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Implications on the Electroweak Parameters of a Precise Measurement of the Z mass

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Abstract

The implications of the presently most precise low energy neutral current measurements on the W mass and Z peak observables are investigated in the framework of the $SU(2)_L \times U(1)$ Standard Model, where the free parameters are the top quark mass m_t , the Higgs boson mass m_H , and the ρ parameter. It is found that, once m_Z is precisely measured,

- i) the W mass is predicted to ± 315 Mev;
- ii) the coupling constants of light fermions (e, μ, τ, u, d, s, c) to the Z are predicted with a precision equivalent to knowing the effective weak mixing angle $\sin^2 \vartheta_w^* \equiv \frac{e^2}{g^2}(m_Z^2)$ to ± 0.002 .
- iii) the decay width of the Z into $b\bar{b}$, and thereby the total width, do not exhibit the degeneracy between the effects of large values of m_t and departure of ρ_0 from 1 which is the rule for other observables. A precise measurement of these quantities could be used to set limits on m_t and ρ_0 independently.

Numerical predictions as a function of the Z mass are given.

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1 Introduction: $\sin^2\vartheta_w$ and $\sin^2\vartheta_w^*$

The measurement of the Z mass with a precision of $\Delta m_Z = \pm 50 \text{ Mev}$ or better will be one of the first outcomes of LEP/SLC. Combined with the QED coupling constant α and the muon decay constant G_μ , it can be related to the electroweak mixing angle in its most common definition, $\sin^2\vartheta_w \equiv 1 - \frac{m_W^2}{m_Z^2}$, by the relation:

$$m_Z^2 = \frac{\pi\alpha}{\sqrt{2}G_\mu \sin^2\vartheta_w (1 - \sin^2\vartheta_w)(1 - \Delta r)} \quad (1)$$

where Δr is the usual 'radiative correction parameter' [1]. In the Minimal Standard Model (MSM) with only one doublet of Higgs bosons ($\rho = 1$), three families of quarks and leptons, and if the masses of the top quark and of the Higgs boson were known, Δr can be calculated with a small error, $\Delta(\Delta r) = \pm 0.0009$ [2]; this turns out to dominate the error in extracting $\sin^2\vartheta_w$ from equation (1), $\Delta \sin^2\vartheta_w = \pm 0.0003$. However we do not know m_t and m_H , and have no experimental evidence for the Higgs mechanism, so that $\sin^2\vartheta_w$ is simply a free parameter.

In the following the symbol $\rho_0 \equiv 1 + \Delta\rho$ will be used to describe not only the tree level effect, due for instance to triplets of Higgs bosons, but also radiative effects that could occur from any new $SU(2)$ -breaking set of particles: further families of fermions or supersymmetric particles with large isotopic splitting would produce similar effects [3]. It is worth noting that the tree level effect can result in $\Delta\rho \leq 0$, while radiative effects lead to $\Delta\rho \geq 0$. The resulting contribution to Δr is $-\cot g^2\vartheta_w \Delta\rho$.

It has been shown by Lynn et al. [3] that there is not a one-to-one relation between the Neutral Current (NC) coupling constants and $\sin^2\vartheta_w$ when varying m_t and m_H or ρ_0 . It has been long noticed [4], and recently emphasized [5] that NC couplings at the Z can be extracted from improved Born approximation formulae, the so-called effective lagrangian, including a redefinition of a running $\sin^2\vartheta_w$, denoted $\sin^2\vartheta_w^*$

$$\sin^2\vartheta_w^* \equiv \frac{e_*^2}{g_*^2}(-m_Z^2) \quad (2)$$

where e_*^2 and g_*^2 are the running electron charge and weak coupling respectively, as defined by Lynn et al. [5].

A large class of radiative effects to Z peak observables, i.e. the renormalization of couplings and masses, (also called *oblique corrections*), can be absorbed in this parameter. In the case of four-fermion processes involving light quarks and leptons, e, μ, τ, u, d, s, c , which belong to complete doublets of $SU(2)_L \times U(1)$, these oblique corrections contain most of the dependence on the unknown parameters of the model. For these light fermions, photonic or gluonic effects as well as purely weak boxes and vertices are large, but in principle well calculable and independent on unknown parameters. This is not the case for the b quark, which couples directly to the top quark. The couplings of the b have a specific m_t dependence [6] which could lead to surprising effects, discussed in section 2.4.

It seems that $\sin^2\vartheta_w^*$ is the relevant parameter for the interpretation of the Z partial widths, interference effects and asymmetries [8] involving light fermions. Measurements of these observables can be related to $\sin^2\vartheta_w^*$ without assumptions on unknown parameters, but only assuming the algebraic structure of $SU(2) \times U(1)$ to be correct [7]. Once m_Z is measured, the variation of $\sin^2\vartheta_w^*$ with m_t, m_H and ρ_0 differs from that of $\sin^2\vartheta_w$. It has been investigated numerically using the program EXPOSTAR [5] [8].

The results are shown in table 1 and drawn in figure 1. It is remarkable that the dependence of $\sin^2\vartheta_w^*$ on unknown parameters is smaller than that of $\sin^2\vartheta_w$ in all cases, by a factor of 2 for the Higgs mass, and by a factor of 3.3 for heavy top masses and ρ_0 . In fact, if one defines a 'radiative correction parameter' for Z observables, Δr_* , in a way similar to Δr ,

$$m_Z^2 = \frac{\pi\alpha}{\sqrt{2}G_\mu \sin^2\vartheta_w^* (1 - \sin^2\vartheta_w^*) (1 - \Delta r_*)} \quad (3)$$

the contribution of $\Delta\rho$ to Δr_* is only $-\Delta\rho$, smaller than the contribution to Δr by a factor $\cot g^2\vartheta_w = 3.3$.

We show here that the most precise measurements of $\sin^2\vartheta_w$ presently available project very differently on $\sin^2\vartheta_w$ and $\sin^2\vartheta_w^*$ once m_Z is known, leading to predictions for the asymmetries at the Z peak that are much more precise than naively expected from the present error on $\sin^2\vartheta_w$ $\Delta\sin^2\vartheta_w = \pm 0.006$, which will not change once m_Z is known.

2 Implications of lower energy experiments

2.1 Electroweak parameters from neutrino nucleon scattering

Neutrino-nucleon scattering experiments provide at present the most precise measurement of $\sin^2\vartheta_w$. Only the two most precise experiments, CDHS [9] and CHARM [10], will be taken into account here, but it has been shown [11] that the result is not significantly changed when using all available measurements.

It has been shown by Stuart [12] that the ratio R_ν of neutrino Neutral Current (NC) to Charged Current (CC) cross-sections on isoscalar nuclei is a measurement of $\sin^2\vartheta_w$ with very little dependence on the top and Higgs masses. The same argument holds for ρ_0 .

The NC and CC cross-sections written at tree level can be interpreted in the presence of radiative effects by using the effective lagrangian notations. In order to do this properly, one has to keep the relation between vector boson masses and the weak couplings free, allowing for unknown radiative effects. At tree level $\sin^2\vartheta_w$ is defined as a ratio of couplings, and in order to keep this in mind it will be written here $\sin^2\vartheta_w^0$. One has:

$$\begin{aligned}
 \sigma_{NC}^\nu &\propto \left(\frac{e^2}{\sin^2\vartheta_w^0 \cos^2\vartheta_w^0} \right)^2 \left(\frac{1}{m_Z^4} \right) (\mathcal{L}g_L^2 + \mathcal{R}g_R^2) \\
 \sigma_{CC}^\nu &\propto \left(\frac{e^2}{\sin^2\vartheta_w^0} \right)^2 \left(\frac{1}{m_W^4} \right) (\mathcal{L}) \\
 \sigma_{NC}^{\bar{\nu}} &\propto \left(\frac{e^2}{\sin^2\vartheta_w^0 \cos^2\vartheta_w^0} \right)^2 \left(\frac{1}{m_Z^4} \right) (\mathcal{L}g_R^2 + \mathcal{R}g_L^2) \\
 \sigma_{CC}^{\bar{\nu}} &\propto \left(\frac{e^2}{\sin^2\vartheta_w^0} \right)^2 \left(\frac{1}{m_W^4} \right) (\mathcal{R}), \tag{4}
 \end{aligned}$$

where

$$\begin{aligned}
 g_{L,R}^2 &= g_{uL,R}^2 + g_{dL,R}^2 \\
 g_{uL} &= \frac{1}{2} - \frac{2}{3}\sin^2\vartheta_w^0
 \end{aligned}$$

$$\begin{aligned}
g_{dL} &= -\frac{1}{2} + \frac{1}{3}\sin^2\vartheta_w^0 \\
g_{uR} &= -\frac{2}{3}\sin^2\vartheta_w^0 \\
g_{dR} &= \frac{1}{3}\sin^2\vartheta_w^0
\end{aligned} \tag{5}$$

In the quark-parton model, the quantities $\mathcal{L}$ and $\mathcal{R}$ are given by integrals over the kinematic variables of the quark distributions:

$$\begin{aligned}
\mathcal{L} &= (U + D) + (\bar{U} + \bar{D})(1 - y)^2 \\
\mathcal{R} &= (U + D)(1 - y)^2 + (\bar{U} + \bar{D}).
\end{aligned}$$

However, the validity of the equations (4) does not depend on the structure of the target provided it is isoscalar [13]. The dependence of these cross-sections on m_W and m_Z comes from the W and Z propagators. From this one can derive:

$$\begin{aligned}
R_\nu &= \frac{\sigma_{NC}^\nu}{\sigma_{CC}^\nu} = \frac{m_W^4}{m_Z^4 \cos^4\vartheta_w^0} (g_L^2 + r g_R^2) \\
&= \frac{m_W^4}{m_Z^4 \cos^4\vartheta_w^0} \left(1/2 - \sin^2\vartheta_w^0 + 5/9(1 + r)\sin^4\vartheta_w^0 \right)
\end{aligned} \tag{6}$$

$$\begin{aligned}
R_{\bar{\nu}} &= \frac{\sigma_{NC}^{\bar{\nu}}}{\sigma_{CC}^{\bar{\nu}}} = \frac{m_W^4}{m_Z^4 \cos^4\vartheta_w^0} (g_L^2 + \bar{r} g_R^2) \\
&= \frac{m_W^4}{m_Z^4 \cos^4\vartheta_w^0} \left(1/2 - \sin^2\vartheta_w^0 + 5/9(1 + \bar{r})\sin^4\vartheta_w^0 \right)
\end{aligned} \tag{7}$$

with

$$\begin{aligned}
r &= \frac{\mathcal{R}}{\mathcal{L}} = \frac{\sigma_{CC}^{\bar{\nu}}}{\sigma_{CC}^\nu} \\
\bar{r} &= 1/r
\end{aligned} \tag{8}$$

It is possible to re-write the equations (6) and (7) either as functions of ρ and $\sin^2\vartheta_w^0$ or as function of $\frac{m_W^2}{m_Z^2}$ and $\sin^2\vartheta_w^0$:

$$R_\nu = \rho^2 \left(1/2 - \sin^2\vartheta_w^0 + 5/9(1 + r)\sin^4\vartheta_w^0 \right) \tag{9}$$

$$R_{\bar{\nu}} = \rho^2 \left(1/2 - \sin^2\vartheta_w^0 + 5/9(1 + \bar{r})\sin^4\vartheta_w^0 \right) \tag{10}$$

$$R_\nu = \frac{1}{2} \frac{m_W^4}{m_Z^4} \frac{1 - 2\sin^2\vartheta_w^0 + 10/9(1+r)\sin^4\vartheta_w^0}{1 - 2\sin^2\vartheta_w^0 + \sin^4\vartheta_w^0} \quad (11)$$

$$R_{\bar{\nu}} = \frac{1}{2} \frac{m_W^4}{m_Z^4} \frac{1 - 2\sin^2\vartheta_w^0 + 10/9(1+\bar{r})\sin^4\vartheta_w^0}{1 - 2\sin^2\vartheta_w^0 + \sin^4\vartheta_w^0} \quad (12)$$

In all these equations, $\rho = \frac{m_W^2}{m_Z^2 \cos^2\vartheta_w^0}$.

It can be seen from the above equations and from the numerical value of $r \approx 0.4$ that:

- R_ν is directly related to $\frac{m_W^2}{m_Z^2}$ with very little dependence on $\sin^2\vartheta_w^0$, equation (11);
- $R_{\bar{\nu}}$ is directly related to ρ with little dependence on $\sin^2\vartheta_w^0$, equation (10).

It follows that one can extract from R_ν and $R_{\bar{\nu}}$ the W-Z mass ratio, or $\sin^2\vartheta_w = 1 - \frac{m_W^2}{m_Z^2}$, and ρ .

Radiative effects include three classes that are calculated in one block in available radiative correction programs i) QED photonic corrections, ii) Weak boxes and vertices, iii) Renormalization of the photon, Z and W propagators and of the coupling constants (oblique corrections). The effects i) and ii) can be calculated without assumptions on unknown particles and masses, at least for R_ν and $R_{\bar{\nu}}$, since the direct coupling of u and d quarks to the top or heavier families and to Higgs particles is very small. The oblique radiative effects can be taken into account either by assuming a given value for $m_t, m_H, \rho_0 = 1$, which is usually done, or by expressing the result as a function of effective lagrangian quantities at the relevant $Q^2, Q_\nu^2 \approx 20\text{GeV}^2$:

$$R_\nu^* = \rho_*^2 \left(1/2 - \sin^2\vartheta_w^* + 5/9(1+r)\sin^4\vartheta_w^* \right) \quad (13)$$

$$R_{\bar{\nu}}^* = \rho_*^2 \left(1/2 - \sin^2\vartheta_w^* + 5/9(1+\bar{r})\sin^4\vartheta_w^* \right) \quad (14)$$

where R_ν^* and $R_{\bar{\nu}}^*$ are the experimentally measured quantities corrected only for usual experimental and quark-parton model effects, charm mass etc.. and for QED, boxes and vertices. The raw experimental results and the respective values of R_ν^* and $R_{\bar{\nu}}^*$ are given in table 2. They can be expressed

as an ellipse in the $\rho_* - \sin^2\vartheta_w^*$ plane as shown in figure 2. The lines of constant m_W, m_Z or $\sin^2\vartheta_w$ are also drawn in this plane for various values of m_t, m_H, ρ_0 . The basic degeneracy between the effects of ρ_0 and m_t is clearly apparent, whereas the effect of the Higgs mass is to thicken these lines.

2.2 Implication on the W mass

From this, one can derive first a value of the mass ratio or of $\sin^2\vartheta_w \equiv 1 - \frac{m_W^2}{m_Z^2}$ which is very much independent on any assumption on m_t, m_H, ρ_0 :

$$\begin{aligned} \sin^2\vartheta_w &= 0.232 \pm 0.006 \\ \frac{m_W}{m_Z} &= 0.876 \pm 0.0035 \\ m_W &= 0.876 \cdot m_Z \pm 0.315 \text{ Mev.} \end{aligned} \quad (15)$$

The relation of R_ν with m_W is shown on figure 3, and the relation with m_W/m_Z on figure 4. The comparison with the direct measurements of the W and Z masses and of their ratio by the UA1 and UA2 collaborations [14] is also given. The upper limit on m_t , $m_t \leq 200$ Gev, which can be derived from figure 3, is valid only for $\rho_0 = 1$; the same is true for the limit extracted from global fits to NC data [11].

2.3 Implication on Z peak observables

One can also derive the constraint that these measurements would give on the effective couplings at the Z peak, once m_Z is known. In order to do this, one has to relate $\sin^2\vartheta_w^*(Q_\nu^2)$ to $\sin^2\vartheta_w^*(-m_Z^2)$. This relation turns out to be independent on m_t, m_H, ρ_0 : $\sin^2\vartheta_w^*(Q_\nu^2) = \sin^2\vartheta_w^*(-m_Z^2) + 0.0050 \pm 0.0003$. The ellipse of figure 2 projects on the lines of constant m_Z to give:

$$\sin^2\vartheta_w^*(-m_Z^2) = 0.2282 - 0.0053(m_Z - 92) \pm 0.0016(\text{exp}) \pm 0.001(m_H). \quad (16)$$

The first error reflects the experimental errors, the second one the uncertainty due to the Higgs mass in the range $m_H = 10\text{-}1000$ Gev.

The asymmetries at the Z peak – corrected for experimental acceptance and QED photonic effects – can be predicted as well:

$$\begin{aligned}
A_{LR} &= A_\tau = 0.168 \pm 0.015 + 0.042(m_Z - 92) \\
A_{FB}^{(\mu)} &= 0.021 \pm 0.004 + 0.011(m_Z - 92) \\
A_{FB}^{(d)} &= 0.118 \pm 0.011 + 0.030(m_Z - 92) \\
A_{FB}^{(u)} &= 0.085 \pm 0.008 + 0.023(m_Z - 92)
\end{aligned} \tag{17}$$

Figure 5 shows the behavior of the left-right asymmetry.

These errors are similar to what can be obtained in LEP, at least until longitudinally polarized beams are available [15].

Similar results can be obtained for the Z partial widths: figure 6 shows the behavior of Γ_{ee} . The effects of varying m_t and ρ_0 are again identical. The same property holds for the other partial widths of the Z into light fermions. This result can be summarized as:

$$\begin{aligned}
\Gamma_{ee} &= 0.0854 \pm 0.0007 + 0.0025(m_Z - 92) \\
\Gamma_{\nu\bar{\nu}} &= 0.170 \pm 0.0015 + 0.0045(m_Z - 92) \\
\Gamma_{u\bar{u}} &= 0.305 \pm 0.0025 + 0.011(m_Z - 92) \\
\Gamma_{d\bar{d}} &= 0.393 \pm 0.0030 + 0.013(m_Z - 92)
\end{aligned} \tag{18}$$

in GeV. The QED and QCD – when appropriate – final state radiation effects have been included. A value of the strong coupling constant $\alpha_s(m_Z^2) = 0.12 \pm 0.02$ has been used.

2.4 The particular case of the $Z \rightarrow b\bar{b}$ partial width

When comparing R_ν with the total width of the Z, figure 7, the degeneracy between m_t and ρ_0 effects is not observed. The origin of this different behavior is found in the $b\bar{b}$ partial width, figure 8, which is affected by vertex corrections sensitive to the top quark mass. This *direct* effect, calculated by Beenakker and Hollik [6], singles out the $b\bar{b}$ partial width.

This interesting property allows to disentangle the top quark mass effect from the ρ_0 effect. A scenario where a large cancellation between these two effects would take place cannot be ruled out by existing data. It would

produce a considerable deficit in the total width with respect to the MSM expectation.

Deficits in the Z width for various values of ρ_0 are shown in table 3. The example of $\rho_0 = 0.9$ is shown in figure 9. One has to be aware, however, that these results have been obtained from first order calculations; given the size of the effect on the $b\bar{b}$ partial width, it is likely that higher orders would not be negligible.

This effect can potentially obscure neutrino counting from the total width measurement: for $\rho_0 = 0.8$, neutral current phenomenology would be respected for $m_t \simeq 970$ Gev, but the Z width would be then reduced by 170 Mev – a full neutrino family! On the other hand, the method proposed by Feldman [16] is immune to this uncertainty: it measures the invisible width $\Gamma_{inv} = N_\nu \Gamma_{\nu\bar{\nu}}$ in units of the charged lepton width, Γ_{ee} , and the ρ_0 - m_t cancellation is valid for both.

3 discussion

Neutrino experiments project on the LEP physics a set of very precise predictions. It is important to summarize the assumptions under which these have been obtained:

- The only intermediate vector bosons are the photon, the W and the Z.
- Quarks and leptons belong to the standard multiplets with coupling constants given by equations (5).
- The correct running of coupling constants from Q_ν^2 to $-m_Z^2$ is essential.
- It was not assumed that $\rho_0 = 1$. These predictions do not depend on the value of the top quark mass, or on all effects that are comparable to it, such as split multiplets in new families of quarks and leptons or their supersymmetric partners.
- The predictions for the asymmetries at the Z peak assume that there is only one Higgs particle with a mass in the range 10-1000 Gev. Unsplit

multiplets of fermions or further degenerate Higgs multiplets would produce effects similar to that of the standard Higgs and typically of the same order of magnitude or smaller. More than one family or extra Higgs would be necessary to obtain a significant deviation.

- The prediction for the mass ratio $\frac{m_W}{m_Z}$ does not depend on the Higgs mass or on the absence of unsplit doublets, but only on the proper algebraic structure of the model.

One could conceivably blame a departure of the Z peak measurements from these predictions on radiative effects, but this would involve the existence of new particles beyond those already known. A departure of the mass ratio to be measured at the $p\bar{p}$ colliders [17] would imply a real breakdown of the structure of the theory. A comparison of the Z peak measurements amongst themselves could be used as a probe of the correctness of the structure of the theory as well, since all observables should correspond to the same value of $\sin^2\vartheta_w^*$. Such scenario has been developed in ref. [7] and [18].

One should not ignore that these measurements are performed on nuclear targets. Intrinsic doubts could exist regarding their validity, but it has been shown by Llewellyn-Smith [13] that possible uncertainties should not exceed the quoted experimental error, especially since the experiments impose rather high energy cuts on the events. The measurement of the NC/CC ratio on purely leptonic target will be performed by the CHARM-II collaboration [19] and at a later stage by the water Cerenkov experiment at Los Alamos [20]. Reaching a precision of $\pm 1\%$ will, however, be rather difficult.

4 Conclusion

The measurements of neutrino NC/CC ratios on nuclear targets have been shown to constrain very severely the measurements of asymmetries at the Z peak and the mass ratio $\frac{m_W}{m_Z}$ to be performed at LEP/SLC or at the $p\bar{p}$ colliders respectively. As soon as the Z mass is measured, $\sin^2\vartheta_w \equiv 1 - \frac{m_W^2}{m_Z^2}$, obviously redundant with the knowledge of the W mass, has a completely different meaning than $\sin^2\vartheta_w^* \equiv \frac{e^2}{g^2}(m_Z^2)$, which determines the

asymmetries at the Z pole. Their values differ, but also their error bars and their sensitivity to physical effects.

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m_Z	ρ_0	m_H	m_t	$\sin^2\vartheta_w \equiv 1 - \frac{m_W^2}{m_Z^2}$	$\sin^2\vartheta_w^*(-m_Z^2)$
91	1	10	30	0.23497	0.23438
			60	0.23533	0.23406
			90	0.23148	0.23343
			120	0.22821	0.23266
			150	0.22467	0.23173
			200	0.21765	0.22980
91	1	100	30	0.23657	0.23529
			60	0.23692	0.23497
			90	0.23307	0.23434
			120	0.22979	0.23357
			150	0.22625	0.23263
			200	0.21980	0.23069
91	1	1000	30	0.23980	0.23659
			60	0.24014	0.23626
			90	0.23627	0.23562
			120	0.23298	0.23483
			150	0.22942	0.23388
			200	0.22235	0.23191
93	1	100	60	0.22318	0.22110
93	0.98	100	60	0.24507	0.22751
93	0.98	100	230	0.22327	0.22220

Table 1: Values of $\sin^2\vartheta_w$ and $\sin^2\vartheta_w^*$ for various values of m_Z , m_H and ρ_0 , calculated with EXPOSTAR [8]

	CDHS	CHARM
R_ν	0.3072 ± 0.0031	0.3093 ± 0.0031
R_ν^*	0.3104 ± 0.0045	0.3045 ± 0.0045
$R_{\bar{\nu}}$	0.375 ± 0.011	0.390 ± 0.014
$R_{\bar{\nu}}^*$	0.372 ± 0.012	0.388 ± 0.016
r	0.393 ± 0.016	0.456 ± 0.011
r^*	0.376 ± 0.016	0.433 ± 0.011

Table 2: Measured values of R_ν , $R_{\bar{\nu}}$ and r and values of R_ν^* and $R_{\bar{\nu}}^*$ extracted by applying corrections for non-isoscalarity in the quark-parton model, photonic effects, weak boxes and vertices, but no oblique corrections. The errors on R_ν^* , $R_{\bar{\nu}}^*$ and r^* include the additional errors due to these corrections, and in particular that due to the charm-quark mass. The resulting correlations between these variables were taken into account when extracting the weak parameters.

ρ_0	$m_t(\text{Gev})$	$\Delta\Gamma_Z(\text{Mev})$
1.	120.	0.
0.98	300.	-18.
0.90	600.	-80.
0.84	780.	-140.
0.80	970.	-170.

Table 3: Modification to the Z width due to the $b\bar{b}$ vertex correction. Couples of values for m_t and ρ_0 have been chosen such that the neutral current phenomenology remains mostly unchanged.

Figure 1: The relation between $\sin^2 \vartheta_w$ and $\sin^2 \vartheta_w^*$ when varying m_Z , m_t , m_H and ρ_0 . The variations upon the various parameters are practically independent of each other and have been represented only once.

Figure 2: Result of the fit to the neutrino NC/CC ratios in the $\sin^2 \theta_w^*(Q^2) - \rho^*(Q^2)$ plane. The lines of constant m_W , m_Z , $\sin^2 \theta_w$, are indicated. Also shown is the dependence of ρ^* on m_t . Full lines correspond to $m_H = 100$ GeV.

Figure 3: Relation between R_V and m_W for various values of m_Z , m_t , m_H and ρ_0 . For display purposes the quantity R_V^0 has been formed: R_V^0 is the average NC/CC ratio extracted from CDHS and CHARM data, corrected for non-isoscalarity in the quark parton model, photonic effects and weak boxes and vertices, reduced to the kinematical conditions of the CDHS experiment. Masses in GeV. Unless otherwise specified, $m_H = 100$. The effect of changing m_H to 10 (dashed line) or 1000 (dotted line), is also shown for $m_Z = 91$, $\rho_0 = 1$.

Figure 4: Relation between R_V^0 and the mass ratio m_W/m_Z , showing the equivalence of these two quantities in the $SU(2)_L \times U(1)$ gauge structure. Masses in GeV. Unless otherwise specified, $m_H = 100$. The effect of changing m_H to 10 (dashed line) or 1000 (dotted line), is also shown for $m_Z = 90$, $\rho_0 = 1$.

Figure 5: Relation between R_ν and A_{LR} for various values of m_Z , m_t , m_H and ρ_0 . Masses in GeV. Unless otherwise specified, $m_H = 100$. The effect of changing m_H to 10 (dashed line) or 1000 (dotted line), is also shown for $m_Z = 91$, $\rho_0 = 1$.

Figure 6: Relation between R_V and Γ_{ee} for various values of m_Z , m_t , m_H and ρ_0 . Masses in GeV. Unless otherwise specified, $m_H = 100$. The effect of changing m_H to 10 (dashed line) or 1000 (dotted line), is also shown for $m_Z = 91$, $\rho_0 = 1$.

Figure 7: Relation between R_ν and Γ_Z for various values of m_Z , m_t , m_H and ρ_0 . Masses in GeV. Unless otherwise specified, $m_H = 100$. The effect of changing m_H to 10 (dashed line) or 1000 (dotted line), is also shown for $m_Z = 91$, $\rho_0 = 1$.

Figure 8: Relation between R_V and $\Gamma_{b\bar{b}}$ for various values of m_Z , m_t , m_H and ρ_0 . Masses in GeV. Unless otherwise specified, $m_H = 100$. The effect of changing m_H to 10 (dashed line) or 1000 (dotted line), is also shown for $m_Z = 91$, $\rho_0 = 1$.

Figure 9: The relation between R_V and $\Gamma_{b\bar{b}}$ for $\rho_0 = 1$ and $\rho_0 = 0.9$ for various values of m_t , showing the effect of the $b\bar{b}$ vertex correction.