

Forward production in $d + \text{Au}$ collisions by parton recombinationRudolph C. Hwa,¹ C. B. Yang,^{1,2} and R. J. Fries³¹*Institute of Theoretical Science and Department of Physics, University of Oregon, Eugene, Oregon 97403-5203*²*Institute of Particle Physics, Hua-Zhong Normal University, Wuhan 430079, China*³*School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota 55455*

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Hadron production at forward rapidities in $d + \text{Au}$ collisions is studied in the framework of parton recombination in the final state. Multiple scattering and gluon saturation in the initial state are not explicitly considered. The recombination of soft and shower partons is found to be important. The soft parton densities are determined by extrapolation from the parametrization fixed at $\eta = 0$ with no unconstrained adjustments. The suppression of R_{CP} observed at high η is understood as the simple consequence of the reduction of the soft parton density on the deuteron side compared to that on the gold side. The effect of momentum degradation responsible for baryon stopping is also considered. The asymmetry of backward-to-forward spectra can be reproduced within the same framework without any change in the basic physics.

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I. INTRODUCTION

Particle production at forward rapidities in $d + \text{Au}$ collisions has recently been recognized as a fertile ground for testing models of hadron production that embody diverse physical mechanisms. Because no hot and dense medium is created in $d + \text{Au}$ collisions, they have generally been regarded as a type of collision process where the effects of final-state interaction (FSI) are minimal, thus allowing the physics of initial-state interaction (ISI) to manifest itself most transparently [1–3]. This is especially true at forward rapidities where the saturation effect is expected to be important and the physics of color glass condensate (CGC) may dominate [1–6]. Alternative approaches to the problem based primarily on perturbative QCD (pQCD) have also been considered with emphasis on the effects of nuclear shadowing [7,8]. The results do not provide unambiguous interpretation of the data from BRAHMS [9]. We consider in this paper yet another approach that emphasizes the hadronization part of the FSI and takes into account hard scattering in pQCD; however, instead of fragmentation we consider the recombination of soft and shower partons. Our treatment is an extension to the forward region of what has been found to be successful at midrapidity for Au + Au collisions [10] and for $d + \text{Au}$ collisions [11] and is a natural mechanism for hadronization at intermediate transverse momentum p_T . It does not, in principle, contradict the physics of CGC. The issues are whether hadronization by recombination is important and which one of the competing effects is dominant in the kinematical region under examination. Our results indicate that the BRAHMS data [9] can be well reproduced in our approach even when no adjustable parameters are used.

Experiments at the Relativistic Heavy Ion Collider (RHIC) have found that the ratio, R_{CP} , of $d + \text{Au}$ central to peripheral inclusive spectra for $1 < p_T < 3 \text{ GeV}/c$ decreases monotonically from a value ~ 1.8 at pseudorapidity $\eta \sim -2$ to a value ~ 0.5 at $\eta \sim 3.2$ [9,12]. 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 ($\eta > 0$) [1]. For $\eta \leq 0$

the enhancement of the particle yield at intermediate p_T with respect to binary collision scaling, that is, the Cronin effect [13], is generally regarded as the result of multiple scattering in ISI [14,15]. For $\eta > 0$ saturation physics is considered to be dominant, especially at large η , so that there is suppression, instead of enhancement, in particle production [3,5,6]. Neither effect takes into account any details about hadronization in FSI. Such explanations of the data cannot account for the phenomenological fact that R_{CP}^p (for protons) is larger than R_{CP}^π (for pions) at intermediate p_T [16]. Hadronization of partons to a proton or a pion is an issue that involves the final state, and the use of fragmentation functions (FFs) appropriate for the produced hadrons in the usual factorizable way would necessarily yield a p/π ratio < 1 by virtue of the nature of the FFs, contrary to what has been observed [17].

The subject of a large p/π ratio has been addressed by several groups that consider parton recombination as the hadronization process in the final state in Au + Au collisions [18–20]. For hadrons produced at intermediate p_T it is the recombination of thermal partons at lower p_T that gives rise to the higher yield of the baryons compared to mesons. In Ref. [10] the additional component of the recombination of thermal and shower partons is introduced, and it is shown to be dominant in the $3 < p_T < 9 \text{ GeV}/c$ range. That component turns out to be crucial to explain the Cronin effect, when the formalism is extended to $d + \text{Au}$ collisions, without the need for any k_T broadening in ISI [11]. Although there are no thermal partons in $d + \text{Au}$ collisions as in Au + Au collisions, there are soft partons that play the same role. It is found that the property $R_{\text{CP}}^p > R_{\text{CP}}^\pi$ at intermediate p_T can readily be reproduced in the recombination model [11,21]. Based on the success of that description of particle production at midrapidity in $d + \text{Au}$ collisions, we now extend the treatment to the forward region ($\eta > 0$) without the introduction of any new physics. This extension should be considered whether or not the signature of new physics is present in the forward region, since the contribution from conventional physics forms the background that must be understood to facilitate the identification of any new signal. As we shall show, it seems

that recombination in FSI is completely adequate to explain the suppression at large η .

The main reason for R_{CP} to decrease with increasing η is simple. Since the recombination process that involves soft partons is important, the dependencies of the soft parton density on rapidity and centrality directly affect the particle spectra at intermediate p_T . The density that is reflected in $dN/d\eta$ is known to decrease with increasing η with the consequence that R_{CP} also decreases with η . Since CGC has successfully reproduced the hadron multiplicity $dN/d\eta$, one may take the view that the suppression at large η has its origin in saturation physics. That may be the case. From the point of view of FSI the suppression is a direct result of parton recombination involving soft partons whose density decreases with η ; indeed, our treatment of hadron production is compatible with any model that can generate the soft parton spectra that we shall determine phenomenologically.

Before we consider hadron production quantitatively, let us make some general remarks here on recombination. Since the formation of a pion by a $q\bar{q}$ pair implies the loss of degrees of freedom, it is sometimes thought that the recombination process leads to a decrease of entropy. However, the entropy principle should not be applied locally. A global consideration must recognize that the bulk volume is increasing during the hadronization process, and thus this compensates the decrease of entropy density that is a local quantity. Furthermore, in the $q\bar{q} \rightarrow \pi$ process a color singlet is formed by color mutation of the quarks through soft gluon radiation that carries the extra degrees of freedom without significantly altering the local relation that the sum of the parton momenta equals the pion momentum. All gluons hadronize by conversion to $q\bar{q}$ pairs first, so there is a cascading of the degrees of freedom to lower and lower momentum regions where the pion multiplicity accumulates. Eventually all degrees of freedom are converted from partons to hadrons. Such nonperturbative processes cannot be calculated, and our formalism does not contain explicitly the feed-down process of partons cascading to the very low p_T region before recombination. Indeed, such a process need not be made explicit in our approach, since we do not determine the soft parton distribution in a model of evolution from the initial state. Instead, we determine the soft parton distribution from the observed pion distribution in the $0.5 < p_T < 2$ GeV/ c region. The soft partons thus obtained are defined in the context of recombination. We use them in the same context when we consider their recombination with shower partons. Thus our procedure of treating hadronization at all $p_T > 0.5$ GeV/ c is totally self-consistent.

It is also appropriate at this point to make another general remark about our treatment of recombination. In a one-dimensional (1D) formulation of the recombination process in momentum space, one may question whether we are ignoring the spatial extent of the recombining subsystem normal to the collinear momentum vectors of the quarks and hadrons. Partons that are separated by a distance of the order of the transverse size of the bulk volume but have parallel momenta are not likely to recombine. That is indeed an issue that has to be faced in a model in which the spatial and momentum distributions of the partons are generated from the initial state and evolve according to some sensible dynamics. However,

that is not what we do, as we have already stated at the end of the preceding paragraph. For the soft parton distribution, which forms the crux of the issue here, we start from the observed soft pion distribution. For every \vec{p} of such a pion we claim that it can only arise from the recombination of a quark at \vec{p}_1 and an antiquark at \vec{p}_2 that are not only collinear in momentum vectors but also spatially overlapping within a transverse space of the order of a hadron. In other words, because we determine the soft parton distribution from the final state, the result automatically implies that only those partons can recombine to give the observed hadron. The 1D formulation of recombination is therefore appropriate for the way in which it is applied.

II. PION PRODUCTION AT $\eta = 0$

We summarize first the production of pions by parton recombination at midrapidity in $d + Au$ collisions and make minor adjustments to align our calculation for the centrality cuts of the BRAHMS experiment [9]. We use the formalism for hadronization described in Refs. [10,11], where the inclusive distribution of a pion at $\eta = 0$ in a 1D description is given by

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

where p is in the direction of the detected pion, $F_{q\bar{q}'}(p_1, p_2)$ is the joint distribution of a q and a \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 : $R_\pi(p_1, p_2, p) = (p_1 p_2 / p) \delta(p_1 + p_2 - p)$. For p in the transverse plane so that $p_T = p$, the distribution $dN_\pi/d^2p d\eta|_{\eta=0}$, averaged over all ϕ , is

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

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

$$F_{q\bar{q}'} = \mathcal{T}\mathcal{T} + \mathcal{T}\mathcal{S} + \mathcal{S}\mathcal{S}, \quad (3)$$

where \mathcal{T} stands for soft parton distribution and \mathcal{S} for shower parton distribution. For Au + Au collisions \mathcal{T} would refer to the thermal partons [10], but in $d + Au$ collisions the notion of thermalization is inappropriate, but soft partons nevertheless exist. Since they are treated in the same way, the same notation is used with \mathcal{T} , which can be regarded as referring to the last letter of ‘‘soft.’’ At low p_T the observed pion distribution is exponential, which suggests the form

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

so that the $\mathcal{T}\mathcal{T}$ component in Eq. (3) yields

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

The values of C and T have been determined in Ref. [11] already from the low- p_T $d + Au$ data. Since our approach to hadron production at intermediate p_T at RHIC is to emphasize parton recombination in the final state, we use the phenomenological input for the soft component, without

relying on any specific model for soft partons so that our result will be independent of the reliability of such models.

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

$$\mathcal{S}_j(p_1) = \sum_i \int_{k_{\min}} dk k f_i(k) S_i^j(p_1/k) \quad (6)$$

where k_{\min} is set at 3 GeV/c, below which the pQCD derivation of $f_i(k)$ is invalid. For each i , $f_i(k)$ depends on the parton distribution functions, nuclear shadowing, and hard scattering cross sections. The result is presented in power-law form, whose parameters are tabulated in Ref. [11]. The SPDs are obtained from the FFs and are given in Ref. [22].

It is sufficient with this specification of \mathcal{T} and \mathcal{S} to calculate the p_T spectrum of the pion by use of Eq. (2). However, for comparison with the BRAHMS data we need the values of C for the corresponding centrality cuts. Let us use β to denote the centrality cut, which is an experimental quantity related to the impact parameter b . In Ref. [11] it is found that $C(\beta, \eta)$ varies with β at $\eta = 0$ as $C(\beta, 0) = 12, 11, 7.8,$ and $5.65 \text{ (GeV/c)}^{-1}$ for $\beta = 0\text{--}20, 20\text{--}40, 40\text{--}60,$ and $60\text{--}90\%$, respectively. The centrality cuts of BRAHMS [9] are $\beta = 0\text{--}20, 30\text{--}50,$ and $60\text{--}80\%$. We therefore make the interpolation and set $C(\beta, 0) = 12, 9.0,$ and $6.55 \text{ (GeV/c)}^{-1}$, respectively. The value of the inverse slope is $T = 0.208 \text{ GeV/c}$, as determined in Ref. [11].

Before showing the result, we remark that the $\mathcal{S}\mathcal{S}$ component in Eq. (3) corresponds to fragmentation, if the two shower partons originate from the same hard parton, that is,

$$(\mathcal{S}_j \mathcal{S}_{j'}) (p_1, p_2) = \sum_i \int_{k_{\min}} dk k f_i(k) \times \left\{ S_i^j \left(\frac{p_1}{k} \right), S_i^{j'} \left(\frac{p_2}{k - p_1} \right) \right\}, \quad (7)$$

where the curly braces signify the symmetrization of the leading parton momentum fraction [10,22]. If the two shower partons are from two independent jets, then there would be two $f_i(k)$ distributions. The recombination of such partons is very unlikely to occur in $d + \text{Au}$ collisions at 200 GeV/c and will be ignored.

The results of our calculation for π^+ production are shown in Fig. 1 for the three centralities, displaced by factors of 10^2 from neighboring ones. The light solid lines show the soft-soft ($\mathcal{T}\mathcal{T}$) components that are straight lines in the log plot. The dashed lines show the soft-shower ($\mathcal{T}\mathcal{S}$) contributions and the dash-dotted lines the shower-shower ($\mathcal{S}\mathcal{S}$) contributions. The heavy solid lines are the sums, whose deviations from the straight lines are indicative of the effects of hard scattering. Note that the $\mathcal{T}\mathcal{S}$ contribution becomes less important as β increases because $C(\beta, 0)$ decreases. Indeed, if the $\beta = 60\text{--}80\%$ case is regarded as being almost like the pp collision, we see from Fig. 1 that the neglect of the $\mathcal{T}\mathcal{S}$ contribution does not constitute a bad approximation, and the large p_T behavior is essentially governed by jet fragmentation, as has traditionally been used to treat pp collisions. However, that is not the case for central $d + \text{Au}$ collisions. The $\mathcal{T}\mathcal{S}$ contribution to the spectra is what accounts for the Cronin enhancement at

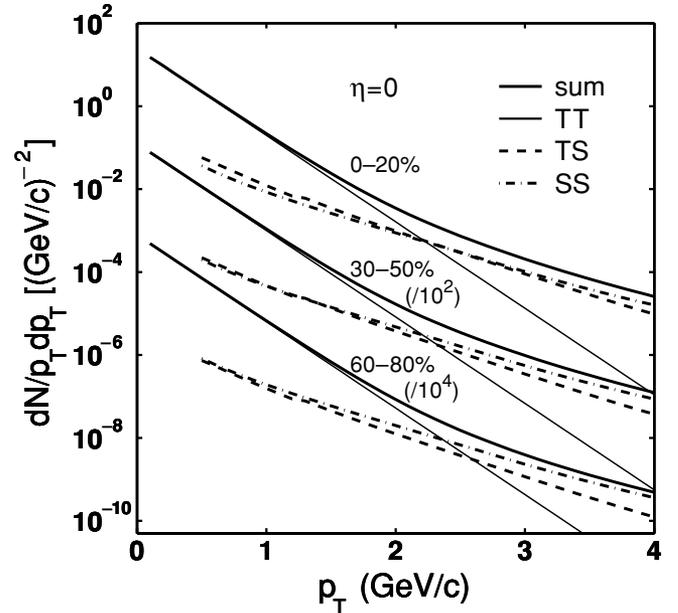


FIG. 1. Transverse momentum distributions of π^+ produced at midrapidity in $d + \text{Au}$ collisions for three centrality cuts. Light solid lines are for the recombination from the $\mathcal{T}\mathcal{T}$ component, dashed lines for $\mathcal{T}\mathcal{S}$, and dashed-dotted lines for $\mathcal{S}\mathcal{S}$ components. Heavy solid lines are the sums of all three components.

intermediate p_T without k_T broadening due to ISI [11]. The p_T distributions have been shown to agree with the PHENIX data [16]. The R_{CP} ratio for the β values of the BRAHMS data will be shown in Fig. 5 later.

III. PION PRODUCTION AT $\eta > 0$

Because the formalism for pion production at $\eta = 0$ described in the preceding section successfully reproduces the experimental p_T spectra at all centralities, we now make a straightforward extension to the $\eta > 0$ region. This extension should be made with no change in the basic physics underlying the formalism to provide a baseline for comparison with the data before the search for the signature of any other physical origin.

The quantities that must be modified for the $\eta > 0$ region are $C(\beta, \eta)$ for \mathcal{T} and $f_i(k)$ for \mathcal{S} . For the inverse slope T we shall proceed in two steps. First, we keep T fixed as η is increased, since no data on low- p_T π^+ spectra are available to serve as our guide for its modification. It is of interest to see how close the calculated R_{CP} will turn out to be in comparison to the data, when the constant- T assumption is applied for the purpose of introducing no adjustable parameter. Later, we shall allow T to depend weakly on β and η and show that the fit of R_{CP} can be improved.

Since the observed rapidity density $dN_{\text{ch}}/d\eta$ is an integral over the p_T distribution, which is dominated by the soft contribution at low p_T , we see from Eq. (5) that $dN_{\text{ch}}/d\eta$ should be proportional to $C^2(\beta, \eta)$. We can therefore determine

TABLE I. Values of $C(\beta, \eta)$ in $(\text{GeV}/c)^{-1}$.

β	η			
	0	1	2.2	3.2
0–20%	12.0	11.1	9.01	7.05
30–50%	9.0	8.5	7.9	6.0
60–80%	6.55	6.6	6.1	5.1

$C(\beta, \eta)$ by use of the formula

$$C(\beta, \eta) = C(\beta, 0) \left[\frac{dN_{\text{ch}}/d\eta(\beta)}{dN_{\text{ch}}/d\eta|_{\eta=0}(\beta)} \right]^{1/2}, \quad (8)$$

where $C(\beta, 0)$ is given in the preceding section, and $dN_{\text{ch}}/d\eta(\beta)$ is known from PHOBOS data [23]. We thus obtain the values of $C(\beta, \eta)$ as shown in Table I. Since PHOBOS does not have exactly the same centrality cuts as BRAHMS, some interpolation between neighboring values have been made to deduce the numbers in Table I.

We have parametrized the hard parton distributions $f_i(k_T, y)$, as before [11,24], in the power-law form

$$f_i(k_T, y) \equiv \frac{1}{\sigma_{\text{in}}} \frac{d\sigma_i^{d+\text{Au}}}{d^2k_T dy} = K A_i \left(1 + \frac{k_T}{B_i} \right)^{-n_i} \quad (9)$$

for $y \leq 1$. For larger values of y the spectra are increasingly suppressed at high k_T because of the phase space boundary that requires $k_T < k_0(y)$. The kinematic limit is given by $k_0(\eta) = \sqrt{s}/(2 \cosh y)$ and takes the values 21.9 and

8.13 GeV/ c for $y = 2.2$ and 3.2 , respectively. To take into account the change of $f_i(k_T, y)$ from positive to negative curvature around $k_T \approx 0.5 k_0$, Eq. (9) must be modified by a dampening factor. Therefore we use the parametrization

$$f_i(k_T, y) = K A_i \left(\pm 1 + \frac{k_T}{B_i} \right)^{-n_i} \left(1 - \frac{k_T}{k_0} \right)^{m_i} \quad (10)$$

for $y > 1$, where the ± 1 sign is used in accordance to whether the given value of B_i is preceded by a + or – sign.

The parametrizations are obtained from leading order minijet calculations using the CTEQ5 parton distributions [25]. EKS98 shadowing [26] was used for the Au nucleus whereas the deuteron was treated as a superposition of a proton and a neutron without further nuclear modifications. The values of all the parameters for central $d + \text{Au}$ collisions ($\beta = 0\text{--}20\%$) are given in Table II, corresponding to $\sigma_{\text{in}} = 40.3$ mb and an unspecified K factor. For other centralities, scaling in the number of binary collisions, N_{coll} , is assumed. We set $K = 2$ in our calculation that follows.

Using $C(\beta, \eta)$ in Eq. (4) and $f_i(k_T, y)$ in Eq. (6), neglecting the difference between η and y for $\eta \geq 1$, and fixing T at 0.208 GeV/ c as for $\eta = 0$, we can now calculate $dN_{\pi^+}/p dp d\eta$ according to Eqs. (2) and (3) and obtain the results shown in Fig. 2 for $\beta = 0\text{--}20\%$ and $60\text{--}80\%$, with that for $30\text{--}50\%$ being in between the two. Clearly, the p_T distributions are affected by the increase of η mainly in the large- p_T region. There are smaller changes at low p_T as seen in the log scale, although they are not negligible in the linear scale, since the spectra there are proportional to $C^2(\beta, \eta)$, which varies substantially

TABLE II. Parameters in Eqs. (9) and (10).

y	i	g	u	d	s	\bar{u}	\bar{d}
–0.75	A	196.52	55.65	60.74	3.114	11.55	12.23
	B	1.442	1.064	1.045	1.657	1.330	1.292
	n	8.654	7.533	7.483	8.798	8.385	8.319
–0.25	A	254.06	61.64	65.26	3.953	13.35	13.27
	B	1.265	0.996	0.990	1.456	1.228	1.223
	n	8.207	7.314	7.293	8.320	8.102	8.101
0.25	A	244.63	59.51	61.57	3.786	13.02	12.50
	B	1.260	0.991	0.993	1.453	1.218	1.229
	n	8.175	7.281	7.280	8.292	8.068	8.099
0.75	A	177.86	51.35	51.93	2.745	10.88	10.34
	B	1.419	1.039	1.050	1.646	1.291	1.308
	n	8.546	7.420	7.439	8.711	8.263	8.308
1.0	A	132.78	43.64	43.70	2.030	9.016	8.580
	B	1.600	1.103	1.120	1.874	1.384	1.402
	n	8.959	7.590	7.621	9.192	8.496	8.544
2.2 ($k_0 = 21.9$)	A	12460	5.68×10^6	1.77×10^7	65.35	6.562×10^{12}	1.045×10^8
	B	0.3184	(–)0.03396	(–)0.0277	0.4420	0.2662×10^{-3}	0.02054
	n	5.939	4.873	4.897	5.900	5.191	5.241
	m	7.000	5.320	5.341	7.657	5.966	5.951
3.2 ($k_0 = 8.13$)	A	10080	2.391×10^5	2.349×10^5	30.396	485.45	814.80
	B	0.3360	(–)0.05117	(–)0.05218	0.6214	(–)0.1410	(–)0.1287
	n	5.977	4.539	4.555	6.545	4.574	4.607
	m	6.024	4.548	4.559	6.189	4.943	4.948

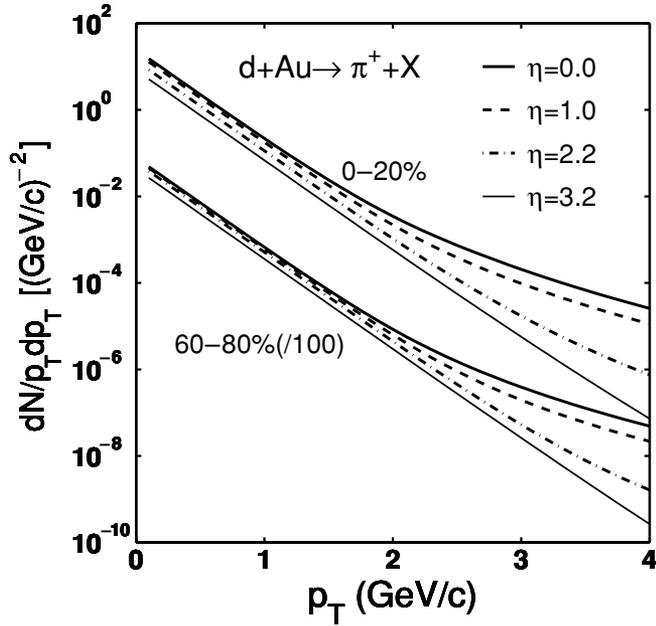


FIG. 2. Transverse momentum distributions of π^+ produced at different pseudorapidities for two centrality cuts.

with η according to Table I. The η dependence of the p_T distributions in Fig. 2 is our prediction for which we have not adjusted any free parameters. No data on identified pions are currently available to check those results.

The notable feature of Fig. 2 is that at $\eta = 3.2$ the p_T distributions behave nearly as straight lines in the log plot. The exponential behavior suggests that only the soft partons contribute to the pion formation. To see this more clearly, we show in Fig. 3 the different contributions to the spectra for $\beta = 0-20\%$ and $\eta = 3.2$. Indeed, the TS and SS components

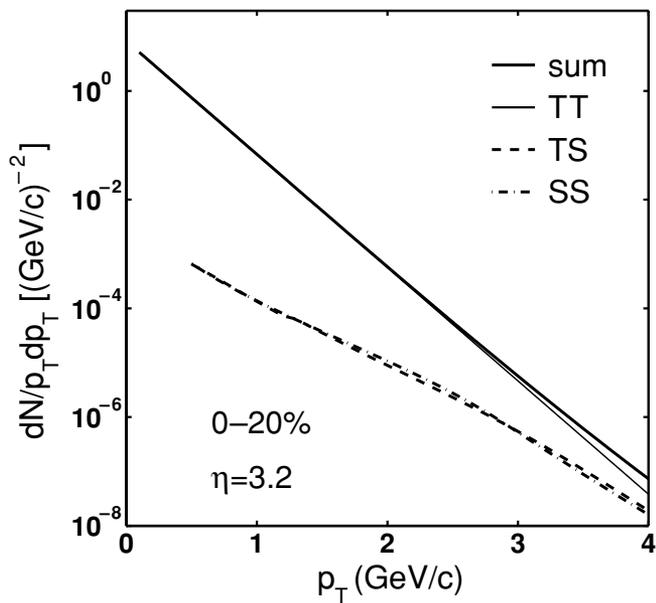


FIG. 3. Transverse momentum distributions of π^+ produced at $\eta = 3.2$ for 0–20% centrality, showing the three components.

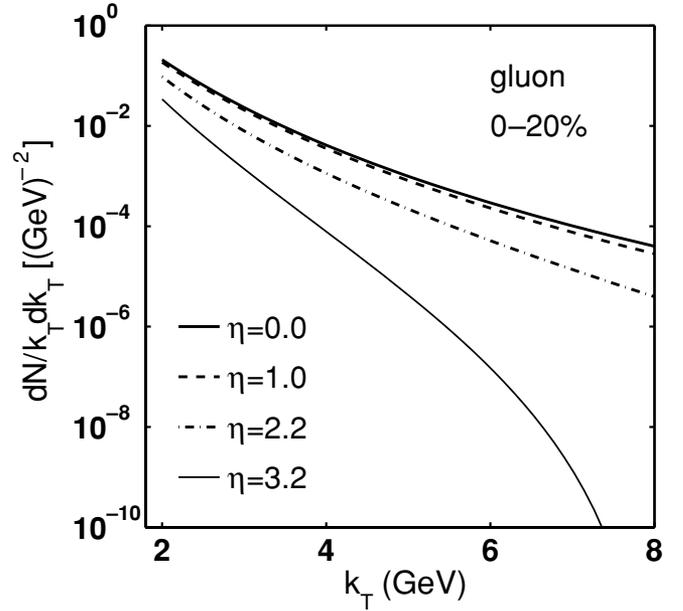


FIG. 4. Distribution of gluons produced in central $d + \text{Au}$ collisions at four pseudorapidities.

are much smaller than the TT component, and they are insignificant for $p_T < 3 \text{ GeV}/c$. The reasons are twofold: The soft parton density is lower at $\eta = 3.2$, and the hard parton distributions are severely suppressed at high k_T . The former is evident in Table I; the latter is not as obvious in Table II. We plot the gluon distributions in Fig. 4 for the four values of η , and we see the precipitous fall for $\eta = 3.2$, as k_T approaches the kinematical limit at $k_T = 8.13 \text{ GeV}/c$. The suppression of $f_i(k_T, \eta)$ does not reduce the S term quadratically because $f_i(k_T, \eta)$ appears only once in Eq. (7). Consequently, the TS and SS components can have comparable magnitudes in Fig. 3. Their significantly reduced contribution to the overall distribution exposes the TT contribution to be the dominant component for p_T up to 3 GeV/c . One can reasonably question the validity of extrapolating the soft parton distribution $\mathcal{T}(p_1)$ to $p_1 \sim 1.5 \text{ GeV}/c$ in its exponential form. Our view is that, instead of adopting some low- p_T model, which has its own ambiguities, it is sensible to use the exponential form of Eq. (4) for the soft parton distribution as a working hypothesis without introducing extra free parameters so as to make predictions that can be tested experimentally. The important observation is that the hard partons are suppressed at high η and that any prediction by pQCD should not neglect the soft background, which is shown to be more important than fragmentation at high η .

Having obtained the pion spectra at all β and η , we can now calculate the central-to-peripheral ratio

$$R_{\text{CP}}(\beta, \eta) = \frac{dN_{\pi}/p_T dp_T d\eta(\beta)/\langle N_{\text{coll}}(\beta) \rangle}{dN_{\pi}/p_T dp_T d\eta(\beta_p)/\langle N_{\text{coll}}(\beta_p) \rangle}, \quad (11)$$

where the reference $\beta_p = 60-80\%$ and $\langle N_{\text{coll}}(\beta) \rangle$ is the average number of binary collisions at β . The results for $\beta = 0-20\%$ and 30–50% are shown in Fig. 5 for the four values of η . The data points are for $(h^+ + h^-)/2$ for $\eta = 0$ and 1, and

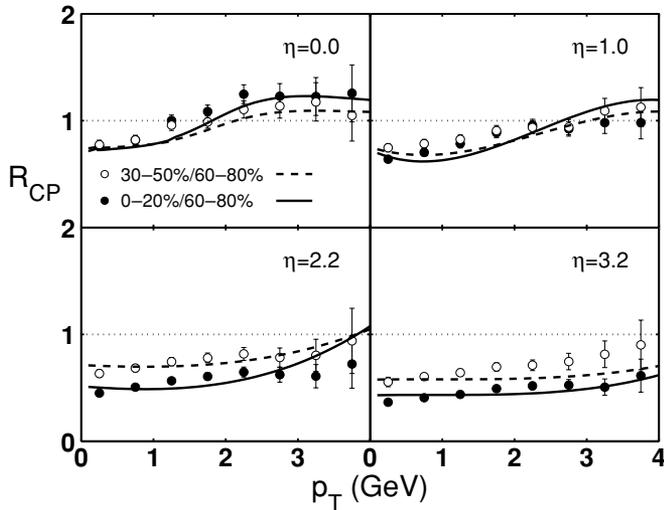


FIG. 5. R_{CP} for 0–20%/60–80% (filled circles and solid lines) and 30–50%/60–80% (open circles and dashed lines) for four pseudorapidities when T is assumed to be constant. Data are from [9]. No momentum degradation is considered in the calculation.

for h^- for $\eta = 2.2$ and 3.2 [9]. The case of $\eta = 0$ shows the Cronin effect, which is well described by our result, where the solid line is for $\beta = 0$ –20% and the dashed line for $\beta = 30$ –50%. As in Ref. [11], no k_T broadening by multiple scattering in ISI has been put in. For $\eta \geq 1$, although the agreement of our results with the data is not perfect, they nevertheless exhibit the essence of the trend; that is, R_{CP} becomes smaller as η is increased. That feature has been regarded as a distinctive characteristic of forward production and is now approximately reproduced by our treatment, which contains no new physics and no adjustable parameters. The case of $\eta = 3.2$ is the simplest to interpret, since the shower contribution is insignificant. The constancy of R_{CP} in our result for $p_T < 3$ GeV/ c is a consequence of the fact that we have fixed the value of the inverse slope T for the soft parton distribution, independent of centrality. The suppression of R_{CP} at $\eta = 3.2$ is due to the decrease of $C(\beta, \eta)$ with increasing η and the insufficiently fast decrease of $C(\beta, \eta)$ with increasing β to overcome the decrease of $\langle N_{coll}(\beta) \rangle$ that rescales the spectra in Eq. (11). In short, since the density of soft partons diminishes as one goes far into the deuteron side, less particles are produced by the recombination of those soft partons.

In the foregoing we have fixed T for all β and η as an assumption for the sake of not making it an adjustable parameter. The theoretical results, as shown in Fig. 5, are remarkably close to the data. However, a mild dependence of T on β and η cannot be excluded. Indeed, the increase of R_{CP} with p_T in the data at $\eta = 3.2$ suggests a decrease of T with β . We adopt a simple parametrization of that dependence as follows:

$$T(\beta, \eta) = T_0(1 - \varepsilon\beta\eta). \quad (12)$$

Since R_{CP} is plotted in linear scale in Fig. 5, it is possible to determine ε by fitting the data at $\eta = 3.2$, despite the absence of the spectra themselves (which would be in log scale and insufficiently accurate to determine small differences in

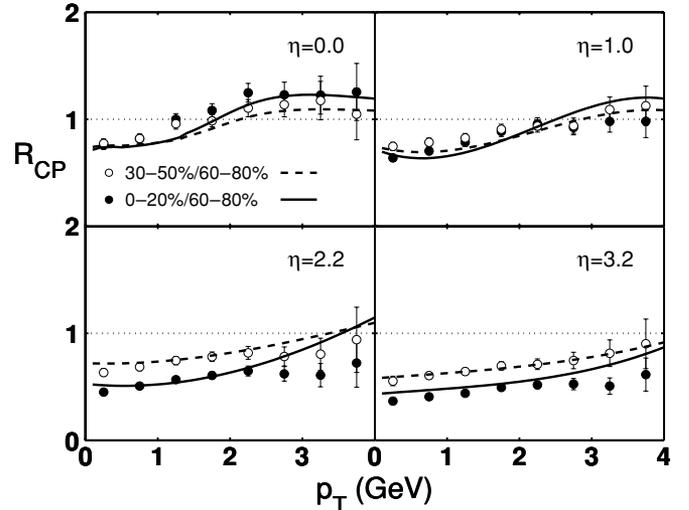


FIG. 6. Same as for Fig. 5 but with $T(\beta, \eta)$ given by Eqs. (12) and (13).

T by themselves separately). We fix $T_0 = 0.208$ GeV (more precisely, $T_0^{-1} = 4.8/\text{GeV}$), and we set $\beta = 0.1, 0.4,$ and 0.7 for 0–20%, 30–50%, and 60–80% centrality, respectively. We vary ε to obtain the best fit of the data in open circles at $\eta = 3.2$ in Fig. 5, obtaining

$$\varepsilon = 0.0205. \quad (13)$$

The results for all other values of β and η are shown in Fig. 6. Compared to Fig. 5, there is a slight improvement of the agreement with data at $\eta = 1.0$, but the theoretical result is a little higher than the data at $\eta = 2.2$ for $p_T > 2.5$ GeV/ c . Generally speaking, the trend of the data with increasing p_T is better reproduced when $T(\beta, \eta)$ is allowed to decrease slightly with β and η . That decrease is less than 4.6%, even at the highest values of β (0.7) and η (3.2). Thus the constant- T assumption is not a bad approximation and serves to reproduce the data reasonably well as in Fig. 5. However, we have not yet exhausted all aspects of physics that can influence the fit of the data.

IV. MOMENTUM DEGRADATION

There is a piece of physics that we have not yet considered, but it is a phenomenological fact that should not be ignored. Baryon stopping generally refers to the loss of projectile proton momentum in pA collisions, as it passes through a target nucleus. Although such nomenclature is misleading from the point of view of the role that the proton constituents play, empirical evidence for the momentum degradation of the detected nucleon as a function of the nuclear size is not disputed. A number of experiments have shown that the produced nucleon distribution in pA collisions has an exponential form in x_F :

$$\frac{dN_N}{dx_F} \propto \exp[-\Lambda(\nu)x_F], \quad (14)$$

where the slope $\Lambda(\nu)$ depends on the average number of collisions ν [27,28]. Baryon stopping loosely refers to the

phenomenon that $\Lambda(\nu)$ increases with ν . Our question here is whether such a behavior has a dynamical origin that can affect our treatment of forward production in $d + Au$ collisions. The question is relevant, since in both problems there is suppression of production probability at high η .

The production of leading nucleon in pA collisions has been studied in the framework of the valon model for low- p_T processes [29], and the distribution in Eq. (14) is obtained by attributing the momentum degradation effect to the projectile valons as they traverse the target nucleus [30]. This is not contradictory to the information gained from the more recent experiments at RHIC, where energy loss effects are found to be absent at large p_T in $d + Au$ collisions [31–34]. The former problem is at low p_T and valons are dressed valence quarks of the proton, whereas the latter refers to hard partons that go through the nucleus at large angles with negligible interaction with the cold medium. It is the interpolation between these two extremes that is pertinent to the η dependence in our problem here.

The nucleon distribution in Eq. (14) has been converted in the valon model to the pion distribution in the form

$$\frac{dN_\pi}{dx_F} \propto \exp[-\lambda(\nu - 1)x_F], \quad (15)$$

where $\lambda = 0.2$ [35]. There is no reliable way to relate that behavior in x_F at low p_T to the η dependence at intermediate p_T without treating the transition from soft to hard processes. Since the boundary condition is that there is no energy loss at $\eta = 0$, we adopt the ansatz that the degradation factor is

$$\zeta(\beta, \eta) = \exp[-\kappa(N_c - 1)\eta], \quad (16)$$

where $N_c = \langle N_{\text{coll}}(\beta) \rangle$ and κ is a parameter to be determined from λ by matching Eqs. (15) and (16) at forward rapidity. The expression for $\zeta(\beta, \eta)$ represents the property that the larger η is, the more time the constituents of the projectile spend in the valon state, while the valons propagate through the nuclear medium and suffer momentum degradation.

To relate Eqs. (15) and (16) we note that at $\eta = 3.2$, if $\langle p_T \rangle = 2 \text{ GeV}/c$, the corresponding $\langle x_F \rangle = 0.25$. For $\beta = 0\text{--}20\%$, we use the values $\nu \approx 9$ (for $p+Au$ collisions) and $N_c \approx 15$ (for $d + Au$ collisions) and get

$$\kappa \approx 0.01. \quad (17)$$

We now use this value of κ in Eq. (16) and apply $\zeta(\beta, \eta)$ multiplicatively to the shower distribution \mathcal{S} , but not to the soft distribution \mathcal{T} , since the effect of degradation is already included in the determination of $C(\beta, \eta)$ through the use of the experimental values of $dN_{\text{ch}}/d\eta(\beta)$ in Eq. (8). Equation (12) is used for $T(\beta, \eta)$. For $\mathcal{S}\mathcal{S}$ recombination we do not apply $\zeta(\beta, \eta)$ quadratically, since the shower partons are from one jet.

With the degradation effect taken into account the results on the ratio R_{CP} are shown in Fig. 7. We note that there is improvement in the agreement with data compared to Fig. 6, especially at $\eta = 2.2$. At $\eta = 1.0$ the solid line no longer overshoots the dashed line at high p_T . There is no change at $\eta = 0$ since $\zeta(\beta, 0) = 1$, and there is an improvement of the fit at $\eta = 3.2$. Since the data are for either $(h^+ + h^-)/2$ or h^- , whereas our calculation is for π^+ specifically, perfect

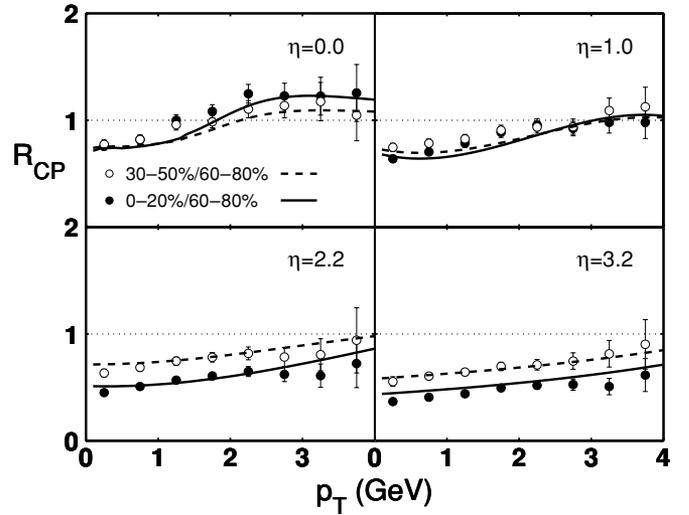


FIG. 7. Same as for Fig. 6 but with momentum degradation considered.

agreement between theory and experiment should not be expected. The effect of momentum degradation is at most 30% on the p_T distributions at $\eta = 2.2$, so such changes are barely perceptible in the log plots of the spectra in Fig. 2, which therefore remain as the prediction of our treatment. The ratio R_{CP} in linear scale reveals the degradation effect more sensitively. It is evident from Fig. 7 that the essence of forward production of pions in $d + Au$ collisions is essentially captured in our description of hadronization by parton recombination, when T is allowed to depend on β and η , and when the effects of momentum degradation is taken into account.

V. ASYMMETRY RATIO FOR BACKWARD TO FORWARD RAPIDITIES

So far we have restricted our study to only the forward region. The backward region on the gold side contains the properties of the nucleus not present at large η and should therefore behave differently from what we have obtained in previous sections. Recent data from STAR show significant asymmetry in the ratio of the charged hadron spectra for backward to forward rapidities in the range $0.5 < |\eta| < 1.0$ [36]. That ratio reaches a peak higher than 1.3 for $2 < p_T < 3 \text{ GeV}/c$. At a qualitative level the phenomenon can easily be understood in our approach to the problem, since there are more soft partons at $\eta < 0$ than at $\eta > 0$. We now want to examine the asymmetry quantitatively as another test of our treatment of hadronization.

The formalism for particle production at $\eta < 0$ is the same as for $\eta > 0$. Both \mathcal{T} and \mathcal{S} must, however, change, as η enters the negative region. The parametrizations of the hard parton distributions $f_i(k_T, y)$ are already given in Table II. Since the data for the backward region are for the range $-1.0 < \eta < -0.5$, we shall use the parameters for $y = -0.75$ in Table II. Similarly, the values for $y = 0.75$ will be used for the forward region. For the soft parton distribution $\mathcal{T}(p_1)$ we continue to use Eq. (8) to determine $C(\beta, \eta)$ with $dN_{\text{ch}}/d\eta(\beta)$

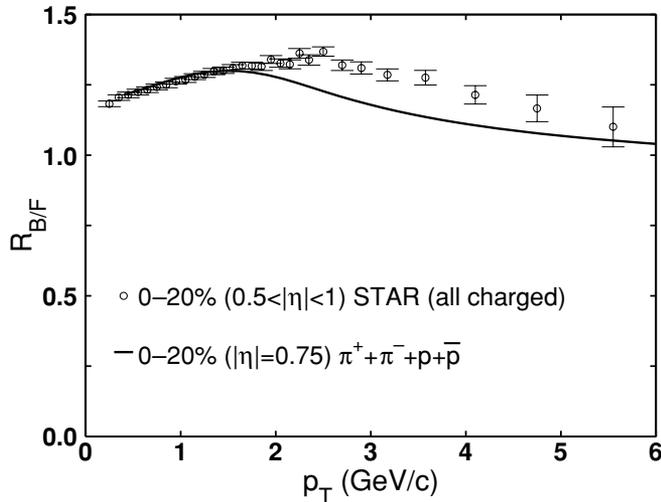


FIG. 8. Ratio of p_T distributions for backward to forward pseudorapidities at $|\eta| = 0.75$. Data are for all charged hadrons from [36]. Solid line is the calculated ratio for $\pi^+ + \pi^- + p + \bar{p}$.

taken directly from the data [23]. For $\beta = 0$ –20%, we obtain $C(\beta, -0.75) = 12.372$ and $C(\beta, 0.75) = 11.527$ $(\text{GeV}/c)^{-1}$. This represents a small, but significant, asymmetry of the soft parton density. For the η dependence of the inverse slope $T(\beta, \eta)$ we use the formula, Eq. (12), already determined in Sec. III from the region $\eta > 0$, now applied to $\eta = \pm 0.75$.

We now can calculate the p_T distributions for π^+ using the appropriate values of C , T , and f_i at $\eta = \pm 0.75$. The results are, of course, not visually distinguishable from that at $\eta = 0$ in Fig. 2 plotted in log scale. However, their ratio plotted in linear scale is more sensitive to the small changes. The backward/forward asymmetry ratio is defined by

$$R_{B/F}(p_T, |\eta|) = \frac{dN_\pi/dp_T d\eta(\eta = -|\eta|)}{dN_\pi/dp_T d\eta(\eta = +|\eta|)}. \quad (18)$$

The data for $R_{B/F}(p_T, 0.75)$ as shown in Fig. 8 are for all charged hadrons [36]. Thus our calculation for π^+ alone is not enough for the purpose of comparison with the currently available data. In the same way that we have treated proton production in Au + Au [10] and d + Au collisions [21], we calculate the proton spectrum at $\eta = \pm 0.75$. Furthermore, we take the π^- yield to be the same as for π^+ and take the \bar{p} yield to be 0.7 of that of p . The sum of $\pi^+ + \pi^- + p + \bar{p}$ is shown by the solid line in Fig. 8. The result has the correct rise for $p_T < 2$ GeV/ c but is lower than the data at higher p_T . We expect that the production of kaons can further increase the theoretical curve, but since they involve strange quarks that are enhanced in the soft component, we do not digress here to that peripheral subject. Our present result from the nonstrange sector is sufficient to indicate that the asymmetry data can be understood in our approach to hadronization. Note that our result on $R_{B/F}$ has been obtained without any new free parameter. A better way to compare theory with data would be to have identified pions at $\eta = \pm 0.75$, which is within the feasibility of some RHIC experiments.

The conclusion that one can draw from this study of the backward-forward asymmetry is that there is no transition of

basic physics from multiple scattering in ISI on the $\eta < 0$ side to gluon saturation on the $\eta > 0$ side [1]. Our emphasis on the hadronization process in the final state provides a universal framework for the description of particle production at all η , β , and p_T .

Based on saturation physics, a recent calculation of the low- p_T distribution of charged hadrons in minimum-bias d + Au collisions at $\eta = 3.2$ appears to have good agreement with data, when only the scattering of the $q\bar{q}$ dipole on the nucleus described as CGC is taken into account [37]. However, the contribution of gluons to the cross section is not negligible, since the density of gluons in a proton at $x = 0.25$ is more than half the density of the quarks at $Q \leq 5$ GeV/ c [38]. Furthermore, hadronization by use of the fragmentation function is subject to the usual question about the p/π ratio, which has shown the inadequacy of the fragmentation model. Thus the agreement with data at low p_T seems fortuitous.

It has recently been stated that the Cronin effect seen at midrapidity goes away at forward rapidities because the supposed origin of the enhancement at $\eta = 0$ (i.e., multiple scattering in the initial state) is replaced by CGC, which is responsible for the suppression at $\eta > 0$ [1,2,37]. The results of this work combined with those of Refs. [11,21] suggest that neither mechanisms are the primary causes of the enhancement and suppression and that both phenomena are the consequences of the same hadronization process by recombination.

VI. CONCLUSION

On the basis of parton recombination we have successfully described pion production at intermediate p_T in d + Au collisions in the forward rapidity region. The formalism is an extension of the one at midrapidity where the Cronin effect has been explained in terms of FSI only, and where the experimental fact $R_{CP}^p > R_{CP}^\pi$ is interpreted as a consequence of the dominance of three-quark recombination over fragmentation. In the extension to $\eta > 0$ only one new parameter, ε , is introduced to describe the β and η dependence of T , but no new physics has been added. The suppression of R_{CP} at $\eta > 1$ is due mainly to the reduction of the density of soft partons that recombine either among themselves or with the semihard shower partons. The effect of momentum degradation responsible for baryon stopping has been considered and is found to have a minor effect on R_{CP} , although it does render a better agreement with the data at all η and p_T . The reduction of soft parton density in the forward direction may be related to gluon saturation, but there is no explicit reliance on small- x physics in the calculation. At large η the production of hard partons is suppressed, so pQCD calculations supplemented by fragmentation is likely to underestimate the pion spectra at intermediate p_T .

Extending the consideration to the backward region, we have used the same dependence of the inverse slope $T(\beta, \eta)$ on η , now extrapolated from $\eta > 0$ to $\eta < 0$. We find that the general properties of the backward-to-forward ratio of the charged hadron p_T distributions can be reproduced by our calculation of only the nonstrange sector. Thus, particle

production at all η can be described by the same formalism for all p_T at any centrality. There is no need for any change of physics in going from the backward to the forward region.

To further verify the validity of our treatment, the predicted pion spectra in Fig. 2 should be checked by experiments. To have the correct R_{CP} , as in Fig. 7, is only the necessary condition for the underlying physics to be relevant, but it is not sufficient. Spectra themselves may disagree with the data, yet still have their ratio come out right. Proton spectra should also be measured at $\eta > 0$ and the p/π ratio shown as a function of p_T , β , and η . Although we have not calculated the p_T distribution of protons for $\eta > 1$, we expect that the p/π ratio would not be small for $\eta > 1$, although it would be lower than the maximum of the ratio for $\eta = 0$ because the lower soft parton density at $\eta > 1$ inhibits the formation of protons more than it does pions. The measurement of that ratio will provide a severe test on any model of particle production at any η .

Another area of investigation that can shed light on forward physics is to determine the presence or absence of back-to-back jets in azimuthal correlation when a particle is detected at large η and intermediate p_T . If the p_T distributions of the various components contributing to the pion spectrum at $\eta = 3.2$ in Fig. 3 is correct, then we do not expect any significant jet signature until $p_T > 3 \text{ GeV}/c$. Even at $p_T = 4 \text{ GeV}/c$ the dominant component is $\mathcal{T}\mathcal{T}$ recombination, so at $\Delta\phi = \pi$

there should be only a small jetlike component that stands above a high level of background uniform in ϕ . Some aspect of that feature has already been observed in the preliminary data of STAR [39].

Since hadronization of partons by recombination is a process in the final stage of evolution of the partons, it is not in conflict with any dynamical model that correctly describes the beginning and subsequent evolution of those partons. Thus our work here provides the necessary link between the predicted parton spectra and the observed hadronic data for testing the validity of any proposed model.

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