Why the $\tau$ is Boring and Why that is Exciting

Tau Review WIN02
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The Tau in Other Fields

The TAU is the last letter of the Greek alphabet and in spiritual terms represents the end or the fulfillment of the revealed word. It is a sign of life and salvation. In the Old Testament the prophet marks those with a Tau who have chosen to reject a sinful lifestyle (Ezekiel 9:4).

From: Hospital Sisters of St Francis web site
Outline

- Overview of the \( \tau \)
- Leptonic \( \tau \) Decays
- Lepton Universality
- Lorentz Structure & Michel Parameters
- Inclusive Hadronic Decays
  - Spectral Functions
  - CVC
  - \( \text{Alpha}_s \)
  - Vacuum Polarization
- Tau as Hadron Factories
- Rare Decays
- Forbidden Decays
- CP Violation
- Neutrino Properties
Overview of the $\tau$

- $m_{\tau} = 1777.0 (0.3) \text{ MeV}$ – BES
- Lifetime = 290.6 (1.1) fs (LEP, CLEO)
- $B_e = B(\tau \rightarrow e\nu\nu) = 17.80 (0.05) \%$ (tau2K WA)
- $B(\tau \rightarrow \mu\nu\nu) = 17.34 (0.05) \%$ (tau2K WA)
- $B(\tau \rightarrow e\gamma\nu\nu) = 1.75(0.18) \%$  
  $B(\tau \rightarrow \mu\gamma\nu\nu) = 0.361(0.038) \%$  
  $E_\gamma > 10 \text{MeV}$ CLEO
- $B(1/3/5\text{prong}) = 85.27(0.13) \% \text{ / } 14.56(0.13) \% \text{ / } 0.17(0.04) \%$
- Expected final states:
  - $e\nu\nu, \mu\nu\nu$
  - $n\pi\nu, \nu = 1,2,3,4,5,6$
  - $K\pi\nu, \nu = 0,1,2,3$
  - $K\eta\pi\nu, \eta\pi\nu, \eta\pi\nu$
  - $\eta K\pi\nu, \omega\pi\nu, \omega\pi\nu$
Leptonic Tau Decays

- SM predicts

\[ B_\ell \equiv B(\tau \rightarrow \ell \nu \nu) \propto \tau_\tau m_\tau^5 f(m_\ell) \]

- Mass: \( M_\tau = 1777.0(0.3) \) MeV (BES)
- Lifetime: \( \tau_\tau = 290.6 (1.1) \) fs (LEP+CLEO)
- \( B_e = 17.80(0.05)\% \) (LEP+CLEO)
- \( B_\mu = 17.34(0.05)\% \) (LEP+CLEO)

\[ d_\theta \equiv \cos \theta_c d + \sin \theta_c s \]
Lepton Universality: Tau Decay

- Full SM prediction for Lepton Decay

\[ B(\tau^{-} \to \ell^{-} \bar{\nu}_{\ell} \nu_{\tau}) = \left( \frac{m_{\tau}^{5} \tau_{\tau}}{192 \pi^{3}} \right) \left( \frac{g_{\ell}^{2} g_{\tau}^{2}}{32 m_{W}^{4}} \right) f(m_{\ell})(1 + S_{EW}) \]

Compare \( g \) from tau decays to each other and other weak decays

- \( B_{e} \) vs \( B_{\mu} \):
  \[ g_{\mu} / g_{e} = 1.0010 \pm 0.0020 \]

- \( \pi \) to \( e \nu \), \( \mu \nu \):
  \[ g_{\mu} / g_{e} = 1.0020 \pm 0.0016 \]

- \( B_{e} \) vs \( < B_{\mu} > \):
  \[ g_{\tau} / g_{\mu} = 0.9994 \pm 0.0023 \]

- \( B_{\mu} \) vs \( < B_{e} > \):
  \[ g_{\tau} / g_{e} = 1.0000 \pm 0.0023 \]

- \( g_{e} = g_{\mu} \):
  \[ g_{\tau} / g_{l} = 0.9997 \pm 0.0020 \]

- \( \tau \) to \( \pi \nu \), \( K \nu \):
  \[ g_{\tau} / g_{\mu} = 1.0029 \pm 0.042 \]

- W to \( l \nu \) Universality good at 2.5% level from LEP and CDF/D0
Lorentz Structure

Theorists Prefer

- General, local, derivative free, lepton number conserving, Lorentz invariant structure for fully leptonic decay
- SM: $g_{\text{LL}}^V = 1$ ; 11 others = 0

Experimentalists Prefer Something they can measure

Michel Parameters use Observed Quantities

$$\frac{1}{\Gamma} \frac{d\Gamma}{dx \cos \theta} = \frac{x_\ell^2}{2} \left\{ 12(1-x_\ell) + \frac{4\rho}{3} (8x_\ell - 6) + 24\eta \frac{m_\ell}{m_e} \frac{1-x_\ell}{x_\ell} - P_\ell \xi \cos \theta \left[ 4(1-x_\ell) + \frac{4}{3} \delta (8x_\ell - 6) \right] \right\}$$

$$x_\ell = \frac{E_\ell}{E_{\text{max}}}$$

SM: $\rho = \frac{3}{4}$, $\eta = 0$, $\xi = 1$, $\xi \delta = \frac{3}{4}$
CLEO’s Analysis

- At CLEO - no polarized beams
- But τ+ and τ- spins are 95 % correlated
- Use τ to ρν decay as spin analyzer vs τ to lνν
- Promising future at BELLE, Babar: stat error dominates

\[
\frac{1}{\Gamma} \frac{d\Gamma}{dx_\ell} = h_0 + \eta h_\eta + \rho h_\rho - \{\xi h_\xi + \xi \delta h_\xi \delta\}
\]

Polarization
• SM is still OK
• $\chi^2$/dof is too good
• CLEO dominates all but $\eta$ value (DELPHI, OPAL)
• Other Michel param exist in radiative decays - CLEOc, BES2?

$\chi^2$/ndf = 3.6 / 7
World Summary of $g_{ij}^{\gamma}$ Couplings

- Coupling to right handed currents excluded
- Coupling limits from mu are still more stringent than limits from taus
- No LL limits - need $\nu$ scattering to separate $S$ from $V$
Hadronic Tau Decays

• Weak current (final state) - first class currents:
  – V: G=+1, J^P=1^- ρ- (2n) π
  – A: G=-1, J^P=0^-,1^+ π-, a1- (2n+1) π

• Opposite G parity = second class
  – suppressed (Isospin violation) - soon to be observed?

• Use to study inclusive QCD properties, CVC

• Use as a lab to generate lighter mesons
Inclusive Hadronic Decays

*Spectral Function*:

Decay product Mass Spectrum, after $\nu$ decay kinematic correction + branching ratio normalization

This can be broken up into $V,A$, +Strange contributions, and studied as a function of $q^2$

\[ \nu(s) = \frac{B_x}{B_e} \]

Branching Ratio Norm  
$q^2$ Spectrum  
V-A kinematics
CVC

- CVC (Isospin): weak coupling in $\tau$ decay is related to $e^+e^-$ scattering, eg:

$$B(\tau^- \rightarrow \pi^- \pi^0 \nu) = f(\tau, m_\tau) \int dq^2 g(q^2) \sigma^{I=1}_{ee \rightarrow \pi\pi}(q^2)$$

$$B_{\pi\pi}^{WA} = 25.17(14) \%$$

$$B_{\pi\pi}^{CVC} = 24.94(23) \%$$

CLEO

Tau2000
CVC (cont)

Global test of CVC

CVC is (mostly) OK

2 $\sigma$ discrepancy in $3\pi\pi^0$ and $\pi\omega$

$\tau^– \rightarrow \pi^- \omega \nu$

$e^+e^- \rightarrow \pi^0 \omega$
The tau mass is just large enough to allow a believable calculation of:

\[ R_\tau = \frac{\Gamma(\tau \rightarrow \text{hadrons } \nu)}{\Gamma(\tau \rightarrow e \nu \nu)} \]

\[ \alpha_S(m^2_\tau) = 0.345(0.020) \]

\[ \alpha_S(m^2_Z) = 0.1208(0.025) \]
Strange Quark Mass

- Use a moments analysis

\[ R_{\tau,S}^{kl} = \int_0^{m_{\tau}^2} ds \left( 1 - \frac{s}{m_{\tau}^2} \right)^k \left( \frac{s}{m_{\tau}^2} \right)^l \frac{dR_{\tau,S}}{ds} \]

Compare moments Strange=1 and S=0 moments

Allows optimal balancing of theory uncertainties, experimental errors at different \( s \)

\[ m_s(m_{\tau}^2) = 112(23) \text{ MeV} \]
Hadronic Vacuum Polarization

• What is the probability of popping qq out of the Vacuum? 
  \( \gamma^* \rightarrow qq \rightarrow \gamma^* \)

• Use e+e- \( \rightarrow \gamma^* \rightarrow qq \rightarrow \text{hadrons} \)

• CVC relates this to \( \tau \) spectral functions \( \tau \rightarrow \text{hadrons} \nu \)

• Direct impact on \( \alpha_{\text{QED}}, \ (g-2)_\mu \)

\[
\Delta \alpha_{\text{had}}(M_Z^2) = (...) \int ds \sigma_{e^+e^-}(s) \tilde{K}(s)
\]

\[
a^\text{had}_\mu = (...) \int ds \sigma_{e^+e^-}(s) K(s)
\]
Rare Decays

- \( \mathcal{B}(\tau \to (\omega\pi)_{1++}\nu) < 1.3 \times 10^{-3} \) (2\textsuperscript{nd} Class) CLEO99
- \( \mathcal{B}(\tau \to \eta K\pi\nu) = 5.0 (1.2) \times 10^{-4} \) CLEO98
- \( \mathcal{B}(\tau \to \eta 3\pi\nu) = 4.8 (1.1) \times 10^{-4} \) CLEO98
- \( \mathcal{B}(\tau \to \pi^-K^0\bar{K}^0\nu) = 3.1(2.3) \times 10^{-4} \) ALEPH98
- \( \mathcal{B}(\tau \to K^-K^+K^-\nu) < 1.9 \times 10^{-4} \) ALEPH98
- \( \mathcal{B}(\tau \to \eta \pi\nu) < 1.4 \times 10^{-4} \) (2\textsuperscript{nd} Class) CLEO96
- \( \mathcal{B}(\tau \to e^+e^-e^+\nu\nu) = 2.8(1.5) \times 10^{-5} \) CLEO98
- \( \mathcal{B}(\tau \to 7\pi^{\pm/-}\nu) < 2.4 \times 10^{-6} \) CLEO97

Lots of room for Improvement from B factories
Forbidden Decays

Massive neutrinos could induce neutrinoless decays

- In some L-R sym SUSY models

“Weak” $\tau$ Limits Can Beat “Tight” $\mu$ Limits

$$B(\tau \to \mu \gamma) \approx (10^5 - 10^6)B(\mu \to e \gamma)$$

$B(\tau \to \mu^-\gamma) < 1.0 \times 10^{-6}$ (Belle 2001) 19M $\tau\tau$

$B(\mu \to e^-\gamma) < 1.2 \times 10^{-11}$ (MEGA /LAMPF 99)

$B(\tau \to \mu^-\gamma) < 1.1 \times 10^{-6}$ (CLEO00) 12M $\tau\tau$
Forbidden Decays (cont)

PDG: big list of limits for neutrinoless modes

\[ B(\tau \to X Y) < 10^{-3} \text{ to } 10^{-6} \]

\[ X=(e,\mu,p) \quad Y=(\gamma, m\pi, nK) \]

Newcomer: Belle 2001 - 21.5M \( \tau \tau \)

\[ B(\tau \to e^{-}K^{0}) < 1.8 \times 10^{-6} \]

\[ B(\tau \to \mu^{-}K^{0}) < 1.8 \times 10^{-6} \]

Lots of Potential for Belle and Babar
Search for CP violation in processes with interfering amplitudes

isospin violation in $\tau \rightarrow 2\pi \nu$

Su(3) violation in $\tau \rightarrow K \pi \nu$
Belle CPV in $\tau \rightarrow \pi \pi^0 \nu$

Use one side of events

$\tau \rightarrow \pi \pi^0 \nu$

$\beta$ - measured

$\Psi$ – kinematic constraint

$$|A_{CP}(\cos \beta \cos \psi)| = \left| \frac{N^+ (\cos \beta \cos \psi) - N^- (\cos \beta \cos \psi)}{N^+ (\cos \beta \cos \psi) + N^- (\cos \beta \cos \psi)} \right| < 0.016$$

BELLE-CONF-0019 - 2M $\tau$ pairs

Similar CLEO analysis for $K\pi$ final state - PRL81,3823(1998)
CLEO CPV in $\tau \rightarrow \pi\pi^0\nu$

$\tau$ pairs are produced coherently : Can use info from other $\tau$

Use $\tau \rightarrow \pi\pi^0\nu$ vs $\tau \rightarrow \pi\pi^0\nu$

“optimal observable”

D. Atwood, A. Soni

PRD45(1992)2405

$\xi = \frac{CevenPodd}{CevenPeven}$

Model dependent limit on relative Higgs like coupling

$-0.046 < \text{Im}(\Lambda) < 0.022 \ @ 90\% \text{CL}$

12M $\tau$ pairs

PRD64, 092005(2001) hep-ex/0104009
CLEO CPV in $\tau \to K^0\pi \nu$

$\tau \to K^0\pi \nu$ vs $\tau \to X\nu$ (use only 1 side)

Optimal Observable $\xi$ from CP odd interference between $K^*$ and $K_{0}^{*}(1430)$

Limit on Higgs like coupling relative to W

$-0.174 < \text{Im}(\Lambda) < 0.049 \text{ @90\% CL}$

sub to PRL – hep-ex/0111095
$\nu_\tau$ Properties

- Observed by DONUT !!!
- Mixing??
- Mass limit (irrelevant??)
  - $M_\nu<18$ MeV Aleph
    Method has oddities - see tau2000 writeup
  - $M_\nu<37$ MeV from $B_\nu$
- Helicity :Michel Params
  - $\xi_h=-0.996(0.007)$
- EDM, magnetic moment
Tau Review Conclusions 1

- Leptonic $\tau$ are apparently “very Standard Model”
- Hadronic $\tau$ decays are well measured
- Hadronic $\tau$ decays provide a lab for QCD with applications well beyond $\tau$
- $\nu$ mixing make $\tau$ neutrinoless decay searches exciting
- CP Violation studies will improve
- Belle is off to a running start (Babar?)
- BES2/CLEO-C have interesting niches
Tau Review Conclusions 2

Remember the τ on the forehead?

• Ezekiel 9:4 ...Walk through the streets of Jerusalem and put a mark on the foreheads of all those who weep and sigh because of the sins they see around them...

Why you really should learn about τ’s:

• Ezekiel 9:5 ...Follow him through the city and kill everyone whose forehead is not marked. Show no mercy; have no pity!...