14. CONSTRAINTS ON NEW PHYSICS FROM ELECTROWEAK ANALYSES

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Precision electroweak experiments are sensitive to loop effects, allowing a prediction of the top quark mass m_t, constraints on the Higgs mass M_H, and a search for certain types of new physics that have not been directly detected. This article will mainly discuss m_t, M_H, and the effects of exotic particles with masses large compared to M_Z on the gauge boson self-energies. Brief remarks are made on new physics which is not of this type. The effects of m_t and M_H on the radiative corrections are treated exactly to one-loop order. This can in principle be done for other types of new physics, but this necessitates a case-by-case discussion. Instead, the article will discuss in detail only the constraints on particles with heavy masses $M_{\rm new} \gg M_Z$ in an expansion in $M_Z/M_{\rm new}$. In this case, most of the effects on precision measurements can be described by three gauge self-energy parameters S, T, and U, and a $Zb\overline{b}$ vertex correction parameter γ_b.

A large value of $|m_t - m_b|$ breaks vector SU(2) symmetry and significantly affects many precision electroweak observables. The major sensitivity for processes involving light external fermions is through t- and b-quark loop contributions to the W and Z self-energies [1]. Most of the shift in M_W is absorbed into the measured value of the Fermi constant G_F, while the prediction for M_Z,

$$M_Z = \frac{M_W}{\widehat{\rho}^{1/2}\widehat{c}_Z} \ , \tag{14.1}$$

decreases rapidly for large m_t. In Eq. (14.1) $\widehat{\rho} \simeq 1 + \rho_t$, where

$$\rho_t = \frac{3 G_F m_t^2}{8\sqrt{2}\pi^2} \sim 0.0100 \left(\frac{m_t}{180 \text{ GeV}}\right)^2 \ , \tag{14.2}$$

and $\widehat{c}_Z = \cos\widehat{\theta}_W(M_Z)$, the cosine of the weak angle in the $\overline{\rm MS}$ scheme evaluated at M_Z [2]. In addition to M_Z itself, neutral current amplitudes and the coefficient of $G_F M_Z^3$ in the expression for Γ_Z are multiplied by $\widehat{\rho}$. There is additional logarithmic m_t dependence in these quantities and in M_W. Vertex and box diagrams also introduce large (quadratic) m_t dependence, which is especially important in quantities involving external b quarks (in order to avoid mixing angle suppressions), such as in the $Z \to b\overline{b}$ partial width or in $B - \overline{B}$ mixing. Finally, in the on-shell renormalization scheme, significant but somewhat artificial m_t dependence is introduced into Z vertices through the definition [2] $s_W^2 \equiv 1 - M_W^2/M_Z^2$.

As discussed in the section on the Standard Model of Electroweak Interactions (Sec. 10) (see especially Fig. 10.1), the consistency of the various observables allows a prediction for m_t. A global fit to all indirect data (see Table 10.5 of the Standard Model Section) yields

$$m_t = 179 \pm 8^{+17}_{-20} \text{ GeV} \ , \tag{14.3}$$

where the central value is for a Higgs mass $M_H = 300$ GeV and the second uncertainty is from varying M_H in the range 60 GeV $(-)$ to 1000 GeV $(+)$. This is in remarkable agreement with the direct determination $m_t = 180 \pm 12$ GeV by the CDF [3] and DØ [4] collaborations. (The indirect prediction is for the pole mass, which corresponds approximately to the kinematic mass determined by CDF and DØ.) A combined fit to both the indirect and direct data yields [2]

$$m_t = 180 \pm 7^{+12}_{-13} \text{ GeV} . \tag{14.4}$$

As discussed in Ref. 2, the combination of indirect data with the direct CDF and DØ value for m_t allows stringent limits on new physics. In particular, many extensions of the Standard Model are described by the ρ_0 parameter:

$$\rho_0 \equiv M_W^2/(M_Z^2\, \widehat{c}_Z^{\,2}\, \widehat{\rho}) , \tag{14.5}$$

which describes new sources of SU(2) breaking that cannot be accounted for by Higgs doublets or m_t effects. It has previously been difficult to distinguish ρ_0 from $\widehat{\rho} \simeq 1 + \rho_t$ experimentally, though some separation could be done utilizing R_b [5]. Using the direct m_t value as an independent constraint, however, one can calculate $\widehat{\rho}$ and thus obtain the precise value [2] $\rho_0 = 1.0002 \pm 0.0013 \pm 0.0018$, where the second error is from M_H. In Ref. 2, this result was used to constrain the vacuum expectation values of higher-dimensional Higgs representations. It can also be used to constrain other types of new physics. For example, nondegenerate multiplets of heavy fermions or scalars break the vector part of weak SU(2) and lead to a decrease in the value of M_Z/M_W. A nondegenerate SU(2) doublet $\binom{f_1}{f_2}$ yields a positive contribution to ρ_t of [1]

$$\frac{C G_F}{8\sqrt{2}\pi^2} \Delta m^2 , \tag{14.6}$$

where

$$\Delta m^2 \equiv m_1^2 + m_2^2 - \frac{4 m_1^2 m_2^2}{m_1^2 - m_2^2} \ln \frac{m_1}{m_2} \geq (m_1 - m_2)^2 , \tag{14.7}$$

and $C = 1$ (3) for color singlets (triplets). Thus, in the presence of such multiplets, one has

$$\frac{3 G_F}{8\sqrt{2}\pi^2} \sum_i \frac{C_i}{3} \Delta m_i^2 = \rho_0 - 1 , \tag{14.8}$$

where the sum includes fourth-family quark or lepton doublets, $\binom{t'}{b'}$ or $\binom{E^0}{E^-}$, and scalar doublets such as $\binom{\tilde{t}}{\tilde{b}}$ in supersymmetry (in the absence of $L - R$ mixing). This implies

$$\sum_i \frac{C_i}{3} \Delta m_i^2 < (76 \text{ GeV})^2 , \ (98 \text{ GeV})^2 , \ (122 \text{ GeV})^2 \tag{14.9}$$

for $M_H = 60$, 300, or 1000 GeV at 90% CL.

Nondegenerate multiplets usually imply $\rho_0 > 1$. Similarly, heavy Z' bosons decrease the prediction for M_Z due to mixing and generally lead to $\rho_0 > 1$ [6]. On the other hand, additional Higgs doublets which participate in spontaneous symmetry breaking [7], heavy lepton doublets involving Majorana neutrinos [8], and the vacuum expectation values of Higgs triplets or higher-dimensional representations can contribute to ρ_0 with either sign. Allowing for the presence of heavy degenerate chiral multiplets (the S parameter, to be discussed below) affects the determination of ρ_0 from the data, at present leading to a smaller value.

As discussed in the Standard Model of Electroweak Interactions section (Sec. 10), the indirect data exhibit a moderate preference for a smaller Higgs mass. The best fit to m_t as a function of M_H is roughly

$$m_t \sim 180 \pm 7 + 13 \ \ln\left(\frac{M_H}{300 \ \text{GeV}}\right) \tag{14.10}$$

including the direct CDF/DØ constraint. The χ^2 for $M_H = 60$ GeV is lower by 7.9 than that for $M_H = 1000$ GeV, implying $M_H \lesssim 320(430)$ GeV at 90(95)% CL. This result is consistent with the minimal supersymmetric extension of the Standard Model, which acts much like the Standard Model with a light Higgs as far as precision experiments are concerned. However, the M_H constraint is largely driven by R_b and A^0_{LR}, which differ significantly from the Standard Model predictions. In particular, the conclusions for M_H could be invalidated if other new physics modifies the precision observables significantly [9–15].

A number of authors have considered the general effects on neutral current and Z and W-pole observables of various types of heavy (*i.e.*, $M \gg M_Z$) physics which contribute to the W and Z self-energies but which do not have any direct coupling to the ordinary fermions. In addition to nondegenerate multiplets, which break the vector part of weak SU(2), these include heavy degenerate multiplets of chiral fermions which break the axial generators. The effects of one degenerate chiral doublet are small, but in technicolor theories there may be many chiral doublets and therefore significant effects [9].

Such effects can be described by just three parameters, S, T, and U at the one (electroweak) loop level. (Three additional parameters are needed if the new physics scale is comparable to M_Z [16].) T is proportional to the difference between the W and Z self-energies at $Q^2 = 0$ (*i.e.*, vector SU(2)-breaking), while S ($S + U$) is associated with the difference between the Z (W) self-energy at $Q^2 = M^2_{Z,W}$ and $Q^2 = 0$ (axial SU(2)-breaking). In the $\overline{\text{MS}}$ scheme [10]

$$\alpha(M_Z)T \equiv \frac{\Pi^{\text{new}}_{WW}(0)}{M_W^2} - \frac{\Pi^{\text{new}}_{ZZ}(0)}{M_Z^2}$$

$$\frac{\alpha(M_Z)}{4\hat{s}^2_Z\hat{c}^2_Z}S \equiv \frac{\Pi^{\text{new}}_{ZZ}(M_Z^2) - \Pi^{\text{new}}_{ZZ}(0)}{M_Z^2}$$

$$\frac{\alpha(M_Z)}{4\widehat{s}_Z^2}(S+U) \equiv \frac{\Pi_{WW}^{\rm new}(M_W^2) - \Pi_{WW}^{\rm new}(0)}{M_W^2} \ , \tag{14.11}$$

where $\Pi_{WW}^{\rm new}$ and $\Pi_{ZZ}^{\rm new}$ are respectively the contributions of the new physics to the W and Z self-energies, $\widehat{s}_Z^2 = \sin^2\widehat{\theta}_W(M_Z)$, $\widehat{c}_Z^2 = 1 - \widehat{s}_Z^2$, and $\alpha(M_Z) \sim 1/129$ [2] is the running coupling evaluated at M_Z. S, T, and U are defined with a factor of α removed, so that they are expected to be of order unity in the presence of new physics. S, T, and U are related to other parameters ($\widehat{\epsilon}_i$, h_i, S_i) defined in [10–12] by

$$\begin{aligned} T &= h_V = \widehat{\epsilon}_1/\alpha \\ S &= h_{AZ} = S_Z = 4\widehat{s}_Z^2\widehat{\epsilon}_3/\alpha \\ U &= h_{AW} - h_{AZ} = S_W - S_Z = -4\widehat{s}_Z^2\widehat{\epsilon}_2/\alpha \ . \end{aligned} \tag{14.12}$$

A heavy nondegenerate multiplet of fermions or scalars contributes positively to T as

$$\rho_0 = \frac{1}{1-\alpha T} \simeq 1 + \alpha T \ , \tag{14.13}$$

where ρ_0 is given in Eq. (14.8). If there are non-doublet Higgs representations, their vacuum expectation values also contribute to ρ_0. The effects of such nonstandard Higgs representations cannot be separated from heavy nondegenerate multiplets unless the new physics has other consequences, such as vertex corrections. Most of the original papers defined T to include the effects of loops only. However, we will redefine T to include all new sources of SU(2) breaking, including nonstandard Higgs, so that T and ρ_0 are equivalent by Eq. (14.13).

A multiplet of heavy degenerate chiral fermions yields

$$S = C\sum_i \Big(t_{3L}(i) - t_{3R}(i)\Big)^2/3\pi \ , \tag{14.14}$$

where $t_{3L,R}(i)$ is the third component of weak isospin of the left- (right-) handed component of fermion i and C is the number of colors. For example, a heavy degenerate ordinary or mirror family would contribute $2/3\pi$ to S. In technicolor models with QCD-like dynamics, one expects [9] $S \sim 0.45$ for an isodoublet of technifermions, assuming N_{TC} =4 technicolors, while $S \sim 1.62$ for a full technigeneration with N_{TC} =4; T is harder to estimate because it is model dependent. In these examples one has $S \geq 0$. However, the QCD-like models are excluded on other grounds (flavor-changing neutral currents, and too-light quarks and pseudo-Goldstone bosons [17]). In particular, these estimates do not apply to models of walking technicolor [17], for which S can be smaller or even negative [18]. Other situations in which $S < 0$, such as loops involving scalars or Majorana particles, are also possible [19]. Supersymmetric extensions of the Standard Model generally give very small effects [20]. Most simple types of new physics yield U

$= 0$, although there are counter-examples, such as the effects of anomalous triple-gauge vertices [12].

It is also possible to parametrize the effects of large $m_t \gg M_Z$ (except for the $b\bar{b}$ vertex) or $M_H \gg M_Z$ in terms of S, T, and U. If one takes $m_t = m_t^{\rm ref}, M_H = M_H^{\rm ref}$ as a reference point, then other values of m_t and M_H can be expressed for large m_t, M_H as [11]

$$\begin{aligned}
\Delta T &= \frac{\rho_t(m_t) - \rho_t(m_t^{\rm ref})}{\alpha} \\
&\quad - \frac{3G_F}{4\sqrt{2}\alpha\pi^2}(M_Z^2 - M_W^2)\ln(M_H/M_H^{\rm ref}) \\
\Delta S &= c_S \ln(m_t/m_t^{\rm ref}) + \frac{1}{6\pi}\ln(M_H/M_H^{\rm ref}) \\
\Delta U &= c_U \ln(m_t/m_t^{\rm ref}) \ ,
\end{aligned} \tag{14.15}$$

where the coefficients c_S and c_U depend on the renormalization scheme. Prior to the direct obsevation of the t quark it was difficult to separate the effects of m_t and M_H from the new physics contributions to S, T, and U. Most authors therefore picked fixed arbitrary reference values for m_t and M_H, so that the values of S, T, U extracted from the data included both new physics and $\Delta S, \Delta T, \Delta U$. Now that m_t is known independently this is no longer necessary [21]. In the following, S, T, and U will represent the contributions of new physics only. The full m_t and M_H dependence of all observables will be included in the fits separately, with the uncertainties in m_t and M_H appearing as uncertainties in the extracted S, T, U.

The Standard Model expressions for observables are replaced by

$$\begin{aligned}
M_Z^2 &= M_{Z0}^2 \frac{1-\alpha T}{\rho_0} \frac{1}{1 - G_F M_{Z0}^2 S/2\sqrt{2}\pi} \\
M_W^2 &= M_{W0}^2 \frac{1}{1 - G_F M_{W0}^2 (S+U)/2\sqrt{2}\pi} \ ,
\end{aligned} \tag{14.16}$$

where M_{Z0} and M_{W0} are the Standard Model expressions (as functions of m_t and M_H) in the $\overline{\rm MS}$ scheme. Furthermore,

$$\begin{aligned}
\Gamma_Z &= \frac{\rho_0}{1-\alpha T} M_Z^3 \beta_Z \\
\Gamma_W &= M_W^3 \beta_W \\
A_i &= \frac{\rho_0}{1-\alpha T} A_{i0} \ ,
\end{aligned} \tag{14.17}$$

where β_Z and β_W are the Standard Model expressions for the reduced widths Γ_{Z0}/M_{Z0}^3 and Γ_{W0}/M_{W0}^3, M_Z and M_W are the physical masses, and A_i (A_{i0}) is a neutral current amplitude (in the Standard Model).

The $Z \to b\bar{b}$ vertex is sensitive to certain types of new physics which primarily couple to heavy families. It is useful to introduce an additional parameter γ_b by [22]

$$\Gamma(Z \to b\bar{b}) = \Gamma^0(Z \to b\bar{b})(1 + \gamma_b) \ , \tag{14.18}$$

where Γ^0 is the Standard Model expression (or the expression modified by S, T, and U). Experimentally, $R_b \equiv \Gamma(Z \to b\bar{b})/\Gamma(\text{had})$ is more than 3σ above the Standard Model expectations, favoring a positive γ_b. (See the discussion in Ref. 2.) Extended technicolor interactions generally yield negative values of γ_b of a few percent [23], although it is possible to obtain a positive γ_b in models for which the extended technicolor group does not commute with the electroweak gauge group [24] or for which diagonal interactions related to the extended technicolor dominate [25]. Topcolor and topcolor-assisted technicolor models do not generally give a significant contribution to γ_b because the extended technicolor contribution to m_t is small [26]. Supersymmetry can yield (typically small) contributions of either sign [27,28].

The data allow a simultaneous determination of $\widehat{s}^{\,2}_Z$ (*e.g.*, from the Z-pole asymmetries), S (from M_Z), U (from M_W), T (*e.g.*, from the Z-decay widths), α_s (from $\Gamma(Z \to \text{had})/\Gamma(\ell\bar{\ell})$, m_t (from CDF and DØ), and γ_b (from R_b) with little correlation except between α_s and γ_b.

$$\begin{aligned} S &= -0.28 \pm 0.19^{-0.08}_{+0.17} \\ T &= -0.20 \pm 0.26^{+0.17}_{-0.12} \\ U &= -0.31 \pm 0.54 \\ \gamma_b &= 0.032 \pm 0.010 \ , \end{aligned} \tag{14.19}$$

and $\widehat{s}^{\,2}_Z = 0.2311 \pm 0.0003$, $\alpha_s = 0.103 \pm 0.008$, $m_t = 181 \pm 12$ GeV, where the first uncertainties are from the inputs. The central values assume $M_H = 300$ GeV, and the second uncertainty, when given, is the change for $M_H = 1000$ GeV (upper) and 60 GeV (lower). S, T, and U, which are due to new physics only, are all consistent with the Standard Model value of zero at or near the 1σ level, although there is a slight tendency for negative S and T. Using Eq. (14.13) the value of ρ_0 corresponding to T is $0.9985 \pm 0.0019^{+0.0012}_{-0.0009}$. The values of the $\widehat{\epsilon}$ parameters defined in Eq. (14.12) are

$$\begin{aligned} \widehat{\epsilon}_3 &= -0.0022 \pm 0.0015^{-0.0007}_{+0.0013} \ , \\ \widehat{\epsilon}_1 &= -0.0015 \pm 0.0019^{+0.0013}_{-0.0008} \ , \\ \widehat{\epsilon}_2 &= +0.0024 \pm 0.0033 \ . \end{aligned} \tag{14.20}$$

There is a strong correlation between γ_b and the predicted α_s, just as in the model with $S = T = U = 0$ [2,21]. For $\gamma_b = 0$ one obtains $\alpha_s = 0.122 \pm 0.005$ and $T = -0.04 \pm 0.25^{+0.17}_{-0.11}$, with little change in the other parameters. The allowed region in S–T is shown in Fig. 14.1. From Eq. (14.19) one obtains $S < 0.12\,(0.21)$ and

$T < 0.29\,(0.38)$ at $90\,(95)\%$ CL. If one requires the constraint $S \geq 0$ (as in QCD-like technicolor models) then $S < 0.25\,(0.30)$. Allowing arbitrary S, only one heavy generation of ordinary fermions is allowed at 95% CL. The favored value of S is problematic for simple technicolor models with many techni-doublets and QCD-like dynamics, as is the value of γ_b. Although S is consistent with zero, the electroweak asymmetries, especially the SLD left-right asymmetry, favor $S < 0$. The simplest origin of $S < 0$ would probably be an additional heavy Z' boson [6], which could mimic $S < 0$. Similarly, there is a slight indication of negative T, while, as discussed above, nondegenerate scalar or fermion multiplets generally predict $T > 0$.

There is no simple parametrization that is powerful enough to describe the effects of every type of new physics on every possible observable. The S, T, and U formalism describes many types of heavy physics which affect only the gauge self-energies, and it can be applied to all precision observables. However, new physics which couples directly to ordinary fermions, such as heavy Z' bosons or mixing with exotic fermions cannot be fully parametrized in the S, T, and U framework. It is convenient to treat these types of new physics by parametrizations that are specialized to that particular class of theories (*e.g.*, extra Z' bosons), or to consider specific models (which might contain, *e.g.*, Z' bosons and exotic fermions with correlated parameters). Constraints on various types of new physics are reviewed in [29,30,31]. Fits to models with technicolor, extended technicolor, and supersymmetry are described respectively in [32], [24], and [33]. Versions of these which allow $\gamma_b > 0$ can, for that reason, give better fits than the Standard Model. An alternate formalism [34] defines parameters, ϵ_1, ϵ_2, ϵ_3, ϵ_b in terms of the specific observables M_W/M_Z, the leptonic Z width $\Gamma_{\ell\ell}$, the forward-backward asymmetry [2] at the Z pole $A_{FB}^{(0,\ell)}$, and R_b. The definitions coincide with those for $\widehat{\epsilon}_i$ in Eqs. (14.11) and (14.12) for physics which affects gauge self-energies only, but the ϵ's now parametrize arbitrary types of new physics and can also incorporate all of the effects of m_t and M_H on the four basic observables. However, the ϵ's are not related to other observables unless additional model-dependent assumptions are made. Another approach [35,36] parametrizes new physics in terms of gauge-invariant sets of operators. It is especially powerful in studying the effects of new physics on nonabelian gauge vertices. The most general approach introduces deviation vectors [29]. Each type of new physics defines a deviation vector, the components of which are the deviations of each observable from its Standard Model prediction, normalized to the experimental uncertainty. The length (direction) of the vector represents the strength (type) of new physics.

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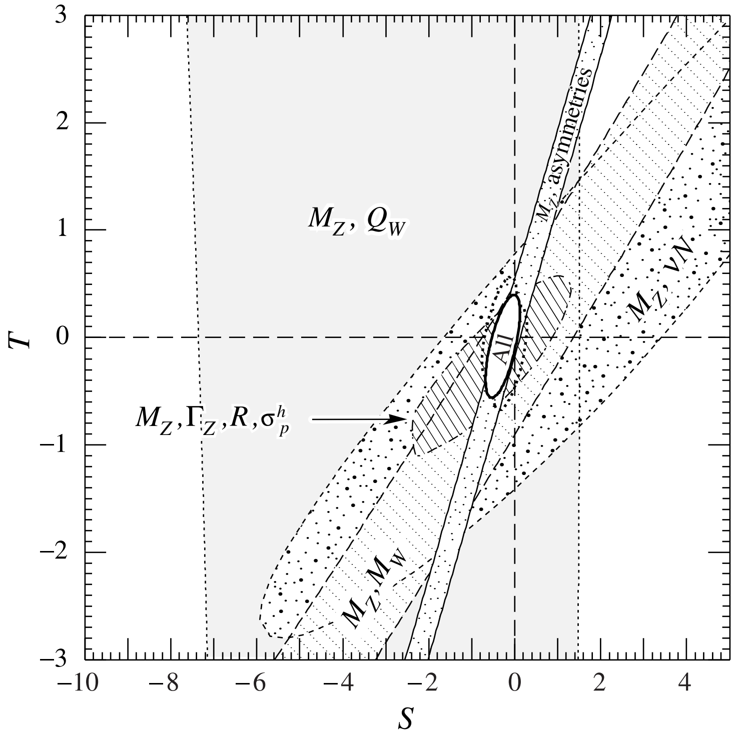

Figure 14.1: 90% CL limits on S and T from various inputs. S and T represent the contributions of new physics only: uncertainties from m_t are included in the errors. The contours assume $M_H = 300$ GeV, with the exception of the two contours for all data which are displaced slightly upward (downward), corresponding to $M_H = 1000$ (60) GeV. The fit to M_W and M_Z assumes $U = 0$, while U is arbitrary in the other fits.

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