Physics of τ lepton

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XXXIInd Rencontres des Moriond
Electroweak interactions and Unified Theories
Les Arcs,Savoie,France.
15-22 March, 1997

Introduction

The physics of the third generation of lepton families:

- simple in principle
- complex in practice

simple

- sequential lepton after e and μ

complex

- many decay modes
- short lifetime $\rightarrow$ interesting $\rightarrow$ τ decays in experimental set-up. Information on its properties from E, p of decay products.
- τ is heavy enough to decay hadronically. It allows to study the hadronic current at rather low momentum transfer in a simple experimental enviroment.

$N_\nu = 3$ LEP

$\boxed{\tau \text{ is last family}}$

♣ τ, ν_τ are truly elementary? pontlike and structureless?

♣ Is τ a sequential lepton? same vertices and coupling of e , μ?

YES is a lepton as the other in S.M. with its mass and its leptonic number conserved

NO progress on understanding the raison d'être for a lepton so heavy.

20 YEARS after its Discovery

a large number of $\tau^+\tau^-$ available from e$^+$e$^-$. τ is a tool to answer some fundamental questions: test SM,strong interactions, new physics

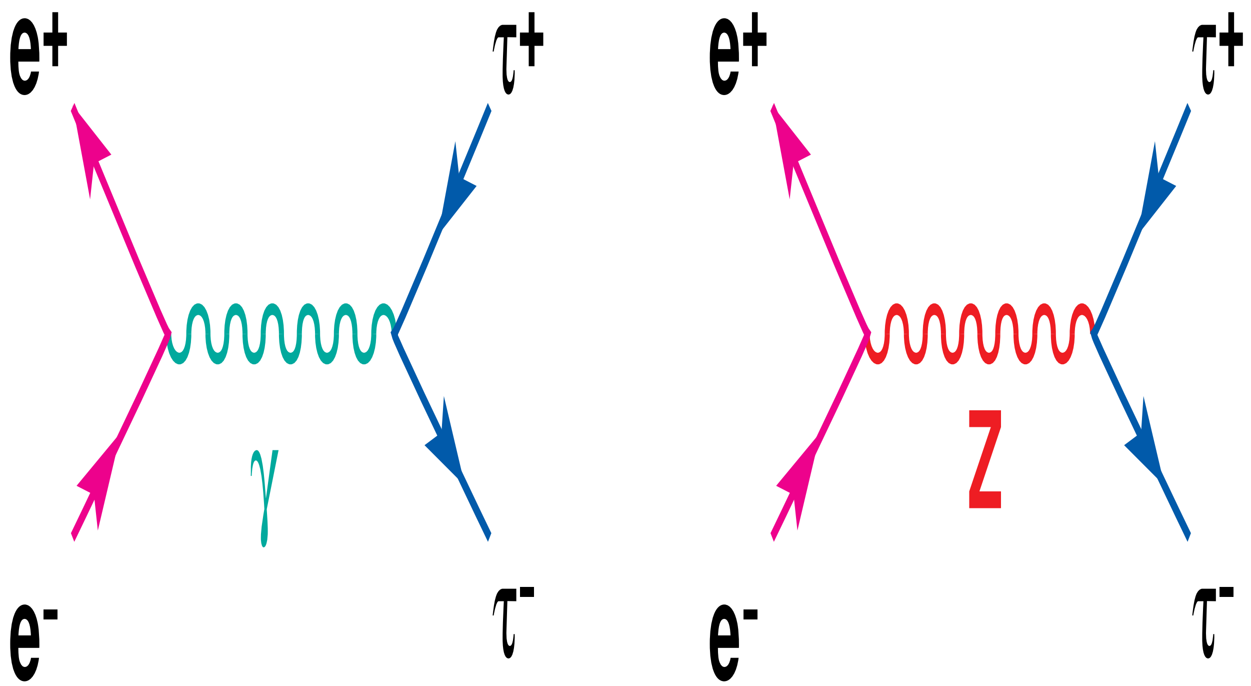
Outlook

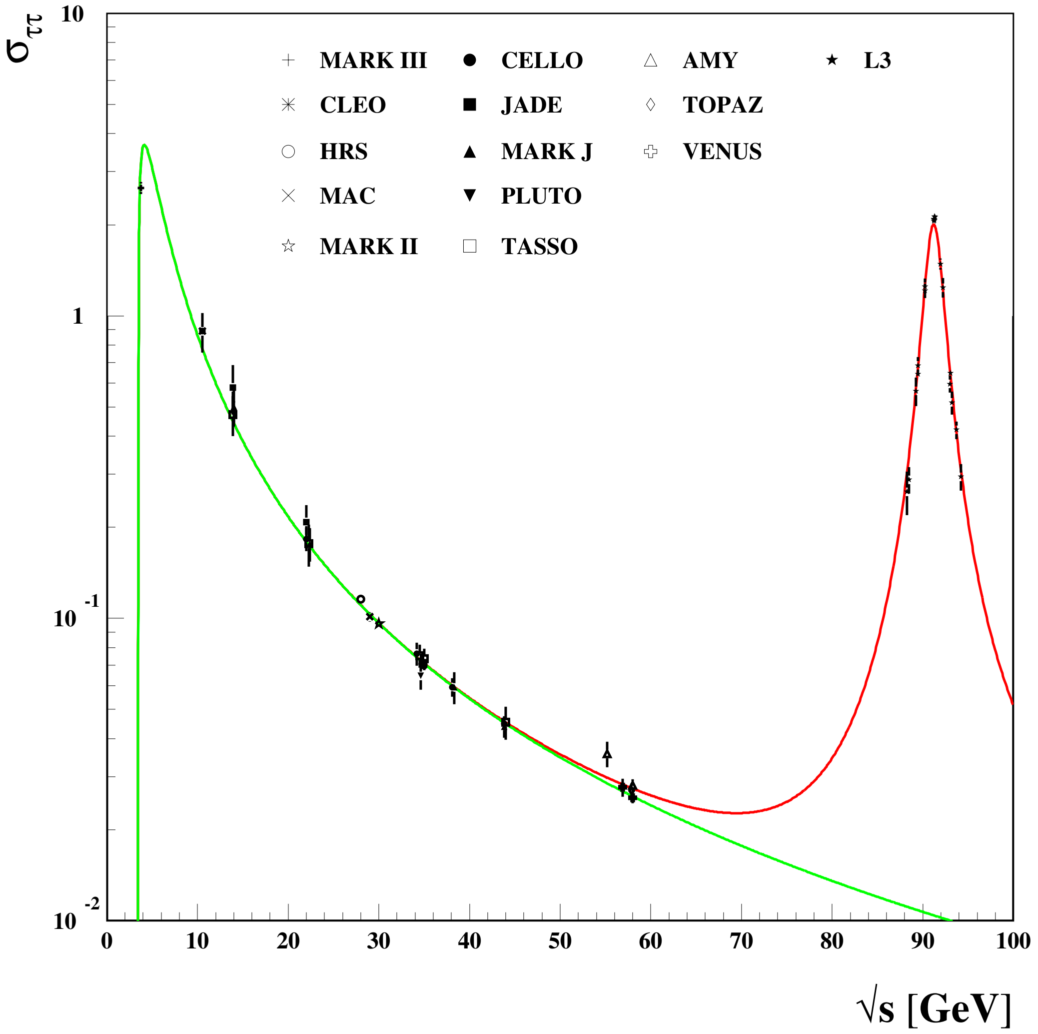
- ♠ Experimental conditions
- ♠ Static properties of τ, ν_τ: m_τ,m_{ν_τ}
  oscillations $\nu_e \to \nu_\tau$,$\nu_\mu \to \nu_\tau$
- ♠ τ Production by electroweak neutral current interaction
- ♠ τ Decays by weak charged current interaction:
  - $\Gamma_Z, \Gamma_{\ell\ell}$, Lorentz structure, τ decays and hadronic charged current
- ♠ Strong interactions and τ decays
- ♠ New physics
  - $\mathcal{CP}$ violation in production
  - Lepton number and flavor violation
- ♠ Conclusions

Experimental conditions

Main contribution from e^+e^-, in the energy range from threshold to Z and beyond: (recently $\rightarrow$140 ,172 GeV)

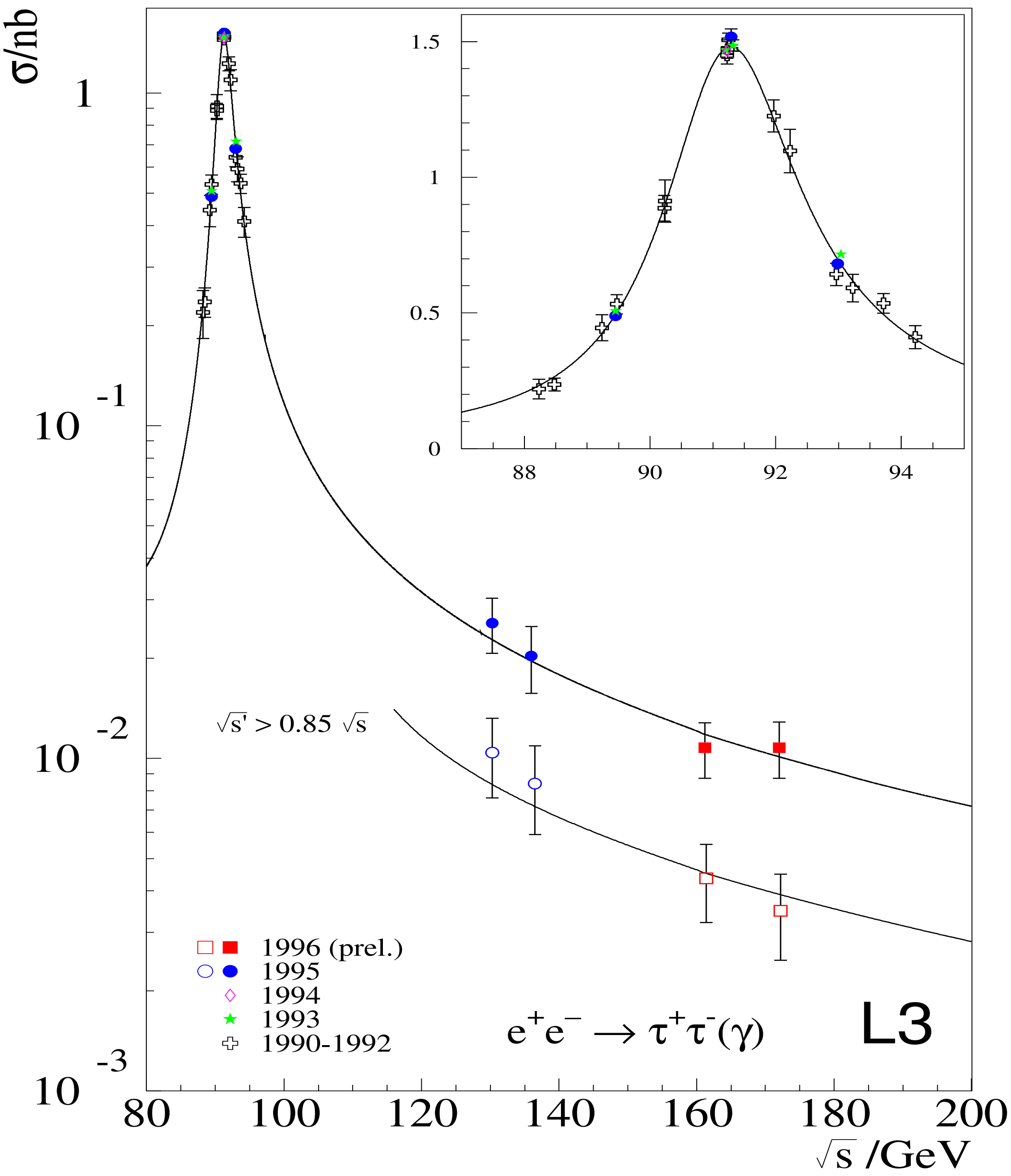
- **Threshold:** SPEAR and BEPC
- Heavy quarks resonance region:CESR($\approx$ 3000000 pairs) ,DORIS:
- Electroweak interference region:PETRA,PEP,TRISTAN
- Z region SLC,LEP($\approx$ 120K at Z *4,$\approx$ 100 *4 (high energy))

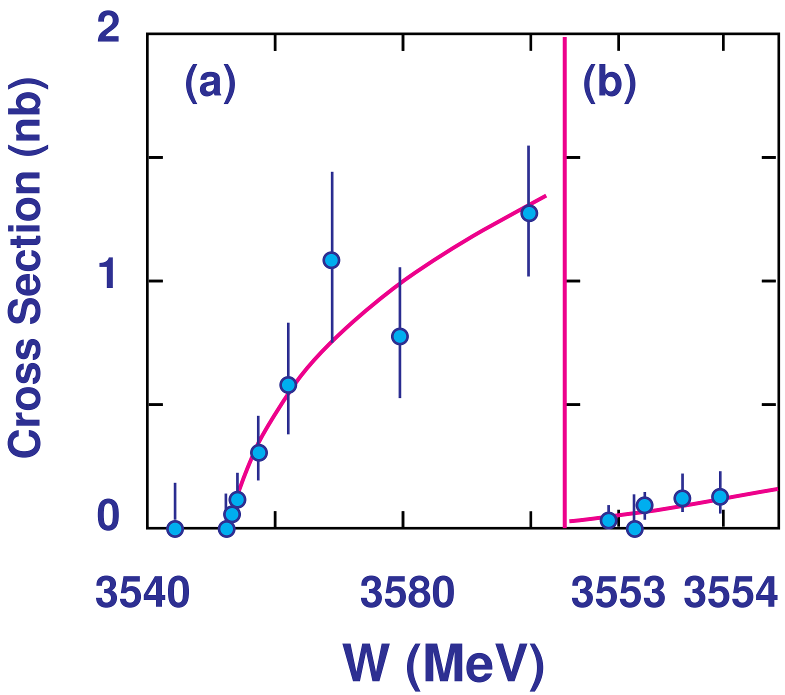


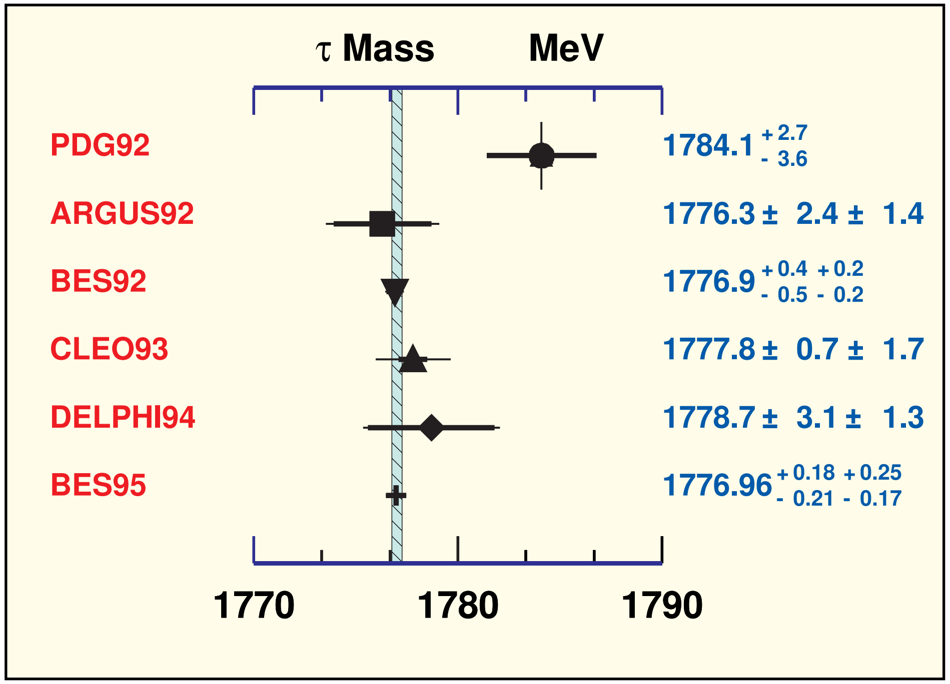


$\sigma_{\tau\tau}$
10
1
10^{-1}
10^{-2}
MARK III
CLEO
HRS
MAC
MARK II
CELLO
JADE
MARK J
PLUTO
TASSO
AMY
TOPAZ
VENUS
L3
0
10
20
30
40
50
60
70
80
90
100
$\sqrt{s}$ [GeV]

$\tau^+\tau^-$ Cross section ($\xi < 90$ deg)







$$m_\tau = 1777.00^{+0.30}_{-0.27}\ \mathrm{MeV}$$

PDG 96

Production of τ leptons by electroweak neutral current interactions

Lorentz structure of electroweak theory involves different coupling to Z.

- High rate at Z pole. Measurement of neutral current coupling

$$\Downarrow$$

$$\sigma^0, A_{FB}, A_{pol}^{FB}, \mathcal{P}$$

contain information on neutral couplings

$$\sigma^0(s \simeq M_Z^2) \Rightarrow g_V^2(f) + g_A^2(f) \qquad A_{FB} = \frac{g_V^2(f)}{g_A^2(f)}$$

The parity is violated twice in Z production and decay

$$\Downarrow$$

final τ leptons are polarized even if produced from unpolarized beam, with a degree depending on g_V and g_A and θ (angle $e^-$and τ^-). Relative production rate is:

$$\mathrm{A}_\tau(\theta) \equiv \frac{\sigma^{\mathrm{h}_\tau=+1/2}(\theta) - \sigma^{\mathrm{h}_\tau=-1/2}(\theta)}{\sigma^{\mathrm{h}_\tau=+1/2}(\theta) + \sigma^{\mathrm{h}_\tau=-1/2}(\theta)} = \frac{\mathrm{A}_\tau(1+\cos^2\theta) + 2\mathrm{A_e}\cos\theta}{(1+\cos^2\theta) + 2\mathrm{A_e}\mathrm{A}_\tau\cos\theta}$$

Average final state polarization is

$$\int_{-1}^{+1} A_\tau(\theta)\; d\cos\theta \equiv -\mathcal{P}_\tau = A_\tau \qquad \textit{τ coupling to Z}$$

$$\mathrm{A_f} = \frac{2\mathrm{g_V(f)g_A(f)}}{\mathrm{g_V^2(f) + g_A^2(f)}} \qquad \Leftarrow \qquad \text{coupling parameters}$$

τ Polarization

The Z$\rightarrow \tau^+\tau^-$ is the only place where τ polarization is observable. Assuming left-handed ν_τ the τ helicity determines the ν_τ direction.

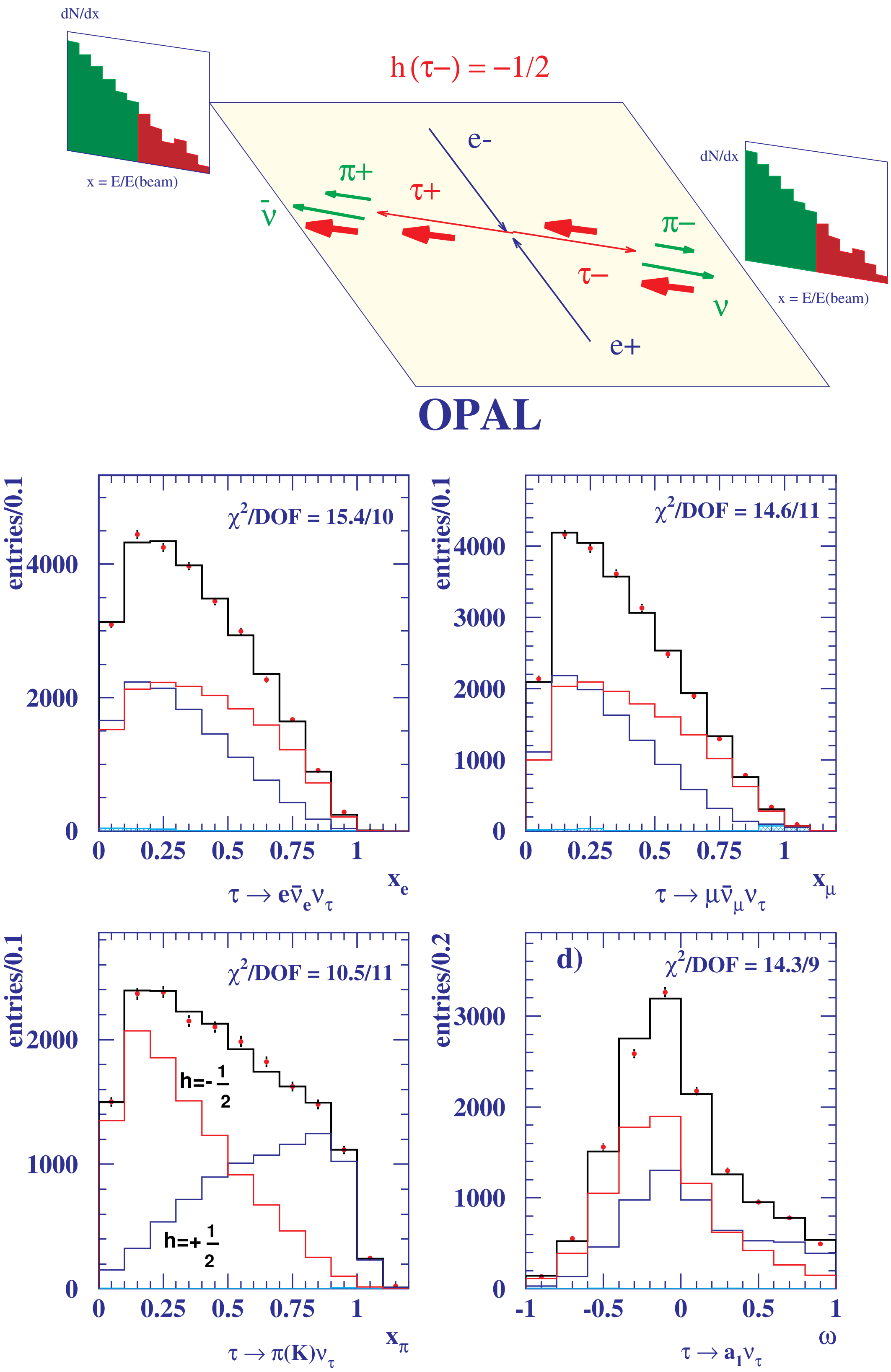
♣ The information on average τ helicity is contained in decay products.

$\Downarrow$

to extract use kinematical variables:energy, decay angles

Branchig ratios

Value [%]PDG96	Decay mode	Decay Characteristics
17.83 $\pm$ .08	$\tau \rightarrow e\nu\nu$	3 bodies, 2 particles
17.35 $\pm$ 0.10	$\tau \rightarrow \mu\nu\nu$	not detectable
		$\rightarrow$ loss in sensitivity
11.31 $\pm$ .15	$\tau \rightarrow \pi\nu$	2 bodies, 1 particles
		not detectable
		$\rightarrow$ most sensitive
25.24 $\pm$ .16	$\tau \rightarrow \pi\pi^0\nu$	decays of ρ, a_1
9.27$\pm$ .14	$\tau \rightarrow \pi 2\pi^0\nu$	analysis of decay products
		more complex



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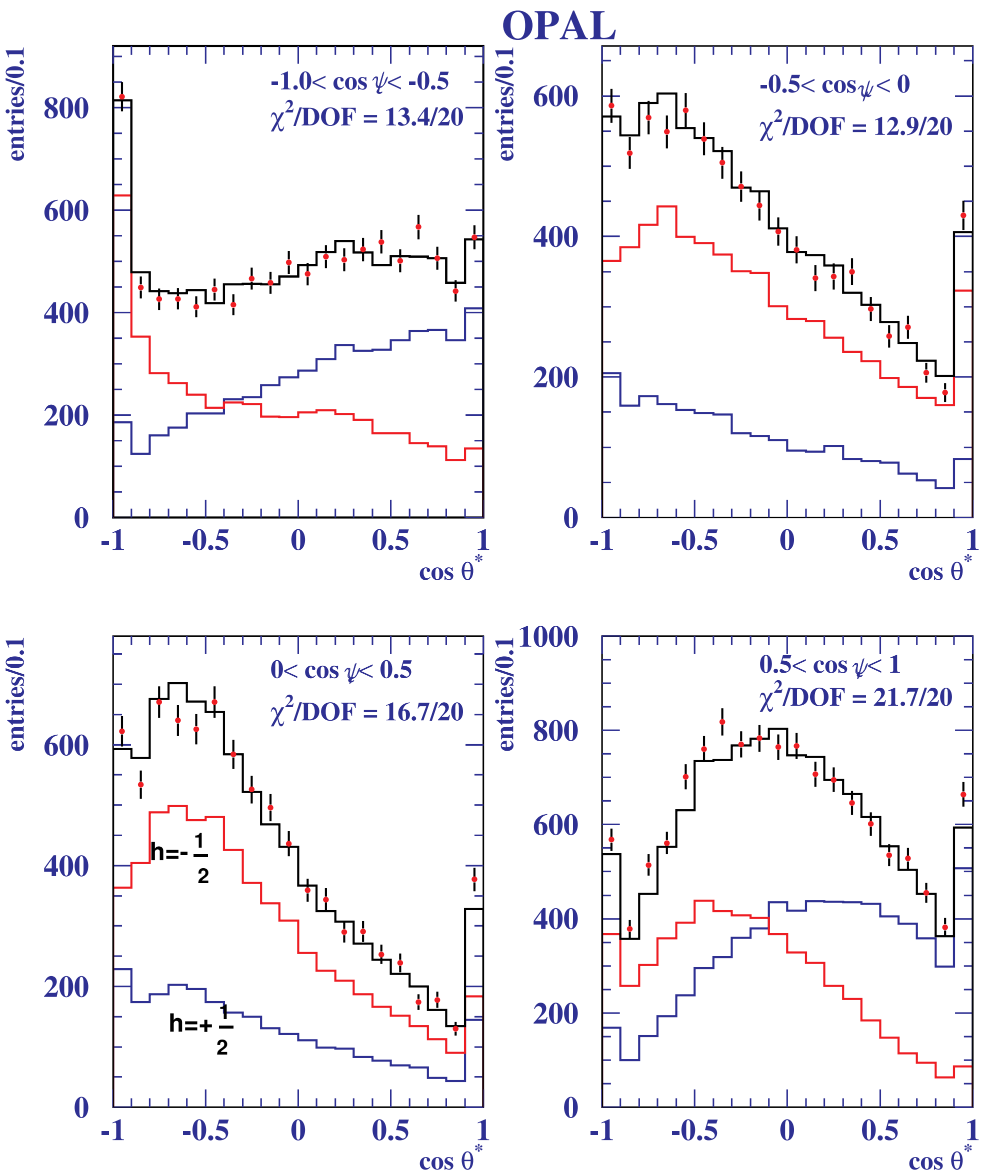
$\tau \to \rho\nu$



$$\cos\psi^*_\rho = \frac{m_\rho \quad E_{\pi^\circ} - E_{\pi^\pm}}{\sqrt{m_\rho^2 - 4m_\pi^2} \quad |\vec{p}_{\pi^\circ} + \vec{p}_{\pi^\pm}|}$$

$$\cos\theta^*_\rho = f(m_\tau, E_{\pi^\circ}, E_{\pi^\pm}, \ldots)$$

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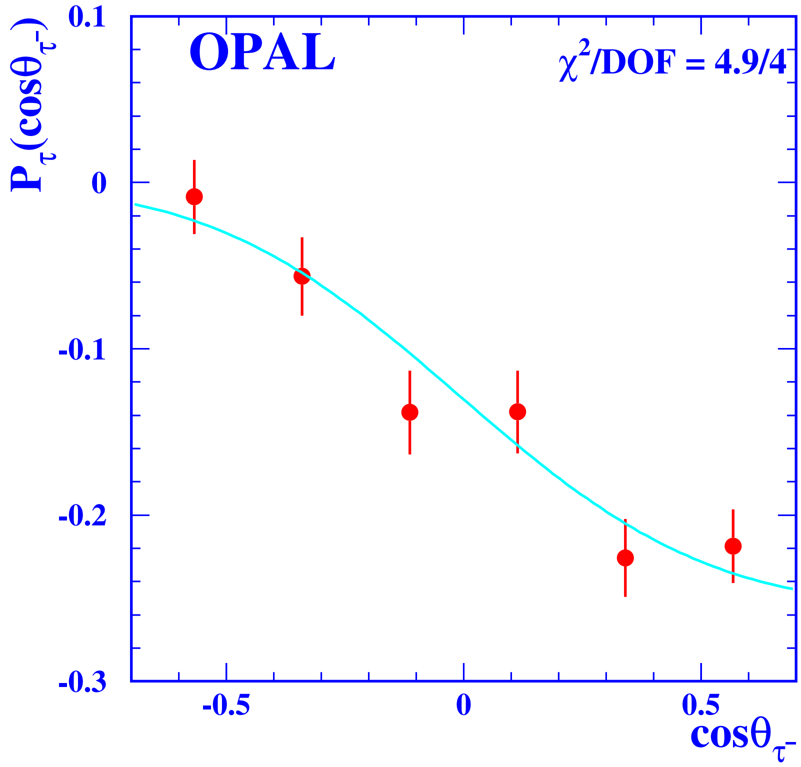


LEP average value

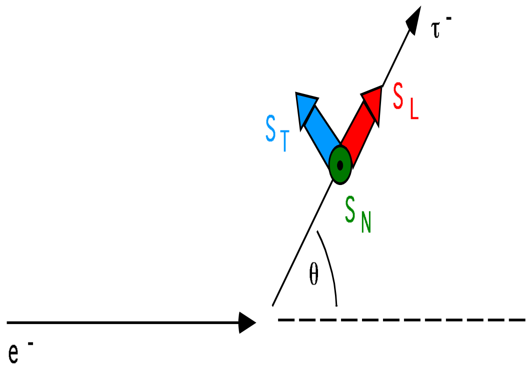
$$A_e = 0.1382 \pm 0.0076 \quad A_\tau = 0.1401 \pm 0.0067$$

excellent agreement with lepton universality of neutral current

Coupling	Combined Result (LEP+SLC)
$\bar{g}_V(\mathrm{e})$	-0.03851 ± 0.00072
$\bar{g}_V(\mu)$	-0.0362 ± 0.0032
$\bar{g}_V(\tau)$	-0.0368 ± 0.0016
$\bar{g}_A(\mathrm{e})$	-0.50111 ± 0.00045
$\bar{g}_A(\mu)$	-0.50080 ± 0.00067
$\bar{g}_A(\tau)$	-0.50092 ± 0.00078

Further information on coupling constant

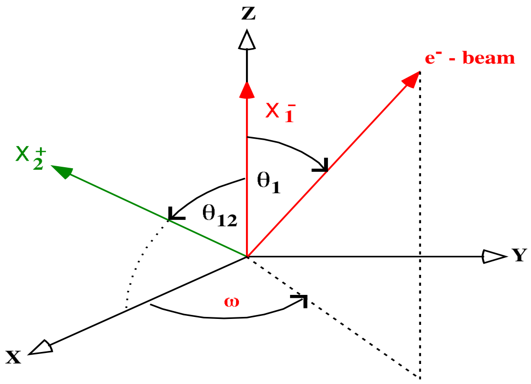
♠ spin-spin correlation



$$\frac{d\sigma}{d\Omega_{\tau^-} ds_{\tau^-} ds_{\tau^+}} = f(\theta, s^L_{\tau^-}, s^L_{\tau^+}, s^N_{\tau^-}, s^N_{\tau^+}, s^T_{\tau^-}, s^T_{\tau^+})$$

The spin correlations give rise to angular correlations of decay products sensible to:

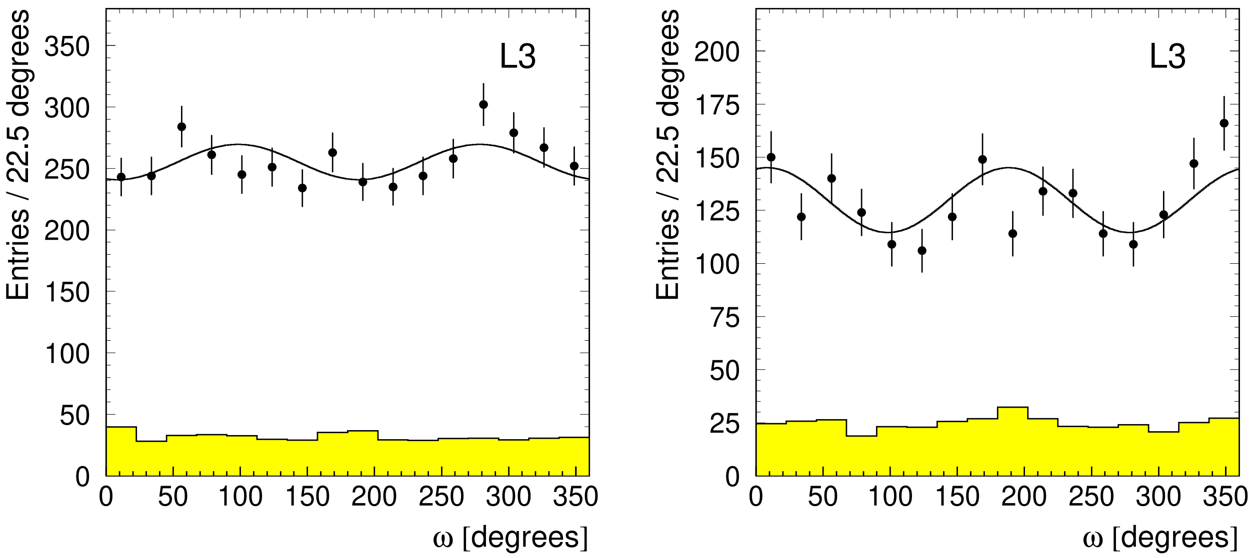
$$C_{TT} = \frac{|g_a(\tau)|^2 - |g_v(\tau)|^2}{|g_a(\tau)|^2 + |g_v(\tau)|^2} \qquad C_{TN} = \frac{-2Im((g_a(\tau))^* \cdot g_v(\tau))}{|g_a(\tau)|^2 + |g(\tau)|^2}$$



$\epsilon = \pi - \theta_{12}$

$$\frac{d\sigma^{i,j}}{d\epsilon d\theta_1 d\omega} = f(\theta_1, C_{TT}\cos 2\omega, C_{TN}\sin 2\omega)$$

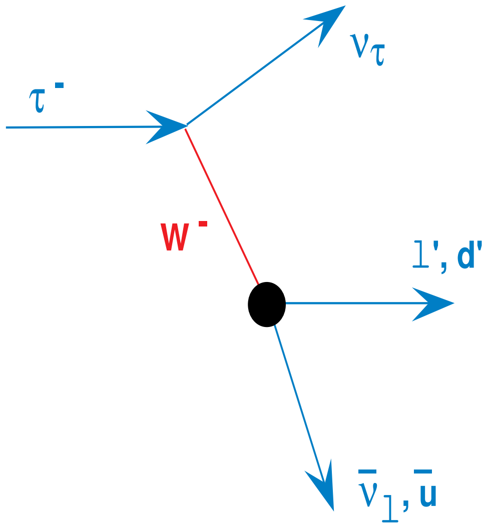
$\tau^+\tau^- \to$ lepton, hadron $\quad \tau^+\tau^- \to$ hadrons



	ALEPH	L3 (new)	Delphi (new)	S.M.
C_{TT}	$1.00 \pm 0.14 \pm 0.04$	$1.04 \pm 0.26 \pm 0.06$	$0.87 \pm 0.20^{+.10}_{-0.12}$	0.989
C_{TN}	$-0.08 \pm 0.14 \pm 0.02$	$0.36 \pm 0.26 \pm 0.05$	-	0

Decays by weak charged current interactions

- τ mass is high enough to decay into hadrons
- low multiplicity $\Rightarrow$ study hadronic resonances production
- interesting q^2 region



♣ Study the possible deviations from lepton universality

$$\Gamma(\mu^- \to e^- \bar{\nu}_e \nu_\mu) = \frac{G_F^2 m_\mu^5}{192\pi^3} \left[1 + \delta_m(y_e)\right] (1 + \delta_W) (1 + \delta_{rad})$$

- $y_e = m_e^2/m_\mu^2 \simeq 2 \times 10^{-5} \to \delta_m(y_e) \approx 0.2$ permille for μ decays, negligible $\tau^- \to e^- \bar{\nu}_e \nu_\mu$, 2.7% for $\tau^- \to \mu^- \bar{\nu}_\mu \nu_\mu$
- δ_W negligible
- δ_{rad} W propagator effects$\to$ negligible

♣ Analogously for τ replacing $\mu \Rightarrow \tau$

Instead of comparing the width

$$\boxed{\Gamma(\tau^- \to e^- \bar{\nu}_e \nu_\tau) = \Gamma_\tau \, BR(\tau^- \to e^- \bar{\nu}_e \nu_\tau) = \frac{BR(\tau^- \to e^- \bar{\nu}_e \nu_\tau)}{\tau_\tau}}$$

m_τ has been measured very precisely

$\Downarrow$

τ_τ proportional to BR

with exactly known proportional factor

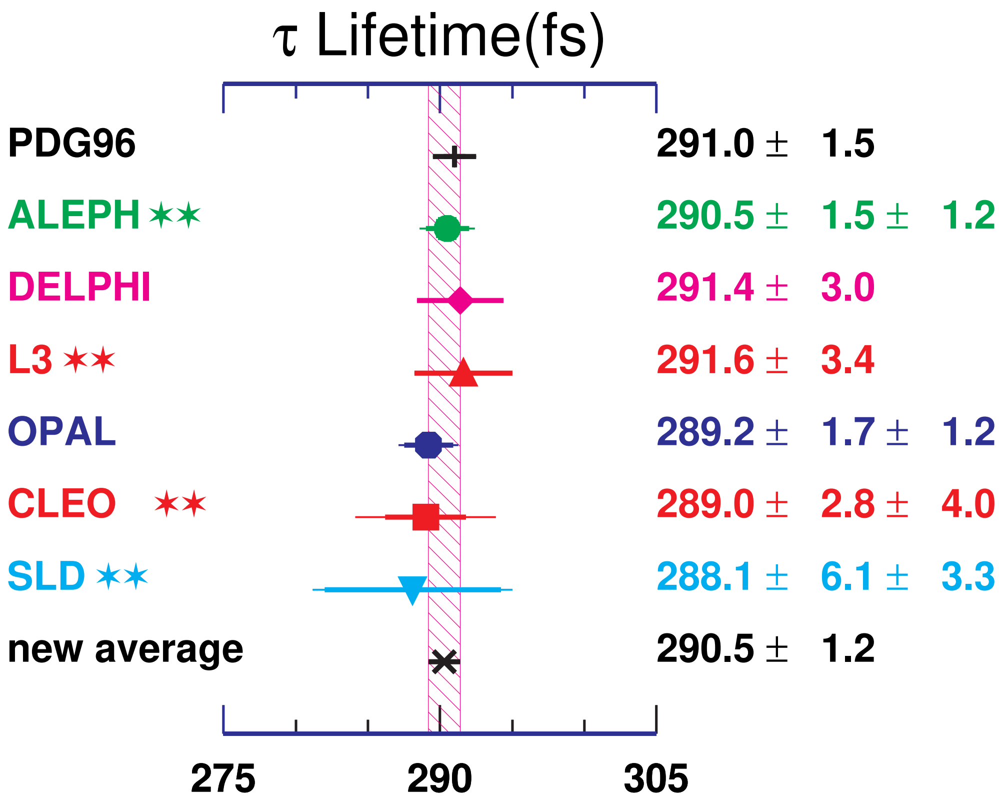
♠ Lifetime

Big progress mainly due to:

- boost factor at Z pole L$\simeq$ 2.5 mm (at $\Upsilon \simeq 270\mu$m)
- precision of vertex measurement device $\approx$ 25 μm on impact parameter.
- size of beam spot:
  - LEP $\sigma_x \simeq 150\mu$m $\sigma_y \simeq 5\mu$m
  - SLC $\sigma_x \simeq 2.6\mu$m $\sigma_y \simeq .8\mu$m
- Combination of various independent methods with different sensitivity and sistematics:
  - Decay length: 3 prong decays
  - Impact Parameter : 1 prong decays (high statistics)

$\triangle$ two main unknown variables:

- τ production point
- τ direction



↓

New average **290.5 ± 1.2**

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♣ Leptonic branching fraction

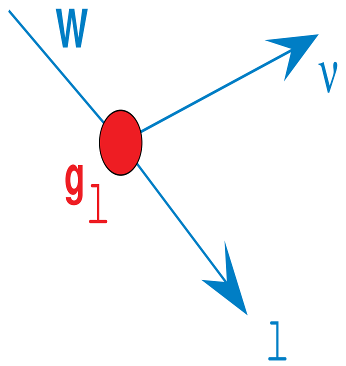
In conjunction with the lifetimes measurement the

$$\mathrm{BR}(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau) \qquad \mathrm{BR}(\tau^- \to \mathrm{e}^- \bar{\nu}_\mathrm{e} \nu_\tau)$$

are necessary **to test the universality of lepton charged current.**

Improvement due to : good resolution, coverage,homogeneity of detectors

$$G_F^2 \to G_\tau G_l \qquad (l = e, \mu) \qquad G_l = \frac{\mathrm{g}_\mathrm{l}^2}{\sqrt{32} M_W^2} \qquad (l = e, \mu, \tau)$$



$$\frac{\mathrm{BR}(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau)}{\mathrm{BR}(\tau^- \to \mathrm{e}^- \bar{\nu}_\mathrm{e} \nu_\tau)} = \frac{1 + \delta_m(y_\mu)}{1 + \delta_m(y_e)} \frac{\mathrm{g}_\mu^2}{\mathrm{g}_\mathrm{e}^2} \qquad (\Rightarrow \quad 1)$$

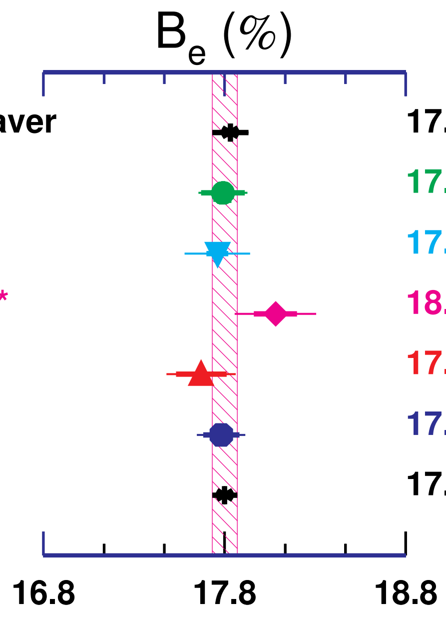
$\Downarrow$ **mass correction term 0.9726**

$\boxed{\frac{g_\mu}{g_e} = 1.000 \pm 0.003}$ $\Rightarrow$ μ-e universality

- From $\tau^- \to \mathrm{e}^- \bar{\nu}_\mathrm{e} \nu_\tau$ and $\mu^- \to e^- \bar{\nu}_\mathrm{e} \nu_\mu$

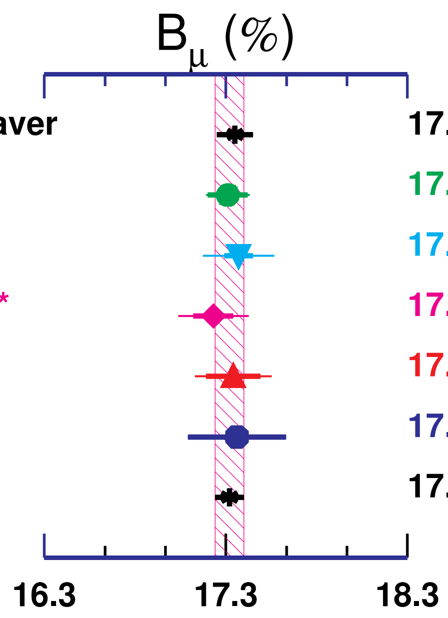
$\boxed{\frac{g_\tau}{g_\mu} = 1.000 \pm 0.003}$ $\Rightarrow$ μ-τuniversality

τ Branching Fraction into Electrons %



	B_e (%)
PDG 96 aver	17.83 ± 0.10
ALEPH	17.79 ± 0.12 ± 0.06
CLEO**	17.76 ± 0.06 ± 0.17
DELPHI**	18.08 ± 0.12 ± 0.19
L3**	17.67 ± 0.14 ± 0.13
OPAL	17.78 ± 0.10 ± 0.09
average	17.80 ± 0.07

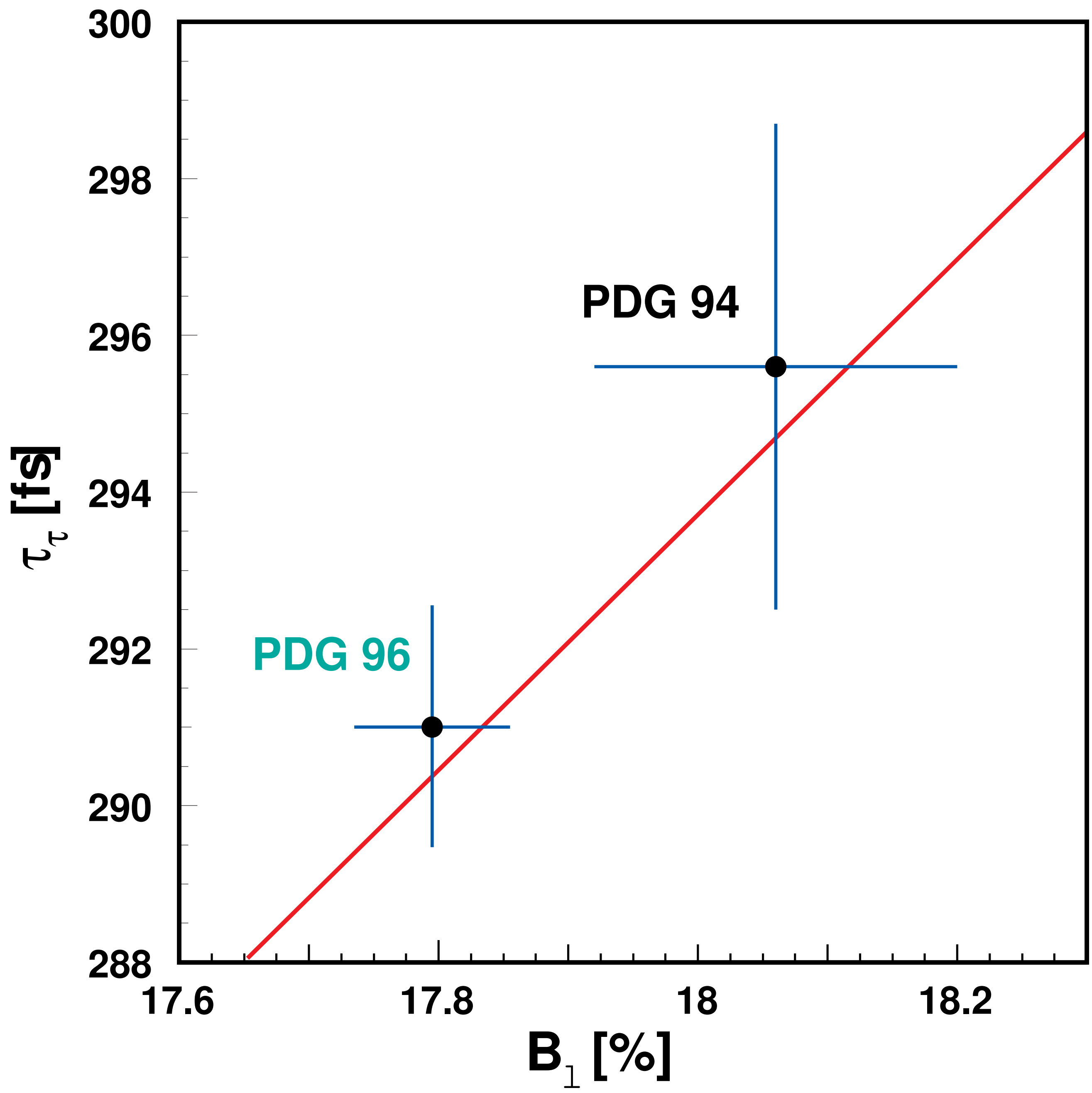
τ Branching Fraction into Muons %



	B_μ (%)
PDG 96 aver	17.35 ± 0.10
ALEPH	17.31 ± 0.11 ± 0.05
CLEO**	17.37 ± 0.08 ± 0.18
DELPHI**	17.23 ± 0.11 ± 0.16
L3**	17.34 ± 0.15 ± 0.15
OPAL	17.36 ± 0.27
average	17.32 ± 0.08

17.80 ± 0.07% $\Leftarrow$ **New average** $\Rightarrow$ **17.32 ± 0.08%**

Combined mean $\Rightarrow$ **Br** $(\tau^- \rightarrow l^- \bar{\nu}_l \nu_\tau)$ **=17.80 ± 0.05%**



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Lorentz structure of charged current

After having established the coupling constants, we can write the most general Lorentz structure of 4 fermions interactions for leptonic τ decays

$$\mathcal{M} = \frac{4G_F}{\sqrt{2}} \sum_{\gamma=S,V,T} \sum_{\alpha,\beta=R,L} \mathrm{g}^{\gamma}_{\alpha\beta} \left(\bar{\mathrm{u}}^{\alpha}_{\mathrm{l}} \Gamma_{\gamma} \mathrm{v}_{\nu_{\mathrm{l}}}\right) \left(\bar{\mathrm{v}}_{\nu_\tau} \Gamma_{\gamma} \mathrm{u}^{\beta}_{\tau}\right)$$

- γ current label (S, V, T = scalar, vector and tensor),
- α and β handedness of chiral spinors (L, R = left-, righthanded)
- $g^{\gamma}_{\alpha\beta}$ = 10 complex constant

pure V-A in Standard Model $\Rightarrow g^{V}_{LL} = 1$,but in most general case the coupling depends from final states (i.e. $\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau \neq \tau^- \to \mathrm{e}^- \bar{\nu}_{\mathrm{e}} \nu_\tau$).

$$\Downarrow$$

A combination of couplings $g^{\gamma}_{\alpha\beta}$ con be determined from decay angles and their correlation in $\mathrm{e}^+\mathrm{e}^- \to \tau^+\tau^-$
Michel Parameters ρ, η, ξ and $\xi\delta$:

$$\begin{aligned}\rho &= \frac{3}{16}\left(|g^{S}_{RR}|^2 + |g^{S}_{LR}|^2 + |g^{S}_{RL}|^2 + |g^{S}_{LL}|^2\right) \\ &\quad + \frac{3}{4}\left(|g^{V}_{RR}|^2 + |g^{V}_{LR}|^2 + |g^{T}_{RL}|^2 + |g^{T}_{LL}|^2 + \mathrm{Re}(g^{S}_{LR} g^{*T}_{LR} + g^{S}_{RL} g^{*T}_{RL})\right)\end{aligned}$$

for a single τ decay:

♠ Decay lepton spectrum

$$\frac{1}{\Gamma}\frac{d\Gamma}{dx} = h_0(x) + \eta h_\eta(x) + \rho h_\rho(x) - \mathcal{P}_\tau \; (\xi h_\xi(x) + \xi\delta h_{\xi\delta}(x))$$

where $h_i(x)$ = polinomials and $x = E_l/E_\tau \simeq E_l/E_b$

♠ For hadronic decays:

$$\frac{1}{\Gamma}\frac{d\Gamma}{dx} = g_0(x) + \mathcal{P}_\tau \xi_h g_1(x)$$

where ξ_h = the chirality parameter, g_i are the corresponding spectral functions, $x = E_{had}/E_\tau$, Standard Model $\xi_h = 2h_\nu = -1$ (average neutrino helicity) for all hadronic decays.

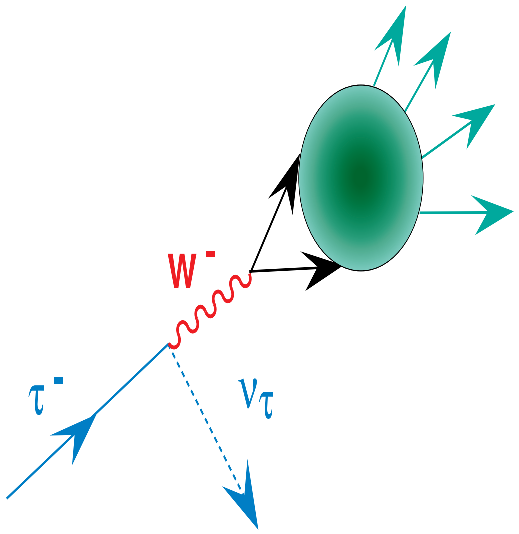
♠It is possible to use the complete information of 2 τ

	SLD (new)	L3 (new)	$\mu \to e\nu\nu$	$V-A$
ρ	0.69 ± 0.14	0.79 ± 0.05	0.7518 ± 0.0026	$3/4$
η	-0.13 ± 0.49	$+0.25 \pm 0.20$	-0.007 ± 0.013	0
ξ	1.02 ± 0.36	0.94 ± 0.22	1.0027 ± 0.0085	1
$\xi\delta$	0.87 ± 0.27	0.81 ± 0.15	0.751 ± 0.007	$3/4$
ξ_h	-0.93 ± 0.10	-0.97 ± 0.05		-1

	CLEO(new)	PDG96	new average
ρ	0.747 ± 0.012	0.742 ± 0.027	0.748 ± 0.01
η	-0.015 ± 0.097	-0.01 ± 0.14	$+0.15 \pm 0.069$
ξ	1.007 ± 0.042	1.03 ± 0.12	1.008 ± 0.054
$\xi\delta$	0.745 ± 0.275	0.76 ± 0.11	0.749 ± 0.026
ξ_h	-0.995 ± 0.010	-1.01 ± 0.03	-0.996 ± 0.01

excellent agreement with Standard Model

Hadronic decay



- τ is massive enough to have hadronic decay channels
- It is a clear enviroment to study weak hadronic current and some features of QCD

Many new results due to:

- Large τ sample with a large purity make accesibles Br$<$ 1 %
- Precise calorimeters and good tracking:
  - high γ reconstruction efficiency
  - π^0
  - Identification K/π ($\frac{dE}{dX}$, RICH....)
  - Recognizing of K_L^o using pattern recognition

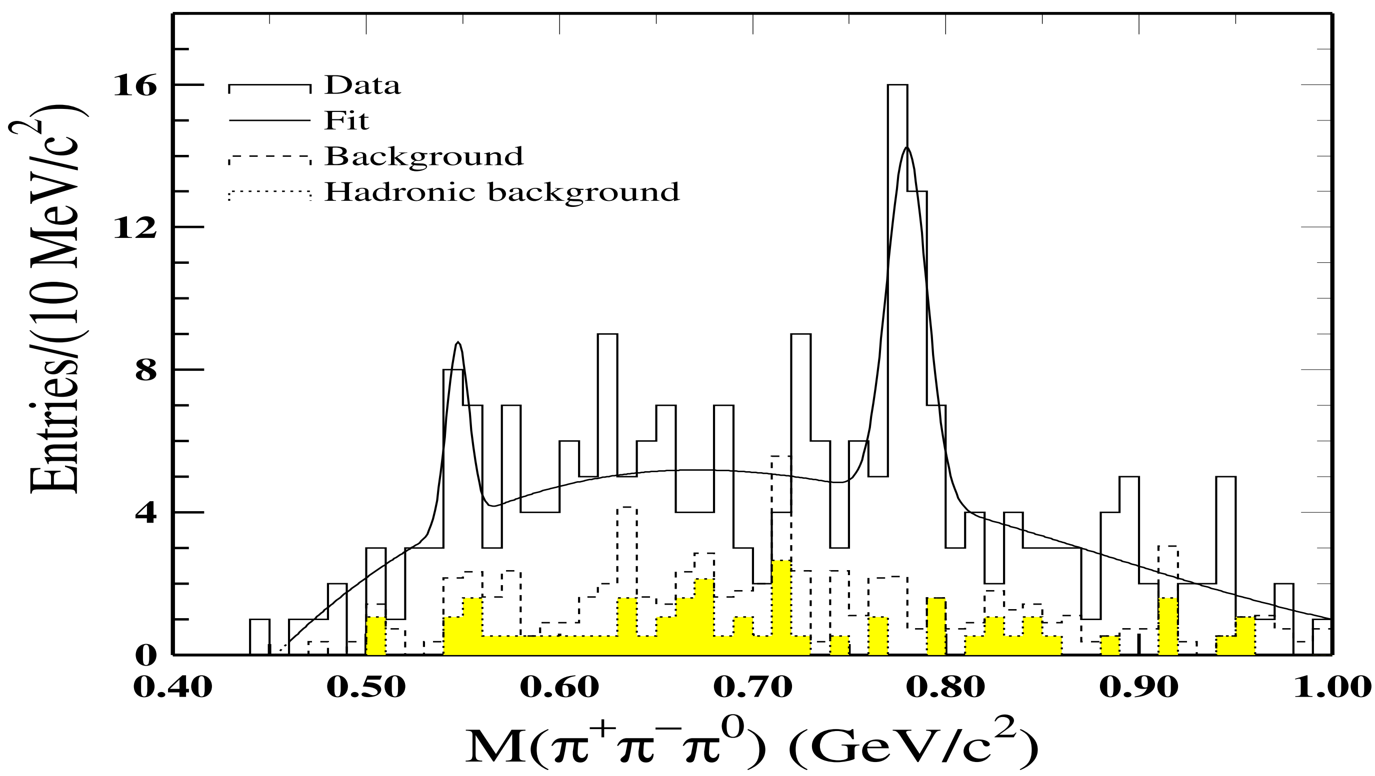
the theoretical predictions are complicate also for the presence of resonances

△ Many decay modes involving K have been measured

- $\tau^- \rightarrow \pi^-\pi^0\nu_\tau$ appears saturated by ρ^-
- $\tau^- \rightarrow K^-\pi^0\nu_\tau$ is dominated by K^*
- $\tau^- \rightarrow \pi^-\pi^+\pi^-\nu_\tau$ has a peak to a_1

△ NOW: decay mode involving $KK, \omega, \eta...$ have been measured (ref H.Evans presented at TAU96)

- $K^-K^+\pi^-\nu_\tau, K^-K^0\pi^0\nu_\tau, K^0K^0\nu_\tau$
- $h^-\omega\pi^0\nu_\tau, h^-\eta\pi^0\nu_\tau,\ \pi^-f_1\nu_\tau = (6.7 \pm 1.4 \pm 2.2)\cdot 10^{-4}$ (CLEO),3h $3\pi 0\ \nu_\tau = (2.69\pm 0.49\pm 0.47)10^{-4}$(CLEO) **(PRELIMINARY)**



Hadronic decay: Decay dynamics

The decay width into hadronic final states is

$$\Gamma(\tau^- \to hadrons + \nu_\tau) = \frac{G^2}{32\pi^2 m_\tau^3} \int_0^{m_\tau^2} dq^2 (m_\tau^2 - q^2)(m_\tau^2 - 2q^2)$$
$$([\mathrm{v_1}(\mathrm{q^2}) + \mathrm{a_1}(\mathrm{q^2})]\cos^2\theta_c[\mathrm{v_1^s}(\mathrm{q^2}) + \mathrm{a_1^s}(\mathrm{q^2})]\mathrm{sen}^2\theta_c)$$

where v and a are vector and axial spectal functions, associated to a well defined spin parity and strangeness

Spectral function	Spin parity J^P	Strangeness S	Possible final States
$\mathrm{v_1}$	1^-	0	$\rho(770)$,$\rho^{'}(1600)$,2π,4π
$\mathrm{a_1}$	1^+	0	π,3π

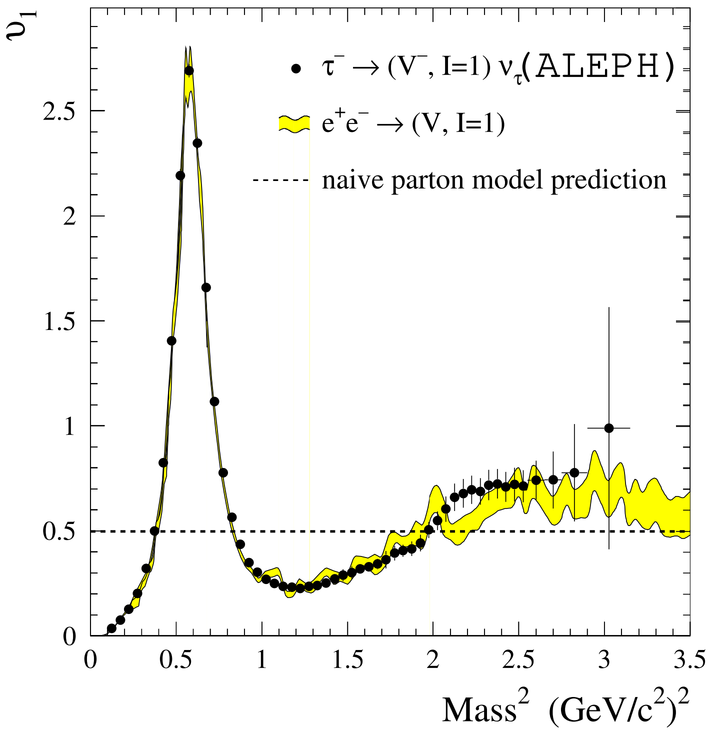
CVC relates the vector part to the strangeness conserving charged weak current to the isovector part of the total cross section $e^+e^- \to$ hadrons.

$$v_1(q^2) = \frac{\sigma_{I=1}(e^+e^- \to hadrons)}{\sigma_{pt}}$$

♠ALEPH has measured the axial and axial-vector spectral functions.

$$v_1 = C\frac{1}{N_V}\frac{dN_V}{ds}$$

C= normalizzation factor,N_V is the measured τ decays in a hadronic final state V via vector current for a given hadronic mass squared s



- There is a good agreement between vector spectral functions and isovector contribution e^+e^-
- Pion form factor $\tau^- \to \pi^-\pi^0\nu$ CLEO,ALEPH
- Clear contribution of ρ'(fit Kuhn Santamaria Model)
- Good agreement with prediction $e^-e^+ \to \pi^+\pi^-$ →good test CVC

Kuhn Santamaria model

	CLEO	ALEPH	e^+e^-
M_ρ(MeV)	774.3 ± 1.1	774.9 ± 0.9	773
Γ_ρ(MeV)	149.1 ± 1.6	144.2 ± 1.5	144
β	-0.091 ± 0.009	-0.094 ± 0.007	-0.103
$M_{\rho'}$(MeV)	1370 ± 12	1363 ± 15	1320
$\Gamma_{\rho'}$(MeV)	386 ± 43	$\equiv 310$	390
γ	–	-0.015 ± 0.008	–

Conclusions

The physics of τ leptons made enormous progress from its discovery.
Mainly for the tremendous progress in accelerator and detector tecnology

- Static properties:
  - m_τ is known now with sub-Mev precision $\rightarrow$ possible to test electroweak theory
- Electroweak properties: τ has a pointlike electroweak vertex up to $q^2 = m_z^2$. Same coupling of e, μ
- Hadronic decay: Almost all decay with Br$\sim$ 10^{-5} have been observed. Classification of final states accomplished. $\Rightarrow$ PDG96
- New physics: τ lepton is a powerful tool to search for new physics. Its high mass often enhances those effects.

$\Rightarrow$ τ is another sequential lepton.

- CLEO and LEP experiments have collected high statistics data with excellent detectors. Other results are expexcted soon.
- Other measurents will come from large data samples of τ at CESR