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**JET MEASURES AND HADRONIC
EVENT SHAPES AT THE CERN $\bar{p}p$ COLLIDER**

The UA2 Collaboration

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ABSTRACT

We analyze the energy density distribution in hadronic final states as a function of their total transverse energy measured in the segmented central calorimeter of the UA2 detector. The energy dependence of collective shape variables is investigated.

The data, collected at the CERN $\bar{p}p$ Collider at $\sqrt{s} = 630$ GeV, exhibit strong variations in all these variables over the transverse energy range between 15 and 210 GeV, corresponding to substantial modifications in the structure of multihadronic final states. The evolution of the energy density distribution and of the collective shape variables shows a clear transition between two extreme dynamical regimes, respectively dominated by p_T -limited phase space and by collimated two-jet configurations.

A study of the relative populations of two- and three-jet systems reveals two different sources of configurations having three distinct lobes in the pattern of the energy-flow. A first component, steeply falling with energy, receives substantial contributions from soft parton collisions at lower transverse energies. Above 60 GeV a new hard component emerges, characterized by an approximately constant rate with respect to the dominant two-jet structures.

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1. INTRODUCTION

At the CERN antiproton-proton Collider the basic features of strong interactions at large transverse momenta can be simply understood in terms of hard parton scattering, as demonstrated by the observation of high- p_T jets [1] dominating the event structure at large transverse energy E_T . However, the structure of the final states receives significant contributions from other processes such as the radiation of soft QCD quanta off the initial and final partons in the hard scattering process, or interactions between the spectator partons. Detailed analyses of inclusive and multijet production data by the UA2 [2-7] and UA1 [8-14] Collaborations provide increasing evidence for this picture of parton configurations, giving further support to QCD as the fundamental theory of strong interactions among hadronic constituents.

Perturbative QCD, however, is restricted to the description of a few partons within a limited space-time domain, and only the hard component of the final state, the jet structure at the hadron level, can be used to derive information about the fundamental interactions at the constituent level. Yet, it has been observed at the Collider [2-15] that the transverse energy distribution of particles produced in association with the hard jet structure is a major contribution to the final state for which we have no satisfactory model. In particular minimum bias events, which have a smaller average transverse energy, do not provide an accurate description of these associated hadrons. In practice, comparing experimental data with perturbative QCD predictions usually requires a separation of the observed final state into a set of large- p_T jets which are identified with the outgoing partons and a set of softer particles assumed to be decoupled from the short distance collision products. This separation is somewhat arbitrary, in particular at lower energies where jet production is far from being dominant. In fact, from the transition region [15] between soft and hard regimes, where different production mechanisms are in competition [16,17], through the region dominated by soft configurations [18-20], which arise from collective constituent interactions, the unambiguous definition of hadron jets becomes increasingly difficult.

In this context, global measures of jettiness and of energy density distribution over the full accessible phase space provide complementary information with respect to more conventional analyses of hard parton collisions. The opportunity of extending this method over the widest possible energy range represents a most natural and unbiased approach to a comprehensive description of the entire hadronic final state.

The present investigation makes no attempt to separate different contributions to the final state by selecting specific configurations, rather it uses the whole energy flow of the observed event for studying the geometrical structure of multiparticle and multijet final states in momentum space. The aim of this work is to analyse the dependence of several quantities related to the structure of the energy density distribution on the total transverse energy of the event. We gain in this way further insight into the transition [15,16] from events characterized by longitudinal phase-space to the onset of two-jet dominance and the emergence of multijet configurations.

All steps of the present analysis were also performed on sets of Monte Carlo events generated from different models in the appropriate energy domains, in order to control instrumental effects and to compare model predictions with data.

The UA2 detector elements relevant to the present analysis and the data taking procedure are briefly described in Sect. 2. The experimental method and the procedures of analysis, including Monte Carlo simulations, are reported in Sect. 3. The main results are discussed and compared to theoretical models in Sect. 4, with subsection 4.3 being devoted to a specific study of three-jet production. Finally, our conclusions are given in Sect. 5.

2. APPARATUS AND DATA TAKING

The results presented in this paper are based on inclusive energy measurements in the high granularity central calorimeter [21] of the UA2 apparatus, which detects electromagnetic and hadronic showers in the pseudo-rapidity region $-1 \leq \eta \leq +1$ over the full azimuthal range. The calorimeter is segmented in 240 cells, each covering 15° in ϕ and 10° in θ and built in a tower structure pointing to the centre of the interaction region. Each cell is segmented longitudinally into a 17 radiation lengths thick electromagnetic compartment (lead-scintillator), followed by two hadronic compartments (iron-scintillator) of two absorption lengths each.

The response of the calorimeter to electromagnetic and hadronic showers has been studied using electron, muon and hadron beams from 1 to 70 GeV. Electromagnetic showers are measured with an energy resolution of $\sigma_E/E = 0.14/\sqrt{E}$ (E in GeV), whereas the energy resolution for single pions varies from 32% at 1 GeV to 11% at 70 GeV, approximately proportional to $E^{-1/4}$. The energy resolution for hadron jets is estimated from a Monte Carlo simulation [22] and test-beam data to be 12% at 40 GeV and 9% at 100 GeV, in agreement with a direct determination from the two-jet p_T imbalance which gives a value of $14 \pm 2.5\%$ for jets of 40 GeV [4].

The systematic uncertainty on the energy calibration for the data discussed here is estimated to be less than $\pm 1.5\%$ for the electromagnetic calorimeter and less than $\pm 6\%$ for the hadronic one. They combine in a global systematic error of less than $\pm 4\%$ on the transverse energy scale. Details of the construction, calibration and performance of the calorimeter are reported in Ref. [21].

The data of the present study were recorded during the 1984 and 1985 CERN $\bar{p}p$ Collider runs. The trigger was obtained from a coincidence between a minimum bias signal [23], ensuring the occurrence of a non-diffractive $\bar{p}p$ interaction, and the requirement that the total transverse energy measured in the 240 calorimeter cells exceeds a given threshold (usually 60 GeV). Lower threshold data, including minimum bias data at zero threshold, were collected for a small fraction of the running time. The data were obtained at $\sqrt{s} = 630$ GeV and correspond to total integrated luminosities of $5.8 \mu\text{b}^{-1}$ (minimum bias), 1.1 nb^{-1} (25 GeV threshold) and 562 nb^{-1} (60 GeV threshold). Higher software thresholds were applied off-line to ensure full efficiency for all trigger samples near threshold. The resulting large sample of hadronic events, consisting of about 2.1×10^6 triggers, allows the analysis to proceed without statistical limitations.

A small background contamination arising from the interactions of beam halo particles in the UA2 calorimeter is reduced to a negligible level ($< 2\%$ independent of E_T) after rejecting events with wrong timing and characteristic background configurations in their pattern of energy deposition [6].

3. DATA ANALYSIS

3.1 Event selection and energy flow variables.

Multihadron production at the energies of the $S\bar{p}p$ S Collider has been described using a two-component model [15-16]. Small transverse energies are dominated by a soft component with a steep E_T dependence and characterized by a rather uniform sharing of E_T among many particles exhibiting only little clustering. A second component, with a shallower E_T dependence, takes over at higher transverse energies with a rapid evolution into configurations dominated by jet structures.

The granularity and longitudinal segmentation of the UA2 central calorimeter are well suited for a detailed measurement of different energy configurations including the sizeable neutral component and large particle density in jets. Total transverse energy triggers over the full pseudorapidity acceptance ($|\eta| < 1$) allow an unbiased selection of events, with neutral and charged secondaries equally well measured.

Collective shape variables, built from the energy deposited in each calorimeter cell, can be used to classify the geometrical properties and the evolution of the overall energy flow of the event, thus providing an inclusive calorimetric description of the hadronic final states. To this end no explicit clustering algorithm is applied to the data. Rather, the complete information from the high angular segmentation of the calorimeter is exploited by treating each cell energy independently.

At the highest transverse energies, the shape variables already approach their kinematic limits and the values obtained in the present analysis could be affected by systematic effects arising from the angular dimensions of the hadronic showers in the calorimeter. These effects have been investigated using Monte Carlo events and turn out to be negligible when compared to the actual measurements reported in Sect. 4.

For each event we build energy vectors $\vec{E}_i$ pointing from the centre of the detector to the centre of each cell having $E_{T}^{\text{cell}} > 0.5$ GeV. Neglecting masses, the total energy E and total momentum $\vec{P}$ of each event are given by the scalar and vector sum of the cell vectors, respectively : $E = \sum E_i$, $\vec{P} = \sum \vec{E}_i$.

We select an event sample suitable for the present analysis according to three general criteria which reject only about 20 % of the initial sample :

- a. In order to obtain reliable values of the computed shape variables, a lower limit must be set on the number of energy vectors in each event;
- b. in order to minimize distortions arising from the limited rapidity coverage of the detector, bounds must be applied on the longitudinal (P_L) and transverse momentum (P_T) components of the detected hadronic system;
- c. for similar reasons, the direction of maximal energy flow must be within the detector acceptance.

According to these criteria, the selected events must satisfy the following requirements :

$$n_v > 10 \quad (1a)$$

$$|P_L|/E < 0.5 \quad (1b)$$

$$|P_T| < 10 + 0.1 * M \text{ (GeV)} \quad (1c)$$

$$|\eta_T| < 0.76 \quad (1d)$$

where n_v is the number of energy vectors in each event, $M = \sqrt{E^2 - P^2}$ the invariant mass and η_T the pseudorapidity of the thrust axis in the laboratory frame.

In the energy intervals selected for the analysis, the cuts (1a-1d) act uniformly on the different trigger samples, retaining about 78% of the events for the minimum bias data, 88% and 81% of the events for the low threshold and high threshold data respectively. The sensitivity of the results to the selection procedure is discussed in Sect. 3.2.

The events surviving the selection criteria are transformed into the rest frame of the detected hadronic system. The effects of this Lorentz boost on their kinematic structure are negligible, as discussed in Sect. 3.2. The following event shape measures are then evaluated using the calorimetric energy vectors of each event :

- i. the normalized sphericity tensor [24],

$$D_{\alpha\beta} = \Sigma_j E_{j\alpha} E_{j\beta} / \Sigma_j E_j^2 \quad (\alpha, \beta = x, y, z) \quad (2)$$

where $E_{j\alpha}$ are the cartesian components of the j -th energy vector. Diagonalization of $D_{\alpha\beta}$ yields the unit eigenvectors $\hat{e}_i$ and the corresponding normalized eigenvalues

$$Q_i = \Sigma_j (\vec{E}_j \cdot \hat{e}_i)^2 / \Sigma_j E_j^2 ; \quad \Sigma_i Q_i = 1 \quad (3)$$

If these are ordered such that $Q_1 < Q_2 < Q_3$, they measure the flatness (Q_1), the width (Q_2) and the length (Q_3) of the energy ellipsoid of the event. The plane spanned by $\hat{e}_2$ and $\hat{e}_3$ is called the event plane and $\hat{e}_3$ the jet axis.

In terms of the normalized eigenvalues (3), sphericity and aplanarity are given by

$$S = 3/2 (Q_1 + Q_2) = 3/2 (1 - Q_3) \quad (4)$$

$$A = 3/2 Q_1$$

ii. thrust [25-27],

$$T = \max \Sigma_j |\vec{E}_j \cdot \hat{n}_1| / \Sigma_j E_j \quad (5)$$

To determine thrust, the orientation of the unit vector $\hat{n}_1$ is varied in order to maximize the quantity (5). The resultant T is the thrust value, and the corresponding $\hat{n}_1$ is the thrust axis direction, i.e. the direction along which the projected energy flow is maximal. The principal reference frame is defined by $\hat{n}_1$ and by an orthogonal basis ($\hat{n}_2, \hat{n}_3$) in the plane perpendicular to $\hat{n}_1$. After projecting all the energy vectors onto this plane, a further maximization determines the major axis $\hat{n}_2$, with the minor axis given by $\hat{n}_3 = \hat{n}_1 \times \hat{n}_2$;

iii. the Fox-Wolfram moments [28],

$$H_\ell = E^{-2} \Sigma_{ij} E_i E_j P_\ell(\hat{E}_i \cdot \hat{E}_j) \quad (6)$$

computed from normalized bilinear products of cell energies weighted by a Legendre polynomial of the cosine of the angle between each pair of energy vectors. The H_ℓ form a complete set of rotationally invariant shape parameters which do not depend on maximization procedures with respect to a specific direction. For this reason they can be used to classify the topology and the symmetry properties of the energy flow, circumventing the difficulties of spurious jet structures often introduced by the combined ordering and minimization procedures [29] required for other shape variables computed in a privileged frame.

The Fox-Wolfram moments reflect the structure of the Legendre polynomials, hence moments of even order are most suitable to display symmetry properties of the events, whereas moments of odd order identify asymmetries in the event energy-flow. In particular, all moments with $\ell \geq 2$ vanish for spherical configurations, whereas an ideal process leading to two collinear collimated jets gives $H_\ell = 1$ for even ℓ and $H_\ell = 0$ for odd ℓ . For fully symmetric three jets configurations H_2 and H_3 attain the limiting values $1/4$ and $5/8$ respectively;

iv. jet broadness [30], defined as

$$\omega^\pm = \langle E_i \sin^2 \delta_i / \Sigma_j E_j \rangle \quad (7)$$

where the average is taken over all energy vectors with energies E_i and angles δ_i with respect to the thrust axis. The quantities $\omega^\pm$, computed separately in the positive and negative hemispheres of the principal reference frame, can be considered as energy-weighted mean square opening angles for a system of two jets.

3.2 Sensitivity to selection procedures

Before evaluating the distortions induced by the selection procedures and the methods of analysis, we checked the stability of the variables against variations of the cuts (1a-1d). In general all the results, mean values and differential distributions of the quantities (3) to (8), turn out to be almost insensitive to these selection criteria over the entire range of transverse energies explored by this experiment.

The request for a minimal number of energy vectors, condition (1a), is the only cut on which the shape variables display some dependence. This is confined to the lowest transverse energies, and turns out to be a trivial consequence of the correlation between n_T and E_T introduced by the cut on the energy of each calorimeter cell. At $E_T = 15$ GeV the mean values of the shape variables exhibit systematic shifts smaller than 5% for 50% variations in the cut (1a). Above 20 GeV, the results are essentially independent of the cut on n_T . A similar result is obtained when varying the cut on E_T^{cell} by the same fraction.

Variations of the cuts (1b) and (1c) on the longitudinal and transverse motion of the hadronic system by 50% do not appreciably affect the results over the entire E_T range. The quantities (3) to (8) are constant within errors in each E_T bin with mean deviations smaller than 3%; consequently, no appreciable distortion arises from the Lorentz boost.

Similarly, the results do not depend appreciably on the choice of the fiducial region for the thrust direction, condition (1d), throughout the entire interval of transverse energies. As expected, the azimuthal angular distribution of the thrust axis is uniform, whereas the polar angular distribution exhibits different behaviours at low and high transverse energies. For minimum bias data the distribution of the cosine of the polar angle of the thrust axis is uniform. At higher transverse energies, above 100 GeV, the distribution becomes very similar to the polar distribution of two-jet events at large E_T [4].

In conclusion, it is estimated that the cuts and selection criteria applied to the data produce an overall systematic uncertainty on the mean values of less than 4% independent of E_T , with a 7% uncertainty on the first data point at 15 GeV.

3.3 Monte Carlo simulations and measurement accuracy

For the interpretation of the data, we used simulated events, generated by different Monte Carlo programs. The aim was to determine the accuracy of the measured shape variables and to evaluate possible corrections to the data arising from selection criteria, detector acceptance and energy response of the calorimeter. Simulated events are also used to interpret the results in terms of fundamental physical processes.

Up to values of total transverse energy, $E_T < 120$ GeV, soft interactions were generated according to a low- p_T cluster model. To this end a longitudinal phase space program [31] was used, reproducing the main features of minimum bias Collider events [18-20,32].

For hard parton collisions two different event generators were used. The first one was the QCD parton shower model of Ref. [33], which incorporates soft gluon interference in the jet fragmentation. In this model hadronization occurs through a mechanism of preconfinement of colour singlet clusters,

which decay according to a phase-space scheme [34]. The spectator scattering contribution was simulated by superimposing a real minimum bias event onto each generated hard collision. The minimum bias event was scaled [7] by weight factors between 1 and 2 in order to reproduce the measured level of underlying energy in hard jet events [2,15]. The results of this simulation, as well as for the LPS Monte Carlo, are compared with data in the next section.

At transverse energies above 80 GeV, the QCD ISAJET program [22] was used for evaluating instrumental effects, after adjusting some parameters to reproduce the UA2 jet data more closely. With these modifications, the main jet features and the level of associated energy flow outside the jet regions observed in our data [2] are well reproduced.

The same analysis and reconstruction procedures used for the real data were also applied to the Monte Carlo events, once assuming that the particles in the final state are undistorted by detector effects, and a second time after including a complete simulation of the detector. From an event-by-event comparison between the sets of observables obtained from these two cases, we derived the detector response and the measurement accuracies for all variables as a function of E_T and of the variables themselves.

The relative response of the detector and of the analysis chain for a given variable is obtained as the ratio of the distributions produced at particle and at detector level. As a function of E_T , this function is everywhere uniform and close to unity for all variables considered. Under the simplifying assumption that the transition region can be modelled as a linear combination of the two extreme dynamical behaviours [15], the mean values of all the variables are measured to typically $\pm 5\%$ over the entire range of transverse energies between 15 GeV and 210 GeV spanned by the available hadronic data.

Similarly, in both energy regions of the MC data, the differential distributions in the shape variables display a uniform response over essentially their full range of variation. Local deviations from uniformity larger than 10% only occur on tails of the distributions containing always less than 2% of the data.

4. RESULTS

4.1 Energy dependence of event shapes

The patterns of energy-flow and jet measures from this experiment cover the interval of transverse energies from 15 to 210 GeV. The experimental values of the shape variables, as well as the specific coordinate systems to which they refer, were obtained from the whole set of energy vectors of each event, as described in Sect. 3.1. Given the results on the reconstruction accuracies discussed in the previous section, no corrections were applied to the data.

Figures 1(a) through 1(c) show the mean values of sphericity (S), thrust complement ($1-T$) and aplanarity (A) as a function of total transverse energy E_T . They start at low E_T with large values, typical of almost spherical configurations, and reach limiting values characteristic of collimated two-jet structures at higher E_T . A clear transition between these widely different regimes takes place between 40 and 90 GeV in all variables, with little energy dependence left at both smaller and larger energies. It should be noted that the present results apply to the actual experimental configuration of the UA2 detector at $\sqrt{s} = 630$ GeV. The energy region in which the transition between soft and hard regimes takes place is expected to depend on the detector acceptance, increasing approximately in proportion with the rapidity interval covered by the apparatus [16].

The strong energy dependence of the distributions, with a drop by almost an order of magnitude for S and A, clearly reflects the onset of final states dominated by two-jet configurations. In the E_T range accessible at the Collider, all variables reach values which saturate the predictions of the QCD jet model [33]. Above approximately 90 GeV, experimental data display only a small energy dependence and fall within the band of QCD simulations. In contrast, the predictions of the low- p_T cluster model [31] seem to reproduce the experimental data only at the lowest transverse energies and deviate monotonically from the data as the energy increases. Across the transition region, these predictions approach the asymptotic values which each variable attains when all the cells of the calorimeter are given the same energy deposition. The shape of the QCD simulation in the same range of transverse energies shows that only a limited amount of the E_T dependence can be attributed to the QCD component. The complex behaviour of the data in the transition region cannot be described by any one of the two types of dynamical models, but seems to require a mixture of mechanisms having different energy dependence.

The correlation between sphericity and aplanarity is shown in Fig. 2(a) and (b), for the energy regions $E_T < 25$ GeV and $E_T > 160$ GeV respectively. In agreement with the previous picture, the rather uniform density distribution observed at low E_T develops a strong correlation between S and A with increasing energy. From Fig. 2(b) it is evident that the event population at the highest energies is almost completely planar, even on the tail of the sphericity distribution.

The first two Fox-Wolfram moments and the energy-weighted angular openings of the forward and backward jet hemispheres are shown in Fig. 3(a) through 3(c). The E_T dependence of H_2 and of the quantities $\omega^\pm$ display a behaviour very similar to that of the variables of Fig. 1. In particular, the transition to final states dominated by collimated jet structures turns out to be independent and almost identical in the two hemispheres of the principal reference frame, with jet openings which shrink with increasing E_T while keeping a constant difference throughout the whole energy interval. Again the comparison between data and MC simulations shows the same features as discussed in Fig. 1.

The third Fox-Wolfram moment H_3 , the first non-trivial odd moment, shows a completely different behaviour. At all energies above the minimum-bias region it has a small and approximately constant value, whereas a rising tail develops towards the lowest E_T bins. These properties will be further discussed in Sect. 4.3.

4.2 Energy flow

For analyzing the pattern of the energy flow [29], all energy vectors are projected onto the event plane spanned by the unit vectors $(\hat{n}_1, \hat{n}_2)$. The orientation of each event in this plane is chosen by requiring that more energy flows in the positive $\hat{n}_2$ direction. After this azimuthal ordering around the thrust axis, the normalized energy flow is plotted as a polar diagram in the thrust-major plane.

Figure 4 shows the evolution of the polar energy flow in the interval $15 < E_T < 210$ GeV, together with the differential sphericity distributions in the same slices of E_T . The radial scale is different in each polar plot, and is given in units of GeV/10° per event. The ratio between the largest and the smallest scales in Fig. 4 is about 35.

The impressive evolution of the multi-lobe pattern with increasing transverse energy is clearly seen, together with a corresponding large shift in the normalized sphericity distributions. This evolution starts with configurations that reflect the almost random direction of the thrust axis, as expected from final states dominated by phase-space configurations, together with the known effects of the ordering procedures. In particular, the width of the main lobe in the lowest E_T interval reflects the angular aperture of the calorimeter. In crossing the transition region, structures typical of back-to-back jets appear, shrinking toward highly collimated configurations as energy increases. At high energies, the dominant two-jet pattern shows a small trace of a third energy lobe, consistent with the behaviour of H_3 .

The energy dependence of the differential sphericity distribution is reflected also in the other shape variables, as shown in Figs. 5 through 8. In all distributions the shift in relative importance between different final state configurations is clearly visible with increasing E_T . The comparison between models calculations and data reflects the relative behaviour of mean values as shown in Fig. 1 and 3. We note that across the transition region it is not possible to reproduce the data with any combination of the two models. At high transverse energies the QCD simulation provides a good description of the differential distributions. The agreement between the QCD Monte Carlo and the H_3 differential distribution is satisfactory even if the calculation [33] does not explicitly include all the contributions to the three hard jets production.

4.3 Three-jet events

As already discussed in Sect. 3.1, the Fox-Wolfram moments represent a convenient means for identifying specific jet topologies, since they classify the structure and the symmetry of the energy flow by using quantities which are independent of specific maximization procedures and invariant under energy rescaling. Using these variables, specific topologies can be selected without relying on fixed angular or energy cuts, which might introduce inefficiencies with substantial dependence on the total transverse energy of the event.

Pure samples of two-jet and three-jet events can be isolated by requiring large values of the moments H_2 and H_3 , as clearly seen from the corresponding polar energy-flow diagrams. In particular, requiring H_2 and H_3 to be substantially larger than their respective mean values selects events having narrow back-to-back two-jet configurations, and symmetric three-jet configurations with no secondary lobes. Consequently, these cuts on dimensionless variables provide a simple approach to investigate the energy dependence of the two populations in a region of phase space containing well-identified topologies.

The data of Fig. 8 reveal that the main peak of the differential H_3 distribution keeps shrinking and moving to smaller values as energy increases. Above 60 GeV the mean value of the distribution remains approximately constant (see Fig. 3), as a consequence of a substantial increase in the tail of the distribution at large values of H_3 . Investigating this behaviour in more detail, Fig. 9 shows the fraction of nearly symmetric three-lobe configurations as a function of E_T for two different cuts on H_3 . In both cases a minimum occurs in the transition region, with an increase at lower energies where fluctuations of the produced clusters are more likely to occur. Indeed, an inspection of the energy flow patterns and of the configurations of individual events in separate regions of the plot reveals that distinct production mechanisms are at play at different energies. Figures 10(a) and 10(b) show the energy flow diagrams for events with $H_3 > 0.22$ in two energy intervals around 20 GeV and 150 GeV respectively. The three-lobe structures selected by the H_3 cut show striking differences, with the low energy data displaying wider angular apertures and more uniform energy sharing among the lobes. For a quantitative interpretation of these differences we define a pseudo-sphericity for each lobe

$$S_i = 3/2 \sum_j p_{j,i}^2 \sin^2 \theta_{j,i} / \sum_j p_{j,i}^2 \quad (i = 1, 2, 3) \quad (8)$$

with j running over all cells of each lobe i . In (8), the momenta p_j are measured in the principal reference frame of the event and the angles $\theta_{j,i}$ are computed with respect to the total vector momentum of each lobe. The normalized distributions of S_1 and S_3 in the two energy regions are compared in Fig. 10(c) and Fig. 10(d). The overall behaviour of the data shown in Fig. 10 indicates that the structures observed in the minimum bias sample originate mostly from angular correlations of particles having broader energy and angular distributions than in high- p_T events.

In contrast to the complex energy dependence of the data sample selected by the H_3 cut, the population of two-lobe events selected by the cut on H_2 increases monotonically with increasing transverse energy. The ratio of event fractions selected by the H_2 and H_3 cuts is shown in Fig. 11 for

$H_2 > 0.7$ and $H_3 > 0.22$, i.e. for “hard” two- and three-jet configurations. Following a drop by two orders of magnitude at lower energies, the ratio becomes almost constant above 60 GeV, showing that in the transition region and above, the energy dependence of the two event configurations becomes essentially identical.

The present data indicate that a phenomenon specific to three-jet configurations takes place in the transition region. The smooth variation of the mean value of H_3 , seen in Fig. 3(b), arises from the superposition of two effects. At intermediate values of E_T a low-energy source of events mimicking three-jet configurations vanishes, and a new component with approximately constant probability with respect to the hard two-jet population takes over.

5. CONCLUSIONS

We have presented a study of the energy flow in hadronic events at the CERN $\bar{p}p$ Collider using a total transverse energy trigger at $\sqrt{s} = 630$ GeV. The behaviour of the overall hadronic final state, measured with the highly segmented central calorimeter of the UA2 detector in the E_T range between 15 and 210 GeV, provides accurate unbiased information on the evolution of jet measures and of the energy flow, in a way insensitive to details of model calculations incorporating phenomenological parametrizations of unknown nonperturbative effects.

The configurations of the events selected for the present analysis have been described by global jet measures in the center of mass of the detected hadronic system. All variables display a marked localized transition between low-energy configurations typical of p_T -limited phase-space configurations and final states dominated by highly collimated and stable two-jet structures. The main features of the event appear to be independently shared by the two hemispheres of the principal reference frame, in which the “narrow” and the “wide” lobes of the energy flow respectively develop. A strong similarity in the evolution of the energy flow in the two hemispheres is observed over the entire interval of transverse energies.

The present analysis shows that substantial modifications of the structure of multihadronic final states occur within the transverse energy region accessible at the Collider. We have selected variables for which the LPS and QCD models give clean separate predictions in the extreme E_T ranges. Below 25 GeV little room seems to be left for configurations other than those predicted by a p_T -limited phase space and cluster model. At transverse energies above typically 100 GeV an almost stable hard scattering regime takes over, with features which are entirely described by jet models based on perturbative QCD calculations. The transition between the two dynamical regimes takes place in a region of E_T , 40 to 90 GeV, which is expected to depend upon the actual experimental conditions, namely $\sqrt{s}$ and the rapidity coverage of the detector. In this region a smooth evolution between the two regimes is observed, in agreement with previous observations [15]. We have shown in Ref. 15 that a linear mixture of events generated from models describing independently the soft and hard regimes and having the global features of the LPS and QCD simulators used here, was able to reproduce the energy dependence of the mean values of some global event parameters. We have checked that this remains approximately valid when we compare the predictions of the same linear mixture of LPS and QCD models to the mean values of shape variables such as S and H_2 . However this result should not be used to claim that events in the transition region are either of the LPS or the QCD type. Evidence against such an interpretation is visible in figures 5 to 7 where the differential distributions of the shape parameters are seen to be incompatible with the predictions of a linear mixture model: in this region events are usually neither of the LPS nor of the QCD type but exhibit intermediate features.

When the topology of the energy flow is classified in terms of the Fox-Wolfram moments, events having their energy concentrated in given numbers of distinctly narrow lobes can be easily selected at all energies. Comparing the relative probability of three-jet and two-jet configurations, two different

sources of three-jet events are observed in the data. A first component, dominating over back-to-back configurations at small transverse energies, is mainly associated with the complex topology of soft parton collisions. This source is steeply falling with increasing transverse energy, and within the transition region it rapidly gives way to a second component, with a totally different energy dependence. Above 60 GeV this second component is approximately constant with energy at a level of about 20% relative to the dominant two-jet configurations.

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FIGURE CAPTIONS

1. Mean values of sphericity (a), 1-thrust (b) and aplanarity (c) as a function of total transverse energy E_T . The solid curve and the dashed band represent the predictions of the LPS model and of the QCD jet model including detector effects, as discussed in the text. The range of values representing the QCD simulations includes the effects of different initial state parton subprocesses [34] and of the entire variation of the weight factors entering the underlying event contribution. The dashed line shows the limiting value that the variables can attain when all the calorimeter cells are given the same energy deposition.
2. Distributions of events as a function of sphericity and aplanarity for the transverse energy regions (a) $E_T < 25$ GeV, (b) $E_T > 160$ GeV.
3. Mean values of the second Fox-Wolfram moment H_2 (a), the third moment H_3 (b), the energy-weighted mean square opening angles $\omega^\pm$ of jets in the positive and negative thrust hemispheres (c) as a function of total transverse energy E_T . The solid curve and the dashed band represent the predictions of the LPS model and of the QCD jet model including detector effects, as discussed in the text. The range of values representing the QCD simulations includes the effects of different initial state parton subprocesses [34] and of the entire variation of the weight factors entering the underlying event contribution. The dashed line shows the limiting value that the variables can attain when all the calorimeter cells are given the same energy deposition.
4. Polar energy-flow diagrams in the thrust-major plane and corresponding normalized sphericity distributions in different intervals of total transverse energy : (a) $E_T < 25$ GeV, (b) $40 < E_T < 60$ GeV, (c) $60 < E_T < 90$ GeV, (d) $E_T > 160$ GeV. The scale of the polar plots is given in $\text{GeV}/10^\circ$ per event. The solid and dashed curves represent the predictions of the LPS and QCD models respectively including detector effects.
5. Normalized thrust distributions in different E_T intervals : (a) $E_T < 25$ GeV, (b) $40 < E_T < 60$ GeV, (c) $60 < E_T < 90$ GeV, (d) $E_T > 160$ GeV. The solid and dashed curves represent the predictions of the LPS and QCD models respectively including detector effects.
6. Normalized aplanarity distributions in different E_T intervals : (a) $E_T < 25$ GeV, (b) $40 < E_T < 60$ GeV, (c) $60 < E_T < 90$ GeV, (d) $E_T > 160$ GeV. The solid and dashed curves represent the predictions of the LPS and QCD models respectively including detector effects.
7. Normalized distributions in the second Fox-Wolfram moment H_2 in different E_T intervals : (a) $E_T < 25$ GeV, (b) $40 < E_T < 60$ GeV, (c) $60 < E_T < 90$ GeV, (d) $E_T > 160$ GeV. The solid and dashed curves represent the predictions of the LPS and QCD models respectively including detector effects.
8. Normalized distributions in the third Fox-Wolfram moment H_3 in different E_T intervals : (a) $E_T < 25$ GeV, (b) $40 < E_T < 60$ GeV, (c) $60 < E_T < 90$ GeV, (d) $E_T > 160$ GeV. The solid and dashed curves represent the predictions of the LPS and QCD models respectively including detector effects.
9. Fraction R_3 of events having $H_3 > 0.22$ and $H_3 > 0.25$ as a function of total transverse energy E_T .
10. (a) Polar energy-flow diagram for events with $H_3 > 0.22$ in the transverse energy interval $15 < E_T < 25$ GeV.

- (b) Same as in (a) for the interval $125 < E_T < 175$ GeV. The radial scale is 12 times that in (a).
 - (c) Normalized distributions in the pseudo-sphericity S_1 (see text) for the first energy lobe of the events in (a) and (b). The curves represent the predictions of the LPS and of the QCD models, including detector effects.
 - (d) Normalized distributions in the pseudo-sphericity S_3 (see text) for the third energy lobe of the events in (a) and (b). The curves represent the predictions of the LPS and of the QCD models, including detector effects.
11. Ratio R_3/R_2 of the fractions of events with strong two- and three-jet signatures as a function of E_T . The events in the R_2 and R_3 samples have been selected by the cuts $H_2 > 0.70$ and $H_3 > 0.22$ respectively.

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