**DIJET PRODUCTION CROSS-SECTION AND FRAGMENTATION OF JETS
PRODUCED IN pp COLLISIONS AT $\sqrt{s} = 63$ GeV****The Axial Field Spectrometer Collaboration**

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ABSTRACT

We present studies of events triggered on two high- p_T jets, produced in pp collisions at the CERN Intersecting Storage Rings (ISR) at $\sqrt{s} = 63$ GeV, using a large solid angle calorimeter. The cross-section for producing two jets is measured in the dijet mass range 17–50 GeV/ c^2 . A high-statistics sample of dijet events, where each jet has transverse energy above 10 GeV, is used to study the structure of jets and the associated event. We find the longitudinal fragmentation function to be similar to that of jets emerging from e^+e^- collisions but considerably harder than that observed at the Super Proton Synchrotron (SPS) $p\bar{p}$ Collider. A steepening of the fragmentation function is observed when increasing the jet energy. Studies of the charge distribution in jets show that these predominantly originate from fragmenting valence quarks. The transverse energy and particle flows are presented as functions of the azimuthal distance from the jet axis.

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1. INTRODUCTION

High- p_T jets have been shown to dominate the event structure in hadronic collisions at high centre-of-mass (c.m.) energies when sufficiently large transverse energy E_T is required. This was demonstrated by experiments using calorimeters with large solid angles compared to the jet size, both at $\sqrt{s} = 63$ GeV [1,2,3] and at $\sqrt{s} = 540$ GeV [4]. In the framework of QCD, high- E_T events originate mainly from a single hard scattering of the nucleon constituents, and the observed dijet structure is naturally explained by their subsequent fragmentation. At lower c.m. energies or at lower transverse energies, the same elementary processes are believed to occur. But, since the jets are wider and because of contributions from other sources, such as initial- and final-state gluon bremsstrahlung and multiple scattering of quarks and gluons, less striking event topologies can be created, as indeed seems to be the case experimentally [3,5,6]. Nevertheless, by demanding a closer match between the typical jet size and the trigger solid angle, events dominated by two jets can be measured more efficiently over a wider range of transverse energy [7]. The results presented in this paper are based on a large-statistics sample of events with a dijet trigger, requiring large E_T (> 10 GeV) in each of two non-overlapping regions of our calorimeter.

In hadronic collisions, events with two clear transverse jets allow the study of single hard scattering of the nucleon constituents, and their fragmentation into the observed jets. The relative contributions from quark, gluon, and antiquark scattering depend on the subprocess cross-sections and also on the constituent structure functions of the colliding hadrons. From measurements of these structure functions (in deep inelastic lepton scattering) we expect large relative variations of these contributions as a function of the fractional parton momentum x . Measurement of the charge content in jets provides a means to distinguish statistically between these processes for our typical value of $x \approx 0.4$.

Jets have been observed in other hard scattering processes, such as e^+e^- collisions and deep inelastic lepton-nucleon scattering [8,9]. Direct comparisons between jets in e^+e^- interactions and jets in hadronic collisions always encounter the basic problem that it is impossible in the latter case to distinguish completely between particles belonging to the high- p_T jets and particles not directly associated with the hard process, and care must be taken to evaluate their relative contributions.

We have previously presented measurements of total E_T distributions and single-jet production cross-sections at various values of $\sqrt{s}$ [3], and in Ref. [10] we discussed the properties of jets in events with E_T in excess of 30 GeV in a full azimuthal coverage calorimeter, at $\sqrt{s} = 63$ GeV. In this paper we present a measurement of the dijet cross-section $d^3\sigma/dM d\eta_1 d\eta_2|_{\eta_1=\eta_2=0}$ for pp collisions at $\sqrt{s} = 63$ GeV, and the properties of the jets and the associated events in a high-statistics sample of events containing two jets above 10 GeV. Section 2 describes the apparatus and the trigger. In Section 3 we discuss the analysis procedure, including the selection of events, jet definition, and Monte Carlo corrections. The results are presented in Section 4, and finally conclusions are given in Section 5.

2. APPARATUS

The data were taken with the Axial Field Spectrometer (AFS) at the CERN Intersecting Storage Rings (ISR). All the data were obtained from proton-proton collisions at $\sqrt{s} = 63$ GeV, and the integrated luminosity for this analysis is $\int \mathcal{L} dt = 1.7 \times 10^{37} \text{ cm}^{-2}$.

The AFS has been described in detail elsewhere [11]. Figure 1 shows the elements of the detector used in this analysis. The interaction region is surrounded by an inner hodoscope of 44 scintillator elements, a cylindrical drift chamber, and a uranium/copper/scintillator calorimeter with full azimuthal coverage.

The calorimeter [12] consists of four walls of uranium/scintillator calorimeters at a distance of ~ 118 cm from the interaction region, supplemented in the corners by copper/scintillator modules. The polar-angle coverage varies with azimuth owing to the square structure and the motion of the c.m. of the colliding protons; the pseudorapidity range covered lies between $|\eta| < 0.7$ and $|\eta| < 1.2$, giving a total solid angle coverage of 8.6 sr. Each of the four walls is segmented into a square tower geometry with 2×16 modules along the beam direction, each optically subdivided into 6 towers of 20×20.8 cm². In depth, the wavelength shifter readout separates the electromagnetic (6 radiation lengths) and hadronic (3.8 absorption lengths) sections for each tower. The 16 copper modules in each of the four corners were not subdivided in depth.

The energy scale and the resolution of the calorimeter were studied in test beams of electrons and pions [12]. The response for electromagnetic showers was measured to be linear and has been used to define the energy scale of the calorimeter. This choice of energy scale results in an underestimate of the hadronic shower energy above 2 GeV by about 10%. At lower energies the energy response for hadrons is non-linear. No correction of the hadronic energy due to this choice of scale was attempted on an event-by-event basis, but a statistical correction is applied by a Monte Carlo simulation, as described in Section 3.3. Throughout the data-taking periods the energy scale was maintained at a constant value to an accuracy of $\pm 2\%$ by exploiting the constant level of natural radioactivity from the uranium. (Each copper module contained a radioactive source in a central rod for the same purpose.) At the time of data taking, the energy resolution (σ/E) in the uranium calorimeter was approximately $18\%/\sqrt{E}$ (E in GeV) for electromagnetic showers and $42\%/\sqrt{E}$ for hadronic showers.

Charged-particle tracking was provided by the cylindrical drift chamber [13], operated in an axially symmetric magnetic field of 0.5 T. The chamber was segmented into 82 four-degree sectors in azimuth; each sector contained 42 sense wires parallel to the bisector of the colliding beams. Except for two 16° wedges in the vertical plane, used mainly for mechanical support, the active volume of the chamber extended over 2π in azimuth. The coordinates in the transverse plane were provided by drift-time measurements with a spatial resolution of $230 \mu\text{m}$, and the coordinates along the beam direction by charge division with 1.5 cm resolution. Over the azimuthal coverage of 328° and rapidities $|y| < 0.7$ the track acceptance (including reconstruction efficiency) was uniform, and equal to 100%, for isolated tracks with $p_T > 200$ MeV/c. The momentum resolution is given by $(\Delta p/p)^2 = [(0.025p)^2 + 0.01^2]$, where p is in GeV/c.

The data were obtained by triggering on two separated jets anywhere in the calorimeter. Using photomultiplier dynode signals from all of the 16 towers in a calorimeter row (corresponding to an azimuthal range of $\Delta\phi \approx 7.5^\circ$, and polar angles $45^\circ < \theta < 135^\circ$), a weighted sum was formed, proportional to the total c.m. transverse energy $E_T = \Sigma E_{\text{cm}} \cdot \sin \theta$ deposited in this row. Separate sums were formed for the electromagnetic and hadronic sections and for the copper modules, resulting in a total of 100 transverse-energy sums, each at constant azimuth ϕ . By a further electronic adding of sums in adjacent rows, 24 ‘jet sums’ were formed, each spanning 6 rows of the calorimeter, with an overlap of 4 rows in order to minimize

geometrical acceptance losses. Each of these jet sums thus represents the total c.m. transverse energy in a part of the calorimeter covering on the average $\Delta\phi \approx 45^\circ$, $45^\circ < \theta < 135^\circ$. Owing to the motion of the c.m. of the colliding protons and the square structure of the calorimeter, the coverage of the jet sums varies from $\Delta\phi \approx 60^\circ$ at $\phi \approx 0^\circ$ to $\Delta\phi \approx 30^\circ$ at $\phi \approx 135^\circ$. Further details of the trigger system are given in Ref. [14].

The data presented here required two non-overlapping jet sums to exceed a threshold which was varied between 4 GeV and 9 GeV. Except for the cross-section measurements, all results are based on events satisfying the highest threshold of 9 GeV. In addition to the energy deposition in the calorimeter, the dijet trigger required at least two charged-particle hits in the 44-element inner hodoscope of scintillation counters. Two sets of scintillation counters, located downstream from both beams at small angles, were used as luminosity monitors and, in conjunction with the inner hodoscope, to provide timing information.

Some data were taken with a ‘minimum bias’ trigger, requiring at least two charged-particle hits in the inner hodoscope, or at least one particle hit in each set of downstream scintillation counters.

3. DATA ANALYSIS

3.1 Event selection and reconstruction

In the off-line analysis, the events were processed through the standard AFS cluster-finding procedure for the calorimeter [12], and the track and vertex reconstruction program for the central drift chamber [13].

The first stage of the analysis consisted of sharpening the dijet trigger condition by use of the fully calibrated calorimeter response of individual towers of the calorimeter. The procedure included a fine adjustment for each individual tower of the average energy offset introduced by the radioactive noise from the uranium, using measured energy in events triggered out of time with real pp collisions.

Events were rejected if no vertex point from the charged-particle tracks was found in the beam-crossing region. Timing information from the inner hodoscope and downstream beam counters was used to ensure that the event was consistent with an interaction at the correct event time and that no other interaction was observed within the 120 ns sensitive time of the calorimeter. Finally, timing signals on the triggering calorimeter sums were required to agree with the above event time. All these cuts were applied in order to reject cosmic rays or beam-induced background particles depositing energy in the calorimeter, possibly overlapping a real pp interaction close in time. The cuts removed $\sim 10\%$ of all events, and the remaining background is estimated to be negligible. The loss of real dijet events due to the vertex requirement is also negligible, since the number of tracks fitted to the vertex is on the average 18. Events satisfying the improved trigger condition and timing cuts were passed through a full reconstruction procedure.

The cluster-finding algorithm for the calorimeter uses shower profiles known from test-beam measurements to join neighbouring towers into clusters representing single particles or unresolved groups of particles. Preclusters consisting of 3×3 tower masks are formed around towers with significant energy. Neighbouring towers are added if their energies are consistent with the amount of light expected to propagate along a calorimeter module. The preclusters are

then tested against the known shower profiles and may be split or merged into a final set of clusters. Care is taken to add both positive and negative energy contributions to a cluster due to the fluctuations in the radioactive noise from the uranium. Each calorimeter wall is treated separately and the copper calorimeters are incorporated into each adjacent wall as an additional row. In each event, a number of low-energy clusters (~ 100 MeV) are generated by upwards fluctuations in the uranium noise. We have reduced the effect of these event-unrelated clusters in the analysis by only considering those with energies above 200 MeV, and have corrected for the loss of real low-energy clusters by Monte Carlo simulation. Figure 2 shows the calorimeter information in a reconstructed dijet event.

Tracking of charged particles and vertex reconstruction use the information from the cylindrical drift chamber. Quality cuts on the reconstructed tracks include a minimum of 16 time digitizings and 5 charge-division measurements; the χ^2/NDF is required to be less than 5, and the error on the momentum measurement $\Delta p/p$ below $0.025p$ (p in GeV/c). With these requirements, the acceptance for charged particles with $p_T > 200$ MeV/c in the central region ($|y| < 0.7$) and not passing through the blind wedges is generally very close to 100%, estimated from a full Monte Carlo simulation of the drift-chamber response. For a pair of very close tracks or tracks which cross at small angles, a loss of efficiency has been seen both in the Monte Carlo simulation and by observing relatively fewer particles at very small relative angles in real events. For example, the overall track reconstruction efficiency inside the region of a narrow jet ($\Delta\phi < 10^\circ$) is estimated to be about 74%, rising smoothly to 100% for $\Delta\phi > 30^\circ$. Owing to the chamber geometry, the longitudinal separation, Δz , of the tracks is generally unimportant, except for very small $\Delta\phi$.

The reconstructed charged-particle tracks and calorimeter clusters were transformed into the pp c.m. system, using the reconstructed charged-particle vertex as origin and assuming pion masses and zero masses, respectively. As mentioned above, clusters were only used if their energies exceeded 200 MeV. To ensure a uniform azimuthal acceptance, only tracks and clusters in the central (pseudo)rapidity region ($|y| < 0.7$ for tracks, $|\eta| < 0.7$ for clusters) were considered in the subsequent analysis. No attempt was made to associate individual tracks with clusters, an almost impossible task in the presence of the high local multiplicities in the jet regions. Instead, the calorimeter information was used whenever overall energy distributions (including neutral particles) were important, whereas the charged-particle tracks were used for good momentum measurements of individual particles and for studies involving the charge of the particles.

3.2 Monte Carlo simulation

For the interpretation and correction of the data, we used simulated events, generated by the QCD-based ISAJET Monte Carlo program [15]. The aim was primarily to correct the data fully for effects of data-selection and -analysis methods, calorimeter resolution, calorimeter energy response and drift-chamber acceptance, but in some cases also to interpret the results in terms of the underlying physical processes. Since corrections rely on a good representation of the data by the simulation, care was taken in the fine tuning of the model parameters.

The ISAJET program was used to generate dijet events over the full p_T range observed. ISAJET generates high- p_T jets from partons, which scatter according to lowest-order perturbative QCD. The scattered partons are evolved into a cascade of quarks and gluons which finally fragment independently following the Feynman-Field model [16]. Beam jets are generated

with leading baryons and mesons with multiplicities chosen to satisfy approximate KNO-scaling [17]. The structure functions used are those of Duke and Owens [18] with $\Lambda_{\text{QCD}} = 0.2 \text{ GeV}$. Some parameters in ISAJET were adjusted to reproduce our data more closely. The effects were mainly to increase the width of the jets by about 35%, and to raise the central multiplicity from the beam-jet fragments with respect to the standard ISAJET value. The increase was made dependent on jet energy, amounting to $\sim 45\%$ at our average jet E_T of 13.5 GeV. Initial-state gluon bremsstrahlung is not incorporated in ISAJET, but an effective primordial k_T was introduced by a Lorentz boost of the dijet system such as to give it an average transverse momentum of 0.8 GeV/c in each component. The momentum balance was maintained by an opposite Lorentz boost of the beam jets. Details of the modified ISAJET Monte Carlo program are given in Appendix A. With these modifications, the jet widths and the level of associated particle multiplicity and energy flow outside the jet regions reproduce well those observed in the data, as will be shown in the following section.

The generated events were passed through a detailed simulation of the calorimeter [19,12]. Hadronic and electromagnetic shower profiles follow the longitudinal parametrization suggested by Bock et al. [20] and use a lateral development described by a two-dimensional Gaussian distribution with the sigma taken to be one half of an ‘average absorption length’ or ‘average radiation length’ for hadrons and photons, respectively. The full tower geometry with wavelength shifter readout and light-coupling between towers is incorporated, as well as the minimum-ionizing energy loss of charged particles, depth of interaction point, particle decays, electromagnetic and hadronic energy response and resolution, and the uranium noise. The simulated tower pulse heights were finally analysed through the same programs as were used for the real data.

A number of events were passed through a full drift-chamber simulation, and subsequent pattern-recognition and tracking programs. This enabled us to calculate an average track acceptance in the central rapidity region as a function of the azimuthal distance $\Delta\phi$ to the nearest jet axis. The average acceptance was found to be 74% for $\Delta\phi < 10^\circ$, rising smoothly to 100% for $\Delta\phi > 30^\circ$. The two blind wedges in the drift chamber were explicitly incorporated, as was the momentum smearing of the measured charged particles.

We have used this Monte Carlo simulation to correct measurements presented here for efficiencies and resolution effects. In most cases, the correction has been made by calculating the correction factor as the ratio between the Monte Carlo generated distribution and the same distribution after the Monte Carlo events have passed through the detector simulation and analysis. The corrections are typically less than 20%, and the associated systematic errors are small. A different approach was taken when correcting the measured jet energies. Since the measured jet energy in addition to the calorimeter response also depends on which clusters were chosen to be part of the jet, rather large differences may appear when comparing the jet energy of individual Monte Carlo events before and after the detector simulation and analysis. Details of the statistical procedure used to correct the observed jet energies are given together with the presentation of the data in Section 4.1.

The absolute energy scale was defined by test-beam measurements to an accuracy of $\pm 1\%$, but because of additional systematic errors due to uncertainties in the electromagnetic/hadronic energy response and the electromagnetic/hadronic particle composition in real events, pedestal determinations, and overall stability of the calorimeter, we estimate an uncertainty in the

calorimeter energy scale of $\pm 4\%$. Systematic errors from the correction procedures have been estimated by varying individual parameters in the Monte Carlo input, and whenever they were found to be important compared to the statistical errors they will be quoted separately.

3.3 Jet reconstruction and Monte Carlo comparisons

A rigorous identification of a jet emerging from a hadronic interaction is clearly not possible. The separation between the fragments from the hard scattering constituents on the one hand and the particles associated with the spectator partons and the redistribution of energy in the final state on the other is impossible, even in principle. However, in a large- E_T event the energy distribution usually leaves little doubt about the presence and direction of the jets, as illustrated by the example in Fig. 2, although the assignment of total energy to the jets involves a definition of how much of the energy around the jet axis to include and what fraction of the energy to attribute to soft ‘non-jet’ contributions.

In this analysis we have chosen to base our definition of a jet on the same simple principle of summing up transverse energy in a fixed solid angle as was used in the trigger. Sums were found of the transverse energy of all clusters with pseudorapidities $|\eta| < 0.7$ and azimuth within a window of fixed opening angle Φ . The position of the window in azimuth was chosen such as to maximize the transverse energy flow into the window, and if this transverse energy sum exceeded a threshold, $E_T^{\min}$, a jet momentum vector was formed as the vector sum of all cluster momenta inside the window. The procedure was repeated on the remaining clusters to form the second jet.

The choice of window width Φ must reflect the observed angular extent of jets at these energies but will remain a compromise between the loss of clusters that belong to the jet and the inclusion of non-jet clusters, a choice which cannot be strictly correct on an event-by-event basis. In particular, the calculated jet energy depends on the choice of Φ . However, the jet energies can be corrected statistically by use of the Monte Carlo events, as described in Section 4.1. We have carried out this analysis with both $\Phi = 60^\circ$ and $\Phi = 40^\circ$ and found differences of less than 15% for both the dijet cross-section after corrections, and the corrected fragmentation function. In the following we use $\Phi = 60^\circ$.

Except for the cross-section measurements presented in Section 4.1, where lower thresholds were used, all of the subsequent analysis requires two separated jets with $E_T > E_T^{\min} = 10$ GeV, well above the hardware threshold. Also, in order to minimize the effect of clusters outside the pseudorapidity cut $|\eta| < 0.7$ belonging to the jet, all jet momentum vectors are required to point to the central rapidity region $|\eta^{\text{jet}}| < 0.4$. After all these cuts, 29225 events with two centrally produced large- p_T jets remained.

To illustrate the degree to which the selected dijet events exhibit prominent jet structures, Fig. 3 shows the distribution of thrust, T , in the transverse plane, calculated from the calorimeter clusters. The thrust variable is here defined as

$$T = \max \left(\sum |\vec{e} \cdot \vec{p}_i| / \sum |\vec{p}_i| \right),$$

where the sums are over all clusters with momenta $\vec{p}_i$ in the transverse plane and $\vec{e}$ is a unit vector in the transverse plane along the jet direction. It can range from $2/\pi = 0.64$ for an isotropic event to 1 for a perfectly collimated two-jet event. The observed average thrust value in this event sample is $\langle T \rangle = 0.92$.

The angular difference between the two jet momenta in azimuth, $\Delta\phi_{jj}$, reflects both the uncertainty in the angular definition of the jet and any momentum imbalance in the dijet system. With two jets defined in each event as described above, Fig. 4 shows $\Delta\phi_{jj}$ as observed in the data, together with the results of an identical analysis of the Monte Carlo events. The observed jets are back-to-back in azimuth with an r.m.s. width of $\sim 9^\circ$, consistent with the Monte Carlo curve. The result is also consistent with the observation that, in Monte Carlo events, the difference in azimuth between the generated jet direction and the reconstructed one for each of the two jets has an r.m.s. spread of $\sim 6^\circ$, corresponding to less than the angular extent of one calorimeter tower.

The correction of the measured jet energies relies on a good representation in the Monte Carlo simulation of the energy leakage and energy resolution of the calorimeter as well as the angular width of the jets and the level of associated particles. Several comparisons with the data were made to ensure this. Figure 5 shows, in bins of total transverse jet energy, the transverse energy flow within $|\eta| < 0.7$ as measured in the calorimeter, as a function of the azimuthal angle $\Delta\phi$ relative to the direction of the highest- E_T jet. Both the widths and magnitudes of the high energy density in the two jet regions $\Delta\phi < 30^\circ$, $\Delta\phi > 150^\circ$, and the level near $\Delta\phi = 90^\circ$, are well reproduced by the Monte Carlo data, represented by the imposed curves. The adjustments of the Monte Carlo parameters mentioned in the previous section were mostly made to ensure agreement with data in these energy-flow distributions. Figure 6 shows the observed momentum imbalance of the dijet system in the transverse plane, in two bins of jet energies. The p_T imbalance is well represented by the Monte Carlo calculations, demonstrating that cosmic-ray and beam-gas backgrounds have been efficiently removed by the cuts described in Section 3.1.

4. RESULTS

4.1 Dijet cross-section

We have previously presented the total transverse energy distribution [3], and shown that most events with very high total E_T exhibit a clear dijet structure. In this analysis we present the fully corrected dijet cross-section at $\theta = 90^\circ$, and extend the measurement down into a range of jet energies where jets are not a dominant feature of events triggered on total transverse energy.

We first present the differential cross-section $d^3\sigma/E_T^{jj}d\eta_1d\eta_2$ as a function of the total transverse energy, $E_T^{jj} = E_T^{\text{jet}1} + E_T^{\text{jet}2}$, inside the fixed opening angles of the two jets, $\Delta\phi < 30^\circ$, $|\eta| < 0.7$, corrected for instrumental effects. While E_T^{jj} is a well-defined experimental observable, the interpretation in terms of the constituent-constituent centre-of-mass collision energy $\sqrt{\hat{s}}$ to some degree depends on the model used to describe the data. In particular, the observed energy in the jet regions depends on the loss of jet particles emitted at relatively large angles to the jet direction, and the contribution from particles inside the jet region which are not fragments of the hard scattered constituents. We have used the QCD-based model described above to correct the observed invariant dijet mass (M_{jj}) statistically to give the dijet mass M , equivalent to the constituent-constituent c.m. energy $\sqrt{\hat{s}}$, and we present the dijet cross-section $d^3\sigma/dM d\eta_1 d\eta_2|_{\eta_1=\eta_2=0}$ as a function of M .

In order to perform a statistical correction of the observed jet energies, a matrix was formed of Monte Carlo generated jet energy versus the observed energy after full detector simulation and an analysis identical to the one used for the data. Rather than treating the two jets in each event

separately, we used directly the total dijet transverse energy, E_T^{jj} , or the dijet invariant mass, M , in the correction procedure. Figure 7 shows the matrix of generated dijet mass, M , versus the detected invariant mass M_{jj} , calculated from the total four-momentum vector of the clusters in the reconstructed dijet system. The average detected mass is smaller than the true M , mainly owing to the choice of electromagnetic energy scale for the calorimeter, but also because of jet particles depositing their energy outside the jet window, and because of leakage at the back of the calorimeter. Using this matrix and the shape of a given input spectrum, a probability distribution was formed of the true M for each measured dijet mass. The curves on the figure show the parametrization used when correcting the dijet mass spectrum. The correction of the observed spectrum is now an unfolding procedure relating each observed dijet mass M_{jj} with a corrected M according to the parametrized probability distributions. The shape of the observed spectrum is well reproduced by the Monte Carlo events, and only a few iterations were necessary to obtain the final spectrum. An identical procedure was used to correct the transverse energy, E_T^{jj} .

Figure 8 shows the corrected cross-section, $d^3\sigma/dE_T^{jj}d\eta_1d\eta_2$, where E_T^{jj} is the total transverse energy inside the two jet regions, defined by the pseudorapidity cut $|\eta| < 0.7$ and the azimuthal jet window $\Phi = 60^\circ$ (i.e. $\Delta\phi < 30^\circ$, where $\Delta\phi$ is measured with respect to the jet direction). The values are given in Table 1. The complete cross-section is formed by combining data sets with different jet thresholds, normalizing each data set to the corresponding luminosity. In this case no corrections are made for the fact that the jet regions may contain particles not directly associated with the jets and that real jet particles may fall outside the chosen jet regions. The systematic error is dominated by the $\pm 4\%$ uncertainty in the energy scale. It includes the uncertainty in the Monte Carlo representation of the detector and the error ($\pm 10\%$) associated with the luminosity measurement. On the figure, statistical error bars are shown, and the systematic errors are given by the outer bars.

The dijet cross-section, $d^3\sigma/dM d\eta_1 d\eta_2|_{\eta_1=\eta_2=0}$, where M is the invariant mass of the dijet system, is presented in Fig. 9 and in Table 2. Through the specific model (Section 3.2), and the procedure described above, the cross-section has been corrected for instrumental effects as well as the contribution of energy in the jet regions from particles not belonging to the dijet system and loss of energy outside the jet windows. We have varied the jet opening angle Φ and found that the corrected cross-sections differed by less than 15%. We estimate this value to be the systematic error associated with the use of a specific jet definition. In addition, the same systematic errors mentioned above apply. Combined errors are quoted in the table and shown as outer errors in the figure.

The curves in Fig. 9 represent leading-order QCD calculations of the cross-section. The curves are obtained from the two sets of structure functions extracted by Duke and Owens [18], using $Q^2 = M^2/3$ and four flavours. The resulting variations illustrate the uncertainties in the theoretical calculations. The inclusion of higher-order QCD diagrams is expected to increase the predicted cross-section by roughly a factor of 2. Within these theoretical errors and the experimental errors, we find agreement between the data and the theoretical calculations both in shape and absolute magnitude. This result can be considered as a success in the understanding of hard hadronic interactions in QCD.

4.2 Longitudinal jet structure

We now turn to the discussion of the composition of the jets in terms of charged particles, measured in the drift chamber. For this purpose, only events where both jets were measured to

have an E_T in excess of 10 GeV have been considered; the corrected average value of the dijet invariant mass for this sample is $\langle M \rangle = 27 \text{ GeV}/c^2$, and each jet has an average E_T of 13.5 GeV.

As a measure of the fraction of the jet momentum carried by a charged particle in the fragmentation of the jet, we define $z = 2p_L/M$, where p_L is the momentum component of the charged particle parallel to the direction of the jet momentum as found in the calorimeter, and $M/2$ is used as a measure of the energy of each jet in the event. Figure 10 shows the measured longitudinal fragmentation function, $D(z) = 1/N_{\text{jet}} (dn/dz)$, for all charged particles within $|y| < 0.7$, and the values are listed in Table 3. In each event the two jets are treated separately, and particles are assigned to the nearest jet in azimuth ($\Delta\phi < 90^\circ$). The distribution has been corrected for effects of drift-chamber acceptance and momentum resolution as well as the determination of M , using an iterative Monte Carlo procedure. For a given fragmentation function $D(z)$ as input to the program, a prediction of the measured z distribution was calculated, using the probability distributions described in Section 4.1 to determine the observed dijet mass M_{jj} , and the known momentum resolution and track acceptance (Sections 3.1 and 3.2) to determine the track momentum. The procedure was iterated to reproduce the z distribution of the real data. Two iterations were sufficient to reproduce the data. Finally, an unfolding procedure was used, as in Section 4.1, to translate the observed distribution into the true fragmentation function shown in the figure, using the now known correspondence between generated and observed z . As the theoretical fragmentation function used as input to the Monte Carlo procedure has no particles with $z > 1$, the procedure ensures the same to be the case for our corrected distribution. The errors shown are statistical only. Systematic errors due to the model and the correction procedure were estimated by varying individual parameters and found to be comparable to the statistical errors for $z < 0.7$, increasing to $\sim 50\%$ at $z = 1$. The uncertainty in the energy scale of the calorimeter translates into an additional systematic error, varying from 3% at $z = 0.01$ to 15% at $z = 1$. These systematic errors are indicated by outer bars in the figure.

Superimposed on Fig. 10 are the fragmentation functions measured in e^+e^- interactions at comparable energies [8] and at the SPS $p\bar{p}$ Collider [21], for jets with $\langle p_T \rangle = 36 \text{ GeV}/c$. The present data are similar to the e^+e^- results, while the $p\bar{p}$ data have a steeper variation with z . The line on the figure is a fit to our data in the interval $0.02 < z < 1.0$ to the form

$$D(z) = a z^{-b} e^{-cz};$$

the parameters in the fit were found to be

$$a = 2.86 \pm 0.14, \quad b = 0.85 \pm 0.05, \quad c = 4.23 \pm 0.21, \quad \text{with } \chi^2/\text{NDF} = 1.8.$$

Given the high statistics obtained in the region near $z = 1$, we have investigated the sensitivity to jets that consist of a single charged particle with $z = 1$. From the shape of the distribution near $z = 1$ we can set an upper limit for this special fragmentation mode of 2% of all jets with $p_T > 10 \text{ GeV}/c$. This limit, however, is not an improvement on our previous value of $\sim 1\%$ obtained from the ratio of jet cross-section to single-particle cross-section [1].

The fragmentation function in Fig. 10 is somewhat harder than that previously presented from data using a ΣE_T trigger in full azimuth [10], although the two agree within the combined systematic errors.

Figure 11 shows the variation of the fragmentation function with jet energy. The value of $1/N_{\text{jet}} (dn/dz)$ is shown as a function of the dijet mass M in bins of the fractional momentum z . Over the region of jet energies spanned, we observe a change of the fragmentation function towards a steepening at higher jet energies, in agreement with the corresponding measurement in e^+e^- collisions [8].

The comparison between the data sets in Fig. 10 suggests different fragmentation functions for quark and gluon jets, to the extent that our data and the e^+e^- data are dominated by quark jets and the $p\bar{p}$ data by gluon jets. It should be noted, however, that the $p\bar{p}$ data are at higher Q^2 . Given the energy dependence observed in Fig. 11 we cannot exclude that the difference in the fragmentation function is due to the difference in jet energies.

4.3 Transverse jet structure

We have also studied the distribution of the momentum component, q_T , of charged particles transverse to the jet axis. In standard jet fragmentation models, q_T is expected to be small compared to the longitudinal momentum component p_L for leading jet fragments. The open circles in Fig. 12 show the average transverse momentum $\langle q_T \rangle$ for charged particles with respect to the jet direction determined by the calorimeter, as a function of z . The almost linear rise of $\langle q_T \rangle$ with z is to a large degree explained by the uncertainty of 6° in the measurement of the true jet direction, consistent with the angular resolution of the calorimeter (Section 3.3). To illustrate this, the line in Fig. 12 shows the result from the ISAJET Monte Carlo events which have $\langle q_T \rangle \approx 0.5 \text{ GeV}/c$ at $z \approx 0.5$. Both the data and the Monte Carlo events are uncorrected for errors in the observed z values.

We also selected those jets where at least 70% of the jet energy was carried by charged particles, and defined the jet direction by adding up the charged-particle momenta. The resulting $\langle q_T \rangle$ versus z is shown as full circles in Fig. 12. We observe an increase from $\langle q_T \rangle \approx 0.3 \text{ GeV}/c$ at $z \approx 0.1$ to $\langle q_T \rangle \approx 0.5 \text{ GeV}/c$ for $z > 0.3$, in qualitative agreement with measurements in e^+e^- interactions [8] and at the SPS $p\bar{p}$ Collider [22]. The measurements are consistent with the superimposed ISAJET Monte Carlo curve. It should be stressed, however, that the value of $\langle q_T \rangle$ at high z is very sensitive to the precision with which the jet direction is found, and care must be exercised when comparing experiments.

4.4 Charge distribution in jets

The charge structure of the individual jets and of the dijet system has been studied with the aim of obtaining information about their origin at the constituent level. The leading particles are expected to carry information about the quantum numbers of the original constituents, specifically their charge, and short- as well as long-range charge correlations within the dijet system are expected. In QCD-based models, the ratio between the expected contribution of different constituent scattering processes depends primarily on the structure functions. In our Q^2 and x range, the Duke and Owens structure functions [18] predict about equal contributions from quark-quark and quark-gluon scattering. The amount of gluon-gluon scattering is expected to be small ($\sim 10\%$).

Figure 13 shows the measured ratio R between the number of positive and negative particles as a function of z . The values of z are statistically corrected as in Section 4.2. The rising ratio reflects the dominance of jets originating from positive constituents (such as u quarks) rather

than neutral and negative partons (such as gluons and d quarks). Naïvely, a ratio of u-quark jets to d-quark jets of 2:1 would predict a ratio for leading particles close to the observed value of 2. Superimposed on the figure are the predicted charge ratios from the ISAJET Monte Carlo, separated into the different subprocesses: quark-quark (qq), quark-gluon (qg), and gluon-gluon (gg) scattering. Comparison with the observations shows that qq scattering is dominant.

The overall charge structure of the dijet system was studied in terms of the charge compensation as a function of the rapidity along the direction of the jet axis, $Y = 0.5 \log\{(E + p_L)/(E - p_L)\}$. (The two jets were Lorentz boosted in order to align the axes back-to-back). We define the charge correlation function [23]

$$\Phi(Y, Y') = d^2\sigma/dYdY'|_{oc} - d^2\sigma/dYdY'|_{sc}$$

between two charged particles at rapidities Y and Y' along the jet axis. OC (SC) stands for opposite charge (same charge) of the two particles. For a fixed value of Y' , Φ measures the way in which the charge at Y' is compensated along the jet axis. We have integrated Y' over small intervals $A < Y' < B$, separately for positive and negative 'test' particles in this Y' interval. Figure 14 shows the normalized charge compensation

$$\Psi(Y) = \int \Phi(Y, Y') dY' / \int (d\sigma/dY') dY'$$

as a function of Y , for (a) positive and (b) negative particles in the Y' interval, and for four intervals of Y' . The Y' interval and 'test' particle charge are indicated in each figure. Only particles with $p_T > 0.8$ GeV/c were considered, in order to reduce the contributions from low- z particles which are confused with the non-jet particles. No corrections were made for the loss of charged particles, momentum smearing, or mismeasurements of the jet axes. In order to reduce the loss of oppositely charged particles that are emitted close in azimuth and whose trajectories cross inside the volume of the drift chamber, because of the magnetic field, we only used two-particle combinations where the sign of the relative azimuthal angle $\Delta\phi$ was such as to exclude the two tracks overlapping in space. With these precautions we find the integrated loss of charged particle pairs to be 10%, equal for OC and SC combinations.

A short-range charge compensation is seen for both charges of the test particle, but for leading particles (large Y') the correlation is clearly strongest for a negative particle, reflecting the overall positive charge in the jets noted above. At $Y < 0$ the compensation is of opposite sign and roughly equal magnitude when comparing positive and negative test particles, indicating that the charge distribution in the opposite jet is largely independent of the leading charge and reflecting the overall larger density of positive particles.

We have compared the observed charge compensation $\Psi(Y)$ with the expectations from ISAJET, again separating into the different subprocesses: quark-quark (qq), quark-gluon (qg), and gluon-gluon (gg) scattering. Superimposed in Fig. 14 are the qq predictions for all the Y' intervals and charges. The overall agreement with data is quite good. To illustrate the predictions from the other subprocesses, Fig. 15 shows the charge correlation in more detail for the Y' interval $2 < Y' < 3$, together with the expectations from all of the three subprocesses. We conclude that the data are consistent with being predominantly quark-quark scattering, and, taking into account the previously mentioned 10% loss, estimate from the size of the observed

correlations the contribution from quark–gluon scattering to be $25 \pm 10\%$. The error includes our estimate of the uncertainty due to possible differences in longitudinal fragmentation of quarks and gluons, not accounted for by ISAJET. The above value is in contradiction with the theoretical prediction of approximately equal contributions from quark–quark and quark–gluon scattering in our region of x and Q^2 , as mentioned above.

4.5 Energy and particle flow

The overall structure of the dijet system and the associated event has been investigated in terms of the distribution of energy and charged particles in the transverse plane, relative to the jet direction. Figure 16 shows the distribution $dE_T/d\Delta\phi$ of charged and total transverse energy within $|\eta| < 0.7$, as measured by the drift chamber and the calorimeter respectively, as a function of the azimuthal angle $\Delta\phi$ relative to the direction of the jet with the highest E_T . The strong peaks at $\Delta\phi \simeq 0^\circ$ and $\Delta\phi \simeq 180^\circ$ correspond to the two jet regions; the asymmetry around $\Delta\phi = 90^\circ$ is caused by the choice of the highest- E_T jet to have $\Delta\phi = 0^\circ$ and not forcing the opposite jet to be exactly back-to-back in azimuth (see Fig. 4). On the average, 48% and 43% of the total event E_T is contained within the two jet regions $\Delta\phi < 30^\circ$ and $\Delta\phi > 150^\circ$, respectively. The fraction of the energy carried by charged particles is roughly independent of $\Delta\phi$ and equal to 0.5.

The distribution of the charged-particle multiplicity as a function of $\Delta\phi$ is given in Fig. 17 and the average p_T in Fig. 18. Both an increase in multiplicity and in average particle momentum contribute to the strong energy concentration in the jets. An illustration of this is given in Fig. 19, which shows the measured p_T spectrum of charged particles in a $\pm 30^\circ$ azimuthal region around the jet axis and in a corresponding region around the direction perpendicular to the jets, $|\Delta\phi - 90^\circ| < 30^\circ$.

A question of obvious interest is: To what extent are the energy and particle flow in the region perpendicular to the jet axes similar to those of an average inelastic event? Superimposed on Figs. 16–19 are the corresponding values in ‘minimum bias’ events. The ‘minimum bias’ values were calculated by analysing events obtained by a trigger which was efficient for all non-single diffractive events. A randomly distributed jet axis was imposed on the events to define $\Delta\phi$. The data were taken at $\sqrt{s} = 63$ GeV, but the values were rescaled to the average available c.m. energy $\sqrt{s}^* = 63$ GeV – $\langle M \rangle = 36$ GeV for the associated events in the dijet sample, using the measured energy dependence from previous experiments [24]. In all figures, the region at $\Delta\phi = 90^\circ \pm 30^\circ$ in the jet events looks similar to minimum bias, except for an increase of about 50% in the multiplicity. This can be contrasted with the case of using a ΣE_T trigger in the full azimuth [10], where a strong enhancement in energy flow is seen perpendicular to the jet axes when compared to the minimum bias level. It is interesting to note that in this region perpendicular to the jets, the p_T spectrum shows a departure from an exponential fall-off above 2 GeV/c similar to that observed in minimum bias events and which, when first observed in minimum bias, was the origin of experimental high- p_T physics. It is likely that this strong high- p_T tail in the jet events has its origin in gluon bremsstrahlung from the hard scattered partons.

5. CONCLUSIONS

We have measured the invariant cross-section for dijet production in pp collisions at $\sqrt{s} = 63$ GeV in the dijet mass range 17–50 GeV/ c^2 and find agreement with QCD calculations within

the experimental and theoretical uncertainties. Note, however, that in view of our disagreement with the Duke–Owens prediction of the relative contributions of quarks and gluons, the agreement in cross-section may be somewhat fortuitous. If an increased quark–quark contribution would result in a lower predicted cross-section, then the inclusion of higher-order terms may recover the agreement.

Using a high-statistics sample of events with jets above 10 GeV, we have measured the jet fragmentation function $D(z)$ out to $z = 1$ and find agreement with the fragmentation of jets originating from e^+e^- interactions. The corresponding measurement at the SPS $p\bar{p}$ Collider gives a more rapidly decreasing fragmentation function, suggesting a difference in the fragmentation of quark and gluon jets. Over the range of dijet masses spanned, $20 < M < 40 \text{ GeV}/c^2$, we observe a softening of the fragmentation function with increasing mass.

By studies of charge ratios in the jet fragmentation and charge compensation in the dijet system, we conclude that the dijet events are consistent with a model where jets predominantly originate from valence quark scattering. The estimated contribution from quark–gluon scattering is $25 \pm 10\%$ in our kinematical range at $x \approx 0.4$. This is in disagreement with the prediction from the Duke and Owens structure functions of approximately equal contributions from quark–quark and quark–gluon scattering.

The energy and particle flows in the selected events show a dominant dijet structure. Perpendicular to the jet directions, the particle distribution is similar to that of an average inelastic event, except for an increase of about 50% in the multiplicity. About 3 GeV of transverse energy is observed outside the jet regions, inside $|\eta| < 0.7$.

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$$dE_T/dy = [-0.571 + 0.485 \ln(\sqrt{s}/\text{GeV})] \text{ GeV}$$

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Table 1

Dijet transverse-energy cross-section

E_T^{jj} [GeV]	$d^3\sigma/dE_T^{jj}d\eta_1d\eta_2$ [cm ² /GeV]	Statistical error	Systematic error (factor)
12.45	0.160×10^{-30}	$\pm 0.029 \times 10^{-30}$	1.31
13.45	0.788×10^{-31}	$\pm 0.172 \times 10^{-31}$	1.34
14.42	0.478×10^{-31}	$\pm 0.115 \times 10^{-31}$	1.36
15.42	0.210×10^{-31}	$\pm 0.044 \times 10^{-31}$	1.39
16.42	0.196×10^{-31}	$\pm 0.060 \times 10^{-31}$	1.41
17.42	0.927×10^{-32}	$\pm 0.085 \times 10^{-32}$	1.44
18.42	0.606×10^{-32}	$\pm 0.065 \times 10^{-32}$	1.47
19.42	0.404×10^{-32}	$\pm 0.049 \times 10^{-32}$	1.50
20.42	0.197×10^{-32}	$\pm 0.030 \times 10^{-32}$	1.53
21.42	0.191×10^{-32}	$\pm 0.030 \times 10^{-32}$	1.56
22.42	0.968×10^{-33}	$\pm 0.144 \times 10^{-33}$	1.59
23.42	0.603×10^{-33}	$\pm 0.062 \times 10^{-33}$	1.62
24.42	0.546×10^{-33}	$\pm 0.109 \times 10^{-33}$	1.65
25.42	0.304×10^{-33}	$\pm 0.047 \times 10^{-33}$	1.69
26.42	0.196×10^{-33}	$\pm 0.038 \times 10^{-33}$	1.72
27.85	0.140×10^{-33}	$\pm 0.022 \times 10^{-33}$	1.77
29.85	0.738×10^{-34}	$\pm 0.156 \times 10^{-34}$	1.84
31.42	0.238×10^{-34}	$\pm 0.099 \times 10^{-34}$	1.90
32.42	0.180×10^{-34}	$\pm 0.056 \times 10^{-34}$	1.94
33.42	0.104×10^{-34}	$\pm 0.010 \times 10^{-34}$	1.98
34.42	0.687×10^{-35}	$\pm 0.084 \times 10^{-35}$	2.02
35.42	0.351×10^{-35}	$\pm 0.060 \times 10^{-35}$	2.06
36.42	0.249×10^{-35}	$\pm 0.051 \times 10^{-35}$	2.10
37.42	0.167×10^{-35}	$\pm 0.042 \times 10^{-35}$	2.14
38.42	0.114×10^{-35}	$\pm 0.035 \times 10^{-35}$	2.19
39.42	0.826×10^{-36}	$\pm 0.292 \times 10^{-36}$	2.23
40.85	0.508×10^{-36}	$\pm 0.161 \times 10^{-36}$	2.30
42.83	0.148×10^{-36}	$\pm 0.085 \times 10^{-36}$	2.39
44.81	0.901×10^{-37}	$\pm 0.637 \times 10^{-37}$	2.49

Table 2

Dijet mass cross-section

M [GeV/c ²]	$d^3\sigma/dM d\eta_1 d\eta_2$ [cm ² /GeV]	Statistical error	Systematic error (factor)
17.45	0.518×10^{-31}	$\pm 0.152 \times 10^{-31}$	1.45
18.88	0.206×10^{-31}	$\pm 0.058 \times 10^{-31}$	1.49
20.88	0.101×10^{-31}	$\pm 0.031 \times 10^{-31}$	1.54
22.44	0.282×10^{-32}	$\pm 0.040 \times 10^{-32}$	1.58
23.44	0.279×10^{-32}	$\pm 0.040 \times 10^{-32}$	1.61
24.44	0.147×10^{-32}	$\pm 0.025 \times 10^{-32}$	1.64
25.44	0.136×10^{-32}	$\pm 0.023 \times 10^{-32}$	1.66
26.44	0.638×10^{-33}	$\pm 0.115 \times 10^{-33}$	1.69
27.44	0.722×10^{-33}	$\pm 0.157 \times 10^{-33}$	1.72
28.44	0.689×10^{-33}	$\pm 0.158 \times 10^{-33}$	1.76
29.44	0.311×10^{-33}	$\pm 0.084 \times 10^{-33}$	1.79
30.44	0.217×10^{-33}	$\pm 0.028 \times 10^{-33}$	1.82
31.44	0.136×10^{-33}	$\pm 0.022 \times 10^{-33}$	1.85
32.44	0.141×10^{-33}	$\pm 0.023 \times 10^{-33}$	1.88
33.44	0.830×10^{-34}	$\pm 0.175 \times 10^{-34}$	1.92
34.88	0.607×10^{-34}	$\pm 0.106 \times 10^{-34}$	1.97
36.86	0.203×10^{-34}	$\pm 0.052 \times 10^{-34}$	2.04
38.85	0.107×10^{-34}	$\pm 0.040 \times 10^{-34}$	2.12
40.85	0.878×10^{-35}	$\pm 0.413 \times 10^{-35}$	2.20
42.82	0.402×10^{-35}	$\pm 0.308 \times 10^{-35}$	2.28
44.82	0.735×10^{-36}	$\pm 0.204 \times 10^{-36}$	2.36
46.79	0.109×10^{-36}	$\pm 0.077 \times 10^{-36}$	2.45
48.76	0.507×10^{-37}	$\pm 0.507 \times 10^{-37}$	2.54

Table 3

Fragmentation function $D(z)$ for $E_T^{\text{jet}} > 10 \text{ GeV}$

z	$D(z)$	Statistical error	Systematic error
0.01	93.49	± 0.28	± 2.84
0.03	50.47	± 0.21	± 1.66
0.05	30.07	± 0.16	± 1.06
0.07	20.26	± 0.13	± 0.77
0.09	15.13	± 0.11	± 0.61
0.11	11.74	± 0.10	± 0.51
0.13	9.501	± 0.090	± 0.433
0.15	7.466	± 0.080	± 0.360
0.17	6.236	± 0.073	± 0.317
0.19	5.326	± 0.067	± 0.284
0.21	4.572	± 0.062	± 0.256
0.23	3.870	± 0.057	± 0.226
0.25	3.196	± 0.052	± 0.196
0.27	2.899	± 0.050	± 0.185
0.29	2.455	± 0.046	± 0.163
0.31	2.138	± 0.043	± 0.148
0.33	1.795	± 0.039	± 0.129
0.35	1.630	± 0.037	± 0.122
0.37	1.387	± 0.034	± 0.108
0.39	1.210	± 0.032	± 0.097
0.41	1.007	± 0.029	± 0.084
0.43	1.006	± 0.029	± 0.086
0.45	0.842	± 0.027	± 0.075
0.47	0.740	± 0.025	± 0.068
0.49	0.664	± 0.024	± 0.063

z	$D(z)$	Statistical error	Systematic error
0.51	0.621	± 0.023	± 0.060
0.53	0.529	± 0.021	± 0.053
0.55	0.413	± 0.019	± 0.043
0.57	0.425	± 0.019	± 0.046
0.59	0.351	± 0.017	± 0.039
0.61	0.345	± 0.017	± 0.039
0.63	0.279	± 0.015	± 0.033
0.65	0.241	± 0.014	± 0.030
0.67	0.251	± 0.015	± 0.031
0.69	0.225	± 0.014	± 0.029
0.71	0.196	± 0.013	± 0.031
0.73	0.162	± 0.012	± 0.028
0.75	0.152	± 0.011	± 0.029
0.77	0.131	± 0.011	± 0.027
0.79	0.117	± 0.010	± 0.027
0.81	0.088	± 0.009	± 0.022
0.83	0.115	± 0.010	± 0.033
0.85	0.078	± 0.008	± 0.026
0.87	0.077	± 0.008	± 0.028
0.89	0.069	± 0.008	± 0.028
0.91	0.064	± 0.007	± 0.028
0.93	0.072	± 0.008	± 0.035
0.95	0.063	± 0.007	± 0.033
0.97	0.047	± 0.006	± 0.024
0.99	0.050	± 0.007	± 0.026

APPENDIX A

DETAILS OF THE MONTE CARLO EVENT GENERATION

To ensure an accurate description of jets at ISR energies, properties of ISAJET-generated high- E_T jets, such as longitudinal fragmentation and jet width, were compared with experimental data from the AFS [10]. Agreement with data was achieved after adjustment of parameters of the ‘splitting function’ governing the longitudinal fragmentation of a parton into hadrons (softer fragmentation was needed) and through an increase of the jet width. The jet widening was produced partly by increasing the sigma of the p_T distribution of jet fragments in the parton-parton c.m. system by $\sim 25\%$ and partly by reducing the mass cut-off ($\sqrt{t_{\text{cut}}}$) for the final-state parton cascade development (i.e. final-state gluon bremsstrahlung) from 7 to 6 GeV/c thus producing more multijet events.

Of serious concern to us was the ability of ISAJET to describe contributions to high- E_T events from processes other than the hard scattering itself. Since, according to our measurements [25], the distributions of multiplicity and momentum of the non-jet particles in two-jet events are similar to those in minimum bias events, it was natural to attempt to modify the beam-jet generation in ISAJET to reproduce the amount of energy carried by these particles. The framework used by ISAJET to generate beam-jets with appropriate built-in correlations is the ‘cut Reggeon field theory’ [15]. For each event a number of cut Pomerons is produced, sharing the beam energy with two leading baryons. Beam-jet fragments are the hadronization products of these Pomerons — hence, the amount of energy carried by these ‘soft’ particles can be increased by increasing the average Pomeron multiplicity and by raising the fraction of the beam-jet energy assigned to the Pomerons. The level of ‘soft energy’ was adjusted by comparing the transverse energy distributions perpendicular to the jet axis in Monte Carlo events and in our two-jet data. The comparison was performed as a function of jet E_T . The result can be expressed in terms of a single parameter R , namely the ratio of the amount of ‘soft energy’ per unit rapidity and the minimum bias level [24]. Agreement was obtained with $R = 3.28$ for jet $E_T = 5$ GeV decreasing linearly to $R = 1.37$ for jet $E_T > 15$ GeV. The latter value of R corresponds to an increase of $\sim 20\%$ with respect to standard ISAJET which describes non-single diffractive events.

Figure captions

- Fig. 1 Experimental set-up.
- Fig. 2 Example of a dijet event with two jets above 14 GeV. The transverse energy is plotted in bins of $\Delta\phi = 5^\circ$ and $\Delta\eta = 0.1$. This event has a thrust of $T = 0.94$.
- Fig. 3 Distribution of thrust in the transverse plane for events with two jets of $E_T > 10$ GeV.
- Fig. 4 Distribution of the difference $\Delta\phi_{jj}$ in azimuth between the two jet momenta. The curve was obtained from Monte Carlo events.
- Fig. 5 Uncorrected transverse energy flow within $|\eta| < 0.7$, as a function of the relative azimuthal angle $\Delta\phi$ from the highest- E_T jet is shown in four bins of E_T^{jj} . Superimposed are the corresponding Monte Carlo distributions.
- Fig. 6 Uncorrected distribution of the total p_T imbalance of the dijet system as measured in the calorimeter within $|\eta| < 0.7$, for (a) $20 \text{ GeV} < E_T^{jj} < 25 \text{ GeV}$ and (b) $30 \text{ GeV} < E_T^{jj} < 40 \text{ GeV}$. The curves were obtained from Monte Carlo events.
- Fig. 7 Monte Carlo calculation of observed dijet mass M_{jj} in intervals of generated mass, M . The curves are parametrizations used for the correction of real data, as explained in the text.
- Fig. 8 The differential cross-section $d^3\sigma/dE_T^{jj}\eta_1\eta_2$, where E_T^{jj} is the total transverse energy inside the two jet windows of angular width $\Phi = 60^\circ$, $|\eta| < 0.7$. The outer error bars show the systematic errors originating mostly from the uncertainty in the energy scale.
- Fig. 9 The dijet cross-section at 90° as a function of the constituent-constituent centre-of-mass energy, M . The outer error bars show the systematic errors originating from uncertainties in the energy scale and the Monte Carlo correction of M . Shown are also the results of leading-order QCD calculations based on the structure functions of Ref. [18], taking $Q^2 = M^2/3$ and four flavours.
- Fig. 10 Longitudinal fragmentation function $D(z)$ for charged particles in jets above 10 GeV. The outer bars indicate the systematic errors. The line shows the fit to our data as given in the text. For comparison, results from e^+e^- collisions (TASSO) [8] and the SPS $p\bar{p}$ Collider (UA1) [21] are also shown.
- Fig. 11 The variation of the fragmentation function $D(z)$ as a function of the dijet mass M .
- Fig. 12 Average transverse momentum $\langle q_T \rangle$ of charged particles with respect to the jet axis as measured by the calorimeter (open circles) or using the charged-particle jet axis in events with at least 70% charged energy (full circles). The z values were not corrected. Monte Carlo curves are superimposed.
- Fig. 13 Ratio between the numbers of positive and negative particles as a function of the corrected fractional momentum z . For comparison are shown predictions by the ISAJET Monte Carlo for qq , qg , and gg scattering. The bands reflect the statistical errors in the Monte Carlo calculations.
- Fig. 14 Charge compensation for particles with $p_T > 0.8 \text{ GeV}/c$ as a function of rapidity Y along the jet axis, for positive (a) and negative (b) particles in the Y' intervals indicated. The definition of the charge compensation $\Psi(Y)$ is given in the text. Superimposed are the ISAJET predictions for quark-quark interactions.
- Fig. 15 Charge compensation for particles with $p_T > 0.8 \text{ GeV}/c$ and a test particle in the interval $2 < Y' < 3$. Shown are also the ISAJET predictions for pure quark-quark (qq), quark-gluon (qg), and gluon-gluon (gg) scattering.

- Fig. 16 Transverse energy flow within $|\eta| < 0.7$ and charged E_T flow within $|y| < 0.7$ as a function of the azimuthal angle $\Delta\phi$ measured relative to the largest- E_T jet. The corresponding minimum bias levels are indicated.
- Fig. 17 The distribution of charged-particle multiplicity within $|y| < 0.7$ as a function of $\Delta\phi$. The corresponding minimum bias level is indicated.
- Fig. 18 Average transverse momentum of charged particles as a function of $\Delta\phi$. The corresponding minimum bias level is indicated.
- Fig. 19 Distributions of transverse momenta for charged particles in the jet region ($\Delta\phi < 30^\circ$), perpendicular to the jets ($60^\circ < \Delta\phi < 120^\circ$) and in minimum bias events.

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