LEP Summary on Weak Dipole Moments of the τ Lepton

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Outline

- Weak dipole moments in Standard Model and beyond
- Weak dipole moments from single τ polarisation
- Observables from spins of both τ's
- Data and systematic uncertainties
- LEP results

Weak Dipole Moments

Weak dipole moments are introduced by an effective Lagrangian:

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

$a_\tau^w \equiv F_2^w$ (Weak anomalous magnetic dipole moment)

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

Standard Model:

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

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

The SM predictions are far below the present experimental sensitivity. The experimental measurement of non-zero weak dipole moments would be a clear evidence of new physics. In particular, non-zero value of d_τ^w leads to CP violation $Z \to \tau\tau$.

Weak Dipole Moments

In the SM there is only one source of CP violation: δ_{CKM} phase of CKM mixing matrix.

There are several extensions of SM where the dominant contributions to d_τ^w are 1–loop effects.

Weak electric moment d_τ^w

Model	maximum expectation
multi-Higgs	$2 \times 10^{-20}\ e \cdot cm$
MSSM	$3 \times 10^{-20}\ e \cdot cm$
lepto-quark	$2 \times 10^{-19}\ e \cdot cm$

Weak anomalous magnetic moment a_τ^w

Model	maximum expectation
multi-Higgs	comparable to SM contribution
MSSM	7×10^{-6}
composite	up to 10^{-3}

Indirect Limit on $|d_\tau^w|$

An indirect limit on $|d_\tau^w|$ can be derived from its contribution to the partial width $Z \to \tau\tau$:

$$\Gamma_{exp}(Z \to \tau\tau) = \Gamma_{SM}(Z \to \tau\tau) + \Delta\Gamma_{CP}$$

$$\Delta\Gamma_{CP} \sim |d_\tau^w|^2$$

Direct measurement

$$\Gamma_{exp} = 83.68 \pm 0.24 \;\; MeV$$

Standard Model

$$\Gamma_{SM} = 83.97 \pm 0.06 \;\; MeV$$

lead to a limit at 95% CL:

$$|d_\tau^w| < 0.7 \times 10^{-17} \, e \cdot cm$$

Methods of measurement

The energy and angular distributions of the τ decay products allow to extract information about single τ polarisation and spin–spin correlations.

A set of observables can be constructed which are sensitive to the weak dipole moments.

- L3: single transverse and normal τ polarisation (azimuthal asymmetries)
- ALEPH, OPAL, DELPHI: spin-spin correlations (optimal observables)

All LEP 1 statistics is used

L3 Method of the Measurement

Differential cross section $e^+e^- \to Z \to \tau^+\tau^-$

$$\frac{d\sigma}{d\Omega_{\tau^-}} = \frac{d\sigma^0}{d\Omega_{\tau^-}} + \frac{d\sigma^{Spin}}{d\Omega_{\tau^-}} + \frac{d\sigma^{Spin-Spin}}{d\Omega_{\tau^-}}$$

In the given coordinate system spin-dependent part

$$\frac{d\sigma^{Spin}(\tau^+\tau^- \to h^+\bar{\nu}_\tau h^-\nu_\tau)}{d(\cos\theta_{\tau^-})d\phi_{h^\pm}} = \frac{\alpha^2\beta\pi}{128\sin^3\theta_W\cos^3\theta_W\Gamma_Z^2}\alpha_{h^\pm}$$

$$\times\left[\mp X_+\cos\phi_{h^\pm} + (Y_- \mp Y_+)\sin\phi_{h^\pm}\right]$$

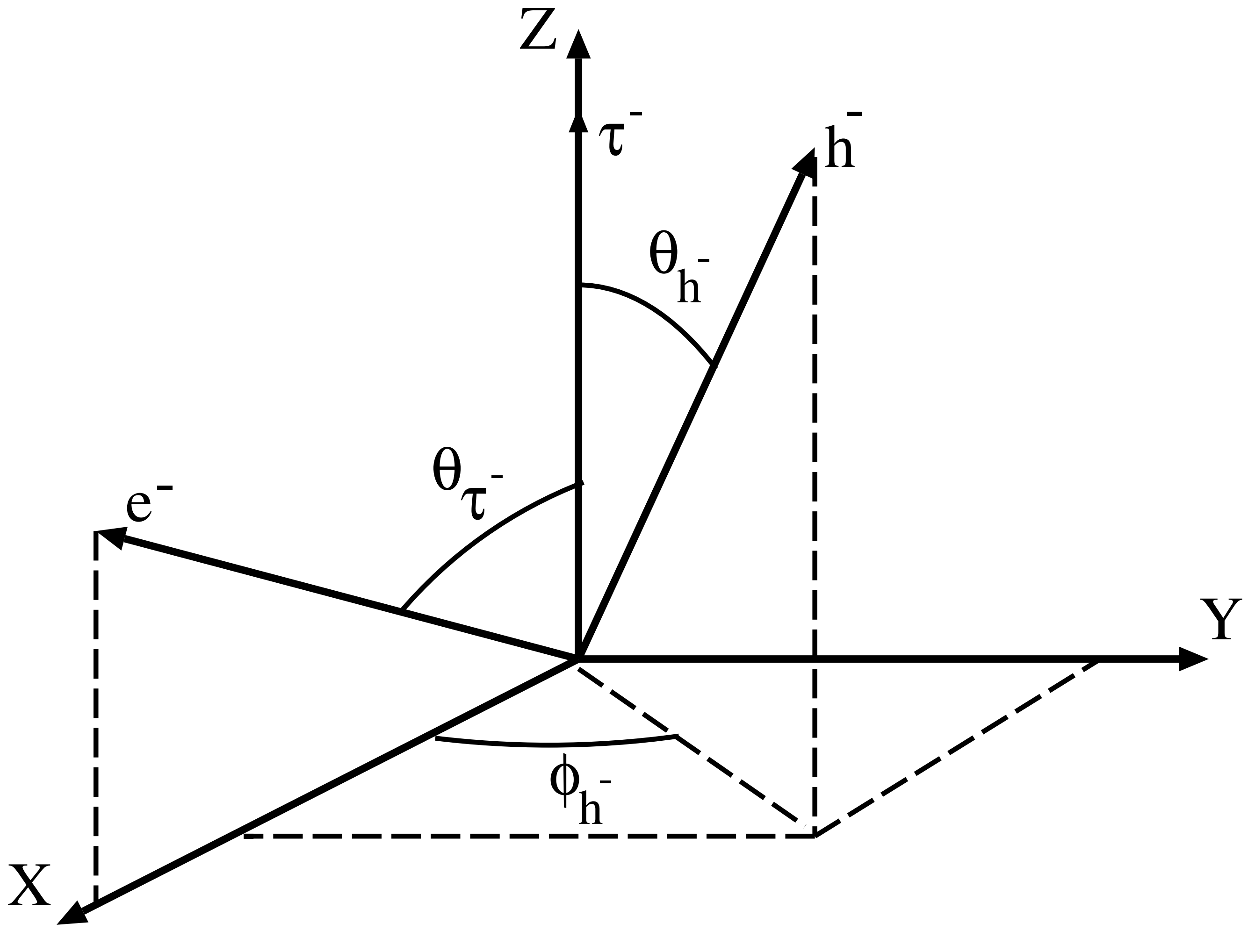
where

$$X_+ = X_+(Re(a_\tau^w), \theta_{\tau^-})$$

$$Y_+ = Y_+(Im(a_\tau^w), \theta_{\tau^-})$$

$$Y_- = Y_-(Re(d_\tau^w), \theta_{\tau^-})$$

Weak dipole moments produce asymmetries in the azimuthal angular distributions of the τ charged decay products in a co-ordinate system defined by the τ direction of flight and the electron beam.

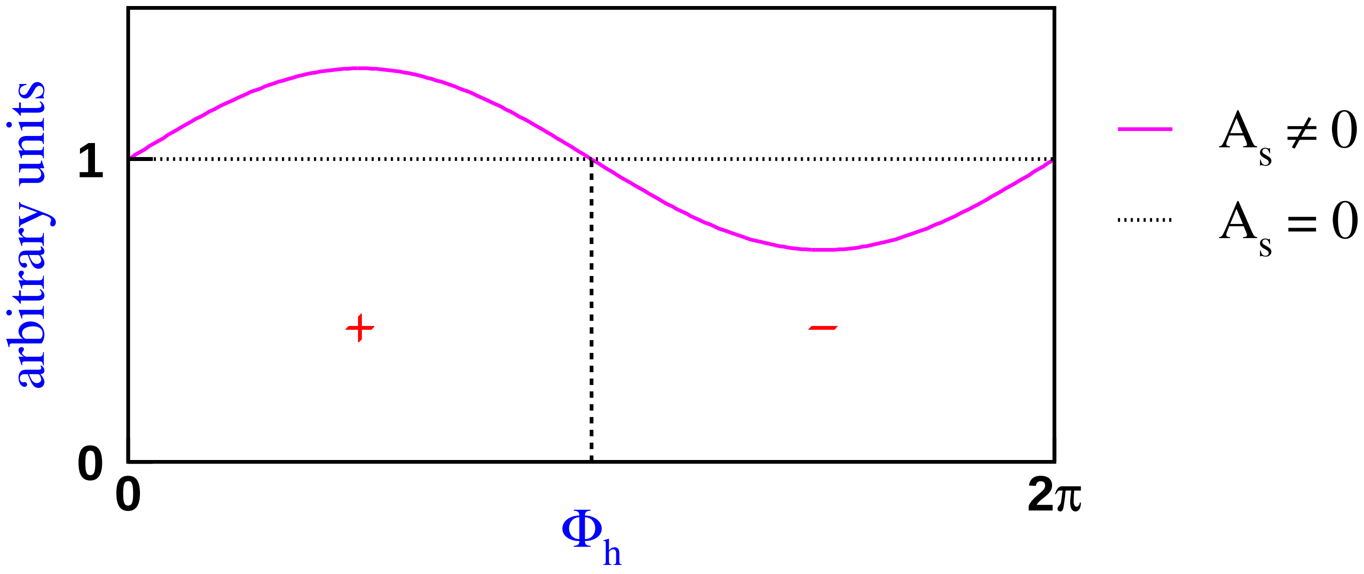


The Z-axis points in the direction of the τ^- lepton.
The X-Z plane contains both the electron and τ^-.

Observables

Asymmetry for $Im(a_\tau^w)$: $A_s^\mp = \frac{\sigma_s^\mp(+)-\sigma_s^\mp(-)}{\sigma_s^\mp(+)+\sigma_s^\mp(-)}$

$$\sigma_s^\mp(+) = \sigma(\sin\phi_{h^\mp} > 0) \qquad \sigma_s^\mp(-) = \sigma(\sin\phi_{h^\mp} < 0)$$



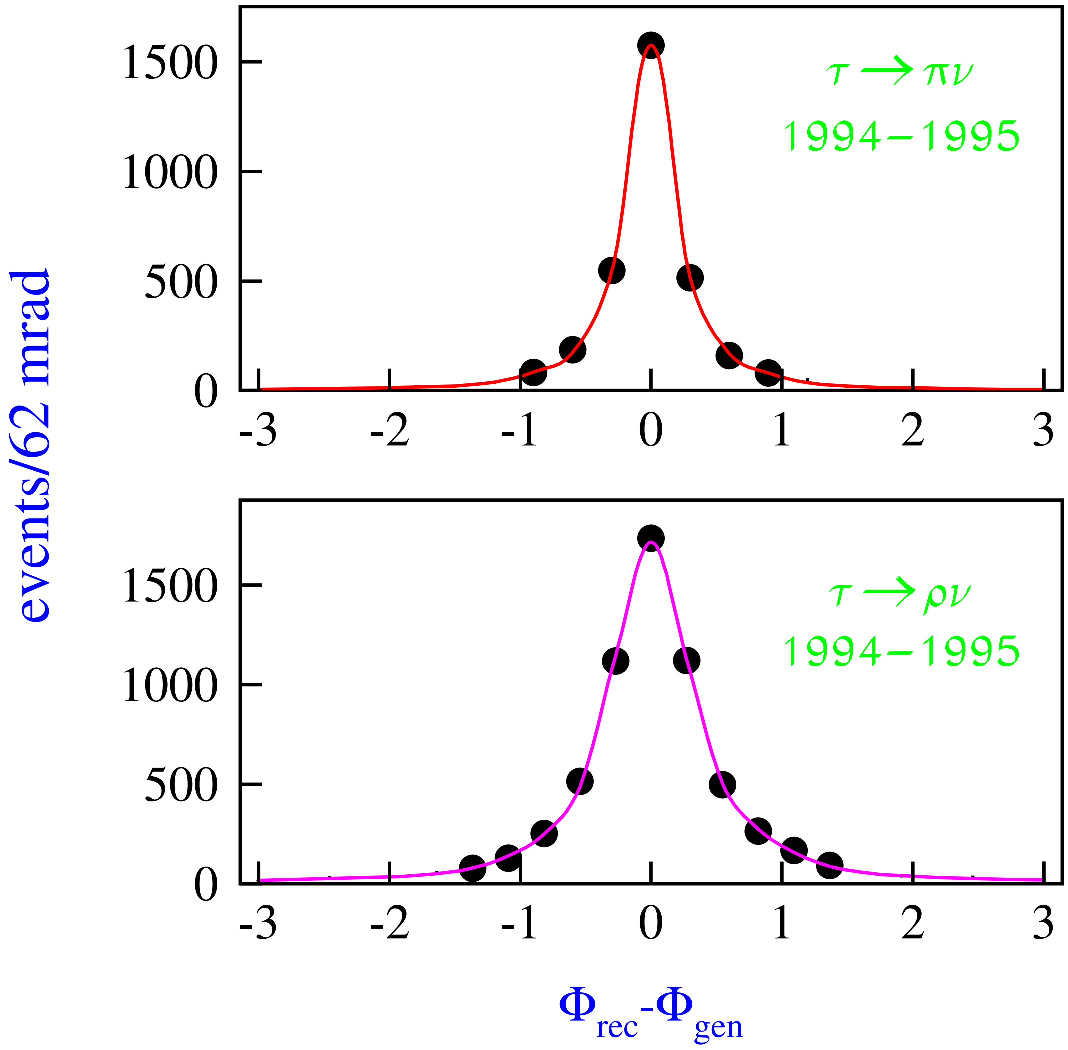
Relations to the weak dipole moments

$A_{cc}^+ = -A_{cc}^-$ $\quad A_s^+ = -A_s^-$ $\quad A_{sc}^+ = A_{sc}^-$

$A_{cc}^{\pi^-} = 0.0007 + 10.6\ Re(a_\tau^w)$ $\quad A_s^{\pi^-} = 3.6\ Im(a_\tau^w)$ $\quad A_{sc}^{\pi^-} = -10.6\ \frac{2m_\tau}{e} Re(d_\tau^w)$

$A_{cc}^{\rho^-} = 0.0003 + 5.0\ Re(a_\tau^w)$ $\quad A_s^{\rho^-} = 1.7 Im(a_\tau^w)$ $\quad A_{sc}^{\rho^-} = -3.8\ \frac{2m_\tau}{e} Re(d_\tau^w)$

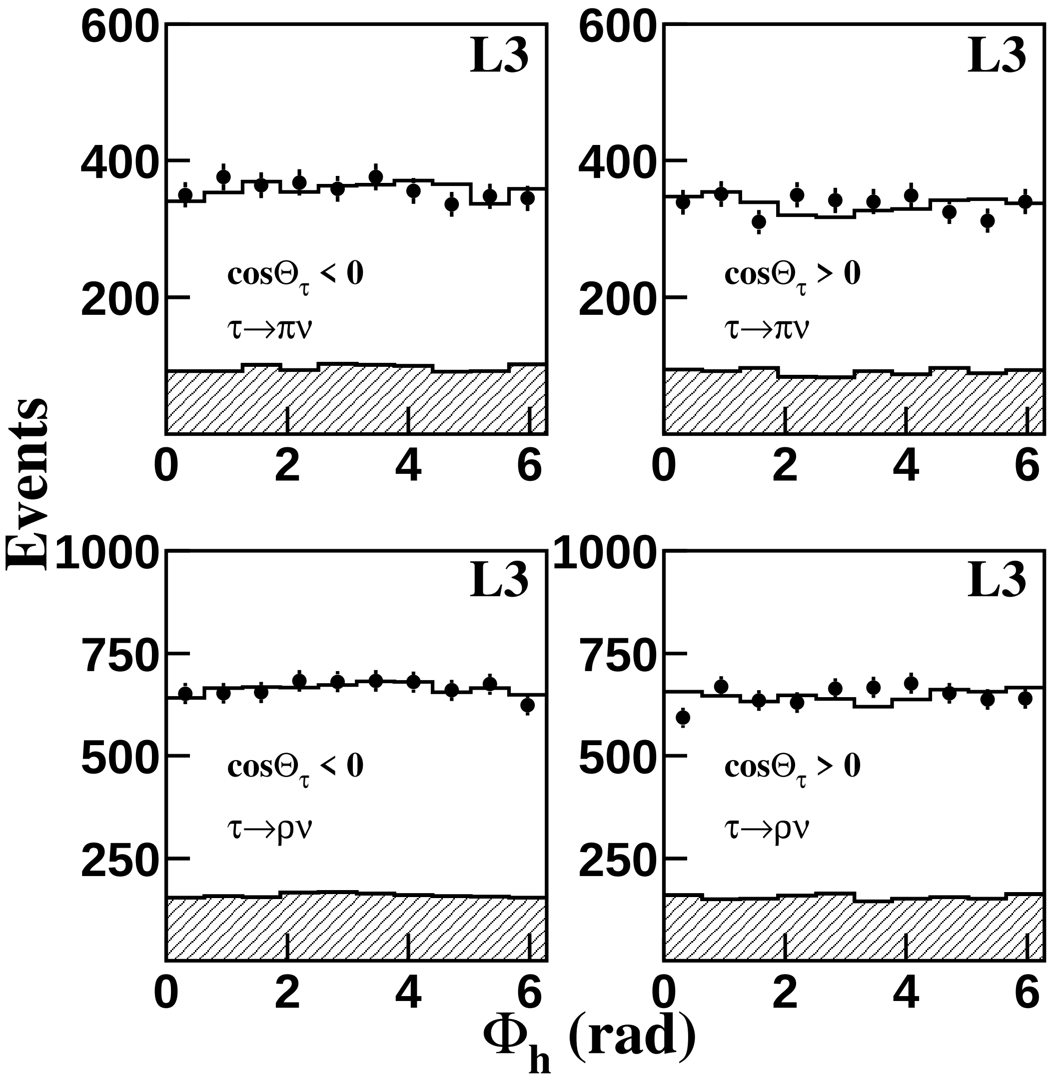
Resolution functions for π and ρ channels



Recalculated asymmetries for π channel

$$\begin{pmatrix} A_{cc} \\ A_{sc} \\ A_s \end{pmatrix} = \begin{pmatrix} 7.24 & -0.02 & 0.00 \\ -0.02 & -7.23 & 0.54 \\ 0.00 & -0.24 & 3.21 \end{pmatrix} \begin{pmatrix} Re(a_\tau^w) \\ 2m_\tau Re(d_\tau^w)/e \\ Im(a_\tau^w) \end{pmatrix}$$

Data 1991-95 9000 events



The first direct measurement of a_τ^w:

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

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

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

Optimal Observables

$$\mathrm{e}^+\mathrm{e}^- \to Z \to \tau^+\tau^- \to AB\nu\nu$$

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

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

CP-odd optimal observables

$$O^{Re} = \frac{M_{CP}^{Re}}{M_{SM}} \qquad O^{Im} = \frac{M_{CP}^{Im}}{M_{SM}}$$

$$M_{CP}^{Re} = (\hat{\boldsymbol{k}}\hat{\boldsymbol{q}}_e)(\hat{\boldsymbol{k}} \times (\boldsymbol{s}_+ - \boldsymbol{s}_-))\hat{\boldsymbol{q}}_e$$

$$M_{CP}^{Im} = (\hat{\boldsymbol{k}}\hat{\boldsymbol{q}}_e)[(\hat{\boldsymbol{k}}\boldsymbol{s}_-)(\hat{\boldsymbol{q}}_e\boldsymbol{s}_+) - (\hat{\boldsymbol{k}}\boldsymbol{s}_+)(\hat{\boldsymbol{q}}_e\boldsymbol{s}_-)]$$

$$M_{SM} = 1 + (\hat{\boldsymbol{k}}\hat{\boldsymbol{q}}_e)^2 + \boldsymbol{s}_+\boldsymbol{s}_-(1 - (\hat{\boldsymbol{k}}\hat{\boldsymbol{q}}_e)^2) - 2(\hat{\boldsymbol{q}}_e\boldsymbol{s}_+)(\hat{\boldsymbol{q}}_e\boldsymbol{s}_-)$$

$$+ 2(\hat{\boldsymbol{k}}\hat{\boldsymbol{q}}_e)[(\hat{\boldsymbol{k}}\boldsymbol{s}_+)(\hat{\boldsymbol{q}}_e\boldsymbol{s}_-) + (\hat{\boldsymbol{k}}\boldsymbol{s}_-)(\hat{\boldsymbol{q}}_e\boldsymbol{s}_+)]$$

$\hat{\boldsymbol{q}}_e$ – direction of incoming electron

$\hat{\boldsymbol{k}}$ – flight direction of τ^+

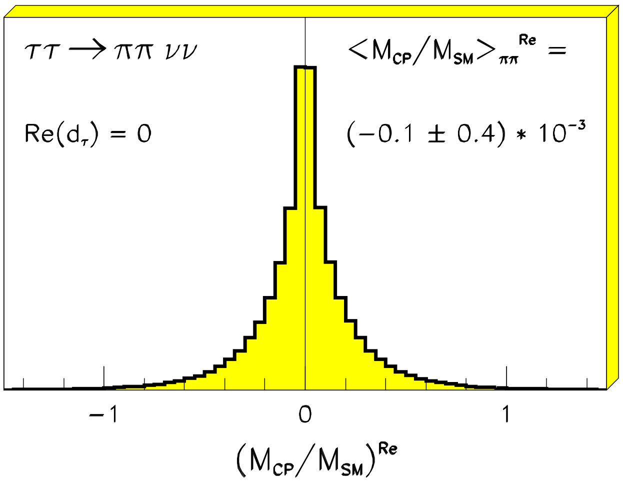
$\boldsymbol{s}_\pm$ – spin vectors of $\tau^\pm$ in their rest systems

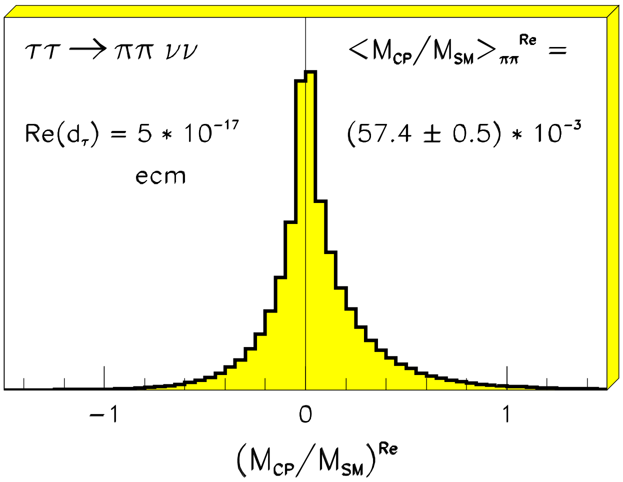
Optimal Observables

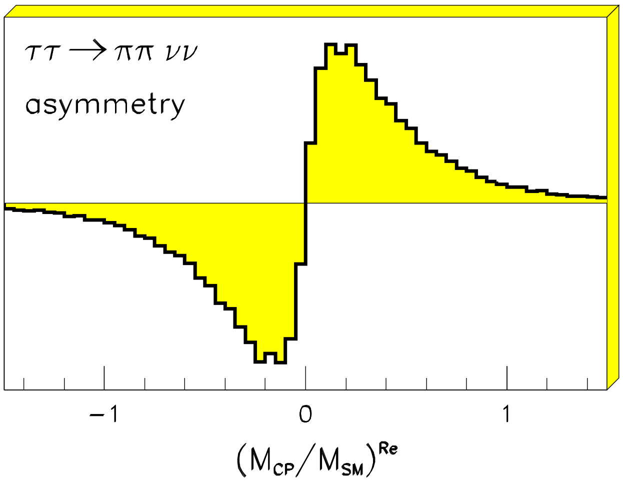
$$\langle O^{Re} \rangle_{AB} = \frac{M_Z}{e} c_{AB} Re(d_\tau^w)$$

$$\langle O^{Im} \rangle_{AB} = \frac{M_Z}{e} f_{AB} Im(d_\tau^w)$$

$d_\tau^w = 0 \Rightarrow \langle O \rangle = 0$ $\qquad$ $\langle O \rangle \neq 0 \Rightarrow d_\tau^w \neq 0$

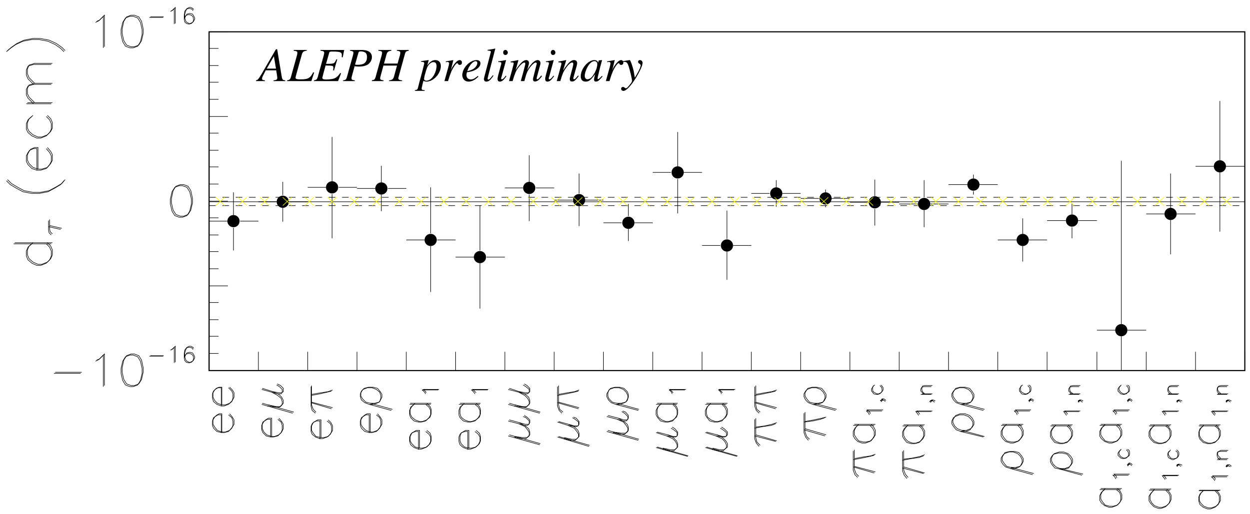






ALEPH Results (*)

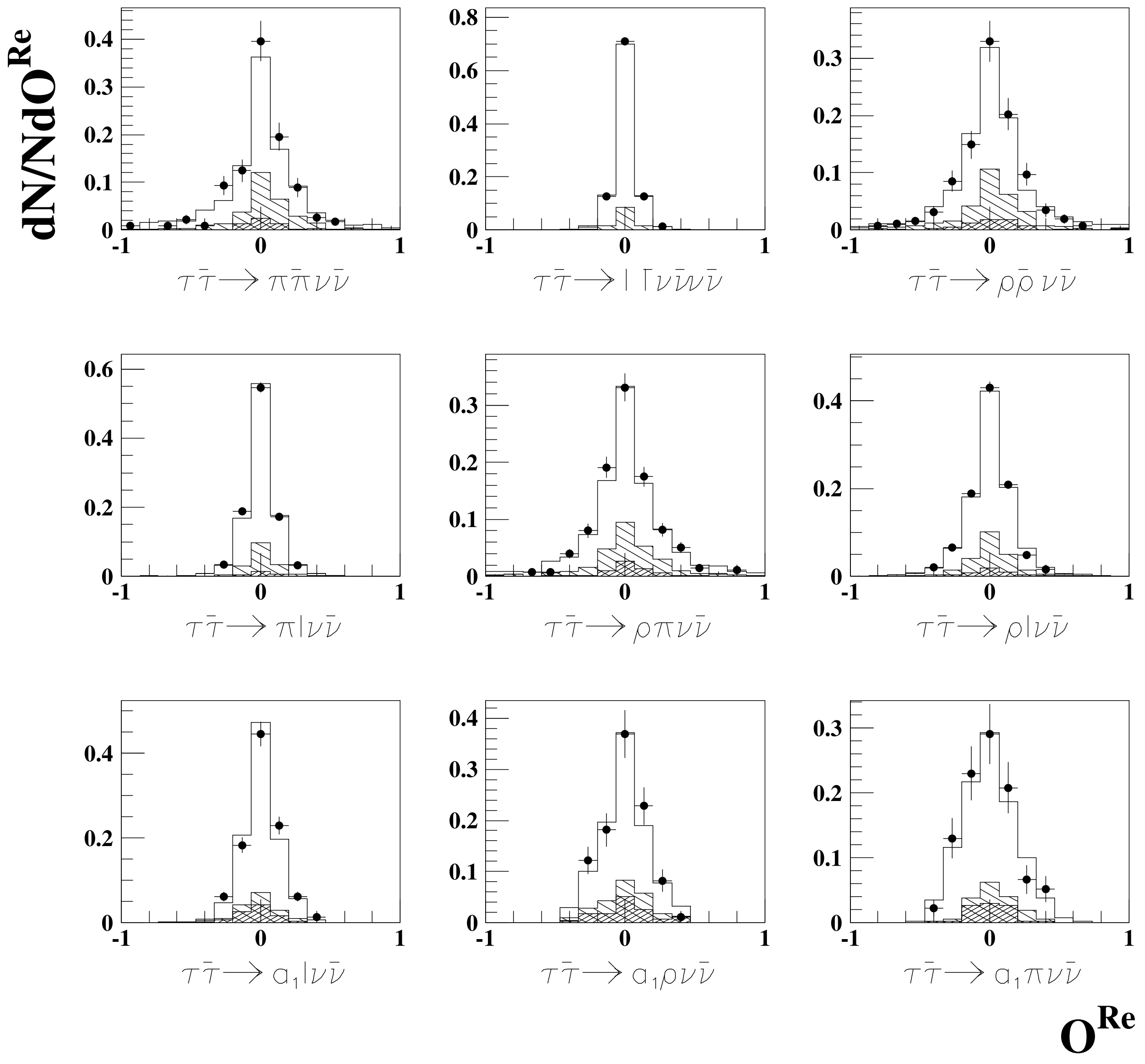
Data 1990-95 83000 events



$$Re(d_\tau^w) = (-0.29 \pm 2.59 \pm 0.88) \times 10^{-18}\, e \cdot cm$$

DELPHI Results (*)

Data 1992-95 22000 events

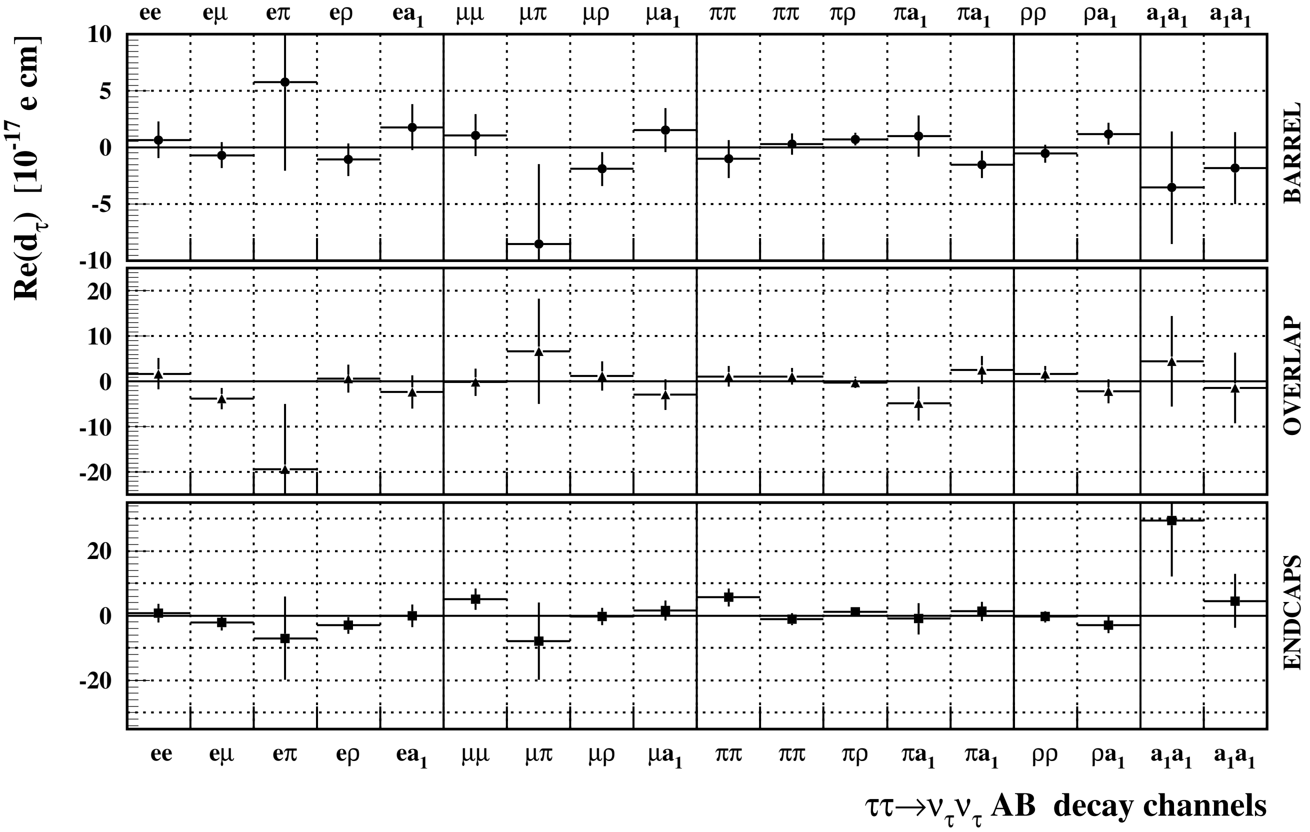


$$Re(d_\tau^w) = (-1.48 \pm 2.64 \pm 0.27) \times 10^{-18}\, e \cdot cm$$

$$Im(d_\tau^w) = (-0.44 \pm 0.77 \pm 0.13) \times 10^{-17}\, e \cdot cm$$

OPAL Results

Data 1991-95   70000 events



$$Re(d_\tau^w) = (0.72 \pm 2.46 \pm 0.24) \times 10^{-18}\, e \cdot cm$$

$$Im(d_\tau^w) = (0.35 \pm 0.57 \pm 0.08) \times 10^{-17}\, e \cdot cm$$

Standard procedure for selection of τ pairs and identification of decay channels

$|\cos\theta|$ range:

0.95 (ALEPH, OPAL), 0.94 (DELPHI), 0.7 (L3)

Experiment	Data	#events	Decay channels
ALEPH$^{(*)}$	1990-95	83000	e, μ, π, ρ, a_1
DELPHI$^{(*)}$	1992-95	22000	e, μ, π, ρ, $a_{1(3pr)}$
OPAL	1991-95	70000	e, μ, π, ρ, $a_{1(3pr)}$
L3	1991-95	9000	π, ρ

- Reconstruction of the τ flight direction (L3)

- Alignment and homogeneity of the detector

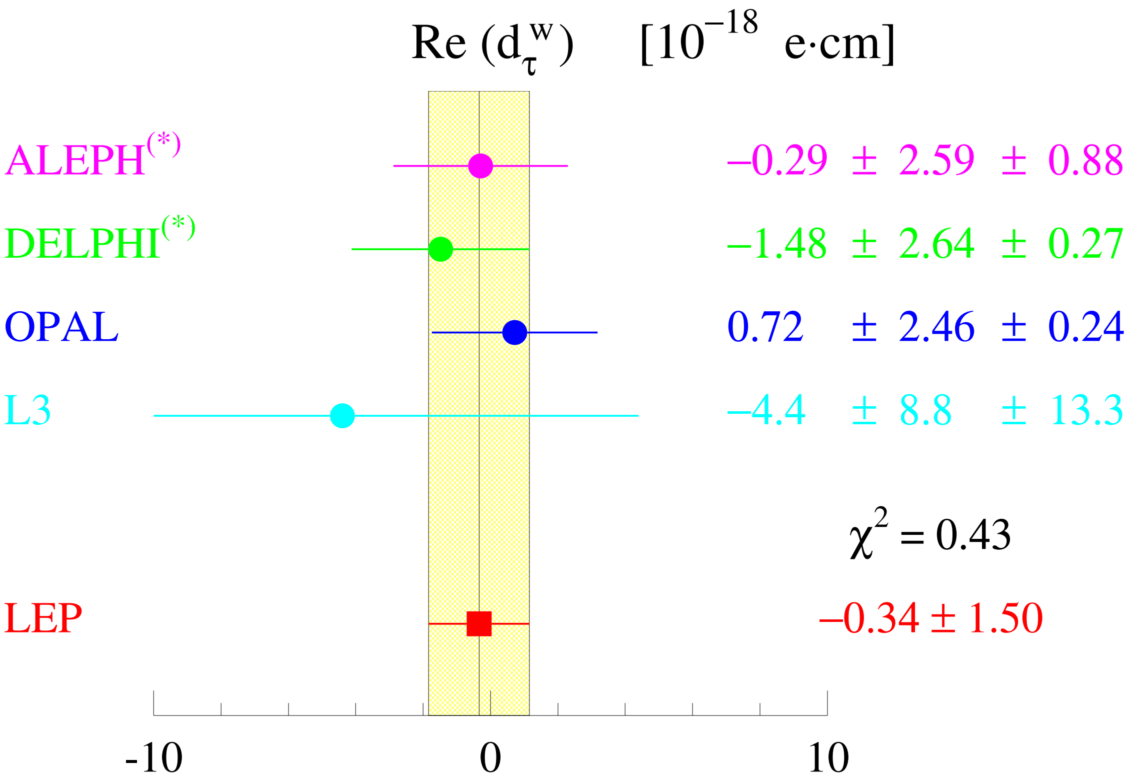
- CP symmetry of the detector

Checked to a level of $|Re(d_\tau^w)| < 0.5 \times 10^{-18}\ e \cdot cm$

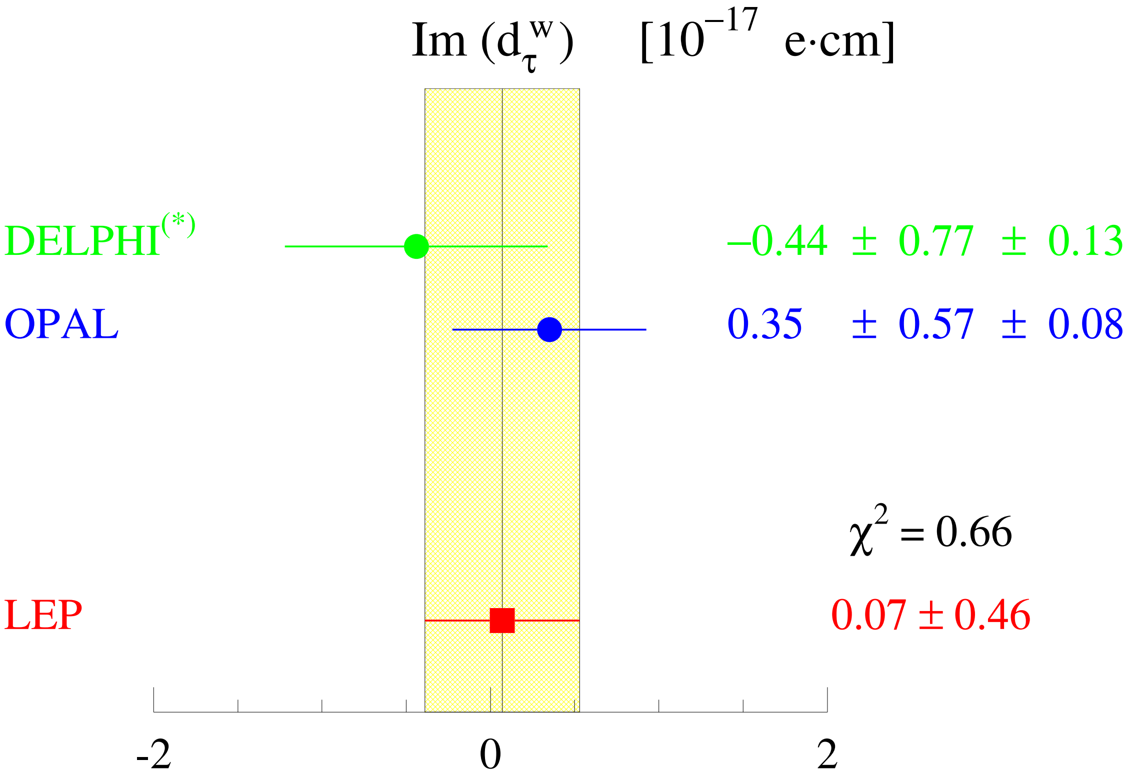
$|Im(d_\tau^w)| < 0.9 \times 10^{-18}\ e \cdot cm$ (OPAL)

- Background

LEP Results



Re (d_τ^w) $[10^{-18}$ e·cm]
ALEPH(*)
$-0.29 \pm 2.59 \pm 0.88$
DELPHI(*)
$-1.48 \pm 2.64 \pm 0.27$
OPAL
$0.72 \pm 2.46 \pm 0.24$
L3
$-4.4 \pm 8.8 \pm 13.3$
$\chi^2 = 0.43$
LEP
-0.34 ± 1.50
-10
0
10



Im (d_τ^w) $[10^{-17}$ e·cm]
DELPHI(*)
$-0.44 \pm 0.77 \pm 0.13$
OPAL
$0.35 \pm 0.57 \pm 0.08$
$\chi^2 = 0.66$
LEP
0.07 ± 0.46
-2
0
2

Summary

Limits on the weak dipole moments (95% CL):

$$|Re\,(d_\tau^w)| < 3.0 \times 10^{-18} \quad e\cdot cm$$
$$|Im\,(d_\tau^w)| < 9.2 \times 10^{-18} \quad e\cdot cm$$
$$|d_\tau^w| < 9.4 \times 10^{-18} \quad e\cdot cm$$

$$|Re\,(a_\tau^w)| < 4.5 \times 10^{-3}$$
$$|Im\,(a_\tau^w)| < 9.9 \times 10^{-3}$$

No deviation from the Standard Model

No evidence for CP violation