{k_{\min}} \mathrm{d}k\, k f_i(k,\eta)\, S_i^j(p_1/k)\ , \quad (5)$$

where $k_{\min}$ is set at $3\,\mathrm{GeV}/c$, below which the pQCD derivation of $f_i(k,\eta)$ is invalid. A power-law parametrization of $f_i(k,\eta)$ for $d+\mathrm{Au}$ collisions is given in [6], and of $S_i^j(z)$ in [8].

At midrapidity, $\eta = 0$, the particle production rate at a fixed high p_T in $d+\mathrm{Au}$ collisions increases with centrality, a phenomenon that has been known for nearly thirty years [9] and referred to as the Cronin effect. The traditional interpretation of the centrality dependence is in terms of multiple scattering of projectile partons by the target nucleus before the production of a minijet by a hard scattering, which is followed by the fragmentation of the hard-scattered parton. Since the fragmentation process occurs outside the nucleus, the ratio of the proton-to-pion production rates should be just the ratio of the fragmentation functions D^h for the two types of hadrons h, when all else is kept the same. It is known that D^p is much smaller than D^π. However, the early data from PHENIX showed that R_{CP}^p for a proton is greater than R_{CP}^π for a pion in the range $1 < p_T < 3\,\mathrm{GeV}/c$ [10], where R_{CP}^h is the ratio of central-to-peripheral production of hadron h. That finding puts into question the reliability of the hadronization scheme in terms of fragmentation. The fragmentation model has been successful in describing hadron production in leptonic and hadronic collisions. But in nuclear collisions its inadequacy points to the relevance of the soft partons associated with the nuclear medium that are absent in the collision of simpler systems. The dynamical process of hadronization that involves the soft partons is recombination.

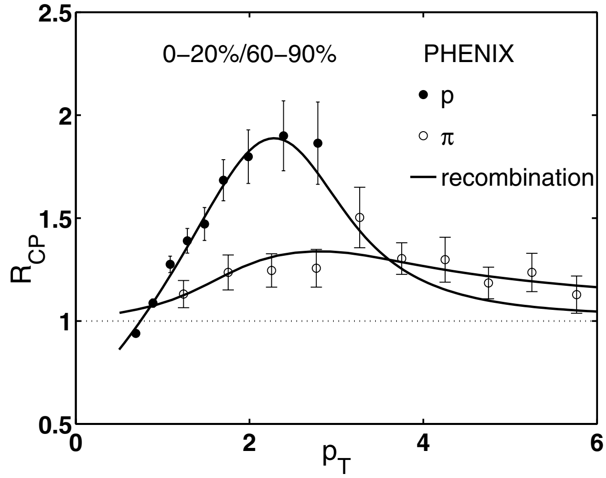

Fig. 1. Comparison of calculated ratios for R_{CP} for π and p with the data from [10]

The recombination formalism summarized in (1)–(5) can be applied to the production of mesons. For proton production one only needs to generalize the two-parton distribution $F_{q\bar{q}'}$ to the three-quark distribution F_{uud} with a corresponding generalization of the recombination function R to take into account the wave function of the proton in terms of the valons [5,11]. In Fig. 1 we show the results of our calculations of R_{CP} for pion and proton; they agree very well with the data [10]. The physical reason for the success is that when soft partons are considered in the formation of hadrons in the final state, their abundance enhances the formation of protons more than pions. Shower partons are needed to increase the hadronic p_T, but the soft partons increase the yield. Since no initial-state broadening of the parton transverse momenta has been put in, it is the final-state rather than the initial-state interaction that is mainly responsible for the Cronin effect. Item (2) listed in the introduction as one of the puzzles associated with fragmentation is therefore resolved.

The above is concerned with $d+\mathrm{Au}$ collisions at midrapidity. Let us now consider what happens at forward and backward rapidities. We can proceed to the calculation of the pion distribution given by (2), using (3)–(5), provided that we specify $C(\beta,\eta)$ and $T(\beta,\eta)$ in (4). In [5] we have determined $C(\beta,0)$ and $T(\beta,0)$; now we need to extend them to $\eta > 0$. Since the observed rapidity density

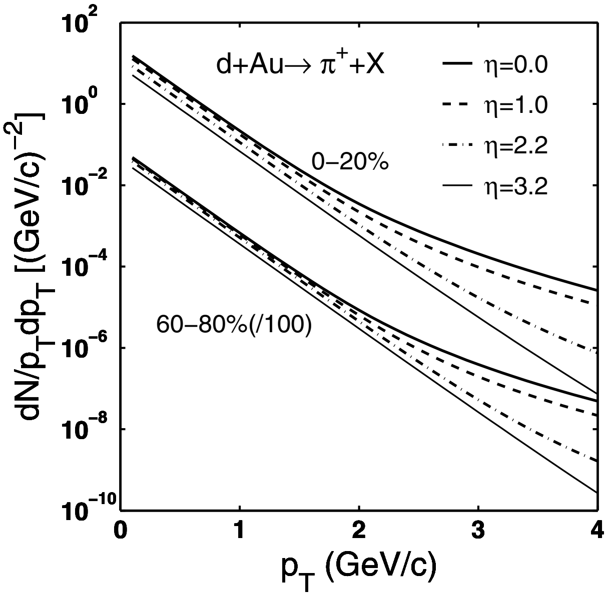

Fig. 2. Transverse momentum distributions of π^+ produced in $d+$Au collisions at different pseudorapidities for two centrality cuts

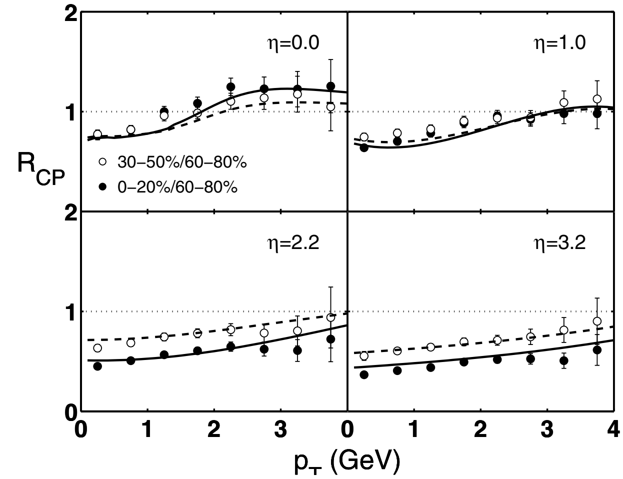

Fig. 3. R_{CP} for 0–20%/60–80% (filled circles and solid lines) and 30–50%/60–80% (open circles and dashed lines) for four pseudorapidities. Data are from [2]; lines are the results of calculations in the recombination model

at $\mathrm{d}N_{ch}/\mathrm{d}\eta$ is an integral over the p_T distribution that is dominated by the soft contribution at low p_T, i. e., the $\mathcal{TT}$ term in (3), it should be proportional to $C^2(\beta,\eta)$. We can therefore determine $C(\beta,\eta)$ by rescaling from $C(\beta,0)$

$$C(\beta,\eta) = C(\beta,0)\left[\frac{\mathrm{d}N_{ch}/\mathrm{d}\eta(\beta)}{\mathrm{d}N_{ch}/\mathrm{d}\eta|_{\eta=0}(\beta)}\right]^{1/2} . \qquad (6)$$

Using PHOBOS data on $\mathrm{d}N_{ch}/\mathrm{d}\eta(\beta)$, we can obtain $C(\beta,\eta)$, as shown in [6]. For $T(\beta,\eta)$ the assumption that it is independent of η is not a bad approximation. However, a slight decrease with increasing η yields a better fit. We use

$$T(\beta,\eta) = T_0(1-\epsilon\beta\eta) \qquad (7)$$

where $T_0 = 0.208\,\mathrm{GeV}$ and $\epsilon = 0.0205$.

With the soft parton distribution specified, we can now calculate the pion distribution for all p_T and η. The results for π^+ production are shown in Fig. 2 for two extreme centralities in $d+$Au collisions and for four values of η. Note how the distributions are progressively more suppressed at high p_T as η is increased. That has to do with the hard partons at high k approaching the kinematical limit as η becomes large. In addition to that suppression at high p_T and large η, there is also the suppression at high β. That is a result of the β dependence prescribed by (6), which corresponds physically to the fact that there are less soft partons in more peripheral collisions.

A quantitative measure of the β and η dependences is the ratio R_{CP} given by

$$R_{CP}(\beta,\eta) = \frac{\mathrm{d}N_\pi/p_\mathrm{T}\mathrm{d}p_\mathrm{T}\mathrm{d}\eta(\beta)/\left\langle N_\mathrm{coll}(\beta)\right\rangle}{\mathrm{d}N_\pi/p_\mathrm{T}\mathrm{d}p_\mathrm{T}\mathrm{d}\eta(\beta_p)/\left\langle N_\mathrm{coll}(\beta_p)\right\rangle}, \qquad (8)$$

where the reference centrality is $\beta_p = 0.7$. We have calculated that ratio for all β and η values of the data from BRAHMS [2]. The results are shown in Fig. 3 and compared with the data. Evidently, the theoretical curves agree well with the data. No new physics such as gluon saturation has been considered explicitly, although the data on $\mathrm{d}N_{ch}/\mathrm{d}\eta$ used in (6) may in turn be described by saturation physics. For us here that part is a phenomenological input. The curves in Fig. 3 also take into account the effect of momentum degradation that is responsible for baryon stopping, but it is a minor effect unworthy of extended discussion in this short summary here.

Finally, let us summarize the situation with Au + Au collisions. RHIC experiments have convincingly proven that the away-side jets are attenuated due to energy loss of partons traversing a thick hot medium, suggesting that the near-side jets are created mainly by hard collisions close to the near-side surface. Since our hadronization formalism does not trace the space-time properties of the colliding system and its subsequent evolution, we use a phenomenological parameter ξ to denote the average fraction of hard partons that emerge from the bulk medium to hadronize. While such a factor ξ is 1 in $d+$Au collision due to the absence of energy loss in a cold medium, it must be included as a multiplicative factor on the right-hand side of (5), when applied to Au + Au collisions. All other formulas are the same in appearance, although the functions $C(\beta,\eta), T(\beta,\eta)$ and $f_i(k,\eta)$ are all different when the colliding nuclei are changed from $d+$Au to Au + Au. Again, $C(\beta,\eta)$ and $T(\beta,\eta)$ are determined from low-p_T pion production data, and $f_i(k,\eta)$ is obtained by calculation. When all three contributions from (3) are considered, ξ is the only parameter that must be adjusted to fit the normalization of the pion spectrum at high p_T. The shape is predicted, since the properties of the shower partons are already fixed by other considerations independent of the Au + Au collisions [8].

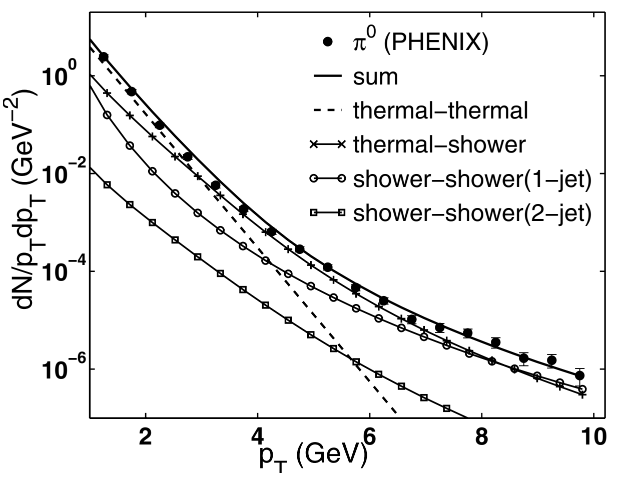

Fig. 4. Transverse momentum distribution of π^0 in central Au-Au collisions at $\sqrt{s}_{NN} = 200\,\text{GeV}$. Data are from [12]

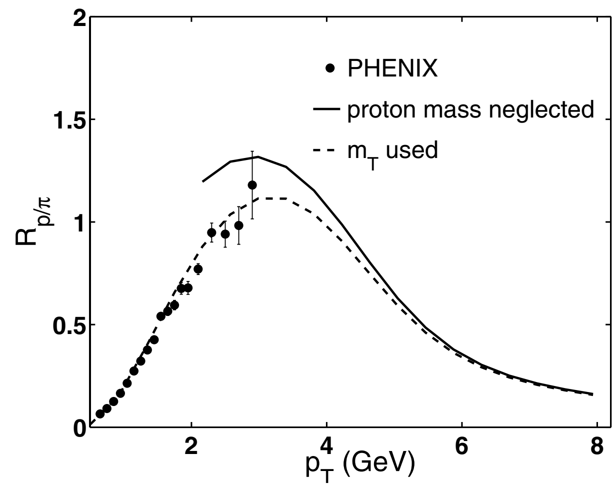

Fig. 5. Comparison of calculated p/π ratio with the data from [13]. The difference between the solid and dashed lines is described in [7]

Figure 4 shows the pion distribution in p_T at midrapidity in Au + Au at 200 GeV [7]. The values of ξ used to achieve the fit is $\xi = 0.07$. The overall shape agrees well with the data [12]. Note that the thermal-shower recombination is dominant in the region $3 < p_T < 9\,\text{GeV}/c$. The shower–shower recombination in one jet is equivalent to fragmentation, and is important only for $p_T > 9\,\text{GeV}/c$. The thermal partons therefore have a previously unsuspected important effect on hadron production in the intermediate p_T region. The significance of that effect is made convincingly clear when the p/π ratio is studied.

As in the $d+$Au collision case, the proton distribution in p_T can likewise be calculated for Au + Au collisions. When the result is used to compute the p/π ratio, we find that the ratio exceeds 1 at $p_T \sim 3\,\text{GeV}/c$ [7]. That is shown in Fig. 5. Such a high observed ratio [13] has been an anomaly in the fragmentation picture. Hadronization by recombination resolves the anomaly. A similar result has also been obtained by other groups using different implementations of the recombination model [14,15].

The success of the recombination mechanism for hadronization in the intermediate p_T region can be traced to the following simple reasons. In recombination the hadron momentum is the sum of the momenta of the partons that recombine. Thus the parton momenta are lower than the hadron momentum; the probability of finding those lower momenta partons is therefore higher. That is a far more efficient mechanism than fragmentation, which requires a hard parton at a much higher momentum, for which a penalty is paid in yield, and then the application of a fragmentation function to produce a hadron at a momentum fraction causes another suppression in the yield.

To conclude we have successfully described hadron production at intermediate p_T in heavy-ion collisions on the basis of parton recombination. For d + Au collisions we have shown that parton recombination is sufficient to account for all the experimental features found in both the mid and forward rapidity regions, namely, the enhancement of $\eta \sim 0$ and suppression at $\eta > 0$. As η is increased from negative to positive values, no change of physics has been built in, i.e., from transverse momentum broadening to gluon saturation, both in the initial state. We have also indicated how the pion and proton spectra in Au+Au collisions can be obtained and can explain the large p/π ratio that agrees well with the data. Even at very high p_T where the fragmentation picture is valid, hadron production can still be interpreted as the result of the recombination of shower partons. Since hadronization of partons by recombination is a process in the final stage of the evolution of the partons, it is not in conflict with any dynamical model that correctly describes the beginning and subsequent evolution of those partons. Indeed, given any predicted parton spectra in any such model, the work presented here provides the necessary link to the observed hadronic data.

Acknowledgements. The work reported here is the result of collaboration mainly with C.B. Yang and also with R.J. Fries. It was supported, in part, by the U.S. Department of Energy under Grant No. DE-FG03-96ER40972.

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