# Anomalous charged current couplings of the tau and implications for tau compositeness and two-Higgs doublet models

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(December 20, 2013)

The leptonic branching fractions of the tau lepton are sensitive to anomalous charged current interactions. We use recent experimental measurements to determine the weak charged current magnetic and electric dipole moments and the Michel parameter $\eta$ with unprecedented precision. These results are then used to constrain the tau compositeness scale and the allowed parameter space for Higgs doublet models.

12.60.Cn, 12.60.Fr, 13.35.Dx, 14.60.Fg, 14.80.Cp

## I. INTRODUCTION

The tau lepton in the Standard Model is an exact duplicate of the electron and muon, apart from its greater mass and separately conserved quantum number. Its charged current interactions are expected to be mediated by the $W$ boson with pure $V-A$ coupling. In this paper we present constraints on anomalous charged current couplings of the $\tau$ derived from an analysis of the branching fractions for $\tau^- \to \mathrm{e}^-\bar{\nu}_\mathrm{e}\nu_\tau$ and $\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$, where charge-conjugate decays are implied.

In particular, we consider derivative terms in the Hamiltonian which describe anomalous weak charged current magnetic and electric dipole couplings [1,2] and deviations from the $V-A$ structure of the charged current, to which the Michel parameter $\eta$ is sensitive [3]. The results for the $\eta$ parameter are used to constrain extensions of the Standard Model which contain more than one Higgs doublet and hence charged Higgs bosons.

## II. EFFECTS OF ANOMALOUS COUPLINGS

The theoretical predictions for the branching fractions $\mathcal{B}_\ell$ for the decay $\tau^- \to \ell^-\bar{\nu}_\ell\nu_\tau(X_\mathrm{EM})$, with $\ell^- = \mathrm{e}^-, \mu^-$ and $X_\mathrm{EM} = \gamma,\ \gamma\gamma,\ e^+e^-, \ldots$, are given by:

$$\mathcal{B}_\ell^\mathrm{theory} = \left(\frac{G_\mathrm{F}^2 m_\tau^5}{192\pi^3}\right)\tau_\tau\left(1-8x-12x^2\mathrm{ln}x+8x^3-x^4\right) \times\left[\left(1-\frac{\alpha(m_\tau)}{2\pi}\left(\pi^2-\frac{25}{4}\right)\right) \times\left(1+\frac{3}{5}\frac{m_\tau^2}{m_W^2}-2\frac{m_\ell^2}{m_W^2}\right)\right][1+\Delta_\ell]\,, \quad (1)$$

where $G_\mathrm{F} = (1.16639 \pm 0.00002)\times 10^{-5}\mathrm{GeV}^{-2}$ is the Fermi constant [4]; $\tau_\tau = (290.55 \pm 1.06)\mathrm{fs}$ is the tau lifetime [5]; $m_\tau = (1776.96^{+0.18+0.25}_{-0.21-0.17})\mathrm{MeV}$ [6] is the tau mass; and $x = m_\ell^2/m_\tau^2$. The first term in brackets allows for radiative corrections [7–10], where $\alpha(m_\tau) \simeq 1/133.3$ is the QED coupling constant [10] and $m_W = 80.400 \pm 0.075\,\mathrm{GeV}$ is the $W$ mass [11]. The second term in brackets describes the effects of new physics where the various $\Delta_\ell$ we consider are defined below. The sensitivity of these branching ratios to a non-zero neutrino mass and mixing with a heavy fourth generation neutrino has been considered elsewhere [12,13].

The effects of anomalous weak charged current dipole moment couplings at the $\tau\nu_\tau W$ vertex are described by the effective Lagrangian

$$\mathcal{L}_{\tau\nu W} = \frac{g}{\sqrt{2}}\bar{\tau}\left[\gamma_\mu + \frac{i}{2m_\tau}\sigma_{\mu\nu}q^\nu(\kappa_\tau - i\tilde{\kappa}\gamma_5)\right]P_L\nu_\tau W^\mu + (\text{Hermitian conjugate}), \quad (2)$$

where $P_L$ is the left-handed projection operator and the parameters $\kappa$ and $\tilde{\kappa}$ are the (CP-conserving) magnetic and (CP-violating) electric dipole form factors respectively [1]. They are the charged current analogues of the weak neutral current dipole moments, measured using $Z \to \tau^+\tau^-$ events [14], and the electromagnetic dipole moments, measured using $Z \to \tau^+\tau^-\gamma$ events [15–17]. In conjunction with Eq. 1, the effects of non-zero values of $\kappa$ and $\tilde{\kappa}$ on the tau leptonic branching fractions may be described by [1]

$$\Delta_\ell^\kappa = \kappa/2 + \kappa^2/10; \quad (3)$$

$$\Delta_\ell^{\tilde{\kappa}} = \tilde{\kappa}^2/10. \quad (4)$$

The dependence of the tau leptonic branching ratios on $\eta$ is given, in conjunction with Eq. 1, by [18]

$$\Delta_\ell^\eta = 4\eta_{\tau\ell}\sqrt{x}, \quad (5)$$

where the subscripts on $\eta$ denote the initial and final state charged leptons. Both leptonic tau decay modes probe the charged current couplings of the transverse $W$, and are sensitive to $\kappa$ and $\tilde{\kappa}$. In contrast, only the $\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$ channel is sensitive to $\eta$ due to a relative suppression factor of $m_e/m_\mu$ for the $\tau^- \to \mathrm{e}^-\bar{\nu}_\mathrm{e}\nu_\tau$ channel. Semi-leptonic tau branching fractions are not considered here since they are insensitive to $\kappa$, $\tilde{\kappa}$, and $\eta$.

## III. RESULTS

We use the recently updated world average values for the measured tau branching fractions [5]: $\mathcal{B}_e = (17.786 \pm 0.072)\%$ and $\mathcal{B}_\mu = (17.356 \pm 0.064)\%$. Substituting in Eq. 1 for these and the other measured quantities we obtain $\Delta_e = -0.0008 \pm 0.0055$ and $\Delta_\mu = +0.0026 \pm 0.0053$ where the errors include the effects of the uncertainties on all the measured quantities appearing in Eq. 1. These results are consistent with zero which, assuming that there are no fortuitous cancellations, indicates the absence of anomalous effects within the experimental precision.

We therefore proceed to derive constraints on $\kappa$, $\tilde{\kappa}$, and $\eta_{\tau\mu}$ from a combined likelihood fit to both tau decay channels. The likelihood is constructed numerically following the procedure of Ref. [19] by randomly sampling all the quantities used according to their errors, conservatively assuming for each parameter that the other two parameters are zero.

We determine $\kappa = 0.001 \pm 0.008$, where the errors correspond to one standard deviation, and constrain it to the range $-0.014 < \kappa < 0.016$ at the 95% confidence level (C.L.). This result improves on the 95% C.L. constraint of $|\kappa| < 0.0283$ determined by Rizzo [1].

We determine $\tilde{\kappa} = 0.00 \pm 0.16$ and constrain it to the range $|\tilde{\kappa}| < 0.26$ at the 95% C.L. Our constraint, which is the first on this quantity, is considerably less stringent than that on $\kappa$ due to the lack of linear terms. This also means that the results for $\tilde{\kappa}$ are symmetric by construction. Were $\tilde{\kappa}$ to differ significantly from zero, then the likelihood distribution would have two distinct peaks either side of zero. Such structure was not, however, observed. The decay $W \to \tau\nu$ is also sensitive to charged current dipole terms but, given that the energy scale is $m_W$, the interpretation in terms of the static properties $\kappa$ and $\tilde{\kappa}$ is less clear.

We determine $\eta_{\tau\mu} = 0.009 \pm 0.022$ and constrain it to the range $-0.034 < \eta_{\tau\mu} < 0.053$ at the 95% C.L. The uncertainty on our measurement of $\eta_{\tau\mu}$ is significantly smaller than that obtained by Stahl using the same technique ($\eta_{\tau\mu} = 0.01 \pm 0.05$) [18] and more recent determinations using the shape of momentum spectra of muons from $\tau$ decays ($\eta_{\tau\mu} = -0.04 \pm 0.20$) [14].

## IV. DISCUSSION

Derivative couplings necessarily involve the introduction of a length or mass scale. Anomalous magnetic moments due to compositeness are expected to be of order $m_\tau/\Lambda$ where $\Lambda$ is the compositeness scale [20]. We can then interpret the 95% confidence level on $\kappa$, the quantity for which we have a more stringent bound, as a statement that the $\tau$ appears to be a point-like Dirac particle up to an energy scale of $\Lambda \approx m_\tau/0.016 = 110\,\mathrm{GeV}$. These results are comparable to those obtained from anomalous weak neutral current couplings [14] and more stringent than those obtained for anomalous electromagnetic couplings [15].

Many extensions of the Standard Model, such as Supersymmetry (SUSY), involve an extended Higgs sector with more than one Higgs doublet. Such models contain charged Higgs bosons which contribute to the weak charged current with couplings which depend on the fermion masses. Of all the Michel parameters, $\eta_{\tau\mu}$ is especially sensitive to the exchange of a charged Higgs. Following Stahl [18], $\eta_{\tau\mu}$ can be written as

$$\eta_{\tau\mu} = -\left(\frac{m_\tau m_\mu}{2}\right)\left(\frac{\tan\beta}{m_H}\right)^2 \tag{6}$$

where $\tan\beta$ is the ratio of vacuum expectation values of the two Higgs fields, and $m_H$ is the mass of the charged Higgs. This expression applies to type II extended Higgs sector models in which the up-type quarks get their masses from one doublet and the down-type quarks get their masses from the other.

We determine the one-sided constraint $\eta_{\tau\mu} > -0.0186$ at the 95% C.L. which rules out the region $m_H < (1.86 \tan\beta)\,\mathrm{GeV}$ at the 95% C.L. as shown in Fig. 1. An almost identical constraint on the high $\tan\beta$ region of type II models may be obtained from the process $B \to \tau\nu$ [21]. The most stringent constraint, from the L3 experiment, rules out the region $m_H < (2.09 \tan\beta)\,\mathrm{GeV}$ at the 95% C.L. [22]. Within the specific framework of the minimal supersymmetric standard model, the process $B \to \tau\nu X$ rules out the region $m_H < (2.33 \tan\beta)\,\mathrm{GeV}$ at the 95% C.L. [23]. This limit, however, depends on the value of the Higgsino mixing parameter $\mu$ and can be evaded completely for $\mu > 0$. The non-observation of proton decay also tends to rule out the large $\tan\beta$ region but these constraints are particularly model-dependent. The very low $\tan\beta$ region is ruled out by measurements of the partial width $\Gamma(Z \to b\bar{b})$. For type II models the approximate region excluded is $\tan\beta < 0.7$ at the $2.5\sigma$ C.L. for any value of $M_H$ [24]. Complementary bounds for the full $\tan\beta$ region are derived from the CLEO measurement of $BR(b \to s\gamma) = (2.32 \pm 0.57 \pm 0.35) \times 10^{-4}$ which rules out, for type II models, the region $M_H < 244 + 63/(\tan\beta)^{1.3}$ [25]. This constraint can, however, be circumvented in SUSY models where other particles in the loops can cancel out the effect of the charged Higgs. Direct searches at LEP II exclude the region $m_H < 54.5\,\mathrm{GeV}$ for all values of $\tan\beta$ [26]. The CDF search for charged Higgs bosons in the process $t \to bH^+$ rules out the region of low $m_H$ and high $\tan\beta$ [27].

The 95% C.L. constraints in the $m_H$ *vs.* $\tan\beta$ plane, from this and other analyses, are shown in Fig. 1.

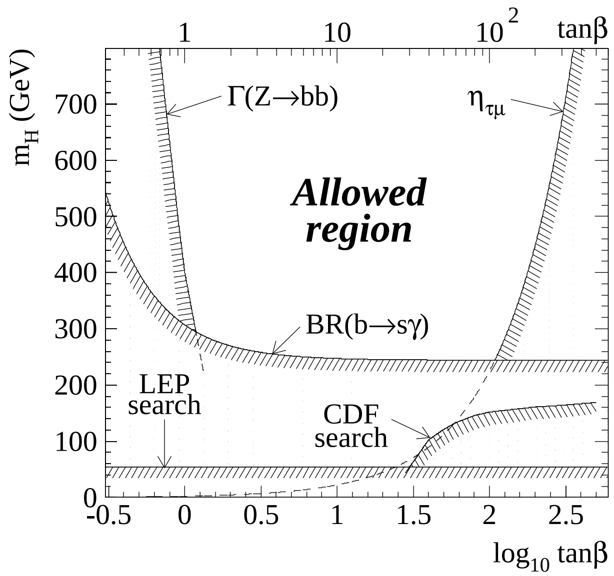

FIG. 1. Constraints on $m_H$ as a function of $\tan\beta$ at the 95% C.L., from this analysis of $\eta_{\tau\mu}$ and the other analyses described in the text.

## V. SUMMARY

From an analysis of tau leptonic branching fractions we determine

$$\kappa = 0.001 \pm 0.008; \tag{7}$$

$$\tilde{\kappa} = 0.00 \pm 0.16; \tag{8}$$

$$\eta_{\tau\mu} = 0.009 \pm 0.022. \tag{9}$$

Each of these results is the most precise determination to date. The result for $\kappa$ indicates that the tau is point-like up to an energy scale of approximately 110 GeV. The result for $\eta_{\tau\mu}$ constrains the charged Higgs of type II two-Higgs doublet models, such that the region

$$m_H < (1.86 \tan\beta)\,\mathrm{GeV} \tag{10}$$

is excluded at the 95% C.L.

## ACKNOWLEDGEMENTS

We would like to thank Carlos García Canal for bringing the topic of derivative couplings in tau decays to our attention, and for his continuing support. MTD acknowledges the support of CONICET, Argentina. JS and LT would like to thank the Department of Physics, Universidad Nacional de La Plata for their generous hospitality and the National Science Foundation for financial support. JS gratefully acknowledges the support of the International Centre for Theoretical Physics, Trieste.

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