Physics with the τ Lepton

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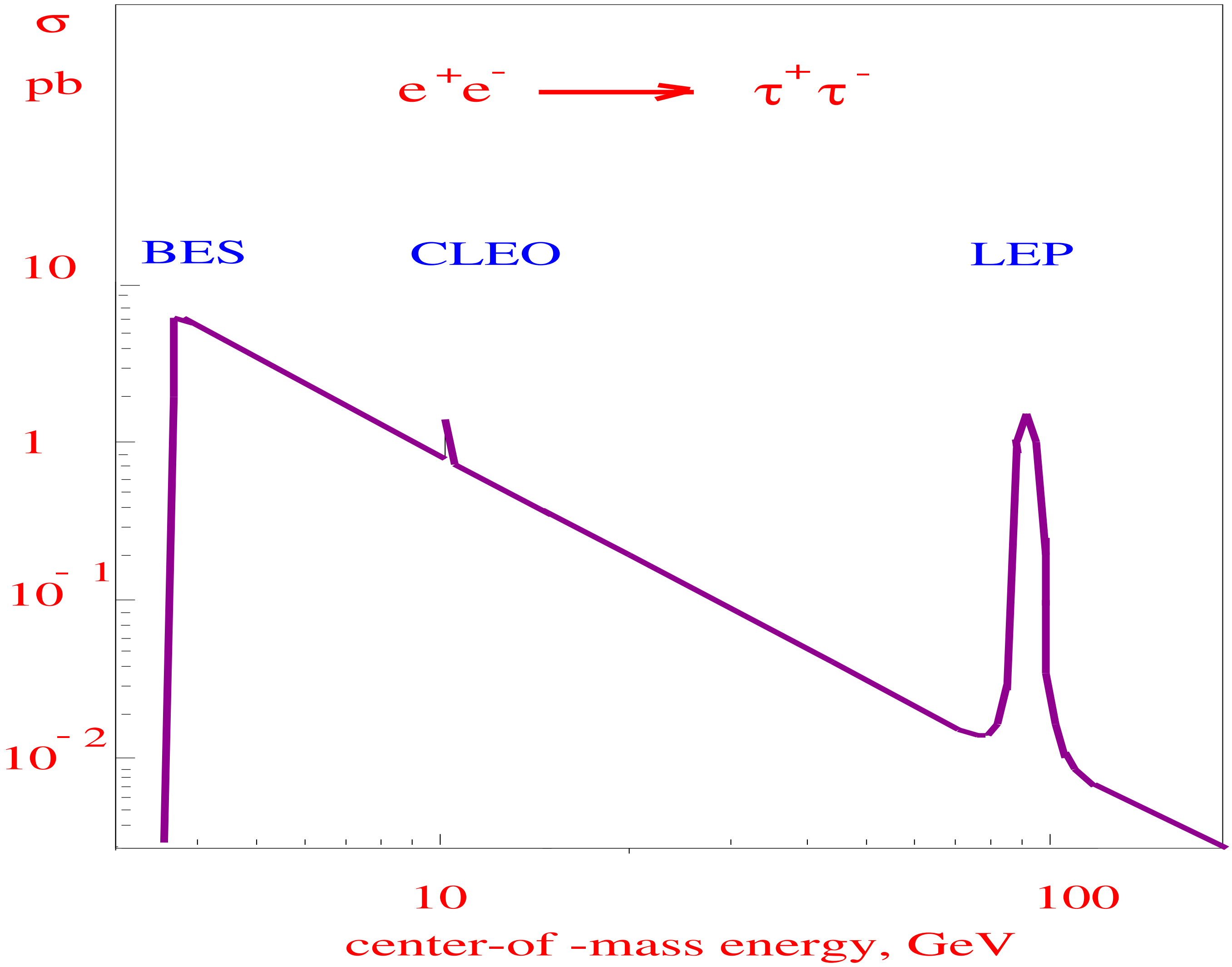
(L3 Collaboration)

- Introduction
- Intrinsic Properties of the τ Lepton
- Charged Current Couplings
- Neutral Current Coulplings
- Outlook

NINTH LOMONOSOV CONFERENCE ON ELEMENTARY PARTICLE PHYSICS

Moscow, 20 - 26 September, 1999

$$e^+e^- \longrightarrow \tau^+\tau^-$$



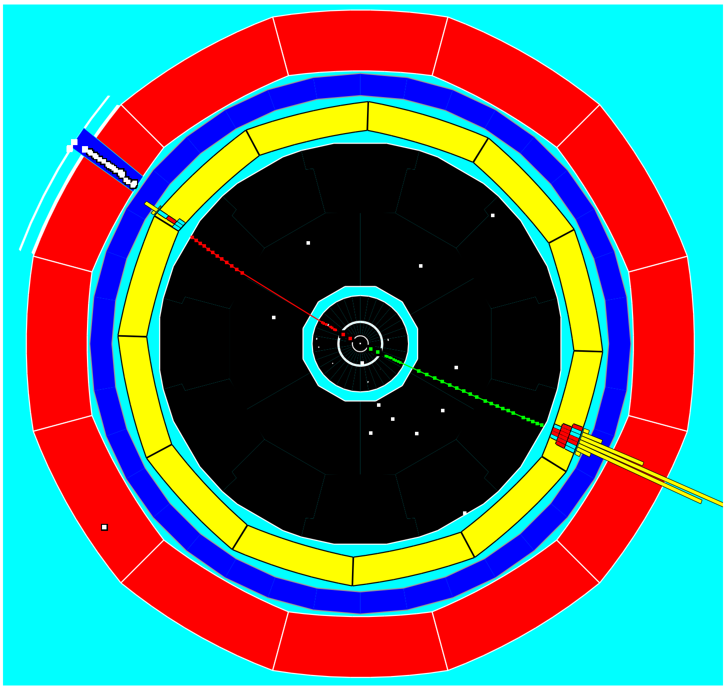
Experiments	BES	CLEO	ALEPH,DELPHI, L3, OPAL
storage ring	BEPC	CESR	LEP
$\sqrt{s}$,GeV	~ 4	~ 10	~ 90
$\tau\tau$ statistics	9×10^4	4.5×10^6	2×10^5

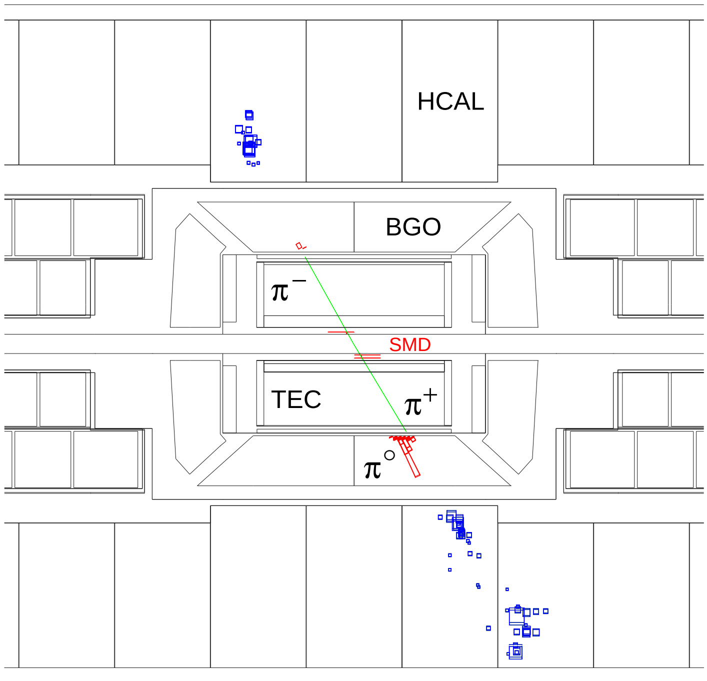
introduction

$e^+e^- \rightarrow \tau^+\tau^-$ in collider detectors

ALEPH

L3

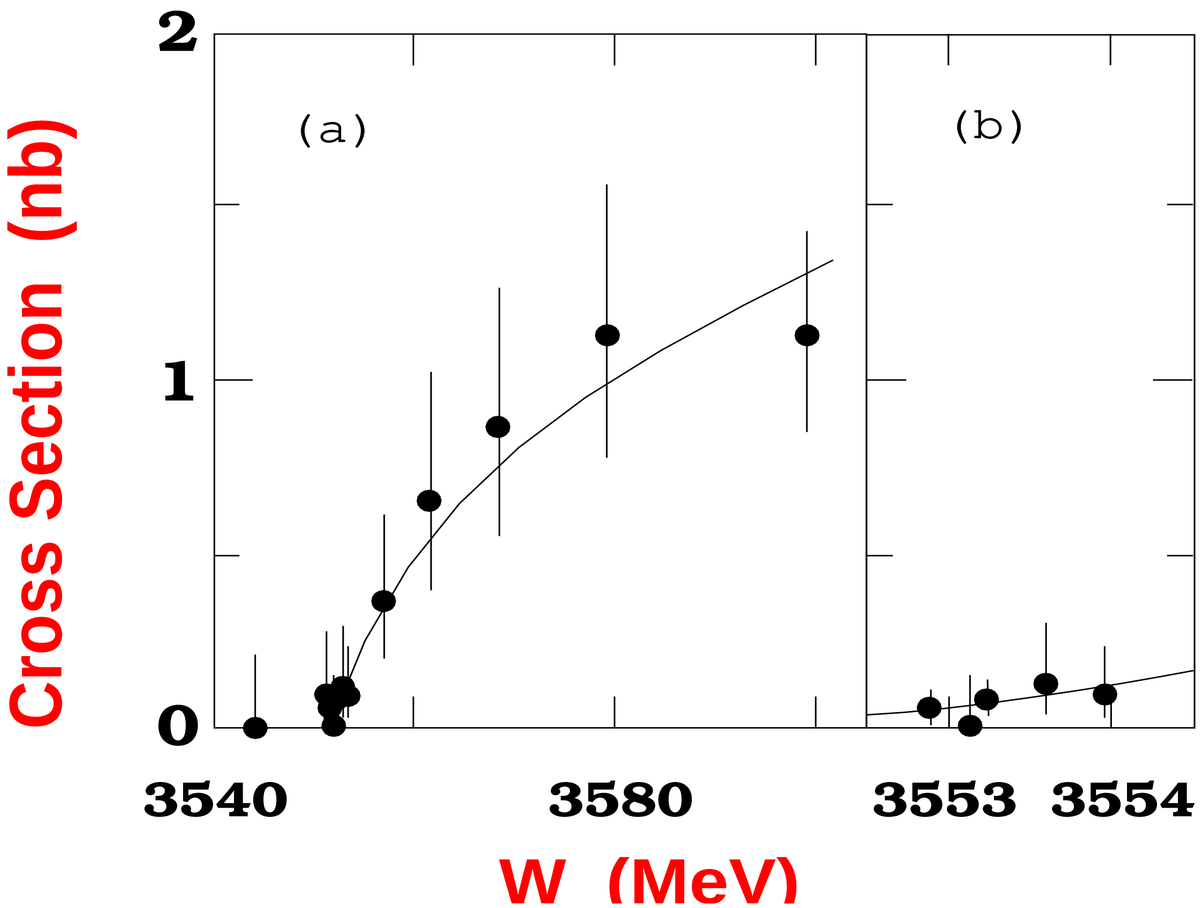




- $e^+e^- \rightarrow \tau^+\tau^-$ easy to identify via τ decay products
  $\Rightarrow$ low multiplicity jets, small non–τ background contributions (O(few%))
- identification based on response of subdetectors
- clean channels, especially: e, μ: (O few%), π (O(10%))

The mass of the τ

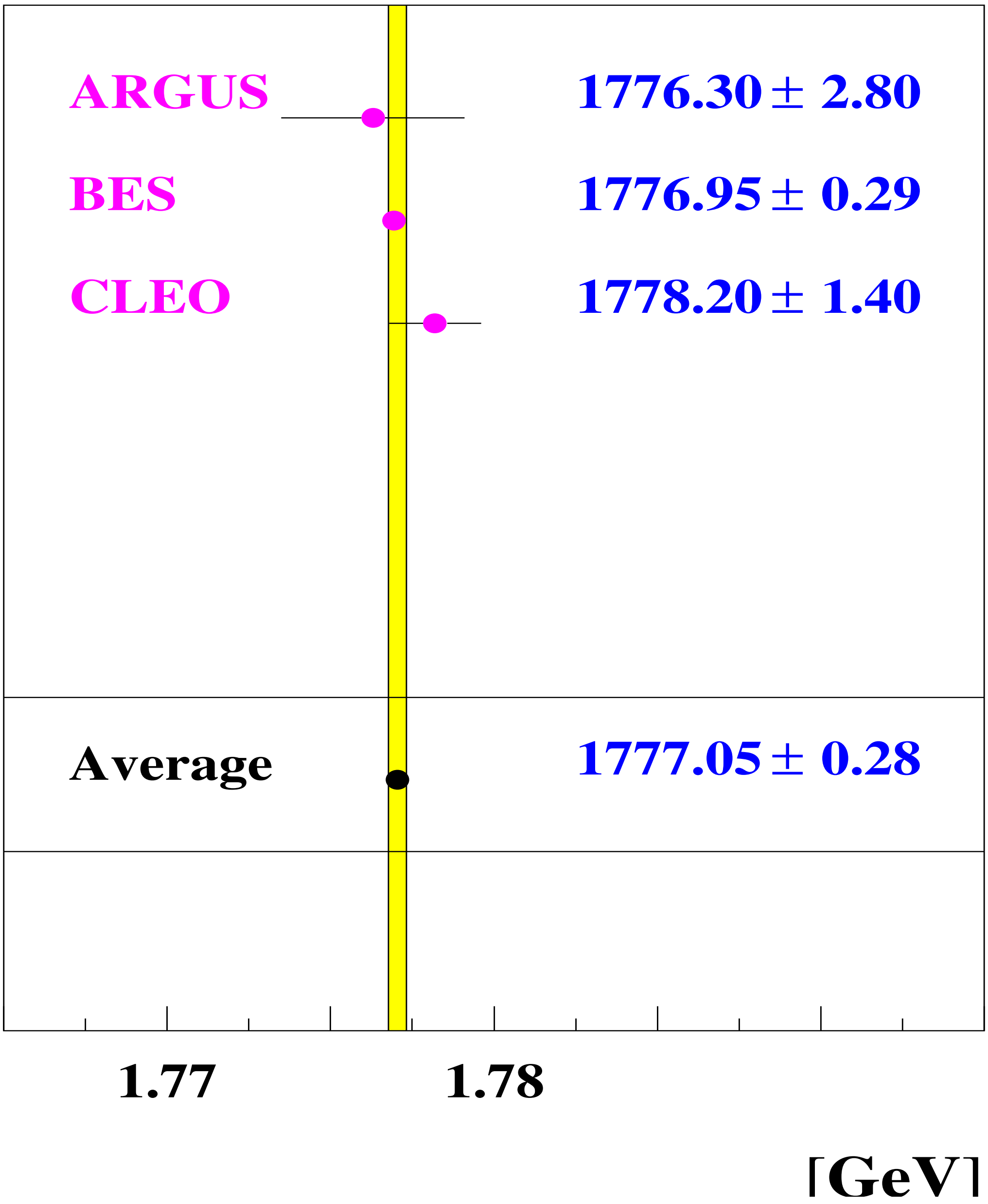
BES experiment



Threshold scan:

$$\mathbf{m_\tau = 1776.96}\ {}^{+0.18+0.25}_{-0.21-0.17}\ \text{MeV}$$

summary of recent τ mass measurements

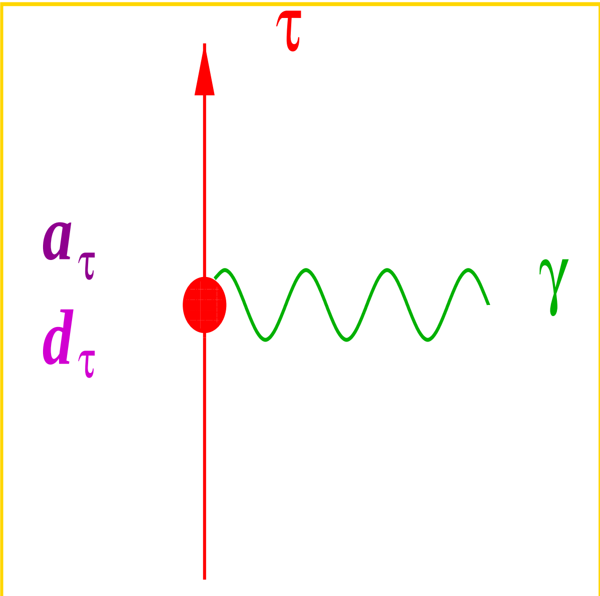


the moments of the τ

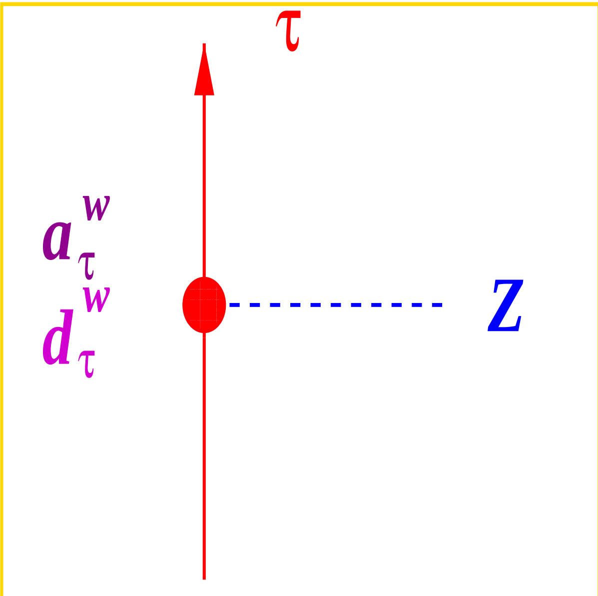
$\longrightarrow$ No measurement done
($\textit{spin precession technique}$??)
$\longrightarrow$ Substructure of the τ lepton

$\longrightarrow$ Lepton Universality

At LEP energies both electromagnetic and weak moments of the τ lepton are accessible



$Q^2 = 0$ (real photon)

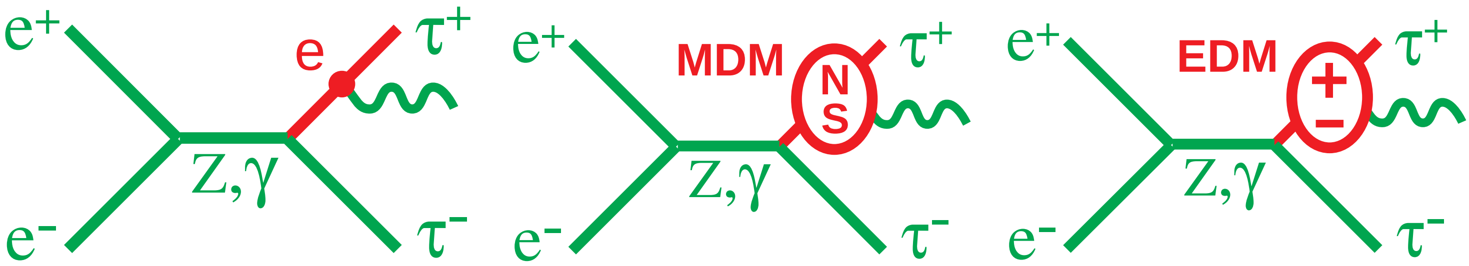


$Q^2 = m_Z^2$

Non-zero values of d_τ or d_τ^w reveal <u>new sources</u> of CP violation

Electromagnetic Dipole Moments

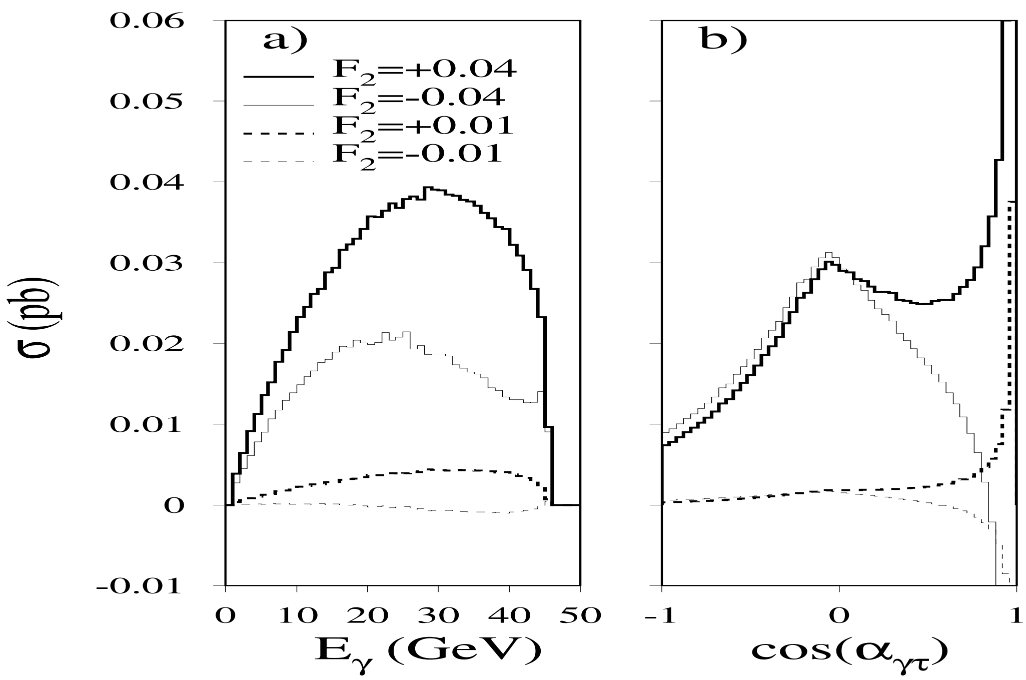
electromagnetic moments



Electric charge, e	Anomalous Magnetic Dipole Moment, a_τ	Electric Dipole Moment, d_τ
$e \equiv F_1(q^2\!=\!0)$	$a_\tau \equiv F_2(q^2\!=\!0)$	$d_\tau \equiv eF_3(q^2\!=\!0)$
	$a_\tau^{\mathrm{SM}} = \alpha/2\pi + \ldots$	$d_\tau^{\mathrm{SM}} = 0$
	≈ 0.0012	$(\neq 0 \Rightarrow \not{T} \,\&\, \not{P})$

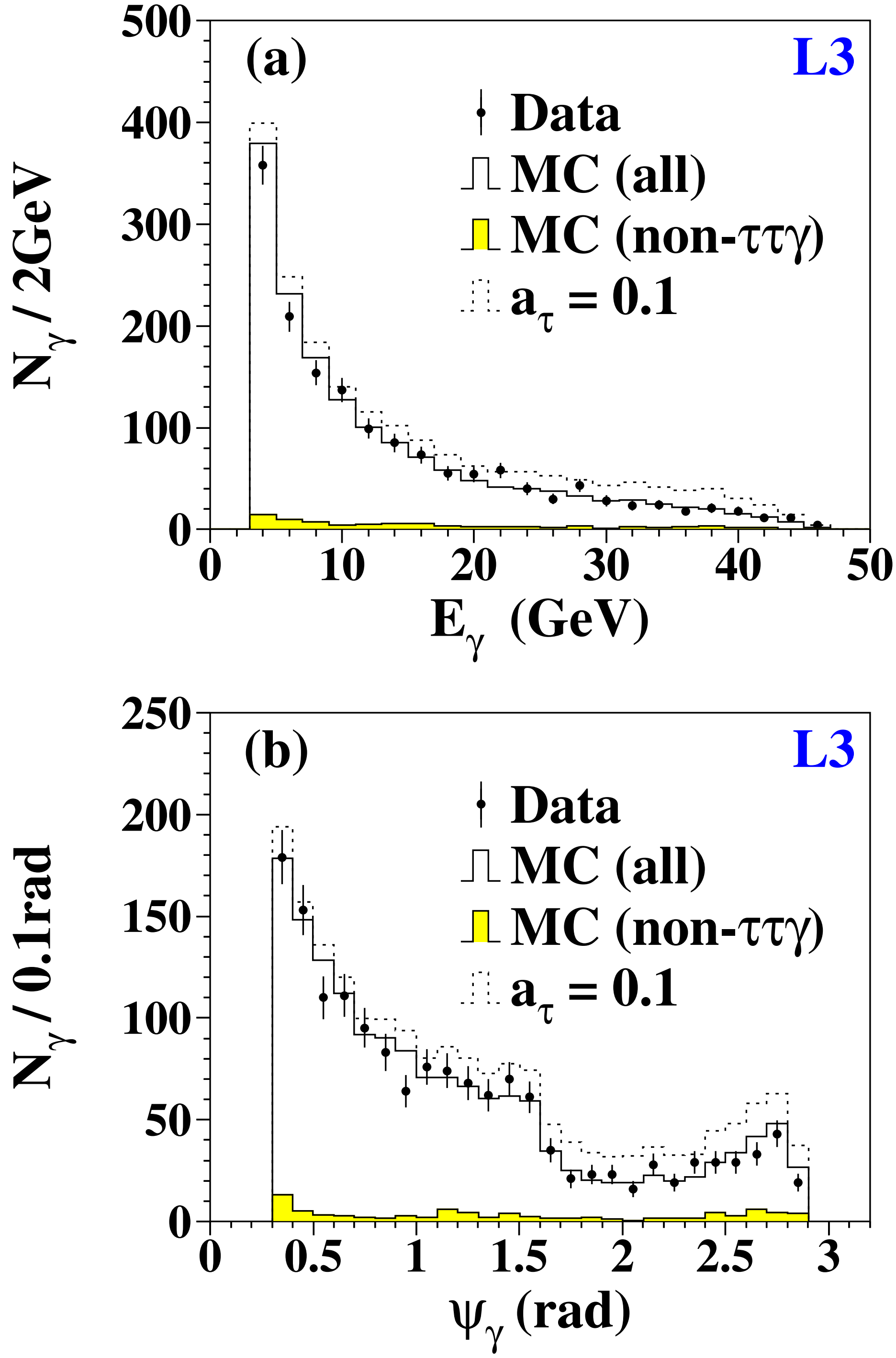
Generic ansatz to describe anomalous $\tau\tau\gamma$ couplings:

$$\gamma^\mu \longrightarrow F_1(q^2)\gamma^\mu + F_2(q^2)\frac{i}{2m_\ell}\sigma^{\mu\nu}q_\nu - F_3(q^2)\sigma^{\mu\nu}\gamma^5 q_\nu .$$



L3 fits for a_τ and d_τ

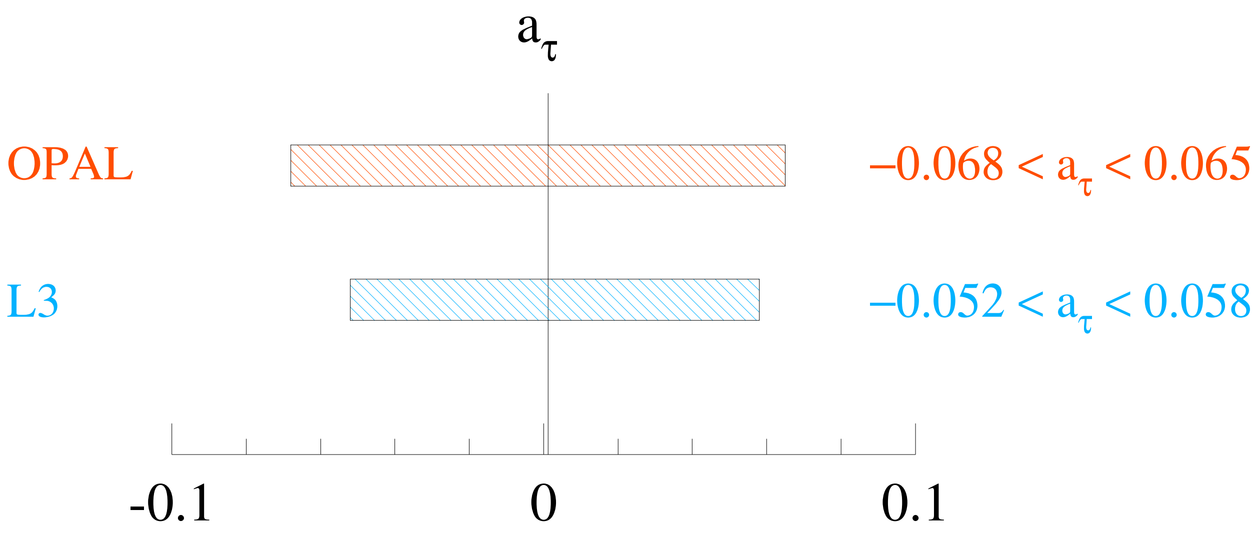
electromagnetic moments

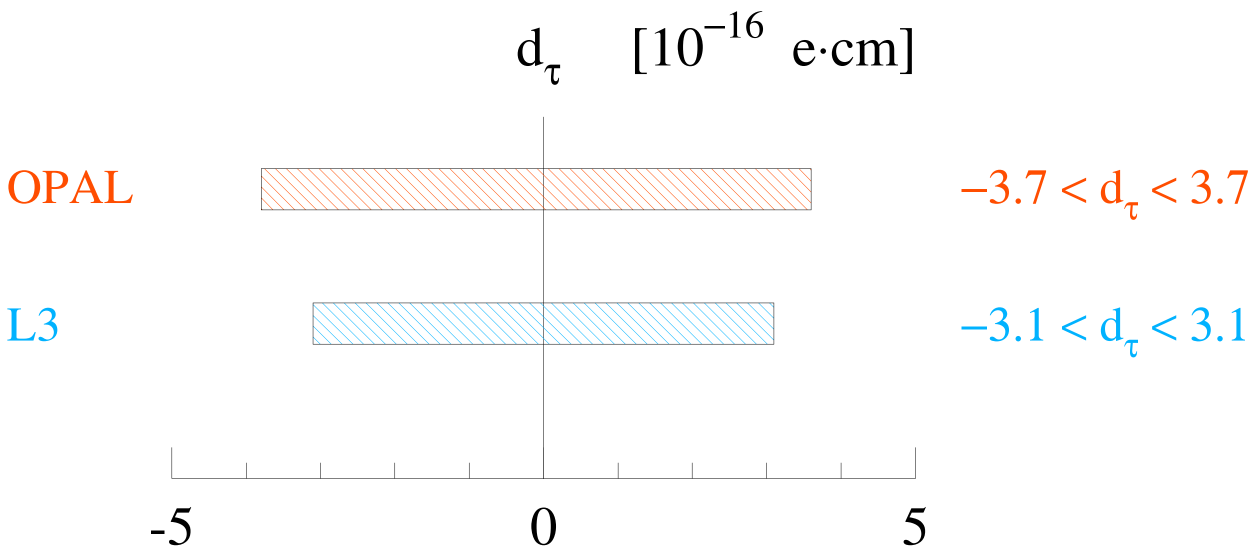


$$a_\tau = 0.004 \pm 0.027 \pm 0.023$$

$$d_\tau = 0.0 \pm 1.5 \pm 1.3 \cdot 10^{-16} ecm$$

Summary on a_τ and d_τ





all limits at 95% C. L.

≈ No evidence for new physics beyond the Standard Model ≈

(no indication for CP violation)

Weak Dipole Moments

weak dipole moments

Ansatz analogous to the e.m. dipole moments

$$a_\tau^w \equiv F_2^w \quad \text{(Weak anomalous magnetic dipole moment)}$$

$$d_\tau^w \equiv \frac{eF_3^w}{2m_\tau} \quad \text{(Weak electric dipole moment)}$$

Standard Model:

$$a_\tau^w = -(2.10 + 0.61i) \times 10^{-6}$$

$$d_\tau^w \sim 3 \times 10^{-37} e \cdot cm$$

several extensions of SM predict via 1–loop effects larger values of a_τ^w and d_τ^w, e. g.:

composite models: a_τ^w up to 10^{-3}

lepto-quarks: $d_\tau^w \approx 2 \times 10^{-19} \; e \cdot cm$

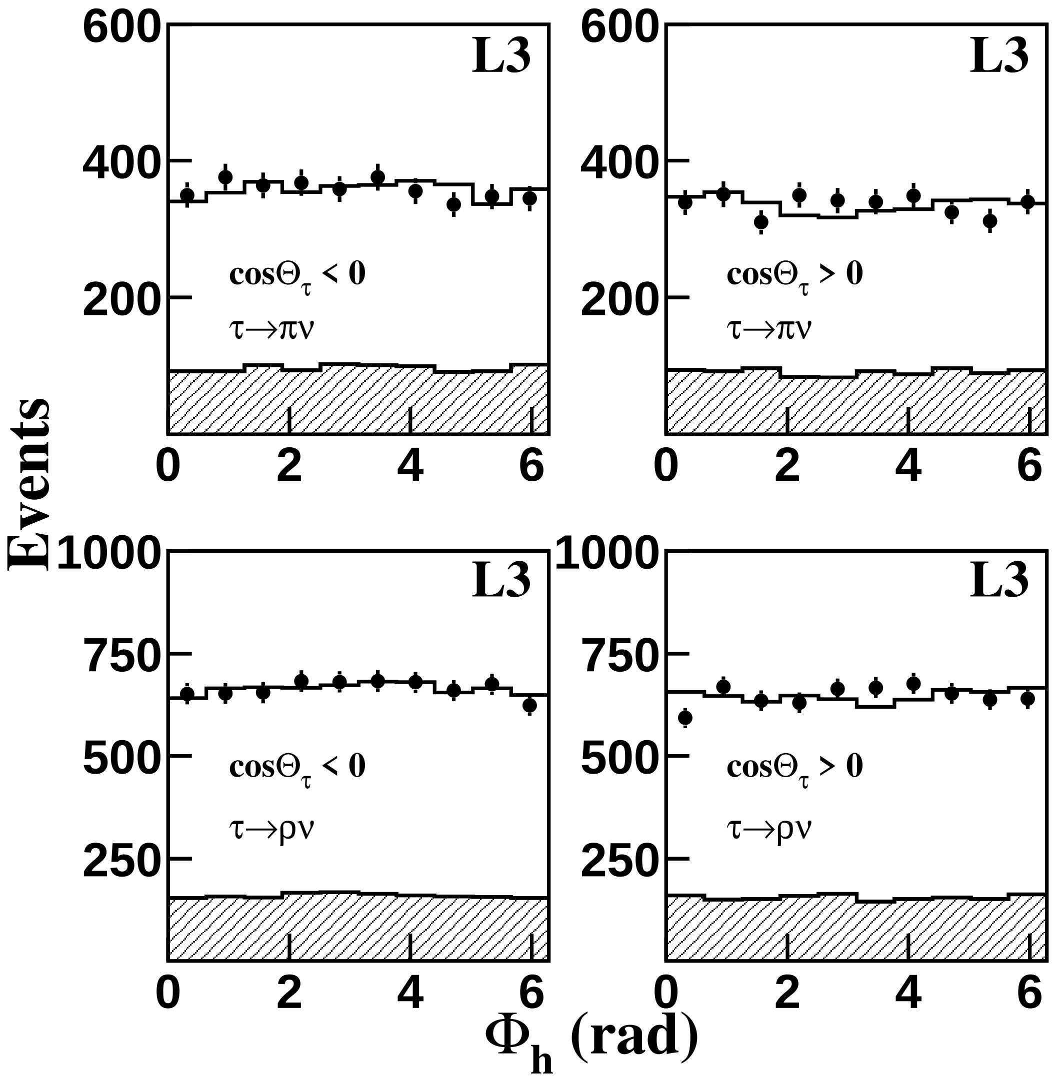
accessible in exclusive hadronic τ decays: $\tau^- \rightarrow h^- \nu_\tau$

$$\frac{d\sigma^{Spin}(\tau^+\tau^-)}{d(\cos\theta_{\tau^-})d\phi_{h^\pm}} = C \cdot [\mp X_+ \cos\phi_{h^\pm} + (Y_- \mp Y_+) \sin\phi_{h^\pm}]$$

L3 Results

using $\tau \to \rho\nu$ and $\tau \to \pi\nu$ decays,

Data 1991-95 :$\approx$ 9000 events



The first direct measurement of a_τ^w:

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

$$Im(a_\tau^w) = (-1.0 \pm 3.6 \pm 4.3) \times 10^{-3}$$

$$Re(d_\tau^w) = (-0.44 \pm 0.88 \pm 1.33) \times 10^{-17} e \cdot cm$$

Use all τ decay modes,

$$e^+e^- \to \tau^+\tau^- \to A\,B + n\nu$$

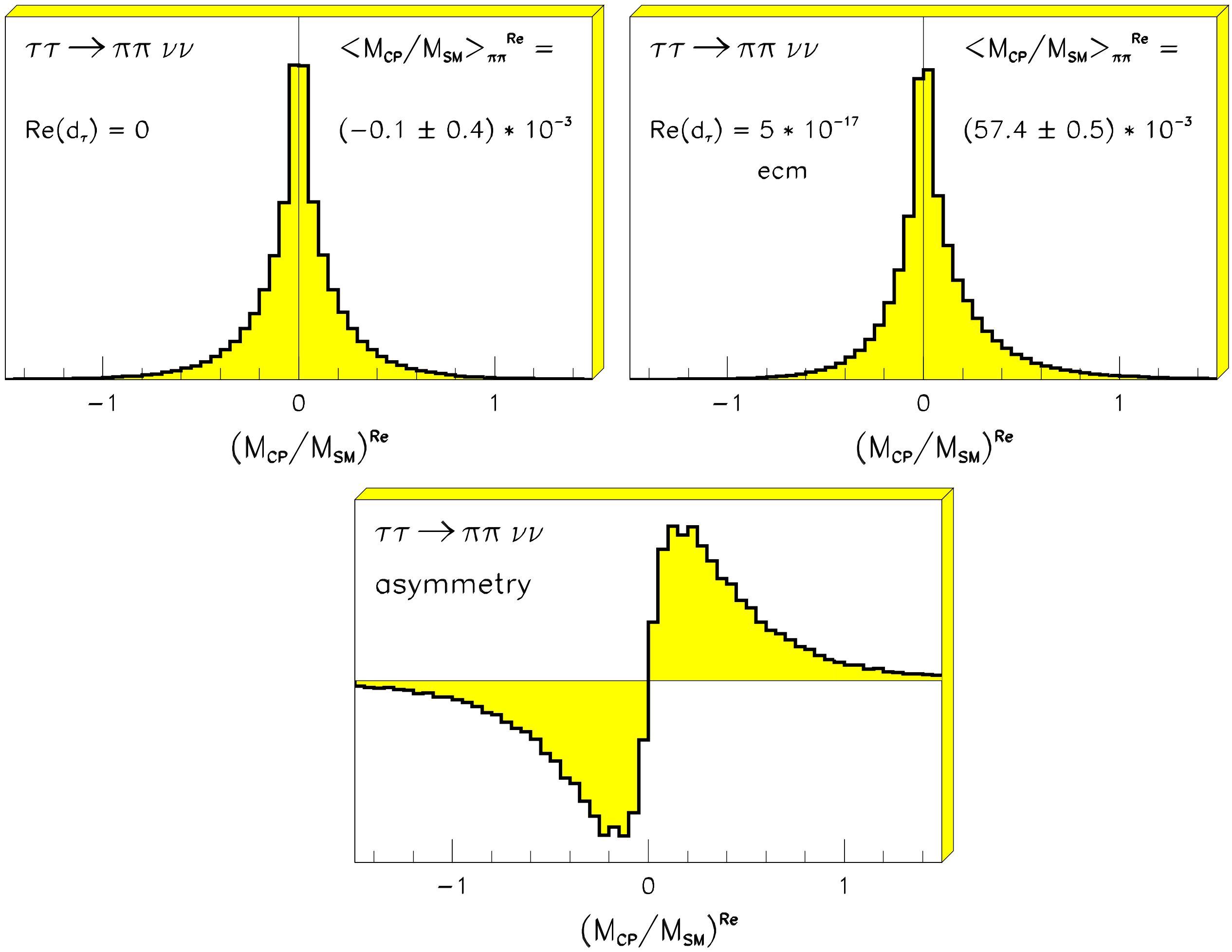
and describe with the ansatz:

$$d\sigma \propto |T_{SM} + T_{CP}|^2 = |T_{SM}|^2 + 2Re(T_{SM}^* T_{CP}) + |T_{CP}|^2$$

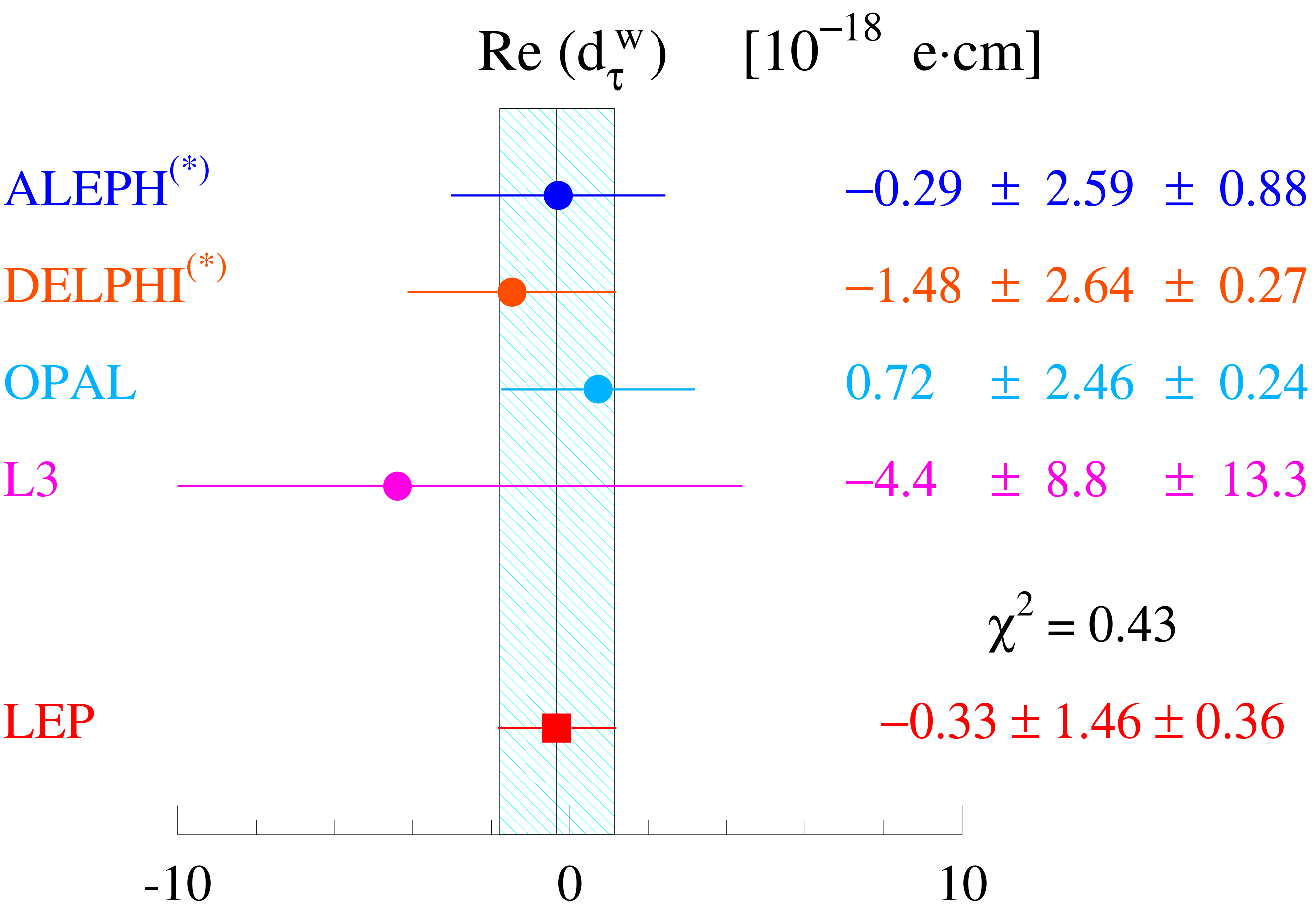
$$2Re(T_{SM}^* T_{CP}) = Re(d_\tau^w)\mathcal{M}_{CP}^{Re} + Im(d_\tau^w)\mathcal{M}_{CP}^{Im}$$

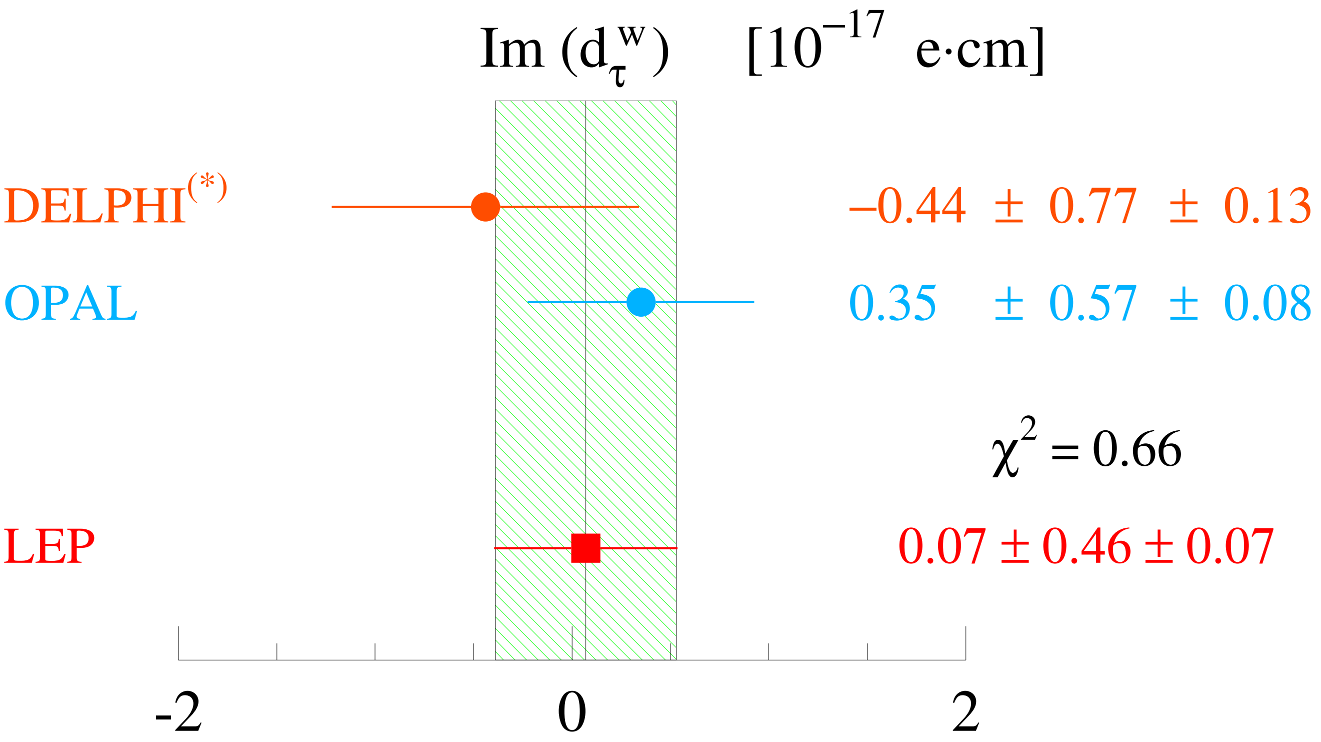
CP–odd observables:

$$\mathcal{O}^{\mathrm{Re}} = \frac{\mathcal{M}_{\mathrm{CP}}^{\mathrm{Re}}}{\mathcal{M}_{\mathrm{SM}}} \quad , \quad \mathcal{O}^{\mathrm{Im}} = \frac{\mathcal{M}_{\mathrm{CP}}^{\mathrm{Im}}}{\mathcal{M}_{\mathrm{SM}}}$$

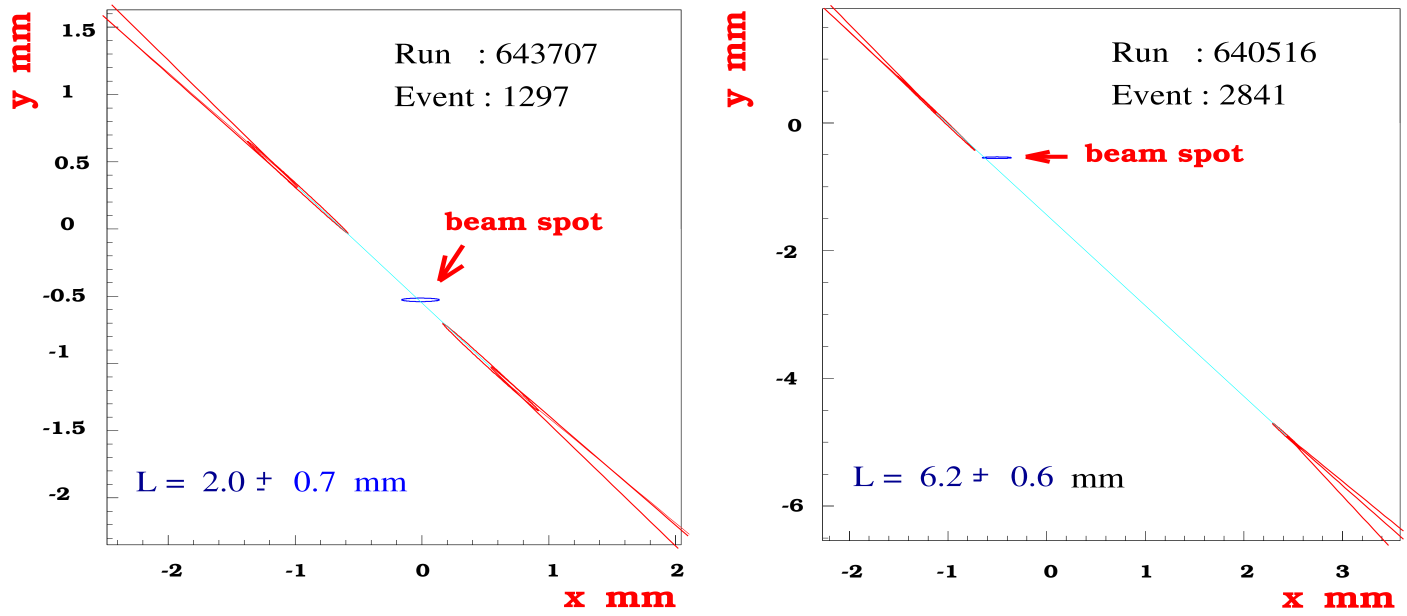


weak dipole moments-LEP Result

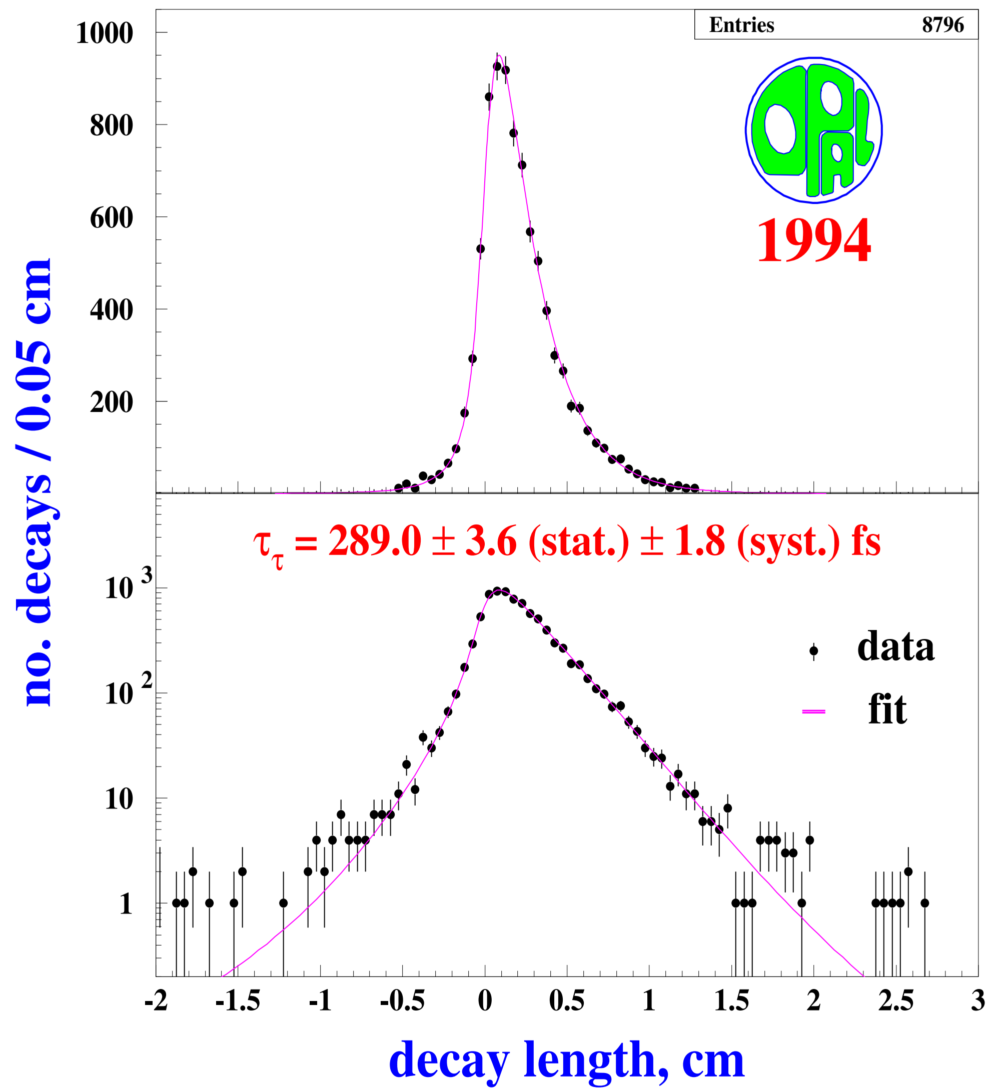




Lifetime of the τ lepton

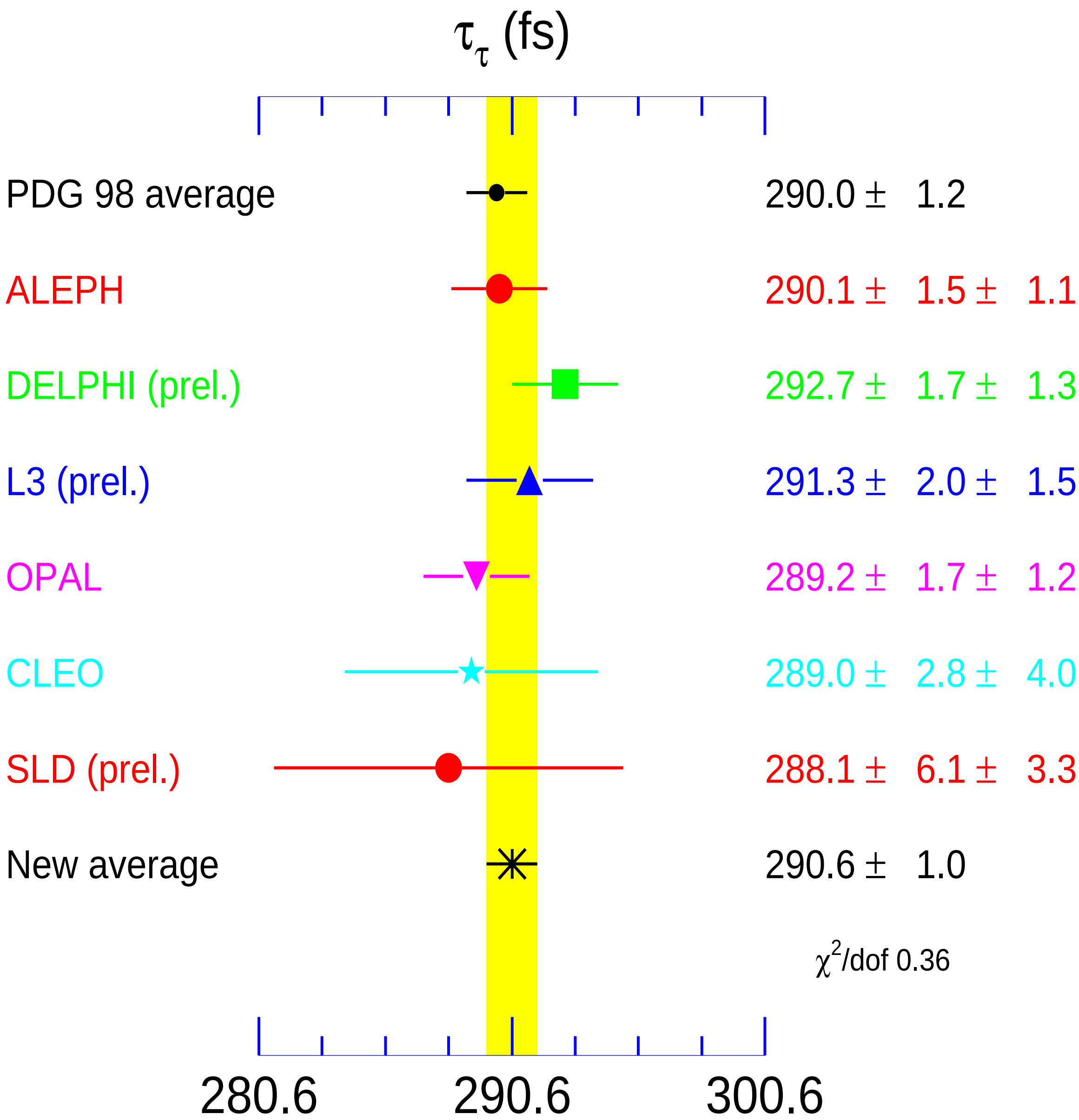


tau lifetime, decay length method

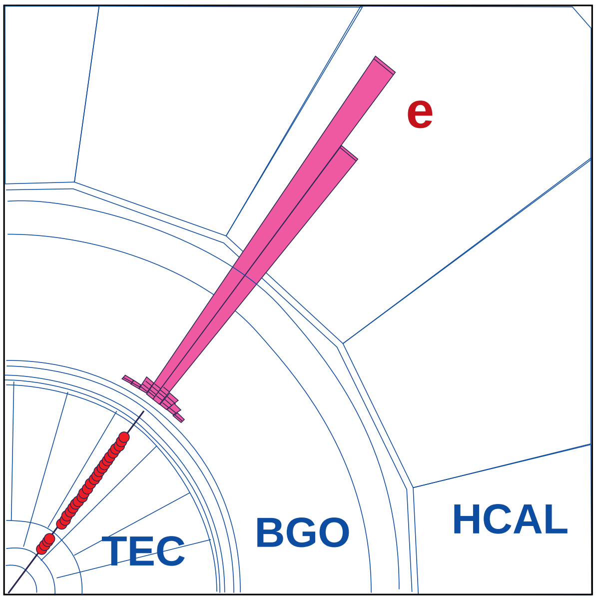


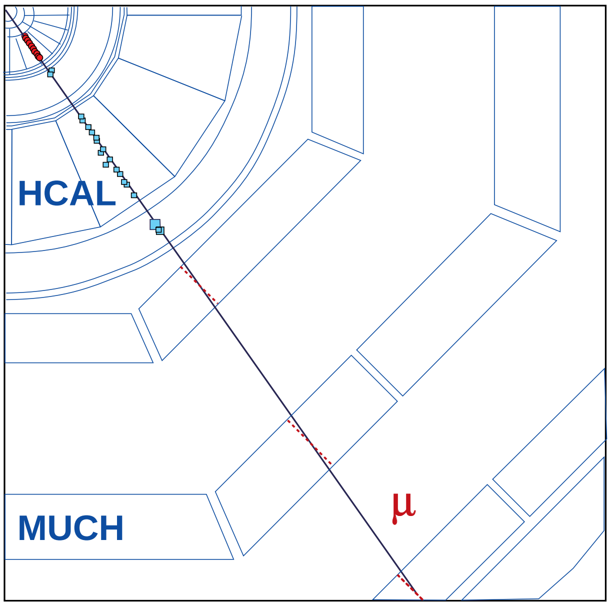
τ lifetime compilation

Summary of τ lifetime measurements

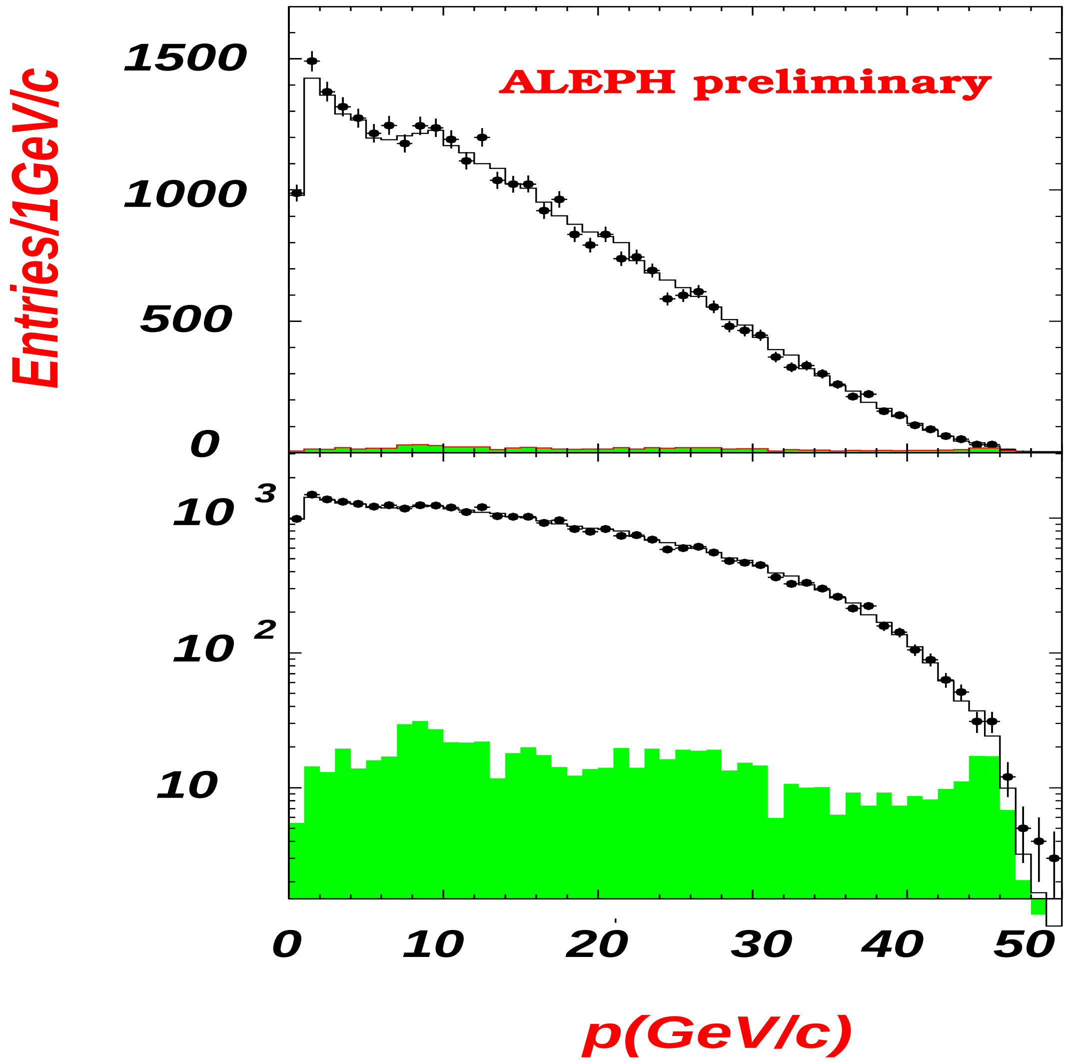


τ decays into leptons

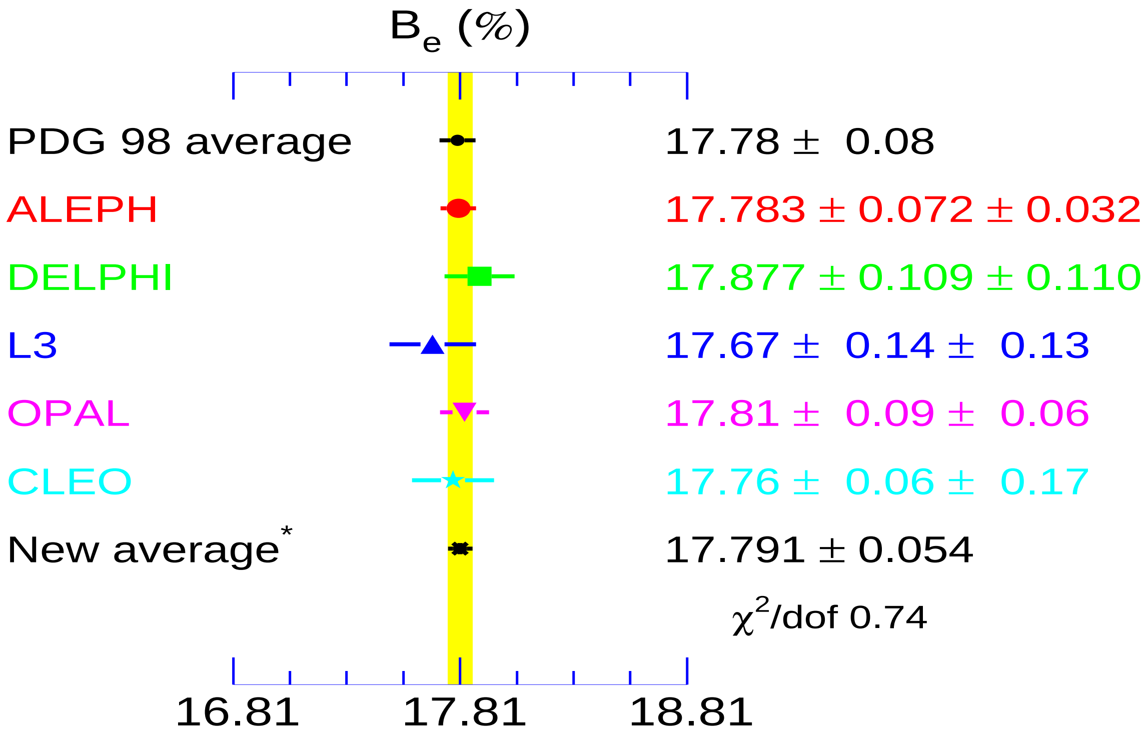


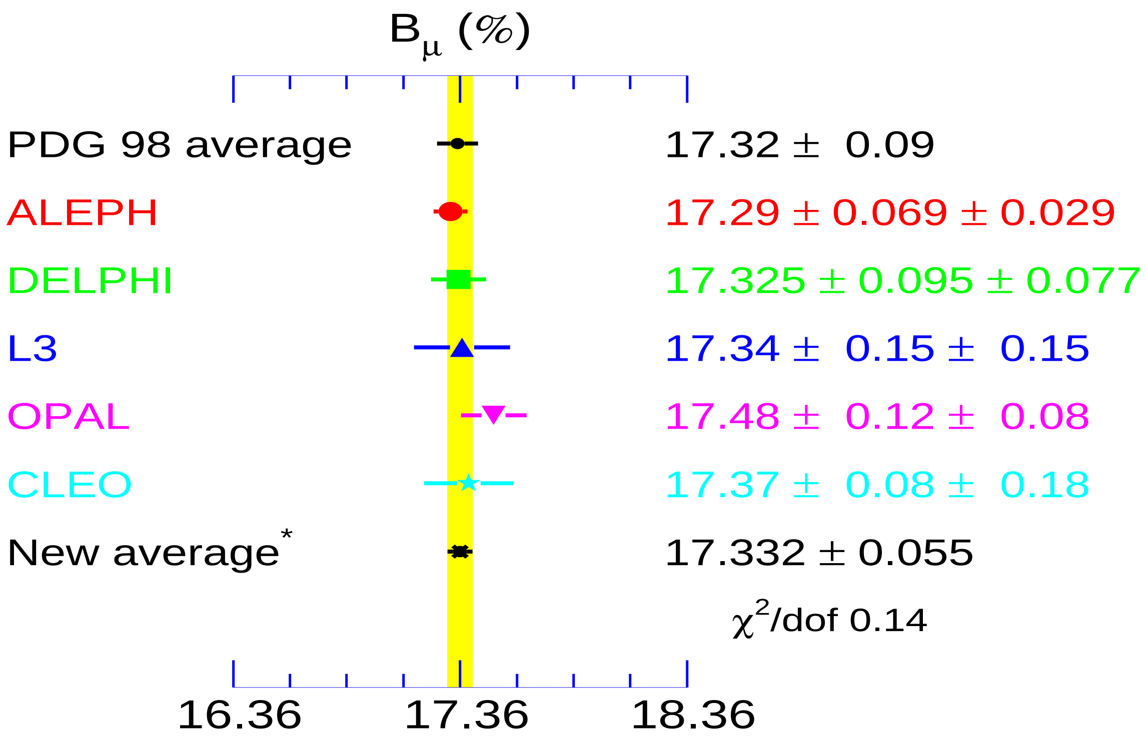


momentum spectrum of $\tau \to e\nu\overline{\nu}$



τ decays into leptons





τ decays into leptons

$$\frac{1}{\tau_\tau} = \Gamma(\tau \to \ell\nu\nu) \cdot \frac{1}{\mathcal{B}_\ell}$$

$$= \frac{G_\tau \cdot G_\ell \cdot m_\tau^5}{192 \cdot \pi^3} \cdot f_m\left(\frac{m_\ell}{m_\tau}\right) \cdot f_W(m_\ell, m_\tau) \cdot f_{rad}(m_\tau) \cdot \frac{1}{\mathcal{B}_\ell}$$

Tests of Lepton Universality

e.g.:

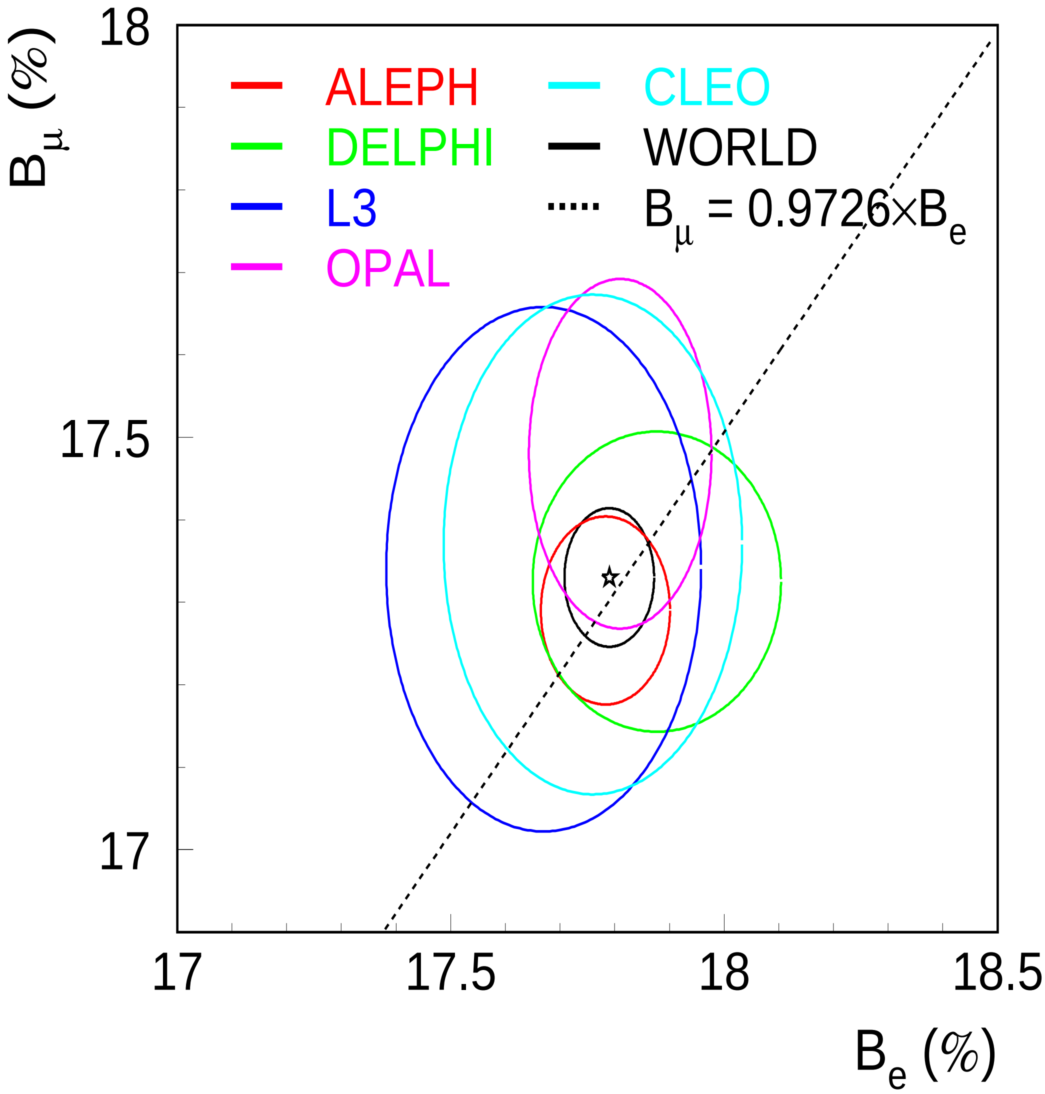
$$\frac{\Gamma(\tau \to \mu\nu\nu)}{\Gamma(\tau \to e\nu\nu)} = \frac{\mathcal{B}_e}{\mathcal{B}_\mu} = 0.9726 \cdot \frac{G_\mu}{G_e}$$

$$\frac{\Gamma(\tau \to e\nu\nu)}{\Gamma(\mu \to e\nu\nu)} = \mathcal{B}_e \cdot \frac{\tau_\mu}{\tau_\tau} = 1.004 \cdot \frac{G_\tau}{G_\mu} \cdot \frac{m_\tau^5}{m_\mu^5}$$

redefinition:

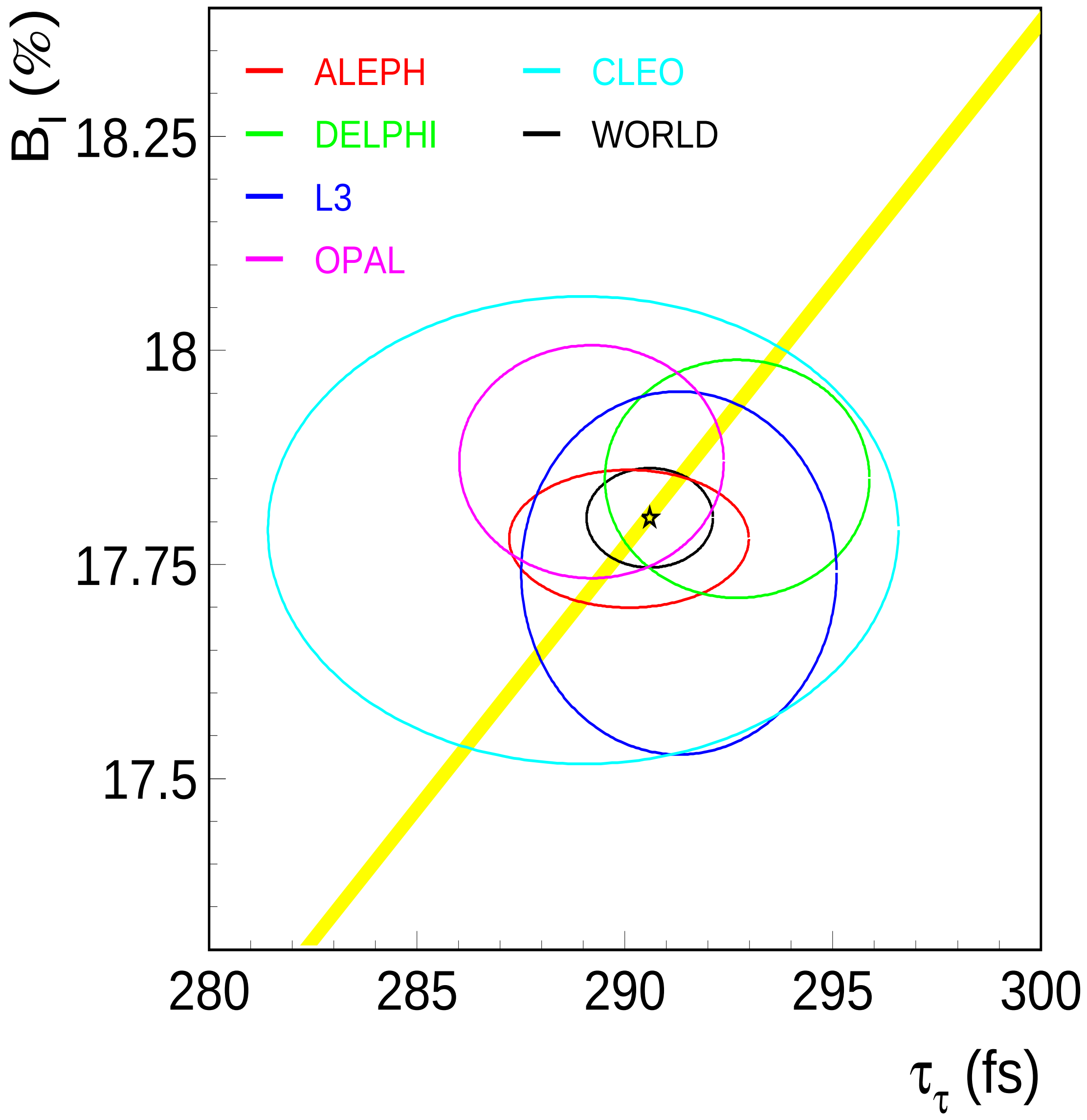
$$G_\ell = \frac{g_\ell^2}{4 \cdot \sqrt{2} \cdot m_W^2}$$

e-μ universality



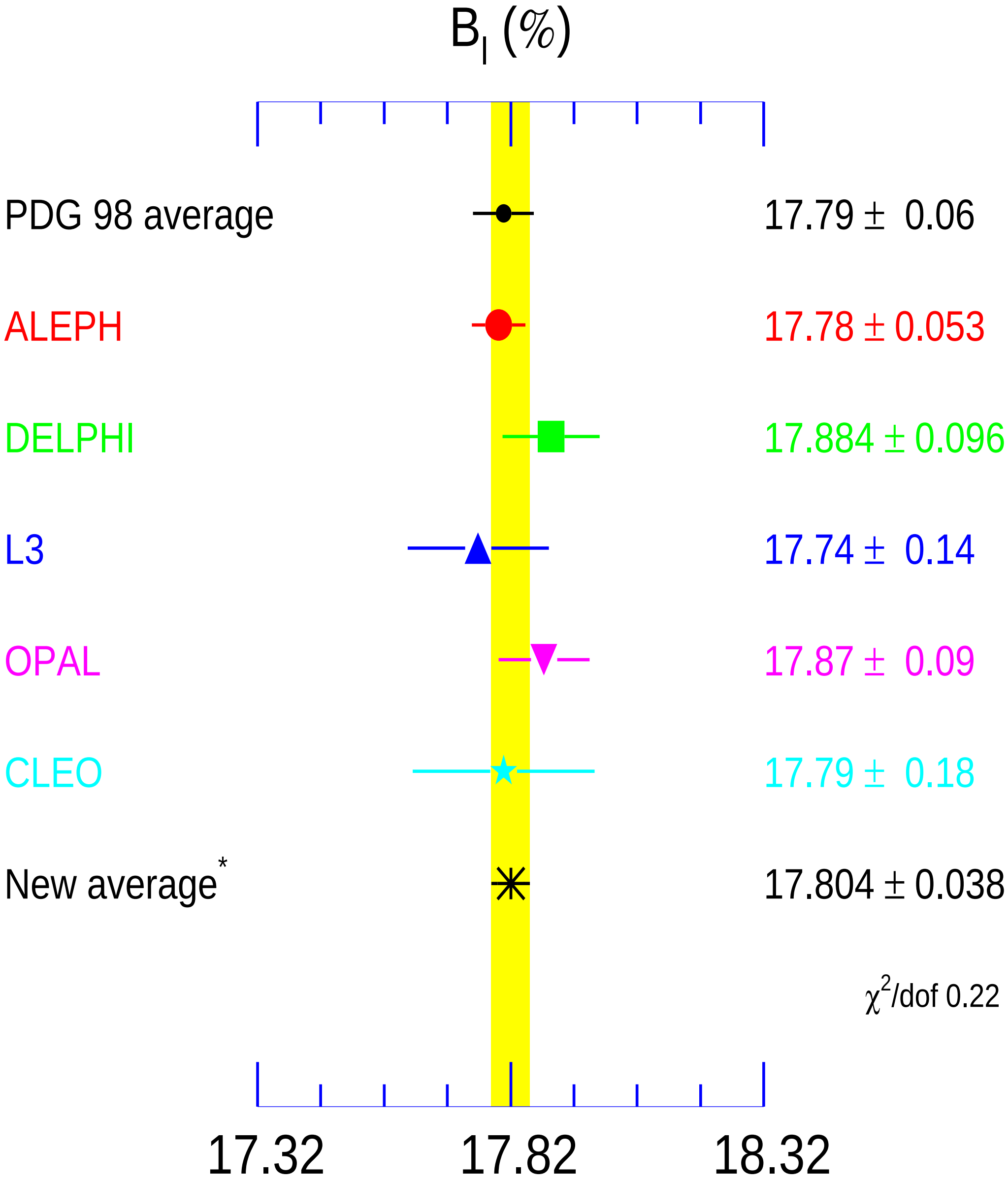
$$\frac{g_\mu}{g_e} = 1.0013 \pm 0.0021$$

$\mu - \tau$ universality



$$\frac{g_\mu}{g_\tau} = 0.9997 \pm 0.0024$$

combine $\mathcal{B}_e$ and $\mathcal{B}_\mu$



$$G_F = (1.1663 \pm 0.0025) \times 10^{-5}\ \mathrm{GeV}^{-2}$$

Lorentz Structure in τ decays

Most general four fermion contact interaction Matrix element for $\tau \to \ell\nu\overline{\nu}$:

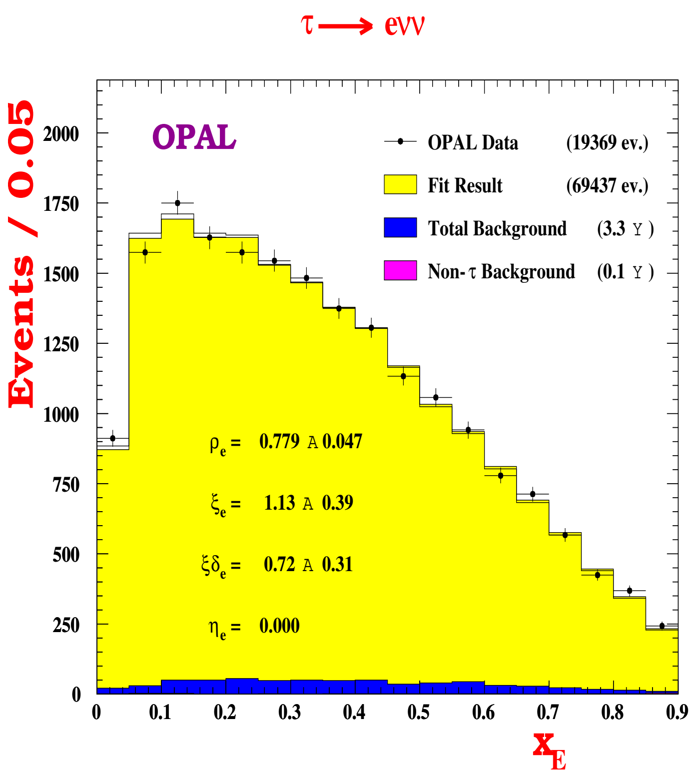
$$\mathcal{M} = \frac{4G_F}{\sqrt{2}} \sum_{\substack{\gamma=S,V,T \\ \lambda,\iota=R,L}} g^{\gamma}_{\lambda\iota} < \overline{\ell}_\lambda|\Gamma^\gamma|(\nu_\ell)_n >< (\overline{\nu}_\tau)_m|\Gamma_\gamma|\tau_\iota > .$$

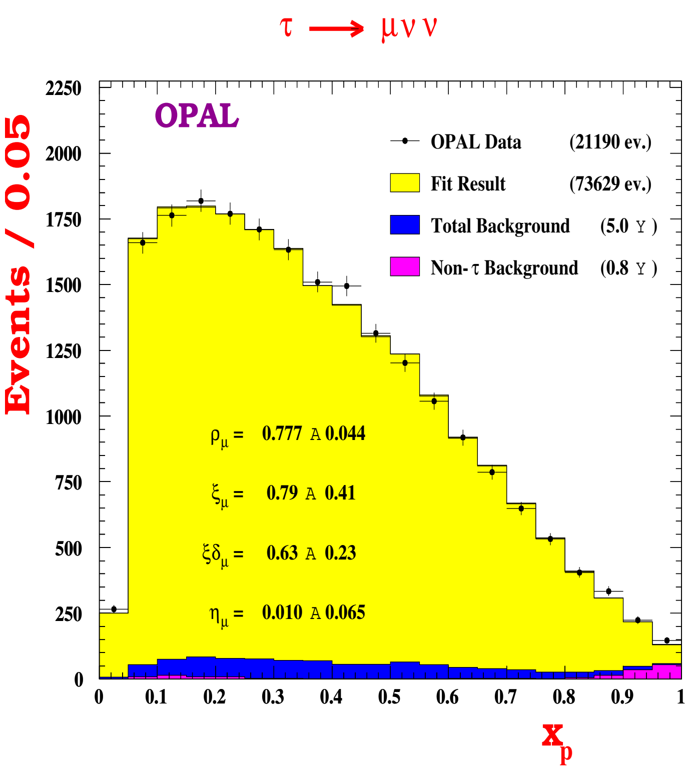
$\rightarrow$ 19 independent couplings, combined to Michel parameters

the τ decay spectra depend on the parameters:

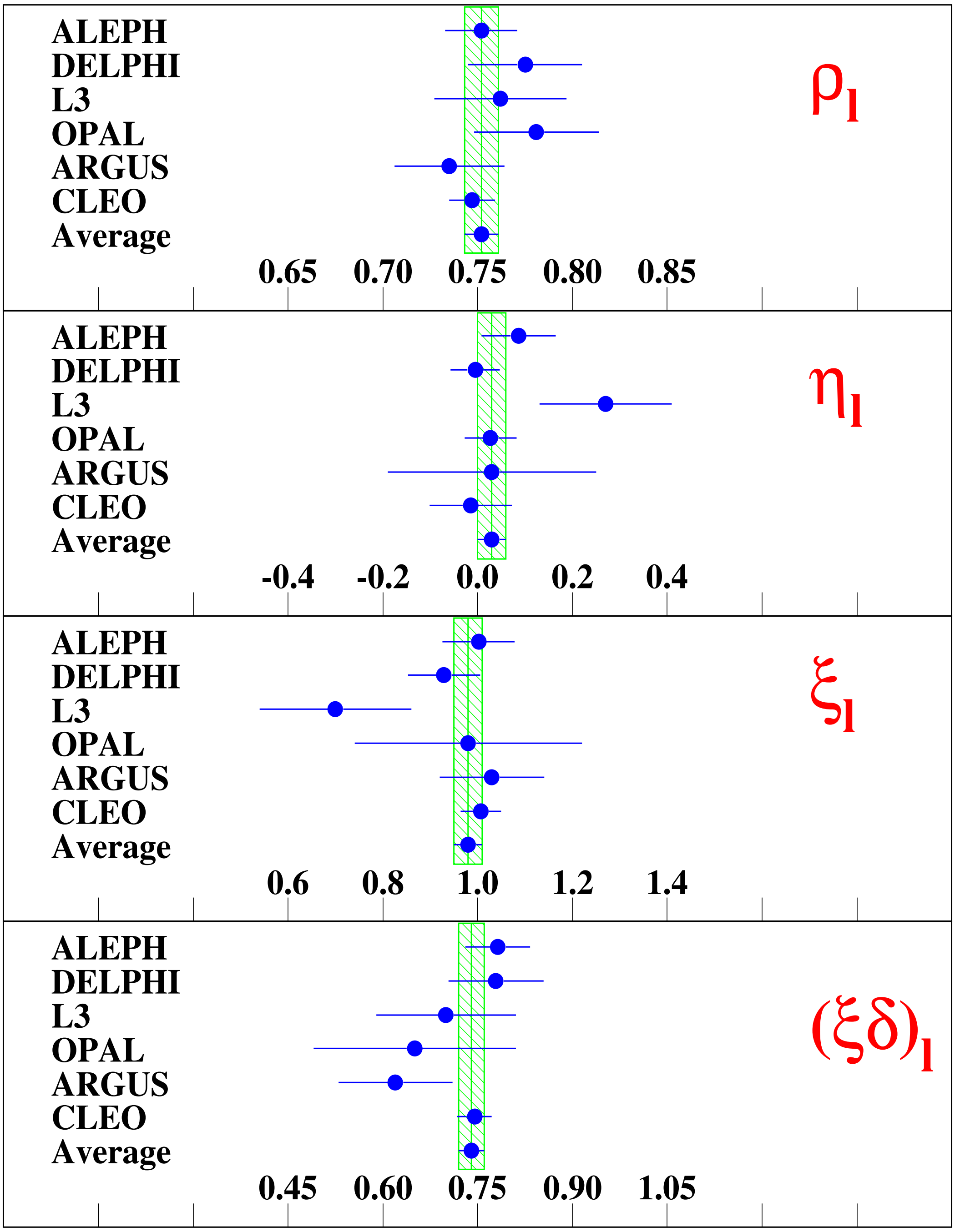
ρ, η (spectrum parameter)

ξ, δ (asymmetry parameter)





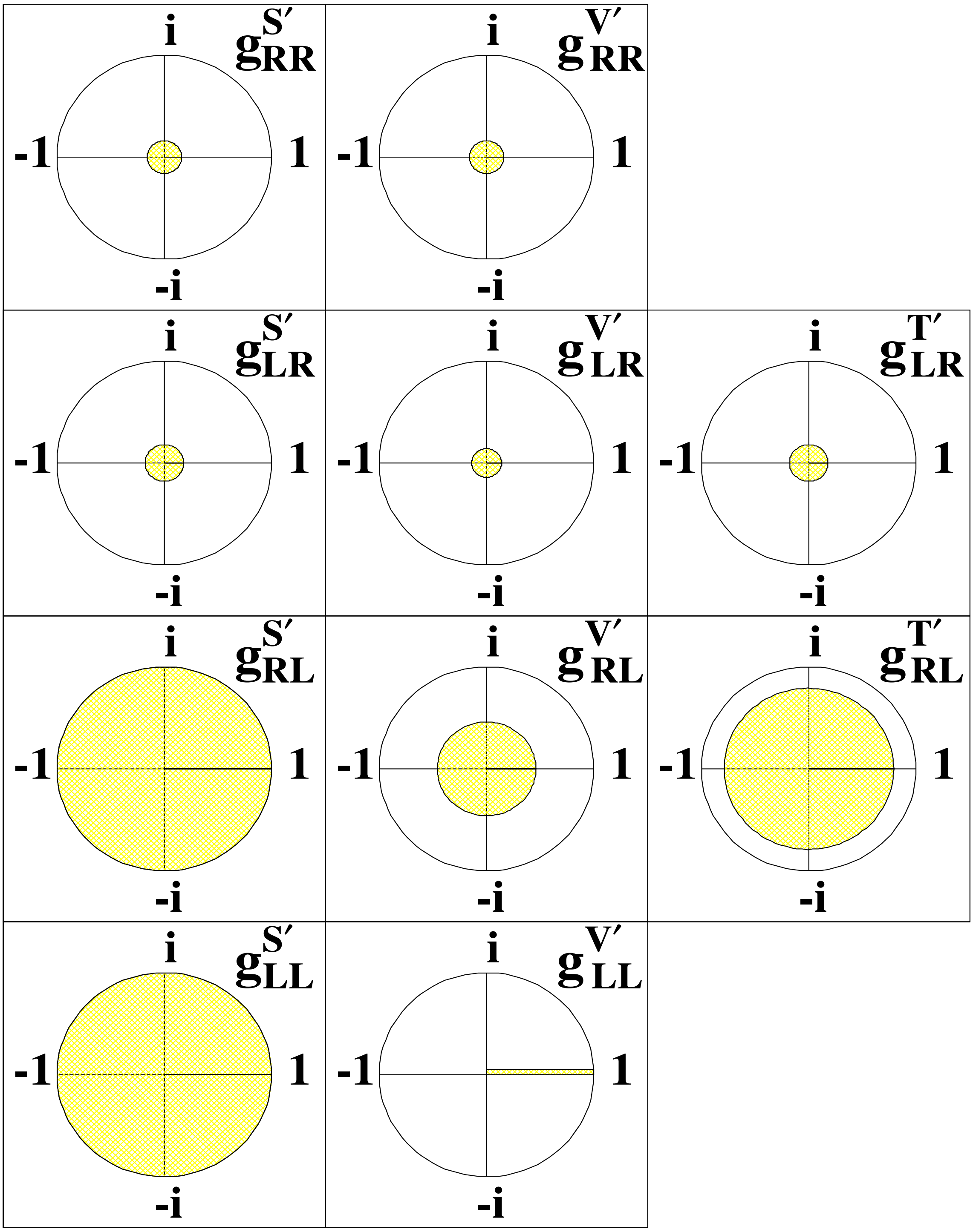
summary of Michel parameter measurements



consistent with (V-A) structure of the charged current

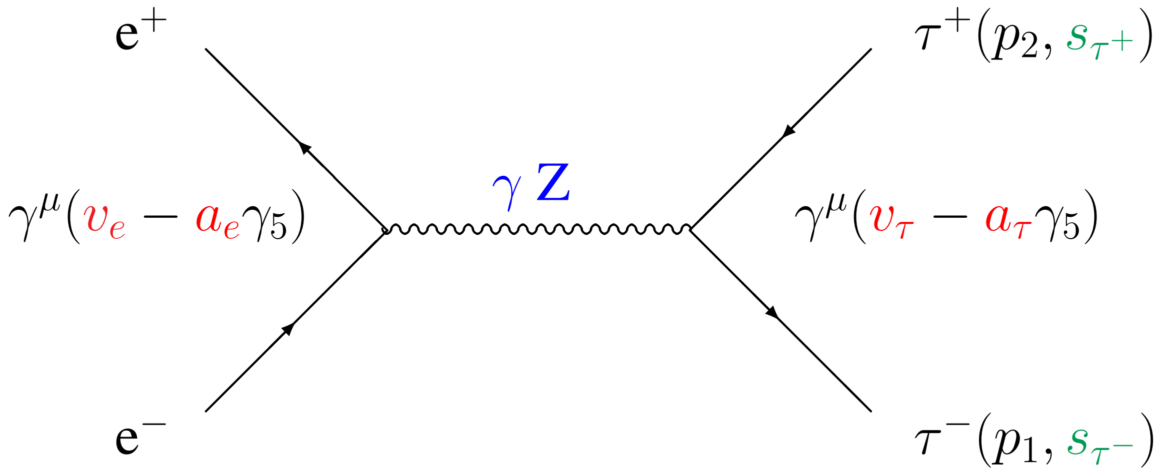
τ charged current couplings

Limits on the charged current τ couplings, obtained from the CLEO measurement of Michel parameters



neutral current couplings

$$e^+e^- \rightarrow \tau^+\tau^-$$



in the SM:

$$\begin{aligned} v_f &= T_f^3 - 2\,Q_f \sin^2\theta_{\mathrm{W}} \\ a_f &= T_f^3 \end{aligned}$$

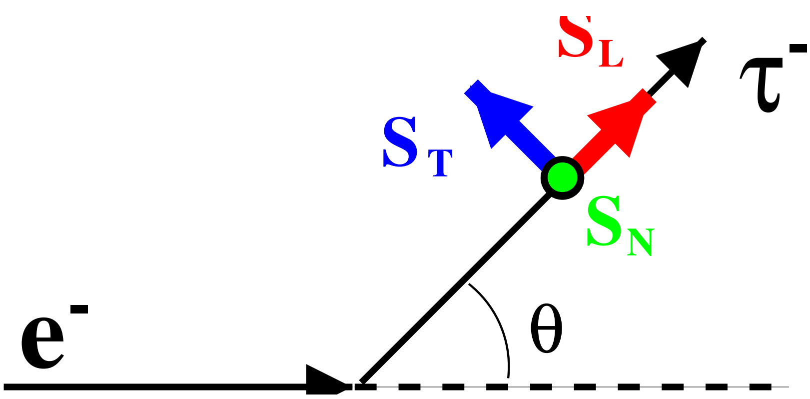
$$v_e = v_\mu = v_\tau \qquad a_e = a_\mu = a_\tau$$

$e^+e^- \longrightarrow \tau^+\tau^-$ cross section at $\sqrt{s} \approx M_Z$

$$
\begin{aligned}
\frac{d^5\sigma}{ds_{\tau^-}ds_{\tau^+}d\Omega} = \tfrac{1}{4}\;|P(q^2)|^2\,\{ &\quad \left[C_0\,(1+\cos^2\theta) + C_1\,2\cos\theta\right] \\
&- s^L_{\tau^-}s^L_{\tau^+} \quad \left[C_0\,(1+\cos^2\theta) + C_1\,2\cos\theta\right] \\
&- (s^L_{\tau^-} - s^L_{\tau^+})\;\left[D_0\,(1+\cos^2\theta) + D_1\,2\cos\theta\right] \\
&+ C_2\,(s^N_{\tau^-}s^N_{\tau^+} - s^T_{\tau^-}s^T_{\tau^+})\;\sin^2\theta \\
&+ D_2\,(s^N_{\tau^-}s^T_{\tau^+} + s^N_{\tau^+}s^T_{\tau^-})\;\sin^2\theta\}
\end{aligned}
$$

with

$$
\begin{aligned}
C_0 &= (v_e^2 + a_e^2)\,(v_\tau^2 + a_\tau^2) \\
C_1 &= 4\,\mathrm{Re}(v_e a_e^*)\,\mathrm{Re}(v_\tau a_\tau^*) \\
C_2 &= (v_e^2 + a_e^2)\,(a_\tau^2 - v_\tau^2) \\
D_0 &= 2\,\mathrm{Re}(v_\tau a_\tau^*)\,(v_e^2 + a_e^2) \\
D_1 &= 2\,\mathrm{Re}(v_e a_e^*)\,(v_\tau^2 + a_\tau^2) \\
D_2 &= -2\,\mathrm{Im}(v_\tau a_\tau^*)\,(v_e^2 + a_e^2)
\end{aligned}
$$



neutral current couplings

$$e^+e^- \rightarrow \tau^+\tau^-$$

cross section:

$$\sigma \approx (v_e^2 + a_e^2) \cdot (a_\tau^2 + v_\tau^2) \approx \Gamma_{ee} \cdot \Gamma_{\tau\tau}$$

angular distribution:

$$A_{FB} \approx \frac{2\,a_e\,v_e}{a_e^2 + v_e^2} \cdot \frac{2\,a_\tau\,v_\tau}{a_\tau^2 + v_\tau^2} = \mathcal{A}_e \cdot \mathcal{A}_\tau$$

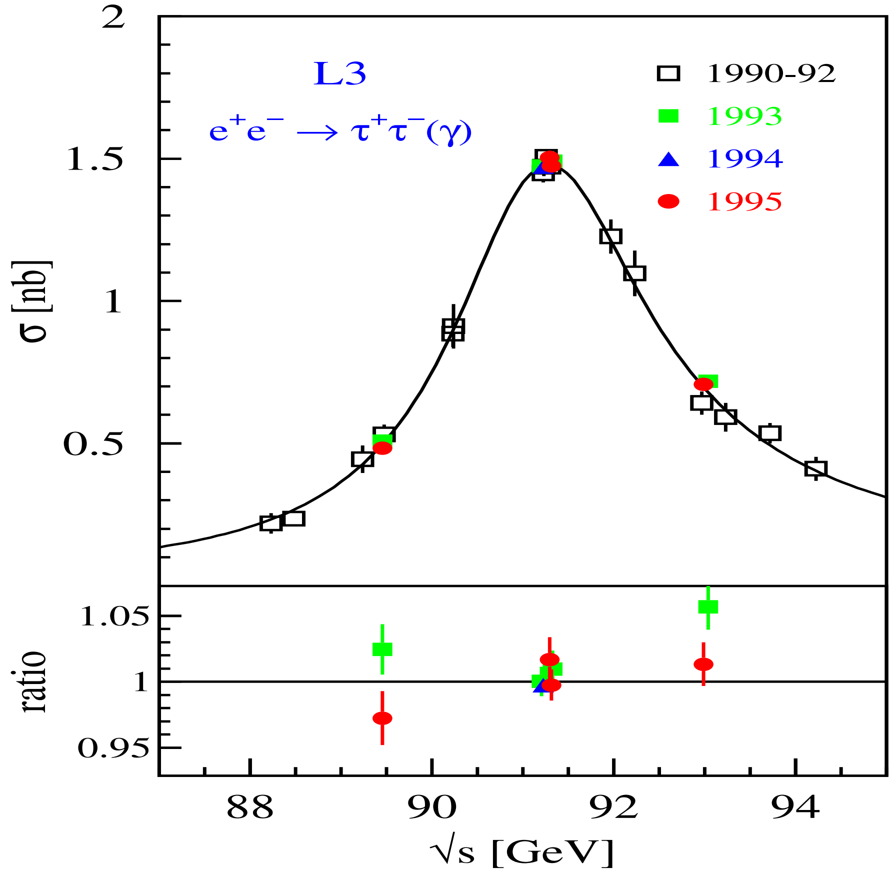
polarisation:

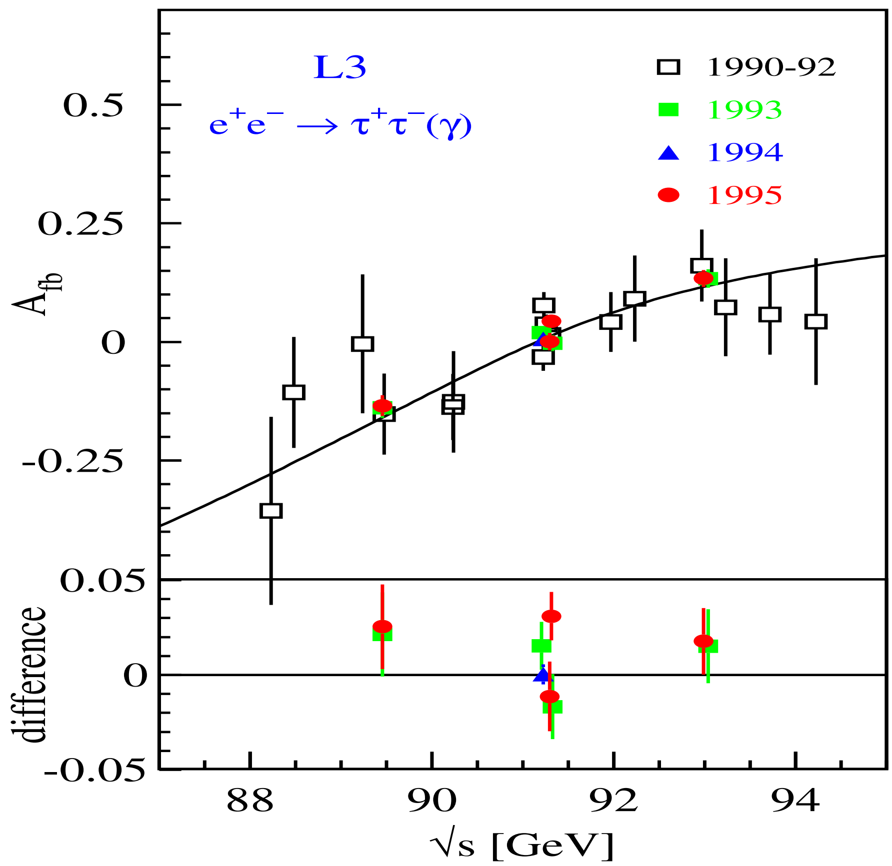
$$\mathcal{P}_\tau \approx \frac{2\,a_\tau\,v_\tau}{a_\tau^2 + v_\tau^2} = \mathcal{A}_\tau$$

polarisation angular asymmetry:

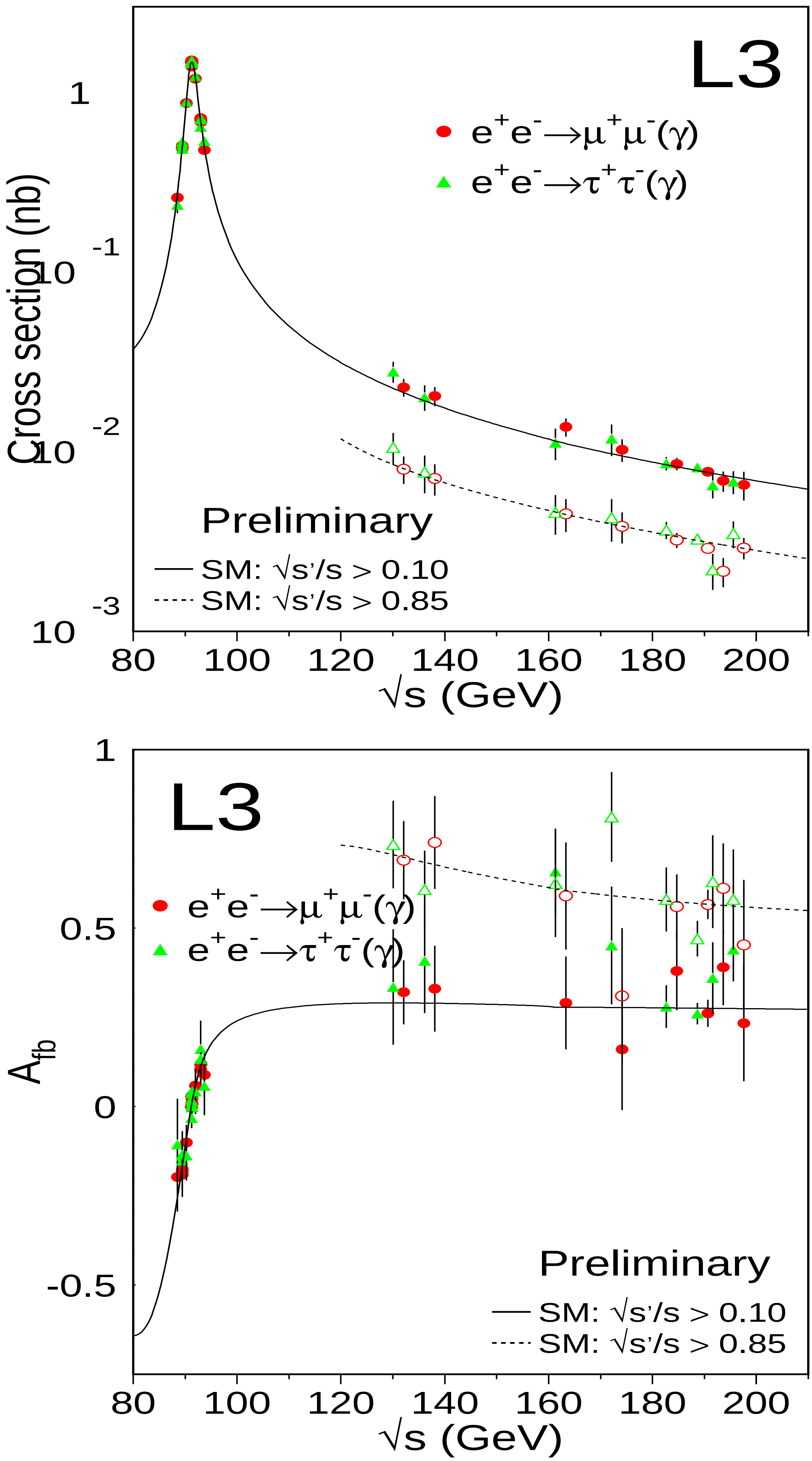
$$A_{FB}^{pol} \approx \frac{2\,a_e\,v_e}{a_e^2 + v_e^2} = \mathcal{A}_e$$

cross section and A_{FB}

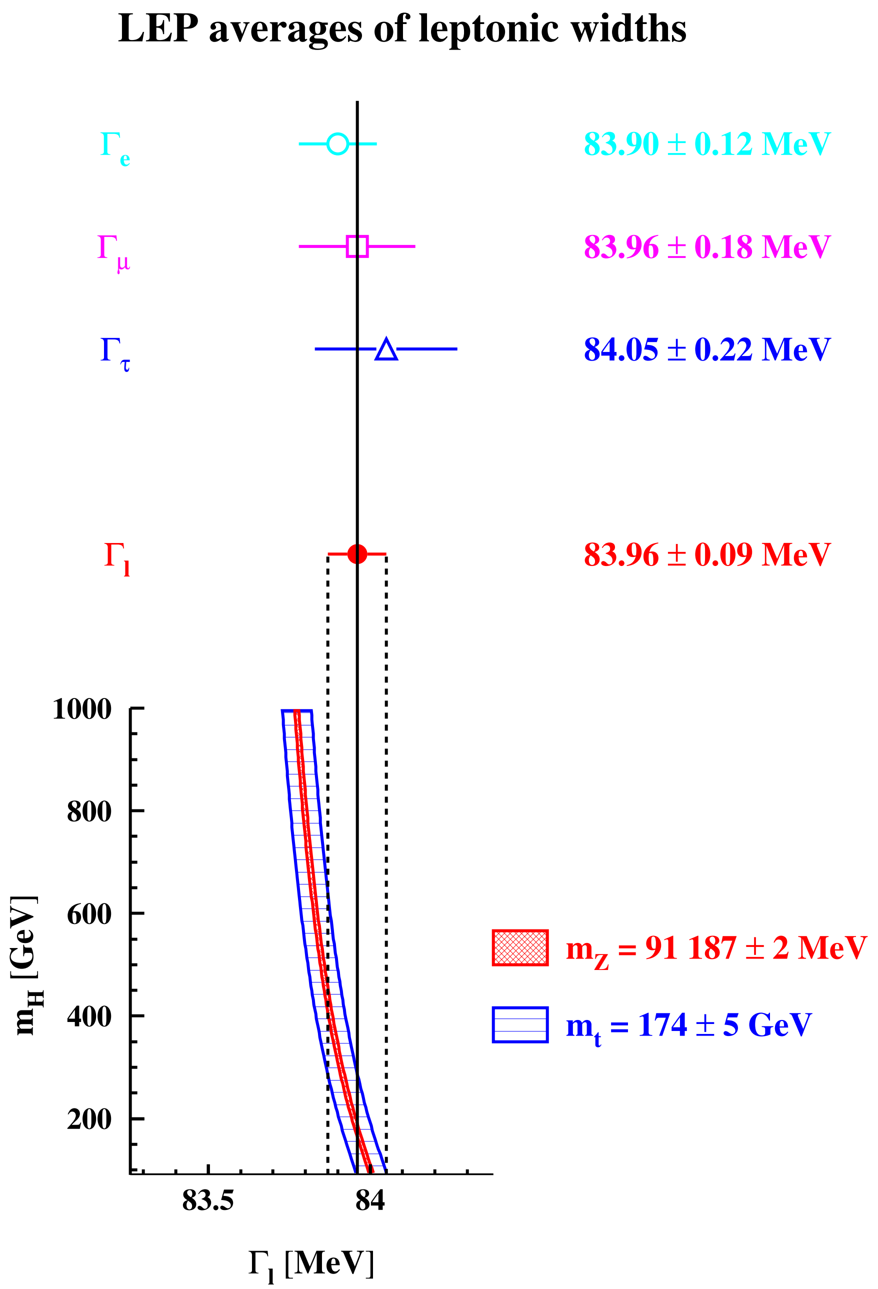




cross section and A_{FB}



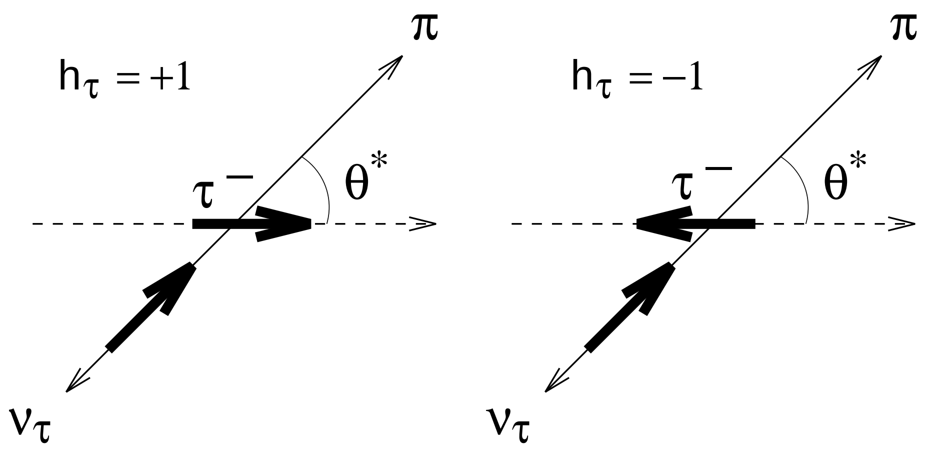
leptonic width of the Z



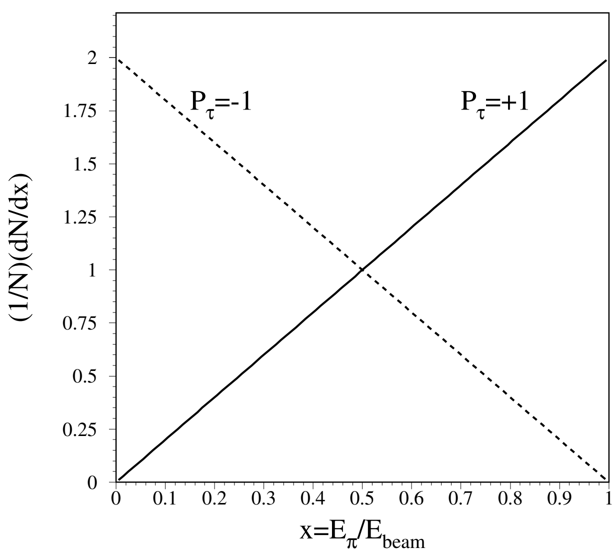
Polarisation

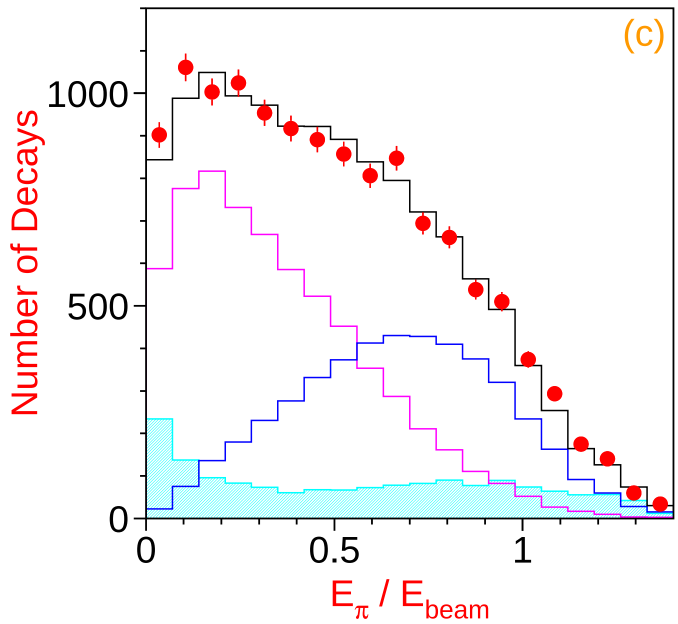
$$\mathcal{P}_\tau(\cos\theta) = \frac{\sigma(s^L_{\tau^-}=+1)-\sigma(s^L_{\tau^-}=-1)}{\sigma(s^L_{\tau^-}=+1)+\sigma(s^L_{\tau^-}=-1)}$$

$\mathcal{P}_\tau$ measurement: consider helicity states for $\tau \to \pi\nu$



τ restframe: $\cos\theta^* \leftrightarrow$ lab frame: $x = E_\pi/E_\tau$





$$\frac{1}{N}\frac{dN}{dx} = 1 + \mathcal{P}_\tau(2x-1)$$

$\Rightarrow$ energy spectra of τ decay products are polarization dependent

Experimental Method

decay distributions:

$\tau \longrightarrow l\nu\nu \quad l = e, \mu$:

$$h(x) = 1/3\left[(5 - 9x^2 + 4x^3) + \mathcal{P}_\tau\,(1 - 9x^2 + 8x^3)\right] \tag{1}$$

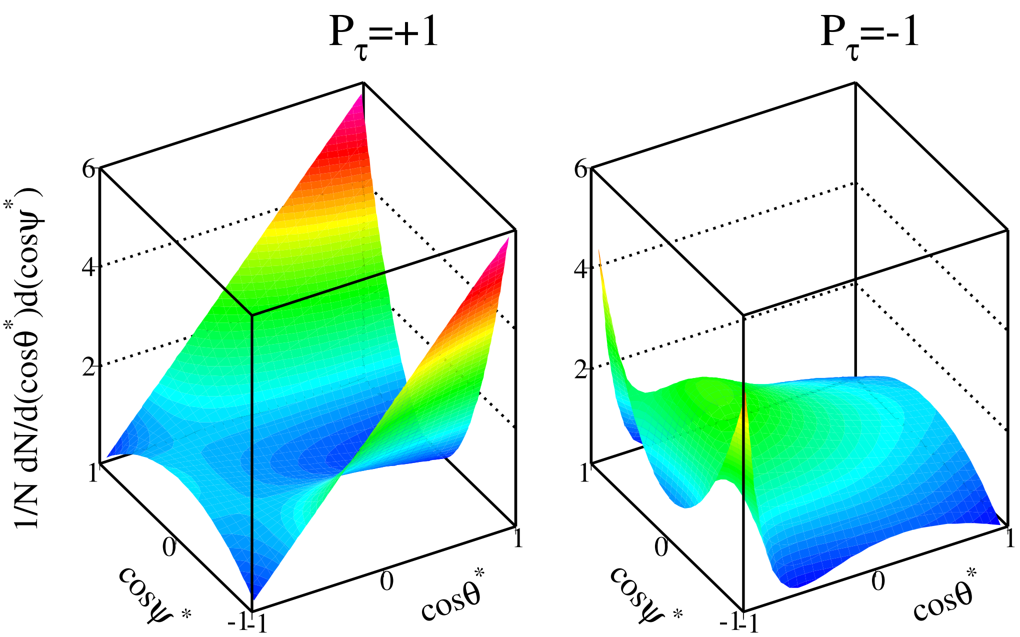
$\tau \longrightarrow h\nu \quad h = \pi, \rho, a_1$:

$$h(x) = 1 + \mathcal{P}_\tau\,\alpha_h\,(2x - 1) \tag{2}$$

ρ, a_1 spin 1 particles $\Rightarrow$ two spin states possible
$\Rightarrow$ sensitivity reduced by α_h ($\alpha_\pi = 1 \quad \alpha_\rho = 0.46 \quad \alpha_{a_1} \approx 0.12$)

recover sensitivity loss

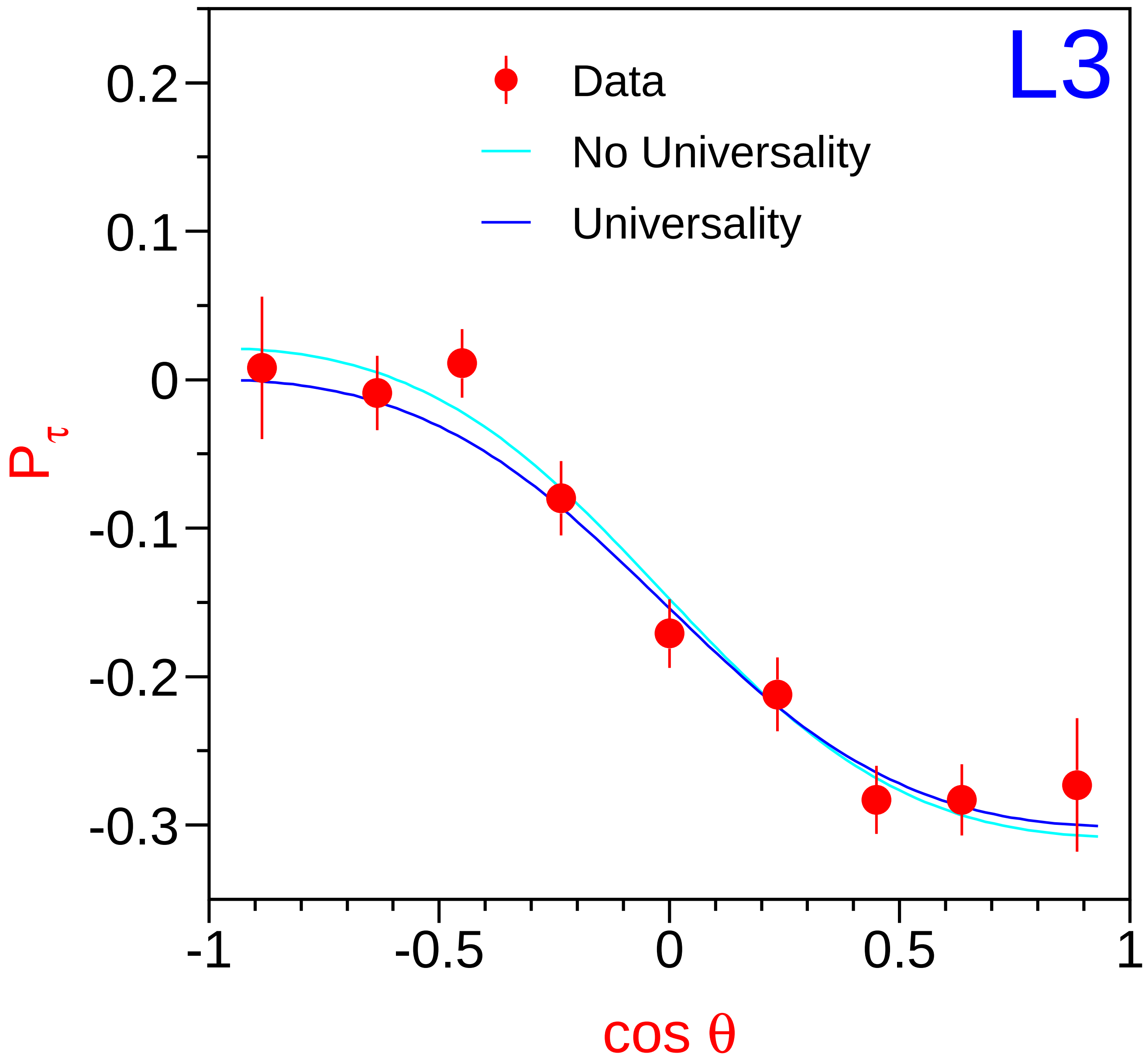
1. analyze ρ decay $\theta^* = \angle(\tau, \rho)$, $\psi^* = \angle(\rho, \pi)$ (L3, OPAL)
2. introduce an optimal variable ω (ALEPH, DELPHI)



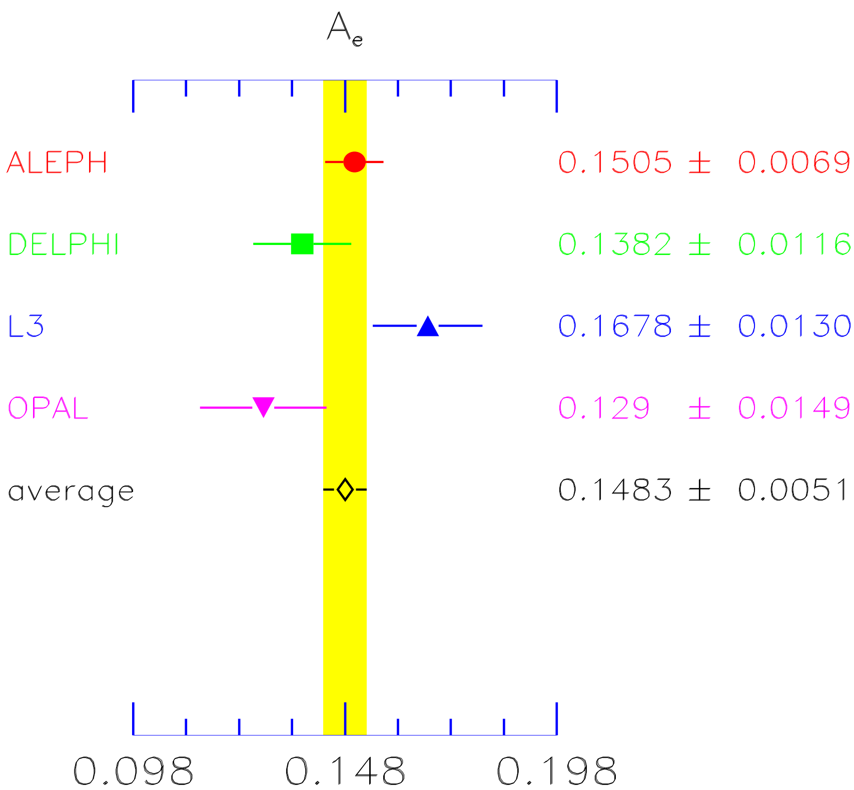
$\tau \longrightarrow \rho\nu$

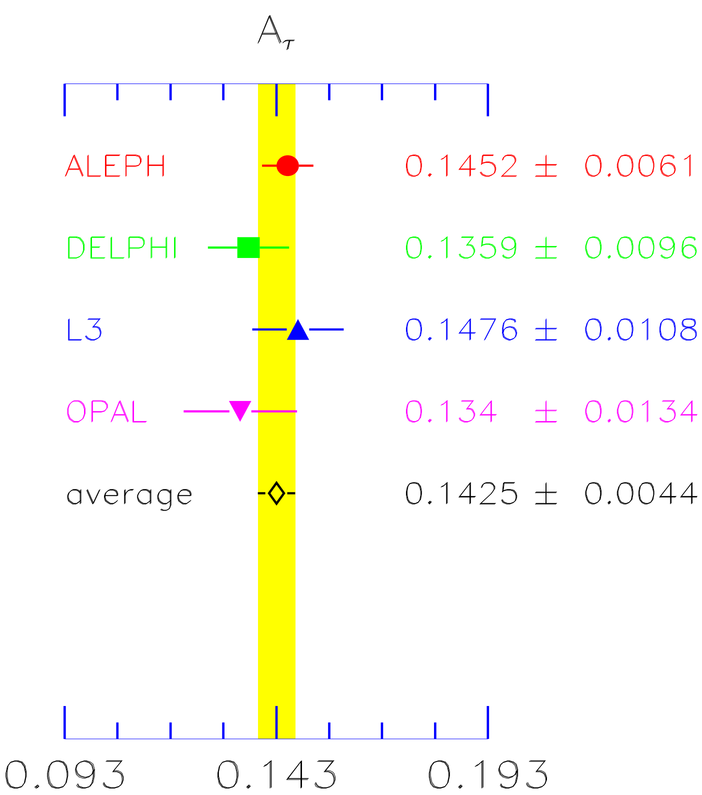
$\mathcal{P}_\tau$ as function of $\cos\theta$

$$\mathcal{P}_\tau(\cos\theta) = \frac{\mathcal{A}_\tau(1+\cos^2\theta) + 2\mathcal{A}_e\cos\theta}{(1+\cos^2\theta) + 2\mathcal{A}_e\mathcal{A}_\tau\cos\theta}$$

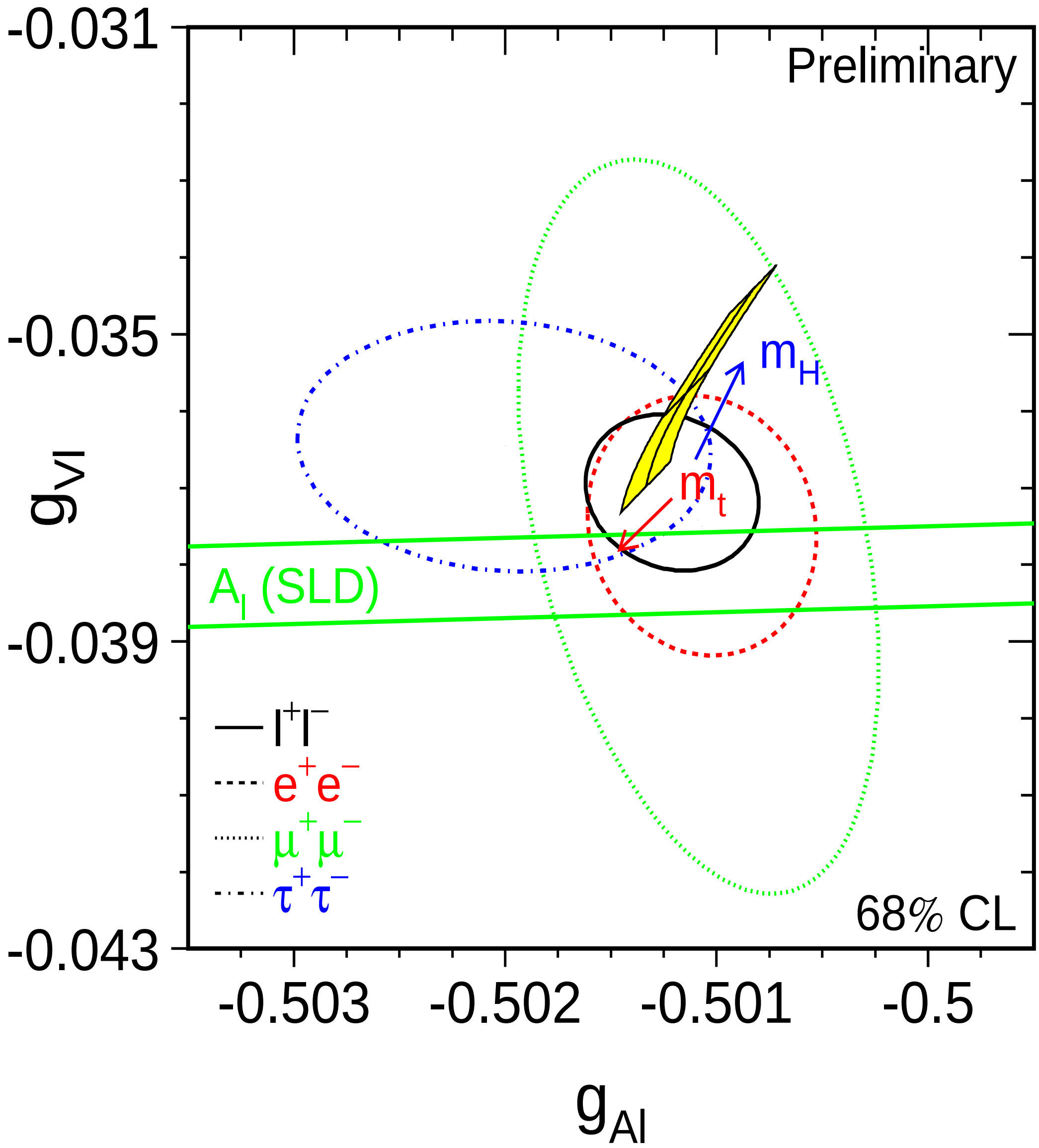


$\mathcal{A}_e$ and $\mathcal{A}_\tau$ measurements





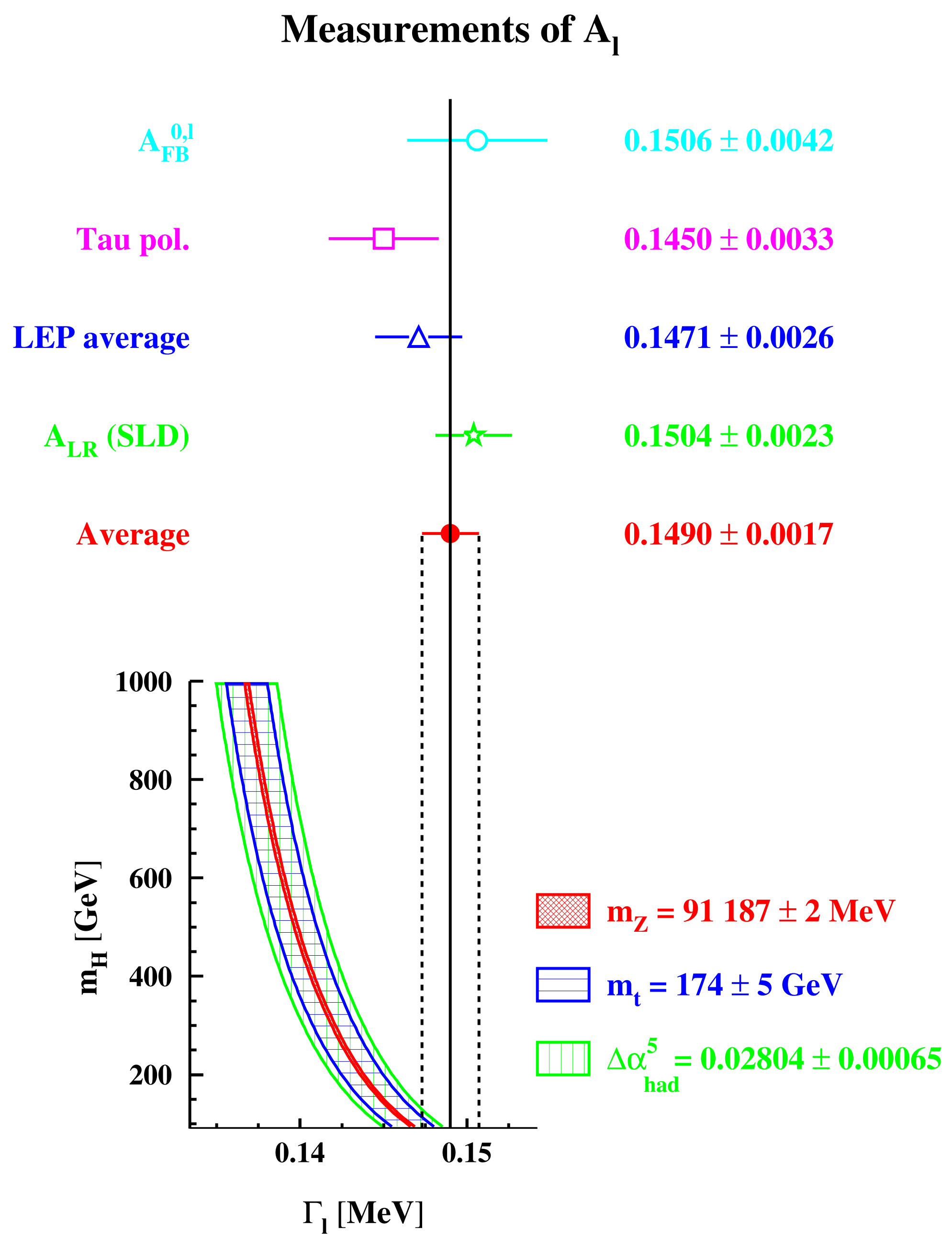
lepton couplings to the Z



$$\frac{a_\mu}{a_\tau} = 0.9983 \pm 0.0015 \qquad \frac{a_e}{a_\tau} = 0.9981 \pm 0.0015$$

$$\frac{v_\mu}{v_\tau} = 0.989 \pm 0.072 \qquad \frac{v_e}{v_\tau} = 1.047 \pm 0.030$$

lepton couplings to the Z

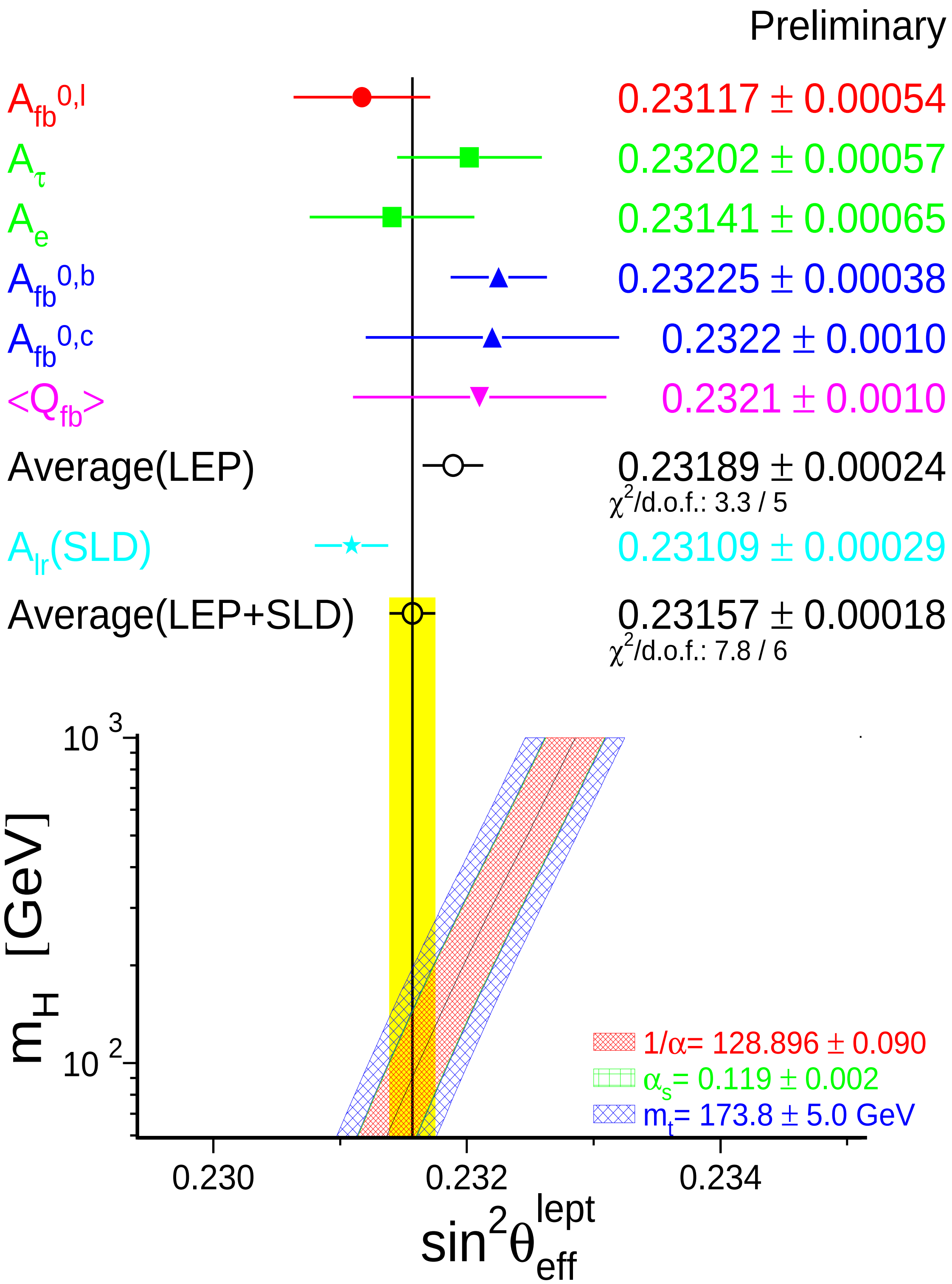


lepton couplings to the Z

the electroweak mixing angle $\sin\theta_W$

$$\frac{v_l}{a_l} = 1 - 4\sin^2\bar{\theta}_{\rm W}$$

$$\Delta\sin^2\bar{\theta}_{\rm W} \simeq \frac{1}{8}\Delta\mathcal{A}_l$$



Spin Correlations

Spin correlations in $e^+e^- \to \tau^+\tau^-$

Consider transverse-transverse and transverse-normal spin correlations

$$C_{TT} \equiv \frac{C_2}{C_0} \propto \frac{\sigma(s^T_{\tau^-}s^T_{\tau^+} = +1) - \sigma(s^T_{\tau^-}s^T_{\tau^+} = -1)}{\sigma(s^T_{\tau^-}s^T_{\tau^+} = +1) + \sigma(s^T_{\tau^-}s^T_{\tau^+} = -1)}$$

$$C_{TN} \equiv \frac{D_2}{C_0} \propto \frac{\sigma(s^T_{\tau^-}s^N_{\tau^+} = +1) - \sigma(s^T_{\tau^-}s^N_{\tau^+} = -1)}{\sigma(s^T_{\tau^-}s^N_{\tau^+} = +1) + \sigma(s^T_{\tau^-}s^N_{\tau^+} = -1)}$$

e.g.: $s^T_{\tau^-}s^T_{\tau^+} = ++, --, +-, -+$

$$C_{TT} = \frac{|a_\tau|^2 - |v_\tau|^2}{|a_\tau|^2 + |v_\tau|^2}$$

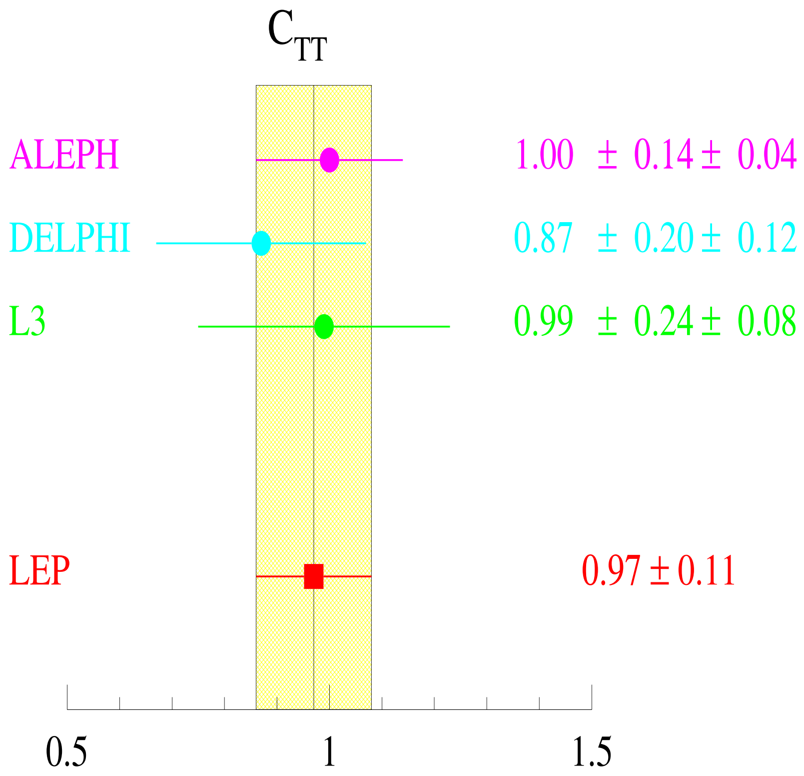
$$C_{TN} = -\frac{2\,\mathrm{Im}(v_\tau a_\tau^*)}{|a_\tau|^2 + |v_\tau|^2} + \text{interf.}$$

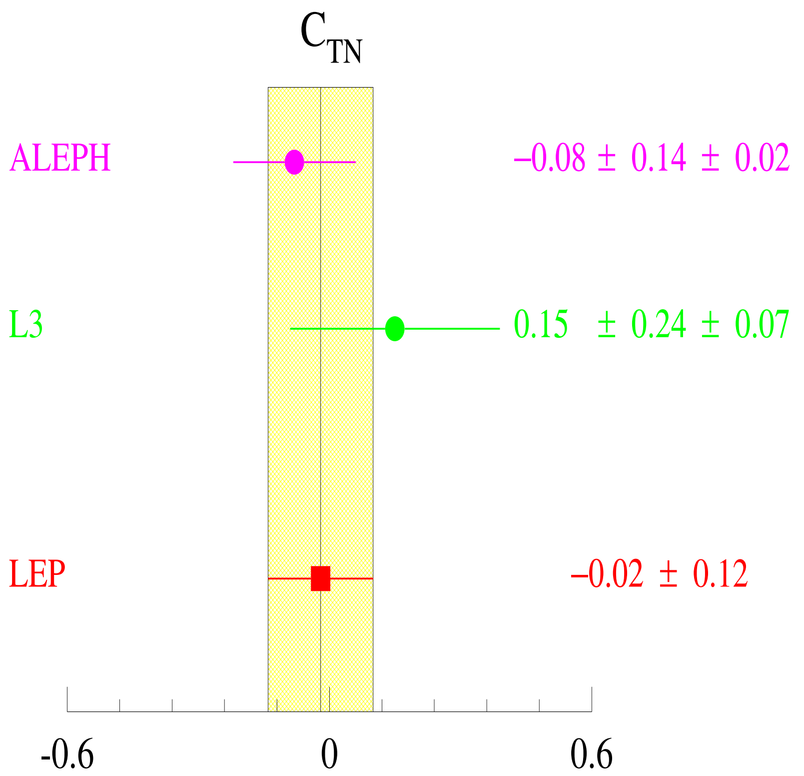
Standard Model prediction:

$$C_{TT} \approx 0.99$$
$$C_{TN} \approx 0.025 - 0.012$$

$$\frac{d\sigma}{d\Phi} \propto C_{TT}\cos(2\Phi) + C_{TN}\sin(2\Phi)$$

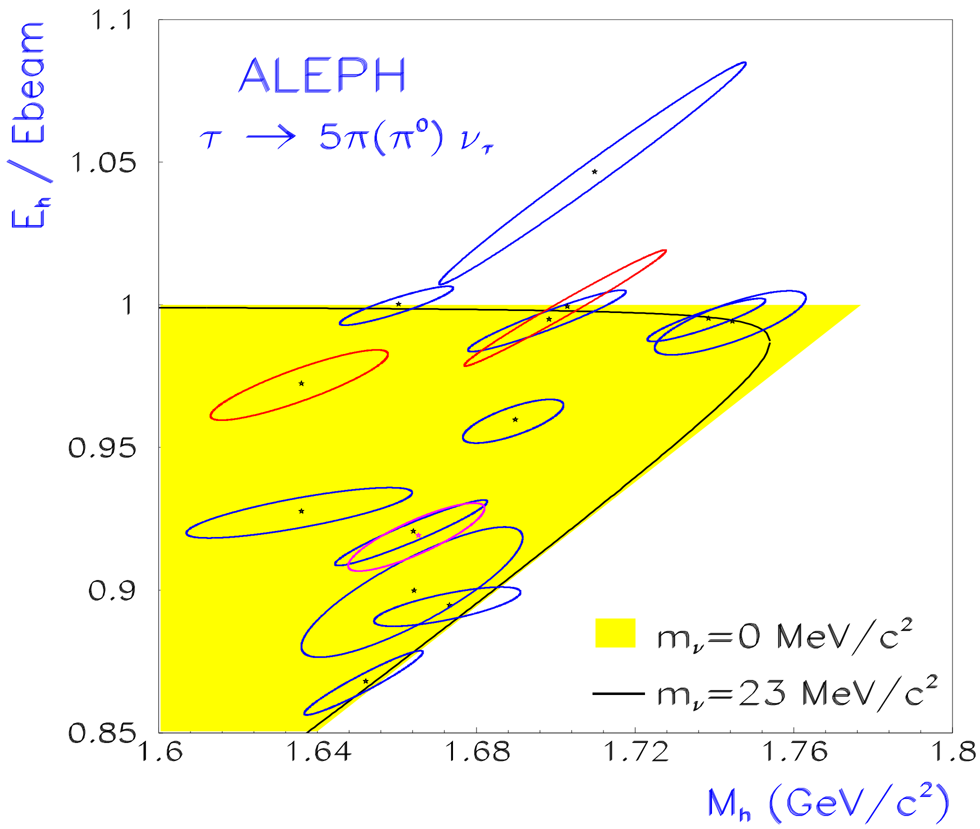
Spin correlations summary





ν_τ mass

derived from τ decays into (heavy) hadronic mass using the phase space endpoint



Experiment	ALEPH	ARGUS	CLEO	OPAL
ν_τ mass limit, MeV	18.2	31.0	28	27.6

Conclusion

Tsai 1973:

Since muons exist in nature for no appearent reason, it is possible that other heavy leptons may also exist in nature. If one discovers heavy leptons, one may be able to understand why muons exist and obtain some clue as to why the ratio of m_μ to m_e is roughly 210

The τ was discovered 1975 and we know that $\frac{m_\tau}{m_\mu}$ is about 20. What else we have found?

The mass of the τ is measured with a precision of 10^{-4}

The lifetime of the τ is measured with a precision of 3 per mille

Lepton universality in charged- and neutral current interactions holds on the per cent to per mille level

There is no hint for CP violation in the τ couplings

There is no hint for Lepton number violation

The τ neutrino is lighter than O(10MeV)

There was no additional heavy lepton with masses below 90 GeV found at LEP

Conclusion

Prospects

Prospects: Wait for new experiments with at least an order of magnitude more statistics

CLEO, BES

B- factories (SLAC, KEK), τ- charm factory (?)