Soft contamination of hard hadron jets produced in nuclei

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The anomalous A dependence of the cross section for production of large-P_T particle jets in nuclei can be explained in terms of a contamination of the jet by soft particles.

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The cross sections for hard reactions are proportional to the parton density in the colliding particles. For nuclear targets this proportionality implies $\sigma \sim A^1$, where A is the atomic number, and this relationship holds well for deep inelastic scattering and for the Drell-Yang process.[1] In inclusive production of hadrons with large p_T, however, the A dependence is anomalously strong: $\sigma \sim A^{\alpha}$ with $\alpha^{(1)} = 1.1$–1.3 (Ref. 2). The first observations of the production of large-p_T jets in nuclei complicated the situation even further[3]: For jets it was found that $\alpha_j^{(1)} > \alpha^{(1)}$, with $\alpha_j^{(1)}(p_T \gtrsim 4$ GeV) $\gtrsim 1.5$. For pairs of jets with large p_T, the value of $\alpha_j^{(2)}$ also reaches 1.5 (Ref. 4), although for pairs of symmetric particles the value $\alpha^{(2)} = 1$ is found (Ref. 5). These values of $\alpha_j^{(1)}$ and $\alpha_j^{(2)}$ are incompatible with the interpretation that the large-p_T particles are fragments of a jet.

In this letter we show that this phenomenon can be explained by correctly allowing for the contamination of hard jets by small-p_T particles. In a collision of hadrons the final state is a superposition of four jets: two along the beams of colliding particles and two with large p_T. The soft particles with $p_T \approx 0.3$ GeV cannot be assigned unambiguously to any of these jets. This point is unimportant if the structure of the jet is independent of the target, but in the case of nuclei the particle density in the pionization region increases with increasing A, and parts of the beam jet fall in a solid angle $\Delta\Omega \sim \pi$. The particles in this group are assumed to belong to a jet with a large p_T. The nature of the distortions that arise is clear: The momentum of the jet and the multiplicity in it are overestimated, as is the cross section for jet production; and the spectrum of jet fragments becomes softer. The renormalization of the cross section has been discussed by Bromberg *et al.*,[3] but they neglected several effects and drew the incorrect conclusion that the soft contamination is inconsequential.

We need the transverse-momentum flux of soft particles with rapidities $|y| \leqslant 0.5$ in the c.m. frame into a calorimeter with $\Delta\phi \approx \pi/2$ (Refs. 3 and 4; here and below, $p_T = p$). The momenta (or energies) add in magnitude. The average multiplicity of the particles in the solid angle of the calorimeter, $\Delta\Omega$, is $\langle \Delta n_s \rangle = C\Delta y \Delta\phi/2\pi$, where C is the height of the pionization plateau. For hydrogen we have $C_{H_2} \cong 2.5$ and $\langle \Delta n_s \rangle \cong 0.7$, while for aluminum we have $C_{\mathrm{Al}} = (1.4\text{–}1.5)C_{H_2}$ (Refs. 6 and 1). For an isolated, soft particle the p distribution is $f_1(p) = B_s^2 p \exp[-B_s p]$ with $B_s = 6$ GeV^{-1}, and for n soft particles we find

$$f_n(p) = \left(B_s^2\right)^n p^{2n-1} \exp[-B_s p]/(2n-1)! \,. \tag{1}$$

The cross section for the production of a contaminated jet is

$$d\sigma_j/dp = \int_0^p dq\,[d\sigma_j^0(p-q)/dp]\sum_n w_n f_n(q)\,, \tag{2}$$

where w_n is the distribution in the multiplicity of soft particles in the angle $\Delta\Omega$. This cross section should be compared with the cross section for production of a pure jet, $d\sigma_j^0/dp = \sigma_j^0 B_j^2 p \exp[-B_j p]$ with $B_j = 3.2$ GeV^{-1} (Ref. 3). The ratio is ($\Delta B = B_s - B_j$)

$$R(p) = (d\sigma_j/dp)/(d\sigma_j^0/dp) = w_0 + (1/p)\int_0^p dq\,(p-q)\exp[-\Delta B q] \times \sum_{n=1}^{\infty} w_n (B_s^2)^n q^{2n-1}/(2n-1)! \tag{3}$$

In the limit $\Delta Bp \gg 1$ we find from (3) that $R(\infty) = \Sigma_n w_n L^n$, where $L = (B_s/\Delta B)^2 = 4$, so that large multiplicities n are important (they were neglected in Ref. 3).

An important point for numerical calculations is that the rapidity correlations of the pionization particles are large: $R_2(0,0) = R_2 = 0.06\text{–}0.7$ (Ref. 7). To take into account the two-particle rapidity correlations and a large part of the three-particle rapidity correlations, we should assume that

$$w_n = \begin{cases} [R_2 + \exp(-N)]/(1 + R_2)\,, & n = 0 \\ N^n \exp(-N)/[n!\,(1 + R_2)], & n \geq 1 \end{cases}\,, \tag{4}$$

where $N = \langle \Delta n_s \rangle (1 + R_2)$. The ratio $R_{\mathrm{Al/H_2}}$ was measured in Ref. 3; for the case $\Delta Bp \gg 1$ the result $R_{\mathrm{Al/H_2}} \cong \exp[(L-1)(N_{\mathrm{Al}} - N_{\mathrm{H_2}})]$, was found. In other words, only the increment in the multiplicity in the switch from hydrogen to aluminum, $\langle \Delta n_s \rangle$, appears in the ratio. Converting to $\Delta\alpha(p)$ in the parametrization $R_{\mathrm{Al/H_2}} = (A_{\mathrm{Al}})^{\Delta\alpha(p)}$ we find ($A_{\mathrm{Al}} = 27$) that

$$\Delta\alpha(\infty) = (L-1)\,(N_{\mathrm{Al}} - N_{\mathrm{H_2}})/\ln 27 \approx 0{,}5. \tag{5}$$

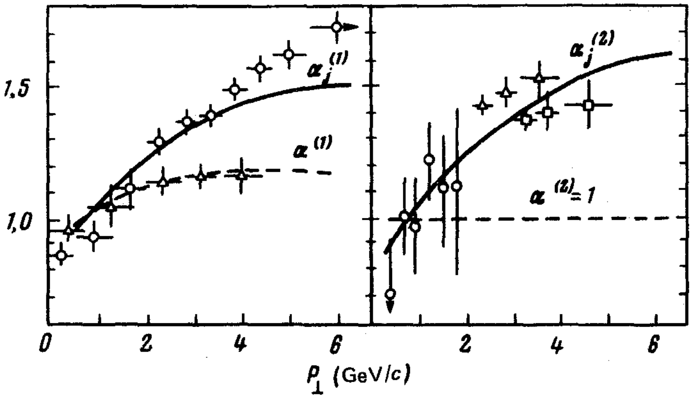

FIG. 1. Comparison of the calculations of $\alpha_j^{(1)}$ and $\alpha_j^{(2)}$ with the experimental data of Refs. 3 and 4. The curve for $\alpha^{(1)}$ is a rough fit of the experimental points.

Calculations of $\alpha_j^{(1)}(p) = \alpha^{(1)} + \Delta\alpha(p)$ from (3) reproduce the experimental results of Ref. 3 well (Fig. 1). For a pair of jets, $\langle \Delta n_s \rangle$ should be doubled. The calculations of $\alpha_j^{(2)}(p)$ also agree well with the experiments of Ref. 4 [Fig. 1; we are using $\alpha^{(2)} = 1$ (Refs. 5 and 6)].

To calculate the multiplicity in the contaminated jet, we should add $n_j^0(p-q) + n$ under the summation sign in (2), where $n_j^0(p)$ is the multiplicity in a pure jet. Assuming that the pure jets are identical in the cases of hydrogen and aluminum, and assuming that $\Delta Bp \gg 1$, in which case we have $n_j^0(p-q) \approx n_j^0(p)$ we find the increment in the multiplicity in the contaminated jet to be

$$\langle n_j \rangle_{\mathrm{Al}} - \langle n_j \rangle_{\mathrm{H}_2} \approx 2L\,(N_{\mathrm{Al}} - N_{\mathrm{H}_2})/3 \approx 2{,}8\,\Delta\alpha\,(\infty)\,. \qquad (6)$$

A calculation for the final momenta gives values of $\langle n_j \rangle_{\mathrm{Al}}$, in good agreement with experiment (Fig. 2).

The ratio of the jet fragmentation functions $D_{\mathrm{Al}}(z)/D_{\mathrm{H}_2}(z)$ for the case of contaminated jets is described by a rather lengthy expression, which we shall not write out here. The calculated results are compared with experiment in Fig. 3, where we

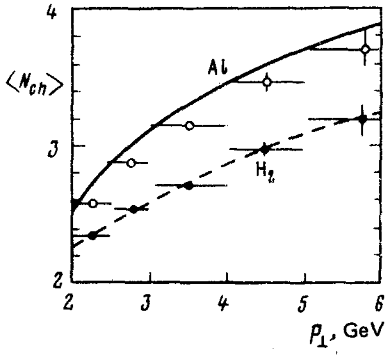

FIG. 2. Comparison of the data of Ref. 3 with the calculated charged-particle multiplicity in a jet for the case of an aluminum nucleus. The curve for the hydrogen nucleus is a rough fit of the points.

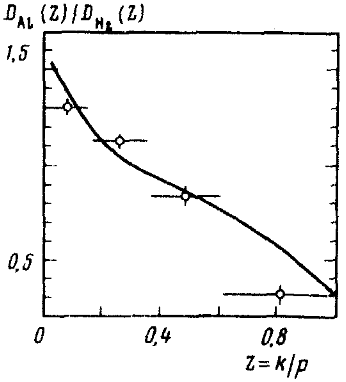

FIG. 3. Comparison of the data of Ref. 3 with the calculations for the ratio of the fragmentation functions for jets produced in Al and H_2 nuclei.

again find a good agreement. As the jet momentum increases, this ratio should approach unity at large values of $p_\perp$.

All the anomalous features in the production of jets of particles with large $p_\perp$ can be attributed to a contamination of the jets by soft particles—without introducing any free parameters. The contamination effects are large and very sensitive to the dimensions of the calorimeter. Consequently, for the method proposed in Ref. 6 for testing the mechanism for multiple hard scattering we should measure the cross section for production of pairs of particles, rather than for pairs of jets, with large $p_\perp$.

The NA5 experiment at CERN use a calorimeter with a cylindrical geometry. It is not difficult to calculate the total momentum flux (or the total energy flux) of the soft particles into such a colorimeter:

$$d\sigma_s/dp = \sigma_{abs}\,(1/p)[2NB_s^2\,p^2]^{1/6}\,(6\pi)^{-1/2} \times \exp[(3/2)(2NB_s^2\,p^2)^{1/3} - B_s p]\,. \qquad (7)$$

There is a high probability that both jets with large $p_\perp$ and $B_j \approx 1.6\ \mathrm{GeV}^{-1}$ will enter such a calorimeter. By simply comparing the exponential factors we easily see that the soft flux is predominant in the calorimeter up to very high energies:

$$B_s p \approx 2N\,[3B_s/2(B_s - B_j)]^3 \approx 25 < \Delta n_s > \approx \begin{cases} 60, & H_2 \\ 90, & \mathrm{Al} \end{cases} . \qquad (8)$$

The coefficient of the exponential function reduces the momenta in (8) by a factor of about 1.5. Estimate (8) cannot be taken literally, since it corresponds to multiplicities $n \approx (1/2)(2NB_s^2\,p^2)^{1/2} \sim 10 \langle \Delta n_s \rangle$, for which the values of w_n are unknown. One thing is obvious, however: In a search for jets with a large energy release as a trigger, the production of soft particles may be a strong background.

Zmushko[8] and Takagi[9] have discussed a more exotic mechanism for the anomalous A dependence: a simultaneous hard scattering of two partons from the incident hadron, which by chance fall in the same solid angle $\Delta\Omega$. We are not ruling out the possibility that this pseudojet mechanism is also operating, but it does not seem to be predominant.

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