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THE WEAK NEUTRAL CURRENT*

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Abstract

The status and implications of the weak neutral current experiments are briefly reviewed.

It is now generally accepted that the standard electroweak model [1] is correct to an excellent first approximation, and almost all activity in the field is devoted to searching for or predicting the form of new physics beyond the standard model. It is sometimes useful, however, to step back and reexamine how well the standard model is really tested, and how stringent the constraints on possible new physics really are.

Ever since the discovery of weak neutral current-induced neutrino scattering events by the Gargamelle collaboration [2] at CERN in 1973, the weak neutral current (combined with the W and Z masses) has provided one of the most important quantitative tests of the standard model. The first set of neutrino scattering experiments in the mid 1970's confirmed the existence of the neutral current and that its form was compatible with the predictions of the $SU_2 \times U_1$ model. A second generation of experiments [3], completed around 1980, probed the neutral current couplings of the $\overset{(-)}{\nu}_\mu$, e, u, and d quantitatively in neutrino-hadron (deep inelastic scattering, $\overset{(-)}{\nu} p$ elastic scattering, exclusive and inclusive pion production, and

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deuteron dissociation). $\overset{(-)}{\nu}_\mu e$ and $\bar{\nu}_e e$ scattering, and weak-electromagnetic interference effects in polarized eD asymmetries and parity violation in heavy atoms. The experiments obtained accurate values for $\sin^2\theta_W$ (for comparison with grand unification) and for $\rho \equiv M_W^2/(M_Z^2\cos^2\theta_W)$, which is sensitive to the $SU_2\times U_1$ properties of the Higgs fields in the theory. In addition, it was found that the neutral current couplings relevant to $\nu_\mu u$ and $\nu_\mu d$ interactions were *uniquely* determined - in agreement with the standard model predictions - as were the eu and ed couplings relevant to parity violation in heavy atoms; *i.e.* the interactions were those of the standard model (plus possible small perturbations), and not those of some completely different gauge theory. The νe couplings were determined to within a two-fold ambiguity.

A third generation of experiments[1], completed in the last few years, has extended the results in several ways. Many more reactions and quantities have been studied, including the W and Z masses, coherent pion production in $\nu N\to\nu\pi^0 N$, $\nu_e e$ scattering, precise measurements of atomic parity violation in cesium, asymmetries in polarized μC and quasi-elastic e Be scattering, forward-backward asymmetries in $e^+e^-\to e^+e^-$, $\mu^+\mu^-$, $\tau^+\tau^-$, $c\bar{c}$, and $b\bar{b}$, as well as weak contributions to the total cross section for $e^+e^-\to\mu^+\mu^-$, $\tau^+\tau^-$, and hadrons. Not only do these probe a great variety of couplings, they extend over an enormous kinematic range (from $\sim 10^{-6}$ GeV^2 to 10^4 GeV^2.) Finally, the third generation of experiments are very precise (to $\sim 1\%$ accuracy for the deep inelastic neutrino scattering experiments). Because of these improvements, the recent experiments allow precise quantitative tests of the tree level structure of the standard model, and even a rough test of the radiative corrections. Combined with charged current data it is now possible to prove directly from the data that the $SU_2\times U_1$ assignments of all of the known fermions (*i.e.* left-handed doublets and right-handed singlets) are unique [6]. The standard model really is correct to first approximation (at least for the tree level gauge couplings of the known fermions) down to a distance scale of some 10^{-16} cm. Furthermore, the data set an upper limit on the top quark mass and place significant limits on many possible types of new physics beyond the standard model, with a sensitivity extending up to several hundred GeV.

A fourth generation of experiments of much greater sensitivity will be running in the next few years. These include ultra-precise measurements of M_Z (and later a less precise measurement of M_W) and of forward-backward and polarization asymmetries at LEP and SLC, a new $\nu_\mu e$ experiment at CERN which will

[1] For complete sets of references see [4,5]

measure $\sin^2\theta_W$ to ± 0.005 (and a later Los Alamos experiment accurate to ± 0.002) in an environment free from theoretical uncertainties, and improved atomic parity violation experiments in cesium at Paris and Boulder which should be accurate to 1% (including uncertainties from the atomic wave functions). Collectively, these experiments will yield an order of magnitude increase in the sensitivity of the tests of the electroweak model, allowing precise tests of the radiative corrections and probing many types of new physics up to the $500\ GeV - 1\ TeV$ range. These will be an important complement to direct searches for new particles at high energy colliders.

About five years ago U. Amaldi, A. Böhm, L. S. Durkin, A. K. Mann, W. J. Marciano, A. Sirlin, H. H. Williams, and I decided that it would be useful to form an ongoing collaboration to collect and systematically study all neutral current results. In particular we wanted to provide a systematic critical analysis of the experiments, apply the best possible theoretical analysis (with similar experiments treated uniformly), and to derive realistic theoretical uncertainties for the derived quantities. Our goals were to extract a global average value for $\sin^2\theta_W$ with meaningful uncertainties for comparison with the predictions of grand unification, test the standard model at the level of radiative corrections, and to search for and set limits on possible deviations from the standard model. The results of the first phase of this project, based on the third generation of experiments, was completed about a year ago [4]. A similar analysis, with results in reasonable agreement, was performed by Costa et al [5]. Here, I will summarize the conclusions of these and some related studies.

Formalism

The neutral current interaction in the standard $SU_2 \times U_1$ model is given by $L_{NC} = -gJ_Z^\mu Z_\mu/(2\cos\theta_W)$, where Z is the massive neutral gauge boson, $\theta_W \equiv \tan^{-1}(g'/g)$ is the weak angle, and g and g' are the SU_2 and U_1 gauge couplings, respectively. The positron electric charge is related by $e = g\sin\theta$. The neutral current is given by

$$\begin{aligned} J_Z^\mu &= \sum_i t_{3L}(i)\ \bar{\psi}_i\gamma^\mu(1+\gamma^5)\psi_i + t_{3R}(i)\ \bar{\psi}_i\gamma^\mu(1-\gamma^5)\psi_i - 2\sin^2\theta_W J_{EM}^\mu \\ &= \sum_i \bar{\psi}_i\gamma^\mu(V^i + A^i\gamma^5)\psi_i, \end{aligned} \tag{1}$$

where $t_{3L}(i)$ is the T_3 eigenvalue of the left-handed component of fermion i ($+1/2$ for u_i and ν_i; $-1/2$ for d_i and e_i). Similarly, $t_{3R}(i)$ is the T_3 eigenvalue of the right-handed component of ψ_i. It is zero in the standard model but could be non-zero in generalizations with exotic fermions in right-handed doublets. The vector and axial couplings are $V^i \equiv t_{3L}(i) + t_{3R}(i) - 2\sin^2\theta_W q_i$ and $A^i \equiv t_{3L}(i) - t_{3R}(i)$. At low momenta the neutral current interaction is described by the effective interaction

$$-L^{NC}_{eff} = \rho \frac{G_F}{\sqrt{2}} J^\mu_Z J_{Z\mu}, \tag{2}$$

where $\rho \equiv M_W^2/(M_Z^2 \cos^2\theta_W)$ is unity in the minimal model and in generalizations with extra Higgs doublets, but can differ from one in models which have Higgs triplets, *etc.*, with nonzero vacuum expectation values (VEV's).

The data are now sufficiently precise that one must include higher order (radiative) corrections. For this one must choose a set of renormalized parameters. It is convenient to trade g, g', and M_W (which measures the SSB scale), by the fine structure constant (defined conventionally), the Fermi constant (defined in terms of the muon lifetime), and the weak angle. A useful definition (used below) of the latter quantity is the Sirlin mass definition [7], in which one takes the tree level formula $\sin^2\theta_W = 1 - M_W^2/M_Z^2$ as the definition of the renormalized $\sin^2\theta_W$ to all orders in perturbation theory. An alternative is to use the modified minimal subtraction ($\overline{MS}$) quantity $\sin^2\hat{\theta}_W(\mu)$, where μ is conveniently chosen to be M_W for electroweak processes. The two definitions are related by $\sin^2\hat{\theta}_W(M_W) = C(m_t, M_H)\sin^2\theta_W$, where $C = 0.9907$ for top quark and Higgs masses of $m_t = 45\ GeV$ and $M_H = 100\ GeV$. Yet another possibility is to take M_Z rather than $\sin^2\theta_W$ as the third fundamental parameter. This will be useful when very precise values of M_Z are determined at SLC and LEP. In the mass definition scheme one has

$$M_W = \frac{A_o}{\sin\theta_W (1-\Delta r)^{\frac{1}{2}}}, \qquad M_Z = \frac{M_W}{\cos\theta_W} \tag{3}$$

where $A_o = (\pi\alpha/\sqrt{2}G_F)^{1/2} = 37.281\ GeV$. The radiative correction parameter Δr is predicted to be 0.0713 ± 0.0013 for $m_t = 45\ GeV$ and $M_H = 100\ GeV$, while $\Delta r \to 0$ for $m_t \sim 245\ GeV$.

Model Independent Analysis

It is convenient to write the terms in $-L^{NC}_{eff}$ relevant to ν-hadron, νe, and e-hadron processes in a form that is valid in an arbitrary gauge theory (assuming massless left-handed neutrinos). One has

$$-L^{\nu H} = \frac{G_F}{\sqrt{2}} \bar{\nu}\gamma^\mu(1+\gamma^5)\nu \left\{ \sum_i [\epsilon_L(i)\, \bar{q}_i\gamma_\mu(1+\gamma^5)q_i + \epsilon_R(i)\, \bar{q}_i\gamma_\mu(1-\gamma^5)q_i] \right\}, \tag{4}$$

$$-L^{\nu e} = \frac{G_F}{\sqrt{2}} \bar{\nu}_\mu \gamma^\mu (1 - \gamma^5) \nu_\mu \ \bar{e} \gamma_\mu (g_V^e - g_A^e \gamma^5) e \quad (5)$$

(for $\overset{(-)}{\nu}_e e$ the charged current contribution must be included), and

$$-L^{eH} = \frac{G_F}{\sqrt{2}} \sum_i [C_{1i} \, \bar{e}\gamma_\mu\gamma^5 e \ \bar{q}_i\gamma^\mu q_i + C_{2i} \, \bar{e}\gamma_\mu e \ \bar{q}_i\gamma^\mu\gamma^5 q_i] \quad (6)$$

The standard model expressions for $\epsilon_{L,R}(i)$, $g^e_{V,A}$ and C_{ij} are given in Table 1. The results of model independent fits to the data to determine these parameters are given in Figures 1-3 and in Table 2, along with the predictions of the standard model. It is seen that the standard model expressions for the neutral current couplings of the light fermions are correct to an excellent first approximation.

$\sin^2\theta_W$, m_t, and radiative corrections.

$\sin^2\theta_W$ and, equivalently, M_Z have been determined from the W and Z masses and in a variety of neutral current processes spanning a very wide Q^2 range. The results [4], shown in Table 3 and Figure 4, are in impressive agreement with each other, indicating the quantitative success of the standard model. The best fit to all data yields $\sin^2\theta_W = 0.230 \pm 0.0048$ and $M_Z = 92.0 \pm 0.7$ GeV, where the errors (as well as those given below for other neutral current parameters) include full statistical, systematic, and theoretical uncertainties. The corresponding value of $\sin^2\hat{\theta}_W(M_W)$ (for fixed $m_t = 45$ GeV, $M_H = 100$ GeV) is 0.228 ± 0.0044. This is larger by $\simeq 2.5\ \sigma$ than the prediction $0.214^{+0.003}_{-0.004}$ of minimal SU_5 (for $\Lambda^{(4)}_{\overline{MS}} = 150^{+150}_{-75}$ MeV) and other "great desert" models. It is closer to (but still somewhat below) the prediction of the simplest supersymmetric GUTs. (Typically $0.237^{+0.003}_{-0.004}$ for $M_{SUSY} \sim M_W$, decreasing by ~ 0.003 for $M_{SUSY} \sim 10$ TeV). Similar conclusions hold for all values of m_t and M_H, as can be seen in Figure 5. The discrepancy with minimal SU_5 can also be seen in Figure 6, in which are shown the couplings $\alpha_i(Q^2)^{-1}$ determined by the experimental values of α, $\Lambda^{(4)}_{\overline{MS}}$, and $\sin^2\hat{\theta}_W(M_W)$. It is seen that the α_i^{-1} do not all meet at a point, although the statistical significance is not compelling.

The radiative corrections are sensitive to the isospin breaking associated with a large m_t. The $\sin^2\theta_W$ values determined from the various reactions are consistent with each other for $m_t \lesssim 200$ GeV, but disagree for very large m_t. A simultaneous fit to $\sin^2\theta_W$ and m_t requires $m_t < 180$ GeV at 90% $c.l.$ for $M_H \leq 100$ GeV, with a slightly weaker limit for larger M_H. The allowed region in $\sin^2\hat{\theta}_W(M_W)$ and m_t is shown in Figure 5. Similar limits hold for the mass splittings between fourth generation quarks or leptons. These results assume that there is no compensating new physics such as non-doublet Higgs representations (discussed below). In the future precise determinations of the Z mass at SLC and LEP, combined with existing neutral current data (and eventually with e^+e^- asymmetries), will tightly constrain m_t or imply new physics [9].

The measured values of M_W and M_Z are given in Table 4. They are in excellent agreement with the predictions of the standard model when full radiative corrections (to both the W and Z mass formulas and to deep inelastic scattering) are included, but disagree significantly when the corrections are excluded. From the data one obtains $\Delta r = 0.077 \pm 0.037$, in excellent agreement with the value 0.0713 ± 0.0013 predicted for $m_t = 45\ GeV$ and $M_H = 100\ GeV$. The allowed region for $\sin^2\theta_W$ and Δr is shown in Figure 7.

A related parameter [4] δ_W is defined by

$$M_W = \frac{A_o}{\sin\theta^o(1-\delta_W)^{\frac{1}{2}}}. \tag{7}$$

where $\sin^2\theta^o$ is the value ($.242 \pm .006$) obtained for the weak angle from deep inelastic scattering if all radiative corrections (to both σ^{NC} and σ^{CC}) are ignored. δ_W, which incorporates all of the radiative corrections relating deep inelastic scattering, the W and Z masses, and muon decay, is found to be 0.112 ± 0.037. This agrees with the prediction 0.106 ± 0.004 (for the same m_t and M_H as above) and establishes the existence of radiative corrections at the 3σ level.

ρ and $\sin^2\theta_W$

The W and Z masses and neutral current data can be used to search for and set limits on deviations from the standard model. For example, the parameter $\rho \equiv M_W^2/(M_Z^2\cos^2\theta_W)$ can differ from unity if there are Higgs multiplets with weak isospin $> \frac{1}{2}$ with significant vacuum expectation values. One has the tree level result

$$\rho = \frac{\sum_i(t_i^2 - t_{3i}^2 - t_i) < \phi_i >^2}{\sum_i 2t_{3i}^2 < \phi_i >^2} \tag{8}$$

where $<\phi_i>$ is the VEV of a Higgs field ϕ_i with weak isospin and z-component t_i and t_{3i}, respectively.

If the new physics which yields $\rho \neq 1$ is a small perturbation which does not significantly affect the radiative corrections, one can use the standard model expressions for Δr and the other radiative correction parameters in Table 1. Then ρ can be regarded as a phenomenological parameter which multiplies L_{eff}^{NC} in (2). (Also, the expression for M_Z in (3) is divided by $\sqrt{\rho}$; the M_W formula is unchanged.) The allowed regions in the $\rho - \sin^2\theta_W$ plane are shown in Figure 8, and the values of $\sin^2\theta_W$ and ρ from various reactions are given in Table 5. A global fit to all data yields [4] $\rho = 0.998 \pm 0.0086$, remarkably close to unity (justifying the neglect of $\rho - 1$ in the radiative corrections). This implies 90% *c.l.* upper limits of 0.047 and 0.081 for the VEVs (relative to those of Higgs doublets) for Higgs triplets with $t_{3i} = 0$ or ±1, respectively.

Extra Z bosons

Many extensions of the standard model predict the existence of extra Z bosons. These affect the neutral current because (a) the mass of the ordinary Z is reduced because of mixing, (b) the couplings of the ordinary Z are modified by mixing, and (c) the extra Z boson can be exchanged. For a large class of E_6 models, for example, the extra boson is $Z(\beta) = \cos\beta Z_\chi + \sin\beta Z_\psi$, where Z_χ and Z_ψ are the gauge bosons which occur for $SO_{10} \to SU_5 \times U_{1\chi}$ and $E_6 \to SO_{10} \times U_{1\psi}$, respectively. The special case $Z_\eta = \sqrt{\frac{3}{8}} Z_\chi - \sqrt{\frac{5}{8}} Z_\psi = -Z(\beta = \pi - \tan^{-1}\sqrt{\frac{5}{3}})$ occurs in many superstring models. At present the best limits on extra Z's are usually from the neutral current data rather than from direct searches at hadron colliders, but the limits are fairly weak (typically 120 - 300 GeV for GUT-inspired bosons) because of the relatively weak coupling to ordinary fermions predicted in most models. The limits for the E_6 bosons are shown in Figure 9 and Table 6 for two cases: (a) in the constrained Higgs case, in which it is assumed that all SU_2 breaking is due to Higgs doublets (analogous to $\rho = 1$), there is a relation between the masses of the two Z's and the mixing angle [12]. (b) In the unconstrained case no assumption is made concerning the Higgs sector.

It is seen that the limits on the Z_η are extremely weak. That is because the effects of mixing and of Z_η exchange largely cancel each other for large negative mixing angles. Fortunately, most specific models require positive angles, so the limits are considerably more stringent in those special cases. In particular, in supersymmetric E_6 models (including superstrings) it is generally assumed that the Higgs doublets transform as $\underline{27}$-plets. The mixing depends on a parameter $\lambda = v_1^2/v_2^2$, where v_1 and v_2 are the expectation values of the two appropriate Higgs doublets. For $\lambda > 1$, which is favored by most models (in order to explain why $m_t \gg m_b$, for example), one has much more stringent limits, as can be seen in Table 6 and Figure 10.

In the future, indirect limits on heavy Z's from LEP/SLC asymmetries should extend up to 500 - 1000 GeV, and direct searches at the SSC would be sensitive to several TeV.

Other Implications

There are a number of other implications of neutral current data. For example, there are now enough constraints from charged and neutral current experiments to prove directly that all known left-handed fermions transform as SU_2 doublets and that all known right-handed fermions are SU_2 singlets[2] [6]. As one example, the axial couplings of the μ, τ, c, and b in Table 2 (given the reasonable assumption that A^e is canonical) are in agreement with the standard model. This implies that the τ_L and b_L must belong to SU_2 doublets if there are no fermions with exotic charges, and hence that the ν_τ and the t quark *must exist*. (Many but not all topless models are also excluded by the long b lifetime and the absence of flavor-changing b decays.) Similarly, charged and neutral current data can be combined to set fairly stringent limits [14] on the possible mixing between ordinary fermions and the new fermions with unusual weak interactions (*e.g.* right-handed doublets or left-handed singlets) that are predicted by many extensions of the standard model.

Many types of new physics (*e.g.* composite fermions) lead to effective new four fermion operators. For example, Martyn [15] has recently analyzed limits on electron-quark contact terms of the form

$$L^{eq} = \pm \sum_{a,b=L,R} \frac{g^2}{\Lambda_\pm^2} \eta_{ab}\, \bar{e}_a\gamma^\mu e_a\, \bar{q}_b\gamma_\mu q_b, \qquad (9)$$

where each η_{ab} is zero or one, from the e^+e^- annihilation cross section. He obtains lower limits on the various Λ's that are typically in the range 1 - 3 TeV from existing data (with the conventional definition $g^2 = 4\pi$.) These should be improved by a factor of two by measurements at HERA [15]. Similarly, the precise experiments on atomic parity violation in cesium from Paris and Boulder [16] are extremely sensitive to the particular electron-quark contact term

$$L^{eq} = \pm \frac{g^2}{\Lambda_\pm^2} \bar{e}\gamma^\mu\gamma^5 e\, (\bar{u}\gamma_\mu u + \bar{d}\gamma_\mu d). \qquad (10)$$

For $g^2 = 4\pi$ one obtains [17] the extremely impressive limits $\Lambda_+ > 14.6\ TeV$, $\Lambda_- > 10.2\ TeV$ at 90% $c.l.$ Future improvements in the measurments (and the calculation of the atomic effects) should improve these limits by a factor of 3.

One can also use the atomic parity violation data to set lower limits of order 300 GeV (for couplings of electromagnetic strength) on the masses of lepto-quark bosons [17]. For certain types of couplings these are the only existing constraints.

[2] The only major assumption is that the known particles are not in SU_2 multiplets with particles with exotic electric charges.

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Table 1: Standard model expressions for the neutral current parameters for ν-hadron, νe, and e-hadron processes. If radiative corrections are ignored, $\rho = \kappa = 1$, $\lambda = 0$. The $O(\alpha)$ values are given in [4].

Quantity	Standard Model Expression
$\epsilon_L(u)$	$\rho_{\nu N}^{NC}[\frac{1}{2} - \frac{2}{3}\kappa_{\nu N}\sin^2\theta_W + \lambda_{u_L}]$
$\epsilon_L(d)$	$\rho_{\nu N}^{NC}[-\frac{1}{2} + \frac{1}{3}\kappa_{\nu N}\sin^2\theta_W + \lambda_{d_L}]$
$\epsilon_R(u)$	$\rho_{\nu N}^{NC}[-\frac{2}{3}\kappa_{\nu N}\sin^2\theta_W + \lambda_{u_R}]$
$\epsilon_R(d)$	$\rho_{\nu N}^{NC}[\frac{1}{3}\kappa_{\nu N}\sin^2\theta_W + \lambda_{d_R}]$
g_V^e	$\rho_{\nu e}[-\frac{1}{2} + 2\kappa_{\nu e}\sin^2\theta_W]$
g_A^e	$\rho_{\nu e}[-\frac{1}{2}]$
C_{1u}	$\rho'_{eq}[-\frac{1}{2} + \frac{4}{3}\kappa'_{eq}\sin^2\theta_W]$
C_{1d}	$\rho'_{eq}[\frac{1}{2} - \frac{2}{3}\kappa'_{eq}\sin^2\theta_W]$
C_{2u}	$\rho_{eq}[-\frac{1}{2} + 2\kappa_{eq}\sin^2\theta_W]$
C_{2d}	$-C_{2u}$

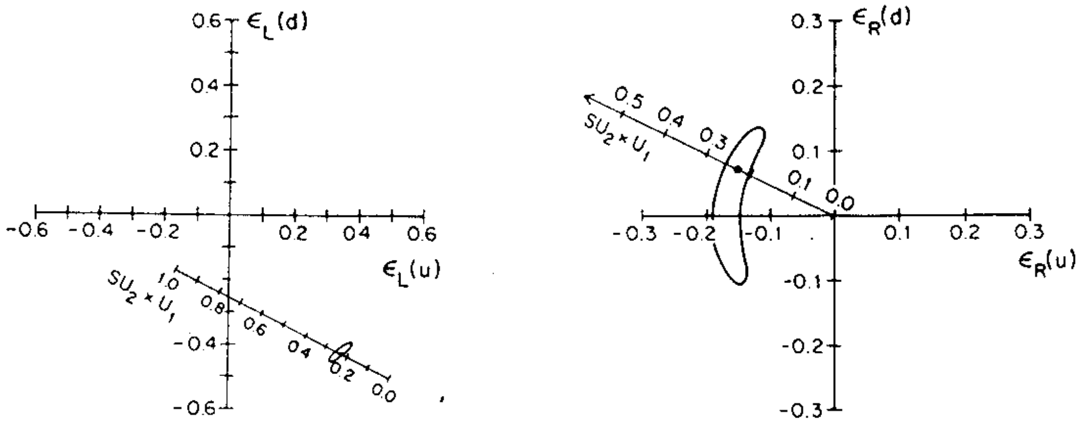

Figure 1: Allowed regions at 90% *c.l.* for the (weak) model independent νq parameters $\epsilon_i(u)$ and $\epsilon_i(d)$, $i = L$ or R and the predictions of the standard model as a function of $\sin^2\theta_W$.

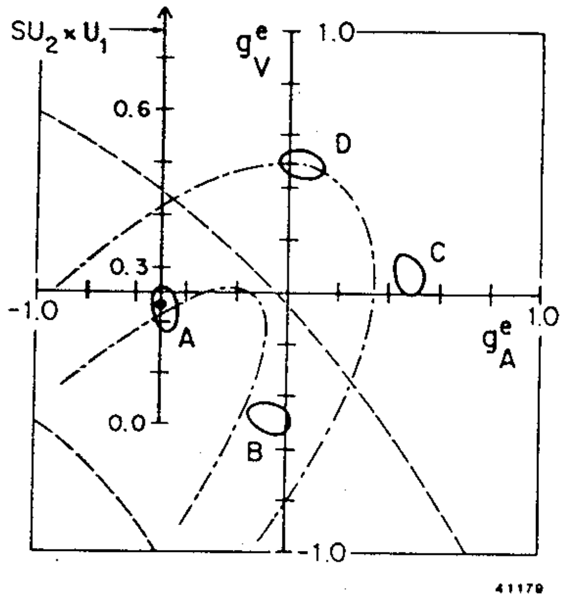

Figure 2: Allowed regions (90% *c.l.*) for the νe parameters g_V^e and g_A^e, for $\overset{(-)}{\nu}_\mu e$ (solid lines), reactor $\bar{\nu}_e e$ (dot-dash), and $\nu_e e$ (dash). The latter reactions, which involve the interference between charged and neutral current contributions, eliminate two solutions ((C) and (D)) that are allowed by $\overset{(-)}{\nu}_\mu e$. There are still two solutions (axial dominant (A) and vector dominant (B)) that are consistent with all νe data. However, solution (B) is eliminated by the $e^+e^- \to \mu^+\mu^-$ forward-backward asymmetry under the (now very reasonable) assumption that the neutral current is dominated by the exchange of a single Z.

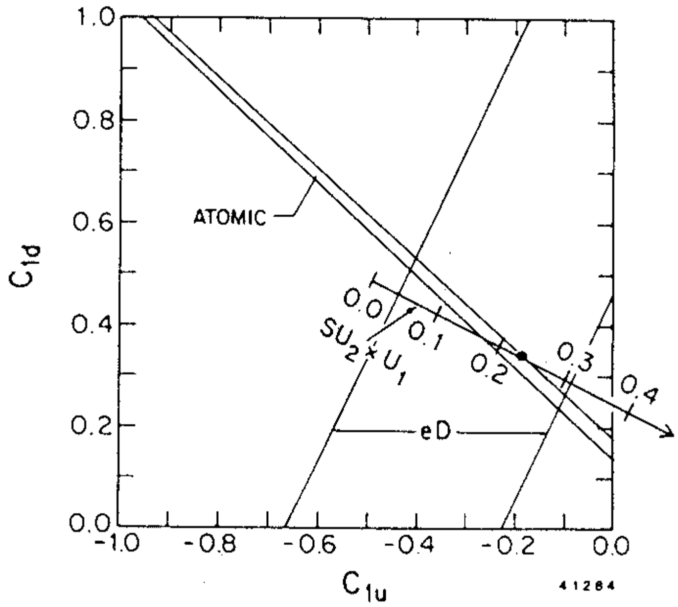

Figure 3: Allowed regions (90% *c.l.*) for the parity-violating eq parameters C_{1u} and C_{1d} allowed by atomic parity violation and the SLAC polarized eD asymmetry (which yield nearly orthogonal constraints), compared with the predictions of the standard model as a function of $\sin^2\theta_W$.

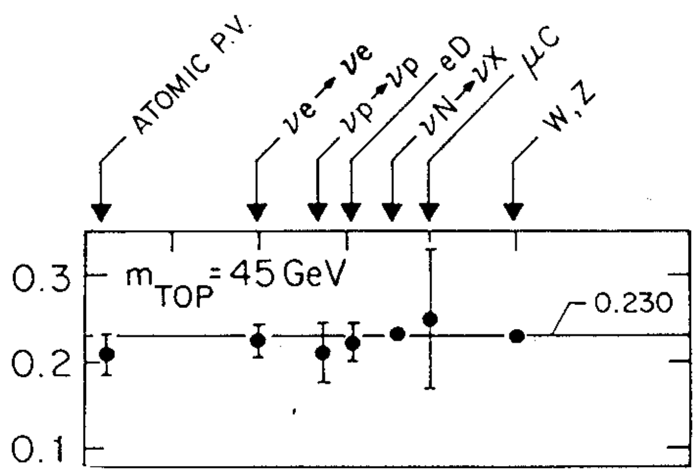

Figure 4: $\sin^2\theta_W$ for various reactions as a function of the typical Q^2, determined for $m_t = 45$ GeV. The best fit line $\sin^2\theta_W = 0.230$ is also shown.

Table 2: Values of the model independent neutral current parameters, compared with the standard model prediction for $\sin^2\theta_W = 0.230$. Correlations are not given for the neutrino-hadron couplings because of the non-Gaussian χ^2 distributions. However, the neutrino-hadron constraints are accurately represented by the ranges listed for the variables $g_i^2 \equiv \epsilon_i(u)^2 + \epsilon_i(d)^2$ and $\theta_i \equiv \tan^{-1}(\epsilon_i(u)/\epsilon_i(d))$, $i = L$ or R, which are very weakly correlated. Also listed are the products of axial couplings obtained from forward-backward asymmetries in e^+e^- annihilation, obtained assuming that only a single Z is relevant [4,8].

Quantity	Experimental Value	Standard Model Prediction	Correlation	
$\epsilon_L(u)$	$0.339 \pm .017$	0.345		
$\epsilon_L(d)$	$-0.429 \pm .014$	-0.427		
$\epsilon_R(u)$	$-0.172 \pm .014$	-0.152		
$\epsilon_R(d)$	$-0.011^{+.081}_{-.057}$	0.076		
g_L^2	0.2996 ± 0.0044	0.301		
g_R^2	0.0298 ± 0.0038	0.029		
θ_L	2.47 ± 0.04	2.46		
θ_R	$4.65^{+0.48}_{-0.32}$	5.18		
g_A^e	$-0.498 \pm .027$	-0.503		-0.08
g_V^e	$-0.044 \pm .036$	-0.045		
C_{1u}	-0.249 ± 0.071	-0.191	-0.98	-0.88
C_{1d}	0.381 ± 0.064	0.340		0.88
$C_{2u} - \frac{1}{2}C_{2d}$	0.19 ± 0.37	-0.039		
$A^e A^\mu$	0.272 ± 0.015	1/4		
$A^e A^\tau$	0.232 ± 0.026	1/4		
$A^e A^c$	-0.33 ± 0.08	$-1/4$		
$A^e A^b$	0.27 ± 0.07	1/4		

Table 3: Determination of $\sin^2\theta_W$ and M_Z (in GeV) from various reactions. The central values of all fits assume $m_t = 45\ GeV$ and $M_H = 100\ GeV$ in the radiative corrections. Where two errors are shown the first is experimental and the second (in square brackets) is theoretical, computed assuming 3 fermion families, $m_t < 100\ GeV$, and $M_H < 1\ TeV$. In the other cases the theoretical and experimental uncertainties are combined. When m_t is allowed to be totally arbitrary the fits to all data yield $\sin^2\theta_W = 0.229 \pm 0.007$ and $M_Z = 91.8 \pm 0.9\ GeV$. The existing e^+e^- data do not yield a useful determination of $\sin^2\theta_W$: at PEP and PETRA energies the asymmetries are nearly an absolute prediction of the model, and all values of $\sin^2\theta_W$ from 0.1 to 0.4 give a good description of the data. (The e^+e^- asymmetries are nearly independent of m_t as well.)

Reaction	$\sin^2\theta_W$	M_Z
Deep inelastic (isoscalar)	$0.233 \pm .003 \pm [.005]$	$91.6 \pm 0.4 \pm [0.8]$
$\overset{(-)}{\nu}_\mu p \to \overset{(-)}{\nu}_\mu p$	$0.210 \pm .033$	95.0 ± 5.2
$\overset{(-)}{\nu}_\mu e \to \overset{(-)}{\nu}_\mu e$	$0.223 \pm .018 \pm [.002]$	93.0 ± 2.7
W, Z	$0.228 \pm .007 \pm [.002]$	92.3 ± 1.1
Atomic parity violation	$0.209 \pm .018 \pm [.014]$	95.1 ± 3.9
SLAC eD	$0.221 \pm .015 \pm [.013]$	93.3 ± 2.7
μC	$0.25 \pm .08$	89.6 ± 9.7
All data	0.230 ± 0.0048	92.0 ± 0.7

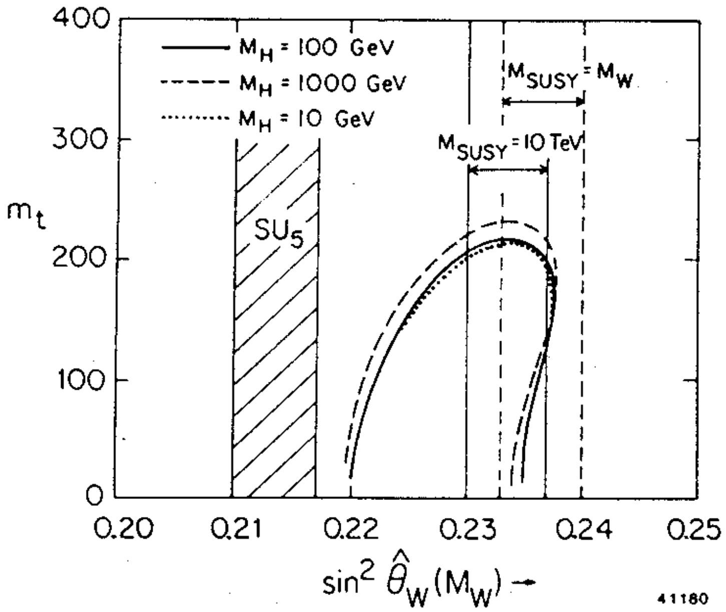

Figure 5: Allowed regions (90% *c.l.*) in $\sin^2 \hat{\theta}_W(M_W)$ and m_t for fixed values of M_H. Also shown are the predictions of ordinary and supersymmetric GUTs, assuming no new thresholds between M_W or M_{SUSY} and the unification scale.

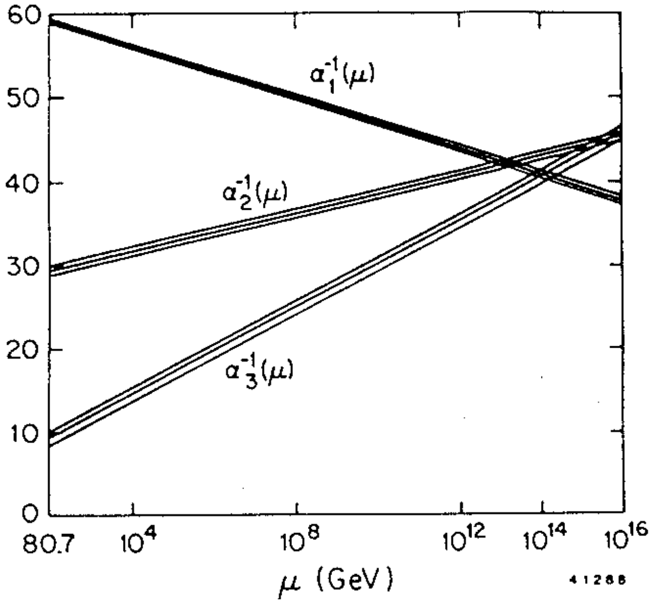

Figure 6: The running couplings $\alpha_i^{-1}(Q^2)$ (68% *c.l.* bands), from ref [4].

Table 4: The W and Z masses (in GeV). The first uncertainties are mainly statistical and the second are energy calibration uncertainties that are 100% correlated between M_W and M_Z for each group. The last two rows are predictions of the standard model, using $\sin^2\theta_W$ determined from deep inelastic scattering, with and without radiative corrections, respectively.

Group	M_W	M_Z
UA2 [10]	$80.2 \pm 0.8 \pm 1.3$	$91.5 \pm 1.2 \pm 1.7$
UA1 [11]	$83.5^{+1.1}_{-1.0} \pm 2.7$	$93.0 \pm 1.4 \pm 3.0$
UA1 + UA2 combined	80.9 ± 1.4	91.9 ± 1.8
Prediction (with radiative corrections)	80.2 ± 1.1	91.6 ± 0.9
Prediction (without radiative corrections)	75.9 ± 1.0	87.1 ± 0.7

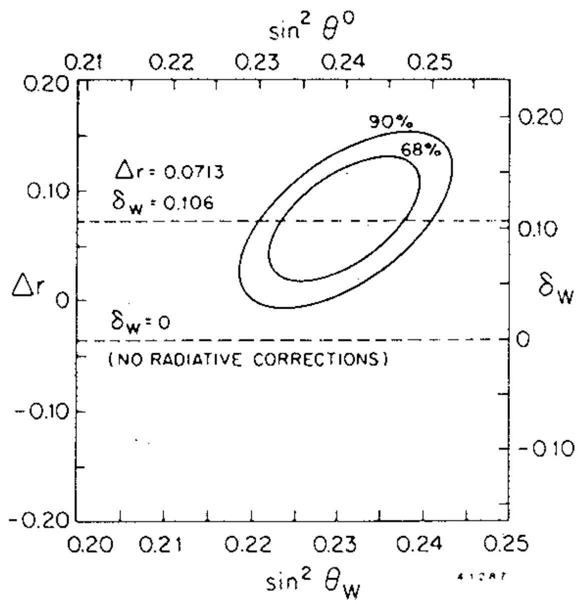

Figure 7: The allowed region in the $\sin^2\theta_W - \Delta r$ (or $\sin^2\theta^o - \delta_w$) plane determined from deep inelastic (isoscalar) data and the W and Z masses.

Table 5: Determination of ρ and $\sin^2\theta_W$ from various reactions. Where two errors are shown the first is experimental and the second (in square brackets) is theoretical.

Reaction	$\sin^2\theta_W$	ρ	Correlation
deep inelastic (isoscalar)	$0.232 \pm 0.014 \pm [.008]$	$0.999 \pm .013 \pm [.008]$	.90
$\overset{(-)}{\nu}_\mu p \to \overset{(-)}{\nu}_\mu p$	$0.205 \pm .041$	$0.98 \pm .06 \pm [.05]$	—
$\overset{(-)}{\nu}_\mu e \to \overset{(-)}{\nu}_\mu e$	$0.221 \pm .021 \pm [.003]$	$0.976 \pm .056 \pm [.002]$	.12
W, Z	$0.228 \pm .008 \pm [.003]$	$1.015 \pm .026 \pm [.004]$	.19
all data	$0.229 \pm .0064$	$0.998 \pm .0086$	.63

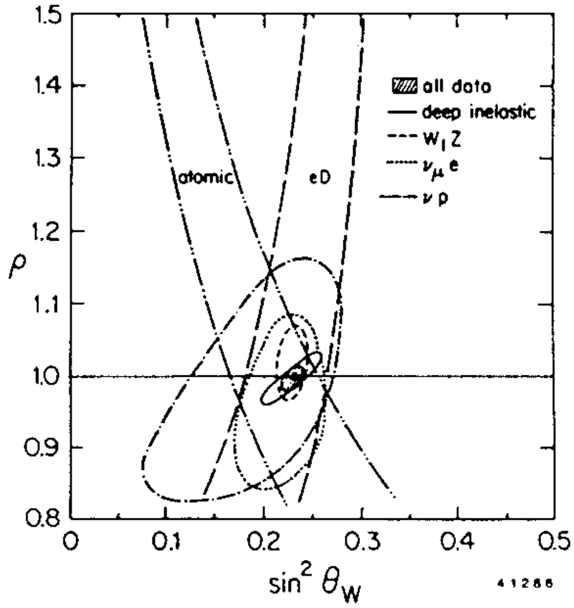

Figure 8: The allowed regions in $\sin^2\theta_W - \rho$ at 90% *c.l.* for various reactions.

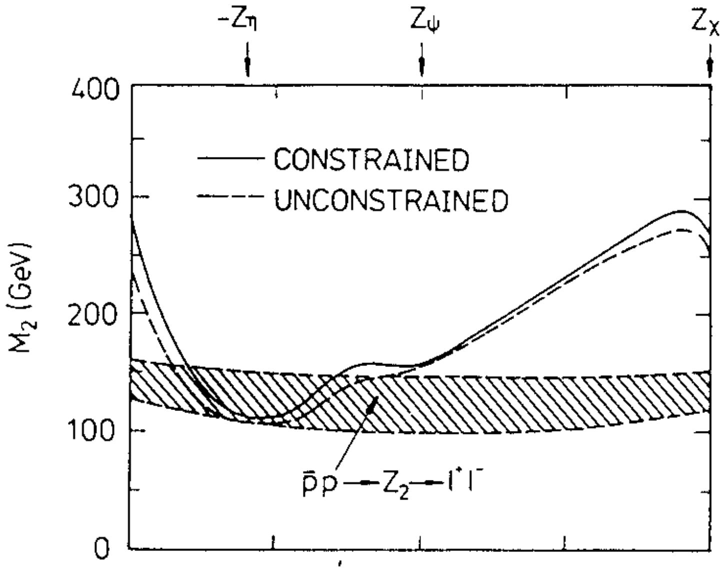

Figure 9: Lower limits on M_{Z_2} (at 90% *c.l.*) for an E_6 boson $Z(\beta) = \cos\beta\, Z_\chi + \sin\beta\, Z_\psi$ for constrained and unconstrained Higgs. The special cases Z_χ, Z_ψ, and $-Z_\eta$ are indicated. Also shown are the direct production limits from searches for $\bar{p}p \to Z_2 \to l^+l^-$ from Ref. [12,13]. The error band is due to the fact that the limit depends on whether the exotic fermions predicted in the E_6 model are light enough to reduce the $Z_2 \to l^+l^-$ branching ratio.

Table 6: Lower limits (90% $c.l.$) on the masses in GeV of various extra Z bosons. Z_{LR} refers to the extra Z in the $SU_{2L} \times SU_{2R} \times U_1$ model. See [4] for the detailed assumptions concerning coupling constants, *etc.*

	Constrained	Unconstrained
Z_χ	273	249
Z_ψ	154	151
Z_{LR}	325	343
Z_η (λ free)	111	112
Z_η ($\lambda = 0$)	116	
Z_η ($\lambda = \frac{1}{2}$)	222	
Z_η ($\lambda = 1$)	318	
Z_η ($\lambda = 2$)	410	
Z_η ($\lambda = 5$)	496	

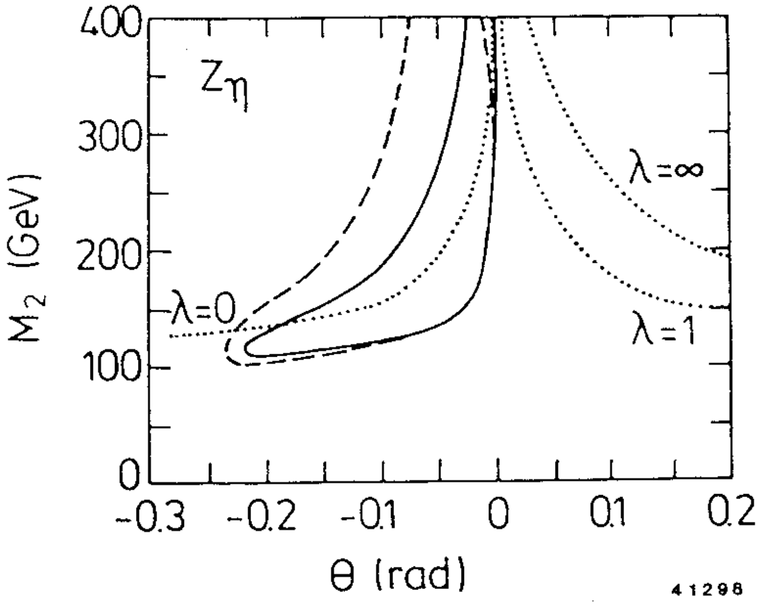

Figure 10: Allowed region for M_2 and the Z_1 - Z_2 mixing angle θ (at 90% $c.l.$) for the superstring-inspired Z_η, along with the additional constraints imposed for fixed $\lambda \equiv v_1^2/v_2^2$.