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ABSTRACT

Several pursuits of "New Physics" via precision measurements are surveyed. The inconsistency between tau lifetime-mass values and measured leptonic branching ratios is updated and a heavy fourth generation neutrino solution is described. Constraints on the Peskin-Takeuchi S and T parameters are given. Consequences of low energy supersymmetry for grand unified theories are summarized.

The Fermi Constant, G_μ, defined via the muon lifetime

$$\begin{aligned} \tau_\mu^{-1} &= \frac{G_\mu^2 m_\mu^5}{192\pi^3} f\left(\frac{m_e^2}{m_\mu^2}\right)\left(1+\frac{3}{5}\frac{m_\mu^2}{m_W^2}\right)\left[1+\frac{\alpha\,(m_\mu)}{2\pi}\left(\frac{25}{4}-\pi^2\right)\right] \\ f\,(X) &= 1-8X+8X^3-X^4-12X^2\ell nX \\ \alpha^{-1}\,(m_\mu) &\simeq 136 \end{aligned} \tag{1}$$

is precisely determined from experiment

$$G_\mu = 1.16637 \pm 0.00002 \times 10^{-5}\ \text{GeV}^{-2} \tag{2}$$

and thus convenient for normalizing other weak-interaction processes.[1] Except for the classic long-distance QED corrections[2] factored out in (1), all other electroweak radiative corrections to muon decay are absorbed into G_μ. The most interesting such effect is the top-bottom loop correction to the W boson propagator. When weak neutral current rates are normalized in terms of G_μ, that contribution comes back via $\rho_{NC} G_\mu$ where

$$\rho_{NC} \simeq 1 + \frac{3\alpha}{16\pi \sin^2\theta_W}\frac{m_t^2}{m_W^2} \tag{3}$$

That important rho parameter (Veltman factor[3]) is the source of all top quark mass sensitivity at LEP.

In the case of other charged current amplitudes, their m_t dependence is generally the same as in muon decay; so, they have no m_t sensitivity when normalized via G_μ. Instead, one obtains very precise predictions that can be used to test the standard model. A nice example is the leptonic decay width of the tau[4](for $\ell = e$ or μ)

$$\Gamma(\tau \to \ell\nu\overline{\nu}) = \frac{G_\mu^2 m_\tau^5}{192\pi^3} f\left(\frac{m_\ell^2}{m_\tau^2}\right)\left(1+\frac{3}{5}\frac{m_\tau^2}{m_W^2}\right)\left(1+\frac{\alpha(m_\tau)}{2\pi}\left(\frac{25}{4}-\pi^2\right)\right) \tag{4}$$
$$\alpha^{-1}(m_\tau) \simeq 133.3$$

Using that formula, along with the particle data table mass

$$m_\tau = 1784.1^{+2.7}_{-3.6} \text{ MeV} \tag{5}$$

implies

$$\Gamma(\tau \to e\nu\overline{\nu}) = 1.028\Gamma(\tau \to \mu\nu\overline{\nu}) = 4.114^{+0.031}_{-0.041} \times 10^{-13} \text{ GeV} \tag{6}$$

where the error is entirely due to the uncertainty in m_τ. Combining that prediction with the measured total decay rate[5]

$$\Gamma(\tau \to \text{ all}) = 2.165 \pm 0.050 \times 10^{-12} \text{ GeV} \tag{7}$$

obtained from the lifetime average $\tau_{tau} = 3.04 \pm 0.07 \times 10^{-13} s$ leads to the leptonic branching ratio

$$BR(\tau \to e\nu\overline{\nu})^{expected} = 0.1900 \pm 0.0044^{+0.0014}_{-0.0019} \tag{8}$$

where the first error comes from τ_{tau} and the second from m_τ. That prediction is to be compared with the world average (from e and μ data)[5]

$$BR(\tau \to e\nu\overline{\nu})_{ave} = 0.1780 \pm 0.0017 \tag{9}$$

There is a 2.4 σ discrepancy between (8) and (9) which may be due to: 1) An incorrect lifetime and/or mass used to obtain (8). Lifetime measurements do often settle down to smaller values as they improve. In the case of the mass, only one precision measurement (by the DELCO collaboration[6]) was ever carried out. To bring (8) into accord with (9) would require a 6% reduction of τ_{tau} to about 2.85 ps or a reduction in m_τ by 23 MeV or some combined movement in both quantities. Clearly, new high precision measurements of τ_{tau} and m_τ are warranted. 2) A second possibility is that the world average $BR(\tau \to e\nu\overline{\nu})$ in (9) is wrong. Indeed, the CLEO collaboration recently reported[7] a value of $0.190 \pm 0.004 \pm 0.007$ which is in excellent agreement with (8). However, new measurements at LEP[5] confirm the smaller values in (9) and it is difficult to see how a mistake could occur in their very clean tau data. 3) A "New Physics" explanation[8] of the above requires introducing a heavy fourth generation neutrino with $m_{\nu_4} \gtrsim 45$ GeV (LEP constraint) and $\sin^2\theta_{34} \simeq 0.06$. That mixing would reduce the prediction in (4) by $\cos^2\theta_{34} \simeq 0.94$ and bring (8) into accord with (9). It is interesting that such a neutrino would not have shown up in any other experiments if one assumes negligible mixing with the first and second generations.

On the theoretical side, QCD perturbation theory can be used to predict[9]

$$R_H \equiv \frac{\Gamma(\tau \to \nu_\tau + \text{hadrons})}{\Gamma(\tau \to e\nu\overline{\nu})} \tag{10}$$

Including electroweak radiative corrections[4] and small non-perturbative effects[9,10]

$$\begin{aligned} R_H^{theory} &= 3\left(|V_{ud}|^2 + |V_{us}|^2\right)(1.02)(0.985 \pm 0.010) \\ &\times \left(1 + \frac{\alpha_s(m_\tau)}{\pi} + 5.2\left(\frac{\alpha_s(m_\tau)}{\pi}\right)^2 + 26.4\left(\frac{\alpha_s(m_\tau)}{\pi}\right)^3\right) \end{aligned} \tag{11}$$

For $\alpha_s(m_\tau) \simeq 0.232 \pm 0.053$ ($\Lambda^{(4)}_{\overline{MS}} \simeq 150 \pm 100$ MeV), one expects $R_H \simeq 3.35 \pm 0.12$, which suggests

$$\begin{aligned} \tau_{tau}(QCD) &= 2.99 \pm 0.07 \times 10^{-13} s \\ BR(\tau \to e\nu\overline{\nu})_{QCD} &= 18.8 \pm 0.4\% \end{aligned} \tag{12}$$

That would favor a future increase in the leptonic branching ratio and perhaps some small reduction in the lifetime. It will be interesting to watch new high precision measurements of τ_{tau}, m_τ and $BR(\tau \to e\nu\overline{\nu})$. The most likely scenario suggests changes that will accord with the standard model. On the other hand, we may be seeing the first sign of a heavy neutrino, a much more exciting possibility.

If heavy new fermions are appended to the standard model in the form of a fourth generation, technicolor, etc., they can give rise to observable loop corrections to gauge boson self-energies.[11] Taking α, G_μ, $m_Z = 91.17$ GeV, the known fermion masses, $m_t \simeq 130$ GeV and $m_H \simeq 100$ GeV, the standard model predicts[1]

$$\begin{aligned} \sin^2\theta_W(m_Z)_{\overline{MS}} &= 0.2326 + 0.00365 S_Z - 0.00261 T \\ m_W &= 80.14 + 0.45 T - 0.63 S_Z + 0.34 S_W \text{ GeV} \\ \rho_{NC} &= 1 + 0.078 T \end{aligned} \tag{13}$$

where nonvanishing T, S_W and S_Z (loop effects) would signal deviations from $m_t \simeq 130$ GeV, $m_H \simeq 100$ GeV or the presence of "new physics" such as technicolor. For example, arbitrary m_t and m_H approximately imply

$$\begin{aligned} S_W &\simeq \frac{1}{6\pi}\ell n\left(\frac{m_H}{100\text{ GeV}}\right) + \frac{2}{3\pi}\ell n\left(\frac{m_t}{130\text{ GeV}}\right) \\ S_z &\simeq \frac{1}{6\pi}\ell n\left(\frac{m_H}{100\text{ GeV}}\right) - \frac{1}{3\pi}\ell n\left(\frac{m_t}{130\text{ GeV}}\right) \\ T &\simeq \frac{3}{16\pi\sin^2\theta_W}\left(\frac{m_t^2 - (130\text{ GeV})^2}{m_W^2}\right) - \frac{3}{8\pi\cos^2\theta_W}\ell n\left(\frac{m_H}{100\text{ GeV}}\right) \end{aligned} \tag{14}$$

Table 1

Present constraints on S_W, S_Z and T from various experiments and projected future sensitivieies. This analysis follows Ref. (7), but uses m_t = 130 GeV and m_H = 100 GeV.

Experiment	Present Constraint	Future Sensitivity
$m_W = 80.14 \pm 0.31$ GeV	$T - 1.4S_Z + 0.76S_W = 0 \pm 0.75$	± 0.13
$Q_W(Cs) = -71.04 \pm 1.58 \pm 0.88$	$S_Z + 0.006T = -2.7 \pm 2.0 \pm 1.1$	± 0.5
$\Gamma(Z \to \text{all}) = 2487 \pm 9$MeV	$T - 0.36S_Z = -0.11 \pm 0.34$	± 0.3
$\Gamma(Z \to \ell^+\ell^-) = 83.3 \pm 0.4$MeV	$T - 0.23S_Z = -0.39 \pm 0.51$	± 0.45
$A(Z)_{FB}$ (LEP)	$S_Z - 0.69T = -0.71 \pm 0.81$	± 0.3
$A(Z)_{LR}$ (ALEPH)	$S_Z - 0.69T = -0.43 \pm 1.88$	± 0.1
$R_\nu \equiv \sigma(\nu_\mu N)_{NC}/\sigma(\nu_\mu N)_{CC}$	$T - 0.37S_Z = -0.37 \pm 0.62$	± 0.24
$R_{\bar\nu}$	$T - 0.02S_Z = 1.4 \pm 1.3$	± 0.65
$\sigma(\nu_\mu e)/\sigma(\bar\nu_\mu e)$	$S_Z - 0.69T = 0.01 \pm 2.7$	± 1.4
$\frac{\sigma(\nu_\mu e)}{\sigma(\nu_e e)+\sigma(\bar\nu_\mu e)}$	$T - 0.8S_Z$	± 0.3
Polarized eC	$S_Z - 0.19T = -8.76 \pm 13.75$	± 0.63

Some present constraints on S_W, S_Z and T are listed in table 1 where possible future sensitivities are also given.[1] Existing data are very consistent with $T \simeq 0$ which suggests m_t near the assumed 130 GeV (at 90% CL $m_t < 180$ GeV). For a given value of T, one finds assuming $S \equiv S_Z \simeq S_W$

$$S \simeq -0.10 + 1.64T \pm 0.47 \tag{15}$$

Future measurements should reduce the error to ± 0.1. At present there is no hint of "new physics" in the S value of (15). Some individual measurements are sensitive to S independent of T. For example, atomic parity violation in Cs gives[12]

$$S_Z \simeq -2.7 \pm 2.3 \quad \text{Atomic Parity Violation} \tag{16}$$

Comparison of m_W with Z decay asymmetries yields

$$S_W \simeq -1.0 \pm 1.6 \tag{17}$$

independent of T. Those constraints are consistent with $S \simeq 0$, but could be the first signal of a negative S value. That would not bode well for theories with many new heavy $SU(2)_L$ doublets. Each such degenerate doublet gives[13] $\Delta S \simeq +1/6\pi$. So, a one-generation, $SU(4)$ technicolor model (with 16 doublets) would naively be expected to give $S \simeq +1$ (QCD sum rule analogies tend to give $S \simeq +2$). A negative S could be accommodated but it is not the most natural expectation in technicolor models.

If a non-zero S is to emerge, it would likely occur in the new atomic parity violation experiment at Boulder or improved Z asymmetry measurements used in conjunction with m_W via

$$S_W \simeq 118\left(2\,\frac{m_W - 80.14\text{ GeV}}{80.14\text{ GeV}} + \frac{\sin^2\theta_W(m_Z)_{\overline{MS}} - 0.2326}{0.2326}\right) \tag{18}$$

Both should yield new S determinations during the coming year.

My final comment is directed at grand unified theories and the effect of minimal supersymmetry (with two Higgs doublets) on predictions. Assuming $\sin^2\theta_W^0 = 3/8$ as in $SU(5)$, $SO(10)$, E_6, etc., unification at m_X and supersymmetry at m_{SUSY}, one finds the predictions[14]

$$m_X \simeq \frac{m_Z}{2} exp\left[\frac{\pi}{2}\left(\frac{\sin^2\theta_W(m_Z)_{\overline{MS}}}{\alpha(m_Z)_{\overline{MS}}} - \frac{1}{\alpha_3(m_Z)_{\overline{MS}}}\right)\right] \tag{19}$$

independent of m_{SUSY} and

$$m_{SUSY} \simeq 100 m_Z\, exp\left[\frac{3\pi}{4}\left(\frac{1-5\sin^2\theta_W(m_Z)_{\overline{MS}}}{\alpha(m_Z)_{\overline{MS}}} + \frac{7}{3\alpha_3(m_Z)_{\overline{MS}}}\right)\right] \tag{20}$$

Using $\alpha^{-1}(m_Z)_{\overline{MS}} = 127.8\pm0.2$, $\sin^2\theta_W(m_Z) = 0.2326\pm0.0005$ and $\alpha_3(m_Z)_{\overline{MS}} = 0.106 \pm 0.006$ then leads to the predictions

$$\begin{aligned} m_X &\simeq 3.2^{+4}_{-2} \times 10^{15}\ \text{GeV} \\ \tau\left(p \to e^+\pi^0\right) &\simeq 1 \times 10^{34\pm0.7\pm1.5} yr \end{aligned} \tag{21}$$

which is to be compared with the IMB bound[15] $\tau(p \to e^+\pi^0) > 5.5 \times 10^{32}$ yr and

$$m_{SUSY} \lesssim 2 \times 10^7\ \text{GeV} \tag{22}$$

with a best value near 100 TeV. If one believes that $\Lambda^{(4)}_{\overline{MS}}$ is actually larger than the 150^{+100}_{-50} MeV assumed above, τ_P gets longer but m_{SUSY} is reduced. Indeed, for $\Lambda^{(4)}_{\overline{MS}} = 350$ MeV, one finds $m_{SUSY} \simeq 350$ GeV and $\tau_p \sim 10^{37}$ yr (they scale roughly as Λ^{-8} and Λ^8 respectively). That is quite interesting since the leptonic τ branching ratio discussed above suggests a $\Lambda^{(4)}_{\overline{MS}}$ of about that magnitude. Perhaps supersymmetry has sent its first harbingers. If that is the case, SUSY spectroscopy should be unveiled at the SSC.

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