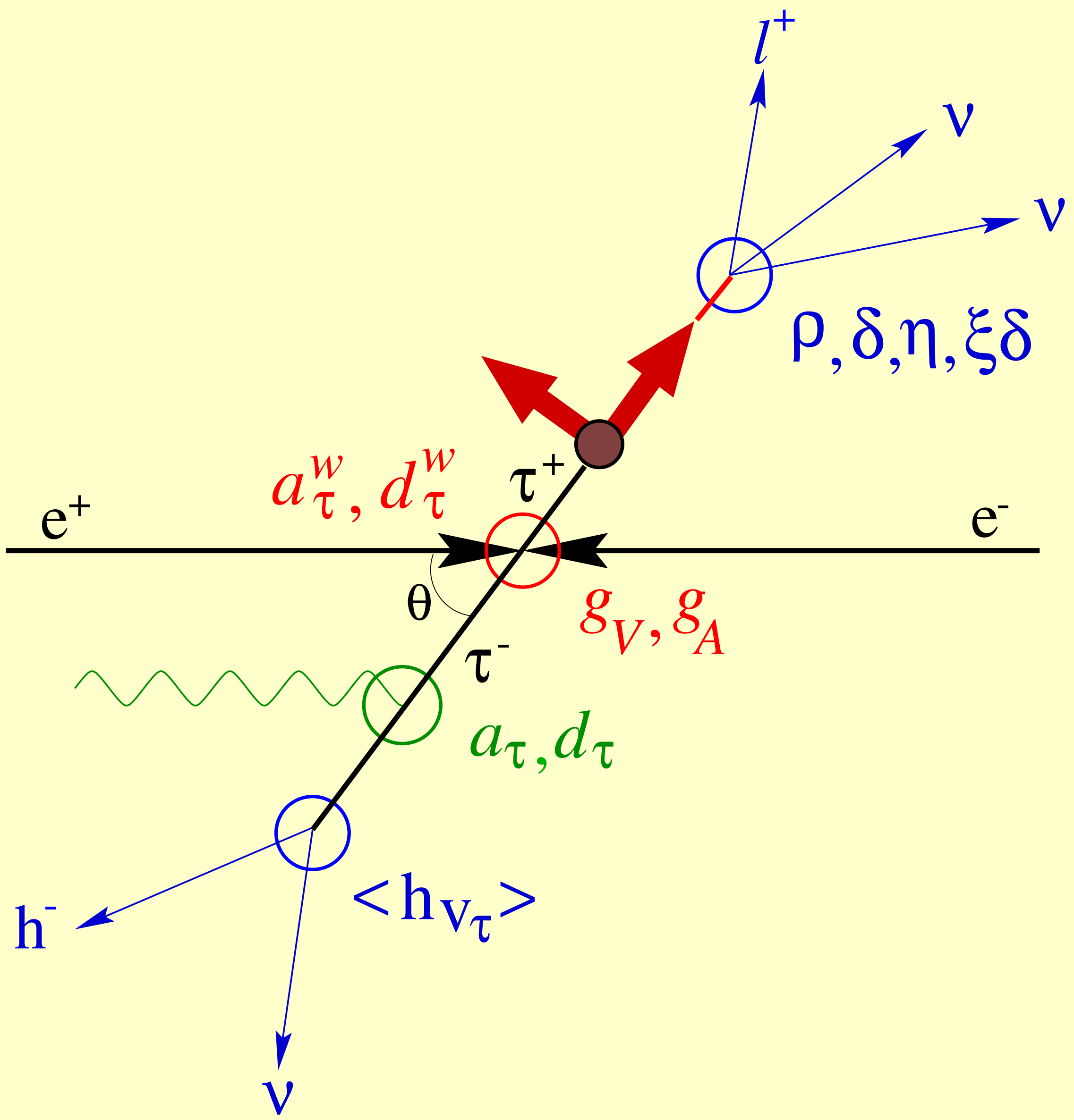
Measurements of electroweak couplings of the τ lepton at L3

Tom Paul
Northeastern University, Boston / L3

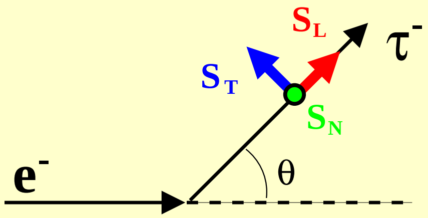
5-9 January
DPF99, Los Angeles

- L3 collected $\approx 150\ pb^{-1}$ near the Z between 1991-95.
- Several analyses of gauge boson couplings to τ finalized (or nearly so).
- Z: Γ_τ, A_{FB}, full spin analysis, weak dipole moments
- W: Michel parameters
- γ: anomalous electromagnetic moments

Introduction



Spin Analysis of $e^+e^- \to \tau^+\tau^-$



$$\Gamma_{\tau\tau} \propto \mid g_V^\tau \mid^2 + \mid g_A^\tau \mid^2$$

$$\mathcal{P}_\tau = -\mathcal{A}_\tau = \frac{2Re(g_V^\tau g_A^{\tau\,*})}{\mid g_V^\tau \mid^2 + \mid g_A^\tau \mid^2} \propto \frac{\sigma(s^L_{\tau^-}=+1)-\sigma(s^L_{\tau^-}=-1)}{\sigma(s^L_{\tau^-}=+1)+\sigma(s^L_{\tau^-}=-1)}$$

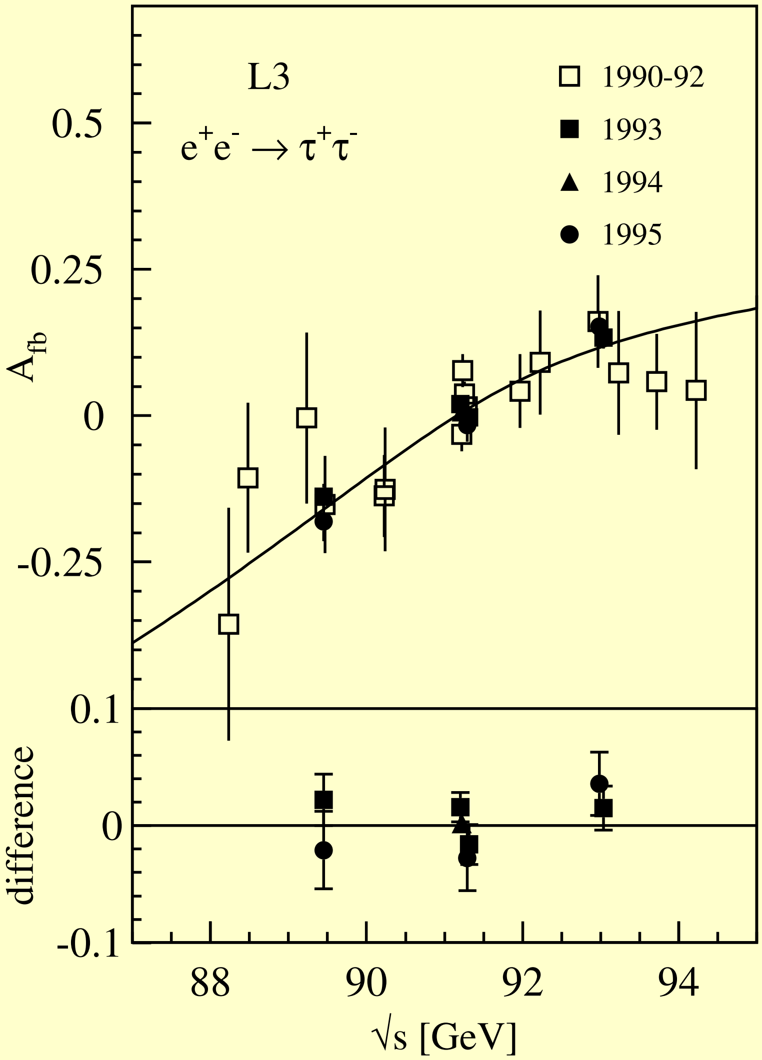
$$A_{FB} = (3/4)\mathcal{A}\tau\mathcal{A}_e = \frac{\sigma(\cos\theta>0)-\sigma(\cos\theta<0)}{\sigma(\cos\theta>0)+\sigma(\cos\theta<0)}$$

$$C_{TT} = \frac{\mid g_A^\tau \mid^2 - \mid g_V^\tau \mid^2}{\mid g_A^\tau \mid^2 + \mid g_V^\tau \mid^2} \propto \frac{\sigma(s^T_{\tau^-} s^T_{\tau^+}=+1)-\sigma(s^T_{\tau^-} s^T_{\tau^+}=-1)}{\sigma(s^T_{\tau^-} s^T_{\tau^+}=+1)+\sigma(s^T_{\tau^-} s^T_{\tau^+}=-1)}$$

$$C_{TN} = -\frac{2Im(g_V^\tau g_A^{\tau\,*})}{\mid g_A^\tau \mid^2 + \mid g_V^\tau \mid^2} \propto \frac{\sigma(s^T_{\tau^-} s^N_{\tau^+}=+1)-\sigma(s^T_{\tau^-} s^N_{\tau^+}=-1)}{\sigma(s^T_{\tau^-} s^N_{\tau^+}=+1)+\sigma(s^T_{\tau^-} s^N_{\tau^+}=-1)}$$

- $\mathcal{A}_\tau$ sensitive to relative sign of g_V^τ, g_A^τ.
- $\mathcal{A}_\tau$ symmetric under $g_V^\tau \leftrightarrow g_A^\tau$.
- C_{TT} breaks g_V^τ, g_A^τ symmetry (for purely weak processes).
- C_{TN} is sensitive to CP violating effects

Lineshape and A_{FB}



$$\Gamma_\tau = 84.23 \pm 0.62 \text{ MeV}$$
$$A_{FB} = 0.307 \pm 0.092$$

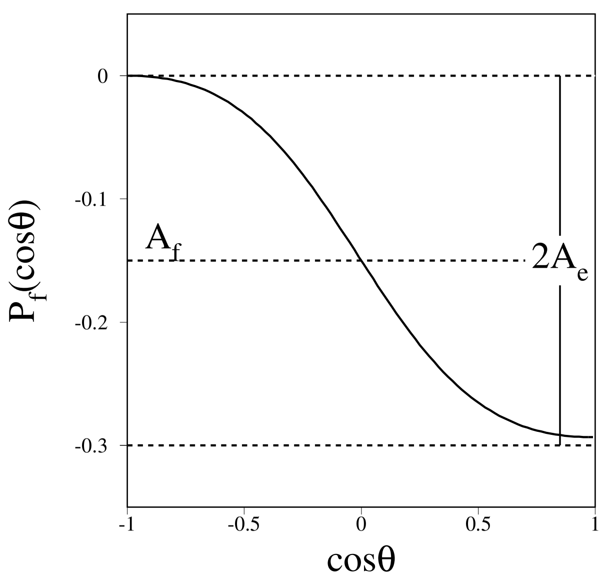
Results are preliminary

Tau Longitudinal Polarization

Parity Violation in $e^+e^- \to Z \to \tau^+\tau^- \Rightarrow \tau$'s polarized (and Z's)

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

$$\mathcal{A}_\ell = \frac{2g_V^\tau g_A^\tau}{|\, g_V^\tau \,|^2 + |\, g_A^\tau \,|^2}$$



- Sensitive to relative sign of g_V^τ and g_A^τ.
- Measure $\mathcal{A}_\tau$ and $\mathcal{A}_e$ simultaneously.
- Check universality.

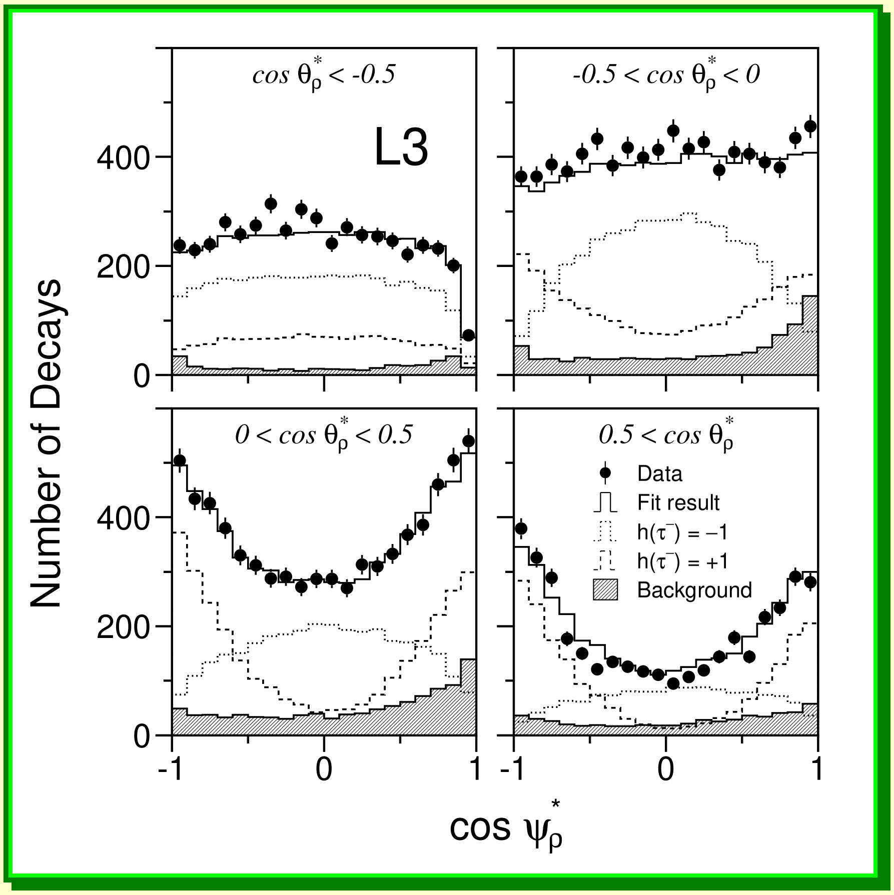
Tau Longitudinal Polarization

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

$$\boxed{\begin{array}{lll} \tau^- \longrightarrow & \rho^- & \nu_\tau \\ & \hookrightarrow & \pi^-\pi^0 \end{array}}$$

$$\cos\theta_\rho^* = \frac{4m_\tau^2}{m_\tau^2 - m_\rho^2}\,\frac{E_{\pi^-} + E_{\pi^0}}{\sqrt{s}} - \frac{m_\tau^2 + m_\rho^2}{m_\tau^2 - m_\rho^2}$$

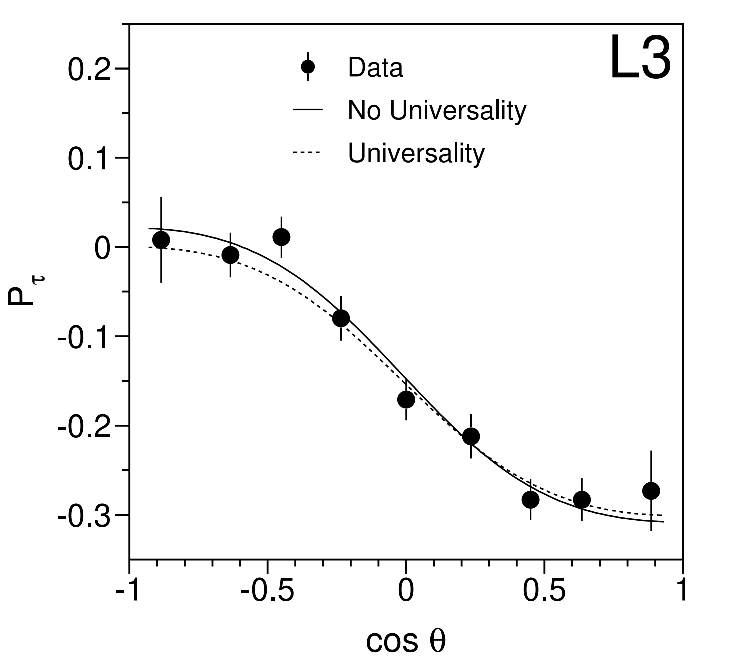
$$\cos\psi_\rho^* = \frac{m_\rho}{\sqrt{m_\rho^2 - 4m_\pi^2}}\,\frac{E_\pi^- - E_p i^0}{\vec{p}_{\pi^-} + \vec{p}_{\pi^0}}$$



Tau Longitudinal Polarization

Several complimentary analyses are employed:

- Exclusive: $\tau \longrightarrow h\nu_\tau$ with $h = \pi, \rho, a_1$
  $\tau \longrightarrow \ell\nu_\tau\nu_\ell$
- Inclusive hadronic: uses generalized θ^*, ψ^*
- Acollinearity



$$g_V^\tau / g_A^\tau = 0.0742 \pm 0.0055$$
$$g_V^e / g_A^e = 0.0845 \pm 0.0067$$

Assuming universality:

$$g_V^\ell / g_A^\ell = 0.0775 \pm 0.0044$$
$$\sin^2 \overline{\theta}_W = 0.2306 \pm 0.0011$$

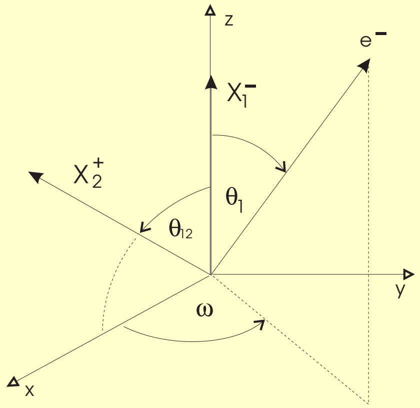
Combining with lineshape results :

$$g_V^\tau = -0.0394 \pm 0.0032$$
$$g_A^\tau = -0.5015 \pm 0.0019$$

Results are preliminary

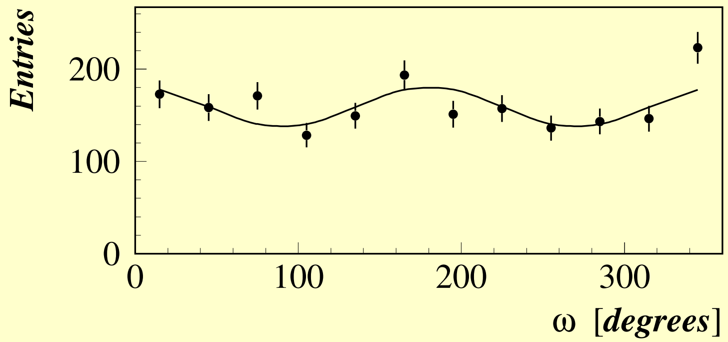
Transverse and Normal spin correlations

$$e^+e^- \rightarrow \tau^+\tau^- \rightarrow X_1^- X_2^+ + n\nu.$$

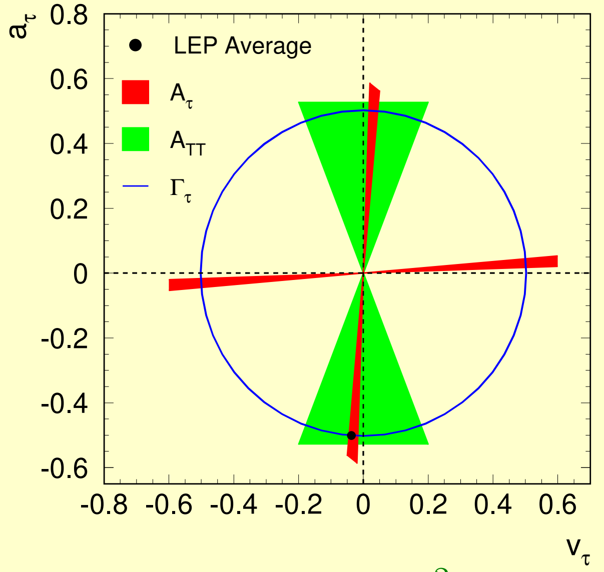


$$\frac{d\sigma}{d\omega} = C_{TT}\cos 2\omega + C_{TN}\sin 2\omega$$

$$\tau^+\tau^- \rightarrow h^+h^-$$



$$C_{TT} = 0.99 \pm 0.24 \pm 0.08$$
$$C_{TN} = 0.15 \pm 0.24 \pm 0.07$$
SM: $C_{TT} = 0.99$, $C_{TN} = -0.01$



- Not a sensitive probe of $\sin^2\theta_W$.
- C_{TT} is an on-peak quantity that breaks $g_V^\tau \leftrightarrow g_A^\tau$.
- C_{TN} sensitive to CP violation from source other than dipole moment.

results are preliminary

Weak Dipole Moments

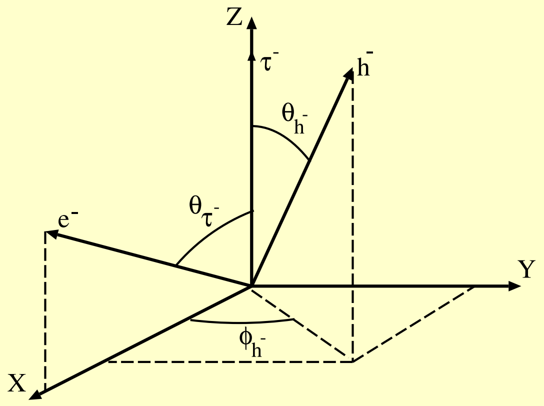
Introduce new $Z\tau\tau$ interactions:

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

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

SM Values (from loops):
$a_\tau^w = -(2.10 + 0.61i) \times 10^{-6}, d_\tau^w \sim 3 \times 10^{-37} e\mathrm{cm}$
Beyond experimental sensitivity, but large value $\Rightarrow$ new physics.

For $e^+e^- \to \tau + \tau - \to h^+\overline{\nu}_\tau h^- \nu_\tau$

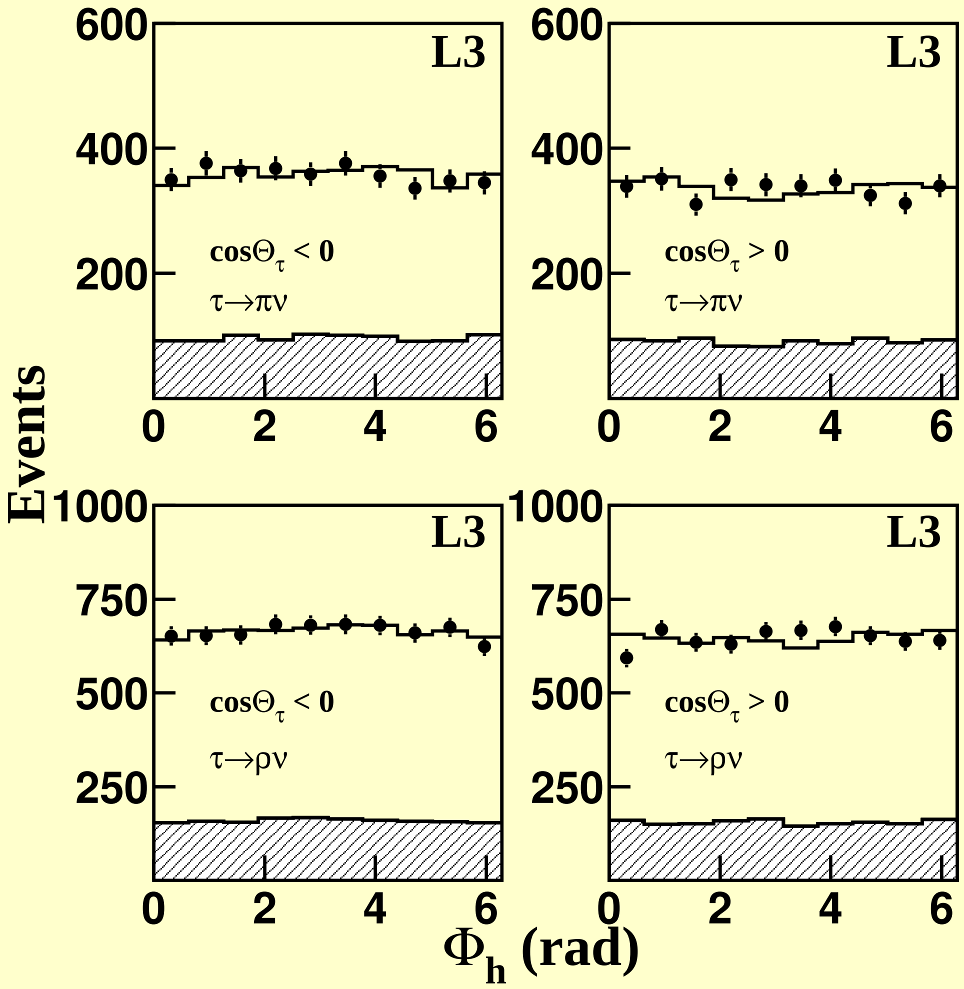


$$\frac{d\sigma}{d(\cos\theta_{\tau^\pm})d\phi_{h^\pm}} = \mathrm{SM} \quad \mathrm{part} + \alpha_{h^\pm}(X_\pm \cos\phi_{h^\pm} + Y_\pm \sin\phi_{h^\pm})$$

$$X_\pm = X_\pm(\theta_{\tau^\pm}, F_2^w)$$
$$Y_\pm = Y_\pm(\theta_{\tau^\pm}, F_3^w)$$

- $\phi_{h^\pm}$ asymmetry between $[0,\pi],[\pi,2\pi] \Rightarrow d_\tau \neq 0$.
- $\phi_{h^\pm}$ asymmetry between $[-\pi/2,\pi/2],[\pi/2,3\pi/2] \Rightarrow a_\tau \neq 0$.
- Construct asymmetries using $\phi_h^\pm, \theta_{\tau^\pm}$.
- Requires τ flight direction to obtain τ rest frame.

Weak Dipole Moments



$$Re(a_\tau^w) = (0.0 \pm 1.6 \pm 2.3) \times 10^{-3}$$
$$Im(a_\tau^w) = (-1.0 \pm 2.6 \pm 5.3) \times 10^{-3}$$
$$Re(d_\tau^w) = (-0.44 \pm 0.88 \pm 1.33) \times 10^{-17} e \cdot \mathrm{cm}$$

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 $\mathcal{P}_\tau$:

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

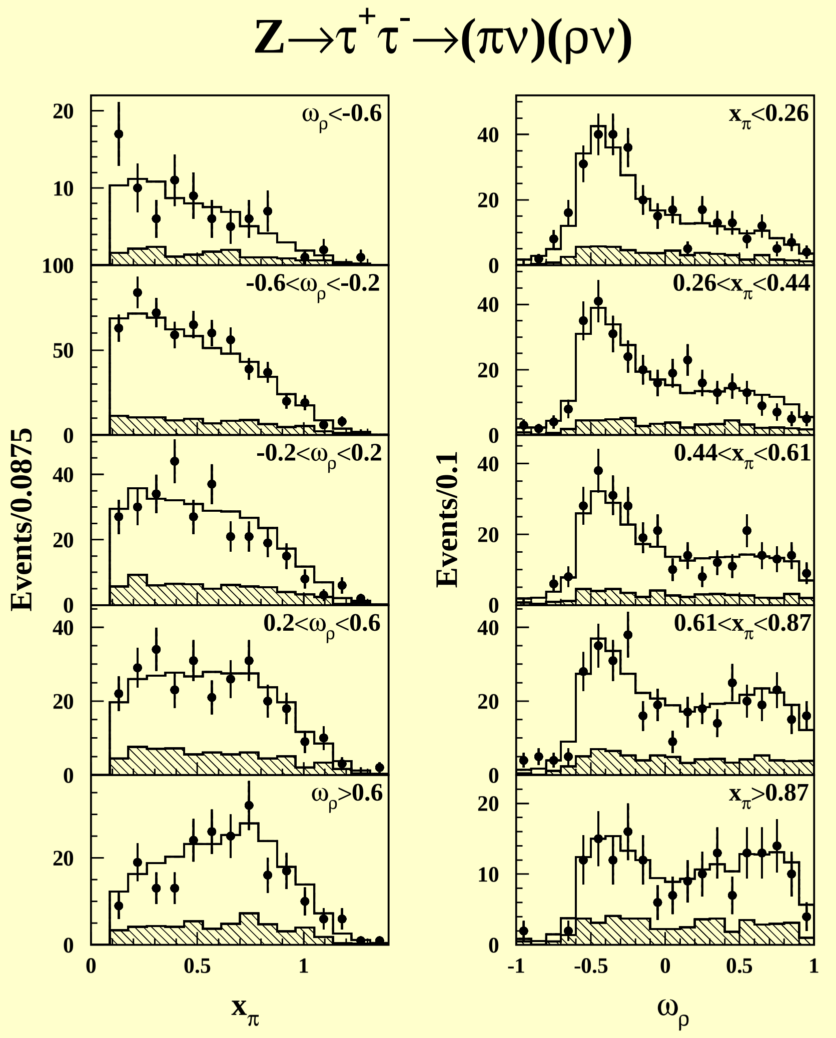
- Similarly for semileptonic decays:

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

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

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

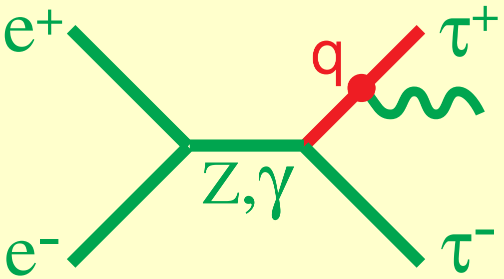
Lorentz structure of charged current



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

Parameter				SM expectation
ρ	0.762	$\pm$	0.035	0.75
η	0.27	$\pm$	0.14	0
ξ	0.70	$\pm$	0.16	1
$\xi\delta$	0.70	$\pm$	0.11	0.75
ξ_h	-1.032	$\pm$	0.031	-1
$\mathcal{P}_\tau$	-0.164	$\pm$	0.016	

Anomalous Electromagnetic Moments

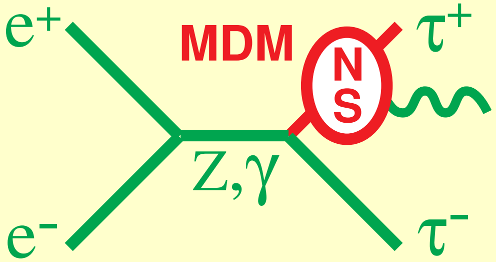


$F_1(q^2)\gamma^\mu$

$\Downarrow$

Electric charge, q_τ

$q_\tau \equiv F_1(q^2\!=\!0)$



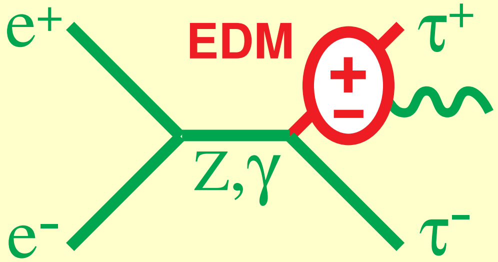
$F_2(q^2)\frac{i}{2m_f}\sigma^{\mu\nu}q_\nu$

$\Downarrow$

Anomalous Magnetic Moment, a_τ

$$a_\tau \equiv F_2(q^2\!=\!0) = (g-2)/2$$

$$a_\tau(\mathrm{SM}) = \alpha/2\pi + \ldots \approx 0.0011$$



$F_3(q^2)\sigma^{\mu\nu}\gamma^5 q_\nu$

$\Downarrow$

Electric Dipole Moment, d_τ

$d_\tau \equiv eF_3(q^2\!=\!0)$

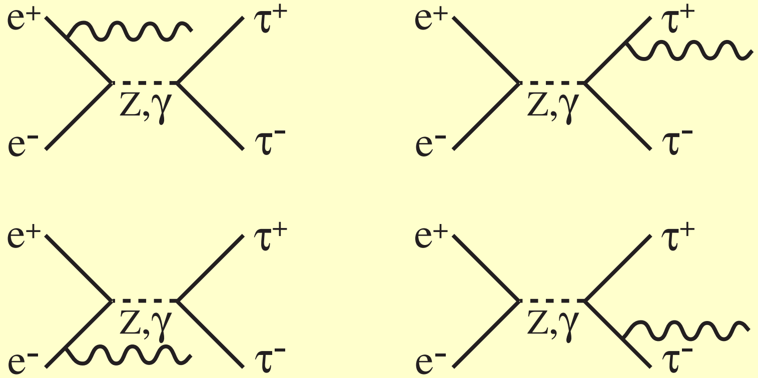
$d_\tau(\mathrm{SM}) = 0$

(non-zero $\Rightarrow \not{T}$ & $\not{P}$)

Anomalous Electromagnetic Moments

Effects of F_2 and F_3 on photon radiation:

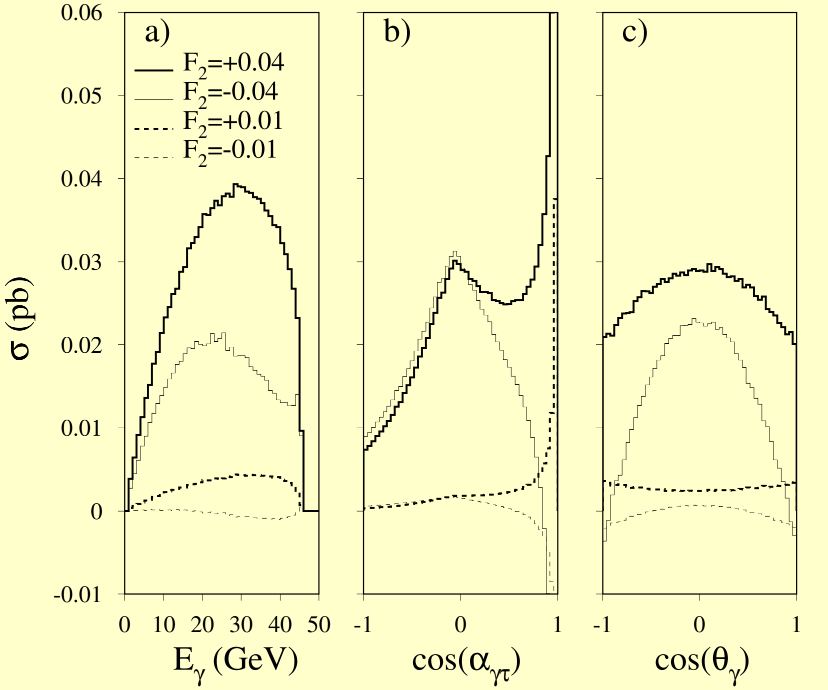
$$\gamma^\mu \rightarrow \gamma^\mu + \frac{iF_2}{2m_\tau}\sigma^{\mu\nu}q_\nu - F_3\sigma^{\mu\nu}\gamma^5 q_\nu$$



Add tree-level amplitudes for all diagrams:

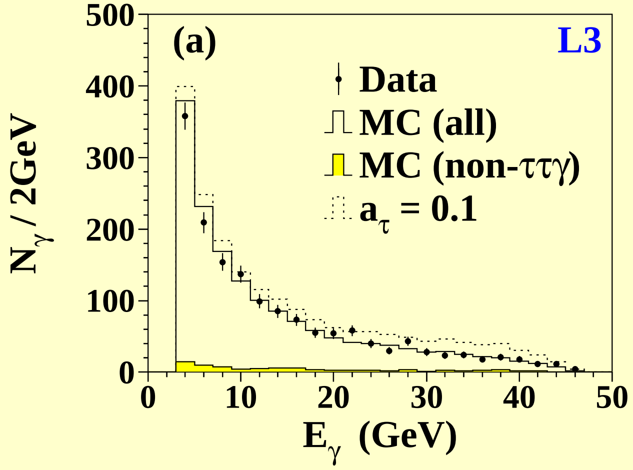
- Z and γ exchange
- ISR
- FSR
- contributions from F_2 and F_3
- All interferences between these

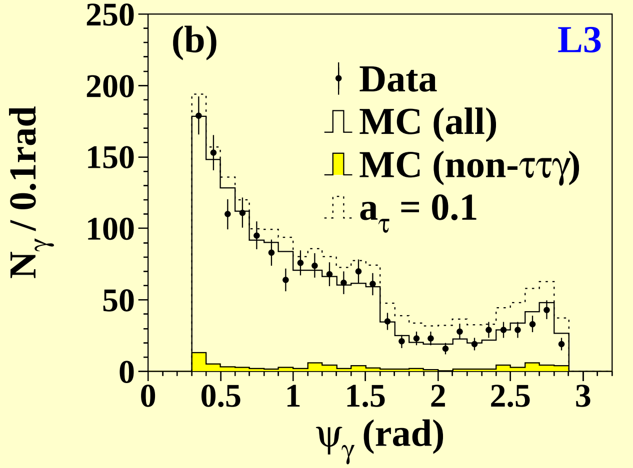
- Increased rate of $\tau\tau\gamma$ events.
- Changes the shapes of energy and angular distributions.

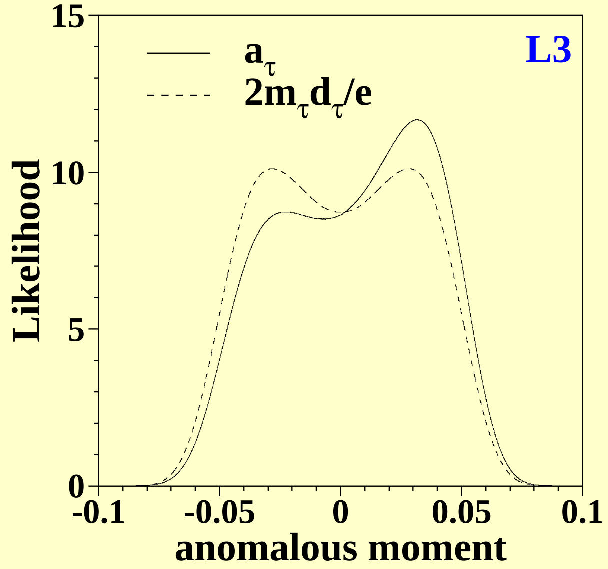


Anomalous Electromagnetic Moments

- 2-D fit to E_γ and Ψ_γ
- Normalization fixed to $\int \mathcal{L}$







95% C.L. limits:

$$-0.052 < F_2(q^2=0) < 0.058$$

$$(-3.1 < F_3(q^2=0) < 3.1) \cdot 10^{-16}\mathrm{e{\cdot}cm}$$

Summary

- Precision measurements of g_V^τ, g_A^τ $(\Gamma_\tau, A_{FB}, \mathcal{P}_\tau(\cos\theta))$.
- Consistency with lepton universality.
- Analysis of spin-spin correlations has been performed (no evidence for CP violation in C_{TN}.
- Measurements of weak dipole moments (including first of a_τ^w) (no evidence for CP violation in d_τ^w.
- Measurement of Lorentz structure of τ dacays consistent with $V - A$.
- Most precise measurements of AMDM, EDM form factors at $q^2 = 0$ (no evidence for CP violation in d_τ.

extra stuff

Correlation matrix for Michel parameters :

	η	ξ	$\xi\delta$	ξ_h	$\mathcal{P}_\tau$
ρ	0.455	−0.165	−0.279	−0.324	0.421
η		0.119	0.076	−0.010	0.020
ξ			0.033	0.106	0.144
$\xi\delta$				0.365	−0.262
ξ_h					−0.447