Intermediate Vector Boson Cross-sections at the CERN Super Proton Synchrotron Collider and the Number of Neutrino Types

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Abstract

We present updated results from the UA1 experiment on cross-sections times leptonic branching ratios for Intermediate Vector Bosons produced in proton-antiproton collisions at a centre-of-mass energy of 0.630 TeV. We find that $\sigma.B(W \rightarrow \ell \nu) = 0.63 \pm 0.04 \pm 0.10$ nb and $\sigma.B(Z^0 \rightarrow \ell^+ \ell^-) = 0.071 \pm 0.011 \pm 0.011$ nb, where ℓ denotes an average of electron and muon channels. An average over all data (electron and muon channels at 0.546 and 0.630 TeV) gives a ratio of $R \equiv \sigma.B(W \rightarrow \ell \nu) / \sigma.B(Z^0 \rightarrow \ell^+ \ell^-) = 9.1^{+1.7}_{-1.2}$. Using current theoretical predictions for this quantity, limits are extracted on the number of light neutrino types. Combining UA1 and UA2 data and imposing the bound $N_\nu \geq 3$ we find that $N_\nu \leq 5.9$ at 90 % confidence level. Constraints on the mass of the top quark are also discussed.

I. Introduction

Data taken at the CERN Super Proton Synchrotron proton - antiproton Collider during the period 1982 to 1984 have firmly established [1,2] the existence of the charged (W) and neutral (Z^0) Intermediate Vector Bosons (IVBs) and enabled their production and decay properties to be measured. The production properties [3,4] of the W and Z^0 were found to be consistent with the theoretical expectations for IVBs produced by the Drell-Yan mechanism [5] modified by higher order QCD corrections [6,7]. The decay properties [3,8] of the IVBs were found to be consistent with the expectations of the $SU(2) \otimes U(1)$ standard model [9]. The previously published results from the UA1 experiment were based upon an integrated luminosity of 399 nb^{-1} for the decay channels [4,8]

$$W \rightarrow e \nu \quad \text{and} \quad Z^0 \rightarrow e^+ e^- \quad (1),$$

and 108 nb^{-1} for the decay channels [10]

$$W \rightarrow \mu \nu \quad \text{and} \quad Z^0 \rightarrow \mu^+ \mu^- \quad (2).$$

Further data were collected in 1985, and results based upon an integrated luminosity of 686 nb^{-1} for the channel

$$W \rightarrow \tau \nu \quad (3)$$

have been published [11].

In this paper we update the published UA1 measurements of the IVB production cross-sections times branching ratios ($\sigma.B$) for the electron and muon decay channels listed above, and compare our experimental results with theoretical expectations [6]. Current results, which are based on an integrated luminosity of 704 nb^{-1} for the electron channels and $659 (663) \text{ nb}^{-1}$ for the W (Z^0) muon channels, are used to determine the ratio R, which is defined as

$$R \equiv (\sigma.B)_W / (\sigma.B)_Z \quad (4),$$

where $(\sigma.B)_W$ is the W production cross-section times the branching ratio for leptonic W decay, and $(\sigma.B)_Z$ is the Z^0 production cross-section times the branching ratio for charged leptonic Z^0 decay. Our measurement for the ratio R is consistent with our previous result [8] and with the equivalent result from the UA2 collaboration [12]. Finally, a comparison of the combined UA1 plus UA2 measurements of R with recent theoretical calculations [13,14,15], enables limits to be extracted on the number of light neutrino types in the universe [16,17]. Constraints on the mass of the top quark are also discussed.

II. Data Samples, Efficiencies, and Backgrounds

A summary of the UA1 data samples, and their associated selection and reconstruction efficiencies, backgrounds, and integrated luminosities is given in table 1. Full details of the UA1 W and Z^0 selection procedures can be found in refs. [4,8,10], together with a description of the main features of the UA1 detector, and the method used to evaluate selection efficiencies and backgrounds. The essential details relevant to the results presented in this paper are :

- i) **W and Z^0 Selection :** W decays in the (e ν) and ($\mu\nu$) channels were selected by requiring the presence of an isolated charged lepton (electron or muon) with transverse energy in excess of 15 GeV produced in association with a missing transverse energy (neutrino) in excess of 15 GeV. Events containing a Z^0 decay in the (e $^+e^-$) channel were selected by requiring the presence of two isolated electrons with transverse energy in excess of 15 GeV, and two-electron mass in excess of 70 GeV/c 2 . Events containing a Z^0 decay in the ($\mu^+\mu^-$) channel were selected by requiring a muon with transverse momentum in excess of 15 GeV/c produced in association with a second minimum ionizing charged particle with transverse momentum in excess of 15 GeV/c. To exclude low mass Drell - Yan pairs the invariant mass of the candidate ($\mu^+\mu^-$) - pair was required to be in excess of 50 GeV/c 2 .
- ii) **Background Evaluation :** Backgrounds from processes involving the production of energetic leptons (heavy flavour production and semileptonic decay, and tau lepton decays of the W and Z^0) have been calculated using the ISAJET Monte Carlo program [18] together with a full simulation of the UA1 detector. We have studied the contribution from top - quark production and decay as a function of m_t using the EUROJET Monte Carlo program [19]. For a light top quark ($m_t \leq 50$ GeV/c 2) we expect a contribution of ~ 3 % to the W decay channels, and a negligible contribution to the Z^0 channels. For a heavier top quark this background contribution is smaller. The potential 3 % background to the UA1 W samples from top quark related processes is the dominant source of systematic error on the determination of R. A detailed evaluation has also been made of backgrounds faking a lepton signature, namely the fluctuation of a hadronic jet that fakes an electron signature, or the production of secondary muons from meson decays. Excluding possible top - quark related backgrounds, the total background contribution from all other sources does not exceed 12 % for any of the leptonic W and Z^0 decay channels considered.
- iii) **Selection and Reconstruction Efficiencies :** Two methods have been used to calculate the selection and reconstruction efficiencies for the (lv) decays of the W ; (a) the ISAJET Monte Carlo program has been used together with a full simulation of the UA1 detector, and (b) a randomised W decay technique has been used in which the charged lepton from real W events is replaced by a lepton from a random (V-A) decay of the observed W and the modified events passed through the

W selection program. Both methods give consistent results. We have used the ISAJET results for our selection and reconstruction efficiencies, since the precision of this method is not limited by statistics. The ISAJET efficiency calculation has also been used for Z^0 decays in the (e^+e^-) and $(\mu^+\mu^-)$ channels.

III. Cross-Sections times Branching Ratios and Lepton Universality

The UA1 cross - sections times branching ratios, measured at two proton - antiproton centre-of-mass energies ($\sqrt{s} = 0.546$ TeV and 0.630 TeV), are given in table 2 along with the equivalent results from the UA2 collaboration [12], and the current theoretical expectations [6]. Averaging over electron and muon channels at $\sqrt{s} = 0.630$ TeV the UA1 results are $(\sigma.B)_W = 0.63 \pm 0.04 \pm 0.10$ nb and $(\sigma.B)_Z = 0.071 \pm 0.011 \pm 0.011$ nb. The first errors quoted on the tabulated UA1 cross-sections are statistical, and the second errors reflect a 15 % systematic uncertainty which is common to all the UA1 cross-section measurements and arises mainly from the uncertainty on the integrated luminosity of the experiment. If the top quark mass is less than about 50 GeV/c² the results for $(\sigma.B)_W$ should be reduced by 3 % to account for the top quark related background contributions to the W samples. The UA1 measurements, which are consistent with the equivalent UA2 results [12], are systematically above the theoretical expectations of [6] by about one standard deviation. New precise measurements of $F_2^{\mu p}(x)$ by the BCDMS Collaboration [20] imply a rescaling of the predictions of [6] by a factor 1.29. This would bring theory and data into good agreement. The leptonic branching ratios, and hence expectations for $\sigma.B$, depend on m_t . For a light top ($m_t \sim 44$ GeV/c²) $B_W \sim 0.09$, while for a heavy top ($m_t \sim 80$ GeV/c²) $B_W \sim 0.11$. The precision of the W cross-section measurement does not yet allow any statement about the top mass based on this 20% variation.

The predicted $\sigma.B$ also depend upon the number of quark colour degrees of freedom, which enter both in the predictions for the production cross - sections σ and the leptonic branching ratios B . Our results support the existence of three quark colours. The precision of the W cross - section measurements is sufficient to enable us to count the quark colours; i.e. at 90 % confidence level we can exclude the existence of ≤ 2 colours (which would increase the predicted $\sigma.B$ by a factor of 1.9 to 2.0 depending on m_t), and also the existence of ≥ 4 colours (which would decrease the predicted $\sigma.B$ by a factor of 0.6).

The ratios of the $\sigma.B$ for the various $W \rightarrow \ell \nu$ channels provide us with a test of lepton universality of the weak couplings of the W. We define the weak charged coupling constants g :

$$(g_1 / g_2)^2 = \Gamma(W \rightarrow \ell_1 \nu) / \Gamma(W \rightarrow \ell_2 \nu) = \sigma.B(W \rightarrow \ell_1 \nu) / \sigma.B(W \rightarrow \ell_2 \nu) \quad (5).$$

After combining $\sqrt{s} = 0.546$ TeV and 0.63 TeV data samples our results are

$$g_{\tau} / g_e = 1.01 \pm 0.10 \pm 0.06$$

and

$$g_{\mu} / g_e = 1.00 \pm 0.07 \pm 0.04 \quad (6).$$

These updated results, which provide direct experimental verification of electron - muon - tau universality of the weak charged coupling at $Q^2 = m_W^2$, are essentially the same as those of our previous publication [11].

Similarly, defining the weak neutral coupling constants k :

$$(k_1 / k_2)^2 = \Gamma(Z \rightarrow \ell_1^+ \ell_1^-) / \Gamma(Z \rightarrow \ell_2^+ \ell_2^-) \quad (7),$$

we obtain

$$k_{\mu} / k_e = 1.02 \pm 0.15 \pm 0.04 \quad (8).$$

IV. The Determination of R

The systematic errors on the measurements of the W and Z^0 cross-sections times branching ratios largely cancel in the ratio R and hence the precision of the experimental determination of R is currently limited by the available Z^0 statistics. To obtain the most precise value for R it is necessary to combine all measurements in one overall fit. In doing this we assume lepton universality of the weak couplings, which is consistent with our results (6) and (8). Using the results in table 1 there are four independent UA1 measurements of R [corresponding to the electron channels (1) measured at $\sqrt{s} = 0.546$ TeV and 0.630 TeV, and the muon channels (2) measured at the two energies].

To extract the best value of R and determine the associated experimental uncertainty we have used the maximum likelihood method. After computing the likelihood curves for each of the four R measurements, the four curves have been combined to obtain an overall fit. In this procedure the statistical error on the observed number of events, the uncertainties on the selection and reconstruction efficiencies, and on the number of background events, are all taken into account. The resulting measurements of R are shown in table 3, and the overall likelihood curve is shown in figure 1. All four determinations of R are consistent with each other. The final result is

$$R = 9.1^{+1.7}_{-1.2} \quad (9),$$

where the error reflects the limited Z^0 statistics (52 events) with a small contribution from the W statistics (367 events) and the uncertainties on the experimental efficiencies and backgrounds. If the top quark mass is less than ~ 50 GeV/ c^2 the measured value of R should be decreased by $\approx 3\%$ (see table 3) to account for the additional background in the W samples. The UA1 measurement of

R is consistent with the equivalent UA2 result [12] $R = 7.2^{+1.7}_{-1.2}$. The maximum value of R consistent with the UA1 measurement is

$$\begin{aligned} R &\leq 11.5 && (90\% \text{ C.L.}) \\ R &\leq 12.2 && (95\% \text{ C.L.}) \end{aligned} \tag{10}.$$

These limits should be decreased by 3 % if the top quark is light.

V. Interpretation

The theoretical prediction for R

$$R \equiv \sigma_W \cdot B(W \rightarrow \ell \nu) / \sigma_Z \cdot B(Z \rightarrow \ell^+ \ell^-) \equiv R_\sigma B_W / B_Z \tag{11}$$

depends upon :

- i) the predicted ratio of the production cross-sections $R_\sigma \equiv \sigma_W / \sigma_Z$. For a fixed number of neutrino types and top quark mass the uncertainty on R_σ dominates the overall uncertainty on the prediction for R. Recent calculations have given $R_\sigma = 3.25 \pm 0.20$ [6], 3.36 ± 0.09 [13], 3.41 ± 0.08 [14], and 3.28 ± 0.15 [15] for $\sqrt{s} = 0.630$ TeV, where the different theoretical results come from different analyses of the nucleon structure functions [16]. Note that the uncertainty on R_σ is small compared to the statistical uncertainty on the measurement of R. The predicted value of R_σ is not sensitive to small changes in $\sqrt{s}$. In particular, at $\sqrt{s} = 0.546$ TeV, $R_\sigma = 3.40 \pm 0.09$ [13]. In the following analysis we have combined the $\sqrt{s} = 0.630$ and 0.546 TeV data to maximize the statistics.
- ii) the prediction for B_W , the leptonic branching ratio for the W, and hence Γ_W , the total width of the W. If we assume that we know all the decay modes of the W (three leptonic modes and three quark modes) the only remaining uncertainty in the standard model prediction for Γ_W arises from the unknown partial width for the decay $W \rightarrow t \bar{b}$, where t is the top quark. This partial width, and hence B_W , depends upon the top mass m_t .
- iii) the prediction for B_Z , the charged leptonic branching ratio of the Z^0 , and hence Γ_Z , the total width of the Z^0 . The branching ratio B_Z depends upon the partial width for the decay $Z^0 \rightarrow t \bar{t}$, and hence on m_t . If we assume that we know all the decay modes of the Z^0 , but allow for an unknown number of light neutrino types, and therefore decay channels of the type

$$Z^0 \rightarrow \nu_i \bar{\nu}_i \tag{12}$$

then Γ_Z , and hence B_Z , depends upon the number of light neutrino types ν_i [16,17], where "light" means m_ν small compared to $m_Z/2$.

Thus, the standard model prediction for R depends upon the total number of light neutrino types and the mass of the top quark. The theoretical prediction for R from ref. 13 is shown as a function of m_t and the number of light neutrino types in figure 2. Using the expectation for R_σ from ref. 13 {15} together with the UA1 measured value of R , and noting that the current limit on the top quark mass [21] is $m_t \geq 44 \text{ GeV}/c^2$ (95% C.L.), we find that $N_\nu \leq 6.5\{7.0\}$ (90 % C.L.). If the top quark is heavier than $44 \text{ GeV}/c^2$ this limit becomes more restrictive. The UA1 value of R corresponds to $2.9^{+2.9}_{-2.0} \pm 0.7$ [$0.9^{+2.5}_{-1.7} \pm 0.6$] neutrino types for a light [heavy] top quark, where the second errors reflect the spread in theoretical predictions for R_σ (taken to be 3.28 ± 0.15). The 90%, 95%, and 99% confidence limits on R are shown as a function of m_t in figure 2a, where they are compared with predictions for R as a function of N_ν . In computing these limits the background contribution to the W samples from top related processes has been taken into account.

Previously published results [8,12,22] placing limits on N_ν have been obtained without imposing the condition $N_\nu \geq 3$. Imposing this bound makes the experimental limits on N_ν less stringent. To study this we have used the method recommended in [23] for obtaining limits in the case of a bounded physical region, and imposed the bound $N_\nu \geq 3$. Treating N_ν as a continuous variable the resulting UA1 limits on N_ν are shown as a function of m_t in figure 3a. Using the value of R_σ from ref. 13 {15} we find that $N_\nu \leq 7.7 \{8.0\}$ at 90 % C.L. for all $m_t \geq 44 \text{ GeV}/c^2$. Repeating the analysis but allowing only integer values for N_ν we find that $N_\nu \leq 7 \{8\}$ (90 % C.L., $m_t \geq 44 \text{ GeV}/c^2$).

An alternative method of obtaining a conservative limit on N_ν is to use the value of R_σ corresponding to the lower edge of the band of theoretical predictions, which we take to be $R_\sigma = 3.13$. We then obtain limits on N_ν for $m_t = 44 \text{ GeV}/c^2$ (figure 2c) similar to those from our previous method (in which we applied the bound $N_\nu \geq 3$).

Using the published UA2 results [12] for the number of observed IVBs, efficiencies, backgrounds, and integrated luminosities, and the likelihood fitting procedure used to determine the UA1 result, we have reproduced the published UA2 value of R and the associated errors. Combining the UA1 and UA2 likelihood curves associated with the measurement of R the overall collider result is

$$R = 8.4^{+1.2}_{-0.9} \quad (13),$$

which should be decreased by 3 % if the top quark is light. This value of R gives $N_\nu = 1.8^{+2.0}_{-1.5} \pm 0.6$ ($-0.1^{+1.7}_{-1.3} \pm 0.6$) neutrino types for a light (heavy) top quark. The associated upper limits on R are :

$$R \leq 10.1 \quad (90\% \text{ C.L.})$$

$$R \leq 10.5 \quad (95\% \text{ C.L.}) \quad (14).$$

Once again these numbers should be reduced by 3 % if the top quark mass is light. The upper limits are shown as a function of m_t in figure 2b, where they are compared with predictions for R as a function of N_ν . The combined (UA1 + UA2) limit on N_ν as a function of m_t is shown in figure 3b, where the bound $N_\nu \geq 3$ has been imposed. In computing these limits the background contributions to the W samples from top related processes have been taken into account, assuming a similar background contribution for both UA1 and UA2. Using the value of R_σ from ref. 13 {15} we find that $N_\nu \leq 5.7$ {5.9} at 90 % C.L. for all $m_t \geq 44 \text{ GeV}/c^2$. If we allow only integer values for N_ν in obtaining our limit we find $N_\nu \leq 5$ {6} at 90 % C.L. Note that for $m_t = 44 \text{ GeV}/c^2$ similar limits on N_ν are obtained if, instead of imposing the bound $N_\nu \geq 3$, we take the conservative value of $R_\sigma = 3.13$ (figure 2c). The two methods give differing results at large m_t , where the bound $N_\nu \geq 3$ keeps the limit relatively conservative. Without the bound the data come close to excluding the existence of a heavy top quark, however we stress that the measured central value of R corresponds to $N_\nu < 3$ which this method does not take into account. We therefore choose the more conservative results for which the bound on N_ν has been imposed. Our limits depend upon the estimated background from $t\bar{t}$ production and semileptonic decay. If the $t\bar{t}$ production cross - section is larger than the one we have used [19] by a factor of two, our confidence limits on N_ν at low m_t become more stringent by about 0.5 neutrino types. Finally, we have considered the sensitivity of our results to the existence of a fourth generation heavy charged lepton L , and the associated decay $W \rightarrow L\nu_L$. The current UA1 limit [24] on the mass m_L is $m_L > 41 \text{ GeV}/c^2$ (90 % C.L.). If a lepton exists with this mass our limits on N_ν become less restrictive by one neutrino type.

VI Conclusions

We have updated our previous results for the cross - sections times leptonic branching ratios of the W and Z^0 , determined that three quark colours are required to obtain agreement with theoretical predictions, tested lepton universality of the weak couplings, and determined the ratio R of W and Z^0 cross - sections times leptonic branching ratios. We find $R = 9.1^{+1.7}_{-1.2}$. Combining with UA2 data [12] we obtain $R = 8.4^{+1.2}_{-0.9}$. If we (i) take $m_t \geq 44 \text{ GeV}/c^2$ [21], (ii) use the prediction for R_σ from ref. [15] which yields the least stringent limit, and (iii) impose the bound $N_\nu \geq 3$ which also makes the limit less stringent, then the UA1 limit on R implies that there are less than or equal to 8.0 light neutrino types (90 % C.L.). If no bound on N_ν is imposed the limit is $N_\nu \leq 7.0$. The combined UA1 plus UA2 result implies that there are less than or equal to 5.9 light neutrino types with the bound $N_\nu \geq 3$ imposed, and $N_\nu \leq 4.6$ if no bound is imposed. We stress that (i) the value of R is only sensitive to the existence of neutrino types with a mass less than half of the Z^0 mass and our results for N_ν are for neutrinos with mass $m_\nu \ll m_Z/2$, and (ii) these

conclusions assume that the theoretical analyses [13,14,15] giving R_σ are correct, and that there are no new decay modes of the W or Z^0 unaccounted for. If a new heavy charged lepton exists with a mass corresponding to the UA1 lower limit of 41 GeV/c² (90 % C.L.) our limits on N_ν become less restrictive by one neutrino type. Our final conclusion ($N_\nu \leq 5.9$ at 90 % C.L.) is more conservative than those of references [14] and [15] since we have imposed the physical bound $N_\nu \geq 3$.

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Table 1: UA1 event samples, efficiencies, backgrounds, and integrated luminosities for the various W and Z⁰ samples.

$\sqrt{s}$ (TeV)	Channel	Events	Background ^{*)} Events	Efficiency	Luminosity (nb ⁻¹)
0.546	W → eν	59	6.8 ± 2.0	0.69 ± 0.03	136 ± 20
	W → μν ⁺⁾	10	0.70 ± 0.10	0.16 ± 0.02	108 ± 16
	Z ⁰ → e ⁺ e ⁻	4	< 0.1	0.69 ± 0.03	136 ± 20
	Z ⁰ → μ ⁺ μ ⁻ ⁺⁾	4	0.07 ± 0.03	0.37 ± 0.05	108 ± 16
0.630	W → eν	240	19.3 ± 1.7	0.61 ± 0.02	568 ± 85
	W → μν	57	3.3 ± 0.5	0.15 ± 0.01	551 ± 83
	Z ⁰ → e ⁺ e ⁻	29	0.20 ± 0.02	0.69 ± 0.02	568 ± 85
	Z ⁰ → μ ⁺ μ ⁻	15	0.35 ± 0.16	0.40 ± 0.02	555 ± 83
0.546 + 0.630	W → τν ⁺⁾	32	2.7 ± 0.6	0.068 ± 0.004 ± 0.007 ⁺⁺⁾	686 ± 103

^{*)} Note : no contributions from top quark production and semileptonic decay have been included in these background estimates.

⁺⁾ Numbers for this channel have been updated since our earlier publications.

⁺⁺⁾ This additional systematic error is due to the uncertainty on energy scale and τ selection.

Table 2: Cross-sections times branching ratios ($\sigma.B$); a comparison of UA1 results, UA2 results [12], and theoretical expectations [6].

Source	$\sqrt{s}$ (TeV)	Channel	$\sigma.B$ (nb) ^{*)}	
			$m_t = 44 \text{ GeV}/c^2$	$m_t \geq 80 \text{ GeV}/c^2$
UA1	0.546	$W \rightarrow e \nu$	$0.53 \pm 0.08 \pm 0.09$	$0.55 \pm 0.08 \pm 0.09$
UA1		$W \rightarrow \mu \nu$	$0.54 \pm 0.17 \pm 0.12$	$0.56 \pm 0.18 \pm 0.12$
UA2		$W \rightarrow e \nu$	—	$0.61 \pm 0.10 \pm 0.07$
Theory ^{+))}		$W \rightarrow \ell \nu$	$0.38^{+0.12}_{-0.16}$	$0.46^{+0.15}_{-0.07}$
UA1	0.630	$W \rightarrow e \nu$	$0.61 \pm 0.04 \pm 0.09$	$0.63 \pm 0.05 \pm 0.10$
UA1		$W \rightarrow \mu \nu$	$0.61 \pm 0.08 \pm 0.11$	$0.63 \pm 0.08 \pm 0.11$
UA2		$W \rightarrow e \nu$	—	$0.57 \pm 0.04 \pm 0.07$
Theory ^{+))}		$W \rightarrow \ell \nu$	$0.48^{+0.13}_{-0.07}$	$0.59^{+0.16}_{-0.09}$
UA1	$0.546^{**}) + 0.630$	$W \rightarrow \tau \nu$	$0.63 \pm 0.13 \pm 0.12$	$0.63 \pm 0.13 \pm 0.12$
UA1	0.546	$Z^0 \rightarrow e^+ e^-$	$0.042^{+0.033}_{-0.020} \pm 0.006$	$0.042^{+0.033}_{-0.020} \pm 0.006$
UA1		$Z^0 \rightarrow \mu^+ \mu^-$	$0.098^{+0.078}_{-0.046} \pm 0.020$	$0.098^{+0.078}_{-0.046} \pm 0.020$
UA2		$Z^0 \rightarrow e^+ e^-$	$0.116 \pm 0.039 \pm 0.011$	$0.116 \pm 0.039 \pm 0.011$
Theory ^{+))}		$Z^0 \rightarrow \ell^+ \ell^-$	$0.043^{+0.013}_{-0.007}$	$0.044^{+0.014}_{-0.008}$
UA1	0.630	$Z^0 \rightarrow e^+ e^-$	$0.074 \pm 0.014 \pm 0.011$	$0.074 \pm 0.014 \pm 0.011$
UA1		$Z^0 \rightarrow \mu^+ \mu^-$	$0.066 \pm 0.017 \pm 0.011$	$0.066 \pm 0.017 \pm 0.011$
UA2		$Z^0 \rightarrow e^+ e^-$	$0.073 \pm 0.014 \pm 0.007$	$0.073 \pm 0.014 \pm 0.007$
Theory ^{+))}		$Z^0 \rightarrow \ell^+ \ell^-$	$0.053^{+0.016}_{-0.010}$	$0.054^{+0.017}_{-0.011}$

+) $\ell = e$ or μ . Theoretical cross-sections for σ_W and σ_Z at $\sqrt{s} = 0.54 \text{ TeV}$ and 0.63 TeV are taken from [6]. The leptonic branching ratios used are $B_W = 0.09$, $B_Z = 0.033$ for $m_t = 44 \text{ GeV}/c^2$ and $B_W = 0.11$, $B_Z = 0.034$ for $m_t = 80 \text{ GeV}/c^2$.

*) The first error on the measured cross-sections is statistical, and the second error systematic.

**) The $\sigma.B$ for this channel is the luminosity weighted average of the two energies. The result is slightly different from the one quoted in reference [11] due to an improved evaluation of the integrated luminosity at $\sqrt{s} = 0.630 \text{ TeV}$. The luminosities are 118 nb^{-1} (568 nb^{-1}) at $\sqrt{s} = 0.546$ (0.630) TeV .

Table 3: Determinations of $R \equiv \sigma.B(W \rightarrow \ell\nu) / \sigma.B(Z \rightarrow \ell^+\ell^-)$. Background from top quark related processes depends upon m_t . Results are given for a light top quark ($m_t = 44$ GeV/c²) and a heavy top quark ($m_t \geq 80$ GeV/c², for which top related backgrounds are negligible).

Experiment	$\sqrt{s}$ (TeV)	Channels	R	
			$m_t = 44$ GeV/c ²	$m_t \geq 80$ GeV/c ²
UA1	0.546	$W \rightarrow e\nu$ and $Z^0 \rightarrow e^+e^-$	$12.7^{+9.2}_{-3.9}$	$13.2^{+9.1}_{-4.0}$
UA1		$W \rightarrow \mu\nu$ and $Z^0 \rightarrow \mu^+\mu^-$	$5.4^{+6.6}_{-1.8}$	$5.6^{+6.6}_{-1.9}$
UA1	0.630	$W \rightarrow e\nu$ and $Z^0 \rightarrow e^+e^-$	$8.3^{+2.2}_{-1.3}$	$8.6^{+2.3}_{-1.4}$
UA1		$W \rightarrow \mu\nu$ and $Z^0 \rightarrow \mu^+\mu^-$	$9.2^{+3.9}_{-2.0}$	$9.5^{+3.9}_{-2.0}$
UA1	0.546	ALL	$9.7^{+4.5}_{-2.5}$	$9.9^{+4.5}_{-2.6}$
UA1	0.630	ALL	$8.7^{+1.8}_{-1.2}$	$8.9^{+1.9}_{-1.2}$
UA1	0.546 + 0.630	ALL	$8.8^{+1.7}_{-1.1}$	$9.1^{+1.7}_{-1.2}$
UA2 [12]	0.546 + 0.630	$W \rightarrow e\nu$ and $Z^0 \rightarrow e^+e^-$	—	$7.2^{+1.7}_{-1.2}$
UA1 + UA2	0.546 + 0.630	ALL	$8.2^{+1.2}_{-0.9}$	$8.4^{+1.2}_{-0.9}$

Figure Captions

- Figure 1 : Log(likelihood) curve for the measurement of the ratio R (see text) using all the UA1 data samples listed in table 1.
- Figure 2 : Measurement of the ratio R , and the associated 90%, 95%, and 99% confidence limits, shown as a function of the top - quark mass for (a) UA1 and (b) combined UA1 + UA2 data. The shaded bands show the predictions for $N_\nu = 3, 5$, and 7 using $R_\sigma = 3.36 \pm 0.09$, and are from ref. [13]. The theoretical uncertainty on R_σ is dominated by the uncertainty on the parton densities. The UA1 and combined UA1 + UA2 limits on N_ν (90 % C.L.) are shown as a function of m_t in (c) where the conservative value $R_\sigma = 3.13$ has been used (see text).
- Figure 3 : Limits on the number of light neutrinos. Results are shown as a function of the top quark mass for (a) UA1 and (b) UA1 + UA2 . The bound $N_\nu \geq 3$ imposed (see text). The solid and broken curves correspond to the prediction for R_σ from references[13] and [15] respectively. The vertical line labeled "UA1 Limit" corresponds to the current limit (95 % C.L.) on the top quark mass [21].

Fig. 1

Fig. 2a

Fig. 2b

Fig. 2c

Fig. 3a

Fig. 3b