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The Tau Lepton and Tests of the Standard Model

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ABSTRACT

Using a new value for the mass of the tau lepton we reconsider various tests of the Standard Model (SM) for the tau. The agreement with the SM is much improved. All tests agree within 1.2σ or smaller. We also obtain bounds on the mass of the tau neutrino.

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The tau lepton which was discovered in 1975 by M. Perl[1], is a wonderful system for testing the Standard Model (SM). It is the only known lepton heavy enough to decay into hadrons, with α_s (M_τ) still being small enough, to provide a test of perturbative Quantum Chromodynamics (PQCD). M_τ is the lowest energy where PQCD can be tested. Moreover it appears to behave like a heavy SM lepton.[2]

However, there are some bothersome discrepancies which have persisted for several years and some people have questioned whether or not the tau is really a S.M. lepton. Recently, however, there have been new measurements[3,4] of the mass of the tau lepton M_τ. The new values are 2σ below the Particle Properties Data Book (PPDB) 1992 value, which has remained unchanged for many years. Moreover there have also been new measurements of the electronic branching ratio B_e, the muonic branching ratio B_μ and the τ lifetime τ_τ. In this paper we will show that the new values of B_e, B_μ, M_τ, and τ_τ effectively remove the discrepancies with the SM and all predictions agree within 1.2σ.

We will use the following values for the tau branching ratios[5] and lifetime[6]:

$$B(\tau \to e\nu\bar{\nu}) = 17.73\,(23)\,\% \tag{1}$$

$$B(\tau \to \mu\nu\bar{\nu}) = 17.41\,(24)\% \tag{2}$$

$$\tau_\tau = .2957(32) \times 10^{-12} s \tag{3}$$

The new BEPC value for the mass of the tau lepton is[3]

$$M_\tau = 1776.9(5) MeV \tag{4}$$

We begin with the value of R_T.

$$R_\tau = \frac{1 - B_e - B_\mu}{B_e} \qquad (5)$$
$$= 3.66(7)$$

This agrees with the present world-averaged value[5]

$$R_\tau^{exp} = 3.63(3) \qquad (6)$$

at 0.4σ.

We now turn to the so-called "tau-lifetime problem". The partial decay widths are given by

$$\Gamma(\tau \to e\nu\bar{\nu}) = \frac{G_F^2 M_\tau^5}{192\pi^3}(1 + r) \qquad (7)$$

$$\textit{and} \quad \Gamma(\tau \to \mu\nu\bar{\nu}) = f(m_\mu^2/M_\tau^2)\,\Gamma(\tau \to e\nu\bar{\nu}) \qquad (8)$$

$$\textit{where} \quad f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \log x, \qquad (9)$$

G_F is the Fermi coupling constant and r = -.4% arises from radiative corrections and the non-local structure of the W propagator.[7,8] Equations (7), (8) and (9) imply the following values for the tau leptonic branching ratios.

$$B_e = \frac{\tau_\tau}{1.6325(24)\ x\ 10^{-12}S} \tag{10}$$

$$and\ \ B_\mu = .9728(1)B_e \tag{11}$$

Using eq (3) we obtain the following predictions:

$$B_e = 18.11(22)\% \tag{12}$$

$$and\ \ B_\mu = 17.62(21)\% \tag{13}$$

Comparing eqs (12) & (13) with eqs (1) and (2) respectively we obtain agreement to within 1.2σ and $.66\sigma$ respectively.

Now from eqs (3), (7) and (8) we obtain the widths as follows:

$$\begin{aligned} \Gamma_{tot} &= 2.226(24)\ x\ 10^{-9}MeV \\ \Gamma_e &= 4.032(6)\ x\ 10^{-10}MeV \\ and\ \Gamma_\mu &= 3.922(6)\ x\ 10^{-10}MeV \end{aligned} \tag{14}$$

We can now calculate R_τ^Γ:

$$\begin{aligned} R_\tau^\Gamma &= \frac{\Gamma_{tot} - \Gamma_e - \Gamma_\mu}{\Gamma_e} \\ &= 3.55(7) \end{aligned} \tag{15}$$

Comparing eq (15) with eq (6) this represents a difference of 1.0σ.

We now show how one can, from these results, obtain bounds on the mass of the tau neutrino,[9] M_ν. The decay width for $\tau \to e\nu\bar{\nu}$ is modified due to $M_\nu \neq 0$ as follows,

$$\Gamma(\epsilon) = \frac{G_F^2 M_\tau^5}{192\,\pi^3} f(\epsilon) \qquad (16)$$

where $f(\epsilon)$ is the <u>same function</u> which occurs for non-zero m_e or m_μ and is given in eq (9). It is interesting to note that the differences in the branching ratios B_e (eqs (1) and (12)) and B_μ (eqs (2) and (13)) is in the right direction for a non-zero M_ν.

Using eqs. (1), (12) and (16) we obtain the bound from the electron branching ratio

$$M_{\nu_\tau} < 141\, MeV\ (95\%\ C.L.) \qquad (17)$$

From the muon branching ratio in eq (2) and eqs (13) and (16) we obtain the bound

$$M_{\nu_\tau} < 128\, MeV\ (95\%\ C.L.) \qquad (18)$$

The best bound we presently have from direct experiment[10] is

$$M_{\nu_\tau} < 31\, MeV\ (95\%\ C.L.) \qquad (19)$$

In general if one could measure both B_e (or B_μ) and τ_τ with a relative error of $\alpha\%$ one could obtain the limit

$$M_{\nu_\tau} < 80\ \sqrt{\alpha}\ MeV\ (95\%\ \ C.L.) \qquad (20)$$

Thus, to do better than the present bound in eq (19) we need to measure B_e (or B_μ) and τ_τ with an accuracy of

$$\alpha\% = 0.15\% \qquad (21)$$

The results for R_τ in eqs (5) and (6) enable us to also obtain an accurate value for the strong interaction coupling constant at the tau mass $\alpha_s(M_\tau)$. We will use the following:

$$R_\tau = R_\tau^{pert} + R_\tau^{nonpert} + R_\tau^{weak} \quad (22)$$

$$where^{11}\ R_\tau^{nonpert} = -.45\%\ R_\tau^{pert} \quad (23)$$

$$R_\tau^{weak} = +\ 2\%\ R_\tau^{pert} \quad (24)$$

$$and^{12}\ R_\tau^{pert} = 3\left\{1 + \frac{\alpha_s}{\pi} + 5.20\left(\frac{\alpha_s}{\pi}\right)^2 + 26.38\left(\frac{\alpha_s}{\pi}\right)^3\right\} \quad (25)$$

If we use eq (6) for R_τ our result is

$$\alpha_s(M_\tau) = .328^{+.009}_{-.012} \quad (26)$$

If we use our estimate[14] $\left(134\left(\frac{\alpha_s}{\pi}\right)^4\right)$ for the next term in eq (25) we obtain the result

$$\alpha_s(M_\tau) = .312^{+.010}_{-.009} \quad (27)$$

However if we sum all terms of the perturbation series for R_τ^{pert}, we obtain

$$\alpha_s(M_\tau) = .300(8) \quad (28)$$

After this work was completed we received a preprint[13] from A. Pich in which a similar analysis is done. Since he uses different experimental results, our results and conclusions differ.

In our case, all of our tests agree within 1.2σ or smaller and we conclude that the τ lepton is a S.M. lepton and the S.M. continues to be successful!

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(4) See also Argus and CLEO collaborations in ref (3). These measurements are consistent with ref (3).

(5) We will use averages of LEP results and the Particle Data Group (1992) values, as given by A. Pich in ref (3).

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