Measurement of the ratio $R \equiv \sigma_W Br(W \to \mu\nu) / \sigma_Z Br(Z \to \mu\mu)$ and Γ_W^{tot} at the CERN proton–antiproton collider

UA1 Collaboration, CERN, Geneva, Switzerland

Aachen–Amsterdam (NIKHEF)–Annecy (LAPP)–Birmingham–Boston–CERN–Helsinki–Kiel–Imperial College, London–Queen Mary College, London–Madrid (CIEMAT)–MIT–Padua–Paris (Collége de France)–Rome–Rutherford Appleton Laboratory–Saclay (CEN)–UCLA–Vienna

C. Albajar [a], M.G. Albrow [b], O.C. Allkofer [c,1], K. Ankoviak [d], R. Apsimon [b], B. Aubert [e], C. Bacci [f], S. Bartha [c], G. Bauer [g], A. Bettini [h], A. Bezaguet [a], P. Biddulph [i], H. Bohn [c], A. Böhrer [j], R. Bonino [a], K. Bos [k], M. Botlo [a], D. Brockhausen [c], C. Buchanan [d], B. Buschbeck [ℓ], G. Busetto [h], A. Caner [h], P. Casoli [h], H. Castilla-Valdez [d], F. Cavanna [e], P. Cennini [a], S. Centro [h], F. Ceradini [f], G. Ciapetti [f], S. Cittolin [a], E. Clayton [m], D. Cline [d], J. Colas [e], R. Conte [h], J.A. Coughlan [b], D. Dau [c], C. Daum [k], M. Della Negra [a], M. Demoulin [a], D. Denegri [n], H. Dibon [ℓ], A. DiCiaccio [f], F.J. Diez Hedo [a], L. Dobrzynski [p], J. Dorenbosch [k], J.D. Dowell [o], D. Drijard [a], K. Eggert [a], E. Eisenhandler [i], N. Ellis [o], H. Evans [d], H. Faissner [j], M. Felcini [g], I.F. Fensome [o], A. Ferrando [q], L. Fortson [d], T. Fuess [r], J. Garvey [o], A. Geiser [j], A. Givernaud [a], A. Gonidec [a], B. Gonzalez [d,1], J.M. Gregory [o], J. Gronberg [d], D.J. Holthuizen [k], W. Jank [a], G. Jorat [a], M.I. Josa [q], P.I.P. Kalmus [k], V. Karimäki [s], I. Kenyon [o], R. Kinnunen [s], M. Krammer [ℓ], F. Lacava [f], S. Lammel [j], M. Landon [i], Y. Lemoigne [n], S. Levegrün [c], D. Linglin [e], P. Lipa [ℓ], C. Markou [m], M. Markytan [ℓ], M.A. Marquina [a], R. Martinelli [h], G. Maurin [a], S. McMahon [m], J.-P. Mendiburu [p], A. Meneguzzo [h], J.P. Merlo [n], T. Meyer [a], T. Moers [j], M. Mohammadi [d], K. Morgan [g], A. Morsch [c], A. Moulin [j], Th. Muller [a], R. Munoz [a], L. Naumann [a], P. Nedelec [p], M. Nikitas [o], A. Nisati [f], A. Norton [a], V. O'Dell [b], S. Otwinowski [g], G. Pancheri [r], M. Passaseo [f], F. Pauss [a], E. Petrolo [f], G. Piano Mortari [f], E. Pietarinen [s], M. Pimiä [s], A. Placci [a], L. Pontecorvo [f], J.-P. Porte [a], R. Priem [j], R. Prosi [c], E. Radermacher [a], M. Rauschkolb [c], H. Reithler [j], J.-P. Revol [a,r], S. Robins [i], D. Robinson [i], T. Rodrigo [a], J. Rohlf [g], C. Rubbia [a], G. Sajot [p], J.M. Salicio [q], D. Samyn [a], D. Schinzel [a], R. Schleichert [j], M. Schröder [k], C. Seez [m], T.P. Shah [a,b], P. Sphicas [a], D. Stork [d], C. Stubenrauch [a], K. Sumorok [r], F. Szoncso [ℓ], C.H. Tan [r], A. Taurok [ℓ], L. Taylor [m], S. Tether [r], H. Teykal [j], G. Thompson [i], E. Torrente-Lujan [q], H. Tuchscherer [j], J. Tuominiemi [s], W. van de Guchte [k], A. van Dijk [k], M. Vargas [d], S. Veneziano [f], J.P. Vialle [e], T.S. Virdee [a,m], W. von Schlippe [i], J. Vrana [p], V. Vuillemin [a], K. Wacker [j], H. Wagner [j], X. Wu [r], C.-E. Wulz [ℓ], M. Yvert [e], I. Zacharov [a], L. Zanello [f], Y. Zolnierowski [h] and P. Zotto [a]

[a] *CERN, CH-1211 Geneva 23, Switzerland*
[b] *Rutherford Appleton Laboratory, Chilton, Didcot, Oxon 0X11 0QX, UK*
[c] *Institut für Reine und Angewandte Kernphysik, Christian Albrechts Universität, Olshausenstraße 40-60, W-2300 Kiel, FRG*
[d] *UCLA, University of California, Los Angeles, CA 90024, USA*
[e] *LAPP, Chemin de Bellevue, B.P. 909, F-74019 Annecy le Vieux Cedex, France*
[f] *Dipartimento di Fisica, Università "La Sapienza", Piazzale Aldo Moro 2, I-00185 Rome, Italy*
[g] *Department of Physics, Boston University, Boston, MA 02215, USA*
[h] *Department of Physics and INFN, Via F. Marzalo 8, I-35131 Padua, Italy*
[i] *Department of Physics, Queen Mary College, Mile End Road, London E1 4NS, UK*

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[j] III. Physikalisches Institut A, Physikzentrum RWTH, Arnold Sommerfield Straße, W-5100 Aachen, FRG
[k] NIKHEF-H, Kruislaan 409, Postbus 41882, NL-1009 DB Amsterdam, The Netherlands
[ℓ] Institut für Hochenergiesphysik, Österreichische Akademie der Wissenschaften, Nikolsdorfergasse 18, A-1050 Vienna, Austria
[m] Imperial College, London SW7 2AZ, UK
[n] DPHPE/SECB, CEN Saclay, B.P. 2, F-91190 Gif-sur-Yvette, France
[o] Department of Physics, University of Birmingham, P.O. Box 363, Birmingham B15 2TT, UK
[p] Laboratoire de Physique Corpusculaire, Collège de France, 11, Place Marcelin Berthelot, F-75231 Paris Cedex 05, France
[q] CIEMAT, E-28040 Madrid, Spain
[r] MIT, Cambridge, MA 02139, USA
[s] Department of Physics, Helsinki University, Siltavuorenpenger 20C, SF-00170 Helsinki 17, Finland

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An analysis of W and Z boson production at UA1, using 4.66 pb^{-1} of data from the 1988 and 1989 CERN $p\bar{p}$ Collider runs at $\sqrt{s}=0.63$ TeV, yields $R\equiv\sigma_W Br(W\to\mu\nu)/\sigma_Z Br(Z\to\mu\mu)=10.4^{+1.8}_{-1.5}$(stat.)$\pm0.8$(syst). We find $R=9.5^{+1.1}_{-1.0}$(stat.+syst.) when combining all available UA1 data, in both the electron and muon channel, taken in the period 1983–1989. In the framework of the standard model, the value of R is used to infer the total width of the W boson, $\Gamma_W^{tot}=2.18^{+0.26}_{-0.24}$(exp.)$\pm0.04$(theory) GeV/$c^2$.

1. Introduction

Data taken at the CERN $p\bar{p}$ Collider in the period 1983–1985, in the following referred to as the old data, has been used by the UA1 experiment to determine the production cross sections of the W and Z bosons [1]. A new data sample, corresponding to an integrated luminosity of 4.66 pb^{-1}, has been collected in the 1988 and 1989 runs. During these runs, the UA1 detector was operated without an electromagnetic calorimeter. Therefore W and Z detection was only possible in the muon channel, in contrast to the earlier runs where both electrons and muons were available (the acceptance being much larger for electrons than for muons). The new sample is used to calculate values of the production cross sections times branching ratios $\sigma_W^{\mu\nu}\equiv\sigma(p\bar{p}\to W+X)\times BR(W\to\mu\nu)$ and $\sigma_Z^{\mu\mu}\equiv\sigma(p\bar{p}\to Z+X)\times BR(Z\to\mu\mu)$ at $\sqrt{s}=0.63$ TeV.

Many of the systematic uncertainties, both experimental and theoretical, that contribute to the individual cross sections cancel in the ratio R, which is expressed by the following relation:

$$R\equiv\frac{\sigma_W^{\ell\nu}}{\sigma_Z^{\ell\ell}}=\frac{\sigma_W}{\sigma_Z}\frac{\Gamma_W^{\ell\nu}\Gamma_Z^{tot}}{\Gamma_Z^{\ell\ell}\Gamma_W^{tot}}, \qquad (1)$$

where $\sigma_W(\sigma_Z)$ is the total W(Z) production cross section and the Γs are the total and partial widths for the vector boson decays. The total width of the Z, Γ_Z^{tot}, is known to great accuracy from recent LEP measurements. In the standard model $\Gamma_W^{\ell\nu}/\Gamma_Z^{\ell\ell}$ can be expressed in terms of M_W/M_Z and $\sin^2\theta_w$. The ratio of the vector boson masses has been measured in experiments at hadron colliders [2,3] and can be inferred from results from deep inelastic scattering experiments [4,5] while $\sin^2\theta_w$ is determined by M_Z and M_W [6]. With this input, the ratio of the partial widths is known with an uncertainty of about 1%. Finally, data from BCDMS [7] and NMC [8] can be used to reduce the theoretical uncertainty on σ_W/σ_Z to about 3% by a constraint on the choice of structure functions. A measurement of R thus provides a means to extract Γ_W^{tot} indirectly. In present experiments at hadron colliders the uncertainty on Γ_W^{tot} is still dominated by the experimental uncertainty on R, which mainly comes from the limited statistics of the available Z samples. While a direct measurement of Γ_W^{tot} from a fit to the W transverse mass spectrum has an uncertainty of about 70% [1], the indirect method brings it down to about 10%.

In this analysis we present a measurement of R, which has been extracted from the new data. We then combine the result with our earlier measurement [9] and extract a value for Γ_W^{tot}. The addition of the new data more than doubles the available $Z\to\ell\ell$ statistics.

[1] Deceased.

2. UA1 apparatus

For the runs after 1985, several important changes were made to the UA1 detector. The central electromagnetic calorimeters (Gondolas and Bouchons) and the forward calorimeters were removed in preparation for the planned installation of a new Uranium-TMP calorimeter [10]. The calorimetric measurements now rely on the hadron calorimeters alone, which have an energy resolution of $\Delta E/E = 80\%/\sqrt{E}$ (the energy being measured in units of GeV). The resolution on the missing transverse energy E_T^{miss} can be parametrized as $\sigma(E_T^{miss}) = 0.8\sqrt{\sum E_T}$.

The Central Detector (CD) was operated in a new mode in order to cope with the higher currents induced by the increased Collider luminosity. The wire gain was lowered by a factor four, which was partially compensated by increasing the electronics gain by a factor three. This resulted in a degradation of the charge-division resolution by about 50% (position along the wires). Averaging over the whole chamber volume, the resolution in the drift-time measurement is essentially unchanged at ≈ 300 μm.

The muon detection system, consisting of external drift chambers and iron walls instrumented with limited streamer tube chambers, was improved by the addition of 820 tons of iron shielding in the forward region. The external muon chambers allow muon detection in the rapidity range $|\eta| < 2.3$, however, the single muon trigger is limited to $|\eta| < 1.5$.

3. Muon momentum measurement

In the analysis presented here, two methods are considered to measure the muon momentum. The first is generally used in UA1 analysis and only makes use of hits recorded in the CD. In this case we use the notation: p_T^μ, for the transverse momentum of the muon. The second method, which is applied only after muons have been identified with method one, uses the full muon detection capability of the UA1 spectrometer. It consists of an overall momentum fit (OMF) of the position information from the drift chambers and the limited streamer tube chambers outside the calorimeter, the fitted (by method one) starting point of the muon track in the CD and the event vertex. The transverse muon momentum defined as such, is indicated by p_T^μ (OMF). For both methods the event vertex was fitted excluding tracks with a CD momentum larger than 10 GeV/c from the fit.

For high momentum tracks, where multiple scattering is small, OMF yields an equally good momentum measurement as the one obtained with the CD. The best resolution is obtained by averaging the two momentum measurements.

An important feature of OMF is to identify muons, which come from pion or kaon (π/K) decays in flight. Most of these decays can be detected by method one alone. However, some fraction remains undetected if the decay point (kink) in the CD is not recognized, so that the two tracks are reconstructed as a single one faking a high momentum track, or the decay occurs outside the CD in the empty space between the CD and the hadron calorimeter. Most of the decays, which method one failed to recognize, are reconstructed as low momentum tracks by OMF due to the long lever arm provided by the hits in the muon chambers. In this case OMF and CD momenta do not match.

There is some trade off between a good momentum resolution (from an average of the two measurements) and a good rejection power against muons from π/K decays (from OMF alone). The final choice of method depends on the specific application.

4. Event selection

4.1. Preselection

W and Z candidates were selected from a common inclusive muon event sample obtained by the following loose requirements:

- a CD track with a projected length of >40 cm in the plane perpendicular to the magnetic field and with a minimum of 20 points,
- a track in the muon chambers pointing to the nominal interaction point within 150 mrad,
- matching in space between the extrapolated CD track and the muon chamber track and,
- rejection of cosmics, of muons from π/K decays in flight where the decay point is recognized in the CD and of leakage from hadronic showers.

This procedure selects about 42 000 events with a muon candidate of $p_T^\mu > 8$ GeV/c. The inclusive muon spectrum for $p_T^\mu < 20$ GeV/c consists of the following components: the Drell–Yan mechanism, $\Upsilon \to \mu^+\mu^-$, $J/\psi \to \mu^+\mu^-$, semileptonic decays of heavy flavour particles and π/K decays in flight. At large p_T^μ, the spectrum is dominated by $W \to \mu\nu$ and $Z \to \mu\mu$ decays with a large contribution from π/K decays. In this region, the latter component can be reduced by an order of magnitude using the OMF momentum measurement and by requiring an agreement between the muon momenta computed with both methods.

4.2. $W \to \mu\nu$ selection, backgrounds and efficiencies

(i) *$W \to \mu\nu$ selection*

The final selection of $W \to \mu\nu$ candidates starts by requiring a good quality track in the CD matched to a track in the muon chambers asking for p_T^μ (OMF) > 15 GeV/c. The background from heavy flavours can be suppressed by requiring that the muon be isolated and that the transverse mass of the muon-neutrino pair be large. The following cuts were made:
- Matching between the OMF and CD momenta: $\chi^2_{1/p} < 9$,
- CD isolation: the summed p_T or other tracks in the CD in a cone of $\Delta R = 0.4$ ($\Delta R \equiv \sqrt{\Delta\eta^2 + \Delta\phi^2}$) around the muon must be less than 1 GeV/c,
- Calorimeter isolation: the summed E_T in the calorimeter in a cone of $\Delta R = 0.7$ around the muon must be less than 5 GeV,
- No jet nearby or back-to-back with the muon is allowed: no calorimeter jet with $E_T > 10$ GeV in a cone of $\Delta R = 0.7$ around the muon and no CD jet with $P_T > 5$ GeV/c in $\Delta\phi > 150°$ in the transverse plane,
- Transverse mass cut: $M_T(\mu, \nu) > 30$ GeV/c^2, where $M_T(\mu, \nu) \equiv \sqrt{2 p_T^\mu (\text{OMF}) p_T^\nu (1 - \cos \Delta\phi_{\mu\nu})}$ and the neutrino is identified by the energy imbalance in the calorimeter corrected for the muon energy deposition.

These criteria were satisfied by 305 events, which were validated on a high resolution graphics device.

(ii) *Background evaluation*

We have used the ISAJET [11] Monte Carlo program with a full simulation of the UA1 detector to estimate the sources of background passing our $W \to \mu\nu$ selection requirements. We predict 7 ± 1 $Z \to \mu\mu$ and 12 ± 4 Drell–Yan events, with one of the muons undetected. Another 13 ± 2 events are expected to come from $W \to \tau\nu$ with a subsequent $\tau \to \mu\nu\nu$ decay. The background from semileptonic decays of b and c quarks was estimated to be 5 ± 3 events. The background from π/K decays in flight has been obtained using a technique described in ref. [12]; we predict 9 ± 4 events.

The observed number of $W \to \mu\nu$ events becomes 259 ± 17(stat.) ± 7(syst.). Fig. 1 shows the $M_T(\mu, \nu)$ distribution for the data compared to the expected W and background contributions.

The resolution can be improved by averaging the CD and OMF momenta as mentioned in section 3. However, the weight of the CD momentum partially compensates the effect of OMF, thereby increasing the background from π/K decays. This increase can be compensated by a stronger requirement on the matching between the two momentum measurements at the expense of $W \to \mu\nu$ statistics. Fig. 2 shows the transverse momentum spectrum of muons (CD+OMF average) for $\chi^2_{1/p} < 1$. The jacobian peak smeared out by the momentum resolution is transformed into a broad enhancement near 20 GeV/c.

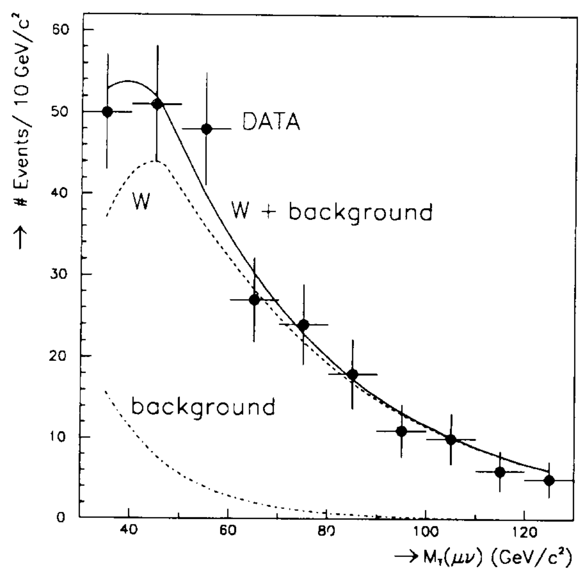

Fig. 1. Transverse mass distribution of muon-neutrino pairs for events passing the $W \to \mu\nu$ selection.

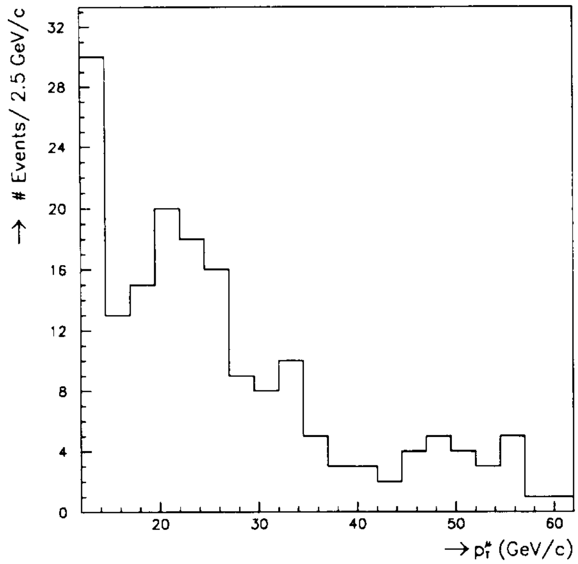

Fig. 2. Transverse muon momentum distribution (CD+OMF average) for events passing the W→μν selection and with $\chi^2_{1/p} < 1$, for the 1988–1989 data.

(iii) *Selection and reconstruction efficiencies*

We have used the ISAJET Monte Carlo program together with a simulation of the UA1 detector to calculate the selection and reconstruction efficiencies. A detailed summary is given in table 1. With the observed number of W→μν events given above, we measure a cross section times branching ratio $\sigma^{\mu\nu}_W W = 609 \pm 41\,(\text{stat.}) \pm 94\,(\text{syst.})$ pb. The main contributions to the systematic error come from the luminosity (8%) and the CD reconstruction efficiency (8%).

Table 1
Summary of the 1988–1989 W→μν acceptances and efficiencies.

	W→μν
geometrical acceptance and trigger efficiency	0.28 ±0.01
kink, cosmic and leakage rejection	0.96 ±0.01
matching between CD track and muon chamber track	0.95 ±0.05
vertex refit	0.92 ±0.03
OMF reconstruction	0.87 ±0.04
p_T^μ (OMF) > 15 GeV/c	0.79 ±0.02
track quality	0.72 ±0.06
isolation	0.83 ±0.03
$M_T(\mu\nu) > 30$ GeV/c^2	0.95 ±0.02
overall	0.091±0.012

4.3. *Z→μμ selection, backgrounds and efficiencies*

(i) *Z→μμ selection and background evaluation*

Although a dimuon trigger was active for most of the data taking, it was not explicitly required in making the final Z→μμ selection. Instead, Z candidates were selected by demanding at least one muon track that satisfies the single muon trigger.

As the expected background from π/K decays is small, the OMF procedure was not used in the final Z analysis to make use of the highest possible statistics. The cuts on the first muon are similar to the ones used in the W→μν selection but without a jet back-to-back veto and using a track quality requirement which is slightly less severe. The second muon is identified as a second CD track with $p_T > 10$ GeV/c which must be loosely isolated; it may have poorer track quality. if the CD track extrapolates to an active area of the muon chambers, an external muon track is required in addition. Finally, a cut is made requiring a dimuon mass of $M_{\mu\mu} > 50$ GeV/c^2 in order to reject intermediate-mass Drell–Yan events or

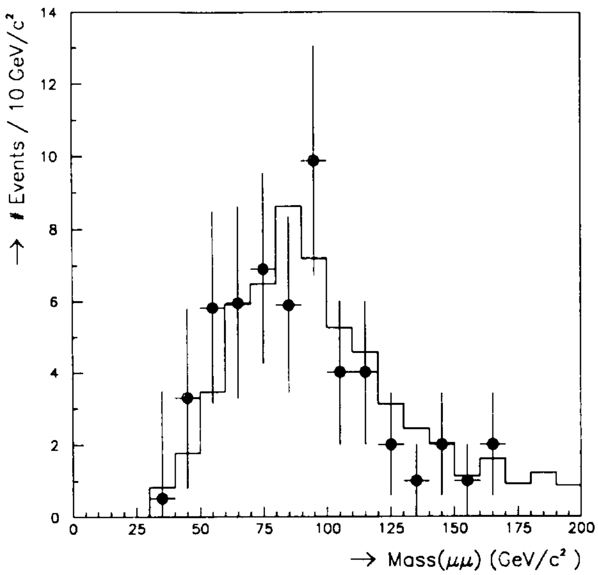

Fig. 3. Dimuon mass distribution of unlike sign dimuons for events passing the Z→μμ selection (crosses: 1988–1989 data, histogram: ISAJET prediction).

$Z \to \tau\tau$ decays in which both τ's subsequently decay into muons. We select 60 events which were validated by scanning on a high resolution graphics display.

The requirement of a second track with $p_T > 10$ GeV/c eliminates all background from heavy flavour and π/K decays. The only background remaining is 2 ± 1 Drell-Yan events. Fig. 3 shows the mass distribution of unlike sign dimuons with a mass cut at 30 GeV/c^2 for the data after background subtraction and for a full detector simulation of $Z \to \mu\mu$ events generated with ISAJET. The observed width of the Z^0 peak is well reproduced by our Monte Carlo calculation and is dominated by the momentum measurement error.

(ii) *Selection and reconstruction efficiencies*

A detailed summary of efficiencies is given in table 2. The efficiencies are split into two categories: (a) events where only one muon leg points into the active muon chamber area, (b) events where both muons point into active areas. With 58 $Z \to \mu\mu$ events observed, we measure a cross section times branching ratio $\sigma_Z^{\mu\mu} = 58.6 \pm 7.8\,(\text{stat.}) \pm 8.4\,(\text{syst.})$ pb. The dominant contributions to the systematic error are

Table 2
Summary of the 1988–1989 $Z \to \mu\mu$ acceptances and efficiencies.

	$Z \to \mu\mu$	
	One muon in active muon chamber area	both muons in active muon chamber area
geometrical acceptance and trigger efficiency	0.36 ± 0.02	0.21 ± 0.01
kink, cosmic and leakage rejection	0.96 ± 0.01	1.00 ± 0.01
matching between CD track and muon chamber track	0.95 ± 0.05	1.00 ± 0.01
vertex refit	0.92 ± 0.03	0.92 ± 0.03
muon 1: $p_T > 15$ GeV/c	0.64 ± 0.02	0.91 ± 0.03
track quality	0.76 ± 0.06	0.89 ± 0.07
isolation	0.81 ± 0.02	0.95 ± 0.03
muon 2: $p_T > 10$ GeV/c	0.78 ± 0.02	0.95 ± 0.03
track quality	0.96 ± 0.02	0.98 ± 0.02
isolation	0.92 ± 0.01	0.99 ± 0.01
$M(\mu\mu) > 50$ GeV/c^2	0.97 ± 0.01	0.98 ± 0.01
overall	0.212 ± 0.025	

similar to the ones mentioned in the case of $W \to \mu\nu$.

5. The determination of R and Γ_W^{tot}

The ratio R can be expressed in terms of experimentally measured quantities as follows:

$$R = \frac{N_W}{\varepsilon_W} \frac{\varepsilon_Z}{N_Z}\,, \qquad (2)$$

where N_W and N_Z are the numbers of $W \to \mu\nu$ and $Z \to \mu\mu$ candidates after background subtraction and ε is the overall efficiency; the luminosity cancels in the ratio.

Errors were propagated by carrying out small Monte Carlo experiments in which values for R were generated by using Poisson statistics for the observed number of events, and by keeping the efficiencies fixed to their mean values as given in tables 1 and 2. At this level, the width of the obtained distribution of R ($w_{stat.}$) yields the statistical error. The systematic error was obtained by fluctuating the different components of ε_W and ε_Z according to uniform distributions with means and errors as given in tables 1 and 2. Partial correlations between systematic uncertainties in the muon efficiencies were taken into account. From the width of the final R distribution (w_{final}) we deduce the effect of the systematic error: $w_{syst} = \sqrt{w_{final}^2 - w_{stat}^2}$. The following result was obtained using the 1988–1989 data:

$$R = 10.4^{+1.8}_{-1.5}\,(\text{stat.}) \pm 0.8\,(\text{syst.})\,. \qquad (3)$$

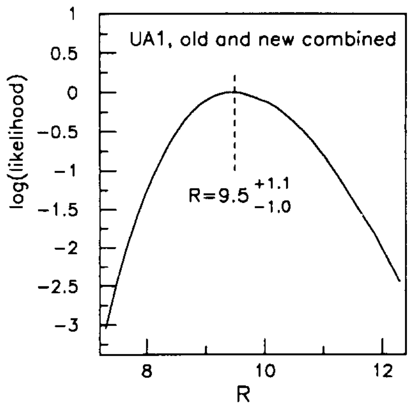

Fig. 4. log(likelihood) versus R of the combined old and new UA1 measurements.

An earlier measurement by UA1 [7] of the same quantity gave $R=9.1^{+1.7}_{-1.2}$ (stat. + syst.). Since this result mainly comes from the electron channel, the systematic uncertainty is small. To have the best possible statistics we combined the two results by the method of maximum likelihood. The likelihood curve for the new R measurement, computed with the Monte Carlo method, was combined with the one for the old result [7] to obtain the overall likelihood curve shown in fig. 4. Note that in combining results from the muon and electron channel we assume lepton universality, as indicated by UA1 results on electron and muon vector boson decays [1]. The combined value for R becomes

$$R=9.5^{+1.1}_{-1.0}(\text{stat.}+\text{syst.})\,. \qquad (4)$$

In order to extract $\Gamma^{\text{tot}}_{\text{W}}$, we use recent LEP results [13], namely: $\Gamma^{\text{tot}}_{\text{Z}}=2.498\pm0.020$ GeV/c^2 and $M_{\text{Z}}=91.172\pm0.031$ GeV/c^2. In the standard model the ratio of the partial widths is given by the following relation: $\Gamma^{\ell\nu}_{\text{W}}/\Gamma^{\ell\ell}_{\text{Z}}=2(M^3_{\text{W}}/M^3_{\text{Z}})/(1-4\sin^2\theta_{\text{w}}+8\sin^4\theta_{\text{w}})$. The ratio $M_{\text{W}}/M_{\text{Z}}$ has been measured by UA2 [2] and CDF [3] and can be inferred from measurements by CHARM [4] and CDHS [5]. A weighted average gives $M_{\text{W}}/M_{\text{Z}}=0.8794\pm0.0027$, which together with M_{Z} yields for the W mass $M_{\text{W}}=80.18\pm0.28$ GeV/c^2. For $\sin^2\theta_{\text{w}}$ we use the value given in eq. (15) of ref. [6], updated for our values of M_{W} and M_{Z}: $\sin^2\theta_{\text{w}}=0.2322\pm0.0014$. The ratio of the partial widths thus becomes $\Gamma^{\ell\nu}_{\text{W}}/\Gamma^{\ell\ell}_{\text{Z}}=2.707\pm0.025$. The main theoretical uncertainty comes from the ratio of the W and Z production cross sections: $R_\sigma\equiv\sigma_{\text{W}}/\sigma_{\text{Z}}$. This ratio can be reliably calculated in QCD at the parton level. The uncertainty comes from the parton flux factors relating p$\bar{\text{p}}$ and q$\bar{\text{q}}$ cross sections. This factor depends on the $u(x)/d(x)$ ratio of quark densities in the region $x_{\text{W}}=M_{\text{W}}/\sqrt{s}\approx0.13$ and $x_{\text{Z}}=M_{\text{Z}}/\sqrt{s}\approx0.15$ (at $\sqrt{s}=630$ GeV). As the ratio $u(x)/d(x)$ is an almost linear function of the ratio of the F_2 structure functions, $F^{\text{n}}_2(x)/F^{\text{p}}_2(x)$, the experimental measurement of this ratio can be used to constrain R_σ [14]. A calculation at $\sqrt{s}=630$ GeV using a large variety of structure function parametrizations yields values for R_σ in the range 3.08–3.46. However, if one selects structure functions on the basis of how well they describe $F^{\text{n}}_2/F^{\text{p}}_2$ as measured by BCDMS [7] and NMC [8], the value is restricted to $R_\sigma=3.23\pm0.05$ [#1]. A one standard deviation variation in $\sin^2\theta_{\text{w}}$ introduces an additional uncertainty δR_σ of ≈0.01. Higher order corrections to the cross sections have a negligible impact on R_σ.

The likelihoods in R, corresponding to the old and new UA1 result, are transformed into new likelihoods in $\Gamma^{\text{tot}}_{\text{W}}$ using eq. (1) and the parameters given above. The two curves are then used to obtain an overall fit from which we get the following combined value for $\Gamma^{\text{tot}}_{\text{W}}$:

$$\Gamma^{\text{tot}}_{\text{W}}=2.18^{+0.26}_{-0.24}\,(\text{exp.})\pm0.04(\text{theory})\ \text{GeV}/c^2\,. \qquad (5)$$

The theoretical error is due to the errors on the parameters in eq. (1) as described above. For $M_{\text{W}}=80.18\pm0.28$ GeV/c^2, $\alpha_{\text{s}}=0.11\pm0.02$ and $m_{\text{top}}>M_{\text{W}}-m_{\text{bottom}}$ the standard model prediction is $\Gamma^{\text{tot}}_{\text{W}}=2.08\pm0.02$ GeV/c^2.

Measurements of R and $\Gamma^{\text{tot}}_{\text{W}}$ have also been reported by the UA2 [16] and CDF [17] Collaborations. We use their published values of R together with our choice of parameters in eq. (1) to compute a weighted average for $\Gamma^{\text{tot}}_{\text{W}}$. In the case of CDF, R_σ had to be reevaluated as the quantity depends on $\sqrt{s}$ ($R_\sigma=3.27\pm0.05$ at $\sqrt{s}=1.8$ TeV). We obtained the following values, for UA2 $\Gamma^{\text{tot}}_{\text{W}}=2.32\pm0.20\pm0.04$ GeV/c^2, and for CDF $\Gamma^{\text{tot}}_{\text{W}}=2.15\pm0.19\pm0.04$ GeV/c^2. A weighted average for UA1, UA2 and CDF then gives $\Gamma^{\text{tot}}_{\text{W}}=2.22\pm0.12\pm0.04$ GeV/c^2.

As $\Gamma^{\text{tot}}_{\text{W}}$ depends strongly on m_{top} for $m_{\text{top}}<M_{\text{W}}-m_{\text{bottom}}$, a lower limit on m_{top} can be obtained from the comparison of the measured value of $\Gamma^{\text{tot}}_{\text{W}}$ with its theoretical expectation. Fig. 5 shows the theoretical prediction for $\Gamma^{\text{tot}}_{\text{W}}$ as a function of m_{top}. For the m_{top} dependent QCD correction terms we used the calculations of ref. [18]. Also shown are the UA1 result and the weighted average of the three experimental results given above. The 90% CL upper limit on $\Gamma^{\text{tot}}_{\text{W}}$ shown in fig. 5, yields a lower limit on m_{top} of 38 GeV/c^2 for the UA1 result alone and of 51 GeV/c^2 for the three experiments combined. This limit is essentially model independent, in contrast to direct top quark searches at p$\bar{\text{p}}$ colliders where always a value for the leptonic branching ration BR(t→bℓν) of $\frac{1}{9}$ is assumed.

[#1] Details for different sets of structure functions can be found in ref. [15].

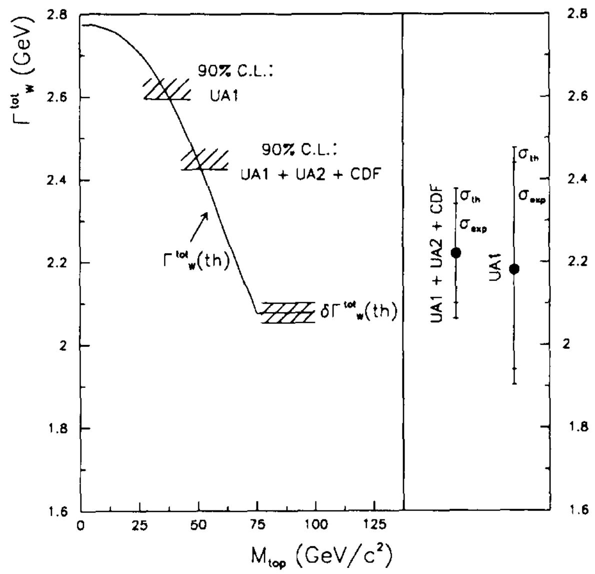

Fig. 5. Dependence of Γ_W^{tot} on m_{top} according to the standard model, the UA1 measurement, a weighted average of UA1, UA2 and CDF measurements (see text) and their 90% CL upper limits.

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