EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP/87-226
10 December 1987

EXPERIMENTAL REVIEW OF W AND Z PRODUCTION AND DECAY
AT THE CERN $p\bar{p}$ COLLIDER

P. Jenni
CERN, Geneva, Switzerland

Invited talk given at the
1987 International Symposium on
Lepton and Photon Interactions at High Energies
Hamburg, 27 July-3 August 1987

EXPERIMENTAL REVIEW OF W AND Z PRODUCTION AND DECAY AT THE CERN $p\bar{p}$ COLLIDER

Peter JENNI

CERN, Geneva, Switzerland

The main results from the UA1 and UA2 experiments at the CERN SPS $p\bar{p}$ Collider on Intermediate Vector Boson (IVB) physics are reviewed. These results include measurements of the production cross-sections, of the transverse-momentum distributions, of the leptonic and hadronic decay modes, and of the IVB masses from the complete data samples accumulated so far. The data agree well with the Standard Model predictions. An outlook on IVB physics in the near future at $p\bar{p}$ colliders is given.

1. INTRODUCTION

The successful transformation of the CERN Super Proton Synchrotron (SPS) into a $p\bar{p}$ Collider¹ in 1981 was motivated by the search for the Intermediate Vector Bosons (IVBs) of the electroweak interactions². Only two years later the first observations of the W and Z particles were published by the UA1³ and UA2⁴ Collaborations. Since then the excellent performance of the SPS $p\bar{p}$ Collider at $\sqrt{s} = 546$ and 630 GeV has allowed the two experiments to accumulate together about 800 W and about 100 Z particles decaying leptonically, and enabled studies of the IVBs' hadronic decay modes. Clear evidence for observation of IVBs through leptonic decays has been obtained recently also at the FNAL Tevatron $p\bar{p}$ Collider at $\sqrt{s} = 1.8$ TeV by the CDF Collaboration⁵. Experimentation at the CERN $p\bar{p}$ Collider will soon enter a new phase with the first operation, in November 1987, of the improved machine complex including the new Antiproton Collector (ACOL)⁶ and the upgraded UA2 detector⁷ followed by the upgraded UA1 detector⁸ in 1988.

This review is organized in the following way. A very brief description of the UA1 and UA2 experiments and their data samples is given in Section 2. The results of the inclusive production cross-section measurements are summarized in Section 3. In Section 4 follows a description of production and decay properties, in particular of the decay angular distributions and of the transverse-momentum distributions. Section 5 deals with different decay modes, namely a comparison of the leptonic decays leading

to a test of lepton universality, a first observation of IVB decays into quark pairs detected in the two-jet invariant mass distribution, a search for the W decay into top (t) and antibottom ($\bar{b}$) quarks, and searches for exotic decay modes. The final IVB mass determinations from the full data samples are reported in Section 6 together with the Standard Model parameters deduced from them. The review ends with an outlook (Section 7) and conclusions (Section 8).

2. THE UA1 AND UA2 EXPERIMENTS

The concepts of the UA1 and UA2 detectors at the CERN $p\bar{p}$ Collider are by now well known. Their main features for the data-taking periods 1981 to 1985 can be summarized very briefly in the following way.

The UA1 detector⁹ is characterized by electromagnetic and hadronic calorimetry and tracking down to small polar angles. Momentum analysis for charged particles is provided by a magnetic dipole field, and the detector is equipped with a large-coverage muon-identification system.

The UA2 detector¹⁰ consists of a non-magnetic central part extending over polar angles θ from 40° to 140° with respect to the beam line and of forward spectrometers ($20^\circ < \theta < 40^\circ$ and $140^\circ < \theta < 160^\circ$) with toroidal magnetic fields. The central region is covered by a good-granularity electromagnetic (e.m.) and hadronic calorimeter, whereas the forward region has only electromagnetic calorimetry. Tracking and preshower detectors provide electron identification over the full polar angle range of the experiment.

The IVB data reviewed in this talk are based on the CERN $p\bar{p}$ Collider runs up to 1985. The data samples used in the UA1 analyses correspond to integrated luminosities of 136 nb^{-1} and 568 nb^{-1} at the Collider energies of $\sqrt{s} = 546 \text{ GeV}$ and 630 GeV respectively. The UA2 results are based on 142 nb^{-1} and 768 nb^{-1} at the two energies.

3. PRODUCTION CROSS-SECTIONS

The UA1 and UA2 Collaborations have measured the product of the inclusive IVB production cross-sections times the leptonic branching ratio σ_l^{IVB} from the rate of observed leptonic decays, the measurement of the integrated luminosity, and the knowledge of the detector acceptance and efficiency. The results from UA1¹¹ and UA2¹² are summarized in Table 1 and displayed in Fig. 1. There is good agreement between the two experiments on the cross-section measurements for the electron decay modes which are measured with the highest accuracy. The UA1 data furthermore show good consistency among all the observed leptonic decay modes (see also Section 5).

The systematic errors for the experimental results are dominated by the systematic uncertainties in the measurements of the integrated luminosity. These errors cancel to a

Table 1
Production cross-sections times leptonic branching ratios σ_ℓ^{IVB}

Source Channel	σ_ℓ^{IVB} (nb)		Ratio 630/546
	$\sqrt{s} = 546 \text{ GeV}$	$\sqrt{s} = 630 \text{ GeV}$	
UA1 $W \rightarrow e\nu$ $W \rightarrow \mu\nu$ $W \rightarrow \tau\nu$	$0.55 \pm 0.08 \pm 0.09$	$0.63 \pm 0.05 \pm 0.10$	$1.14 \pm 0.18 \pm 0.06$
	$0.56 \pm 0.18 \pm 0.12$	$0.63 \pm 0.08 \pm 0.11$	$1.14 \pm 0.40 \pm 0.18$
	$0.63 \pm 0.13 \pm 0.12$		
UA2 $W \rightarrow e\nu$	$0.61 \pm 0.10 \pm 0.07$	$0.57 \pm 0.04 \pm 0.07$	0.93 ± 0.17
UA1 $Z^0 \rightarrow e^+e^-$ $Z^0 \rightarrow \mu^+\mu^-$	$0.042 \begin{smallmatrix} +0.033 \\ -0.020 \end{smallmatrix} \pm 0.006$	$0.074 \pm 0.014 \pm 0.011$	
	$0.098 \begin{smallmatrix} +0.078 \\ -0.046 \end{smallmatrix} \pm 0.020$	$0.066 \pm 0.017 \pm 0.011$	
UA2 $Z^0 \rightarrow e^+e^-$	$0.116 \pm 0.039 \pm 0.011$	$0.073 \pm 0.014 \pm 0.007$	
Theory $W \rightarrow \ell\nu$	$0.37 \begin{smallmatrix} +0.12 \\ -0.05 \end{smallmatrix}$	$0.47 \begin{smallmatrix} +0.14 \\ -0.08 \end{smallmatrix}$	1.26 ± 0.02
Theory $Z^0 \rightarrow \ell^+\ell^-$	$0.042 \begin{smallmatrix} +0.013 \\ -0.006 \end{smallmatrix}$	$0.051 \begin{smallmatrix} +0.016 \\ -0.010 \end{smallmatrix}$	

Note: The data are from Ref. 11 for UA1, from Ref. 12 for UA2, and from Ref. 13 for the theoretical predictions which assume IVB masses of $m_W = 83 \text{ GeV}$ and $m_Z = 94 \text{ GeV}$, and a top-quark mass of $m_t = 40 \text{ GeV}$. The theoretical values correspond to $\sqrt{s} = 540$ and 630 GeV . Both statistical and systematic errors are listed for the experimental results.

good approximation in the ratios of the cross-sections at the two $\sqrt{s}$ values, also listed in Table 1.

The data are in satisfactory agreement with theoretical predictions. Shown in Fig. 1 as a function of $\sqrt{s}$ and given also in Table 1 are the calculations of Altarelli et al.¹³, which were obtained under the assumptions of a top-quark mass $m_t = 40 \text{ GeV}$ and IVB masses of $m_W = 83 \text{ GeV}$ and $m_Z = 94 \text{ GeV}$. The errors of these theoretical predictions reflect uncertainties in the structure functions and ambiguities in the choice of the Q^2 scale. A detailed study of the dependence of the theoretical predictions on the structure functions, higher-order (α_s^2) strong corrections, $\sin^2 \theta_w$, IVB and top-quark masses, and the number of light neutrinos has been reported recently¹⁴. From that work one can note that a higher top mass would improve the agreement between theory and experiment for σ_ℓ^W . On the other hand, the experimental errors on σ_ℓ^W are at present too large to provide a firm constraint on m_t .

FIGURE 1

Intermediate Vector Boson production cross-sections times leptonic branching ratios in $p\bar{p}$ collisions. The data^{11,12} correspond to $\sqrt{s} = 546$ and 630 GeV for the electron and muon channels, and to a luminosity weighted average for the two $\sqrt{s}$ for the tau channel. Only statistical errors are shown. The theoretical predictions of Ref. 13 are indicated with their estimated uncertainties over the CERN and FNAL $p\bar{p}$ collider energy ranges. See Table 1 and the text for details.

4. PRODUCTION AND DECAY PROPERTIES

At the CERN $p\bar{p}$ Collider energy the IVB production arises mainly from the annihilation of valence quarks and antiquarks¹⁵.

The W 's are almost fully polarized along the $\bar{p}$ direction according to the Standard Model expectation. Assuming a universal $V - A$ coupling of the W to fermions, one expects from helicity conservation a distinct charge asymmetry in the $W \rightarrow \ell \nu$ decay, with a lepton angular distribution of the form $dn/d(\cos \theta^*) \propto (1 + q \cos \theta^*)^2$, where θ^* is the angle of the emitted charged lepton with respect to the W polarization in the W rest frame and q is the charge of the emitted lepton. The analysis of the data has to

FIGURE 2

Intermediate Vector Boson decay angular distributions. The decay electron (positron) $dn/d(q \cos \theta^*)$ distributions are shown in (a) and (b) for the UA1¹⁶ and UA2¹⁷ data respectively, for $W \rightarrow e\nu$ decays with unambiguous measurements of the charge q and the angle θ^* in the W rest frame with respect to the incident proton direction. Superimposed is the expectation from W decays including higher-order QCD effects. The Z decay angular distribution from UA1¹⁶ is displayed in (c) for the combined electron and muon data. The curves show the expectation for two values of $\sin^2 \theta_W$.

overcome the fact that the $W \rightarrow \ell\nu$ events are not fully reconstructed (the longitudinal momentum component of the ν is not measured) and that the definition of $\cos \theta^*$ is affected by the intrinsic p_T of the W . The UA1¹⁶ and UA2¹⁷ $W \rightarrow e\nu$ decay angular distributions for well-measured events are given in Figs. 2a and 2b together with the Standard Model prediction. The good agreement supports the expectation that the W spin is 1 and that the weak couplings involved are of the form $V \pm A$, leaving however the relative sign of the V and A terms undetermined¹⁸.

Only a small charge asymmetry is expected for the leptons from the $Z^0 \rightarrow \ell^+ \ell^-$ decay since the vector coupling of the Z^0 to leptons is proportional to $1 - 4\sin^2 \theta_w$ and $\sin^2 \theta_w$ is close to 0.25. The UA1 Z^0 decay angular distribution¹⁶ for the combined $Z^0 \rightarrow e^+ e^-$ and $Z^0 \rightarrow \mu^+ \mu^-$ channels is shown in Fig. 2c together with the expectation for two values of $\sin^2 \theta_w$. The data provide a measurement of $\sin^2 \theta_w = 0.18 \pm 0.04$ consistent with the more precise determinations from the IVB masses discussed in Section 6.

The production of the IVBs by quark–antiquark annihilation (Drell–Yan process) is in general accompanied by the radiation of gluons from the incoming partons giving rise to a non-zero IVB transverse momentum p_T^{IVB} . The radiation can include hard (large-transverse-momentum) gluons observable as hadronic jets causing a significant tail in the p_T^{IVB} distributions.

Experimentally only p_T^Z can be measured directly from the transverse momenta of the two final-state leptons whereas for p_T^W one has to measure also the transverse momentum of the recoiling hadrons. The best precision is reached for the $Z^0 \rightarrow e^+ e^-$ channel for which UA2¹² have evaluated an accuracy for p_T^Z of ± 2 GeV, dominated by the uncertainty of the energy measurement for the electrons. An even better accuracy of ~ 0.2 GeV is obtained for the p_T^Z component p_{η}^Z perpendicular to the bisector of the e^+ and e^- transverse-momentum vectors, which is mostly affected by the small angular measurement errors. The UA2 distribution of p_{η}^Z is compared in Fig. 3a with the theoretical prediction obtained from Ref. 13 for two sets of structure functions (see Ref. 12 for details). The UA2 data correspond to an average value $\langle p_T^Z \rangle = 8.6 \pm 1.5$ GeV.

The normalized W transverse-momentum distributions p_T^W are shown in Fig. 3b. The UA1 data¹⁹ consist of 266 $W \rightarrow e\nu$ and 57 $W \rightarrow \mu\nu$ events. The UA2 results^{12,20} are only shown for $p_T^W > 15$ GeV, the region where UA2 evaluates that this quantity can be measured reliably, given the estimated experimental uncertainty for p_T^W of about 5 GeV due to the measurement errors on the recoil hadrons. The curves in Fig. 3b show the behaviour expected from QCD calculations as reported by UA1¹⁹. The solid line below 25 GeV corresponds to a full QCD calculation from Ref. 13 using a soft gluon resummation technique. The shaded band between 25 and 60 GeV results from a perturbative calculation (order α_s) normalized by the lowest-order W cross-section, whereas the expectation shown for the region $p_T^W > 60$ GeV corresponds to a Monte Carlo extrapolation (ISAJET) which has been adjusted in the region $25 < p_T^W < 60$ GeV.

The two measurements agree with the QCD expectation. Special attention has been given to the events with very large p_T^W . The three events (two from UA1 and one from UA2) with $p_T^W > 60$ GeV are statistically compatible with the QCD expectation of about one event. However, the two events from UA1 both contain a W recoiling against a two-jet system jj. In both cases the Wjj mass is in excess of 250 GeV, and the jj mass is compatible with an IVB decaying into a quark–antiquark pair. This topology cannot be easily explained by order α_s^2 QCD calculations, which predict only 0.05 ± 0.03 events,

a) $Z^0 \rightarrow e^+e^-$ data from UA2¹². The transverse-momentum component p_T^Z defined in the text is compared with theoretical predictions using two different sets of structure functions (see Ref. 12).

b) W transverse-momentum distributions from UA1¹⁹ (full points) and UA2²⁰ (open points). Only data with $p_T^W > 15$ GeV are shown for UA2. The curves are QCD predictions as reported in Ref. 19 based on calculations of Ref. 13 and extrapolated to high p_T^W .

FIGURE 3

Intermediate Vector Boson transverse-momentum distributions.

or by Standard Model boson-pair production contributing even less events (see Ref. 19 for details). The future $p\bar{p}$ runs at CERN and FNAL are expected to clarify this question soon.

5. DECAY MODES

The first observations of the IVBs at the CERN $p\bar{p}$ Collider have been made using their electronic decay modes. Subsequently, other leptonic and hadronic decay modes have been searched for and several of them have been detected. This section summarizes first the measurements of the leptonic decay modes, then reports on searches for hadronic decays in the two-jet mass distribution from quark-antiquark pairs and in the exclusive channel $W \rightarrow t\bar{b}$ followed by a semileptonic top-quark decay. Searches for exotic decays are briefly mentioned, as well as an extraction of a limit on the number of light neutrinos as a function of m_t from the ratio of the IVB widths.

All three expected leptonic decays of the W and the $Z^0 \rightarrow e^+e^-$ and $\mu^+\mu^-$ decay modes have been measured by UA1^{11,21}. The cross-sections times branching ratio measurements listed in Table 1 provide an experimental test of the lepton universality expected in the Standard Model for the weak charged and neutral current couplings at $Q^2 = m_{IVB}^2$. Defining the weak charged coupling constants by $(g_i/g_j)^2 = \Gamma(W \rightarrow \ell_i \nu)/\Gamma(W \rightarrow \ell_j \nu) = \sigma_{\ell_i}^W/\sigma_{\ell_j}^W$ and similarly for the weak neutral couplings k_i (i, j charged-lepton types), UA1 have obtained the following results combining the $\sqrt{s} = 546$ GeV and 630 GeV data samples

$$\begin{aligned} g_\mu/g_e &= 1.00 \pm 0.07 \pm 0.04 \\ g_\tau/g_e &= 1.01 \pm 0.10 \pm 0.06 \\ k_\mu/k_e &= 1.02 \pm 0.15 \pm 0.04, \end{aligned}$$

where the first error is statistical and the second one is due to systematic uncertainties. These measurements give support to the validity of lepton universality in the IVB decays to a level of about 15%.

The σ_e^{IVB} data from UA2¹² have been used to extract the electronic branching ratios (BR) of the IVBs using the theoretical total IVB production cross-sections of Ref. 13. The results contain the same information as shown in Fig. 1 and can be expressed as

$$\begin{aligned} \text{BR}(W \rightarrow e\nu) &= 0.10 \pm 0.014 \pm_{-0.03}^{+0.02} \\ \text{BR}(Z^0 \rightarrow e^+e^-) &= 0.046 \pm 0.009 \pm_{-0.014}^{+0.008} \end{aligned}$$

where the data of both $\sqrt{s}$ have been combined and where the first error is experimental (statistical and systematic errors are added in quadrature) and the second reflects the

theoretical uncertainties. These values agree with the Standard Model predictions for three fermion families, which depend on m_t (see, for example, Refs. 13 and 14).

Internal bremsstrahlung can produce experimentally observable photons accompanying the leptonic IVB decays. Two unambiguous events of the type $Z^0 \rightarrow \ell^+ \ell^- \gamma$ have been reported by the UA1²² and the UA2²³ experiments. The rate of these events is statistically compatible with the expectation from internal bremsstrahlung. In particular, UA2¹⁷ have updated their probability calculation of observing at least one event with a 24 GeV photon separated by 31° from an 11 GeV electron, corresponding to the $ee\gamma$ configuration of their $Z^0 \rightarrow e^+e^- \gamma$ event. About 0.4 such events are expected in their full Z^0 data sample of 39 events.

The dominant decay modes of the IVBs are expected to proceed through quark-antiquark pairs followed, in general, by fragmentation into a pair of final-state hadronic jets. The experimental difficulties to detect this signature at hadron colliders arise from the presence of a copious background of two-jet events produced by strong interactions (QCD) between the colliding partons. A signal of only a few per cent is expected over the QCD background. Therefore, both a good two-jet mass resolution and a large integrated luminosity are required in searching for $IVB \rightarrow \text{jet} + \text{jet}$ events. The UA2 Collaboration²⁴ have recently reported the result of such a search, which is shown in Fig. 4. A signal of about 3 standard deviations significance is observed above a large QCD background. The peak contains 632 ± 190 events compared with an expectation of 340 ± 80 events from W and Z^0 decays (excluding modes with a top quark). The fitted W mass is $m_W = 82.3^{+3.0}_{-2.4}$ GeV. The UA2 result is consistent with the expectation from the Standard Model. However, stronger evidence for a signal and a significant quantitative measurement of the IVB branching fractions into quark-antiquark pairs will require the collection of a much larger data sample.

FIGURE 4

Two-jet invariant mass distribution from UA2²⁴. The smooth curves are the results of the best fits to the QCD background alone (curve a) or including two Gaussians describing W and Z decays (curve b).

One of the great experimental challenges at the CERN and FNAL $p\bar{p}$ Colliders is the search for the top quark. For small top masses ($m_t < m_W$) a clear signature is expected from the $W \rightarrow t\bar{b}$ decay followed by a semileptonic top-quark decay yielding events with an isolated lepton accompanied by two (or more) jets and a neutrino. A second source of similar events is provided by direct QCD $t\bar{t}$ production via gluon fusion and quark-antiquark annihilation. A very comprehensive report on a search for the top quark has been given recently by UA1²⁵ using both their electron and muon data samples. Figure 5 shows the expected production number of top-quark events from IVB decays and QCD production with one semileptonic top decay as a function of m_t for an integrated luminosity $\int L dt = 700 \text{ nb}^{-1}$ corresponding to the UA1 data sample. Tight selection criteria have to be applied in order to discriminate against experimental background due to lepton misidentification in QCD jet events, or physics background due to heavy-flavour ($c\bar{c}$, $b\bar{b}$), high- p_T Drell-Yan lepton pairs, and J/ψ or Υ production processes accompanied by jets. Only a small fraction, typically 5%, of the events given in Fig. 5 are expected to survive the present UA1 selection criteria. A global analysis of various kinematical distributions and event topologies in electron + jets and muon

FIGURE 5

Expected top-quark production from IVB decays and $t\bar{t}$ continuum (taken from UA1²⁵). The raw number of events with one semileptonic t decay are shown as a function of the mass m_t for $\int L dt = 700 \text{ nb}^{-1}$ corresponding to the UA1 data sample. The IVB production cross-sections are normalized to the measured ones whereas the continuum $t\bar{t}$ is the prediction of EUROJET, see Ref. 25.

+ jets events led UA1 to the conclusion that remaining background contributions from known sources are able to account for the observed data without the need for a new quark. This result has been converted into upper limits on top-quark production as shown in Fig. 6a. It can be seen that with the present data sample the analysis is not yet sensitive to the $W \rightarrow t\bar{b}$ process alone (for all $m_t < m_W$). However, by adding the expectation from QCD $t\bar{t}$ production, a lower limit on m_t can be obtained. This QCD cross-section is affected by several uncertainties, in particular those coming from the

a) 90% and 95% confidence level contours for the experimental upper limits on the t cross-section compared to the expected ones as a function of the mass.

b) Sensitivity of the mass limit to the details of the $t\bar{t}$ continuum EUROJET calculation. $K = 1$ corresponds to cross-sections $\sigma = \sigma_0$, the mean of the lowest-order calculations. Curve 1 shows the full EUROJET prediction, whereas curves 2 to 5 are lowest-order calculations with various choices for the structure functions and the Q^2 scale, see Ref. 25.

FIGURE 6

Lower top-quark mass limits from UA1²⁵ for the combined electron and muon data. The previous lower limit from the PETRA e^+e^- experiments is indicated.

quark and gluon structure functions, from the choice of the Q^2 scale, and from the higher-order QCD corrections (K-factor). The sensitivity of the lower top-quark mass limit as a function of various choices of structure functions and Q^2 scales is shown in Fig. 6b, where cross-sections are expressed as ratios $K = \sigma(t\bar{t})/\sigma_0$, with σ_0 representing a lowest-order calculation [see Ref. 25 for details; both $\sigma(t\bar{t})$ and σ_0 include the $W \rightarrow t\bar{b}$ contribution]. From the lowest-order calculation, using the choice of structure functions and Q^2 scale that give the lowest cross-section (curve 5 of Fig. 6b) UA1 find $m_t > 44$ GeV at the 95% confidence level (CL). Including an estimate of the next higher order (α_s^3) corrections in the EUROJET QCD Monte Carlo simulation with less extreme choices for the structure functions and Q^2 scale (curve 1 of Fig. 6b) yields a 95% CL lower limit of $m_t > 56$ GeV.

Searches for exotic decay modes of the IVBs involving unknown new particles have so far been fruitless except for placing significant lower mass limits on hypothetical particles in several cases. The UA1 Collaboration have searched for a sequential heavy charged lepton, $L^\pm$ in the decay $W \rightarrow L\nu$ yielding²⁶ $m_L > 41$ GeV at the 90% CL. Using the energy and angular distributions of the $W \rightarrow e\nu$ decay, UA1 have also excluded the $W \rightarrow \tilde{e}\tilde{\nu}$ decay in a mass region of the scalar electron ($\tilde{e}$) and neutrino ($\tilde{\nu}$) plane²⁷. The UA2 Collaboration have searched for exotic IVB decays and the resulting mass limits²⁸ include the channels $Z \rightarrow \tilde{e}^+\tilde{e}^-$, $Z \rightarrow \tilde{W}^+\tilde{W}^-$, and $W \rightarrow e^*\nu$ where e^* is an excited electron.

The Standard Model provides a definite prediction for the decay widths $Z \rightarrow \nu_i\bar{\nu}_i$ for each light ($m_{\nu_i} \ll m_Z/2$) neutrino type ν_i . If one assumes that all other IVB decay modes are known, then the total width of the Z (Γ_Z) depends on the unknown m_t and on the number N_ν of light neutrino types giving rise to a partial width of $\sum \Gamma_Z^{\nu_i\bar{\nu}_i}$ ($i = 1, \dots, N_\nu$). A direct measurement of Γ_Z is experimentally difficult since a precise knowledge of the shape of the mass resolution is required. Typical average measurement errors on m_Z are estimated by UA2¹⁷ to be about 3 GeV, which is the same order as the expected Γ_Z and much larger than $\Gamma_Z^{\nu\bar{\nu}}$. However, significant bounds on N_ν and m_t ²⁹ can be obtained from the total IVB width ratio Γ_W/Γ_Z , which can be evaluated in a model-dependent way from the ratio of the measured production cross-sections times leptonic branching ratios σ_ℓ^{IVB} and the theoretically expected total production cross-sections σ^{IVB} and partial leptonic widths Γ_{IVB}^ℓ :

$$\Gamma_Z/\Gamma_W = (\sigma_\ell^W/\sigma_\ell^Z) \cdot (\sigma^Z/\sigma^W) \cdot (\Gamma_Z^\ell/\Gamma_W^\ell).$$

The theoretical input depends essentially on the structure functions and $\sin^2 \theta_w$ (see, for example, Refs. 11, 14, and 17). The dependence of Γ_Z/Γ_W on m_t and N_ν is shown in Fig. 7a and compared with the UA2 result¹⁷. At the 95% CL the UA2 data allow up to 7 light neutrino types if no restriction is placed on m_t . A limit of $N_\nu \leq 3$ is obtained for $m_t > 74$ GeV, leaving no room for unknown light neutrinos. The UA1 Collaboration¹¹ have combined their data with those of UA2, and have deduced the conservative limits

a) The width ratio Γ_Z/Γ_W from UA2¹⁷ with statistical and systematic errors and the 95% confidence level upper limit are compared with the predicted values in the Standard Model for various numbers of light neutrino types.

b) Limits from the combined UA1 and UA2 data as reported in Ref. 11. The bound $N_\nu \geq 3$ is imposed. The solid and broken curves correspond to two different theoretical calculations (see Ref. 11).

FIGURE 7

Upper limits on the number of light neutrino types N_ν as a function of the top-quark mass.

shown in Fig. 7b by taking into account in the analysis that N_ν has to be an integer value ≥ 3 .

6. IVB MASSES AND STANDARD MODEL PARAMETERS

The W and Z masses (m_W, m_Z) are the two parameters of the Standard Model which can be measured directly by the collider experiments. For the Z the mass can be evaluated in a straightforward way from the lepton-pair mass distribution in the e^+e^- and $\mu^+\mu^-$ final states, taking into account the effects of the experimental mass resolution on the relativistic Breit-Wigner shape of the Z peak. The W mass cannot be measured directly from the $W \rightarrow \ell\nu$ decays because of the unknown longitudinal momentum component of the neutrino. Only its transverse component can be inferred from the missing transverse momentum $\not{p}_T$ in the events. The W mass has been evaluated from fits to the transverse-mass distributions defined as

$$m_T = [2p_T^i \not{p}_T (1 - \cos \Delta\phi)]^{1/2},$$

where p_T^i is the electron, muon, or tau-jet transverse momentum, $\not{p}_T$ the missing transverse momentum in the events due to the neutrino(s), and $\Delta\phi$ the angle between $\vec{p}_T^i$ and $\vec{\not{p}}_T$. The distributions of m_T depend only weakly on the W production mechanism. Nevertheless, Monte Carlo techniques are needed when extracting m_W from m_T in order to simulate the expected W longitudinal- and transverse-momentum distributions and to take into account the detector characteristics. The W mass can alternatively be determined from the p_T^ℓ distribution. This method is less sensitive to the $\not{p}_T$ evaluation, but depends directly on a detailed knowledge of the shape of the p_T^W distribution.

The transverse-mass distributions for the $W \rightarrow \ell\nu$ channels and the lepton-pair mass distributions for the $Z^0 \rightarrow e^+e^-$ decays are shown in Figs. 8 and 9 for the UA1 data^{21,31} and in Fig. 10 for the UA2 data¹⁷. Estimated background contributions as well

FIGURE 8

Transverse-mass m_T distributions from UA1^{21,30} for the leptonic W decays: a) $W \rightarrow e\nu$, b) $W \rightarrow \mu\nu$, and c) $W \rightarrow \tau\nu$. The histograms show the data and the curve shows the best fits. Background contributions are shown in the case of the $W \rightarrow \mu\nu$ and $W \rightarrow \tau\nu$ distributions.

FIGURE 9

Dilepton-mass distributions from UA1³⁰ which were used to evaluate the Z mass m_Z from (a) the $Z \rightarrow e^+ e^-$ decay and from (b) the $Z \rightarrow \mu^+ \mu^-$ decay.

as expected IVB signal distributions are indicated. In the case of the muonic W decay, Fig. 8b, UA1 choose to present the inverse transverse-mass distribution ($1/m_T$), which reflects more adequately the errors in the muon-track momentum determination.

The IVB mass determinations from both experiments agree with each other and are summarized in Table 2 and displayed graphically in Fig. 11a. The most precise values are obtained from the electron channels in spite of the fact that here the errors are already dominated by the systematic energy-scale uncertainties of the UA1 and UA2 electromagnetic calorimeters, which are estimated to be about $\pm 3\%$ and $\pm 1.5\%$ respectively. The UA2 Collaboration have checked their energy-calibration procedure by remeasuring a sample of their central calorimeter cells (40 out of 240) in a test beam after the last data taking. The result is given in Fig. 11b, where the ratio of the reconstructed energy to the beam energy is shown for 40 GeV electrons. Further systematic uncertainties can arise from possible systematic biases in the evaluation of p_T in the case of m_W as quoted separately in Table 2 for the UA2 result.

The mass distributions of the electronic decay channels have also been used to extract 90% CL upper limits on the total widths Γ_{IVB} . The results are $\Gamma_W < 5.4$ GeV and $\Gamma_Z < 5.2$ GeV from UA1³⁰ and $\Gamma_W < 7.0$ GeV and $\Gamma_Z < 5.6$ GeV from UA2¹⁷.

FIGURE 10

Intermediate Vector Boson distributions from UA2¹⁷.

a) Transverse-mass distribution for the $W \rightarrow e\nu$ channel showing all the data (histogram), the fitted $W \rightarrow e\nu$ signal (dash-dotted curve), and the overall fit (solid curve) including all background contributions.

b) Electron-pair-mass distribution with the expected background curve reproducing well the low-mass events. The hatched region corresponds to the sample of 25 events used in the evaluation of m_Z .

FIGURE 11

a) A comparison of the IVB-mass measurements showing in an explicit way the statistical and systematic errors (added linearly).

b) Results of a recalibration in a beam of 40 cells of the UA2 central electromagnetic calorimeter (out of 240 cells) after about 5 years of operation.

Table 2
IVB mass values

Source	Channel	m_W (GeV)
UA1	$W \rightarrow e\nu$	$82.7 \pm 1.0 \pm 2.7$
	$W \rightarrow \mu\nu$	$81.8^{+6.0}_{-5.3} \pm 2.6$
	$W \rightarrow \tau\nu$	$89 \pm 3 \pm 6$
UA2	$W \rightarrow e\nu$	$80.2 \pm 0.6 \pm 0.5 \pm 1.3$
UA1 + UA2	$W \rightarrow e\nu$ (a)	81.0 ± 2.0
	(b)	80.8 ± 1.3

Source	Channel	m_Z (GeV)
UA1	$Z \rightarrow e^+e^-$	$93.1 \pm 1.0 \pm 3.1$
	$Z \rightarrow \mu^+\mu^-$	$90.7^{+5.2}_{-4.8} \pm 3.2$
UA2	$Z \rightarrow e^+e^-$	$91.5 \pm 1.2 \pm 1.7$
UA1 + UA2	$Z \rightarrow e^+e^-$ (a)	92.0 ± 2.4
	(b)	92.0 ± 1.8

Source	Channel	$m_Z - m_W$ (GeV)
UA1	e-channel	$10.4 \pm 1.4 \pm 0.8$
	μ -channel	$8.9^{+7.4}_{-7.7} \pm 1.9$
UA2	e-channel	$11.3 \pm 1.3 \pm 0.5 \pm 0.8$

Note: The first errors on the UA1^{21,30} and UA2¹⁷ data are statistical, followed by the systematic uncertainties which are given in the case of m_W from UA2 separately for the uncertainties in the transverse-mass determination and for the energy scale. In the combined values, statistical and systematic errors are added linearly (a) or in quadrature (b) for each experiment.

The IVB masses are two important parameters of the Standard Model, which relates them in its minimal expression to the fine structure constant α , the Fermi constant G_F , and the weak mixing angle $\sin^2 \theta_w$ by the following relations³¹:

$$m_W^2 = A^2/(1 - \Delta r) \sin^2 \theta_w \quad (1)$$

$$m_Z^2 = A^2/(1 - \Delta r) \sin^2 \theta_w \cos^2 \theta_w, \quad (2)$$

where³²

$$A = (\pi\alpha/\sqrt{2} G_F)^{1/2} = 37.2810 \pm 0.0003 \text{ GeV}.$$

The quantity Δr accounts for the effects of the one-loop radiative corrections on the IVB masses and has been calculated to be^{31,33}

$$\Delta r = 0.0711 \pm 0.0013,$$

assuming that $m_t = 35 \text{ GeV}$ and that the Higgs boson mass $m_H = 100 \text{ GeV}$. From a measurement of the ratio m_W/m_Z , for which in first order uncertainties of the calorimeter calibration cancel, a direct measurement of $\sin^2 \theta_w$ is provided by the relation

$$\sin^2 \theta_w = 1 - (m_W/m_Z)^2. \quad (3)$$

The determination of $\sin^2 \theta_w$ from Eq. (3) is independent of other experiments and of theoretical uncertainties. On the other hand, a best fit to Eqs. (1) and (2) using accurate measurements of A ³² and the calculation^{31,33} for Δr gives a more precise measurement of $\sin^2 \theta_w$. The results from UA1³⁰ and UA2¹⁷ are summarized in Table 3 for both methods. All the measurements are in excellent agreement with the average value $\sin^2 \theta_w = 0.232 \pm 0.004 \pm 0.003$ obtained in neutrino experiments³⁴, where the first error is experimental and the second one is due to theoretical uncertainties. This weighted mean is evaluated on the basis of the experimental errors, assuming a charm-quark mass $m_c = 1.5 \text{ GeV}$, and ignoring the uncertainties on the theoretical error due to m_c .

Deviations from the minimal Standard Model could be detected in particular in the quantity³⁵

$$\rho = m_W^2 / m_Z^2 \cos^2 \theta_w, \quad (4)$$

which was assumed to be $\rho = 1$ in the above formalism to determine $\sin^2 \theta_w$. Using the measurements of m_W , m_Z , and the value of $\sin^2 \theta_w$ deduced from Eqs. (1) and (2), the ρ values given in Table 3 have been derived. They are consistent with the minimal

Standard Model hypothesis $\varrho = 1$. Finally, the relations (1) and (2) can also be used to measure the radiative correction parameter

$$1 - \Delta r_1 = (A^2/m_W^2)/[1 - (m_W^2/m_Z^2)]. \quad (5)$$

A more precise value (Δr_2) may be obtained using the $\sin^2 \theta_w$ value from the neutrino experiments as additional input. Both estimates (Table 3) are consistent with the expected radiative corrections, even though the experimental errors are still too large for a definite conclusion. The experimental results are also summarized in Fig. 12 where correlations between the uncertainties of the m_W and m_Z measurements are shown in the $(m_Z, m_Z - m_W)$ plane.

Table 3
Standard Model parameters

Source	Channel	Direct measurements $\sin^2 \theta_w$ [Eq. (3)]
UA1	e-channel	0.211 ± 0.025
	μ -channel	$0.187 \pm 0.148 \pm 0.033$
UA2	e-channel	$0.232 \pm 0.025 \pm 0.010$

Source	Channel	Indirect measurements	
		$\sin^2 \theta_w$ [Eqs. (1), (2)]	ϱ [Eq. (4)]
UA1	e-channel	$0.218 \pm 0.005 \pm 0.014$	$1.009 \pm 0.028 \pm 0.020$
	μ -channel	$0.223 \pm \begin{smallmatrix} 0.033 \\ -0.029 \end{smallmatrix} \pm 0.014$	$1.05 \pm 0.16 \pm 0.05$
UA2	e-channel	$0.232 \pm 0.003 \pm 0.008$	$1.001 \pm 0.028 \pm 0.006$

Source	Δr_1	Δr_2
UA1	$0.038 \pm 0.100 \pm 0.067$	$0.125 \pm 0.021 \pm 0.057$
UA2	$0.068 \pm 0.087 \pm 0.030$	$0.068 \pm 0.022 \pm 0.032$

Note: The first errors are statistical and the second ones describe the systematic uncertainty. The data are from UA1³⁰ and UA2¹⁷.

FIGURE 12

Confidence contours (68% level) in the $(m_Z, m_Z - m_W)$ plane from UA1³⁰ and UA2¹⁷. The dashed ellipses show the statistical errors and the solid ellipses show the statistical and systematic errors combined in quadrature. The hatched region corresponds to $\sin^2 \theta_w = 0.232 \pm 0.004$ as allowed from the average of recent neutrino scattering measurements. The solid curve is the Standard Model prediction for $g \equiv 1$ with radiative corrections Δr , whereas the dash-dotted curve is the expectation ignoring all radiative corrections.

7. OUTLOOK

The physics potential of the forthcoming $p\bar{p}$ Collider runs at CERN and FNAL as well as at future hadron colliders has been reviewed recently³⁶, in particular the expected measurements concerning the Standard Model IVB and IVB-pair physics.

At CERN the $p\bar{p}$ Collider complex is now undergoing an important upgrade programme⁶, the major item being the addition of a new separate antiproton collector ring (ACOL) to the existing antiproton accumulator (AA), and the 'six-bunch' operation of the SPS in $p\bar{p}$ storage mode. The peak luminosity is expected to increase by a factor of 10, or even more, over the past performance, reaching about $5 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$. The experiments can therefore expect data samples corresponding to $L \geq 10 \text{ pb}^{-1}$ to result from the 1987 and 1988 Collider runs at $\sqrt{s} = 630 \text{ GeV}$. At the same time the two large

experiments UA1 and UA2 have been, or are being, upgraded in order to be ready for an optimal exploitation of the physics potential that will be offered by the Collider. The main emphasis of the improvement programme for the UA1 experiment⁸ is on the replacement of the old central and forward e.m. calorimeters by a uranium/tetramethyl pentane (TMP) calorimeter. Other components of the UA1 detector will be improved as well, in particular the data-acquisition system with a new multilevel trigger structure using information both from the calorimetry and from the muon detection system.

The upgrading of the UA2 experiment, described in detail elsewhere⁷, aims at mainly two aspects: i) full calorimeter coverage, and ii) better electron identification at low p_T . Full e.m. and hadron calorimeter coverage is achieved with the addition of new end-cap modules covering the angular region $6^\circ < \theta < 40^\circ$ with respect to the beam directions. Electron identification in UA2 will be improved by the use of a completely new central detector assembly. The upgraded UA2 detector is now ready for the first CERN $p\bar{p}$ Collider run with ACOL at the end of 1987.

The highest-energy hadron collider for the coming years will be the FNAL Tevatron $p\bar{p}$ Collider, which produced its first collisions in 1985 at $\sqrt{s} = 1.6$ TeV. A detailed account of its present and expected future performance, and a description of the two large experiments, the Collider Detector at Fermilab (CDF) and the D0, can be found elsewhere in these proceedings⁵.

Two examples of future Standard Model measurements at hadron colliders follow.

For future W -mass measurements a realistic error estimate has been made for the upgraded UA2 experiment, taking into account all known experimental details and assuming $L = 10 \text{ pb}^{-1}$. One expects a δm_W of $\pm 0.22 \pm 0.20 \pm 0.81$ GeV (errors due to statistics, method, and calibration, respectively) for the direct m_W measurements, and a δR of $\pm 0.003 \pm 0.002$ (statistical and systematic errors) for the mass ratio $R = m_W/m_Z$. The latter will give $\delta m_W = 350$ MeV for a known m_Z . The direct determination of $\sin^2 \theta_w$ from the mass ratio will have statistical and systematic errors of $\pm 0.006 \pm 0.004$, and Δr will be determined directly only to an accuracy of $\pm 0.024 \pm 0.014$. It has to be anticipated that precision m_W measurements will become even more difficult at hadron colliders with higher $\sqrt{s}$, in spite of the increasing production cross-section. The gain in rate will then be ruined by broader p_T^W distributions and by less central production of the W 's. Furthermore, experiments will have to cope with a more severe background from QCD two-jet production for which the cross-sections (σ_{jet}) increase even more rapidly than that for W production. Comparing, for example, the Tevatron with the CERN $p\bar{p}$ Collider, one expects a factor of 4 increase in σ_W and a factor of 10 increase for σ_{jet} with p_T 's of around 40 GeV at central pseudorapidities; the mean p_T^W is expected to double, thus broadening the Jacobian peak. It therefore seems doubtful that experiments at very high $\sqrt{s}$ hadron colliders will further improve the accuracy on m_W .

The intrinsic interest in electroweak gauge-boson pair production as a test of the structure of the Standard Model is well known, and the production of W^+W^- , $W^\pm Z^0$, Z^0Z^0 , and $W^\pm\gamma$ pairs is one of the 'bench-mark' physics processes for future hadron colliders. In addition, the W^+W^- and Z^0Z^0 final states will also be most important in the search for a possible Higgs boson if $m_H > 2m_W$. The boson-pair events will have to be selected from a copious background of QCD jet events and from standard $W + 2\text{-jet}$ production. This can be illustrated by comparing the order of magnitude $p\bar{p}$ cross-sections at $\sqrt{s} = 2 \text{ TeV}$: 10 pb for W^+W^- , 10^3 pb for $W + \text{jets}$, and 10^5 pb for four jets. There is little hope of observing Standard Model W^+W^- , $W^\pm Z^0$, or Z^0Z^0 production at the SPS and Tevatron $p\bar{p}$ Colliders. In fact it has been estimated that if one assumes, for example, that at least one of the bosons has to decay so as to give an electron (or e^+e^-) with $p_T > 10 \text{ GeV}$ and $|\eta| < 3$, one would observe 0.5 (4) W^+W^- pairs, 0.02 (0.2) $W^\pm Z^0$ pairs, and 0.03 (0.4) Z^0Z^0 pairs at $\sqrt{s} = 630 \text{ GeV}$ ($\sqrt{s} = 1.6 \text{ TeV}$, respectively) for $L = 10 \text{ pb}^{-1}$, whereas $W^\pm\gamma$ production would become marginally observable with 3 (10) events. Such events are however expected to be clearly observable at high luminosity with large $\sqrt{s}$ hadron colliders³⁶.

8. CONCLUSIONS

The present measurements of IVB production and decay properties are well described by the Standard Model. However, the experimental errors are in many cases still too large to provide very significant tests on its predictions. There is a clear need to improve the statistical and systematic measurement errors. This will become possible in the coming years with the improved $p\bar{p}$ Collider and the upgraded experiments at CERN, and with the FNAL Tevatron Collider and its experiments coming into full operation.

Acknowledgements

It is a pleasure to thank my colleagues from UA1 and UA2, in particular J.D. Dowell, M. Della Negra, L. DiLella, D. Froidevaux and S.N. Tovey, for many clarifying discussions.

REFERENCES

- 1) The Staff of the CERN Proton–Antiproton Project, Phys. Lett. **107B** (1981) 306.
- 2) C. Rubbia, Nobel Lecture, Rev. Mod. Phys. **57** (1985) 699.
- 3) UA1 Collaboration, G. Arnison et al., Phys. Lett. **122B** (1983) 103; **126B** (1983) 398.
- 4) UA2 Collaboration, M. Banner et al., Phys. Lett. **122B** (1983) 476; P. Bagnaia et al., Phys. Lett. **129B** (1983) 130.
- 5) R. Schwitters, these Proceedings.
- 6) E. Jones et al., Design study of an antiproton collector (ACOL), ed. E.J.N. Wilson (CERN 83-10, Geneva, 1983).
E. Jones et al., IEEE Trans. Nucl. Sci. **NS-30** (1983) 2778.
- 7) UA2 Collaboration, C. Booth, Proc. 6th Topical Workshop on Proton–Antiproton Collider Physics, Aachen, 1986, eds. K. Eggert et al. (World Scientific, Singapore, 1987), p. 381.
- 8) UA1 Collaboration, J.D. Dowell, *ibid.*, p. 419.
- 9) A. Astbury et al., UA1 proposal, CERN/SPSC/78-6/P92 (1978).
M. Calvetti et al., Nucl. Instrum. Methods **176** (1980) 225.
K. Eggert et al., Nucl. Instrum. Methods **176** (1980) 217 and 223.
C. Cochet et al., Nucl. Instrum. Methods **A243** (1986) 45.
- 10) B. Mansoulié, The UA2 apparatus at the CERN $p\bar{p}$ Collider, Proc. 3rd Moriond Workshop on $p\bar{p}$ Physics, 1983 (Editions Frontières, Gif-sur-Yvette, 1983), p. 609.
M. Dialinas et al., Orsay preprint LAL-RT/83-14 (1983).
C. Conta et al., Nucl. Instrum. Methods **224** (1984) 65.
A. Beer et al., Nucl. Instrum. Methods **224** (1984) 360.
K. Borer et al., Nucl. Instrum. Methods **227** (1984) 29.
- 11) UA1 Collaboration, C. Albajar et al., preprint CERN-EP/87-149 (1987), submitted to Phys. Lett. B.
- 12) UA2 Collaboration, R. Ansari et al., Phys. Lett. **194B** (1987) 158.
- 13) G. Altarelli et al., Nucl. Phys. **B246** (1984) 12, and Z. Phys. **C27** (1985) 617.
- 14) A.D. Martin et al., University of Durham preprint, DTP/87/18, submitted to Phys. Lett. B.
W.J. Stirling, these Proceedings.
- 15) C. Quigg, Rev. Mod. Phys. **44** (1977) 297.

- 16) UA1 Collaboration, G. Arnison et al., *Europhys. Lett.* **1** (1986) 327, and *Phys. Lett.* **166B** (1986) 484.
- 17) UA2 Collaboration, R. Ansari et al., *Phys. Lett.* **186B** (1987) 440; **190B** (1987) 238E.
- 18) M. Jacob, *Nuovo Cimento* **9** (1958) 826.
- 19) UA1 Collaboration, C. Albajar et al., *Phys. Lett.* **193B** (1987) 389.
- 20) K. Jakobs, private communication.
- 21) UA1 Collaboration, C. Albajar et al., *Phys. Lett.* **185B** (1987) 233; **191B** (1987) 462A.
- 22) UA1 Collaboration, G. Arnison et al., *Phys. Lett.* **147B** (1984) 241.
- 23) UA2 Collaboration, P. Bagnaia et al., *Phys. Lett.* **129B** (1983) 130.
- 24) UA2 Collaboration, R. Ansari et al., *Phys. Lett.* **186B** (1987) 452.
- 25) UA1 Collaboration, C. Albajar et al., preprint CERN-EP/87-190 (1987), submitted to *Z. Phys. C*.
- 26) UA1 Collaboration, C. Albajar et al., *Phys. Lett.* **185B** (1987) 241, 463A, and 565E.
- 27) UA1 Collaboration, C. Albajar et al., in preparation; and S. Geer, to be published in *Proc. Int. Europhysics Conf. on High-Energy Physics, Uppsala, 1987*.
- 28) UA2 Collaboration, R. Ansari et al., *Phys. Lett.* **195B** (1987) 613.
- 29) F. Halzen and K. Mursula, *Phys. Rev. Lett.* **51** (1983) 857.
K. Hikasa, *Phys. Rev.* **D29** (1984) 1939.
N.G. Deshpande et al., *Phys. Rev. Lett.* **54** (1985) 1757.
- 30) UA1 Collaboration, E. Locci, preprint CERN-EP/87-154 (1987), to be published in *Proc. Int. Europhysics Conf. on High-Energy Physics, Uppsala, 1987*.
- 31) A. Sirlin, *Phys. Rev.* **D22** (1980) 971.
W.J. Marciano, *Phys. Rev.* **D20** (1979) 274.
M. Veltman, *Phys. Rev.* **91B** (1980) 95.
F. Antonelli et al., *Phys. Rev.* **91B** (1980) 90.
- 32) Particle Data Group, *Phys. Lett.* **170B** (1986) 1.
- 33) F. Jegerlehner, Bielefeld preprint BI-TP 1986/8 (1986).
W. Hollick, preprint DESY 86-049 (1986).
W.J. Marciano and A. Sirlin, *Phys. Rev.* **D22** (1980) 2695; **D29** (1984) 945.

- 34) CDHSW Collaboration, H. Abramowicz et al., Phys. Rev. Lett. **57** (1986) 298.
CHARM Collaboration, J.V. Allaby et al., Phys. Lett. **177B** (1986) 446.
CCFR Collaboration, F. Merrit, Proc. 12th Int. Conf. on Neutrino Physics and Astrophysics, Sendai, 1986, eds. T. Kitagaki and H. Yuta (World Scientific, Singapore, 1986), p. 435.
FMMF Collaboration, R. Brock, *ibid.*, p. 456.
- 35) D. Ross and J. Veltman, Nucl. Phys. **B95** (1975) 135.
P.Q. Hung and J.J. Sakurai, Nucl. Phys. **B143** (1978) 81.
- 36) P. Jenni, Future physics at hadron colliders, Proc. ECFA Workshop on LEP 200, Aachen, 1986, eds. A. Böhm and W. Hoogland (CERN 87-08, Geneva, 1987), p. 486, and references therein.