TAU PHYSICS FROM LEP

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The L3 Experiment

CONTENTS

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I. INTRODUCTION

TAU PARTICLE

- The third lepton found in 1975 by Perl et al.
  So far no heavier lepton.
  $\Rightarrow$ seems equal to e, μ.
- (But) Heavy mass $\sim 1777.00^{+0.30}_{-0.27}$ MeV.
- Decays in leptons and hadrons.
  Leptonic: $e\nu\nu$, $\mu\nu\nu$.
  Hadronic: $\pi^-\nu$, $K^-\nu$, $\pi^-\pi^0\nu$, $\pi^-X\nu$, $K^-X\nu$, ...
  $\Rightarrow$ In reality, complex.
- Short lifetime $\sim 10^{-13}$ s.
  $\Rightarrow$ Not easy to see itself.
  $\Rightarrow$ One should be content with its decays instead.
- Kinematics of τ decay particles contain τ spin information.

OPEN TOPICS

- A real sequential lepton? Lepton universality, pointlike,...
- Is ν_τ massless?
- More decay channels More physics possibilities.
  $\Rightarrow$ Electroweak, QCD, CP violation,...

II. LIFETIME AND LEPTONIC BR

- SM (Standard Model) leptonic decay rates of heavier leptons,

$$\Gamma(L^- \to l^- \bar{\nu}_l \nu_L) = \frac{G_L G_l m_L^5}{192\pi^3}(1+\delta_{ph})(1+\delta_W)(1+\delta_{rad})$$

δ_{ph}: Phase space factor, function of $(m_l/m_L)^2$

δ_W: W propagator effect, negligible

δ_{rad}: Radiative correction. Uncertainty negligible.

G_l: Fermi constant $\sim g_l^2/\sqrt{32}M_W^2$ ($l = e, \mu, \tau$)

- Experimentally,

$$\Gamma(L^- \to l^- \bar{\nu}_l \nu_L) = \frac{BR(L^- \to l^- \bar{\nu}_l \nu_L)}{\tau_L}$$

$\Rightarrow$ Lepton Universality checks between
$\Gamma(\mu^- \to e^- \bar{\nu}_e \nu_\mu)$, $\Gamma(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau)$, $\Gamma(\tau^- \to e^- \bar{\nu}_e \nu_\tau)$.

$\Rightarrow$ Excellent τ mass by BES (Threshold energy scan).
$\Delta m/m \sim$ 0.017 %, helps precision test.

LIFETIME

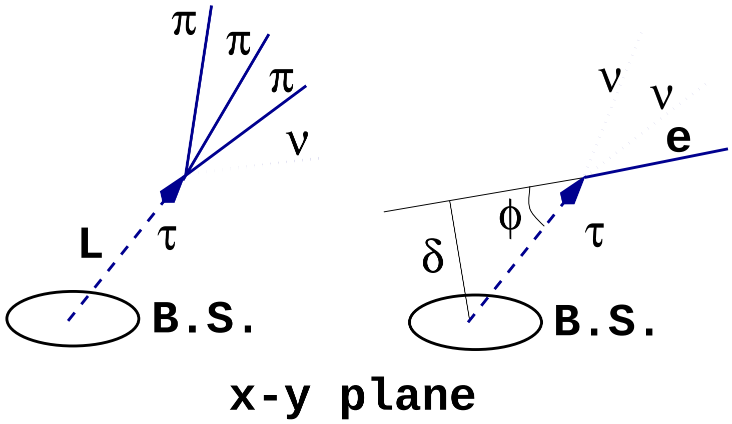
- Boost of τ produced at Z peak, L(Decay Length) $\sim 2.2mm$.
- High precision silicon vertex detectors,
  $\sigma_\delta \sim 25\mu m$ on impact parameters.
- Small beam spot size, $\sigma_y \sim 10(0.8)\mu m$,
  $\sigma_x \sim 150(2.6)\mu m$ for LEP(SLC)s.

$\Rightarrow$ Reconstruction of τ decay points with small errors,
in $x-y$ plane (perpendicular to the beam axis).

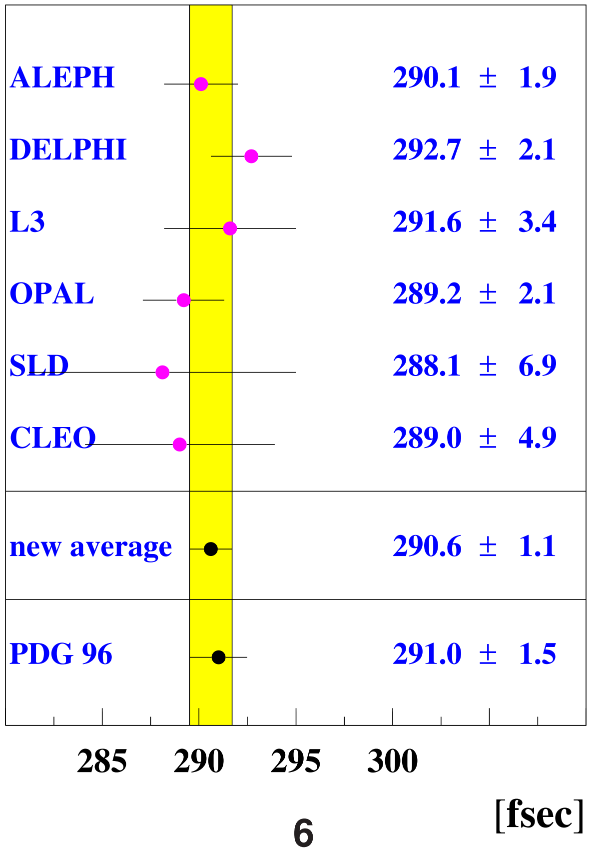
II. LIFETIME AND LEPTONIC BR

LIFETIME CONTINUES

- 3-prong τ decay $\rightarrow$ Decay length (L $\equiv \gamma\beta\tau_\tau \sin\theta$).
  1-prong τ decay $\rightarrow$ Impact parameter ($\delta \equiv \gamma\beta\tau_\tau \sin\theta \sin\phi$).



- Also combination of impact parameters from $\tau^+\tau^-$.
- Results from LEP and SLC (Preliminary included.)



II. LIFETIME AND LEPTONIC BR

LEPTONIC BRANCH RATIO

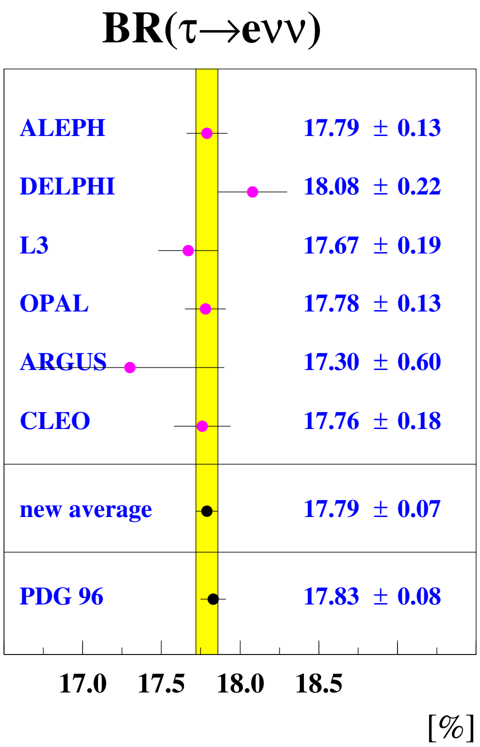
- **Lepton Identification.**

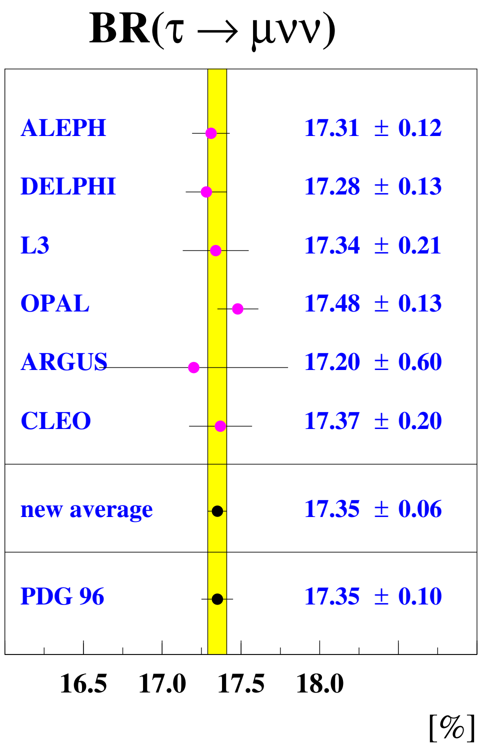
  $\sim$ **Improvements due to good detectors.**

  e $\leftarrow$ **Single track $\oplus$ high dE/dx, sharp matching shower pattern in electromagnetic calorimeters, ...**

  μ $\leftarrow$ **Minimum ionizing in hadronic calorimeters or track in outmost muon detectors.**

- **New Results (Including preliminary)**





$$\frac{\Gamma(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau)}{\Gamma(\tau^- \to e^- \bar{\nu}_e \nu_\tau)} \to \frac{g_\mu}{g_e} = 1.001 \pm 0.003 \to \mu - e \textit{ universality}$$

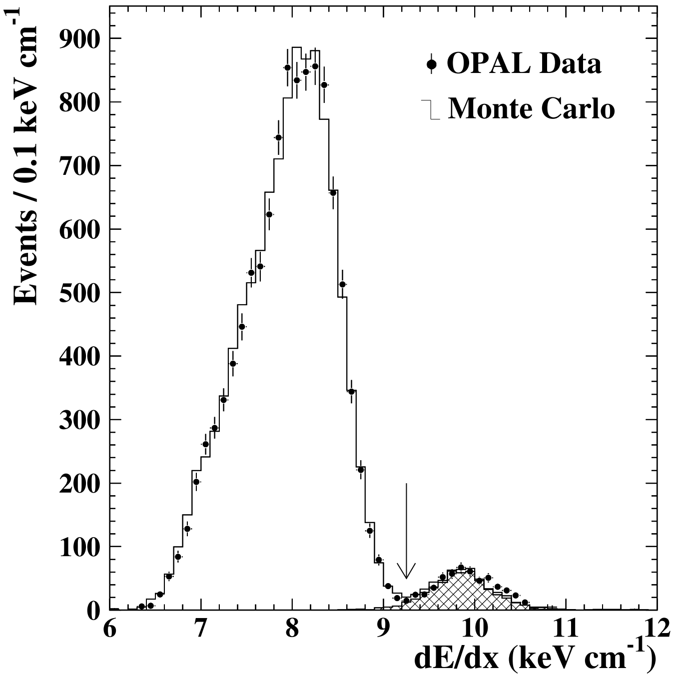
$$\frac{\Gamma(\tau^- \to e^- \bar{\nu}_e \nu_\tau)}{\Gamma(\mu^- \to e^- \bar{\nu}_e \nu_\mu)} \to \frac{g_\tau}{g_\mu} = 1.000 \pm 0.003 \to \tau - \mu \textit{ universality}$$

III. HADRONIC DECAYS

- High τ mass $\rightarrow$ Hadronic Decays,
  usually proceed via intermediate resonance. ρ, K^*, a_1, ...
- Decay widths predicted by chiral Lagrangian reasonable.
- Particle identification:

  $\pi^{\pm}$,$K^{\pm}$ $\leftarrow$ Single track $\oplus$ dE/dx, showers in hadron calorimeter, ...

  π^0 $\leftarrow$ Sharp narrow photon showers in EM calorimeters. ($\pi^0 \rightarrow 2\gamma$)



(Shade Area: Electon Background in Charged Hadron Sample)

♣ Major hadronic decay channels.

$n\pi$	Modes	BR(PDG96)	Note
1	$\pi^-\nu_\tau$	11.31 ± 0.15	
2	$\pi^-\pi^0\nu_\tau$	$\boxed{25.24}$ ± 0.16	~ 100 % ρ
3	$2\pi^-\pi^+\nu_\tau$,$\pi^-2\pi^0\nu_\tau$	~ 9 each	Most a_1

III. HADRONIC DECAYS

MASS PARAMETERS OF a_1

- G-parity argues dominent Axial-Vector contribution ($\sim a_1$) in $\tau \to 3\pi\nu_\tau$ decay.
  ($\Gamma(non\ A - V)/\Gamma(tot) < 26.1\%$ OPAL, 95% CL).
- Fitting M and Γ model dependent(KS, IMR, Feindt). But theoretical prediction for structure functions cannot explain data fully.
  $\Rightarrow$ Non resonance contribution in $\tau \to 3\pi\nu_\tau$ decay ? Excited states of a_1?
- Candidate: $a_1'(1700) \to f_1\pi,\ f_1 \to 2\pi$ (Delphi).
- Results.

Exp.	M(KS) (MeV)	Γ(KS)	M(IMR)	Γ(IMR)
DELPHI	1255 ± 9	587 ± 34	1207 ± 9	478 ± 15
OPAL	1262 ± 11	621 ± 66	1210 ± 7	457 ± 23

KS = Kühn and Santamaria
(point-like strong form factors, $a_1 \to \rho\pi, \rho'\pi$ in S-wave, $\rho \to 2\pi$).
IMR = Isgur, Morningstar and Reader
(flux-tube breaking model, $a1 \to \rho\pi, K^*K$ in S/D-wave,
also polynomial for background.)

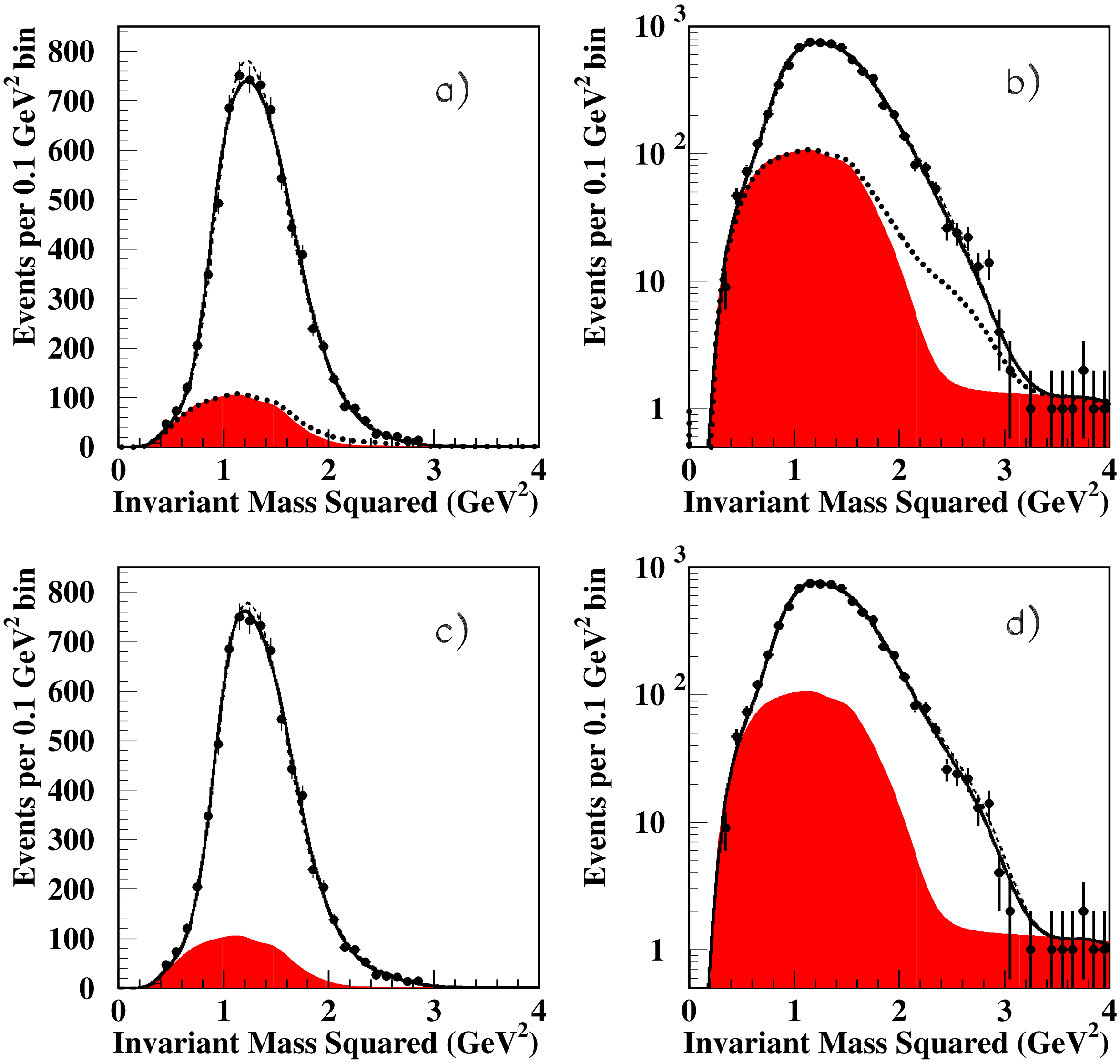
- Old Results.

Exp.	M (MeV)	Γ
PDG96	1230 ± 40	~ 400
♠ ARGUS	1211 ± 7	446 ± 21

♠ Argus uses IMR model.

III. HADRONIC DECAYS

PLOTS FROM DELPHI $(\tau \to 3\pi\nu_\tau)$



a) Invariant Mass of 3π system. The dashed curve is KS model. The solid one is IMR model. The dotted one is the background contribution to IMR model.

b) a) on a log scale.

c) a) with a_1' candidate included in the mass fit by Feindt approach.

d) c) on a log scale.

III. HADRONIC DECAYS

DECAYS WITH KAONS

- **Suppressed by KM (Kobayashi-Maskawa) matrix, but great progress recently to identify all the channels down to Branch Ratio $\boxed{10^{-3}}$. Most of them found.**
- **Particle Identification**

  $K^{\pm} \leftarrow K^{\pm}/\pi^{\pm}$ **separation crucial.** dE/dx, **TOF(Time of Flight), RICH(Ring Image Cherenkov Counter)**

  $K^{0} \leftarrow$ **Shower shape in hadronic calorimeters (long lived), Secondary vertex reconstruction (short lived).**

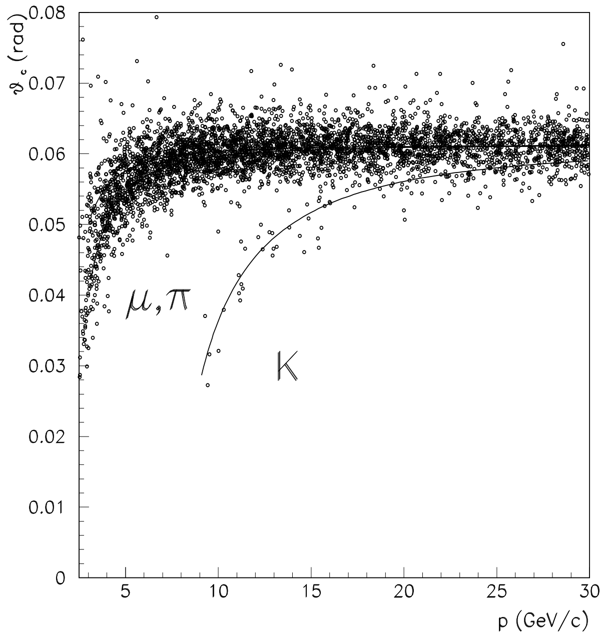
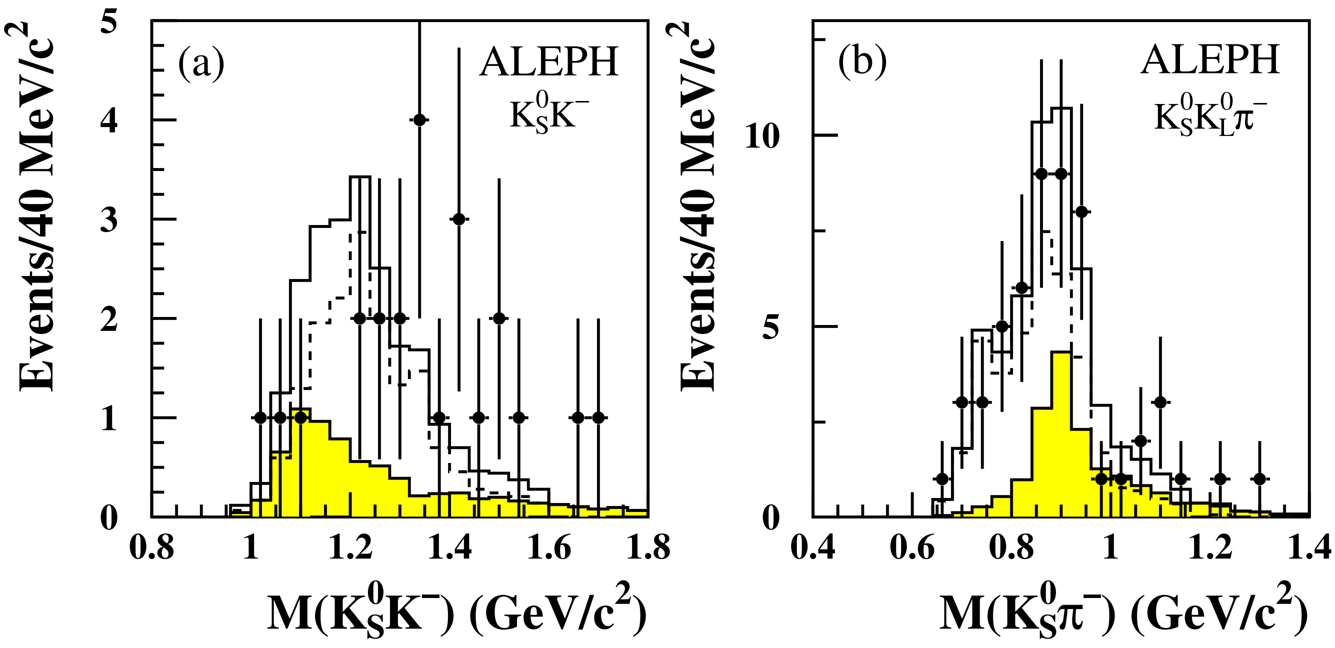


Figure 2: Measured Cherenkov angle versus momentum for single prong τ decays. The expected angle for K, π and μ are also shown.

Delphi: Angle vs Momentum in RICH

III. HADRONIC DECAYS

DECAYS WITH KAONS CONTINUES



(Dashed: Signal, Shade: Background)

- **Published Results since 1997**

Exp.	Channel	Branch Ratio (Unit $\boxed{10^{-3}}$)
Aleph	$\bar{K}^0\pi^-\nu_\tau$	$8.55 \pm 1.17 \pm 0.66$
	$\bar{K}^0\pi^-\pi^0\nu_\tau$	$2.94 \pm 0.73 \pm 0.37$
	$\bar{K}^0 K^-\nu_\tau$	$1.58 \pm 0.42 \pm 0.17$
	$\bar{K}^0 K^-\pi^0\nu_\tau$	$1.52 \pm 0.76 \pm 0.21$
$* \rightarrow$	$K^0_S K^0_L \pi^-\nu_\tau$	$1.01 \pm 0.23 \pm 0.13$
Aleph	$K^-K^+\pi^-\nu_\tau$	$1.63 \pm 0.21 \pm 0.17$
	$K^-\pi^+\pi^-\nu_\tau$	$2.14 \pm 0.37 \pm 0.29$
$* \rightarrow$	$K^-K^+\pi^-\pi^0\nu_\tau$	$0.75 \pm 0.29 \pm 0.15$
$* \rightarrow$	$K^-\pi^+\pi^-\pi^0\nu_\tau$	$0.61 \pm 0.39 \pm 0.18$
	$K^-K^+K^-\nu_\tau$	< 0.19 (95 %)

$\leftarrow *$ **First Measurement in the World.**

III. HADRONIC DECAYS

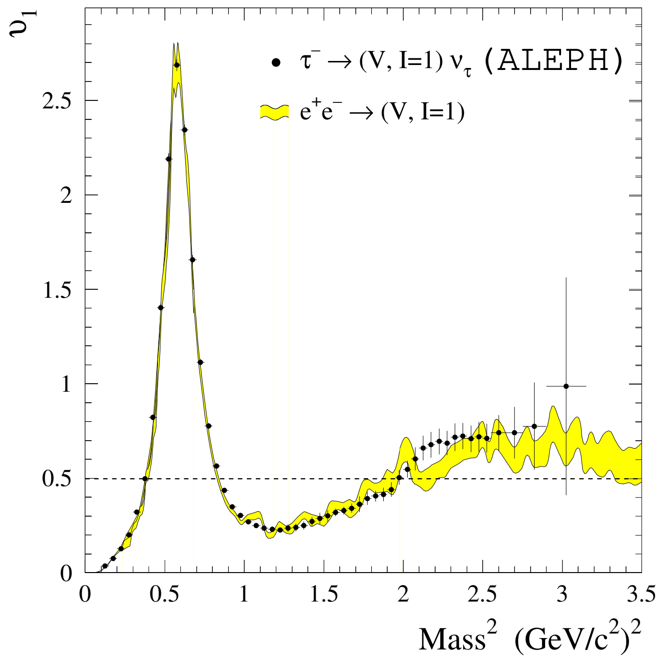
SPECTRAL FUNCTIONS AND QCD

- Most of τ decay channels are found $\rightarrow$ Full analysis possible with total hadronic τ decay width.
- Spectral functions $\sim$ distribution of $\Gamma(\tau^- \rightarrow h^- \nu_\tau)$ over the invariant mass of daughter hadron system. (Aleph, Cleo)

$$\Gamma(\tau^- \rightarrow h^- \nu_\tau) = \frac{G_F^2}{32\pi^2 m_\tau^3} \int_0^{m_\tau^2} dq^2 (m_\tau^2 - q^2)(m_\tau^2 - 2q^2) \{[v_1(q^2) + a_1(q^2)] \cos^2\theta_c + strange\ part\}$$

(v_1 = Vector part, ρ,4π,... a_1 = Axial-Vector part, a_1, 5π, ...)

- $v_1(q^2) \rightarrow$ Test of CVC, compare to $\Gamma(e^+e^- \rightarrow h)$.
  $2\pi, 4\pi, \ldots$



Dot: Data
Shade: CVC prediction
Dashed: Naive Parton

III. HADRONIC DECAYS

SPECTRAL FUNCTIONS AND QCD CONTINUES

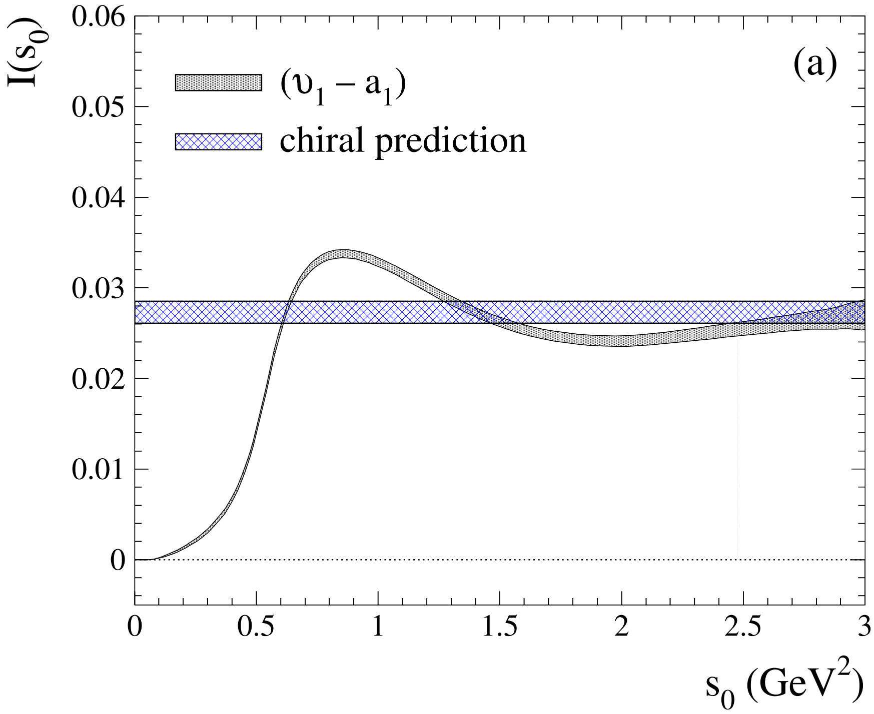
- v_1+a_1 $\rightarrow \alpha_s(m_\tau^2) = 0.334 \pm 0.022$ from Aleph.
  0.306 ± 0.024 from Cleo.

  By extrapolation, $\alpha_s(M_Z^2)$ = 0.1202 ± 0.0027 from Aleph.
  0.114 ± 0.003 from Cleo.
  (~ 0.118, WA.)

- v_1-a_1 $\rightarrow$ Test of chiral sum rule up to m_τ^2. For example,

$$\frac{1}{4\pi^2}\int_0^{s_0\to\infty} ds \frac{1}{s}[v_1(s) - a_1(s)] = f_\pi^2 \frac{< r_\pi^2 >}{3} - F_A$$

(Das-Mathur-Okubo sum rule)



IV. LORENTZ STRUCTURE OF τ DECAY

MICHEL PARAMETERS

- In leptonic τ decays, the most general local four fermion interaction (with lepton number conservation) is,

$$\mathcal{M} = \frac{4G_F}{\sqrt{2}} \sum_{\gamma=S,V,T} \sum_{\alpha,\beta=R,L} g^{\gamma}_{\alpha,\beta} (\overline{u}^{\alpha}_{l} \Gamma_{\gamma} v_{\nu_l})(\overline{v}^{v}_{\nu_\tau} \Gamma_{\gamma} u^{\beta}_{\tau})$$

(S, V, T = Scalar, Vector, Tensor. R, L = Handedness)
(SM: $g^V_{LL} = 1$, others 0)

10 independent complex $g^{\gamma}_{\alpha,\beta}$ or
their binomial combination, Michel parameters.

- For example, energy spectrum of the leptons from τ decays,

$$\frac{1}{\Gamma}\frac{d\Gamma}{dx} = h_0(x) + \eta h_\eta(x) + \rho h_\rho(x) - \bar{\mathcal{P}}_\tau(\xi h_\xi(x) + \xi\delta h_{\xi\delta}(x))$$

(η, ρ, ξ, $\xi\delta$: Michel Parameters, $\bar{\mathcal{P}}_\tau$: Average τ polarization)
($x = E_l/E_\tau$, h = polynomial)

- Likewise in hadronic τ decays,

$$\frac{1}{\Gamma}\frac{d\Gamma}{dx} = g_0(x) + \bar{\mathcal{P}}_\tau \xi_h g_\xi(x) a \quad (\xi_h = \nu_\tau \textit{ chirality})$$

- Double decay spectrum can separate ξ, ξ_h from $\bar{\mathcal{P}}_\tau$. $e^+e^- \to \tau^+\tau^-$
$\to x_+ x_-$

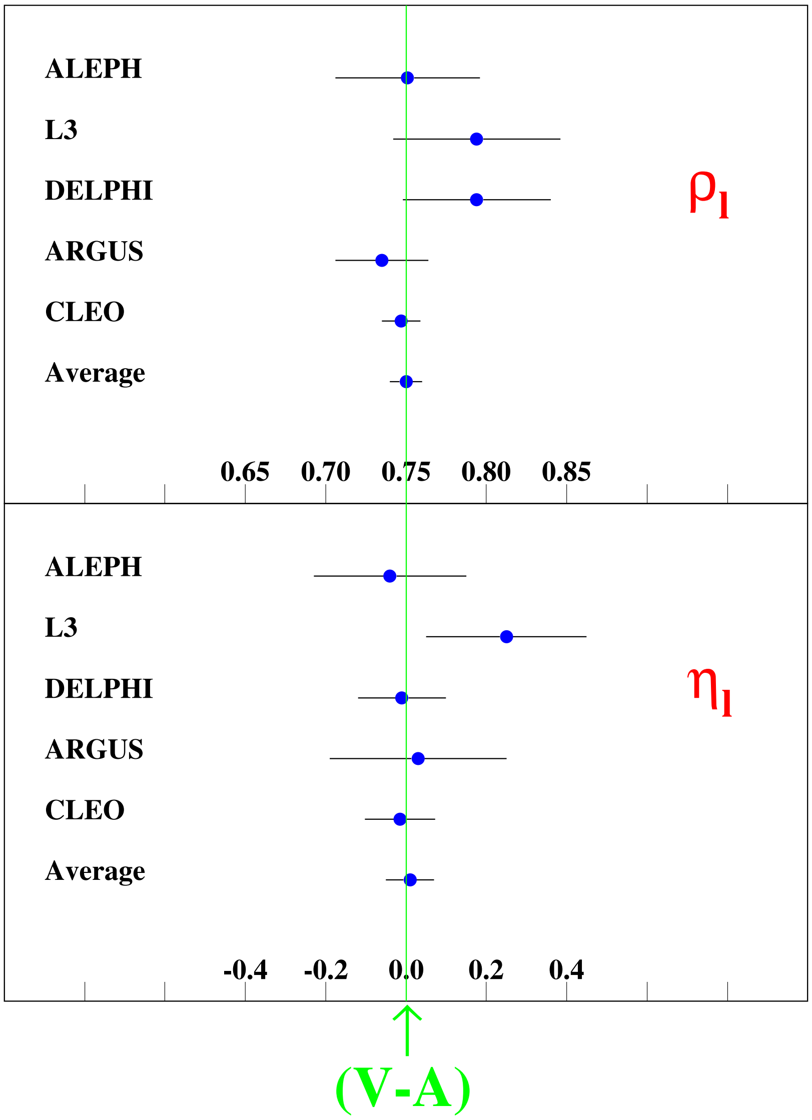
$$\begin{aligned}\frac{1}{\Gamma}\frac{d\Gamma}{dx_+ dx_-} &= F[(\eta,\rho,\xi,\xi\delta,\xi_h) \otimes h(x) \otimes g(x)] \\ &+ \bar{\mathcal{P}}_\tau F'[(\eta,\rho,\xi,\xi\delta,\xi_h) \otimes h'(x) \otimes g'(x)]\end{aligned}$$

- lepton-hadron decay: η, ρ, $\xi\xi_h$, $\xi\delta\xi_h$
  hadron-hadron decay: ξ_h^2
  Use independent methods to measure ξ_h and its sign. (Argus, SLD, OPAL)

IV. LORENTZ STRUCTURE OF τ DECAY

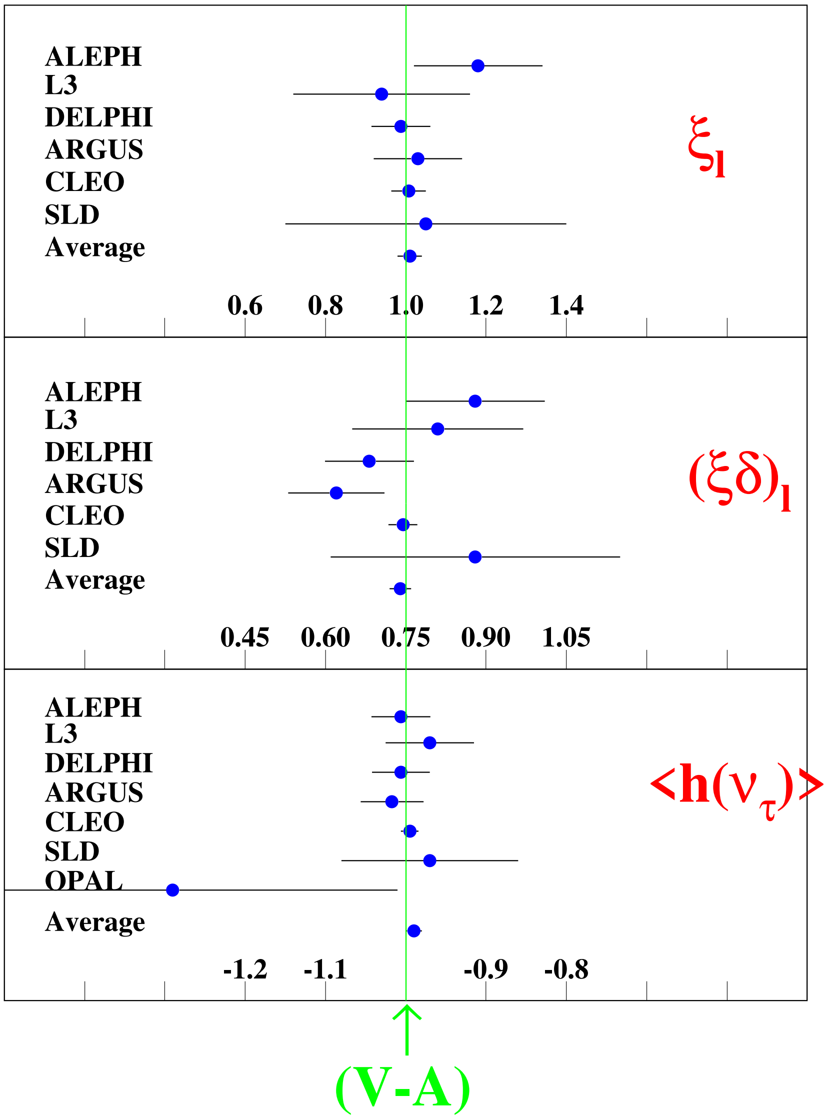
MICHEL PARAMETERS CONTINUES

- Results (Preliminary included)



IV. LORENTZ STRUCTURE OF τ DECAY

MICHEL PARAMETERS CONTINUES



- Delphi gave a preliminary limit on the tensor coupling.

$$-0.15 < \kappa_\tau^W < 0.1$$

- Conclusion No Violation of V-A Structure.

Way to Go to Reach Precision of Muon Michel Measure.

V. NEUTRAL CURRENTS AND τ PRODUCTION

- Standard Model says only neutral weak current (and photon exchange) is involved in $e^+e^- \to \tau^+\tau^-$ production,

$\sim 10^6 \tau^+\tau^-$

$\Rightarrow$ precision test on $g_A, g_V, \sin^2\theta_W^{eff}$ ($\to$ M_H by loop correction).

$\Rightarrow$ Use σ^0, A_{FB}, A_{pol}^{FB}, (longitudinal) $\mathcal{P}_\tau$.

(LONGITUDINAL) τ POLARIZATION, $\mathcal{P}_\tau$

- In the improved Born approximation, the polarization asymmetry is,

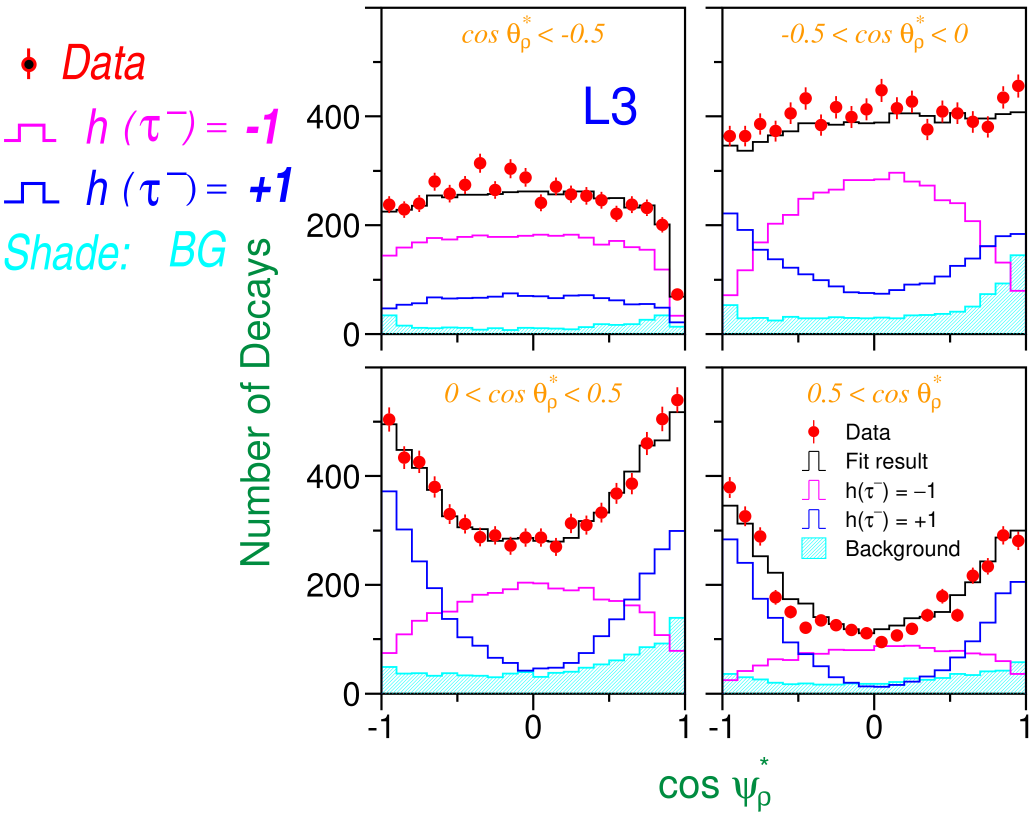
$$\mathcal{P}_\tau \equiv \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \Rightarrow -\frac{A_\tau + 2A_e \cos\theta/(1+\cos^2\theta)}{1 + 2A_\tau A_e \cos\theta/(1+\cos^2\theta)}.$$

where A_τ and A_e are a function of g_V/g_A (vector/ axial vector coupling constants) for τ and e, respectively.

$$A_l \equiv \frac{2 g_{A_l} g_{V_l}}{g_{A_l}^2 + g_{V_l}^2} \Rightarrow = \frac{2(1 - 4\sin^2\theta_W^{eff})}{1 + (1 - 4\sin^2\theta_W^{eff})^2}$$

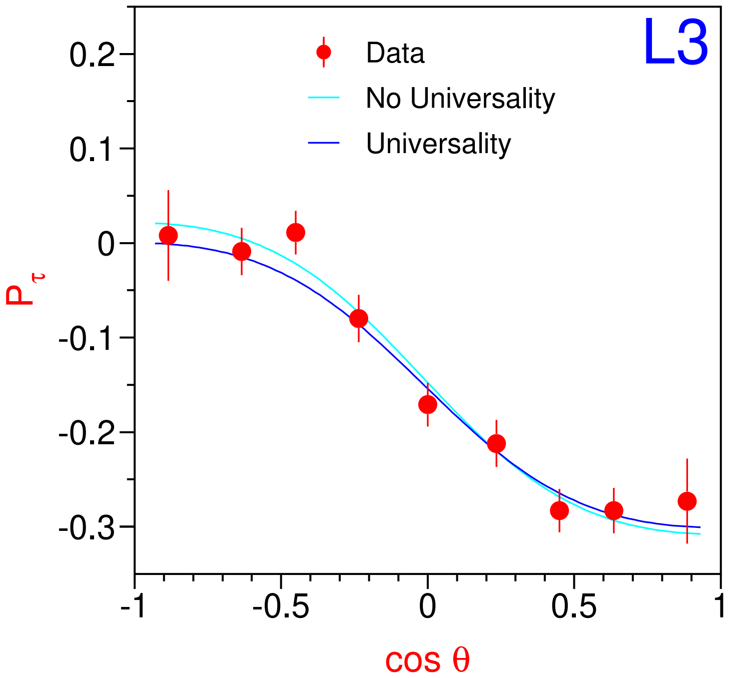
- Assuming negative neutrino helicity, energy(mainly) and decay angles of particles from τ decay depend on longitudinal τ spin components. $\Rightarrow$ their distribution used as $\mathcal{P}_\tau$ analyser.
- Acollinearity between τ pairs also can be used as analyser.

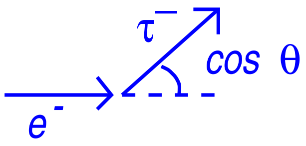
V. NEUTRAL CURRENTS AND τ PRODUCTION



$\tau^\pm \to \rho^\pm \nu_\tau$
$\quad \hookrightarrow \pi^\pm \pi^0$

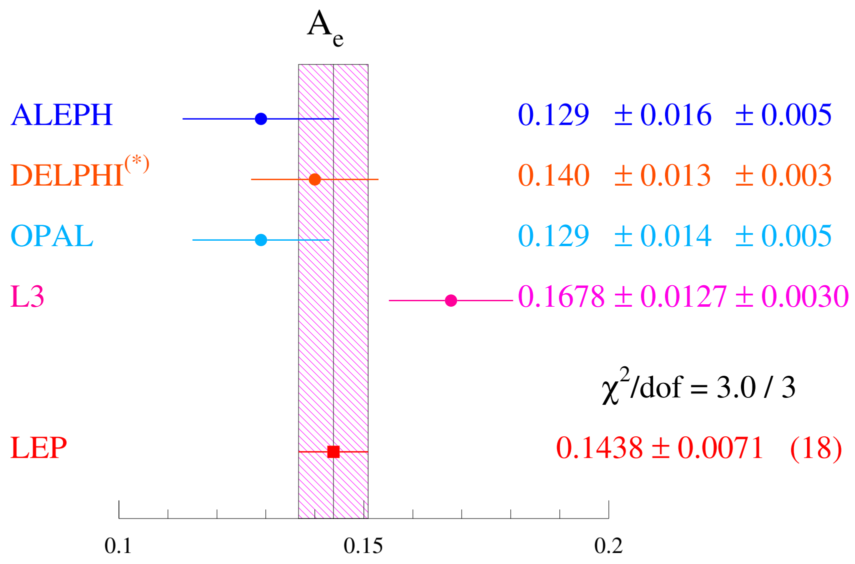
$\cos\theta^*_\rho$, $\cos\psi^*_\rho$: ρ decay angles in τ rest frame .

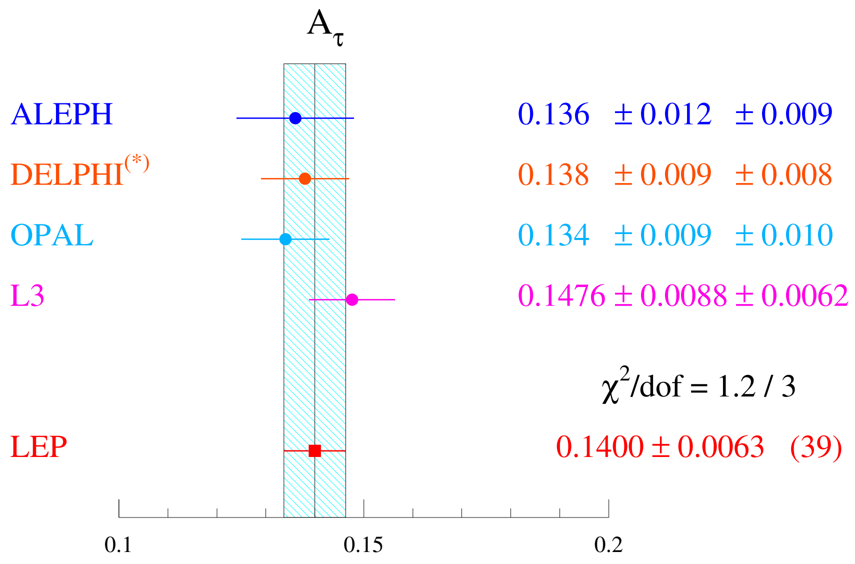




V. NEUTRAL CURRENTS AND τ PRODUCTION

- **Results from $\mathcal{P}_\tau$. (Preliminary Included)**





Lepton Universality $\rightarrow A_l = 0.1417 \pm 0.0063$

$$\Rightarrow \sin^2\theta_W^{eff} = 0.2322 \pm 0.0006$$

VI. DIPOLE MOMENTS

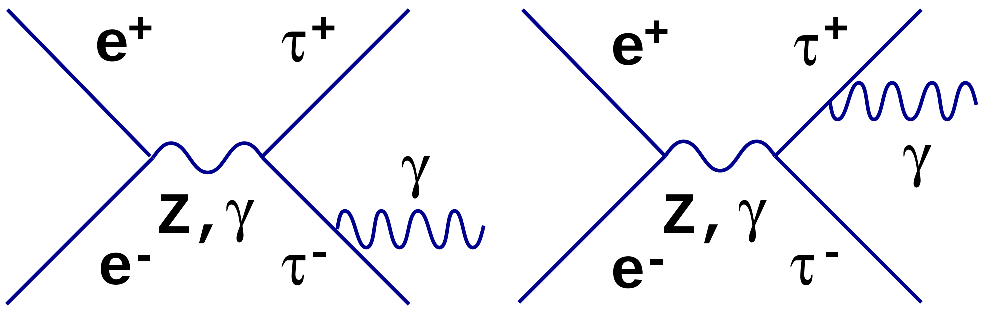
ANOMALOUS MAGNETIC MOMENT

- τ to photon coupling in current algebra,

$$\sim F_1(q^2)\gamma_\mu + i\frac{F_2(q^2)}{2m_\tau}\sigma_{\mu\nu}q^\nu - F_3(q^2)\sigma_{\mu\nu}q^\nu\gamma_5$$

$(F_1(0) \equiv q_\tau, F_2(0) \equiv a_\tau, F_3(0) \equiv d_\tau/q_\tau)$

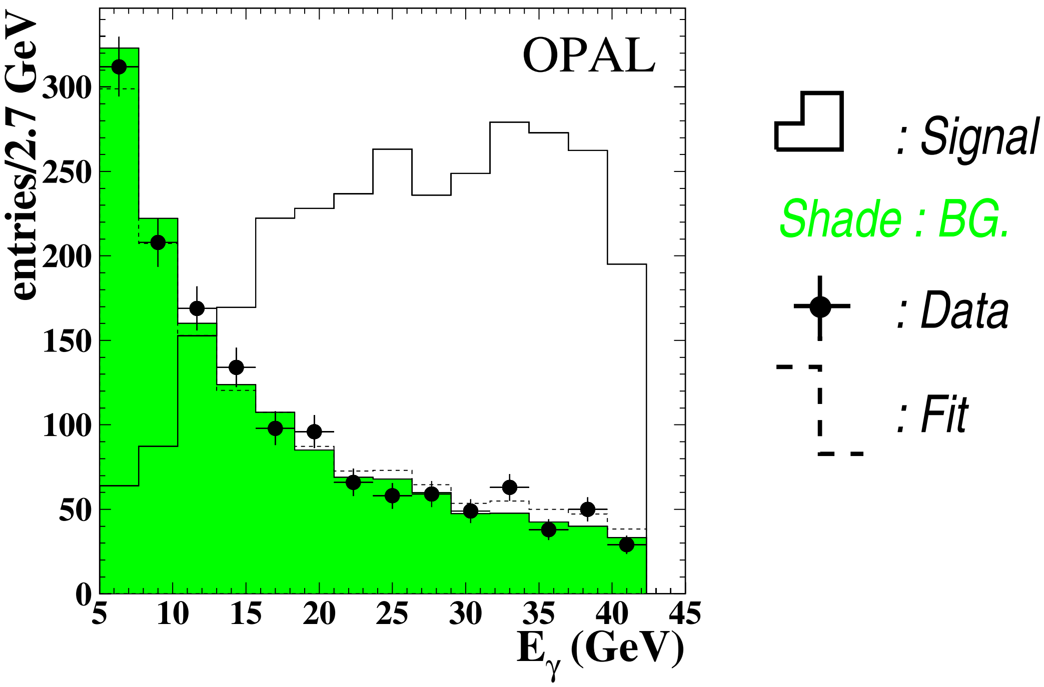
- Short τ_τ $\Rightarrow$ Spin precession method not possible. (cf: e, μ)
- Indirect bounds from $\Gamma(Z^0 \to \tau^+\tau^-)$ review
  $\Rightarrow$ q^2 of photon $\neq$ 0. $\sim m_Z^2$
- Analysis of radiative $Z^0 \to \tau^+\tau^-(\gamma)$ event;
  photons from the anomalous term $\sim$ higher energy, more isolated from both τ's.
  $\Rightarrow$ one τ still off-shell, but q^2 of photon $=$ 0.



- Inteference between normal and dipole terms in the square matrix is recounted in recent L3 and Opal papers.
- Major background: ISR(Initial State Radiation).
- Fit distribution of photon energy and/or isolation angle.

VI. DIPOLE MOMENTS

ANOMALOUS MAGNETIC MOMENT CONTINUES



♣ **RESULTS (95% CL)**

Exp.	a_τ	d_τ(unit $10^{-16} e \cdot cm$)
L3	$-0.052 < a_\tau < 0.058$	$-3.1 < d_\tau < 3.1$ ♣
OPAL	$-0.068 < a_\tau < 0.065$	$-3.8 < d_\tau < 3.6$ ♢
♠ Review	$-0.004 < a_\tau < 0.006$	$-0.11 < d_\tau < 0.11$ ($\leftarrow d_\tau^w$)
SM	$0.0011773(3)$	$\sim$ 0 by P,T invariance

♣ $d_\tau =$ SM when fitting a_τ, vice versa.

♢ $d_\tau =$ 0 when fitting a_τ, then converted from a_τ.

♠ Indirect result, Review from $\Gamma(Z^0 \to \tau^+\tau^-)$
d_τ converted from $\leftarrow d_\tau^w$. (Escribano, Massó)

NO INDICATION OF SUBSTRUCTURE OR CP VIOLATION

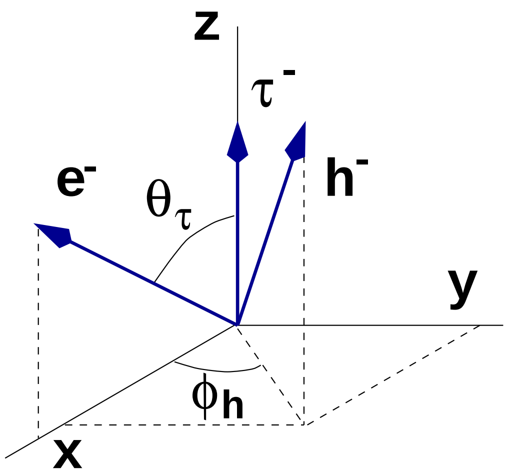
VI. DIPOLE MOMENTS

WEAK (MAGNETIC) DIPOLE MOMENT

- SM loop corrections give small a_τ^w, d_τ^w at $q^2 = M_Z$. Otherwise new physics $\Rightarrow$ τ substructure, CP violation in anomalous d_τ^w.
- a_τ^w, d_τ^w related to spin dependent parts of $e^+e^- \to \tau^+\tau^-$ cross-section. Analysis requires
  $\Rightarrow$ Reconstruction of of τ flight direction, τ spin.
  $\Rightarrow$ When neutrinos gives ambiguity in τ flight, $\to$ solutions averaged.
- Several analyser approach: Optimal observables on $\hat{p}_+$, $\hat{S}_+$, $\hat{S}_-$. Or Tensor components on correlations between τ pairs.

$$\hat{T}_{ij} = (\hat{p}_+ - \hat{p}_-)_i \frac{(\hat{p}_+ - \hat{p}_-)_j}{|\hat{p}_+ - \hat{p}_-|} + (i \leftrightarrow j)(i, j = 1, 2, 3)$$

- Another: Asymmetry on decay angles of single τ (L3).

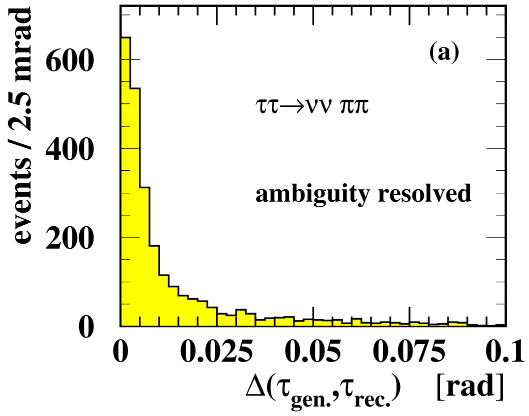


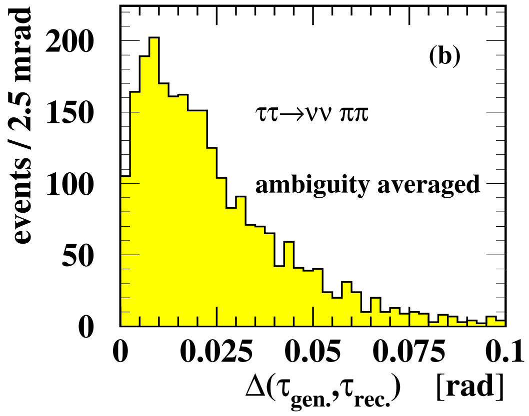
VI. DIPOLE MOMENTS

WEAK (MAGNETIC) DIPOLE MOMENT

Plots from Opal

Difference between $\hat{\tau}_{gen}$ direction and $\hat{\tau}_{rec}$ direction





♣ Results (95% CL)

Exp.	$Re(d^w_\tau)$ (unit $e \cdot cm$)	$Im(d^w_\tau)$ (unit $e \cdot cm$)
ALEPH	$\|Re(d^w_\tau)\| < 1.5 \times 10^{-17}$	
DELPHI	$\|Re(d^w_\tau)\| < 0.66 \times 10^{-17}$	$\|Im(d^w_\tau)\| < 2.0 \times 10^{-17}$
L3	$\|Re(d^w_\tau)\| < 3.0 \times 10^{-17}$	
OPAL	$\|Re(d^w_\tau)\| < 0.56 \times 10^{-17}$	$\|Im(d^w_\tau)\| < 1.5 \times 10^{-17}$
SM	$\sim 3 \times 10^{-37}$	~ 0 by CPT

♣ New Result(First Measurement, 95% CL) on a^w_τ

Exp.	$Re(a^w_\tau)$	$Im(a^w_\tau)$
L3	$\|Re(a^w_\tau)\| < 4.5 \times 10^{-3}$	$\|Im(a^w_\tau)\| < 9.9 \times 10^{-3}$
SM	-2.10×10^{-6}	0.61×10^{-6}

No Indication of New Physics

VII. MASS OF TAU NEUTRINO

- Cosmology, astrophysics give indirect bounds ($< \mathcal{O}(1MeV)$).
- On the earth, $\tau^- \rightarrow h^- \nu_\tau$ with higher hadronic invariant mass. $\sim$ Less phase space for energy of ν_τ
  $\Rightarrow$ Sensitive to m_{ν_τ}.
- Classic : Endpoint of m_h spectrum.
  Also : E_h (Phase space limited by m_{ν_τ}) (Aleph)
  E_Δ, M^2_Δ ($\Delta = p_\tau^{estimated} - p_h$) (Opal)
- Used decay channels: $\tau^- \rightarrow 3\pi^- 2\pi^+ (\pi^0)\nu_\tau$(sensitivity),
  $\tau^- \rightarrow 2\pi^- \pi^+ (\pi^0)\nu_\tau$(statistics).
  Branch Ratio too small for $\tau^- \rightarrow n\pi\nu_\tau$ with $n > 6$.

♣ **RESULTS (95% CL)**

Exp.	Fit	m_τ
ARGUS	1-D	$< 31\ MeV$
CLEO	1-D	$< 30 MeV$
ALEPH	2-D	$< 18.2 MeV$
DELPHI	1-D	♠ Note
OPAL	2-D	$< 29.9 MeV$

♠ Preliminary, depends on $2\pi^-\pi^+$ structure models.
The bounds are 31MeV(KS)/33MeV(IMR)/62MeV(Conservative)
♠ 2-D fitting is not sensitive to $2\pi^-\pi^+$ structures.

VIII. CONCLUSION

- With a vast amount of $\tau^+\tau^-$samples, excellent detector performance and improved analysis skills, LEP experiments tested fairly broad area of τ physics.
- Measuremnts support electroweak nature of τ is that of the Standard Model, where tau is a point-like particle and its decay has V-A structure.
- (Along with CLEO) Most decay channels of τ are found down to Branch Ratio 10^{-5}.
- Nevertheless, some intrigues still left. To prove them up to electron or muon study precision, more data will be needed from next generation experiments.