OBSERVATION OF VERY LARGE TRANSVERSE MOMENTUM JETS AT THE CERN $\bar{p}p$ COLLIDER

The UA2 Collaboration

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The distribution of total transverse energy ΣE_T over the pseudorapidity interval $-1 < \eta < 1$ and an azimuthal range $\Delta\phi = 300°$ has been measured in the UA2 experiment at the CERN $\bar{p}p$ collider ($\sqrt{s} = 540$ GeV) using a highly segmented total absorption calorimeter. In the events with very large ΣE_T ($\Sigma E_T \gtrsim 60$ GeV) most of the transverse energy is found to be contained in small angular regions as expected for high transverse momentum hadron jets. We discuss the properties of a sample of two-jet events with invariant two-jet masses up to 140 GeV/c^2 and we measure the cross section for inclusive jet production in the range of jet transverse momenta between 15 and 60 GeV/c.

1. Introduction. The suggestion that hard scattering of hadron constituents should result in two jets with the same momenta as the scattered partons [1] has motivated an intense experimental effort [2]. Earlier ISR experiments [3] have reported observations of such double-jet structures. However these jets were not as clearly identified as they are in the hadronic final states of high-energy e^+e^- annihilations [4], because in hadronic collisions the jets carry only a fraction of the total energy available. As a consequence, jets are accompanied by several soft hadrons which may make their identification more difficult and in general they are not collinear.

The recent successful operation of the CERN $\bar{p}p$ collider [5] has opened a new possibility to observe high transverse momentum hadron jets. At $\sqrt{s} = 540$ GeV the yield of jets with $E_T > 20$ GeV is expected to increase by about four orders of magnitude with respect to the top ISR energy [6] whereas the average particle density in the central region for an ordinary collision has increased by less than a factor of 2 [7].

We report here on results from the UA2 experiment at the CERN $\bar{p}p$ collider. This experiment uses a large

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solid angle total absorption hadron calorimeter subdivided in small cells, a device well suited to the detection of hadron jets.

2. Apparatus. A cross section of the UA2 detector is shown in fig. 1. At the centre of the apparatus a vertex detector consisting of cylindrical proportional and drift chambers measures particle trajectories in a region without magnetic field.

The vertex detector is surrounded by a highly segmented electromagnetic and hadronic calorimeter (the central calorimeter) which covers the pseudorapidity interval $-1 < \eta < 1$ (polar angle $40° < \theta < 140°$) and an azimuthal range of 300°. In the present stage of the experiment the remaining azimuthal interval (±30° around the horizontal plane) is covered by a single arm spectrometer to measure charged and neutral particle production [8].

The forward and backward regions ($20° < \theta < 37.5°$ and $142.5° < \theta < 160°$, respectively), are each instrumented by twelve toroidal magnet sectors followed by drift chambers, multitube proportional chambers and electromagnetic calorimeters.

The central calorimeter is segmented into 200 cells, each covering 15° in ϕ and 10° in θ and built in a tower structure pointing to the centre of the interaction region. The cells are segmented longitudinally into a 17 radiation length thick electromagnetic compartment (lead-scintillator) followed by two hadronic compartments (iron-scintillator) of two absorption lengths each. The light from each compartment is collected by two BBQ-doped light guide plates on opposite sides of the cell.

All calorimeters, including the forward–backward modules, have been calibrated in a 10 GeV/c beam from the CERN PS using incident electrons and muons. The calibration has since been tracked with a Xe light flasher system. In addition, the response of the electromagnetic compartments is checked regularly by accurately positioning a Co^{60} source in front of each cell and measuring the direct current from each photomultiplier. The systematic uncertainty in the energy calibration for the data discussed here is less than ±2% for the electromagnetic calorimeter and less than ±3% for the hadronic one.

The response of the calorimeter to electrons, single hadrons and multi-hadrons (produced in a target located in front of the calorimeter) has been measured at the CERN PS and SPS machines using beams from 1 to 70 GeV. In particular, we have studied the longi-

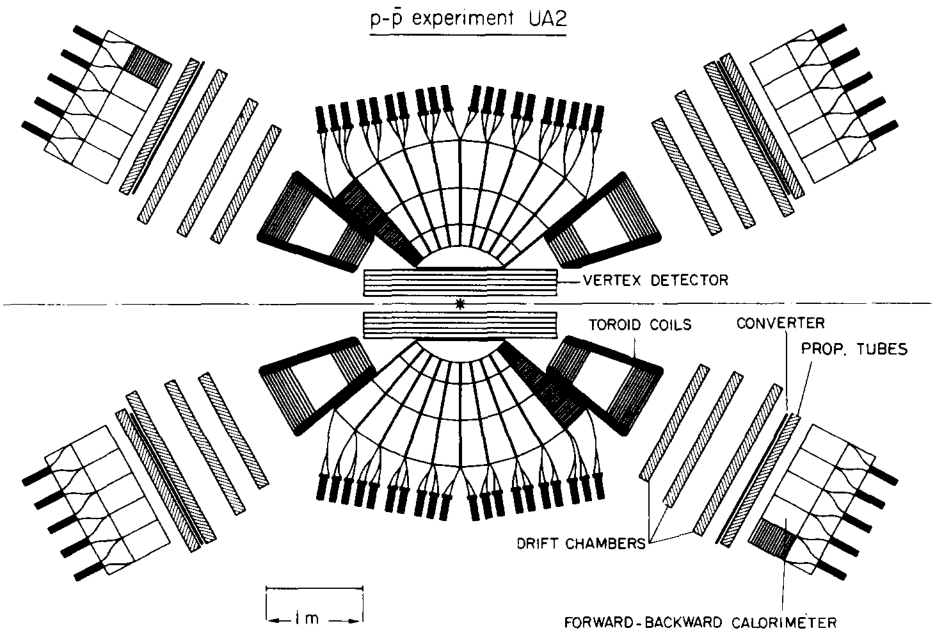

Fig. 1. The UA2 detector: schematic cross section in the vertical plane containing the beam.

tudinal and transverse shower development and the effect of particles impinging near the cell boundaries.

The energy resolution for electrons is measured to be $\sigma_E/E = 0.14/\sqrt{E}$ (E in GeV). In the case of hadrons, σ_E/E varies from 32% at 1 GeV to 11% at 70 GeV. The resolution for multi-hadron systems of more than 20 GeV is similar to that of single hadrons.

Details of the construction and performance of the calorimeter are reported elsewhere [9].

3. Data taking. The data discussed in this paper were recorded using a trigger sensitive to events with large transverse energy in the central calorimeter [10]. The gains of the photomultipliers were adjusted so that their signals were proportional to transverse energy. The signals were linearly added and their sum was required to exceed a given threshold (typically set at 20 GeV).

In order to suppress background from sources other than $\bar{p}p$ collisions, we required a coincidence with two additional signals obtained from two scintillator arrays surrounding the vacuum chamber 10.3 metres downstream of the interaction point and covering an interval $\Delta\eta = 1.1$ around $\eta = \pm 4.7$.

A sample of "minimum bias" data was recorded simultaneously by using only the coincidence of the signals from the two scintillator arrays. The rate of such coincidences provided also a measurement of the luminosity [8].

Furthermore the electronics were enabled between $\bar{p}p$ crossings and the cosmic ray background was found to be negligible.

4. Data reduction. Data have been recorded for an integrated luminosity of 79 μb^{-1}. The full data sample has been used in the following analysis for $\Sigma E_T > 30$ GeV. Partial samples are used for $\Sigma E_T < 30$ GeV and for minimum bias events.

The background events from beam halo particles and the accidental overlap of beam halo particles with minimum bias events exhibit a characteristic pattern in the detector different from that for events from $\bar{p}p$ collisions. A series of selection criteria is applied to remove background events:

– A fast filter requires that the pattern of hits in the vertex detector be consistent with charged particles coming from a common vertex.

– The ratios of the energies in each calorimeter layer (electromagnetic, first and second hadronic) to the total observed energy must be physically sensible.

– The local patterns of energy deposition in depth in the central calorimeter have to be consistent with that expected for particles emerging from a $\bar{p}p$ collision.

– Finally, for the highest ΣE_T events we reconstruct the event vertex and verify that it is within the collision region.

The combination of these requirements reduces strongly the number of background events. We find that the ratio of signal to background triggers in the initial event sample is ΣE_T-dependent, varying from ~10 at $\Sigma E_T \lesssim 10$ GeV to ~1 at 30 GeV and ~0.25 at $\Sigma E_T > 60$ GeV. After applying all of the above cuts we estimate from a visual scan of events that the final event sample contains less than 10% of background events independently of ΣE_T.

To study the loss of good events introduced by the cuts described above we use test beam data, Monte Carlo simulations and we investigate the effect of varying the cuts on the data. We estimate that the loss of good events is $\lesssim$15%, independent of ΣE_T.

5. Transverse energy distribution. The total hadronic energy in a cell is measured as the sum of the energies in the three compartments (at least one compartment must have 150 MeV, well above pedestal fluctuations).

The distribution of events as a function of the transverse energy ΣE_T in the interval $-1 < \eta < +1$, $30° < \phi < 330°$ is presented in fig. 2a; it is observed to fall off exponentially as has been observed in experiments [11] with a similar solid angle coverage at the SPS nd at Fermilab ($\sqrt{s} = 24$ GeV). There are 10 events having $\Sigma E_T > 60$ GeV.

We estimate that the uncertainty in the energy scale due to systematic effects (150 MeV minimum cell energy, variation in response of the electromagnetic compartment for charged and neutral pions, and calibration errors [‡1] to be ±5%. In the lower energy experiments, events with large ΣE_T (the largest accessible value is approximately 20 GeV) have predominantly high multiplicity, cylindrically symmetrical

[‡1] The response to hadrons has been measured to be linear to within 2% over the whole energy range, that of the electromagnetic compartment differs by 17% between charged and neutral pions.

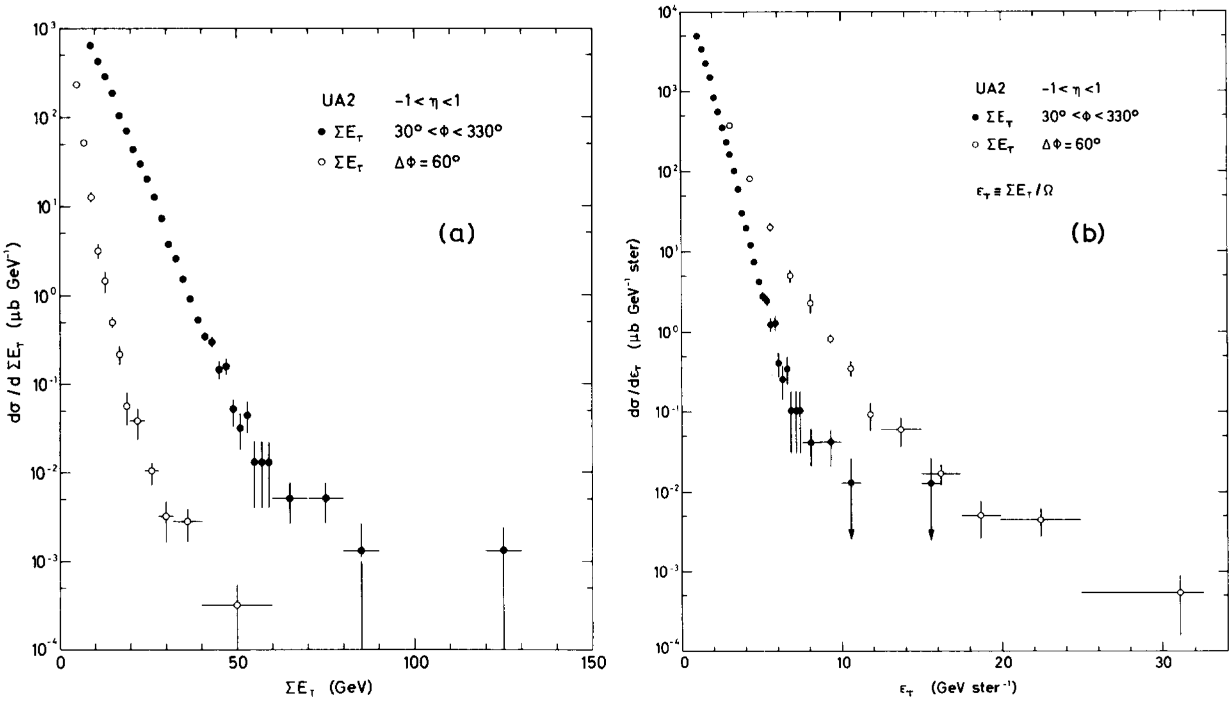

Fig. 2. Transverse energy (a) and its average density (b): observed distributions over the whole azimuthal acceptance (full dots) and over a restricted azimuthal region, $\Delta\phi$ = 60° (open circles).

configurations. It is however commonly expected [12] that at the present collider energy, $\sqrt{s}$ = 540 GeV, sufficiently large values of ΣE_T can be reached that two-jet configurations resulting from hard scattering will dominate. An indication of this is already provided by the fact that the two highest energy points in fig. 2a lie significantly above the exponential.

A more sensitive test is provided by studying the ΣE_T distribution into a solid angle which is substantially smaller though still sufficiently large to contain most of the energy for hadron jets in the E_T region of interest ($E_T > 15$ GeV). The $d\sigma/d\Sigma E_T$ distribution for $-1 < \eta < 1, \Delta\phi = 60°$ is shown in fig. 2a; it demonstrates a clear departure from an exponential. In fig. 2b, the same data samples are plotted as a function of the transverse energy density, $\epsilon_T = \Sigma E_T/\Delta\Omega$. Figs. 2a,b illustrate that regions of high energy density are confined to within a small solid angle.

Direct evidence for an increase of the energy clustering towards higher values of ΣE_T is obtained by constructing clusters of adjacent cells, each cell containing more than a fraction f of the total energy deposited in the central calorimeter. When ΣE_T increases from 30 to >60 GeV, the number of such clusters decreases from $\simeq$15 to $\simeq$6 on the average for f = 1%, while it increases from $\simeq$0.7 to $\simeq$2 for f = 8%: events with a high value of ΣE_T are made of relatively less numerous but more energetic clusters.

The same fact is illustrated by determining for each event the two non-overlapping 45° X 40° solid angles which together contain the largest fraction, g, of the total transverse energy, and studying g as a function of ΣE_T; the average value of g increases from $\simeq$40% at ΣE_T = 30 GeV to $\simeq$60% for ΣE_T > 60 GeV.

To study these high ΣE_T events in detail we use a clustering algorithm which joins into a cluster all cells which share a common side and contain an energy $E_{cell} > E_{cell}^{min}$; E_{cell}^{min} is normally chosen to be 400 MeV, though the results obtained are relatively insensitive to the exact value chosen. Clusters having two or more local maxima separated by a valley deeper than 2 GeV are then split. On the average, for ΣE_T > 30 GeV, we obtain $\simeq$4.4 clusters having E_T > 2 GeV per event, each cluster consisting of typically 4 cells.

The cluster (resp. the two clusters) with the largest transverse energy in an event accounts for a fraction

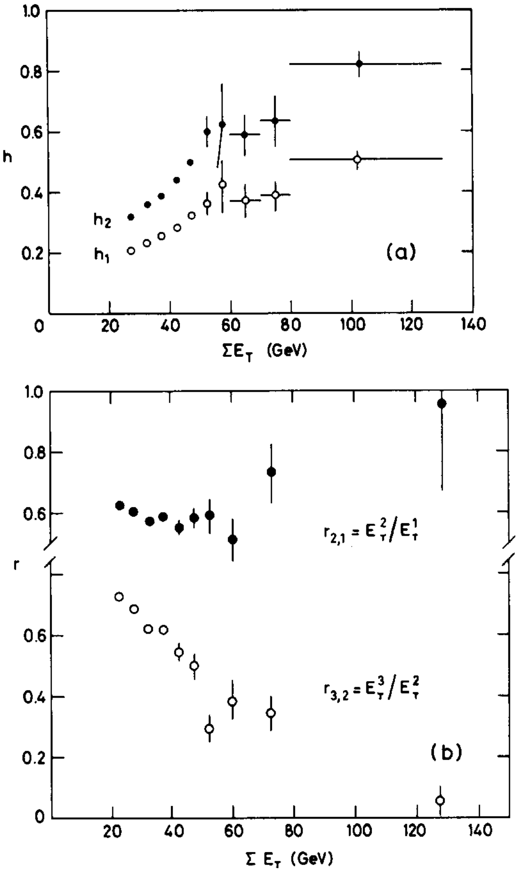

Fig. 3. (a) The fractions h_1 and h_2 of the total transverse energy ΣE_T contained in the cluster, and respectively the two clusters, having the largest E_T are displayed versus ΣE_T. (b) Dependence upon ΣE_T of the ratios $r_{21} = E_T^2/E_T^1$ and $r_{32} = E_T^3/E_T^2$ (see text).

h_1 (resp. h_2) of the total transverse energy ΣE_T measured in the central calorimeter. The dependence upon ΣE_T of h_1 and h_2 is illustrated in fig. 3a. In particular all events with ΣE_T in excess of 60 GeV have an average of 67% of the transverse energy contained in only two clusters.

6. Two-jet events. Fig. 4 shows the configuration of the event with the largest value of ΣE_T, 127 GeV. It exhibits striking features: energy is concentrated within two small regions separated in azimuth by $\Delta\phi \simeq 180°$ and towards which several collimated tracks are observed to point. In addition the transverse energies of the two clusters are approximately equal (57 and 60 GeV).

We now investigate to which extent such characteristics are also present in the other events having a large value of ΣE_T.

In each event we rank the central calorimeter clusters (C1, C2, ...) in order of decreasing transverse energies ($E_T^1 > E_T^2 > ...$). Fig. 5a shows the azimuthal separation $\Delta\phi$ between C1 and C2 for $E_T^{1,2} > 10$ GeV and $E_T^{1,2} > 14$ GeV. It peaks strongly near $\Delta\phi \simeq 180°$. If however we release the constraint that both E_T^1 and E_T^2 must exceed a high threshold, we find events in which E_T^2 may be only a small fraction of E_T^1: for example, in the sample of 59 events having $E_T^1 > 20$ GeV, 41 have $E_T^2/E_T^1 < 0.4$. For those $\Delta\phi$ is observed to have a uniform distribution between 0 and 180° while it always exceeds 140° in the rest of the sample. It is then natural to consider the possibility that a large localised transverse energy be produced outside the central calorimeter acceptance. Indeed, of 385 events having $E_T^1 > 10$ GeV and $E_T^2/E_T^1 < 0.4$, 22 deposit more than 5 GeV transverse energy in a sector of one of the forward/backward electromagnetic calorimeters: in such cases the azimuthal separation $\Delta\phi$ between this sector and C1 is nearing 180° (fig. 5b). These observations suggest an interpretation of the events in terms of a hard parton collision, a characteristic feature of which is the coplanarity of the scattered partons with the incident beams.

Further evidence is obtained from the fact that C1 and C2 are associated with jets of particles. We select a sample S_{JJ} (55 events) by requiring $E_T^{1,2} > 10$ GeV and $\Delta\phi > 140°$. We make the following observations:

(i) several tracks, measured in the vertex detector, are observed to aim towards the cluster centers (to within 13° on the average for $E_T > 20$ GeV);

(ii) longitudinal shower developments, measured from the contributions of electromagnetic and hadronic compartments, are inconsistent with that of a single particle but consistent with that of a jet fragmenting into charged and neutral pions;

(iii) cluster diameters are ≈80% larger than expected from the transverse extension of showers induced by single particles but are consistent with fragmenting jets.

We use the same event sample S_{JJ} to investigate a third property of hard parton collisions: the approximate equality of the transverse momenta of the scattered partons. We calculate the transverse momentum P_T and the invariant mass M associated with the pair

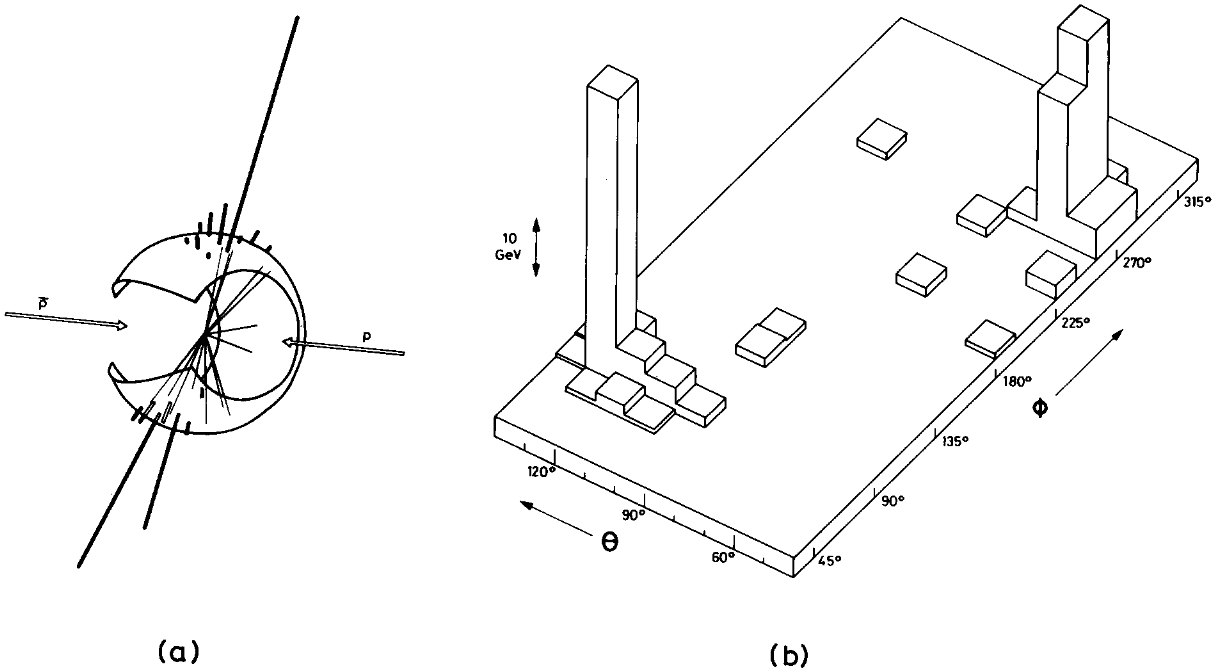

Fig. 4. Configuration of the event with the largest value of ΣE_T, 127 GeV (M = 140 GeV): (a) charged tracks pointing to the inner face of the central calorimeter are shown together with cell energies (indicated by heavy lines with lengths proportional to cell energies). (b) the cell energy distribution as a function of polar angle θ and azimuth ϕ.

(C1, C2) in each event (we assign to each cluster a four-momentum $(E\boldsymbol{u}, E)$, E being the cluster energy and $\boldsymbol{u}$ the unit vector pointing from the event vertex to the cluster center). We measure P_T to be 6 GeV/c on the average, of which at least 3 GeV/c are of instrumental nature (non-inclusion of large angle fragments in the cluster, energy resolution, edge effects, etc.).

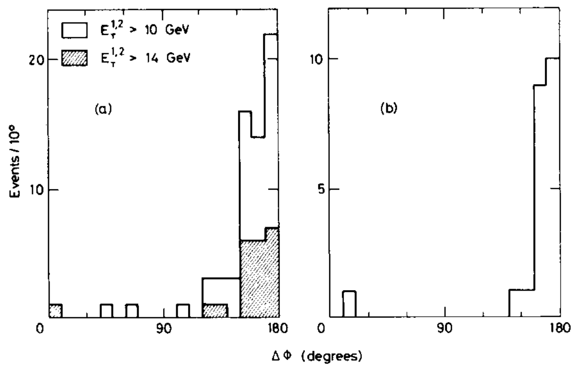

Fig. 5. (a) Azimuthal separation between C1 and C2 (see text) for $E_T^{1,2} > 10$ and 14 GeV. (b) Azimuthal separation between C1 and the forward/backward sector having $E_T > 5$ GeV for $E_T^1 > 10$ GeV and $E_T^2/E_T^1 < 0.4$ (see text).

The above observations support the interpretation of S_{JJ} as a sample of two-jet events resulting from a hard parton collision. We remark however that the spectacular configuration illustrated in fig. 4 is not representative of the whole sample. As shown in fig. 3a the two-jet system accounts for only a fraction of ΣE_T. The rest of the transverse energy in the event, $\widetilde{E}_T$, is distributed among clusters, of which typically 2 to 3 are in excess of 1 GeV. Their detailed study is beyond the scope of the present report. We simply remark that they are only weakly correlated with the jet directions and that their multiplicity and transverse energy distributions are the same as in events having $\Sigma E_T = \widetilde{E}_T$.

Given the presence of relatively abundant and hard clusters accompanying the two-jet system, we further ascertain the emergence of a two-jet (as opposed to multi-jet) structure by measuring the dependence upon ΣE_T of the ratios $r_{21} = E_T^2/E_T^1$ and $r_{32} = E_T^3/E_T^2$. As ΣE_T increases, r_{21} increases and r_{32} decreases (fig. 3b), again illustrating the dominance of two-jet events for ΣE_T exceeding $\simeq$60 GeV.

7. Inclusive jet production. There are 59 events containing at least one cluster with $E_T > 20$ GeV. The evaluation of the inclusive jet production cross section from these events requires the knowledge of the detector acceptance and luminosity.

The detector acceptance is obtained from a Monte Carlo simulation that generates jets with the E_T-distribution given in ref. [6], superimposed on a system of soft hadrons accounting for the remaining fraction of $\sqrt{s}$. The jets fragment into hadrons with an average transverse momentum of 0.45 GeV/c with respect to the jet axis according to a fragmentation function of the form $(1-x)^2/x$ (x is the fractional momentum of the fragment along the jet axis). All of these hadrons (assumed to be charged and neutral pions only) are then followed into the calorimeters to generate a pattern of energy depositions. Both the longitudinal and lateral shower developments as well as the energy resolution are taken into account.

The data generated by the Monte Carlo simulation undergo the same analysis chain as the real data. In particular, we find that the distribution of cluster size in the Monte Carlo data is very similar to that of the real data, indicating that both hadronic fragmentation and shower developments are correctly described in the simulation program.

The comparison of the E_T-distribution of the Monte Carlo data with that used as an input provides the correction function $\alpha(E_T)$ by which the observed cross section must be divided to obtain the jet inclusive cross section. We have checked that varying some of the analysis parameters, in particular those related to the cluster definition, changes both the observed E_T distribution and $\alpha(E_T)$ but the correct cross section always varies by less than 10%. The function $\alpha(E_T)$ varies by less than a factor of 2 over the range $20 < E_T < 60$ GeV.

The integrated luminosity is obtained by counting the total number of minimum bias events which occurred during data taking. From the fluctuations measured during different running conditions we assign an uncertainty of ±17% to its value. An additional uncertainty results from the fact that, as already mentioned, the trigger to record large-E_T events required a coincidence with a pair of small angle charged secondaries. This requirement introduces a bias which may affect both the absolute magnitude of the cross section and its E_T-dependence.

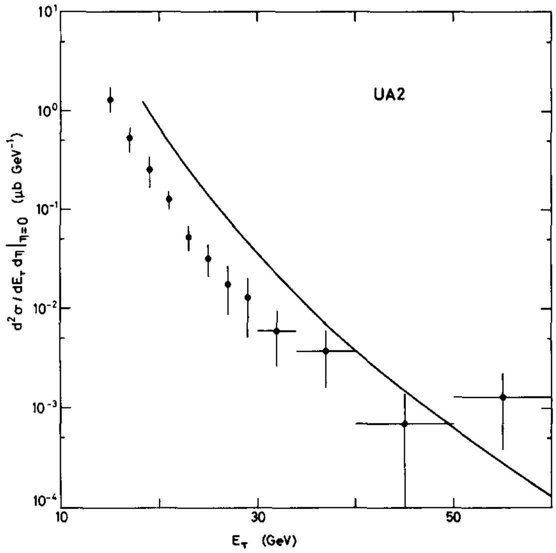

Fig. 6. Inclusive jet production cross section. The solid line (ref. [6]) uses $\Lambda = 0.5$ GeV while $\Lambda = 0.15$ GeV would bring the calculated rates in better agreement with the data. However various uncertainties preclude a determination of Λ from the data [13].

Fig. 6 shows the cross section for inclusive jet production as a function of the jet transverse energy E_T. The errors shown are only statistical. There is an overall uncertainty of ±20% in the vertical scale reflecting the uncertainties in the knowledge of the total luminosity and in the Monte Carlo calculated acceptance. An uncertainty of ±2.5% in the E_T-scale, reflecting the calorimeter energy calibration uncertainties, results in an additional vertical uncertainty of ±20%. From a visual scan of the events the contribution from sources other than $\bar{p}p$ collisions is estimated to be <10%, independent of E_T.

Our measured cross section is at a level comparable with the QCD calculation of Horgan and Jacob [6], which is also shown in fig. 6. In the framework of this model, inclusive jet production is dominated by gluon–gluon scattering in the kinematical region of this experiment.

We finally note that the possible merging of two high E_T clusters produced with a small angular separation may increase the measured cluster energy by as much as 2 GeV on the average. This effect is not accounted for in ref. [6] where jet fragmentation is ignored.

8. Conclusion. We have observed that events with a large transverse energy (in excess of $\simeq 60$ GeV) in a rapidity interval of two units around 90° have a dominant two-jet structure at $\sqrt{s} = 540$ GeV. This is in strong contrast with the situation at $\sqrt{s} = 24$ GeV [11]. The inclusive jet production cross section is measured at a level similar to that predicted by QCD calculations [6]. A sample of two-jet events has been studied and observed to feature properties characteristic of hard scattering of partons. This observation provides the first evidence for highly collimated jets produced in hadron collisions.

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