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Analysis of the Highest Transverse Energy Events Seen in the UA1 Detector at the Sp $\bar{p}$ S Collider

UA1 Collaboration, CERN, Geneva, Switzerland.

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Abstract

This is the first full solid angle analysis of large transverse energy events in $p\bar{p}$ collisions at the CERN collider. Events with transverse energies in excess of 200 GeV at $\sqrt{s} = 630$ GeV are studied for any non-standard physics and quantitatively compared with expectations from perturbative QCD Monte Carlo models. A corrected differential cross section is presented. A detailed examination is made of jet profiles, event jet multiplicities and the fraction of the transverse energy carried by the two jets with the highest transverse jet energies. There is good agreement with standard theory for events with transverse energies up to the largest observed values ($\approx \sqrt{s}/2$) and the analysis shows no evidence for any non-QCD mechanism to account for the event characteristics.

1. Introduction

Early studies of large- p_t events in hadron-hadron collisions used a large- p_t single-particle trigger.¹ These studies led to the discovery of anomalously high yields of particles at high p_t and subsequently to the discovery of a four-jet structure of these events with two wide-angle jets resembling the jets previously seen in e^+e^- colliders. However, it was soon realised that the single-particle triggers used in these early experiments introduced a serious trigger bias into the interpretation of the data in terms of a hard subprocess. The first calorimeter-triggered jet experiment was experiment E260 at Fermilab.² The jet and single-particle cross sections were found to have a similar shape but the jet cross section was over two orders of magnitude larger. Subsequent experimental effort was directed towards the construction of detectors of increasing acceptance with much emphasis on calorimeter triggers. The first detector specifically designed to overcome the problem of the trigger bias was the detector of the NA5 collaboration at CERN.³ Although in this experiment a small number of events containing two wide-angle back-to-back jets were seen, the dominant feature of the data was that the large transverse energy was the result of a large number of particles with rather small transverse momenta: no dominant jet structure emerged even at the highest $\sum |E_t|$ attained (~ 18 GeV).⁴ This was confirmed by similar experiments at FNAL.⁵ Subsequent experiments at the CERN ISR⁶ and at the Sp $\bar{p}$ S collider^{7,8} showed that at larger $\sum |E_t|$ most events have a clear two-jet structure. In these studies the coverage in polar angle (or in pseudorapidity) remained restricted and later studies of jet events were again carried out using a localisation requirement in the trigger (jet trigger). Tests of perturbative QCD at the UA1 detector have so far concentrated mainly on studies of the inclusive jet spectrum and on the properties of events with two or three jets.⁹ These studies were carried out using a jet trigger in the calorimeters. As such they are efficient tests of perturbative QCD, but they may exclude other possible phenomena.

In this paper we present results from a complementary approach to the study of hard scattering processes in $p\bar{p}$ collisions in which the trigger bias is minimised by asking that there be a large deposit of transverse energy $\sum |E_t|$ in the calorimeters without a localisation requirement. Unlike any jet trigger, this trigger makes

no demands of the resultant event topologies in that it is insensitive to jet widths and will accept the more isotropic events to be expected from, e.g., multi-parton interactions,¹⁰ very heavy flavours or more exotic processes such as a quark-gluon phase transition, supersymmetric particle production,¹¹ or “centauro” events.¹² In the context of the present paper $\sum |E_t|$ is the summed (scalar) transverse energy in *all* calorimeters of the UA1 detector, i.e. the central calorimeters (*gondolas* and *C*'s) which cover the angular range $\theta \in [25^\circ, 155^\circ]$, the end cap calorimeters (*bouchons* and *F*'s) covering $\theta \in [5^\circ, 25^\circ]$ and $\theta \in [155^\circ, 175^\circ]$, and the forward calorimeters covering $\theta \in [0.2^\circ, 5^\circ]$ and $\theta \in [175^\circ, 179.8^\circ]$. Together these calorimeters¹³ ensure an almost complete coverage of the 4π solid angle around the interaction point with only small geometric losses along the beam pipe and through cracks between calorimeter cells.

In section 2 the experimental data sample is discussed. In section 3 we describe the generation of QCD events using Monte Carlo programs leading to a simulated data sample which is then analysed in the same way as the experimental data. In sections 4-6 the data are compared with the Monte Carlo predictions and in section 7 the conclusions are presented.

2. The Experimental Data Sample

The data sample is from the 1984 run of the Sp $\bar{p}$ S collider at $\sqrt{s} = 630$ GeV which yielded a total integrated luminosity of 261 nb^{-1} on tape based on a pretrigger cross section of 37 mb .¹⁴ The hardware trigger was based on the requirement of a transverse energy $\sum |E_t|^{Cent} > 80 \text{ GeV}$ in the pseudorapidity interval $|\eta| < 1.5$ covered by the UA1 central calorimeters.¹⁾ A software filter, run on reconstructed data, then selected events with $\sum |E_t|^{Cent} > 100 \text{ GeV}$, yielding ≈ 35000 events. In Fig. 1 we show a scatter plot of total energy in the calorimeters (E_{tot}) against the summed scalar transverse energy ($\sum |E_t|$) in the whole event for the data which pass the above cuts. As $\sum |E_t|$ increases the data become dominated by multiple interaction events which give rise to a large total energy that exceeds the available energy $\sqrt{s} = 630 \text{ GeV}$. The present data were taken at luminosity values ranging from 0.6 to $2.7 \times 10^{29} \text{ cm}^{-2} \text{ sec}^{-1}$, with a bunch crossing every 7.6 microseconds. Given that an interaction has occurred in a bunch crossing (for which the probability is a few percent) the probability that a second event occurs rises in proportion to the luminosity and approximately as the square of $\sum |E_t|$. At the present luminosities double interactions become more probable than single interactions for $\sum |E_t| > 200 \text{ GeV}$, as can be seen in Fig. 1. We have verified that the ratio of double interactions to single interactions is proportional to the luminosity, as expected. The bulk of the multiple interactions were rejected with a cut on the total observed energy at 650 GeV . This left a contamination at

¹⁾ In UA1 data taking many triggers are run concurrently. The complete data sample of 681 events passing all software cuts contains four events not satisfying this specific hardware trigger.

Fig. 1. Scatter plot of the total energy (E_{tot}) versus total scalar transverse energy ($\Sigma |E_t|$) for high- $\Sigma |E_t|$ triggered events. (Not all events are shown for the clarity of presentation.)

the 1% level, which was removed using central detector information on the number of fitted tracks to the reconstructed vertices.¹⁵

Figure 2 is a scatter plot of $\Sigma |E_t|^{Cent}$ against the total $\Sigma |E_t|$ after this cut. A cut of 200 GeV in $\Sigma |E_t|$ eliminates bias from the $\Sigma |E_t|^{Cent}$ selection.²⁾ Requiring $\Sigma |E_t| > 200$ GeV yielded a total of 762 events. A sample of about 200 events were scanned on an interactive graphics device in order to develop software cuts to exclude remaining contaminating events from the data and to examine the events with the largest $\Sigma |E_t|$.

The cuts¹⁶ were designed to remove false triggers that had arisen from accidental in-time cosmic ray events and from beam halo and electronic read-out problems. Events that failed these cuts were scanned separately to ensure that no genuine events were removed. A further cut, also verified by scanning, was imposed to remove events where an overestimate of the transverse energy could have

²⁾ A preliminary study of the 1985 data where the initial trigger conditions were more inclusive has shown that the $\Sigma |E_t|^{Cent}$ cut does not exclude any events which have a large $\Sigma |E_t|$ but low $\Sigma |E_t|^{Cent}$.

Fig. 2. Scatter plot of the summed scalar transverse energy in the central region of the UA1 detector ($\sum |E_t|^{Cent}$) versus $\sum |E_t|$ for high- $\sum |E_t|$ triggered events which have $E_{tot} < 650$ GeV. (Not all events are shown for the clarity of presentation.)

occurred through reconstruction problems due to multiple hits in the gondolas. It must be emphasised that the same selection was imposed on the simulated Monte Carlo sample to be discussed in the next section.

One of the selection criteria used is expressed in terms of missing transverse energy E_t^{miss} , which is defined as the magnitude of the vector sum of transverse energy flows as measured in the calorimeters. Previous studies¹⁷ have shown that calorimeter response fluctuations give an r.m.s. spread in E_t^{miss} that can be well parametrised by $\sigma = 0.7\sqrt{\sum |E_t|}$. Events with a missing transverse energy greater than 4σ were scanned. Above 7σ , all triggers were found to be consistent with apparatus malfunction, cosmic ray events or beam halo problems. These events were therefore removed.³⁾ Between 4σ and 7σ the missing energy was found to be dominated by geometric losses in the UA1 apparatus. None of the scanned

³⁾ Note that previous analyses¹⁸ of the *phenomenon* of missing E_t used the opposite approach of rejecting events in which large E_t^{miss} was attributable to geometrical losses. All the remaining events of Ref. 18 were found to have $\sum |E_t|$ well below the threshold for this analysis and no similar events were observed in the high- $\sum |E_t|$ data sample.

events had a missing energy that could be clearly attributed to neutrinos. It will be shown that losses due to geometric cracks are well described by our Monte Carlo simulation so that it was possible to retain these events for analysis.

The final data sample with $\sum |E_t| > 200$ GeV consists of 681 events.

The plots of Fig. 3 show the geometric pattern of the transverse energy deposition for three events in the (η, ϕ) plane, where η is the pseudorapidity and ϕ is the azimuthal angle. These events were chosen to be (a) the event with the highest $\sum |E_t|$ ($\sum |E_t| = 327$ GeV), (b) an event from the middle of the $\sum |E_t|$ range ($\sum |E_t| = 246$ GeV) which shows obvious three-jet structure and (c) a more isotropic event with $\sum |E_t| = 209$ GeV. The topology of these events in relation to the total event sample will be discussed in Sec. 5, however, the prominent feature of most events in this sample is the strong localisation of transverse energy.

Fig. 3. Plots of three high $\sum |E_t|$ events; (a) $\sum |E_t| = 327$ GeV, (b) $\sum |E_t| = 246$ GeV, (c) $\sum |E_t| = 209$ GeV.

In Fig. 4 we present the uncorrected $\sum |E_t|$ spectrum of the present data sample together with three other sets of UA1 data: the high- $\sum |E_t|$ data¹⁹ at $\sqrt{s} = 546$ GeV and the low- $\sum |E_t|$ minimum bias data^{20,21} at $\sqrt{s} = 546$ and 630 GeV. As will be seen in Sec. 4, the effect of corrections for losses is to move the $\sum |E_t|$ scale by 10-15%. The minimum bias data at $\sqrt{s} = 630$ GeV peak at a higher $\sum |E_t|$ than the $\sqrt{s} = 546$ GeV data and remain above them. This is consistent with the trend in the $\sqrt{s}$ dependence of the high- $\sum |E_t|$ data. The combined

$\sum |E_t|$ spectrum spans a range of over nine orders of magnitude in the cross section. Monte Carlo expectations are in accord with these data and, in particular, show the same flattening of the spectrum at high $\sum |E_t|$ where contributions from the spectator system are less important. Nevertheless simulations indicate²² that even in the region of interest to this analysis ($\sum |E_t| > 200$ GeV) some 20-25% of transverse energy is contributed by the spectator fragments.

Fig. 4. The uncorrected $\sum |E_t|$ spectrum of UA1 data from the 1983 run ($\sqrt{s} = 546$ GeV) and from the 1984 run ($\sqrt{s} = 630$ GeV)

3. The Simulated QCD Data Sample

In order to compare the data with current theoretical expectations we have produced simulated data sets using Monte Carlo event generators and have analysed them in the same way as the experimental data. To check for systematic differences two such event generators COJETS²³ and ISAJET²⁴ were used. Both event generators follow the independent jet fragmentation model, with incoherent initial and final state bremsstrahlung and a $2 \rightarrow 2$ body hard collision calculated in the lowest order of perturbative QCD. In the case of COJETS the spectator

system is described by an ansatz which reproduces the UA5 minimum bias multiplicity distributions at $\sqrt{s} = 540$ GeV, whereas in ISAJET a multiple pomeron exchange model has been tuned to give the correct transverse energy density in jet profiles in UA1 data. We have generated several Monte Carlo samples of events with different values of Λ_{QCD} (100, 200 and 500 MeV) and with different numbers of flavours. For the purpose of detailed comparisons with the data we use mainly our largest Monte Carlo event samples of 1861 (1057) events which were generated by program COJETS (ISAJET) with $\Lambda_{QCD} = 200$ MeV and six flavours in the final state, fully simulated and reconstructed with the same programs as the data.

In order to generate simulated data sets with greater statistics than the experimental data it was necessary to generate about four million Monte Carlo events. The controlling variable for Monte Carlo generation is the transverse momentum of the hard collision, p_t^{hard} ; the distribution in p_t^{hard} for the generated events corresponding to COJETS with $\Lambda_{QCD} = 200$ MeV is shown in Fig. 5.

Fig. 5. p_t^{hard} distribution for generated COJETS events (solid line) and for those Monte Carlo events passing the observed $\sum |E_t| > 200$ GeV selection (solid line: COJETS; dashed line: ISAJET).

Some twenty thousand of these generated Monte Carlo events satisfied a (conservative) cut of *generated* $\sum |E_t| > 195$ GeV. These events were fully simulated through the UA1 apparatus. Only Monte Carlo events that satisfied the same criteria as the experimental data after full simulation of the apparatus response were retained, i.e. events with *observed* $\sum |E_t| > 200$ GeV. The distribution in p_t^{hard} for these events is also shown in Fig. 5, demonstrating the falling efficiency at low p_t^{hard} . This forced us to generate events with a cut at $p_t^{hard} = 30$ GeV resulting in an estimated loss of some $3 \pm 1\%$ of events. Also shown in Fig. 5 is the distribution in p_t^{hard} of events passing the $\sum |E_t| > 200$ GeV cut from the ISAJET generation (normalised to the same area): here it can be seen that there is a radically different behaviour at low p_t^{hard} . This is attributable to the different modelling of the spectator system, since ISAJET does not have the large fluctuations of multiplicities as observed e.g. in KNO distributions.

One of the results of this Monte Carlo study is an estimate of the number of events with top quarks expected in the final state. Using a top quark mass of $45 \text{ GeV}/c^2$, it was found that only ~ 1 event with a $t\bar{t}$ quark pair would be expected in the present data sample, essentially because of the 200 GeV cut in $\sum |E_t|$. This event would have properties broadly similar to those of all the other events. Further studies have shown that a top quark mass of $\sim 90 \text{ GeV}/c^2$ gives rise to events with more jets but only at the level of 0.2 events, because of the smaller production cross section. We are therefore sensitive to high masses of heavy flavours only if they are associated with anomalously high production cross sections.

The two major Monte Carlo event samples give broadly consistent results. Any differences between the results obtained with these two programs must be attributable to their different treatment of the spectator system, of the QCD bremsstrahlung and of the jet fragmentation. In addition the COJETS program utilises a normalisation factor $K = 2$ on the cross section of the hard subprocess to account for the contribution of loop diagrams.

Before proceeding with a detailed comparison between simulated and experimental data it is important to check that those features of the data that are most sensitive to the proper simulation of the apparatus are reasonably reproduced. Such a quantity is the missing transverse energy. The comparison of E_t^{miss} for data and Monte Carlo in Fig. 6 clearly indicates satisfactory simulation of the apparatus.

In this and the following figures, except where stated otherwise, the Monte Carlo sample has been normalised to the same total number of events. A solid line represents the result obtained with program COJETS and a dashed line is used for ISAJET results whenever the two differ appreciably.

In Fig. 7 the reconstructed (scalar) E_t spectrum is compared with the Monte Carlo prediction. The agreement is good for both Monte Carlo programs over the entire range of the present data.

Fig. 6. Missing transverse energy in units of σ .

The average transverse energy E_t per event as a function of pseudorapidity η is shown in Fig. 8 and here there are greater divergences from Monte Carlo simulations ⁴⁾: in the Monte Carlo more transverse energy is located centrally. Although there is no normalisation imposed on this histogram, the requirement of $\sum |E_t| > 200$ GeV, coupled with a good reproduction of the differential cross section, means that the average $\sum |E_t|$ deposited per event is the same in the simulation as it is in the data and hence produces an effective normalisation. In this way the discrepancy may be understood as being due to the systematic shortfall of simulated transverse energy beyond $|\eta| > 2$. This corresponds to forward angles of less than 20° and is the area dominated by initial state bremsstrahlung and spectator system effects.

4. Differential Cross Section

In order to obtain the differential cross section $d\sigma/d\sum |E_t|$ it is necessary to

⁴⁾ Note that the *statistical* error on E_t is a convolution of factors involving the location of the energy deposit. In the combined calorimeters of the UA1 detector test beam results indicate an average hadronic resolution of $\sim 0.8/\sqrt{E}$, where E is the hadron energy measured in GeV.

Fig. 7. Spectrum of observed total scalar transverse energy ($\sum |E_t|$).

correct the data for energy losses and resolution smearing and for event losses due to the software filter cuts.

The discussion of the previous sections has shown that the Monte Carlo represents a good approximation to the shape of the differential cross section and that the apparatus response is well simulated. Therefore the Monte Carlo sample (COJETS) was used to correct the data in order to obtain the differential cross section. This correction²⁵ was performed statistically (i.e. *not* event by event) but the net effect is equivalent to an increase of the $\sum |E_t|$ scale of about 12%. The corrected cross section is shown in Fig. 9 and is tabulated in Table 1.

To a good approximation the differential cross section falls one order of magnitude for every 40 GeV in this region of $\sum |E_t|$. The error bars on Fig. 9 are the cumulative statistical errors of the data and of the correction procedure. There is in addition a 2-3% systematic effect in $\sum |E_t|$ losses between the two Monte Carlo programs, but the corrections to the cross section are independent of the value of Λ_{QCD} used. The shaded region on the diagram corresponds to perturbative QCD expectations as calculated with various parameters using the Monte Carlo programs of Refs. 23 and 24. Although the rate of fall-off is the same, the overall

Fig. 8. Transverse energy as a function of pseudorapidity η .

magnitude is too low. The upper edge of the shaded region of the Monte Carlo results corresponds to the calculation using COJETS with six flavours, $\Lambda_{QCD} = 200$ MeV and $K = 2$. The lower edge is ISAJET with the same values for the parameters except $K = 1$. The combined effects of the $\sim 7\%$ UA1 E_t scale uncertainty and other systematic errors is shown with the use of dot-dashed lines and with such a shift the discrepancy between theory and data can be resolved.

5. Event Jet Topology

It has been noted in Sec. 2 that the data are characterised by strong localisation of transverse energy, i.e. hadronic jets. For the purposes of this analysis jets are defined according to the standard UA1 jet-finding algorithm.²⁶ In essence this algorithm sums the four-momenta in a geometric cone of $\Delta R = 1$, where ΔR is the distance between a given energy flow vector E_i and the jet axis in (η, ϕ) space, where the azimuthal angle ϕ is in radians. At low jet energies the correspondence between reconstructed jets and partons is poor. This is true in particular in the case of low-energy parton bremsstrahlung. However, this analysis is insensitive to any arbitrariness in the jet definition since it is used identically on data and Monte Carlo events.

Fig. 9. Differential cross section as a function of total scalar transverse energy compared with Monte Carlo predictions using various parameters (shaded region). The dot-dashed curve shows the extent of combined systematic errors on the data.

Table 1 Corrected cross-sections as a function of $\sum |E_t|$.

$\sum E_t $ interval (GeV)	σ (nb/GeV)
200-220	0.383 ± 0.078
220-230	0.153 ± 0.030
230-240	0.075 ± 0.012
240-255	0.040 ± 0.006
255-265	0.022 ± 0.003
265-270	0.013 ± 0.003
270-275	0.008 ± 0.002
275-280	0.009 ± 0.002
280-295	0.006 ± 0.002
295-310	0.003 ± 0.001
310-325	0.001 ± 0.001

In this section data and Monte Carlo results are compared in detail for some observables which characterise the event jet topology, *viz.* the inclusive jet transverse energy spectrum, the jet multiplicities and the variable H_2 which charac-

terises the degree to which the two jets with the highest transverse energy dominate $\sum |E_t|$.

The spectrum of jet transverse energies (E_t^{jet}) for the high- $\sum |E_t|$ data is shown in Fig. 10. The distribution is totally inclusive in that the analysis imposes no limitation on the fiducial area in (η, ϕ) space for the found jet axes. The same procedure is followed for the equivalent Monte Carlo samples. Both data and Monte Carlo distributions have broad maxima near 70 GeV, as might be expected with the $\sum |E_t|$ threshold cut, and large numbers of low-energy jets from parton bremsstrahlung. The agreement with Monte Carlo is good. It should be noted that the number of Monte Carlo events has been normalised to the data as mentioned before.

Fig. 10. Inclusive jet spectrum for all jets with $E_t^{jet} > 10$ GeV.

In Figs. 11 a,b and c we compare the jet multiplicities in the data and Monte Carlo for events with $E_t^{jet} > 10, 20$ and 30 GeV, respectively. As expected, fewer jets per event are seen at higher threshold values of E_t^{jet} both in the data and in the Monte Carlo. The average multiplicity for jets above 10 GeV in E_t^{jet} is 3.75 ± 0.05 in the data and 3.84 ± 0.03 in the Monte Carlo (for COJETS).

Fig. 11. Fraction of events with given jet multiplicities for different E_t^{jet} cuts: (a) $E_t^{jet} > 10$ GeV, (b) $E_t^{jet} > 20$ GeV, (c) $E_t^{jet} > 30$ GeV.

There is no excess of events with 4, 5 or 6 jets in the data above the Monte Carlo predictions. This fact indicates that there is no significant contribution from multiparton interactions at these transverse energies, in agreement with theoretical expectations.¹⁰ The occurrence of a small number of events with a single jet is an effect of raising the threshold and is not to be confused with UA1 monojet events

in which there is also significant missing transverse energy.¹⁸

Although there are a large number of jets at high $\sum |E_t|$, the decrease of α_s with increasing Q^2 has the consequence that the two jets with the highest values of E_t^{jet} have a steadily bigger proportion of the event $\sum |E_t|$.²⁷ This can be seen by considering the quantity H_2 which is defined by

$$H_2 = (E_t^{jet_1} + E_t^{jet_2}) / \sum |E_t|$$

where $E_t^{jet_1}$ and $E_t^{jet_2}$ refer to the jet with the highest and second-highest E_t^{jet} , respectively. Since the definition of a jet is somewhat arbitrary and certainly analysis dependent, caution should be exercised in comparing this quantity from experiment to experiment. Given the UA1 jet-finding algorithm, H_2 has an effective threshold at $H_2 \approx 0.2$ in our region of $\sum |E_t|$. Other experiments with non-hermetic detectors²⁸ have used a similar quantity without having the complete $\sum |E_t|$ for normalisation and have hence reported larger values of H_2 than those quoted here.

In Fig. 12 the distribution of H_2 is shown for all events. In particular, the values of H_2 for the events shown in Fig. 3 a, b and c are indicated. This allows one to relate the subjective impression of the extent of two-jet dominance to the variable H_2 . Also shown in Fig. 12 are the corresponding Monte Carlo curves. Above $H_2 \approx 0.4$ the agreement is good, especially for COJETS, but below this value one observes an apparent excess of data above the Monte Carlo expectations. Low values of H_2 are strongly correlated with small momentum transfer p_t^{hard} of the hard collision and, as shown in Sec. 3 and in Fig. 5, the COJETS sample has a loss of events arising from the cut-off at 30 GeV. A separate study has indicated that all such events would be reconstructed with $H_2 < 0.4$ and an estimate of this effect is shown in Fig. 12. The 7% $\sum |E_t|$ scale error introduces an uncertainty in the shape of the H_2 distribution (H_2 is dependent on $\sum |E_t|$ as will be shown in Fig. 13). The vertical error bar on the estimated Monte Carlo low- H_2 point allows for this effect. At low H_2 , and hence low p_t^{hard} , a relatively large contribution to $\sum |E_t|$ comes from the spectator system and the ansatz which models this dependence becomes increasingly important. This then explains the relatively large difference between COJETS and ISAJET predictions at low H_2 and also at low p_t^{hard} as discussed in Sec. 3. The shape of the H_2 distributions for both Monte Carlo programs is also dependent on the choice of Λ_{QCD} : the lower part of the distribution becomes more populated as Λ_{QCD} increases.

Events in the region of low H_2 , of which Fig. 3 c is a typical example, have been inspected and found to be genuine. Although they constitute multi-jet events as defined by the UA1 algorithm, there is no visual impression of localisation of energy. The region in question is populated solely by events with $\sum |E_t|$ below 220 GeV. These events follow the general trend of more isotropy towards lower $\sum |E_t|$ which will be shown in Fig. 13. Even assuming that there is a real excess of data over the number of events predicted by the Monte Carlo programs, this is not consistent with any new phenomena resulting in more isotropic events with increasing $\sum |E_t|$. In particular, these events have the same fraction of $\sum |E_t|$ contributed

Fig. 12. Distribution of H_2 for all events with Monte Carlo predictions. The letters a , b and c indicate the positions of the events shown in Fig. 3a, b and c, respectively. The single point for $0.2 \leq H_2 \leq 0.4$ is a COJETS expectation with estimate for known losses (see text).

from charged tracks as the total data sample and hence are not consistent with a “centauro” description.¹²

The variation of the mean H_2 with $\sum |E_t|$ is shown in Fig. 13 and an increase of $\sim 20\%$ over the $\sum |E_t|$ range from 200 to 300 GeV is clear. These data are consistent with previous results¹⁹ at lower $\sum |E_t|$ although the data of Ref. 19 are at the significantly lower centre-of-mass energy of $\sqrt{s} = 546$ GeV. The data are also consistent with Monte Carlo expectations for $\sqrt{s} = 630$ GeV. Studies of Monte Carlo events suggest that the slowly decreasing fractional contribution of the spectator system accounts for an increase of H_2 of less than 5%. This indicates that the rise of H_2 is dominated by perturbative QCD.

6. Jet Profiles

The jet transverse energy profile is defined as the transverse energy per unit of pseudorapidity η deposited either side of the jet axis normalised to the number

Fig. 13. Average H_2 as a function of event E_t .

of jets. Only the transverse energy deposited in the same azimuthal semi-cylinder as the jet axis is counted ($\Delta\phi = \pi$), but otherwise the profile is totally inclusive.

Typical jet profiles for two bands of E_t^{jet} are shown in Figs. 14 *a, b*.⁴⁾ For a given band, the data display a central core (note the logarithmic scale) and flat “wings” which fall off very slowly. The core width narrows with increasing E_t^{jet} from $\Delta\eta \approx 0.3$ at 30 GeV to $\Delta\eta \approx 0.1$ at 110 GeV. Simultaneously, it can be seen that with the present $\Sigma|E_t|$ trigger the level in the wings falls from ≈ 8 to ≈ 4 GeV per unit of pseudorapidity. The simple explanation of this is that the higher E_t^{jet} threshold at fixed $\Sigma|E_t|$ threshold implies less background activity. The comparison with Monte Carlo is good in both intervals of E_t^{jet} shown, although the core of the jets in the data is not so narrow, or high.⁵⁾ Note that there is no overall normalisation imposed in these figures.

The shape of the jets shown suggests a comparison between the relative

⁵⁾ We have shown in a preliminary study that the jet profiles are insensitive to the parameter that controls the cut-off of the perturbative showering in the Monte Carlo and to the $\langle p_t \rangle$ used in jet hadronisation, but that they do depend on the value of Λ_{QCD} chosen. This is the subject of continuing analysis.^{22,29}

Fig. 14. Transverse energy flow per unit of rapidity about jet axis for all jets with (a) $30 < E_t^{jet} < 70$ GeV and (b) $70 < E_t^{jet} < 110$ GeV.

heights of the core and wings by defining a ratio of transverse energies,

$$\langle F_{0.2} \rangle = \frac{\sum_{\Delta R < 0.2} |E_t|}{\sum_{\Delta R < 1.0} |E_t|}$$

The E_t^{jet} dependence of this variable may be seen from Fig. 15, which also includes data from low- $\sum |E_t|$ minimum bias studies and from jet trigger studies.²¹ The increased jet collimation with E_t^{jet} is clear. The value of $\langle F_{0.2} \rangle$ depends strongly

on the event trigger: as has been pointed out, a jet of ~ 40 GeV, say, that is embedded in a high- $\sum |E_t|$ event must have higher background activity (wings) than a similar jet in an event which is triggered on jets and this will depress $\langle F_{0.2} \rangle$ in the high- $\sum |E_t|$ case. As E_t^{jet} increases this argument is no longer true and, as can be seen, $\langle F_{0.2} \rangle$ becomes less dependent on the trigger.

Fig. 15. Average $F_{0.2}$ versus E_t^{jet} for minimum bias data, jet trigger data and high- $\sum |E_t|$ data.

An alternative variable which measures the jet width directly is

$$W^{jet} = \sum_{s.c.} |E_t| \Delta R / \sum_{s.c.} |E_t|$$

where the sum extends over the azimuthal semi-cylinder that contains the jet axis. A plot of W^{jet} against the $\sum |E_t|$ of the event (Fig. 16) is a means of detecting islands of broad jets, which would be a possible signature for super-heavy flavours being created or of supersymmetry,¹¹ or of detecting islands of narrow jets which have also been suggested as a possible signature for supersymmetry.³⁰ In fact Fig. 16a shows a continuous distribution without any islands. The agreement with the Monte Carlo expectation (Fig. 16b) is not as good as that for $\langle F_{0.2} \rangle$ in that the

Fig. 16. W^{jet} for all jets with $E_t^{jet} > 30$ GeV as a function of event $\sum |E_t|$. (a) Data (681 events), (b) COJETS (1861 events). The points show the mean values.

Monte Carlo jets are narrower overall, possibly because of the increased sensitivity of the W^{jet} variable to non-perturbative fragmentation.

In summary, we have used two measures of jet width which, taken together, demonstrate increased jet collimation both with E_t^{jet} and with event $\sum |E_t|$.

7. Conclusions

We have studied events with a transverse energy in excess of 200 GeV seen in $p\bar{p}$ collisions at $\sqrt{s} = 630$ GeV by the UA1 detector. The properties of these events are compared with those of events generated by the QCD-based Monte Carlo programs COJETS and ISAJET.

The prediction for the differential cross section has the correct shape but the magnitude is too low. This difference is within the systematic error on the experimental energy scale.

Within the theoretical uncertainties implicit in the use of these models there is good agreement between the properties of the data and Monte Carlo events. At these high transverse energies the perturbative aspects of QCD dominate the event properties. This is shown by the clear evidence for multi-jet production in the data at rates close to those predicted by the Monte Carlo and by the observed trend for the fraction of $\sum |E_t|$ contributed by the two leading jets to increase with $\sum |E_t|$. Detailed jet properties, such as energy profiles and two measures of jet collimation, are in good agreement with expectations with the exception that the Monte Carlo events appear to have slightly more localised energy deposition than that seen in the data. Possible explanations lie in the difficulty of reproducing the spectator system or in the existence of low- $\sum |E_t|$ events in which non-perturbative effects are more prominent.⁴ Another possibility is an energy scale error consistent with the cross section discrepancy which would imply that the Monte Carlo has systematically sampled rather less isotropic events at larger transverse energy than the data.

In conclusion, all high transverse energy data from the $p\bar{p}$ collider are well described by independent jet fragmentation Monte Carlo programs having as their basis perturbative QCD in leading pole approximation with Λ_{QCD} in the range of 100-500 MeV. Not only does this theory give a good description of the data, but it also leaves no room for any significantly different mechanism of comparable cross section.

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