Can the Higgs Sector Be Probed in Tau-Lepton Decays?

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Abstract

It is unlikely that a high statistics study of τ-lepton decays will be sensitive to the Higgs boson sector of electroweak physics.

A Tau-Charm Factory is an ideal facility for the study of rare decays of the τ-lepton. At a machine discussed in these Proceedings, one might expect to produce on the order of 10^7 τ's per year. It is an interesting exercise to consider whether such a data sample is sufficiently large to shed any light on the Higgs boson sector of electroweak physics. In this note, I will consider possible effects in the context of the Standard Model with minimal Higgs structure, and in modest extensions thereof.

In the Standard Model, there exists one physical neutral CP-even Higgs scalar, which couples to any particle A with coupling strength proportional to m_A/m_W. However, the mass of the Higgs boson is a free parameter of the model. There are numerous experimental results which have significant implications for the possible existence of a Standard Model Higgs boson with mass less than 5 GeV.[1,2] Although the existence of a Higgs boson in this mass range is rather unlikely, various theoretical (and some experimental) uncertainties may still allow for the existence of a light Higgs boson with mass less than m_τ. If such a light scalar were to exist, then it would be possible to produce the Higgs boson in τ decay via $\tau \to \nu_\tau X + H^0$ (where X is any final state that can be produced in τ decay). The Higgs boson can, in principle, be emitted from any particle (virtual or real) in the decay $\tau \to \nu_\tau X$. In the Standard Model, all τ decays proceed through the emission of a virtual W, which then converts into light fermions. Since the Higgs coupling to these light fermions is negligible, the dominant contributions to $\tau \to \nu_\tau X + H^0$ are from diagrams in which the H^0 is emitted either from the initial τ or the virtual W. In ref. 1, the decay rate for $\tau \to \ell \nu_\ell \nu_\tau H^0$ ($\ell = \mu$ or e) has been calculated as a function of m_{H^0}. For example, for $m_{H^0} = 200$ MeV, one finds $BR(\tau \to \mu \nu_\mu \nu_\tau H^0) \simeq 10^{-7}$. The total inclusive branching ratio for $\tau \to \nu_\tau X + H^0$ would be roughly a factor of 10 larger. Thus, in the unlikely circumstance that a light Higgs scalar exists but has so far escaped detection,* it is may be possible to detect or rule out a light Higgs boson with a mass of a few hundred MeV, with a data sample consisting of 10^7 τ decays.

What about the effects of virtual Higgs exchange? In the Standard Model with minimal Higgs structure (and massless neutrinos), lepton number is exactly conserved, so there are no flavor changing neutral current (FCNC) τ-decays induced by Higgs exchange to all orders in perturbation theory. Thus, the only effects of neutral Higgs exchange would be in electroweak radiative corrections of known τ-decay modes. Such effects are extremely small, and cannot be observed.

To have any hope of seeing the effects of virtual Higgs bosons in τ-decays, there must exist *charged* Higgs bosons. Such scalars exist in models with extended Higgs structures. There is a large literature on extended Higgs models (for a review, see ref. 3). However, for most purposes, it suffices to examine the simplest extension of the Standard Model, where one simply adds a second Higgs doublet to the model. Such a theory will possess charged Higgs bosons as well as neutral Higgs bosons. If the charged Higgs boson were lighter than the τ, then $\tau^+ \to \nu_\tau H^+$ would be the dominant τ decay mode! Of course, we know that this is not the case. Furthermore, experimental results from PETRA[4] already limit the charged Higgs mass to be

* In extended Higgs models, it is possible to have *different* Higgs bosons couple to the leptons and quarks. In such a case, none of the experimental results alluded to above would be relevant to the question of whether a light Higgs boson can exist which couples to the τ.

greater than about 20 GeV; and data from SLC and LEP will soon double this mass limit. Thus, I shall focus on the possible effects of virtual charged Higgs boson exchange in τ-decays, under the assumption that $m_{H^\pm} \gtrsim m_Z/2$.

Before proceeding, there are two simplifications I shall make. First, I assume that the Higgs-fermion couplings are chosen in such a way that there are no tree-level FCNC's induced by Higgs exchange. (This can be done naturally, as shown many years ago by Glashow and Weinberg.[5]) It will be certainly useful to improve limits on FCNC's in τ physics. However, the absence of observed FCNC's in μ, K and B decays already imposes severe limits on the possible theoretical structure of FCNC's, so that it is very unlikely that Higgs-induced FCNC's would be first observed in τ-decay. Second, I assume that the Higgs sector is CP-conserving. The possibility of CP-violating effects arising *in part* from the Higgs sector is an interesting possibility that cannot be ruled out at present. Whether τ-decays can provide constraints on the origins of CP-violation is an open question.

If a charged Higgs boson exists, then there will be a new contribution to all τ-decays in which the virtual W is replaced by a virtual charged Higgs boson. This leads to three possible types of observable effects:

1. Violations in lepton universality. Since the charged Higgs boson couples to mass, the virtual Higgs will prefer to decay into the heaviest fermion pair.

2. Evidence for scalar currents. By studying in detail the angular and energy distributions of the decay of the τ, one can in principle detect the existence of a virtual scalar exchange contribution.

3. Existence of second-class currents. Higgs-exchange can yield final states, $\tau \to \nu_\tau X$, in which the hadronic system X possesses quantum numbers such that $GP(-1)^J = -1$, where G is the G-parity of X.[6] This should be contrasted with "first-class" currents such as W-exchange which yield final states with $GP(-1)^J = 1$ (in the limit where isospin is an exact symmetry).

Consider first the possible violation of lepton universality. Let us define:

$$R_\tau \equiv \frac{\Gamma(\tau \to \mu\nu_\mu\nu_\tau)}{\Gamma(\tau \to e\nu_e\nu_\tau)} . \tag{1}$$

In the Standard Model, we expect $R_\tau \simeq 1$, with small deviations from unity due to phase space effects arising from the fact that $m_\mu \neq m_e$. Including charged Higgs exchange,[7] I obtain the approximate expression:

$$R_\tau \simeq 1 - 2x^2 \left(1 - \frac{m_\tau^2 \tan^2\beta}{4m_{H^\pm}^2}\right) , \tag{2}$$

where $x \simeq 2m_\mu/m_\tau$, and $\tan\beta$ is the ratio of Higgs vacuum expectation values in the two-Higgs doublet model. Since $\tan\beta$ is a free parameter of the model, one can set limits on $\tan\beta/m_{H^\pm}$ by carefully measuring R_τ. However, assuming that $m_{H^\pm} > m_Z/2$, one would need an improbably large value of $\tan\beta$ in order to be sensitive to Higgs exchange in this case.

Next, consider the search for scalar currents in τ-decay. The amplitude for $\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$ due to W^- and H^- exchange can be conventionally written (after employing a Fierz identity) as:[8,7]

$$\mathcal{M} = \frac{G_F}{\sqrt{2}} \bar{u}_{\nu_\tau}\gamma_\mu(1-\gamma_5)v_{\nu_\mu}\bar{u}_{\mu^+}(C_V\gamma^\mu + C_A\gamma^\mu\gamma^5)u_{\tau^+} , \tag{3}$$

where

$$\begin{aligned} C_V &= 1 + \frac{m_\mu m_\tau \tan^2\beta}{2m_{H^\pm}^2} , \\ C_A &= -1 + \frac{m_\mu m_\tau \tan^2\beta}{2m_{H^\pm}^2} , \end{aligned} \tag{4}$$

The angular and energy distribution of unpolarized tau-decay can be written as:[9]

$$\begin{aligned} \frac{d\Gamma}{dE\, d\cos\theta} = \frac{G_F^2 m_\tau}{6\pi^3} Ep \Bigg[& 3(E_{max} - E) + 2\rho\left(\tfrac{4}{3}E - E_{max}\frac{m_\mu^2}{3E}\right) \\ & + \frac{3m_\mu\eta(E_{max} - E)}{E} - \frac{p}{E}\xi\cos\theta\left(E_{max} - E + 2\delta\left[\tfrac{4}{3}E - E_{max} - \frac{m_\mu^2}{3m_\tau}\right]\right)\Bigg] \end{aligned} \tag{5}$$

where

$$E_{max} = \frac{m_\tau^2 + m_\mu^2}{2m_\tau}$$
$$p = (E^2 - m_\mu^2)^{1/2} \,. \tag{6}$$

The Michel parameters, ρ, δ, ξ and η can be used to detect the presence of new currents beyond W-exchange. In fact, for theories in which the ν_τ is purely left-handed, it is easy to see that $\rho = \delta = \frac{3}{4}$. In addition, I find:

$$\xi = \frac{-2C_A C_V}{C_A^2 + C_V^2} \simeq 1 + \mathcal{O}\left(\frac{m_\tau^2 m_\mu^2}{m_{H^\pm}^4}\right) \,,$$
$$\eta = \frac{C_A^2 - C_V^2}{2(C_A^2 + C_V^2)} \simeq \frac{-m_\tau m_\mu \tan^2\beta}{2m_{H^\pm}^2} \,, \tag{7}$$

where terms of $\mathcal{O}(m_\tau^2/m_W^2)$ have been neglected. In addition, the helicity of the outgoing muon is equal to $-\xi$. In the case of polarized τ decay, there would be additional parameters one could measure experimentally which are sensitive to scalar currents.[10] However, once again, we see that for charged Higgs masses larger than $m_Z/2$, one would need unreasonably large values of $\tan\beta$ in order to see any effects.

Finally, let us consider the possibility of second-class currents. Examples would be: $\tau^+ \to \nu_\tau a_0^+$, $\tau^+ \to \nu_\tau \eta \pi^+$, $\tau^+ \to \nu_\tau \bar{K}^0 K^+$ (with $\bar{K}^0 K^+$ in a $J^{PC} = 0^{++}$ state), and $\tau^+ \to \nu_\tau b_1^+$. For readers not familiar with the new Particle Data Group notation,[11] $a_0 \equiv \delta(980)$ and $b_1 \equiv B(1235)$. In general, second class currents can arise due to either isospin violating effects (*e.g.*, $m_u \neq m_d$) or due to scalar currents. However, the possibility of observing Higgs effects here are small since the Higgs contribution to second-class currents is *not* an interference effect and thus is the square of a small quantity. Therefore, Higgs boson effects are likely to be much smaller than isospin breaking effects. The most optimistic estimate I can imagine for the charged Higgs contribution to second-class current induced τ-decay is:

$$\begin{aligned} BR(\text{Higgs induced 2nd class current } \tau \text{ decay}) &\simeq \frac{m_\tau^2 m_s^2 \sin^2\theta_c \tan^4\beta}{m_{H^\pm}^4} \\ &\simeq 5\times 10^{-11}\left(\frac{m_Z \tan\beta}{m_{H^\pm}}\right)^4 . \end{aligned} \tag{8}$$

Theoretical predictions for second-class current decays due to isospin breaking effects vary,[12] but the inclusive branching ratio for such decays is probably not less than 10^{-5}. Thus, the detection of Higgs effects in second-class current induced τ-decay is very improbable.

In conclusion, I find it extremely unlikely that the effects of the Higgs sector can be detected in high statistics τ decay studies which could be performed at a Tau-Charm Factory. The branching ratio for the direct decay of the τ into a very light neutral Higgs boson may be observable for $m_{H^0} \lesssim 300$ MeV, although such a conventional Higgs boson is probably ruled out by rare K-decay experiments.[2] The effects of virtual charged Higgs exchange is unobservable, assuming $m_{H^\pm} > m_Z/2$ (which will be known after the first year of running at SLC and LEP). The only way to avoid the latter conclusion is if the parameter $\tan\beta$ of the Higgs model is unduly large. Were this to be the case, the coupling of Higgs bosons to down-type quarks and leptons would be extremely enhanced, and I would expect Higgs effects to be first observed elsewhere. For example, as noted by Suzuki,[13] if charged Higgs effects are observable in τ-decays, then they should already have been detected in B-decays in the process $b \to c\tau\nu_\tau$, mediated by charged Higgs exchange. I conclude that observable Higgs effects in τ-decays would require a rather exotic Higgs sector very different from the one considered in this paper.

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