EXPERIMENTAL STUDY OF THE Fragmentation OF LARGE TRANSVERSE MOMENTUM JETS IN HIGH-ENERGY p-p COLLISIONS

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ABSTRACT

We report on an experiment performed at the CERN ISR using large lead-glass arrays to trigger on high transverse momentum π₀'s. There is evidence of strong rapidity correlations both among the trigger π₀'s and with associated charged particles. Measurements are presented of the jet multiplicity and of the transverse and longitudinal distributions within the jet. Their dependence upon the trigger transverse momentum obeys scaling to a good accuracy. Estimates of the η and ρ⁺ inclusive production cross-sections are presented.

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1. **INTRODUCTION**

Previous intersecting storage rings (ISR) experiments [1-8] have reported an enhancement of particle density in the region of phase space surrounding large transverse momentum hadrons. They have measured, among the large transverse momentum products of proton-proton collisions, strong positive correlations in transverse momentum, in rapidity, and in azimuth. They also observed a second enhancement at opposite azimuth, and established that the remaining secondaries were otherwise distributed as in a typical non-diffractive collision.

The interpretation of these observations in the framework of parton models [9-11] has generated much interest. According to these models, two partons, one from each incident proton, experience a two-body collision and then fragment independently to produce the observed enhancements (jets). The remaining partons are responsible for the simultaneous production of low transverse momentum secondaries over a wide rapidity range. Three ingredients are essential for obtaining quantitative predictions in the framework of such models: the parton momentum distribution in each incident proton, the hadron momentum distribution resulting from parton fragmentation, and the scattering amplitude between the colliding partons. In the case of quark partons, deep inelastic collisions of electrons, muons, and neutrinos on protons provide measurements of the first quantity. The second is directly accessible to $e^+e^-$ annihilation experiments. A comparative study of these data with the properties of large transverse momentum final states in proton-proton collisions should therefore establish whether the partons relevant to strong interactions are the same as those revealed by electromagnetic and weak probes. If so, studies of parton-parton interactions would become possible.

For such studies to be successful, an unambiguous separation of the final-state jets from the low transverse momentum products is essential. In contrast with $e^+e^-$ annihilation experiments, where some jet structure is already apparent at low energies [12], this implies that in proton-proton collisions there is the necessity to select secondaries with transverse momenta much larger than usually observed. Technically, the selection of such events at the CERN ISR is most
conveniently performed by using electromagnetic shower calorimeters to trigger on large transverse momentum \( \pi^0 \)'s. Hadron calorimeters would in principle be more appropriate since they can provide unbiased jet triggers \([13-15]\). However, their operation in ISR experiments is difficult because they would need to cover a large solid angle and provide a good energy resolution at low energies.

In the present experiment we have used a double-arm spectrometer at the CERN ISR, triggered on large transverse momentum \( \pi^0 \)'s by means of large lead-glass arrays. The geometry and performance of the detector are well suited to the study of jet structure in the observed collisions. In the present publication we discuss only the fragmentation properties of large transverse momentum jets; that is, correlations between the trigger \( \pi^0 \)'s and particles produced in the same region of phase space. Correlations with and amongst particles in the opposite azimuthal hemisphere will be reported later.

Results are presented for centre-of-mass energies \( \sqrt{s} = 52.4 \) and \( 62.7 \) GeV and for an integrated luminosity of \( 1.5 \times 10^{37} \) cm\(^{-2}\).

2. EXPERIMENTAL SET-UP

The experimental set-up, shown in Fig. 1, has already been described \([16]\). It consists of two spectrometers, one on each side of the intersecting beams. Each spectrometer contains a large-aperture magnet equipped with two sets of drift chambers (front and back) for momentum measurement of charged particles. It is followed by a lead-glass array, which provides a trigger on large transverse momentum \( \pi^0 \)'s and measures their energy. The magnets are located as close as possible to the ISR vacuum chamber in order to cover a large solid angle (0.7 sr, with 0.5 sr for the lead-glass array). To reduce beam perturbations, the magnetic fields in each arm are of opposite polarity. The magnet polarities are frequently alternated to minimize experimental bias.

2.1 Chamber system

The momentum \( p \) of charged particles is measured from their magnetic deflection which is \( 0.1/p(\text{GeV/c}) \). The lever arms for direction measurement are 19 cm
and 40 cm in the front and back chambers, respectively. To obtain the high spatial accuracy required in the bending plane, drift chambers with a drift space of 2.5 cm are used. Shaping potential wires with 2 mm separation achieve the uniform electric field required for high-precision measurements. The sense wires are doublets with 0.5 mm separation to avoid left-right ambiguities.

The chambers have one of three possible wire orientations: parallel to the magnetic field (X) or at small angle to it (U and V). In the vertical direction, since there is no bend, the lever arm is the full spectrometer length (2 m). Therefore it is sufficient for the U and V chambers to have a small wire inclination, namely 10° in the front and 7° in the back. Such small stereo angles have the advantage of resolving ambiguities at the track reconstruction level.

The chamber arrangement can be read from Fig. 1. The front chambers (4X and 3U) have sense wires 30 cm long and are 1 m wide. The back chambers (3X, 2U, 1V on one side and 2X, 1U, 1V on the other) have sense wires 120 cm long and are 3 m wide.

All chambers were initially filled by an argon-isobutane-methylal mixture (65:31:4). Because of severe radiation damage in the front chambers closest to the beams, an argon-ethane-methylal mixture (49:49:2), which is less sensitive to radiation damage, was later used in the front chambers [17].

The drift time, of the order of 200 nsec/cm, is digitized in 2 nsec bins [18]. A scintillator hodoscope (A) described below is used to start the time measurement for the chambers. The ability to resolve two signals from the same wire is limited to ~2 mm.

To achieve optimal spatial accuracy, a large number of parameters must be determined. These include geometrical constants, an evaluation of the relationship between the track intercept and the drift time for different angles of incidence (up to 45° in these data), and a measurement of the relative delays due to different cable lengths from each wire. For this purpose, data were frequently collected with the magnetic fields turned off. The effect of the magnetic field on the
trajectories of the drifting electrons is significant in the last two front chambers where it reaches 0.3 T. The corresponding correction is evaluated by comparing adjacent drift chamber cells, where the effect of the magnetic field is of opposite signs.

The chamber redundancy allows a measurement of both the spatial resolution and the track reconstruction efficiency in each set of chambers. In both the front and back chambers a spatial resolution of $\left[ (150)^2 + (300 \tan \theta)^2 \right]^{1/2}$ mm is achieved. The observed width of the $J/\psi \rightarrow e^+ e^-$ peak [16] is well described by this relation, once radiative losses and multiple scattering are included. For the duration of the experiment a global momentum accuracy $\Delta p/p = 1^{-2} \left[ 9 + (4.2p)^2 \right]^{1/2}$ was maintained.

The track reconstruction efficiency in each set of chambers is 97%, except for one back chamber set (2X, 1U, 1V) where it is 85% because of the lack of redundancy.

2.2 Lead-glass arrays

Each lead-glass array, located 2.3 m from the beams, consists of 138 lead-glass blocks arranged in 7 horizontal rows. Each block (15 $\times$ 15 cm$^2$ in cross-section and 14.8 radiation lengths thick) is equipped with a 5" phototube, shielded from the stray magnetic field by the 2 cm iron plate of the iron-scintillator sandwich described below (see Section 2.3). Anode pulses are analysed in 10-bit analog-to-digital converters (ADCs), while pulses from the last dynode are added for subsequent energy discrimination.

The calibration of the energy response of the detector is of crucial importance. Before installation, each block was calibrated in a 2 GeV electron beam at the CERN Proton Synchrotron (PS) and its phototube voltage was adjusted to ensure a uniform gain over the full array. This calibration was maintained throughout the experiment by means of reference light-sources ($^{24}$Am deposited on a small plastic scintillator which is glued to the front face of each block). To obtain a response similar to that of a 1.5 GeV photon, the anode pulses were amplified
by a factor of 10 during calibration. The gain and linearity of each amplifier were known from a separate measurement. In addition, the lead-glass arrays were periodically recessed to 4 m from the intersection, at which distance π° + γγ decays yield two spatially resolved photons. Data collected in this configuration enable a check of the calibration of each cell to within ±5% for photon energies between 0.5 and 2 GeV. The energy-loss in the iron-scintillator sandwich (see Section 2.3) is also evaluated from these data (∼ 30 MeV per minimum ionizing pulse-height in the back scintillators). Using in addition a set of 1000 J/ψ → e⁺e⁻ decays in which the electrons are detected in opposite arms, we estimate an uncertainty of ±3% on the energy measurement in the 1-2 GeV range. The energy resolution, including uncertainties on the absolute cell-to-cell calibration, is found to have the form

\[ \frac{\Delta E}{E} = \pm \left[ (0.05)^2 + \frac{(0.02)^2}{E\text{(GeV)}} \right]^{1/2}. \]

The linearity of the energy response to electrons between 2 and 12 GeV was measured at the CERN PS both for normal and 34° incidence. It was corroborated to within 2%. Small deviations from linearity at low pulse height, occurring at the input stage of the ADCs, have been measured with standard pulses and corrected.

2.3 Scintillator hodoscopes

Three sets of scintillator hodoscopes, A, E, and F (Fig. 1) are used. The pulse height is recorded for each counter, and the time-of-flight between the A and E hodoscopes is measured. The A hodoscope, located behind the first two drift chambers, is a double layer of scintillators, each equipped with its own photocathode. The detector is triggered when a signal above threshold (ranging between 4 and 8 GeV c.m. energy depending on the run) in one of the lead-glass arrays is recorded in coincidence with a signal from any scintillator of one of the A hodoscopes.

The E and F hodoscopes are segmented into 22 and 20 vertical strips, respectively. They are separated by a 2 cm thick iron plate corresponding to a 56% conversion probability for photons.
In addition, air-filled Čerenkov counters are located in the magnet gaps for electron identification. They are of little relevance to the present work and are not discussed further.

2.4 Trigger

The detector is triggered when a signal above threshold is recorded in one of the lead-glass arrays in coincidence with a signal from any scintillator of one of the A hodoscopes. Different threshold values have been used in different runs, ranging from 5 to 8 GeV/c in c.m. energy. We kept a detailed account of the integrated luminosities associated with each threshold value for use in the subsequent analysis.

3. DATA REDUCTION: $\pi^0$ AND $\eta$ MESONS

The trigger mode of the present experiment strongly favours configurations where a large fraction of the transverse momentum is shared among particles having a large branching fraction for radiative decays (in practice, $\pi^0$ and $\eta$ mesons). This "trigger bias" [19] results from the steep fall of their transverse momentum spectra. For these neutral particles, however, an unbiased trigger is obtained with no dependence on either their multiplicity or energy sharing. For this reason we initially consider $\pi^0$ and $\eta$ mesons, leaving the study of associated charged particles for a later section.

For each event, the pattern of energy deposition in the lead-glass array giving a trigger is analysed and reduced to a number of clusters. Each cluster is defined as a set of adjacent cells having energies above 100 MeV. Possible halo contributions from surrounding cells are added to its energy. When the energy distribution within a cluster is observed to peak in two non-adjacent cells, the cluster is split into two different sub-clusters. Two-photon clusters can be resolved down to a minimum separation between the photon impacts on the lead-glass array which, depending on the energy, angle of incidence, and location with respect to the cell lattice, varies between 18 and 38 cm.

Initially we select events where the sum of the cluster energies exceeds the trigger threshold. To reject events not associated with beam-beam interactions,
the cluster with the largest energy in each event must have less than 90% of its energy in a single cell, less than 60% of its energy in the top or bottom row, no energy in the extreme vertical columns of the lead-glass array, and extend over less than four cells horizontally and less than three cells vertically. Similar cuts were described in detail in a previous publication [16]. The small resulting biases are corrected for in the subsequent analysis.

To separate the jet from the low transverse momentum secondaries which are simultaneously produced, an 800 MeV/c cut is imposed on the c.m. transverse momentum of each cluster. In a p-p collision without any trigger requirement, the probability for a charged secondary with a c.m. transverse momentum larger than 800 MeV/c to be produced within the acceptance of one of the spectrometers is only 0.7%. Since π^0 decays yield two resolved photons in this range of transverse momentum, less than 10^{-3} of all p-p collisions produce a cluster with a c.m. transverse momentum larger than 800 MeV/c in one of the lead-glass arrays.

The adequacy of the 800 MeV/c transverse momentum cut is apparent from the effect it has on correlations. For events with at least two clusters on the trigger side, we consider the pair correlation function

\[ R = \sigma \frac{d^2\sigma/d\eta_i d\eta_j}{(d\sigma/d\eta_i) (d\sigma/d\eta_j)} \]

where \(\eta_i, \eta_j\) are the c.m. pseudo-rapidities of any two clusters on the trigger side. The above expression is not sensitive to acceptance factors. The function \(R\), averaged over \(|\eta_i + \eta_j|\) is displayed versus \(|\eta_i - \eta_j|\) in Fig. 2. When the 800 MeV/c cut is applied, \(R\) is observed to shrink and to become strongly depressed at large pseudo-rapidity differences.

The strong rapidity correlation evidenced in Fig. 2 suggests a global treatment of all secondaries on the trigger side having transverse momenta larger than 800 MeV/c. We shall refer to them collectively as forming a jet. To perform a reliable study of the jet structure a detailed knowledge of the detector properties is required. For example, the decrease of \(R\) at low values of \(|\eta_i - \eta_j|\) results
from unresolved cluster pairs, an effect which we take into account in the subsequent analysis.

We use one set of variables to describe a jet as observed in the detector and another set to describe the original jet of particles produced in the collision. The relation between the two sets is obtained from a Monte Carlo simulation of the detector. We define (Fig. 3):

\( n, \) the number of clusters in the observed jet,
\( n^* \), the number of \( \pi^0 \) and \( \eta \) mesons in the original jet,
\( \vec{P}_i \), the c.m. vector momenta associated with each cluster in the observed jet \( (p_{T_i} > 800 \text{ MeV/c}) \),
\( \vec{P}^{*}_i \), the c.m. vector momenta associated with each \( \pi^0 \) and \( \eta \) meson in the original jet \( (p_{T_i}^{*} > 800 \text{ MeV/c}) \),

\[ \vec{P}^0 = \sum_i \vec{P}_i \]
\[ \vec{P}^{0*} = \sum_i \vec{P}^{*}_i \]

\( x_i, q_i, \) and \( q_i^* \) such that

\[ \vec{P}_i = x_i \vec{P}^0 + q_i, \quad q_i \cdot \vec{P}^0 = 0, \]
\[ \vec{P}^{*}_i = x_i^{*} \vec{P}^{0*} + q_i^*, \quad q_i^* \cdot \vec{P}^{0*} = 0. \]

Note that \( \sum_i x_i = \sum_i^{n*} x_i^* = 1 \),
and \( \sum_i q_i = \sum_i^{n*} q_i^* = 0. \)

Finally, we introduce two orthonormal vector sets \( (\hat{u}, \hat{v}, \hat{w}) \) and \( (\hat{u}^*, \hat{v}^*, \hat{w}^*) \) such that

\( \hat{u}, (\hat{u}^*) \) are parallel to \( \vec{P}^0 \) \( (\vec{P}^{0*}) \)

\( \hat{v}, (\hat{v}^*) \) are parallel to the plane of the intersecting beams.

4. RESULTS: \( \pi^0 \) AND \( \eta \) MESONS

The Monte Carlo simulation of the detector used to relate the observed jet to the original jet must deal with event configurations as close as possible to reality. For this purpose we use a simple production model similar to that introduced by several authors to describe the fragmentation of quark jets [20]. Jet momenta are distributed uniformly in azimuth and pseudo-rapidity, with transverse
momenta adjusted to reproduce correctly the measured inclusive cross-section for $\pi^0$ production [16].

Fragmentation proceeds according to an infinite sequence of independent hadron emissions in which each emitted hadron takes away a fraction $z$ of the remaining momentum of the original jet. The hadron is given, in addition, an independent transverse momentum $\vec{k}$ with respect to the original jet momentum with a distribution $d^2\sigma/dk^2 \propto \exp (k^2 - 7.2 \sqrt{k^2 + m^2_\eta})$. This parametrization gives a good description of low transverse momentum secondaries at ISR energies [21]. The hadron is chosen to decay into two photons with probability 1/3, either as a $\pi^0$ or as an $\eta$ with respective probabilities of 85% and 15% in agreement with available measurements of the $\eta \rightarrow \gamma\gamma$ branching fraction and of the $\eta/\pi$ ratio [22].

The model is completely defined once the distribution of particles in $z$ is specified. Following Field and Feynman [20] we choose a distribution of the form $F(z) = \varepsilon + 3 (1 - \varepsilon) (1 - z)^2$. Monte Carlo results are in good agreement with the data if we choose $\varepsilon = 0.2$; this must not at this stage be interpreted as evidence for the validity of the model, nor a fortiori as a measurement of $\varepsilon$. It is nevertheless remarkable that such a simple model gives a qualitative account of most properties of the observed jet structure: multiplicity (Fig. 4), longitudinal distributions (Figs. 5, 6, 7), and transverse distributions (Figs. 8, 9).

Having obtained an adequate description of the data, we can reliably unfold the effects of decay kinematics, limited aperture, and resolution from the data. We select variables for which the observed distributions are close to the original ones in order to present results which are minimally distorted and free of experimental bias. In particular we require that only a narrow spectrum of original values be associated with any given observed value, and we take its width into account when evaluating systematic uncertainties.

4.1 Jet multiplicity: $\pi^0$ and $\eta$ mesons

Jet multiplicity distributions are distorted by the decay process as well as by the limited aperture and finite spatial resolution of the detector. For instance, only 17% of events with $n = 4$ are of $n^* = 4$ parentage. Distortions are,
however, less severe at low multiplicities, where the probabilities for an $n^* = n$ parentage are 75% and 61% for $n = 1$ and $n = 2$, respectively. We therefore evaluate the quantities

$$\rho_1^* = \frac{\sigma(n^* = 1)}{\sigma_{all}}$$

and

$$\rho_{12}^* = \frac{\sigma(n^* = 2)}{\sigma(n^* = 1)}$$

for which reliable measurements are obtained. The results are listed in Table 1 and displayed in Figs. 10 and 11 as functions of $p_T^0$. The quoted uncertainties account for point-to-point systematics. In addition, normalization uncertainties $\Delta \rho_1^*/\rho_1^* = \pm 8\%$ and $\Delta \rho_{12}^*/\rho_{12}^* = \pm 20\%$ apply globally. When $p_T^0$ increases from 5 to 10 GeV/c, $\rho_1^*$ is observed to decrease from 36% to 25% and $\rho_{12}^*$ to increase from 0.9 to 1.6 approximately. Fits of the form

$$\rho^* = \lambda + \mu \ln p_T^0, \quad p_T^0 \text{ in GeV/c}$$

yield

$$\lambda_1 = 0.65 \pm 0.05 \quad \lambda_{12} = -0.74 \pm 0.26$$

$$\mu_1 = -0.176 \pm 0.022 \quad \mu_{12} = 1.01 \pm 0.14$$

The simple jet fragmentation model used in the analysis, with $F(z)$ independent of $p_T^0$, obeys scaling. Although the data are in qualitative agreement with this hypothesis it is difficult to perform a quantitative test of the scaling prediction $\langle n^* \rangle \propto \ln p_T^0$ since large distortions at high multiplicities preclude an accurate measurement of $\langle n^* \rangle$.

4.2 Longitudinal distributions: $\pi^0$ and $\eta$ mesons

From the Monte Carlo comparison of the measured $x$ distributions with the original $x^*$ distributions, we observe that the leading jet fragments are only slightly affected by the decay and measurement processes. In particular the ratio $r^* = x_2^*/x_1^*$, where the $x^*$ have been ordered in descending order, can be reliably measured. We have evaluated $r^*$ distributions for three different intervals
of $P_T^{\pi^\ast}$. Results are listed in Table 2 and displayed in Fig. 12. Quoted uncertainties include systematic errors.

4.3 Transverse distributions: $\pi^0$ and $\eta$ mesons

The detector aperture is much larger in polar angle than in azimuth. This results in an acceptance which is much wider in $q_v^\ast$ than in $q_w^\ast$ ($q_v^\ast = q_v^\ast \tau_v^\ast + q_w^\ast \tau_w^\ast$). We therefore evaluate $q_v^\ast$ distributions which are virtually free of experimental bias. Results are presented in Table 3 and Fig. 13 for three intervals of $P_T^{\pi^\ast}$. Fits of the form $d\sigma/dq_v^\ast \propto \exp (-|q_v^\ast/Q|^2)$ yield

\[
Q = 409 \pm 13 \text{ MeV/c} \\
= 453 \pm 13 \text{ MeV/c} \\
= 429 \pm 25 \text{ MeV/c}
\]

for each of the three $P_T^{\pi^\ast}$ intervals, in good agreement with scaling.

We also evaluate $q_w^\ast$ distributions which are consistent with being identical to those in $q_v^\ast$. Under the assumption of exact isotropy with respect to the jet axis, namely $d\sigma/dq_w^\ast = d\sigma/dq_v^\ast$, we find

\[
\langle q_v^\ast \rangle = \frac{1}{2} \sqrt{\pi} \, Q = 386 \pm 7 \text{ MeV/c}.
\]

4.4 Inclusive production of $\eta$ and $\omega$ mesons

The identification of $\eta \to \gamma\gamma$ and $\omega \to \pi^0\gamma$ decays is possible over a momentum range for which the decay photons are clearly resolved in the lead-glass arrays. In the case of $\eta \to \gamma\gamma$ decays, this implies c.m. transverse momenta below approximately 6 GeV/c.

In the previous analysis, to reject events not associated with beam-beam interactions, the cluster with the largest energy in each event was required to have less than 90% of its energy in a single cell; this does not significantly affect high-energy $\pi^0$'s but strongly depresses the single photon population. We therefore release this requirement in the present analysis, where events not associated with beam-beam interactions are of lesser concern since they are not expected to contribute preferentially to the $\eta$ and $\omega$ mass peaks.
The invariant mass distribution of photon pairs, each photon having a c.m. transverse momentum $p_{T1}$ larger than 0.8 GeV/c, is shown in Fig. 14a for the interval $4 < p_{T1} + p_{T2} < 5$ GeV/c. The displayed sample includes only data collected in one of the two spectrometers and for a fraction of the running time, the trigger thresholds being otherwise too high. The $\eta \to \gamma \gamma$ signal is clearly visible above a slowly varying background. Its position and width are in good agreement with the result of a Monte Carlo calculation. In the interval $4 < p_{T1} + p_{T2} < 6$ GeV/c we evaluate the ratio between invariant cross-sections for inclusive productions of $\eta$ and $\pi^0$ mesons, $\eta/\pi^0 = 0.3 \pm 0.1$, where the quoted uncertainty is mostly of systematic origin. This value is significantly lower than previously published results $[2,4]$.

In searching for $\omega \to \pi^0\gamma$ decays, for which the branching ratio is 8.8%, we require that the $\pi^0$ decays into two resolved photons. This limits the range of the analysis to $\omega$ transverse momenta between 4 and 6 GeV/c but provides a clear signature: only photon triplets for which one of the three possible pairs has an invariant mass compatible with the $\pi^0$ mass are considered. Their invariant mass distribution is displayed in Fig. 14b, where no signal is visible. From this result we deduce an upper limit for the ratio between invariant cross-sections for inclusive productions of $\omega$ and $\pi^0$ mesons

$$\omega/\pi^0 < 0.3 \quad (90\% \text{ CL}) .$$

In the acceptance calculation the $\omega$ meson is assumed to be unpolarized. If, instead, it was assumed to be produced with helicity 1, the above limit would become 0.36.

5. ASSOCIATED CHARGED PARTICLES

The method used in the study of charged particles associated with the trigger (neutral) jet is similar to that developed in the previous sections for $\pi^0$ and $\eta$ mesons. In particular we extend our definition of a jet to include charged particles produced on the trigger side with a c.m. transverse momentum larger than 800 MeV/c. The effect of this cut is illustrated in Fig. 15a, where the correlation function
\[ R = \frac{d^2\sigma/d\eta_1 d\eta^0}{(d\sigma/d\eta_1)(d\sigma/d\eta^0)}, \] averaged over \( \eta_1 + \eta^0 \),

is displayed versus \( |\eta_1 - \eta^0| \). Here \( \eta^0 \) is the pseudo-rapidity associated with the neutral jet momentum \( p^0 \) and \( \eta_1 \) is that of an accompanying charged particle with transverse momentum larger than 800 MeV/c. Evidence for a strong transverse momentum correlation between the jet of \( \pi^0 \) and \( \eta \) mesons and the charged particles detected on the trigger side is presented in Fig. 15b, which displays the probability per \( p-p \) collision to observe a large transverse-momentum charged particle within the spectrometer acceptance. This probability is strongly enhanced for interactions producing a jet of \( \pi^0 \) and \( \eta \) mesons, the more the larger their transverse momentum \( p_T^0 \).

We describe the charged jet fragments with variables similar to those introduced for \( \pi^0 \) and \( \eta \) mesons. However, we account for the fact that charged particles do not contribute to the trigger by referring their momenta \( p_i^0 \) to the neutral jet momentum \( \vec{p}^0 \) rather than to the total jet momentum \( \vec{p}^0 + \sum_{i} \vec{p}_i^0 \), where \( \nu \) is the number of charged particles in the jet. Thus we write

\[ \vec{p}_i^0 = \xi_i \vec{p}^0 + \vec{t}_i^0, \quad \vec{t}_i^0 \cdot \vec{p}^0 = 0. \]

Again we use an asterisk to designate variables associated with the original jet as opposed to the observed jet.

5.1 Data reduction

Track segments are reconstructed in each of the front and back drift-chamber modules, and paired by requiring a good match in the spectrometer magnet. Details of the track reconstruction procedure have been given elsewhere [16].

Charged hadrons usually deposit some energy in the lead-glass array, typically equivalent to 400 MeV. They may occasionally deposit much more when they undergo a nuclear interaction within the lead-glass cell. On the other hand, occasional overlaps between a charged hadron and a \( \pi^0 \)-decay photon result in a similar pattern. The interpretation of charged tracks pointing to a high-energy lead-glass cluster
is therefore ambiguous. To evaluate this effect we have performed two independent analyses. In the first one, when dealing with \( \pi^0 \) and \( \eta \) mesons, we retain only clusters to which no track is pointing within a 12.5 cm radius. In the second one, all lead-glass clusters are included in the \( \pi^0 \) and \( \eta \) sample, and all reconstructed tracks are included in the charged hadron sample, but the cluster energy is decreased by 400 MeV in the case of overlap. No significant difference was observed between the two analyses, neither in the \( \pi^0 \) and \( \eta \) sample nor in the charged hadron sample.

The most probable value of the mass associated with each charged particle is estimated from the combined measurements of momentum, time of flight between the A and E hodoscopes, and ionization losses in their scintillators.

From an inspection of the Čerenkov pulse-height distribution associated with charged particles, we estimate that approximately 4.2% are in fact background electrons, in agreement with the expected yield of converted photons.

5.2 Relation between the original and observed jets

The jet fragmentation model introduced in Section 3 can be compared to the data after inclusion, in the Monte Carlo simulation, of the detector response to charged particles. We have assumed all charged hadrons to be positive or negative pions with equal probabilities. Results are displayed in Figs. 16 to 18.

Given the crudeness of the model, the multiplicity distribution (Fig. 16) is remarkably well reproduced. This, however, does not imply that the form chosen for \( F(z) \) is the most appropriate; if neutral and charged pions are produced independently, the \( \nu \) distribution depends mostly on the \( \pi^\pm \) to \( \pi^0 \) ratio and upon the transverse momentum dependence of the jet production cross-section \( [19] \).

The \( \pi_\nu \) distribution (Fig. 18) deviates significantly from the data at low values of \( \pi_\nu \). This can originate from an important \( \rho^\pm \) contribution to the sample. We provide evidence for this interpretation in Fig. 19, where the invariant mass distribution of charged hadron-neutral cluster pairs is shown for jets containing a single neutral cluster, and under the assumption that both particles are pions.
A clear bump is visible around the $\rho$ mass in the data. We have therefore modified the production model to include $\rho$ production with a $\rho/\pi$ ratio equal to unity [6]. Results are indicated as dotted lines on Figs. 16 to 19.

5.3 Multiplicity distributions: charged particles

The larger aperture for charged particles (see Section 2) and the absence of decay complications permit a reliable evaluation of the charged particle multiplicity distribution, although they do not contribute to the trigger. Results for charged particles having $\xi_1^* > 0.2$ are listed in Table 4 for three intervals of $p_T^*$. The fraction of jets with no charged particle is observed to increase slightly with $p_T^*$, in disagreement with scaling. The effect is, however, barely significant.

5.4 Longitudinal distributions: charged particles

Normalized $\xi^*$ distributions are listed in Table 5 and displayed in Fig. 20 for three intervals of $p_T^*$. No significant difference is observed between each of the three distributions. A common fit of the form

$$\frac{d\sigma}{d\xi^*} \propto \exp \left(-\frac{\xi^*}{\Xi}\right)/\xi^*$$

yields $\Xi = 0.13 \pm 0.01$.

5.5 Transverse distributions: charged particles

Here again we evaluate $\pi^*_T$ distributions, for which the detector has a large acceptance. Results are displayed in Fig. 21 and listed in Table 6 for three intervals of $p_T^*$. Fits of the form

$$\frac{d\sigma}{d\pi^*_T} \propto \exp \left(-\frac{\pi^*_T}{\Pi}\right)^2$$

yield

$$\Pi = 681 \pm 25 \text{ MeV/c}$$
$$= 651 \pm 22 \text{ MeV/c}$$
$$= 664 \pm 16 \text{ MeV/c}$$
for each of the three $P_T^*$ intervals, respectively. Under the assumption that 
$\frac{d\sigma}{d\pi^*_T} = \frac{d\sigma}{d\pi^*_T}$, we find 

$$\langle \pi^*_T \rangle = \frac{1}{2} \sqrt{P_T} = 589 \pm 14 \text{ MeV/c}.$$ 

This value is substantially higher than that found for $\pi^0$ and $\eta$ mesons. This results in part from the additional transverse momentum of the $\rho$ decay and in part from the fact that $\pi^*_T$ is defined with respect to $\vec{P}$ rather than to the total jet momentum.

5.6 Charge correlations

The ratio of positive to negative hadron charges can be evaluated directly from the data. It is listed in Table 7 and displayed in Fig. 22 where it is observed to increase with $\xi$. For events with a single neutral cluster, it is displayed as a function of the $\pi^0\pi^\pm$ invariant mass in Fig. 19. We note that a $\pi^\pm$ from a $\rho^\pm$ decay owes its charge to the parent $\rho^\pm$, which carries a larger fraction of the total jet momentum than a directly produced $\pi^\pm$ at the same value of the $\pi^0\pi^\pm$ invariant mass.

For jets containing at least two charged hadrons, a large excess of opposite charge pairs is observed. The relative populations of each of the three possible charge combinations are listed in Table 8. When both particles have opposite charges, the positive is observed to have a larger $\xi$ than the negative in $(49 \pm 3)\%$ of the cases. Defining as $\xi^+$ and $\xi^-$ the values of $\xi$ corresponding to the positive and negative particle, respectively, we show in Fig. 23 the distribution of $\xi^+ - \xi^-$. No significant asymmetry is observed. This somewhat surprising result may indicate that opposite charge pairs are decay products of a same neutral parent; the $\pi^+\pi^-$ invariant mass and, in the case of jets with a single neutral cluster, the $\pi^+\pi^-\pi^0$ invariant mass are displayed in Fig. 24. No significant structure is observed. In particular, the enhancement observed in the $\pi^+\pi^-$ mass spectrum around 500 MeV/c$^2$ is too wide to correspond to $K_S \rightarrow \pi^+\pi^-$ decays. This is confirmed by a study of the associated vertex distribution.
5.7 Protons and antiprotons

Particle identification from time-of-flight measurement is difficult in the high momentum range of the present analysis. In particular, τ-K separation is not possible, and π-p separation is limited to momenta below 1.5 GeV/c. Figure 25 shows the distributions in mass squared for positive and negative particles having less than 1.5 GeV/c momentum in the laboratory. This corresponds to a narrow c.m. transverse momentum interval centred at 1.06 GeV/c in which we estimate the following ratios between invariant cross-sections:

\[
p/\text{all positive} = (10.3 \pm 2.0)\% \\
\bar{p}/\text{all negative} = (5.8 \pm 1.6)\%
\]

and \( p/\bar{p} = 2.3 \pm 0.6 \).

The same ratios, when evaluated inclusively [23] in the same interval of transverse momentum, take approximate values of 18\%, 14\%, and 1.6 respectively.

5.8 Inclusive production of \( \rho^\pm \) mesons

Asymmetric \( \rho^\pm \) decays, where the \( \pi^0 \) has a large fraction of the \( \rho^\pm \) momentum, are favoured by the trigger. We evaluate the ratio \( \rho^\pm/\pi^0 \) between invariant cross-sections for inclusive productions of \( \rho^\pm \) and \( \pi^0 \) mesons in the kinematic region defined as

\[
p_T(\pi^+) > 0.8 \text{ GeV/c} \\
6 < p_T(\rho^\pm) < 10 \text{ GeV/c} \\
4 < p_T(\pi^0) < 8 \text{ GeV/c},
\]

where the acceptance can be reliably calculated and where the background of \( \pi^0\pi^\pm \) pairs is not too important. The distribution of the \( \pi^0\pi^\pm \) invariant mass is displayed in Fig. 26. We estimate \( (\rho^+ + \rho^-)/\pi^0 = 1.0 \pm 0.5 \) and \( \rho^+/\rho^- = 1.2 \pm 0.3 \).

6. CONCLUSIONS

We have presented a study of the jet structure observed in p-p collisions yielding large transverse momentum secondaries. Throughout the analysis a jet
was defined as the set of particles on the trigger side having more than 800 MeV/c transverse momentum.

A feature specific of the experiment is the enhancement of jet configurations where a large fraction of the jet momentum is shared by \( \pi^0 \) and \( \eta \) mesons. For this reason we have used as reference the total momentum of \( \pi^0 \) and \( \eta \) fragments, rather than the total jet momentum, to evaluate quantities related to the longitudinal and transverse structure within a jet.

In spite of the limited aperture of the detector, the very high transverse momentum range explored in the experiment (substantially higher than in earlier measurements) has permitted detailed informations to be obtained on the jet structure. The analysis involved the use of a very simple jet fragmentation model together with a detailed simulation of the detector properties. However, we paid a great deal of attention to the presentation of results which are free of experimental bias and independent of the model chosen. For both the neutral and charged jet fragments, strong rapidity correlations were observed, and quantities relevant to the multiplicity distribution, the longitudinal structure, and the transverse structure were evaluated for three different intervals of the total momentum of \( \pi^0 \) and \( \eta \) mesons. No significant scaling violation was observed.

The \( \eta \) and \( \rho^\pm \) populations have been evaluated, but most observed features, including in particular the mere existence of a strong \( \pi^0-\pi^0 \) correlation, suggest a non-resonant fragmentation mechanism, similar to that observed in \( e^+e^- \) annihilations at lower energies \(^{12}\).

An excess of positive over negative charges, increasing with the momentum fraction, has been measured.

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    publication in Nucl. Phys. B.

    Lett.


    G. Hanson, SLAC-PUB-2118 (1978), and references given therein.


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    events, Fermilab report No. 77-89.
A.C. Clark et al., Large transverse momentum π⁰ production in p-p, d-p and d-d collisions at the CERN ISR, submitted for publication in Nucl. Phys. B.
A.C. Clark et al., Electron pair production at the CERN ISR, to be published in Nucl. Phys. B.


Table 1

The fraction $\rho_1^*$ of multiplicity-one jets, and the fraction $\rho_{12}^*$ between multiplicity-two and multiplicity-one jets, as functions of $P_T^R$. In addition to the quoted uncertainties, which include point-to-point systematics, normalization errors of respectively $\pm 8\%$ and $\pm 20\%$ must be applied.

<table>
<thead>
<tr>
<th>$P_T^R$ (GeV/c)</th>
<th>$\rho_1^*$</th>
<th>$\rho_{12}^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.5</td>
<td>0.367 ± 0.017</td>
<td>0.96 ± 0.03</td>
</tr>
<tr>
<td>6.5</td>
<td>0.313 ± 0.013</td>
<td>1.23 ± 0.05</td>
</tr>
<tr>
<td>7.5</td>
<td>0.286 ± 0.012</td>
<td>1.33 ± 0.06</td>
</tr>
<tr>
<td>8.5</td>
<td>0.269 ± 0.012</td>
<td>1.29 ± 0.10</td>
</tr>
<tr>
<td>9.5</td>
<td>0.244 ± 0.012</td>
<td>1.57 ± 0.17</td>
</tr>
<tr>
<td>11</td>
<td>0.226 ± 0.011</td>
<td>1.68 ± 0.27</td>
</tr>
<tr>
<td>14</td>
<td></td>
<td>1.30 ± 0.45</td>
</tr>
</tbody>
</table>
Table 2

Distributions in $r^*$ for three intervals of $P_T^{0*}$. The three distributions are normalized to a same value for $0.16 < r^* < 1$

<table>
<thead>
<tr>
<th>$r^*$</th>
<th>$5 &lt; P_T^{0*} &lt; 6$ GeV/c</th>
<th>$6 &lt; P_T^{0*} &lt; 8$ GeV/c</th>
<th>$P_T^{0*} &gt; 8$ GeV/c</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.10</td>
<td>-</td>
<td>-</td>
<td>65 ± 7</td>
</tr>
<tr>
<td>0.14</td>
<td>-</td>
<td>57 ± 3</td>
<td></td>
</tr>
<tr>
<td>0.18</td>
<td>49 ± 3</td>
<td>68 ± 4</td>
<td></td>
</tr>
<tr>
<td>0.22</td>
<td>53 ± 4</td>
<td>63 ± 4</td>
<td>53 ± 7</td>
</tr>
<tr>
<td>0.26</td>
<td>62 ± 4</td>
<td>70 ± 4</td>
<td></td>
</tr>
<tr>
<td>0.30</td>
<td>58 ± 4</td>
<td>64 ± 4</td>
<td>64 ± 8</td>
</tr>
<tr>
<td>0.34</td>
<td>53 ± 4</td>
<td>54 ± 4</td>
<td></td>
</tr>
<tr>
<td>0.38</td>
<td>50 ± 4</td>
<td>54 ± 4</td>
<td>48 ± 8</td>
</tr>
<tr>
<td>0.42</td>
<td>58 ± 4</td>
<td>49 ± 4</td>
<td></td>
</tr>
<tr>
<td>0.46</td>
<td>48 ± 4</td>
<td>56 ± 5</td>
<td>48 ± 8</td>
</tr>
<tr>
<td>0.50</td>
<td>52 ± 5</td>
<td>53 ± 5</td>
<td></td>
</tr>
<tr>
<td>0.54</td>
<td>49 ± 4</td>
<td>43 ± 4</td>
<td>46 ± 8</td>
</tr>
<tr>
<td>0.58</td>
<td>53 ± 5</td>
<td>53 ± 5</td>
<td></td>
</tr>
<tr>
<td>0.62</td>
<td>48 ± 5</td>
<td>45 ± 4</td>
<td>50 ± 9</td>
</tr>
<tr>
<td>0.66</td>
<td>40 ± 4</td>
<td>35 ± 4</td>
<td></td>
</tr>
<tr>
<td>0.70</td>
<td>44 ± 5</td>
<td>43 ± 4</td>
<td>42 ± 8</td>
</tr>
<tr>
<td>0.74</td>
<td>41 ± 4</td>
<td>38 ± 4</td>
<td></td>
</tr>
<tr>
<td>0.78</td>
<td>42 ± 5</td>
<td>45 ± 4</td>
<td>43 ± 9</td>
</tr>
<tr>
<td>0.82</td>
<td>41 ± 5</td>
<td>40 ± 4</td>
<td></td>
</tr>
<tr>
<td>0.86</td>
<td>40 ± 4</td>
<td>32 ± 4</td>
<td>50 ± 10</td>
</tr>
<tr>
<td>0.90</td>
<td>44 ± 5</td>
<td>33 ± 4</td>
<td></td>
</tr>
<tr>
<td>0.94</td>
<td>40 ± 5</td>
<td>31 ± 4</td>
<td>36 ± 9</td>
</tr>
<tr>
<td>0.98</td>
<td>36 ± 4</td>
<td>34 ± 4</td>
<td>-</td>
</tr>
</tbody>
</table>
Table 3
Distributions in $q_w$ for three intervals of $p_T^{\phi*}$. The three distributions are normalized to a same value for $0 < q_w < 1$ GeV/c

<table>
<thead>
<tr>
<th>$q_w$ (GeV/c)</th>
<th>$5 &lt; p_T^{\phi*} &lt; 6$ GeV/c</th>
<th>$6 &lt; p_T^{\phi*} &lt; 8$ GeV/c</th>
<th>$p_T^{\phi*} &gt; 8$ GeV/c</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>116 ± 3</td>
<td>103 ± 3</td>
<td>117 ± 12</td>
</tr>
<tr>
<td>0.15</td>
<td>98 ± 2</td>
<td>92 ± 2</td>
<td>102 ± 6</td>
</tr>
<tr>
<td>0.25</td>
<td>71.5 ± 2.0</td>
<td>76.2 ± 2.0</td>
<td>79 ± 5</td>
</tr>
<tr>
<td>0.35</td>
<td>52.0 ± 2.2</td>
<td>51.6 ± 1.8</td>
<td>48 ± 4</td>
</tr>
<tr>
<td>0.45</td>
<td>43.1 ± 3.9</td>
<td>37.5 ± 2.3</td>
<td>37 ± 5</td>
</tr>
<tr>
<td>0.55</td>
<td>37.1 ± 7.4</td>
<td>32.7 ± 3.6</td>
<td>28 ± 6</td>
</tr>
<tr>
<td>0.65</td>
<td>36.2 ± 13.2</td>
<td>28.8 ± 6.1</td>
<td>38 ± 11</td>
</tr>
<tr>
<td>0.75</td>
<td>22.8 ± 14.4</td>
<td>28.2 ± 11.0</td>
<td>19 ± 11</td>
</tr>
<tr>
<td>0.85</td>
<td>14.0 ± 8.8</td>
<td>18.4 ± 15.0</td>
<td>11 ± 11</td>
</tr>
<tr>
<td>0.95</td>
<td>3.0 ± 1.2</td>
<td>19.5 ± 21.1</td>
<td>10 ± 10</td>
</tr>
</tbody>
</table>
Table 4

Multiplicity distributions of associated charged particles having $\xi^* > 0.2$ for three intervals of $P_T^0$

<table>
<thead>
<tr>
<th>$\nu^*$</th>
<th>$5 &lt; P_T^0 &lt; 6$ GeV/c</th>
<th>$6 &lt; P_T^0 &lt; 8$ GeV/c</th>
<th>$P_T^0 &gt; 8$ GeV/c</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.889 ± 0.010</td>
<td>0.898 ± 0.010</td>
<td>0.927 ± 0.008</td>
</tr>
<tr>
<td>1</td>
<td>0.096 ± 0.009</td>
<td>0.091 ± 0.009</td>
<td>0.061 ± 0.009</td>
</tr>
<tr>
<td>2</td>
<td>0.015 ± 0.005</td>
<td>0.011 ± 0.005</td>
<td>0.012 ± 0.010</td>
</tr>
</tbody>
</table>
Table 5

Distributions in $\xi^*$ for three intervals of $p_T^{\pi^*}$. The three distributions are normalized to a same value for $0.15 < \xi^* < 1$

<table>
<thead>
<tr>
<th>$\xi^*$</th>
<th>$5 &lt; p_T^{\pi^*} &lt; 6$ GeV/c</th>
<th>$6 &lt; p_T^{\pi^*} &lt; 8$ GeV/c</th>
<th>$p_T^{\pi^*} &gt; 8$ GeV/c</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.125</td>
<td>-</td>
<td>-</td>
<td>118 ± 10</td>
</tr>
<tr>
<td>0.175</td>
<td>42 ± 2</td>
<td>47 ± 2</td>
<td>43 ± 6</td>
</tr>
<tr>
<td>0.225</td>
<td>22 ± 1</td>
<td>23 ± 1</td>
<td>24 ± 4</td>
</tr>
<tr>
<td>0.275</td>
<td>13 ± 1</td>
<td>12.5 ± 1.0</td>
<td>11.8 ± 2.8</td>
</tr>
<tr>
<td>0.325</td>
<td>7.4 ± 0.7</td>
<td>6.0 ± 0.7</td>
<td>7.6 ± 2.2</td>
</tr>
<tr>
<td>0.375</td>
<td>5.3 ± 0.5</td>
<td>4.1 ± 0.5</td>
<td>6.4 ± 1.9</td>
</tr>
<tr>
<td>0.425</td>
<td>3.4 ± 0.4</td>
<td>2.3 ± 0.4</td>
<td>3.7 ± 1.4</td>
</tr>
<tr>
<td>0.475</td>
<td>2.0 ± 0.3</td>
<td>1.5 ± 0.3</td>
<td>1.4 ± 0.8</td>
</tr>
<tr>
<td>0.525</td>
<td>1.6 ± 0.3</td>
<td>0.8 ± 0.2</td>
<td>1.7 ± 0.9</td>
</tr>
<tr>
<td>0.575</td>
<td>0.76 ± 0.19</td>
<td>0.5 ± 0.2</td>
<td>1.2 ± 0.6</td>
</tr>
<tr>
<td>0.625</td>
<td>0.37 ± 0.13</td>
<td>0.6 ± 0.2</td>
<td>-</td>
</tr>
<tr>
<td>0.675</td>
<td>0.69 ± 0.18</td>
<td>0.13 ± 0.09</td>
<td>-</td>
</tr>
<tr>
<td>0.725</td>
<td>0.19 ± 0.09</td>
<td>0.14 ± 0.10</td>
<td>-</td>
</tr>
<tr>
<td>0.775</td>
<td>0.28 ± 0.12</td>
<td>0.25 ± 0.14</td>
<td>-</td>
</tr>
<tr>
<td>0.825</td>
<td>0.25 ± 0.11</td>
<td>0.20 ± 0.14</td>
<td>-</td>
</tr>
<tr>
<td>0.875</td>
<td>0.05 ± 0.05</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>0.925</td>
<td>0.06 ± 0.06</td>
<td>0.24 ± 0.24</td>
<td>-</td>
</tr>
<tr>
<td>0.975</td>
<td>0.09 ± 0.09</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Table 6

Distributions in $\pi^*$ for three intervals of $p_T^{\pi^*}$. The three distributions are normalized to a same value for $0 < \eta^*_V < 1$ GeV/c.

<table>
<thead>
<tr>
<th>$\eta^*_V$ (GeV/c)</th>
<th>$5 &lt; p_T^{\pi^*} &lt; 6$ GeV/c</th>
<th>$6 &lt; p_T^{\pi^*} &lt; 8$ GeV/c</th>
<th>$p_T^{\pi^*} &gt; 8$ GeV/c</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>$175 \pm 10$</td>
<td>$170 \pm 11$</td>
<td>$171 \pm 23$</td>
</tr>
<tr>
<td>0.15</td>
<td>$159 \pm 10$</td>
<td>$156 \pm 10$</td>
<td>$171 \pm 23$</td>
</tr>
<tr>
<td>0.25</td>
<td>$147 \pm 9$</td>
<td>$160 \pm 10$</td>
<td>$158 \pm 23$</td>
</tr>
<tr>
<td>0.35</td>
<td>$129 \pm 9$</td>
<td>$129 \pm 9$</td>
<td>$112 \pm 20$</td>
</tr>
<tr>
<td>0.45</td>
<td>$97 \pm 8$</td>
<td>$92 \pm 8$</td>
<td>$95 \pm 16$</td>
</tr>
<tr>
<td>0.55</td>
<td>$66 \pm 6$</td>
<td>$70 \pm 7$</td>
<td>$69 \pm 16$</td>
</tr>
<tr>
<td>0.65</td>
<td>$55 \pm 6$</td>
<td>$61 \pm 6$</td>
<td>$66 \pm 16$</td>
</tr>
<tr>
<td>0.75</td>
<td>$57 \pm 7$</td>
<td>$48 \pm 7$</td>
<td>$59 \pm 16$</td>
</tr>
<tr>
<td>0.85</td>
<td>$53 \pm 7$</td>
<td>$34 \pm 6$</td>
<td>$33 \pm 13$</td>
</tr>
<tr>
<td>0.95</td>
<td>$41 \pm 7$</td>
<td>$35 \pm 8$</td>
<td>$33 \pm 16$</td>
</tr>
</tbody>
</table>
Table 7
Positive to negative charge ratio as a function of $\xi$

<table>
<thead>
<tr>
<th>$\xi$</th>
<th>(+/-) Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 to 0.1</td>
<td>1.24 ± 0.20</td>
</tr>
<tr>
<td>0.1 to 0.2</td>
<td>1.30 ± 0.06</td>
</tr>
<tr>
<td>0.2 to 0.3</td>
<td>1.54 ± 0.10</td>
</tr>
<tr>
<td>0.3 to 0.6</td>
<td>1.52 ± 0.13</td>
</tr>
<tr>
<td>0.6 to 1.0</td>
<td>2.2 ± 0.6</td>
</tr>
</tbody>
</table>

Table 8
Relative populations of the three possible charge combinations for jets with more than one charged fragment

<table>
<thead>
<tr>
<th>Charge combination</th>
<th>Population (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>++</td>
<td>23 ± 2</td>
</tr>
<tr>
<td>+ -</td>
<td>60 ± 2</td>
</tr>
<tr>
<td>- -</td>
<td>17 ± 2</td>
</tr>
</tbody>
</table>
Figure captions

Fig. 1 : Exploded view of one of the two spectrometers showing its various elements.

Fig. 2 : Pair correlation function for:
   a) all lead-glass clusters on the trigger side (open circles);
   b) Lead-glass clusters on the trigger side having more than 800 MeV/c transverse momentum (full dots).

   The pair correlation function is displayed versus the pseudo-rapidity difference and averaged over the mean pseudo-rapidity of the cluster pair.

Fig. 3 : Variables used in the description of a jet (see text).

Fig. 4 : Experimental multiplicity distributions (full dots) are compared to the model calculation described in the text (histogram) for three intervals of $P_T^0$: a) $5 < P_T^0 < 6$ GeV/c; b) $6 < P_T^0 < 8$ GeV/c; and c) $P_T^0 > 8$ GeV/c.

Fig. 5 : Experimental $x$ distributions (full dots) are compared to the model calculation described in the text (histograms) for three values of the jet multiplicity: a) $n = 2$, b) $n = 3$, and c) $n = 4$.

Fig. 6 : Experimental $x$ distributions (full dots) are compared to the model calculation described in the text (histograms) for three intervals of $P_T^0$: a) $5 < P_T^0 < 6$ GeV/c; b) $6 < P_T^0 < 8$ GeV/c; and c) $P_T^0 > 8$ GeV/c.

Fig. 7 : Experimental distributions (full dots) of the quantity $r = x_2/x_1$ (see Section 4.2) are compared to the model calculation described in the text (histograms) for three intervals of $P_T^0$: a) $5 < P_T^0 < 6$ GeV/c; b) $6 < P_T^0 < 8$ GeV/c; and c) $P_T^0 > 8$ GeV/c.

Fig. 8 : Experimental $q$ distributions (full dots) are compared to the model calculation described in the text (histograms) for three intervals of $P_T^0$: a) $5 < P_T^0 < 6$ GeV/c; b) $6 < P_T^0 < 8$ GeV/c; and c) $P_T^0 > 8$ GeV/c.
Fig. 9: Experimental $q_y$ distributions (full dots) are compared to the model calculation described in the text (histograms) for three intervals of $P_T^0$: a) $5 < P_T^0 < 6$ GeV/c; b) $6 < P_T^0 < 8$ GeV/c; and c) $P_T^0 > 8$ GeV/c.

Fig. 10: Fraction $\rho_1^*$ of multiplicity-one jets as a function of $P_T^{0*}$. The line is the result of a linear fit in $\ln P_T^{0*}$ (see text).

Fig. 11: Ratio $\rho_{12}^*$ between multiplicity-two and multiplicity-one jets as a function of $P_T^{0*}$. The line is the result of a linear fit in $\log P_T^{0*}$ (see text).

Fig. 12: Normalized $t^*$ distributions for three intervals of $P_T^{0*}$: a) $5 < P_T^{0*} < 6$ GeV/c; b) $6 < P_T^{0*} < 8$ GeV/c; and c) $P_T^{0*} > 8$ GeV/c.

Fig. 13: Normalized $q_y$ distributions for three intervals of $P_T^{0*}$: a) $5 < P_T^{0*} < 6$ GeV/c; b) $6 < P_T^{0*} < 8$ GeV/c; and c) $P_T^{0*} > 8$ GeV/c.

Fig. 14: a) Invariant mass distribution of photon pairs with transverse momenta between 4 and 6 GeV/c (see text).

b) Invariant mass distribution of photon triplets with transverse momentum between 4 and 6 GeV/c. The line indicates the contribution for $\omega/m_\omega = 1$, calculated under the assumption that the $\omega$ meson is unpolarized.

Fig. 15: a) Pair correlation function between the trigger jet (pseudo-rapidity $\eta^0$) and associated charged particles (pseudo-rapidity $\eta_i$), averaged over $\eta_i + \eta^0$:

i) for all charged particles on the trigger side (open circles);

ii) for all charged particles on the trigger side having more than 800 MeV/c c.m. transverse momentum (full dots).

b) Distribution in c.m. transverse momentum of all charged particles on the trigger side having more than 800 MeV/c c.m. transverse momentum:

i) per interaction with a trigger jet having $P_T^0 > 7$ GeV/c (full dots);
ii) per interaction with a trigger jet having $5 < p_T^0 < 7$ GeV/c (open circles);

iii) per any p-p interaction, calculated from Refs. 21 and 23 with the detector acceptance folded in (full line).

Fig. 16: The experimental multiplicity distribution of associated charged particles is compared to the model calculations described in the text: a) all charged hadrons are pions (full line), and b) $\rho$ and $\pi$ mesons are produced with equal probabilities (dashed line).

Fig. 17: The experimental $\xi$ distribution of associated charged particles (full dots) is compared to the model calculations described in the text: a) all charged hadrons are pions (full line); and b) $\rho$ and $\pi$ mesons are produced with equal probabilities (dashed lines).

Fig. 18: The experimental $\pi_v$ distribution of associated charged particles (full dots) is compared to the model calculations described in the text: a) all charged hadrons are pions (full line); and b) $\rho$ and $\pi$ mesons are produced with equal probabilities (dashed lines).

Fig. 19: a) The experimental distribution of the $\pi^0\pi^\pm$ invariant mass $M_{\pi^0\pi^\pm}$ for events with $n = 1$ (full dots) is compared to the model calculations described in the text: 1) all charged hadrons are pions (full line); and 2) $\rho$ and $\pi$ mesons are produced with equal probabilities (dashed line).

b) The positive to negative charge ratio as a function of the $\pi^0\pi^\pm$ invariant mass $M_{\pi^0\pi^\pm}$.

Fig. 20: Normalized $\xi^*$ distributions for three intervals of $p_T^{\pi^*}$: a) $5 < p_T^{\pi^*} < 6$ GeV/c; b) $6 < p_T^{\pi^*} < 8$ GeV/c; and c) $p_T^{\pi^*} > 8$ GeV/c. The lines are the result of a common fit (see text).

Fig. 21: Normalized $\pi_v^*$ distributions for three intervals of $p_T^{\pi^*}$: a) $5 < p_T^{\pi^*} < 6$ GeV/c; b) $6 < p_T^{\pi^*} < 8$ GeV/c; and c) $p_T^{\pi^*} > 8$ GeV/c. The lines are the result of a common Gaussian fit (see text).
Fig. 22 : Positive to negative charge ratio as a function of $\xi$.

Fig. 23 : Distribution in $\xi^+ - \xi^-$ for jets having both a positive ($\xi^+$) and a negative ($\xi^-$) associated charged particle.

Fig. 24 : Invariant mass distributions for jets having both a positive and a negative charged particle
   a) of the charged particle pair under the assumption of both being pions;
   b) of the charged particle pair with the neutral cluster (for events having only one neutral cluster) under the assumption of all three particles being pions.

Fig. 25 : Distribution in mass squared of associated charged particles having less than 1.5 GeV/c laboratory momentum for positive charged (full dots), negative charged (full triangles), or all charged (open circles).

Fig. 26 : Distribution of the $\pi^0\pi^+$ invariant mass at $\sqrt{s} = 63$ GeV in the kinematic region defined in the text.
Fig. 6
Fig. 8

Number of events (arbitrary scale)
Fig. 12
Fig. 13
Fig. 15
Fig. 19
Fig. 24
Fig. 26