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FURTHER EVIDENCE FOR JET PRODUCTION FROM THE CHARGED PARTICLES

PRODUCED IN pp COLLISIONS AT $\sqrt{s} = 63$ GeV

TRIGGERED ON LARGE TRANSVERSE ENERGY

The Axial Field Spectrometer Collaboration

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ABSTRACT

The detailed shape of events triggered by a 1.7 sr hadron calorimeter is studied using charged track information in the Axial Field Spectrometer at the CERN ISR. With increasing transverse energy (E_T) a large fraction of the events are seen to have a limited transverse momentum relative to the trigger direction. A comparison of the circularity of the events with a prediction of a QCD-motivated Monte Carlo model shows that at high E_T the events originate predominantly from two-constituent scattering.

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The study of hadron-hadron collisions in order to investigate constituent scattering has been done using both calorimeter and single-particle triggers [1]. The expectation is that events with large transverse energy (E_T) will be dominated by hard scattering of the hadron constituents, whose fragments will give rise to the large E_T . The contribution to the E_T spectrum by particles not directly associated with the primary constituent scattering, but coming mainly from the fragments of the beam particles, can be a serious background preventing the observation of the underlying structure [2]. Here we report on striking correlations seen in the charged particles in events triggered on a large transverse energy (E_T) deposited in a hadron calorimeter, the size of which is large compared with the measured spread of the scattered constituent fragments.

In the preceding Letter [3] an analysis is presented using only calorimeter information. Here, we present results on event structure using charged particles measured in the central drift chamber of the Axial Field Spectrometer (AFS). The spectrometer was triggered by the requirement of a large transverse energy deposition in a 1.7 sr hadron calorimeter covering $|y| < 0.93$. The details of the trigger and the calorimeter properties are described in ref. [4]. The central detector's tracking capabilities provide the spatial resolution not obtainable from the calorimeter, but important for a detailed study of the event structure. The experimental set-up and trigger of the AFS have been described elsewhere [3]. The main component used in this analysis is the cylindrical drift chamber, 1.4 m long, which extends radially from 0.2 to 0.8 m from the centre of the intersection. The drift chamber is segmented azimuthally in 4° sectors, each with 42 radially distributed sense wires from which both time and pulse-height signals are recorded. The ϕ position is measured by drift time and the z position using charge division. The drift chamber extends over 2π in azimuth except for two 16° wedges used for mechanical support. The spatial resolution of the chamber is $230 \mu\text{m}$ (r.m.s.) in the azimuthal direction and 1.5 cm in the axial coordinate (charge division direction). The central detector is situated in an axially symmetric magnetic field of 0.56 T. The transverse

momentum resolution for tracks in the central region $45^\circ \leq \theta \leq 135^\circ$ is given approximately by $(\Delta p/p)^2 = [(0.025 p)^2 + (0.01)^2]$, where p is in GeV. The first term arises from measurement error and the second from multiple scattering in the chamber gas and wires.

The data was taken with an integrated luminosity of $3.6 \times 10^{35} \text{ cm}^{-2}$ taken with an average instantaneous luminosity of $1.43 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$.

All selected triggers were processed through our standard charged-particle tracking and vertex reconstruction programs for the central detector [4]. The precision of the vertex determination is approximately 1 mm in the transverse plane and better than 2 cm along z . Timing information from the finely segmented scintillation counters surrounding the beam pipe (IH) and forward beam-beam counters (BB) is used to reduce pile-up of events, beam gas, and cosmic-ray background. All events are required to have a charged particle vertex. These cuts removed $\sim 30\%$ of the triggers. We estimate the remaining background (predominantly from pile-up) to be less than 9% (21%) at $E_T = 6$ (14) GeV. This background would tend to mask any existing structure of the real events. No explicit corrections have been made for the loss of zero and one-prong events due to vertex requirements. Since the average multiplicity detected is about ten, the number of zero and one-prong events rejected should be small over our E_T range.

To investigate the distribution of the charged tracks as a function of the detected E_T in the calorimeter, we have divided the data into six bins in E_T . For each event the clusters found in the calorimeter are ordered in decreasing p_T , assuming zero mass particles. All clusters below 25 MeV are neglected. From the remaining clusters one then constructs the vector sum $\vec{E}'$ using the most energetic clusters containing 80% of the measured transverse energy. A Monte Carlo simulation of four-jet events (ISAJET) [5] indicates that this algorithm yields an azimuthal r.m.s. error of less than 6° and a y error of less than 0.1 from the true jet direction for all $E_T > 6$ GeV. The chosen limit of 80% is somewhat arbitrary. To check for the possible effect of this, the analysis was repeated using different fractions and similar results were obtained. A fiducial volume cut on the $\vec{E}'$ direction in

the laboratory requires that it be in a $\pm 25^\circ$ bin in azimuth from the centre of the wall and at $|y| < 0.5$. In addition it was required that less than 15% of the energy be on the edge of the calorimeter. These cuts were made in order to reduce the problems of acceptance and energy leakage near the edges of the calorimeter. In the following analysis only tracks with p_T greater than 0.075 GeV and less than 10 GeV are used. All tracks are required to have $|y| < 0.8$. The cuts on track quality and geometry give rise to a relatively flat acceptance for $|y| < 0.6$, but falling as $|y|$ approaches 0.8. None of our results is found sensitive to these cuts.

To investigate the distribution of charged particles relative to the vector $\vec{E}'$, the standard variables employed in the analysis of single-particle triggers are defined relative to $\vec{E}'$, the energy flow directed into the calorimeter. In fig. 1a we define the variable q_T , the three-dimensional transverse momentum between the vector $\vec{E}'$ and the momentum vector of each charged track. p_{out} is the corresponding variable defined in the plane transverse to the beam axis in the centre-of-mass system (c.m.s.). Tracks are classified as same side or away side according to their space angle relative to the E' axis.

In fig. 1b the $\langle q_T \rangle$ relative to $\vec{E}'$ for both the same and away side tracks are shown. The $\langle q_T \rangle$ is about 400 MeV on the same side and constant with E_T . These results are consistent with the $\langle q_T \rangle$ measured using a single-particle trigger and from values observed in e^+e^- jets [6]. On the away side $\langle q_T \rangle$ is somewhat higher. This is not unexpected, since in the overall centre-of-mass of pp collisions, the scattered constituents are not expected to be back to back. Figure 1c shows the $\langle p_{out} \rangle$ for both the same and away side. They are both constant with E_T with values similar to those observed using single-particle triggers.

In fig. 2 we show the $\langle p_T \rangle$ for tracks on the trigger side, $\Delta\phi < 50^\circ$; at 90° to the trigger direction, $50^\circ \leq \Delta\phi \leq 130^\circ$; and for tracks with $\Delta\phi > 130^\circ$ where $\Delta\phi$ is difference in the azimuthal angle of $\vec{E}'$ and the momentum vector of each charged track. Note the increase in the average particle p_T with increasing E_T both on the trigger and on the away side. The small difference in the $\langle p_T \rangle$ observed

on opposite sides could result partly from trigger bias. Since the constituents lie on a steeply falling p_T spectrum, a small amount of primordial transverse momentum (k_T) in the initial hadrons can boost the observed p_T of final particles [7]. After fragmentation the $\langle p_T \rangle$ on the trigger side is increased by this factor while on the opposite side it is reduced. Because the jets are uncorrelated in rapidity, the fraction of low p_T beam fragments in our rapidity acceptance is higher on the away side, thus diluting the $\langle p_T \rangle$. It is also worth while noting that $\langle p_T \rangle$ of tracks at 90° is constant with increasing trigger E_T .

In fig. 3, we plot the $\Delta\phi$ distribution of transverse energy flow in charged tracks, relative to the $\vec{E}'$ axis. This quantity is derived by summing E_T per track in azimuthal bins and then normalizing to unity. dE/dx information from the drift chamber is used when possible to make a mass assignment to π , K, or p. The pion mass is used when no identification can be made. Only tracks with $p_T > 0.250$ GeV are used. A correction for our ϕ acceptance was calculated by rotating each event randomly, and evaluating the losses in $\Delta\phi$ due to gaps in the chamber. No correction has been made for the loss of some tracks due to overlap in our 4° ϕ sectors. The lack of this correction could only dilute the result. The general features of the energy flow distributions follow those observed in $\pi^0\pi^0$ correlation data [1]: very strong forward and backward peaks develop as the E_T increases. These peaks appear to narrow with increasing E_T . The level at 90° diminishes, consistent with a small but largely constant contribution to E_T of the whole event. The width of the energy flow distribution on the trigger side is seen to decrease with E_T , reaching a value of about 10 degrees.

The narrowing of the $\Delta\phi$ plots with increasing energy has been observed before in single particle triggers. This is the first time however that this effect has been observed in a "minimally biased" trigger on a collection of particles. The naïve expectation is that randomly distributed tracks collected in our solid angle would not get narrower in $\Delta\phi$ with increasing E_T . The observation of shrinkage in the $\Delta\phi$ distribution is a strong indication of jet structure.

Next a shape analysis of the distribution of charged particles is performed. Here, no explicit corrections for chamber gaps in ϕ have been made, however the gaps were introduced in our Monte Carlo calculations. For each event the momentum tensor in the transverse plane is diagonalized, using the particles combined over the full azimuth, or in each hemisphere separately. The quantity C' (semi-circularity) is formed from the eigenvalues A and B ($A < B$):

$$C' = 1 - (A - B)/(A + B) .$$

If the whole event is employed the circularity (C) is related to the planarity (P) by $C = 1 - P$. The diagonalization procedure finds the principal axis against which the transverse momentum squared is minimized. Small values of C' correspond to events which are collimated (jet-like), while $C' \approx 0.5$ is typical of the minimum bias events triggered in our apparatus. To calculate C' , we require separately ≥ 3 tracks for each hemisphere employed. The distributions for each side, and for the whole event (where ≥ 4 tracks are required) are shown in fig. 4. The evident change is a shrinkage in C' both on the same and away sides, with increasing E_T . The effect is somewhat stronger on the same side, presumably because a larger portion of total E_T is confined in y by the trigger. For E_T between 6-7.5 GeV only $\sim 20\%$ of the events have $C' < 0.20$; a significant rise is seen over the whole range, and for E_T between 12-14 GeV this fraction increases to $\sim 55\%$.

A four jet constituent scattering QCD Monte Carlo (ISAJET) [5] has been used in order to understand the circularity plots and the event shape observed as a function of E_T . The prediction of the model for generated minimum bias events depositing substantial energy in the calorimeter and two-jet events has been fitted to the data in an attempt to extract the fraction of events at each E_T consistent with the shapes expected from these processes. Three sets of fits were done for each of three E_T bins; the first used only tracks on same side, the second used tracks on the away side, and the third used the full event. All 3 sets of fits give a consistent result for the percentage of two-jet events in a given E_T bin. The fraction of two jet events obtained is $30 \pm 15\%$ at E_T between 6-8.5 GeV, $40 \pm 10\%$ at E_T of 8.5-11 GeV, and $60 \pm 10\%$ at E_T

of 11-14 GeV. The observed rise in the fraction of two-jet events with rising E_T is in good agreement with the results we obtain by analysing the structure observed in the calorimeter using the clusters of both charged and neutral energy but over a more limited solid angle [3]. These two analyses are independent of each other. The calorimeter method measures most of the energy with coarse angular resolution while the drift chamber measures only the charged particles but with fine angular and momentum resolutions. The fact that the results are nearly identical increases our confidence in the methods and the results obtained.

We have presented data on charged particles in a spectrometer triggered only on large transverse energy. As the E_T increases, we observe that the trigger is dominated by events where the energy flow is considerably narrower than the dimension over which E_T is collected, and the whole event shows features consistent with that of hard constituent scattering. In particular, q_T is limited relative to the energy flow axis. An analysis of the observed circularity of the events and a comparison to a hard constituent scattering model (ISAJET) indicates that the fraction of jet-like events increases with increasing E_T and is consistent with our analysis using only calorimetric information [3]. The above results constitute direct evidence that a large fraction of the high E_T events selected in our trigger originate from hard parton-parton scatters.

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Figure Captions

- Fig. 1 a) Definition of the variables q_T , and p_{out} . $\hat{z}$ is in the direction of the beams.
- b) $\langle q_T \rangle$ for same side (circles) and away side (squares), versus E_T .
- c) $\langle p_{out} \rangle$ for the same side (circles) and away side (squares) versus E_T .
- Fig. 2 $\langle p_T \rangle$ in c.m.s. for the tracks with $\Delta\phi$ relative to $\vec{E}'$ for $\Delta\phi \leq 50^\circ$ (circles), $50^\circ \leq \Delta\phi \leq 130^\circ$ (open circles), $\Delta\phi > 130^\circ$ (squares) versus E_T .
- Fig. 3 Fraction of visible energy flow for the tracks for $\Delta\phi$ bins of 10° for E_T bins of: a) 1.5-3 GeV; b) 6-7.5 GeV; c) 7.5-8.5 GeV; d) 8.5-10 GeV; e) 10-11 GeV; f) 11-12 GeV; and g) 12-14 GeV.
- Fig. 4 Circularity (or semi-circularity) for the tracks calculated for the different E_T bins: a), d), and g) 6-8.5 GeV; b), e) and h) 8.5-11 GeV; and c), f), and i) 11-14 GeV. The semi-circularity for same side tracks in (a), (b), and (c); the semi-circularity for away side tracks in (d), (e), and (f); and the circularity for the full event in (g), (h), and (i). The curves are the results of the prediction using the ISAJET Monte Carlo; shaded regions represent the two-jet component.

Fig. 1

Fig. 2

Fig. 3

Fig. 4