

Electroweak Physics and Precision Studies

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Electroweak Physics: Precision Studies *

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The utility of precision electroweak measurements for predicting the Standard Model Higgs mass via quantum loop effects is discussed. Current values of m_W , $\sin^2 \theta_W(m_Z)_{\overline{MS}}$ and m_t imply a relatively light Higgs which is below the direct experimental bound but possibly consistent with Supersymmetry expectations. The existence of Supersymmetry is further suggested by a 2σ discrepancy between experiment and theory for the muon anomalous magnetic moment. Constraints from precision studies on other types of “New Physics” are also briefly described.

The Standard $SU(3)_C \times SU(2)_L \times U(1)_Y$ Model of strong and electroweak interactions has been enormously successful. Based on the principle of local gauge invariance, it follows the modern approach to elementary particle physics in which “Symmetry Dictates Dynamics”. Amazingly, the $SU(3)_C$ symmetry of Quantum Chromodynamics (QCD) describes all of strong interaction physics via simple quark-gluon interactions. On its own, QCD has no free parameters [1]. However, if a unit of mass is introduced via electroweak physics, then the QCD coupling becomes its single parameter and is found to be (at scale $m_Z = 91.1875$ GeV) [2]

$$\alpha_s(m_Z) \equiv \frac{g_s^2(m_Z)}{4\pi} = 0.118(2) \quad \overline{MS} \text{ definition} \quad (1)$$

The $SU(2)_L \times U(1)_Y$ sector is much more arbitrary [3]. Depending on ones counting, it has at least 24 independent parameters. They include: 2 bare gauge couplings g_{2_0} and g_{1_0} (usually traded in for $\tan \theta_W^0 = \sqrt{3/5} g_{1_0}/g_{2_0}$ and $e_0 = g_{2_0} \sin \theta_W^0$), 2 Higgs potential parameters λ_0 (the self coupling) and v_0 (vacuum expectation value) and 36 complex Yukawa couplings connecting the Higgs doublet and 3 generations of quarks and leptons. Of the 72 Yukawa coupling (real) parameters, only 20 are observable as quark and lepton masses and mixing (phase) angles. Other possibilities include $\bar{\theta}$ (a QCD enhanced CP violating parameter), 2 relative phases in the case of Majorana neutrinos, and right-handed neutrino mass scales if a see-saw mechanism for neutrino masses is adhered to.

A goal of particle physics is to measure the electroweak parameters as precisely as possible while at the same time trying to directly uncover new physics or deeper insights [1]. Theoretical studies aim to refine or better understand Standard Model predictions while also exploring ideas for physics beyond the Standard Model. The latter include additional symmetries such as grand unification, supersymmetry, extra dimensions etc. Ultimately, one aims for a parameter free description of Nature, a noble but difficult goal.

Tests of the Standard Model have been extremely successful. They entail 25 years of discovery and precision measurements. Collectively, they have uncovered all Standard Model gauge bosons and 3 generations of fermions. In addition, measurements at the $\pm 0.1\%$ or better level have tested quantum loop effects. What remains elusive is the so-called Higgs scalar particle, H , a remnant of the fundamental Higgs mechanism responsible for electroweak mass generation.

It has been known for some time that Standard Model quantum loops exhibit a small but important dependence on the Higgs mass, m_H [4, 5]. As a result, the value of m_H can, in principle, be predicted by comparing a variety of precision electroweak measurements with one another. Toward that end, recent global fits to *all* precision electroweak data (see J. Erler and P. Langacker [6]) give

$$m_H = 113_{-40}^{+56} \text{ GeV} \quad (2)$$

* Invited Talk at PANIC 05

$$m_H < 241 \text{ GeV} \quad (95\% \text{ CL}) \quad (3)$$

Those constraints are very consistent with bounds [2] from direct searches for the Higgs boson at LEP II via $e^+e^- \rightarrow ZH$

$$m_H > 114.4 \text{ GeV} \quad (4)$$

Together, they seem to suggest the range $114 \text{ GeV} < m_H < 241 \text{ GeV}$, and imply very good consistency between the minimal Standard Model theory and experiment.

Global fits [7] are very useful, when many different measurements of similar precision are included. However, sometimes it is instructive to be subjective, particularly with regard to systematic errors including theory uncertainties. Global fits, if blindly accepted, may be washing out interesting aspects of the data. We have a subset of very clean precise measurements that can on their own overconstrain the Standard Model and be used to predict the Higgs mass and/or search for “New Physics”. Concentrating on those measurements instead of the global fit allows for a more transparent discussion of the m_H sensitivity. It also suggests, as we shall see, a lighter Higgs and possibly the advent of supersymmetry (if you stretch your imagination). Alternatively, they may be indicating new strong dynamics if the very precise leptonic $\sin^2 \theta_W(m_Z)_{\overline{MS}}^{\text{leptonic}}$ is incorrect.

Sometimes, due to a symmetry, two parameters are related at the bare level, such that the same relationship is maintained at the renormalized level, up to finite calculable radiative corrections. When that is the case, the relationship is called natural. Let me give a few simple examples.

i) Electron-Muon-Tau Universality: All lepton doublets have the same $SU(2)_L$ coupling, g_{2_0} , due to local $SU(2)_L$ gauge invariance. Therefore, all $W\ell\nu$ renormalized couplings differ from g_{2_0} by the same infinite renormalization [8]. Hence, ratios such as $\Gamma(W \rightarrow e\nu)/\Gamma(W \rightarrow \mu\nu)$ etc. are finite and calculable to all orders in perturbation theory. Such relations have been well confirmed with high precision (better than $\pm 0.1\%$) in many weak decays of the W^\pm , τ^\pm , π^\pm etc.

ii) CKM Unitarity: Unitarity among CKM quark mixing parameters requires $\sum_k V_{ik}^0 V_{jk}^{0*} = \delta_{ij}$ for the bare matrix elements. So, for example, the first row should satisfy

$$|V_{ud}^0|^2 + |V_{us}^0|^2 + |V_{ub}^0|^2 = 1 \quad (5)$$

After applying renormalizations that preserve unitarity, one finds at present good confirmation [9]

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9992(10) \quad (6)$$

Natural relations among bare parameters is clearly a powerful constraint, particularly when the quantities involved appear to be so different. In the Standard Model, there is a custodial global $SU(2)_V$ isospin like symmetry that is preserved by the simple Higgs doublet symmetry breaking mechanism. It gives rise to the natural relationships [18]

$$\frac{e_0^2}{g_{2_0}^2} = 1 - (m_W^0/m_Z^0)^2 = \sin^2 \theta_W^0 \quad (7)$$

Eq. (7) is quite amazing. It relates gauge boson masses, couplings and the weak mixing angle. Each of the 3 quantities in eq. (7) exhibit the same ultraviolet divergencies. However, they have different finite radiative corrections [4]. Those finite part differences are sensitive to fermion loop effects, m_t , m_H and potential new physics effects via loop or tree level effects.

Using the bare Fermi constant

$$G_\mu^0 = \frac{g_{2_0}^2}{4\sqrt{2}m_W^0} \quad (8)$$

one can recast eq. (7) into the forms

$$\begin{aligned} G_\mu^0 &= \frac{\pi\alpha_0}{\sqrt{2}m_W^0(1-m_W^0/m_Z^0)} = \frac{\pi\alpha_0}{\sqrt{2}m_W^0\sin^2\theta_W^0} \\ &= \frac{2\sqrt{2}\pi\alpha_0}{m_Z^0\sin^2 2\theta_W^0} \end{aligned} \quad (9)$$

Those same relations hold among renormalized parameters, up to finite calculable corrections. Of course, the actual finite corrections will depend on the exact definitions of renormalized parameters employed. So, for example, one expects [11]

$$G_\mu(1-\Delta r) = \frac{\pi\alpha}{\sqrt{2}m_W^2(1-m_W^2/m_Z^2)} \quad (10)$$

where Δr represents finite radiative corrections. Similarly, one finds [3]

$$G_\mu(1-\Delta\hat{r}) = \frac{2\sqrt{2}\pi\alpha}{m_Z^2\sin^2 2\theta_W(m_Z)_{\overline{MS}}} \quad (11)$$

$$G_\mu(1-\Delta r_{\overline{MS}}) = \frac{\pi\alpha}{\sqrt{2}m_W^2\sin^2\theta_W(m_Z)_{\overline{MS}}} \quad (12)$$

where $\Delta\hat{r}$ and $\Delta r_{\overline{MS}}$ represent distinct finite radiative corrections with different sensitivities to m_H and New Physics.

What types of radiative corrections have been absorbed into G_μ ? There are many vertex, self-energy and box diagrams that are effectively in G_μ . However, the most interesting are those that contribute to the W propagator self-energy that go into the W boson mass and wavefunction renormalization. Included in that category are 1) a top-bottom loop [11, 12], 2) a Higgs loop contribution to the W self-energy [4] and 3) Potential New Physics loops from, for example, as yet unknown, very heavy fermion loops [13].

The loop information in G_μ can be exposed by comparing it with α , m_Z , m_W and $\sin^2\theta_W(m_Z)_{\overline{MS}}$ via the natural relations in eqs. (10)–(12). It is embodied in the radiative corrections. So, for example Δr obtained by comparing α , G_μ , m_Z and m_W will depend on m_t , m_H and any heavy new particle contributions to W propagator loops. The usual approach in that comparison is to start by ignoring the possibility of New Physics and use Δr to extract information regarding m_t and m_H . However, now that m_t is fairly well determined from direct measurements (following Run II Tevatron results) [2]

$$m_t = 172.7 \pm 2.9 \text{ GeV} \quad (13)$$

one can use Δr to focus on m_H alone.

A number of precision electroweak measurements have reached the $\pm 0.1\%$ level or better. In table I, I summarize some of those quantities

TABLE I: Values of some precisely determined electroweak parameters

$$\begin{aligned}
\alpha^{-1} &= 137.03599890(50) \\
G_\mu &= 1.16637(1) \times 10^{-5} \text{ GeV}^{-2} \\
m_Z &= 91.1875(21) \text{ GeV} \\
m_W &= 80.426(34) \text{ GeV} \\
\sin^2 \theta_W(m_Z)_{\overline{MS}}^{\text{leptonic}} &= 0.23085(21) \\
\sin^2 \theta_W(m_Z)_{\overline{MS}}^{\text{hadronic}} &= 0.2320(3) \\
\Gamma_Z &= 2.4952(23) \text{ GeV} \\
\Gamma(Z \rightarrow \ell^+ \ell^-) &= 83.984(86) \text{ MeV} \\
\Gamma(Z \rightarrow \text{invisible}) &= 499.0(1.5) \text{ MeV}
\end{aligned}$$

Because the electroweak corrections to those quantities have been computed and are connected by natural relations, they provide powerful constraints on m_H and New Physics effects. Although I will not discuss the Z width properties, they are competitive with the other measurements in table I when it comes to certain types of New Physics. Note also, the leptonic and hadronic weak mixing angles disagree. I will refrain from averaging them, since they individually imply very different physics.

One of the original utilizations of radiative corrections and precision measurements was to bound the top quark mass before the top quark discovery [7]. Those studies gave the bound $m_t < 200$ GeV and favored a value around 165 GeV. Later, the top quark was discovered at Fermilab and its mass settled down at 174.3 ± 5.1 GeV. Then it moved up to ~ 178 GeV, followed by the decrease reflected in eq. (13). That reduction has extremely important implications.

The natural relations among the quantities in table I are very sensitive to m_t and some types of new physics. They are much less dependent on m_H . For example, the Δr in eq. (10) has the following m_t and m_H dependence [11]

$$\begin{aligned}
\Delta r \simeq \frac{\alpha}{\pi s^2} \left\{ -\frac{3}{16} \frac{m_t^2}{m_W^2} \frac{c^2}{s^2} + \frac{11}{48} \ell n \frac{m_H^2}{m_Z^2} \right\} + 0.070 + 2\text{loops} \\
s^2 = \sin^2 \theta_W \quad , \quad c^2 = \cos^2 \theta_W
\end{aligned} \tag{14}$$

Similar types of corrections occur for $\Delta \hat{r}$ (see eq. (11))

although it is somewhat less sensitive to m_t and m_H . On the other hand, the radiative correction derived from eq. (12)

$$\Delta r_{\overline{MS}} = 1 - \frac{\pi \alpha}{\sqrt{2} m_W^2 G_\mu \sin^2 \theta_W(m_Z)_{\overline{MS}}} \tag{15}$$

includes almost no dependence on m_t or m_H . For that reason, $\Delta r_{\overline{MS}}$ provides a consistency check on the Standard Model and a more direct probe for new physics. It is predicted to be

$$\Delta r_{\overline{MS}} = 0.0695(5) \tag{16}$$

where the uncertainty corresponds to a generous range in m_t and m_H .

If eq. (15) is found to disagree with eq. (16), it would indicate new physics or a mistake in the input.

Let me check the consistency of m_W and $\sin^2 \theta_W(m_Z)_{\overline{MS}}^{\text{leptonic}}$ in table I. Inserting those values in eq. (15) gives

$$\Delta r_{\overline{MS}} = 0.0692(11) \quad \text{for} \quad \sin^2 \theta_W(m_Z)_{\overline{MS}}^{\text{leptonic}} = 0.23085(21) \tag{17}$$

which is in very good accord with eq. (16). On the other hand, employing $\sin^2 \theta_W(m_Z)_{\overline{MS}}^{\text{hadronic}} = 0.2320(3)$ in that relation leads to

$$\Delta r_{\overline{MS}} = 0.0738(14) \text{ for } \sin^2 \theta_W^{\text{hadronic}} = 0.2320(3) \quad (18)$$

which is inconsistent with eq. (16) at about the 3σ level. That discrepancy illustrates why I often reject $\sin^2 \theta_W(m_Z)_{\overline{MS}}^{\text{hadronic}}$ for being inconsistent with m_W in the Standard Model. They can be rendered consistent only if new physics is introduced.

A convenient set of formulas that nicely illustrate the relationship between m_W and $\sin^2 \theta_W(m_Z)_{\overline{MS}}$ and various input parameters (to one and partial two loop order) [14, 15]. Normalized to my input implies

$$m_W/(\text{GeV}) = 80.366 - 0.50 \left(\frac{\Delta\alpha_h^{(5)}}{0.02767} - 1 \right) + 0.53 \left[\left(\frac{m_t}{172.7 \text{ GeV}} \right)^2 - 1 \right] - 0.055 \ln(m_H/100 \text{ GeV}) - 0.0090 \ln^2(m_H/100 \text{ GeV}) \quad (19)$$

$$\sin^2 \theta_W(m_Z)_{\overline{MS}} = 0.23117 + 0.0097 \left(\frac{\Delta\alpha_h^{(5)}}{0.02767} - 1 \right) - 0.00277 \left[\left(\frac{m_t}{172.7 \text{ GeV}} \right)^2 - 1 \right] + 0.00048 \ln(m_H/100 \text{ GeV}) + 0.000034 \ln^2(m_H/100 \text{ GeV}) \quad (20)$$

where $\Delta\alpha_h^{(5)}$ represents hadronic vacuum polarization corrections to α . Those formulas can be inverted to predict m_H for a given m_W or $\sin^2 \theta_W(m_Z)_{\overline{MS}}$.

Employing the formulas in eqs. (19) and (20) along with the range of m_t in eq. (13), one finds the Higgs mass predictions

$$m_W = 80.426(34) \text{ GeV} \rightarrow m_H = 24_{-19}^{+42} \text{ GeV}, \quad < 108 \text{ GeV (95\% CL)} \quad (21)$$

$$\sin^2 \theta_W(m_Z)_{\overline{MS}}^{\text{leptonic}} = 0.23085(21) \rightarrow m_H = 50_{-23}^{+34} \text{ GeV}, \quad < 118 \text{ GeV (95\% CL)} \quad (22)$$

Those constraints are very consistent with one another. Taken literally, they are near or below the experimental bound in eq. (4) and seem to rule out the Standard Model.

Such a low Higgs mass may be very suggestive of supersymmetric models in which one expects $m_H \lesssim 135$ GeV for the lightest supersymmetric scalar.

If one employs $\sin^2 \theta_W(m_Z)_{\overline{MS}}^{\text{hadronic}} = 0.2320(3)$ alone, it leads to $m_H \simeq 480_{-230}^{+350}$ GeV, which is inconsistent with eqs. (21) and (22). That result illustrates an interesting feature. Because there is only a logarithmic sensitivity to m_H , the uncertainty in m_H scales with its central value. Because the central values in eqs. (21) and (22) are small, the errors are also small. If the central value of m_H were much larger, the errors would scale up and we would likely conclude that there was not much of a constraint on m_H .

So, it seems that m_W and $\sin^2 \theta_W(m_Z)_{\overline{MS}}^{\text{leptonic}}$ are very consistent with one another and both are indicating a very light Higgs scalar. If on the other hand $\sin^2 \theta_W(m_Z)_{\overline{MS}}^{\text{hadronic}}$ is correct, it suggests a heavy Higgs and New Physics.

If new physics in the form of heavy fermion loops contribute to gauge boson self-energies, they will manifest themselves in the natural relations via Δr , $\Delta \hat{r}$ and $\Delta r_{\overline{MS}}$. A nice parametrization of such effects has been given by Peskin and Takeuchi [13] in terms of an isospin conserving quantity, S , and isospin violating parameter T . Full discussions of the sensitivity to S and T via precision measurements are given in ref. [16]. Here, I will mainly comment on S .

Bounds on S and T have been given using global fits to all electroweak data. One such recent fit gives [16]

$$\begin{aligned} S &\simeq -0.1 \pm 0.1 \\ T &\simeq -0.1 \pm 0.1 \end{aligned} \quad (23)$$

which are consistent with zero and imply no evidence for new physics. (In the Standard Model, one expects $S = T = 0$, modulo the m_H uncertainty.) A simple way to constrain S comes from a comparison of m_W and $\sin^2 \theta_W(m_Z)_{\overline{MS}}$. In fact, there is a very nice, but little known formula [16]

$$S \simeq 118 \left[2 \frac{m_W - 80.366 \text{ GeV}}{80.366 \text{ GeV}} + \frac{\sin^2 \theta_W(m_Z)_{\overline{MS}} - 0.23117}{0.23117} \right] \quad (24)$$

Using the values of m_W and $\sin^2 \theta_W(m_Z)_{\overline{MS}}^{\text{leptonic}}$ in table I gives

$$S = +0.01 \pm 0.1 \pm 0.1 \quad (25)$$

which is nearly as constraining as eq. (23), but more transparent in its origin.

The constraint in eq. (23) or (25) can be used to rule out or limit various new physics scenarios. Each new heavy chiral fermion doublet contributes [13, 17] $+1/6\pi$ to S . A full 4th generation of quarks and leptons (4 doublets) should contribute $+0.21$ to S and that seems to be ruled out or at least unlikely. It also strongly disfavors dynamical symmetry breaking models which generally have many heavy fermion doublets and tend to give $S \simeq \mathcal{O}(1)$. In fact, the constraint on S is rather devastating for most New Physics scenarios, with the exception of supersymmetry or other symmetry constrained theories where one expects $S \simeq 0$.

If instead of $\sin^2 \theta_W(m_Z)_{\overline{MS}}^{\text{leptonic}}$, we compare $\sin^2 \theta_W(m_Z)_{\overline{MS}}^{\text{hadronic}} = 0.2320(3)$ with m_W , then we find from eq. (23) $S \simeq 0.50 \pm 0.18$. At face value, that would seem to suggest the appearance of New Physics in S at the 3 sigma level.

Clearly, it would be very nice to reduce further the uncertainties in m_W and $\sin^2 \theta_W(m_Z)_{\overline{MS}}$ as a means of pinpointing m_H and determining S more precisely. Toward that end, a giga Z factory ($\gtrsim 10^9 Z$ bosons) with polarized e^+ and e^- beams could potentially measure $\sin^2 \theta_W(m_Z)_{\overline{MS}}^{\text{leptonic}}$ to an incredible $\pm 0.00002!$ Also, running near the W^+W^- threshold, it could determine m_W to about ± 0.006 GeV. At those levels, $\Delta m_H/m_H$ could be predicted to $\pm 5\%$ or S constrained to ± 0.02 . Such advances would be spectacular probes of the Standard Model and beyond.

Currently, there is also a discrepancy between the experimental and Standard Model (SM) values of the muon anomalous magnetic moment, a_μ . That difference could be an experimental issue, an incorrect evaluation of hadronic loops or New Physics.

The E821 experiment at Brookhaven has completed its measurements of $a_{\mu^+}^{\text{exp}}$ and $a_{\mu^-}^{\text{exp}}$. They are consistent with one another and average to [18]

$$a_\mu^{\text{exp}} = 11659208(6) \times 10^{-10}, \quad (26)$$

about a factor of 14 improvement over the classic CERN experiments of the 1970s. A new upgraded version of that experiment E969 has been approved, but requires funding. It would reduce the error in eq. (26) by a factor of 2.5, to about $\pm 25 \times 10^{-11}$. As we shall see, there are strong reasons to push for such improvement.

To utilize the result in eq. (26) requires a Standard Model calculation of comparable precision. That theory prediction is generally divided into 3 parts

$$a_\mu^{\text{SM}} = a_\mu^{\text{QED}} + a_\mu^{\text{EW}} + a_\mu^{\text{Hadronic}} \quad (27)$$

Recent updates [19] give

$$\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = 251(93) \times 10^{-11} \quad (28)$$

It is anticipated [19] that improved measurements of $e^+e^- \rightarrow \text{hadrons} + \gamma$ at KLOE and BaBar will (relatively soon) reduce the error in a_μ^{SM} by about a factor of 2. More problematic than the error in Eq. (28) at this time is a

discrepancy between $e^+e^- \rightarrow$ hadrons in the $I = 1$ channel and $\tau \rightarrow \nu_\tau +$ hadrons data, even after isospin violating corrections are taken into account. Indeed, using $\tau^- \rightarrow \nu_\tau \pi^- \pi^0$ data [19] around (and above) the rho resonance in the hadronic vacuum polarization dispersion relation increases a_μ^{Hadronic} by about $+137 \times 10^{-11}$. Such a shift would reduce the a_μ discrepancy to a not so interesting 1.3 sigma effect

$$a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = 114(89) \times 10^{-11} \quad (\tau^- \rightarrow \nu_\tau \pi^- \pi^0 \text{ data}) \quad (29)$$

The leading ‘‘New Physics’’ explanation for the discrepancy in Eq. (28) is supersymmetry [20–22]. It enters at the one loop level via charginos, sneutrinos, neutralinos and sleptons. The exact prediction is of course model dependent. One can get a good feel for a_μ^{SUSY} by taking all SUSY loop masses to be degenerate and given by m_{SUSY} . In that way [22], one finds to leading order in large $\tan\beta$ (including 2 loop leading QED log corrections) [23]

$$a_\mu^{\text{SUSY}} \simeq (\text{sign}\mu) \times 130 \times 10^{-11} \tan\beta \left(\frac{100 \text{ GeV}}{m_{\text{SUSY}}} \right)^2 \quad (30)$$

where $\text{sign}\mu = +$ or $-$ (depending on the sign of the 2 Higgs mixing term in the Lagrangian) and

$$\tan\beta = \frac{\langle\phi_2\rangle}{\langle\phi_1\rangle} = \frac{v_2}{v_1} \quad (31)$$

is the ratio of Higgs doublet vacuum expectation values.

A significant development, over the last 20 years, has been a change in the mindset $\tan\beta \simeq 1$ to the more likely higher values

$$\tan\beta \simeq 3 - 40 \quad (32)$$

which would imply an enhancement of a_μ^{SUSY} .

Equating Eqs. (28) and (30) leads to the constraint

$$\text{sign}\mu = + \quad (33)$$

$$m_{\text{SUSY}} \simeq 72\sqrt{\tan\beta} \text{ GeV} \quad (34)$$

Those generic implications are very powerful. The first one eliminates about half of all SUSY models (those with $\text{sign}\mu = -$) and is consistent with $b \rightarrow s\gamma$ results. The second (rough) constraint in Eq. (34) suggests $m_{\text{SUSY}} \simeq 100\text{--}500$ GeV, just where many advocates expect it.

If Δa_μ is suggestive of SUSY, it would join other potential early signs of supersymmetry: 1) SUSY GUT Unification, 2) Precision measurements that suggest a relatively light Higgs and 3) Dark Matter. Interestingly, $\text{sign}\mu = +$ makes it more likely that underground detectors will be able to detect dark matter recoil signals, an exciting possibility.

The Z pole measurements at LEP and the SLC set a high standard for precision, attaining $\pm 0.1\%$ (or better) determinations of many electroweak quantities. A similar level of precision has also been achieved in low energy charged current interaction studies: $\mu, \tau, \pi, \beta \dots$ decays. In the case of weak neutral current studies at $q^2 \ll m_Z^2$, experiments have been less precise, only achieving about $\pm 0.5 - 1\%$ accuracy, but have nevertheless played an extremely important role in testing the structure of the Standard Model and probing for new physics. An early example is the famous SLAC polarized eD experiment [24] that measured A_{LR} and established the correctness of the Standard Model’s weak neutral current. That experiment set a historical milestone and provided a relatively precise (for its day) measurement of $\sin^2\theta_W$.

Atomic parity violation (APV) experiments started out missing the predicted Standard Model effects. Those efforts rebounded with some beautiful measurements, achieving $\pm 0.5\%$ precision in C_s studies [25]. That level of accuracy

has played a significant role in ruling out new physics scenarios, via the S parameter [16]. In addition, APV is very sensitive to Z' bosons [16], leptoquarks, extra dimensions etc.

More recently, deep-inelastic $\nu_\mu N$ -scattering has caused some fuss. By measuring $R_\nu \equiv \sigma(\nu_\mu N \rightarrow \nu_\mu X)/\sigma(\nu_\mu N \rightarrow \mu^- X)$ and $R_{\bar{\nu}}$, the NuTeV collaboration [26] at Fermilab found a 3 sigma deviation from Standard Model expectations. That anomaly has called into question aspects of $s\bar{s}$ and isospin asymmetries in quark distributions and the application of radiative corrections [27] to the data. An alternate explanation could be a very heavy Higgs mass loop effects, but that interpretation conflicts with m_W and leptonic Z pole asymmetry results. It will be interesting to see how this deviation ultimately plays out.

I. OUTLOOK AND CONCLUSION

The recent update of m_t to ~ 173 GeV renders the values of m_W and $\sin^2 \theta_W(m_Z)_{\text{leptonic}}^{\frac{1}{MS}}$ very consistent within the Standard Model framework and together they imply a very light Higgs. That constraint indirectly suggests supersymmetry may be real and will soon be uncovered at the LHC. The discrepancy in $a_\mu^{\text{exp}} - a_\mu^{\text{SM}}$ can also be interpreted as a hint of supersymmetry.

Alternatively, $\sin^2 \theta_W(m_Z)_{\text{hadronic}}^{\frac{1}{MS}} \simeq 0.2320$ as suggested by $Z \rightarrow b\bar{b}$ at LEP may be closer to the truth. If so, it could be pointing toward a heavy Higgs or new physics such as S>O as in dynamical symmetry breaking scenarios. If that is the case, it would be an illustration of global fits washing out an interesting effect.

High precision low energy experiments such as atomic parity violation, neutrino scattering and polarized electron scattering also have a complementary role to play in constraining New Physics effects. However, it will be extremely difficult to push the current $\pm 1\%$ uncertainty to $\pm 0.1\%$, a challenging but appropriate long term goal.

Of course, high precision studies are only part of our future agenda. Thorough exploration of neutrino oscillations, including CP violation, search for edms and charged lepton flavor violation e.g. $\mu \rightarrow e\gamma$, $\mu^- N \rightarrow e^- N$, high energy collider probes and many other experiments will round out a progressive program of future discovery.

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