Implications of Precision Electroweak Measurements for Physics Beyond the SM

Jens Erler
University of Pennsylvania

We perform a global analysis of electroweak precision measurements to find constraints on physics beyond the Standard Model. In particular, we discuss oblique parameters, which are useful to constrain additional matter fields, as well as extra Z bosons, and supersymmetry. We also summarize the present information on the Higgs boson mass.

I. INTRODUCTION

Using the top quark and Z boson masses, m_t and M_Z, the QED coupling, α, and the Fermi constant, G_F, as input, other precision observables can be computed within the SM as functions of the Higgs boson mass, M_H. For relatively low values of M_H, the agreement with the measurements is found to be excellent, establishing the SM at the one-loop level. I will briefly review the constraints on M_H and the experimental situation before moving beyond the SM.

Besides the recent high precision measurements of the W boson mass [1,2], M_W, the most important input into precision tests of electroweak theory continues to come from the Z factories LEP 1 [1] and SLC [3]. The vanguard of the physics program at LEP 1 with about 20 million recorded Z events is the analysis of the Z lineshape. Its parameters are M_Z, the total Z width, , $_Z$, the hadronic peak cross section, $\sigma_{\rm had}$, and the ratios of hadronic to leptonic decay widths, $R_\ell = \frac{\Gamma(\rm had)}{\Gamma(\ell^+\ell^-)}$, where $\ell = e$, μ, or τ. They are determined in a common fit with the leptonic forward-backward (FB) asymmetries, $A_{FB}(\ell) = \frac{3}{4}A_e A_\ell$. With f denoting the fermion index,

$$A_f = \frac{2v_f a_f}{v_f^2 + a_f^2} \tag{1}$$

is defined in terms of the vector ($v_f = I_{3,f} - 2Q_f \sin^2\theta_f^{\rm eff}$) and axial-vector ($a_f = I_{3,f}$) $Zf\bar{f}$ coupling; Q_f and $I_{3,f}$ are the electric charge and third component of isospin, respectively, and $\sin^2\theta_f^{\rm eff} \equiv \bar{s}_f^2$ is an effective mixing angle.

An average of about 73% polarization of the electron beam at the SLC allows for a set of competitive and complementary measurements with a much smaller number of Z's ($\gtrsim 500,000$). In particular, the left-right (LR) cross section asymmetry, $A_{LR} = A_e$, represents the most precise determination of the weak mixing angle by a single experiment (SLD) [3]. Mixed FB-LR asymmetries, $A_{LR}^{FB}(f) = \frac{3}{4}A_f$, single out the final state coupling of the Z boson.

For several years there has been an experimental discrepancy at the 2σ level between A_ℓ from LEP and the SLC. With the 1997/98 high statistics run at the SLC, and a revised value for the FB asymmetry of the τ polarization, $\mathcal{P}_\tau^{FB}$, the two determinations are now consistent with each other,

$$\begin{array}{l} A_\ell({\rm LEP}) = 0.1470 \pm 0.0027, \\ A_\ell({\rm SLD}) = 0.1503 \pm 0.0023. \end{array} \tag{2}$$

The LEP value is from $A_{FB}(\ell)$, $\mathcal{P}_\tau$, and $\mathcal{P}_\tau^{FB}$, while the SLD value is from A_{LR} and $A_{LR}^{FB}(\ell)$. The data is consistent with lepton universality, which is assumed here. There remains, however, a 2.5σ discrepancy between the two most precise determinations of $\bar{s}_\ell^2$, namely A_{LR} and $A_{FB}(b)$ (assuming no new physics in A_b).

Of particular interest are the results on the heavy flavor sector [1] including $R_q = \frac{\Gamma(q\bar{q})}{\Gamma(\rm had)}$, $A_{FB}(q)$, and $A_{LR}^{FB}(q)$, with $q = b$ or c. There is a theoretical prejudice that the third family is the one which is most likely affected by new physics. Interestingly, the heavy flavor sector has always shown the largest deviations from the SM. E.g., R_b deviated at times by almost 4σ. Now, however, R_b is in good agreement with the SM, and thus puts strong constraints on many types of new physics. At present, there is some discrepancy in $A_{LR}^{FB}(b) = \frac{3}{4}A_b$, and $A_{FB}(b) = \frac{3}{4}A_e A_b$, both at the 2σ level. Using the average of Eqs. (2), $A_\ell = 0.1489 \pm 0.0018$, both can be interpreted as measurements of A_b. From $A_{FB}(b)$ one would obtain $A_b = 0.887 \pm 0.022$, and the combination with $A_{LR}^{FB}(b) = \frac{3}{4}(0.867 \pm 0.035)$ would yield $A_b = 0.881 \pm 0.019$, which is almost 3σ below the SM prediction. Alternatively, one could use A_ℓ(LEP) above (which is closer to the SM prediction) to determine $A_b({\rm LEP}) = 0.898 \pm 0.025$, and $A_b = 0.888 \pm 0.020$ after combination with

$A_{LR}^{FB}(b)$, i.e., still a 2.3σ discrepancy. An explanation of the 5–6% deviation in A_b in terms of new physics in loops, would need a 25–30% radiative correction to $\hat{\kappa}_b$, defined by $\bar{s}_b^2 \equiv \hat{\kappa}_b \sin^2\hat{\theta}_{\overline{\rm MS}}(M_Z) \equiv \hat{s}_Z^2$. Only a new type of physics which couples at the tree level preferentially to the third generation [4], and which does not contradict R_b (including the off-peak measurements by DELPHI [5]), can conceivably account for a low A_b. Given this and that none of the observables deviates by 2σ or more, we can presently conclude that there is no compelling evidence for new physics in the precision observables, some of which are listed in Table I. Very good agreement with the SM is observed. Only A_{LR} and the two measurements sensitive to A_b discussed above, show some deviation, but even those are below 2σ.

The data show a strong preference for a low $M_H \sim \mathcal{O}(M_Z)$. Unlike in previous analyses, the central value of the global fit to all precision data, including m_t and excluding further constraints from direct searches,

$$M_H = 107^{+67}_{-45}\ \text{GeV}, \tag{3}$$

is now above the direct lower limit, $M_H > 90$ GeV [95% CL], from searches at LEP 2 [6]. It coincides with the 5σ discovery limit from LEP 2 running at 200 GeV center of mass energy with 200 pb^{-1} integrated luminosity per experiment [6]. The 90% central confidence interval from precision data only is given by 39 GeV $< M_H <$ 226 GeV. The fit result (3) is consistent with the predictions for the lightest neutral Higgs boson [7], $m_{h^0} \lesssim 130$ [150] GeV, within the Minimal Supersymmetric Standard Model (MSSM) [and its extensions].

TABLE I. Principal precision observables from CERN, FNAL, SLAC, and elsewhere. Shown are the experimental results, the SM predictions, and the pulls. The SM errors are from the uncertainties in M_Z, $\ln M_H$, m_t, $\alpha(M_Z)$, and α_s. They have been treated as Gaussian and their correlations have been taken into account. $\bar{s}_\ell^2(Q_{FB}(q))$ is the weak mixing angle from the hadronic charge asymmetry; R^- and R^ν are cross section ratios from deep inelastic ν-hadron scattering; $g_{V,A}^{\nu e}$ are effective four-Fermi coefficients in ν-e scattering; and the Q_W are the weak charges from parity violation measurements in atoms. The uncertainty in the $b \to s\gamma$ observable includes theoretical errors from the physics model, the finite photon energy cut-off, and from uncalculated higher order effects. There are other precision observables which are not shown but included in the fits.

Quantity	Group(s)	Value	Standard Model	pull
M_Z [GeV]	LEP	91.1867 ± 0.0021	91.1865 ± 0.0021	0.1
Γ_Z [GeV]	LEP	2.4939 ± 0.0024	2.4957 ± 0.0017	-0.8
$\sigma_{\rm had}$ [nb]	LEP	41.491 ± 0.058	41.473 ± 0.015	0.3
R_e	LEP	20.783 ± 0.052	20.748 ± 0.019	0.7
R_μ	LEP	20.789 ± 0.034	20.749 ± 0.019	1.2
R_τ	LEP	20.764 ± 0.045	20.794 ± 0.019	-0.7
$A_{FB}(e)$	LEP	0.0153 ± 0.0025	0.0161 ± 0.0003	-0.3
$A_{FB}(\mu)$	LEP	0.0164 ± 0.0013		0.2
$A_{FB}(\tau)$	LEP	0.0183 ± 0.0017		1.3
R_b	LEP + SLD	0.21656 ± 0.00074	0.2158 ± 0.0002	1.0
R_c	LEP + SLD	0.1735 ± 0.0044	0.1723 ± 0.0001	0.3
$A_{FB}(b)$	LEP	0.0990 ± 0.0021	0.1028 ± 0.0010	-1.8
$A_{FB}(c)$	LEP	0.0709 ± 0.0044	0.0734 ± 0.0008	-0.6
A_b	SLD	0.867 ± 0.035	0.9347 ± 0.0001	-1.9
A_c	SLD	0.647 ± 0.040	0.6676 ± 0.0006	-0.5
$A_{LR} + A_\ell$	SLD	0.1503 ± 0.0023	0.1466 ± 0.0015	1.6
$\mathcal{P}_\tau : A_e + A_\tau$	LEP	0.1452 ± 0.0034		-0.4
$\bar{s}_\ell^2(Q_{FB})$	LEP	0.2321 ± 0.0010	0.2316 ± 0.0002	0.5
m_t [GeV]	Tevatron	173.8 ± 5.0	171.4 ± 4.8	0.5
M_W [GeV]	all	80.388 ± 0.063	80.362 ± 0.023	0.4
R^-	NuTeV	$0.2277 \pm 0.0021 \pm 0.0007$	0.2297 ± 0.0003	-0.9
R^ν	CCFR	$0.5820 \pm 0.0027 \pm 0.0031$	0.5827 ± 0.0005	-0.2
R^ν	CDHS	$0.3096 \pm 0.0033 \pm 0.0028$	0.3089 ± 0.0003	0.2
R^ν	CHARM	$0.3021 \pm 0.0031 \pm 0.0026$		-1.7
$g_V^{\nu e}$	all	-0.041 ± 0.015	-0.0395 ± 0.0004	-0.1
$g_A^{\nu e}$	all	-0.507 ± 0.014	-0.5063 ± 0.0002	-0.1
Q_W(Cs)	Boulder	$-72.41 \pm 0.25 \pm 0.80$	-73.10 ± 0.04	0.8
Q_W(Tl)	Oxford + Seattle	$-114.8 \pm 1.2 \pm 3.4$	-116.7 ± 0.1	0.5
$\frac{\Gamma(b\to s\gamma)}{\Gamma(b\to c e\nu)}$	CLEO	$3.26^{+0.75}_{-0.68} \times 10^{-3}$	$3.14^{+0.19}_{-0.18} \times 10^{-3}$	0.1

For the determination of the proper M_H upper limits, we scan equidistantly over $\ln M_H$, combining the likelihood χ^2 function from the precision data with the exclusion curve (interpreted as a prior probability distribution function) from LEP 2 [6]. This curve is from Higgs searches at center of mass energies up to 183 GeV. We find the 90 (95, 99)% confidence upper limits,

$$M_H < 220\ (255,\ 335)\ \text{GeV}. \tag{4}$$

Notice, that the LEP 2 exclusion curve increases the 95% upper limit by almost 30 GeV. The upper limits (4) are rather insensitive to the $\alpha(M_Z)$ used in the fits. This is due to compensating effects from the larger central value of $\alpha(M_Z)$ (corresponding to lower extracted Higgs masses) and the larger error bars in the data driven approach [8] as compared to evaluations relying more strongly on perturbative QCD [9]. While the limits are therefore robust within the SM, it should be cautioned that the results on M_H are strongly correlated with certain new physics parameters, as discussed in Section II.

The accurate agreement of theory and experiment allows severe constraints on possible TeV scale physics, such as unification or compositeness. For example, the ideas of technicolor and non-supersymmetric Grand Unified Theories (GUTs) are strongly disfavored. On the other hand, supersymmetric unification, as generically predicted by heterotic string theory, is supported by the observed approximate gauge coupling unification at an energy slightly below the Planck scale, and by the decoupling of supersymmetric particles from the precision observables. As I will discuss in the following Sections, those types of new physics which tend to decouple from the SM are favored, while non-decoupling new physics generally conflicts with the data.

II. OBLIQUE PARAMETERS: BOUNDS ON EXTRA MATTER

The data is precise enough to constrain additional parameters describing physics beyond the SM. Of particular interest is the ρ_0-parameter, which is a measure of the neutral to charged current interaction strength and defined by

$$\rho_0 = \frac{M_W^2}{M_Z^2 \hat{c}_Z^2 \hat{\rho}(m_t, M_H)}. \tag{5}$$

The SM contributions are absorbed in $\hat{\rho}$. Examples for sources of $\rho_0 \neq 1$ include *non-degenerate* extra fermion or boson doublets, and non-standard Higgs representations.

In a fit to all data with ρ_0 as an extra fit parameter, there is a strong (73%) correlation[1] with M_H. As a result, upper limits on M_H are weaker when ρ_0 is allowed. Indeed, $\chi^2(M_H)$ is very shallow with $\Delta\chi^2 = \chi^2(1\ \text{TeV}) - \chi^2(M_Z) = 4.5$, and its minimum is at $M_H = 46$ GeV, which is already excluded. For comparison, within the SM a 1 TeV Higgs boson is excluded at the 5 σ level. We obtain,

$$\begin{aligned} \rho_0 &= 0.9996^{+0.0009}_{-0.0006}, \\ m_t &= 172.9 \pm 4.8\ \text{GeV}, \\ \alpha_s(M_Z) &= 0.1212 \pm 0.0031, \end{aligned} \tag{6}$$

in excellent agreement with the SM ($\rho_0 = 1$). The central values are for $M_H = M_Z$, and the uncertainties are 1σ errors and include the range, $M_Z \leq M_H \leq 167$ GeV, in which the minimum χ^2 varies within one unit. Note, that the uncertainties for $\ln M_H$ and ρ_0 are non-Gaussian: at the 2σ level ($\Delta\chi^2 \leq 4$), Higgs boson masses up to 800 GeV are allowed, and we find

$$\rho_0 = 0.9996^{+0.0031}_{-0.0013}\ (2\sigma). \tag{7}$$

---

[1] ρ_0 is also strongly anticorrelated with the strong coupling α_s (-53%) and m_t (-46%).

This implies strong constraints on the mass splittings of extra fermion and boson doublets [10],

$$\Delta m^2 = m_1^2 + m_2^2 - \frac{4m_1^2 m_2^2}{m_1^2 - m_2^2} \ln \frac{m_1}{m_2} \geq (m_1 - m_2)^2, \tag{8}$$

namely, at the 1σ and 2σ levels, respectively, (C_i is the color factor)

$$\sum_i \frac{C_i}{3} \Delta m_i^2 < \ (38 \text{ GeV})^2 \text{ and } (93 \text{ GeV})^2. \tag{9}$$

Due to the restricted Higgs mass range in the presence of supersymmetry (SUSY), stronger 2σ constraints result here,

$$\rho_0 \text{ (MSSM)} \ = 0.9996^{+0.0017}_{-0.0013} \ (2\sigma). \tag{10}$$

The 2σ constraint in (9) would therefore tighten from $(93 \text{ GeV})^2$ to $(64 \text{ GeV})^2$.

Constraints on heavy *degenerate chiral fermions* can be obtained through the S parameter [11], defined as a difference of Z boson self-energies,

$$\frac{\hat{\alpha}(M_Z)}{4\hat{s}_Z^2 \hat{c}_Z^2} S \equiv \frac{\Pi_{ZZ}^{\text{new}}(M_Z^2) - \Pi_{ZZ}^{\text{new}}(0)}{M_Z^2}. \tag{11}$$

The superscripts indicate that S includes new physics contributions only. Likewise, $T = (1 - \rho_0^{-1})/\hat{\alpha}$ and the third oblique parameter, U, also vanish in the SM. A fit to all data with S allowed yields,

$$\begin{array}{rcr} S & = & -0.20^{+0.24}_{-0.17}, \\ M_H & = & 390^{+690}_{-310} \text{ GeV}, \\ m_t & = & 172.9 \pm 4.8 \text{ GeV}, \\ \alpha_s & = & 0.1221 \pm 0.0035. \end{array} \tag{12}$$

It is seen, that in the presence of S constraints on M_H virtually disappear. In fact, S and M_H are almost perfectly anticorrelated (-92%). By requiring $M_Z \leq M_H \leq 1$ TeV, we find at the 3σ level,

$$S = -0.20^{+0.40}_{-0.33} \ (3\sigma). \tag{13}$$

A heavy degenerate ordinary or mirror family contributes $2/3\pi$ to S. A degenerate fourth generation is therefore excluded at the 99.8% CL on the basis of the S parameter alone. Due to the correlation with T, the fit becomes slightly better in the presence of a non-degeneracy of the new doublets. A non-vanishing $T = 0.15 \pm 0.08$ is favored, but even in this case a fourth family is excluded at least at the 98.2% CL. This is in agreement with a different constraint on the generation number, using very different assumptions: allowing the invisible Z width as a free parameter, yields the constraint, $N_\nu = 2.992 \pm 0.011$, on the number of light standard neutrino flavors.

A simultaneous fit to S, T, and U, can be performed only relative to a specified M_H. If one fixes $M_H = 600$ GeV, as is appropriate in QCD-like technicolor models, one finds

$$\begin{array}{rcr} S & = & -0.27 \pm 0.12, \\ T & = & 0.00 \pm 0.15, \\ U & = & 0.19 \pm 0.21. \end{array} \tag{14}$$

Notice, that in such a fit the S parameter is significantly smaller than zero. From this an isodoublet of technifermions, assuming $N_{TC} = 4$ technicolors, is excluded by almost 6 standard deviations, and a full technigeneration by more than 15σ. However, the QCD-like models are excluded on other grounds, such as FCNC. These can be avoided in models of walking technicolor in which S can also be smaller or even negative [12].

III. EXTRA Z' BOSONS

Many GUTs and string models predict extra gauge symmetries and new exotic states. For example, $SO(10)$ GUT contains an extra $U(1)$ as can be seen from its maximal subgroup, $SU(5) \times U(1)_\chi$. The Z_χ boson is also the unique solution to the conditions of (i) no extra matter other than the right-handed neutrino, (ii) absence of gauge and mixed gauge/gravitational anomalies, and (iii) orthogonality to the hypercharge generator. Relaxing condition (iii) allows other solutions (including the Z_{LR} appearing in left-right models with $SU(2)_L \times SU(2)_R \times U(1)$ gauge symmetry) which differ from the Z_χ boson by a shift proportional to the third component of the right-handed isospin generator [13]. Equivalently, a non-vanishing kinetic mixing term [14] can also parametrize these other solutions [13].

Similarly, E_6 GUT contains the subgroup $SO(10) \times U(1)_\psi$, giving rise to another Z'. It possesses only axial-vector couplings to the ordinary fermions. As a consequence its mass, $M_{Z'_\psi}$, is generally less constrained (see Fig 1).

The Z_η boson is the linear combination $\sqrt{3/8}\, Z_\chi - \sqrt{5/8}\, Z_\psi$. It occurs in Calabi-Yau compactifications of the heterotic string if E_6 breaks directly to a rank 5 subgroup [15] via the Hosotani mechanism.

The potential Z' boson is in general a superposition of the SM Z and the new boson associated with the extra $U(1)$. The mixing angle θ satisfies the relation [16],

$$\tan^2\theta = \frac{M^2_{Z^0_1} - M^2_Z}{M^2_{Z'} - M^2_{Z^0_1}}, \tag{15}$$

where $M_{Z^0_1}$ is the SM value for M_Z in the absence of mixing. Note that $M_Z < M_{Z^0_1}$, and that the SM Z couplings are changed by the mixing. If the Higgs $U(1)'$ quantum numbers are known, as well, there will be an extra constraint,

$$\theta = C\frac{g_2}{g_1}\frac{M^2_Z}{M^2_{Z'}}, \tag{16}$$

where $g_{1,2}$ are the $U(1)$ and $U(1)'$ gauge couplings with $g_2 = \sqrt{\frac{5}{3}}\sin\theta_W\sqrt{\lambda}\, g_1$. $\lambda = 1$ (which we assume) if the GUT group breaks directly to $SU(3) \times SU(2) \times U(1) \times U(1)'$. C is a function of vacuum expectation values (VEVs). For minimal Higgs sectors it can be found in Table III of reference [17]. Fig. 1 shows allowed contours for ρ_0 free (see Section II), as well as $\rho_0 = 1$ (only Higgs doublets and singlets). Notice, that in the cases of minimal Higgs sectors the Z' mass limits are pushed into the TeV region. For more details and other examples see Ref. [13].

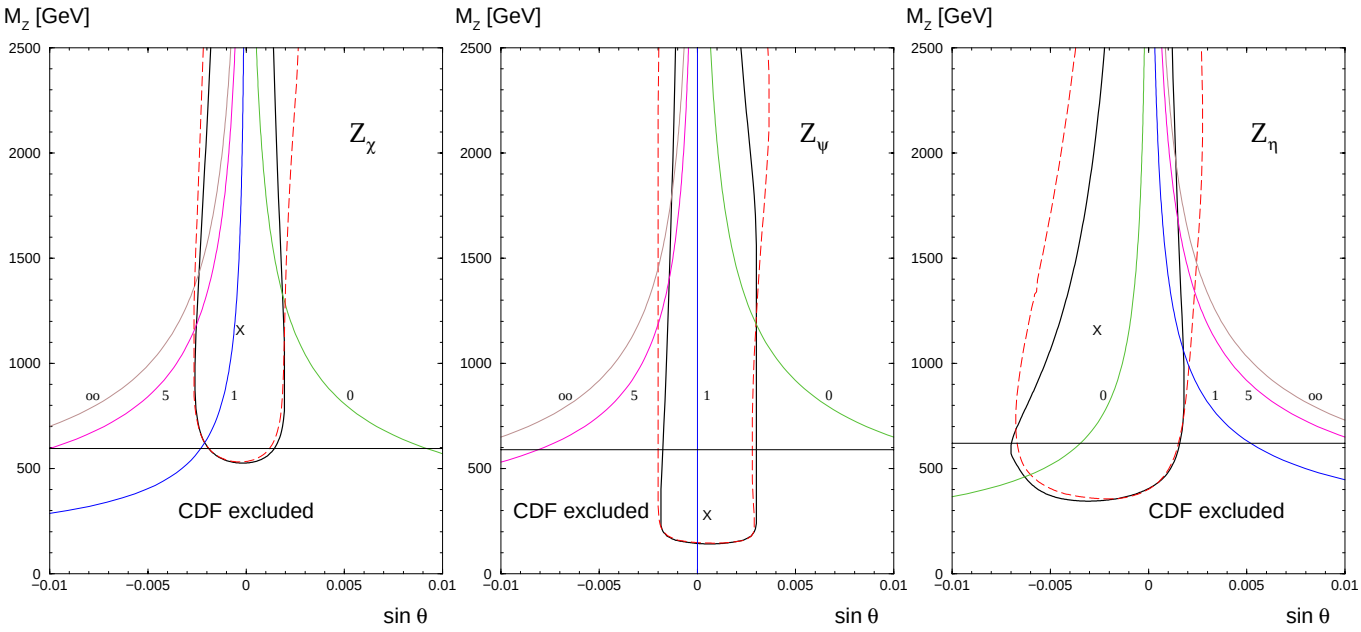

FIG. 1. 90% CL contours for different Z' models. The solid contour lines use the constraint $\rho_0 = 1$ (the cross denotes the best fit for the $\rho_0 = 1$ case) while the long-dashed lines are for arbitrary Higgs sectors. Also shown are the additional constraints in minimal Higgs scenarios for several ratios of VEVs. The lower direct production limits from CDF [18] are also shown.

IV. SUPERSYMMETRY

The good agreement between the SM predictions and the data favors those types of new physics for which contributions decouple from the precision observables. In particular, supersymmetric extensions of the SM with heavy (decoupling) superpartners are in perfect agreement with observation. Other regions of parameter space, however, where some of the supersymmetric states are relatively light are strongly constraint by the data.

In a recent analysis [19] we systematically studied these constraints within the MSSM with various assumptions about the mediation of SUSY breaking (i.e. about the soft SUSY breaking terms). In a first step, we identified the allowed region in parameter space taking into account all direct search limits on superparticles, but ignoring the additional information from the precision data. We then added the indirect constraints arising from SUSY loop contributions. We found that a significant region of MSSM parameter space has to be excluded, and that the lower limits on superparticles and extra Higgs states strengthen. See the results in Fig. II from an update of our analysis for this conference [20].

	universal				non-universal			
	$\mu < 0$		$\mu > 0$		$\mu < 0$		$\mu > 0$	
	direct	ΔM	direct	ΔM	direct	ΔM	direct	ΔM
H	100	50	105	155	90	15	94	90
h	94	0	92	0	83	0	84	0
H^+	125	40	130	140	115	15	116	90
A	100	50	105	155	84	20	86	95
$\tilde{t}_1$	295	60	310	20	149	160	302	0
$\tilde{t}_2$	52	0	57	20	52	0	57	20
$\tilde{b}_1$	190	115	255	30	190	45	245	0
$\tilde{b}_2$	245	130	315	20	135	35	175	50
$\tilde{u}_L$	280	105	320	20	255	20	320	10
$\tilde{u}_R$	275	100	310	20	230	0	275	35
$\tilde{\tau}_1$	115	15	120	5	51	30	51	15
$\tilde{\tau}_2$	53	25	56	10	51	10	56	0
$\tilde{e}_L$	115	20	120	0	82	15	69	10
$\tilde{e}_R$	80	5	80	0	68	0	76	0
$\tilde{\nu}_\tau$	83	30	85	15	45	10	43	10
$\tilde{\nu}_e$	84	30	95	5	45	30	44	10
$\tilde{\chi}_1^0$	48	0	50	0	43	5	45	5
$\tilde{\chi}_2^0$	87	5	90	0	83	5	83	5
$\tilde{\chi}_1^+$	87	5	85	0	83	5	83	5
$\tilde{\chi}_2^+$	190	0	210	0	175	15	210	0

TABLE II. Shifts (ΔM) in the lower limits of superpartners and extra Higgs states. Considered are the two cases of universal and non-universal boundary conditions within the model of supergravity mediated SUSY breaking. We separate the two cases of positive and negative sign of the supersymmetric bilinear Higgs (μ) term.

V. CONCLUSIONS

The precision data confirms the validity of the SM at the electroweak loop level, and there is presently no compelling evidence for deviations. A low Higgs mass is strongly favored by the data. While the precise range of M_H is rather sensitive to $\alpha(M_Z)$, the upper limit is not. However, in the presence of non-standard contributions to the S or T parameters, no strong M_H bounds can be found.

There are stringent constraints on parameters beyond the SM, such as S, T, U, and others. This is a serious problem for models of dynamical symmetry breaking, compositeness, and the like, and excludes a fourth generation of quarks and leptons at the 3σ level. Those constraints are, however, consistent with the MSSM, favoring its decoupling limit. Moreover, the low favored M_H is in agreement with the expected mass range for the lightest neutral Higgs boson in the MSSM. Precision tests also impose stringent limits on extra Z' bosons suggested in many GUT and string models. They limit their mixing with the ordinary Z, and put competitive lower limits on their masses, especially in concrete models in which the $U(1)'$ charges of the Higgs sector are specified.

ACKNOWLEDGEMENT

It is a pleasure to thank Paul Langacker and Damien Pierce for collaboration.

---

[1] D. Karlen, *Experimental Status of the Standard Model*, Talk presented at the XXIXth International Conference on High Energy Physics (ICHEP 98), Vancouver, Canada, July 1998;
The LEP Collaborations ALEPH, DELPHI, L3, OPAL, the LEP Electroweak Working Group, and the SLD Heavy Flavour and Electroweak Groups: D. Abbaneo *et al.*, Internal Note CERN–EP/99–15.
[2] T. Dorigo for the CDF Collaboration: *Electroweak Results from the Tevatron Collider*, Talk presented at PASCOS 98;
DØ Collaboration: B. Abbott *et al.*, *Phys. Rev. Lett.* **80**, 3008 (1998).
[3] K. Baird for the SLD Collaboration: *Measurements of A_{LR} and $A_{\rm lepton}$ from SLD*, Talk presented at ICHEP 98.
[4] J. Erler, *Phys. Rev.* **D52**, 28 (1995);
J. Erler, J.L. Feng, and N. Polonsky, *Phys. Rev. Lett.* **78**, 3063 (1997).
[5] DELPHI Collaboration: P. Abreu *et al.*, *Z. Phys.* **C70**, 531 (1996); and
G.J. Barker *et al.*, paper (#123) contributed to ICHEP 98.
[6] P. McNamara, *Standard Model Higgs at LEP*, Talk presented at ICHEP 98.
[7] M. Carena, M. Quiros, and C.E.M. Wagner, *Nucl. Phys.* **B461**, 407 (1996);
D.M. Pierce, J.A. Bagger, K. Matchev, and R.J. Zhang, *Nucl. Phys.* **B491**, 3 (1997);
H.E. Haber, R. Hempfling, and A.H. Hoang, *Z. Phys.* **C75**, 539 (1997);
M. Masip, R. Muñoz-Tapia, and A. Pomarol, *Phys. Rev.* **D57**, 5340 (1998);
S. Heinemeyer, W. Hollik, and G. Weiglein, *Phys. Rev.* **D58**, 091701 (1998) and *Phys. Lett.* **440B**, 296 (1998).
[8] S. Eidelman and F. Jegerlehner, *Z. Phys.* **C67**, 585 (1995);
H. Burkhardt and B. Pietrzyk, *Phys. Lett.* **356B**, 398 (1995);
M.L. Swartz, *Phys. Rev.* **D53**, 5268 (1996);
R. Alemany, M. Davier, and A. Höcker, *Eur. Phys. J.* **C2**, 123 (1998).
[9] A.D. Martin and D. Zeppenfeld, *Phys. Lett.* **345B**, 558 (1995);
M. Davier and A. Höcker, *Phys. Lett.* **419B**, 419 (1998);
J.H. Kühn and M. Steinhauser, *Phys. Lett.* **437B**, 425 (1998);
S. Groote, J.G. Körner, K. Schilcher, and N.F. Nasrallah, *Phys. Lett.* **440B**, 375 (1998);
J. Erler, *Phys. Rev.* **D59**, 054008 (1999).
[10] M. Veltman, *Nucl. Phys.* **B123**, 89 (1977);
M. Chanowitz, M.A. Furman, and I. Hinchliffe, *Phys. Lett.* **78B**, 285 (1978).
[11] M. Peskin and T. Takeuchi, *Phys. Rev. Lett.* **65**, 964 (1990) and *Phys. Rev.* **D46**, 381 (1992).
[12] E. Gates and J. Terning, *Phys. Rev. Lett.* **67**, 1840 (1991);
T. Appelquist and J. Terning, *Phys. Lett.* **315B**, 139 (1993);
M. Luty and R. Sundrum, *Phys. Rev. Lett.* **70**, 529 (1993);
R. Sundrum and S.D.H. Hsu, *Nucl. Phys.* **B391**, 127 (1993);
R. Sundrum, *Nucl. Phys.* **B395**, 60 (1993).
[13] J. Erler and P. Langacker, *Constraints on Extended Neutral Gauge Structures*, preprint UPR–839–T.
[14] K.S. Babu, C. Kolda, and J. March-Russell, *Phys. Rev.* **D54**, 4635 (1996) and *ibid.* **57**, 6788 (1998).
[15] E. Witten, *Nucl. Phys.* **B258**, 75 (1985).
[16] P. Langacker, *Phys. Rev.* **D30**, 2008 (1984).
[17] P. Langacker and M. Luo, *Phys. Rev.* **D45**, 278 (1992).
[18] CDF Collaboration: F. Abe *et al.*, *Phys. Rev. Lett.* **79**, 2192 (1997).
[19] J. Erler and D.M. Pierce, *Nucl. Phys.* **B526**, 53 (1998).
[20] D.M. Pierce, *Electroweak fits within the MSSM*, these Proceedings.