Forward Production in d+Au Collisions by Parton Recombination

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Abstract. We discuss parton recombination as a hadronization mechanism for d+Au collisions. We show that several features of hadron production measured at the Relativistic Heavy Ion Collider (RHIC) can be explained by recombination, including the Cronin effect at midrapidity and the suppression of hadrons in forward direction.

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Recombination of partons has been suggested as a possible hadronization mechanism in high energy scattering reactions with final state hadrons almost 30 years ago [1]. Quarks pick other partons in their neighborhood and cluster to objects that have the quantum numbers of QCD bound states. This happens after the virtuality of the scattered partons has been reduced by radiation to values well in the non-perturbative regime $\sim \Lambda_{QCD}$ and before the system is so dilute that colored partons have an average distance of more than the confinement radius.

Of course, a full description of this process would be equivalent to solving the QCD equations of motion in the non-perturbative regime, so it is not surprising that the recombination idea sketched above was only implemented in the form of simplified models. Nevertheless, these models have turned out to be very useful in understanding certain aspects of hadronization, e.g. for the leading particle effect [2] or, most recently, in high energy nuclear collisions [3, 4, 5, 6].

It has been realized that if thermalization of partons is achieved in nuclear collisions, this acts like a reset button that wipes out a lot of the complicated dynamics present in other collisions. Recombination of thermal partons has become an extremely successful concept to describe the relative behavior of hadron species, e.g. pions compared with protons, kaons compared with Lambdas etc. This is true for most single inclusive hadron observables in high energy nuclear collisions. E.g. in order to describe the transverse momentum spectrum or elliptic flow of the dozen or so *hadron* species identified in Au+Au collisions at the Relativistic Heavy Ion Collider (RHIC), it is sufficient to start from one universal parameterization of the corresponding *parton* quantity just before hadronization [7].

It was the unexpected baryon excess observed in Au+Au at RHIC that triggered the success of recombination models. Because the ejection probability of clusters of particles with a given relativistic momentum p from a thermal ensemble is independent of the number of particles in the cluster, the production probability for baryons is intrinsically equal to that of mesons, leading to a much higher baryon yield than expected from vacuum fragmentation. Surprisingly, when first data on hadron production in $d+Au$

from RHIC was presented, a similar, though smaller effect could be observed [8]. The modification factor R^h_{dAu} is defined as the ratio of the yield of a certain hadron species h in $d+Au$ over the yield of h in $p+p$ scaled by the number of binary nucleon-nucleon collisions in d+Au. It is unity if a d+Au collision is only a superposition of individual nucleon-nucleon collisions. One expects to see the typical Cronin enhancement at intermediate p_T, i.e. between roughly 2 and 6 GeV/c [9]. Indeed a slight Cronin effect was seen for pions, with $R^\pi_{dAu} \approx 1.1$. However, for protons the nuclear modification seems to be much larger in the same momentum range. This is completely at odds with the explanation of the Cronin effect as a broadening by multiple initial state scatterings in the nucleus [10]. There must be a final state effect that can have a much larger influence on the momentum spectrum than the initial state multiple scattering.

Hwa and Yang suggested that although there is no thermalization of partons in a rather "cold" d+Au collision, the exponential shape of the low and intermediate p_T spectra could still make the production of baryons through the recombination channel so important that it significantly increases the overall baryon yield at intermediate p_T. Indeed in their calculation they can explain the Cronin enhancement for pions and the even larger effect for protons entirely by additional recombination of partons which is not present in $p+p$ collisions, without having to invoke any conventional initial state multiple scattering at all [11].

Let us pause here and add a brief review of the recombination formalism in the version of Hwa and Yang [6]. The yield of, e.g., a π^+ is given by

$$\frac{dN_\pi}{p_T dp_T} = \frac{1}{p_T^2} \int \frac{dq_1}{q_1} \frac{dq_2}{q_2} F_{u\bar{d}}(q_1,q_2) R_\pi(q_1,q_2;p_T) \tag{1}$$

with the recombination function R_π. The two particle distribution $F_{u\bar{d}}$ for the u and $\bar{d}$ quarks is given by four different contributions, schematically written as

$$F_{u\bar{d}} = TT + TS + (SS) + SS'. \tag{2}$$

The nomenclature is as follows: TT are pairs where both partons are from the "soft" exponential part of the parton spectrum; TS are pairs where one parton is soft and the other is from the shower induced by a jet; (SS) is the situation where both partons are from the shower (of the same jet) and SS' is the contribution where both partons are from different jets.

The (SS) contribution, the recombination of 2 partons from the shower of a jet is nothing else than the fragmentation of a pion from a jet. Therefore the shower parton distributions have been parameterized to fit the known fragmentation functions. While the SS' contribution is negligible, TS and TT are small for $p+p$ but have increasing importance when going to d+Au and Au+Au collisions.

The BRAHMS experiment has reported that at forward rapidities in d+Au the enhancement of the nuclear modification factor changes to suppression for (unidentified) hadrons [12]. This has been seen as a possible earmark of gluon saturation in the Au nucleus at small Bjorken x which would be an exciting first piece of evidence for the existence of a color glass condensate [13, 14, 15] . However, any alternative explanations for this phenomenon have to be discussed thoroughly [16].

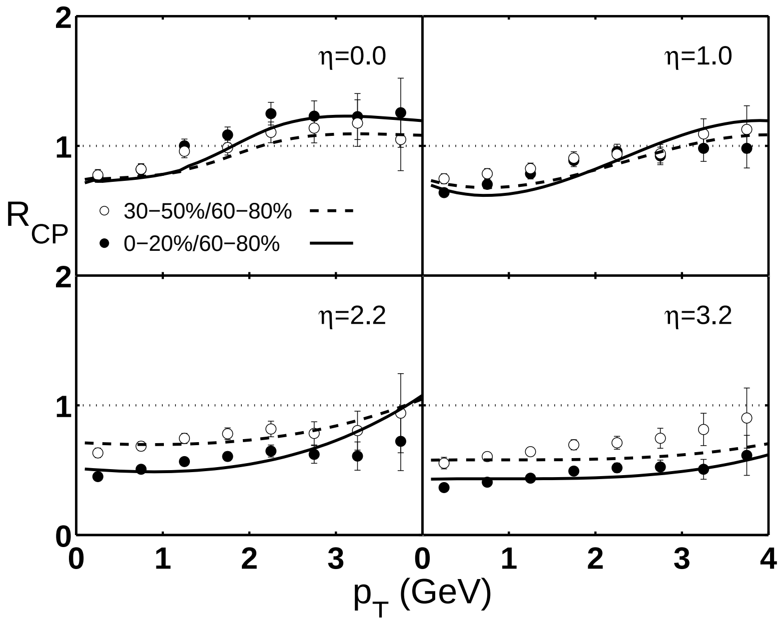

FIGURE 1. R_{CP} for 0-20%/60-80% (filled circles and solid lines) and 30-50%/60-80% (open circles and dashed lines) for four pseudorapidities. Data are from [12].

It was noted that in very forward direction the phase space for hard jet production is very small. The kinematic limit for the jet p_T is 8.1 GeV/c for rapidity $\eta = 3.2$. This leads to a dramatic decrease in the (SS) term in Eq. (2). Now the scaling property depends on the competing TT and TS channels. A first principle calculation of the soft parton spectrum T in the event is not available and the shape of the spectrum at forward rapidity has not been published yet. We assume here that the slope of the exponential $T = Cp_T \exp(-\beta p_T)$ does not vary with η and take the value obtained from a fit at midrapidity ($\beta^{-1} = 0.21$ GeV). The normalization C can be fixed by the measured charged hadron multiplicity $dN_{ch}/d\eta$. See [16] for details.

Our results for the ratio R_{CP}, a relative of R_{dAu} comparing different centrality classes for d+Au, are shown in Fig. 1 for pions. We compare with BRAHMS data for four different values of rapidity. Our results show the characteristic suppression at forward rapidity. This is indeed due to the fact that hadron production, even for pions, is dominated by parton recombination at very forward rapidities. The developing dominance of the soft component with increasing η can also be seen in Fig. 2 where the predicted pion spectrum is shown for 4 different rapidities and 2 centralities. The spectrum above $p_T = 2$ GeV/c cleary evolves from a power-law (hard) spectrum for $\eta = 0$ to an exponential (soft) spectrum at $\eta = 3.2$.

To conclude, we have reported about an alternative way to understand the suppression of hadrons at forward rapidities in d+Au collisions. It is based on the assumption that recombination of soft partons is dominating in this kinematic region. This is motivated by the observation that recombination effects have likely been observed at midrapidity through the particular dependence of the Cronin effect on the hadron species. It should be emphasized that in this framework nothing can be said about the origin of the soft

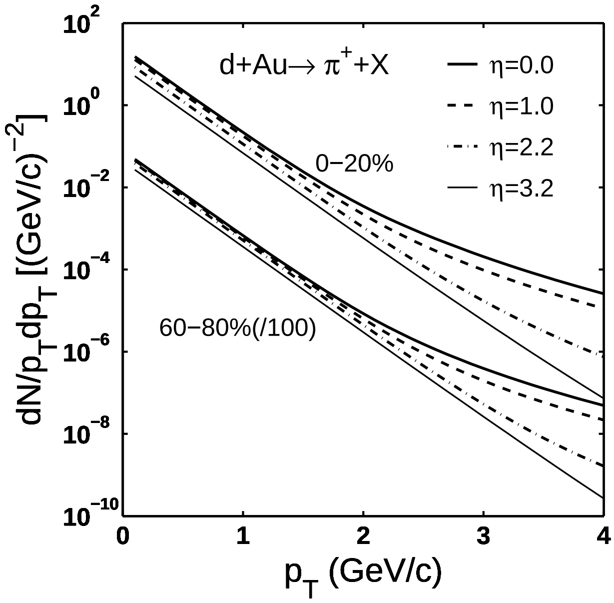

FIGURE 2. The spectrum $dN/(p_T dp_T)$ for pions for different centralities and rapidities.

parton spectrum.

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