Limits on the Weak Magnetic and Electric Dipole Moments of the Tau Lepton

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Representing the L3 collaboration

Outline

- Theoretical Motivation

- Definition of Measured Asymmetries

- Reconstruction of $\tau^+\tau^-$ Kinematics

- Systematic Uncertainties

- Results

Postulate new $Z\tau\tau$ interaction (effective Lagrangian):

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

where

$$Z_{\mu\nu} \equiv \partial_\mu Z_\nu - \partial_\nu Z_\mu$$

Define (anomalous) <u>weak</u> magnetic (a_τ^w) and electric (d_τ^w) dipole moments:

$$a_\tau^w \equiv F_2^w \qquad\qquad d_\tau^w \equiv \frac{eF_3^w}{2\,m_\tau} \text{ (CP-violating)}$$

Standard Model (Bernabeu *et al.*):

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

$$d_\tau^w \approx \text{“Very Small”}$$

Indirect limits on d_τ^w and a_τ^w from $\Gamma(Z \rightarrow \tau^+\tau^-)$:

$$|d_\tau^w| \quad < \quad O(10^{-17}\mathrm{e}{-}cm) \qquad\qquad |a_\tau^w| \quad < \quad O(10^{-2})$$

Previous direct limits on d_τ^w based on CP-odd observables:

- Example: define tensor using momenta $\vec{q}_\pm$ of $\tau^\pm$ decay products:

$$\hat{T}_{ij} \quad \equiv \quad \frac{(\hat{q}_+ - \hat{q}_-)_i}{|\hat{q}_+ - \hat{q}_-|}(\hat{q}_+ \times \hat{q}_-)_j \quad + \quad (i \leftrightarrow j)$$

- If $< T_{ij} > \neq 0 \quad \Rightarrow \quad$ CP Violation $\quad \Rightarrow \quad d_\tau^w \neq 0$

Published direct limits on d_τ^w from LEP

OPAL:

$$|\mathrm{Re}(d_\tau^w)| < 7.8 \times 10^{-18}\, e\text{-cm} \qquad |\mathrm{Im}(d_\tau^w)| < 4.5 \times 10^{-17}\, e\text{-cm}$$

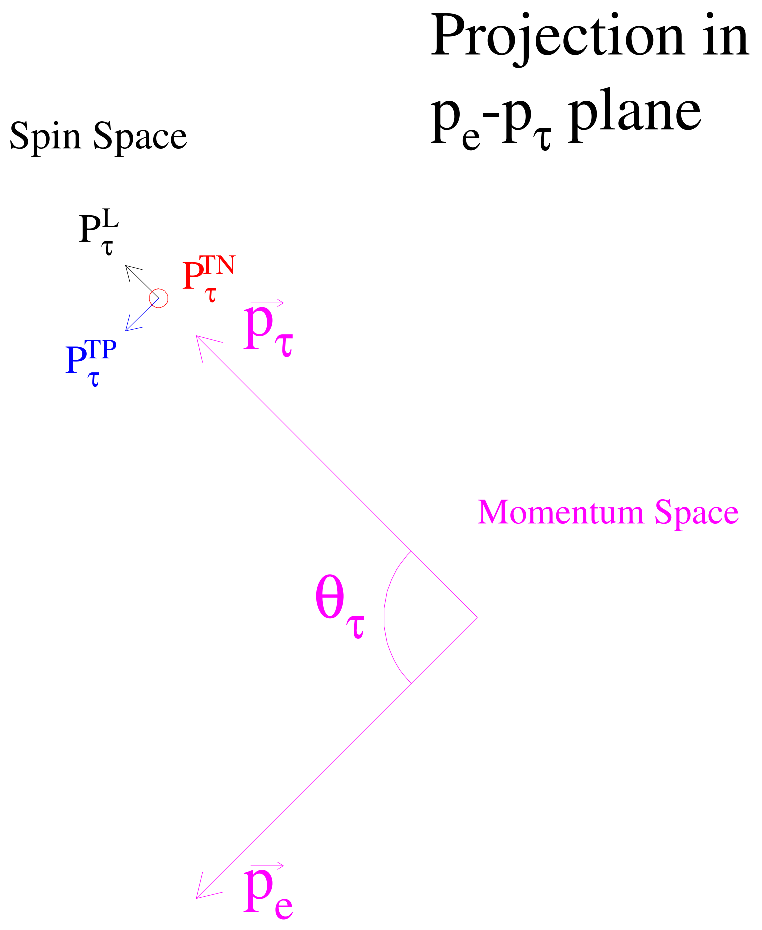
ALEPH:

$$|\mathrm{Re}(d_\tau^w)| < 1.5 \times 10^{-17}\, e\text{-cm}$$

$\boxed{\text{NO previous direct limits on } a_\tau^w}$

Alternative approach to measure both a_τ^w and d_τ^w:

Transverse Tau Polarization



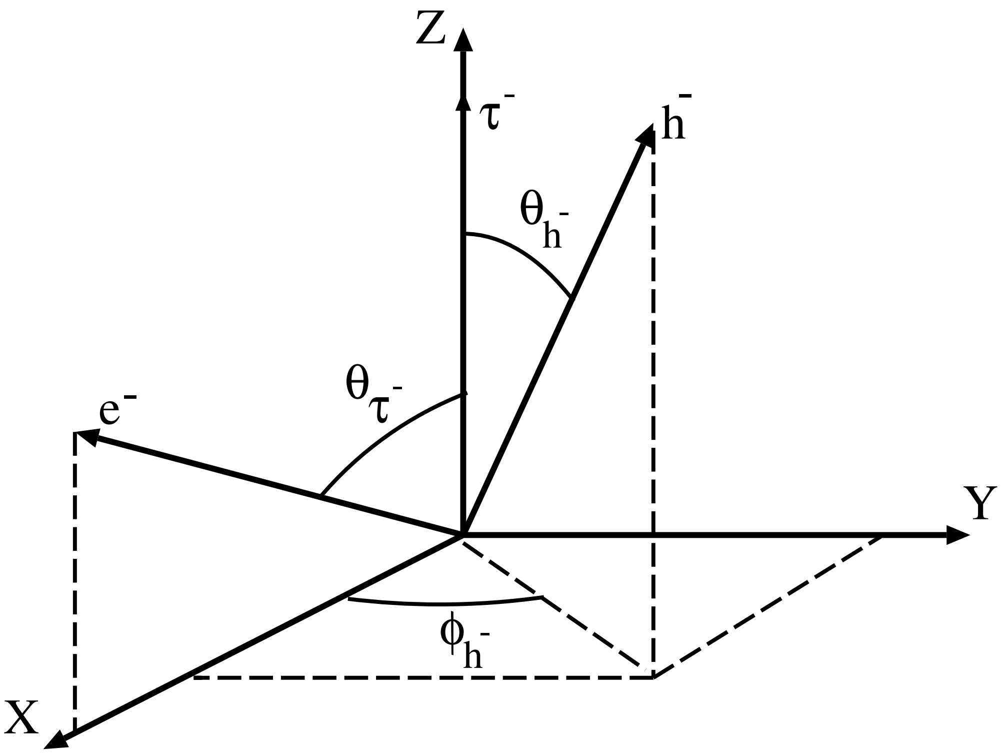
TP $\equiv$ Transverse – Parallel to $e^- - \tau^-$ plane

TN $\equiv$ Transverse – Normal to $e^- - \tau^-$ plane

Exploit $V-A$ coupling of τ decay to measure polarization

Similar to conventional longitudinal polarization measurement

- **But simpler: Count events**
- **But more complicated: Must reconstruct original τ direction**



$$\frac{d\sigma}{d\cos\theta_{\tau^-}\, d\phi_{h^\pm}} = \left(\frac{d\sigma}{d\cos\theta_{\tau^-}\, d\phi_{h^\pm}}\right)_{\mathrm{SM}} + X'_\pm \cos\phi_{h^\pm} + Y'_\pm \sin\phi_{h^\pm}$$

where

$$X'_\pm = X'_\pm(\theta_{\tau^-}, F_2^w)$$

$$Y'_\pm = Y'_\pm(\theta_{\tau^-}, F_3^w)$$

and where we use $h^\pm = \pi^\pm$ and $\rho^\pm$ in these measurements

Definition of Measured Asymmetries

Lessons:

- **Non-zero $\phi_{h^\pm}$ asymmetry between $[0,\pi]$ and $[\pi, 2\pi]$**
  $\Rightarrow \quad F_3^w \neq 0 \quad \Rightarrow \quad d_\tau^w \neq 0$

- **Non-zero $\phi_{h^\pm}$ asymmetry between $[-\frac{\pi}{2},\frac{\pi}{2}]$ and $[\frac{\pi}{2},\frac{3\pi}{2}]$**
  $\Rightarrow \quad F_2^w \neq 0 \quad \Rightarrow \quad a_\tau^w \neq 0$

Define:

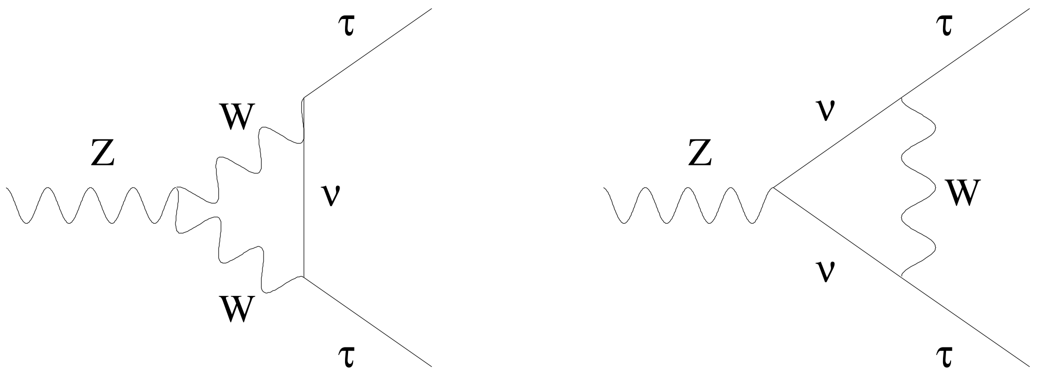
$$\begin{aligned}
\sigma^\pm_{\mathrm{SC}}(+) \quad &\equiv \quad \sigma(\cos\theta_{\tau^-} > 0,\ 0 < \phi_{h^\pm} < \pi) \quad + \\
&\quad\quad \sigma(\cos\theta_{\tau^-} < 0,\ \pi < \phi_{h^\pm} < 2\pi) \\
\sigma^\pm_{\mathrm{SC}}(-) \quad &\equiv \quad \sigma(\cos\theta_{\tau^-} < 0,\ 0 < \phi_{h^\pm} < \pi) \quad + \\
&\quad\quad \sigma(\cos\theta_{\tau^-} > 0,\ \pi < \phi_{h^\pm} < 2\pi)
\end{aligned}$$

$$A^\pm_{\mathrm{SC}} \quad \equiv \quad \frac{\sigma^\pm_{\mathrm{SC}}(+) - \sigma^\pm_{\mathrm{SC}}(-)}{\sigma^\pm_{\mathrm{SC}}(+) + \sigma^\pm_{\mathrm{SC}}(-)} \quad \Longrightarrow \quad d^w_\tau$$

$$\begin{aligned}
\sigma^\pm_{\mathrm{CC}}(+) \quad &\equiv \quad \sigma(\cos\theta_{\tau^-} > 0,\ -\frac{\pi}{2} < \phi_{h^\pm} < \frac{\pi}{2}) \quad + \\
&\quad\quad \sigma(\cos\theta_{\tau^-} < 0,\ \frac{\pi}{2} < \phi_{h^\pm} < \frac{3\pi}{2}) \\
\sigma^\pm_{\mathrm{CC}}(-) \quad &\equiv \quad \sigma(\cos\theta_{\tau^-} < 0,\ -\frac{\pi}{2} < \phi_{h^\pm} < \frac{\pi}{2}) \quad + \\
&\quad\quad \sigma(\cos\theta_{\tau^-} > 0,\ \frac{\pi}{2} < \phi_{h^\pm} < \frac{3\pi}{2})
\end{aligned}$$

$$A^\pm_{\mathrm{CC}} \quad \equiv \quad \frac{\sigma^\pm_{\mathrm{CC}}(+) - \sigma^\pm_{\mathrm{CC}}(-)}{\sigma^\pm_{\mathrm{CC}}(+) + \sigma^\pm_{\mathrm{CC}}(-)} \quad \Longrightarrow \quad a^w_\tau$$

SM Loops Contribute to $A^{\pm}_{CC}$:



[Dominant Contributions]

More Important: Helicity-Flip Tree-Level Terms

Ideal:

$$
\begin{aligned}
A^{\rho^-}_{sc} &= +A^{\rho^+}_{sc} = -3.8F^w_3 \\
A^{\rho^-}_{cc} &= -A^{\rho^+}_{cc} = +5.0F^w_2 + 0.0003 \\
A^{\pi^-}_{sc} &= +A^{\pi^+}_{sc} = -10.6F^w_3 \\
A^{\pi^-}_{cc} &= -A^{\pi^+}_{cc} = +10.6F^w_2 + 0.0007
\end{aligned}
$$

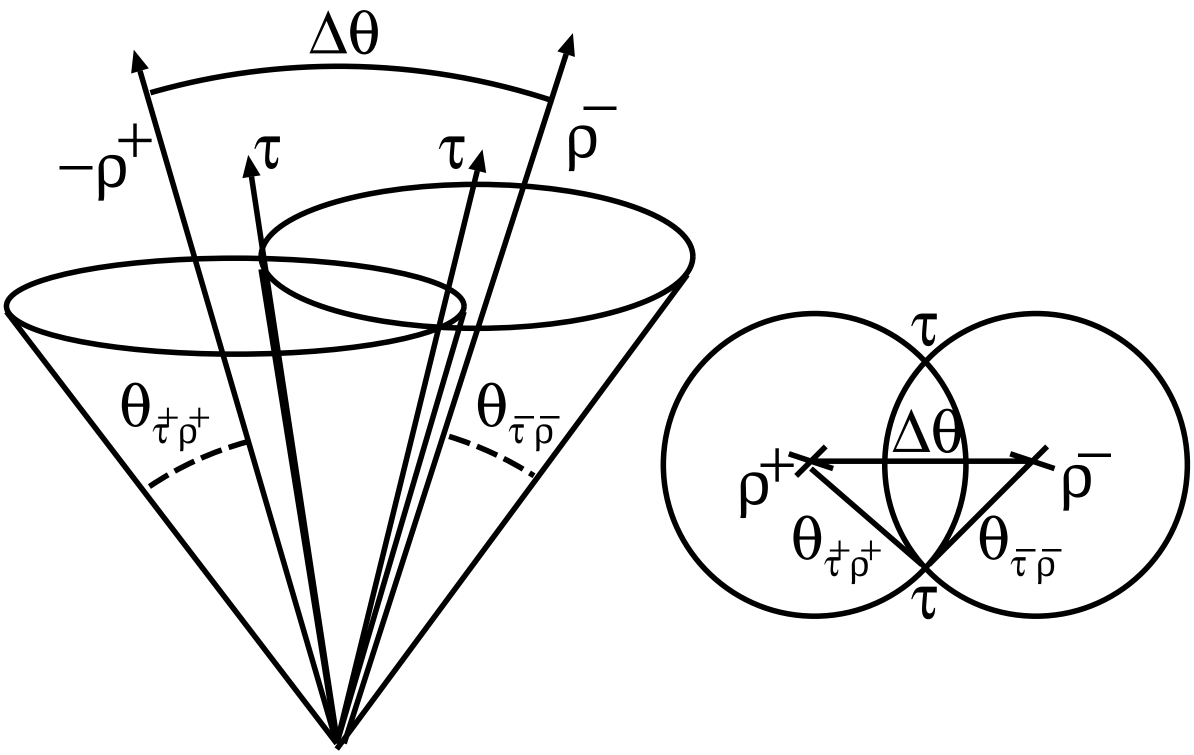
But now reality intrudes...

$$Z \quad \rightarrow \quad \tau^+\tau^- \quad \rightarrow \quad h^+h^-\nu_\tau\bar{\nu}_\tau$$

Two missing ν's	$\Longrightarrow$	6 Unknowns
E / $\vec{p}$ Conservation	$\Longrightarrow$	4 Constraints
$m_{h^\pm\nu} \quad = \quad m_\tau$	$\Longrightarrow$	2 Constraints

6 unknowns $+$ 6 constraints $\Longrightarrow$ Solution(s)

Graphically...



Express unknown τ^- direction as:

$$\vec{p}_{\tau^-} \quad = \quad a \cdot \hat{n}_1 \quad + \quad b \cdot \hat{n}_2 \quad + \quad c \cdot \hat{n}_3$$

where

$$\begin{aligned} \hat{n}_3 \quad &\parallel \quad \vec{p}_{h^+} \\ \hat{n}_2 \quad &\parallel \quad \vec{p}_{h^-} \times \vec{p}_{h^+} \\ \hat{n}_1 \quad &= \quad \hat{n}_2 \times \hat{n}_3 \end{aligned}$$

Solve constraint equations for $a, c \quad \Longrightarrow \quad b$

$$b \quad = \quad \sqrt{1 - a^2 - c^2}$$

$\Longrightarrow$ **Two-fold ambiguity in sign of** b

Consequence:

- **Reconstructed ϕ_h is wrong half the time**

  $\Rightarrow$ **both F_2^w, F_3^w contribute to reconstructed $A_{\rm SC}$, $A_{\rm CC}$**

Reconstruction of $\tau^+\tau^-$ Kinematics

More reality:

- **Imperfect Detector Resolution**
- **Initial + Final State Radiation**

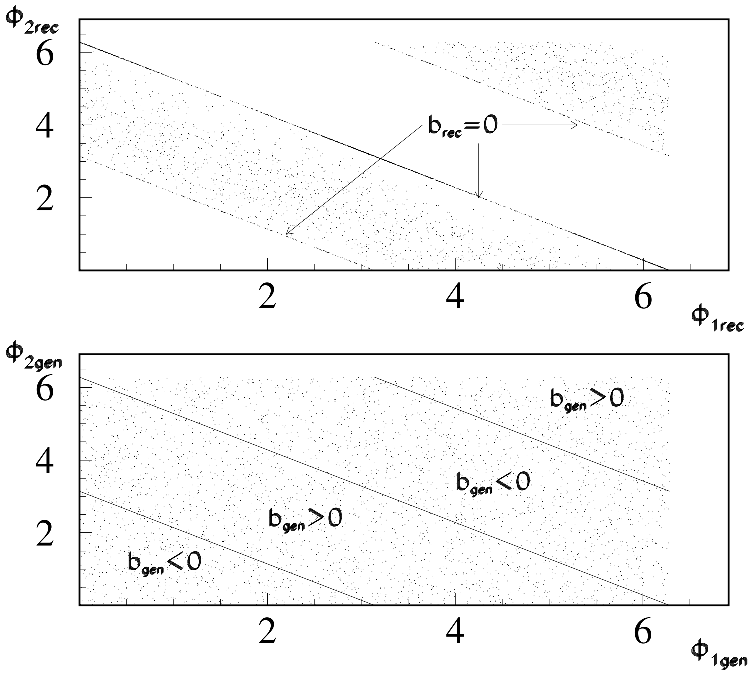
$\Rightarrow$ **Reject events with no real solution for b**

Consequence:

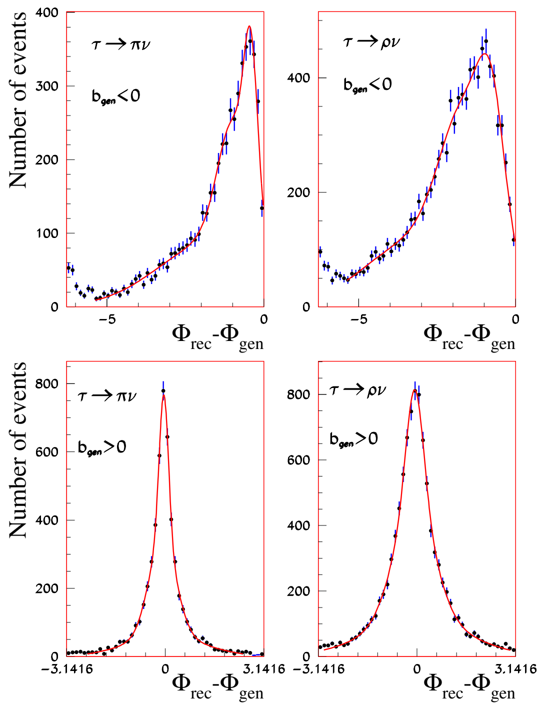
$\vec{p}_\tau$ **Reconstruction Efficiency** $\approx$ **50%**

Monte Carlo Studies

Reconstructed (top) and True (bottom) ϕ_h



Resulting Resolution on ϕ_h ($b^2_{reco} > 0$)



Detailed Monte Carlo simulation yields:

$$
\begin{aligned}
A_{sc}^{\rho^-} &= +A_{sc}^{\rho^+} = 0.0001 + 1.59F_2^w - 2.53F_3^w \\
A_{cc}^{\rho^-} &= -A_{cc}^{\rho^+} = 0.0002 + 2.54F_2^w + 1.59F_3^w \\
A_{sc}^{\pi^-} &= +A_{sc}^{\pi^+} = 0.0002 + 2.59F_2^w - 7.41F_3^w \\
A_{cc}^{\pi^-} &= -A_{cc}^{\pi^+} = 0.0005 + 7.41F_2^w + 2.59F_3^w
\end{aligned}
$$

$\Longrightarrow$ **Must disentangle a_τ^w and d_τ^w via $\geq$ two asymmetries**

Fortunately, we have eight...

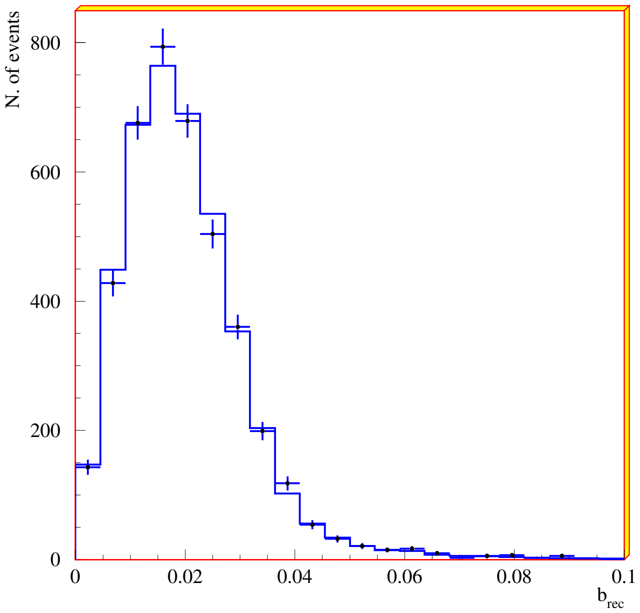
Systematic Uncertainties

Main systematic uncertainties in measuring $A_{sc,cc}$:

Source	ρ channel	π channel
Finite MC statistics	0.006	0.008
Uncertainty in background	0.004	0.004
Reconstruction method	0.034	0.062

$\Longrightarrow$ **Reconstruction errors dominate precision**

Reconstructed b (data *vs.* Monte Carlo):



Raw Event Counts:

	Angular Region	τ^-	τ^+
A^{ρ}_{sc}	$\cos\theta_\tau > 0\ \phi_h < \pi$	696	654
	$\cos\theta_\tau < 0\ \phi_h > \pi$	664	677
	$\cos\theta_\tau > 0\ \phi_h > \pi$	653	711
	$\cos\theta_\tau < 0\ \phi_h < \pi$	623	685
A^{ρ}_{cc}	$\cos\theta_\tau > 0\ \phi_h \in (-\pi/2, \pi/2)$	672	701
	$\cos\theta_\tau < 0\ \phi_h \in (\pi/2, 3\pi/2)$	640	714
	$\cos\theta_\tau > 0\ \phi_h \in (\pi/2, 3\pi/2)$	677	664
	$\cos\theta_\tau < 0\ \phi_h \in (-\pi/2, \pi/2)$	647	648
A^{π}_{sc}	$\cos\theta_\tau > 0\ \phi_h < \pi$	362	333
	$\cos\theta_\tau < 0\ \phi_h > \pi$	374	363
	$\cos\theta_\tau > 0\ \phi_h > \pi$	378	299
	$\cos\theta_\tau < 0\ \phi_h < \pi$	336	364
A^{π}_{cc}	$\cos\theta_\tau > 0\ \phi_h \in (-\pi/2, \pi/2)$	370	332
	$\cos\theta_\tau < 0\ \phi_h \in (\pi/2, 3\pi/2)$	350	370
	$\cos\theta_\tau > 0\ \phi_h \in (\pi/2, 3\pi/2)$	370	300
	$\cos\theta_\tau < 0\ \phi_h \in (-\pi/2, \pi/2)$	360	357

Background-Corrected Asymmetries

$\tau \to \rho\nu$:

$$A_{cc}^{\rho^-} = -0.001 \pm 0.021 \pm 0.035$$
$$A_{cc}^{\rho^+} = +0.032 \pm 0.020 \pm 0.035$$
$$A_{sc}^{\rho^-} = +0.035 \pm 0.021 \pm 0.035$$
$$A_{sc}^{\rho^+} = -0.023 \pm 0.020 \pm 0.035$$

$\tau \to \pi\nu$:

$$A_{cc}^{\pi^-} = -0.015 \pm 0.029 \pm 0.063$$
$$A_{cc}^{\pi^+} = +0.037 \pm 0.029 \pm 0.063$$
$$A_{sc}^{\pi^-} = +0.017 \pm 0.029 \pm 0.063$$
$$A_{sc}^{\pi^+} = +0.029 \pm 0.029 \pm 0.063$$

$\Longrightarrow$ **Dominated by systematic uncertainties**

PRELIMINARY L3 RESULTS:

$$d_\tau^w = (-2.2 \pm 3.9) \times 10^{-17}\, e \cdot cm$$
$$a_\tau^w = -0.0025 \pm 0.0070$$

Limits (95% C.L.):

$$-9.8 \times 10^{-17} e \cdot cm < d_\tau^w < 5.4 \times 10^{-17} e \cdot cm$$
$$-0.016 < a_\tau^w < 0.011$$

Remarks:

- **Limit on d_τ^w not (yet) competitive with CP-odd triple product method**
- **First direct limit on a_τ^w**
- **Conclusion:** $\boxed{\text{No evidence for new physics}}$