LARGE TRANSVERSE MOMENTUM JETS
IN HIGH-ENERGY PROTON-PROTON COLLISIONS

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ABSTRACT

We present a study of pp collisions producing large transverse momentum π^0 's. The data collected at c.m. energies $\sqrt{s} = 52.4$ and 62.7 GeV, give evidence for a two-jet structure. The fragmentation of the jets is studied and correlations between the two jets are investigated. Results are compared with e^+e^- and vp data.

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1. INTRODUCTION

Previous intersecting storage rings (ISR) experiments [1-9] have reported an enhancement of particle density in the region of phase space surrounding large transverse momentum hadrons. They measure, among the large transverse momentum products of proton-proton collisions, strong positive correlations in transverse momentum, in rapidity, and in azimuth. They also observe a second enhancement at opposite azimuth, and they establish that the remaining secondaries are otherwise distributed as in a typical non-diffractive collision.

The interpretation of these observations in the framework of parton models [10-12] 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 being 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 of the colliding partons.

In the case of quark partons, measurements of the first two quantities are obtained from a number of experiments: Drell-Yan production of lepton pairs; e^+e^- annihilation into hadrons; deep inelastic collisions of electrons, muons, and neutrinos on protons. 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.

Recent progress in developing a strong interaction theory in the framework of QCD [13-16] has added some theoretical justification to the phenomenology of parton models.

A detailed study of large transverse momentum hadron production should reveal the radiative effects resulting from gluon bremsstrahlung and also the existence of gluon-gluon interactions. QCD models have already been used to successfully describe the inclusive production of neutral pions [16,17].

The present experiment uses a double-arm spectrometer to measure the event structure associated with a large transverse momentum π^0 , the trigger being provided by large lead-glass arrays. Preliminary accounts of this experiment have been given elsewhere [18,19].

The paper is organized as follows. Section 2 describes the apparatus and its performance. The method of data reduction and analysis is introduced in Section 3. Gross features of the event topology, giving evidence for a two-jet structure, are presented in Section 4. The remaining sections are devoted to a quantitative evaluation of some of those parameters relevant to the description of the final states. This requires a detailed investigation of the detector acceptance, which is presented in Section 5. Section 6 studies jet fragmentation, Section 7 charge correlations, and Section 8 jet-jet correlations. A summary of the main results is presented in Section 9.

2. EXPERIMENTAL SET-UP

The experimental set-up, shown in figs. 1 and 2, has been described elsewhere [20]. 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 the momentum measurement of charged particles. It is followed by a lead-glass array, which provides a trigger for large transverse momentum π^0 's and which measures their energy. The magnets are located as close as possible to the ISR vacuum chamber 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.

An additional lead-glass array is inserted between the two spectrometers and above the plane of the beams. It provides a trigger on large transverse momentum π^0 's produced with an azimuth separation of approximately 90° with respect to the particles entering the spectrometer aperture.

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. 2. 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 those 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 [21].

The drift time, of the order of 200 nsec/cm, is digitized in 2 nsec bins [22]. 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 $[(150)^2 + (300 \tan \theta)^2]^{1/2} \mu\text{m}$ is achieved. The observed width of the $J/\psi \rightarrow e^+e^-$ peak [20] is well described by this relation, once radiative losses and multiple scattering are included. For the duration of the experiment a global momentum accuracy $\Delta p/p = 10^{-2} [9 + (4.2p)^2]^{1/2}$ 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 of the spectrometer lead-glass arrays is located 2.3 m from the beams and consists of 138 lead-glass blocks arranged in seven horizontal rows. The lead-glass array located above the beams consists of 32 blocks arranged in four longitudinal rows; its distance from the beam plane is 1.35 m. Each block ($15 \times 15 \text{ cm}^2$ in cross-section and 14.8 radiation lengths thick) is equipped with a 5" phototube, shielded from the stray magnetic field by an iron plate (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 (^{241}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 spectrometer lead-glass arrays were periodically recessed to 4 m from the intersection, at which distance $\pi^0 \rightarrow \gamma\gamma$ decays yield two spatially resolved photons. Data collected in this configuration enable a check of the calibration of each cell to within $\pm 5\%$ 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 $1000 \text{ J}/\psi \rightarrow e^+e^-$ decays in which the electrons are detected in opposite arms, we estimate an uncertainty of $\pm 3\%$ 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

$$\frac{\Delta E}{E} = \pm \left[(0.05)^2 + \frac{(0.12)^2}{E(\text{GeV})} \right]^{1/2}.$$

The linearity of the energy response to electrons between 2 and 12 GeV was measured at the CERN PS both for normal and for 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. 2), 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 phototube.

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.

The arrangement differs slightly above the beams where the iron converter is provided by a 2 cm thick magnetic shield located near the beam pipe. Proportional chamber planes followed by four scintillator strips parallel to the beams play the role of the F hodoscope.

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 at least one of the lead-glass arrays. Trigger threshold c.m. energies of between 5 and 8 GeV have been used. The integrated luminosity appropriate to each threshold value is taken into account in the subsequent analysis.

Additional conditions are required to suppress background. In the case of the spectrometer lead-glass arrays, a coincidence with a signal from any scintillator of either A hodoscope is required. In the case of the array above the beams, a coincidence with a signal from the F hodoscope is required. These have been shown to introduce a negligible bias.

A more restrictive trigger was obtained by requiring the coincidence of a signal above threshold in each of the two spectrometer lead-glass arrays. Lower thresholds, of typically 3 GeV c.m. energy, were used for this trigger.

3. THE DATA SAMPLE

The data sample of the present analysis corresponds to an integrated luminosity of $1.5 \times 10^{37} \text{ cm}^{-2}$ of which two thirds are at a centre-of-mass energy $\sqrt{s} = 52.4 \text{ GeV}$ and one third at $\sqrt{s} = 62.7 \text{ GeV}$.

The set of particles detected in each spectrometer is constructed from the clusters of lead-glass energy and from reconstructed tracks. Charged hadrons usually deposit some energy in the lead-glass array, typically equivalent to 400 MeV. When a lead-glass cluster is observed within less than 12.5 cm from the point of impact of a reconstructed track, it is therefore attributed to the charged particle which generated the track. Some ambiguity exists, however, when the cluster energy is significantly higher than 400 MeV: the charged hadron may have undergone a nuclear interaction within the lead-glass cell, or its impact may have accidentally overlapped that of a π^0 or photon. In the analysis, we retain as π^0 or photon any lead-glass cluster having a c.m. transverse momentum larger than 800 MeV/c provided that no charged track having more than 800 MeV/c c.m. transverse momentum points to within 12.5 cm from its centre. This implies that we systematically consider a (low-momentum track, high-energy cluster) pair as an accidental overlap. The resulting uncertainty is taken into account in the subsequent analysis. When a lead-glass cluster and a track, both with more than 800 MeV/c, are less than 12.5 cm apart, only the charged track is kept, thereby retaining the nuclear interaction hypothesis. The subsequent loss of π^0 's due to charged particle overlaps is corrected by applying the above criterion to our evaluation of the detector acceptance.

A 4% contamination of the charged hadron sample by electrons resulting from photon conversions is identified and subtracted.

Any multiplicity bias resulting from threshold effects is avoided by requiring that on the trigger side the total energy of all clusters having more than 800 MeV/c c.m. transverse momentum, and not associated with a charged particle, exceeds the trigger threshold.

4. EVENT STRUCTURE: EVIDENCE FOR JETS

A clear two-jet structure is visible in a number of individual events (see, for example, fig. 3). In this section we present gross features of the final state, providing evidence for this two-jet structure, that are visible in the raw data.

A sample of "minimum-bias" events is used as a term of comparison and reference to final states involving a high transverse momentum trigger. A special trigger was devised to record such events. It only requires the presence of at least one charged particle in either spectrometer. Apart from a small bias resulting from rapidity correlations in the central region [23], the particles observed in *the other* spectrometer should behave as in a typical inelastic non-diffractive event.

We first evaluate the multiplicity and transverse momentum distributions of charged particles produced in one (S) of the two spectrometers under different trigger conditions: "minimum bias" or large transverse momentum π^0 production. In the latter case we require that π^0 's with a total c.m. transverse momentum of at least 5 GeV/c be produced in a solid angle of 0.25 sr centred at about 90° polar angle and with an azimuth angle centred at about 0° , 90° , or 180° with respect to the axis of (S).

In each trigger configuration we measure the transverse momentum and multiplicity distributions of charged particles, dn/dp_T and $\Delta n/\Delta N$. We define normalized distributions

$$\frac{d\bar{n}}{dp_T} = \left[\int \frac{dn}{dp_T} dp_T \right]^{-1} \frac{dn}{dp_T}$$

and

$$\frac{\Delta\bar{n}}{\Delta N} = \left[\sum \frac{\Delta n}{\Delta N} \Delta N \right]^{-1} \frac{\Delta n}{\Delta N},$$

and we evaluate their ratios to those of the minimum bias sample,

$$\rho_{p_T} = \frac{d\bar{n}}{dp_T} / \frac{d\bar{n} \text{ (min. bias)}}{dp_T}$$

$$\rho_N = \frac{\Delta\bar{n}}{\Delta N} / \frac{\Delta\bar{n} \text{ (min. bias)}}{\Delta N}.$$

These ratios are free of acceptance factors. Distributions in ρ_{p_T} are shown in fig. 4. Particles produced outside the "beam-trigger" plane (which contains

the incident protons and the large transverse momentum trigger) have a transverse momentum spectrum very similar to that of the "minimum-bias" sample. In contrast, particles produced in the "beam-trigger" plane have larger transverse momenta than "minimum-bias" particles.

Distributions in ρ_N have a similar behaviour (fig. 5). The production of a large transverse momentum particle is associated with an excess of other large transverse momentum particles near the "beam-trigger" plane but has little influence on the event structure outside this plane. This property of coplanarity is predicted by parton models in which the elementary interaction is a two-body collision between free partons.

In the "beam-trigger" plane we distinguish between "same-side" particles, which are produced with an azimuth approximately equal to that of the trigger, and "opposite-side" particles, which are produced with an azimuth difference of $\sim 180^\circ$. While "same-side" and "opposite-side" particles are observed to have transverse momentum spectra of similar shapes, the multiplicity of the latter is measured to be much larger. In jet models this is a direct consequence of the "trigger-bias" effect [24] which favours "same-side" jets in which the leading fragments are π^0 's. This effect depresses the charged particle multiplicity on the trigger side but does not significantly affect the shape of their transverse momentum spectrum [24].

Coplanarity is not sufficient to characterize a two-jet structure: collimation in polar angle θ -- or in pseudo-rapidity $\eta = \log \tan \theta/2$ -- is necessary in addition.

Such a collimation can be seen as an enhancement of the pair density function, $\rho(\eta_i, \eta_j)$, near $|\eta_i - \eta_j| = 0$. Here $\rho(\eta_i, \eta_j)$ is defined as

$$\rho(\eta_i, \eta_j) = \frac{dN(\eta_i, \eta_j)}{d\eta_i d\eta_j},$$

where $dN(\eta_i, \eta_j)$ is the number of particle pairs observed with one particle having a pseudo-rapidity between η_i and $\eta_i + d\eta_i$ and the other between η_j and $\eta_j + d\eta_j$. It is in fact more convenient to introduce the pair correlation function $R(\eta_i, \eta_j)$, which is related to $\rho(\eta_i, \eta_j)$ via the relation

$$R(\eta_i, \eta_j) = \frac{\iint \rho(\eta_i, \eta_j) d\eta_i d\eta_j}{\int \rho(\eta_i, \eta_j) d\eta_i \int \rho(\eta_i, \eta_j) d\eta_j} \rho(\eta_i, \eta_j) ,$$

and which is free to first order of acceptance and efficiency factors. In the absence of correlation, $R(\eta_i, \eta_j) = 1$, while short-range correlations cause $R(\eta_i, \eta_j)$ to peak in the vicinity of $|\eta_i - \eta_j| = 0$.

We first look for correlations between the large transverse momentum π^0 trigger and the charged particles in the "beam-trigger" plane. The corresponding pair correlation function, averaged over $\eta_i + \eta_j$ and plotted versus $|\eta_i - \eta_j|$, is shown in fig. 6a. "Same-side" particles are strongly correlated to the trigger; the correlation increases with their transverse momentum. This provides evidence for a jet on the trigger side. Such a collimation, increasing towards larger transverse momenta, is predicted by parton models in which the fragments of the scattered parton are produced with limited transverse momenta with respect to the parton momentum.

On the contrary, "opposite-side" particles (fig. 6b) show no significant correlation to the trigger, the pair correlation function being consistent with unity over the whole (η_i, η_j) domain. This may result either from the absence of an "opposite-side" jet or, if there is such a jet, from the absence of a significant correlation between the polar angles of the "opposite-side" and "same-side" jets. To distinguish between these possibilities, we evaluate the pair correlation function between charged particles produced in the "beam-trigger" plane on the "opposite-side". The result, shown in fig. 6c, indicates a clear jet structure; here again the collimation increases with transverse momentum. This observation completes our investigation of the gross features of the event structure. It has provided direct evidence for two coplanar, large transverse momentum jets. For clarity the discussion has been limited to charged particles, but identical results are obtained for neutral pions.

5. ACCEPTANCE CALCULATION

A quantitative evaluation of the parameters which describe the event structure requires a good knowledge of the detector acceptance: the solid angle covered by the spectrometers is often insufficient to contain all hadron fragments of the jets. To this end we use a Monte Carlo simulation of the detector which includes a detailed description of all major factors contributing to the acceptance: aperture, spatial resolution and resolving power, energy and momentum resolution, run-to-run variations of the energy thresholds in the lead-glass arrays, etc. It permits an evaluation of the distortions induced by the detector on event configurations similar to those realized in the actual experiment. The generation of such events follows a simple algorithm which is described in detail in a previous publication [19]; its adequacy is demonstrated there. It follows that introduced by several authors to describe the fragmentation of quark jets [25].

A jet axis is chosen on the trigger side with uniform azimuth and rapidity distributions. Fragmentation proceeds according to an infinite sequence of independent hadron emissions in which the 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 jet axis with a distribution $d^2\sigma/dk^2 \propto \exp(-k^2/2\Delta k^2)$ ($\Delta k = 0.45$ GeV/c is found to give a good fit to the data). Charges are randomly distributed, 2/3 for charged hadrons and 1/3 for π^0 and η 's decaying into two photons. The z distribution is taken of the form

$$F^S(z) = 0.2 + 2.4(1 - z)^2 ,$$

with parameters adjusted to reproduce the observed multiplicity distribution. The transverse momentum distribution of the trigger-side jet is adjusted to reproduce single π^0 inclusive spectra [20]. The generation of the away-side jet proceeds in a similar way. It involves defining the total momentum of the away-side jet and its mode of fragmentation. The transverse momentum of the away-side jet is taken to be a fraction f of that of the trigger-side jet, and its axis is assumed to span a region $\Delta\eta\Delta\phi$ in pseudo-rapidity azimuth space. Small f -values or large $\Delta\eta\Delta\phi$ -values both result in a low transverse momentum balance between the two jets.

This aside, different distributions of the away-jet axis in the $\Delta\eta\Delta\phi$ region, with the possible inclusion of correlations to the trigger-jet axis, can be adopted without significantly affecting the observed distributions. These ambiguities are inherent to the limited aperture of the detector and set limits on its ability to measure correlations between the two jets. For the purpose of measuring the fragmentation functions they are of little relevance; we have checked that the results are unaffected, by using widely different values for f and $\Delta\eta\Delta\phi$. We therefore adopt an empirical algorithm which gives a good description of the data: the pseudo-rapidity of the away-side jet axis has a Gaussian distribution centred at 0 and is uncorrelated to the pseudo-rapidity of the trigger-side jet. The azimuth of the away-side jet axis has a Gaussian distribution centred at opposite azimuth to the trigger-jet axis. The fraction f has a Gaussian distribution centred at 0.8 with variance 0.1. The fragmentation of the away-side jet is described in the same way as on the trigger-side, but the fragmentation function is chosen to be of the form $F^A(z) = 3(1 - z)^2$. Justification for this choice is obtained from a study of the probability for the away-side jet to consist of a single particle (track or cluster). For jets having a transverse momentum larger than 3 GeV/c, this probability is measured to be $12 \pm 2\%$, as compared to $15 \pm 2\%$ and $23 \pm 2\%$ for Monte Carlo calculations using respectively $F^A(z)$ and $F^S(z)$ to describe the fragmentation of the away-side jet.

We emphasize the *ad hoc* nature of this generation algorithm, which has been obtained with a purely pragmatic approach to the problem of evaluating the detector acceptance: the results of this section should not be given a deeper meaning.

6. JET FRAGMENTATION

In this section we study the structure of a jet observed in one of the spectrometers with no reference to particles detected in the other spectrometer.

The trigger condition is that the energy deposited in the spectrometer lead-glass arrays be above threshold in at least one of the spectrometers. In most events this condition is satisfied in only one of the two arrays. Thus we can

usually define a "trigger jet" and an "opposite-side jet". As noted previously, the trigger jet is strongly biased towards leading π^0 and η mesons; it is reasonably well contained in the detector acceptance. On the contrary, the opposite-side jet is virtually unbiased but spans a wide rapidity range, which results in a poorer containment. We consider only the reduced sample of opposite-side jets having a total transverse momentum of at least 3 GeV/c. The total jet momentum is defined as

$$\vec{P}_{\text{jet}} = \sum \vec{p}_i ,$$

where the sum extends over all charged particles and neutral lead-glass clusters having a transverse momentum $p_{T_i} > 0.8$ GeV/c. As noted in Section 3, this limitation selects particles having jet-like correlations.

For each jet fragment we define two parameters, x_i and $\vec{q}_i$, such that

$$\vec{p}_i = x_i \vec{P}_{\text{jet}} + \vec{q}_i ; \quad \vec{q}_i \cdot \vec{P}_{\text{jet}} = 0 , \quad (1)$$

which refer to the longitudinal and the transverse fragmentation, respectively. We use the method of Section 5 to unfold effects of aperture, resolution, π^0 and η decays, etc.

6.1 Multiplicity

We evaluate independently the neutral multiplicity n_0 (π^0 and η mesons), the charged multiplicity n_{ch} , and the total multiplicity $n = n_0 + n_{\text{ch}}$ of opposite-side jets. This evaluation is subject to important acceptance corrections, particularly in the neutral case. Mean multiplicities are displayed versus $P_{T\text{jet}}$ in fig. 7. Within experimental errors the neutral multiplicity is consistent with being half the charged multiplicity. A fit of the form

$$\langle n_{\text{ch}} \rangle = \lambda + \mu \ln P_{T\text{jet}}$$

yields

$$\lambda = 0.3 \pm 0.6$$

$$\mu = 1.8 \pm 0.3 .$$

These results can be compared with charged particle multiplicities n_{ch}^{ee} , measured in e^+e^- collisions at a c.m. energy $\sqrt{s^{ee}}$. The analogues of $\sqrt{s^{ee}}$ and n_{ch}^{ee} are respectively $2(\tilde{E}_{jet} + \tilde{E}_{soft})$ and $2(n_{ch} + n_{soft})$, where $\tilde{E}_{jet}$ is the jet energy measured in the rest frame of the two jets (trigger side and opposite side) and where $\tilde{E}_{soft}$ and n_{soft} account for jet fragments having $p_{T_i} < 0.8$ GeV/c.

To estimate these corrections, we subtract from the transverse momentum distribution of soft charged particles measured in the spectrometers that of minimum-bias events. Extrapolation in rapidity and azimuth outside the spectrometer aperture is made using streamer chamber data [4]. We find $\langle n_{soft} \rangle = 1.5 \pm 0.5$ and $\langle \tilde{E}_{soft} \rangle = 1.0 \pm 0.5$ GeV.

The corrected data (fig. 8) fall in line with lower-energy e^+e^- data [26] and with neutrino-proton data [27] (in the latter case the total hadronic mass W is a measure of $\sqrt{s^{ee}}$). This could indicate that a similar fragmentation mechanism governs the three processes. In parton models this similarity is a consequence of the presence, in the three cases, of quark jets which fragment and radiate gluons in a unique way. We note, however, important differences between the three processes: different quark flavours are involved and the hadronic systems are of different types (quark-diquark in νp interactions, quark-antiquark in e^+e^- collisions, and quark-quark, quark-gluon, gluon-gluon, etc., in pp collisions).

6.2 Transverse fragmentation

The presence of a collimated jet structure implies that jet fragments are produced with limited transverse momenta $\vec{q}_i$ with respect to the jet axis. The detector aperture, which is much larger in polar angle than in azimuth, permits a relatively unbiased measurement of $q_{i\parallel}$ (that component of $\vec{q}_i$ parallel to the plane of the beams).

Distributions in $q_{i\parallel}$ have been evaluated for charged and neutral fragments of opposite-side jets; they are well represented by Gaussian distributions (fig. 9) which do not significantly depend upon P_{Tjet} (table 1).

Assuming exact isotropy with respect to the jet axis (as recently noted by the CERN-Columbia-Oxford-Rockefeller (CCOR) Collaboration [8]), $\langle q_i \rangle$ and $\sqrt{\langle q_i^2 \rangle}$ can be inferred from the $q_{i\parallel}$ distributions. For both charged and neutral fragments we find

$$\begin{aligned}\langle q_i \rangle &\approx 0.55 \pm 0.05 \text{ GeV/c} \\ \sqrt{\langle q_i^2 \rangle} &\approx 0.62 \pm 0.06 \text{ GeV/c} .\end{aligned}$$

These results are compared in fig. 10 with e^+e^- [26,28] and νp [29] data for which much lower values of $\langle q_i \rangle$ are obtained when low x_i hadrons are included ("sea-gull" effect). For large x_i hadrons, however, our data are in good agreement with neutrino results, while e^+e^- data remain at a lower level. We stress that, in addition to their flavour content, the jets of the three processes may differ in several respects; for example, in the νp case, the jet axis is obtained globally from the quark and diquark jets, and neutral particles are ignored. Under such conditions it is still unclear whether the data show the increase of $\langle q_i \rangle$ with $\sqrt{s^{ee}}$ which results from gluon bremsstrahlung corrections in QCD models.

6.3 Longitudinal fragmentation

We now consider trigger-side jets: owing to their better containment they are well suited to the study of the longitudinal fragmentation. For this purpose we rewrite eq. (1) as

$$\vec{p}_i = x_i^0 \vec{p}_{\text{jet}}^0 + \vec{q}_i^0 ; \quad \vec{q}_i^0 \cdot \vec{p}_{\text{jet}}^0 = 0 , \quad (2)$$

where $\vec{p}_{\text{jet}}^0$ is the total momentum of the π^0 and η fragments having $p_{Ti} > 0.8 \text{ GeV/c}$. We evaluate the x_i^0 distributions of charged particles for different intervals of $p_{T\text{jet}}^0$. To do this the algorithm described in Section 4 has been modified to include ρ -meson production, which has significant effects in the trigger-side jet [19]. The shape of the x_i^0 distributions (fig. 11) is measured to be independent of $p_{T\text{jet}}^0$ and is well described by a form $dn/dx_i^0 \propto \exp(-x_i^0/\alpha)/x_i^0$, with $\alpha = 0.13 \pm 0.01$.

This distribution depends upon both the fragmentation mechanism and the momentum spectrum of the parent jet; the effect of the latter is to depress the charged

particle population at large x_1^0 , resulting in a steeper fall than would be observed in an unbiased jet. We have unfolded the contribution of the parent jet momentum spectrum to obtain the x-distribution of charged particles in an unbiased jet, assuming that neutral and charged fragments are not correlated. The result is shown in fig. 12 where comparison is made with e^+e^- [26] and νp [27] data.

For this comparison we use the variable $x^{ee} = x_i (P_{jet}/E_{jet})$, where P_{jet} and E_{jet} are evaluated in the rest frame of the two-jet system and include soft fragment corrections.

Once more, and despite the different flavour distributions expected in the three processes, a remarkable agreement is obtained.

This result suggests that there is little correlation between the π^0 and $\pi^\pm$ fragments of a jet (other than $\rho^\pm$ production, which has been taken into account); the effect of such a correlation would be enhanced by the trigger bias.

7. CHARGE CORRELATIONS

Jet fragments of positive charge are found to exceed those of negative charge. Such an excess, increasing with transverse momentum, has been previously observed in many experiments for inclusively produced pions. We evaluate the ratio R between the densities of positively and negatively charged jet fragments in a given p_T range. This evaluation is performed directly on the raw data, since the detector acceptance is known to be charge-independent. The dependence of R on x_1^0 is shown in fig. 13 for trigger jets. For away-side jets, to reduce the dependence of the evaluation of x_i on acceptance, we refer it to the transverse momentum of the trigger jet, and discard jets having less than 3 GeV/c visible transverse momentum. The result is compared in fig. 14 with data of the Chicago-Princeton Collaboration [30] on inclusive pions. For both trigger jets and opposite-side jets, R increases with the momentum fraction in a way similar to that for inclusive pion production.

We now consider charge correlations among the jet fragments having more than 0.8 GeV/c transverse momentum; if there were no correlation, we should expect the populations of the charge combinations $(++)$, $(\pm\mp)$, and $(--)$ to be in the proportion

$R^2:2R:1$. The ratio $r = (\pm\mp)/[2\sqrt{(++)(--)}]$ is therefore a measure of the correlation between charges of opposite signs. We evaluate r for three different configurations:

- a) for the pair of leading charged fragments in the trigger jet, $r = 1.52 \pm 0.05$;
- b) for the pair of leading charged fragments in the opposite-side jet, $r = 1.60 \pm 0.03$;
- c) for the pair of leading charged fragments in each jet, $r = 1.00 \pm 0.03$.

While a similar correlation is observed within each jet, favouring neutral pairs over doubly-charged pairs, no correlation is found between the leading charged fragments of the trigger-side and opposite-side jets. These results are in qualitative agreement with the expectations of quark-parton models, where the flavours of the colliding quarks are uncorrelated but where fragmentation is assumed to proceed via a sequence of quark lines: it is not possible to produce a pair of charged hadrons having the same charge in two successive steps of the fragmentation chain.

We note that the value of r measured within each jet is similar to that measured for low transverse momentum products of pp collisions [31].

8. CORRELATIONS BETWEEN THE TWO JETS

In this section we evaluate the correlation between the total momenta $\vec{P}_1$ and $\vec{P}_2$ of the two jets.

In the naive parton model, the jets are the fragments of two colliding partons with incident momenta $\vec{k}_1$ and $\vec{k}_2$, and the correlation takes the very simple form

$$\vec{P}_1 + \vec{P}_2 = \vec{k}_1 + \vec{k}_2 . \quad (3)$$

Projecting $\vec{k}_1$ and $\vec{k}_2$ on the incident proton momenta $\vec{P}_0$ and $-\vec{P}_0$,

$$\begin{aligned} \vec{k}_1 &= x_1 \vec{P}_0 + \vec{k}_{T1} \\ \vec{k}_2 &= -x_2 \vec{P}_0 + \vec{k}_{T2} , \end{aligned}$$

we rewrite (3) as

$$\begin{aligned} P_{L_1} + P_{L_2} &= (x_1 - x_2)P_0 \\ \vec{P}_{T_1} + \vec{P}_{T_2} &= \vec{k}_{T_1} + \vec{k}_{T_2} \end{aligned} \quad (4)$$

This illustrates the relation between the longitudinal correlation and the structure function on the one hand, and the transverse correlation and the parton Fermi motion on the other. These general features result from purely kinematic considerations and remain valid in more realistic parton models.

We first evaluate the longitudinal correlation between the two jets. To ensure a good containment of the jets in the spectrometers, we consider events where the trigger jet and the away-side jet have visible transverse momenta larger than 5 GeV/c and 3 GeV/c, respectively. We introduce the pseudo-rapidities $\eta_{1,2} = -\ln \tan(\theta_{1,2}/2)$, where θ_1 and θ_2 are the polar angles of the jet momenta.

We observe no significant deviation between the event distribution in the (η_1, η_2) plane, $d^2N/d\eta_1 d\eta_2$, and its uncorrelated analogue $(1/N) (dN/d\eta_1) (dN/d\eta_2)$. This is illustrated in fig. 15 where the ratio of these quantities, averaged over $\eta_1 \pm \eta_2$, is displayed versus $|\eta_1 \mp \eta_2|$. We note, however, a small dip near $\eta_1 = \eta_2$ which can be enhanced by requiring $P_{T_1} + P_{T_2} > 12$ GeV/c, thus indicating a small but significant preference for the "back-to-back" configuration ($\eta_1 + \eta_2 = 0$). The prominent result of this study is nevertheless the weakness of the correlation; the limited aperture of the detector does not permit an evaluation of the separate contributions from the structure functions and from the parton-parton scattering amplitudes used in parton models.

We now perform two independent evaluations of the transverse correlation.

The first one uses the same events as above, for which a good jet containment is achieved by requiring

$$\begin{aligned} P_{T_1} &> 5 \text{ GeV/c} \\ P_{T_2} &> 3 \text{ GeV/c} \\ P_{T_1} + P_{T_2} &> 12 \text{ GeV/c} . \end{aligned}$$

The azimuthal correlation function

$$R = \frac{N d^2 N / [d(\tan \phi_1) d(\tan \phi_2)]}{[dN/d(\tan \phi_1)] [dN/d(\tan \phi_2)]},$$

where ϕ_1 and ϕ_2 are the azimuths of the jet momenta, is shown in fig. 16 versus $|\tan \phi_1 - \tan \phi_2|$. Despite the narrow acceptance of the detector, a strong positive correlation is observed, in qualitative agreement with our previous observation of an approximate jet coplanarity with the incident protons. Using Monte Carlo calculations where $P_{out} = P_{T_2} (\tan \phi_1 - \tan \phi_2)$ is generated with a Gaussian distribution, we find that a value

$$\langle P_{out} \rangle = 1.3 \pm 0.3 \text{ GeV/c}$$

is required to reproduce the data.

This result is in agreement with ISR data [8,9] obtained by two other groups. Their approach differs from that mentioned above because the larger azimuthal acceptance of their detectors allows them to consider individual jet fragments. For a single-particle trigger with transverse momentum $\vec{p}_{T_1}$ and a secondary in the opposite azimuthal hemisphere with transverse momentum $\vec{p}_{T_2}$, they define

$$x_e = \frac{\vec{p}_{T_2} \cdot \vec{p}_{T_1}}{|\vec{p}_{T_1}|^2}$$

$$p_{out}(x_e) = |\vec{p}_{T_2} + x_e \vec{p}_{T_1}|.$$

The relation between P_{out} and the above quantities is simply

$$\langle P_{out} \rangle = \lim_{x_e \rightarrow 1} \langle p_{out}(x_e) \rangle,$$

yielding values of the order of 1.2 GeV/c.

Another independent evaluation of the transverse correlation uses data collected with a different trigger: an energy deposition above threshold is required in each spectrometer lead-glass array in coincidence. This results in events where both jets are well contained in the detector acceptance but are distorted by the trigger bias effect. Lower threshold values than for single-arm triggers, of typically 3 GeV/c, are used.

Using identical fiducial volume cuts and threshold conditions in both spectrometers, we calculate for each event the total transverse momenta $\vec{P}_{T_1}$ and $\vec{P}_{T_2}$ of the accepted jet fragments. We evaluate the asymmetry

$$\alpha = \frac{P_{TH_1} + P_{TH_2}}{|P_{TH_1} - P_{TH_2}|} = \frac{|P_{TH_1}| - |P_{TH_2}|}{|P_{TH_1}| + |P_{TH_2}|},$$

where $P_{TH_{1,2}}$ is the horizontal projection of $\vec{P}_{T_{1,2}}$. We select the region

$$8 \text{ GeV/c} < |P_{TH_1} + P_{TH_2}| < 12 \text{ GeV/c}$$

for which a wide α range (-0.25 to +0.25) is spanned with uniform acceptance. After aperture and resolution corrections, the data are well described by a form

$$\frac{dN}{d(P_{TH_1} + P_{TH_2})} \propto \exp \left[- \frac{(P_{TH_1} + P_{TH_2})^2}{2\sigma_{TH}^2} \right],$$

with $\sigma_{TH} = 1.0 \pm 0.1 \text{ GeV/c}$ (fig. 17).

The results obtained for $\langle P_{out} \rangle$ and σ_{TH} can be related to the k_T distribution if we assume that $\vec{P}_{T_1} + \vec{P}_{T_2}$ is the sum of two uncorrelated momenta, $\vec{k}_{T_1}$ and $\vec{k}_{T_2}$, each having a uniform azimuthal distribution. Taking a k_T distribution of the form

$$\frac{dN}{dk_T} \propto k_T \exp \left(-k_T^2 / 2\Delta k_T^2 \right),$$

we find

$$\langle k_T \rangle \approx 1.1 \langle P_{out} \rangle \approx 0.86 \sigma_{TH},$$

namely

$$\langle k_T \rangle \approx 1.4 \pm 0.3 \text{ GeV/c}$$

from the P_{out} measurement

and

$$\langle k_T \rangle \approx 0.9 \pm 0.1 \text{ GeV/c}$$

from the σ_{TH} measurement.

The difference between these estimates may result from the crudeness of our assumptions or from the different jet configurations (two "biased" jets below 12 GeV/c in one case, one "biased" and one "unbiased" jet above 12 GeV/c in the other).

These results can be compared with Drell-Yan data collected at the ISR by the CCOR Collaboration [32]. They have measured the average transverse momentum of the lepton pair, $\langle P_{\ell^+\ell^-} \rangle = 1.65 \pm 0.20$ GeV/c. Assuming $\langle P_{\ell^+\ell^-} \rangle \approx \sqrt{2} \langle k_T \rangle$, $\langle k_T \rangle = 1.17 \pm 0.14$ GeV/c.

Despite the crudeness of these estimates they all point to similar $\langle k_T \rangle$ values, on the average 1.1 ± 0.2 GeV/c, for a c.m. energy $\sqrt{s} \approx 60$ GeV (see fig. 18).

9. SUMMARY AND CONCLUSIONS

We have reported on an experiment performed at the CERN ISR and using large lead-glass arrays to trigger on very high transverse momentum π^0 's. Despite the limited aperture of the detector, the very high transverse momentum range explored in the experiment (higher than in earlier measurements) has allowed us to see the coplanar two-jet structure of the final states. Owing to the ability of the apparatus to detect and momentum analyse both π^0 's and charged particles, detailed information has been obtained on the properties of this two-jet structure. In most of the analysis, to select particles having jet-like correlations, we have considered collision products having more than 800 MeV/c transverse momentum.

A feature specific to the experiment is the enhancement on the trigger side of jet configurations where a large fraction of the jet momentum is shared by π^0 and η mesons. For this reason a different treatment has often been applied to particles on the trigger side and particles on the opposite side in the course of the analysis.

We summarize the main conclusions of the study:

- The production of a large transverse momentum particle is associated with an excess of other large transverse momentum particles near the "beam-trigger" plane, but has little influence on the event structure far from this plane. The excess of large transverse momentum particles near the "beam-trigger" plane is shared between two collimated jets (Section 4).
- The internal structure of each jet (multiplicity, transverse fragmentation, and longitudinal fragmentation) is very similar to that observed in e^+e^- and

vp collisions. Differences are, however, observed with the transverse fragmentation of e^+e^- jets, and it is unclear whether the data show the increase of $\langle q^2 \rangle$ with P_{Tjet} expected in QCD models (Section 6).

- Charge correlations favouring neutral pairs over doubly-charged pairs are measured within each jet, of a size similar to those between the low transverse momentum products of pp collisions. But we find no correlation between the charges of the leading charged particles in each of the two jets (Section 7). These results are in qualitative agreement with the expectations of most parton models producing two quark jets.
- The correlation between the polar angles of the two jets is very weak, with a slight preference for the back-to-back configuration.

Azimuthal correlation and transverse momentum balance between the two jets have been analysed in the parton picture in terms of the Fermi motion of the incident partons. The data, together with Drell-Yan production data, point to a mean k_T value of the order of 1.1 ± 0.2 GeV/c at $\sqrt{s} \approx 60$ GeV (Section 8).

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Table 1

P_{Tjet} (GeV/c)	r.m.s. ($q_{i }$) (GeV/c)	
	Neutral fragments	Charged fragments
3 to 4	0.44 ± 0.05	0.44 ± 0.04
4 to 6	0.44 ± 0.05	0.42 ± 0.04
above 6	0.43 ± 0.05	0.49 ± 0.04

Figure captions

- Fig. 1 : A cross-section of the apparatus showing its main components: drift chambers (DC), magnets (M), lead-glass arrays (LG), E hodoscopes (E), F hodoscopes (F), proportional chambers (PC), iron converters (Fe C), Čerenkov counters (Č), and A hodoscopes (A).
- Fig. 2 : Exploded view of one of the spectrometers.
- Fig. 3 : An event typical of those where a large fraction of the trigger jet transverse momentum is balanced on the away side. Jet fragments are indicated with heavy lines, soft secondaries with thin lines, charged particles with full lines, and neutrals with dashed lines. The charges and momenta of the three particles on the trigger side and of the four particles on the away side are indicated in the inset.
- Fig. 4 : Ratio ρ_{P_T} of normalized p_T distributions in large P_T triggers to those in minimum bias events. Three different configurations with respect to the large P_T trigger are considered, with azimuthal separations $\Delta\phi = 0^\circ, 90^\circ$, and 180° .
- Fig. 5 : Ratio ρ_N of normalized multiplicity distributions in large P_T triggers to those in minimum bias events. Three different configurations with respect to the large P_T trigger are considered, with azimuthal separations $\Delta\phi = 0^\circ, 90^\circ$, and 180° .
- Fig. 6 : Pair-correlation functions near the beam-trigger plane:
a) between the trigger and charged particles on the same side;
b) between the trigger and charged particles having $p_T > 800$ MeV/c;
c) between charged particles on the opposite side.
Smooth lines have been drawn through the data for clarity.
- Fig. 7 : Mean multiplicities of the away-side jet, acceptance corrected, for π^0 and η fragments (open circles), charged fragments (open triangles), and all fragments (full dots) as a function of P_{Tjet} . The line is the result of a fit of the form $\langle n_{ch} \rangle = \lambda + \mu \ln P_{Tjet}$ (see text).

Fig. 8 : Charged multiplicity of a pair of hadron jets in three different processes (see text).

Fig. 9 : Distributions of the measured value of $q_{i\parallel}$ for charged fragments (left side) and neutral fragments (right side) of opposite-side jets having $P_{Tjet} > 3$ GeV/c. The lines are the results of Monte Carlo calculations using:

- a) r.m.s. ($q_{i\parallel}$) = 0.30 GeV/c;
- b) r.m.s. ($q_{i\parallel}$) = 0.45 GeV/c;
- c) r.m.s. ($q_{i\parallel}$) = 0.60 GeV/c.

Fig. 10 : Fragmentation transverse to the jet axis in the present data (full circles) is compared to e^+e^- data (crosses) and νp data (triangles). The full triangles are for high-x neutrino data (see text).

Fig. 11 : Normalized x_i^0 distributions for three intervals of P_{Tjet}^0 :

- a) $5 < P_{Tjet}^0 < 6$ GeV/c;
- b) $6 < P_{Tjet}^0 < 8$ GeV/c;
- c) $P_{Tjet}^0 > 8$ GeV/c.

The lines are the result of a common exponential fit $dn/dx_i^0 \propto \exp(-x_i^0/\alpha)/x_i^0$ with $\alpha = 0.13$.

Fig. 12 : Longitudinal jet fragmentation in three different processes: e^+e^- collisions (full line), νp interactions (triangles), and the present data (circles). In each case the distribution is normalized to unity in the interval $0.2 \leq x^{ee} \leq 0.8$.

Fig. 13 : Ratio of positively to negatively charged fragments of the trigger jet as a function of their momentum fraction x_i^0 .

Fig. 14 : Ratio of positively to negatively charged fragments of opposite-side jets having more than 3 GeV/c visible transverse momentum as a function of their momentum fraction x_i referred to the trigger jet (see text). Inclusive data on single-pion production [30] are shown for comparison.

Fig. 15 : Correlation in pseudo-rapidity between trigger jets having more than 5 GeV/c transverse momentum and opposite-side jets having more than 3 GeV/c visible transverse momentum. In (b) and (d) it is required, in addition, that the sum of the visible transverse momenta of the two jets exceed 12 GeV/c. In (a) and (b) the data are averaged over $|\eta_1 + \eta_2|$ and displayed versus $|\eta_1 - \eta_2|$. In (c) and (d) they are averaged over $|\eta_1 - \eta_2|$ and displayed versus $|\eta_1 + \eta_2|$.

Fig. 16 : Azimuthal correlation function between two jets having transverse momenta, the sum of which exceeds 12 GeV/c. The data are compared to three Monte Carlo calculations having:

- a) $\langle P_{\text{out}} \rangle = 0$;
- b) $\langle P_{\text{out}} \rangle = 0.65 \text{ GeV/c}$;
- c) $\langle P_{\text{out}} \rangle = 1.3 \text{ GeV/c}$.

Fig. 17 : Distribution of the asymmetry α between the horizontal projections p_{TH1} and p_{TH2} of the jet momenta (see text). The region selected is shown in the inset. The histogram is the result of a calculation using $\sigma_{TH} = 1 \text{ GeV/c}$.

Fig. 18 : Four independent estimates of the Fermi motion of incident partons at $\sqrt{s} \approx 60 \text{ GeV}$:

- a) from extrapolation to $x_e \rightarrow 1$ of P_{out} data [8,9] at $P_T > 7 \text{ GeV/c}$;
- b) from the azimuthal correlation between the two jets in the present experiment (see text);
- c) from the transverse momentum balance of two trigger jets in the present experiment (see text);
- d) from Drell-Yan data measured by the CCOR Collaboration [32].

The cross-hatched region corresponds to $\langle k_T \rangle = 1.1 \pm 0.2 \text{ GeV/c}$.

Fig. 1

Fig. 2

S1	0	5.46 GeV/c
S2	+	2.26 GeV/c
S3	-	0.71 GeV/c
A1	+	1.35 GeV/c
A2	-	2.12 GeV/c
A3	0	2.86 GeV/c
A4	0	0.68 GeV/c

RUN 1947
EVENT 11717

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 12

Fig. 13

Fig. 14

Fig. 15

Fig. 16

Fig. 17

Fig. 18