Events with Large Missing Transverse Energy at the CERN Collider : **$W \rightarrow \tau \nu$ Decay and Test of τ - μ -e Universality at $Q^2 = m_W^2$** **(Paper I)***UA1 Collaboration, CERN, Geneva, Switzerland*

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ABSTRACT

We report results based on a sample of events with large missing transverse energy corresponding to 715 nb^{-1} of data from the UA1 experiment at the CERN proton-antiproton collider. High transverse momentum tau-leptons from W decays are observed for the first time through their semi-hadronic decay modes and associated missing transverse energy. The measured relative rates of $W \rightarrow e\nu$, $W \rightarrow \mu\nu$, and $W \rightarrow \tau\nu$ provide the first direct tests of the electron-muon-tau universality of the weak charged couplings at $Q^2 = m_W^2$. We determine $g_\tau / g_e = 1.01 \pm 0.09 \pm 0.05$ and $g_\mu / g_e = 1.05 \pm 0.07 \pm 0.08$.

1.-Introduction. The UA1 experiment[1] was designed primarily to observe the charged Intermediate Vector Bosons in the decay channels $W \rightarrow e\nu$ and $W \rightarrow \mu\nu$. The emission of the neutrino is signalled by the apparent momentum imbalance in the direction transverse to the beam axis, *i.e.*, the transverse component of the missing energy vector. The missing energy vector is defined as:

$$\mathbf{E}^{\text{miss}} = - \sum_i E_i \mathbf{u}_i,$$

where $\mathbf{u}_i$ is the unit vector between the collision point and the position of the energy deposition observed in the i -th calorimeter cell. In order to measure reliably the missing transverse energy in an event one requires a detector covering the whole solid angle, *i.e.* a hermetic detector. For a perfect 4π calorimeter, one expects $\mathbf{E}^{\text{miss}}=0$ for events in which all final state particles have interacted (neglecting particle masses). If one or more non-interacting particles are emitted with a total momentum $\mathbf{p}_\nu$, then one expects $\mathbf{E}^{\text{miss}} = \mathbf{p}_\nu$. In practice, only the components E_y^{miss} , E_z^{miss} , transverse to the beam direction can be used, since a large and variable amount of energy is lost down the beam pipe. In the absence of non-interacting particles, the resolution is gaussian in each of the transverse components with the distributions centred at zero. For each component, the width of the distribution in GeV is $\sigma = 0.50 \sqrt{\Sigma E_T}$, where ΣE_T is the (scalar) sum of transverse energies in GeV observed in the calorimeter cells[2]. The square of the modulus of the transverse component of $\mathbf{E}^{\text{miss}}$, namely $(E_T^{\text{miss}})^2 = [(E_y^{\text{miss}})^2 + (E_z^{\text{miss}})^2]$ is then exponentially distributed.

The observation of events with large missing transverse energy was crucial in the discovery of the W particles[2]. An inclusive selection of missing transverse energy events provides not only the sample of $W \rightarrow e\nu$ decays, but also a significant number of additional events in which the missing transverse energy recoils against one (the so-called mono-jets) or more high transverse energy jets. Six mono-jet events have been reported by us in a paper[3] based on 118 nb^{-1} integrated luminosity.

In this paper we present further analysis of events with missing transverse energy, based on all the data recorded during the period 1983-85, corresponding to an integrated luminosity of

715 nb⁻¹ at proton-antiproton centre of mass energies of 546 GeV (118 nb⁻¹) and 630 GeV (597 nb⁻¹). This paper concentrates on the observation of the $W \rightarrow \tau \nu$ decay. An accompanying paper[4] addresses the question of additional processes contributing to missing transverse energy events. Given the observed rate of $W \rightarrow e \nu$ decays and the standard model branching ratio of about 8%, our data sample corresponds to the production of roughly 5600 W events.

Events were recorded that satisfied one or more of the following relevant hardware triggers[5]:

- a) *Electromagnetic transverse energy (E_T) trigger*, requiring E_T (energy weighted by the sine of the angle with respect to the beam axis) greater than 10 GeV in two adjacent electromagnetic calorimeter elements, or
- b) *Jet E_T trigger*, requiring a jet with $E_T > 25$ GeV in the pseudo-rapidity range $|\eta| < 2.5$, or
- c) *Transverse energy imbalance trigger*, requiring a jet with $E_T > 15$ GeV together with transverse energy imbalance greater than 17 GeV. The transverse energy imbalance trigger was not used for the 546 GeV data (118 nb⁻¹).

2.-Missing Transverse Energy Event Selection. The objective of the missing transverse energy event selection is to define an event sample for which the background due to fluctuations in the detector response is small, thereby isolating events containing one or more energetic neutrinos (or other non-interacting particles). The missing transverse energy events were selected using the following criteria:

1) *missing transverse energy*, $E_T^{\text{miss}} > 15$ GeV and $N_\sigma > 4$, where N_σ is defined as $E_T^{\text{miss}} / (0.7 \sqrt{\Sigma E_T})$. ΣE_T is the scalar sum of transverse energy observed in all calorimeter cells where transverse energies are measured in GeV. N_σ is thus a measure of the experimental significance of the missing transverse energy.

2) *one or more jets*[6] observed in the calorimeters with $E_T > 12$ GeV and $|\eta| < 2.5$.

3) *one or more tracks* observed in the drift chambers with $p_T > 1$ GeV/c within a cone of size

$\Delta R = 0.4$ centred on the calorimeter jet axis ($\Delta R^2 \equiv \Delta\phi^2 + \Delta\eta^2$, where ϕ is the azimuthal angle and η is the pseudorapidity).

4) *isolation of the missing transverse energy*, by rejecting events with a jet observed in the calorimeter with $E_T > 8$ GeV and $|\eta| < 2.5$ (or a jet observed in the central detector drift chambers with $p_T > 5$ GeV/c) within ± 30 degrees in ϕ of the missing transverse energy direction.

5) *veto of coplanar jet activity*, by rejecting events with a calorimeter jet of $E_T > 8$ GeV and $|\eta| < 2.5$ (or a central detector jet with $p_T > 5$ GeV/c) within 150-210 degrees in ϕ of the direction of the highest E_T jet.

6) *veto of events with an electron or muon candidate* in order to remove contributions from $W \rightarrow e\nu$ or $\mu\nu$ or heavy flavour semi-leptonic decays. For this purpose we have developed an algorithm for removing electrons or muons having tracks with $p_T > 10$ GeV/c. In addition, events were scanned and removed if they had muon candidates with $p_T > 3$ GeV/c. The cuts used to define electrons and muons for veto purposes in this analysis are less stringent, especially on isolation requirements, than those used to select low background samples of W events[2].

Additional technical cuts were applied to remove background events such as cosmic rays, beam halo, and double interactions. At the end of the selection, all events were checked visually on a graphics display, where 40 events were rejected as being background or as having uncertain missing transverse energy due to event reconstruction problems. We expect residual background of this type to be much less than one event.

A total of 56 events pass the selection cuts[7]. These cuts ensure that the missing transverse energy of the surviving events is not simply the result of a fluctuation of the energy measurements. This jet fluctuation background has been evaluated by a Monte Carlo technique in which the energies of jets in real events are fluctuated according to the resolution of the calorimeters as determined from test beam measurements and Monte Carlo simulation of the detector. From these fluctuated events, one obtains an E_T^{miss} spectrum (fig.1) that agrees with the actual missing transverse energy spectrum observed in a sample of low threshold jet data in which no missing transverse energy is expected. Other checks of the reliability of this technique have been made by

confirming that the effects of loosening various E_T^{miss} selection cuts are correctly predicted by the jet fluctuation Monte Carlo. The Monte Carlo generates events that are required to pass the same selection criteria as the data. The number of Monte Carlo events generated corresponds to an integrated luminosity of five times the data. This gives an expected contribution of 3.8 events, compared to the 56 observed.

3.-Separation of the $W \rightarrow \tau \nu$ decay signal. We may now make use of measured properties of semi-hadronic τ -decays[8], namely the low multiplicity, low mass jet, to separate out the production and decay of a $W^\pm$ into tau-lepton plus neutrino, through the process:

$$p \bar{p} \rightarrow W + X; W \rightarrow \tau \nu; \tau \rightarrow \text{hadrons} + \nu.$$

The signature is a high transverse momentum narrow hadronic jet with associated missing transverse energy. For this purpose, we define three variables particularly suitable for separating high p_T τ -jets from ordinary jets :

1) *fraction of jet energy (F)*, as measured in the calorimetry, contained within a cone of size $\Delta R=0.4$ relative to that contained in the jet definition cone of $\Delta R = 1.0$ [6],

2) *angular separation ($r=\Delta R$)* between the leading track of the jet, as measured in the central detector drift chambers, and the jet axis as measured in the calorimeters, and

3) *charged particle multiplicity (n)* of tracks with $p_T > 1 \text{ GeV}/c$ within a cone of $\Delta R = 0.4$ around the calorimeter jet axis.

Using the τ Monte Carlo described later, we have produced the distributions of F , r and n for the jet coming from the τ decay. We calculate a τ -log-likelihood, $L_\tau = \ln (f_F f_r f_n)$, for the highest E_T jet in an event, where f_F , f_r and f_n are the values of the τ Monte Carlo distributions for the measured values of F , r and n for this jet. The distributions of L_τ for the data, τ Monte Carlo, and jet data are shown in fig. 2; the range of L_τ is -16 to $+4$. The probability that a jet comes from a τ decay is greater with increasing L_τ . The cut $L_\tau > 0$ keeps 78% of the $\tau \rightarrow \text{hadrons} + \nu$ decays and rejects 89% of the ordinary jet events. Therefore, we define our final τ sample as those events with $L_\tau > 0$ (32 events)[7].

We have performed extensive Monte Carlo calculations for all known processes contributing events with large missing transverse energy. Important features of these calculations are a) simulation of the full proton-antiproton collision to take into account the effects of spectator particles and b) simulation of the UA1 detector response including hardware trigger.

Calculations were done using a modified version of the ISAJET Monte Carlo program[9] in which the spectator particle parameters have been adjusted to be consistent with UA1 data. The number of events generated corresponds to approximately 10 times our integrated luminosity. The absolute normalisation of the cross sections is obtained from experimental data using our full W and Z^0 data samples. Processes involving a W or Z^0 particle were also simulated using a second method where the electron from an identified W decay event was removed and a Monte Carlo decay of a W or Z^0 with the same momentum vector was superimposed on the spectator particles. The results from this second method are in agreement with the ISAJET calculations within the statistics available from our W and Z^0 data samples.

The $W \rightarrow \tau \nu$ decays have been studied using a special version of ISAJET modified to account for polarization effects and to include the latest experimentally determined branching ratios[8]. The τ Monte Carlo contains the following decay modes for the τ^- [10] (charge conjugate states for the τ^+): $e^- \bar{\nu}$ (18%), $\mu^- \bar{\nu}$ (18%), $\pi^- \bar{\nu}$ (11%), $\rho^- \bar{\nu}$ (22%), $A_1 \bar{\nu} \rightarrow 2\pi^- \pi^+ \bar{\nu}$ (6%), $A_1 \bar{\nu} \rightarrow \pi^- 2\pi^0 \bar{\nu}$ (8%), $2\pi^- \pi^+ \pi^0 \bar{\nu}$ (7%), $\pi^- 3\pi^0 \bar{\nu}$ (8%), $K^{*-} \bar{\nu}$ (1.2%), and $K^- \bar{\nu}$ (0.8%). Assuming τ - μ - e universality the Monte Carlo model predicts 28.7 ± 1.5 events with $L_{\tau} > 0$.

Other known sources of missing E_T include:

- 1) $W \rightarrow e \nu$, $W \rightarrow \mu \nu$, or $W \rightarrow \tau \nu \rightarrow \text{leptons}$, where the electron or muon is not identified and a large p_T jet is produced. The lepton may be below threshold, outside the acceptance or, in the electron case, buried within a jet.
- 2) $W \rightarrow \bar{s} c$ where one or both of the quarks decay semi-leptonically.
- 3) $Z^0 \rightarrow \tau^+ \tau^-$; $Z^0 \rightarrow \bar{c} c$ or $\bar{b} b$ where one or both of the quarks decay semi-leptonically.
- 4) $Z^0 \rightarrow \bar{\nu} \nu$, where the Z^0 is produced at high transverse momentum and is balanced by one or more gluon jets. We assume the existence of three neutrino species coupling to the Z^0 .

5) *Direct production of $\bar{c}c$ or $\bar{b}b$* where one or both of the quarks decay semi-leptonically.

6) *Jet fluctuations* that lead to $L_\tau > 0$ events.

The total contribution from these backgrounds with $L_\tau > 0$ amounts to 2.7 ± 0.6 events. This yields a signal of 29.3 ± 5.7 events, which is compatible with the predicted τ signal of 28.7 ± 1.5 events. The background does not include contributions from a top quark (0.2 ± 0.2 events for a top mass equal to $40 \text{ GeV}/c^2$).

4.-Discussion. All observed properties of our 32 events are consistent with those expected from τ particles produced in W decays. Most of the events have only one narrow hadronic jet (only one event has a second jet with $E_T > 12 \text{ GeV}$), and no other tracks or calorimeter hits with significant transverse momentum or energy. The distribution of n (22 1-prong, 3 2-prong, and 7 3-prong) is in agreement with predictions of the Monte Carlo program where the effects of detector acceptance, photon conversions, and spectator tracks have been taken into account. Non- τ jets passing the $L_\tau > 0$ requirement do not produce such a multiplicity distribution. The jets in the 2- and 3-prong events have a low invariant mass (about $1 \text{ GeV}/c^2$) of the charged particles. The momentum distribution of the tracks and the energies deposited in the electromagnetic and hadronic calorimeters are consistent with our calculations for τ decays. The angular distribution of the τ jet is in agreement with the τ Monte Carlo calculations. Two events are shown in fig. 3: a) a 1-prong τ decay and b) a 3-prong τ decay.

$W \rightarrow \tau\nu$ events have two neutrinos present (tau-neutrino and tau-antineutrino): a hard one from the primary decay of the W and a softer one from the decay of the τ . Thus, we do not expect a Jacobian peak in the jet E_T distribution as observed in the electron E_T spectrum for the $W \rightarrow e\nu$ decay. The jet E_T and missing E_T distributions are shown in figures 4a and 4b for the 32 τ events (histogram) together with the non-tau backgrounds (shaded). The transverse mass is a sensitive variable for deriving the mass of the parent (W) particle. As previously used in the analysis of W decays, we define transverse mass (m_T) as :

$$m_T^2 \equiv 2 E_T^{\text{jet}} E_T^{\text{miss}} (1 - \cos \phi),$$

where ϕ is the angle between the jet direction and the missing energy direction in the plane transverse to the colliding beams. The measured transverse mass is shown in fig. 4c. We have made a maximum likelihood fit to determine the W mass and find the value $m_W = (89 \pm 3 \pm 6) \text{ GeV}/c^2$, where the first error is statistical and the second is the systematic uncertainty of the absolute energy scale determination. The expected transverse mass distribution for $m_W = 83.5 \text{ GeV}/c^2$ [2] is shown in fig. 4c for comparison with the data.

Our calculated acceptance for $W \rightarrow \tau\nu$ is $(6.8 \pm 0.4)\%$, which is made up of the following components: $\tau \rightarrow \text{hadrons}$ branching ratio (64%), trigger efficiency (45%), missing E_T event selection (30%), and τ selection cut $L_\tau > 0$ (78%). We deduce the W production cross section times branching ratio into τ plus neutrino:

$$\sigma B(W \rightarrow \tau\nu) = (600 \pm 120 \pm 110) \text{ pb},$$

where the first error is statistical and the second is systematic. The systematic error is due mainly to the uncertainty in the luminosity and in the prediction of the Monte Carlo τ rates. The corresponding $\sigma B(W \rightarrow e\nu)$ is $(590 \pm 50 \pm 90) \text{ pb}$, obtained from our measurements[11] as a weighted average of integrated luminosities of 118 nb^{-1} at $\sqrt{s} = 546 \text{ GeV}$ and 597 nb^{-1} at $\sqrt{s} = 630 \text{ GeV}$. The component of the systematic error due to the uncertainty in knowledge of the luminosity ($\pm 15\%$) cancels in the calculation of the ratio of branching ratios (R) :

$$R = B(W \rightarrow \tau\nu) / B(W \rightarrow e\nu) = 1.02 \pm 0.20 \pm 0.10.$$

The $W \rightarrow e\nu$ [2,12] and $W \rightarrow \mu\nu$ [13] branching ratios have been measured at the collider to be equal, within the statistical errors of present experiments, providing direct confirmation of the electron-muon universality of the weak couplings of the W. Electron-muon universality of the weak charged current is verified precisely at low energy by comparison of the branching ratios $\pi \rightarrow \mu\nu$ and $\pi \rightarrow e\nu$. That measurement[14] gives the relative strengths of the W couplings to

$e\nu$ (g_e) and $\mu\nu$ (g_μ) to be $g_e / g_\mu = 0.9939 \pm 0.0057$.

Since the discovery of a third lepton family (τ) more than ten years ago[15], the τ has been observed until now only in low energy e^+e^- collisions[16] and in upsilon decay[17]. The universality of the strength of the W coupling to $\tau\nu$ (g_τ) has been checked at low values of momentum-transfer squared (Q^2) by analysis of τ decay rates, made possible by recent measurements of the τ lifetime[18]. From a world average of decay rate measurements, g_τ / g_μ is unity to a precision of about 5%. Our data allow the first check of the universality of the weak charged couplings at high Q^2 . We may express our measured R in terms of the weak charged coupling constants g_e and g_τ :

$$R = \Gamma(W \rightarrow \tau\nu) / \Gamma(W \rightarrow e\nu) = g_\tau^2 / g_e^2,$$

(neglecting very small phase space differences between the electron and τ cases) from which we deduce that

$$g_\tau / g_e = 1.01 \pm 0.09 \pm 0.05.$$

From comparison of the $W \rightarrow \mu\nu$ and $W \rightarrow e\nu$ rates, we derive the analogous result that

$$g_\mu / g_e = 1.05 \pm 0.07 \pm 0.08.$$

These data provide direct experimental verification of electron-muon-tau universality of the weak charged coupling at $Q^2 = m_W^2$.

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FIGURE CAPTIONS

- Fig. 1** Jet fluctuation Monte Carlo predictions for N_{σ}^2 compared with a sample of UA1 low threshold jet events. N_{σ} is defined as $E_T^{\text{miss}} / (0.7 \sqrt{\Sigma E_T})$ where ΣE_T is the scalar sum of transverse energy observed in all calorimeter cells and where transverse energies are measured in GeV.
- Fig. 2** Distributions of τ -log-likelihood for the data (56 events, solid histogram), the $\tau \rightarrow \text{hadrons} + \nu$ Monte Carlo absolutely normalised (solid curve), and UA1 jet data normalised to 56 events (dashed curve).
- Fig. 3a** Event display of a 1-prong τ^+ decay in the UA1 detector. Only tracks with $p_T > 1$ GeV/c (only one is observed) and calorimeter cells with $E_T > 1$ GeV are displayed.
- Fig. 3b** Display of raw digitisings for a 3-prong τ^- decay observed in the UA1 central detector (drift chambers). All tracks observed are low momentum except for the three tracks from the τ decay. The invariant mass of the three tracks is $(0.99 \pm 0.1) \text{ GeV}/c^2$.
- Fig. 4a** Jet transverse energy distribution for events passing the τ selection cut $L_{\tau} > 0$ (32 events, histogram) compared with the prediction for the Monte Carlo for taus from W decay (28.7 events, upper curve) and the predicted background processes (2.7 events, shaded).
- Fig. 4b** Missing transverse energy distribution for events passing the τ selection cut $L_{\tau} > 0$ (32 events, histogram) compared with the prediction for the Monte Carlo for taus from W decay (28.7 events, upper curve) and the predicted background processes (2.7 events, shaded).
- Fig. 4c** Transverse mass distribution for events passing the τ selection cuts $L_{\tau} > 0$ (32 events, histogram) compared with the prediction for the Monte Carlo for taus from W decay (28.7 events, upper curve) and the predicted background processes (2.7 events, shaded).

FIG. 1

FIG. 2

FIG. 3a

$$W^- \rightarrow \tau^- \bar{\nu}_\tau$$

$$m = 0.99 \pm 0.1 \text{ GeV}/c^2$$

$$\begin{aligned} P_T &= -8.64 \text{ GeV}/c \\ P_T &= -7.83 \text{ GeV}/c \\ P_T &= 12.19 \text{ GeV}/c \end{aligned}$$

FIG. 3b

FIG. 4a

FIG 4b

FIG. 4c