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The Status of Neutral Currents

F. Zwirner

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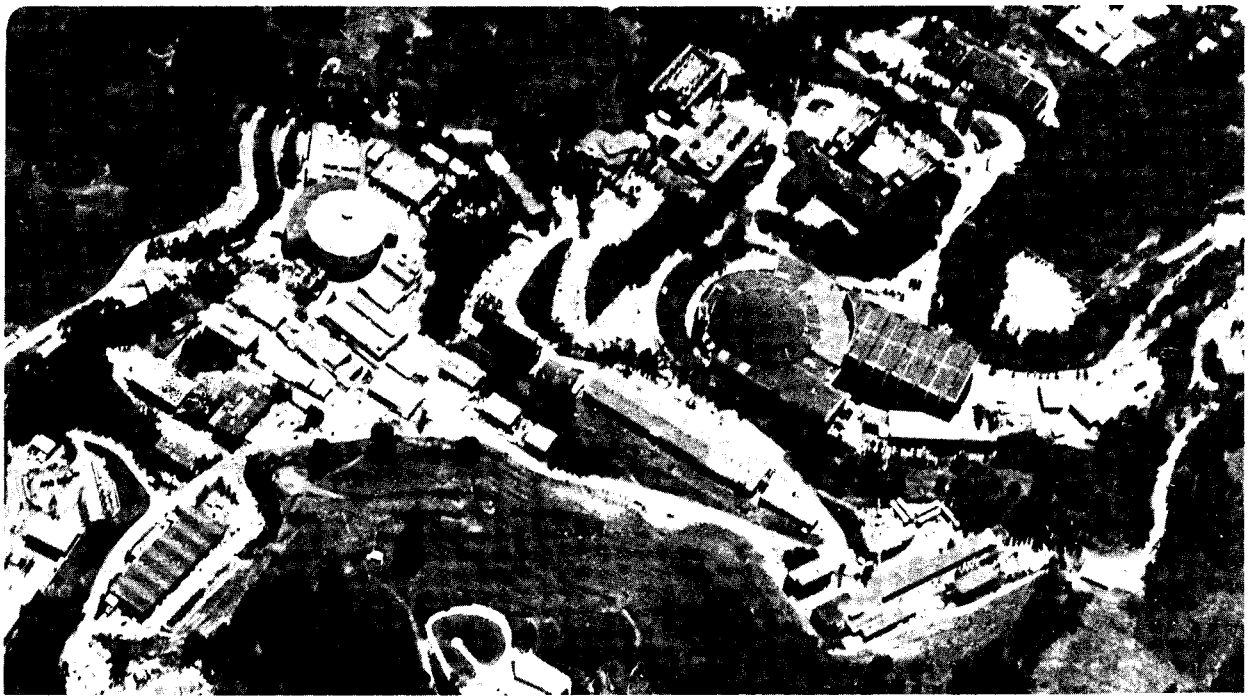

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The status of neutral currents*

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Talk given at the NATO Advanced Studies Institute 'Particle Physics - Cargèse 1987', 3-21 August 1987, Cargèse, France.

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Introduction

As made apparent by many of the previous lectures, the situation of particle physics today is quite puzzling. On the one hand, the Standard Model (SM) of strong and electroweak interactions is consistent with all confirmed experimental data but theoretically rather unsatisfactory. On the other hand, none of the many theoretical speculations which try to go beyond the SM has (yet) received the slightest experimental support. The solution to this dilemma can only come from new data: either from the detection of a new particle threshold at high energy colliders, or from the appearance of some small discrepancy in high-precision experiments. A crucial sector for testing the SM and its extensions is that of neutral currents (NC), where an impressive amount of data has been collected in recent years. While waiting for the next generation of experiments, it is certainly useful to take stock of our knowledge, determining the NC parameters as precisely as we can and putting limits on possible deviations from the SM. The present talk contains the results of a recent analysis along these lines [1]: the first part illustrates how a set of 'model-independent' parameters can be extracted from the available NC data, the second part particularizes the analysis to the SM and to some superstring-inspired models with an additional Z' in their low-energy spectrum.

'Model-independent' analysis

The existing experimental data on neutral currents can be conveniently classified according to the different sectors of the theory they probe: neutrino - quark, neutrino - electron, electron/muon - quark, electron - muon/tau interactions and vector boson masses. A convenient first step in the analysis consists in organizing the information into a set of 'model-independent' parameters, which can then be used as a starting point for fits within different models, including the reader's favourite one. The reason for the quotation marks above lies in the fact that the quality of the data already requires the evaluation of $0(\alpha)$ radiative corrections, which can be done only in a specific calculational framework.

This will be in the following the $SU(3)_C \times SU(2)_L \times U(1)_Y$ SM, in its minimal version with three generations of quarks and leptons and one complex Higgs doublet. Following the on-shell renormalization scheme, one can assume as independent parameters the electromagnetic fine structure constant α, the fermion masses and mixing angles (including the unknown top mass m_t), the unknown Higgs mass m_H and the gauge boson masses m_W, m_{Z^0}. The last two quantities can be traded for the Fermi constant G_F and the electroweak mixing angle θ_W, defined by

$$\sin^2\theta_W \equiv 1 - \frac{m_W^2}{m_{Z^0}^2}, \tag{1}$$

since the following relation holds:

$$\sin^2\theta_W = \frac{A_c}{m_W^2}, \qquad A_c \equiv \frac{\pi\alpha}{\sqrt{2}G_F}\frac{1}{1-\Delta r}, \tag{2}$$

where $\Delta r(m_t, m_H, m_W, m_{Z^0}, \ldots)$ parametrizes the $0(\alpha)$ radiative corrections to the corresponding tree level relation. For the representative values $m_t = 36$ GeV, $m_H = m_{Z^0}$, $\sin^2\theta_W = 0.227$, to be used in the following unless otherwise stated, one has [2] $\Delta r = 0.0711 \pm 0.0013$.

Neutrino - quark sector

Low-energy neutrino-quark interactions can be parametrized by the effective Lagrangian

$$\mathcal{L}_{eff}^{(\nu q)} = -\frac{G_F}{\sqrt{2}}[\bar{\nu}\gamma_\mu(1-\gamma_5)\nu] \quad [u_L\bar{u}\gamma^\mu(1-\gamma_5)u + d_L\bar{d}\gamma^\mu(1-\gamma_5)d + u_R\bar{u}\gamma^\mu(1+\gamma_5)u + d_R\bar{d}\gamma^\mu(1+\gamma_5)d], \tag{3}$$

where colour and generation indices are understood and we use the notation of ref.[3]. The processes probing the neutrino-quark chiral couplings of eq.(3) include deep inelastic neutrino-hadron scattering, exclusive and semi-inclusive pion production, elastic neutrino-hadron scattering and coherent π^0 production. The most important of all these processes is by far deep-inelastic neutrino-hadron scattering, due both to the existence of four recent high-precision experiments (CDHSW [4],

CHARM [5], FMM [6], CCCFRR[7]) and to the relative good control of the theoretical uncertainties of hadronic physics. A recent analysis [8] of all the experiments on isoscalar and on neutron and proton targets gives, after inclusion of $0(\alpha)$ radiative corrections

$$\begin{aligned} u_L &= 0.3562 \pm 0.0192, \\ d_L &= -0.4162 \pm 0.0172, \\ u_R &= -0.1617 \pm 0.0271, \\ d_R &= 0.0639 \pm 0.0551, \end{aligned} \tag{4}$$

with off-diagonal correlation coefficients

$$\rho_{\nu q} = \begin{pmatrix} 0.965 & 0.381 & 0.376 \\ & 0.362 & 0.418 \\ & & 0.903 \end{pmatrix}. \tag{5}$$

Since this is the most accurate information presently available on the structure of NC, it is appropriate to outline the method followed in the derivation of (4,5). The experimental input consists in the ratios $R_\nu \equiv \sigma^\nu_{NC}/\sigma^\nu_{CC}$ and/or $R_{\bar\nu} \equiv \sigma^{\bar\nu}_{NC}/\sigma^{\bar\nu}_{CC}$ on different targets: statistical and systematic experimental errors are added in quadrature to give an overall experimental error. Using a QCD-improved parton model, with a phenomenological parametrization of the parton distribution functions fitted to the most recent experimental data, one obtains some uncorrected values $(u^0_L)^2$,$(d^0_L)^2$,$(u^0_R)^2$,$(d^0_R)^2$ for the squares of the chiral couplings. In the process, a theoretical error is introduced, as a result of different effects: (i) uncertainties in the parametrization of the quark and gluon distribution functions (assuming three generations); (ii) uncertainties in the Callan-Gross relation with respect to the QCD prediction; (iii) deviations of the target from isoscalarity (when applicable). The charm quark threshold is treated by assuming $m_c = 1.5$ GeV, without introducing a corresponding error at this stage, since it would be difficult to combine it with the other errors in a meaningful way when averaging over different experiments. The effects of varying m_c within the range allowed by the present data are calculable and are described in detail in ref.[8]. Experimental and theoretical errors

are then combined in quadrature. Radiative corrections, both to NC and to CC processes, are also applied to each experiment following the lines of ref.[9], but taking into account the effects of the different kinematical cuts, to give the corrected values $u^2_L, d^2_L, u^2_R, d^2_R$. Finally, the sign ambiguity in the chiral couplings is removed by comparison with other processes. All the correlations are taken into account.

Neutrino - electron sector

Being a purely leptonic process, the scattering of neutrinos off electrons is free from the theoretical uncertainties of hadronic physics, but has to face non-trivial experimental problems connected with the very low cross-sections and the properties of neutrino beams. Low-energy neutrino-electron interactions can be parametrized by the effective Lagrangian

$$\mathcal{L}^{(\nu e)}_{eff} = -\frac{G_F}{\sqrt{2}}[\bar\nu\gamma_\mu(1-\gamma_5)\nu][e_L\bar e\gamma^\mu(1-\gamma_5)e + e_R\bar e\gamma^\mu(1+\gamma_5)e]. \tag{6}$$

Measurements of $\sigma(\nu_\mu e)$ and $\sigma(\overline{\nu_\mu} e)$ constrain e^2_L and e^2_R, while measurements of $\sigma(\nu_e e)$ and $\sigma(\overline{\nu_e} e)$ probe the combinations $(1+e_L)^2$ and e^2_R. Even if there are some good recent measurements (CHARM [10], BBKOPST [11] and an experiment at LAMPF [12]), the precision is still lower than in neutrino-hadron scattering. However, this situation could be reversed after the completion of the CHARM II [13] and Los Alamos [14] programs. Using all the available data, including radiative corrections [15] even if they are very small compared with the experimental errors and removing the sign ambiguity by making use of e^+e^- data, a recent analysis [16] finds

$$\begin{aligned} e_L &= -0.273 \pm 0.018, \\ e_R &= 0.228 \pm 0.022, \end{aligned} \tag{7}$$

with correlation

$$\rho_{\nu e} = 0.042. \tag{8}$$

Electron/muon - quark sector

The axial-vector and axial-axial low-energy interactions between charged leptons and quarks can be parametrized by the effective lagrangian

$$\begin{aligned}\mathcal{L}_{eff}^{(lq)} = \frac{G_F}{\sqrt{2}} \quad & [(\bar{e}\gamma_\mu\gamma_5 e)(C_{1u}\bar{u}\gamma^\mu u + C_{1d}\bar{d}\gamma^\mu d) \\ & +(\bar{e}\gamma_\mu e)(C_{2u}\bar{u}\gamma^\mu\gamma_5 u + C_{2d}\bar{d}\gamma^\mu\gamma_5 d) \\ & +(\bar{e}\gamma_\mu\gamma_5 e)(h_{AA}^u\bar{u}\gamma^\mu\gamma_5 u + h_{AA}^d\bar{d}\gamma^\mu\gamma_5 d)]\end{aligned} \tag{9}$$

and are probed in three different classes of experiments: (i) parity violation in atoms; (ii) polarization asymmetries in electron/muon - hadron inelastic scattering; (iii) forward-backward asymmetries in $e^+e^- \to q\bar{q}$.

Experiments on atomic parity violation, among which the most precise are the very recent ones on caesium at Paris [17] and Boulder [18], give an indirect measure (through some atomic physics calculations) of the quantity

$$C_{1u} + \zeta C_{1d}, \quad \zeta \equiv \frac{Z+2N}{2Z+N}, \tag{10}$$

which has been computed for each experiment.

Two experiments have measured polarization asymmetries in charged lepton - hadron scattering. The historical SLAC experiments [19] measured the parity violating asymmetry in the inelastic scattering of longitudinally polarized electrons by deuterium, which is sensitive to the combinations of couplings $(C_{1u} - \frac{1}{2}C_{1d})$ and $(C_{2u} - \frac{1}{2}C_{2d})$. A different kind of asymmetry, sensitive to the combinations of couplings $(h_{AA}^u - \frac{1}{2}h_{AA}^d)$ and $(C_{2u} - \frac{1}{2}C_{2d})$, has been measured at CERN [20] in the scattering of longitudinally polarized muons by an isoscalar carbon target.

Finally, many experiments at PEP and PETRA have studied the forward-backward asymmetries in $e^+e^- \to c\bar{c}$, $e^+e^- \to b\bar{b}$, which in first approximation are proportional to h_{AA}^u and h_{AA}^d, respectively. The quality of these measurements and of their theoretical interpretation is not comparable to that of the previous ones, due to problems with flavour identification, quark-antiquark separation, mass effects in the

final states, hadronization models, $B-\overline{B}$ mixing, etc., however we have included them for completeness.

Taking into account all the correlations, and including radiative corrections [9,21] when required by the quality of the data, we have combined all the available measurements to give the following result

$$\begin{aligned} C_{1u} &= -0.188 \pm 0.058, \\ C_{1d} &= 0.332 \pm 0.052, \\ C_{2u} - \tfrac{1}{2}C_{2d} &= -0.091 \pm 0.251, \\ h_{AA}^u &= 0.612 \pm 0.153, \\ h_{AA}^d &= -0.513 \pm 0.105, \end{aligned} \tag{11}$$

with a correlation matrix

$$\rho_{lq} = \begin{pmatrix} -0.980 & -0.895 & 0.530 & -0.150 \\ & 0.888 & -0.526 & 0.149 \\ & & -0.592 & 0.167 \\ & & & 0.070 \end{pmatrix}. \tag{12}$$

Electron - muon/tau sector

The NC interactions among charged leptons are probed by the PEP, PETRA and TRISTAN measurements of the forward-backward asymmetries in $e^+e^- \to \mu^+\mu^-, \tau^+\tau^-$ [22]. In order to keep the analysis at a model-independent level, we have parametrized the asymmetry by the approximate expansion

$$A_{FB} = \frac{A}{10^4\, GeV^2}s + \frac{B}{10^8\, GeV^4}s^2, \tag{13}$$

where the center of mass energy $\sqrt{s}$ is measured in GeV. Since radiative corrections to these processes are important and part of them are detector-dependent, we have considered only PEP and PETRA data, where they have been explicitly computed. After correcting the experimental numbers for the residual electroweak corrections not included by the experimentalists and for the theoretical approximation used in

eq.(13), we find

$$A = -0.56 \pm 0.13, \quad B = -1.34 \pm 0.96, \tag{14}$$

with a correlation

$$\rho_{ll} = -0.947. \tag{15}$$

Vector boson masses

The only existing measurements of the vector boson masses come from the UA1 and UA2 collaborations at the CERN $p\bar{p}$ collider [23]. Their analyses of the $W \to e\nu$ and $Z \to e^+e^-$ samples give

$$\text{UA1}: \begin{cases} m_W = 82.7 \pm 1.0\,(\text{stat.}) \pm 2.7(\text{syst.})\ \text{GeV} \\ m_Z = 93.1 \pm 1.0\,(\text{stat.}) \pm 3.1(\text{syst.})\ \text{GeV} \end{cases}, \tag{16}$$

$$\text{UA2}: \begin{cases} m_W = 80.2 \pm 0.6(\text{stat.}) \pm 0.5(\text{syst.}_1) \pm 1.3(\text{syst.}_2)\ \text{GeV} \\ m_Z = 91.5 \pm 1.2(\text{stat.}) \pm 1.7(\text{syst.}_2)\ \text{GeV} \end{cases}. \tag{17}$$

In UA1 the systematic errors are mainly due to the overall energy scale uncertainty of the calorimeters. This is also the origin of the systematic error (syst.$_2$) of UA2, while (syst.$_1$) is the systematic error associated with the p_T^ν determination. UA1 has also $W \to \mu\nu, \tau\nu$ and $Z \to \mu^+\mu^-, \tau^+\tau^-$ events, but the corresponding determinations of m_W and m_Z are considerably less precise and have not been used in the analysis. Using total errors as weights, adding linearly the systematic errors and including the correlation between systematic errors of the same origin, we obtain

$$m_W = 80.76 \pm 1.72\ \text{GeV}, \quad m_Z = 91.59 \pm 2.14\ \text{GeV}, \tag{18}$$

with a correlation

$$\rho_{WZ} = 0.879. \tag{19}$$

Fits within the standard model

After collecting all the experimental information in the 15 model-independent parameters introduced above, we can now perform fits within different models.

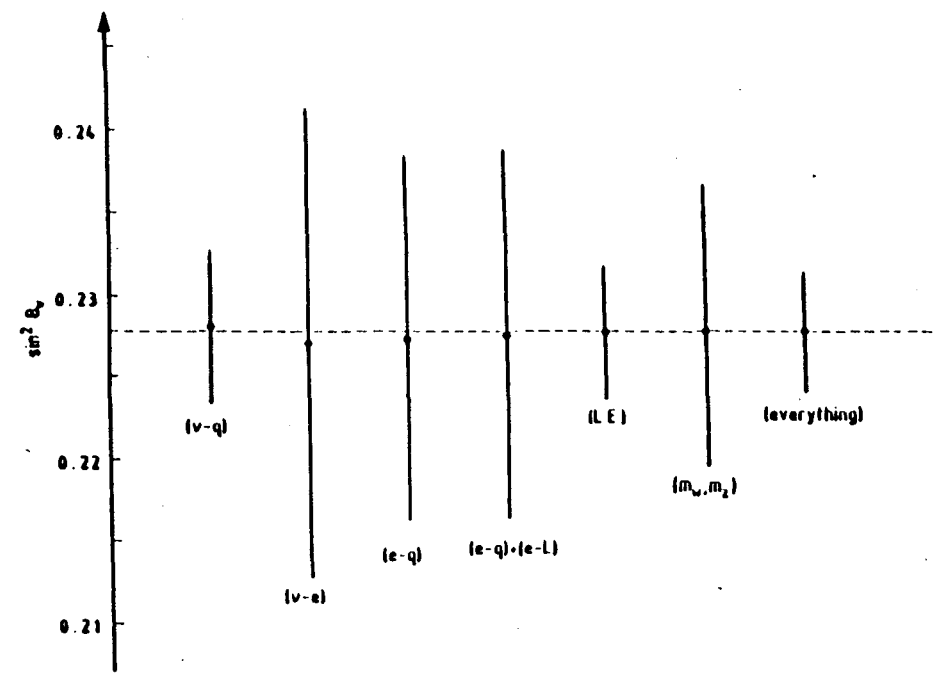


Figure 1: Values of $\sin^2\theta_W$ obtained from the different sectors in one-parameter fits within the minimal SM.

The theoretical expressions for the different parameters in the minimal version of the SM are given in Table 1. The only free parameter in the fit is $\sin^2\theta_W$, for which we obtain

$$\sin^2\theta_W = 0.228 \pm 0.004. \tag{20}$$

As can be seen from Fig.1, which shows the estimates of $\sin^2\theta_W$ derived from different sectors, there is a high degree of consistency of

u_L	=	$\frac{1}{2} - \frac{2}{3}\sin^2\theta_W$
d_L	=	$-\frac{1}{2} + \frac{1}{3}\sin^2\theta_W$
u_R	=	$-\frac{2}{3}\sin^2\theta_W$
d_R	=	$\frac{1}{3}\sin^2\theta_W$
e_L	=	$-\frac{1}{2} + \sin^2\theta_W$
e_R	=	$\sin^2\theta_W$
C_{1u}	=	$-\frac{1}{2} + \frac{4}{3}\sin^2\theta_W$
C_{1d}	=	$\frac{1}{2} - \frac{2}{3}\sin^2\theta_W$
$C_{2u} - \frac{1}{2}C_{2d}$	=	$-\frac{3}{4} + \sin^2\theta_W$
h^u_{AA}	=	$\frac{1}{2}$
h^d_{AA}	=	$-\frac{1}{2}$
A	=	$-\frac{3}{32}\frac{10^4\ \mathrm{GeV}^2}{A_c\ (\mathrm{GeV}^2)}$
B	=	$-\frac{3}{32}\sin^2\theta_W\cos^2\theta_W\frac{10^8\ \mathrm{GeV}^4}{A_c^2\ (\mathrm{GeV}^4)}$
m_W	=	$\sqrt{\frac{A_c}{\sin^2\theta_W}}$
m_Z	=	$\sqrt{\frac{A_c}{\sin^2\theta_W\cos^2\theta_W}}$

Table 1: Standard Model predictions for the neutral current parameters.

the different data sets. Indeed, the lack of dispersion exhibited by Fig.1 is somewhat anomalous from a statistical point of view, but its origin cannot be ascribed to the present analysis. Note also that the forward-backward asymmetries in $e^+e^- \to \mu^+\mu^-, \tau^+\tau^-$ cannot be used alone for the determination of $\sin^2\theta_W$ at PEP and PETRA energies, since the leading coefficient A in eq.(13) is independent of $\sin^2\theta_W$, as shown in Table 1. The result (20) is dominated by the data of the neutrino - quark sector. Therefore it is important to stress once again the main assumptions of our analysis: $m_c = 1.5$ GeV, $m_t = 36$ GeV and $m_H = m_{Z^0}$. Varying m_c inside the experimentally allowed range $m_c = 1.5 \pm 0.3$ GeV, one induces corresponding variations $\Delta\sin^2\theta_W \simeq \pm 0.003 \div 0.004$, with positive correlation. Varying m_t does not have significant effects for $m_t \leq 80$ GeV, but the situation changes dramatically for larger values. Indeed, as it is well known [24], keeping m_t as a free parameter in the evaluation of radiative corrections on can derive an upper limit on the top quark mass. Fixing $m_c = 1.5$ GeV and $m_H = m_{Z^0}$ we find

$$m_t < 168\ \mathrm{GeV} \quad (90\%\ \mathrm{c.l.}). \tag{21}$$

This limit is slightly weakened if one allows simultaneous variations of $m_c = 1.5 \pm 0.3$ GeV and $m_H \leq 1$ TeV, but it still remains below 200 GeV: good news for the forthcoming machines! Finally, as long as the Higgs couplings remain in the perturbative regime, the effects of varying m_H on the final value of $\sin^2\theta_W$ are small with respect to the present accuracy. The result in eq.(20) has important consequences for grand unified models, since it strongly disfavours minimal $SU(5)$, which was already in deep trouble with the unsuccessful searches for nucleon decay. However, acceptable values for $\sin^2\theta_W$ and the nucleon lifetime can be easily recovered in models with a richer structure, e.g. supersymmetric $SU(5)$ with two Higgs doublets.

One can also relax the assumptions of the minimal SM and allow for a richer Higgs content, with vacuum expectation values belonging to higher $SU(2)_L$ representations. In this case there is an additional free parameter $\rho \equiv m^2_{Z^0}/m^2_W\cos^2\theta_W$, with $\sin^2\theta_W$ now *defined* by eq.(2).

A two-parameter fit gives

$$\begin{cases} \sin^2\theta_W &= 0.229 \pm 0.006 \\ \rho &= 1.001 \pm 0.007 \end{cases} . \tag{22}$$

The contributions of the different sectors to the fit are shown in Fig. 2.

Bounds on superstring Z' bosons

Even if the SM is in excellent agreement with the data, there is no theoretical reason to believe that it must remain valid, in its minimal form, as soon as we gain experimental access to higher and higher energy scales. One attractive possibility for new physics beyond the SM is a second massive neutral gauge boson, Z', in addition to the Z observed at the CERN $Sp\bar{p}S$. The results of the model-independent fit can also be used to probe and constrain models with an extra Z'. A general discussion of the theoretical framework for this analysis has been given elsewhere [25]. Here we present the results of the fits for three representative models that could arise from Calabi-Yau compactifications of the $E_8 \times E_8'$ heterotic superstring: (A) the minimal rank-5 model corresponding to non-abelian flux breaking of E_6 at the compactification scale; (B) and (C), two models characterized by large v.e.v.'s of some SM-singlet fields and differing only in the fermion assignments inside the fundamental $\underline{27}$ representation of E_6. Assuming that only $SU(2)_L$ doublets and singlets have non-vanishing v.e.v.'s, as natural in the models under consideration, we obtain the following results

$$\text{Model A}: \begin{cases} m_{Z'} > 129\ \text{GeV} & (90\%\ \text{c.l.}) \\ -0.031 < \theta_3 < 0.204 & (90\%\ \text{c.l.}) \end{cases} , \tag{23}$$

$$\text{Model B}: \begin{cases} m_{Z'} > 352\ \text{GeV} & (90\%\ \text{c.l.}) \\ -0.011 < \theta_3 < 0.047 & (90\%\ \text{c.l.}) \end{cases} , \tag{24}$$

$$\text{Model C}: \begin{cases} m_{Z'} > 180\ \text{GeV} & (90\%\ \text{c.l.}) \\ -0.046 < \theta_3 < 0.029 & (90\%\ \text{c.l.}) \end{cases} , \tag{25}$$

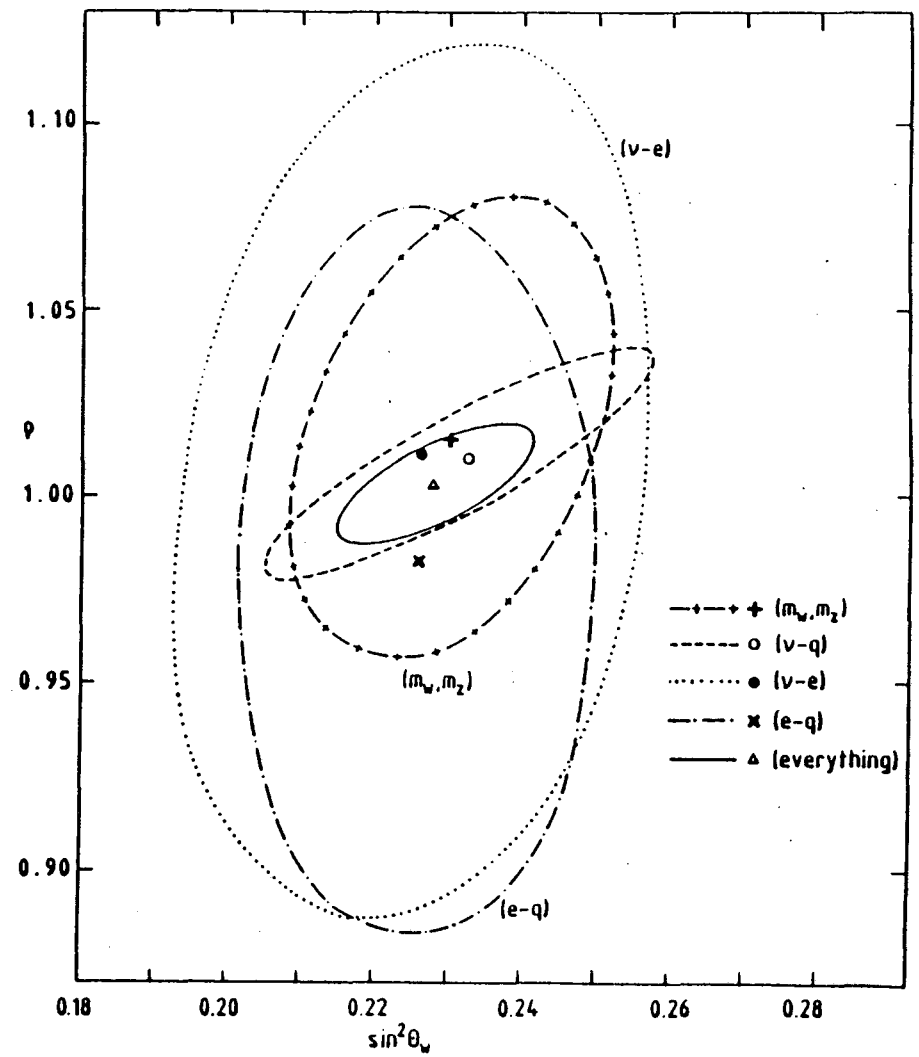


Figure 2: Allowed regions at 90% c.l. in the $(\rho, \sin^2\theta_W)$ plane, obtained from the different sectors in two-parameter fits within the SM.

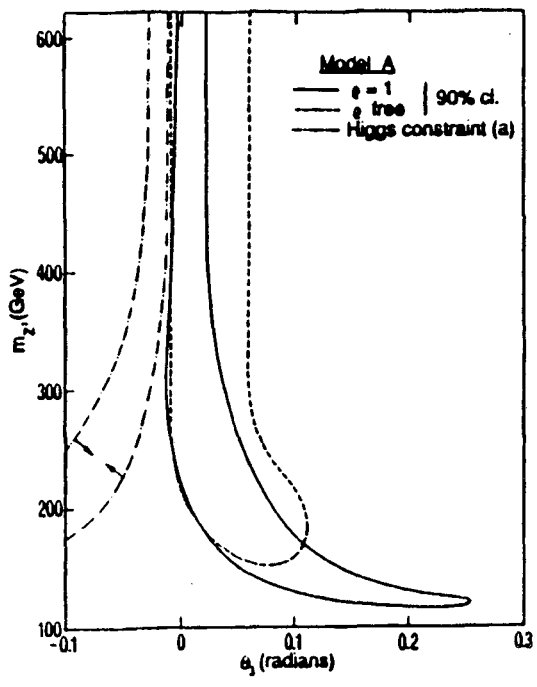
where θ_3 is the $Z - Z'$ mixing angle expressed in radians. These limits improve significantly (at least for models A and B) if one makes the (model-dependent) assumption that the only Higgs doublets with non-vanishing v.e.v.'s are contained in the $\underline{27}$ of E_6 and that $|\bar{v}/v| \leq 1$, where v and $\bar{v}$ give masses to charge-$\frac{2}{3}$ and charge-$\frac{1}{3}$ quarks, respectively:

$$\text{Model A}: \begin{cases} m_{Z'} > 375\ \text{GeV} & (90\%\ \text{c.l.}) \\ -0.014 < \theta_3 < 0. & (90\%\ \text{c.l.}) \end{cases}, \tag{26}$$

$$\text{Model B}: \begin{cases} m_{Z'} > 500\ \text{GeV} & (90\%\ \text{c.l.}) \\ -0.013 < \theta_3 < 0. & (90\%\ \text{c.l.}) \end{cases}, \tag{27}$$

$$\text{Model C}: \begin{cases} m_{Z'} > 181\ \text{GeV} & (90\%\ \text{c.l.}) \\ -0.004 < \theta_3 < 0.017 & (90\%\ \text{c.l.}) \end{cases}. \tag{28}$$

The region of the $(m_{Z'}, \theta_3)$ plane allowed at 90% c.l. is shown in Fig. 3 for the three different models and under different assumptions.



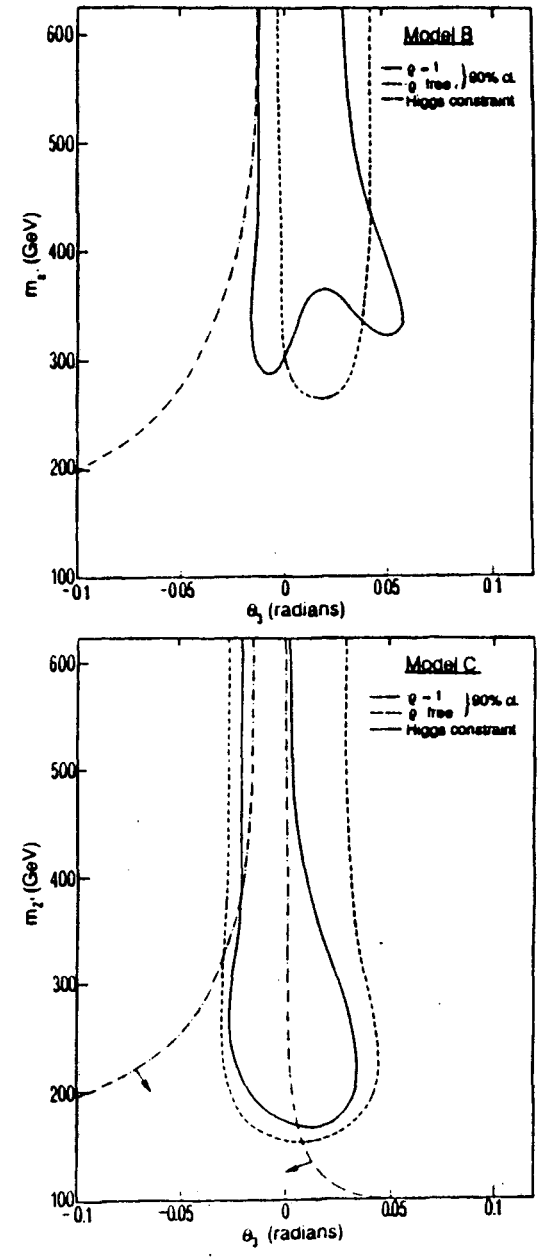


Figure 3: Allowed regions at 90% c.l. in the $(m_{Z'}, \theta_3)$ plane for models A, B and C.

Solid lines correspond to Higgs v.e.v.'s only for doublets and singlets of $SU(2)_L$, dashed lines to arbitrary Higgs v.e.v.'s. The dotted-dashed lines correspond to Higgses in the $\underset{\sim}{27}$ of E_6 and $|\bar{v}/v| \leq 1$.

It is interesting to compare the above limits with those extracted [26] from direct searches at the CERN $p\bar{p}$ collider [27]. Combining the recent UA1 and UA2 limits, one obtains $\sigma(Z')BR(Z' \to e^+e^-) <$ 1.8 pb at 90% c.l. for Z' masses sufficiently higher than the Z mass. Fixing empirically the K-factor by comparison with the Z production data, under the minimal hypothesis that the Z' can only decay into conventional quarks and leptons, one finds at 90% c.l.

$$\begin{aligned} &\text{Model A}: \quad m_{Z'} > 167 \text{ GeV}, \\ &\text{Model B}: \quad m_{Z'} > 170 \text{ GeV}, \\ &\text{Model C}: \quad m_{Z'} > 158 \text{ GeV}, \end{aligned} \tag{29}$$

whereas, under the conservative hypothesis that the Z' can decay into particles and sparticles of 3 $\underset{\sim}{27}$ generations of E_6, with the least favourable spectrum allowed by the present data, one finds at 90% c.l.

$$\begin{aligned} &\text{Model A}: \quad m_{Z'} > 118 \text{ GeV}, \\ &\text{Model B}: \quad m_{Z'} > 140 \text{ GeV}, \\ &\text{Model C}: \quad m_{Z'} > 115 \text{ GeV}. \end{aligned} \tag{30}$$

Conclusions

At the end of the pre-SLC and pre-LEP era, all the available data on neutral currents are highly consistent with the Standard Model. Assuming $m_c = 1.5$ GeV, $m_t = 36$ GeV and $m_H = m_{Z^0}$, one finds $\sin^2\theta_W = 0.228 \pm 0.004$. Leaving m_t free to vary, one finds $m_t <$ 168 GeV at 90% c.l.. Minimal $SU(5)$ grand unification is strongly disfavoured. The ρ parameter is consistent with 1 to a high degree of accuracy. A possible superstring-inspired Z' can be as light as 129 GeV in the minimal rank-5 model if no extra assumptions are made about the Higgs v.e.v.'s. Conservative limits from direct collider searches are still weaker, but ACOL and Tevatron offer prospects for improving them significantly.

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