Sensitivities of one-prong tau branching fractions to tau neutrino mass, mixing, and anomalous charged current couplings

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- J. Swain and L. Taylor, Phys. Rev **D 55**, 1R, (1997).
- M.T. Dova, J. Swain and L. Taylor, Phys. Rev **D 58**, 015005 (1998).

Introduction

We analyse the sensitivity to new physics of the τ partial widths for the following decays:

- $\tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau$
- $\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$
- $\tau^- \rightarrow \pi^- \nu_\tau$
- $\tau^- \rightarrow K^- \nu_\tau$

We consider the effects of the following:

- **mass m_{ν_3} of the third generation neutrino ν_3**
- **mixing of ν_3 with a 4th generation neutrino ν_4 (mass $> M_Z/2$)**
  (kinematically forbidden $\Rightarrow$ suppression of decay rate)
- **anomalous weak charged current magnetic dipole coupling (κ)**
- **anomalous weak charged current electric dipole coupling ($\tilde{\kappa}$)**
- **Michel parameter η**

Theoretical Predictions (m_{ν_τ} and $\sin^2\theta$)

$$\begin{aligned} \mathcal{B}_\ell^{\,\mathrm{th.}} &= \frac{G_F^2 m_\tau^5 \tau_\tau}{192\pi^3}\left(1 - 8x - 12x^2 \ln x + 8x^3 - x^4\right) \\ &\times \left[\left(1 - \frac{\alpha(m_\tau)}{2\pi}\left(\pi^2 - \frac{25}{4}\right)\right)\left(1 + \frac{3}{5}\frac{m_\tau^2}{m_W^2}\right)\right] \\ &\times \left[1 - \sin^2\theta\right]\left[1 - 8y(1-x)^3 + \cdots\right] \qquad (1) \end{aligned}$$

- $x = m_\ell^2/m_\tau^2$, $y = m_{\nu_3}^2/m_\tau^2$
- **QED coupling,** $\alpha(m_\tau) \simeq 1/133.3$
- **W mass,** $m_W = 80.41 \pm 0.10\,\mathrm{GeV}$
- **ellipsis denotes negligible higher order terms**

1st square brackets: radiative corrections
2nd square brackets: mixing of ν_3 and ν_4 $\left(|\nu_\tau\rangle = \cos\theta|\nu_3\rangle + \sin\theta|\nu_4\rangle\right)$
3rd square brackets: phase-space suppression for $m_{\nu_3} > 0$

Theoretical Predictions (m_{ν_τ} and $\sin^2\theta$)

Branching fractions for $\tau^- \to h^-\nu_\tau$, with $h = \pi/K$

$$\mathcal{B}_h^{\text{th.}} = \left(\frac{G_F^2 m_\tau^3}{16\pi}\right) \tau_\tau f_h^2 |V_{\alpha\beta}|^2 (1-x)^2 \left(1 + \frac{2\alpha}{\pi}\ln\left(\frac{m_Z}{m_\tau}\right) + \cdots\right)$$
$$[1-\sin^2\theta]\left[1 - y\left(\frac{2+x-y}{1-x}\right)\left(1 - \frac{y(2+2x-y)}{(1-x)^2}\right)^{\frac{1}{2}}\right] \qquad (2)$$

- $x = m_h^2/m_\tau^2$,
- $f_\pi|V_{ud}| = (127.4 \pm 0.1)\text{MeV}$ (from $\pi^- \to \mu^-\bar{\nu}_\mu$)
- $f_K|V_{us}| = (35.18 \pm 0.05)\text{MeV}$ (from $K^- \to \mu^-\bar{\nu}_\mu$)
- ellipsis represents missing terms estimated to be $\mathcal{O}(\pm 0.01)$

1st term in square brackets: mixing with a fourth generation neutrino

2nd term in square brackets: phase-space suppression for $m_{\nu_3} > 0$

Additional constraint from non-threshold determinations of tau-mass, e.g. CLEO analysis of $\tau^+\tau^- \to (\pi^+ n\pi^0\bar{\nu}_\tau)(\pi^- m\pi^0\nu_\tau)$ (with $n \leq 2, m \leq 2, 1 \leq n+m \leq 3$)

$$m_\tau = (1777.8 \pm 0.7 \pm 1.7) + [m_{\nu_3}(\text{MeV})]^2/1400MeV$$

Theoretical Predictions $(\kappa, \tilde{\kappa}, \eta)$

Anomalous dipole moment couplings described by effective Lagrangian

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

Theoretical predictions for branching fractions $\mathcal{B}_\ell$ for $\tau^- \rightarrow \ell^- \bar{\nu}_\ell \nu_\tau (X_{\rm EM})$, with $\ell^- = e^-, \mu^-$ and $X_{\rm EM} = \gamma,\ \gamma\gamma,\ e^+e^-, \ldots$

$$\begin{aligned} \mathcal{B}_\ell^{\rm th.} &= \frac{G_F^2 m_\tau^5 \tau_\tau}{192\pi^3}\left(1 - 8x - 12x^2 \ln x + 8x^3 - x^4\right) \\ &\times \left(1 - \frac{\alpha(m_\tau)}{2\pi}\left(\pi^2 - \frac{25}{4}\right)\right)\left(1 + \frac{3}{5}\frac{m_\tau^2}{m_W^2}\right)[1 + \Delta_\ell]. \end{aligned} \tag{3}$$

Effects of new physics parametrised by Δ_ℓ

$$\Delta_\ell^\kappa = \kappa/2 + \kappa^2/10 \tag{4}$$

$$\Delta_\ell^{\tilde{\kappa}} = \tilde{\kappa}^2/10 \tag{5}$$

$$\Delta_\ell^\eta = 4\eta_{\tau\ell}\sqrt{x} \tag{6}$$

Both leptonic tau decay modes probe are sensitive to κ and $\tilde{\kappa}$

Only $\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$ sensitive to η (relative suppression of m_e/m_μ for $\tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau$)

Semi-leptonic tau branching fractions are not sensitive

Fits

Three sets of fits are performed

- **Case 1**
  Use current world averages of the experimental measurements.
- **Case 2**
  Use estimated errors on measurements at a τcF
  (assume no improvement in the tau lifetime error)
- **Case 3**
  Use estimated errors on measurements at a τcF
  (and suppose CLEO/b-factories reduce tau lifetime error by $\times 2$)

For Cases 2 and 3 the central values are unknown
$\Rightarrow$ adjust branching fractions to their SM central values, so predictions are not arbitrarily biased by current experimental central values

Input Parameters

	Value	Future Error	
	Case 1	Case 2	Case 3
m_τ (MeV)	$1776.96^{+0.31}_{-0.27}$ (BES)	0.1 (Marbella)	0.1 (Marbella)
τ_τ (fs)	290.5 ± 1.0 (TAU98)	1.0 (TAU98)	0.5 (our hope)
$\mathcal{B}_e$ (%)	17.81 ± 0.06 (TAU98)	0.018 (Marbella)	0.018 (Marbella)
$\mathcal{B}_\mu$ (%)	17.36 ± 0.06 (TAU98)	0.017 (Marbella)	0.017 (Marbella)
$\mathcal{B}_\pi$ (%)	11.08 ± 0.13 (TAU98)	0.011 (Marbella)	0.011 (Marbella)
$\mathcal{B}_K$ (%)	0.695 ± 0.026 (TAU98)	0.003 (Marbella)	0.003 (Marbella)

Fits for m_{ν_τ} and $\sin^2\theta$

- Combined likelihood fits to all four tau decay channels
- Include constraint from CLEO tau mass determination

Fits for κ, $\tilde{\kappa}$, and $\eta_{\tau\mu}$

- Combined likelihood fits two leptonic tau decay channels
- Semi-leptonic decays are not sensitive

Each parameter is analysed separately

- conservatively assume in each case that the other four parameters are zero

Results

Constraints on m_{ν_3}, $\sin^2\theta$, κ, $\tilde{\kappa}$, and $\eta_{\tau\mu}$ (95% C.L.)

Case 1 (now)	Case 2 (τcF, $\sigma_{\tau_\tau} = 1.0\,fs$)	Case 3 (τcF, $\sigma_{\tau_\tau} = 0.5\,fs$)
$m_{\nu_3} < 36$ MeV	$m_{\nu_3} < 34$ MeV	$m_{\nu_3} < 28$ MeV
$\sin^2\theta < 0.0053$	$\sin^2\theta < 0.0039$	$\sin^2\theta < 0.0024$
$-0.011 < \kappa < 0.017$	$-0.011 < \kappa < 0.009$	$-0.006 < \kappa < 0.005$
$\lvert\tilde{\kappa}\rvert < 0.26$	$\lvert\tilde{\kappa}\rvert < 0.20$	$\lvert\tilde{\kappa}\rvert < 0.15$
$-0.030 < \eta_{\tau\mu} < 0.052$	$-0.030 < \eta_{\tau\mu} < 0.029$	$-0.017 < \eta_{\tau\mu} < 0.016$

For Cases 2 and 3 the limiting error is from tau lifetime
(arbitrarily setting all other errors to zero yields negligible improvement)

Discussion (m_{ν_τ})

Limit on m_{ν_3} can be interpreted as limit on m_{ν_τ}
($\sin^2\theta$ is small as is mixing of m_{ν_3} with lighter neutrinos)

Our constraint is less stringent than the best direct constraint ($m_{\nu_\tau} < 18.2$ MeV at 95% C.L. from ALEPH) but it is

- statistically independent
- insensitive to fortuitous or pathological events at kinematic limits
- almost independent of absolute energy scale of the detectors
- independent of details of resonant structure of multi-hadron τ decays

Our constraint on m_{ν_τ} improves only slightly with the τcF input

Our method is not competitive with other τcF analyses
for which expected τcF sensitivity is $O(2\,\mathrm{MeV})$

Discussion ($\sin^2\theta$)

Our upper limit on $\sin^2\theta$ is already the most stringent experimental constraint on mixing of the third and fourth neutrino generations

This constraint will improve by a factor of up to two using future τcF data (depending on the improvement in the error on τ_τ)

We anticipate that this technique will continue to provide the most stringent constraints in the foreseeable future

Discussion (κ, $\tilde{\kappa}$)

Our results on κ and $\tilde{\kappa}$ are currently the most precise

Constraint on $\tilde{\kappa}$ is less stringent compared to κ due to lack of linear terms

Anomalous magnetic moments due to compositeness are expected to be of order m_τ/Λ where Λ is the compositeness scale

$\Rightarrow$ τ **appears to be a point-like Dirac particle up to**

$$\Lambda \approx m_\tau/0.017 = 105\,\mathrm{GeV}$$

Results are comparable to those from anomalous weak neutral current couplings and better than those from anomalous EM couplings

The results for κ and $\tilde{\kappa}$ will improve with τcF data and will probe the point-like nature of the tau up to a scale of

$\Lambda = O(180\,\mathrm{GeV})$ (for no improvement in τ_τ)

$\Lambda = O(300\,\mathrm{GeV})$ (for $\times 2$ improvement on τ_τ error)

Discussion ($\eta_{\tau\mu}$)

This $\eta_{\tau\mu}$ is currently the most precise

Compare to $\eta_{\tau\mu} = -0.04 \pm 0.20$ from momentum spectrum of muons from τ decays

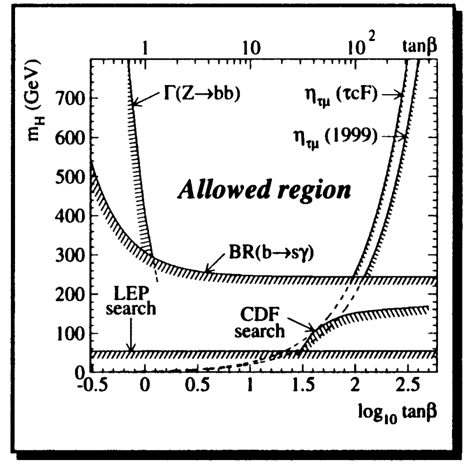
$\eta_{\tau\mu}$ sensitive to type II charged Higgs

$$\eta_{\tau\mu} = -\left(\frac{m_\tau m_\mu}{2}\right)\left(\frac{\tan\beta}{m_H}\right)^2 \qquad (7)$$

- $\tan\beta$ – ratio of VEV's of two Higgs fields
- m_H – mass of the charged Higgs

Our fit yields $\eta_{\tau\mu} > -0.0232 \quad \Rightarrow$

$$m_H < (2.01 \tan\beta)\,\mathrm{GeV}\ (95\% C.L.)$$



For τcF: $\eta_{\tau\mu} > -0.014 \Rightarrow$

$$m_H < (2.55 \tan\beta)\,\mathrm{GeV}\ (95\% C.L.)$$

~25% reduction in maximum value of $\tan\beta$ for given m_H compared to today

Summary

We analyse the sensitivity to new physics of the τ partial widths for: $\tau^- \to e^-\bar{\nu}_e\nu_\tau$, $\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$, $\tau^- \to \pi^-\nu_\tau$, and $\tau^- \to K^-\nu_\tau$

	Today	τ**cF**
m_{ν_τ}	**Worse than e.g. ALEPH (but complementary)**	**Slight improvement Not competitive**
$\sin^2\theta$	**World-best**	$O(\times 2)$ **improvement**
κ	**World-best**	$O(\times 2)$ **improvement**
$\tilde{\kappa}$	**World-best**	$O(\times 2)$ **improvement**
τ **compositeness**	$\Lambda > 105\,\mathrm{GeV}$	$\Lambda > O(300)\,\mathrm{GeV}$
η	**World-best**	$O(\times 2)$ **improvement**
Charged Higgs	$m_H < (2.01\tan\beta)\,\mathrm{GeV}$	$m_H < (2.55\tan\beta)\,\mathrm{GeV}$

Significant improvements using τcF data

Ultimate limitation is the error on the tau lifetime

Tau Neutrino Mass from Decay Rates of Charmed Pseudoscalar Mesons

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The Idea

☛ **Charmed pseudoscalars D and D_s can (just) decay to $\tau\nu_\tau$**

- **Sensitive to neutrino mass**
- **Theoretical errors (f_P; P=D,D_s) can be taken out using ratio of muon and tau decay rates**
- **τcF a good source of charmed pseudoscalars (P. Kim)**

Following R. R. Mendel, *et al.*, Z. Phys. C32 (1986) 517:

$$x_P = \frac{\mathrm{BR}(P \to \tau^+\nu_\tau)}{\mathrm{BR}(P \to \mu^+\nu_\mu)}$$

$$x_P = \sqrt{M_P^4 - 2M_P^2(m_\tau^2 + m_\nu^2) + (m_\tau^2 - m_\nu^2)^2}\,\frac{M_P^2(m_\tau^2 + m_\nu^2) - (m_\tau^2 - m_\nu^2)^2}{(M_P^2 - m_\mu^2)^2 m_\mu^2}$$

Graphically

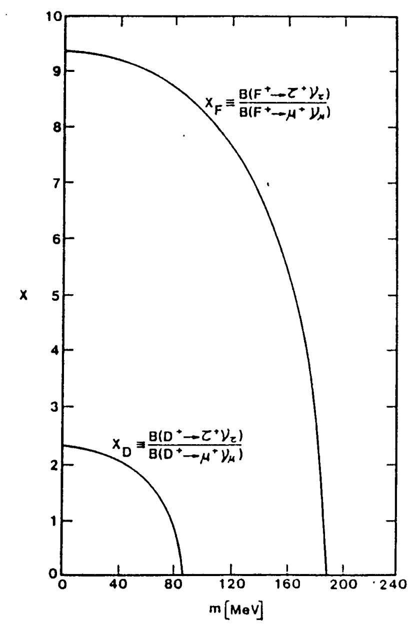

Fig. 4. Curves of x_D and x_F as functions of m. calculated using (20) and the values given in the text for the relevant masses

Tabular Results

m_ν (MeV)	x_D	x_{D_s}
0	2.6382	9.74318
1	2.63809	9.7431
2	2.63766	9.74282
3	2.63702	9.74238
4	2.63612	9.74176
5	2.63491	9.74094
6	2.63349	9.73996
7	2.63176	9.73879
8	2.62982	9.73746
9	2.62756	9.73592
10	2.62508	9.73424
11	2.62227	9.73233
12	2.61924	9.73027
13	2.61594	9.72803
14	2.61234	9.7256
15	2.60846	9.72298
16	2.60433	9.72019

Table 1: Table of x_P values

How Well Could We Do?

Not much of the basic input information is known, so let's estimate freely assuming no theoretical errors and no errors on pseudoscalar masses:

- **Expect 0.9×10^7 D_s pairs per year and 2.0×10^7 $D^{\pm}$ pairs per year at 10fb^{-1}.**
- **Know BR$(D_s \rightarrow \mu\nu) \sim 4 \times 10^{-3}$ (large errors).**
- **Expect BR$(D \rightarrow \mu\nu) \sim 7 \times 10^{-4}$**

Suppose we have 10^7 D_s's and and get 40,000 D_s decaying to muons. Assume the statistical error on this quantity dominates the error on x_{D_s}.

- **5 parts per mil, and an absolute error on x of .05 – *i.e.* about 25 MeV at one sigma.**

Suppose we have 2×10^7 D's. Then we get 14000 D's decaying to muons. Assume again this error dominates (less of a good approximation)

- **8.5 parts per mil, and an absolute error on x of .022 – *i.e.* about 13 MeV at one sigma.**

Conclusions

- Leptonic charmed meson decays can give us some statistically independent information about a possible tau neutrino mass complementary to what comes from kinematics.
- There's a lot we still don't know about charmed mesons, but most of the theoretical uncertainties (form factors) can be eliminated by taking ratios.
- Perhaps not the greatest way to get information on a neutrino mass, but it's one more piece!
- Beware helicity unsuppressed $D \to \mu \nu \gamma$ (Rizzo)
- Bgnds $\to \eta$ make this harder? (P. Kim)

First Steps in Tau Neutrino Mass Determinations from One-Prong Tau Decay Kinematics

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The Idea

☛ **Measure the momentum spectra of pions from τ decays almost at rest (JZK).**

- **Sensitive to neutrino mass**
- **Theoretical errors should be easily controllable**
- **Complementary to multi-pion invariant mass analyses and others.**

☛ 5×10^6 $\tau \rightarrow \pi\nu$ **decays**

☛ **Baseline resolutions (Marbella)**

☛ $\sim$ **5 MeV neutrino mass sensitivity at 1** σ (no beam smear, stats only)

☛ **More work needed, but this looks promising.**
(But see more detailed talk of A. Stahl)