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$W^{\pm}$ AND Z^0 PRODUCTION IN THE UA1 EXPERIMENT
AT THE CERN PROTON-ANTIPROTON COLLIDER

UA1 Collaboration, CERN, Geneva, Switzerland

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

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1. INTRODUCTION

In this presentation I will summarize new physics results concerning the production and decay of the $W^{\pm}$ and Z^0 intermediate bosons obtained during the last year by the UA1 experiment at CERN. The data recorded in the spring of 1983 are from proton-antiproton collisions at a total centre-of-mass energy of 540 GeV, corresponding to an integrated luminosity of 136 nb^{-1} . Preliminary results presented in this paper are extracted from the data obtained during the autumn of 1984 at a centre-of-mass energy of 630 GeV for a total recorded integrated luminosity of 270 nb^{-1} .

This paper deals with three main subjects. The first is the search for the decay of the Intermediate Vector Bosons (IVBs) into two hadronic jets. The second concerns the possible anomalies in the production or the decay of the IVBs. Such anomalies could uncover possible physics phenomena beyond the Standard Model of the electroweak interactions. They are:

- a) the production of hard hadronic jets in association with the IVB and
- b) the presence of the radiative Z^0 's. The third is the observation of a new leptonic decay channel of the $W^{\pm}$ in the τ heavy lepton.

2. SEARCH FOR THE DECAY OF THE IVB INTO TWO HADRONIC JETS

The data sample used is based on an 'inclusive jet' trigger defined by summing transverse energies over calorimeter cells in a sliding geometrical window. The window covered a region of $\Delta\eta = 1$, $\Delta\phi = 180^\circ$ in the range $|\eta| \leq 1.5$, and of $\Delta\eta = 1.5$, $\Delta\phi = 90^\circ$ for $1.5 < |\eta| \leq 3$. The analysis is based on three data samples with different thresholds on the nominal E_T deposition in these windows, in detail:

$E_T \geq 15 \text{ GeV}$ (for an integrated luminosity of 6.1 events per nanobarn),

$E_T \geq 20 \text{ GeV}$ (40.1 events per nanobarn),

$E_T \geq 25 \text{ GeV}$ (64.6 events per nanobarn).

During reconstruction of events, detailed corrections for each calorimeter cell are applied to take into account measured attenuation tables and an average response factor for hadrons in electromagnetic calorimeters. The corrected energies in the window are typically 10-15% higher than the nominal ones.

The algorithm used for defining jets in UA1 calorimeters has been described before¹. It relies on local maxima, initiator cells with a threshold transverse energy (1.5 GeV), around which cells are added in order of decreasing transverse energy to form a cluster. The dependence of jets on the initiator threshold has been shown to be negligible for jet transverse energies of 15 GeV or more. All cells are considered provided they are geometrically close enough in a metric variable ΔR defined by

$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} .$$

Charged track information is not used for finding jets or for defining their energy. An average response factor of 1.13 was used for depositions in electromagnetic calorimeters, to account for the hadron/ π^0 mixture expected in jets.

The use of a clustering algorithm for defining a jet direction and energy entails a number of corrections:

- i) The retained jets will invariably not contain any jet debris that has been emitted further from the jet axis than the cut parameter ΔR . From e^+e^- experiments² and currently accepted fragmentation models³ this is known to have a measurable effect, in particular on the total jet energy.

- ii) Any spectator remains, i.e. parton debris not connected with the hard interaction will be included in the jet by the algorithm if they happen to fall in the angular region defined for the jet.
- iii) The small uninstrumented zones in UA1's calorimeters cause some losses in jet energy as a function of the jet direction, whose average value can only be determined by Monte Carlo techniques, using the detailed knowledge of the detector.

Corrections for these effects have been determined using extensive Monte Carlo calculations. Quantum chromodynamic (QCD) 2-jet events were generated with varying E_T threshold using the QCD event generator ISAJET⁴. The final-state particles resulting from fragmentation and spectator particles were followed through the detector using in particular a suitable approximation for calorimeter deposition⁵. The jet algorithm was then applied, and reconstructed jets were compared with the emitted partons in energy and direction. If the angular difference was too large ($\Delta R > 1$), the event was rejected. Average values for corrections and their r.m.s. errors were evaluated as a function of transverse energy E_T , rapidity η , and azimuthal angle φ .

In Fig. 1 we show the invariant mass of the jet-jet system. Jet energies have been corrected as described above. No structure is observed, either in the IVB mass region or in the higher mass range.

The jet transverse energy resolution has been calculated by Monte Carlo and can be approximated by the following formula:

$$\Delta E_T / E_T = 1.5 / \sqrt{E_T} \quad [E_T \text{ in GeV}] .$$

This translates to a resolution in jet-jet mass of about 20% in the IVB mass range.

3. JET ACTIVITY ASSOCIATED WITH $W^{\pm}$ AND Z^0 PRODUCTION

The majority of the IVBs produced at the CERN $p\bar{p}$ Collider are expected to come from the Drell-Yan mechanism⁶, the annihilation of a quark from the proton with an antiquark from the antiproton. The incoming annihilating quark and antiquark will radiate gluons. These initial-state bremsstrahlung gluons tend to go in the direction of the incoming beams and to have a low transverse momentum. However, occasionally one of these radiated gluons will have a sufficiently high transverse momentum to produce an observable hadronic jet in the event. In this QCD picture of IVB production we expect

- i) the occasional observation of a hadronic jet produced in association with W or Z^0 ;
- ii) that these jets should recoil against the IVB in the transverse plane, and their transverse momentum should tend to balance the IVB transverse momentum;
- iii) that this jet activity should be associated with higher-transverse-momentum IVBs.

A deviation from the QCD expectations would indicate the existence of an unexpected production mechanism creating the IVBs. For example, too many jets at large angle with respect to the beam direction might indicate the production of a massive object X which subsequently decays into an IVB plus one or more jets. On the other hand, too many jets at small angle with respect to the beam direction could indicate the production of W and Z^0 bosons by partons having an unusual colour structure, etc.

In order to look for such phenomena, the standard UA1 jet algorithm¹ has been used to reconstruct the jet activity in our samples of

- i) $68 W^{\pm} \rightarrow e^{\pm} \nu_e$ events⁷
- ii) $9 Z^0 \rightarrow l^+ l^-$ events⁸

coming from the 1982 and 1983 data-taking runs of the UA1 Collaboration. A detailed analysis of these early statistics has been published elsewhere⁹. The same analysis has also been pursued adding the $W^\pm$ and Z^0 candidate events coming from the recent 1984 data-taking run. The overall statistics containing events and candidates (some of these events have not been certified as showing the correct process at the Megatek scanning level) are the following:

- i) 151 $W^\pm \rightarrow e^\pm \nu_e$ events + candidates
- ii) 42 $W^\pm \rightarrow \mu^\pm \nu_\mu$ events + candidates
- iii) 31 $Z^0 \rightarrow l^+ l^-$ events + candidates

The 1984 run data are still highly preliminary and subject to small changes after the complete analysis of $W^\pm$ and Z^0 events has been performed, although the main results will not be modified.

Such jet activity is indeed observed, and examples of it are shown in Figs. 2 and 3 which display a graphic representation of UA1 events. Figure 2 shows a $W^\pm$ decaying into the $(e \nu_e)$ channel accompanied with the emission of a hard central jet of 23 GeV/c, and the muonic decay of a $W^\pm$ with the highest transverse momentum $p_T^W = 38$ GeV/c. Both W's are recoiling back-to-back with the jets in the transverse plane. The same feature is also observed in Z^0 events containing jets as shown in Fig. 3.

Using the entire statistics available on $W^\pm$ events, we verify that the jet activity reconstructed in $W^\pm$ events has the gross features that we expect for jets arising from initial-state gluon bremsstrahlung, namely

- i) the jets tend to recoil against the IVB in the transverse plane, and their transverse momenta tend to balance the IVB transverse momenta,
- ii) the jet activity is associated with the higher-transverse-momentum IVBs (see Figs. 4a,b and 5).

In Fig. 4, the UA1 events are compared with the QCD model of Altarelli et al¹⁰. It can be seen that the number of events having W's of high momentum and containing a hard hadronic jet are quite consistent with what is expected from the tail of the QCD prediction. For comparison, also shown on these plots are the three published events from the UA2 experiment having the highest p_T of the W's¹¹.

The angular distribution of jets reconstructed in W events is strongly peaked in the beam directions. This can be seen in Fig. 6, where the distribution of $|\cos \theta^*|$ is shown, θ^* being the angle between the jet and the average beam direction in the rest frame of the W and the jet. The shape of this distribution is in agreement with our expectation for initial-state gluon bremsstrahlung, namely $(1 - |\cos \theta^*|)^{-1}$.

Finally, for comparison with the jet activity in the IVB event samples, we also use the UA1 jet algorithm to reconstruct jets in a sample of 387 hadronic multijet events satisfying the following requirements:

- i) there must be at least two hadronic jets in the event;
- ii) the two highest transverse-energy jets reconstructed by the algorithm must have a two-jet invariant mass close to the W mass (70-90 GeV/c²);
- iii) the angle θ between the direction of the two highest transverse-energy jets and the average beam direction in the rest frame of the jet pair is required to satisfy $|\cos \theta| < 0.2$.

By selecting angles close to 90° we maximize the separation between initial-state gluon bremsstrahlung which will tend to go along the beam directions, and final-state gluon bremsstrahlung which will tend to go along the jet-jet direction and be absorbed by the jet algorithm into the two highest transverse-energy jets.

From our sample of 387 events satisfying these criteria, 163 events have 'additional' jet activity, i.e. jet activity in addition to the two

highest transverse-energy jets. The properties of these additional jets from hadronic multijet events compare well with the corresponding properties of the jets reconstructed in the IVB events, and our QCD expectations for these properties.

Defining R_W to be the fraction of W events containing jet activity, and R_J to be the corresponding fraction of multijet events containing 'additional' jet activity, we find, after making a small correction for differences in the experimental acceptance, that $R_W/R_J = 0.7 \pm 0.2$. This is in excellent agreement with the lowest-order QCD expectation from Ref. 12 for this ratio, namely 0.69 to 0.73 (depending on the structure function used). The ratio R_W/R_J is expected to be insensitive to experimental and theoretical uncertainties common to both W and multijet events. Individually, however, R_W and R_J will depend on details such as the experimental efficiency for reconstructing low-transverse-energy jets, and on the transverse-energy threshold used to define a jet.

The rates of 'jetty' W and Z^0 events are also in good agreement with the lowest-order QCD expectation¹² mentioned above, as seen in Figs. 7 and 8.

Before we conclude that the jet activity observed in W and Z^0 events is well understood in the framework of QCD, we should at least look at the (W + jet)-mass distribution (Fig. 9) to see if there is any evidence for the production of a state X which subsequently decays into a W and a hadronic jet. There is no clear evidence for such a process, and indeed the shape of the (W + jet)-mass distribution is well described by the lowest-order QCD calculation of Ref. 12; so is the (Z^0 + jet)-mass distribution.

To summarize, the jet activity observed in W and Z events is in agreement with our expectations for QCD corrections to the bare parton-model picture of Drell-Yan annihilation.

4. RADIATIVE Z^0 's

The two events interpreted as $Z^0 \rightarrow l^+ l^- \gamma$ decay may be a possible indication for new physics. A summary of the main parameters of these events is given in Table 1. The dominant feature is the high photon energy and the large opening angle between the charged lepton and the photon. The possibility of a bremsstrahlung with such an energy and angle observed is very small.

Out of a subset of the total statistics taken during the 1984 run and analysed on-line, no event of identical type to the above has been found. Therefore, so far, these effects have not been confirmed. However, it is certainly too early to conclude before a full analysis has been carefully performed on all 1984 events.

5. EXPERIMENTAL EVIDENCE FOR THE HEAVY LEPTON DECAY $W \rightarrow \tau \nu_\tau$

With the observation of the $W \rightarrow \tau \nu$ decay, the 'programme' on the leptonic decay channels of the IVB is complete.

In the case of a $W \rightarrow \tau \nu$ event where the τ decays in the hadronic mode, what we measure is a jet including charged tracks and the corresponding energy deposition in some calorimeter cells (both hadronic and electromagnetic). The measured jet represents the charged and neutral π 's of ν from the W decay and that from the τ decay. Therefore, events with missing transverse energy and one trigger jet were selected in the data recorded during the 1982 and 1983 runs (corresponding to an integrated luminosity of 136 nb^{-1}).

As a consequence of the e, μ, τ universality of the weak current, the $W \rightarrow \tau \nu$ rate is expected to be relatively abundant. Almost half of the τ 's decay into one charged π (10% without neutrals and 38% with) and a neutrino¹³. This suggests a clear signature with a reasonable rate: an isolated high- p_T track of a hadronic type and some missing transverse energy. In this sense,

this search is rather similar to the one for the $W \rightarrow e\nu$, except that now we look for a hadronic track instead of an electromagnetic (e.m.) one and the pion will have a continuous energy spectrum.

The data are selected from the total statistics of the 1982 and 1983 $p\bar{p}$ runs, processed through an off-line filter characterized by a cut on the total missing transverse energy of 15 GeV as already described¹⁴. The following selection criteria are applied to the initial sample of 29,962 events:

- i) A validation of the missing transverse energy defined by $E_T^{\text{miss}} > 2\sigma$, where $\sigma = 0.7 \sqrt{E_T}$ (E_T is the scalar sum, in GeV, of observed transverse-energy contributions from all calorimeter cells). Because of the reduced efficiency of the calorimetry in the region $\pm 15^\circ$ around the vertical axis, we exclude events which have a jet axis in this region and events for which the sum of the p_T of all the central detector (CD) tracks in this region exceeds 15% of the total transverse energy.
- ii) A validation of the trigger jet defined as the calorimeter jet with highest transverse energy in the pseudorapidity range $|\eta| < 1.5$. A matching is required between the calorimeter jet and the CD jet.
- iii) No jet back-to-back with the trigger jet: the backward region is defined by the angle $\phi^{\text{back}} = 180^\circ \pm 30^\circ$ around the jet axis. It is required that there be no jet inside this backward region, with $E_T^{\text{jet}} > 7 \text{ GeV}$ or $p_T^{\text{jet}} > 5 \text{ GeV}$ for a jet rapidity $\eta^{\text{jet}} \leq 2.5$. We are left with 550 events at this stage.
- iv) Events with activity back-to-back to the trigger jet, but with no jet reconstructed by the jet algorithm are rejected. We require that the total sum of the p_T of the tracks included in the backward zone ($\sum_{\text{back}} p_T$) be less than 4 GeV, and the sum of the transverse energy in the calorimeter cells included in this backward zone ($\sum_{\text{back}} E_T$) be less than 6 GeV.

v) We require that the trigger jet has a leading track with a minimum p_T of 4 GeV/c.

We finally remove all events recognized already as $W \rightarrow e\nu$ and scan the remaining sample. We end up with 16 events, which are subdivided into three topological categories:

- Five events with a single high- p_T charged track, which we call the 'one-branch sample'. Two of them have an associated jet with $E_T^{\text{jet}} > 10$ GeV not back-to-back with the trigger jet.
- Four events with two or three charged tracks which we call the 'three-branch sample'.
- Seven events with more than three charged tracks or E_T^{jet} larger than 40 GeV which we call the 'multi-branch sample'.

This paper is concerned only with the one-branch and three-branch categories, which are regarded as τ candidates. The main properties of these events are summarized in Tables 2 and 3. A view of these events is shown in Fig. 10.

We now discuss some kinematical and physical properties of the τ candidates in order to test their consistency with the $W \rightarrow \tau\nu$ hypothesis. We compare some results for the process $W \rightarrow \tau\nu$ with the corresponding ones in the now well-known case of $W \rightarrow e\nu$ ⁷ and with the expectations from a Monte Carlo simulation of $W \rightarrow \tau\nu$ events. The Monte Carlo takes into account polarization effects^{4,15} and includes the effects of trigger and off-line selections.

5.1 Hadronic quality of the one-branch sample

To define this property we use the experience gained during our previous searches for $W \rightarrow e\nu$ ⁷ and $W \rightarrow t\bar{b}$ ¹⁶, where we studied in detail how to identify isolated high- p_T electrons.

Tracks with $p_T > 10$ GeV are classed as hadronic if the deposition in the hadron calorimeter cell behind two adjacent e.m. cells is at least 500 MeV or 1% of the total energy (in e.m. and hadronic calorimeters). In addition, a good e.m. shape in the energy depositions of the four e.m. segments is characterized by its χ_R^2 ¹⁷; we thus require this quality parameter to be larger than 35.

If the charged track has a $p_T < 10$ GeV, it is difficult to recognize the shape of the shower development. On the other hand, a charged hadron can be identified by a clear mismatch in space and/or energy when comparing the CD and the calorimeter information. At least one of the following three factors will be outside the e.m. bounds:

$$[(1/p - 1/E)/\sigma(1/p - 1/E)] > 3, \quad \Delta x/\sigma_\chi > 3, \quad \Delta\phi/\sigma_\phi > 3.$$

The first factor measures the matching between p , the momentum measurement in the CD, and E , the calorimeter energy deposition; $\Delta x/\sigma_\chi$ evaluates the matching along the beam direction; and $\Delta\phi/\sigma_\phi$ gives the matching in azimuth of the CD information compared to the calorimeter information.

In Fig. 11 we give the hadronic characteristics of our five one-branch events. We compare them with the $W \rightarrow e\nu$ case and the expected results from the τ -generated events. There is a significant disagreement with the $W \rightarrow e\nu$ events and a good agreement with the Monte Carlo expectation. We conclude that all five one-branch events pass the hadron quality test.

In addition, as we require the sum of the p_T of all tracks included in a 20° cone around the track candidate to be ≤ 1.5 GeV and no track with

$p_T > 1$ GeV in a cone of 30° , we conclude also that those 5 events are characterized by a single isolated hadron associated with missing transverse energy.

5.2 Kinematical properties of the selected events

The display of E_T^{jet} versus E_T^{miss} for the one-branch and three-branch events is compared with the measured $W \rightarrow e\nu$ sample and the Monte Carlo expectations (Fig. 12). Notice that, as expected, the τ candidates are systematically lower, in the measured transverse energy and in the missing transverse energy, than the $W \rightarrow e\nu$ events.

To calculate the invariant mass of the system $\pi^+(n\pi^0)$ or $\pi^+\pi^-\pi^+(n\pi^0)$, we use the information given by the e.m. central calorimeter and the CD¹⁸. The energy deposited by π^0 's in the electromagnetic calorimeters is obtained by subtracting, from the overall electromagnetic calorimeter deposition the sum of charged track energies as measured in the CD diminished by the amount of energy seen in the hadronic cell(s) behind. An average π^0 impact point in the electromagnetic calorimeter can be computed, allowing the effective mass of the charged and neutral pion(s) to be calculated, thus checking the consistency with a τ decay hypothesis. The transverse mass of the (τ, ν) system is defined as the transverse mass of the system by E_T^{miss} and the measured jet. The masses are plotted in Fig. 13 and show a consistency with the τ hypothesis for the one- and three- branch samples.

5.3 Background from QCD bijets

The main source of background is due to standard bijets, where one or both jets are mismeasured because of either leakage or fluctuations in the calorimeter response. To estimate this background, we use an experi-

mental sample of bijets which we fluctuate in energy according to the resolution of our apparatus. We have also generated QCD bijets using the ISAJET Monte Carlo program in different bins in E_T of the jets. The two samples are in good agreement with each other, yielding a rejection factor of 0(10) for jets with $E_T^{\text{jet}} < 25$ GeV and 0(5) for jets with $E_T^{\text{jet}} > 25$ GeV.

We have so far not constrained the multiplicity of the trigger jet. To define the multiplicity, we only count, in a cone in $\Delta R = (\Delta\eta^2 + \Delta\phi^2)^{1/2} < 0.5$ (where ϕ is the azimuthal angle measured in radians and η is the pseudo-rapidity), those tracks with $p_T \geq 0.5$ GeV. The multiplicities for experimental jets between 15 and 25 GeV are plotted in Fig. 14.

It shows that for one-charged-track events, an additional reduction factor of 10 for jets with $15 \text{ GeV} \leq E_T^{\text{jet}} \leq 25 \text{ GeV}$ and 20 for jets with $E_T^{\text{jet}} > 25 \text{ GeV}$ are obtained. For a multiplicity of two or three, the reduction factor is only two. So we have an overall rejection factor, using the CD information of 0(100) for the one-branch sample and 0(20) for the three-branch sample.

The background due to QCD jet fluctuation is 0.5 ± 0.1 (stat.) for the five one-branch events sample. Thus the signal $W \rightarrow \tau\nu$ events, where $\tau^\pm \rightarrow \pi^\pm (n\pi^0)\nu$ rises clearly above the QCD background. For the four events in the three-branch sample, the background is 2 ± 1 (stat.). If we require $E_T^{\text{miss}} > 3\sigma$, we are left with three events but now the background is reduced to 0.6 ± 0.2 (stat.). In these conditions the signal of τ in three charged π 's begins to be significant. A more detailed study of the background can be found elsewhere¹⁹.

The overall detection efficiency for the τ is 15%. We can then apply this factor to determine the branching ratio R of the process $W \rightarrow \tau\nu$ with respect to the electron mode. From this search we obtain five events compatible with $W^\pm \rightarrow \tau^\pm\nu$ where $\tau^\pm \rightarrow \pi^\pm(n\pi^0)\nu$. With similar selection criteria we have obtained 47 $W \rightarrow e\nu$ events, corresponding to an overall detection

efficiency of 65%. If we apply the factor of 48%, which is the decay rate of τ into one charged-pion and neutrals, we obtain

$$R = (W \rightarrow \tau\nu)/(W \rightarrow e\nu) = 0.96 \pm 0.45 \text{ (stat.)} .$$

The main results obtained from this study of the 1982 and 1983 data are: a clear τ signal has been evidenced for the first time in the channel $W \rightarrow \tau\nu$ ($\tau \rightarrow$ hadronic model); the branching ratio with respect to the electron mode is $W \rightarrow \tau\nu/W \rightarrow e\nu = 0.96 \pm 0.45$, in agreement with the universality of the weak current. The corresponding main background coming from QCD bijets is strongly suppressed by using topological CD information about jets.

About the same amount of data (around 130 nb^{-1}) has been analysed from the 1984 sample with the only requirement of having a validation of the missing transverse energy defined by $E_T^{\text{miss}} > 4\sigma$. This very strong requirement does not pretend to isolate all the $W \rightarrow \tau\nu$ candidates from 1984 data but, on the other hand, the $W \rightarrow \tau\nu$ candidates extracted by this method have a very small background. Two one-branch and three three-branch candidates have been found. The characteristics of those events are listed in Table 4 and two of them are shown in Fig. 14. These very clean events appear to be a nice confirmation of the 1983 data; the whole statistics of the 1984 run, however, still remain to be fully analysed.

6. $Z^0 \rightarrow \tau^+ \tau^-$ CANDIDATES

Out of the same selection criteria described above, three events show topologies and missing energy compatible with the $Z^0 \rightarrow \tau^+ \tau^-$ hypothesis, with the following decays:

$$Z^0 \rightarrow \tau^+ (\tau^+ \rightarrow \mu^+ \nu\nu) \tau^- (\tau^- \rightarrow e^- \nu\nu) \quad (1)$$

$$Z^0 \rightarrow \tau^+ (\tau^+ \rightarrow e^+ \nu\nu) \tau^- [\tau^- \rightarrow \pi^- (n\pi^0)\nu] \quad (2)$$

$$Z^0 \rightarrow \tau^+ (\tau^+ \rightarrow e^+/\pi^+ \dots) \tau^- [\tau^- \rightarrow \pi^- \pi^+ \pi^- (n\pi^0)\nu] \quad (3)$$

The characteristics of these three events are listed in Table 5 and pictures of them are shown in Fig. 15. Again, the complete analysis of the 1984 run, searching for such processes, should clarify the situation.

7. CONCLUSIONS

- i) No peak structure is observed in the jet-jet mass distribution.
- ii) The properties of the jet activity produced in association with charged IVBs are in agreement with our expectations for jets arising predominantly from initial-state gluon bremsstrahlung off the incoming annihilating quark and/or antiquark. This is in agreement with our expectations for QCD corrections to the bare parton-model picture of Drell-Yan annihilation.
- iii) Five events with a single hadronic high- p_T charged track and missing energy are observed in the data of the 1982 and 1983 runs. This signal rises clearly above the background due to the fluctuations of QCD bijets. We interpret these events as evidence of $W \rightarrow \tau\nu$, where $\tau^\pm \rightarrow \pi^\pm (n\pi^0)\nu$. The branching ratio with respect to the electron mode is 0.96 ± 0.45 (stat).
- iv) Possible candidates for the decay $Z^0 \rightarrow \tau^+\tau^-$ are observed in the 1984 data.

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Table 1
Properties of the $l^+l^-\gamma$ events

	$e^+e^-\gamma$	$\mu^+\mu^-\gamma$
E_γ (GeV)	38.8 ± 1.5	28.3 ± 3
E_{l^+} (GeV)	61.0 ± 1.2	$50.6 \begin{smallmatrix} + 5.8 \\ - 4.7 \end{smallmatrix}$
E_{l^-} (GeV)	9 ± 1	$42.2 \begin{smallmatrix} + 44.0 \\ - 14.3 \end{smallmatrix}$
$\Delta\alpha (l^+, \gamma) (^{\circ})^a)$	132.0 ± 4.0	7.9
$\Delta\alpha (l^-, \gamma) (^{\circ})^a)$	14.4 ± 4.0	99.0
$m(l^+l^-)$ (GeV/c ²)	42.7 ± 2.4	$70.9 \begin{smallmatrix} + 37.2 \\ - 12.4 \end{smallmatrix}$
$m(l^+l^-\gamma)$ (GeV/c ²)	98.7 ± 5.0	$88.4 \begin{smallmatrix} + 46.1 \\ - 15.2 \end{smallmatrix}$
$m(l^+\gamma)$ (GeV/c ²)	88.8 ± 2.5	5.0 ± 0.4
$m(l^-\gamma)$ (GeV/c ²)	4.6 ± 1.0	$52.5 \begin{smallmatrix} + 27.5 \\ - 9.3 \end{smallmatrix}$

a) $\Delta\alpha$ is the angular difference in space.

Table 2

Main characteristics of the one-branch τ candidates

Run/Event No.	Track characteristics				Missing energy		' τ -jet'			Aco-planarity ($\cos \theta^{\pm}$)	$M_T(\nu, \tau)$ (GeV/ c^2)	Second-jet charac- teristics
	p_T^{CD} (GeV)	η	ϕ ($^\circ$)	Length (m)	$\Delta p/p$ (%)	ΣE_T (GeV)	E_T^{miss} (GeV)	E_T (GeV)	η	ϕ ($^\circ$)		
5181/126	4.5	-0.72	26.7	1.2	2.8	88.5	20.0	26.2	-0.74	23.2	35.4	- No -
6024/1356	7.1	0.63	-62	1.0	4	48.8	16.7	15.4	0.77	-60	29.5	- No -
6569/1064	6.4	0.23	106.2	0.8	4	80.7	18.6	16	0.31	108	33.1	- No -
7814/86	14.9	0.71	9.9	0.89	17	87.7	28.6	32.1	0.79	11	57.7	E_T^C : 15.8 GeV $\eta = -1.36$ $\phi = 125^\circ$ E_T^{CD} : 12.4 GeV $\eta = -1.38$ $\phi = 115^\circ$
8575/409	11.1	0.97	-66.1	1.5	7	74.9	15.6	19.2	1.02	-69	31.6	E_T^C : 13.6 GeV $\eta = 0.2$ $\phi = 171^\circ$ E_T^{CD} : 2.6 GeV $\eta = 0.1$ $\phi = 137^\circ$

Table 3
Main characteristics of the three-branch τ candidates

Run/Event No.	Track content of the ' τ -jet' candidate					Missing energy		' τ -jet			Aco- plan- arity (%)	Asymmetry ($\cos \theta_{\tau^\pm}^\pm$)	$M_T(\nu, \tau)$ (GeV/ c^2)	Second jet non b/b
	p_T^{CD} (GeV)	η	ϕ ($^\circ$)	Length (m)	$\Delta p/p$ (%)	ΣE_T (GeV)	E_T^{miss} (GeV)	p_T^{CD} E_T (GeV)	η^{CD} η_{calo}	ϕ^{CD} ϕ_{calo} ($^\circ$)				
3303/1289	+1.14	-0.12	-50.6	0.8	14	69.3	21.6	7.6	0.28	-60	8.0	0.29	35.2	- No -
	+1.30	0.53	-62.9	0.9	10			25.6	0.31	-49				
	-5.19	0.29	-60.9	0.9	29									
6378/213	+5.9	-0.72	215.1	1.1	69			9.9	-0.71	-145	0.4	-0.60	30.1	- No -
	-1.0	-0.82	209.9	1.0	23	77.0	15.5	19.2	-0.72	-158				
	+0.35	-0.12	229.9	1.9	-									
7255/103	+1.69	-1.22	72.1	1.6	6	60.6	17.6	6.0	-1.0	63	18.3	+0.79	33.0	- No -
	-4.16	-0.86	58.8	1.3	15			18.9	-1.16	72				
	-0.20	-1.44	82.6	1	-									
8032/1158	-4.78	-0.25	38.6	0.7	64	90.3	36.0	14.8	-0.20	44	5.6	0.28	66.2	- No -
	-7.60	-0.33	41.4	0.7	97			38.3	-0.33	42				

Table 4 $W \rightarrow \tau$ candidates from 130 nb^{-1} (1984 data)

Run/Event No.	Charged tracks P_T^{CD} (GeV)	Missing energy E_T^{miss} (GeV)	' τ -jet' E_T^J (GeV)	$M_T(\nu, \tau)$ (GeV/c ²)
10486/358	- 6.3	36	31	66
10614/803	+13.1	23	26	49
11622/129	+19.7 -13.0 $m = 1.76 \pm 0.17$ + 6.2	27	38	55
11109/247	+23.4 - 6.6 $m = 2.7 \pm 1.02$ - 3.1	22	22	44
11673/499	+12.2 - 8.7 $m = 0.99 \pm 0.03$ - 7.7	19	21	39

Table 5 $z^0 \rightarrow \tau^+ \tau^-$ candidates from 130 nb^{-1} (1984 data)

Run/Event No.	Charged tracks				E_T^{miss} (GeV)	M (GeV/c ²)
	τ^+		τ^-			
	p_T^{CD} (GeV)	p^{CD} (GeV)	p_T^{CD} (GeV)	p^{CD} (GeV)		
(1) 11441/438	24.9	24.9 ± 7.1	13.2	22.3 ± 1.1	21	42 ± 6 ($M_{\mu^+ e^-}$)
(2) 11246/146	22.5	25 ± 6	8.2	8.6 ± 0.5	24	29 ± 3 ($M_{e^+ \pi^-}$)
(3) 11130/100	5.5	5.7 ± 0.3	2.6	-7.4 ± 0.04	25	35 ($M_{\text{jet}, \pi/e}$)

Figure captions

Fig. 1 : Observed two-jet mass spectrum. No significant structure is observed.

Fig. 2 : Graphic representation of:

A) $W \rightarrow e \nu_e$ event;

B) $W \rightarrow \mu \nu_\mu$ event having the W with the largest transverse momentum ($p_T^W = 38 \text{ GeV}/c$).

Both W's are recoiling against a hadronic jet with a reconstructed transverse energy which just balances the W transverse motion.

Fig. 3 : Graphic representation of:

A) $Z^0 \rightarrow e^+ e^-$ event;

B) $Z^0 \rightarrow \mu^+ \mu^-$ event.

Both events contain, in addition, a hadronic jet recoiling against the Z^0 .

Fig. 4 : W transverse momentum distribution for the decays A) in $e \nu$,

B) in $\mu \nu$. The events containing hadronic jet activity dominate the tail of the distribution. The QCD curve is from Ref. 12. UA2 events from Ref. 11.

Fig. 5 : Correlation between W transverse momentum and jet transverse energy. For W events in which more than one jet has been reconstructed, only the highest E_T jet has been plotted.

Fig. 6 : Angular distribution of jets in W events compared with the QCD distribution from Ref. 12.

Fig. 7 : Distribution of the number of jets contained in $W \rightarrow e\nu$ events. The QCD curve is from Ref. 12.

Fig. 8 : Distribution of the number of jets contained in $Z^0 \rightarrow e^+e^-$ and $Z^0 \rightarrow \mu^+\mu^-$ events. The QCD curve is from Ref. 12.

Fig. 9 : (W + jet)-invariant-mass distribution. The QCD curve is from Ref. 12.

Fig. 10 : Megatek views of (A) a one-branch and (B) a three-branch event.

Fig. 11 : Hadronic properties of the one-branch events: the hadron quality of the one-branch sample (A, shaded) is compared with the electron quality of the control sample: $W \rightarrow e\nu$ (B). The quality variables shown are:

- a) the matching along the beam direction: $\Delta X/\sigma_X$;
- b) the matching in azimuth: $\Delta\phi/\sigma_\phi$;
- c) the matching between the momentum measurement and the calorimeter energy deposition;
- d) an overall quality parameter χ_R^2 , measuring the e.m. shape of the longitudinal shower profile and the pulse sharing between the different calorimeter samples;
- e) the energy deposited in the hadron calorimeter behind the e.m. shower.

Fig. 12 : Scatter plot of the total missing transverse energy versus the lepton transverse energy of the sample (A) of the one-branch and three-branch events (candidates $W \rightarrow \tau\nu$), compared to the same plot for the sample $W \rightarrow e\nu$ (B). The missing transverse energy and the lepton transverse energy distributions for the one-branch and the three-branch samples (shaded) are compared with ISAJET Monte Carlo curves for one-branch (dashed curve) and three-branch τ 's (dash-dotted curve). By lepton transverse energy, we mean, in the case of τ candidates, the transverse energy of the measured jet, where the jet includes one or three charged pions and possible additional neutral pions.

Fig. 13 : τ properties of the one-branch and three-branch events (shaded).

It includes parameters which ensure the τ decay (e.g. the invariant mass) or parameters which ensure a $W \rightarrow \tau\nu$ decay (such as the transverse mass).

- a) The invariant mass of the systems $(\pi^{\pm}, n\pi^0)$ and $(\pi^{\pm}, \pi^{\mp}, \pi^{\pm}, n\pi^0)$ is compared with the Monte Carlo predictions (dashed curve), including full apparatus simulation.
- b) The transverse mass of the system (' τ jet', ' ν ') for the total sample of one-branch and three-branch events (shaded) is compared with the reference sample of $W \rightarrow e\nu$ events (solid line) and the one-branch (dash-dotted curve) and three-branch τ 's (dashed line) generated with the ISAJET Monte Carlo, including full detector simulation.

Fig. 14 : Multiplicity distributions: the multiplicity is defined in a cone in $\Delta R = (\Delta\eta^2 + \Delta\phi^2)^{1/2} < 0.5$ and counting only the tracks with $p_T > 0.5$ GeV in this cone.

- a) Multiplicity spectrum for jets which have $E_T^{\text{jet}} > 15$ GeV and satisfy the electron trigger.
- b) Multiplicity spectrum for jets which have $E_T^{\text{jet}} > 25$ GeV and satisfy the electron trigger.
- c) Multiplicity of the one- and three-branch events.

Fig. 15 : Megatek views of (A) a one-branch and (B) a three-branch event selected from 1984 data with the only requirement of having a validation of the missing transverse energy bigger than 4σ . A 1 GeV cut is applied on the transverse energy of the calorimeter cells as well as a 1 GeV/c momentum cut on charged tracks.

Fig. 16 : Megatek views of the three $Z^0 \rightarrow \tau^+ \tau^-$ candidates selected from 1984 data with the only requirement of having a validation of the missing transverse energy bigger than 4σ . A 1 GeV cut is applied on the transverse energy of the calorimeter cells as well as a 1 GeV/c momentum cut on charged tracks. The event topologies are described in the text.

Fig. 1

Fig. 2

b)

a)

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 11

Fig. 12

Fig. 13

Fig. 14