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EXPERIMENTAL OBSERVATION OF EVENTS
WITH LARGE MISSING TRANSVERSE ENERGY

UA1 Collaboration, CERN, Geneva, Switzerland

Aachen-Amsterdam (NIKHEF)-Annecy (LAPP)-Birmingham-CERN-Harvard-Helsinki-
Kiel-London (Queen Mary College)-Paris (Coll. de France)-Riverside-Rome-
Rutherford Appleton Lab.-Saclay (CEN)-Vienna-Wisconsin

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1. INTRODUCTION

This presentation will summarize the results of the missing-energy analysis from the UA1 experiment at CERN. The talk is divided into two parts. The first part will review the 1983 data taken at a total centre-of-mass energy of 540 GeV. These data correspond to an integrated luminosity of 113 nb^{-1} . The second part is a summary of the new data from the first 130 nb^{-1} of the 1984 run taken at a total centre-of-mass energy of 630 GeV.

2. REVIEW OF THE 1983 DATA

2.1 Missing transverse energy

The UA1 detector has 4π calorimetry and detectors covering the full angular range down to 0.2° with a minimal fraction of insensitive areas. For standard events, for example events with no non-interacting particles, the energy balance is expected to be determined by overall calorimeter resolutions. The longitudinal component of energy balance cannot, of course, be measured owing to the loss of energetic particles down the beam pipe. However, the transverse components are fairly well measured. Figure 1 shows the observed distribution of the vertical component of transverse energy E_T for minimum bias events¹. The transverse components ΔE_Y , ΔE_Z of E_T seem to be neatly centred around zero and have a Gaussian shape with an r.m.s. width which can be parametrized as $0.5 \sqrt{|E_T|}$, where $|E_T|$ is the scalar sum of transverse energies observed in all calorimeter cells. The modulus of the resultant missing E_T vector, $|\Delta E_M| = (\Delta E_Y^2 + \Delta E_Z^2)^{1/2}$ is distributed exponentially in the variable $|\Delta E_M|^2$. The same parametrization of the missing E_T resolution also holds for events which have high-transverse-momentum jets. This is demonstrated in Fig. 2, where the missing

E_T observed for a sample of two-jet events is shown. The curve shows the result of a Monte Carlo calculation in which our parametrization of the resolution for each transverse component was used to fluctuate the jets and the underlying event, using a sample of balanced events containing a minimum of two jets. The missing E_T distribution of these fluctuated events seems to be in good agreement with data.

The apparent missing E_T measured in an event can be associated with the emission of one or more neutral, non-interacting particles, such as neutrinos or photinos of supersymmetric theories. As a practical example, the missing E_T distribution of our 1983 $W \rightarrow e\bar{\nu}$ events is shown in Fig. 3. A sharp Jacobian peak at about one-half of the W mass is clearly demonstrated.

2.2 Event selection

The selection of events with large missing E_T is described in detail elsewhere². Here it is emphasized that since there was no dedicated trigger provided by the missing E_T alone, an additional requirement was necessary to trigger the event. This was a) a jet of $E_T > 25$ GeV, b) an electromagnetic cluster of $E_T > 10$ GeV, c) a muon of $p_T > 5$ GeV/c, or d) a scalar transverse energy $|E_T| > 60$ GeV in the region $|\eta| < 1.5$. After requiring the $|\Delta E_M| > 4\sigma$, where $\sigma = 0.7 \sqrt{|E_T|}$, and that the ΔE_M vector did not point to within $\pm 20^\circ$ of the vertical, the selected events were all scanned by physicists. A total of 77 events were found to pass the final selection and the ΔE_M were declared genuine. Figure 4a shows a plot of $|\Delta E_M|^2$ versus $|E_T|$ for these events. Out of the 77 events, 50 were found to be known $W \rightarrow e\bar{\nu}$ decays, and 27 were new. These events are shown in Fig. 4b. The events are classified as having a single electromagnetic cluster, a single jet ($E_T > 12$ GeV), two jets, and three or more jets.

2.3 Isolated electromagnetic clusters

Events G and H of Fig. 4b have a single isolated electromagnetic cluster without an associated hard track. These are called the 'photon' events. An inclusive 'photon' search without a missing energy requirement was performed. The results are shown in Fig. 5, where the 'photon' transverse energy is plotted against the missing transverse energy squared. As can be seen, the low missing E_T events are consistent with jet-jet events where one of the jets has one or more leading π^0 's, and the other fluctuates down and appears to be very soft. However, events G and H have missing E_T far larger than our expected ΔE_M resolution and exhibit quite larger values of missing energy than do the other events.

Events G and H have clear interaction vertices and their electromagnetic showers point to the vertex. One potential background comes from $W \rightarrow e\bar{\nu}$ decays, where the electron track is not recorded in the central tracking chambers. Figure 6 shows the polar versus azimuthal angle of all observed $W \rightarrow e\bar{\nu}$ events. The cross-hatched area corresponds to the insensitive volume of the central detector (CD), which is due to the presence of a foam septum. Although event G is inside this 'blind' area, event H is clearly in an active region of the chamber². But there are no hits found pointing to the shower.

Event H is shown in Fig. 7. The electromagnetic shower has an E_T of 54 GeV. The transverse mass of the system of the 'photon' and ΔE_M is $93 \pm 5 \text{ GeV}/c^2$.

The following is a summary of possible backgrounds considered for the 'photon' events³:

- i) A $W \rightarrow e\bar{\nu}$ event with the electron track not recorded in the central detector. This is possible for event G. For event H there is the possibility that a hard π^0 hit the same shower counter as did an

electron from W decay, shifting the shower position away from the blind region of the CD. This background is measured, by looking at the π^0 rate in W events, to be about 0.002 event.

- ii) Fake photons, i.e. neutrals striking the same electromagnetic counter up and down and faking a single shower with missing E_T . We expect less than 0.007 event.
- iii) Cosmic rays. A normal collision in coincidence with a cosmic ray which may produce an electromagnetic shower profile. This background is about 0.001 event.
- iv) Jet-jet fluctuations. As discussed before, for events G and H this background is very small, less than 0.001 event.

In summary, event H seems to be inconsistent with the backgrounds considered, whilst for event G the $W \rightarrow e\bar{\nu}$ background cannot be excluded.

2.4 Single-jet events

There are 17 events with a single isolated jet. To estimate the backgrounds for these events the ΔE_M cut was relaxed from 4σ to 2σ or 15 GeV, whichever was greater. In addition we required some isolation cuts on the ΔE_M vector² and no vertical jets in the event. At this point we were left with 117 events. The main background is from quantum chromodynamics (QCD) jets, in which, owing to calorimeter fluctuations, all but one jet becomes soft. This background was further rejected by cutting on $\Delta\phi$, the angle in the transverse plane that the rest of the event (jet subtracted and E_T recalculated from the rest of the calorimetry) makes with respect to the jet. The distribution of $(\Delta E_M)^2$ for the remaining events is shown in Fig. 8. The solid curve shows the background expected from jet-jet fluctuations as

calculated from our Monte Carlo. It is evident that the events with $\Delta E_M < 30$ GeV are consistent with background.

Other contributions to the monojet events are as follows:

- i) $W \rightarrow \tau \bar{\nu}$ events, where τ decays hadronically. The missing E_T distribution is shown in Fig. 8. Nine events are expected in total, with about two events with $\Delta E_M > 30$ GeV. Event F, because of its low jet mass, lower jet E_T , and three-prong multiplicity, is a $W \rightarrow \tau \bar{\nu}$ candidate. A hypothetical new sequential lepton of mass > 20 GeV/c² can also contribute at the level of a few events with a softer spectrum.
- ii) $Z^0 + g$. A QCD jet can be produced in association with a Z^0 , which in turn decays into a pair of neutrinos (the branching ratio is expected to be about 19%). This can give a monojet signature. Some $W + \text{jet}$ or $Z^0 + \text{jet}$ events have been observed, but in the 1983 data sample there are no events with a jet of $E_T > 25$ GeV. Thus this background is small for our values of E_T .
- iii) Heavy quark decays. Heavy quark pairs ($c\bar{c}$, $b\bar{b}$, $t\bar{t}$), with one of them decaying into a leading neutrino, can produce a monojet event. Less than 0.1 event is expected for $\Delta E_M > 40$ GeV. Also, a direct search for lepton + jet events with the lepton $E_T > 40$ GeV gives a negative result.

Therefore there are five events that are inconsistent with the backgrounds considered above. Figure 9 shows the transverse energy flow and transverse view for event A. The unusual feature of this event is the presence of an energetic muon within the jet. The momentum of the muon is measured to be 80^{+20}_{-13} GeV/c in the CD and 105^{+59}_{-27} GeV/c measured independently in the muon system. Except for the muon track there are no other charged tracks in the jet. The missing E_T , including the muon, is 66 GeV.

The transverse energy flow and transverse view for event B is shown in Fig. 10. The jet has three charged tracks and a low invariant mass ($0.8 \text{ GeV}/c^2$). Its E_T is 48 GeV and the missing E_T is 59 GeV. Figure 11 shows the transverse view for three events: C, D, and E. For more information on these events, see Ref. 2.

2.5 Multijet events

There are eight such events. All but one are compatible with QCD background and heavy-flavour decays. The remaining event is a three-jet event. Figure 12 shows the transverse energy flow along with transverse view for this event. The jet transverse energies are 51 GeV, 20 GeV, and 14 GeV. The event has a missing E_T of 55 GeV.

The 1983 results are basically summarized in Fig. 13. In (a) the scatter plot of ΔE_M versus E_T of the jet is shown for events A to H; it is evident that ΔE_M is mainly due to a single unbalanced jet. In (b) the transverse mass distribution of the jet and ΔE_M for events A to H is compared with that of a sample of W events with $\Delta E_M > 30 \text{ GeV}$, and one can see that $W \rightarrow e\bar{\nu}$ decays have relatively smaller transverse masses.

3. NEW DATA FROM 1984

3.1 1984 run conditons

As mentioned in the Introduction, the 1984 run was taken at a total centre-of-mass energy of 630 GeV. Another change from the 1983 run was the addition of a new dedicated trigger to record events with a large amount of missing transverse energy. This trigger worked in the following way. The scalar sum of transverse energy was calculated once from all calorimeter cells in the right-half of the detector ($|E_T|_R$) and a second time from all cells in the left-half of the detector ($|E_T|_L$). If the difference between $|E_T|_R$ and $|E_T|_L$ was greater than 17 GeV AND there was also

a jet with $E_T > 15$ GeV, the event was recorded. This ' E_T imbalance' trigger was active throughout the run, as well as other standard triggers. Those relevant to the missing E_T analysis were: i) electromagnetic cluster of $E_T > 10$ GeV; ii) jet of $E_T > 25$ GeV; and iii) $|E_T| (|\eta| < 1.5) > 80$ GeV.

3.2 Event selection

For 1984 all events with ΔE_M larger than 3.5σ ($\sigma = 0.7 \sqrt{|E_T|}$) were written onto special 'Express Line' tapes for rapid processing. A simple $\Delta E_M > 4\sigma$ cut was then applied to these events. A total of 1796 events were selected from the first 130 nb^{-1} . This sample included $W \rightarrow e, \mu, \tau$ decays and some $Z^0 \rightarrow \tau^+ \tau^-$ candidates as well as some junk events such as beam halo and cosmic and vertical jets. After removing $W \rightarrow e, \mu$ decays and rejecting all junk events, the remaining events were scanned by physicists on the Megatek facility. A number of single-jet and two-jet candidates were found, which will be described next. However, it should be emphasized that to date the results are very preliminary and the events presented have to be carefully studied in terms of various potential backgrounds.

3.3 Single-jet events

Figure 14 shows the scatter plot of the missing E_T squared versus $|E_T|$ for all single-jet and two-jet events. There are fifteen single-jet events in total. Eight of them are classified as monojet candidates, whereas the rest are considered to be $W \rightarrow \tau \bar{\nu}$ candidates. The separation of monojet and $W \rightarrow \tau \bar{\nu}$ events is based on two observations: the magnitude of the missing transverse energy ($\Delta E_M > 40$ GeV for monojets); and ii) the characteristics of the jet in terms of size and multiplicity (low mass and ≤ 3 prongs for the τ -jet). For example, an event with $\Delta E_M < 40$ GeV but a jet mass or multiplicity inconsistent with τ would be considered to be a

monojet. Nevertheless this classification is by no means definitive and the results should not be taken as final.

The $W \rightarrow \tau \bar{\nu}$ candidates will be discussed later. As an example of monojet candidates, Fig. 15 shows the transverse energy flow and transverse view for event 9501/822. This event has a missing transverse energy of 46 GeV ($\sigma = 7.4$) and the jet E_T is 44 GeV (28 GeV in electromagnetic and 16 GeV in hadronic energy). The jet has six charged tracks with transverse momentum p_T over 1 GeV/c, including one with p_T as high as 14 GeV/c. Its charged mass is $2.7 \pm 0.5 \text{ GeV}/c^2$ and the transverse mass of the $\Delta E_M + \text{jet}$ is $90 \text{ GeV}/c^2$.

As mentioned in subsection 2.4, there are other contributions to the monojet events, namely: $Z^0 + g$ ⁴, heavy quark decays⁵, and $W \rightarrow \tau \bar{\nu}$ decays. A preliminary estimate of these backgrounds (per 100 nb^{-1}) is demonstrated in Fig. 16. Another background, not shown in the plot, comes from $W + \text{jet}$ events, where W decays into an electron or a τ which happens to overlap with the jet, faking a monojet signature. This background, still to be calculated, could be as large as 0.5 event per 100 nb^{-1} (from naïve phase-space arguments) for $\Delta E_M > 40 \text{ GeV}$.

3.4 Two-jet events

In our selection of events with large missing energy there was no requirement on the number of jets in the event. After events were selected we simply counted the number of jets with $E_T > 12 \text{ GeV}$. In this manner we found eight two-jet events. Figure 14 shows $(\Delta E_M)^2$ versus $|E_T|$ for these events.

There are basically two topologies observed in two-jet events:

i) Viewed in the transverse plane, the jets are on the same side, and the missing transverse energy is balancing them on the other side. Figure 17

shows an example of this configuration. The missing transverse energy of this event is measured to be 65 GeV ($\sigma = 8.3$) and the jet E_T 's are 49 and 16 GeV with $E_T^{\text{em}}/E_T^{\text{had}}$ equal to 41/8 and 9/7, respectively. There are six charged tracks with $p_T > 1$ GeV/c in the big jet and three positively charged tracks in the small one. The transverse mass of the $\Delta E_M + \text{jets}$ is 130 GeV. There are two events of this type in the sample.

ii) The second topology is when the two jets are back-to-back in the transverse plane and the missing E_T is parallel to one of the jets, clearly the smaller one. Event 9986/574, shown in Fig. 18, is an example of this topology. The missing E_T is 50 GeV and the jet transverse energies are 74 and 27 GeV. Events of this type are much harder to evaluate in terms of backgrounds such as jet-jet fluctuations and QCD production of two-jet events, with the energy of one jet incorrectly measured owing to leakage or the presence of energetic muons not detected in the muon chambers. Therefore, for the present they are excluded from the sample.

3.5 $W \rightarrow \tau \bar{\nu}_\tau$, τ decaying into a jet

There are seven such events. Their ΔE_M distribution is shown in Fig. 14. Out of seven candidates, three are three-prong and four are one-prong. Figures 19 and 20 show the transverse energy flow and the transverse view for a three-prong and a one-prong event, respectively. The three-prong event (11673/499) has a missing E_T of 19 GeV ($\sigma = 4.5$) and the jet E_T is 21 GeV ($E_T^{\text{em}}/E_T^{\text{had}} = 7/14$). The missing E_T for the one-prong event (10486/358) is 36 GeV ($\sigma = 7.1$) and the E_T of the jet is 31 GeV ($E_T^{\text{em}}/E_T^{\text{had}} = 25/6$). The transverse masses of these events are 39 and 66 GeV, respectively. Figures 21 and 22 show the CD view for the above events. It can be seen that the events have clean vertices and are relatively quiet, as expected from W decays. The jet in event 11673/499

has three charged tracks ($Q.p_T = +12.2, -8.7, -7.7$ GeV/c) rather collimated. Its charged mass is 1.0 ± 0.03 GeV/c². It is interesting to note that the recording of this event was only due to the E_T imbalance trigger. The one-prong event has $Q.p_T = -6.3$ GeV/c and is a clear candidate for τ decay into $\pi^- + n\pi^0$.

In order to better understand our analysis of events with missing energy and also be able to separate our $W \rightarrow \tau\bar{\nu}$ and monojet candidates effectively, it is very important that we establish a signal in the $W \rightarrow \tau\bar{\nu}$ channel and realize the backgrounds involved. To this end a series of Monte Carlo calculations were carried out using the ISAJET program with certain additions and modifications⁶. Various hadronic decays of τ were calculated with proper branching ratios. After a full detector simulation the results are shown in Fig. 23, where the ΔE_M of these events is plotted before applying any selection cuts. The Monte Carlo sample corresponds to a total integrated luminosity of 4000 nb^{-1} . The dashed area shows the contribution from $\tau \rightarrow 3\text{-prong}$ decays. Notice that a large fraction of events have $\Delta E_M < 15$ GeV. Figure 24 shows the distribution of ΔE_M after including trigger efficiencies and applying our selection cuts of $\Delta E_M > 4\sigma$ and not vertical. This plot is normalized to 130 nb^{-1} total integrated luminosity. A total of eleven events are expected. Our seven candidates seem to agree with the Monte Carlo predictions rather well.

To get an idea of how the τ -jets compare with the jets in our monojet events or with the QCD jets, a calorimetric jet mass is defined. This is basically the invariant mass of all energy cells in calorimeters associated with the jet by the UA1 jet algorithm⁷. This is clearly not a valid measurement of the mass; however, it is useful for the purpose of comparison. Figures 25 and 26 show the distributions of the calorimetric jet mass for the Monte Carlo events, the monojet candidates, and the QCD

jets. It is clear that the τ -jets have lower masses than the QCD ones, but some jets of the monojet events seem to have relatively large masses.

4. CONCLUSIONS

In the first 130 nb^{-1} of the 1984 data we have observed events in which a large missing transverse energy is associated with a single jet. This observation confirms the existence of the monojet events seen in the 1983 data. In addition, we have also observed events in which the missing E_T is associated with two jets.

Decays of the W boson into a τ lepton have been observed, and they seem to be in good agreement with our expectations in terms of missing transverse energy and characteristics of the τ -jets, namely mass and multiplicity.

Any statement about the interpretation of the monojets and the two-jet events would be premature at this time. The remaining data should be analysed and the backgrounds further studied in order to determine the physics behind these events.

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Figure captions

- Fig. 1 : Scatter plot of the transverse component (y component) of missing transverse energy versus the total transverse energy observed in all calorimeter cells.
- Fig. 2 : Missing transverse energy squared normalized to total scalar transverse energy observed for a sample of two-jet events. The solid curve is the result of a Monte Carlo simulation (see text). The number of standard deviations is approximately equal to $\sqrt{2X}$.
- Fig. 3 : Missing transverse energy distribution for $W \rightarrow e\bar{\nu}$ events. The curve is the expectation for a W mass of $81 \text{ GeV}/c^2$, including our expected resolution.
- Fig. 4a : Scatter plot of missing transverse energy squared versus total scalar transverse energy for selected events which have missing E_T more than four standard deviations from zero. The $W \rightarrow e\bar{\nu}$ decays are labelled with a cross.
- Fig. 4b : Same as Fig. 4a with $W \rightarrow e\bar{\nu}$ events removed. The events are labelled according to their topology.
- Fig. 5 : Scatter plot of the transverse energy versus the missing E_T Squared for all selected 'photon' events without a missing energy requirement.

- Fig. 6 : Electron polar angle (with respect to the beam axis) versus azimuthal angle for the 1983 sample of $W \rightarrow e\bar{\nu}$ events. The photon candidates are indicated by open circles. The dashed contour shows the area beyond which at least 20 hits are expected in the central detector.
- Fig. 7 : Event display and transverse energy flow in azimuthal angle (ϕ) and pseudorapidity (η) space for event H.
- Fig. 8 : Distribution of missing E_T squared for single-jet events which pass the 2σ cut and $\cos \Delta\phi > -0.8$. The solid curve is the expected background from jet-jet fluctuations. The dashed curve is the expected contribution from $W \rightarrow \tau\bar{\nu}$ decays.
- Fig. 9 : Transverse energy flow (ϕ versus η) seen in the calorimeters for monojet event A. Also shown are the transverse view and pseudorapidity distribution of the jets.
- Fig. 10 : Same as Fig. 9 for monojet event B.
- Fig. 11 : Same as Fig. 9 for monojet events C, D, and E (from left to right).
- Fig. 12 : Same as Fig. 9 for the three-jet event.
- Fig. 13a : Missing transverse energy versus transverse energy of the jet for events A to H.

Fig. 13b : Distribution of the transverse mass of the jet and missing transverse energy for events A to H and the three-jet event. Also shown is the M_T distribution for a sample of $W \rightarrow e\bar{\nu}$ events.

Fig. 14 : Scatter plot of missing transverse energy squared versus total scalar transverse energy for events with $\Delta E_M > 4\sigma$ from 130 nb^{-1} of 1984 data. The results of 4σ selection from 1983 are also shown.

Fig. 15 : Transverse energy flow observed in the calorimeters and the transverse view for the monojet event 9501/822. Distribution of pseudorapidity of the jets is also shown.

Fig. 16 : Distribution of the missing transverse energy for $Z^0 + g$, $Q\bar{Q}$, and $W \rightarrow \tau\bar{\nu}$ decays.

Fig. 17 : Same as Fig. 15 for two-jet event 13028/1289.

Fig. 18 : Same as Fig. 15 for two-jet event 9986/574.

Fig. 19 : Same as Fig. 15 for $W \rightarrow \tau\bar{\nu}$ event 11673/499.

Fig. 20 : Same as Fig. 15 for $W \rightarrow \tau\bar{\nu}$ event 10486/358.

Fig. 21 : Central detector display of digitization of tracks in event 11673/499.

Fig. 22 : Same as Fig. 21 for event 10486/358.

Fig. 23 : Distribution of missing transverse energy of $W \rightarrow \tau \bar{\nu}$ Monte Carlo events. No selection cuts applied; however, detector smearing effects are included.

Fig. 24 : Same as Fig. 23 with trigger and selection cuts included. The 1984 three-prong and one-prong candidates are also shown.

Fig. 25 : Distribution of the calorimetric jet mass (see text) for $W \rightarrow \tau \bar{\nu}$ Monte Carlo events. The dashed area shows the seven 1984 $W \rightarrow \tau \bar{\nu}$ candidates.

Fig. 26 : Same as Fig. 25 for the monojet events and the QCD jets with $E_T > 40$ GeV.

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Event H

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