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Experimental Status of Electroweak Unified Models

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Experimental status of electroweak unified models

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The more recent experimental information on weak neutral-current phenomena are summarized, and its agreement with gauge models of the SU(2) × U(1) type critically examined. Emphasis is put on the experimental determination of the electroweak mixing parameter $\sin^2\theta_W$.

1. Introduction

One of the major experimental achievements of the past decade has been the discovery of weak neutral-current phenomena, and the subsequent exploration of the structure of the neutral-current interaction. The aim of this paper is to review the experimental situation of the various weak neutral-current phenomena, and to compare the experimental results with predictions of the unified electroweak gauge model proposed by Glashow, Salam and Weinberg (Glashow 1961; Salam 1969; Weinberg 1967), and to check the consistency of the data with possible alternative hypotheses.

The variety of weak neutral-current interactions is depicted in figure 1, where the neutral currents of neutrinos, charged leptons, and quarks form the corners of a triangle. The interactions are then given by all possible current products, including the product of a current with itself.

The self-product of the neutrino current describes neutrino–neutrino scattering, which will hardly ever be seen. Weak neutral quark–quark scattering adds to small admixtures of opposite parity in nuclear states which give rise to observable parity-violating effects. Almost twenty years of hard experimental and theoretical work on this subject has led to very little quantitative information on the charged strangeness-conserving hadronic current. Hence, I doubt we shall learn much about the weak neutral hadronic current from quark–quark scattering. The situation is quite different in the self-coupling of charged leptons, since with the advent of e^+e^- colliding-beam machines like PETRA and PEP, weak scattering processes like $e^+e^- \rightarrow e^+e^-$, $\mu^+\mu^-$, and $\tau^+\tau^-$ are becoming observable. The very first results on this type of process have recently been published. Their significance is as yet marginal, but the exploration of neutral currents with e^+e^- colliding beams will be of ever increasing importance in the years to come.

All existing experimental information on the structure of weak neutral currents stems from processes where the currents from two different sectors are used: the most precise data have been obtained in neutrino–quark scattering, and in electron–quark scattering. The cleanest process is neutrino–electron scattering, because no uncertainty about hadronic structure is involved. It is unfortunate that the precision obtained so far is low.

It is well known that the standard model describes very well all more recent experimental results on neutral-current phenomena (for a recent review, see for example Dydak (1980)). At low energies (s, $Q^2 \ll M_Z^2$), the effective Lagrangian of the standard model is

$$\mathscr{L}_{\text{eff}}^{\text{n.c.}} = -4\frac{G}{\sqrt{2}}(J_\lambda^3 - \sin^2\theta_W\, J_\lambda^{\text{e.m.}})^2, \tag{1}$$

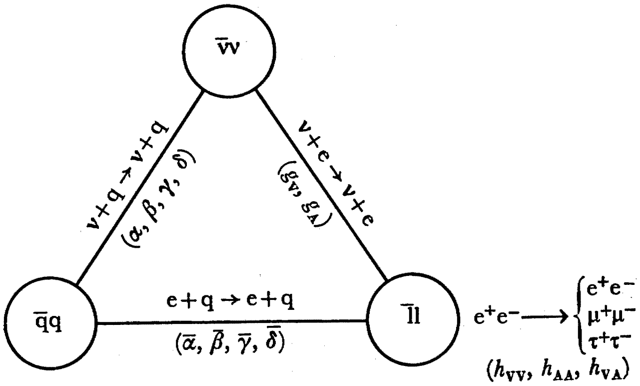


FIGURE 1. Scheme of possible neutral-current interactions.

specifying the strength and the structure of the neutral-current interaction in terms of one single mixing parameter, $\sin^2\theta_W$. While the low energy predictions of the model show very good agreement with the data, the most spectacular predictions of the model are yet to be confirmed: the existence of the W and Z bosons as carriers of the weak force, and of the Higgs scalar particle with its characteristic coupling to fermions.

It is interesting to ask whether there exist alternatives to the standard model that describe equally well the existing low-energy data, while they may exhibit a radically different high-energy behaviour.

Alternatives, which do not invoke the notion of local gauge symmetry, but are consistent with equation (1), have been put forward by Bjorken (1979), and by Hung & Sakurai (1978). The W and Z masses in these models do not necessarily coincide with the standard masses.

Less radical alternatives retain the framework of local gauge symmetry, but enlarge the standard gauge group $SU(2)\times U(1)$. Their general feature is a richer spectrum of heavy intermediate bosons. They include the standard model as a special case. Two groups of models have survived the confrontation with the precise data obtained in the last three years.

(*a*) *The* $SU(2)_L\times SU(2)_R\times U(1)$ *model*

This model was first proposed by Pati & Salam (1974), and taken up later by Fritzsch & Minkowski (1976) and many others. Many special cases of this model have been ruled out by the observation of parity-violating neutral-current scattering of polarized electrons on deuterium nuclei at SLAC (Prescott *et al.* 1978), while other special cases remain valid. A recent study of the compatibility of the $SU(2)_L\times SU(2)_R\times U(1)$ model with neutral-current data has been presented by Liede *et al.* (1978). The version compatible with present data has two intermediate bosons Z_1 and Z_2, with the mass of the lighter boson Z_1 slightly lower than the standard Z-mass, and the mass of the heavier boson Z_2 tending to infinity.

(*b*) $SU(2)\times U(1)\times G$ *models*

Models of this type are tailored so as to reproduce precisely the predictions of the standard model for neutrino–quark and electron–quark scattering. All quarks and leptons are invariant under G and transform under $SU(2)\times U(1)$ in exactly the same way as in the standard model. Models of this type have recently been discussed by de Groot *et al.* (1979, 1980) and by Barger *et al.* (1980*a*). The model of de Groot *et al.* uses $G = U(1)$, and the model of Barger *et al.*

G = SU(2). Both models can be shown to give rise to an effective low energy Lagrangian of the form

$$\mathscr{L}_{\text{eff}}^{\text{n.c.}} = -4(G/\surd 2)\{(J_\lambda^3 - \sin^2\theta_{\text{W}} J_\lambda^{\text{e.m.}})^2 + C(J_\lambda^{\text{e.m.}})^2\}, \tag{2}$$

which differs from the standard model by the occurrence of the last term. The coefficient C is related to the spectrum of the intermediate boson masses. The predictions for neutrino–quark scattering are unaffected, because the neutrino has no electric charge. Also, the predictions for parity violation in polarized electron scattering on deuterium nuclei are unaffected, because $J_\lambda^{\text{e.m.}}$ conserves parity. However, the new term affects the predictions for the processes $e^+e^- \rightarrow e^+e^-$, $\mu^+\mu^-$, $\tau^+\tau^-$. Hence, recent measurements of these reactions may be used to constrain the parameter C.

Given the remarkable success of the standard model to describe all observed properties of weak neutral-current phenomena, the programme for further experimental studies in the low-energy domain has the following objectives:

(i) to extend the test of the standard model to as many reactions as possible;

(ii) to improve the precision of the determination of $\sin^2\theta_{\text{W}}$ such that grand unified theories can be decisively tested; and

(iii) to look for departures from the predictions of the standard model, which either may be interpreted as radiative corrections of the first-order predictions, or may indicate an only approximate validity of the standard model.

The increasing precision of experimental data makes it mandatory for $O(\alpha)$ radiative corrections to be considered. This problem has been neglected in all experimental analyses in the past. This attitude was in part motivated by the absence of a complete theoretical analysis of $O(\alpha)$ electromagnetic and weak corrections. Only recently have several authors considered the problem, and a first complete analysis was presented by Paschos & Wirbel (1981).

The lowest-order theory predicts several relations that can be tested experimentally. For example, the Z-mass is a function of $\sin^2\theta_{\text{W}}$. Since the standard model is renormalizable, finite corrections to the lowest-order predictions are calculable. Radiative corrections cause modifications of the aforementioned relations of the order of 10^{-2}. Since the experimental precision is at the same level, such corrections should no longer be ignored in future analyses.

2. Neutrino–electron scattering

The particularly attractive feature of νe scattering is that there is no hadronic structure involved. Theoretical predictions are straightforward and unambiguous. Owing to the very small cross-section, however, experimental progress is slow.

Since 1979, when the experimental situation of $\nu_\mu e^-$ and $\bar{\nu}_\mu e^-$ scattering was reasonably well settled, only one new result has been published. A counter-experiment of the Virginia–Maryland–NSF Washington–Oxford–Peking collaboration reported a signal of $\nu_\mu e^-$ scattering, obtained in a 350 GeV wide-band neutrino beam exposure at FNAL (Heisterberg *et al.* 1980). The signal is of 34 events on top of a background of 12 events, corresponding to a cross section slope of

$$\sigma/E = (1.4 \pm 0.3) \times 10^{-42}\ \text{cm}^2/\text{GeV},$$

where the quoted error is statistical only. The systematic error is estimated to be of similar magnitude.

This new result agrees well with the previous world average,

$$\sigma/E = (1.6 \pm 0.4) \times 10^{-42}\ \mathrm{cm^2/GeV}.$$

The world averages of $\nu_\mu e^-$ and $\bar{\nu}_\mu e^-$ scattering cross sections, including the new result, are given in table 1 as well as the values of $\sin^2\theta_W$ corresponding to the measured cross sections. The measurements, made at a typical Q^2 of 0.02 $(\mathrm{GeV}/c)^2$, are in agreement with the predictions of the standard model. Clearly, one would like to see the experimental precision greatly improved, but there is not much hope for that in the near future.

Table 1. Summary of $\nu_\mu e^-$ and $\bar{\nu}_\mu e^-$ scattering experiments

process	$(\sigma/E)/(10^{-42}\ \mathrm{cm^2/GeV})$	$\sin^2\theta_W$
$\nu_\mu e^- \rightarrow \nu_\mu e^-$	1.5 ± 0.3	$0.24\{^{+0.06}_{-0.04}\}$
$\bar{\nu}_\mu e^- \rightarrow \bar{\nu}_\mu e^-$	1.3 ± 0.6	$0.23\{^{+0.09}_{-0.23}\}$

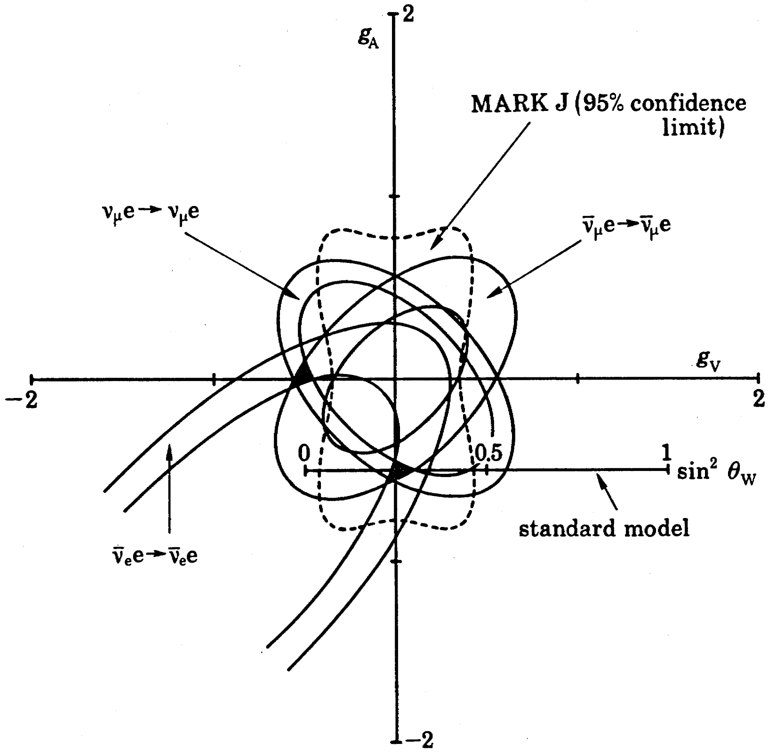


Figure 2. Allowed domains for g_V and g_A as determined from neutrino–electron scattering, and from $e^+e^- \rightarrow l^+l^-$ ($l = e, \mu, \tau$).

In terms of the vector and axial vector coupling constants of the weak neutral electron current, $g_V = -\frac{1}{2} + 2\sin^2\theta_W$ and $g_A = -\frac{1}{2}$, the measured cross sections define elliptic allowed domains in the g_V, g_A plane (figure 2). Together with the $\bar{\nu}_e e^-$ cross-section measured at the Savannah River fission reactor (Reines *et al.* 1976), the allowed regions are restricted to two, one of which (the solution with axial vector dominance) is in agreement with the standard model. No discrimination between the two solutions can be made with νe scattering experiments.

3. Weak-electromagnetic interference results from PETRA

At the energies now available ($s \approx 1000\,\mathrm{GeV}^2$) at the e^+e^- colliding storage ring PETRA, effects caused by the interference of weak and electromagnetic amplitudes start to become visible. Measurable deviations from the pure QED predictions are foreseen by the standard model in cross sections $\sigma(e^+e^- \rightarrow f\bar{f})$, with f denoting any point-like fermion, and in the angular dependence of differential cross sections.

The analysis procedure is as follows: the measured cross section $\mathrm{d}\sigma/\mathrm{d}\Omega$ is corrected for radiative effects δ_R and effects due to the hadronic vacuum polarization δ_H, and then compared with the calculated QED cross section:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}(1+\delta_R+\delta_H) = \left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)_{\mathrm{QED}}(1+\delta).$$

Deviations δ from the QED cross section are interpreted in terms of form factors, which correspond to a finite size of the leptons involved, or alternatively in terms of weak-electromagnetic interference effects. Here, a report is given on an analysis of the experimental data in terms of interference effects, with the assumption of point-like leptons without excited states.

The three purely leptonic processes that have been analysed are $e^+e^- \rightarrow e^+e^-$ (Bhabha scattering), $e^+e^- \rightarrow \mu^+\mu^-$, and $e^+e^- \rightarrow \tau^+\tau^-$. Of these, Bhabha scattering can proceed both via s- and t-channel scattering, whereas $e^+e^- \rightarrow \mu^+\mu^-$ and $e^+e^- \rightarrow \tau^+\tau^-$ are restricted to s-channel scattering.

The weak neutral-current Lagrangian is given by

$$\mathscr{L}^{\mathrm{n.c.}} = -\frac{G}{\sqrt{2}}\frac{M_Z^2}{M_Z^2-s}\{h_{VV}J_V J_V^{+} + h_{VA}(J_V J_A^{+} + J_A J_V^{+}) + h_{AA} J_A J_A^{+}\},$$

where

$$J_V = \bar{e}\gamma_\lambda e + \bar{\mu}\gamma_\lambda \mu + \bar{\tau}\gamma_\lambda \tau$$

and

$$J_A = \bar{e}\gamma_\lambda\gamma_5 e + \mu\gamma_\lambda\gamma_5 e + \tau\gamma_\lambda\gamma_5\tau.$$

The coefficients h_{VV}, h_{VA}, and h_{AA} are phenomenological coupling constants introduced by Hung & Sakurai (1977). In the framework of single Z boson models, and with the assumption of $e-\mu-\tau$ universality, they are related to the vector and axial vector coupling constants g_V and g_A of the weak neutral electron current as follows (including the standard-model predictions):

$$h_{VV} = g_V^2 = (-\tfrac{1}{2}+2\sin^2\theta_W)^2 = 0.0016 \quad (\text{for } \sin^2\theta_W = 0.23),$$

$$h_{AA} = g_A^2 = \tfrac{1}{4},$$

$$h_{VA} = g_V g_A = (-\tfrac{1}{2}+2\sin^2\theta_W)(-\tfrac{1}{2}) = 0.02 \quad (\text{for } \sin^2\theta_W = 0.23).$$

Note that the standard model predicts an almost vanishing vector coupling constant.

The ratio R_{ff} of the cross section of the reaction $e^+e^- \rightarrow f\bar{f}$ to the point-like QED cross section $\sigma_p = 4\pi\alpha^2/3s$, is given by (Ellis & Gaillard 1976)

$$R_{ff} = Q_f^2 - 8sgQ_f g_V g_{V,f}\frac{1}{(s/M_Z^2-1)+\Gamma_Z^2/(s-M_Z^2)} + 16s^2g^2(g_V^2+g_A^2)(g_{V,f}^2+g_{A,f}^2)\frac{1}{(s/M_Z^2-1)^2+\Gamma_Z^2/M_Z^2}, \tag{3}$$

where Q_f is the charge, and $g_{V,f}$ and $g_{A,f}$ are the vector and axial vector coupling constants of the final-state fermion f. The constant g is defined by

$$g = G/8\sqrt{2}\pi\alpha = 4.47\times10^{-5}\ \mathrm{GeV}^{-2}.$$

At energies far below the resonance ($s \ll M_Z^2$), the deviation from the QED point-like cross section is in good approximation given by the interference term only, and thus proportional to $g_V g_{V,f}$. Thus, for example, in the process $e^+e^- \rightarrow \mu^+\mu^-$, one measures essentially the square of the vector coupling constant. In the context of the standard model, one will interpret the absence of a deviation from the QED prediction as $g_V^2 \approx 0$, or equivalently $\sin^2\theta_W \approx 0.25$, which makes the vector coupling constant vanish.

A second measurable quantity is the forward–backward asymmetry of the process $e^+e^- \rightarrow f\bar{f}$. The asymmetry A is defined as

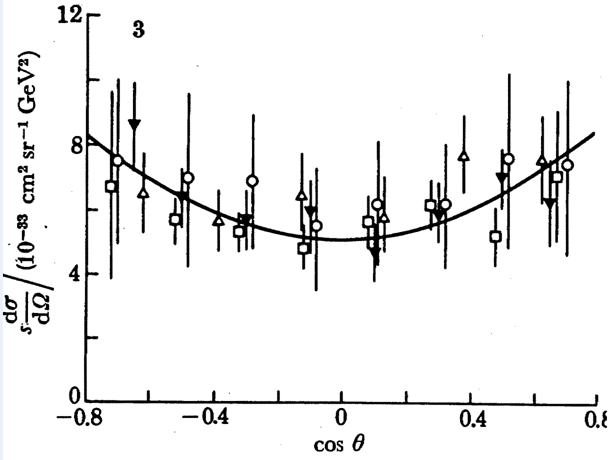
$$A = (F-B)/(F+B),$$

where F and B denote the differential cross section of the μ^- and τ^-, respectively, integrated over the forward and backward hemispheres with respect to the incident e^-. The asymmetry is given by

$$A_{ff} = \frac{6\chi(-Q_f g_A g_{A,f} + 8\chi g_V g_{V,f} g_A g_{A,f})}{Q_f^2 - 8Q_f\chi g_V g_{V,f} + 16\chi^2(g_V^2+g_A^2)(g_{V,f}^2+g_{A,f}^2)}, \qquad (4)$$

with

$$\chi = gsM_Z^2/(s-M_Z^2).$$



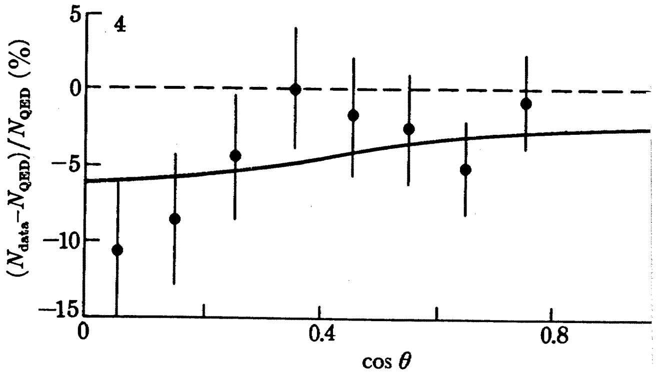


FIGURE 3. The differential cross-section of the process $e^+e^- \rightarrow \mu^+\mu^-$: ▼, JADE; □, MARK J; ○, TASSO; △, PLUTO. The full line shows the pure QED prediction.

FIGURE 4. The deviation from the QED prediction for the differential cross-section of the process $e^+e^- \rightarrow \mu^+\mu^-$ (MARK J data). The full line represents the best fit to the standard electroweak model ($g_V^2 = -0.05$, $g_A^2 = 0.21$).

The decay width Γ_Z, being small compared with M_Z, has been set to zero. Again, at energies far below the resonance, the asymmetry is in good approximation given by

$$A_{ff} \approx -6\chi Q_f g_A g_{Af}.$$

For the process $e^+e^- \rightarrow \mu^+\mu^-$, for example, the asymmetry is proportional to the square of the axial vector coupling constant:

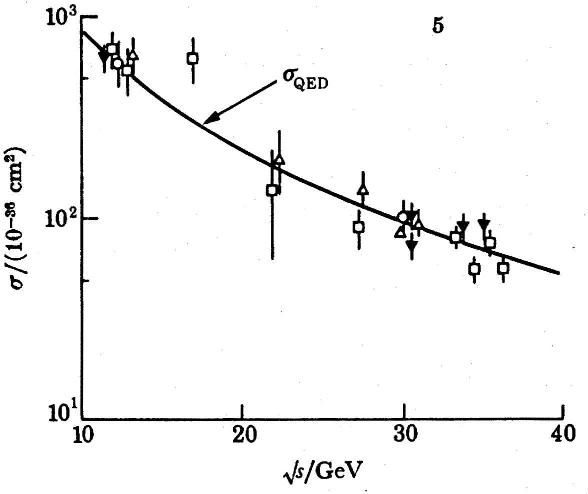
$$A_{\mu\mu} \approx 6\chi g_A^2.$$

This yields an asymmetry of -9.6% at $\sqrt{s} = 35$ GeV, with $g_A^2 = 0.25$. This is within reach of the experiments, while the expected change in $R_{\mu\mu}$ is only 7×10^{-4}, unobservable at currently obtainable energies.

The differential cross section of the process $e^+e^- \rightarrow \mu^+\mu^-$ as a function of $\cos\theta$ (θ being the angle between the outgoing μ^- and the incident e^-) obtained by the various PETRA groups (Wiik 1980; Böhm 1981) is shown in figure 3. The data are consistent with a $(1+\cos^2\theta)$-distribution as expected from QED. No significant forward–backward asymmetry is observed, which allows upper limits to be placed on g_A^2 or, more precisely, on $g_A^e g_A^\mu$. The 95% upper confidence limit is $|g_A| < 0.56$ for the worst case $M_Z = \infty$.

Table 2. Summary of forward–backward asymmetry measurements

	JADE	MARK J	PLUTO	TASSO
$A_{\mu\mu}$ (meas.)	-5 ± 6	-1 ± 6	7 ± 10	7 ± 7
$A_{\mu\mu}$ (theor.)	-6.6	-7.7	-5.8	-6.6
$\langle A_{\mu\mu} \rangle$ (meas.)		-2.8 ± 3.4		
$\langle A_{\mu\mu} \rangle$ (theor.)		-6.7		
$A_{\tau\tau}$ (meas.)	—	-6 ± 12	—	0 ± 11
$A_{\tau\tau}$ (theor.)	—	-7.0	—	-7.5
$\langle A_{\tau\tau} \rangle$ (meas.)		-3 ± 8		
$\langle A_{\tau\tau} \rangle$ (theor.)		-7.2		



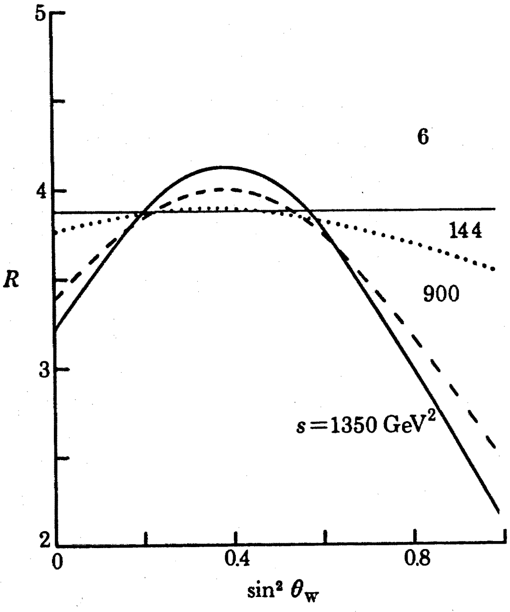


Figure 5. Cross section for $e^+e^- \rightarrow \mu^+\mu^-$ as a function of $\sqrt{s}$: ▼, JADE; □, MARK J; ○, TASSO; △, PLUTO. The full line shows the pure QED prediction.

Figure 6. The variation of R, the ratio of the total cross section $\sigma(e^+e^- \rightarrow q\bar{q})$ to the point-like QED cross section, with $\sin^2\theta_W$. The horizontal line at $R = 3.87$ corresponds to single γ exchange only (Bartel *et al.* 1981).

Similar results have been obtained from the process $e^+e^- \rightarrow \tau^+\tau^-$. The results of the asymmetry measurements are listed in table 2.

The relative deviation of the Bhabha cross section due to weak effects is plotted in figure 4 as a function of the scattering angle (MARK J data (Barber *et al.* 1981)). Although the data are consistent with the QED prediction, the best fit favours the presence of a weak effect consistent with the standard model ($g_V^2 = -0.05$, $g_A^2 = 0.21$). Similar analyses have been made by the CELLO, JADE, PLUTO and TASSO collaborations (Böhm 1981; Bartel *et al.* 1981, in preparation; Berger *et al.* 1981).

Besides the asymmetry of final-state leptons, the ratio R (equation (3)) has been investigated for possible weak effects. This had been done for purely leptonic processes, but recently also for $e^+e^- \rightarrow q\bar{q}$, where q denotes all five quark flavours (u, d, c, s, b) excited at PETRA energies.

The cross section for $e^+e^- \rightarrow \mu^+\mu^-$ obtained by various PETRA groups is shown in figure 5 as a function of $\sqrt{s}$. The observed cross section is consistent with the QED point-like cross section and is also in line with the expectation from the standard model which predicts an unobservably small deviation from QED. The measurement shows, according to formula (3), that there is no unexpectedly large vector coupling constant involved.

Table 3. Summary of results for g_V^2 and g_A^2 from PETRA experiments

	g_V^2	g_A^2
JADE	0.01 ± 0.08	0.18 ± 0.16
MARK J	-0.04 ± 0.09	0.20 ± 0.17
PLUTO	-0.02 ± 0.17	-0.19 ± 0.24
TASSO	-0.14 ± 0.12	0.25 ± 0.14
expected ($\sin^2\theta_W = 0.23$)	0.0016	0.25

All purely leptonic reactions can be used to determine g_V^2 and g_A^2, with the assumption of $e-\mu-\tau$ universality. The best fit results for g_V^2 and g_A^2 from the various PETRA groups are listed in table 3. We notice that the measurements of g_V^2 cluster closely around zero, while the measurements of g_A^2 favour a non-zero value.

The constraints on g_V^2 and g_A^2 from e^+e^- experiments can be combined with the information obtained from νe scattering experiments. The allowed region from MARK J data (Barber *et al.* 1981) is shown in figure 2. The e^+e^- experiments favour clearly the solution with axial vector dominance, which coincides with the prediction of the standard model.

By means of the standard model, the data on $e^+e^- \rightarrow e^+e^-$, $e^+e^- \rightarrow \mu^+\mu^-$, and $e^+e^- \rightarrow \tau^+\tau^-$ can be used to extract values of $\sin^2\theta_W$. The resulting values for $\sin^2\theta_W$ are listed in table 4, together with the type of experimental data that has been used.

Table 4. Summary of determinations of $\sin^2\theta_W$ from purely leptonic reactions at PETRA

	$\sin^2\theta_W$	source of information
CELLO	0.25 ± 0.15†	R_{ee}
JADE	0.25 ± 0.15	R_{ee}, $R_{\mu\mu}$, $A_{\mu\mu}$
MARK J	0.24 ± 0.12	R_{ee}, $R_{\mu\mu}$, $R_{\tau\tau}$, $A_{\mu\mu}$
PLUTO	0.22 ± 0.22	R_{ee}, $R_{\mu\mu}$, $R_{\tau\tau}$, $A_{\mu\mu}$
TASSO	0.24 ± 0.11†	R_{ee}, $A_{\mu\mu}$

† Preliminary.

While there is no doubt that the present results from e^+e^- interactions cannot yet compete with the precision achieved in neutrino–quark scattering experiments, the e^+e^- results are obtained at substantially larger values of Q^2 (*ca.* 1000 GeV^2), and involve all known charged leptons. The fact that the data constrain the vector coupling constant to a value close to zero is a non-trivial result.

The results from purely leptonic reactions have also been used to constrain the parameter C in the Lagrangian (2), which appears in gauge models with a richer boson spectrum. A statistically meaningful result can only be achieved if C is the only free parameter. In such models, $g_V^2 = -\frac{1}{2}+2\sin^2\theta_W+4C$, and $g_V g_A$ and g_A^2 remain unchanged. Then, by fixing $\sin^2\theta_W = 0.23$, stringent limits on C have been obtained; these are listed in table 5. We conclude that there is no evidence of the need for a larger gauge group than $SU(2)\times U(1)$.

TABLE 5. LIMITS ON THE C-PARAMETER FROM PETRA EXPERIMENTS (95% CONFIDENCE LEVEL)

	JADE	MARK J	PLUTO	TASSO
C	< 0.039	< 0.032	< 0.06	< 0.03

Recently, the analysis of R has been extended by the JADE (Bartel *et al.* 1981*a*, *b*) and the MARK J (Barber *et al.* 1981) collaborations to $R(e^+e^- \to q\bar{q} \to \text{hadrons})$. The underlying assumption is that five quark flavours (u, d, c, s, b) describe correctly the data in the energy range $12 < \sqrt{s} < 36.7$ GeV, and resonant effects are absent. It has been argued that this constitutes a test of the standard model in a new domain of large Q^2 and in processes that involve the production of quarks of all three generations.

Of course, it would be of great interest to study the weak coupling constants of all known quark flavours and to compare them with the predictions of the standard model. In practice, this cannot be done at currently obtainable energies. One is forced to assume that all quarks have the couplings as predicted by the standard model, and the only free parameter is then $\sin^2\theta_W$. The dependence of $R(e^+e^- \to q\bar{q})$ on $\sin^2\theta_W$ is shown in figure 6, and it can be seen that, in the context of the standard model, a negative result of the search for weak effects in $R(e^+e^- \to q\bar{q})$ (as is the case) constrains $\sin^2\theta_W$ to values around 0.23. The JADE result for $\sin^2\theta_W$ is 0.22 ± 0.08, and the MARK J result is $\sin^2\theta_W = 0.27\{^{+0.34}_{-0.08}\}$. The main message of the experiment is, however, that at large Q^2 apparently none of the quarks has an unexpectedly large coupling strength.

4. PARITY-VIOLATING OPTICAL TRANSITIONS IN HEAVY ATOMS

The existence of a parity-violating potential between the electrons of the shell and the quarks in the nucleus, due to weak neutral currents, implies that the atomic levels are not pure eigenstates of parity. They receive a small admixture of opposite parity, which causes a mixture of electric and magnetic dipole transitions. Their interference causes a rotation of the polarization plane of a laser beam, or a different absorption cross-section of right- or left-circularly polarized laser light.

Recent parity-violation experiments show a clear trend to exhibit parity violation at approximately the level predicted by the standard model. Unfortunately, the experiments are very difficult to perform, and have given conflicting results in the past. Also, they suffer from uncertainties in the calculation of atomic transition matrix elements, estimated at the level of 10–30%. Their significance in supporting the standard model should therefore not be overestimated.

Table 6 gives a summary of the most recent results on parity-violating optical transitions. As is traditional, the result is expressed as a ratio of the experimentally observed to the theoretically expected effect. Note that the quoted error reflects only experimental uncertainties and does not include uncertainties of the theoretical prediction.

Table 6. Summary of experiments on parity violation in heavy atoms

experiment	atom	transition nm	R†
Novosibirsk (Barkov & Zolotorev 1979)	Bi	648	1.07 ± 0.14
Oxford	Bi	648	in progress
Seattle (Hollister *et al.* 1981)	Bi	876	1.09 ± 0.18
Berkeley (Bucksbaum *et al.* 1981)	Tl	293	1.33 ± 0.45

† Ratio of the experimental result to the prediction of the standard model, with $\sin^2\theta_W = 0.23$.

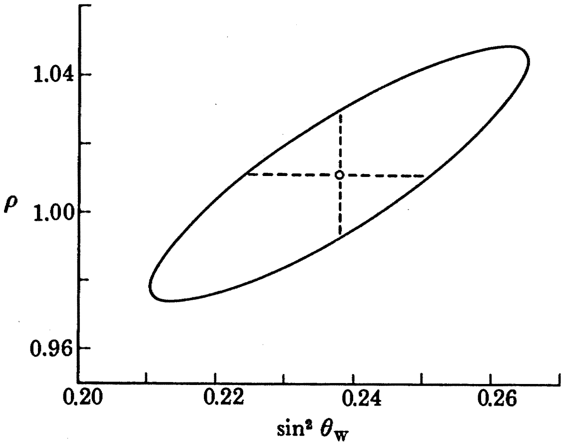


Figure 7. Correlation ellipse in a two-parameter fit of ρ and $\sin^2\theta_W$ (Roos *et al.* 1981).

5. Neutrino scattering on isoscalar nuclei

Inclusive neutral-current reactions on (nearly) isoscalar targets allow the most precise measurement of neutral-current couplings. The measured quantities are the ratios of the inclusive neutral- to charged-current cross sections R_ν and $R_{\bar{\nu}}$, and the y-distribution ($y = E_{\text{had}}/E_\nu$). The latter gives, when interpreted in the framework of the quark–parton model, information on the Lorentz structure of hadronic neutral currents.

The theoretical analysis of the measured quantities assumes in first approximation that the neutrino scatters off free quarks. It has been shown in high precision experiments from the analysis of charged-current events that the quark–parton model is indeed a very good approximation for the internal structure of the nucleon. The precision obtainable today is such that all relevant deviations from the simple quark–parton model, like scaling violation of the structure functions and the amount of the non-strange and strange sea as a function of Q^2, are reasonably well known (uncertainties from this sector are comparable or small compared with experimental errors of neutral-current studies).

Since almost all precision in the determination of neutral-current parameters comes from neutrino scattering on isoscalar nuclei, it seems appropriate to mention here the results of a recent fit to all available data on neutral-current phenomena, performed by Kim *et al.* (1980).

Their aim was to determine as fully as possible the structure of the hadronic and leptonic neutral current without recourse to the standard electroweak model, to search for the effects of small deviations from the standard model, and finally to determine as accurately as possible in the context of the standard model the value of $\sin^2\theta_W$.

The first aim is accomplished by fitting a number of phenomenological coupling constants, with the assumption of vector and axial vector covariants only for the Lorentz structure of the neutral current, and isovector and isoscalar pieces only for the isospin components of the neutral hadronic current. All resulting coupling constants turn out to be consistent with the values predicted by the standard model. For details, refer to the report of Kim *et al.* (1980).

Next, Kim *et al.* tried a fit of a generalized SU(2) × U(1) model, where the third component of the weak isospin of the right-handed fermions is kept as a free parameter. The results of this fit are

Fit 1. $\rho = 1.018 \pm 0.045, \quad \sin^2\theta_W = 0.249 \pm 0.031,$
$I^u_{3R} = -0.010 \pm 0.040, \quad I^d_{3R} = -0.101 \pm 0.058, \quad I^e_{3R} = 0.039 \pm 0.047.$

A deviation of $\rho = M^2_W/M^2_Z \cos^2\theta_W$ from unity would indicate a more complicated Higgs structure than just a doublet of scalar particles. Apparently, there is no need for more than the minimal structure. The third components of the weak isospin of the u and d quarks, and the electron, are consistent with zero, indicating that the assignment of right-handed fermions as singlets under weak isospin is correct. The next fit is therefore done by setting $I^u_{3R} = I^d_{3R} = I^e_{3R}$ to zero.

Fit 2. $\rho = 1.002 \pm 0.015, \quad \sin^2\theta_W = 0.234 \pm 0.013.$

We notice that ρ remains consistent with one, with very good accuracy. This is in line with the standard model which predicts $\rho = 1$ to first order. Therefore, a third fit is performed with the assumption that the standard model is strictly valid, with only $\sin^2\theta_W$ as a free parameter.

Fit 3. $\sin^2\theta_W = 0.233 \pm 0.009 \ (\pm 0.005).$

The error given in brackets reflects an estimate of theoretical uncertainties in the extraction of $\sin^2\theta_W$ out of experimental data.

Undoubtedly, the agreement of all recent experimental data constitutes a triumph for the standard model. However, if we look in more detail at the global fit to the existing data, we see that three caveats may be appropriate:

(i) In the theoretical analysis, as well as in all experimental analyses, weak and electromagnetic corrections have been ignored throughout.

(ii) The fit to all available experiments to get the best value of $\sin^2\theta_W$ can be criticized because the quoted experimental errors are usually not Gaussian, making a χ^2-minimization doubtful.

(iii) The errors quoted by Kim *et al.* (1980) are apparently correlated errors and not uncorrelated errors which are normally quoted as results of multi-parameter fits. This is shown in figure 7, which gives the correlation ellipse for the fit of ρ and $\sin^2\theta_W$ (fit 2). The correlation ellipse is taken from a similar fit performed by Roos and collaborators (1981 private communication). The immediate result of the quotation of correlated errors is that the probability of the correct solution lying within the quoted errors is significantly less than 68 %.

New experimental results on R_ν, $R_{\bar\nu}$, and the neutral-current y-distributions have recently been published by the Cern–Hamburg–Amsterdam–Rome–Moscow (CHARM) collaboration

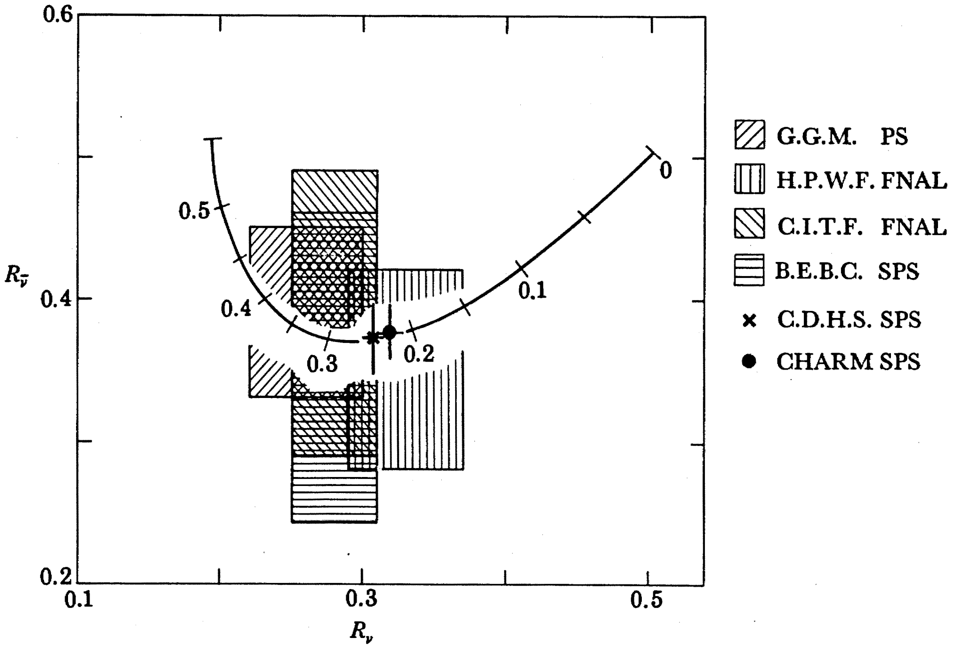


Figure 8. Comparison of the results of various experiments on R_ν and $R_{\bar{\nu}}$ with the standard model (full line).

(Jonker *et al.* 1981*a*, *b*). Since the value of $\sin^2\theta_W$ obtained in this experiment is not corrected for radiative effects, the results can be directly compared with the world average of Kim *et al.*

The CHARM collaboration obtained their results from an exposure of a fine-grain calorimeter to 200 GeV narrow-band neutrino and antineutrino beams at Cern. They obtain the neutral- to charged-current ratios

$$R_\nu = 0.320 \pm 0.009 \; (\pm 0.003 \text{ (systematic error)}),$$
$$R_{\bar{\nu}} = 0.377 \pm 0.020 \; (\pm 0.003 \text{ (systematic error)}),$$

with a hadron energy cut-off of only 2 GeV. By using the same QCD model calculation as Kim *et al.*, a value of

$$\sin^2\theta_W = 0.220 \pm 0.014$$

is deduced (the error does not cover theoretical uncertainties of the model calculation). The new results are in good agreement with previous measurements (see figure 8).

Experiments on neutrino–quark scattering have achieved so far the best precision on neutral-current parameters. Personally, I believe that the precision will not be greatly improved in the future. On the one hand it will be hard to accumulate more statistics, but on the other hand the systematic problems seem to be the more difficult ones. Taking as an example the recent CHARM result on R_ν, one has to notice that the number of neutral-current and charged-current candidates undergo corrections of 17 and 4%, respectively. The limit given by systematic uncertainties both of counter and bubble chamber experiments (which have similar corrections) may be expected to be a small percentage (CHARM quotes a systematic error as low as 1% on R_ν). By translating this limit into an error in $\sin^2\theta_W$, a final uncertainty of about 0.01 in $\sin^2\theta_W$ from neutrino scattering experiments can be achieved. Experiments at high energy e^+e^- storage rings will have to take over to improve the precision on $\sin^2\theta_W$.

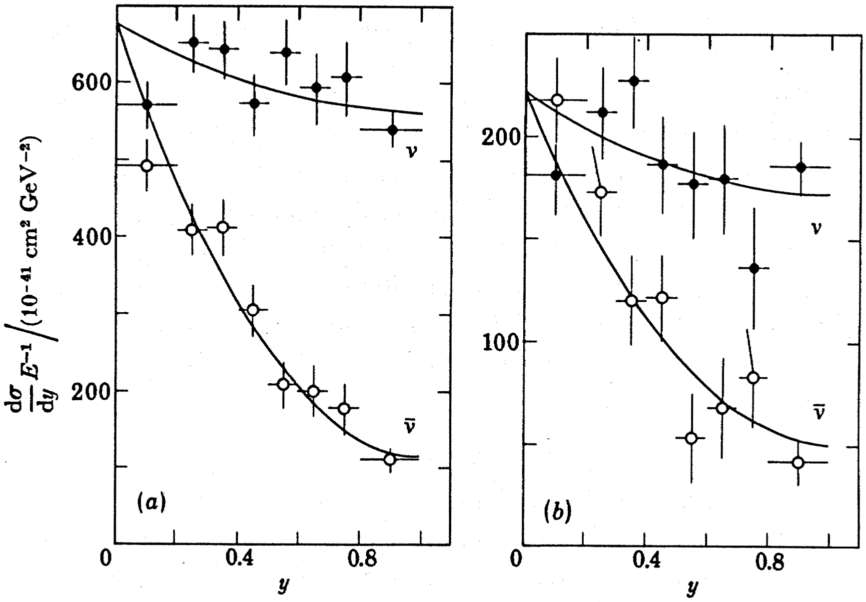


FIGURE 9. The differential cross section $d\sigma/dy$ for (*a*) charged-current and (*b*) neutral-current events (CHARM data).

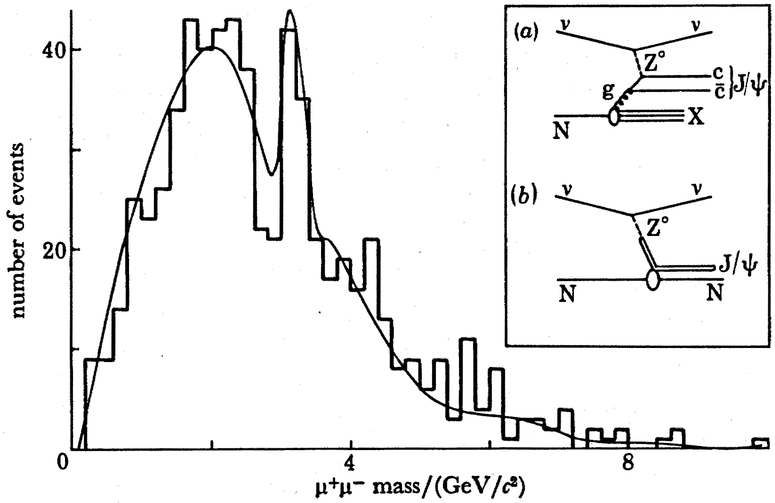


FIGURE 10. Invariant $\mu^+\mu^-$ mass spectrum of events $\nu N \rightarrow \mu^-\mu^+ X$, for hadronic shower energies below 6 GeV (C.D.H.S. data). The insert shows (*a*) Z°-gluon fusion and (*b*) vector meson dominance as possible mechanisms for J/ψ production by neutral-current interactions.

Figure 9 shows the *y*-distribution of charged- and neutral-current neutrino and antineutrino interactions, as obtained by the CHARM collaboration. One sees that the neutral hadronic current is dominantly a V − A current, and there is evidence (especially from the antineutrino high-*y* region) that there is a small admixture of V + A current, as predicted by the standard model. This observation is in line with an earlier result obtained by the Cern–Dortmund–Heidelberg–Saclay (C.D.H.S.) collaboration (Holder *et al.* 1977).

A recent indication of J/ψ production by neutral-current neutrino interactions on iron nuclei may be regarded as preliminary evidence for the coupling of the charmed quark to the Z^0, with a strength roughly as expected by the standard model. The J/ψ production may occur either via Z^0-gluon fusion, or via vector meson dominance (see insert in figure 10).

The experiment was done by the C.D.H.S. collaboration (de Groot *et al.* 1981 in preparation) in an exposure to 350 and 400 GeV wide-band neutrino beams at Cern. The event signature is two muons with opposite charges from $J/\psi \rightarrow \mu^+\mu^-$ decay, together with little hadronic energy, because of the expected diffractive production mechanism. Figure 10 shows the invariant $\mu^+\mu^-$ mass of all candidate events with hadronic shower energy less than 6 GeV. At a mass of 3.17 ± 0.05 GeV there is an excess of 38 ± 8 events above background. Interpreting this excess as a signal of J/ψ production, the resulting spectrum-averaged cross section of $(1.1 \pm 0.4) \times 10^{-40}$ cm² per nucleon favours Z^0–gluon fusion as a production mechanism, but is not inconsistent with vector meson dominance models (Kühn & Rückl 1980; Barger *et al.* 1980*b*).

5. SUMMARY

At low energies ($s, Q^2 \ll M_Z^2$), over a wide range of Q^2, the neutral-current reactions are well described by an effective one-parameter Lagrangian with a definite strength and structure. All recent experimental results are in agreement with the predictions of the standard model, with $\sin^2\theta_W = 0.230 \pm 0.015$.

The remaining experimental work at low energies concerns the extension of the check of the standard model to further neutral-current processes, and the improvement in precision. In future analyses of experimental data, weak and electromagnetic corrections should be applied.

At large energies, in the Z^0 domain, substantial deviations from the local interaction pattern are predicted. They are associated with the Z^0, whose properties are determined by the single parameter $\sin^2\theta_W$ of the low energy Lagrangian. The big experimental challenge is to confirm the predicted high energy behaviour of the standard model.

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