Why the τ is Boring and Why that is Exciting

Tau Review WIN02

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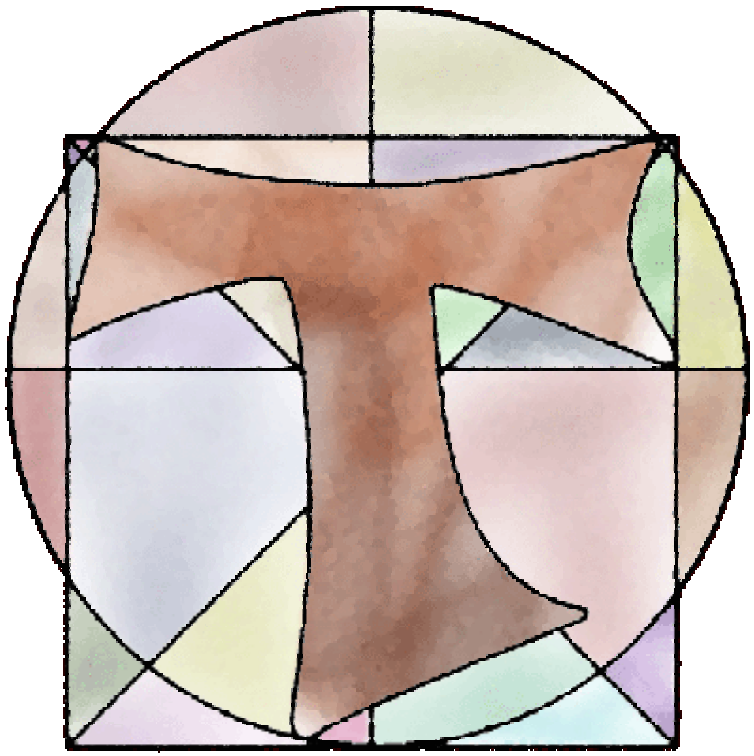
Thanks to: T. Browder, M. Davier, S. Eidelman, H. Evans, KK Gan, R. Kass, A. Pich, M. Roney, R. Sobie, A. Stahl, R. Stroynowski, J. Swain, J. Urheim, A. Weinstein

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 τ
- Leptonic τ Decays
- Lepton Universality
- Lorentz Structure & Michel Parameters
- Inclusive Hadronic Decays
  - Spectral Functions
  - CVC
  - Alpha_s
  - Vacuum Polarization
- Tau as Hadron Factories
- Rare Decays
- Forbidden Decays
- CP Violation
- Neutrino Properties

Overview of the τ

- m_τ= 1777.0 (0.3) 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_γ>10MeV CLEO
- B(1/3/5prong) = 85.27(0.13) % /14.56(0.13) / 0.17(0.04) %
- Expected final states:

$e\nu\nu$, $\mu\nu\nu$

$n\pi\nu$, ν=1,2,3,4,5,6

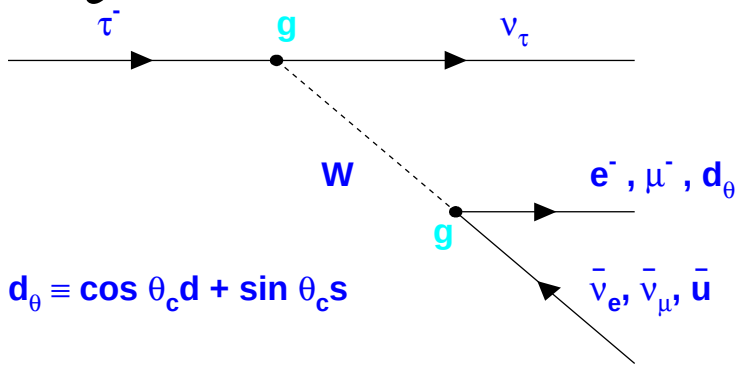
$Kn\pi\nu$, ν=0,1,2,3

$KKn\pi\nu$, n= 0, 1,2

($\eta\pi\nu$), $\eta 2\pi\nu$, $\eta 3\pi\nu$,

$\eta K\pi\nu$, $\omega\pi\nu$, $\omega 2\pi\nu$

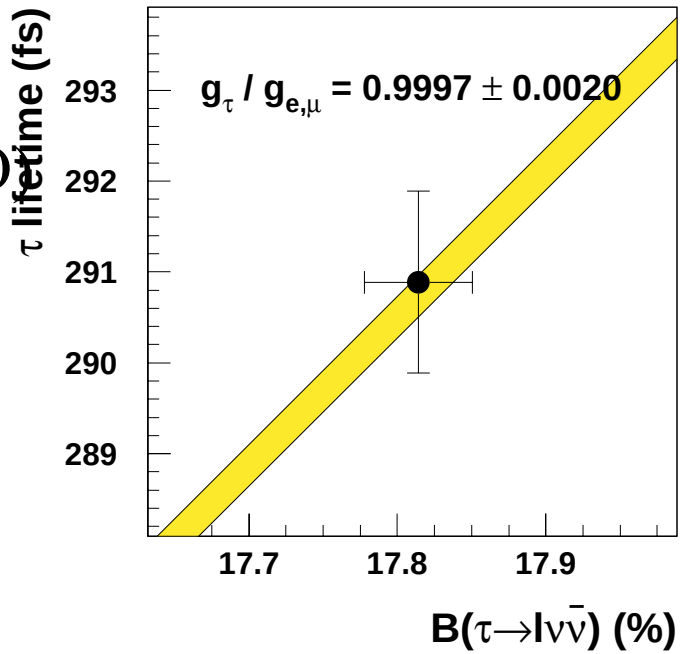
Leptonic Tau Decays



- SM predicts

$$B_\ell \equiv B(\tau \to \ell \nu\nu) \propto \tau_\tau m_\tau^5 f(m_\ell)$$

- Mass: M_τ=1777.0(0.3) MeV (BES)
- Lifetime: τ_τ=290.6 (1.1) fs (LEP+CLEO)
- B_e=17.80(0.05)% (LEP+CLEO)
- B_μ=17.34(0.05)% (LEP+CLEO)



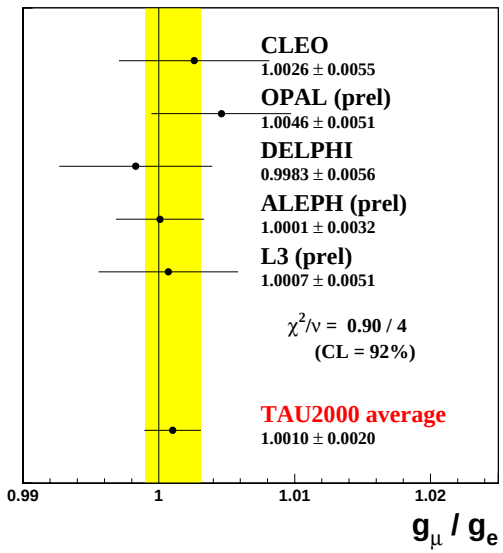
Lepton Universality: Tau Decay

- Full SM prediction for Lepton Decay

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

Compare g from tau decays to each other and other weak decays

B_e vs B_μ:	g_μ/g_e = 1.0010 +/- 0.0020
π to $e\nu$, $\mu\nu$	g_μ/ g_e = 1.0020+/- 0.0016
B_e vs < B_μ >	g_τ/ g_μ = 0.9994 +/- 0.0023
B_μ vs <B_e>	g_τ / g_e = 1.0000 +/- 0.0023
$g_e = g_\mu$	g_τ /g_l = 0.9997 +/- 0.0020
τ to $\pi\nu$, $K\nu$	g_τ / g_μ = 1.0029 +/- 0.042



W to l ν 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: $g^{V}_{LL}=1$; 11 others = 0

$$M = \frac{4G_F}{\sqrt{2}} \sum_{\gamma=S,V,T} \sum_{i,j=L,R} g^{\gamma}_{ij} \left(\bar{\ell}_i \Gamma^{\gamma} \nu_{\ell}\right)\left(\overline{\nu_{\tau}} \Gamma_{\gamma} \tau_j\right)$$

$$\Gamma^{S,V,T} = 1 \ , \ \gamma^{\mu} \ , \ \frac{i}{2\sqrt{2}}\left[\gamma^{\mu},\gamma^{\nu}\right]$$

Experimentalists Prefer Something they can measure

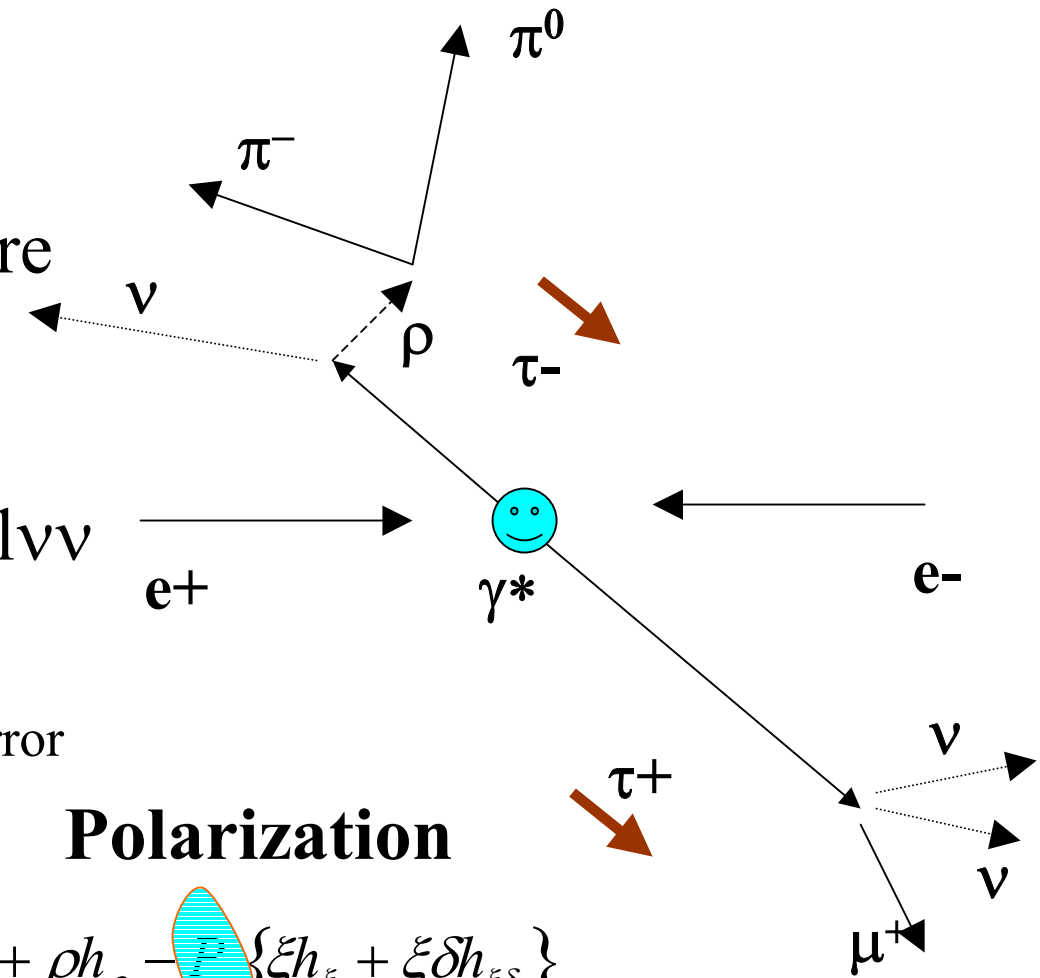
Michel Parameters use Observed Quantities

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

SM: $\rho = 3/4$ $\quad \eta = 0$ $\quad \xi = 1$ $\quad \xi\delta = 3/4$

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

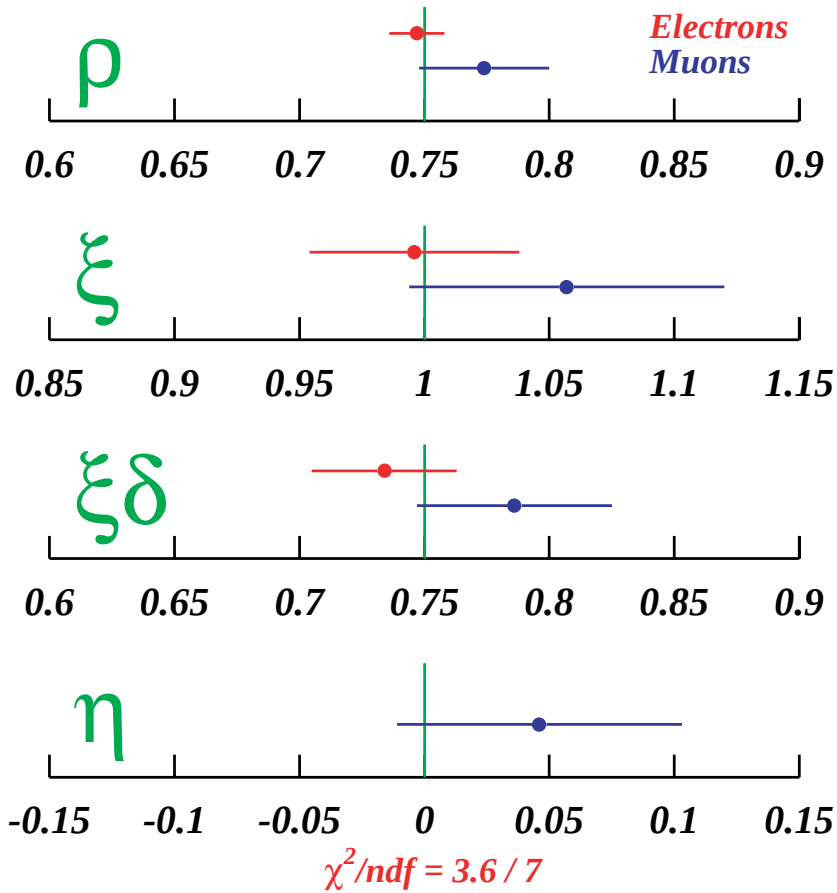


Polarization

$$\frac{1}{\Gamma}\frac{d\Gamma}{dx_\ell} = h_0 + \eta h_\eta + \rho h_\rho - P_\tau \{\xi h_\xi + \xi\delta h_{\xi\delta}\}$$

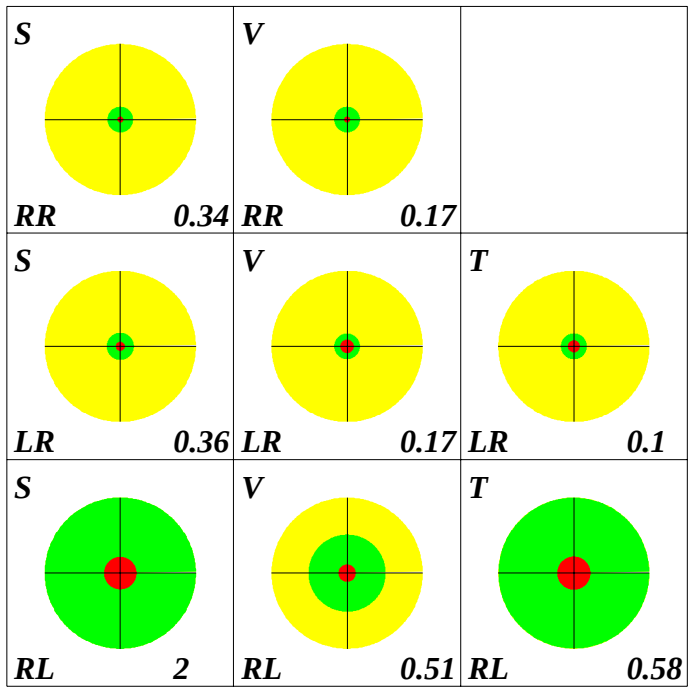
WA of Michel Parameters

- SM is still OK
- χ^2 /dof is too good
- CLEO dominates all but η value (DELPHI,OPAL)
- Other Michel param exist in radiative decays - CLEOc, BES2?



World Summary of g^{γ}_{ij} Couplings

- Coupling to right handed currents excluded
- Coupling limits from mu are still more stringent than limits from taus
- No LL limits - need ν 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

Jargon Alert

Spectral Function:

Decay product Mass Spectrum,

after ν decay kinematic correction +

branching ratio normalization

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

$$v(s) = \frac{B_x}{B_e} \frac{1}{N_x} \frac{dN_x}{ds} \frac{m_\tau^2}{\left(1 - s/m_\tau^2\right)^2 \left(1 + 2s/m_\tau^2\right)}$$

Branching Ratio Norm

q^2 Spectrum

V-A kinematics

CVC

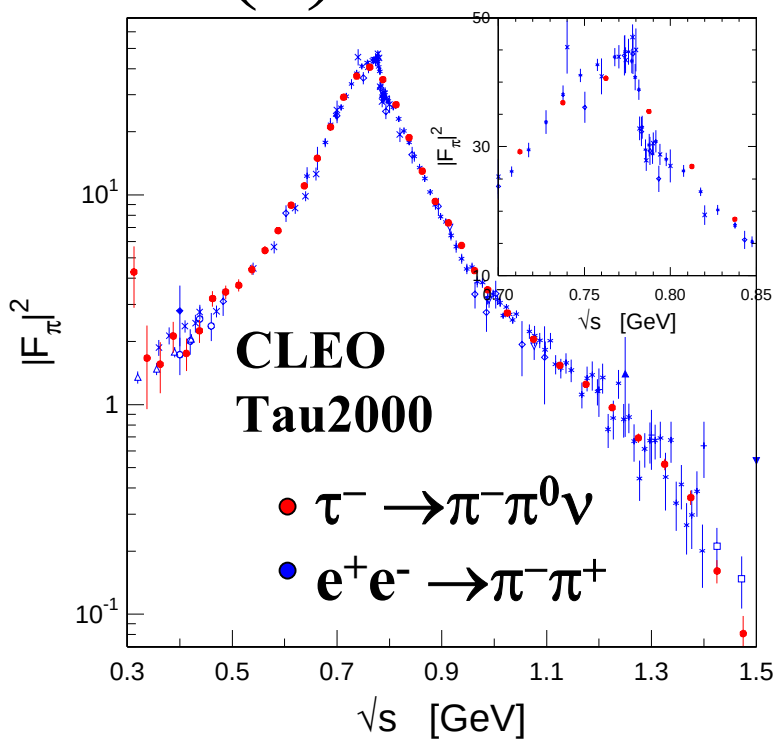
- CVC (Isospin): weak coupling in τ decay is related to e^+e^- scattering, eg:

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

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

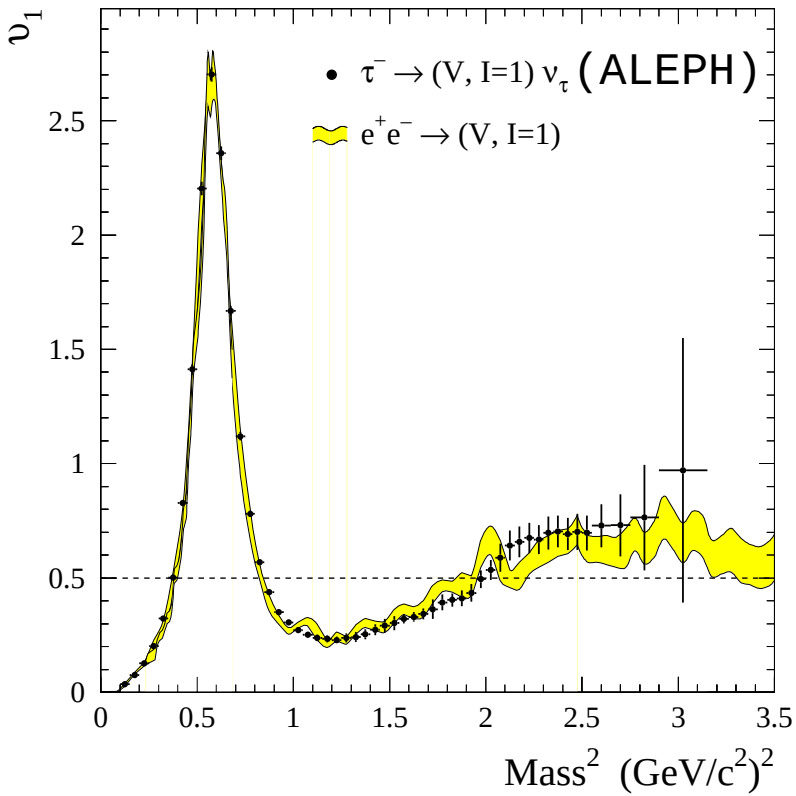
$$B_{\pi\pi}^{CVC} = 24.94(.23)\ \%$$

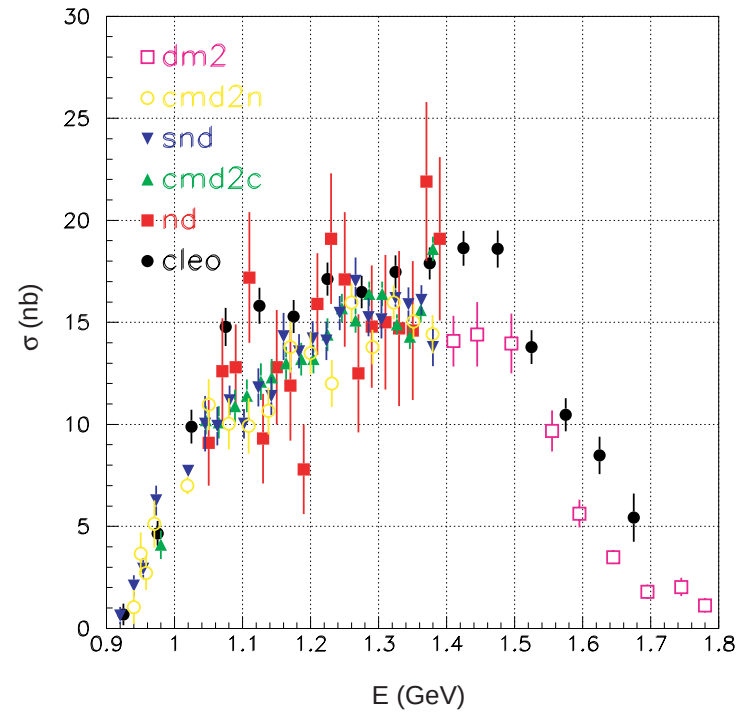
Tau2000



CVC (cont)

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





$\tau^- \to \pi^- \omega \nu$

$e^+e^- \to \pi^0 \omega$

Global test of CVC

CVC is (mostly) OK

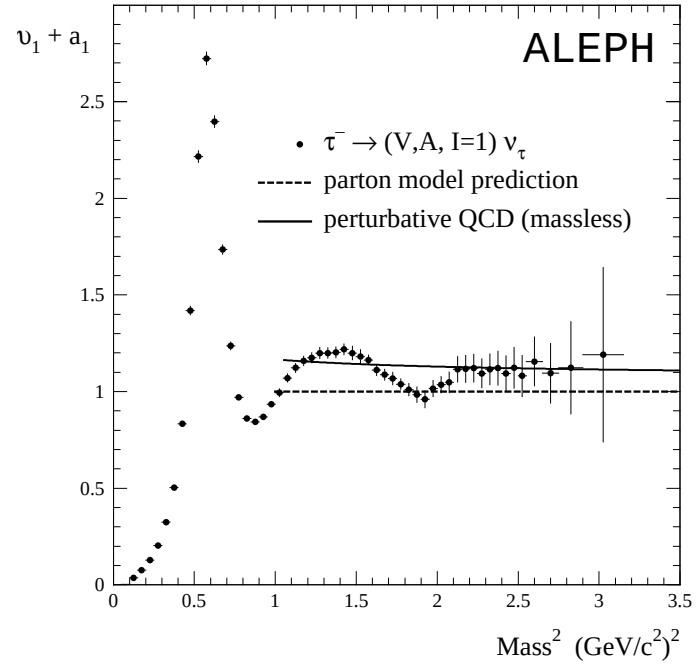
Alpha_s

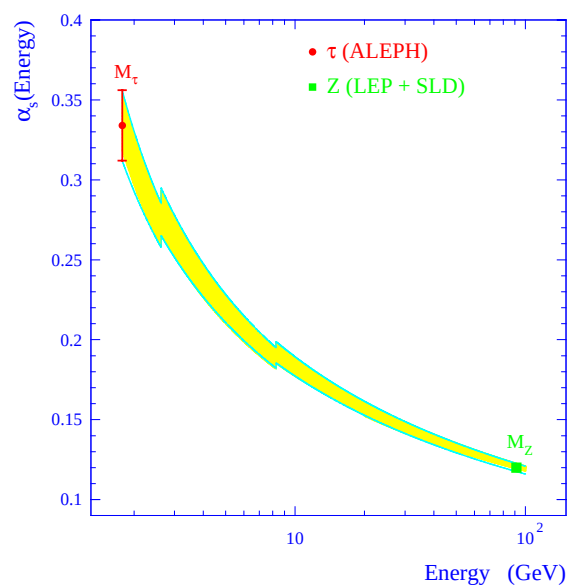
- The tau mass is just large enough to allow a believable calculation of:

$$R_\tau = \frac{\Gamma(\tau \to hadrons\,\nu)}{\Gamma(\tau \to e\nu\nu)}$$

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

$\alpha_S(m^2_Z)$=0.1208(0.025)





Tau2000

Strange Quark Mass

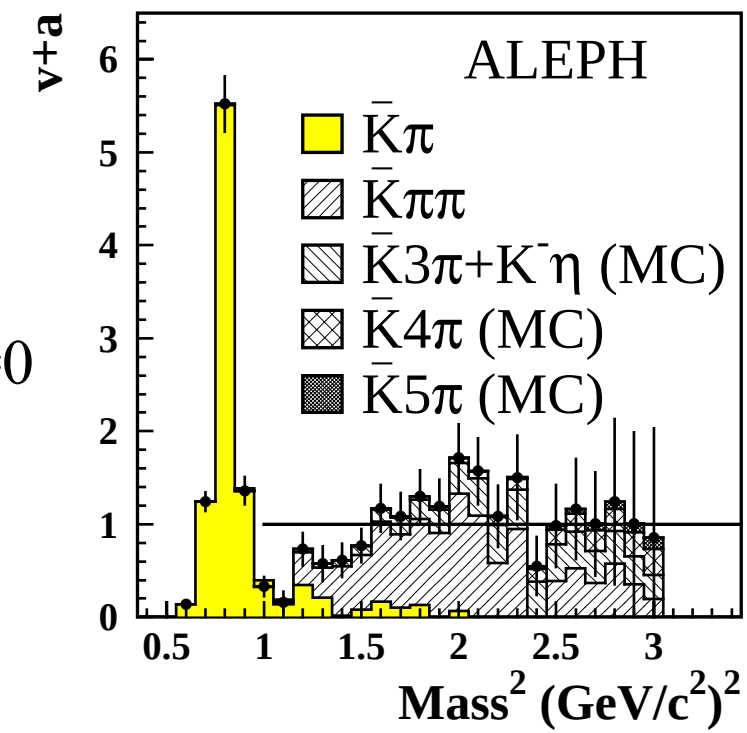
- Use a moments analysis

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

Compare moments Strange=1 and S=0 moments

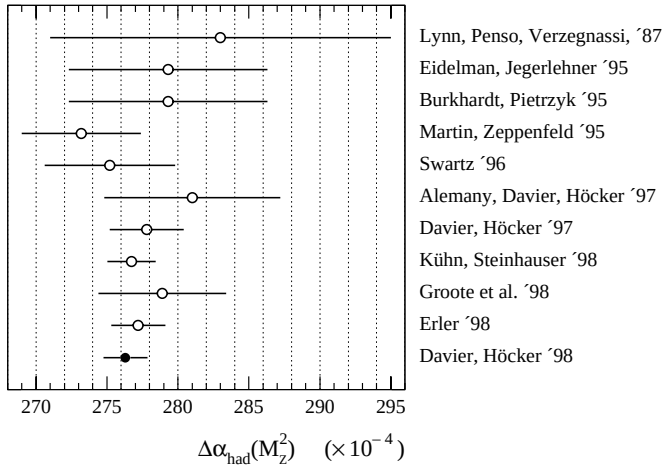
Allows optimal balancing of theory uncertainties, experimental errors at different s

$m_s(m^2_\tau)$= 112(23) MeV



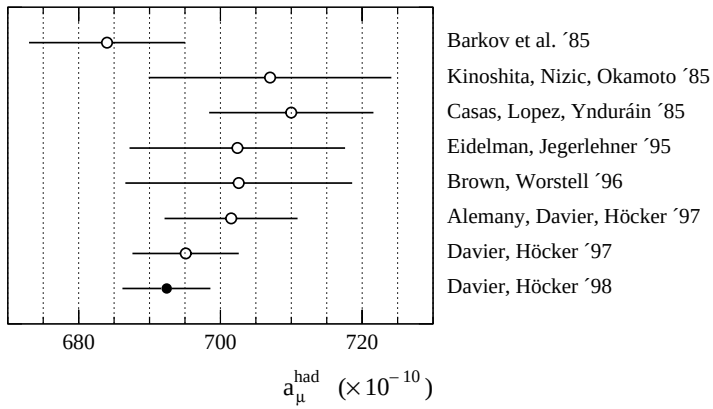
Hadronic Vacuum Polarization

- What is the probability of popping qq out of the Vacuum? $\gamma^* \rightarrow qq \rightarrow \gamma^*$
- Use e+e- ($\rightarrow \gamma^* \rightarrow qq$)$\rightarrow$hadrons
- CVC relates this to τ spectral functions $\tau \rightarrow$hadrons ν
- Direct impact on α_{QED}, $(g-2)_\mu$



$$\Delta\alpha_{had}\left(M_Z^2\right) = (\ldots)\int ds\sigma_{e^+e^-}(s)\tilde{K}(s)$$

$$a_\mu^{had} = (..)\int ds\sigma_{e^+e^-}(s)K(s)$$



Rare Decays

- $B(\tau \rightarrow (\omega\pi)_{1++}\ \nu) < 1.3\text{x}10^{-3}$ (2nd Class) CLEO99
- $B(\tau \rightarrow \eta\ K\ \pi\ \nu) = 5.0\ (1.2)\ \text{x}\ 10^{-4}$ CLEO98
- $B(\tau \rightarrow \eta\ 3\pi\ \nu) = 4.8\ (1.1)\ \text{x}\ 10^{-4}$ CLEO98
- $B(\tau \rightarrow \pi - K^0 K^0 \pi^0 \nu) = 3.1(2.3)\text{x}10^{-4}$ ALEPH98
- $B(\tau \rightarrow K^- K^+ K^- \nu) < 1.9\text{x}10^{-4}$ ALEPH98
- $B(\tau \rightarrow \eta\ \pi\ \nu) < 1.4\text{x}10^{-4}$ (2nd Class) CLEO96
- $B(\tau \rightarrow e^+ e^- e^+\ \nu\nu) = 2.8(1.5)\ \text{x}10^{-5}$ CLEO98
- $B(\tau \rightarrow 7\pi^{+/-}\ \nu) < 2.4\text{x}10^{-6}$ 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" τ Limits Can Beat "Tight" μ Limits

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

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

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

$B(\tau \to \mu^-\gamma) < 1.1\text{x}10^{-6}$ (CLEO00)12M ττ

Forbidden Decays (cont)

PDG : big list of limits for neutrinoless modes

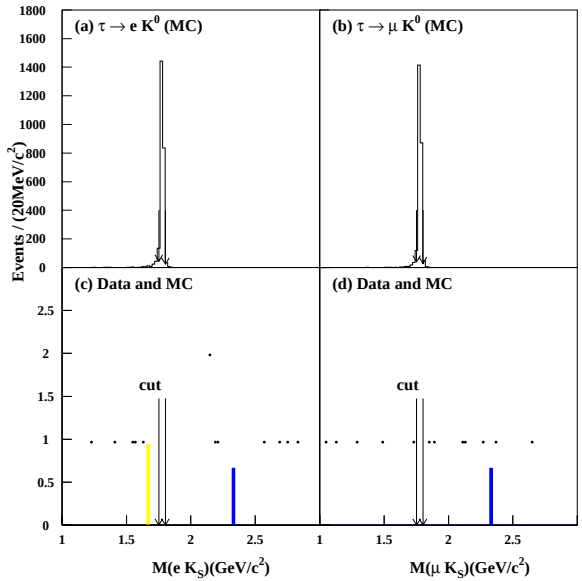
$$B(\tau \rightarrow XY) < 10^{-3} \text{ to } 10^{-6}$$

$$X=(e,\mu,p) \qquad Y=(l\gamma, m\pi, nK)$$

Newcomer: Belle 2001 - 21.5M $\tau\tau$

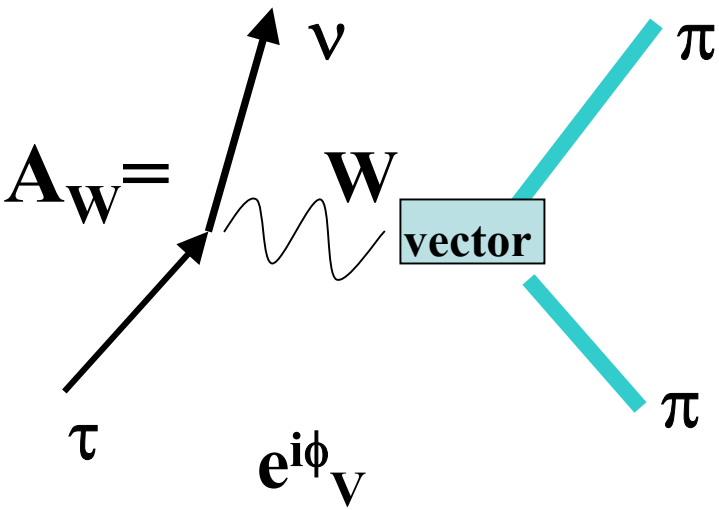
$$\mathbf{B}(\tau \rightarrow e^- K^0) < 1.8\times10^{-6}$$

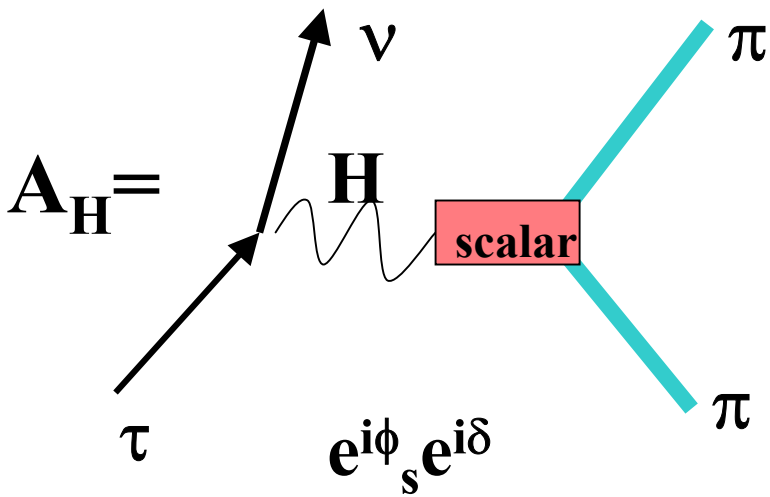
$$\mathbf{B}(\tau \rightarrow \mu^- K^0) < 1.8\times10^{-6}$$



Lots of Potential for Belle and Babar

CP Violation in τ Decay





Search for CP violation in processes with interfering amplitudes

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

Su(3) violation in $\tau \to K\ \pi\ \nu$

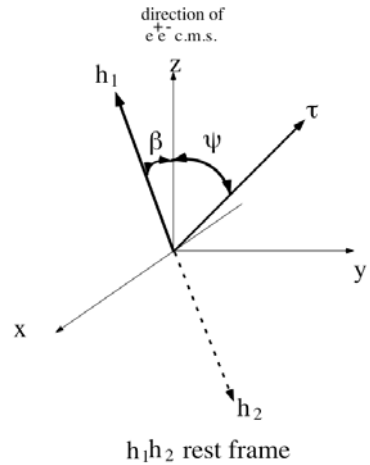
Belle CPV in $\tau \to \pi\pi^0\nu$

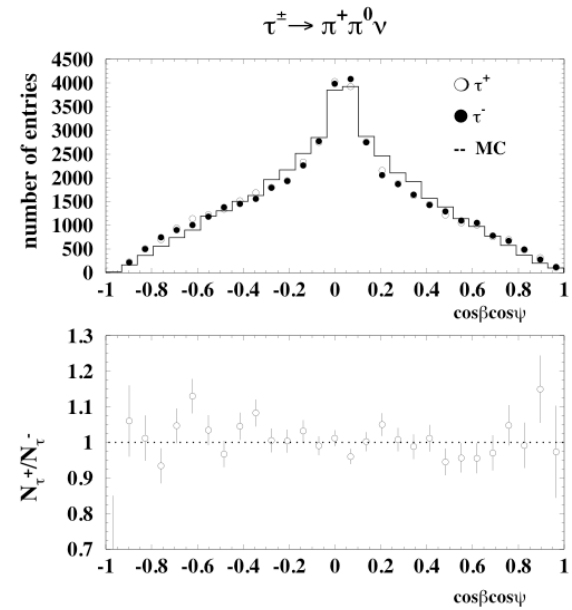
Use one side of events

$\tau \to \pi\, \pi^0\, \nu$

β - measured

Ψ – kinematic constraint





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

BELLE-CONF-0019 - 2M τ pairs

Similar CLEO analysis for $K\pi$ final state - PRL81,3823(1998)

CLEO CPV in $\tau \to \pi\pi^0\nu$

τ pairs are produced coherently : Can use info from other τ

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

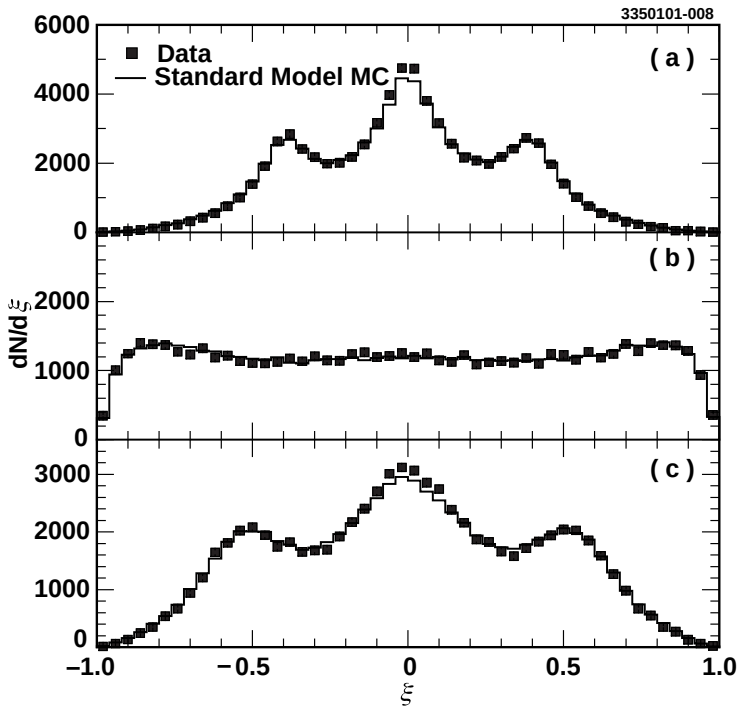
"optimal observable"

D.Atwood, A.Soni

PRD45(1992)2405

$$\xi = CevenPodd / CevenPeven$$

Model dependent limit on relative Higgs like coupling



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

12M τ pairs

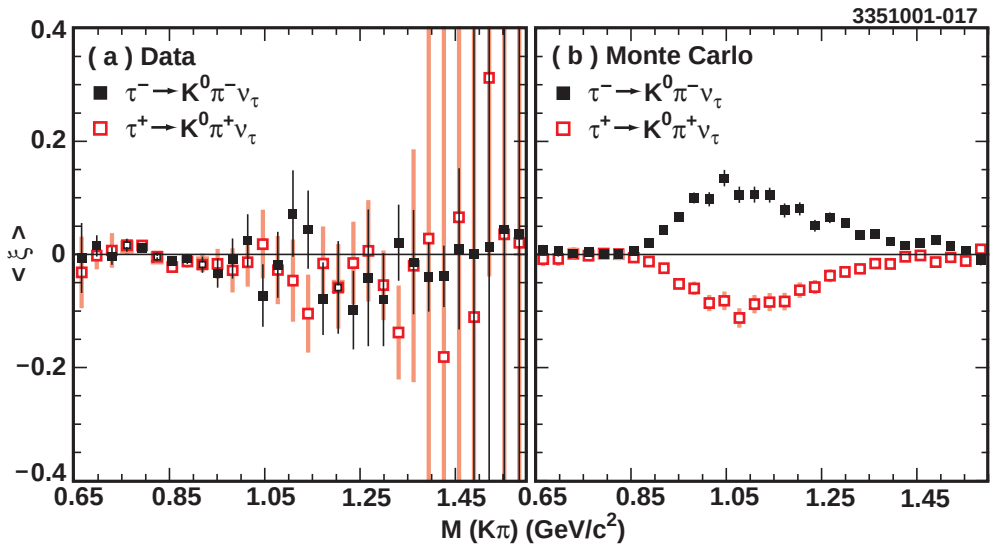
PRD64,092005(2001) hep-ex/0104009

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 ξ from CP odd interference between K^* and $K^*_0(1430)$

Limit on Higgs like coupling relative to W



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

sub to PRL – hep-ex/0111095

ν_τ Properties

- Observed by DONUT !!!
- Mixing??
- Mass limit (irrelevant??)
  - M_ν<18 MeV Aleph

    Method has oddities - see tau2000 writeup
  - M_ν<37 MeV from B_e
- Helicity :Michel Params
  - ξ_h =-0.996(0.007)
- EDM, magnetic moment

Tau Review Conclusions 1

- Leptonic τ are apparently "very Standard Model"
- Hadronic τ decays are well measured
- Hadronic τ decays provide a lab for QCD with applications well beyond τ
- ν mixing make τ 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!...