Spin Analysis of the Process $e^+e^- \to \tau^+\tau^-$ at LEP

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(L3 Collaboration)

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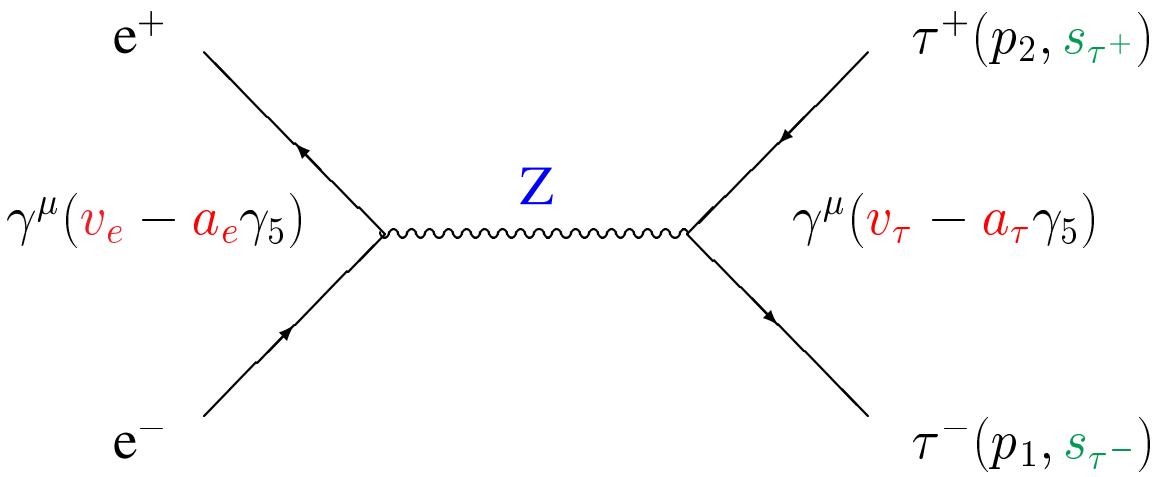
(WWW: *http://l3www.cern.ch/conferences/ps/tau_nashville97.ps.gz)*

- Introduction
- Longitudinal Polarization
- Transverse and Normal Spin Correlations
- Summary and Conclusions

e^+e^- – Annihilation at LEP I



- precise measurement of v_f, a_f
- neutral current couplings of the fermions f in the SM:

$$v_f = T_f^3 - 2\,Q_f \sin^2\theta_W$$
$$a_f = T_f^3$$

- test lepton universality

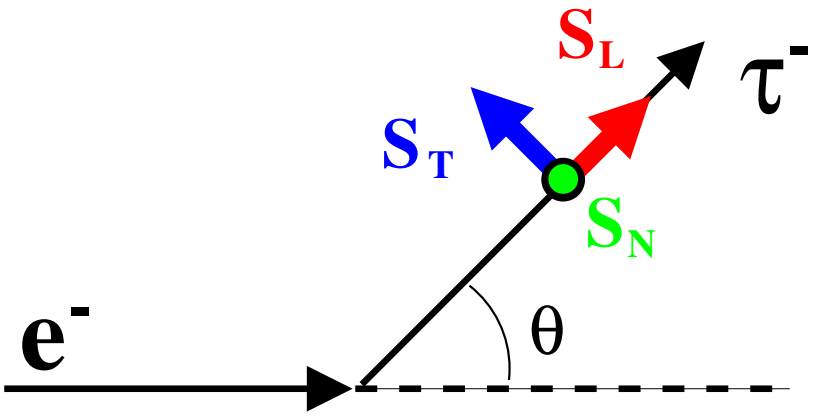
$$v_e = v_\mu = v_\tau \qquad a_e = a_\mu = a_\tau$$

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

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

with

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

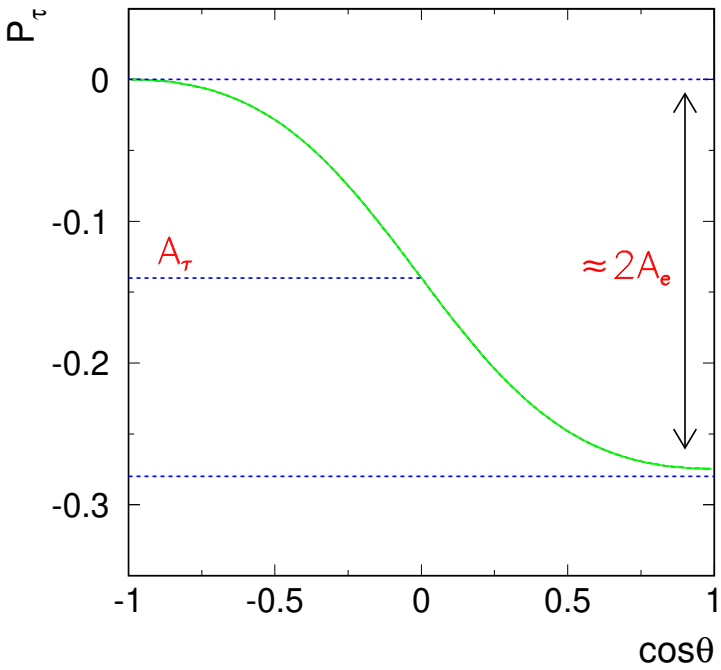


high energy limit $s^L_{\tau-} = h_{\tau-}$

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

with:

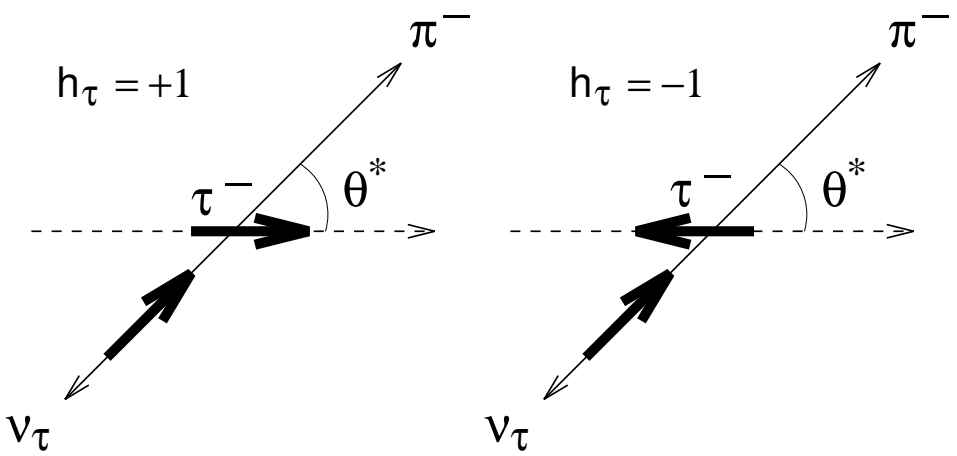
$$\mathcal{A}_l = \frac{2a_l v_l}{|v_l|^2+|a_l|^2} \quad , \quad \frac{v_l}{a_l} = 1-4\sin^2\bar{\theta}_{\mathrm{W}}$$



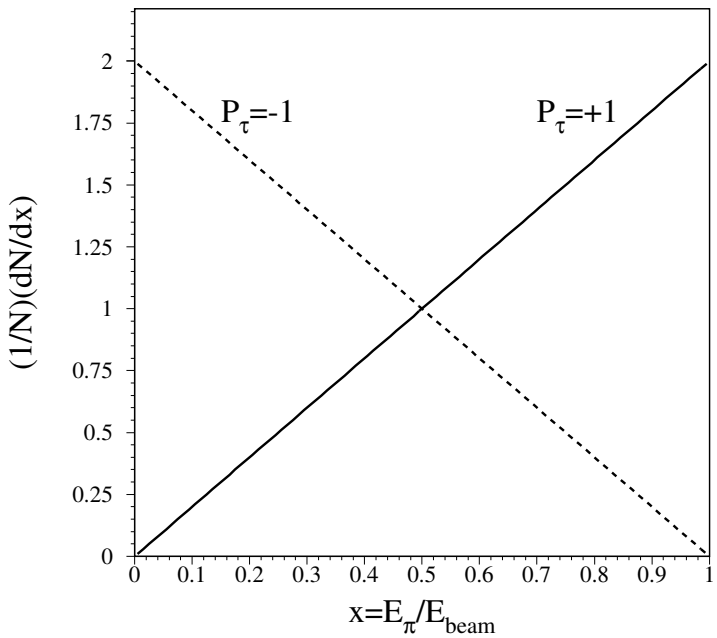
$\Rightarrow$ precision measurement of $\mathcal{A}_\tau$ and $\mathcal{A}_e$ simultaneously

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

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



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

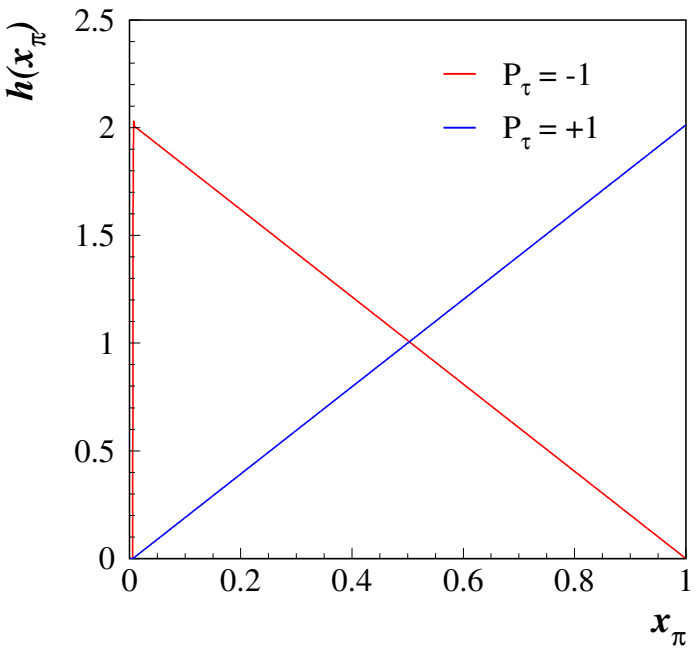


$$\frac{1}{N}\frac{dN}{dx} = 1 + \mathcal{P}_\tau(2x - 1)$$

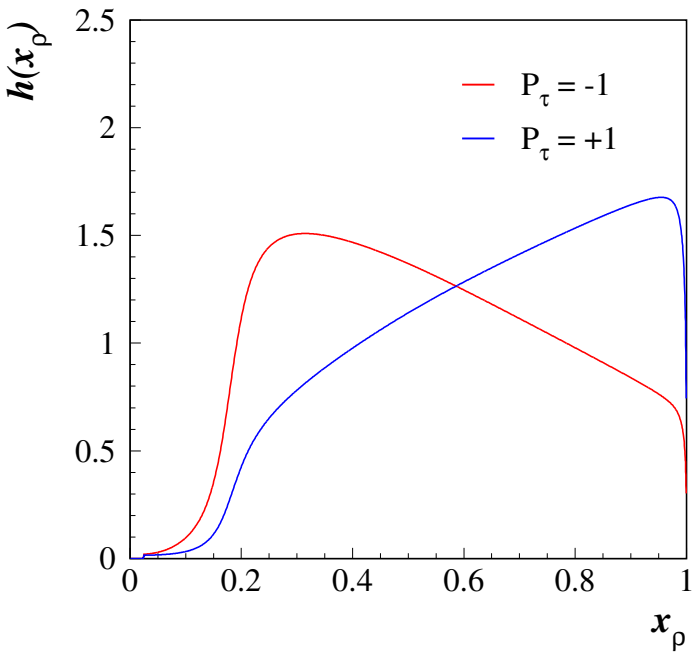
$\Rightarrow$ energy spectra of τ decay products are polarization dependent

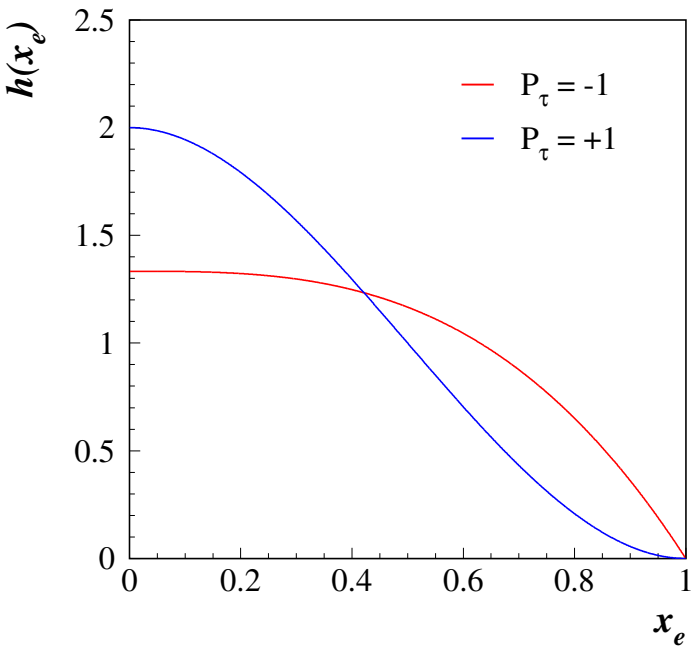
Energy Spectra

$\tau \to \pi\nu$

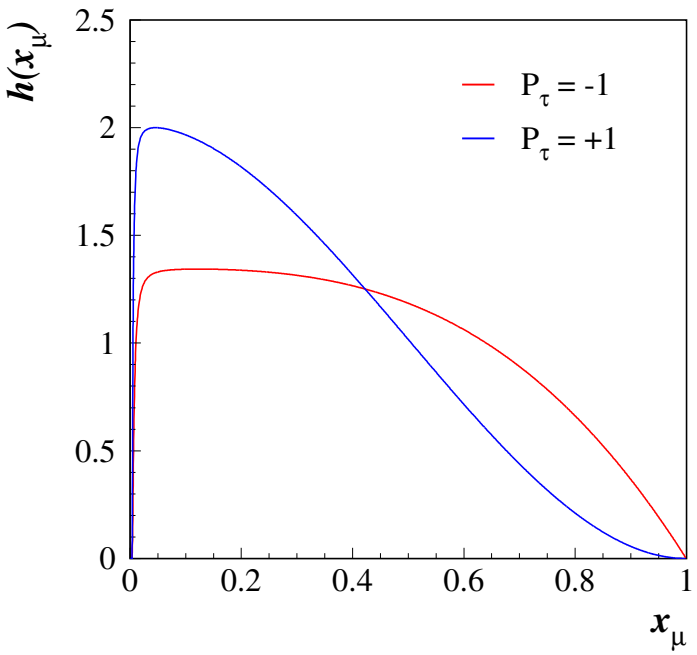


$\tau \to \rho\nu$





$\tau \to e\nu\overline{\nu}$



$\tau \to \mu\nu\overline{\nu}$

Detector effects have to be taken into account using MC technique

decay distributions:

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

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

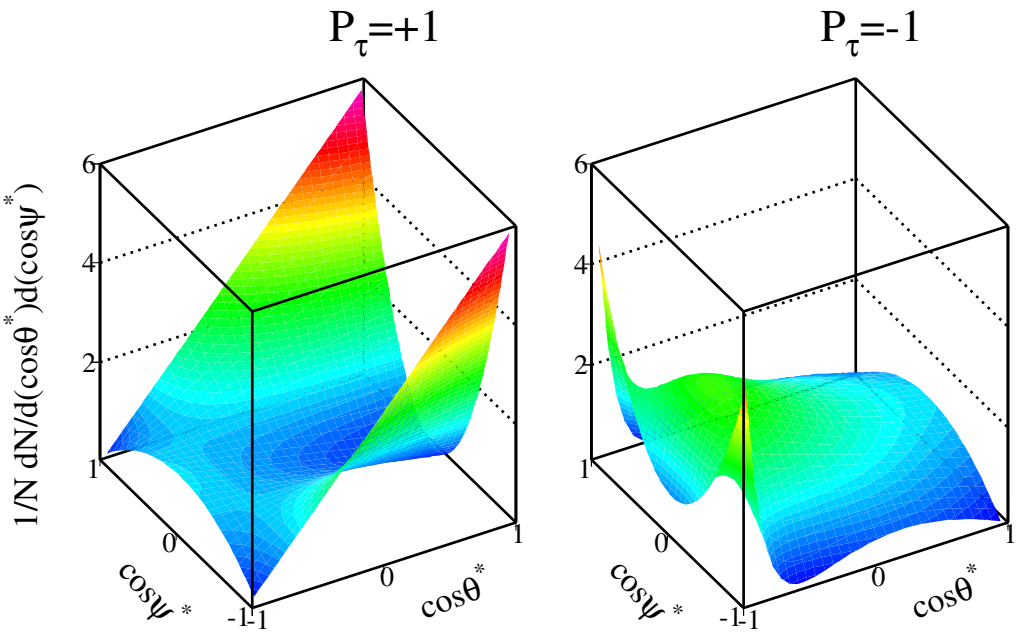
$\tau \to h\nu \quad h = \pi, \rho, a_1$:

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

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

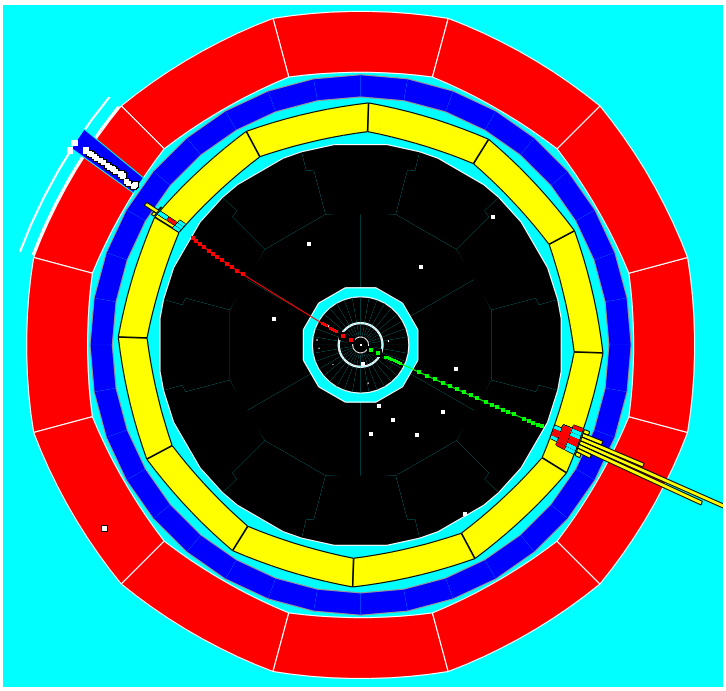


$\tau \to \rho\nu$

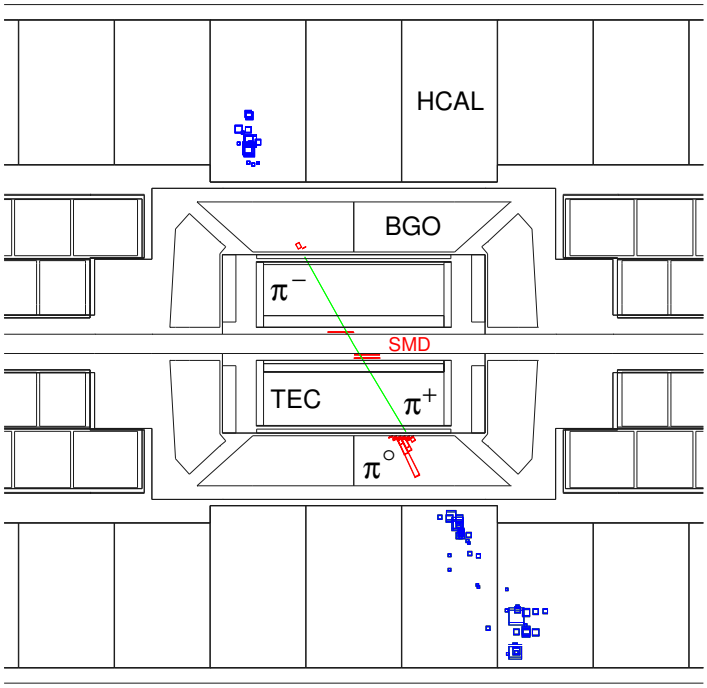
Selection

- select τ decay products: e, μ, π, ρ, a_1

ALEPH



L3



- $e^+e^- \rightarrow \tau^+\tau^-$ easy to identify, low multiplicity jets, small non–τ background contributions
- identification based on all subdetectors
- LEP collaborations use several methods
  classical cuts
  neural network
  likelihood selection
- clean channels, especially: e, μ (π)
- main difficulty: $n\pi$, $n\pi^0$

Data Sample

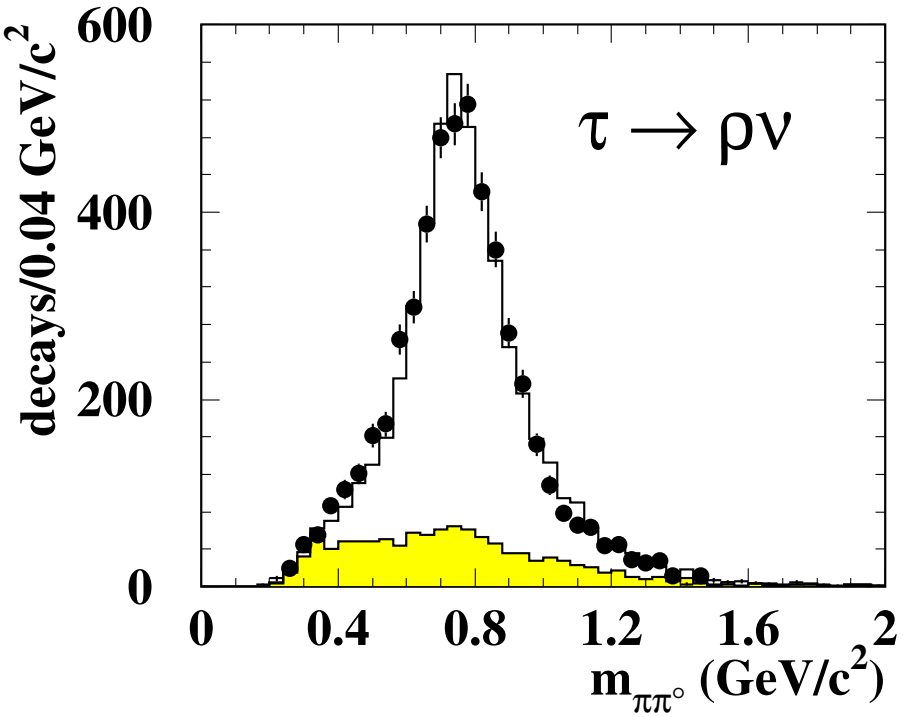
Experiment	Years	e	μ	π	ρ	a_1	# decays
ALEPH	90–92	59	82	71	59	59	52 K
		2	4	7	9	9	
DELPHI	90–94	92	87	60	45	60	71 K
		5	3	10	15	15	(49 K)
L3	90–94	76	70	72	70	33	111 K
		5	5	15	11	28	
OPAL	90–94	96	87	83	70	66	123 K
		3	2	19	27	25	

(Efficiency / BG [%])

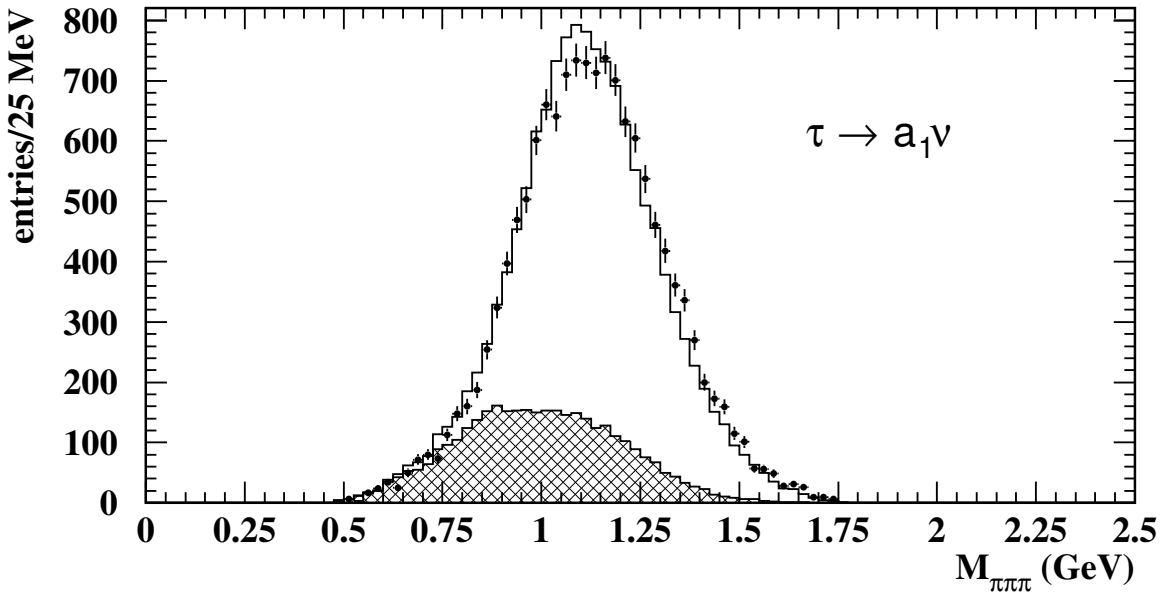
SYSTEMATICS

- energy scales
- non-τ background in the leptonic channels
- π^0 identification in the hadronic channels
- $\mathcal{A}_e$ is affected by non-symmetric effects (Bhabha background)

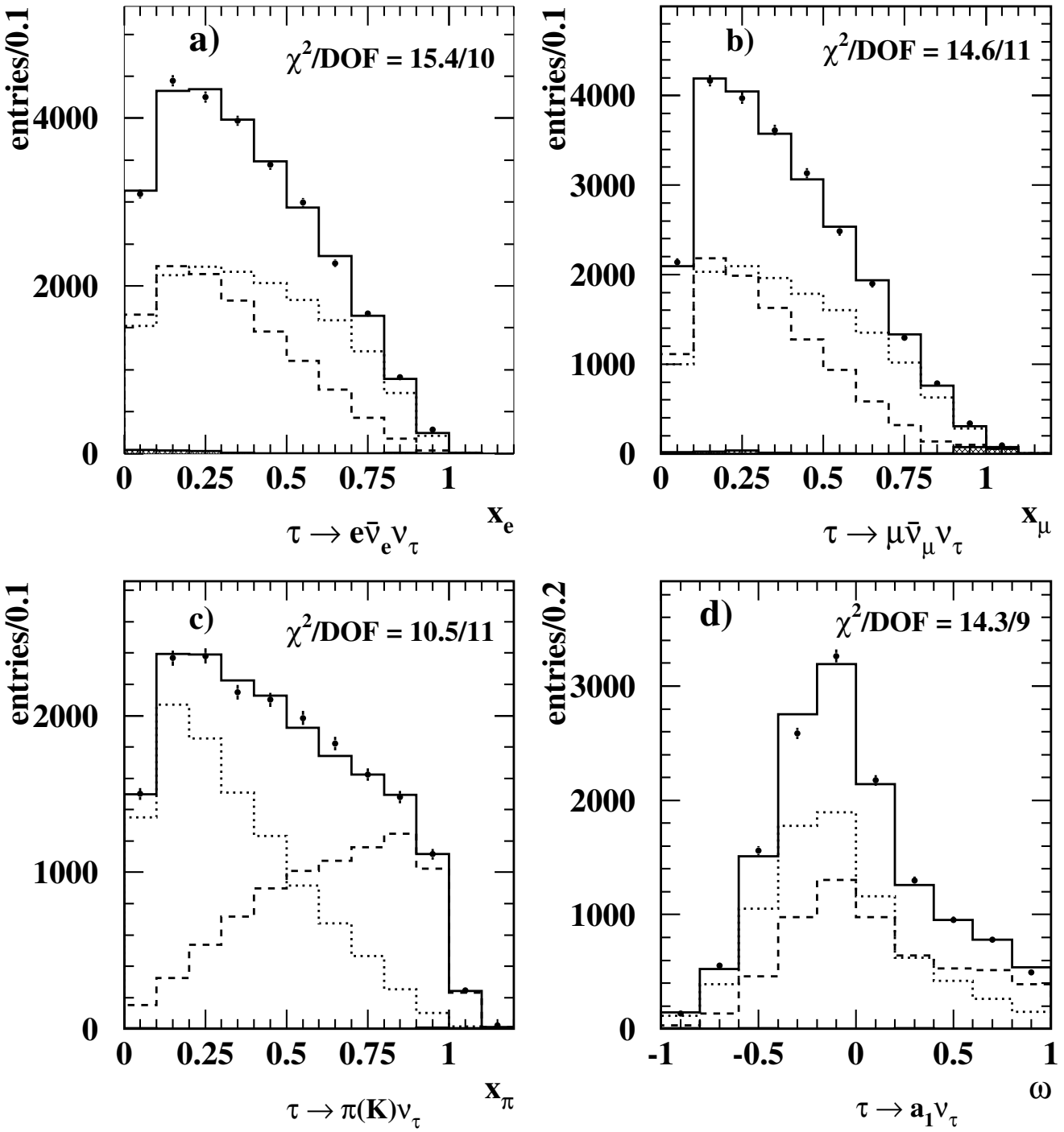
DELPHI


600
400
200
0
decays/0.04 GeV/c^2
$\tau \rightarrow \rho\nu$
0
0.4
0.8
1.2
1.6
2
$m_{\pi\pi^\circ}$ (GeV/c^2)

OPAL


800
700
600
500
400
300
200
100
0
entries/25 MeV
$\tau \rightarrow a_1\nu$
0
0.25
0.5
0.75
1
1.25
1.5
1.75
2
2.25
2.5
$M_{\pi\pi\pi}$ (GeV)

OPAL

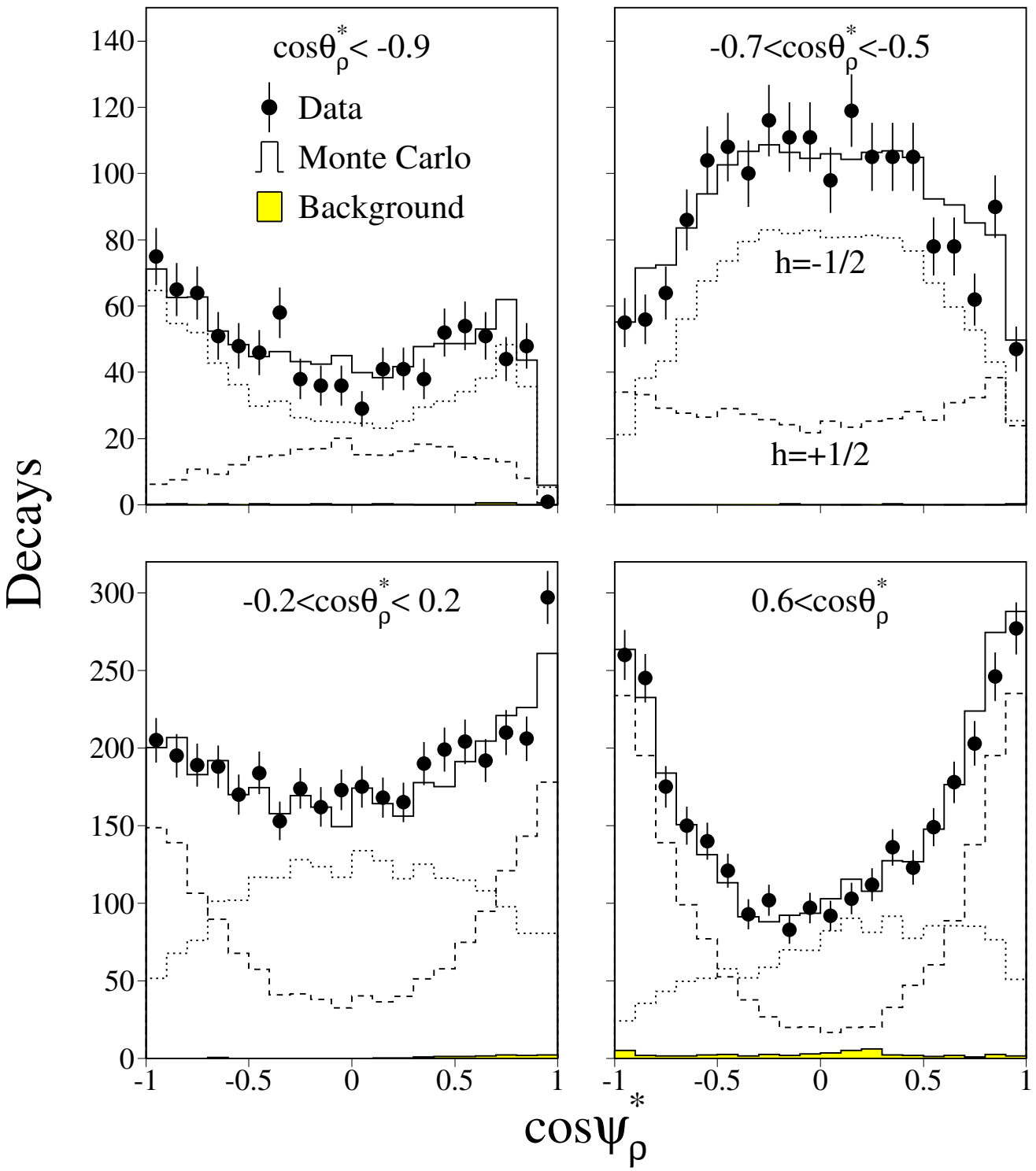


$\cdots\cdots$ $P_\tau = -1$

$- - -$ $P_\tau = +1$

Data Spectra: ρ

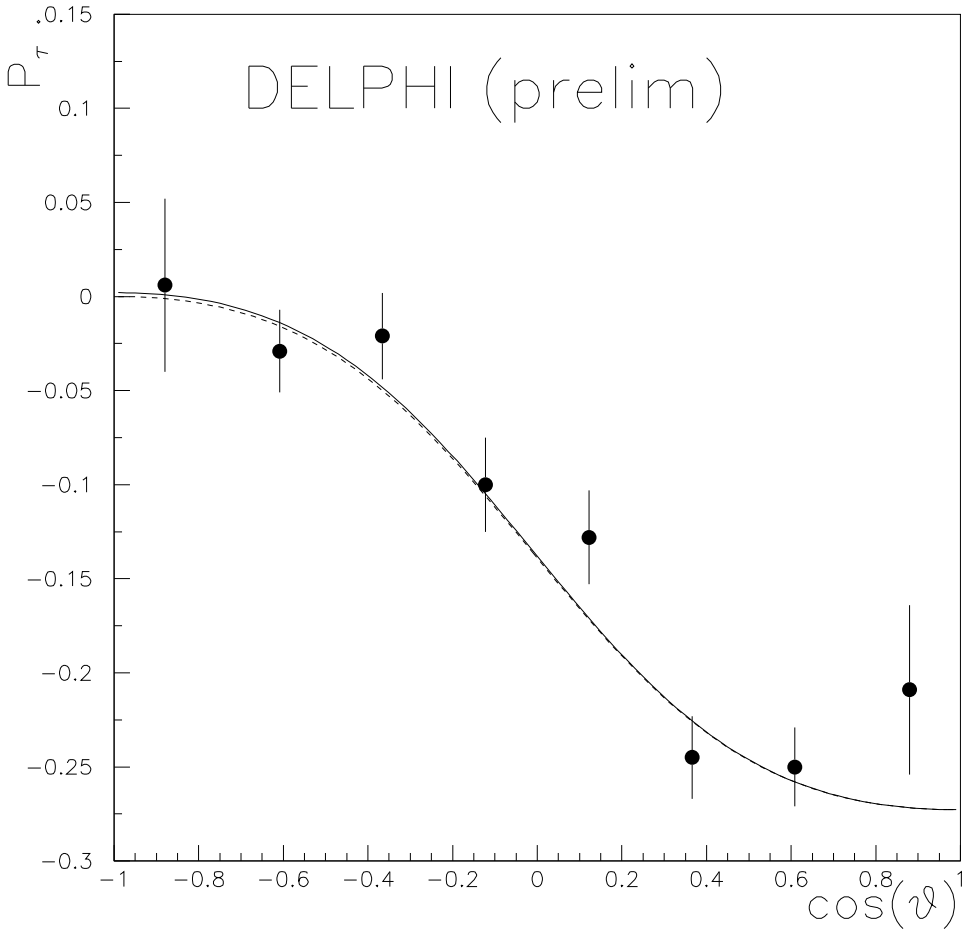
L3



$\mathcal{P}_\tau$ Angular Dependence

$\mathcal{A}_\tau$, $\mathcal{A}_e$ are calculated from:

1. $\mathcal{P}_\tau$ in $\cos\theta$ bins
2. QED radiative effects, γ exchange, $\gamma - Z$ interference (at 10^{-3} level, $\sqrt{s}$, $\cos\theta$ dependent)
3. fit of the distribution $\mathcal{P}_\tau\,(\cos\theta, x_i)$

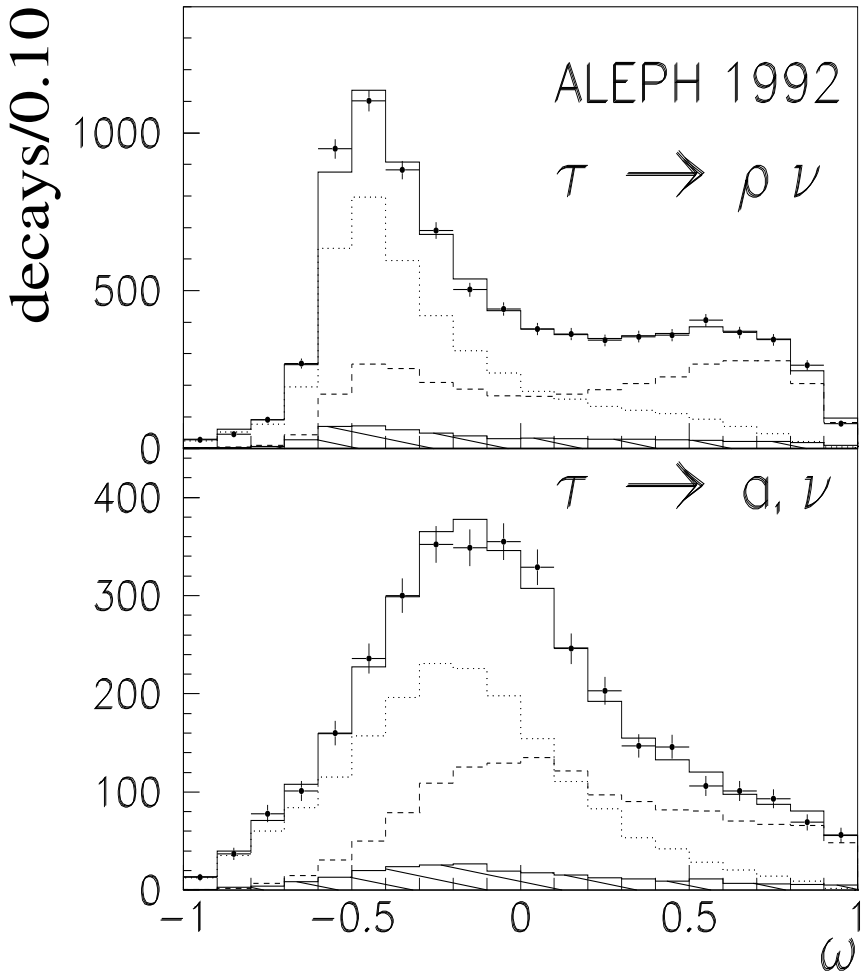


$$\mathcal{P}_\tau(\cos\theta) \;=\; -\frac{\mathcal{A}_\tau(1+\cos^2\theta)+2\mathcal{A}_e\cos\theta}{(1+\cos^2\theta)+2\mathcal{A}_\tau\mathcal{A}_e\cos\theta}$$

ω Distributions

optimal variables:

$$\omega_\rho = \omega_\rho(\text{2 angles}, M_{\pi\pi^0})$$
$$\omega_{a_1} = \omega_{a_1}(\text{3 angles}, M_{\pi_1^-\pi_2^-\pi_3^+}, M_{\pi_1^-\pi_3^+}, M_{\pi_2^-\pi_3^+})$$

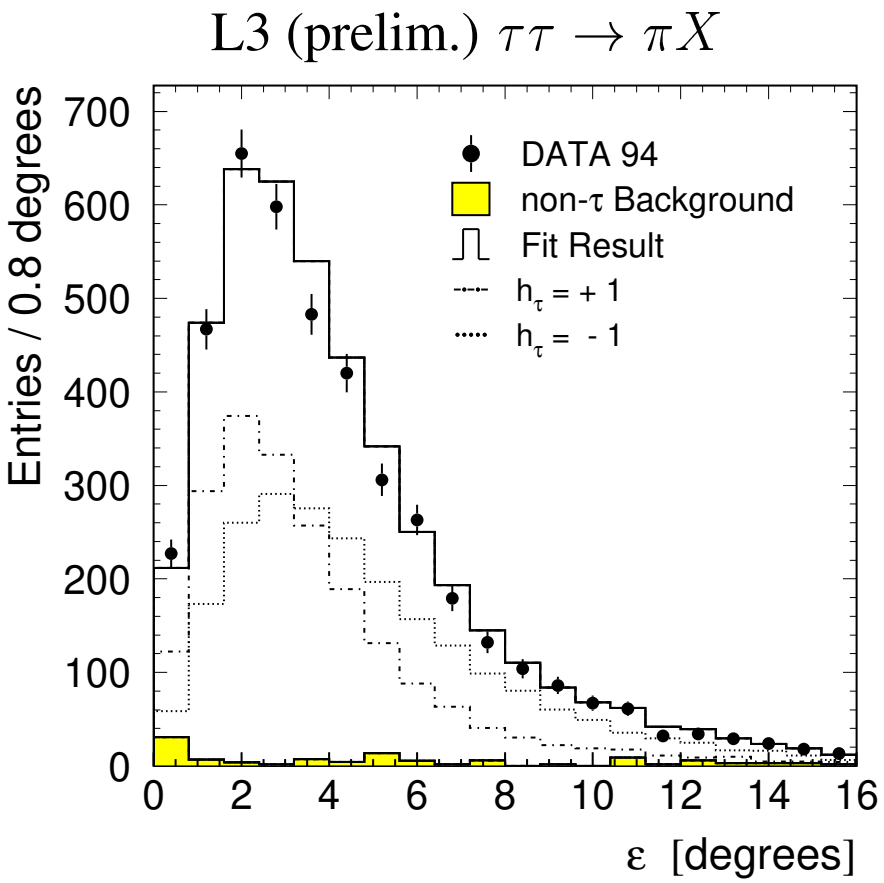


$\cdots\cdots$ $P_\tau = -1$

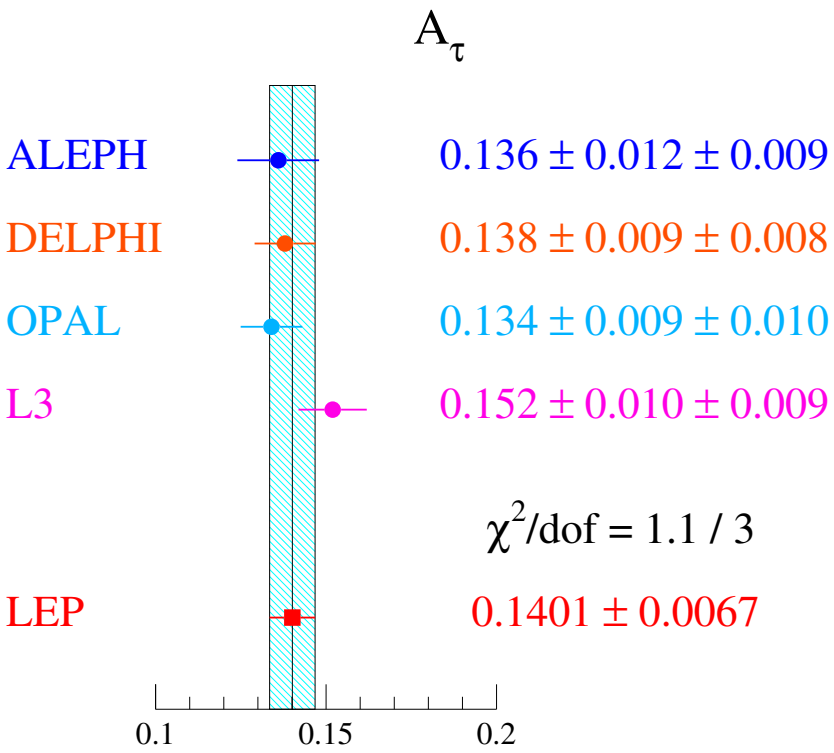
$- - -$ $P_\tau = +1$

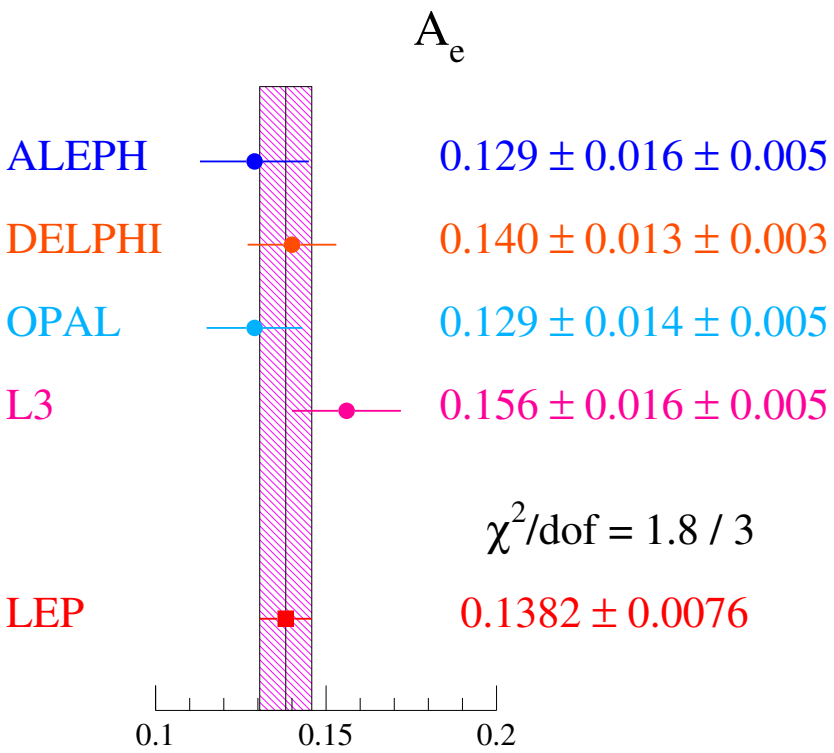
Consistency checks:

- Michel Parameter analysis (ALEPH, L3)
- analysis using analytical functions (L3)
- inclusive hadron 1-prong selection (DELPHI)
- measurement based on the event acolinearity (ALEPH, L3)



Results from $\mathcal{P}_\tau$





Determination of C_i, D_i (i = 0,1,2)

$$\left.\begin{array}{ll} \sigma, A_{fb} & \Longrightarrow C_0, C_1 \\ \mathcal{P}_\tau, A_{pol}^{fb} & \Longrightarrow D_0, D_1 \end{array}\right\} \text{ symmetric under } a_f \leftrightarrow v_f$$

Consider transverse-transverse and transverse-normal spin correlations

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

$$C_{TN} \equiv \frac{D_2}{C_0} \propto \frac{\sigma(s_{\tau^-}^T s_{\tau^+}^N = +1) - \sigma(s_{\tau^-}^T s_{\tau^+}^N = -1)}{\sigma(s_{\tau^-}^T s_{\tau^+}^N = +1) + \sigma(s_{\tau^-}^T s_{\tau^+}^N = -1)}$$

e.g.: $s_{\tau^-}^T s_{\tau^+}^T = ++, --, +-, -+$

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

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

Standard Model prediction:

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

- C_{TT} breaks the symmetry:

$$\begin{aligned} v_\tau \simeq a_\tau &\rightarrow C_{TT} \simeq 0.0 \\ v_\tau \ll a_\tau &\rightarrow C_{TT} \simeq 1.0 \\ v_\tau \gg a_\tau &\rightarrow C_{TT} \simeq -1.0 \end{aligned}$$

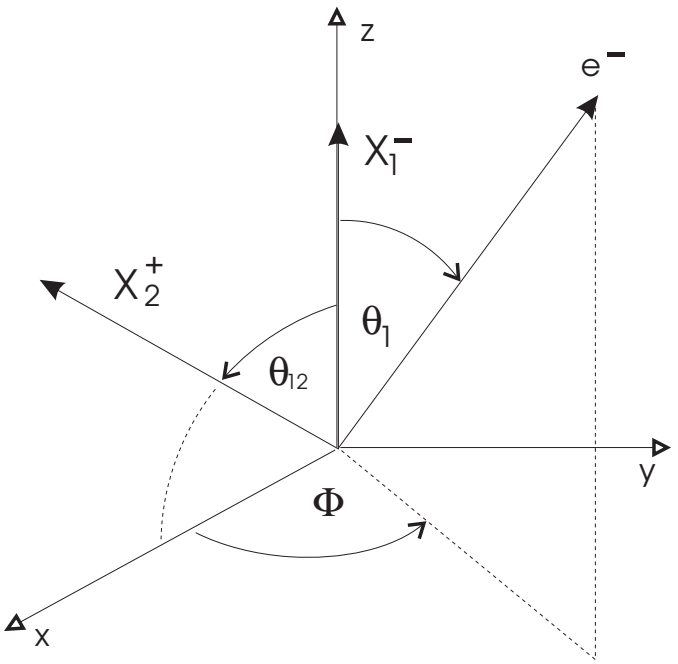
- C_{TN} depends on imaginary part of v_τ, a_τ
- C_{TN} is T–odd, contains interference term on the Z peak

The measurement of C_{TT} and C_{TN}

1. provides an independent test of the neutral current structure
2. completes the determination of observables related to the spin in $Z \rightarrow \tau\tau$ processes

How to measure C_{TT} and C_{TN}?

Processes: $e^+e^- \to \tau^+\tau^- \to X_1^- X_2^+ + n\nu$



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

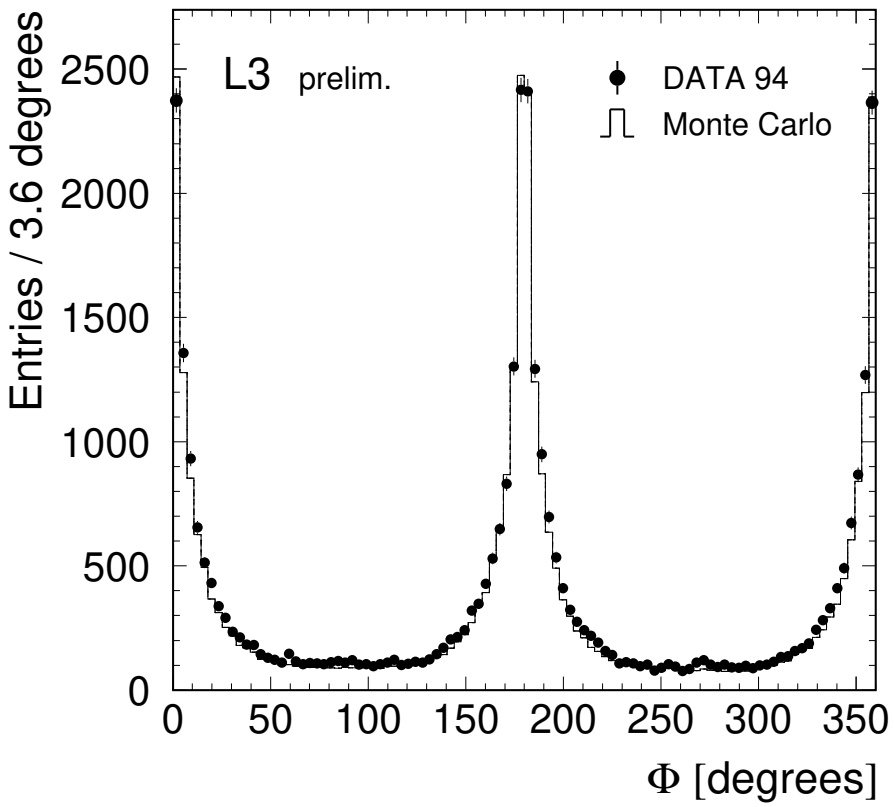
- $\Phi = \Phi(\theta_1, \phi_1, \theta_2, \phi_2) \Rightarrow$ excellent tracking devices
- not necessary to reconstruct the τ direction !
- high statistic needed, low background rates
- sensitivity to spin correlations:

$\pi^\pm\pi^\mp$	(1.0)	$\rho^\pm\rho^\mp$	(0.2)
$\pi^\pm\rho^\mp$	(0.5)	$\rho^\pm l^\mp$	(0.15)
$\pi^\pm l^\mp$	(0.3)	$l^\pm l^\mp$	(0.1)

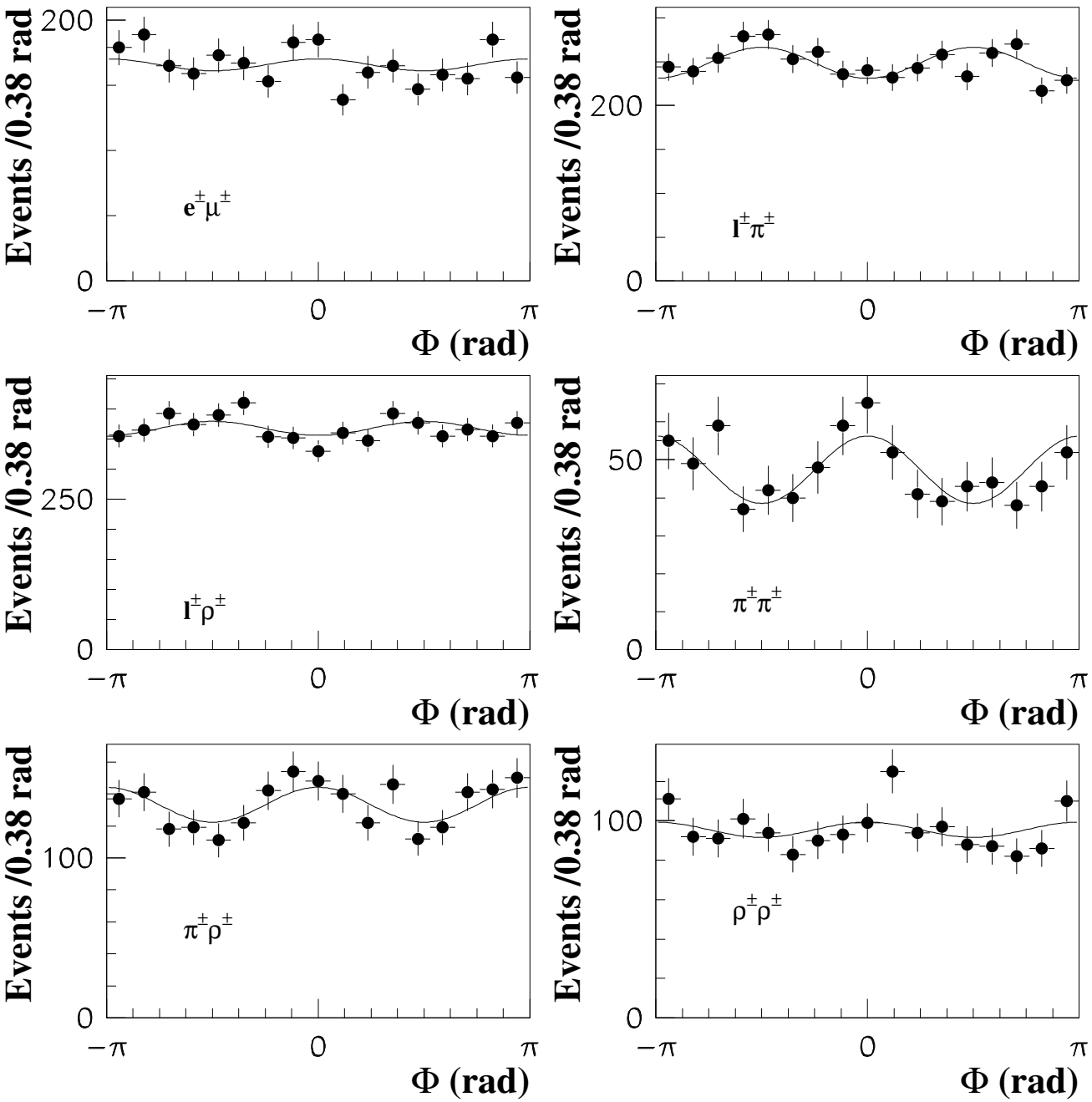
exclusive final states $e\mu$, $l\pi$, $l\rho$, $\pi\pi$, $\pi\rho$, $\rho\rho$

Exp.	Year	eff. [%]	bckgr.[%]	$N_{\tau\tau}$	method
ALEPH	92 – 94	20 – 50	≤ 20	20 K	likelihood fit using $\Phi, \theta_{12}, \theta_1$
DELPHI	92 – 94	11 – 20	≤ 30	10 K	inclusive lh hh analysis, Φ
L3	94	20 – 30	≤ 20	7 K	using Φ

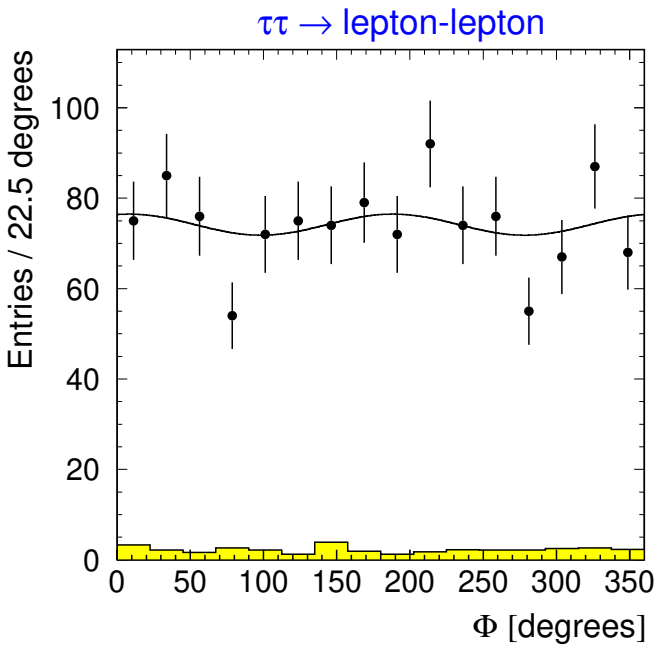
- Detector resolution / alignment is checked with $e^+e^- \rightarrow e^+e^-, \mu^+\mu^-$ events

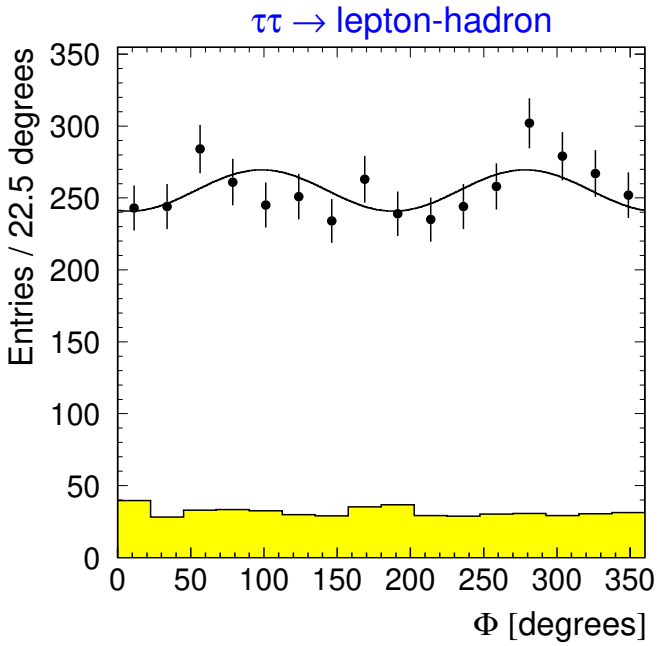


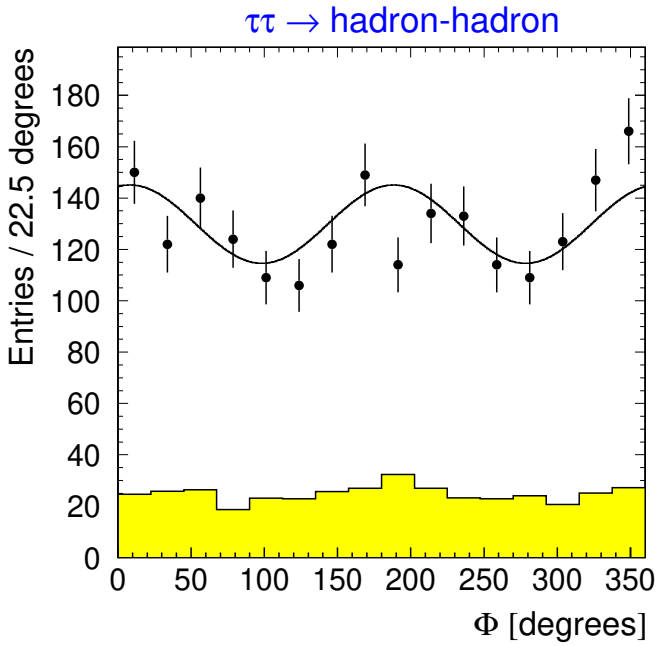
ALEPH


Events /0.38 rad
200
0
$e^{\pm}\mu^{\pm}$
$l^{\pm}\pi^{\pm}$
$l^{\pm}\rho^{\pm}$
$\pi^{\pm}\pi^{\pm}$
$\pi^{\pm}\rho^{\pm}$
$\rho^{\pm}\rho^{\pm}$
250
50
100
$-\pi$
0
π
Φ (rad)

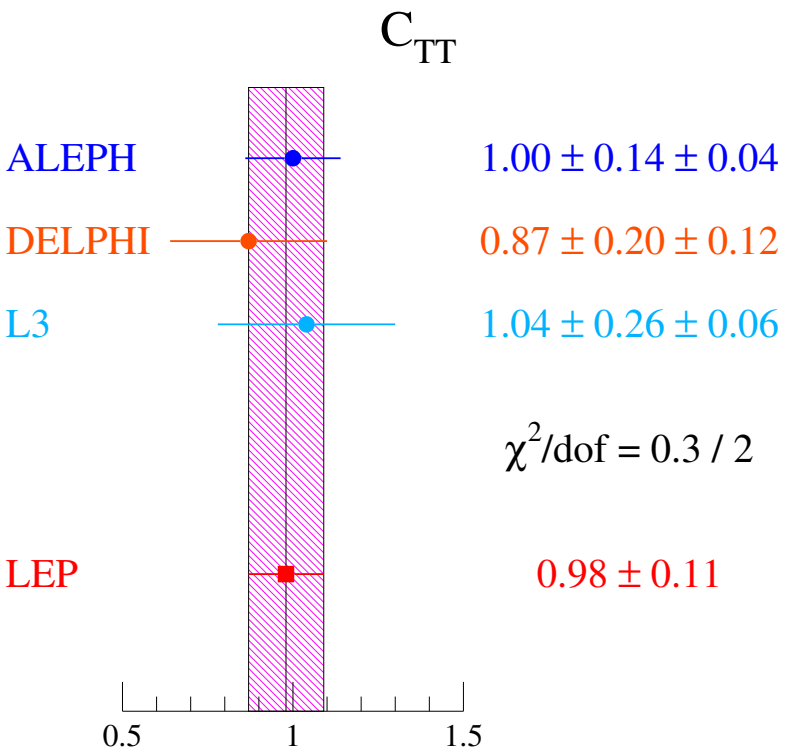
L3 (prelim.)

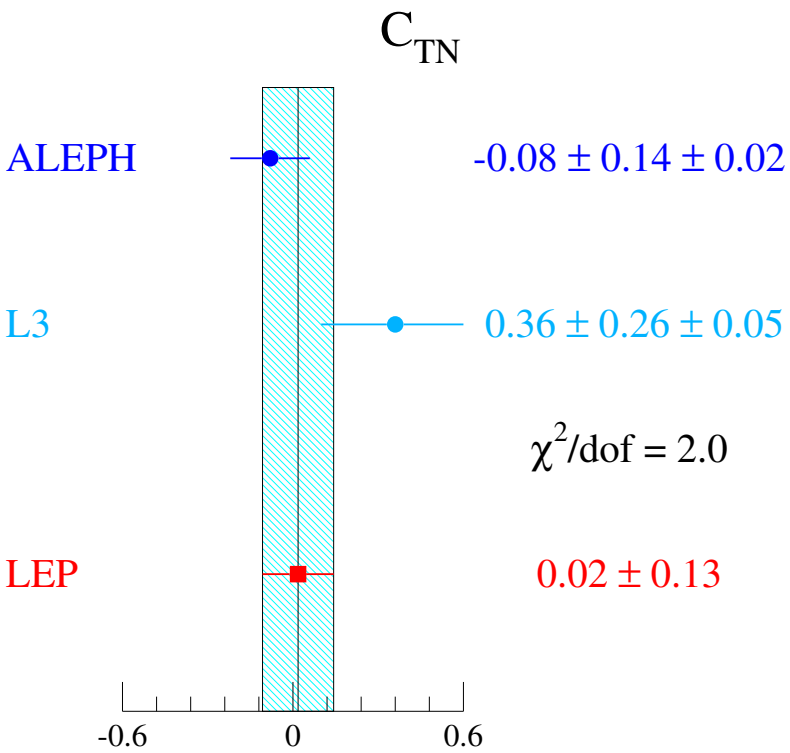

ττ → lepton-lepton
Entries / 22.5 degrees
0
20
40
60
80
100
0
50
100
150
200
250
300
350
Φ [degrees]


ττ → lepton-hadron
Entries / 22.5 degrees
0
50
100
150
200
250
300
350
0
50
100
150
200
250
300
350
Φ [degrees]


ττ → hadron-hadron
Entries / 22.5 degrees
0
20
40
60
80
100
120
140
160
180
0
50
100
150
200
250
300
350
Φ [degrees]

C_{TT} and C_{TN} Results

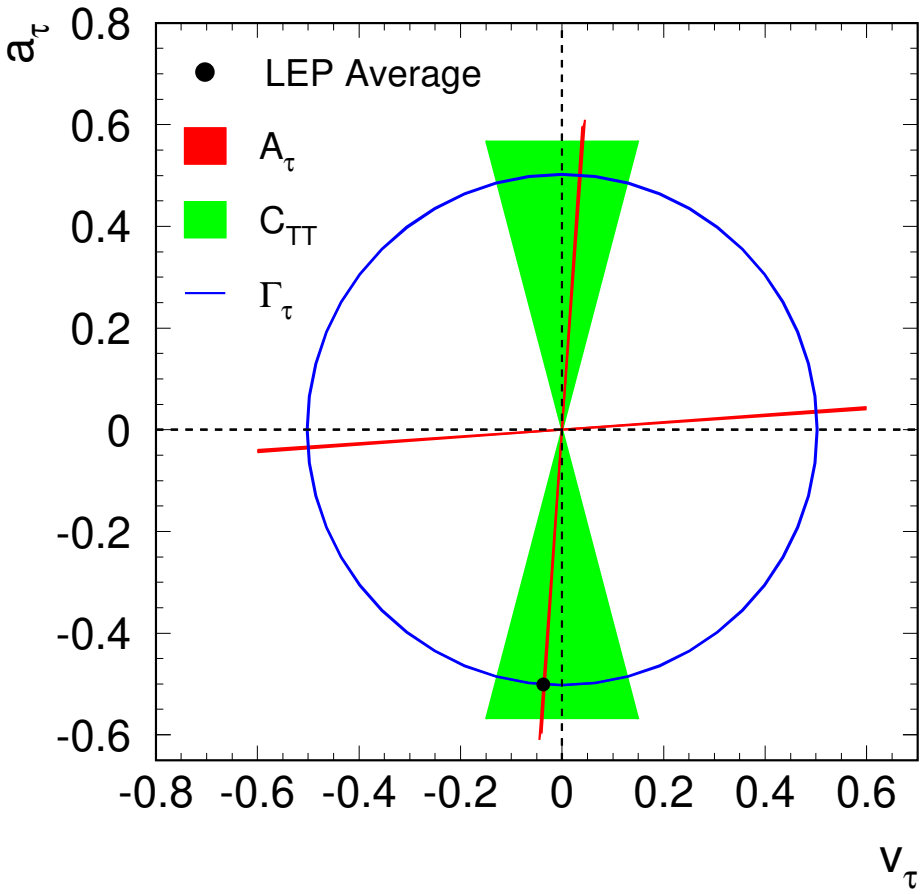




The a_τ - v_τ Plane

- C_{TT} is the only 'on peak' observable which is not symmetric in a_τ and v_τ

  $\Rightarrow$ reduces the fourfold ambiguity of the polarization measurement



- C_{TT} is not very sensitive to measure $\sin^2\bar{\theta}_W$

$$\Delta \sin^2\bar{\theta}_W \approx \Delta C_{TT}$$

Conclusions

Results from $\mathcal{P}_\tau$ analysis:

$$\begin{aligned} \mathcal{A}_\tau &= 0.1401 \pm 0.0067 \\ \mathcal{A}_e &= 0.1382 \pm 0.0076 \\ \mathcal{A}_{e-\tau} &= 0.1393 \pm 0.0050 \end{aligned}$$

- confirmation of lepton universality

$$\mathcal{A}_\tau / \mathcal{A}_e = 1.01 \pm 0.07$$

- weak mixing angle

$$\sin^2 \bar{\theta}_{\mathrm{W}} = 0.2325 \pm 0.0006$$

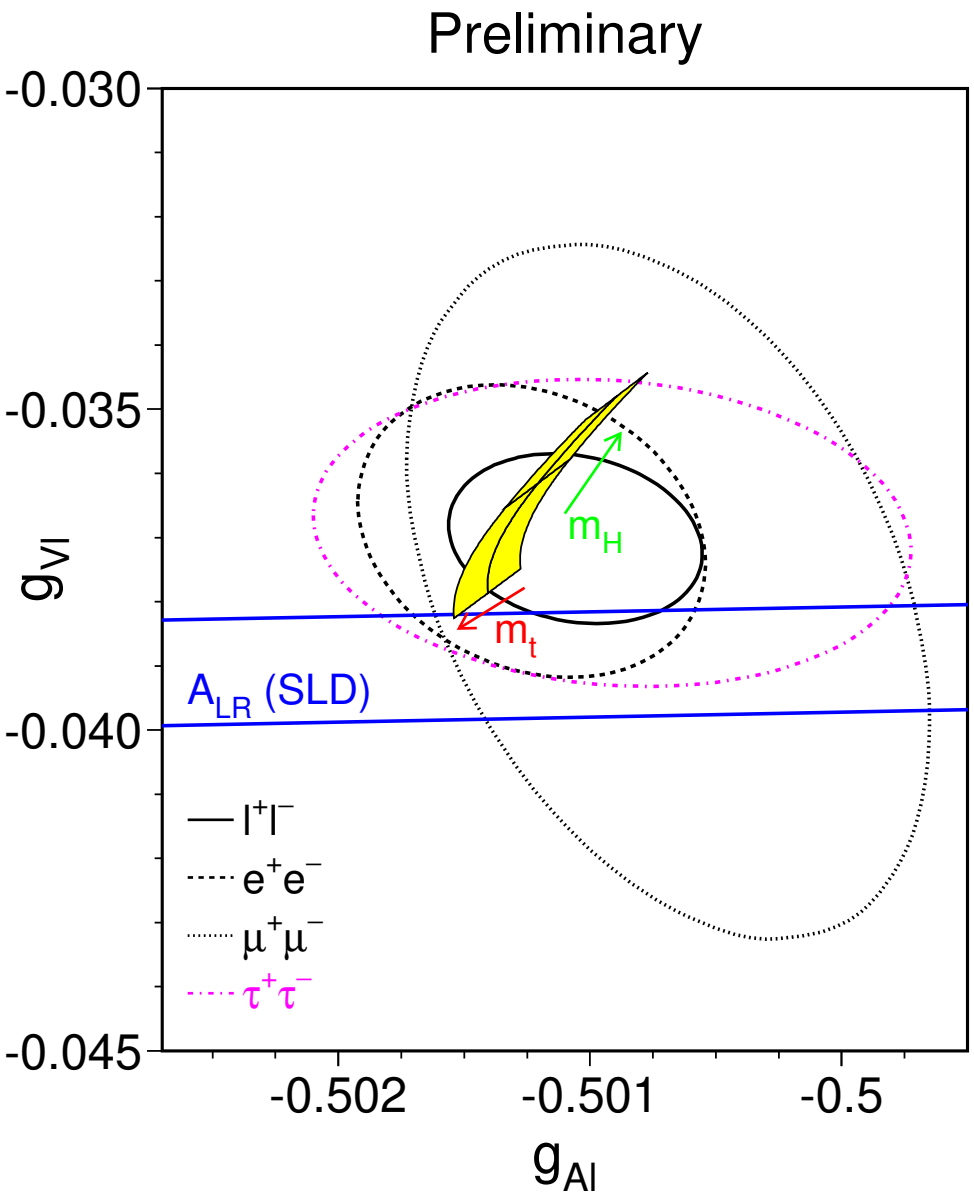
- precision of $\mathcal{A}_\tau$ at systematic limit
- results from C_{TT} and C_{TN} are in agreement with Standard Model predictions
- LEP I data is not completely analyzed ('95 with 30 pb^{-1}) expected accuracy

$$\begin{aligned} \Delta\mathcal{A}_\tau &\approx 0.0058 \\ \Delta\mathcal{A}_e &\approx 0.0064 \end{aligned}$$

$$\begin{aligned} \Delta C_{TT} &\approx 0.09 \\ \Delta C_{TN} &\approx 0.09 \end{aligned}$$

Combined LEP Result

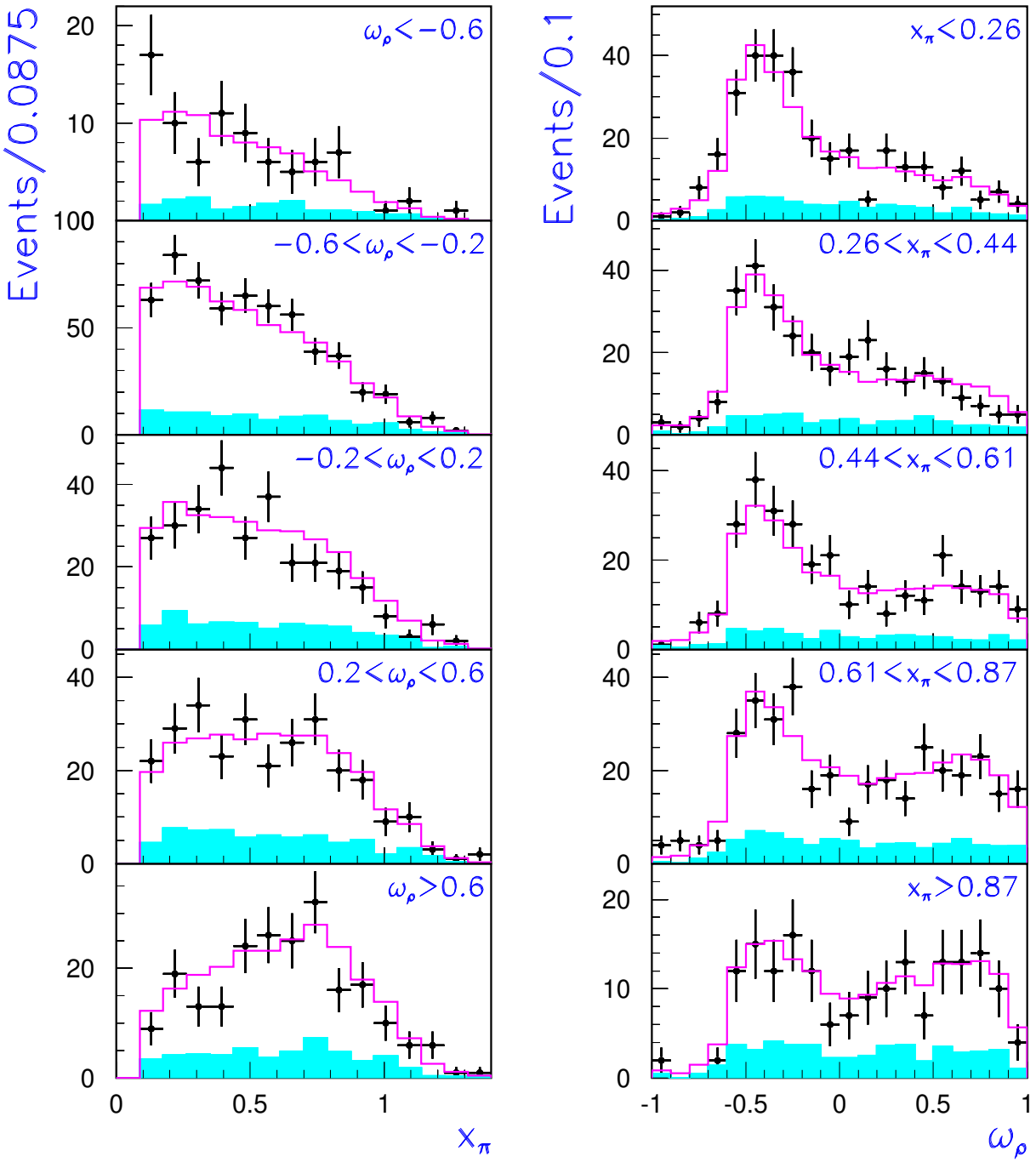
$$v_l = -0.03688 \pm 0.00085$$
$$a_l = -0.50115 \pm 0.00034$$



Standard Model prediction (yellow) for:

$$m_t = 175.6 \pm 5.5 \text{ GeV}$$

$$m_H = 300^{+700}_{-240} \text{ GeV}$$

Michel Parameter analysis (L3):

$$Z^0 \rightarrow \tau^+\tau^- \rightarrow (\pi\nu)(\rho\nu)$$