RESULTS FROM AN ANALYSIS OF MISSING TRANSVERSE ENERGY EVENTS IN THE UA1 EXPERIMENT AT THE CERN p̅p COLLIDER

UA1 Collaboration


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Results from an analysis of missing transverse energy events from a data sample of 715 nb⁻¹ in the UA1 experiment at the CERN Proton-Antiproton Collider are presented. A signal of high-transverse-momentum r-leptons from W decays is observed through their semihadronic decay modes. The measured relative rates of W → eν, W → µν, and W → τν provide the first direct tests of c-τ universality of the weak charged couplings at Q² = m_W. The remaining events that are not clear W → τν candidates are found to be consistent in rate with the expected contributions from Standard Model sources. After accounting for these expected contributions, we obtain the following limits on various possible new physics processes: i) a mass limit for a fourth-generation charged heavy lepton of m_L > 41 GeV/c² (90% CL); ii) a limit on the total number of neutrino species of n_ν < 10 (90% CL); and iii) model-dependent supersymmetric mass limits for squarks and gluinos of m_q > 70 GeV/c² and m_G > 60 GeV/c² (90% CL), respectively. The rate of events with E_T > 40 GeV and which are not τ candidates is found to be slightly higher than theoretical expectations and may indicate increased activity in Z⁰ production at large transverse momentum.

1. PHYSICS MOTIVATION

The analysis of events with large missing transverse energy (E_T^miss) produced in proton-antiproton collisions is a powerful tool for searching for physics processes that produce one or more energetic neutrinos. This method was first used in association with an electron or muon signal, and resulted in the conclusive observation of the decay of the charged intermediate vector boson (W⁺) (1). The technique was then extended to select events with jets and large E_T^miss (2), thus allowing an inclusive search for Standard Model and new physics sources of events with this signature.

There is a variety of Standard Model sources of events having large E_T^miss. Direct heavy-quark production and W or Z⁰ decaying into heavy quarks (with subsequent semileptonic decay of the heavy quark) can lead to energetic neutrinos that are usually emitted along the direction of a jet. This kind of topology is a difficult signal to extract from the large background due to jet events (with no neutrinos) where an apparent E_T^miss is generated by the mis-measurement of the energies of the jets due to the finite energy resolution of the apparatus. We therefore consider only those topologies where the neutrino (i.e. E_T^miss) direction is isolated from jets. The most obvious sources of isolated high transverse mo-

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mentum (p_T) neutrinos are the decays W → eν and W → µν. These sources are now well understood, and are considered to be a background rather than a signal in this analysis. Other Standard Model sources that are expected to give isolated E_T^miss events include W → τν and Z⁰ production at large p_T (with Z⁰ → νF). In the case of the large-p_T Z⁰, the p_T is transformed into large E_T^miss since the neutrinos go undetected. One then observes the recoil gluon(s) which appears as a jet (or jets) in the detector.

In addition to these expected Standard Model sources, there are a number of new physics sources that could produce events with significant E_T^miss. These new physics sources include the following:

i) The decay of the W boson into a new, sequential charged heavy lepton via the process: W → Lν (L → ud + ν or L → cf + ν). The signature is one or two energetic jets with associated E_T^miss.

ii) Any additional low-mass neutrino species (beyond the three known to exist) with the standard coupling to the Z⁰ would be expected to contribute E_T^miss events. As explained in the previous paragraph, the process p̅p → Z⁰ + gluons + X (with Z⁰ → νF), where one observes the radiated gluon(s) from the incoming partons and the E_T^miss is due to the undetected large p_T of the Z⁰. This 'gluon tagging' technique is analogous to the 'photon tagging' technique used in c-ew experiments (3), where one observes a single (radiated) photon and missing energy in the process: e⁻c⁺ → Z⁰ + γ (with Z⁰ → νF).

iii) Production of supersymmetric particles is expected to be a source of large-E_T^miss events, since these par-
ticles will eventually decay into known particles plus the lightest supersymmetric particle, which should be stable and non-interacting. The undetected \( p_t \) of this lightest particle will result in \( E_t^{\text{miss}} \).

A thorough understanding of the expected Standard Model sources will permit a search for these new physics sources in the data, and, in the absence of a signal, significant limits can be set on such new processes.

2. SELECTION OF THE MISSING-\( E_T \) SAMPLE

2.1 The \( E_t^{\text{miss}} \) method

To detect the emission of energetic neutrinos (or other non-interacting particles), one needs to measure all the energy produced in the collision. The missing energy in the event is defined as: \( E_t^{\text{miss}} = - \Sigma E_i \), where \( E_i \) is the measured energy deposition in calorimeter cell \( i \), \( i \) the unit vector from the interaction point to cell \( i \), and the sum is over all calorimeter cells. For a perfect detector, one expects \( E_t^{\text{miss}} = 0 \) when no neutrinos are present, and \( E_t^{\text{miss}} = \vec{p}_T \), when one or more neutrinos with total momentum \( \vec{p}_T \) are produced. In \( p\bar{p} \) collisions, a significant fraction of the energy can escape detection by going down the beam pipe, making a missing-energy measurement impractical. However, the transverse components of the energy flow can still be well measured, allowing an accurate \( E_t^{\text{miss}} \) determination.

To make an optimal measurement of \( E_t^{\text{miss}} \), one still needs to collect as much of the energy created in the collision as possible, i.e. one needs a hermetic detector. The UA1 detector (4) has nearly full calorimeter coverage down to 0.2\(^\circ\) to the beam and > 4.5 interaction lengths in depth. In addition, the central drift chambers provide charged-particle tracking and momentum measurement.

Finally, the large-area muon detection system enclosing the calorimeters prevents most penetrating muons from escaping measurement (which would create false \( E_t^{\text{miss}} \)).

Using minimum bias data, where no real \( E_t^{\text{miss}} \) is expected, the UA1 detector has a resolution in \( E_t^{\text{miss}} \) which is proportional to the activity of the event:

\[
\sigma(E_t^{\text{miss}}) = 0.7 \sqrt{\Sigma |E_i|}.
\]

The scalar sum of the transverse energy over all calorimeter cells can be considered to be a measure of the activity or 'temperature' of the event. A useful variable is \( N_e \), the significance of the \( E_t^{\text{miss}} \) measurement:

\[
N_e = E_t^{\text{miss}}/\sigma(E_t^{\text{miss}}).
\]

2.2 Background rejection and event selection criteria

The goal is to select events with \( E_t^{\text{miss}} \) due to emission of one or more neutrinos (or other non-interacting particles) while minimizing backgrounds that can fake \( E_t^{\text{miss}} \). These backgrounds are of three main types:

i) External backgrounds: Apparent \( E_t^{\text{miss}} \) caused by an energy deposition in the calorimeter, which does not come from the \( p\bar{p} \) collision. Examples are cosmic rays and beam halo interactions.

ii) Instrumental effects: Apparent \( E_t^{\text{miss}} \) from electronic noise, accidental loss of detection capability, and problems in event reconstruction and in pattern recognition.

iii) Jet fluctuations: Apparent \( E_t^{\text{miss}} \) due to detector resolution. The electromagnetic (e.m.) and hadronic showers from the produced particles have measured energies that can fluctuate substantially from their true energy. There are also regions in the calorimeters where there is decreased sensitivity, which can contribute to an apparent but fake \( E_t^{\text{miss}} \).

The starting data sample comes from three periods of data-taking from 1983 to 1985, with a total integrated luminosity of 715 nb\(^{-1}\). Some of the data (118 nb\(^{-1}\)) were taken at a centre-of-mass energy of \( \sqrt{s} = 546 \text{ GeV} \) and the rest (597 nb\(^{-1}\)) at \( \sqrt{s} = 630 \text{ GeV} \). If any one of the three following trigger requirements (5) was satisfied, the event was recorded: i) at least one e.m. calorimeter cluster with \( E_T > 10 \text{ GeV} \); ii) at least one hadronic cluster (jet) with \( E_T > 25 \text{ GeV} \); and iii) at least one jet with \( E_T > 15 \text{ GeV} \) and \( E_t^{\text{miss}} > 17 \text{ GeV} \). These triggers selected 13 million events to be written to tape from the 3 × 10\(^9\) inelastic \( p\bar{p} \) collisions seen by the detector.

The first step of the event selection requires that the event should have at least one jet with \( E_T > 12 \text{ GeV} \) and a significant \( E_t^{\text{miss}} \), \( E_t^{\text{miss}} > 3 \sigma \) and \( E_t^{\text{miss}} > 15 \text{ GeV} \). The \( E_t^{\text{miss}} \) cuts are necessary in order to reduce the very large background from jet fluctuations. We then require that at least one track with \( p_T > 1 \text{ GeV/c} \) point in the direction of the highest \( E_T \) jet. This cut effectively removes external and instrumental backgrounds, which are usually not correlated with charged tracks coming from the collision. Fiducial cuts are made to avoid fake \( E_t^{\text{miss}} \) caused by jets going into regions of the detector where there is reduced sensitivity. These cuts leave a sample of about 6000 events. The \( E_t^{\text{miss}} \) spectrum for these events in terms of the number of sigmas (\( N_e \)) is shown in Fig. 1.

The background from jet fluctuations is expected to have an exponential behaviour in \( N_e \) which is seen as a steep drop-off on this log scale plot (dashed line). However, at larger \( N_e \) there is a substantial deviation from this fall-off, which is due to \( W \to e\nu \) decays and other real \( E_t^{\text{miss}} \) events as well as to some remaining backgrounds.

To further reduce the jet-fluctuation background, the \( E_t^{\text{miss}} \) direction is now required to be isolated. For this, no jets with \( E_T > 8 \text{ GeV} \) in the calorimeters (or \( p_T > 5 \text{ GeV/c} \) in the central detector) should be found within ±30\(^\circ\) in azimuth along the \( E_t^{\text{miss}} \) direction or opposite to the highest \( E_T \) jet. As stated earlier, we are not interested in \( W \to e\nu \) and \( W \to \mu\nu \) events, so events with identifiable electrons or muons are excluded. These and additional \( E_t^{\text{miss}} \) validation cuts result in a sample of 302 events, which are then individually scanned by physicists on a graphics display device. Scanning effectively removes most of the remaining external and instrumental
number of events near the \( N_e > 3 \) cut indicates a large remaining jet fluctuation background contribution. It is therefore essential to know quantitatively the contributions from jet fluctuations and from expected physics sources.

2.3 Determination of physics and background contributions

The jet-fluctuation contribution was determined by a Monte Carlo technique in which ordinary jet events (with no \( E^{\text{jet}} \)) have their jet energies fluctuated according to the known calorimeter resolution as determined by test beam results and other Monte Carlo simulation studies. The \( E^{\text{jet}} \) spectrum from these fluctuated events agrees well with the actual \( E^{\text{jet}} \) spectrum as measured in UA1 jet data. Other checks of the reliability of this technique have been made by confirming that the effects of loosening various \( E^{\text{jet}} \) selection cuts are correctly predicted by the jet-fluctuation Monte Carlo. The sample of fluctuated events corresponds to roughly five times the integrated luminosity of the data sample. The fluctuated events are required to pass the same selection criteria as the data in order to obtain the expected jet-fluctuation background contribution.

The expected contributions from physics sources were evaluated with the ISAJET Monte Carlo program (6), which was extended to provide a full simulation of the UA1 detector including the hardware trigger. Events were generated for all Standard Model processes expected to give \( E^{\text{jet}} \) events. These processes are

i) \( p\bar{p} \rightarrow c\bar{c}, b\bar{b} \) (with semileptonic decay of the c or b quarks);

ii) \( W \rightarrow c\bar{c}, Z^0 \rightarrow c\bar{c}, Z^0 \rightarrow b\bar{b} \) (with semileptonic decay of the c or b);

iii) \( W \rightarrow e\nu, W \rightarrow \mu\nu, W \rightarrow \tau\nu \) leptons (where the lepton is not identified owing to acceptance loss or to being too near a jet);

iv) \( W \rightarrow \tau\nu(\tau \rightarrow \text{hadrons} + \nu) \);

v) \( Z^0 \rightarrow \gamma^* \gamma^*, Z^0 \rightarrow \nu\bar{\nu} \).

The normalization for direct heavy-flavour production was determined from the measured UA1 inclusive muon \( p_T \) spectrum (7). The normalization of the cross-sections for the \( W \) and \( Z \) came from the UA1 \( W \rightarrow e\nu \) and \( Z \rightarrow e^+e^- \) measurements (8) and used the theoretical branching ratios for the decay modes. The statistics of the ISAJET samples corresponded to approximately ten times the integrated luminosity of the data.

We can now compare the \( E^{\text{jet}} \) data with the expected physics plus background contributions. Returning to Fig. 2, the significance \( (N_e) \) of the \( E^{\text{jet}} \) events (histogram) is compared with the prediction for the jet-fluctuation background (shaded region) and with the prediction for background plus expected physics contributions (solid curve). At small \( N_e \), the jet-fluctuation background still dominates. To minimize this background, we now choose to consider only those events with \( N_e > 4 \). This cut results in a final data sample of 56 events (the isolated 4\( \alpha \) sample) with an expected background from jet fluctuations of 3.8 \( \pm \) 1.0 events.
3. THE ISOLATED 4\(\pi\) SAMPLE

We now summarize the important physics selection cuts that lead to the final 4\(\pi\) sample of 56 events: i) \(E_{T}^{\text{miss}} > 15\) GeV and \(E_{T}^{\text{miss}} > 4\); ii) at least one jet with \(E_{T} > 12\) GeV; and iii) \(E_{T}^{\text{miss}}\) isolated. After subtracting the expected background from jet fluctuations (3.8 events), a signal of 52.2 events remains. This agrees with the expected contribution from known physics processes of 48.4 events. A detailed breakdown by processes is given in the first column of numbers in Table 1. The dominant contribution, by far, comes from \(W \to \tau\nu\) (\(\tau \to \text{hadrons} + \nu\)). All other contributions are smaller and come from a variety of sources, although most are due to the decays of the W or Z bosons.

In terms of the number of jets with \(E_{T} > 12\) GeV, the 4\(\pi\) sample contains 53 monojet events, 3 dijet events, and no higher-multiplicity jet events. The \(E_{T}^\nu\) (of the highest \(E_{T}\) jet) and the \(E_{T}^{\text{miss}}\) distributions for the 56 events are shown in Fig. 3a and 3b (histogram). The curves represent the total contribution from expected sources and show good agreement with the data for both distributions.

![Graphs showing distributions for isolated 4\(\pi\) sample](image)

**Figure 3:** a) \(E_{T}^\nu\) and b) \(E_{T}^{\text{miss}}\) distributions for the isolated 4\(\pi\) sample (histogram) compared with the Monte Carlo prediction for all known physics and background sources (solid curve).

<table>
<thead>
<tr>
<th>Process</th>
<th>Events (total)</th>
<th>Events with (L_r &lt; 0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(W \to \nu\bar{\nu}), (W \to \mu\bar{\mu})</td>
<td>3.6, 2.0</td>
<td></td>
</tr>
<tr>
<td>(W \to \tau\nu) ((\tau \to \text{hadrons}))</td>
<td>36.7, 8.0</td>
<td></td>
</tr>
<tr>
<td>(W \to c\bar{c}), (Z^0 \to c\bar{c}), (Z^0 \to b\bar{b})</td>
<td>&lt; 0.1, &lt; 0.1</td>
<td></td>
</tr>
<tr>
<td>(Z^0 \to \gamma\gamma) (three neutrino species)</td>
<td>0.5, 0.1</td>
<td></td>
</tr>
<tr>
<td>(c\bar{c}) and (b\bar{b}) (direct production)</td>
<td>7.4, 7.1</td>
<td></td>
</tr>
<tr>
<td>Total physics contributions</td>
<td>48.4, 17.4</td>
<td></td>
</tr>
<tr>
<td>Background (jet fluctuations)</td>
<td>3.8, 3.4</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>52.2, 20.8 ± 5.0 ± 1.1</td>
<td></td>
</tr>
</tbody>
</table>

4. STUDY OF THE \(W \to \tau\nu\) DECAY

4.1 Selection of the \(W \to \tau\nu\) sample

We now make use of the unique properties of the \(\tau \to \text{hadrons} + \nu\) decay, i.e., a low-multiplicity and low-mass jet, which distinguish it from normal gluon and quark jets. Because of the large boost given to the \(\tau\) from the W decay, the \(\tau \to \text{hadrons} + \nu\) decay forms a narrow, high-\(p_T\) hadronic jet. The following three variables are used for the selection of \(\tau \to \text{hadrons} + \nu\) events:

i) \(F\), the fraction of energy contained in a small cone of size \(\Delta R = 0.4\) relative to the energy contained in the jet definition cone of \(\Delta R = 1.0\) (9);

ii) \(R\), the angular separation in \(\tau - \nu\) space between the leading track of the jet and the calorimeter jet axis;

iii) \(n\), the number of charged tracks with \(p_T > 1\) GeV/c in a cone of \(\Delta R = 0.4\) about the calorimeter jet axis.

For each event we define a \(\tau\) log-likelihood, \(L_\tau = \ln(f_\tau f_\nu / f_\text{nu})\), where \(f_\tau, f_\nu\), and \(f_\text{nu}\) are the values of the predicted (Monte Carlo) \(\tau\) distribution for the measured variables \(F, R,\) and \(n\) of the highest \(E_{T}\) jet. The distributions of \(L_\tau\) for the \(\tau \to \text{hadrons}\) Monte Carlo events (solid line) and for UA1 jet data (dashed line) are shown in Fig. 4. The distribution for the 56 \(E_{T}^{\text{miss}}\) events is the histogram. The requirement \(L_\tau > 0\) retains 78% of \(\tau \to \text{hadrons}\) events and rejects 89% of the jet events. We then define our \(\tau\) sample by requiring \(L_\tau > 0\), which results in 32 events. The total number of events predicted by the Monte Carlo from sources other than \(W \to \tau\nu\) (\(\tau \to \text{hadrons} + \nu\)), with \(L_\tau > 0\), is 2.7 ± 0.6 events.
4.2 W mass determination

In a $W \rightarrow \tau \nu$ event, there are two neutrinos in the final state ($\nu_{\tau}$ and $\bar{\nu}_{\tau}$). These neutrinos smear the $E_{T}$ and $P_{T}^{miss}$ distributions so that one no longer expects a Jacobian peak as observed in $W \rightarrow e\nu$ decay. Nevertheless, the shape of these distributions is still sensitive to the mass of the parent particle (W). We define the transverse mass ($m_{T}$) as:

$$m_{T} = \sqrt{2E_T \cdot E_{T}^{miss}(1 - \cos \Delta \phi)}$$

where $\Delta \phi$ is the azimuthal angle between the jet and the $E_{T}^{miss}$ direction. The measured $m_{T}$ is shown in Fig. 6. A maximum likelihood fit to the distribution gives a W mass of

$$m_{W} = 89 \pm 3 \pm 6 \text{ GeV/c}^2$$

where the first error is statistical and the second is the systematic error due to the uncertainty in the absolute energy scale. The expected $m_{T}$ distribution for $m_{W} = 83.5 \text{ GeV/c}^2$ (10) is shown as the curve in Fig. 6.

![Figure 4](image-url)  
**Figure 4:** The $L_{T}$ distribution for the data (histogram) compared with the $\tau \rightarrow$ hadrons Monte Carlo prediction absolutely normalized (solid curve), and with ordinary UA1 jet data normalized to the data (dashed curve).

This yields a net signal from $\tau \rightarrow$ hadrons of $29.3 \pm 5.7$ events, which is compatible with the Monte Carlo prediction of $28.7 \pm 1.5$ events.

The properties of the $\tau$ sample have been checked for consistency with the $\tau$ hypothesis. The distributions of the track multiplicity, of the invariant mass of the tracks in the multiprong events, of the energy deposits in the calorimeter, and of the angular distribution of the jets are all in agreement with the predictions of the $\tau \rightarrow$ hadrons Monte Carlo. An example of a three-prong $\tau$ candidate is shown in the event display of Fig. 5. One observes the isolated narrow high-$p_{T}$ jet with associated large $E_{T}^{miss}$ (16 GeV) which is expected for a $W \rightarrow \tau \nu(\tau \rightarrow$ hadrons) event.

![Figure 5](image-url)  
**Figure 5:** Display of raw digitizations for a three-prong $W \rightarrow \tau \nu$ decay observed in the UA1 central detector drift chambers. All tracks observed are low-momentum ones except for the three tracks from the $\tau$ decay. The invariant mass of the three tracks is $0.99 \pm 0.1 \text{ GeV/c}^2$.

4.3 $W \rightarrow \tau \nu$ cross-section and test of universality

From the rate of observed $W \rightarrow \tau \nu$ events, we can calculate the cross-section times branching ratio for this process. The acceptance for $W \rightarrow \tau \nu$, determined from the Monte Carlo, is $6.8 \pm 0.4\%$, which has the following components: $\tau \rightarrow$ hadrons branching ratio (64%), trigger efficiency (45%), $E_{T}^{miss}$ event selection (30%), and $\tau$ selection cut $L_{T} > 0$ (78%). We then obtain

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

The systematic error comes from the uncertainty in the luminosity and in the Monte Carlo prediction for the ac-
ceptance. The measurements for the decays $W \to \ell \nu$ and $W \to \mu \nu$ have also been made by UA1 (8):

$$\sigma B(W \to \ell \nu) = 590 \pm 30 \pm 90 \text{ pb},$$
$$\sigma B(W \to \mu \nu) = 650 \pm 70 \pm 140 \text{ pb}.$$

The three $\sigma B$ measurements are weight averages for $\sqrt{s} = 546$ and 630 GeV data (weighted by the integrated luminosity taken each year). The component of the systematic error due to the uncertainty in the luminosity (15%) cancels in the ratio $R$ of these quantities:

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

One can also express $R$ in terms of the weak charged coupling constants $g_\tau/g_\ell$; $R = \Gamma(W \to \tau \nu)/\Gamma(W \to \ell \nu) = g_\tau^2/g_\ell^2$. Thus we obtain for the ratio of the coupling constants,

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

The ratio for the muon and electron is:

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

These results verify the universality of the weak charged couplings to better than 10%. Recent measurements of the $\tau$ lifetime have made it possible to determine that the ratio $g_\tau/g_\ell$ is unity to a precision of about 5% (13). From the measurements of the branching ratios $\tau \to \mu \nu$ and $\pi \to \ell \nu$, the ratio $g_\tau/g_\ell$ has been precisely determined: $g_\tau/g_\ell = 0.9939 \pm 0.0057$ (12). Both of these previous measurements have been made at low energy. Our data provide the first experimental verification of $e-\mu-\tau$ universality of the weak charged coupling at $Q^2 = m_\tau^2$.

5. THE $L_\tau < 0$ SAMPLE

In Fig. 7 the 56 events of the 4$\sigma$ sample are displayed in a scatter-plot of $\tau$ log-likelihood versus $E_T^{\text{clus}}$. In the preceding section we have studied the $W \to \tau \nu$ sample, the 32 events above the $L_\tau = 0$ line. We now consider the 24 events with $L_\tau < 0$, which are expected to have a broader highest $E_T$ jet than for $\tau$ events. The highest $E_T^{\text{clus}}$ event with $L_\tau < 0$ is shown in Fig. 8.

The total expected contribution from known processes for $L_\tau < 0$ is 20.8 events. In the second column of numbers in Table 1 we show the breakdown of this total by source. Unlike for the $L_\tau > 0$ region where the $\tau \to$ hadrons + $\nu$ contribution dominated, the major sources, here, are residual $\tau \to$ hadrons + $\nu$ events, as well as $Z^0 \to \nu \bar{\nu}$ and the jet-fluctuation background, each with substantial contributions. Of these sources, the least well determined is the $Z^0 \to \nu \bar{\nu}$ contribution. Because the $Z^0 \to \nu \bar{\nu}$ events that pass the $4\sigma$ selection must have substantial $E_T^{\text{clus}}$ and hence must have been produced with large $Z^0 p_T$, one needs precise knowledge of the high-$p_T$ tail of the $p_T(Z)$ distribution.

The existing UA1 $Z^0 \to e^+e^-$ sample (53 events) is not large enough to provide statistics at large $p_T(Z)$. The $p_T$ spectra for the $W$ and $Z^0$ are expected to be very similar so we can study our larger sample of $W \to e\nu$ and $W \to \mu\nu$ decays (312 events) (8). The $p_T(W)$ distribution is shown in Fig. 9. The agreement between the data and QCD expectation (13) is quite good for most of the $p_T$ range. The $p_T(W)$ spectrum generated by the standard ISAJET Monte Carlo was modified to agree with the spectrum from the data up to $p_T(W) = 40$ GeV/$c$. Above 40 GeV/$c$, where statistics are poor, the $p_T(W)$ spectrum was extrapolated using the slope from ISAJET. This modified Monte Carlo $p_T(W)$ spectrum is consistent with QCD calculations over the full range of $p_T(W)$. The $p_T(Z)$ spectrum relative to the $p_T(W)$ spectrum is taken from theory. The uncertainty in the Monte Carlo $p_T(W)$ and $p_T(Z)$ distributions is taken into account for the error analysis using the statistics of the measured $p_T(W)$ distribution.

![Figure 7: The $L_\tau$ versus $E_T^{\text{clus}}$ scatter-plot for the isolated 4$\sigma$ sample (56 events).](image)

![Figure 8: Event display of the highest $E_T^{\text{clus}}$ event with $L_\tau < 0$. Two broad high-$E_T$ jets and large $E_T^{\text{clus}}$ are observed. All tracks that have $p_T > 1$ GeV/$c$ and calorimeter cells that have $E_T > 1$ GeV are displayed.](image)
Figure 9: Transverse-momentum distribution for the full UA1 sample of $W \rightarrow l\nu$ events (points) compared with a QCD prediction (curve and shaded region).

We note that there may be an indication of more activity than predicted by theory for $p_T(W) \gtrsim 30$ GeV/c (Fig. 9). If this is statistically significant, it would imply a corresponding larger prediction for $E_T^{miss}$ events at large $E_T^f$. This would make for better agreement between data and the expected contribution since we also observe an excess of events at large $E_T^f$ (Fig. 10). More details on $W$ and $Z^0$ production properties in UA1 data can be found in separate contributions to this conference (8).

The Standard Model processes that we consider do not include contributions from a top quark $t$. The $t$-quark would be expected to contribute $E_T^{miss}$ events from three different processes: $p\bar{p} \rightarrow t\bar{t}$, $W \rightarrow t\bar{b}$, and $Z^0 \rightarrow t\bar{t}$. The $E_T^{miss}$ would come from the neutrino produced by the semileptonic decay of either quark. The ISAJET Monte Carlo predicts the following event rates for the $L_\tau < 0$

sample: 4.3, 2.9, and 1.2 events for $m_t = 30, 40$, and 50 GeV/c$^2$, respectively. Contributions of this size can easily be accommodated in the present data sample. The inclusion of the contribution due to a $t$-quark would improve the limits to be presented.

5.1 General limit on new physics processes

The overall agreement between data and expected contributions for the full $E_T^{miss}$ spectrum (Fig. 10) is good; thus little room is left for contributions from new physics processes. We can place a general limit on any physics process leading to events with isolated $E_T^{miss} > 4\sigma$ and $L_\tau < 0$. The number of observed events is 24, with an expected contribution of $20.8 \pm 5.0 \pm 1.1$ from known sources. The first error includes the statistical error due to the number of Monte Carlo events generated, as well as the statistical error due to the uncertainty in the $W$ and $Z^0$ $p_T$ spectrum normalizations (based on the statistics of our $W \rightarrow l\nu$ sample). The second error is the systematic error due to the uncertainty in i) the absolute energy scale (0.7 events), ii) the normalization of the jet-fluctuation background (0.7 events); iii) the $\tau$ acceptance (0.5 events); and iv) the heavy-flavour cross-sections (0.2 events).

Taking into account the statistical and systematic errors, we obtain the following limit on the total cross-section for any new physics process:

$$\sigma < 20 \, \text{pb (90\% CL)}$$

where $\epsilon$ is the efficiency for events from this process to pass the isolated $E_T^{miss} > 4\sigma$ selection and the $L_\tau < 0$ requirement. Some examples of the value for $\epsilon$ are: for $\tau \rightarrow \text{hadrons} + \nu$, $\epsilon = 11\%$; and for $Z^0 \rightarrow \nu\bar{\nu}$ with $p_T(Z) > 20$ GeV/c, $\epsilon = 15\%$. Note that an accurate determination of $\epsilon$ requires the full UA1 detector simulation.
5.2 The heavy lepton

We now consider the possibility of a fourth-generation, sequential, charged heavy lepton L. Assuming universal strength of coupling to W and Z^0 particles, we look for the process: p\overline{p} \rightarrow W + X (with \ W \rightarrow L\nu_L, \ then \ L \rightarrow q\overline{q} + \nu_L). The current limit for the mass of such a heavy lepton comes from direct searches in e^+e^- experiments and is m_L > 22.7 GeV/c^2 (14). We expect to observe the decay W \rightarrow L\nu as a signal in the one-jet or two-jet plus E_T^{miss} topology.

The expected contributions to the isolated 4\sigma sample from a heavy lepton with a mass ranging from 20 to 75 GeV/c^2 have been determined using ISAJET. The Monte Carlo included spin effects (15) and the full detector simulation. Except for the highest mass values, the heavy-lepton decay usually produces a single jet as defined by the UA1 jet-finding algorithm. The combined effect of the jet definition and the boost received by the heavy lepton from the W decay favours the one-jet over the two-jet topology. The heavy-lepton events also have low \tau log-likelihood and have a softer E_T^{miss} spectrum than the \tau events. Of the heavy-lepton events passing the isolated 4\sigma selection with masses between 35 and 55 GeV/c^2, more than 85\% have L\nu < 0 and E_T^{miss} < 40 GeV. We therefore consider only isolated 4\sigma events that have L\nu < 0 and E_T^{miss} < 40 GeV. In the data, we observe 17 events, with 17.8 \pm 3.7 \pm 1.0 events expected from standard sources. The rate of heavy-lepton events as a function of mass that pass these requirements is shown in Fig. 11. The decreasing event rate with mass is mostly due to the phase-space factor in the branching ratio for W \rightarrow L\nu. Using the heavy-lepton event rates and taking into account the additional neutrino (\nu_L) coupling to the Z^0, we obtain the limit

m_L > 41 GeV/c^2 (90\% CL) .

where the statistical and systematic errors are included in the calculation.

5.3 Additional neutrino families

A major component of the expected physics contribution (7.1 out of 20.8 events) comes from the process Z^0 \rightarrow \nu\overline{\nu}, where we have assumed three neutrino species. The existence of additional light neutrinos or of any other non-interacting neutral particle coupling to the Z^0 would be expected to produce E_T^{miss} events in the same way. As explained previously, the uncertainty of the p_T(Z) spectrum at large p_T leads to uncertainties at large E_T^{miss}. This again leads us to use the region E_T^{miss} < 40 GeV and L\nu < 0, where the contribution for each additional neutrino species is predicted to be 1.9 events. We then obtain a limit on the total number of neutrino species:

n_\nu \leq 10 (90\% CL) .

A summary of the current experimental limits (3, 16) on the number of neutrino species is shown in Fig. 12. Although the limit given above is not the lowest, it is an independent measurement and the first use of the 'gluon tagging' method of neutrino counting.

<table>
<thead>
<tr>
<th>COSMOLOGICAL LIMITS</th>
<th>p\overline{p} COLLIDER LIMITS</th>
<th>e^+e^- COLLIDER LIMITS</th>
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Figure 12: A summary of the current experimental limits on the number of neutrino species.

5.4 Supersymmetry

Production of supersymmetric particles in p\overline{p} collisions would be expected to result in events with E_T^{miss} because these particles would eventually decay into normal particles and the lightest supersymmetric particle. This particle is expected to be stable and non-interacting. There

![Graph showing the rate of heavy-lepton events passing the isolated 4\sigma E_T^{miss} selection and the cuts L\nu < 0 and E_T^{miss} < 40 GeV as a function of the heavy-lepton mass (solid points).]
is a large number of possible scenarios to consider, depending on particle masses and other free parameters. We consider the following model (17):

i) the photino is the lightest supersymmetric particle, and \( m_{\chi} = 0 \); 
ii) the first five squark masses are degenerate (\( m_{\tilde{d}} = m_{\tilde{u}} = m_{\tilde{e}} = m_{\tilde{\tau}} \)); 
iii) the Higgsino, wino, zino, slepton, and supersymmetric t-quark are ignored.

This leaves only the mass of the squark and gluino as free parameters. There are two main regimes for decay modes of the squarks and gluinos: if \( m_{\tilde{g}} > m_{\tilde{q}} \), then \( \tilde{g} \to g\tilde{q} \), \( \tilde{q} \to \tilde{q}\tilde{q} \), and \( g \to q\bar{q} \); if \( m_{\tilde{q}} < m_{\tilde{g}} \), then \( \tilde{g} \to \tilde{g}\tilde{q} \), \( \tilde{q} \to \tilde{q}\tilde{q} \). Since supersymmetric particles would be pair-produced, this could result in as many as six squarks in the final state with two photinos to generate the \( E_T^{miss} \).

To evaluate the contribution of such a model to the 4\( \sigma \) sample, we again use the ISAJET Monte Carlo with full detector simulation. The expected cross-sections for supersymmetric particle production are quite large for low squark and gluino masses, although they fall rapidly with increasing mass. We find that the total acceptance of the isolated 4\( \sigma \) selection for supersymmetry events is quite low (a few percent) for much of the accessible mass range. This is because these events do not usually produce isolated \( E_T^{miss} \) owing to the kinematics of the decays and to the large number of jet present. Nevertheless, for reasonably large ranges of \( m_{\tilde{q}} \) and \( m_{\tilde{g}} \), a sufficiently large number of events pass the selection.

Although the isolation requirement tends to favour events with lower jet multiplicity, multijet events are found to dominate over monojet events. We find that the best limits, given the standard isolated 4\( \sigma \) selection, are obtained with the data sample having \( L_T < 0 \) and greater than one jet with \( E_T > 12 \text{ GeV} \) (multijets). Out of the 24 \( L_T < 0 \) events, 2 are multijet events. The expected contribution from known processes is \( 2.8 \pm 1.7 \pm 0.3 \) events. This leads to the following limits:

\[
m_{\tilde{g}} > 70 \text{ GeV}/c^2 \ (90\% \ CL) , \quad m_{\tilde{g}} > 60 \text{ GeV}/c^2 \ (90\% \ CL) .
\]

The 90\% CL limits are shown as a function of the squark and gluino masses in Fig. 13 along with the previous experimental limits (18). Note that we cannot yet exclude the region \( m_{\tilde{g}} < 10 \text{ GeV}/c^2 \) and \( m_{\tilde{q}} > 100 \text{ GeV}/c^2 \) (the "light gluino window") and work on this subject is still in progress. We are also investigating the optimization of the \( E_T^{miss} \) selection cuts to try to improve further the squark and gluino mass limits.

6. CONCLUSIONS

We have shown that an analysis based on an inclusive selection of events with large isolated \( E_T^{miss} \) provides a check on Standard Model sources of large-\( \tau \) and \( \nu \rightarrow \tau \) neutralinos. This method is also used to make sensitive searches for new physics sources of \( E_T^{miss} \). We have observed the decay \( W \rightarrow \tau \nu \) and have verified \( \tau \rightarrow \nu \tau \) universality at \( Q^2 = m_{\tilde{g}}^2 \). We find that the number of \( E_T^{miss} \) events observed and their general properties are largely in agreement with what is predicted from known Standard Model sources. We have obtained limits on the mass of a new, sequential charged heavy lepton, on the total number of neutrino species, and on the masses of supersymmetric particles. The only deviation from expectations is a slightly higher than predicted rate of non-\( \tau \)-like events at large \( E_T^{miss} \).

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