Proton Enhancement at Large p_T at the CERN Large Hadron Collider without Structure in Associated-Particle Distribution

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The production of pions and protons in the p_T range between 10 and 20 GeV/c for Pb + Pb collisions at CERN LHC is studied in the recombination model. It is shown that the dominant mechanism for hadronization is the recombination of shower partons from neighboring jets when the jet density is high. Protons are more copiously produced than pions in that p_T range because the coalescing partons can have lower momentum fractions, but no thermal partons are involved. The proton-to-pion ratio can be as high as 20. When such high p_T hadrons are used as trigger particles, there will not be any associated particles that are not in the background.

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Particle production at large p_T in pp collisions is well understood in terms of the fragmentation of partons after hard scattering, so the ratio of proton to pion can be related to the ratio of the corresponding fragmentation functions (FF) D^p/D^π, which is roughly of the order of 10^{-1}. In central heavy-ion collisions at the Relativistic Heavy Ion Collider (RHIC), the p/π ratio $R_{p/\pi}$ has been found to be greater than 1 at $p_T \sim 3$ GeV/c before diminishing to $\sim$0.3 at higher p_T [1,2]. Clearly, an alternative mechanism of hadronization is at play at intermediate p_T [3–5]. The question we ask here is whether the same phenomenon will occur in heavy-ion collisions at CERN LHC. In this Letter, we give reasons to expect a new phenomenon to take place that will make $R_{p/\pi}$ be even larger in the $10 < p_T <$ 20 GeV/c range. We further predict that there are no peaks in the $\Delta\phi$ distribution of the particles associated with a trigger in that p_T range.

The alternative mechanism of hadronization referred to above is parton recombination. The dominance of recombination over fragmentation at high p_T (now regarded as intermediate) was recognized long before there were any heavy-ion data on the subject [6]. The high-quality data now available from RHIC make possible more detailed treatment of the recombination process where thermal and shower partons can both contribute at intermediate p_T [7]. The importance of thermal partons recedes as p_T is increased to above 10 GeV/c. At such high p_T at RHIC, the dominant process is fragmentation. However, at LHC where the density of jets is very high, a new phenomenon arises where the recombination of shower partons in neighboring jets can make a significant contribution. We investigate here the p_T distributions of the pion and the proton in the range $10 < p_T < 20$ GeV/c and show that the p/π ratio can be very large, which can therefore serve as an excellent signature of the hitherto unrealized hadronization process.

The study of hadron production in central heavy-ion collisions at RHIC in the intermediate p_T range has been characterized by three features in Ref. [7]: (a) suppression due to energy loss in the medium is represented by a factor ξ; (b) jets produced near the surface create shower partons whose distributions have independently been determined [8]; (c) medium effect on hadron production is taken into account by the recombination of thermal and shower partons. The thermal parton distribution is determined by fitting the low-p_T spectra (<2 GeV/c) in the recombination model. As we look ahead toward LHC, we do not know what the suppression factor ξ is, nor do we have the soft spectra to provide information about the thermal partons. What we do know is the shower parton distributions (SPD), which were determined from the FFs independent of the colliding system. Thus, we want to make predictions that rely heavily on the SPD and minimally on the thermal partons. To that end, we consider a p_T range greater than 10 GeV/c in order to minimize the contribution from the thermal partons. On the other hand, we do not want p_T to be too high, since the central theme of this investigation is the recombination of shower partons from neighboring jets, for which the density of jets must be high. Thus, we focus our attention in the region $10 < p_T < 20$ GeV/c, which is relatively narrow in the overall range available at LHC, reaching up to 100 GeV/c. For ξ, we shall just consider two typical values that seem reasonable.

Our formulation of parton recombination is one-dimensional in the direction of the detected hadron. If there is only one jet, then the recombination of two shower partons in the same jet is equivalent to fragmentation into a meson, since that is how shower partons are defined in the first place [8]. The corresponding invariant distribution for a hadron h is

$$p\frac{dN_h^{(1)}}{dp} = \xi \sum_i \int dk k f_i(k) \frac{p}{k} D_i^h\left(\frac{p}{k}\right), \qquad (1)$$

where p is an abbreviation for p_T and k is the transverse momentum of the scattered hard parton i; its distribution in a heavy-ion collision is $f_i(k)$ that takes into account the parton distribution functions, the shadowing effect in the nuclei, the hard scattering cross section, etc., as parametrized in Ref. [9]. $D_i^h(z)$ is the FF for a parton i to a hadron h; ξ is the suppression factor that was found to be $\xi = 0.07$ for RHIC [7]. We shall use $\xi = 0.01$ and 0.03 as representative values for LHC in the following.

The new component that we consider here is the two-jet contribution $pdN_h^{(2)}/dp$, which is given by

$$p\frac{dN_h^{(2)}}{dp} = \xi^2 \sum_{i,i'} \int dkdk'kf_i(k)k'f_{i'}(k')\Gamma(s,k,k') \int \left(\prod_\ell \frac{dp_\ell}{p_\ell}\right) F_{ii'}(k,k';p_1,p_2,[p_3]) R_h(p_1,p_2,[p_3],p), \tag{2}$$

where $F_{ii'}$ denotes the SPDs in the two jets and R_h the recombination function (RF) for the formation of h at p. The symbol $[p_3]$ means that it is present (absent) for baryon (meson) production. $\Gamma(s, k, k')$ is the overlap function between the two jets, which depends not only on the c.m. energy s but also on the hard parton momentum vectors $\vec{k}$ and $\vec{k}'$ and the widths of their jet cones. That is the main quantity that we do not have sufficient information on for collisions at LHC. We shall approximate it by an average quantity Γ and pull it out of the integral, using several possible values for it. The other parts of the integrand are calculable.

For pion production, we have

$$F_{ii'}(k,k';p_1,p_2) = S_i^j\left(\frac{p_1}{k}\right) S_{i'}^{j'}\left(\frac{p_2}{k'}\right), \tag{3}$$

where $S_i^j(z)$ is the SPD of quark j with momentum fraction z in a jet initiated by parton i [8]. The difference between (3) and the corresponding equation in the one-jet case is that p_1 and p_2 are not bounded by $p_1 + p_2 \le k$, the only jet momentum. Here p_1 and p_2 can both be large (though each bounded by k and k', respectively), resulting in a large pion momentum at $p = p_1 + p_2$. For proton production, we have

$$F_{ii'}(k,k';p_1,p_2,p_3) = S_i^j\left(\frac{p_1}{k}\right) \left\{ S_{i'}^{j'}\left(\frac{p_2}{k'}\right), S_{i'}^{j''}\left(\frac{p_3}{k'-p_2}\right) \right\}, \tag{4}$$

where the curly braces imply a symmetrization of p_2 and p_3. Since there exists symmetry in i and i', there is no need for us to consider two shower partons in jet i. The partons j, j', and j'' are to be permuted among the types u, u, and d for proton formation and are not indicated explicitly in Eq. (2). The partons i and i' are to be summed over all species u, d, s, $\bar{u}$, $\bar{d}$, $\bar{s}$, and g. Thus, there are many terms in the summation that involves valence, sea, and gluon SPDs. The RFs R_h have been given before in Ref. [7] and in references cited therein. They all have the momentum constraints $\delta(\sum_i p_i - p)$.

The SPDs $S_i^j(z)$ have been parametrized in Ref. [8] as

$$S_i^j(z) = Az^a(1-z)^b(1+cz^d). \tag{5}$$

For numerical estimates, let us focus on the shower partons generated by a gluon, since for Pb + Pb collisions at LHC the dominant hard partons at high k are gluons [9]. For $i = g$ and $j = q$ (u or d), the parameters in Eq. (5) are $A = 0.811$, $a = -0.056$, $b = 2.547$, $c = -0.176$, and $d = 1.2$. Thus, we have $S_g^q(1/3) = 0.3$, while $S_g^q(1/2) = 0.13$. There are, therefore, more than twice the number of light quarks in the gluon jet at $z = 1/3$ than at $z = 1/2$. That huge difference leads to a higher probability for proton formation than for pion.

To calculate the p_T distributions of π and p, we need to sum over all hard partons i and i' and integrate over all their momenta k and k'. Let us write

$$\frac{dN_h}{p_T dp_T} = H_h^{(1)}(p_T,\xi) + \Gamma H_h^{(2)}(p_T,\xi), \tag{6}$$

where $H_h^{(1)}(p_T, \xi)$ is the one-jet contribution given in Eq. (1), multiplied by p_T^{-2}, and $H_h^{(2)}(p_T, \xi)$ is the two-jet integral in Eq. (2), also multiplied by p_T^{-2} but without $\Gamma(s, k, k')$, which is approximated by the constant overlap factor Γ taken outside the integral for p_T in the range $10 < p_T < 20$ GeV$/c$. Thus, the total p_T distribution that we can calculate depends on two parameters ξ and Γ, which depend in turn on the suppression of hard partons in their emergence from the dense medium, their density outside the medium, and the overlap of showers from neighboring jets. To account for all possibilities, we allow Γ to vary over a wide range, i.e., $\Gamma = 10^{-n}$, where $n = 1, 2, 3,$ and 4.

In Fig. 1, we show the results of our calculation of pion production for (a) $\xi = 0.01$ and (b) $\xi = 0.03$. The four curves in each panel are for the four values of Γ indicated in the legend. As Γ becomes infinitesimal, i.e., no overlap between two neighboring jet cones, the curves approach limiting curves (not shown) that correspond to the fragmentation from one jet. Thus, what stands above the limiting curves is all due to the recombination of the shower partons from two different jets, and they can be quite large. The reason is that in recombination the pion momentum p is $p_1 + p_2$ and is not limited by either k or k' in Eq. (3), as in the case of one-jet fragmentation. Put differently, for any fixed value of p, the hard parton momenta k and k' in the two-jet case can be lower than the only parton momentum k in the one-jet case, so the rate of production can be higher.

The approximation of constant Γ can be removed by letting Γ vary with p_T in accordance to a power law, since the jet production probability decreases as p_T^{-n}. If we start with $\Gamma = 10^{-1}$ at $p_T = 10$ GeV$/c$, which is reasonable for an expected jet multiplicity of 100 in $|\eta| < 0.5$, and if we let it decrease as $\Gamma(p_T) \propto p_T^{-7}$, then we get the pion distribution as shown by the heavy solid lines in Fig. 1. Evidently, the contribution from two-jet recombination becomes insignificant at $p_T \sim 20$ GeV$/c$.

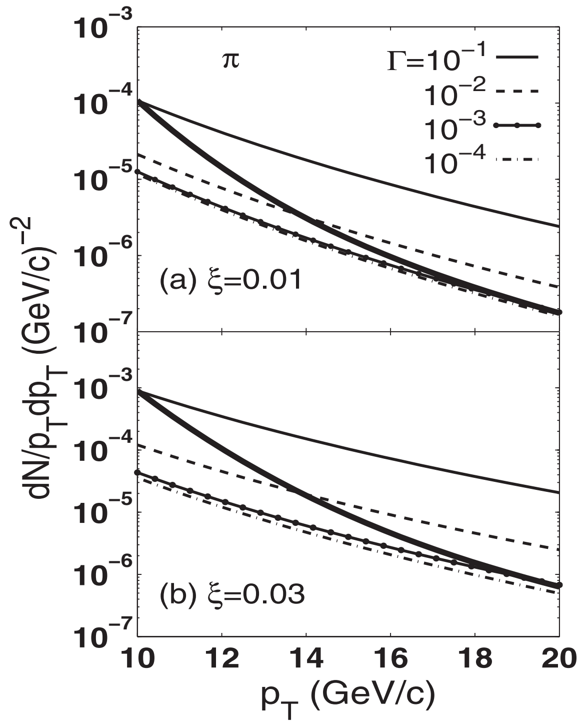

FIG. 1. Transverse momentum distributions of pions for two values of the nuclear suppression factor ξ and for various fixed values of the probability Γ of overlap of neighboring jets. The heavy solid line represents the distribution when $\Gamma(p_T)$ is taken to decrease as p_T^{-7}.

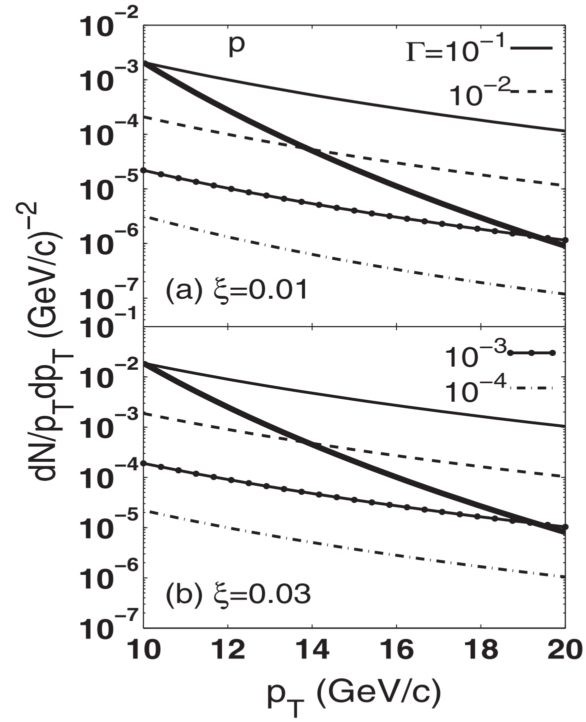

FIG. 2. Same as in Fig. 1 but for proton.

The Γ dependence of the proton distribution is quite different, as shown in Fig. 2. At small Γ, there is no hint of the curves approaching limiting curves. That is, the fragmentation of a parton into a proton has very low probability. However, the contribution from two jets grows very fast with increasing Γ. For $\Gamma = 10^{-1}$, the rate of proton production is more than an order of magnitude higher than that of pion. The reason is similar to that given for pion, but the effect is more amplified. For a fixed $p = p_1 + p_2 + p_3$, the hard parton momenta k or k' need not be greater than p as required by fragmentation. Furthermore, with three shower partons contributing to p, the momentum fractions of each can be lower, resulting in a higher yield.

When we allow $\Gamma(p_T)$ to decrease with p_T as in the case of pion considered above, the proton distribution is shown by the heavy solid line in Fig. 2. It now decreases far more rapidly with p_T but is still higher than the one-jet contribution (not shown) even at $p_T = 20$ GeV$/c$.

Knowing the p_T distributions of pion and proton, we can take their ratio and exhibit the remarkable behavior of the p to π ratio $R_{p/\pi}$, as shown in Fig. 3. First of all, for constant Γ, the ratio increases with p_T, showing the dominance of three-quark recombination for proton formation. However, when the decrease of $\Gamma(p_T)$ with p_T is taken into account, $R_{p/\pi}$ shows also a decrease with p_T (in heavy solid lines) rather than increases in the constant Γ cases. The range of the ratio decreasing from 20 to 5 is significantly higher than that of the one-jet case, as shown by the light solid lines in Fig. 3. A difference of 2 orders of magnitude is a spectacular manifestation of a new hadronization process at high p_T. Figure 3 differs from the

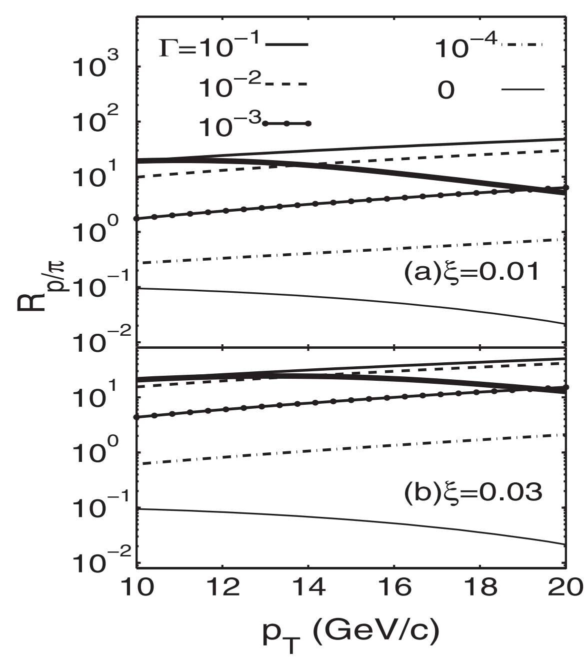

FIG. 3. The proton-to-pion ratio of the p_T distributions at LHC. The heavy solid lines show the ratio when $\Gamma(p_T)$ is taken to decrease as p_T^{-7}. The light solid lines present the ratio when only a single jet contributes.

prediction of Ref. [10] because only the fragmentation term corresponding to $\Gamma = 0$ is shown there.

For $p_T > 20$ GeV$/c$, the mean jet multiplicity is less than 2 in $|\eta| < 0.5$, and $\Gamma(p_T)$ is expected to decrease faster than p_T^{-7}; thus, the heavy solid lines should rapidly join the light solid lines at higher p_T. The pion and proton distributions are roughly proportional to ξ^2, so the ratio is approximately independent of ξ. Furthermore, since $\Gamma(p_T)$ is the same for the two distributions, $R_{p/\pi}$ does not depend crucially on what Γ is exactly at $p_T = 10$ GeV$/c$.

In addition to the surprisingly large p/π ratio, there is another feature about hadron production at large p_T at LHC that is unusual compared to what is routine at RHIC. When there is a large-p_T particle detected at RHIC, it can be used to serve as a trigger, and the associated particles are shown to have structure with peaks and valleys in $\Delta\eta$ and $\Delta\phi$ distributions [2,11–13]. To find the peaks in the associated-particle distribution at RHIC, it is necessary to make a background subtraction so that the jet effects can be clearly isolated from the statistical distribution of particles from the bulk medium that is always present with or without jets. It should be noted that to have a high-p_T particle at RHIC is a rare event and that the jet phenomenon is a signal of hard scattering that stands out above the background.

At LHC, on the other hand, jets are not rare; indeed, we have used the high density of jets to calculate the contribution of two jets to the formation of a single hadron. If jets are numerous in every event, then they are part of the background. Furthermore, for the hadrons that are detected in the $10 < p_T < 20$ GeV$/c$ range, they are not the fragments of any hard parton at much higher p_T. They are the recombination products of semihard partons at lower p_T. Since such semihard shower partons are copiously produced at LHC, treating the detected hadron as a trigger does not select any subset of events that are characterized by anything special. It is not like a jet that is rare at RHIC. For particles correlated to the trigger on the same side, the shower partons in the two jets that give rise to the trigger particle must have other sister shower partons in the same two jets to recombine to form associated particles. Of course, that can occur, but they are a few among many other recombined products of an ocean of shower partons with higher yield. Such associated particles merge with the background and cannot contribute to a recognizable peak on the near side. This is in sharp contrast to the situation at RHIC where such near-side peaks in $\Delta\eta$ and $\Delta\phi$ have been calculated in the recombination model and found to reproduce the data very well [14,15].

When a trigger particle is formed in the way that we have described in this Letter, the recoil partons of the two relevant jets are not different from any of the other hard partons that are abundant. Those recoil partons, if they emerge at all after surviving the quenching effect of the medium that they traverse, are weaker than the ambient minijets produced near the surface on the far side. Hence, we expect no peaks in the away-side $\Delta\phi$ distribution that rise above the background.

In summary, we have shown that when the jet density is high, as is expected at LHC, the recombination of shower partons arising from adjacent jets can give rise to hadron production that dominates over parton fragmentation. At constant jet-overlap probability Γ, the p/π ratio increases with p_T, but with a reasonable p_T dependence ascribed to $\Gamma(p_T)$ the ratio decreases with p_T from roughly 20 to 5 in the interval $10 < p_T < 20$ GeV$/c$. That is still about 2 orders of magnitude higher than the ratio one expects from fragmentation. This prediction offers a striking target for an experimental test of the validity of recombination in an area where fragmentation has conventionally been applied. Our prediction that there are no associated particles beyond the uncorrelated background to be found in connection with trigger particles in the p_T range considered can easily be checked experimentally. Data on these predictions can provide crucial guidance to the understanding of the hadronization problem at high p_T that has until now been uncontroversial.

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