DIRECT EVIDENCE FOR THE EMERGENCE OF JETS IN EVENTS TRIGGERED
ON LARGE TRANSVERSE ENERGY IN pp COLLISIONS AT $\sqrt{s} = 63$ GeV

The Axial Field Spectrometer Collaboration

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ABSTRACT

We present data obtained from a 1.7 sr hadron calorimeter, triggered on transverse energy, in pp collisions at $\sqrt{s} = 63$ GeV at the CERN-ISR. From the change in the distribution of energy in the calorimeter, we extract the cross-section for two-constituent hard scattering for p_T between 6 and 14 GeV at $y = 0$. The decrease of this jet cross-section over this p_T range is consistent with e^{-bp_T} , with $b = (1.02 \pm 0.09) \text{ GeV}^{-1}$. The slope and normalization of the cross-section agree well with a QCD motivated Monte Carlo model. The ratio between jet and single particle cross-sections $[(d\sigma_{\text{JET}}/dp_T)/(d\sigma_{\pi^0}/dp_T)]|_{y=0}$ changes from about 200 at 6 GeV to about 1500 at 14 GeV.

(Submitted to Physics Letters)

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The study of deep inelastic hadron-hadron collisions has evolved away from the reliance on single particle triggers as a probe of hard scattering processes to the theoretically more efficient and supposedly unbiased use of transverse energy triggers [1]. To remain unbiased, the transverse energy $E_T = \sum E_i \sin \theta_i$ should be observed over a solid angle large in comparison to the spread of particles emerging from the fragmentation of the energetic hadron constituents, and it should be free from contamination by beam fragments. This has led to several large hadron-calorimeter experiments [2]. The results presented here were obtained from the Axial Field Spectrometer (AFS), using a uranium-copper calorimeter of 1.7 sr, triggered on large E_T . As will be shown directly from the data, and from hard-constituent scattering simulations, this calorimeter has a large enough solid angle, and sufficient isolation from beam fragmentation, to meet the above criteria. We find that for $E_T \lesssim 7.5$ GeV, the structure of most events is consistent with that expected from the high multiplicity tail of soft inelastic collisions, but as E_T rises above ~ 10 GeV, a collimated structure starts to dominate the events [3].

The trigger and the central tracking system of the AFS have been described elsewhere [4]. Figure 1 shows a view of the spectrometer components used here and details of a calorimeter stack. For this analysis, only the roof stacks of the calorimeter were used in the trigger, but the floor stacks were recorded. The roof is formed of 32 such stacks, each stack consisting of 6 towers creating a matrix of 12×16 towers, each with a 20×21.6 cm² face in a plane 118 cm from the beam intersection. The towers have 4-fold wavelength-shifter read-out: right and left, at each of two depths (the first 6 radiation lengths, and the second ~ 3.6 absorption lengths). An energy resolution of 16% and 37% at 1 GeV is obtained in test beams for electromagnetic and hadronic showers, respectively. This hadronic resolution is consistent with that found at the ISR using low multiplicity minimum bias events, and comparing the energy deposited in the calorimeter to that measured in the drift chamber of the AFS. Inter-tower calibration is maintained to $\pm 2.5\%$ by frequent monitoring of the uranium activity. The systematic error from

calibration and pedestal stability varies from 3 to 2% over the E_T range 6-14 GeV. The estimated uncertainty in our absolute energy scale for isolated showers is $\leq 4\%$. This error is dominated by the calorimeter response for low momentum (< 1 GeV) hadrons. The uncertainty in the E_T measurement is dominated by other factors and is discussed below. The fiducial region of the roof calorimeter subtends 1.93 to 1.69 sr for electromagnetic and hadronic showers, respectively. In the centre of mass system (CMS) this corresponds to a 72° (66°) bite in azimuth, and $|\cos \theta| < 0.70$ (0.68), $|y| \leq 0.93$ for electromagnetic (hadronic) showers. With our non-projective geometry, isolated electromagnetic showers are localized to ~ 1 cm, and hadronic showers to between 3 and 10 cm on the calorimeter face (for energies ≥ 0.5 GeV) depending on the incident angle.

The E_T trigger is formed by addition of the phototube dynode signals, weighted to transform pulse height in the laboratory to transverse energy in the CMS. The calorimeter signal is placed in coincidence with a minimum multiplicity signal of ≥ 2 hits, in the 44 element scintillation counters (IH) surrounding the beam. Upstream and downstream counters (BB), covering $2^\circ < \theta < 6^\circ$ degrees in polar angle, are used to monitor the luminosity.

The data comprise 10^5 triggers recorded at an average luminosity of $1.43 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$ for a total livetime of seven hours. Figure 2 shows the spectrum of E_T in the calorimeter for six trigger thresholds. The E_T is calculated by first clustering energy in the wall, using the 4-fold tower read-outs to determine the shower centroids, and to correct for the non-uniformity of calorimeter response ($\leq 4\%$ of E_T). The clustering aids in reducing the summed r.m.s. noise, and provides good shower localization; however, it is not effective in determining the true electromagnetic-hadronic composition of the incident particles. The knowledge of this composition on an event by event basis is necessary to correct for the small difference in calorimeter response to electromagnetic and hadron showers [4] ($< 14\%$ at 4 GeV). Lacking this knowledge on an event by event basis, no attempt is made at this point to correct the spectrum. Events with 15% or more of their E_T deposited in clusters in edge towers are removed. This is done to

minimize the effect of energy leakage at the edges. The spectrum shown is uncorrected for resolution and the errors shown are statistical only.

All valid triggers were processed through our standard tracking and vertex reconstruction programs for charged particles in the central detector. The following three requirements are made on the events in the analysis:

- i) An event time, as defined by the IH elements, is required to be within ± 15 ns of the nominal event time as defined by timing electronics. This reduces the fraction of accidentals within the longer 60 ns trigger gate.
- ii) No second interaction within ± 150 ns of the nominal event time is allowed. We discriminate to within ± 12 ns of this time. This pile-up protection is performed using the timing of both the IH and BB elements. This window is chosen in order to reject additional inelastic events which deposit energy within the calorimeter recording time of 120 ns. These events are generally of low central multiplicity (< 5 charged tracks), and deposit typically ≤ 400 MeV in the calorimeter wall. Within the ± 12 ns window where no discrimination can be made, even our low accidental rate of $\leq 1.3\%$ can lead to a trigger bias. It is estimated that at 6 (14) GeV, the contribution to the cross-section through pile-up is at most 9% (21%). This type of background would tend to obscure any true event structure.
- iii) All events are required to have a charged track vertex within a small fiducial region around the beam-crossing region. This aids in the removal of beam-gas background and of cosmic rays which deposit sufficient energy in the calorimeter to satisfy the E_T requirement, and then cross the IH, to satisfy the multiplicity requirement.

These cuts reject successively 4.5%, 20%, and 8% of the triggers. The average number of events removed is 30%. The loss of 0 and 1 prong events by the vertex requirement is negligible since the average track multiplicity for $E_T > 6$ GeV is ~ 10 .

Two backgrounds not explicitly rejected are residual beam-gas events, and cosmic rays which deposit energy in the calorimeter, in time with an inelastic event which satisfies the IH requirement. Runs made without beams, indicated that the latter background contributes less than 5% in the 12 to 14 GeV E_T bin, but because of the flatness of the cosmic ray spectrum relative to the falling E_T spectrum of the real events, becomes a significant fraction of the triggers above that point. (See fig. 2.)

Runs with a single beam in the ISR indicate that without any timing and vertex requirements less than $14 \pm 8\%$ of the events with E_T between 12 and 14 GeV are of beam-gas origin satisfying the trigger by themselves. A significant fraction of events arising from upstream interactions in time with a central inelastic event is ruled out, since calorimeter energy is highly correlated with tracks associated with the event vertex.

The data of fig. 2 have been normalized using the BB counters to measure the luminosity. This normalization leads to about a 7% systematic uncertainty. Included in fig. 2 is the E_T spectrum for 7700 events triggered on an "OR" of the IH and BB counters (minimum bias). This trigger records $\approx 95\%$ of the inelastic cross-section. An extrapolation to the lowest calorimeter-triggered spectrum, shows excellent agreement in slope and normalization, indicating the stability of our procedure. In connecting this minimum bias spectrum to the E_T -triggered data, the loss of 0 and 1 prong events by the vertex requirement may lead to as much as a 6.8% relative error. This has been explicitly corrected for in fig. 2, as has the loss of events (14%) due to non-uniformities in the trigger and calorimeter response over the face.

To study the flow of energy within the trigger wall, the data are divided into eight bins of E_T . For each event, the clusters are ordered in E_T , and those less than 25 MeV are rejected. The vector sum ($\vec{E}'$) is formed of the ordered clusters making up 80% of the E_T in the wall. We require that $\vec{E}'$ point in the laboratory to a region on the face of the wall within $\pm 25^\circ$ in azimuth from the centre, and with $|y| < 0.50$. More than 80% of the events satisfy these requirements.

The accepted events have an average multiplicity of four clusters making up E' , which decreases slightly with increasing E' because of merging in our cluster finding technique. The average cluster size is about 3-towers by 3-towers.

Using all clusters in the wall a quantity analogous to thrust (T) is calculated:

$$T = \frac{\sum_i |\hat{E}' \cdot \vec{p}_i|}{\sum_i |\vec{p}_i|}$$

where sums are carried out over clusters, and $\hat{E}'$ is the unit vector along $\vec{E}'$. T is not explicitly maximized by variation of the $\vec{E}'$ direction, and can take on values between 0.7 and 1.0. A pencil-like event would have a value $T \approx 1.0$, while a high multiplicity isotropic one will have a mean $T \approx 0.85$. The minimum value of T in our solid angle is ~ 0.7 which will be achieved by an event with two maximally separated tracks. In fig. 3 we show the distribution of T for different E_T bins. The striking feature observed is the similarity of the data and the predictions of minimum bias for E_T below ~ 6 GeV and then the gradual peaking of the distribution towards unity with increasing E_T . The detailed shapes of these distributions are only weakly dependent on the exact fiducial region chosen, the cut-off energy for clusters or the energy fraction used in defining E' . The level of 80% is arbitrary, as is the 25 MeV cut. Similar results are obtained using 70% or 90%, and raising the lower cut-off to as high as 250 MeV per cluster. The general feature of the peaking of the T distribution with E_T is always preserved.

To test that one is not observing a background effect, we have studied the T distributions for events in which, in addition to the roof trigger, we required either a simultaneous deposition of ≥ 3 GeV in the floor calorimeter, or a visible track multiplicity in excess of the mean (~ 8 charged tracks in $|y| < 0.8$, full azimuth). These cuts would suppress both beam gas and cosmic ray backgrounds which required an in-time inelastic event and themselves put few tracks into the central region. No changes in the general features were observed.

The nature of the T distribution is studied by Monte Carlo generation of events with and without an explicit hard-scattering component. These events are

subjected to a full simulation of the calorimeter response and processed with our normal analysis chain [5]. Events with large E_T but with no explicit hard-scattering component are generated using the program ISAJET [6]. The shape of the E_T spectrum was found to be in reasonable agreement with the data out to ~ 6 GeV where a comparison could be made. In fig. 3a the T distribution obtained from the ISAJET events is compared with the data below 3 GeV. Excellent agreement in shape is seen. To reach values of E_T up to 8 GeV with reasonable statistics, events were generated forcing higher multiplicity [6]. Figure 3b shows the shape of T for both the data and these biased Monte Carlo events from 3 to 6 GeV. Again, good agreement is seen. From 6-8 GeV (not shown), the observed value of $\langle T \rangle$ remains unchanged for the Monte Carlo events but the width is found to diminish slightly reflecting the additional multiplicity.

The ISAJET Monte Carlo has also been used to produce a spectrum of events containing two large p_T jets, and two spectator beam-jets [6]. In each detected E_T bin, the fraction of events consistent with the 4-jet Monte Carlo is evaluated by a maximum likelihood fit of the thrust distribution. Two components are assumed: a signal from the hard scattering model, and a background from the minimum bias model. The latter component produces a shape consistent with a random deposition of energy in the calorimeter largely independent of total E_T . To reduce the model dependence of the result, both components are permitted to move within 1 bin (0.02) in thrust. This corresponds to a small variation of multiplicity and/or the spread of the fragments in the model assumed. The average shifts are less than 0.5 bins.

The curves of fig. 3c-h show the results of the fits, and the data. Good fits are obtained at all E_T . The shape of the thrust distribution is found to be insensitive to the exact value of Λ [6], and to the fragmentation and structure functions used. The fraction of hard-scattering events in the E_T trigger rises linearly from $\sim 20\%$ to 75% as E_T varies from 6 to 14 GeV. The average contribution to E_T from the fragments of the spectator jets in a hard-scattering event is ~ 800 MeV in this model. The curves indicate that the detector is sensitive to changes of the event structure.

Using the 4-jet Monte Carlo a correction is calculated at each detected E_T bin to account for geometrical jet acceptance, beam jet contamination, energy scale, and the effects of resolution [7]. This together with the results of the fit allows the correction of the observed E_T spectrum to the p_T spectrum of the original constituent. The resulting invariant cross-section for inclusive jet production at $y = 0$ is shown in fig. 4. The inner errors reflect the statistics of the fit and correction procedure. The outer errors also include systematics, representing uncertainties in luminosity ($\pm 7\%$), model dependence in the Monte Carlo and representation of the detector (3.5 to 2%), and uncertainties in the energy scale (5 to 3.5%). We find the cross-section between $p_T = 6$ and 14 GeV to be well represented by an exponential $e^{-b p_T}$ with slope $b = (1.02 \pm 0.09) \text{ GeV}^{-1}$. Superimposed on fig. 4 is the predicted cross-section using the Baier et al. [6] structure functions, showing excellent agreement in both shape and normalization. This agreement in slope between data and the model allows direct comparison without modifying the prediction and iterating the procedure. Also shown is the same model with the Owens and Reya [8] structure functions. The main difference is a reduction of the predicted cross-section due to the softer gluon component, however the slopes are quite similar.

The inclusive π^0 cross-section at $\sqrt{s} = 63 \text{ GeV}$ [9] is compared with the jet cross-section in fig. 4. A comparison of the exponential fit of our jet cross-section with the π^0 data gives a ratio rising from about 200 to ~ 1500 as p_T goes from 6 to 14 GeV. Because our technique uses only the fraction of the events consistent with jet production, the ratio of jets to single π^0 production is smaller than that obtained using previous methods (Bromberg et al., ref. 2).

Evidence has been presented for a change in event shape with increasing transverse energy, toward a dominant structure expected from hard constituent scattering. The cross-section for this process agrees well with a QCD motivated prediction. The ratio of jet to single particle production is found to be increasing with increasing p_T to a value of ~ 1500 at 14 GeV/c.

Support from the Research Councils in our home countries is gratefully acknowledged. Four of us (HG, DL, RHS, and IS) would like to acknowledge helpful discussions with F.E. Paige.

The staff at the CERN EP, EF and ISR Divisions and at the collaborating Institutions have worked with competence, dedication and enthusiasm to provide us with a unique tool for studying high-energy collisions. The uranium calorimeter could not have been constructed without the constant support of the CERN Directorate and the assistance by the EF Division Leader, A. Minten. We gratefully acknowledge the full cooperation of the United States Department of Energy and Rockwell International at Rocky Flats in the procurement of the uranium plates.

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CERN Internal Report R807/313] was used to simulate the energy deposition
of different species of particles. For both electromagnetic and hadronic
showers, we have used the mean longitudinal parametrization suggested by
R. Bock et al. [CERN EP/80-206 (1980)]. Since this originated from a
coarser calorimeter, special precautions were taken to ensure linearity
for hadrons below 3 GeV and photons below 0.5 GeV. Each hadronic shower
is divided into two components, pure electromagnetic and pure hadronic.
For the lateral development of the showers we have used a two-dimensional
Gaussian form where the variance was taken as one half of one "equivalent
absorption (radiation) length" for hadrons (photons). This is 24 cm and
1.2 cm, respectively. The hadronic width is allowed to increase with
depth. The magnetic field, minimum-ionization energy loss of charged
particles, depth of interaction point, particle decays, WLS read-out,

light-coupling between towers, and the electromagnetic to hadronic energy response and resolutions were incorporated. These parameters were compared with beam test results and adjusted accordingly.

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$$\alpha_s(Q^2) = 1/B \ln(Q^2/\Lambda^2)$$

$$B = (33 - 2f)/12\pi$$

where f is the number of quark flavours with $M_q < Q$ and $\Lambda = 0.1$ GeV. The effective Q , which must be of the order of the transverse momentum involved, was chosen as [R. Feynman, R. Field, G. Fox, Phys. Rev. D 18 (1978) 3320]: $Q^2 = 2\hat{s}\hat{t}\hat{u}/(\hat{s}^2 + \hat{t}^2 + \hat{u}^2)$, where $\hat{s}$, $\hat{t}$, $\hat{u}$ are the standard invariants of the elementary scattering process. The partons are u , d , s , and g . The structure functions of Baier et al. [Z. Phys. C2 (1979) 265] are used. The program produces two high p_T jets and two spectator jets. In this analysis, the partons are given primordial k_T of 0.88 GeV (FWHM). In the fragmentation process, high p_T partons may emit hard gluons. The value of $\sigma(q_T) = 0.35$ GeV was chosen both for the high p_T and spectator jets. The light-quark jets reproduce properly the data observed in jet production in e^+e^- interactions at PEP/PETRA. By "minimum-bias" event we refer to any inelastic strong interaction leading to multi-particle production at low transverse momentum. ISAJET is also used to generate these events with no explicit high p_T fragmentation component. The program uses a simplified version of the cut-reggeon field theory of Abramovskii, Kanchelli, and Gribov [Sov. J. Nucl. Phys. 18 (1974) 308]. A leading baryon is generated and the remaining energy is divided among several "cut pomerons", which fragment into hadrons using

the modified Field-Feynman [Nucl. Phys. B136 (1978) 1] ansatz. Short range rapidity correlations are introduced through resonances. The multi-pomeron technique approximates well KNO Scaling and is tuned to reproduce the observed multiplicities at the ISR and SPS-collider. Higher multiplicities can be forced by selecting a large number of cut pomerons.

- [7] For a 10 GeV constituent directed into a region near the centre of the calorimeter, an average energy of ~ 8.4 GeV is detected in the calorimeter. It is composed of ~ 7.4 GeV from the fragments of the constituent, ~ 0.9 GeV from the beam jets and ~ 0.1 GeV from the recoiling constituent. Geometric losses and neutrinos account for ~ 0.7 GeV. The remaining undetected energy (~ 1.9 GeV) is accounted for: back leakage, muon punch through and late interactions (~ 0.5 GeV); absorption in material preceding the calorimeter (~ 0.8 GeV); and the choice of energy scale (~ 0.6 GeV). The energy scale was determined by the measured response of the calorimeter to electromagnetic showers. This choice was motivated by the measured non-linearity of the hadronic energy scale for $p < 1$ GeV. To be specific a 2% error in the relative e/π response above 1 GeV leads to a ~ 0.1 GeV shift of the detected energy of the jet, while an error of 10% for particles with $p < 1$ GeV would lead to a change of 0.1 GeV in the energy detected from the beam jets.

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Figure captions

- Fig. 1 : Experimental set-up and details of the calorimeter stacks.
- Fig. 2 : $d\sigma/dE_T$ uncorrected for resolution; error bars are statistical only. Solid circles are from minimum bias triggers. The other symbols refer to data sets taken with different thresholds. The upper limit for the background from cosmic rays is indicated.
- Fig. 3 : Fraction of events per 0.02 units of thrust for the 8 bins of E_T . The shaded area is the hard scattering component; the solid curve is the total fit.
- Fig. 4 : Invariant cross-section at $y = 0$ for inclusive jet production in pp collisions at $\sqrt{s} = 63$ GeV. Also shown is the invariant cross-section for π^0 production at $\sqrt{s} = 63$ GeV, $y = 0$ (ref. 9). Lines are theoretical predictions (see text). Horizontal bars reflect binning.

Fig. 1

Fig. 2

Fig. 3

Fig. 4