NEW PHYSICS FROM UA1

presented by

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I. Introduction

In this presentation I will summarize new physics results of the last year from the UA1 experiment at CERN. These data are from proton-antiproton collisions at a total center-of-mass energy of 540 GeV corresponding to an integrated luminosity of 136 nb^{-1}. The data were recorded mostly in the Spring of 1983. The subject of the top quark search is covered by another talk[1]. This paper is divided into two main sections. The first part deals with the observation of events with large missing transverse energy containing either a) a single electromagnetic cluster or b) a single jet. The second section is concerned with properties of events containing a W or Z^0 boson.

II. Events with Missing Energy

In the absence of any non-interacting particles (e.g., neutrinos) and in the case of an ideal detector we would observe perfect energy and momentum balance in each event. In practice, of course, we do not achieve this, but we can measure the transverse components fairly well. The longitudinal component of momentum balance cannot be measured with our detector due to energetic particles (typically 100 GeV) escaping down the beam pipe. Figure 1 shows how well

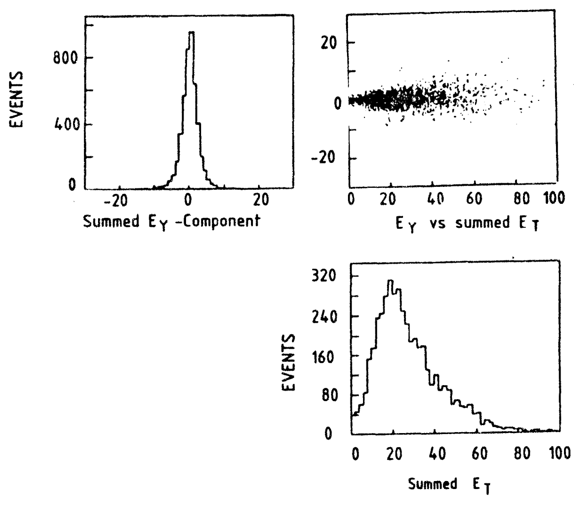

Figure 1. Scatter-plot of the vertical component of missing transverse energy vs. the total transverse energy observed in all calorimeter cells.

the vertical component of transverse energy (E_T) is observed to balance for minimum bias events[2]. The missing E_T resolution for each transverse component may be parameterized as $\sigma = 0.43\ \sqrt{\Sigma E_T}$, where ΣE_T is the scalar sum of transverse energies observed in the entire calorimeter. For events which contain high transverse momentum jets, the parameterization of the missing E_T resolution also holds. This is shown in Figure 2 where we show the missing energy observed for a sample of two jet events along with a monte carlo calculation of the expected distribution based on our

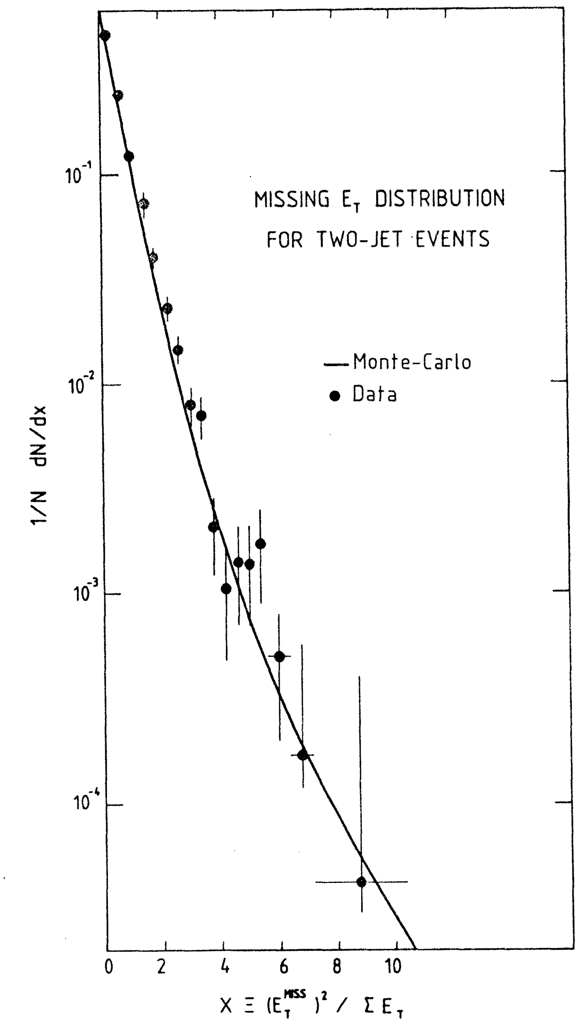

Figure 2. Transverse energy balance observed for a sample of two-jet events. To convert the horizontal scale to number of standard deviations (n), use the relationship $n^2 \simeq 2x$.

parameterization of the resolution for each transverse component. For a typical event with ΣE_T = 80 GeV , we measure the missing transverse energy to about 6 GeV. To demonstrate a practical example, we show the missing transverse energy (ΔE_m) observed in a sample of identified $W \to e\nu$ decays (Figure 3)[3]. We find a sharp Jacobian peak at about one-half of the W mass.

The selection of events with large ΔE_m is detailed in Reference 4. We have looked in detail at all events having ΔE_m more than 4 standard deviations from zero. After vetoing such garbage events as beam halo and cosmic rays, we find 77 events passing the final selection. Figure 4a shows a plot of $(\Delta E_m)^2$ vs. ΣE_T for these events. We find that 50 of these events

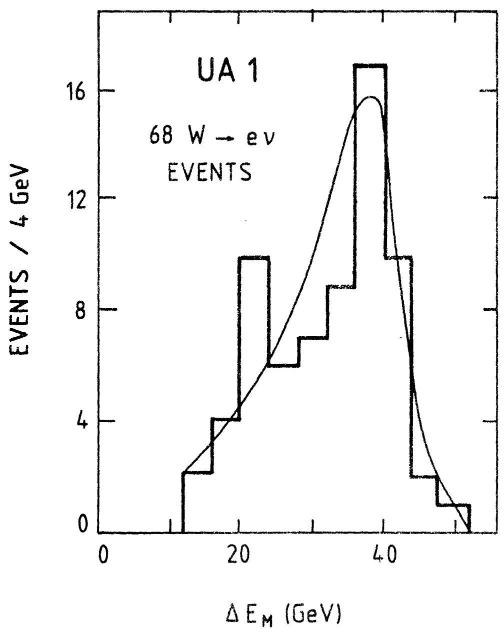

Figure 3. Missing transverse energy in $W \to e\nu$ events. The curve is the expectation for an W mass of 81 GeV including our expected resolution.

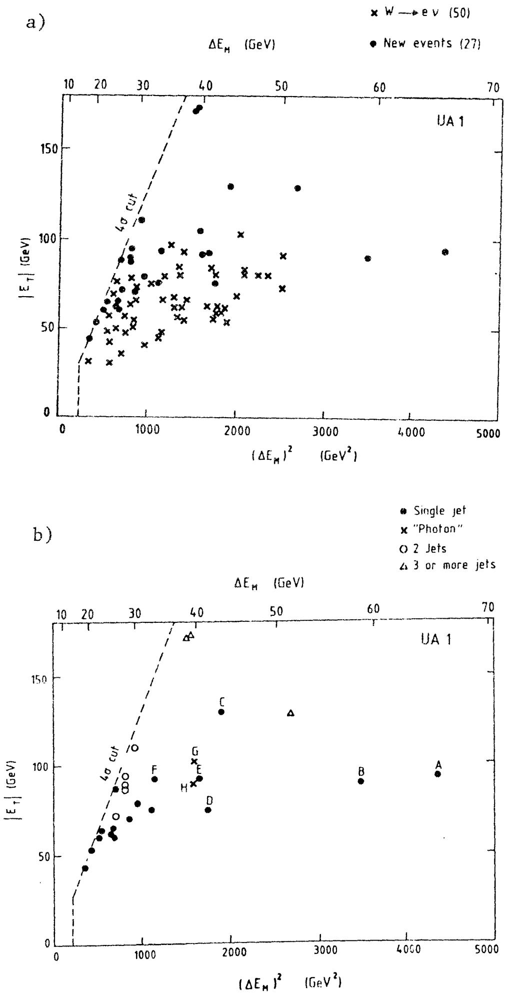

Figure 4. Missing transverse energy squared vs. ΣE_T for all verified events which have ΔE_m more than 4 standard deviations from zero for a) all events and b) events with $W \to e\nu$ decays removed. The events are labeled according to their topology.

are part of the original $W \to e\nu$ sample; 27 events are new. The new events are shown in Figure 4b. We have classified the events as having a single electromagnetic cluster, a single jet (with $E_T > 12$ GeV), two jets, or three or more jets.

Two events (G and H of Figure 4b) have a single electromagnetic cluster without associated hard tracks. We have performed an inclusive "photon" search by selecting all events with an isolated electromagnetic cluster without a missing E_T requirement. This result is shown in Figure 5 where we plot the "photon" transverse energy against the missing E_T squared of the event. The events with low missing E_T

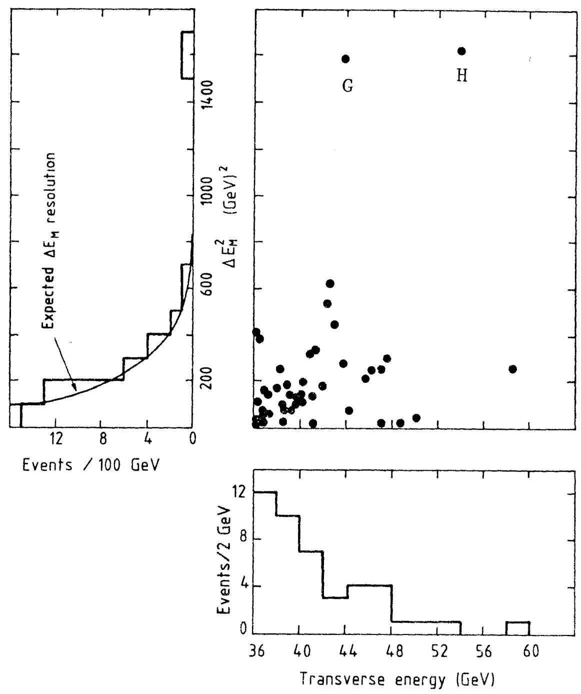

Figure 5. Transverse energy of the "photon" candidate (note suppressed zero) plotted against the missing E_T of the event for the photon selection without a missing E_T cut. The solid curve is the expected missing E_T resolution for balanced events.

are consistent with QCD expectations of direct photon production and jet-jet events where one of the jets fragments as one or more leading π^0's. However, events G and H have missing transverse energy far in excess of the other events. Events G and H represent a relative large effect (about 10%) in the photon spectrum above 40 GeV E_T.

We have checked that the events G and H have clean interaction verticies and that the electromagnetic showers point to the vertex. We have also carefully checked to see if a charged track could have been missed in the central tracking chambers; this would be a potential background from $W \to e\nu$ decays. For event G we find that it is possible to have not detected a track (not even a single hit was observed) because the shower points within resolution to a small insensitive gap between the chambers[2,4]. For event H this is not possible because the shower points to an active region of the chamber where we would expect about 20 hits and none were observed[4].

Figure 6 shows the transverse energy flow for event H. The dominating structure in the event is a single electromagnetic cluster. The shower E_T is 54 GeV.

We find very low backgrounds for the "photon" events. Photon in this context means any number of nearly colinear photons of low (a few GeV) invariant mass. We have considered the following background possibilities:

1) $W \to e\nu$ where the electron track escapes detection.

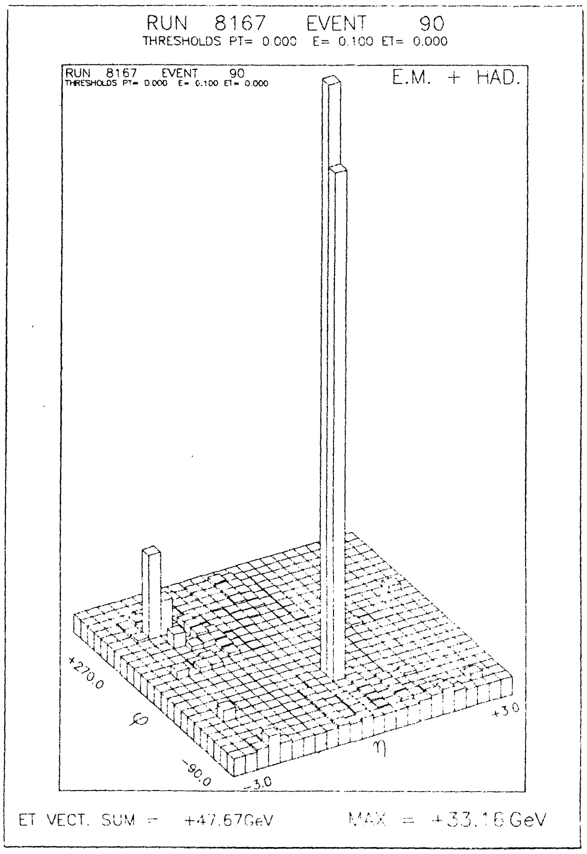

Figure 6. Transverse energy flow binned in azimuthal angle (ϕ) and pseudorapidity (η) for event H. The maximum height corresponds to about 33 GeV. The E_T of the large electromagnetic cluster is 54 GeV.

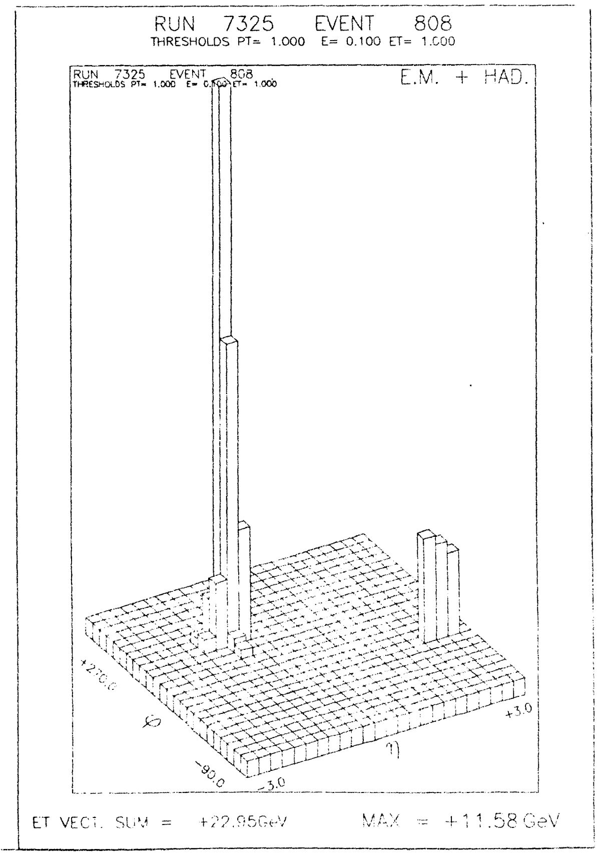

Figure 7. Transverse energy flow observed in the calorimeters for monojet event A. There is in addition an energetic muon in the jet.

This is possible for event G as explained previously although its shower E_T of 44 GeV is somewhat higher than the average electron shower from W decay. For event H we could have a hard π^0 hit in the same shower counter as an electron from W decay, thereby shifting the observed shower position away from the blind region of the central detector. We can measure this background by looking at the π^0 rate in W events and we find this background to be less than 0.002 events.

2) Cosmic rays. Cosmic rays (in coincidence with a proton-antiproton soft collision) may shower in the lead-scintillation counters and fake a photon event. However, in general they do not point to the event vertex. This background is measured to be about 0.001 events.

3)Fake shower response. Multiple π^0's may strike the same shower counter (e.g., one up and one down) and thereby appear as a single shower with missing E_T. This background is measured to be less than 0.007 events.

4)Jet-jet fluctuations. An ordinary QCD two-jet event may fluctate in our calorimeter such that one jet appears very soft and the other jet fragments into leading π^0's. This background is less than 0.001 events.

We now turn to a description of the single jet events of Figure 4b which have the largest missing transverse energy. Event A is a remarkable event. The transverse energy flow observed in the calorimeters is shown in Figure 7. In addition there is an energetic muon within the jet which makes an angle of about 100 mr with the calorimeter cluster. There are no other charged tracks in the jet (see Figure 8). The momentum of the muon is measured independently in the central detector ($p = 80^{+20}_{-13}$ GeV/c) and the muon system ($p = 105^{+59}_{-27}$ GeV/c)[5]. The missing E_T in the event is 66 GeV.

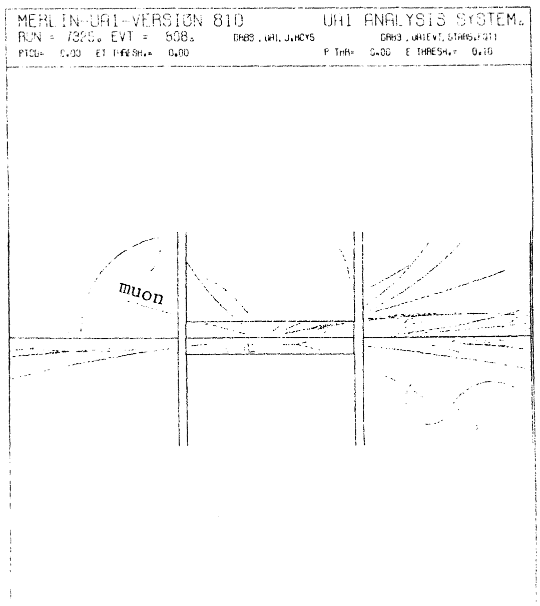

Figure 8. Central detector digitization display for event A. The muon track is labeled. The event has a clean interaction vertex and is relatively low multiplicity (about twenty charged tracks).

The transverse energy flow in event B is shown in Figure 9. A single jet (E_T = 48 GeV) dominates the event structure. The missing energy of this event is 59 GeV. An event display is shown in Figure 10.

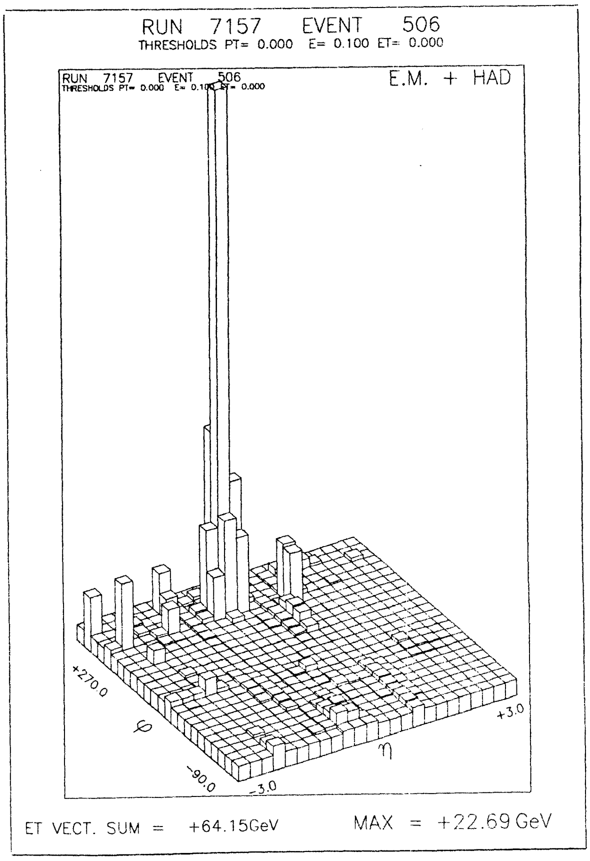

Figure 9. Transverse energy flow for monojet event B. The jet E_T is 48 GeV.

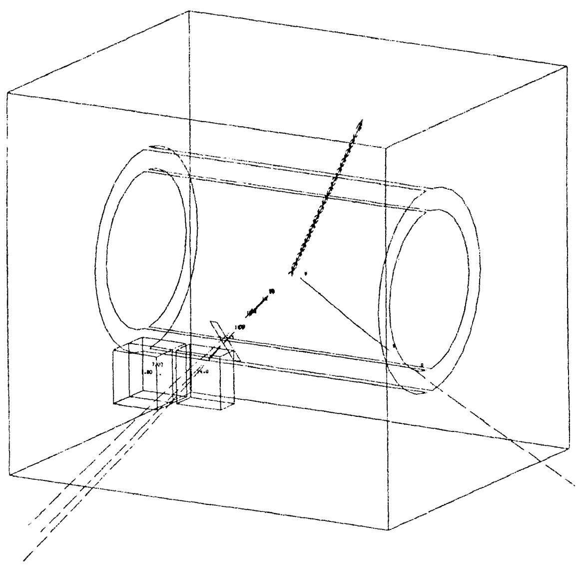

Figure 10. Event display showing tracks with p_T greater than 2 GeV/c and calorimeter hits with E_T greater than 5 GeV. The arrow indicates the direction of the missing E_T (59 GeV).

To help determine the background from two-jet fluctuations, we have relaxed the cut on ΔE_m from four standard deviations to two standard deviations. We have also applied a cut on $\Delta\phi$, the angle in the transverse plane that the rest of the event (jet not included) makes with respect to the jet. This is shown in Figure 11. Events A-F, which all pass the $\Delta\phi$ cut, exceed the background expected from jet

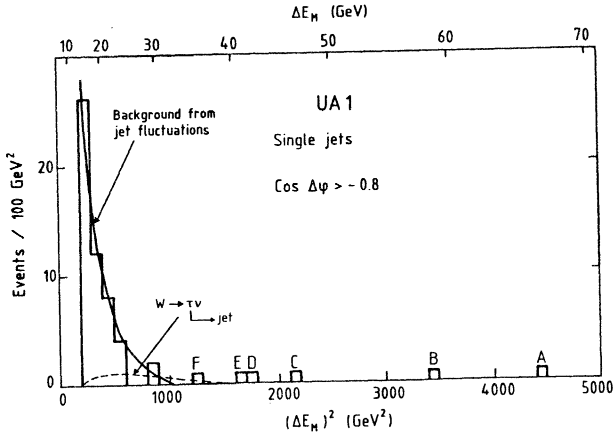

Figure 11. Distribution of missing E_T squared for events passing the 2σ cut on missing E_T and the cut $\cos \Delta\phi < 0.8$.

fluctuations (e.g., a two-jet event where one jet is observed to be very small).

For the monojet events A-F with $\Delta E_m > 30$ GeV we have considered the following backgrounds:

1) $W \rightarrow \tau\nu$. We expect about 2 events with the missing E_T distribution shown in Figure 11. Only event F, by nature of its lower jet E_T, low jet mass, and three prong multiplicity, is consistent with this process.

2) $W \rightarrow L\nu$, where L is a new sequencial heavy lepton. The background for any heavy lepton is smaller than that for the τ due to phase space and decay kinematics.

3) gZ^0. A gluon jet could be produced in association with a Z^0 which could then decay into $\nu\bar{\nu}$ (expected branching ratio is nearly 20%). However, no jets are observed in W or Z^0 events with $E_T >$ 25 GeV.

4) c,b,t quark decay. We could have heavy quark pairs with one of them decaying into a leading neutrino. We expect less than 0.1 events from this process. A direct search for lepton-jet events with electron or muon and jet E_T greater than 30 GeV gives no events.

We find no two-jet events (Figure 4b) to be in excess of expected backgrounds. We find one three-jet event (the one with the largest ΔE_m in Figure 4b) to be far in excess of the background from jet fluctuations. The jets have E_T's of about 55 GeV, 20 GeV. and 15 GeV and the event has a missing transverse energy of about 55 GeV.

A plot of the missing E_T against jet E_T is shown in Figure 12 for events A-H. A clustering near the dashed line ($\Delta E_m = E_T$ jet) indicates that the observed missing E_T is mainly due to a single unbalanced cluster.

Figure 13 shows a plot of transverse mass of the jet and missing E_T for events A-H plus the three-jet event along with a sample of W events with missing E_T greater than 30 GeV. The observed mass distribution of events A-H exceeds that of the $W \rightarrow e\nu$ decays.

The interpretation of these missing E_T events awaits the accumulation of more data. One possibility is that the missing energy is due to some new particle, e.g., the photino ($\tilde{\gamma}$) of supersymmetric theories. These data would then place some constraints on the masses of the supersymmetric particles[6]. Another natural source of missing energy is from the Z^0 decaying into neutrinos. Under the hypothesis that a high mass state X decays into Z^0 + jet, we may calculate the mass range of X allowed for each event from energy and momentum conservation. This is shown in Figure 14. The data do not rule out such a process for the mass of X of about 170 GeV.

Finally, we remark that if these events were due to the production and decay of a new massive state, we might hope to see structure in the two or three jet mass spectrum. No such structure is observed within our present statistics and mass resolution. The two-jet spectrum is shown in Figure 15.

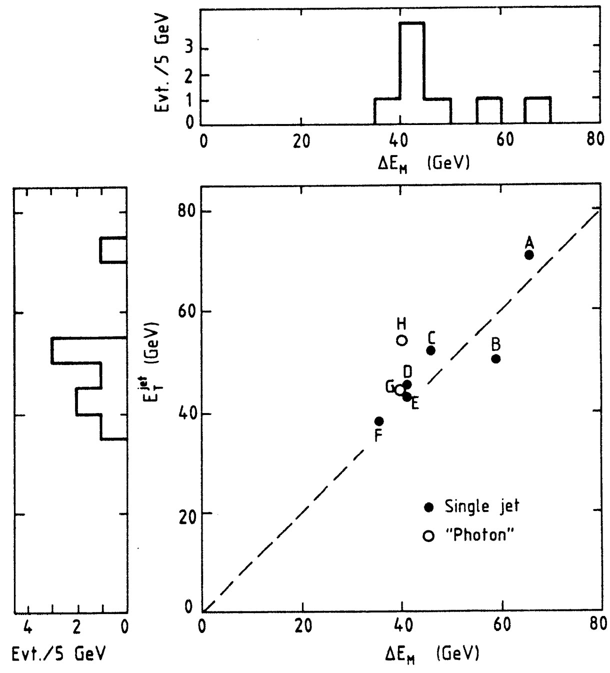

Figure 12. Missing transverse energy vs. cluster E_T for events A-H.

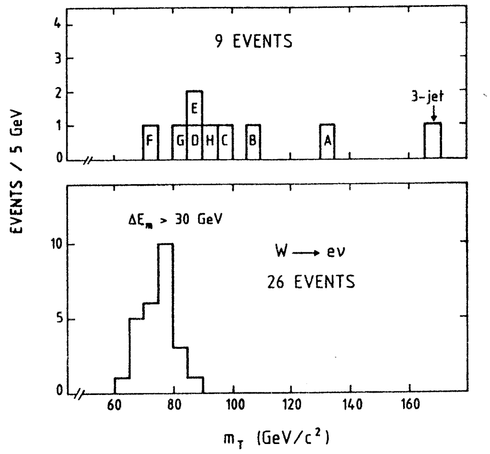

Figure 13. Transverse mass distribution.

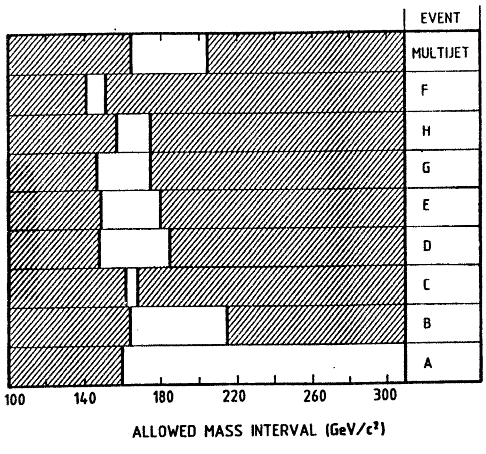

Figure 14. Allowed mass range for hypothetical particle X which decays into Z^0 + jet with the Z^0 decaying into neutrinos. A common mass of about 170 GeV is not ruled out.

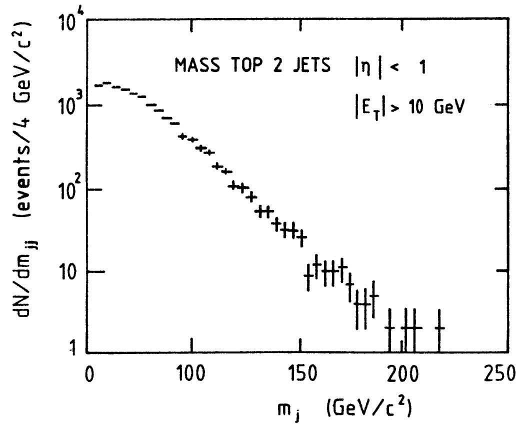

Figure 15. Observed two-jet mass spectrum (not corrected for acceptances). No significant structure is observed.

III. Events Containing Intermediate Vector Bosons

The measured properties of W and Z^0 particles from the UA1 experiment are given in Table I. The observed decays are $W \to e\nu$ (68 events), $W \to \mu\nu$ (14 events), $Z^0 \to e^+e^-$ (4 Events), and $Z^0 \to \mu^+\mu^-$ (5 events). The event signatures are very striking, making the event samples essentially backgroung free.

Measured Properties of IVB's (UA1)

	$W^{\pm}$	Z^o
MASS	80.9 ± 2.8 GeV/c^2	93.9 ± 2.9 GeV/c^2
FULL WIDTH (90% CL)	< 7 GeV	< 8.5 GeV
OBSERVED DECAYS	$e^{\pm}\ \nu$ $\mu^{\pm}\ \nu$	$e^+\ e^-$ $\mu^+\ \mu^-$
$\sigma \cdot B$ $\sqrt{s}$=540GeV $p\bar{p}$	0.53 ± 0.08 nb (± 0.09)	58 ± 21 pb (± 9)
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Table I. Measured properties of W and Z^0 particles. The Z^0 mass value is an average of electron and muon data. The mass errors include systematic effects.

One each of the e^+e^- and $\mu^+\mu^-$ events has an energetic neutral electromagnetic shower, thus making candidates for the processes $Z^0 \to e^+e^-\gamma$ and $Z^0 \to \mu^+\mu^-\gamma$. Details of these event parameters may be found in References 7-8. The UA2 experiment has observed the decays $W \to e\nu$ and $Z^0 \to e^+e^-$ as well as a candidate for $Z^0 \to e^+e^-\gamma$. Latest results may be found in Reference 9.

We have made a detailed study of the hadronic activity in events containing an intermediate vector boson. Figure 16 shows the event "temperature" (the summed E_T of all calorimeter cells, W or Z^0 excluded) for W events, Z^0 events, and minimum bias events. The general feature of the plot shows that the W events

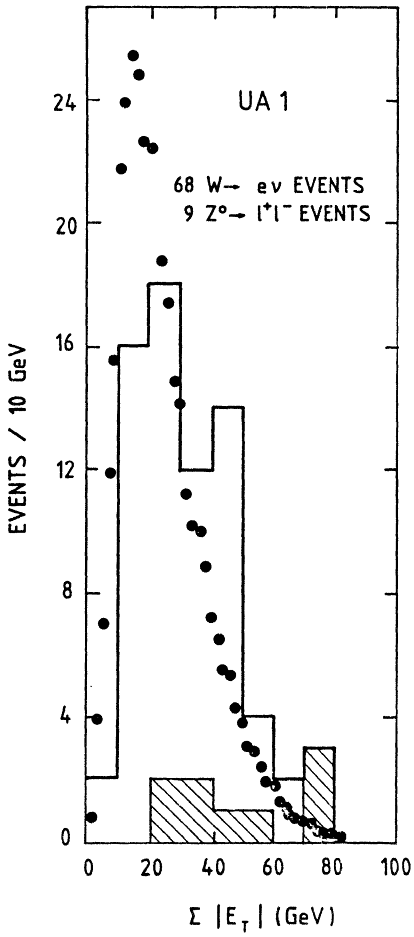

Figure 16. Total scalar E_T distribution for minimum bias events(solid circles), W events (open histogram), and Z^0 events (shaded histogram). The W and Z^0 events have the lepton E_T's excluded.

(lepton removed) have similar hadronic activity to minimum bias events[10]. It is somewhat surprizing that 3 of the Z^0 events have larger ΣE_T than any W event even though the W sample is much larger. Figure 17 shows the rapidity distribution of all charged particles for the same three event samples (W, Z^0 and minimum bias). One observes that the total number of charged tracks is larger for Z^0 events[11].

With some probability (proportional to α_s) the W is expected to be produced in association with a hard initial state gluon radiation. We have observed such events; an example is shown in Figure 18. The W p_T is then expected to be equal and opposite to the jet p_T[12]. This is shown in Figure 19. The jet angular distribution in the center-of-mass frame of the colliding partons is expected to have the characteristic bremsstrahlung shape. Figure 20 shows this for 3-jet events where two of the jets have the invariant mass of the W (open circles) compared with W events (solid circles)[13]. The distributions have been corrected by the color factor of 9/4 to take into account the expected difference between the gluon-gluon coupling and the quark-gluon coupling of QCD. The solid curve is the expected shape $(1-\cos\theta^*)^{-1}$ of the gluon radiation.

The fraction of events with jets is observed to be larger for Z^0 events than for W events (Figure 21). This is about a 3.5 standard deviation effect and is completely unexpected. One of these Z^0 events with jets is shown in Figure 22 indicating the E_T and rapidity of the observed jets and the Z^0.

We conclude this section with a plot of the invariant mass of the IVB_0+ all jets observed for W events (Figure 23a) and Z^0 events (Figure 23b). We

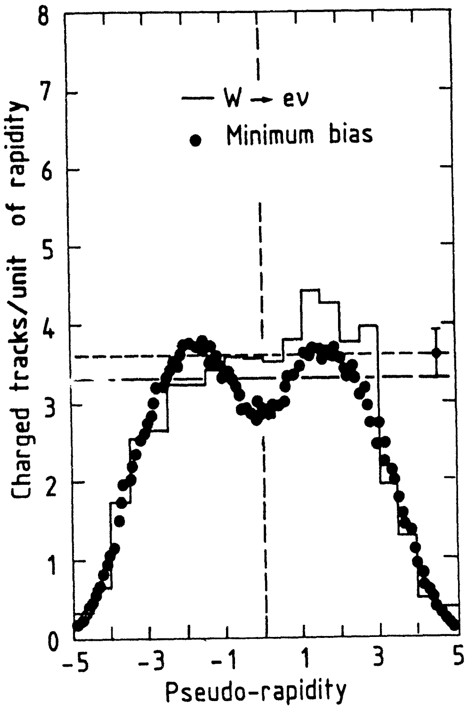

Figure 17a. Pseudorapidity distribution for all observed charged tracks for minimum bias events (solid circles) and W events (histogram). The dip at zero is partially due to acceptance and partially due to kinematics.

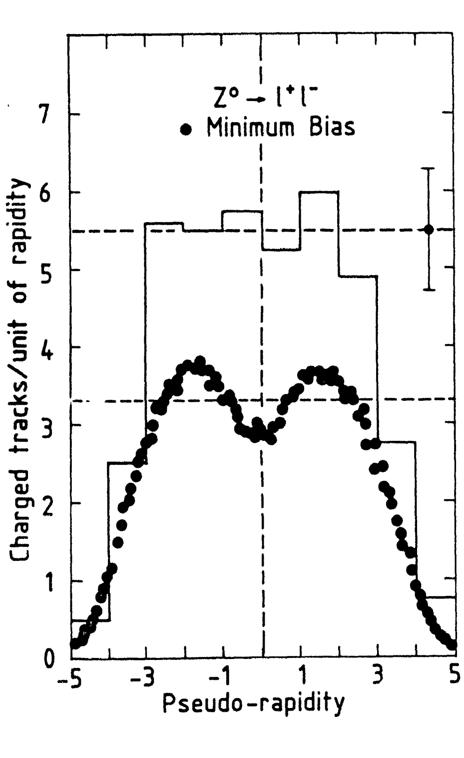

Figure 17b. Pseudorapidity distribution for all observed charged tracks for minimum bias events (solid circles) and Z^0 events (histogram). Compare with Figure 17a.

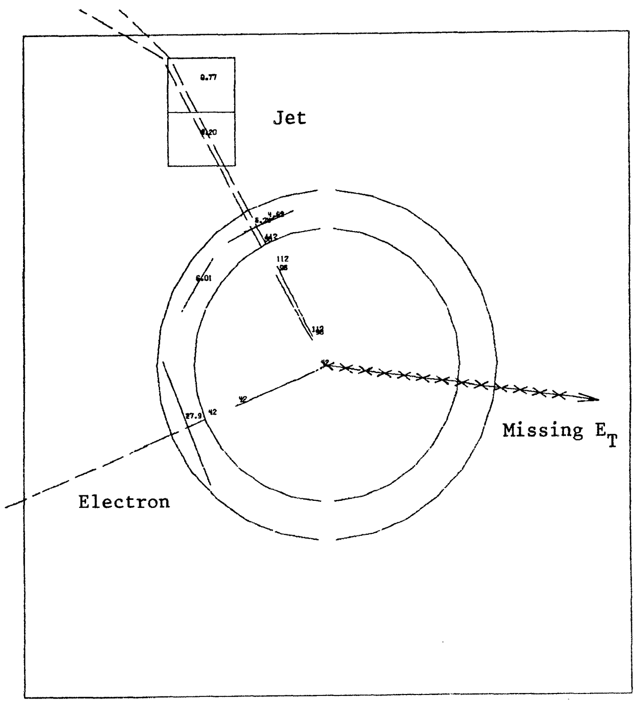

Figure 18. Event display transverse to the colliding beams of the W event with the highest E_T jet. Only tracks and calorimeter cells with more than 1 GeV of E_T are displayed. The jet E_T is 23 GeV, the electron E_T is 30 GeV, and the missing E_T is 43 GeV. The direction of the W motion in the transverse plane is opposite to that of the jet.

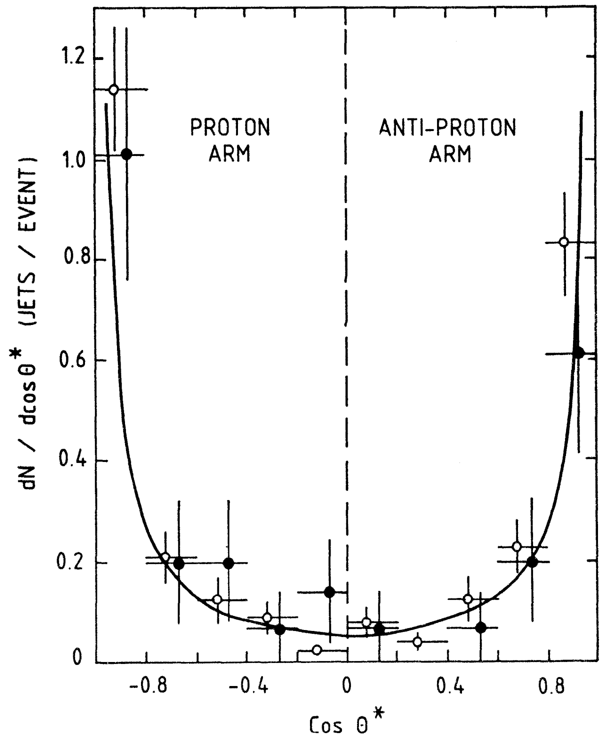

Figure 20. Angular distribution of bremsstrahlung jets in W events (solid circles) and 3-jet events (open circles).

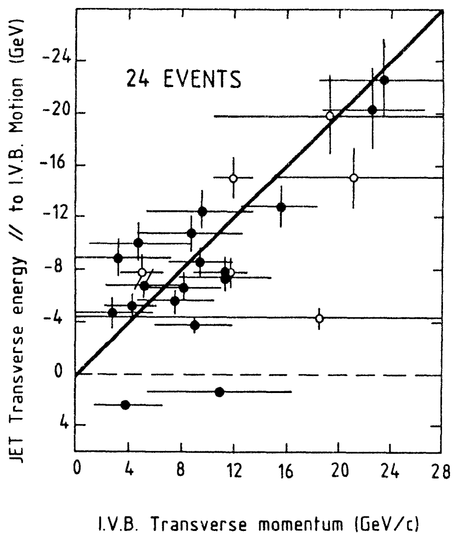

Figure 19. Plot of W transverse momentum (solid circles) or Z^0 transverse momentum (open circles) against the component of jet transverse energy which is parallel to the intermediate vector boson. The transverse motion of the W or Z^0 tends to be balanced by a jet.

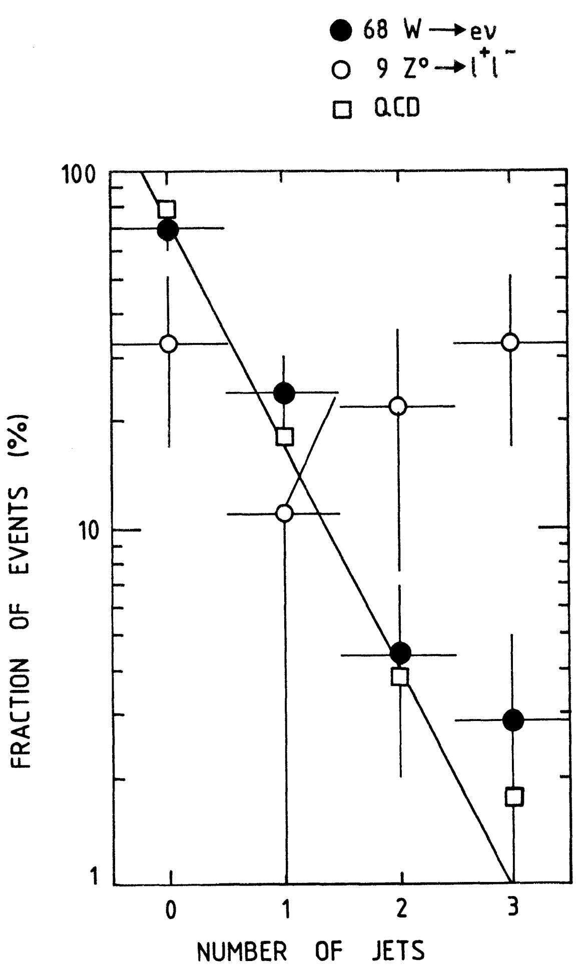

Figure 21. Number of jets observed in W and Z^0 events compared with the QCD bremsstrahlung rate.

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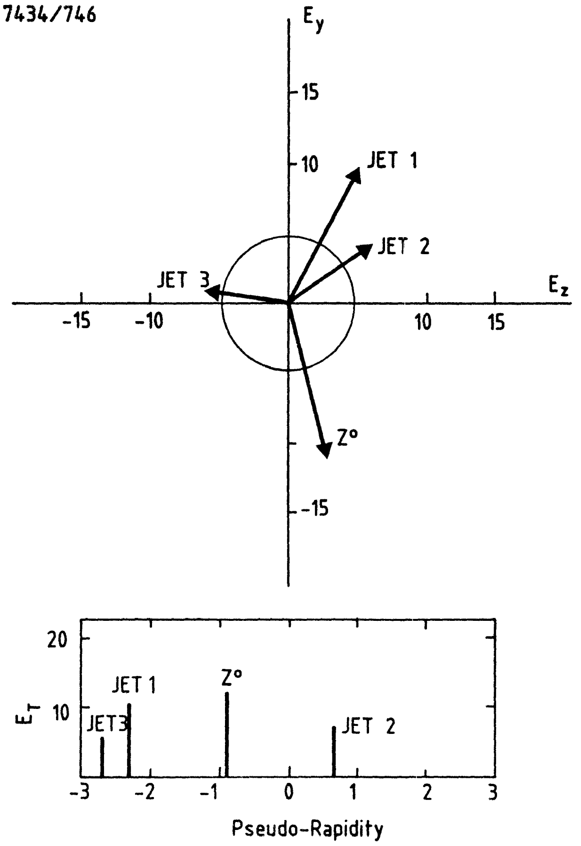

Figure 22. Transverse view of a Z^0 event which contains three additional jets.

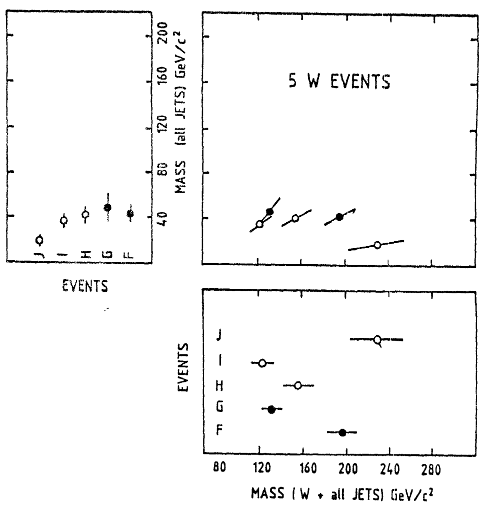

Figure 23a. Plot of the mass of W + all jets against the mass of all jets. The open circles are events with two jets. The closed circles are events with three jets.

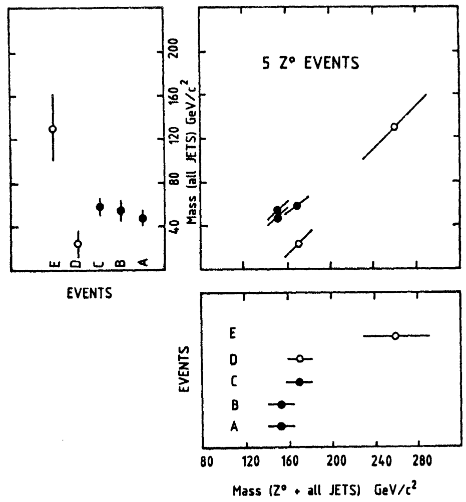

Figure 23b. Plot of the mass of Z^0 + all jets against the mass of all jets. The open circles are events with two jets. The closed circles are events with three jets.

find a tendency for the Z^0 events to cluster in mass (compared to the W events) which could be a hint of an anomolous source of the Z^0 + jet events.

IV. Conclusions

We have observed 2 events with a single electromagnetic cluster and large missing E_T; however, we cannot exclude that one of these events is a $W \to e\nu$ decay. We have also observed 5 events with a single narrow jet and large missing E_T. We can offer no explanation of these events in terms of backgrounds or known physical processes.

We find our W + jet events to be consistent with expectations of QCD. However, we find a hint of an anomaly in the hadronic configuration in events containing a Z^0 decay.

We are anxiously awaiting more data to determine the underlying physics behind these events.

V. Acknowledgements

We are thankful to the management and staff of CERN for vigorous support of the UA1 experiment.

The UA1 experiment is a collaboration of Aachen, Annecy, Birmingham, CERN, Harvard, Helsinki, Kiel, Queen Mary College (London), NIKHEF, College de France (Paris), U. C. Riverside, Roma, Rutherford Appleton LAb., Saclay (CEN), Vienna, and Wisconsin. The results presented here represent the hard work of many collaborators.

It is a pleasure to acknowledge the help of Professor Carlo Rubbia in the preparation of this talk, and also the untiring help of Madame C. Rigoni in the preparation of figures. I thank the conference organizers for a pleasant visit to Leipzig.

This work was supported in part by a grant (DE-FG02-84ER40171) from the U.S. Department of Energy through the Outstanding Junior Investigators program.

VI. References

1. See UA1 results presented by R. Bock, this conference.

2. Minimum bias events are triggered by the presence of one or more charged tracks in each of two large hodoscopes surrounding the beam line. We trigger on about 2/3 of the inelastic cross section. For a description of the detector, see A. Astbury et al., CERN/SPSC/78-06 (1978).

3. For details of the W event selection, see G. Arnison et al., Phys. Lett. 122B, 103 (1983); G. Arnison et al., Phys. Lett. 129B, 273 (1983).

4. G. Arnison et al., Phys. Lett. 139B, 115 (1984).

5. The errors quoted do not include possible additional small systematic effects.

6. For example, for gluino pair production with each gluino decaying into quark, antiquark, and photino (with the photino stable), our event rate places a lower limit on the gluino mass of about 40 GeV. See J. Ellis and H. Kowalski, CERN TH-3843 (1984).

7. G. Arnison et al., Phys. Lett. 126B, 398 (1983); G. Arnison et al., Phys. Lett. 134B, 469 (1984); G. Arnison et al., CERN EP 84-100 (1984), Phys. Lett. in press.

8. G. Arnison et al., Phys. Lett. 135B, 250 (1984).

9. See results presented by UA2, this conference.

10. For some results on theoretical expectations, see F. Halzen et al., Z. Phys. C14, 351 (1982).

11. The p_T distribution of the charged particles in W, Z^0, and minimum bias events have roughly the same exponential shape. For some more details, see S. Geer, Proceedings of the XIX Recontre de Moriond, La Plagne (1984).

12. For a description of the jet finding algorythm, see G. Arnison et al., Phys. Lett. 132B, 214 (1984).

13. The W and Z^0 events with jets show the same angular distribution in θ^* within statistics.

Discussion

J. Poirier, Notre Dame: What is the distribution of the angle of the missing transverse energy relative to the vertical hole in your detection efficiency?

J. Rohlf: It is flat within statistics. We have a small vertical crack in the calorimetry where the light guides are, however, the central detector is 100% efficient in this region for detecting charged particles. To avoid any possible problem with neutrals escaping vertically, we have vetoed events in the selection process if the missing E_T points within ±20 degrees of the crack. Then the missing E_T can point anywhere outside of the 20 degree cut. It is flat.

A. C. Melissinos, Rochester: What is the status of the radiative Z^0 events?

J. Rohlf: We have two events one $e^+e^-\gamma$ and one $\mu^+\mu^-\gamma$. Let me remind you that gamma in this context could be any number of photons of low mass. In the electrom event the photon has an energy of nearly 40 GeV. One needs it to make the Z^0 mass. The mass without the gamma is 43 GeV and the mass with the gamma is 99 GeV. The angle between the electron and the gamma is small but measurable. It is an unlikely configuration for QED radiation. In the muon event the gamma energy is about 30 GeV. It is at a small angle (about 7 degrees) with the positive muon. The three body mass is 88 GeV and the mass without the gamma is 71 GeV. However, the error on the upper side is about 40 GeV (it is much harder to make the masses go lower) so we can't tell if we "need" the gamma to make the Z^0 mass. It also would be an unlikely configuration from QED. As you know UA2 also have an $ee\gamma$ event. We will get the details in the next talk. We have found no analogous events in our W sample. You can be sure that we will watch this issue very carefully this Fall when we run again.

Z. Kunszt, Bern: Could you give some more detail on those events which have large missing transverse energy and have multijet structure? Are they consistent with the three active $Z^0 \to \ell^+\ell^- + X$ events assuming that the Z decays into $\nu\bar{\nu}$ pair?

J. Rohlf: There is only one event (a three jet event) which is inconsistent with backgrounds from jet resolutions. The jets have E_T's of about 55 GeV, 20 GeV, and 15 GeV. The missing E_T is 55 GeV. It is a very nice event, because the jets are very striking. With the asumption that the missing E_T is due to a Z^0 decay into neutrinos, the invariant mass of Z^0 + all three jets is much larger than the active Z^0 events. This is partially because one of the three jets is forward-going and it has a huge energy.

H. Fritzsch, Munich: To what extent are monojets different from normal hadronic jets observed in the UA1 detector?

J. Rohlf: They are very normal except for one property, the jet size (or mass). The monojets seem to be more collimated but it is a hard statement to make on such a small number of events. One property that is normal is the fraction of energy in charged particles; another is the division of energy between the iron and lead sections of the calorimeter. The jets look good to us; we just didn't expect to see them one per event.

W. Allison, Oxford: Can you comment on the conflict between the apparent agreement of the W and Z cross sections with the number of events observed based on a single production mechanism on the one hand and on the other hand the apparent difference between their phenomenology as now shown in your data?

J. Rohlf: There is no conflict within statistics. Our W to Z cross section ratio agrees with theory. If there were an anomolous source of Z's which accounted for half of them, then the other half would still satisfy theory. The statistics are low and besides the theory (let's say phenomenology) is not that good yet. But this is something to watch when we get lots of data. A good bookkeeping of the W's and Z's will be essential.