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Standard and Non-Standard Higgs Bosons in Electroweak Radiative Corrections

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Abstract:

The influence of the standard Higgs and of the additional charged and neutral Higgs bosons in a 2-doublet model with enhanced Yukawa couplings on the 1-loop radiative corrections to leptonic processes is discussed. The magnitude of the Higgs effects is compared with the theoretical uncertainty and the accuracy of present experiments and of precision measurements at LEP and SLC.

*) Talk given at the "IX. Warsaw Symposium on Elementary Particle Physics", May 1986, Kazimierz, Poland

1. Introduction

In spite of the great success of the electroweak standard model the hunt for the Higgs as the signal for spontaneous symmetry breaking is still a challenge to future collider experiments. In an electroweak gauge theory gauge bosons and fermions get their masses via the Higgs mechanism; as a consequence the particle spectrum is enlarged by at least one scalar boson.

The standard model has the minimal number of Higgs fields in SU(2) x U(1): a single scalar doublet with one physical neutral boson. This minimal version predicts the ratio

$$\varrho = \frac{M_W^2}{M_Z^2 \cos^2\theta_W} = 1 .$$

The converse, however, is not true: $\varrho = 1$ remains valid for any number of Higgs doublets automatically.

The investigation of models with more than one Higgs doublet [1] was motivated by the discussion of CP violation [2] , the Peccei-Quinn solution of the strong CP problem [3] , SUSY extensions of the standard model [4] which need at least two scalar doublets, and finally the richer phenomenological implications and their experimental signatures at future colliders.

Whereas the direct production of Higgs bosons in the near future is limited to relatively light bosons ($\lesssim 50$ GeV), indirect effects may manifest in the radiative corrections to the standard fermionic processes: μ-decay, ν-scattering, and e^+e^- annihilation. In this talk we put together the Higgs effects in the standard model 1-loop corrections and discuss in a similar way the minimal extension which has two scalar doublets within SU(2) x U(1).

In order to avoid additional hadronic uncertainties we restrict the discussion to purely leptonic processes.

2. The minimal model

The scalar doublet

$$\Phi = \begin{pmatrix} \phi^+ \\ \frac{v + H_0 + i\chi}{\sqrt{2}} \end{pmatrix}$$

contains the physical Higgs field Ho (mass M_{Ho}) and the vacuum expectation value $v \neq 0$. v determines the $W^{\pm}$, Z masses

$$M_W = \frac{1}{2} g_2 v \,, \qquad M_Z = \frac{1}{2} \sqrt{g_1^2 + g_2^2}\; v$$

as well as the masses of the charged fermions:

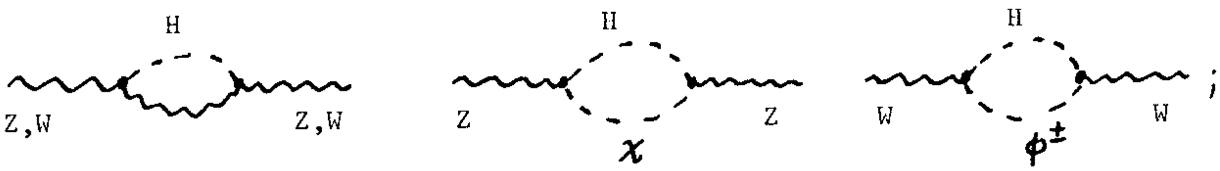
$$m_f = g_f \, v \qquad\qquad (g_f\text{: Yukawa coupling})$$

Since for the known fermions $m_f \ll M_W$, the Yukawa coupling

$$g_f = \frac{1}{2} g_2 \frac{m_f}{M_W} \qquad (2.1)$$

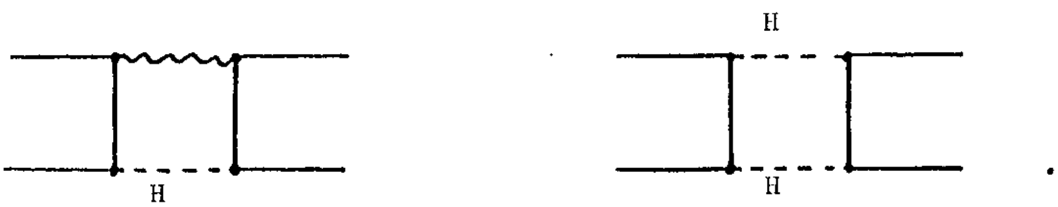
is a very small quantity. This restriction is typical for the minimal model and is lowered in more-doublet models.

Virtual Higgs contributions in 1-loop diagrams appear in the W and Z self energy, e. g.



in the fermionic vertices, typically:

and in box diagrams, e. g.



Due to the small Yukawa couplings (2.1) vertex and box diagrams for fermions involving virtual Higgs lines are suppressed at least by a factor $(m_f/M_w)^2$ and can therefore be neglected unless very heavy fermions are involved. Consequently, in the minimal model a virtual Higgs contributes only via the W, Z propagators to the 1-loop corrections for fermionic processes.

Loop calculations require the choice of a renormalization scheme. We perform our discussion in the on-shell scheme with the particle masses M_W, M_Z, M_{Ho}, m_f and the electromagnetic fine structure constant α in the Thomson limit as renormalized parameters. The corresponding renormalization conditions are the on-shell subtractions of the self energies for the physical fields and the definition of α in the Thomson limit. For details see ref. [6].

Since field renormalization is performed, all the self energies and vertex corrections are finite after renormalization.

The mixing angle as an auxiliary quantity is defined in terms of the gauge boson masses:

$$\sin^2\theta_W = 1 - M_W^2 / M_Z^2 \qquad (2.2)$$

3. The 2-doublet model

The minimal extension of the standard model is the SU(2) x U(1) model with two scalar doublets

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{v_1 + \eta_1 + i\chi_1}{\sqrt{2}} \end{pmatrix}, \qquad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{v_2 + \eta_2 + i\chi_2}{\sqrt{2}} \end{pmatrix} .$$

3 of their eight degress of freedom form the longitudinal polarization states of W^+, W^-, Z and 5 remain as physical particles. These split up into a pair of charged Higgs bosons $\phi^{\pm}$, 2 neutral scalars H_o, H_1, and a neutral pseudoscalar H_2. They are the mass eigenstates of the Higgs potential, which is chosen to be CP-symmetric [1]

$$V(\Phi_1, \Phi_2) = -\mu_1^2 |\Phi_1|^2 - \mu_2^2 |\Phi_2|^2 + \lambda_1 |\Phi_1|^4 + \lambda_2 |\Phi_2|^4$$
$$+ \lambda_3 |\Phi_1|^2 |\Phi_2|^2 + \lambda_4 (\Phi_1^+ \Phi_2)(\Phi_2^+ \Phi_1)$$
$$+ \frac{\lambda_5}{2} \left[(\Phi_1^+ \Phi_2)^2 + (\Phi_2^+ \Phi_1)^2 \right] . \qquad (3.1)$$

The vacuum expectation values v_1, v_2 determine the gauge boson masses:

$$M_W = \frac{1}{2} g_2 \sqrt{v_1^2 + v_2^2} \ , \qquad M_Z = M_W / \cos\theta_W . \; ^{1)} \qquad (3.2)$$

If one assumes that only Φ_2 has Yukawa couplings to fermions (restricting our selves to leptons), the fermion masses arise as

$$m_f = g_f v_2 \qquad (3.3)$$

which implies for the Yukawa couplings:

$$g_f = \frac{1}{2} g_2 \frac{m_f}{M_W} \frac{\sqrt{v_1^2 + v_2^2}}{v_2} . \qquad (3.4)$$

In the limit of very different vacuum expectation values $v_1 \gg v_2$ (according to the different mass scales of gauge bosons and fermions) the Yukawa couplings (3.4) become essentially larger than in the minimal model (2.1), enhanced by the factor

$$\beta = \frac{\sqrt{v_1^2 + v_2^2}}{v_2} \simeq \frac{v_1}{v_2} . \qquad (3.5)$$

Besides the masses β is a further input parameter of the model. In addition, the scalars H_o, H_1 can mix by a further mixing angle ζ, which

[1] Note that $\cos\theta_W = M_W/M_Z$ is also valid in more-doublet models

in the case $v_1 \gg v_2$ is of the order

$$\tan \zeta = v_1 / v_2$$

if the quartic couplings in (3.1) are all of the same order of magnitude.

In such a 2-Higgs model with enhanced Yukawa couplings the physical structure becomes very transparent:
One of the neutral scalars, Ho, behaves like the standard Higgs in the minimal model; in addition, there is a pair of a neutral scalar and pseudoscalar H_1, H_2, and a pair of charged Higgs bosons $\phi^{\pm}$, each of which has enhanced couplings to fermions. H_1 and H_2 can be lighter than the standard Higgs, whereas the mass of the charged Higgs is restricted from e^+e^- experiments [7] to $M_\phi \gtrsim 18$ GeV. Limits on v_1/v_2 from leptonic reactions are not very severe: g - 2 for the muon restricts $v_2/v_1 > 0.015$ [8] for a non-degenerate H_1, H_2 pair (H_1 = 6 GeV); a degenerate H_1, H_2 pair gives essentially weaker bounds [8]. More stringent limits can be deduced from heavy quark systems [9] but this depends on additional assumptions about the Higgs-quark sector.

The strategy of calculating radiative corrections to processes where at least one fermion pair is light (e^+e^-, νe) is as follows:

a) Calculate the additional contributions of H_1, H_2, $\phi^{\pm}$ to the boson self - and mixing energies, boson - fermion vertices, and fermion self energies.

b) Perform the on-shell renormalization as in 2., but now extended by the on-shell conditions for the additional physical Higgs fields. The renormalized input parameters are then α, M_W, M_Z, M_{Ho}, M_1, M_2, M_ϕ; Ho can be identified with the standard Higgs (M_1, M_2, M_ϕ denote the masses of H_1, H_2, $\phi^{\pm}$).

For the details see ref. [10].

4. Radiative Corrections

4.1 The M_Z - M_W and M_Z - $\sin^2\theta_W$ interdependence

Application of the radiative corrections to the μ lifetime and identification with the Fermi model result lead to the formula

$$M_Z^2 = \frac{\pi\alpha}{\sqrt{2}\, G_F} \cdot \frac{1}{\sin^2\theta_W \cos^2\theta_W (1-\Delta\tilde{r})} \tag{4.1}$$

with $$\Delta\tilde{r} = \Delta r(\alpha, \sin^2\theta_W, M_Z, M_{Ho}) + \Delta r_1 . \tag{4.2}$$

Δr is the standard model correction [11]

$$\Delta r = \frac{\Sigma_W(0)}{M_W^2} + \frac{\alpha}{4\pi \sin^2\theta_W}\left[6 + \frac{7-4\sin^2\theta_W}{2\sin^2\theta_W}\log(\cos^2\theta_W)\right] \tag{4.3}$$

with the renormalized W self energy $\Sigma_W(k^2)$, which contains the dependence on the Higgs mass M_{Ho}.

The extension to the 2-doublet case adds the additional term Δr_1, esentially given by

$$\Delta r_1 \approx \frac{\Delta\Sigma_W(0)}{M_W^2} \equiv \Delta r_1(\alpha, \sin^2\theta_W, M_Z; M_1, M_2, M_\phi) \tag{4.4}$$

with the contributions of the extra bosons to the (renormalized) W self energy, $\Delta\Sigma_W(k^2)$.

Eq. (4.1) allows to derive a $\sin^2\theta_W$ value if M_Z is given; together with $M_W = M_Z \cos\theta_W$ this yields also the M_Z - M_W interdependence. These relations depend on the Higgs mass(es).

First we figure out the dependence on M_{Ho} in the minimal model (see also ref's [12 - 14]): Fixing M_Z = 93.2 GeV and varying M_{Ho} the following changes in $\sin^2\theta_W$ resp. M_W appear:

M_{Ho}	$\Delta\sin^2\theta_W$	ΔM_W
10 - 500 GeV	0.0035	-19 MeV
10 - 1000 GeV	0.0048	-25 MeV

The present experimental uncertainty of $\sin^2\theta_W$ is $\Delta\sin^2\theta_W \gtrsim \pm 0.005$, and that of M_W: $\Delta M_W = \pm 1.7$ GeV [15] . These do not allow to look where the Ho is settled between the conservative limits 10 GeV and 1 TeV.

The situation becomes somewhat better if (with LEP II) the ratio $\sin^2\theta_W = 1-M_W^2/M_Z^2$ can be measured with the precision ± 0.0015. The inherent hadronic uncertainty in the relation (4.1) from the light quarks leads to a theoretical uncertainty of $\Delta\sin^2\theta_W = 0.0002$ if the update analysis of Jegerlehner [14] is used. A further uncertainty of similar magnitude is due to the renormalization scheme dependence [16] .

In the 2-doublet model, the effects of the extra Higgs bosons are listed in table 1. Significant deviations from the standard result are obtained if either $\phi^{\pm}$ or H_1, H_2 are heavy, and exceed the variation with Ho discussed above. All the other cases lead only to small modifications (see also ref. [17]). The value for M_W in case of $M_\phi \simeq 5\ M_Z$ is about the 1 - σ limit of the measured M_W [15] .

M_1	M_2	M_ϕ	$\sin^2\theta_W$	M_W (GeV)
M_Z	M_Z	M_Z	0.2208	82.27
10	10	M_Z	0.2194	82.35
0.1	0.1	M_Z	0.2194	82.35
M_Z	M_Z	5 M_Z	0.1995	83.39
10	10	5 M_Z	0.1916	83.80
1	1	5 M_Z	0.1915	83.80
0.1	0.1	5 M_Z	0.1915	83.80
5 M_Z	5 M_Z	M_Z	0.2005	83.33
5 M_Z	M_Z	M_Z	0.2212	82.25
5 M_Z	M_Z	5 M_Z	0.2207	82.28
Standard			0.2208	82.27

Table 1.
$\sin^2\theta_W$ and M_W for M_Z = 93.2 GeV.
(pure numbers mean masses in GeV)

4.2 Neutrino electron scattering

A sensitive quantity to measure $\sin^2\theta_W$ in a leptonic ν scattering process is the ratio

$$R = \frac{\sigma(\nu_\mu e)}{\sigma(\bar{\nu}_\mu e)} , \tag{4.5}$$

in lowest order given by

$$R^\circ = \frac{1+\xi+\xi^2}{1-\xi+\xi^2} , \qquad \xi = 1 - 4\sin^2\theta_W . \tag{4.6}$$

In 1-loop order this becomes

$$R^\circ \longrightarrow R(\sin^2\theta_W, \alpha, M_Z, M_{H_0} [M_1, M_2, M_\phi]) \tag{4.7}$$

R is therefore dependent on the Higgs mass(es).

First we compare the variation of $\sin^2\theta_W$ with M_{Ho} for a given $R^{exp} = 1.26$ [18] in the minimal model with the other sources of uncertainties in (4.7):

M_{Ho} = 10 - 1000 GeV	0.0024
m_t = 30 - 60 GeV	0.0008
ΔM_Z = ±5 GeV	±0.0003
hadronic uncertainty	±0.0003
exp. uncertainty (expected)	±0.005

Althrough the Higgs gives the theoretically largest effect, it is completely within the experimental noise even for the highest expected precision in the CHARM experiment.

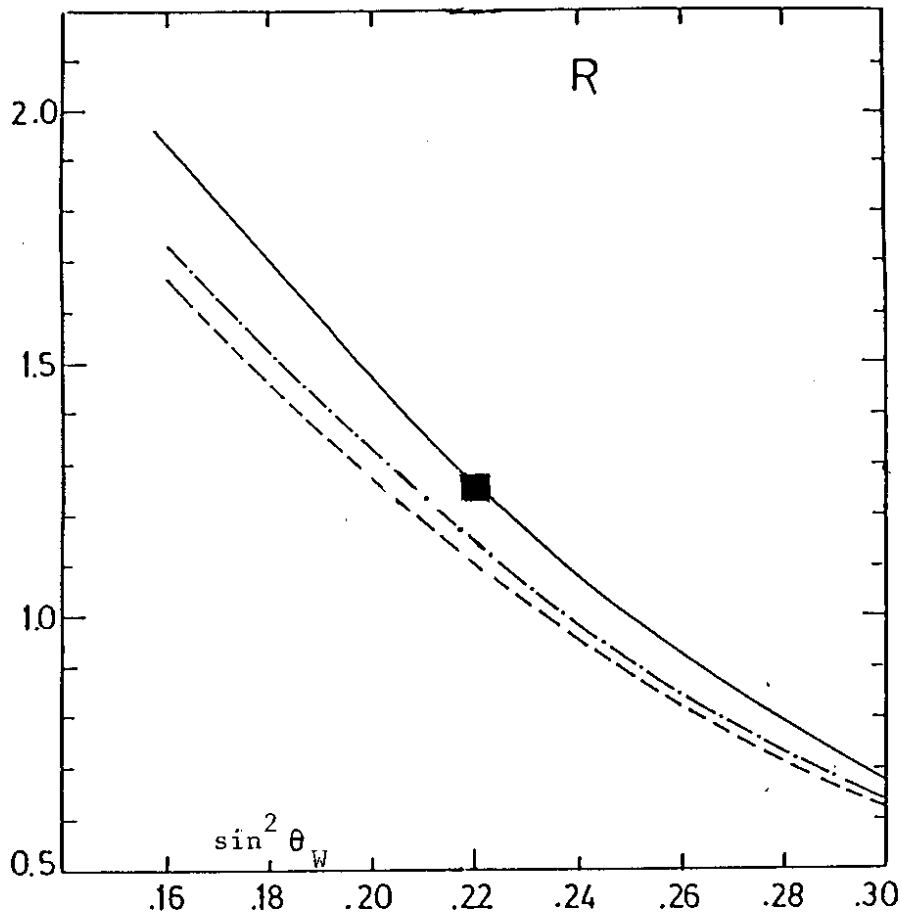


Fig. 1. R from eq. (4.7) in lowest order (——) and for different extra Higgs masses with radiative corrections.

—— · —— · $M_1 = M_2 = M_Z$, $M_\phi = 5\ M_Z$

— — — — $M_1 = M_2 = 10$ GeV, $M_\phi = 5\ M_Z$ $M_Z = 93.2$ GeV.

In the 2-doublet model, the effects of the extra Higgs bosons are depicted in Fig. 1 for the case of large mass splitting between ϕ^+ and H_1, H_2 (other situations give only small deviations from the standard model). The shaded areas indicate the expected accuracy of a measured R (CHARM experiment) and of $\sin^2\theta_W = 1-M_W^2/M_Z^2$ (from LEP) if the present mean values would persist. One can see that forthcoming experiments will become decisive.

4.3 $e^+e^- \longrightarrow l^+l^-$ ($l = \mu, \tau$)

With a longitudinal e-beam polarization P_L the differential cross section has the form

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4s} \left\{ \sigma_u(\theta) + P_L\, \sigma_L(\theta) \right\}, \quad \theta = \measuredangle(e^-, \mu^-) . \tag{4.8}$$

The observables of interest are:

(i) the integrated cross section:

$$\sigma = \int \frac{d\sigma}{d\Omega}\, d\Omega \tag{4.9}$$

(ii) the forward - backward asymmetry A_{FB}:

$$A_{FB} = \frac{1}{\sigma} \left\{ \int_{\cos\theta > 0} d\sigma - \int_{\cos\theta < 0} d\sigma \right\} \tag{4.10}$$

(iii) the polarization asymmetry A_L:

$$A_L = \frac{\sigma(P_L) - \sigma(-P_L)}{\sigma(P_L) + \sigma(-P_L)} \cdot \frac{1}{P_L} \tag{4.11}$$

The electromagnetic and weak corrections in the minimal model have already been discussed in ref's [11, 12, 19 - 25]. In our context here we only concentrate on the Higgs dependence via the weak corrections.

a) Standard model:

Weak corrections (and therefore Higgs effects) at PETRA energies are completely negligible for σ; in A_{FB} the M_{Ho} dependence is also too small to be of practical interest ($\Delta A_{FB} = -0.001$ for M_{Ho} from 10 GeV to 1 TeV).

A quantity of particular interest is the on-resonance polarization asymmetry A_L (for $s = M_Z^2$):

Calculating in 1-loop order

$$A_L = A_L^{\circ}(\sin^2\theta_W, M_Z) + \delta A_L(\sin^2\theta_W, M_Z, M_{H_o}) \quad (4.12)$$

and substituting $\sin^2\theta_W$ (α, G_F, M_Z, M_{Ho}) from (4.1) shows the sensitivity of A_L to the Higgs mass for a given M_Z (here: M_Z = 93.2 GeV)

M_H = 10 - 500 GeV: $\Delta A_L = -0.015$

M_H = 10 - 1000 GeV: $\Delta A_L = -0.018$

Comparing this result with the expected experimental accuracy of $(\Delta A_L)_{exp} = \pm 0.005$ at the SLC one gets a chance to decide at least whether the Higgs is very light or very heavy.

For the unpolarized on-resonance A_{FB} the change ΔA_{FB} with M_{Ho} is about 1/3 of the values for ΔA_L given above.

b) 2-doublet model:

The forward - backward asymmetry for PETRA energy is displayed in Fig. 2 for the case of a heavy ϕ^+ (heavy H_1, H_2 similar).

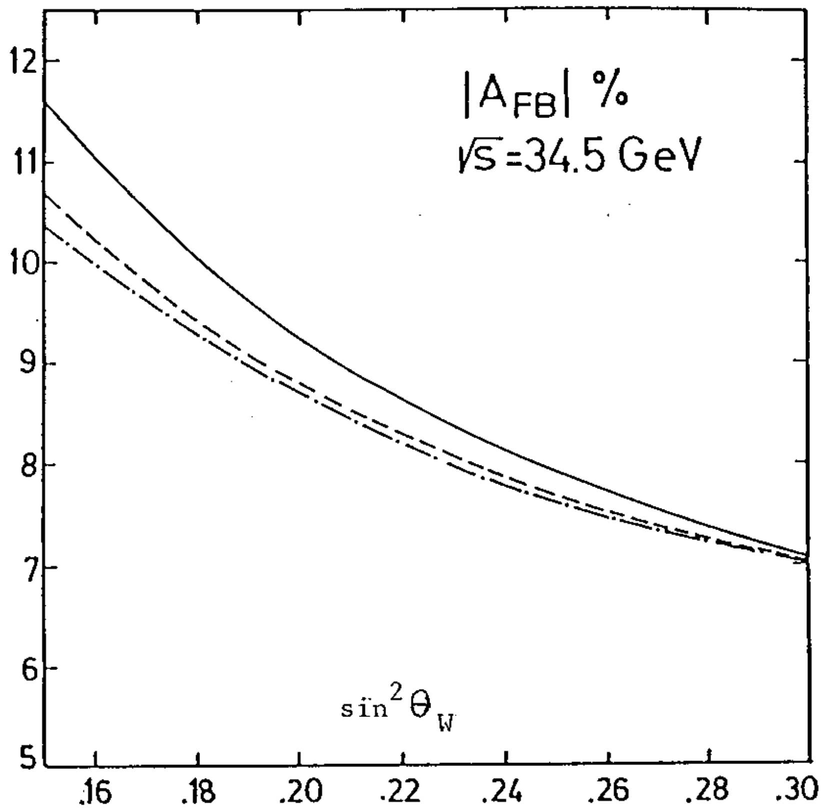


Fig. 2.

A_{FB} as function of $\sin\theta_W$.

- - - $M_1=M_2=M_Z$, $M_\phi = 5M_Z$

—·— $M_1=M_2=10$GeV, $M_\phi = 5M_Z$

——— lowest order

M_z = 93.2 GeV.

As in the case of R in 4.2 the extraction of $\sin^2\theta_W$ from a measured A_{FB}^{exp} would yield smaller values than in the minimal model. This is largely independent of the enhancement factor β and does not lead to a difference between μ and τ final states.

If, however, $\sin^2\theta_W$ is eliminated by (4.1) in favor of α, G_F together with the scalar masses the predicted value for A_{FB} deviates only by +0.003 (for the lower curve in Fig. 2) from the standard model and is below the experimental sensitivity. The reason is that the W self energy in (4.1) and the Z self energy in $e^+e^- \longrightarrow l^+l^-$ largely cancel each other also in their scalar components.

As a last example we consider A_L at $s = M_Z^2$. We show the $\sin^2\theta_W$ dependence of $A_L = A_L^o(\sin^2\theta_W, M_Z) + \delta A_L(\sin^2\theta_W, M_Z, M_{Ho}, M_1, M_2, M_\phi)$ in Fig. 3 for various masses of the extra Higgs bosons. The sensitive dependence on the mass splittings between charged and neutral bosons is obvious.

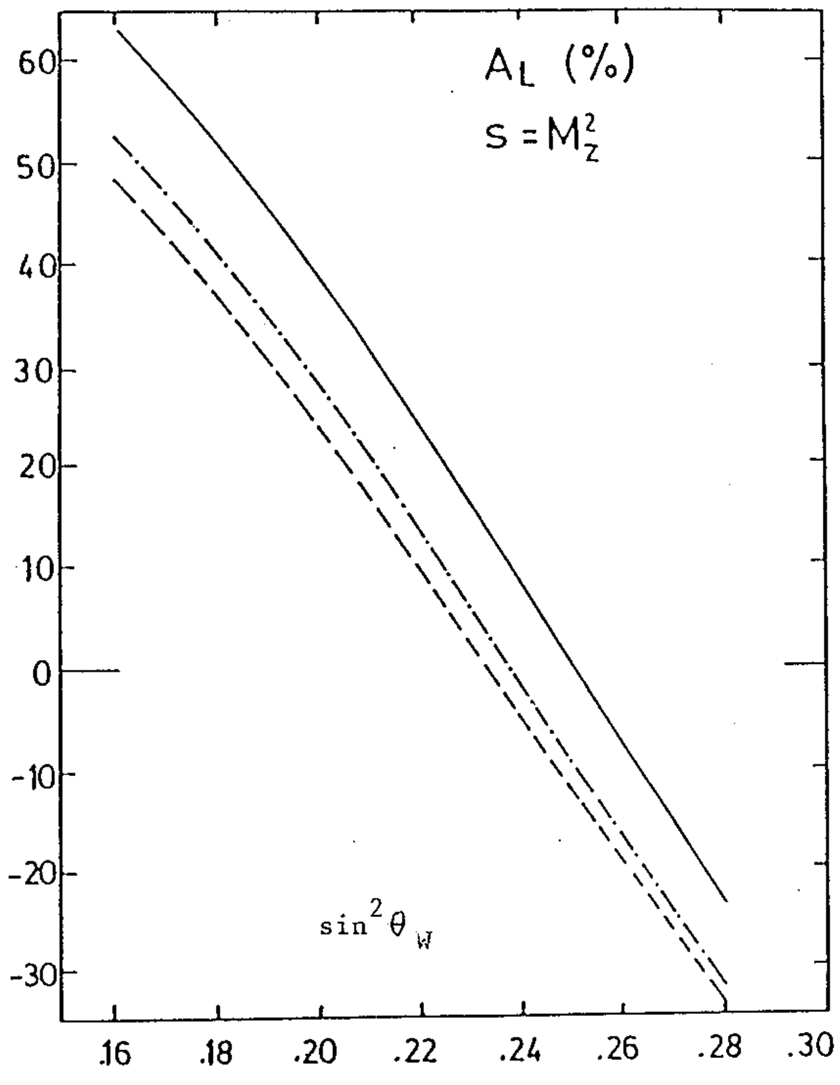


Fig. 3.

On-resonance polarization asymmetry A_L, dependence on $\sin\theta_W$.

——— lowest order

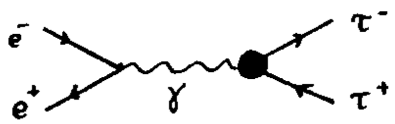
—·—· $M_1 = M_2 = M_Z$, $M = 5\ M_Z$

– – – – $M_1 = M_2 = 10$ GeV, $M = 5\ M_Z$.

$M_Z = 93.2$ GeV.

Eliminating $\sin^2\theta_W$ by (4.1) in each of the models leads to differences in A_L which are measurable at the SLC; e. g. A_L is by 0.07 larger than the standard A_L if $M_\phi = 5\ M_Z$, $M_1 = M_2 = 10$ GeV. Again the situation is practically the same for μ and τ pair production, largely independent of v_1/v_2. Precision measurements of A_L could therefore tightly restrict the possible mass range in 2-doublet models.

In contrast to the asymmetries, the integrated cross section shows a dependence on v_1/v_2 (and on the masses of H_1, H_2, but it is insensitive to a heavy ϕ^+): At PETRA/PEP energies there is a difference between $\sigma(e^+e^- \rightarrow \mu^+\mu^-)$ and $\sigma(e^+e^- \rightarrow \tau^+\tau^-)$ by a few percent, mainly due the γ-vertex correction:



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From the experimental error [26] on $\sigma(e^+e^- \rightarrow \tau^+\tau^-)/\sigma_o$, $\sigma_o = 4\pi\alpha^2/3s$, of ~5 % one can derive the limits

$$v_1/v_2 \lesssim 200 \quad \text{for } M_1 = M_2 = 10 \text{ GeV}$$
$$v_1/v_2 \lesssim 140 \quad \text{for } M_1 = M_2 = 5 \text{ GeV}$$

This is a tighter restriction than from $(g-2)_\mu$ in the degenerate H_1, H_2 case.

5. Conclusions:

The effects of the standard Higgs in 1-loop corrections to fermionic processes are rather small ("screening" [5]). They are too small to be observable in present experiments. In precision experiments at LEP/SLC the Higgs effects will match the experimental accuracy.

In the 2-doublet model measurable effects appear if either the charged Higgs mass or the extra neutral boson masses are heavy. Effects of a light neutral scalar/pseudoscalar could be observed in terms of differences between $\sigma(e^+e^- \longrightarrow \mu^+\mu^-)$ and $\sigma(e^+e^- \longrightarrow \tau^+\tau^-)$.
The experimental uncertainty in the τ cross section can be used to put limits on v_1/v_2 and the neutral masses.

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