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Precision Tests of Electroweak Theory*

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ABSTRACT

Pursuits of "New Physics" via precision measurements are surveyed. The inconsistency between world average tau lifetime-mass values and measured leptonic branching ratios is updated and a heavy neutrino solution is described. The use of $R_\tau \equiv \Gamma(\tau \to \nu_\tau + \text{hadrons})/\Gamma(\tau \to e\overline{\nu}_e\nu_\tau)$ to determine $\Lambda_{\overline{MS}}$ is discussed. Constraints on the Peskin-Takeuchi S and T parameters are given. Possible evidence for low energy supersymmetry from grand unified theories is scrutinized.

The Fermi Constant, G_μ, defined via the muon lifetime

$$\tau_\mu^{-1} = \frac{G_\mu^2 m_\mu^5}{192\pi^3} f\left(\frac{m_e^2}{m_\mu^2}\right)\left(1 + \frac{3}{5}\frac{m_\mu^2}{m_W^2}\right)\left[1 + \frac{\alpha(m_\mu)}{2\pi}\left(\frac{25}{4} - \pi^2\right)\right]$$

$$f(X) = 1 - 8X + 8X^3 - X^4 - 12X^2 \ell n X$$

$$\alpha^{-1}(m_\mu) \simeq 136 \qquad (1)$$

is very precisely determined from experiment

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

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 (for large m_t)

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

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

At present, LEP data, m_W measurements and deep-inelastic neutrino scattering all have about the same sensitivity to m_t and suggest $m_t \simeq 130 \pm 40$ GeV. That range is very consistent with the CDF bound $m_t \gtrsim 91$ GeV.

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 in terms ol G_μ. Instead, one obtains very precise predictions that can be used to test the standard model and probe for new physics. For example, including electroweak radiative corrections one finds the following values of the CKM mixing matrix[1]

$$
\begin{aligned}
|V_{ud}| &= 0.9750 \pm 0.0007 && (^{14}O \text{ Decay}) \\
|V_{us}| &= 0.220 \pm 0.002 && (K_{e3} \text{ and Hyperon Decays}) \\
|V_{cd}| &= 0.215 \pm 0.016 && (\nu_\mu N \text{ Scattering}) \\
|V_{cs}| &= 0.98 \pm 0.12 && (\nu_\mu N \text{and } D_{e3}) \\
|V_{cb}| &= 0.046 \pm 0.005 && (\tau_b, b \to c\ell\nu) \\
|V_{ub}| &= 0.005 \pm 0.002 && (b \to u\ell\nu)
\end{aligned}
$$

From those values, the first row of the CKM matrix gives $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9991 \pm 0.0016$, which provides a beautiful confirmation of three-generation unitarity. (Without the electroweak radiative corrections, one would have found 1.037, an apparent violation of unitarity.) That confirmation of the standard model at the level of its quantum loop corrections can be used to constrain or even rule out all sorts of "new physics" scenarios such as heavy neutrino mixing, supersymmetry, Z' bosons, compositeness, etc.

Another nice example is the leptonic decay width of the tau[4](for $\ell = e$ or μ)

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

Using that formula, along with the particle data table mass

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

implies

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

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

$$\Gamma(\tau \rightarrow \text{ all}) = 2.172 \pm 0.036 \times 10^{-12} \text{ GeV} \tag{7}$$

obtained from the lifetime average $\tau_{tau} = 3.03 \pm 0.05 \times 10^{-13} s$ leads to the leptonic branching ratio

$$BR(\tau \rightarrow e\nu\overline{\nu})^{\text{expected}} = 0.1894 \pm 0.0031^{+0.0014}_{-0.0019} \tag{8}$$

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]

$$BR(\tau \rightarrow e\nu\overline{\nu})_{ave} = 0.1786 \pm 0.0017 \tag{9}$$

There is about a 2.7 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. Fortunately, CLEO II and ARGUS should each be able to measure τ_{tau} to about $\pm 2\%$. Also, the Beijing e^+e^- collider will remeasure the $\tau^+\tau^-$ cross section near threshold, and determine m_τ to about ± 1 MeV. 2) A second possibility is that the world average $BR(\tau \rightarrow e\nu\overline{\nu})$ 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[8,9] of the above requires introducing a heavy fourth generation neutrino with $m_{\nu_4} \gtrsim 45$ GeV (LEP constraint) or a sterile neutrino with $m_\nu \gtrsim m_\tau$ and in both cases $\sin^2\theta_{34} \simeq 0.06$. 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. At present, the best bound on the mixing of a heavy fourth generation neutrino with both ν_e and ν_μ comes from $\mu N \rightarrow eN$ constraints. One finds[10] $| U^*_{4e} U_{4\mu} |^2 \lesssim 10^{-8}$. On the basis of universality checks[1] in β-decays and $\Gamma(\pi \to e\nu)/\Gamma(\pi \to \mu\nu)$[11], one finds the less stringent individual bounds $| U_{4\mu} | \lesssim 0.05$ and $| U_{4e} | \lesssim 0.1$.

On the theoretical side, QCD perturbation theory can be used to predict[12]

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

Including electroweak radiative corrections[4] and small non-perturbative effects[12,13]

$$\begin{aligned} R_\tau^{\text{theory}} &\simeq 3\left(|V_{ud}|^2 + |V_{us}|^2\right)(1.019)(0.983 \pm 0.010) \\ &\left[1 + \frac{\alpha_s(\mu)}{\pi} + \left[5.2 - 2.25\,\ell n\left(\frac{m_\tau^2}{\mu^2}\right)\right]\left(\frac{\alpha_s(\mu)}{\pi}\right)^2 \right. \\ &\left. + \left[26.4 - 27.4\,\ell n\left(\frac{m_\tau^2}{\mu^2}\right) + 5.06\,\ell n^2\left(\frac{m_\tau^2}{\mu^2}\right)\right]\left(\frac{\alpha_s(\mu)}{\pi}\right)^3 + \cdots\right] \end{aligned} \tag{11}$$

For $R_\tau = BR(\tau \to e\overline{\nu}_e\nu_\tau)^{-1} - 1.9728 = 3.628 \pm 0.053$ as suggested by direct branching ratio measurements, one finds[14] using $\mu \simeq 808$ MeV

$$\Lambda_{\overline{MS}}^{(4)} = 280^{+23}_{-28} \pm 25 \text{ MeV} \tag{12a}$$

or extrapolating to $\mu = m_Z$

$$\alpha_s(m_Z) = 0.1172^{+0.0015}_{-0.0021} \pm 0.0020 \tag{12b}$$

where the second error is an estimate of the truncation uncertainty. The central value in (12b) is in good accord with LEP results, but the errors here are smaller. The QCD coupling is, however, larger than results found for J/ψ and upsilon decays which suggest[15] $\Lambda_{\overline{MS}}^{(4)} \simeq 150 \sim 175$ MeV. That difference has important consequences for SUSY GUTS, as we shall subsequently see.

The finding in Eq.(12) implies that the branching ratio in (9) is consistent with QCD perturbative theory. If instead, Eq. (8) were correct, it would correspond to $R_\tau \simeq 3.33$ and $\Lambda_{\overline{MS}}^{(4)} \simeq 115$ MeV which is somewhat on the small side. Until the tau decay inconsistency between leptonic branching ratios and lifetime-mass measurements is resolved, we must assume about a factor of 2 flexibility in $\Lambda_{\overline{MS}}$. The relationship between R_τ and $\Lambda_{\overline{MS}}$ is summarized in table 1, taken from ref. 14.

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.[16,17] Taking α, G_μ, $m_Z = 91.17$ GeV,

Table 1: Extracted values of $\Lambda^{(3)}_{\overline{MS}}$, $\Lambda^{(4)}_{\overline{MS}}$, $\Lambda^{(5)}_{\overline{MS}}$, and $\alpha_S(m_Z)$ (to 3-loop order) for different experimental values of R_τ^{exp} or equivalently, the leptonic branching ratio.

R_τ^{exp}	$BR(\tau \to e\bar{\nu}_e\nu_\tau)$	$\Lambda^{(3)}_{\overline{MS}}$ (MeV)	$\Lambda^{(4)}_{\overline{MS}}$ (MeV)	$\Lambda^{(5)}_{\overline{MS}}$ (MeV)	$\alpha_S(M_Z)$
3.30	0.1897	124	97	61	0.0997
3.32	0.1889	140	111	71	0.1016
3.34	0.1882	156	124	81	0.1033
3.36	0.1875	171	138	91	0.1049
3.38	0.1868	185	151	100	0.1063
3.40	0.1861	199	164	110	0.1076
3.42	0.1854	213	176	119	0.1088
3.44	0.1847	226	188	128	0.1099
3.46	0.1841	238	200	137	0.1110
3.48	0.1834	250	211	145	0.1119
3.50	0.1827	261	222	154	0.1128
3.52	0.1821	271	232	162	0.1136
3.54	0.1814	281	242	169	0.1144
3.56	0.1807	291	251	177	0.1151
3.58	0.1801	300	260	184	0.1158
3.60	0.1794	309	269	191	0.1164
3.62	0.1788	317	277	197	0.1170
3.64	0.1782	325	285	203	0.1176
3.66	0.1775	332	293	209	0.1181
3.68	0.1769	339	300	215	0.1186
3.70	0.1763	346	306	221	0.1190

the known fermion masses, $m_t \simeq 130$ GeV and $m_H \simeq 100$ GeV as input, the standard model predicts[1]

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

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
$m_W = 80.14 \pm 0.27$ GeV	$T - 1.4S_Z + 0.76S_W = 0 \pm 0.65$	± 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
$\Gamma(Z \to \text{all}) = 2487 \pm 9\text{MeV}$	$T - 0.36S_Z = -0.11 \pm 0.34$	± 0.3
$\Gamma(Z \to \ell^+\ell^-) = 83.3 \pm 0.4\text{MeV}$	$T - 0.23S_Z = -0.39 \pm 0.51$	± 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 2 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 particularly sensitive to S independent of T. For example, atomic parity violation in Cs is predicted[17] to have weak charge $Q_W(Cs) = -73.20 - 0.8S_Z$ which implies from table 2.

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

Comparison of m_W with Z decay asymmetries (see Eq. (18) below) 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[18] $\Delta S \simeq +1/6\pi$. So, a one-generation, $SU(4)$ technicolor model (with 16 left-handed doublets) would naively be expected to give $S \simeq +1$ (QCD sum rule analogies[16] tend to give $S \simeq +2$). A negative S could probably be accommodated, but it is not the most natural expectation in technicolor models.

A strong constraint on S would also limit many other "new physics" scenarios such as a fourth generation or any model with many new chiral fermions at high energies. Of course, it would be most interesting to observe a non-zero value of S. If S is positive and $\mathcal{O}(1)$, it could be a harbinger of technicolor. On the other hand, if S is negative, it could be suggestive of Z' bosons.[17]

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[19]

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

independent of m_{SUSY} and

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

Using $\alpha^{-1}(m_Z)_{\overline{MS}} = 127.8 \pm 0.2$, $\sin^2\theta_W(m_Z) = 0.2326 \pm 0.0005$ and $\alpha_s(m_Z)_{\overline{MS}} = 0.117 \pm 0.003$ from τ leptonic branching ratios then leads to the predictions

$$m_X \simeq (1.3 \pm 0.4) \times 10^{16} \text{ GeV}$$
$$\tau\left(p \to e^+\pi^0\right) \simeq 2.7 \times 10^{35 \pm 1 \pm 0.5} yr \tag{21}$$

which is to be compared with the IMB bound[20] $\tau(p \to e^+\pi^0) > 8.5 \times 10^{32}$ yr and

$$m_{SUSY} \simeq 1.0^{+2.5}_{-0.8} \text{ TeV} \tag{22}$$

If one believes that $\Lambda^{(4)}_{\overline{MS}}$ is actually smaller than $\simeq$ 280 MeV assumed above, τ_P gets shorter and m_{SUSY} is increased. Indeed, for $\Lambda^{(4)}_{\overline{MS}}$ = 150 MeV, one finds $m_{SUSY} \simeq 10^5$ GeV and $\tau_p \sim 10^{33}$ yr (they scale roughly as $\Lambda^{-8}_{\overline{MS}}$ and $\Lambda^{8}_{\overline{MS}}$ respectively). That is quite interesting since the τ lifetime and mass suggest a $\Lambda^{(4)}_{\overline{MS}}$ of about that magnitude. However, if the τ leptonic branching ratios are correct, SUSY spectroscopy should be unveiled at the SSC.

In conclusion, we have seen that the standard model has been tested at the level of its quantum loop corrections in both charged and neutral current processes. So far, no clear deviations have been found. There is an interesting puzzle in τ decays which probably indicates that shifts in the τ lifetime, mass, or leptonic branching ratios (perhaps a little movement in all three) are likely. It could, however, be the first signal of a fourth generation with relatively large mixing, an exciting possibility.

In the case of the top quark, precision measurements seem to suggest $m_t \simeq$ 130 GeV. If that is the case, top should be discovered at Fermilab during the 1992 run and its mass should be known to about ±10 GeV. Knowing m_t will allow us to probe for additional signals of "new physics" in the S and T variables. S should be determined to ±0.3 and ultimately ±0.1 as new precision measurements of m_W, Z decay symmetries, etc., are made. It will be particularly interesting to watch the Cesium atomic parity violation experiment. Will the value of S measured there stay negative, or will a value $+1 \sim 2$, as suggested by generic technicolor models, be found?

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