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JET FRAGMENTATION INTO CHARGED PARTICLES AT THE CERN PROTON-ANTIPROTON COLLIDER

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ABSTRACT

Inclusive fragmentation of jets into charged particles has been studied in the UA1 experiment at the CERN Super Proton Synchrotron (SPS) $p\bar{p}$ Collider at $\sqrt{s} = 540$ GeV for jets having a transverse energy above 30 GeV. The observed fragmentation function is very similar to that seen in e^+e^- jets and is therefore indicative of similar hadronization processes for gluons and quarks. Scaling with the energy of the jet is valid to a good approximation, although slight deviations are suggested by the data. The average transverse momentum with respect to the jet axis for jets with $E_T > 30$ GeV is 600 MeV/c for particles having $z > 0.1$ and increases slowly with the jet energy.

1. INTRODUCTION

When it started operation near the end of 1981, the CERN proton-antiproton collider, with 540 GeV in the centre of mass, increased the accessible energy range of the hadronic interactions by almost a factor of 10. At these energies, the constituents of the proton and antiproton — quarks and gluons — can manifest themselves in the form of large-angle jets due to hard scattering [1,2]. As there exist several partons in each hadron, the jets produced in the central region of rapidity are also accompanied by forward and backward jets coming from the fragmentation of the spectator partons. Within the quantum chromodynamics (QCD) hard-scattering framework, gluon jets are expected to dominate over quark jets at large angles in the present energy range [3]. Study of these processes should therefore reveal the details of the gluon hadronization. Detailed comparison with jets observed in e^+e^- annihilations can also be made. High-energy e^+e^- interactions proceed dominantly via the production of quark pairs, and thus fragmentation of quark jets.

In a previous letter [2] we have reported the observation of about 200 jets, with transverse energy E_T above 20 GeV, accumulated in an early run of the proton-antiproton collider in December 1981 for an integrated luminosity of 0.02 nb^{-1} . The present work is based on a much higher data sample corresponding to an integrated luminosity of 18 nb^{-1} , recorded in a 30-day period during November and December 1982. This increase in statistics opens up the possibility to study not only the production but also the detailed fragmentation of the jets into charged particles.

This paper describes the first attempt at collider energies to extract information about gluon hadronization, from the charged-particle fragmentation function and the distribution of the internal transverse momentum p_T along the jet axis. A comparison is made with quark hadronization.

2. DETECTOR, TRIGGER, AND JET SELECTION

The UA1 apparatus has already been described elsewhere [4]. Here we concentrate on some aspects that are relevant to the present analysis.

The study of the fragmentation of jets into charged particles is performed using the central detector: a set of six drift chambers forming a cylindrical volume, 5.8 m long and 2.3 m in diameter, which gives a three-dimensional picture of each $p\bar{p}$ interaction and measures the momentum and ionization of all charged tracks. Relative momentum accuracy for high-momentum tracks produced by energetic jets is typically $\pm 20\%$ for a 1 m long track at $p = 40 \text{ GeV}/c$ in the plane perpendicular to the magnetic field of 0.7 T. The ionization of tracks is measured to an accuracy of 10% by the truncated mean method. This allows us to detect any merged tracks within a jet which could not be resolved because of the finite drift-time resolution.

During the 1982 period of data-taking, the UA1 apparatus was triggered on localized electromagnetic and hadronic energy depositions [5]. The specific requirements for triggering on jets were: i) for $|\eta| < 1.5$, $\geq 15 \text{ GeV}$ of transverse energy in a group of calorimeter cells covering ~ 0.8 units of rapidity and 180° in azimuth or ii) for $1.5 < |\eta| < 3$, $> 15 \text{ GeV}$ in a group of calorimeter cells covering 1.5 units of rapidity and 90° in azimuth. Specific data selection has been described elsewhere [6] and is comprehensively discussed in another paper on the production of jets [7]. This procedure will not be repeated here, in view of the fact that any result on the fragmentation of jets is normalized to the jet population used, and so is largely independent of any specific selection of the sample.

Jet finding in $p\bar{p}$ events is done via a clustering method [2,6,7]. The basis of the method is briefly recalled here. To each calorimeter cell is associated an energy vector. Its direction and magnitude are defined by the spatial position of the cell and the energy contained in the cell. Cells with $E_T > 2.5$ GeV are grouped in clusters if the distance between them in (pseudo-rapidity, azimuth) space [$d = (\Delta\eta^2 + \Delta\phi^2)^{1/2}$, ϕ in radians] is less than 1. Lower energy cells are then associated with a particular existing cluster provided: i) they make a spatial angle of less than 45° with respect to the cluster axis; and ii) their relative transverse energy with respect to that axis is smaller than 1 GeV.

3. METHOD AND ACCEPTANCE CONSIDERATIONS

The present jet fragmentation study has been conducted in a purely inclusive way, using only charged particles as measured by the central drift chambers. All jets with $E_T > 30$ GeV are considered, regardless of the number of accompanying jets.

The jets are found by using exclusively the information coming from the electromagnetic and hadronic calorimeters, via the clustering method explained above and in refs. [2,6,7]. The axis and the total energy of the jet are known from the vectorial sum of all its cell energy vectors. Charged particles are then associated with a particular jet, provided they are confined inside a cone centred around the jet axis. The jet axis and directions of charged particles show obvious correlation up to an angle of 35° , as shown in fig. 1. The half aperture of the cone is then fixed to that value. The dashed curve is an estimate of the background of beam fragments (spectators) not associated with the jet, by a simple Monte Carlo where the particles are generated uncorrelated according to a cylindrical phase-space model.

Owing to the fixed opening angle of the cone, only the central region of the calorimeters is used. This region extends from -1.5 to $+1.5$ in pseudo-rapidity η . To minimize edge effects, we restrict the jet-axis direction to be contained in $-1.25 \leq \eta \leq 1.25$. In order to consider only charged particles pointing to the central calorimeter cells, and consequently depositing their energy in those cells, the pseudo-rapidity range of charged particles is within the limits $-1.5 \leq \eta \leq +1.5$. If the jet axis is close to its pseudo-rapidity limit of 1.25, charged particles can be emitted in the region $|\eta| > 1.5$. The loss of particles due to this situation is small, of the order of 7%.

Because of the horizontal orientation of the magnetic field and the presence of gaps between the two halves of the calorimeters in the vertical plane, the azimuthal angle about the beam line of the jet axis is restricted to lie within four sectors of a 15° half opening angle centred on $\pm 45^\circ$ axes. This restriction in solid angle does not affect any result of the present fragmentation study, as everything is normalized to the final jet population obtained after the above-mentioned cuts.

A loss of 13% is estimated for charged particles emitted outside the sectors. Including the rapidity acceptance, the over-all geometrical acceptance is, then, of the order of 80%. A systematic uncertainty of 10% has been added to the statistical errors. No correction has been introduced for track-finding efficiency within jets. However, visual scanning of a reduced population of events did not show any evidence of unfitted straight tracks. The percentage of tracks giving an ionization larger than 1.7 times that of minimum ionizing particles has been measured in the central drift chamber volumes. The small percentage observed, 4.5%, is compatible with the tail of the dE/dx distribution. We deduce that no undetected multi-tracks are contained in the data sample. A small fraction of the tracks within the 35° cone ($< 5\%$) has been discarded because of non-association

with the main vertex of the interaction. After the acceptance cuts listed above, the jet population used for the present analysis is given in table 1.

4. JET FRAGMENTATION FUNCTION

The inclusive variable used for the jet fragmentation study has been chosen to be

$$z = p_L^{\pm}(\text{jet axis})/E(\text{jet}), \quad 0 \leq z \leq 1,$$

where $p_L^{\pm}(\text{jet axis})$ is the momentum of the charged particle projected on the jet axis. The energy of the jet, $E(\text{jet})$, is defined as the modulus of the vectorial sum of all energy cell vectors belonging to the jet.

The distribution of the variable z — the fragmentation function — is defined as

$$D(z) = (1/N_{\text{jets}})(dN_{\text{ch}}/dz).$$

The integral of $D(z)$ is then the mean charged multiplicity contained in the jet:

$$N_{\text{ch}}(\text{jet}) = \int_0^1 D(z) dz.$$

Several corrections have been applied to $D(z)$. These are discussed below.

The form of the background below $D(z)$ is obtained in the control region $52.5^\circ \leq \theta \leq 70^\circ$, where θ is the spatial angle between the jet axis and the charged particles. Background normalization is given by the Monte Carlo prediction of the number of particles uncorrelated with the jet for $\theta < 35^\circ$ (dashed curve in fig. 1).

For relatively high z 's, all the charged particles are contained in the 35° cone around the jet axis. At low values of z this is no longer true. Many soft particles are emitted at large angles. In particular, below $z < 0.02$ the emission of particles looks so isotropic that the correlation of the particles with the jet is no longer obvious. Loss of jet particles emitted outside the cone varies from 35% for z between 0.02 and 0.03, to 5% for z around 0.07.

The jets we are dealing with in this paper are very energetic; they have a total energy above 30 GeV. Associated charged particles with a high z value (therefore a high momentum) have then a large momentum uncertainty. The smearing in z which creates an important deformation of $D(z)$ for values above 0.7 has been removed from the data, assuming an exponential law for $D(z)$ at large z .

Monte Carlo studies with full calorimeter reconstruction indicate that the uncertainty in the measurement of the jet energy is more or less constant between 30 and 50 GeV, and is of the order of 15%. Five percent of the resolution comes strictly from cell association of the jet cluster algorithm, the rest of it being due to the finite resolution and granularity of the calorimeters. No correction has been applied to the data in order to take into account the jet energy smearing.

Figure 2 shows the plot for $D(z)$ with $z > 0.02$. This distribution falls rapidly with z at low z values. At higher z values its form is approximately exponential.

We can compare the shape and the normalization of $D(z)$ for the present experiment with $(1/\sigma_{\text{tot}}) \times (d\sigma/dx_L)$ obtained by the TASSO Collaboration for jet energies of 17 GeV, where $x_L = p_L^{\pm}/p_{\text{beam}}$, and $p_L^{\pm}$ is the momentum of the charged particles projected on the jet axis whose

direction is determined from minimizing the sphericity of the e^+e^- events [8]. The energies of the jets are of course different for both cases. However, the comparison is meaningful because scaling violations in e^+e^- annihilations are known to be small [9]. No striking differences can be observed between these two sets of data, as can be seen in fig. 2. This means that quark-dominated and gluon-dominated fragmentation functions are, on the whole, not different from each other, at least for values of $z > 0.02$.

Within our own data we can look for possible variations of $D(z)$ as a function of the transverse energy of the jet. After background subtractions and corrections, $D(z)$ is plotted in fig. 3 for three E_T bands: 30–35 GeV, 40–50 GeV, and > 50 GeV; $D(z)$ is approximately independent of the jet energy. A possible tendency for $D(z)$ to shrink at low z with increasing $E_T(\text{jet})$ cannot be excluded. This is not observed in the high- z region, probably on account of the very large uncertainties in the data introduced by the track momentum smearing, which are difficult to remove entirely owing to the lack of statistics [10].

5. TRANSVERSE MOMENTUM WITH RESPECT TO THE JET AXIS

The jet axis given by the calorimeters is not precise enough for studying the transverse momentum p_T of the charged particles with respect to the jet axis. For this reason it is replaced by a charged jet axis whose direction is given by the vectorial sum of all charged-particle momenta. The charged particles used to define this axis are inside the cone of 35° half aperture around the calorimeter jet axis. Of course, the charged jet axis is correct only if we assume that the charged and neutral axes are aligned evenly. If this assumption is not valid on an event-by-event basis, it is probably true statistically.

As we have seen before, the association of particles with the jet is questionable at lower z values. For this reason a cut $z > 0.1$ is applied to select particles unambiguously associated with the jet. Owing to the “seagull effect” discussed below (fig. 4), this cut will result in a higher mean p_T within the jet, compared with a mean p_T value obtained for all particles belonging to the jet regardless of their z value. For all jets with $E_T > 30$ GeV, the variation in the average transverse momentum of charged particles measured with respect to the jet axis is plotted in fig. 4 as a function of z . A “seagull effect” is observed, showing the increase of $\langle p_T \rangle$ from a value of 0.5 GeV/c at a z value around 0.1 to a value approaching 1 GeV/c for z values above 0.5.

The invariant p_T spectrum, $(1/p_T)(dN/dp_T)$, is shown in fig. 5 together with the result of a fit

$$(1/p_T)(dN/dp_T) = A/(p_T + p_{T_0})^N$$

for all jets with $E_T > 30$ GeV. The above function was shown to reproduce well the p_T spectrum of charged particles in minimum bias events [11]. The p_T spectrum is well fitted by the values $p_{T_0} = 4$ GeV/c, $N = 14.8$. The observed mean p_T value internal to the jet is $\langle p_T \rangle = 600$ MeV/c, after having applied the cut $z > 0.1$ on all particles. A large p_T tail is observed up to $p_T = 4$ GeV/c. This tail could well be an indication of gluon bremsstrahlung. On the other hand, it could also be due to an experimental misalignment of the jet axis, or to events whose leading particles are neutrals.

Evolution of the mean p_T within the jet has been studied for the following regions of $E_T(\text{jet})$: 30–35, 40–50, and > 50 GeV. Figure 6 shows the p_T spectrum obtained for each of these transverse energy bands. The mean p_T increases from 600 MeV/c at $E_T = 30$ GeV to 700 MeV/c for $E_T > 50$ GeV.

The slow variation of $\langle p_T \rangle$ with $E_T(\text{jet})$ brings us to the following conclusion. We can write the average opening angle of a jet in the form

$$\langle \theta_{\text{jet}} \rangle \sim \langle n \rangle \langle p_T \rangle / E(\text{jet}),$$

$\langle n \rangle$ being the mean jet multiplicity. As $\langle n \rangle$ and $\langle p_T \rangle$ vary much less than the energy of the jet, it is clear that the jet becomes more and more collimated when its energy increases.

Detailed comparison between the average p_T in this experiment and the e^+e^- annihilation jets depends very much on the energy of the jet and the z cut applied. However, a rough comparison of observed mean p_T values with respect to the jet axis for $z > 0.1$ (or $x_p > 0.1$, $x_p = p/p_{\text{beam}}$, in the case of PETRA data [12]) does not show any big difference for $p\bar{p}$ jets and e^+e^- jets.

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Table 1
Jet population used for the present study
after the cuts mentioned in the text
for different $E_T(\text{jet})$ ranges

N(jets)	$E_T(\text{jet})$ range (GeV)
853	30–35
323	35–40
195	40–50
64	> 50

Figure captions

- Fig. 1 Distribution of the spatial angle between the jet axis as given by the calorimeters and the directions of charged particles. Arrows indicate the 35° cut. The dashed line is the result of a Monte Carlo assuming no correlation between jet axes and charged particles.
- Fig. 2 Charged-particle fragmentation function for $E_T(\text{jet}) > 30$ GeV, compared with similar results from the TASSO detector at PETRA at $W = 34$ GeV.
- Fig. 3 Charged-particle fragmentation functions for $E_T(\text{jet}) = 30\text{--}35$ GeV, $40\text{--}50$ GeV, and > 50 GeV.
- Fig. 4 Variation of $\langle p_T \rangle$ with respect to the jet axis for charged particles as a function of z . Errors are due to statistics only.
- Fig. 5 $(1/p_T)(dN/dp_T)$ spectrum (p_T with respect to the jet axis) for charged particles with $z > 0.1$. The solid line is the result of a fit $1/(p_T + p_{T_0})^N$ with $p_{T_0} = 4.0$ GeV/c, $N = 14.8$.
- Fig. 6 $(1/p_T)(dN/dp_T)$ spectra (p_T with respect to the jet axis) for charged particles with $z > 0.1$ and for three ranges of $E_T(\text{jet}) = 30\text{--}35$ GeV, $40\text{--}50$ GeV, and > 50 GeV.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6