Final-State Interaction as the Origin of the Cronin Effect

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The Cronin effect that refers to the enhancement of hadron spectra at intermediate p_T with increasing A in pA collisions is traditionally explained in terms of the broadening of the parton transverse momentum in the initial state. We show that recent data on the nuclear modification factor at $\eta = 0$ for $d +$ Au collisions can be understood in terms of the recombination of soft and shower partons in the final state. It is the centrality dependence of the soft parton density that leads to the Cronin effect.

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The conventional explanation of the Cronin effect [1], i.e., the enhancement of hadron spectra at intermediate p_T in proton-nucleus (pA) collisions with increasing nuclear size, is that it is due to multiple scattering of projectile partons by the target nucleus before the production of a minijet by a hard scattering [2,3]. All models on the effect are based on the traditional approach to hadron production at intermediate p_T, which is to follow a hard-scattered parton by a fragmentation of that parton. Since in that paradigm there is nothing more one can do with the final state, all models focus on the initial-state interaction (ISI), and they differ only in the way the broadening of the intrinsic transverse momentum is implemented. In this Letter we consider a drastically different approach to the problem by treating the hadronization process by recombination [4]. It will be shown that the Cronin effect can be satisfactorily explained at all centralities by final-state interaction (FSI). Our approach makes possible an understanding of the enhanced Cronin effect for proton compared to that for pion, since $p(\pi)$ involves the recombination of three (two) quarks.

Although there exists experimental evidence in the Drell-Yan process of pA collisions in favor of k_T broadening in ISI [5] (but not for $p_T > 3$ GeV$/c$), there also are data against it [6]. To enable our approach in this Letter to have a clean test, we assume no broadening in ISI, and see to what extent recombination in FSI can account for the Cronin effect observed. We leave open the possibility of a combination of both for future investigation.

The idea that final-state interaction may contribute to the Cronin effect is not new [7]. However, no theoretical model has ever been proposed to demonstrate that the idea can be translated into quantitative accounting of the effect. Here we work in the specific framework of the recombination model and make concrete predictions. Although the model has long been used to treat hadronization in the fragmentation region, a number of groups have recently found that recombination is more important than fragmentation at small and intermediate p_T ($0 < p_T < 8$ GeV$/c$) at midrapidity in heavy-ion collisions at $\sqrt{s} = 200$ GeV [8–10]. A central issue in the model has always been the determination of the appropriate distributions of partons that recombine, and it has been the major problem to tackle for the application of the model at low p_T in hadron-hadron [11] and proton-nucleus [12] collisions. For high p_T we have very recently determined the distributions of shower partons created by a hard-parton [13], and then found that the recombination of thermal and shower partons in Au+Au collisions is crucial in reproducing the observed spectra at intermediate p_T [14]. It is the thermal-shower recombination that also holds the key to the Cronin effect in pA collisions. It is an effect due to the interaction between soft and hard partons during hadronization in the final state.

Unlike the case of Au+Au collisions at the Relativistic Heavy Ion Collider (RHIC) where the hydrodynamical expansion of a hot, dense system that is created leads to a large body of thermal partons, one does not expect such a scenario in pA collisions. Nevertheless, there are soft partons that take the place of the thermal partons. They can participate in the formation of hadrons at intermediate p_T. Since the number of such soft partons decreases with increasing impact parameter, our approach naturally leads to the Cronin effect.

The inclusive distribution for the production of pions can be written in the recombination model, when mass effects are negligible, in the invariant form [4,11]

$$p\frac{dN_\pi}{dp} = \int \frac{dp_1}{p_1}\frac{dp_2}{p_2} F_{q\bar{q}}(p_1, p_2) R_\pi(p_1, p_2, p), \qquad (1)$$

where $F_{q\bar{q}}(p_1, p_2)$ is the joint distribution of a q and $\bar{q}$ at p_1 and p_2, and $R_\pi(p_1, p_2, p)$ is the recombination function for forming a pion at p: $R_\pi(p_1, p_2, p) = (p_1 p_2/p) \times \delta(p_1 + p_2 - p)$. Restricting $\vec{p}$ to the transverse plane, the distribution $dN_\pi/d^2p dy|_{y=0}$, averaged over all ϕ, with p_T denoted by p, is [14]

$$\frac{dN_\pi}{pdp} = \frac{1}{p^3}\int_0^p dp_1 F_{q\bar{q}}(p_1, p - p_1). \qquad (2)$$

This equation is applicable to any of the pp, pA, and AB collision types; only $F_{q\bar{q}}$ depends on the colliding hadron/

nuclei. In general, $F_{q\bar{q}}$ has four contributing components represented schematically by

$$F_{q\bar{q}} = \mathcal{T}\mathcal{T} + \mathcal{T}S + (SS)_1 + (SS)_2, \qquad (3)$$

where $\mathcal{T}$ denotes soft thermal distribution and S shower distribution. $(SS)_1$ signifies two shower partons in the same hard-parton jet, while $(SS)_2$ stands for two shower partons from two nearby jets. For simplicity, we shall at times abbreviate $(SS)_1$ by SS.

For pA collisions it may not be appropriate to refer to any partons as thermal in the sense of a hot plasma as in heavy-ion collisions. However, in order to maintain the same notation for the decomposition in Eq. (3) independent of the collision types, we persist to use the symbol $\mathcal{T}$ to denote the soft parton distribution at low k_T, although they will occasionally be referred to as thermal partons, when it is more convenient. At low p_T the observed pion distribution is exponential; we identify it with the contribution of the $\mathcal{T}\mathcal{T}$ term. By writing $\mathcal{T}$ as

$$\mathcal{T}(p_1) = p_1 \frac{dN_q^{\mathcal{T}}}{dp_1} = Cp_1 \exp(-p_1/T), \qquad (4)$$

we obtain from Eq. (2) [14]

$$\frac{dN_\pi^{\mathcal{T}\mathcal{T}}}{pdp} = \frac{C^2}{6} \exp(-p/T), \qquad (5)$$

where T is the inverse slope. We shall determine C and T by fitting the d + Au data at low p_T. Given the phenomenological behavior of Eq. (5), the form of Eq. (4) is the simplest and most direct way to achieve the result.

For shower partons we can safely ignore the term $(SS)_2$ in Eq. (3) arising from two hard partons, since the density of hard partons in d + Au collisions at RHIC is not high enough to lead to significant jet-jet overlap. S and $(SS)_1$ involve the partons of only one shower. They are convolutions of the hard-parton distribution $f_i(k)$ with transverse momentum k and the shower parton distributions (SPD) $S_i^j(z)$ from hard-parton i to soft parton j (and j') [13]

$$S_j(p_1) = \sum_i \int_{k_0} dk k f_i(k) S_i^j(p_1/k), \qquad (6)$$

$$(S_j S_{j'})_1(p_1, p_2) = \sum_i \int_{k_0} dk k f_i(k) \left\{ S_i^j\left(\frac{p_1}{k}\right), S_i^{j'}\left(\frac{p_2}{k - p_1}\right) \right\}. \qquad (7)$$

The integrals begin at a minimum k_0 below which the perturbative QCD (pQCD) derivation of $f_i(k)$ is invalid. We set $k_0 = 3$ GeV$/c$. The curly brackets in Eq. (7) signify the symmetrization of the leading parton momentum fraction [14]. We have assumed in Eqs. (6) and (7) that the hard partons suffer no energy losses as they traverse the cold nucleus, since the phenomenon has been well confirmed by experiments [15,16].

The hard-parton distributions $f_i(k)$ depend on the parton distribution functions (PDF) in the proton and nucleus, and on the hard scattering cross sections. For d + Au collisions, Fries has performed the convolution and put the inclusive distribution for the production of a hard parton i at $y = 0$ and at 0%–20% centrality in a generic form over a wide range of k

$$f_i(k) \equiv \frac{1}{\sigma_{\rm in}} \frac{d\sigma_i^{d+{\rm Au}}}{d^2kdy}\bigg|_{y=0} = KA_i\left(1 + \frac{k}{k_i}\right)^{-n_i}, \qquad (8)$$

where $\sigma_{\rm in} = 40.3$ mb has been used. The parameters A_i, k_i, and n_i are given in Table I [17]. Nuclear shadowing effects have been taken into account through the use of EKS98 PDF. The K factor is due to higher order corrections in pQCD. We shall set it at 2.5, as in [10,14,18].

We calculate the three contributions $\mathcal{T}\mathcal{T}$, $\mathcal{T}S$, and SS to $F_{q\bar{q}}$ and then to $dN_\pi^{d+{\rm Au}}/pdp$ in Eq. (2). In the calculation there are two parameters: C and T. They are adjusted to fit the low p_T region of the data. The point of view we adopt is that the soft component specified by C and T is not the predictable part of our model. In treating them as free parameters, we do not compromise the predictable part of our model, which is the magnitude of the contribution from the $\mathcal{T}S$ component in the recombination compared to the other components: $\mathcal{T}\mathcal{T}$ at low p_T and SS at high p_T.

For d + Au collisions at RHIC, PHENIX has identified particle data on π^+ production at $\eta = 0$ [19]. Although p_T is limited to 3 GeV$/c$, the range is sufficient to determine C and T, where the $\mathcal{T}\mathcal{T}$ contribution dominates, and where the deviation from the exponential behavior is just enough to reveal the $\mathcal{T}S$ contribution. Our prediction is the spectrum for $p_T > 1$ GeV$/c$.

We show in Fig. 1 the three components together with their sum for 0%–20% centrality. The agreement with the data from [19] is good, considering the fact that only the exponential component is adjusted to fit. The noteworthy features of our result is that the thermal-shower ($\mathcal{T}S$) and shower-shower (SS) components both become more important than the thermal-thermal ($\mathcal{T}\mathcal{T}$) component above $p_T = 2$ GeV$/c$ and that $\mathcal{T}S$ is greater than SS for $p_T < 3$ GeV$/c$. We repeat our emphasis that the word thermal should not be taken literally, as it refers to soft partons in general. The values of the parameters determined are (for 0%–20% centrality)

$$C = 12 \ ({\rm GeV}/c)^{-1}, \qquad T = 0.21 \ {\rm GeV}/c. \qquad (9)$$

TABLE I. Parameters in Eq. (8) [17].

i	u	d	s	$\bar{u}$	$\bar{d}$	g
A_i	12.371	12.888	1.144	2.638	2.613	63.116
k_i	1.440	1.439	1.935	1.768	1.766	1.718
n_i	7.673	7.662	8.721	8.574	8.586	8.592

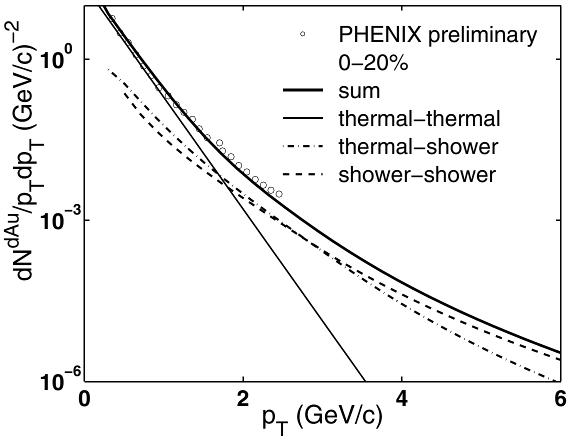

FIG. 1. Pion distribution in transverse momentum compared to the data on π^+ from PHENIX [19] on d + Au collisions at $\sqrt{s} = 200$ GeV and 0%–20% centrality. The three components in the recombination model are $\mathcal{TT}$ (light solid line), $\mathcal{TS}$ (dashed-dot line), and $\mathcal{SS}$ (dashed line). Heavy solid line is the sum of all three components.

With the above value of T we obtain from Eq. (5) for the soft component of the pions ($p_T \equiv p$)

$$\langle p_T \rangle = 2T = 0.42 \text{ GeV/c}, \qquad \langle p_T^2 \rangle = 6T^2 = 0.26(\text{GeV/c})^2, \tag{10}$$

while Eq. (4) implies for the intrinsic transverse momentum k_T of the partons ($k_T \equiv p_1$)

$$\langle k_T \rangle = T = 0.21 \text{ GeV}/c, \qquad \langle k_T^2 \rangle = 2T^2 = 0.09 \ (\text{GeV}/c)^2. \tag{11}$$

While the numbers in Eq. (10) are conventional, the intrinsic width of the partons in Eq. (11) is very small compared to what is needed in the fragmentation models, generally $\langle k_T^2 \rangle > 1$ (GeV/c)^2, even before broadening [3].

The shower-shower component in Fig. 1 is dominant for $p_T > 5$ GeV/c; it is the same as the usual contribution from parton fragmentation [13,14]. The thermal-shower recombination is a unique feature of our model. It makes a dominant contribution in the $3 < p_T < 8$ GeV/c range in Au + Au collisions because of the large thermal component in the hot, dense system [14]. Here in the cold system only slightly excited, the values of C and T are lower, compared to 23.2 (GeV/c)$^{-1}$ and 0.317 GeV/c, respectively, in Au + Au collisions. Thus the $\mathcal{TS}$ contribution is subdued, but still large enough not only to cause a substantial deviation of the spectrum from exponential behavior, but also to give rise to the Cronin effect without large intrinsic $\langle k_T^2 \rangle$ broadening, as we shall show. The ratio $\mathcal{TS}/\mathcal{SS}$ is independent of the normalization of $f_i(k)$ and hence unaffected by the value of K.

For other centralities of d + Au collisions we fix T at the value determined for 0%–20% centrality, i.e., $T =$ 0.21 GeV/c, and use the values of $\langle N_{\rm coll} \rangle$ given in [19] to rescale $f_i(k)$. We adjust the value of C to fit the low p_T normalization of the data [19]. The results we obtain for $dN_\pi^{d+\text{Au}}/pdp$ for all four centralities are shown in Fig. 2 and are in good agreement with the data. The main point to stress is that the soft parton $\langle k_T^2 \rangle$ width remains the same at 0.09 (GeV/c)^2, without being broadened by successive kicks before hard scattering. In our approach what are different at more peripheral collisions are the decreasing values of C, which are 11, 7.8, and 5.65 for 20%–40%, 40%–60%, and 60%–90%, respectively. The decrease of the density of the soft partons is a reasonable property of less central collisions, and can be generated in a Monte Carlo code; we merely take it from data, since it involves no new physics. The physics issue we want to emphasize is that the thermal-shower parton recombination is sensitive to the density of soft partons, and that component of the hadronization product affects the spectra in the moderately higher p_T region, $1 < p_T < 4$ GeV/c.

There are inaccuracies in our calculation due to the use of the lowest order pQCD results for the parameters in Table I, and the SPDs that inherit the uncertainties of the FFs. However, their effects tend to cancel, if we take the ratio of the calculated spectra at different centralities. PHENIX has preliminary data on the central-to-peripheral nuclear modification factor [19]

$$R_{\rm CP}(p_T) = \frac{\langle N_{\rm coll} \rangle_{60\%-90\%} dN_\pi^{d+\text{Au}}/p_T dp_T(0\% - 20\%)}{\langle N_{\rm coll} \rangle_{0\%-20\%} dN_\pi^{d+\text{Au}}/p_T dp_T(60\% - 90\%)} \tag{12}$$

for $p_T < 6$ GeV/c. We can determine $R_{\rm CP}(p_T)$ directly from the results of our calculation; it is shown in Fig. 3. Evidently, the theoretical curve agrees very well with the data [19]. The agreement clearly lends support to our view that the Cronin effect is due to the recombination

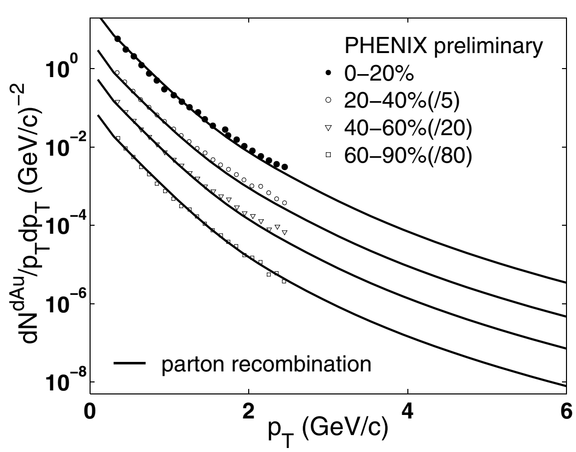

FIG. 2. Same as in Fig. 1 but for different centralities. The inverse slope T is the same in all cases; C is varied to fit the low-p_T region.

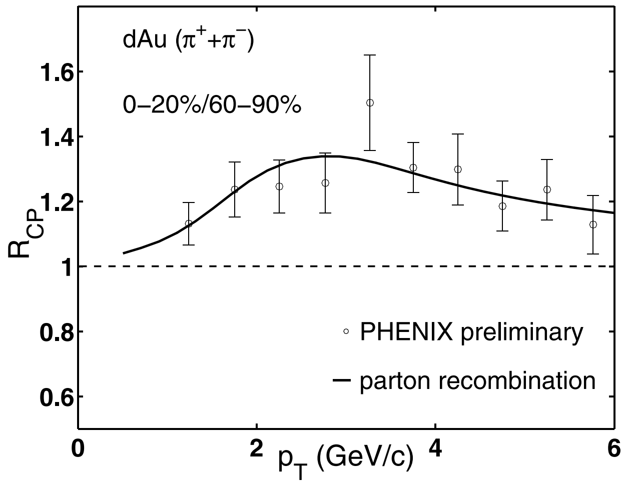

FIG. 3. Central-to-peripheral nuclear modification factor. The data is from PHENIX for $d + \mathrm{Au}$ collisions at $\sqrt{s} = 200$ GeV [19]. The solid curve is the result of our calculation without adjustable parameter.

of soft and shower partons in the final state without initial-state broadening.

Based on the physical reason for the enhancement of $R_{\rm CP}^{\pi}$ in Fig. 3, we can infer qualitatively here that for proton production, the corresponding $R_{\rm CP}^{p}$ should be even higher in the same region. The reason is that for three quarks to recombine in forming a proton, the $\mathcal{TTT}$ contribution has a cubic dependence on C, and is therefore more sensitive to centrality. Consequently, as the collisions become more central, $dN_p^{d+\mathrm{Au}}/p_T dp_T$ should receive a larger boost from $\mathcal{TTT}$ than does $dN_\pi^{d+\mathrm{Au}}/p_T dp_T$ from $\mathcal{TT}$, resulting in $R_{\rm CP}^{p}$ being higher than $R_{\rm CP}^{\pi}$. The data of PHENIX [19] show that such a behavior has already been observed. That behavior is hard to interpret in a fragmentation model, since the broadening of the parton k_T width in the initial state should be independent of what a hard parton fragments into. The details on proton production and $R_{\rm CP}^{\pi}$ are given in [20].

In conclusion, we have shown, both here and in [14], that the separation of final states into independent and noninteracting soft and hard components is invalid, except when p_T is very large. At intermediate p_T where the Cronin effect is found, the interaction between the soft and shower partons is important. Since the density of soft partons depends on the number of participants even in $d + \mathrm{Au}$ collisions, the hadron spectra at intermediate p_T depend on centrality. Thus the enhancement of hadron production in more central collisions is a final-state effect, in contrast to the usual explanation in terms of initial-state fluctuations. The Cronin effect may now be regarded as another phenomenon in support of the recombination model besides the large p/π ratio and scaling elliptical flow [21]. Our result gives credence to our assertion that shower partons form an essential component in the final state of a quark-gluon system produced in a heavy-ion collision before hadronization takes place, but whose existence has hitherto been overlooked.

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