Tau electroweak couplings from LEP

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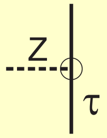
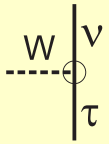
CIPANP2000, Quebec City

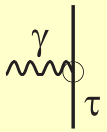
Using τ production and decay to study couplings to the gauge bosons



Γ_τ, $\mathcal{A}_{\mathcal{FB}}$, τ spin analysis



τ decay distributions

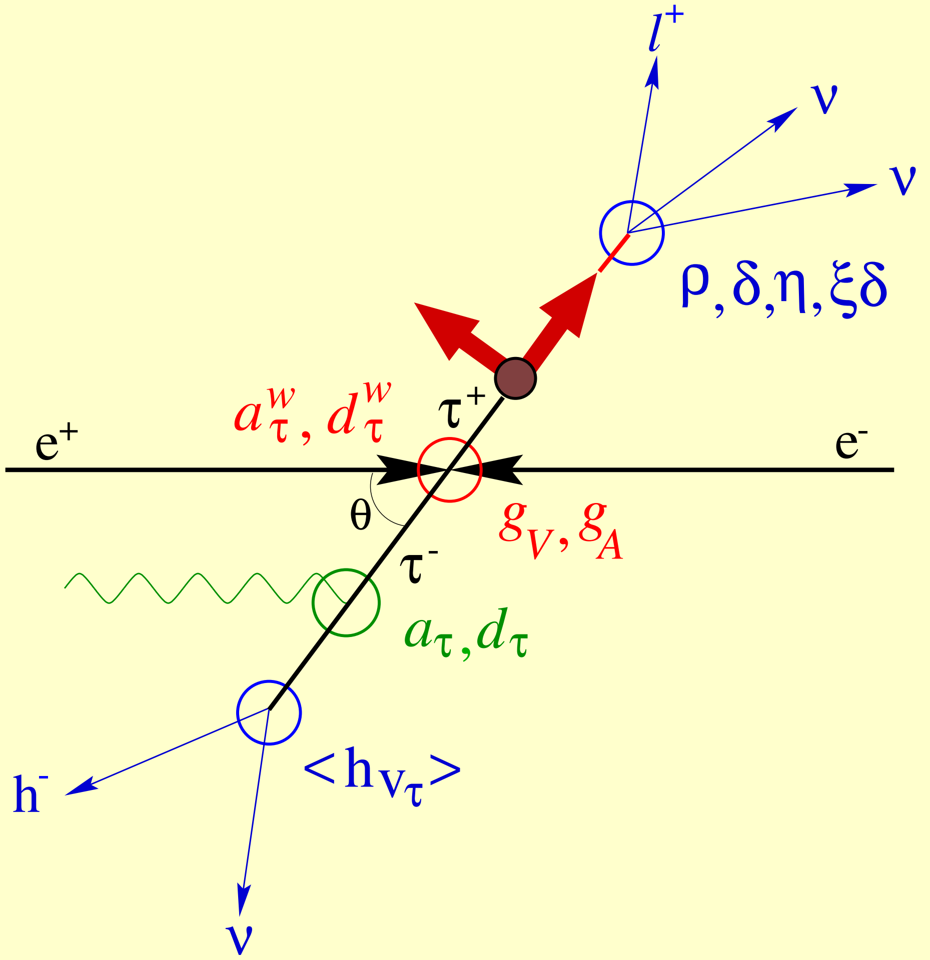


radiative τ pair production

Mostly LEP1 data, but many results are quite recent.

Introduction

Plenty of couplings to measure using τ's



Many topics can be addressed:

- Precision EW program at LEP
- Place to hunt for something new

    universality

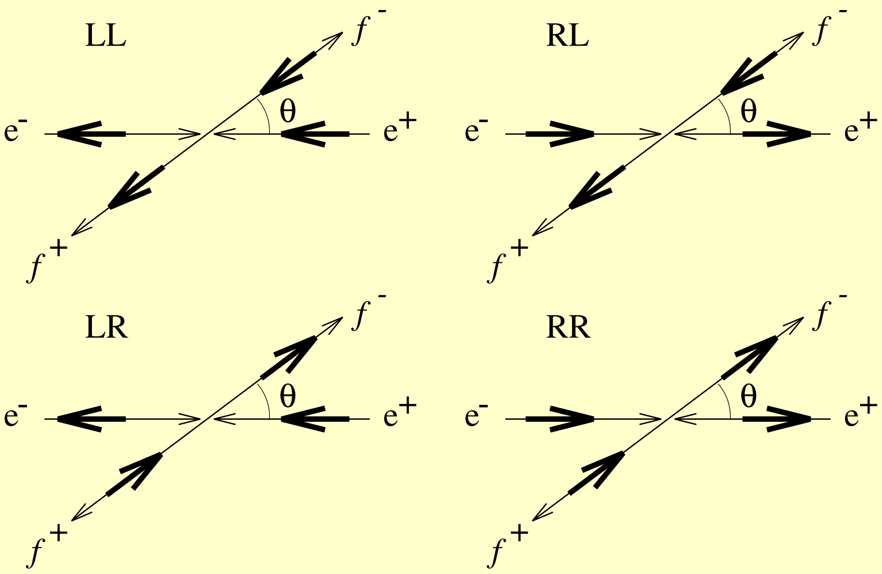
    substructure

    new sources of $\not{C}P$

    MSSM, left-right symmetric models, leptoquarks, ...

Weak Neutral Coupling Constants

LEP observables



$$\sigma_{\text{tot}} = \sigma_{\text{LL}} + \sigma_{\text{RL}} + \sigma_{\text{LR}} + \sigma_{\text{RR}}$$

$$\sigma_{FB} = \sigma_{\text{LL}} + \sigma_{\text{RR}} - (\sigma_{\text{RL}} + \sigma_{\text{LR}})$$

$$\sigma_{\text{pol}} = \sigma_{\text{LL}} + \sigma_{\text{RL}} - (\sigma_{\text{LR}} + \sigma_{\text{RR}})$$

$$\sigma_{\text{pol}}^{FB} = \sigma_{\text{LL}} - \sigma_{\text{RR}} - (\sigma_{\text{RL}} - \sigma_{\text{LR}})$$

$$\sigma_{\text{tot}}(s = M_Z^2) \quad \propto \quad ({a_e}^2 + {v_e}^2)({a_\tau}^2 + {v_\tau}^2)$$

$$A_{FB}(s = M_Z^2) = \frac{\sigma_{fb}}{\sigma_{\text{tot}}} \quad = \quad \frac{a_e v_e a_\tau v_\tau}{({a_e}^2 + {v_e}^2)({v_\tau}^2 + {a_\tau}^2)}$$

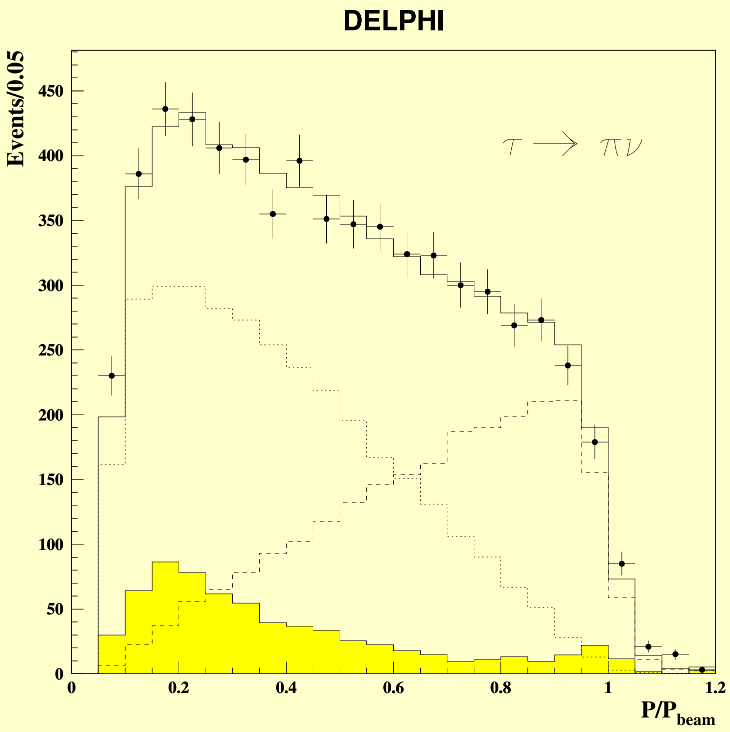
$$\mathcal{P}_\tau(s = M_Z^2) = \frac{\sigma_{\text{pol}}}{\sigma_{\text{tot}}} \quad = \quad 2\frac{a_\tau v_\tau}{{a_\tau}^2 + {v_\tau}^2}$$

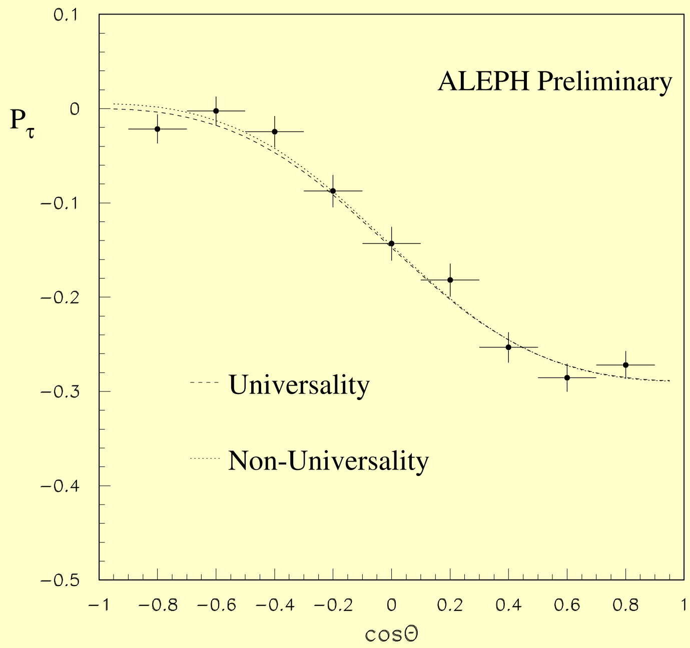
$$\mathcal{P}^{FB}(s = M_Z^2) = \frac{\sigma_{\text{pol}}^{FB}}{\sigma_{\text{tot}}} \quad = \quad -\frac{3}{2}\frac{a_e v_e}{{a_e}^2 {v_e}^2}$$

Unique channel in that polarization is accessible.

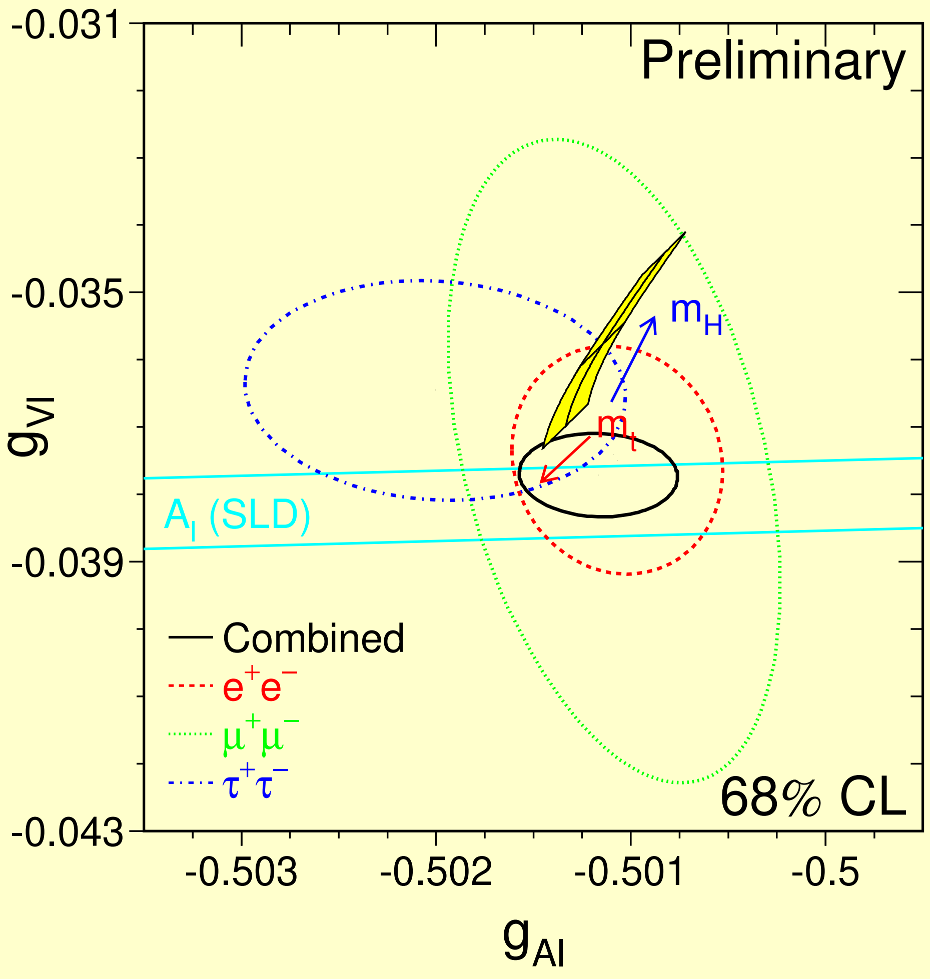
τ longitudinal polarization

- Assume pure $V - A$ in τ decay
- Information about τ helicity transferred to energy and angular distributions of the decay products



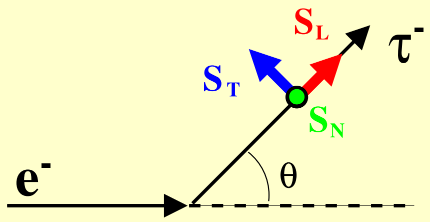


Electroweak couplings summary



$m_t = 174.3 \pm 5.1$ GeV, $m_H = 300^{+700}_{-205}$ GeV
(EWWG, January 2000)

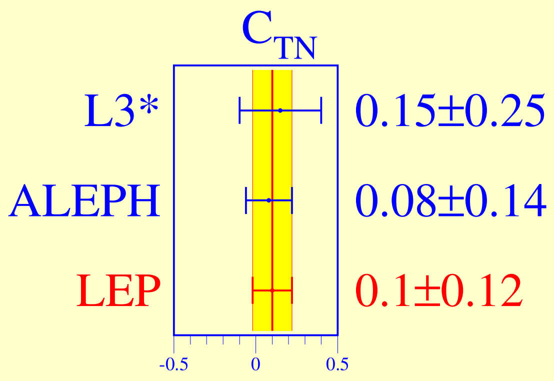
Spin correlations

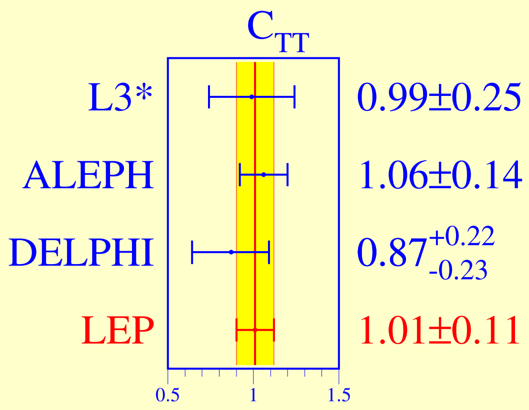


$$C_{TT} = \frac{\sigma(s^T_{\tau^-} s^T_{\tau^+}=+1)-\sigma(s^T_{\tau^-} s^T_{\tau^+}=-1)}{\sigma(s^T_{\tau^-} s^T_{\tau^+}=+1)+\sigma(s^T_{\tau^-} s^T_{\tau^+}=-1)} \propto \frac{|a_\tau|^2-|v_\tau|^2}{|a_\tau|^2+|v_\tau|^2}$$

$$C_{TN} = \frac{\sigma(s^T_{\tau^-} s^N_{\tau^+}=+1)-\sigma(s^T_{\tau^-} s^N_{\tau^+}=-1)}{\sigma(s^T_{\tau^-} s^N_{\tau^+}=+1)+\sigma(s^T_{\tau^-} s^N_{\tau^+}=-1)} \propto -\frac{2Im(v_\tau a_\tau{}^*)}{|a_\tau|^2+|v_\tau|^2}$$

- Can be measured from aplanarity of τ decay products
- Not competitive with other τ electroweak measurements
- C_{TN} is sensitive to CP violating effects





*Preliminary

Weak Dipole Moments

Introduce new $Z\tau\tau$ interactions:

$$\mathcal{L}_{\rm int}^{eff} = \frac{-i}{2}\frac{eF_3^w}{2m_\tau}\overline{\psi}\sigma^{\mu\nu}\gamma_5\psi Z_{\mu\nu} + \frac{1}{2}\frac{eF_2^w}{2m_\tau}\overline{\psi}\sigma^{\mu\nu}\psi Z_{\mu\nu}$$

Weak moments defined as: $a_\tau^w = F_2^w$, $d_\tau^w = eF_3^w/2m_\tau$

SM Values (from loops):

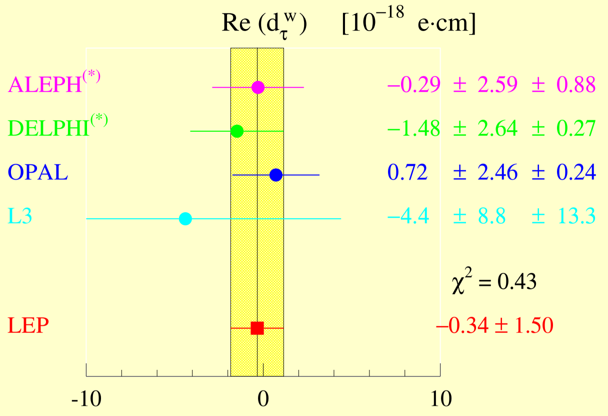
$a_\tau^w = -(2.10 + 0.61i) \times 10^{-6}, d_\tau^w \sim 3 \times 10^{-37} ecm$

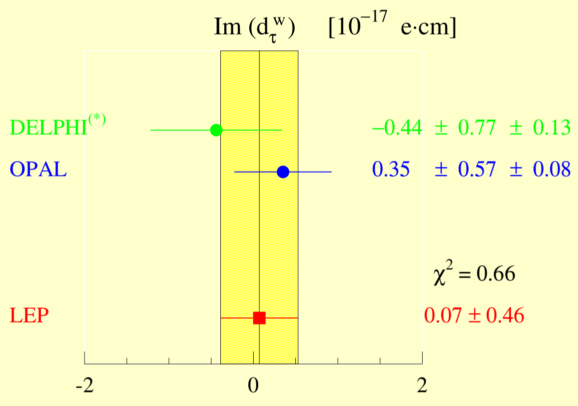
Beyond experimental sensitivity, but large value ⇒ new physics.

(CP violation, various SM extensions)

Strategies for constructing observables sensitive to weak moments:

- L3:Transverse and normal (single) τ polarization (azimuthal asymmetries)
- ALEPH, DELPHI, OPAL CP-odd observables using spin-spin correlations (optimal observables)





$$Re(a_\tau^w) = (0.0 \pm 1.6 \pm 2.3) \times 10^{-3} (L3)$$
$$Im(a_\tau^w) = (-1.0 \pm 2.6 \pm 5.3) \times 10^{-3} (L3)$$

A.Zalite TAU98

Leptonic branching fractions and lifetime

$$\Gamma(\tau \to \ell \nu_\tau \bar{\nu}_\ell) = \frac{\mathcal{B}_\ell}{\tau_\tau} = \frac{G_F^2 m_\tau^2}{192\pi^3} f(x_l^2) r_{\rm RC}$$

$$G_F = \frac{g_\ell g_\tau}{\sqrt{32} M_W^2}$$

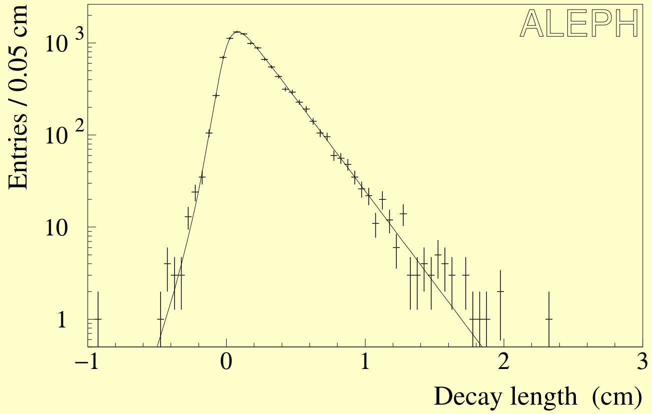
$$\mathcal{B}_e \sim \frac{g_\tau^2}{g_\mu^2} \frac{m_\tau^5}{m_\mu^5} \frac{\tau_\tau}{\tau_\mu}, \; \mathcal{B}_\mu \sim \frac{g_\tau^2}{g_e^2} \frac{m_\tau^5}{m_\mu^5} \frac{\tau_\tau}{\tau_\mu}$$

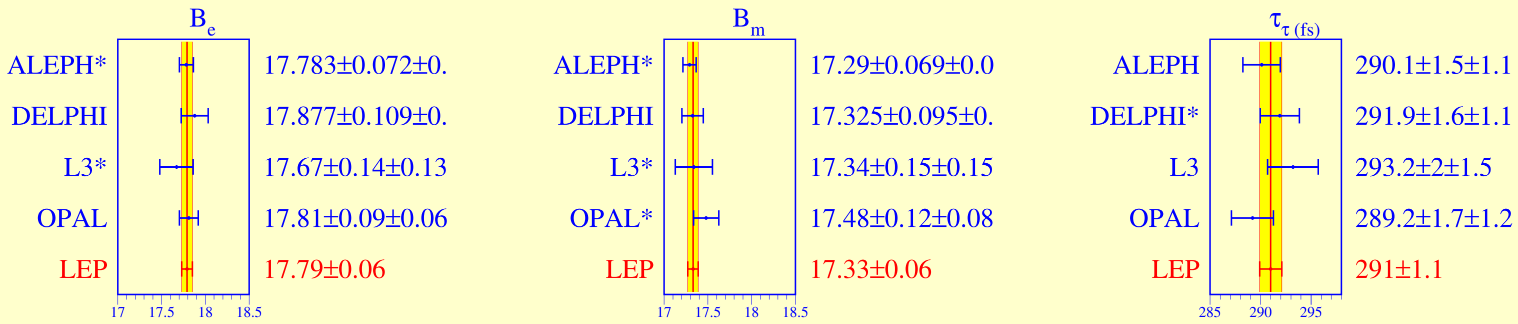
Need to measure:

- Leptonic branching fractions
- τ lifetime

At LEPI energies, τ travels ≈ 2 mm

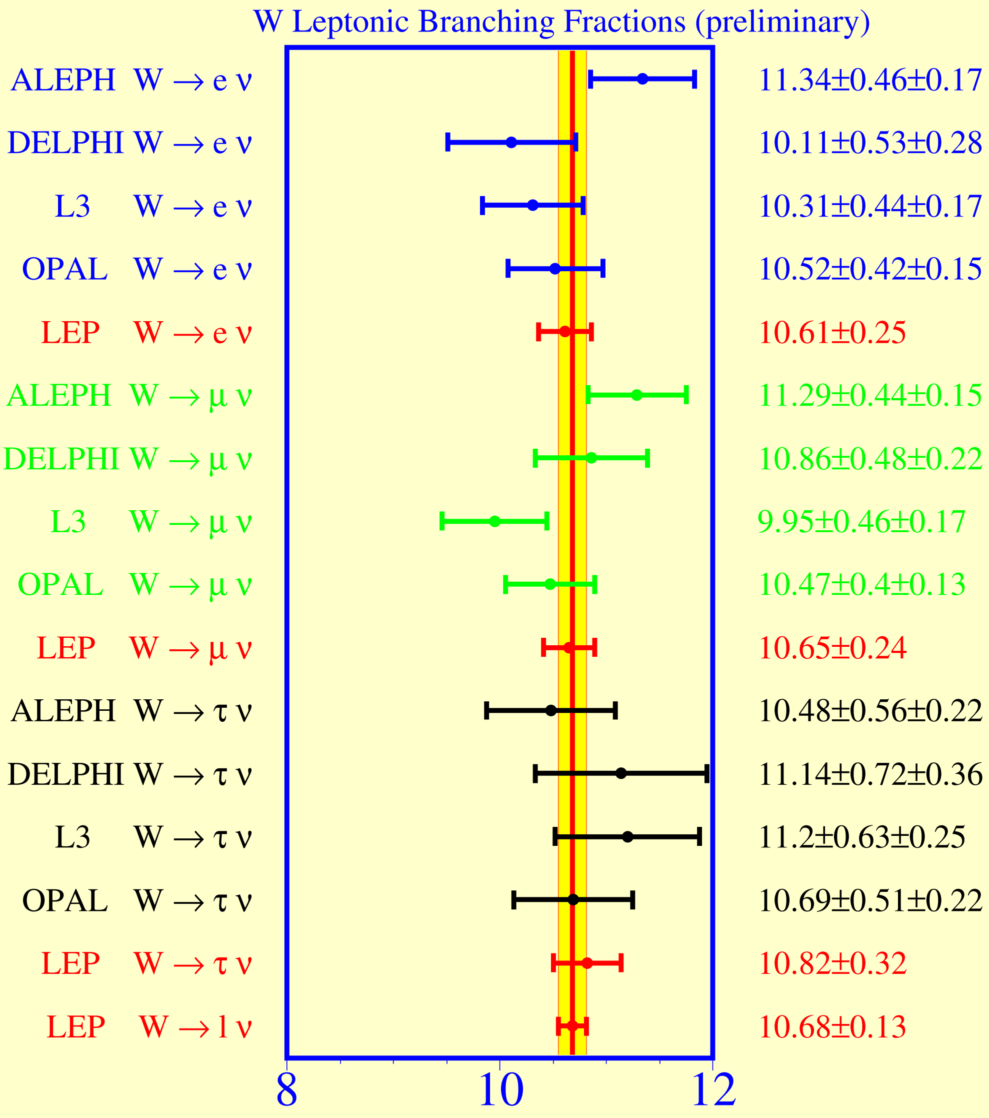
- decay length method for 3-prong
- impact parameter for the rest





$$g_\tau / g_\mu = 0.9996 \pm 0.0025$$
$$g_\tau / g_e = 0.9989 \pm 0.0024$$

On-shell W couplings from LEPII



Not competitive with universality test from lifetime and branching fractions.

EWWG, January 2000

Lorentz structure of charged current

Decays of type $\tau \to \ell\nu_\tau\nu_\ell$ described by general four-fermion contact interaction:

$$\mathcal{M} = \frac{4G_F}{\sqrt{2}} \sum_{\substack{\gamma=S,\,V,\,T \\ \lambda,\,\iota=R,\,L}} g^\gamma_{\lambda\iota} < \bar{l}_\lambda|\Gamma^\gamma|(\nu_l)_n >< (\overline{\nu}_\tau)_m|\Gamma_\gamma|\tau_\iota > .$$

From SM expect: ${g_{\mathrm{LL}}}^{\mathrm{V}} = 1$, others $= 0$.

- $g^\gamma_{\lambda\iota}$ commonly expressed in terms of Michel parameters.
- Leptonic τ decay spectra provide access to 4 Michel parameters and $\mathcal{P}_\tau$:

$$\begin{aligned}\frac{1}{\Gamma}\frac{d\Gamma}{dx_l} &= H^l_0(x_l) - \mathcal{P}_\tau H^l_1(x_l) \\ &= h^l_0(x_l) + \eta h^l_\eta(x_l) + \rho h^l_\rho(x_l) - \mathcal{P}_\tau[\xi h^l_\xi(x_l) + \xi\delta h^l_{\xi\delta}(x_l)]\end{aligned}$$

- Similarly for semileptonic decays:

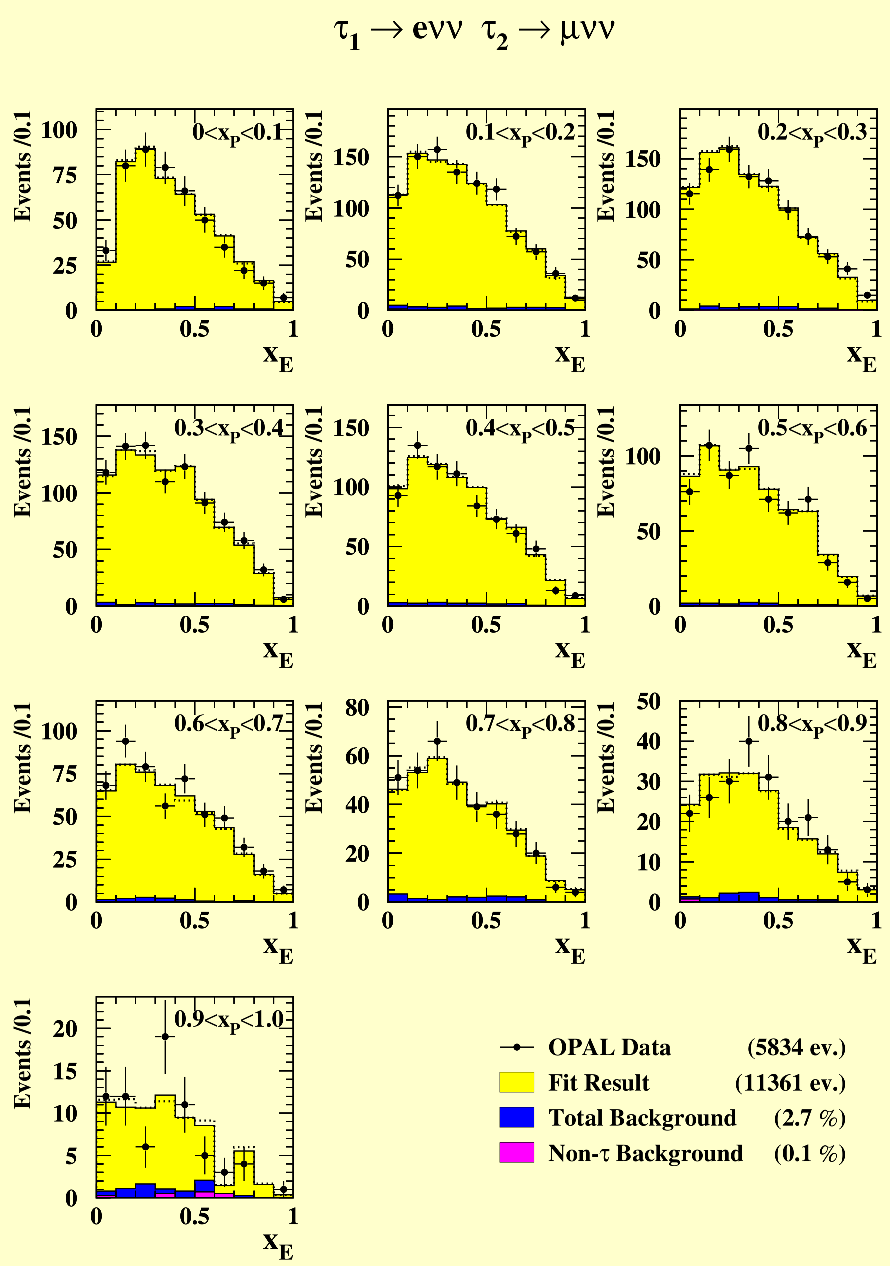
$$\begin{aligned}\frac{1}{\Gamma}\frac{d\Gamma}{dx_h} &= H^h_0(x_h) - \mathcal{P}_\tau H^h_1(x_h) \\ &= h^h_0(x_h) - \mathcal{P}_\tau \xi_h h^h_1(x_h)\end{aligned}$$

- Disentangle $\mathcal{P}_\tau, \xi, \xi\delta$ by exploiting (nearly) 100% anticorrelation of τ helicities (assume only V and A in τ production):

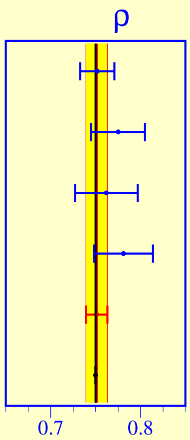
$$\begin{aligned}\frac{1}{\Gamma}\frac{d^2\Gamma}{dx_A dx_B} &= \mathrm{H}^{(\mathrm{A})}_0(x_A)\mathrm{H}^{(B)}_0(x_B) + \mathrm{H}^{(\mathrm{A})}_1(x_A)\mathrm{H}^{(B)}_1(x_B) \\ &\quad - \mathcal{P}_\tau \left[\mathrm{H}^{(\mathrm{A})}_1(\mathrm{x_A})\mathrm{H}^{(B)}_0(x_B) + \mathrm{H}^{(A)}_0(x_A)\mathrm{H}^{(B)}_1(x_B)\right]\end{aligned}$$

Lorentz structure of charged current

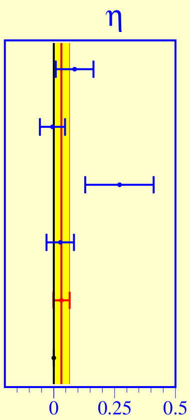
Simultaneous fit for $\rho, \eta, \xi, \xi\delta, \xi_h, \mathcal{P}_\tau$ using joint distributions and single-sided distributions.



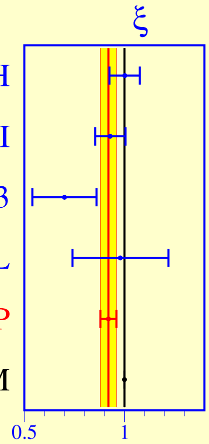
Lorentz structure of charged current



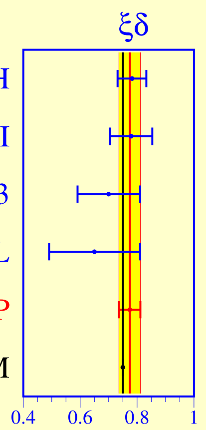
	ρ
ALEPH	0.752±0.019
DELPHI	0.775±0.03
L3	0.762±0.035
OPAL	0.781±0.033
LEP	0.751±0.012
SM	0.75



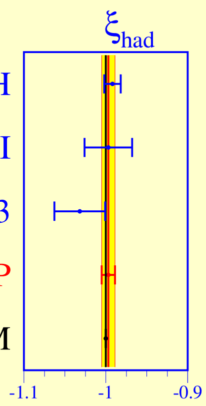
	η
ALEPH	0.086±0.078
DELPHI	-0.005±0.052
L3	0.27±0.14
OPAL	0.027±0.056
LEP	0.032±0.033
SM	0



	ξ
ALEPH	1.002±0.076
DELPHI	0.929±0.076
L3	0.7±0.16
OPAL	0.98±0.24
LEP	0.92±0.04
SM	1



	ξδ
ALEPH	0.782±0.051
DELPHI	0.779±0.075
L3	0.7±0.11
OPAL	0.65±0.16
LEP	0.774±0.038
SM	0.75

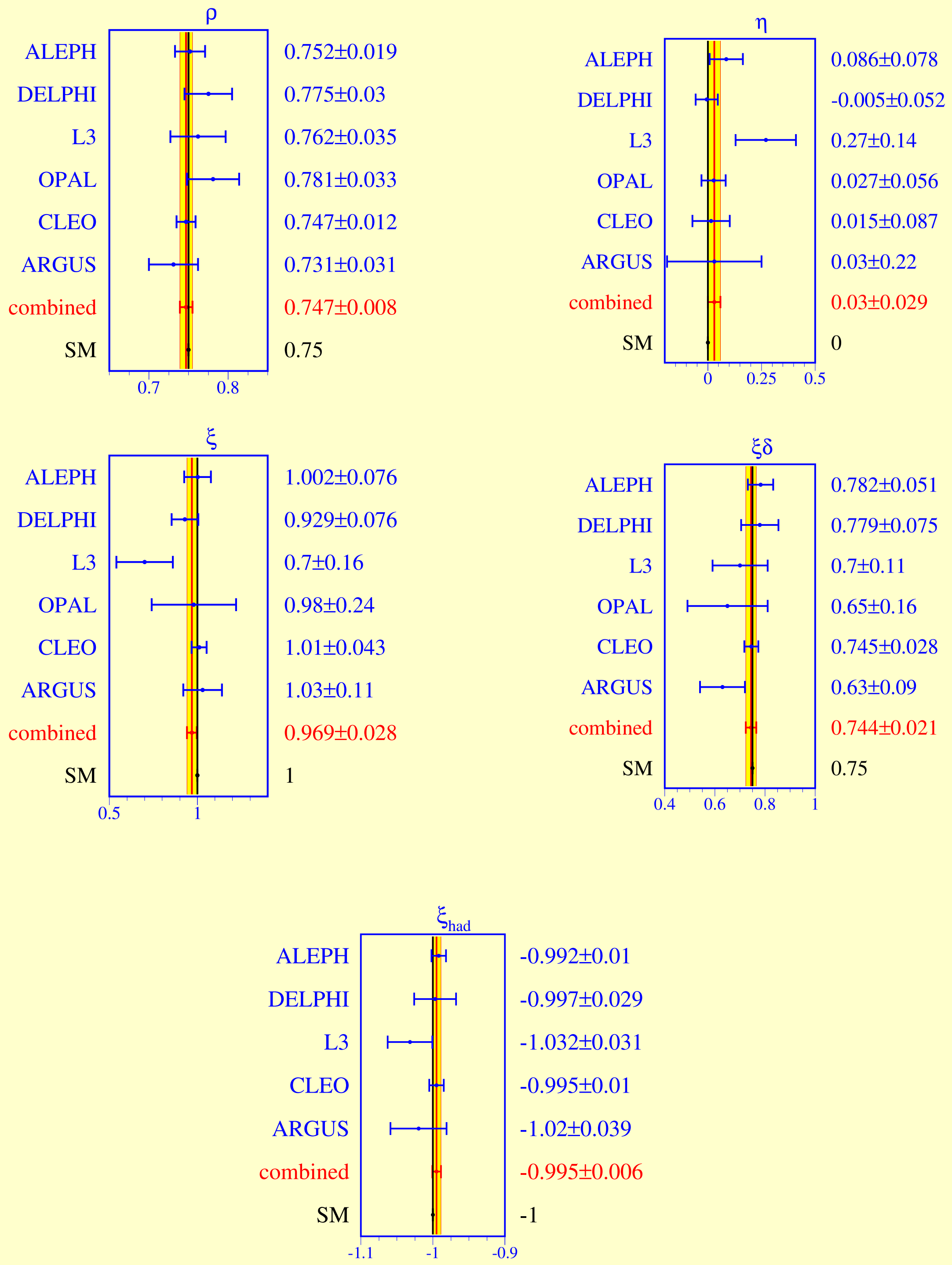


	ξ_{had}
ALEPH	-0.992±0.01
DELPHI	-0.997±0.029
L3	-1.032±0.031
LEP	-0.997±0.008
SM	-1

SM prediction

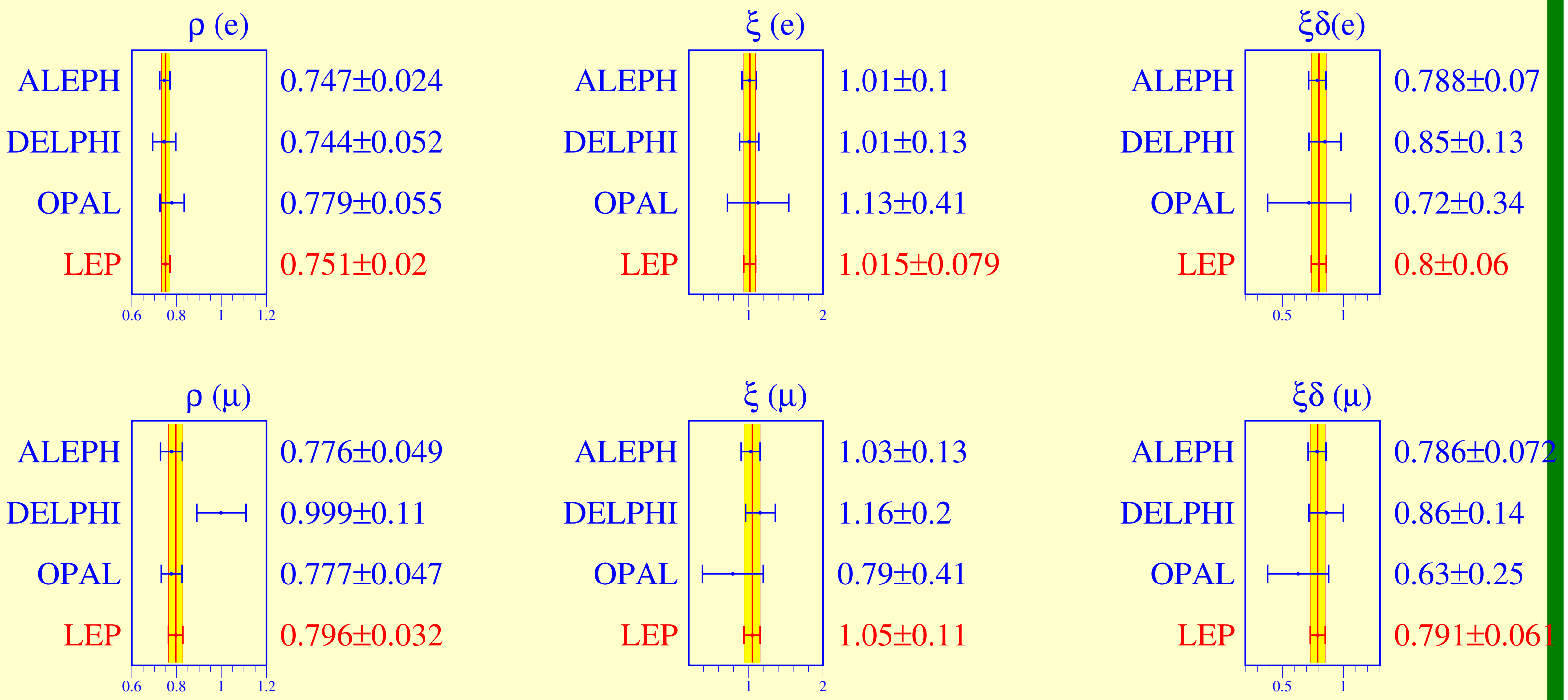
- $\rho = 3/4$
- $\eta = 0$
- $\xi = 1$
- $\xi\delta = 3/4$

Lorentz structure of charged current

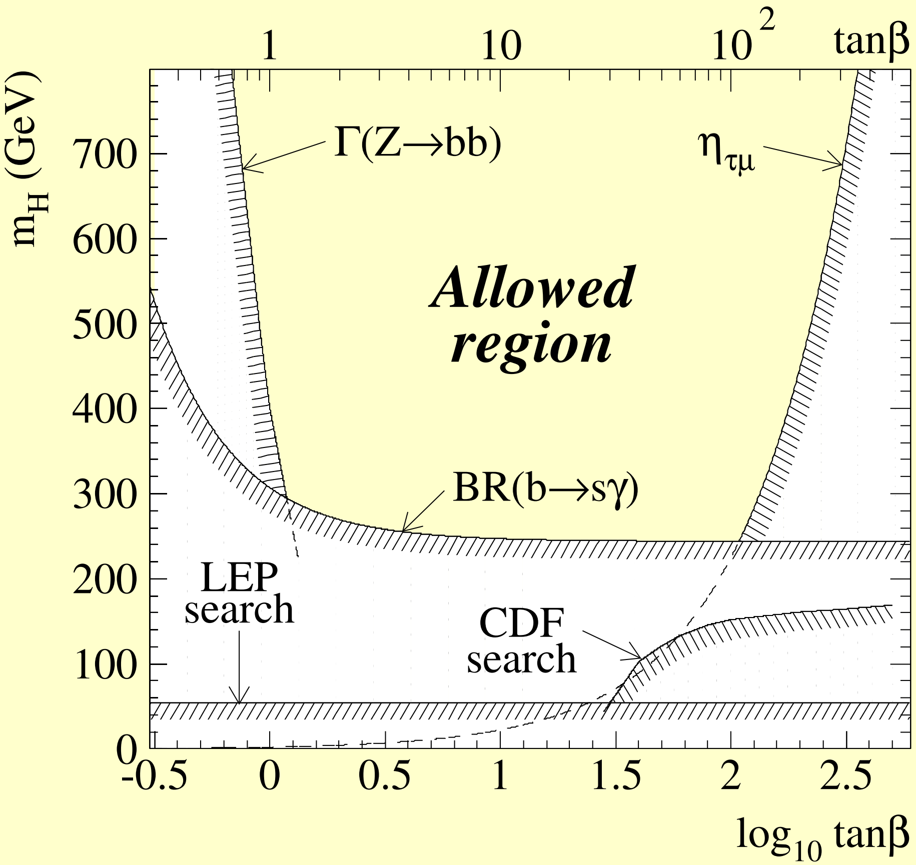


Lorentz structure of charged current

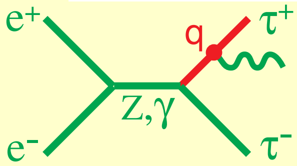
Universality?

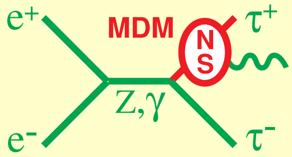


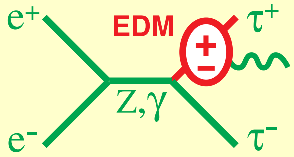
Lorentz structure of charged current



Anomalous Electromagnetic Moments



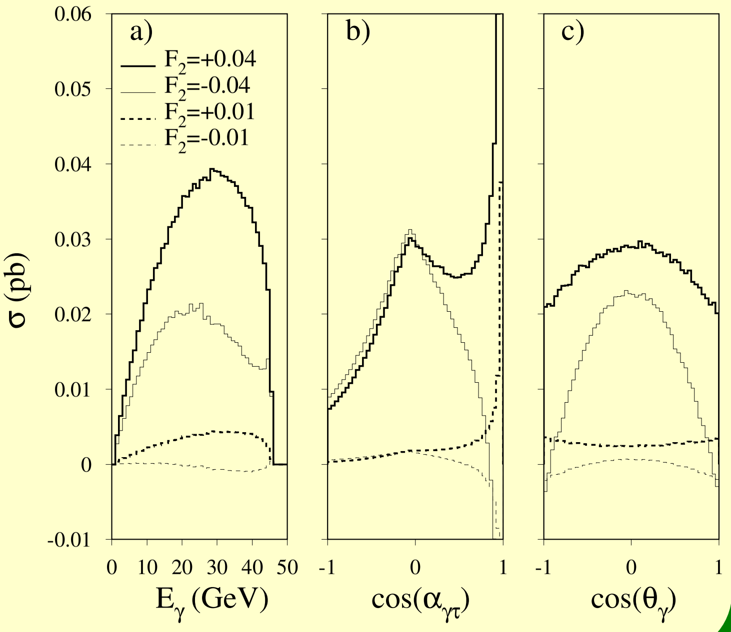




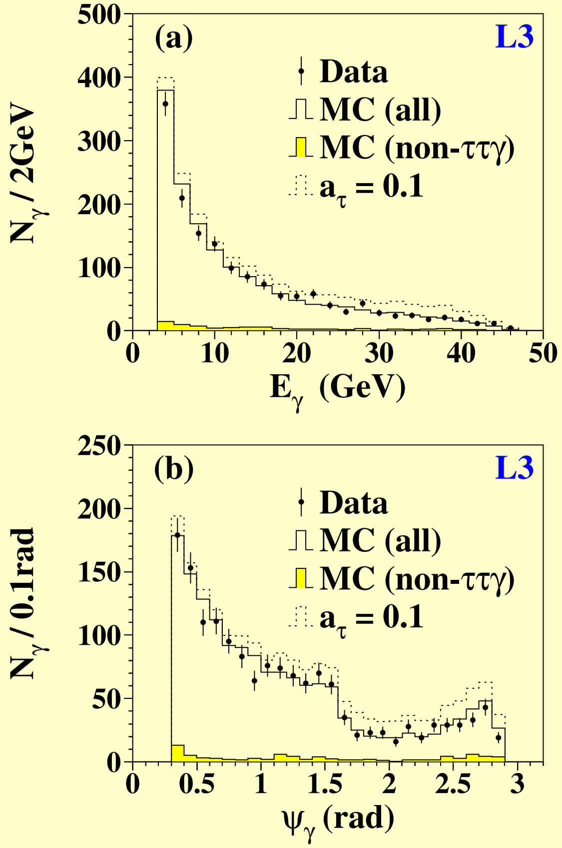
$F_1(q^2)\gamma^\mu$	$F_2(q^2)\frac{i}{2m_f}\sigma^{\mu\nu}q_\nu$	$F_3(q^2)\sigma^{\mu\nu}\gamma^5 q_\nu$
$\Downarrow$	$\Downarrow$	$\Downarrow$
Electric charge, q_τ	Anomalous Magnetic Moment, a_τ	Electric Dipole Moment, d_τ
$q_\tau \equiv F_1(q^2=0)$	$a_\tau \equiv F_2(q^2=0)$ $= (g-2)/2$	$d_\tau \equiv eF_3(q^2=0)$
	$a_\tau(\mathrm{SM}) = \alpha/2\pi + \ldots$ ≈ 0.0011	$d_\tau(\mathrm{SM}) = 0$ (non-zero $\Rightarrow \not{T}$ & $\not{P}$)

$$\boxed{\gamma^\mu \to \gamma^\mu + \frac{iF_2}{2m_\tau}\sigma^{\mu\nu}q_\nu - F_3\sigma^{\mu\nu}\gamma^5 q_\nu}$$

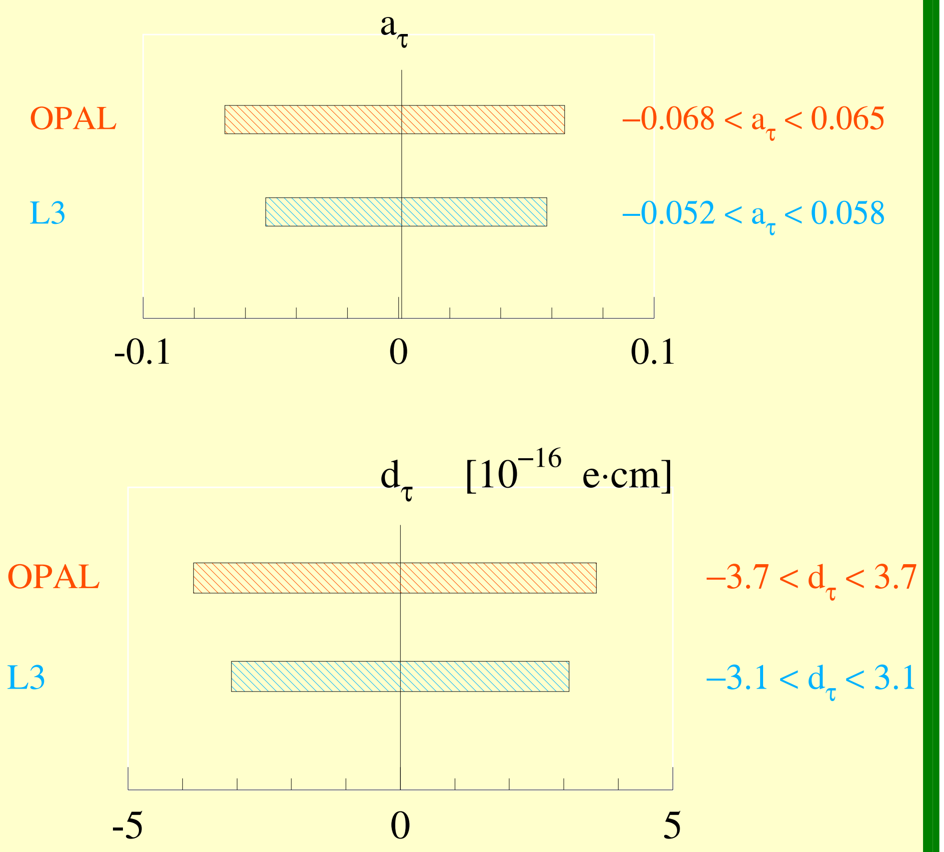
- Increased rate of $\tau\tau\gamma$ events
- Changes shape of energy and angular distributions



Anomalous Electromagnetic Moments

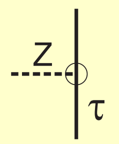


95% CL limits

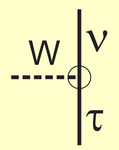


Summary

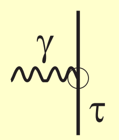
The bulk of τ coupling measurements from LEP are more-or-less finalized. Lots of issues have been addressed. *Some* of them are:



- Precision measurements of v_τ, a_τ (Γ_τ, A_{FB}, $\mathcal{P}_\tau(cos\theta)$)
- Consistent with universality in weak neutral current
- Full spin analyses have been carried out (including transverse and normal components)
- Measurements (searches for..) weak dipole moments (a_τ^w, d_τ^w) have been done, but no evidence for CP violation or new physics.



- Lorentz structure in τ decays has been studied in some detail.
- Thus far, everything is consistent with $V - A$ charged current.
- Universality supported.



- Measurements of AMDM, EDM form factors at $q^2 = 0$.
- No anomalous terms needed to describe this data.