OBSERVATION OF JETS IN HIGH TRANSVERSE ENERGY EVENTSAT THE CERN PROTON ANTIPROTON COLLIDERUA1 Collaboration, CERN, Geneva, Switzerland

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ABSTRACT

With a segmented total absorption calorimeter of large acceptance, we have measured the total transverse energy spectrum for $p\bar{p}$ collisions at $\sqrt{s}=540$ GeV up to $\Sigma E_T=130$ GeV in the pseudo-rapidity range $|\eta| < 1.5$. Using two different algorithms, we have looked for localized depositions of transverse energy (jets). For $\Sigma E_T > 40$ GeV, the fraction of events with two jets increases with ΣE_T ; this event structure is dominant for $\Sigma E_T > 100$ GeV.

We measure the inclusive jet cross-section up to $E_T(\text{jet})=60$ GeV and the two-jet mass distribution up to $120 \text{ GeV}/c^2$. The measured cross-sections are compatible with the predictions of hard scattering models based on QCD.

1. INTRODUCTION. We have recently reported a measurement of the transverse momentum spectrum of charged particles up to 10 GeV¹⁾ and of correlations (in rapidity and azimuthal angle) between charged particles of high transverse momentum²⁾ produced in proton-antiproton collisions at $\sqrt{s}=540$ GeV³⁾.

Those results strongly suggest production of two jets in opposite azimuthal hemispheres, as expected from a picture of hard scattering and fragmentation of partons⁴⁾. That analysis²⁾ and similar studies at the ISR⁶⁾ have exploited the fact that a particle with high p_t "tags" events containing a jet. Selection of such events however allows only the study of a limited class of jet-events.

Calorimetric measurements enable one to search for jets in a less biased way by looking for local energy concentrations above the soft background^{7, 8)}.

In this letter we report on the observation of about 200 jets with transverse energy above 20 GeV, as detected by a total absorption calorimeter in the pseudorapidity range $|\eta| < 1.5$.

2. APPARATUS. The UAl experiment has been extensively described elsewhere⁹⁾, so only those components of the detector relevant to the investigation reported here will be described (see fig. 1).

The central detector was used to validate the beam-beam nature and the geometry of an event (vertex, impact point on calorimeters etc). It consists of a cylindrical drift chamber volume (5.8 m long, 2.3 m in diameter) surrounding the interaction region, in a magnetic dipole field of about 0.56 Tesla.

The central electromagnetic calorimeter is placed inside the magnet coil. It consists of two semi-cylindrical half-shells, one on either side of the beam axis, with an inner radius of 1.36 m. In each half-shell there are 24 modules, each formed from alternate layers of lead (1.2 mm) and scintillator (1.5 mm). They extend over approximately 180° and measure 4 m around the half circumference and 22.5 cm in the beam direction. They are 26.6 radiation lengths deep and are read out in four segments in depth (3.3/6.6/10.1/6.6 r.l. respectively). The light produced in each segment is seen by wave length shifter plates on each side of the counter, which in turn are connected via light guides to 4 photomultipliers (PM's), located outside the magnet (2 PM's at the top and 2 PM's at the bottom, see Fig. 1b). A comparison of the pulse heights of the top and bottom PM's in each segment gives a measurement of the azimuthal angle ϕ for localized energy depositions. The range in pseudorapidity covered by a cell varies with θ , from $\Delta\eta \approx 0.08$ at $\theta = 25^\circ$ to $\Delta\eta \approx 0.16$ at $\theta = 90^\circ$.

Particles which traverse the electromagnetic (e.m.) calorimeters encounter the hadron calorimeter built from scintillator plates inserted into the laminated yoke

of the magnet ; there are 16 iron plates each 5 cm thick, and 16 scintillator plates each 1 cm thick. The calorimeter is segmented into 232 stacks, each with an acceptance of approximately equal size, $\Delta\eta \approx 0.3$, $\Delta\phi \approx 15^\circ$.

3. ENERGY RESPONSE AND CALIBRATION. All types of UA1 calorimeter configurations have been extensively studied in test beams and their responses as a function of angle of incidence, energy and nature of the incident particle have been determined¹⁰⁾. It is found that hadrons deposit a significant fraction of their energy in the e.m. calorimeter. Due to nuclear effects, the response to hadrons of the combined e.m. and hadron calorimeter is smaller than its response to e.m. showers of the same energy. The ratio between the two is ≈ 0.9 for energies above 20 GeV, drops to 0.84 at 5 GeV and decreases further below 5 GeV. For $p < 0.5$ GeV/c the calorimeter response reflects essentially the kinetic energy of the particles. These observations are in good agreement with extensive Monte Carlo calculations on shower development¹¹⁾. These facts introduce for individual events an uncertainty in the energy deduced from measurements in our calorimeters, since the relative electromagnetic and hadronic composition of an event was not determined. However, an average correction factor is applied. The transverse energy is calculated using the expression : $\Sigma E_T = \alpha_{em} \Sigma E_i^{em} \sin\theta_i + \Sigma E_i^{had} \sin\theta_i$, where E_i^{em} is the energy of an electron that would give the observed response in the e.m. cell at θ_i , E_i^{had} is the energy of a hadron giving that response in the hadronic cell at the polar angle θ_i , and α_{em} is the average correction for difference of response. We use $\alpha_{em} = 1.13$ which corresponds to an equal mixture of π^+ , π^- and π^0 at high momenta (≥ 10 GeV/c). At lower momenta, the correction would be expected to be somewhat larger. A significant η^0 production¹²⁾ would tend to reduce α_{em} .

A detailed correction efficiency map of each element of the e.m. calorimeter has been determined and is checked before and after every running period by fine scanning with a collimated γ beam from a 4 Curie ^{60}Co source. The response of e.m. calorimeters to the source was compared with their response to electrons in a test beam. Using this comparison, the energy scale for the e.m. calorimeters in the collider experiment was determined by irradiation with the source. The overall reproducibility of this calibration method was found to be better than $\pm 2\%$.

For the hadron calorimeter this calibration method could not be applied because of insufficient penetration of the γ -rays. In this case, the absolute energy scale has been determined to within $\pm 6\%$ from the observed responses of test modules to hadrons of known energy measured relative to muons of 5 GeV/c.

Cosmic-ray muons were used as an energy reference for the assembled calorimeter and ^{106}Ru β -sources were placed in reproducible positions on every scintillator

at the time of setting up. The absolute calibration is adjusted by reinsertion of these β -sources and by measurement of the calorimeter response to cosmic-ray muons over a restricted set of the calorimeter cells.

The energy resolution for e.m. showers has been found to be $\sigma(E) \approx 0.16 \sqrt{E}$, and the resolution in azimuth for a localized energy deposition was found to be $\sigma(\phi) \approx 0.3/\sqrt{E}$ with E in GeV, ϕ in radians. For hadrons incident on the e.m. and hadronic calorimeter $\sigma(E) \approx 0.8/\sqrt{E}$.

The photomultiplier gains for all calorimeters are monitored as a function of time by laser calibration systems using fibre optics¹⁴⁾, in turn calibrated by precision photodiodes¹⁵⁾ or reference sources. This method has shown reproducibility within 1 - 2% over periods in excess of a year^{13, 15)}.

4. DATA COLLECTION AND REDUCTION. The data were taken during an early run of the SPS proton-antiproton collider in December 1981. As previously described^{1, 2)}, two pairs of hodoscopes subtending polar angles $0.7^\circ < \theta < 3.2^\circ$ and $5^\circ < \theta < 25^\circ$ were used in coincidence to define a $p\bar{p}$ collision (minimum bias trigger). In addition a total transverse energy trigger¹⁶⁾ required a minimum transverse energy deposition in the calorimeters covering the region $|\eta| < 3$. The thresholds used were 20, 30 and 40 GeV. Table 1 gives a summary of the data taken under the various trigger conditions.

Timing information from the trigger hodoscopes was used off-line to reduce the amount of beam-gas interactions to a negligible level ($< 2\%$) as in our previous work^{1, 2)}. These trigger counters were also used as a collision rate monitor ; we estimate our total integrated luminosity corrected for dead-time losses to be $22 \mu\text{b}^{-1}$, assuming a total inelastic cross-section of 40 mb.

For the analysis presented here, only the pseudo-rapidity region $|\eta| < 1.5$ was considered. There are 6051 events with $\Sigma E_T > 40$ GeV, 279 with $\Sigma E_T > 60$ GeV and 5 events with $\Sigma E_T > 100$ GeV. Fig. 2a shows the total transverse energy distribution $d\sigma/d\Sigma E_T$, where ΣE_T is taken over the region $|\eta| < 1.5^{*)}$. In order to get an unbiased spectrum for $\Sigma E_T < 40$ GeV, a sample of minimum bias data was used to obtain that part of the distribution. These data were also used to check the performance of the trigger and the absolute normalisation of the data taken with the high E_T trigger. The loss of events with $\Sigma E_T < 40$ GeV due to the trigger which imposes a condition on $\Sigma' E_T$, (see Table 1) is $< 8\%$.

*)Unless explicitly stated otherwise the symbol ΣE_T refers in the following to the total transverse energy in the pseudo-rapidity region $|\eta| < 1.5$, whereas $\Sigma' E_T$ applies to $|\eta| < 3.0$.

5. SEARCH FOR JETS. In order to find jets in our high ΣE_T event sample, we have to give an operational definition of a "jet" in terms of energy deposition in the calorimeter cells.

A certain arbitrariness is involved, which will affect any quantitative statements made about the jets. In order to estimate the magnitude of the resulting uncertainties, we have used two algorithms, the "window" and the "cluster" algorithm :

(a) The main virtue of the window algorithm is its simplicity ; in each half-shell of the central calorimeter (see fig. 1a), any group of 8 adjacent electromagnetic cells together with the hadronic ones matching them in the projection defines a "window" ($\Delta\eta \approx 1$). In each half-shell, the window with the largest deposition of transverse energy is selected. If this transverse energy exceeds two-thirds of the total transverse energy deposited in that half shell, the window is said to contain a "jet". This yields a simple definition of "0-jet", "1-jet" and "2-jet" events.

The transverse energy of a jet is defined as : $E_T(\text{jet}) = \Sigma E_T(\text{windows}) - \Sigma E_T(\text{background})$, where the background subtraction is done for every event assuming that the transverse energy density (per unit of η) of the soft background within the window is the same as its average outside the window.

(b) the cluster algorithm searches for energy clusters in (η, ϕ) space. An energy vector is associated with each calorimeter cell. In the case of a hadronic cell this vector points from the collision vertex to the centre of the cell. In the case of an electromagnetic cell, the vector points to the energy centroid determined from the 4 pulse height measurements in each segment. At first only cells with $E_T > 2.5$ GeV are considered. They are grouped into clusters if the distance between them in (η, ϕ) space, $d = (\Delta\eta^2 + \Delta\phi^2)^{1/2}$ (with ϕ in radians), is smaller than 1. Vectors with $E_T < 2.5$ GeV are then associated with the closest cluster if they make an angle relative to the cluster axis smaller than 45° and their transverse energy relative to the cluster axis is smaller than 1 GeV. (The cluster axis is defined as the direction of the vector obtained by summing the energy vectors of all cells that have been assigned to the cluster).

6. OBSERVATION OF JET EVENTS. The easiest way of demonstrating the existence of jets in our data is with the window algorithm. Fig. 2b shows the fraction of two-jet events as a function of the total transverse energy ΣE_T . As ΣE_T increases to 40 GeV, the fraction of these events decreases from 23% to 5%. This behaviour can be understood by noting that an increase of total transverse energy is associated with an increase of multiplicity¹⁷⁾. Through statistical fluctuations low multiplicity events can more easily concentrate two-thirds of their energy in the two windows. This is quantitatively reproduced by a Monte Carlo calculation in which particles are generated according to longitudinal phase-space with a multiplicity distribution obeying KNO scaling¹⁸⁾. One can see that the data do not follow this behaviour indefinitely : when ΣE_T increases from 40 to above 100 GeV the fraction of two-jet events increases from 5% to 80%, i.e. a new mechanism takes over which cannot be explained by longitudinal phase-space. The transverse energy distribution of the five events with $\Sigma E_T > 100$ GeV is shown in fig. 3. Four of them are clear two-jet events, the fifth has a multi-jet structure with three or four jets. In the two-jet events, both jets have approximately the same transverse energy. Clearly when ΣE_T becomes large enough, we see the onset of a striking event topology, in which the transverse energy is concentrated into several clusters ; that is, jet production becomes the dominant process. In order to study an arbitrary number of clusters in a less biased way, we make use of the cluster algorithm. In the sample of 279 events with $\Sigma E_T > 60$ GeV, the average multiplicity of clusters with $E_T > 15$ GeV is 0.73, and there are 97 events with at least two clusters of $E_T > 15$ GeV. Fig. 4 shows the distribution of the difference $\Delta\phi$ of azimuthal angle between any two clusters having $E_T > 15$ GeV. The distribution is strongly peaked near $\Delta\phi = 180^\circ$, that is, when two large E_T clusters are found, they tend to be coplanar with the beams. We interpret these clusters as jets originating from hard scattering processes.

The 60 events containing at least one jet with $E_T > 25$ GeV found by either algorithm have been scanned on a high resolution graphic display. Based on examination of the tracks in the central detector, one event was identified as being due to a beam-gas interaction and rejected, while the remaining 59 events revealed a vertex in the collision region. There is a clear correlation between the clustering of tracks in the central detector and the flow of energy as seen in calorimeters. Comparison of the jets found by the two methods shows that 90% of the jets found by the window algorithm are also found by the cluster algorithm. However in the case of three-jet events or large fluctuation of the uncorrelated particle background, the window algorithm tends to miss jets ; on the other hand the cluster algorithm may pick up some spurious cells.

7. CROSS SECTION FOR JET PRODUCTION. The E_T distribution of the jets obtained by the method described above has been corrected for effects due to detector acceptance and experimental procedure by using a Monte Carlo jet simulation. Jets were generated according to a naive parton model without QCD corrections, in which the systems of hard scattered partons and spectators fragment independently, according to longitudinal phase-space with a p_t distribution (p_t = transverse momentum with respect to the jet axis) given by $\exp(-ap_t^2)$, $a = (6 \text{ GeV}/c)^{-2}$, and with fragment multiplicities derived from data for $e^+e^- \rightarrow \text{hadrons}$. All particles are tracked through the magnetic field and the showers in the calorimeters are simulated¹⁹⁾. These "events" are then processed by the same analysis chain as the data, including the jet-finding algorithms. Comparison of the resulting jet E_T spectrum with the generated one yields a correction factor for each E_T bin. The global correction factor for $d\sigma/dE_T$ is 1.1, essentially independent of E_T . The main contributions to the correction are due to (a) geometrical losses at the edge of the rapidity range and in the narrow dead zones between the two halves of the calorimeter, (b) the smearing of the E_T spectrum due to the error in the energy measurement (resolution) and (c) the smearing and shifting of the E_T spectrum because of uncertainties due to the jet finding algorithm. Since our Monte Carlo simulation does not fully reproduce the event topology, this last correction is subject to a larger uncertainty than the previous two.

The inclusive cross-section for jet production $(d\sigma/dE_T d\eta)/_{\eta=0}$ obtained after these corrections is shown in fig. 5 for the two jet-finding algorithms. It can be seen that there is reasonable agreement between the two distributions over the E_T range shown (20 to 60 GeV), although the cluster algorithm tends to give a higher cross-section than the window algorithm, for reasons outlined in section 6. The errors shown are statistical only. Additional systematic errors (not included) are due to :

- the uncertainty in actual value of the inelastic cross-section, postulated to be 40 mb,
- the uncertainties on the transverse energy scale coming from the absolute calibration ($< 6\%$), the response correction α^{em} , the effects of the magnetic field, and the jet definition. The last three uncertainties are somewhat dependent on the jet fragmentation process and at this level are difficult to evaluate we estimate their total effect to be less than 10%. We note that a 10% change in the energy scale will change $d\sigma/dE_T$ by a factor of ≈ 2 .

In Fig. 6 we show the two-jet mass distribution $d\sigma/dm$ for jets with $E_T > 15$ GeV and $|\eta| < 1.4$, again for both algorithms. For those events where the cluster algorithm has found more than two jets, only the two jets with the highest E_T are taken into account. Again the cluster algorithm gives higher cross-sections than the window algorithm, reflecting the trend noted for the E_T distributions.

Superimposed on the experimental points of figs. 5 and 6 are shown the predictions of two QCD motivated models^{20, 21)}. We conclude that our jet transverse energy and invariant mass distributions are compatible with the extrapolation to $\sqrt{s} = 540$ GeV of hard scattering models based on QCD. However our cross-sections are about five times higher than those recently reported at the same energy by the UA2 collaboration⁸⁾ using also a calorimetric technique. Systematic uncertainties and jet definitions are similar to both experiments : they do not seem sufficient in explaining the discrepancy.

8. CONCLUSIONS. We have observed dominance of jet production in events with $\Sigma E_T > 100$ GeV in the range $|\eta| < 1.5$. We have measured the transverse energy distribution of jets in the $E_T(\text{jet})$ range from 20 to 60 GeV and the two-jet effective mass distribution in the mass range from 40 to 120 GeV. Both are found to be compatible with predictions of QCD motivated models.

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TABLE 1

Trigger threshold	Number of triggers	Number of events after beam-beam selection
20	118440	114659
30	64777	45560
40	17376	11940

Table Caption

Summary of data taken under various trigger conditions :

The first column gives the trigger threshold, i.e. the minimum value of $\Sigma'E_T$, where Σ' refers to the region $|\eta| < 3$;

Columns 2 and 3 give the numbers of events before and after off-line beam-beam selection.

Figure Captions

Fig. 1. The UA1 central calorimeters

a) horizontal cut (along the beam axis);

b) cross cut (perpendicular to the beam direction).

Hatched areas represent the calorimeter cells used for this analysis.

The location of the magnet coil (20 cm of aluminium) is indicated.

Fig. 2. a) Total transverse energy distribution $d\sigma/d\Sigma E_T$, where the sum is extended over the region $|\eta| < 1.5$;

b) Fraction of two-jet events selected by the "window" algorithm as a function of the total transverse energy in the region $|\eta| < 1.5$.

The curve is the result of the LPS Monte Carlo calculation mentioned in Sect. 5.

Fig. 3. Distribution of transverse energy vs azimuth ϕ and pseudo-rapidity η , for the five events with the highest ΣE_T .

Fig. 4. Azimuthal angle difference between two clusters with $E_T > 15$ GeV.

Fig. 5. Differential jet cross-section $(d\sigma/dE_T d\eta)|_{\eta=0}$ for jets found by the window algorithm (open circles) and the cluster algorithm (black squares).

The QCD predictions are from Ref. 19 (solid line) and Ref. 20 (dashed line).

Fig. 6. Distribution of the effective mass of the two-jet system, for jets found by the window algorithm (open circles) and the cluster algorithm (black squares), in the rapidity range $|\eta| < 1.4$. For those events where the cluster algorithm has found more than two jets, only the two jets with the highest transverse energy are used. The QCD calculation is from Ref. 20.

UA 1 Central calorimetry

a) Horizontal cut

b) Cross cut

Fig.1

Fig.2

Transverse energy flow of the 5 events with $\sum E_T > 100$ GeV

Fig.3

Fig.4

Fig.5

Fig.6