Neutral Current Physics

with the τ Lepton

at LEP

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DESY – IfH Zeuthen

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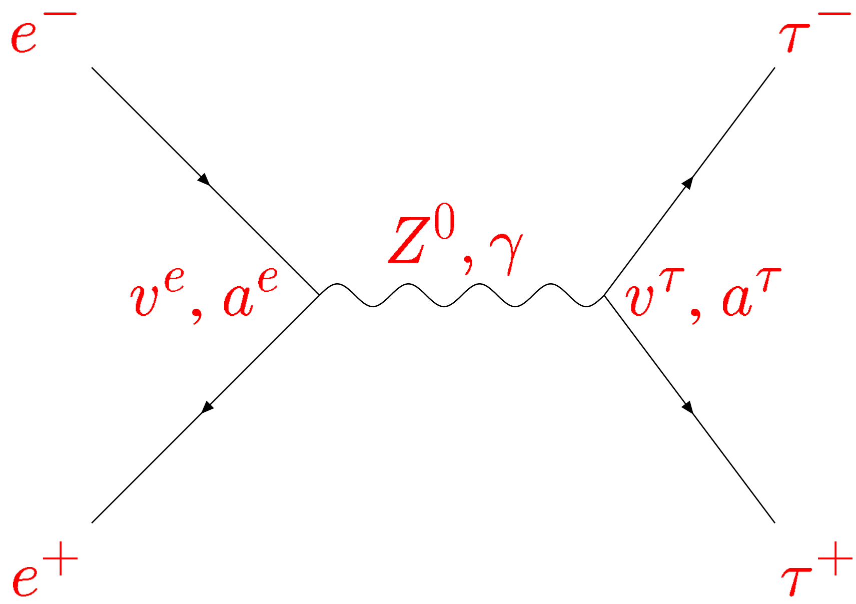


Motivation

$$\sigma \;=\; \sigma(e^- \quad e^+ \quad \longrightarrow \tau^- \quad \tau^+ \;)$$

$$V, A$$
$$\Downarrow$$

$$\begin{aligned}
\sigma_0 &= \sigma(e^-_L \quad e^+_R \quad \longrightarrow \tau^-_L \quad \tau^+_R \;) \\
\sigma_1 &= \sigma(e^-_L \quad e^+_R \quad \longrightarrow \tau^-_R \quad \tau^+_L \;) \\
\sigma_2 &= \sigma(e^-_R \quad e^+_L \quad \longrightarrow \tau^-_R \quad \tau^+_L \;) \\
\sigma_3 &= \sigma(e^-_R \quad e^+_L \quad \longrightarrow \tau^-_L \quad \tau^+_R \;)
\end{aligned}$$

observable at LEP:

$$\begin{aligned}
\sigma_{tot}(s) &= +\sigma_0+\sigma_1+\sigma_2+\sigma_3 \\
\sigma_{fb}(s) &= +\sigma_0-\sigma_1+\sigma_2-\sigma_3 \\
\sigma_{pol}(s) &= +\sigma_0-\sigma_1-\sigma_2+\sigma_3 \\
\sigma_{pol}^{fb}(s) &= +\sigma_0+\sigma_1-\sigma_2-\sigma_3
\end{aligned}$$

Motivation

$$\sigma_{tot}(s = M_Z^2) \sim (a_e^2 + v_e^2)(a_\tau^2 + v_\tau^2)$$

$$A_{fb}(s = M_Z^2) = \frac{\sigma_{fb}}{\sigma_{tot}} \sim \frac{a_e v_e a_\tau v_\tau}{(a_e^2 + v_e^2)(a_\tau^2 + v_\tau^2)}$$

$$P_\tau(s = M_Z^2) = \frac{\sigma_{pol}}{\sigma_{tot}} \sim -\frac{2 a_\tau v_\tau}{a_\tau^2 + v_\tau^2}$$

$$A_{pol}^{fb}(s = M_Z^2) = \frac{\sigma_{pol}^{fb}}{\sigma_{tot}} \sim -\frac{3}{2}\frac{a_e v_e}{a_e^2 + v_e^2}$$

- polarization asymmetries P_τ,A_{pol}^{fb} are linear in the couplings
- e, τ universality could be tested in one Z^0 decay mode
- because the τ decays inside the detector P_τ,A_{pol}^{fb} are measurable

$$\Downarrow$$

the only channel, where a complete cross section analysis is possible :

$$e^- e^+ \longrightarrow \tau^- \tau^+$$

Outline

0. Motivation

1. τ Data at LEP

2. Total Cross Section

3. Forward Backward Asymmetry

4. Polarization Asymmetries

5. τ Couplings, $\sin^2\theta_W^{\mathrm{eff}}$

6. S-Matrix

7. Conclusion

τ Data at LEP

	1989-1991	1992
Aleph	17K	23K
Delphi	10K	17K
L3	10K	15K
Opal	16K	28K
total	53K	83K

136K $\tau^+\tau^-$ pairs are collected at LEP
until end 1992 !

τ Data at LEP

How does a $\tau^+\tau^-$ event look at LEP ?

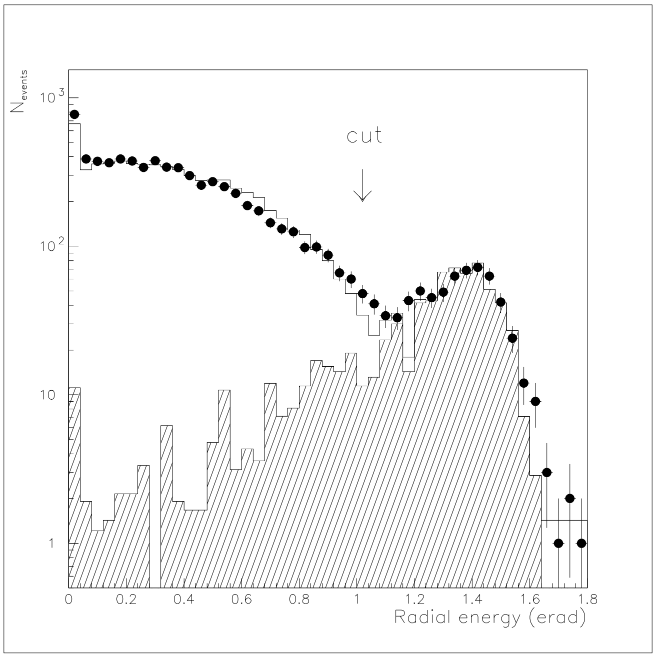
- two collimated back to back jets
- low multiplicity
- missing energy due to ν
- neutral particles

And the background ?

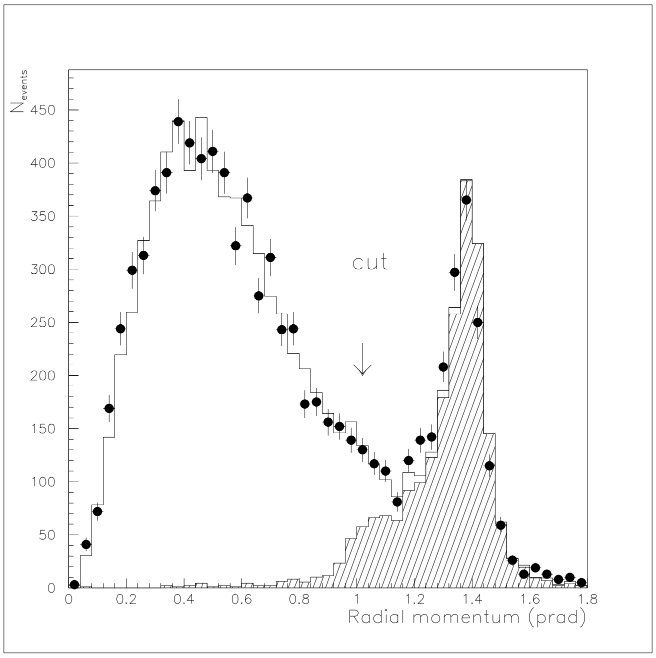
$q\bar{q}$: high multiplicity
e^+e^- : back to back, $E_e \cong E_{beam}$
$\mu^+\mu^-$: back to back, $P_\mu \cong E_{beam}$
2γ : low energy, highly acollinear

Rejection of e^+e^- and $\mu^+\mu^-$ events by DELPHI

$E_{\text{rad}} = \sqrt{E_1^2 + E_2^2}$
reject e^+e^- events



$P_{\text{rad}} = \sqrt{P_1^2 + P_2^2}$
reject $\mu^+\mu^-$ events



Total Cross Section

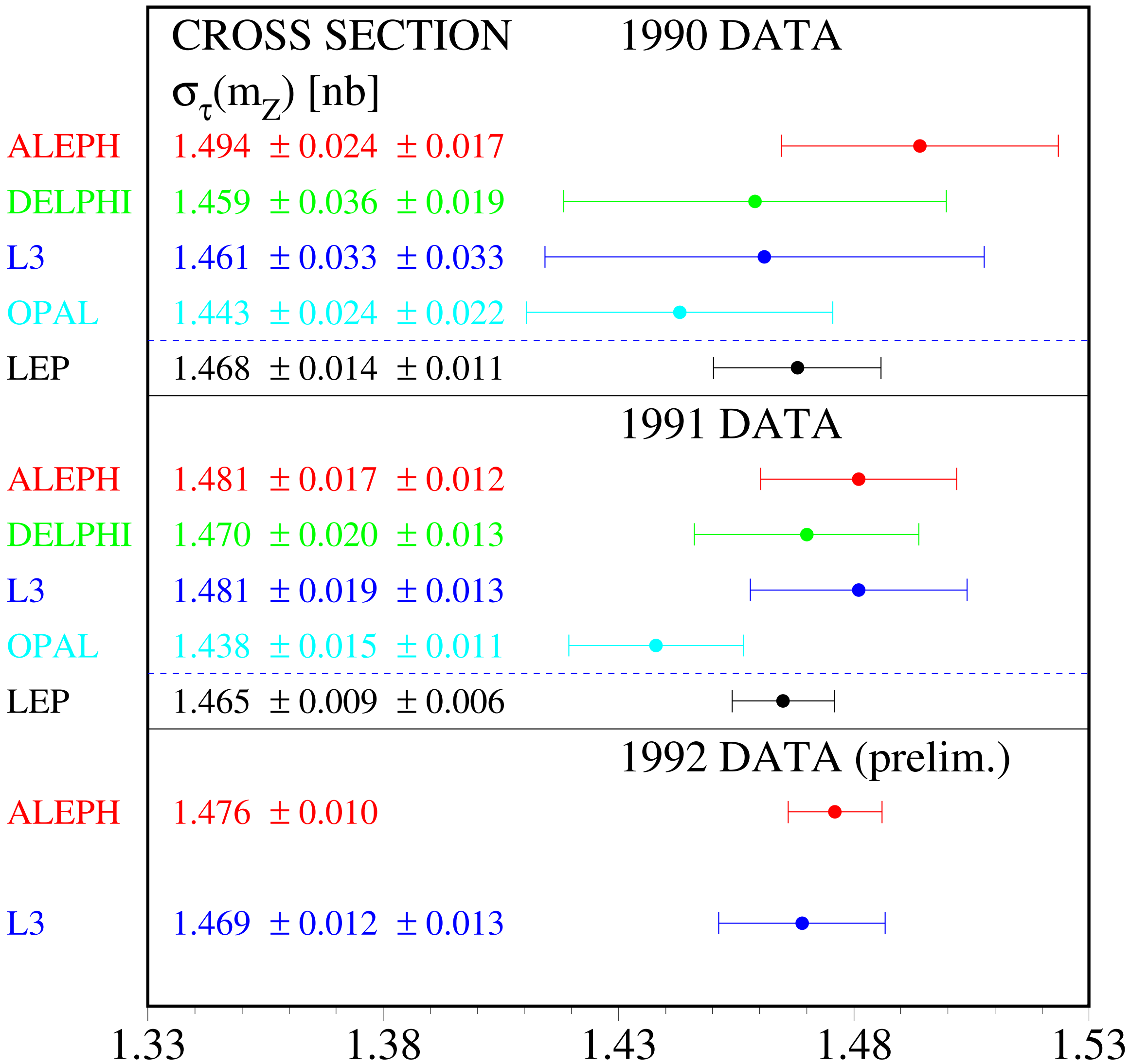
$$\sigma_{tot} = \frac{N^{(sel)}_{\tau^+\tau^-} - BG}{\epsilon \mathcal{L} A}$$

OPAL 1990-91 systematic error

	Uncertainity [%]
Acceptance/Efficiency:	
$e^+e^- \longrightarrow \tau^+\tau^-$Monte Carlo	0.19
τ pair selection cuts	0.42
definition of $\mid cos\theta \mid$	0.39
trigger efficiency	0.06
uncertainty of τ branching fraction	<0.05
other sources	0.10
Background :	0.45
Luminosity :	0.60
overall	0.75

Total Cross Section

$\sigma_\tau(m_Z)$ at LEP



Forward Backward Asymmetry

$$A_{fb} = \frac{\sigma(\cos\theta > 0) - \sigma(\cos\theta < 0)}{\sigma_{tot}}$$

- θ is the angle between e^- and τ^- in the (r, z) – plane

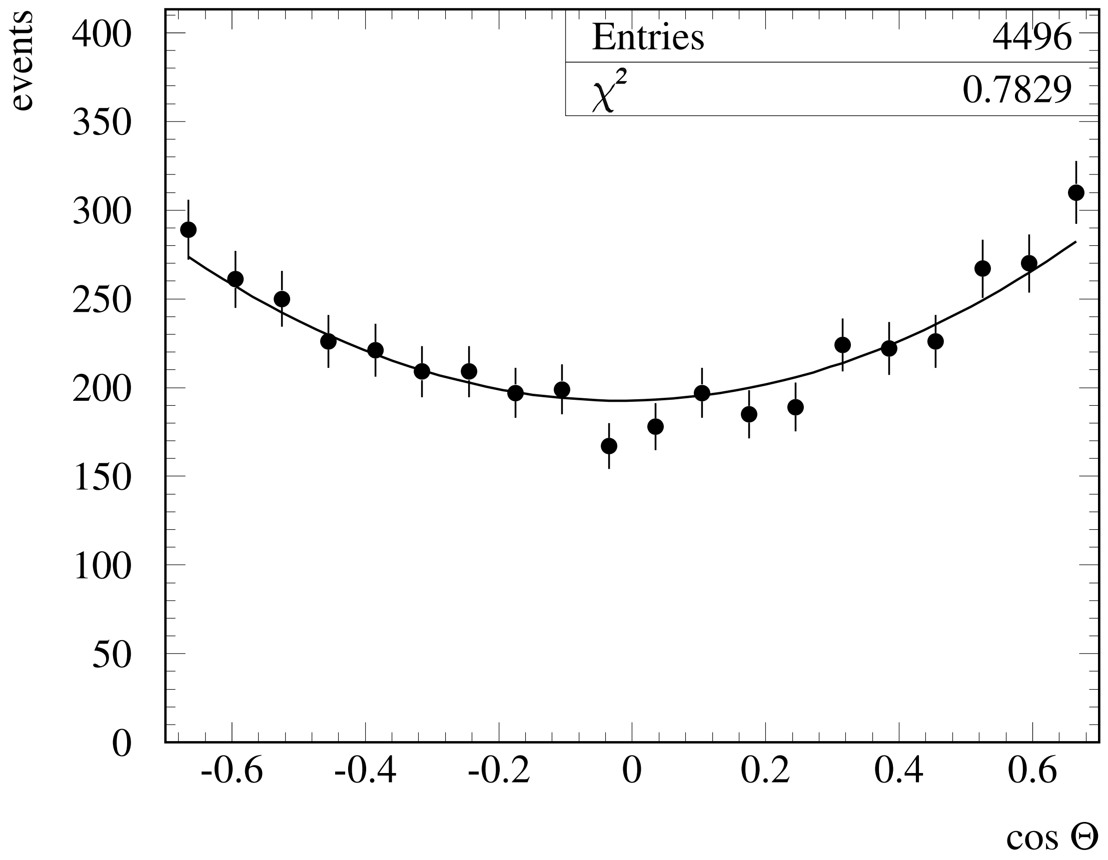
Method : Fit of

$$\frac{1}{\sigma_{tot}(s)} \frac{d\sigma(s)}{d\cos\theta} = \frac{3}{8}(1 + \cos^2\theta) + A_{fb}(s)\cos\theta$$

- systematic error related to normalization cancel out !!!
  - luminosity
  - acceptance
  - efficiency
- charge confusion !

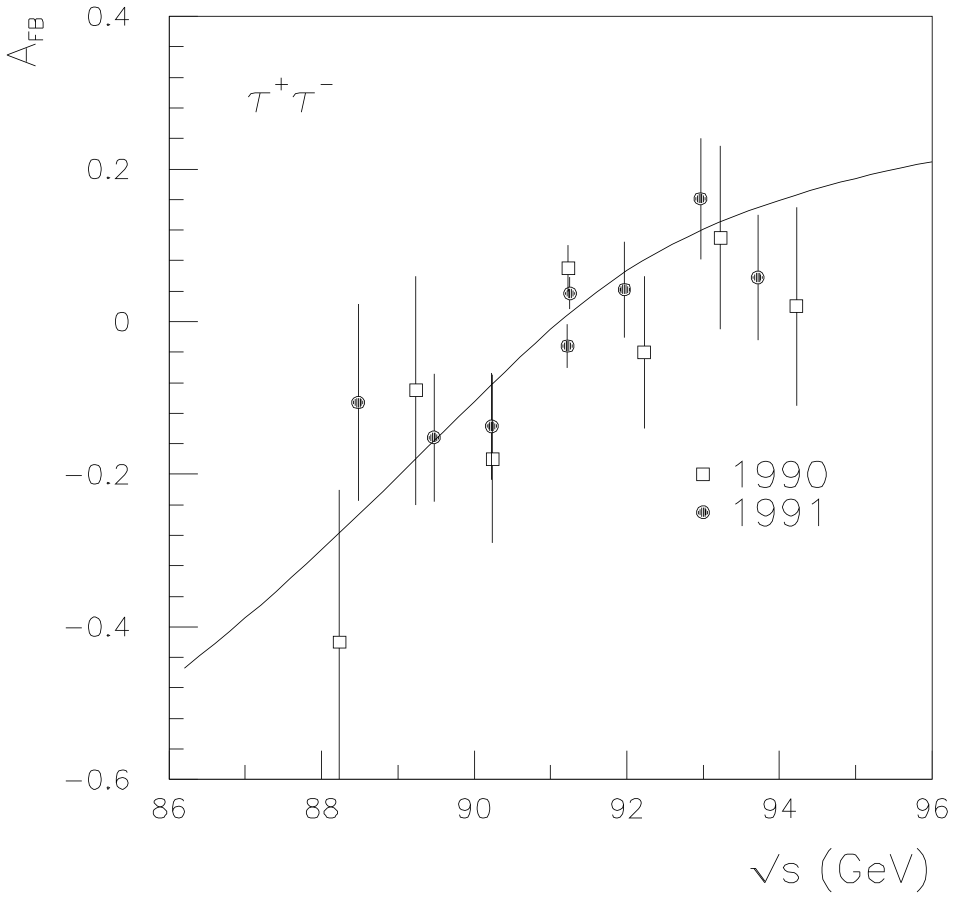
Forward Backward Asymmetry

Distribution of cos Θ (on peak)

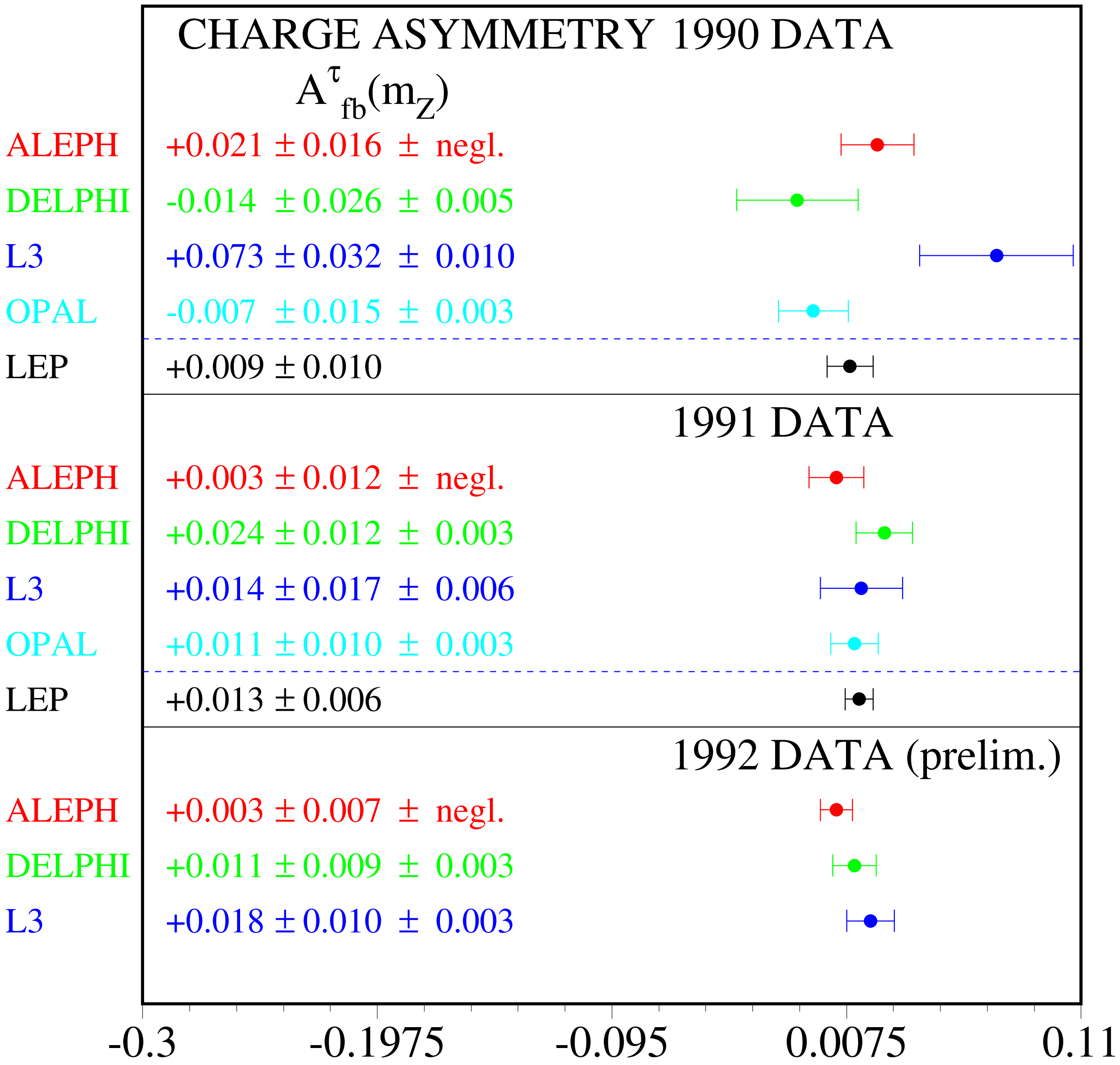


Systematic Error of Charge Asymmetry Measurement	
Source	Systematic Error δA_{fb}
TEC Charge Confusion	$< 0.001 \cdot A_{fb}$
Background Subtraction	0.003
Cosmic Contamination	< 0.001
Total Systematic Error	0.003

Forward Backward Asymmetry



$A^{\tau}_{fb}(m_Z)$ at LEP



Polarization Asymmetry

$$P_\tau(\cos\theta) = \frac{A_\tau(1+\cos^2\theta) + A_e(2\cos\theta)}{(1+\cos^2\theta) + A_\tau A_e(2\cos\theta)}$$

$$P_\tau = -A_\tau \sim -\frac{2a_\tau v_\tau}{a_\tau^2 + v_\tau^2}$$

$$A_{pol}^{fb} = -\frac{3}{4}A_e \sim -\frac{3}{2}\frac{a_e v_e}{a_e^2 + v_e^2}$$

- study of parity violation in the weak neutral current
- assumption: V-A in charged current
- P_τ, A_{pol}^{fb} linear in couplings
- test of e, τ universality
- independent precise measurement of $\sin^2\theta_W^{\mathrm{eff}}$

$$\triangle \sin^2\theta_w = \frac{1}{8} \triangle P_\tau$$

$$\triangle \sin^2\theta_w = \frac{1}{6} \triangle A_{pol}^{fb}$$

$$\triangle \sin^2\theta_w = \frac{1}{2} \triangle A_{fb}$$

Polarization Asymmetry

τ – Decay Modes

Branching Ratio	Decay Mode	Characteristic
18 %	$\tau \longrightarrow e + \nu\nu$	three body decay
18 %	$\tau \longrightarrow \mu + \nu\nu$	two particles not detectable
		$\Rightarrow$ loss of sensitivity
11 %	$\tau \longrightarrow \pi + \nu$	two body decay
		one particle not detectable
		π has spin 0
		$\Rightarrow$ most sensitive channel
23 %	$\tau \longrightarrow \rho + \nu$	two body decay
7 %	$\tau \longrightarrow a_1 + \nu$	ρ, a_1 mesons with $s = 1$
		two spin projections possible
		$\Rightarrow$ sensitivity reduced
		$\Rightarrow$ regain sensitivity by
		analyzing the decay of ρ, a_1

Polarization Asymmetry

ALEPH

- Acceptance $|\cos\theta| < 0.9$
- precise 3D track measurement (TPC)

$\Rightarrow a_1$

- 3D segmentation of ECAL $\longrightarrow \pi^0$, γ separation

$\Rightarrow \rho$, π

DELPHI

- Acceptance $|\cos\theta| < 0.7$
- precise 3D track measurement (TPC)

$\Rightarrow a_1$

L3

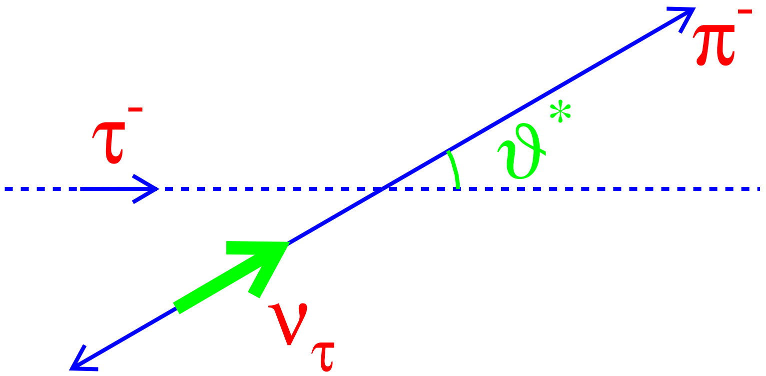
- Acceptance $|\cos\theta| < 0.7$
- very good energy resolution in ECAL (BGO) $\longrightarrow \pi^0$, γ separation

$\Rightarrow$ e, π, ρ

OPAL

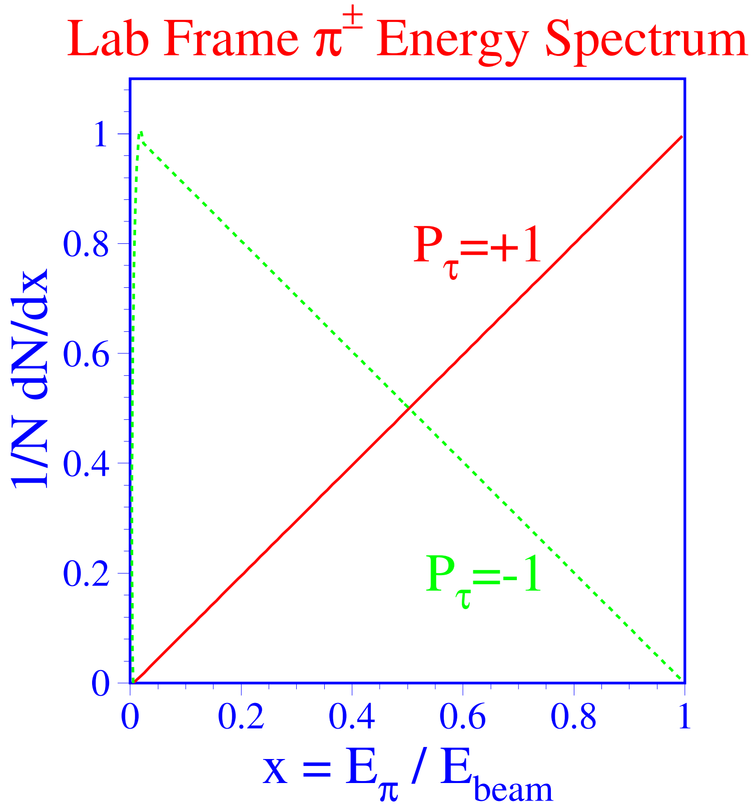
- Acceptance $|\cos\theta| < 0.9$
- high resolution tracker, $\frac{dE}{dx}$

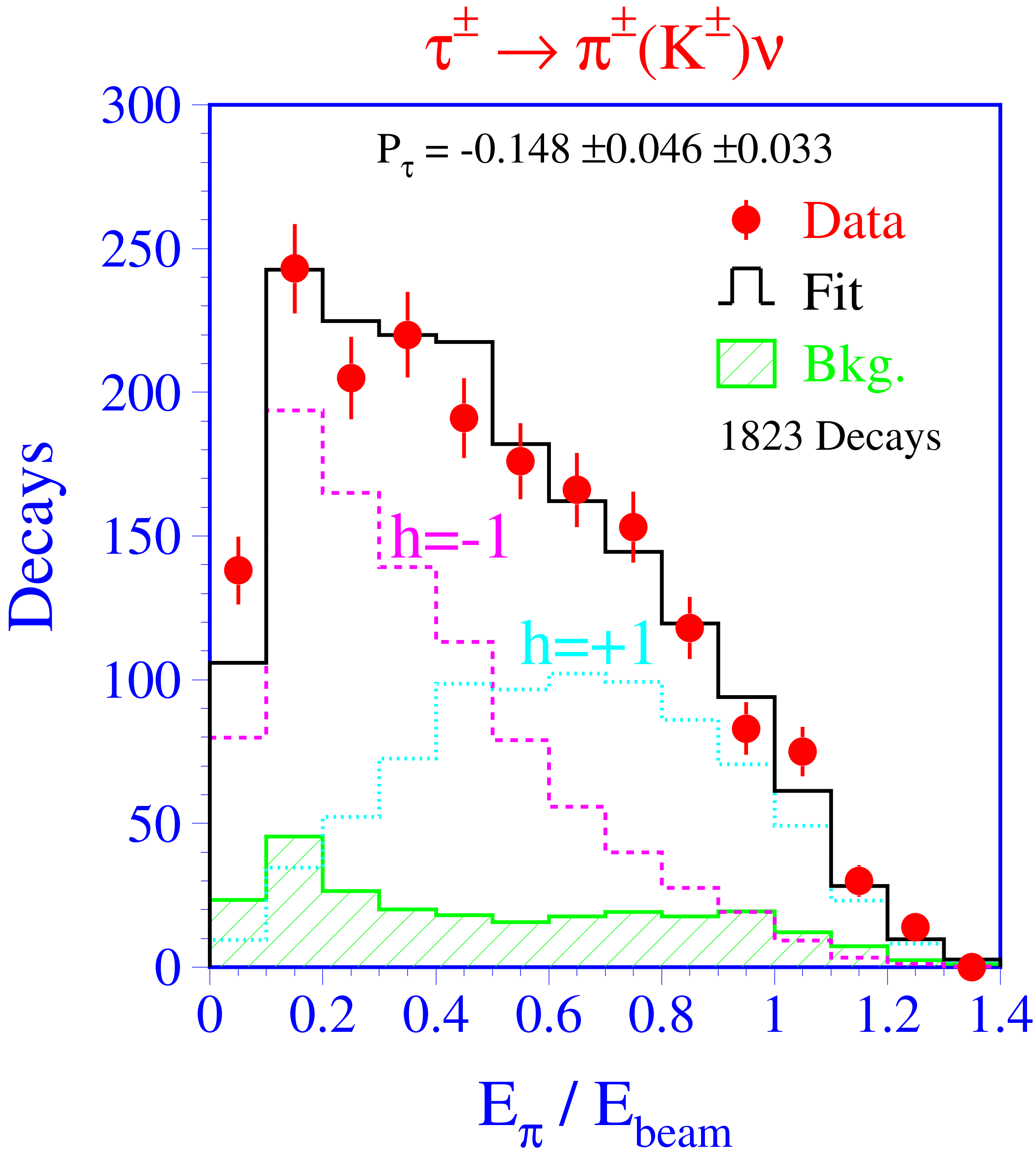
$\Rightarrow$ all channels except a_1



τ rest frame : $\cos\theta^* \Longleftrightarrow$ lab frame : $E_{\pi^\pm}/E_{\text{beam}} \equiv x$

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



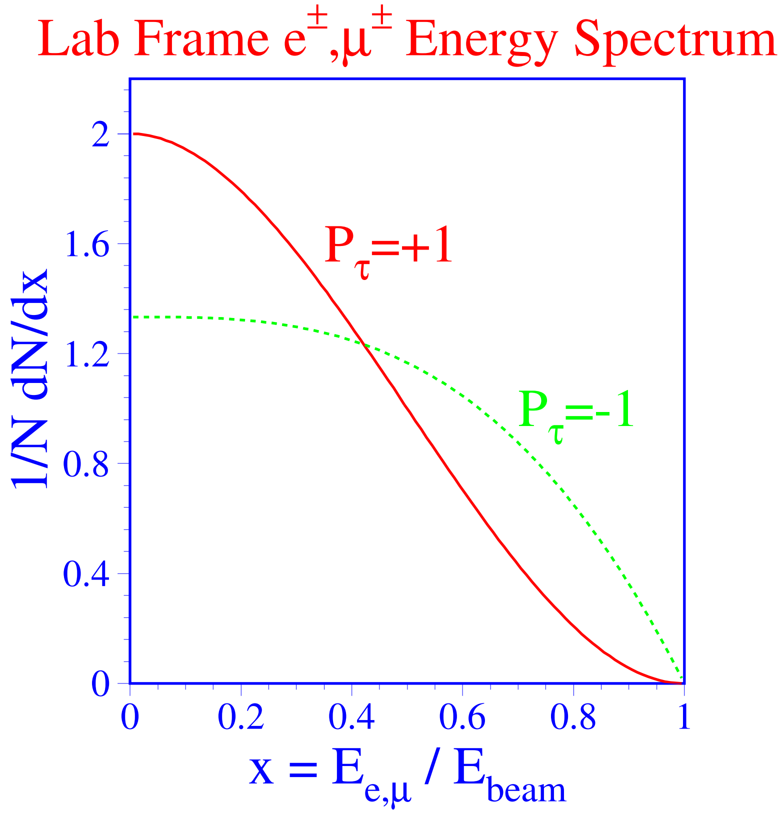


$\tau^\pm \to \pi^\pm(K^\pm)\nu$
P_τ = -0.148 ±0.046 ±0.033
Data
Fit
Bkg.
1823 Decays
h=-1
h=+1
Decays
300
250
200
150
100
50
0
0.2
0.4
0.6
0.8
1
1.2
1.4
E_π / E_{beam}

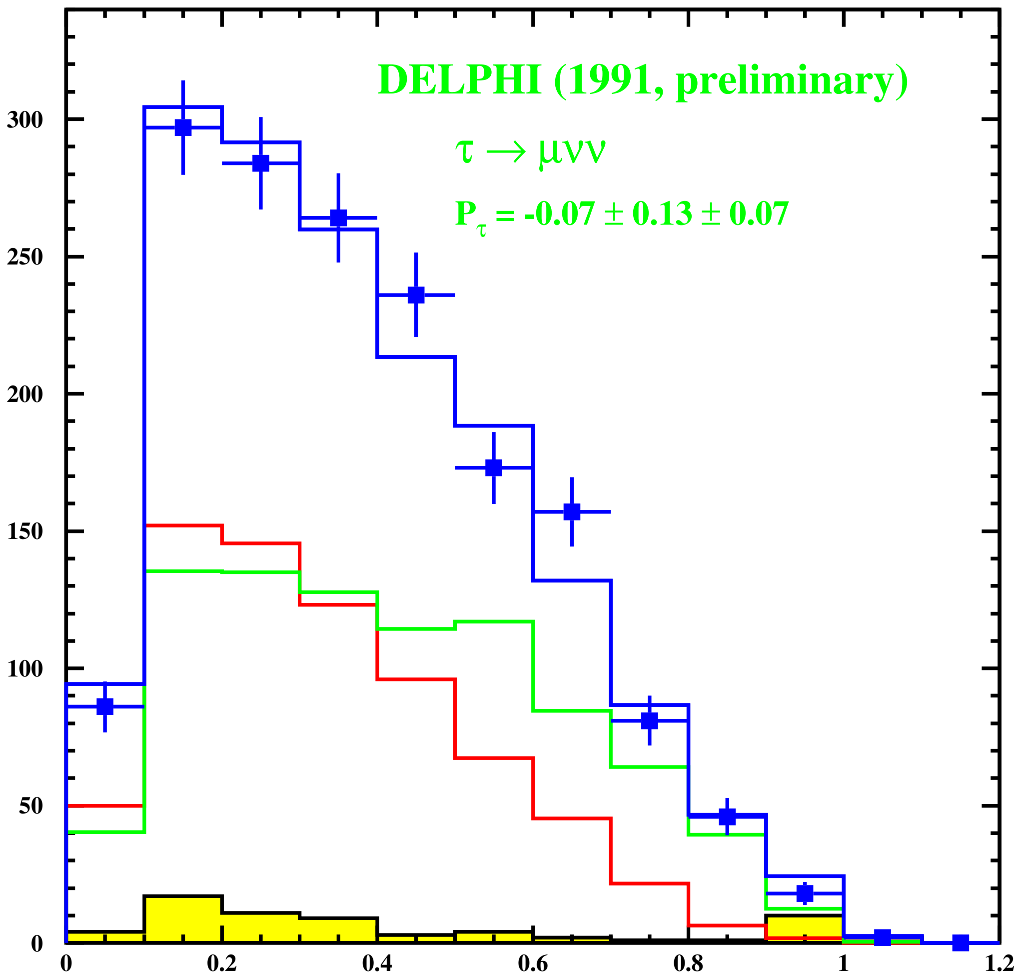
$\tau \longrightarrow e + \nu\nu$ and $\tau \longrightarrow \mu + \nu\nu$

$$\frac{1}{N}\frac{dN}{dx} = \frac{1}{3}[(5 - 9x^2 + 4x^3) + P_\tau(1 - 9x^2 + 8x^3)]$$

$$x = E_\ell / E_{\mathrm{beam}}, \ell = \mathrm{e}^\pm, \mu^\pm$$



$\tau \longrightarrow \mu + \nu\nu$

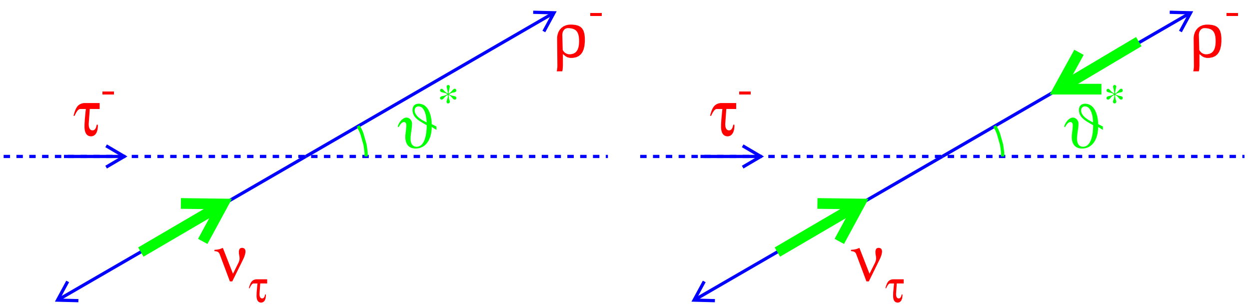


— $h = -1$

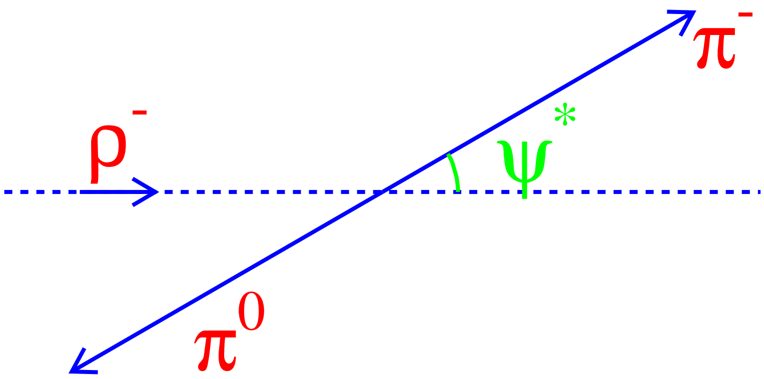
— $h = +1$

$\tau \longrightarrow \rho + \nu$

- two ρ spin states possible



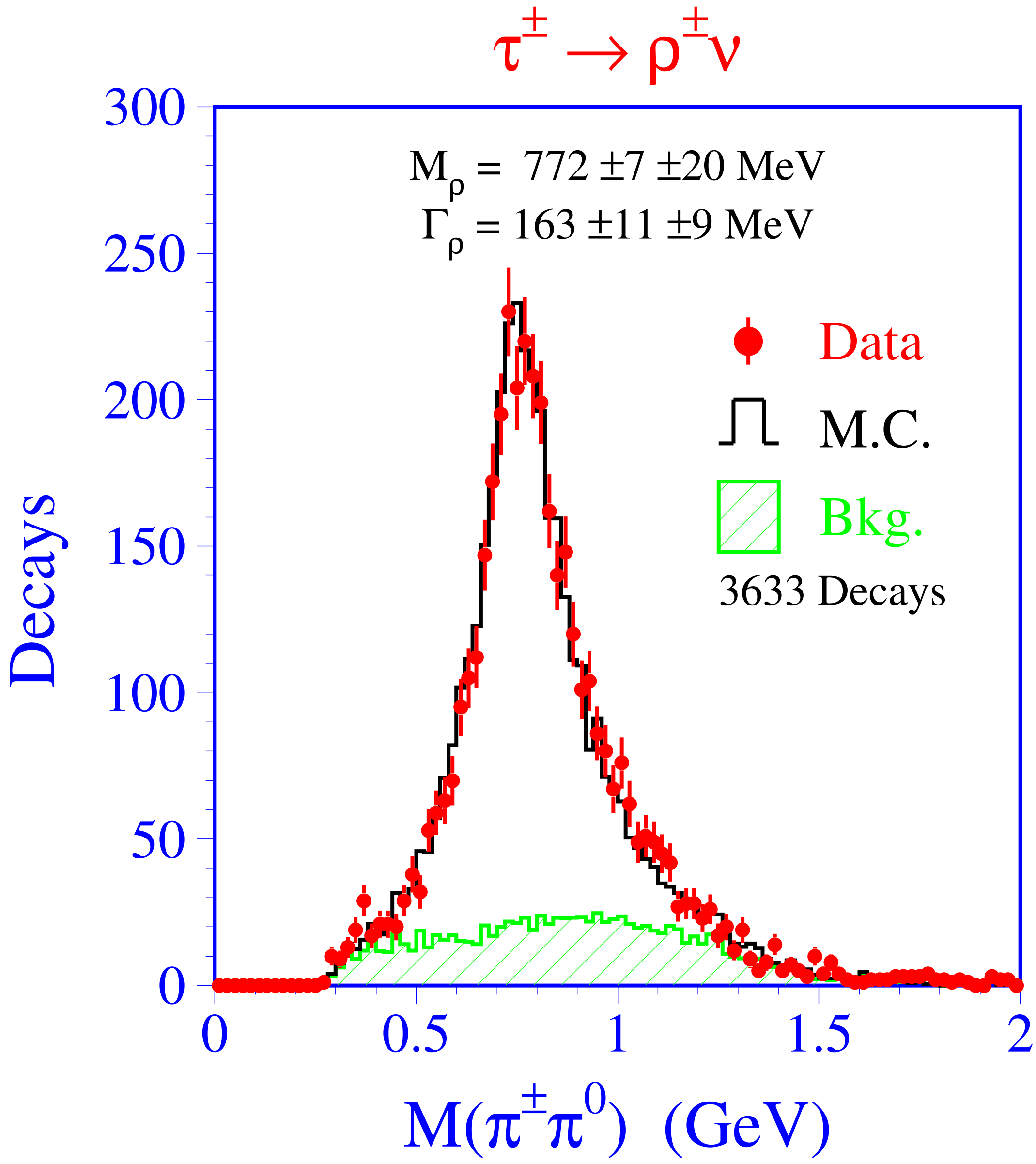
- $\frac{1}{N}\frac{dN}{dx} \approx 1 + \alpha P_\tau(2x-1)$
- sensitivity reduced by factor $\alpha = \frac{{m_\tau}^2 - 2{m_\rho}^2}{{m_\tau}^2 + 2{m_\rho}^2} \approx 0.45$
- recover sensitivity by analyzing the decay of the ρ



- sensitivity depends also on $m_\rho(\Gamma_\rho = 152\text{MeV})$

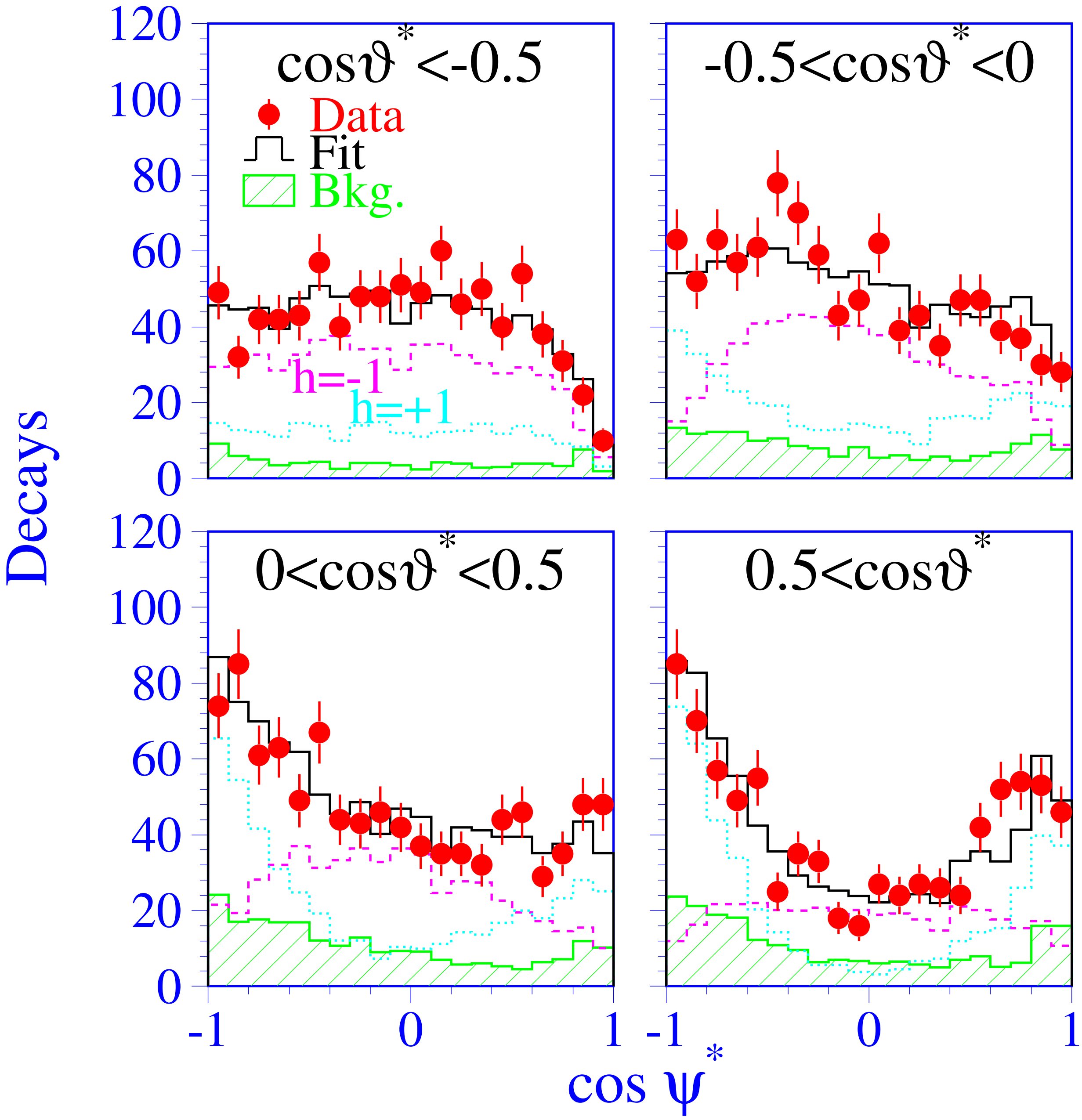
$\Rightarrow$ 3-D fit: $\cos\theta^*$, $\cos\psi^*$, m_ρ

$\tau \longrightarrow \rho + \nu$



$\tau \longrightarrow \rho + \nu$

$P_\tau = -0.152 \pm 0.035 \pm 0.029$



The Optimal Method to Measure the τ Polarization

Ref: M.Davier et al. Preprint LAL 92-73 or X-LPNHE 92-22

For any decay mode $\tau \longrightarrow X\nu$ the probability density distribution for X has the general form:

$$W(\vec{\xi}) = f(\vec{\xi}) + P_\tau g(\vec{\xi})$$

$\vec{\xi}$ – set of variables, which describe the τ decay

$$\begin{array}{lll} \mathrm{e},\ \mu,\ \pi & \Rightarrow & x = E_{e,\mu,\pi}/E_{beam} \\ \rho & \Rightarrow & \cos\theta^*,\ \cos\psi^*,\ m_{\pi\pi^0} \\ a_1 & \Rightarrow & \cos\theta^*,\ \beta,\ \gamma,\ m_{\pi\pi\pi},\ S_1,\ S_2 \end{array}$$

the true polarization maximizes the likelihood

$$\frac{\delta}{\delta P_\tau} \log \mathcal{L} = \sum_i \frac{g(\vec{\xi_i})}{f(\vec{\xi_i}) + P_\tau g(\vec{\xi_i})} = \sum_i \frac{\omega_i}{1 + P_\tau \omega_i} = 0$$

$\Rightarrow \omega = g(\vec{\xi})/f(\vec{\xi})$ optimal variable

The Optimal Method to Measure the τ Polarization

multidimensional Distribution		onedimensional Distribution
$W(\vec{\xi})$	$\Rightarrow$	$W(\omega)$

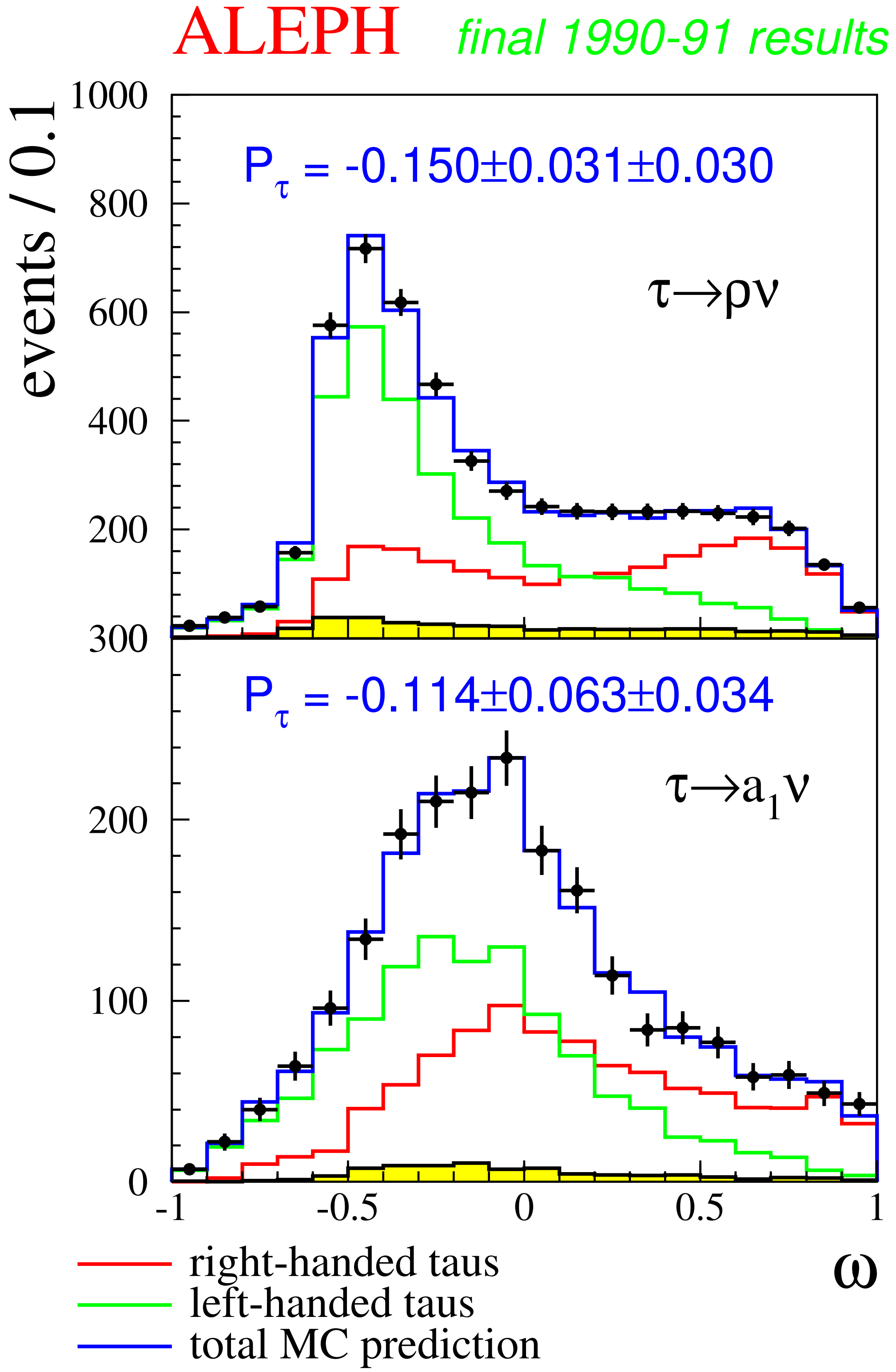
No Loss in Sensitivity !!!

$$S = \frac{1}{\sigma(P_\tau)\sqrt{N}} = \sqrt{\langle \frac{\omega^2}{(1+P_\tau\omega)^2} \rangle}$$

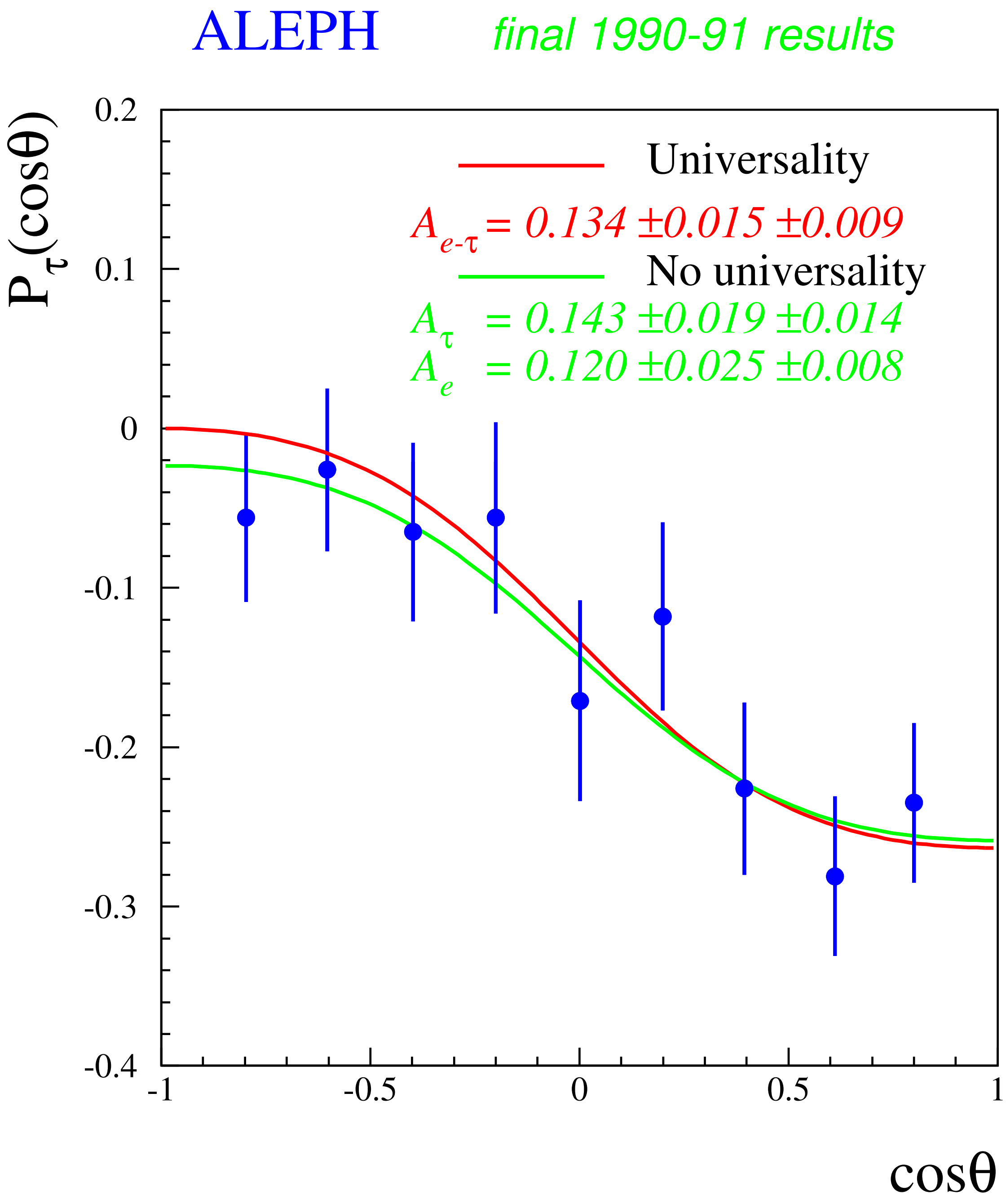
$$W \sim S^2 \times BranchingRatio$$

Channel	Sensitivity Number of Observables				Weight
	1	2	all but τ	with τ	
$\pi\nu$	0.58	-	0.58	0.58	0.32
$\rho\nu$	0.26	0.49	0.49	0.58	0.48
$a_1\nu$	0.10	0.23	0.45	0.58	0.12
$l\nu\nu$	0.22	-	0.22	0.27	0.08

$\tau \longrightarrow a_1 + \nu$



Forward Backward Polarization Asymmetry



τ Polarization Measured from $\tau^+\tau^-$ Decay Correlations

Ref: R.Alemany et al. Nucl.Phys. B379,3 (1992)

- $\frac{m_\tau^2}{m_Z^2} << 1 \Rightarrow$ helicities of the two taus opposite

$\Rightarrow$ $\tau^+\tau^-$ decays are correlated

- LAB frame $\Rightarrow$ energies and angles are correlated !
- Acollinearity of the charged decay particle is a independent measurement

$$\frac{1}{\sigma}\frac{d\sigma}{d\epsilon} = Q_{11}(\epsilon) + \alpha_1\alpha_2 Q_{22}(\epsilon) + P_\tau\{\alpha_1 Q_{21}(\epsilon) + \alpha_2 Q_{12}(\epsilon)\}$$

$\pi - \pi$ $\qquad\qquad$ $\pi - X$

— $h = +1$, ... $h = -1$

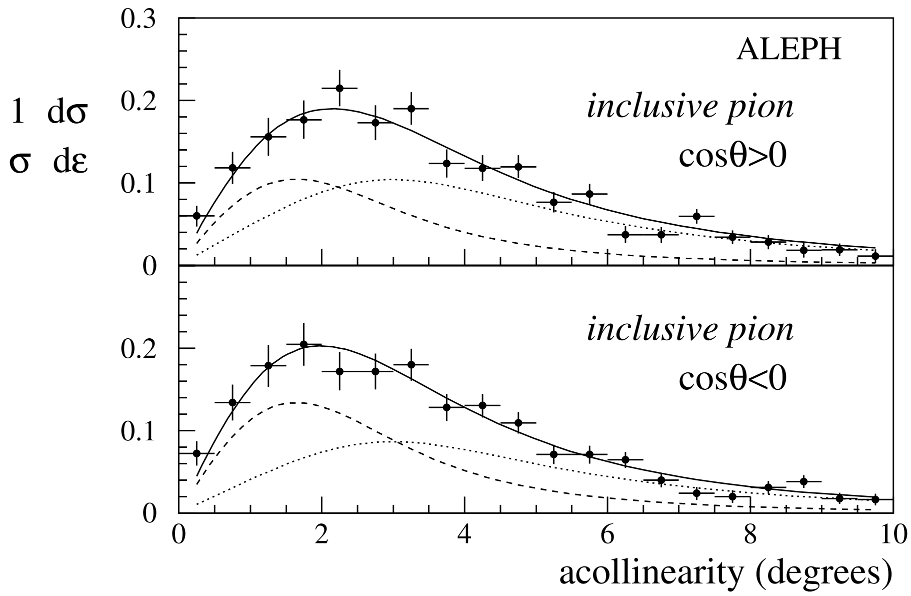
τ Polarization Measured from $\tau^+\tau^-$ Decay Correlations

Measured Channel	Analyzing Power $A = \frac{1}{\sigma(P_\tau)}$	Sensitivity $S = \frac{A}{\sqrt{N}}$
$\mathrm{e} - \mu$	0.33	0.21
$\pi - \pi$	0.98	0.22
$\pi - \mathrm{l}$	0.36	0.13
$\mathrm{l} - \mathrm{X}$	0.23	0.22
$\pi - \mathrm{X}$	0.49	0.44
$\mathrm{h} - \mathrm{h}$	0.26	0.25

- Analyzing Power is normalized to the value for $\tau \rightarrow \pi$ channel in the standard method

$\tau_1 \longrightarrow \pi\nu, \tau_2 \longrightarrow X$

ALEPH final 1990-91 results



- $\pi - X$; 1 – 1
- analytical fit
- data corrected for resolution and radiation effects

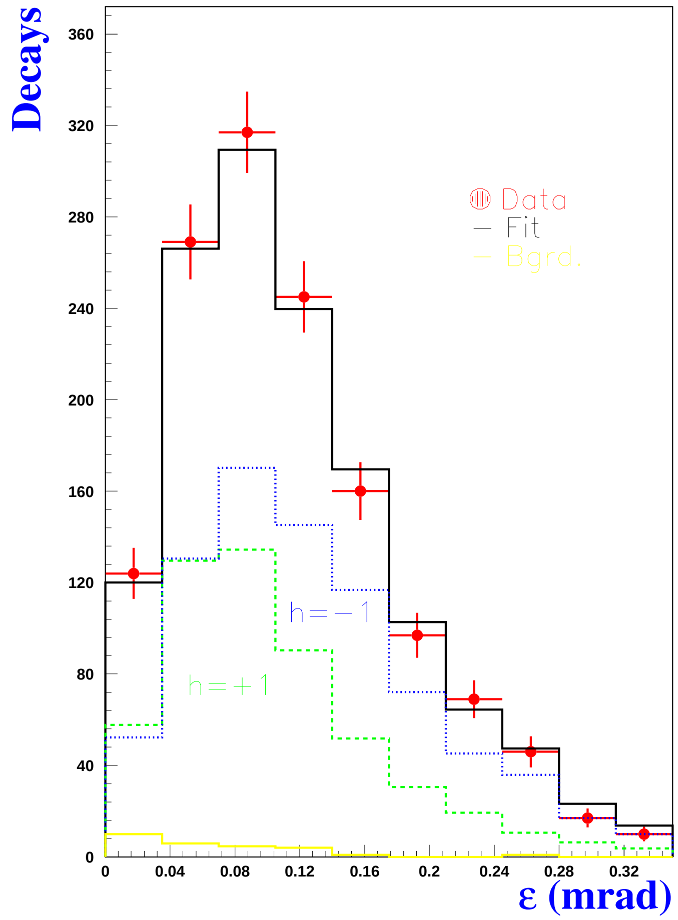
Results

$$A_e = 0.154 \pm 0.079 \pm 0.002$$
$$A_\tau = 0.147 \pm 0.059 \pm 0.011$$

$\tau_1 \longrightarrow \pi\nu, \tau_2 \longrightarrow X$

preliminary 1990-91 result

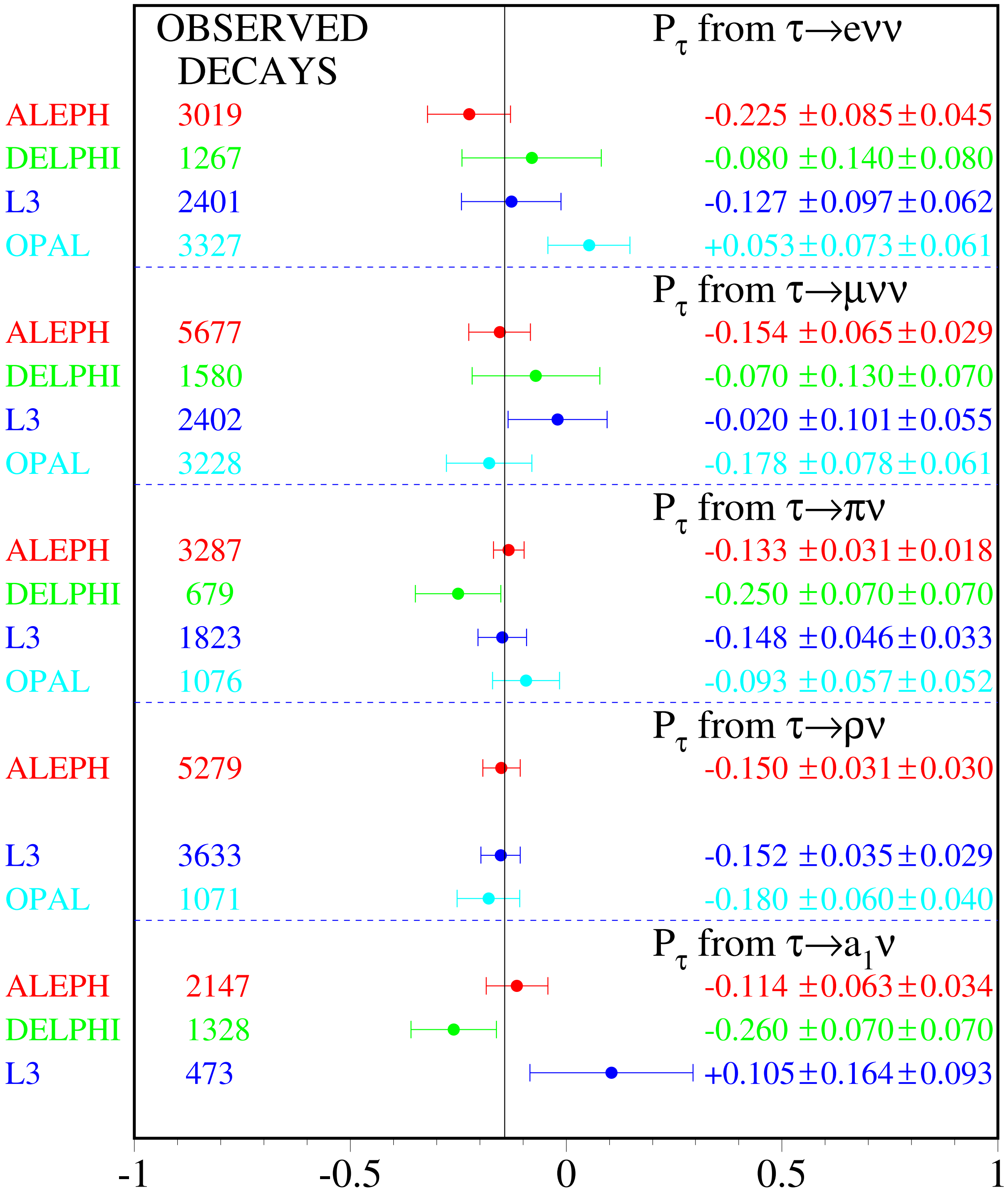
$P_\tau = -0.13 \pm 0.14 \pm 0.03$



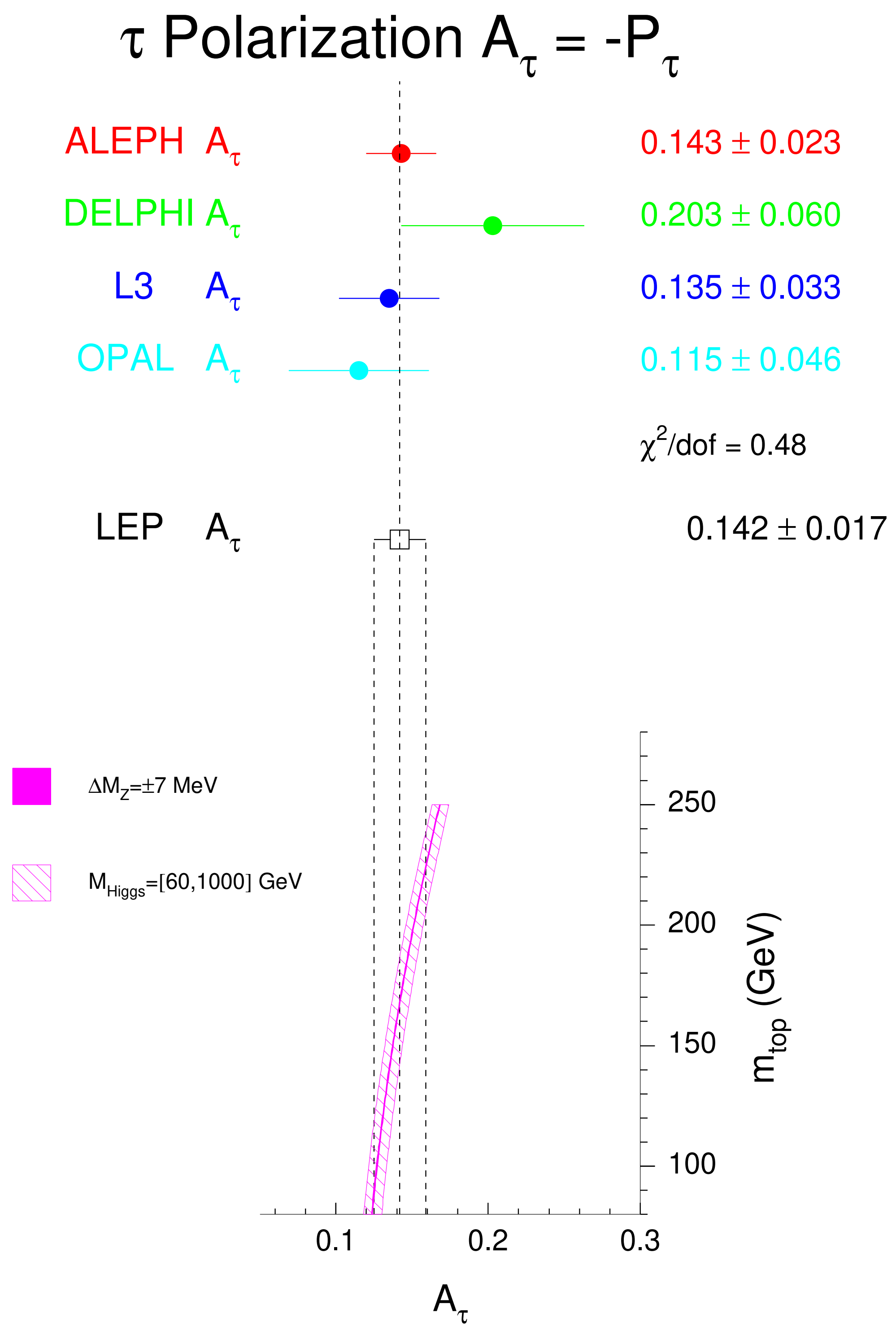
- MC reweighting
- no accurate measurement of the z-vertex

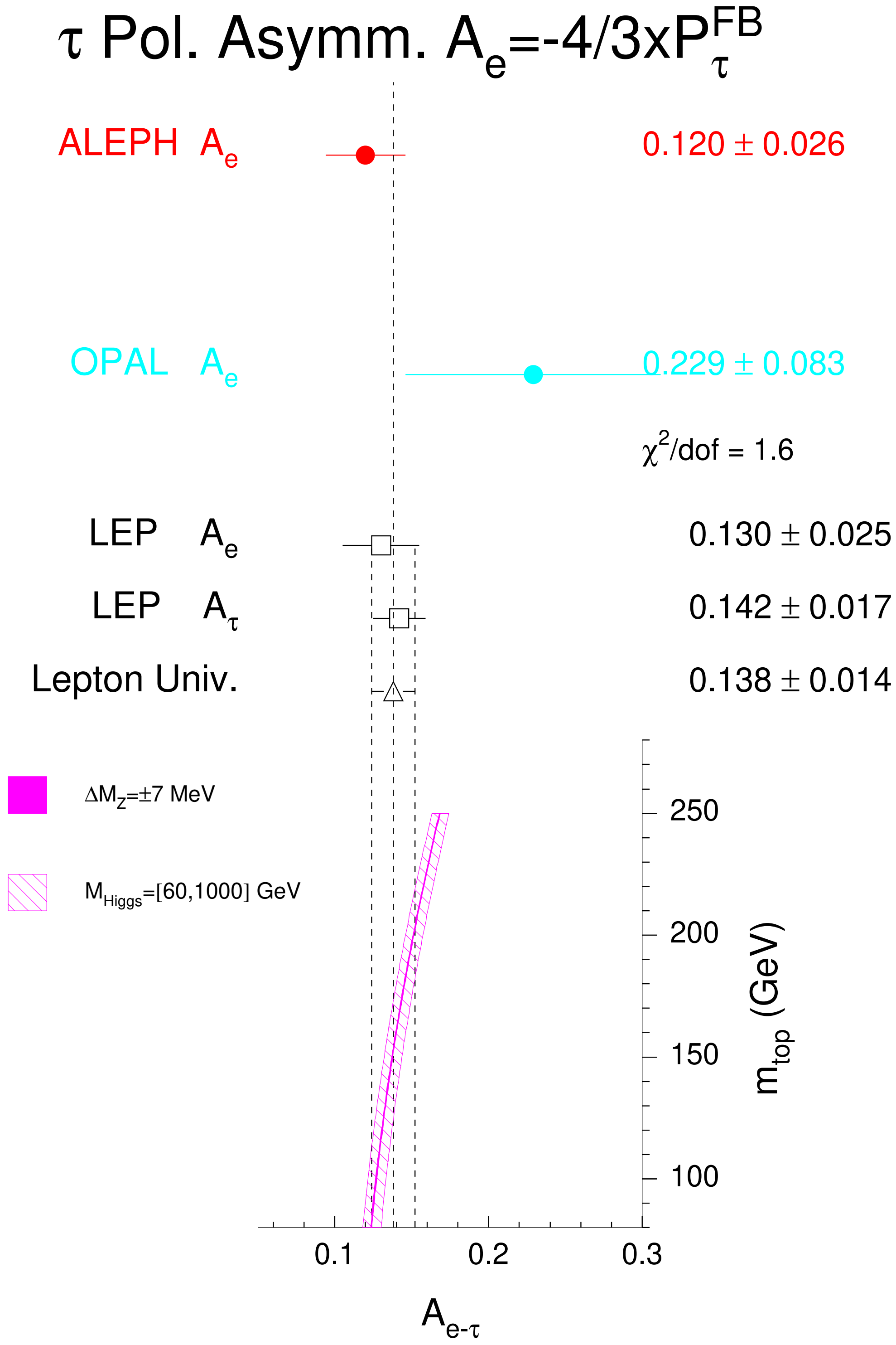
⇒ resolution limited by bunch length

P_τ at LEP


OBSERVED DECAYS
Pτ from τ→eνν
ALEPH 3019 -0.225 ±0.085±0.045
DELPHI 1267 -0.080 ±0.140±0.080
L3 2401 -0.127 ±0.097±0.062
OPAL 3327 +0.053±0.073±0.061
Pτ from τ→μνν
ALEPH 5677 -0.154 ±0.065±0.029
DELPHI 1580 -0.070 ±0.130±0.070
L3 2402 -0.020 ±0.101±0.055
OPAL 3228 -0.178 ±0.078±0.061
Pτ from τ→πν
ALEPH 3287 -0.133 ±0.031±0.018
DELPHI 679 -0.250 ±0.070±0.070
L3 1823 -0.148 ±0.046±0.033
OPAL 1076 -0.093 ±0.057±0.052
Pτ from τ→ρν
ALEPH 5279 -0.150 ±0.031±0.030
L3 3633 -0.152 ±0.035±0.029
OPAL 1071 -0.180 ±0.060±0.040
Pτ from τ→a1ν
ALEPH 2147 -0.114 ±0.063±0.034
DELPHI 1328 -0.260 ±0.070±0.070
L3 473 +0.105±0.164±0.093
-1
-0.5
0
0.5
1

P_τ at LEP


τ Polarization A_τ = -P_τ
ALEPH A_τ
0.143 ± 0.023
DELPHI A_τ
0.203 ± 0.060
L3 A_τ
0.135 ± 0.033
OPAL A_τ
0.115 ± 0.046
χ^2/dof = 0.48
LEP A_τ
0.142 ± 0.017
ΔM_Z=±7 MeV
M_{Higgs}=[60,1000] GeV
250
200
150
100
m_{top} (GeV)
0.1
0.2
0.3
A_τ


τ Pol. Asymm. A_e=-4/3xP_τ^{FB}
ALEPH A_e
0.120 ± 0.026
OPAL A_e
0.229 ± 0.083
χ^2/dof = 1.6
LEP A_e
0.130 ± 0.025
LEP A_τ
0.142 ± 0.017
Lepton Univ.
0.138 ± 0.014
ΔM_Z=±7 MeV
M_{Higgs}=[60,1000] GeV
250
200
150
100
m_{top} (GeV)
0.1
0.2
0.3
$A_{e-\tau}$

e–τ Universality

$$\begin{aligned} A_\tau &= 0.142 \pm 0.017 \\ A_e &= 0.130 \pm 0.025 \end{aligned}$$

- universality holds for A_e, A_τ !

How it looks for the couplings?

$$\begin{aligned} \Gamma_\tau &= 83.33 \pm 0.51 \text{ MeV} \\ \Gamma_e &= 83.60 \pm 0.33 \text{ MeV} \\ A^0_{fb}(\tau^+\tau^-) &= 0.0208 \pm 0.0034 \\ A^0_{fb}(e^+e^-) &= 0.0155 \pm 0.0041 \end{aligned}$$

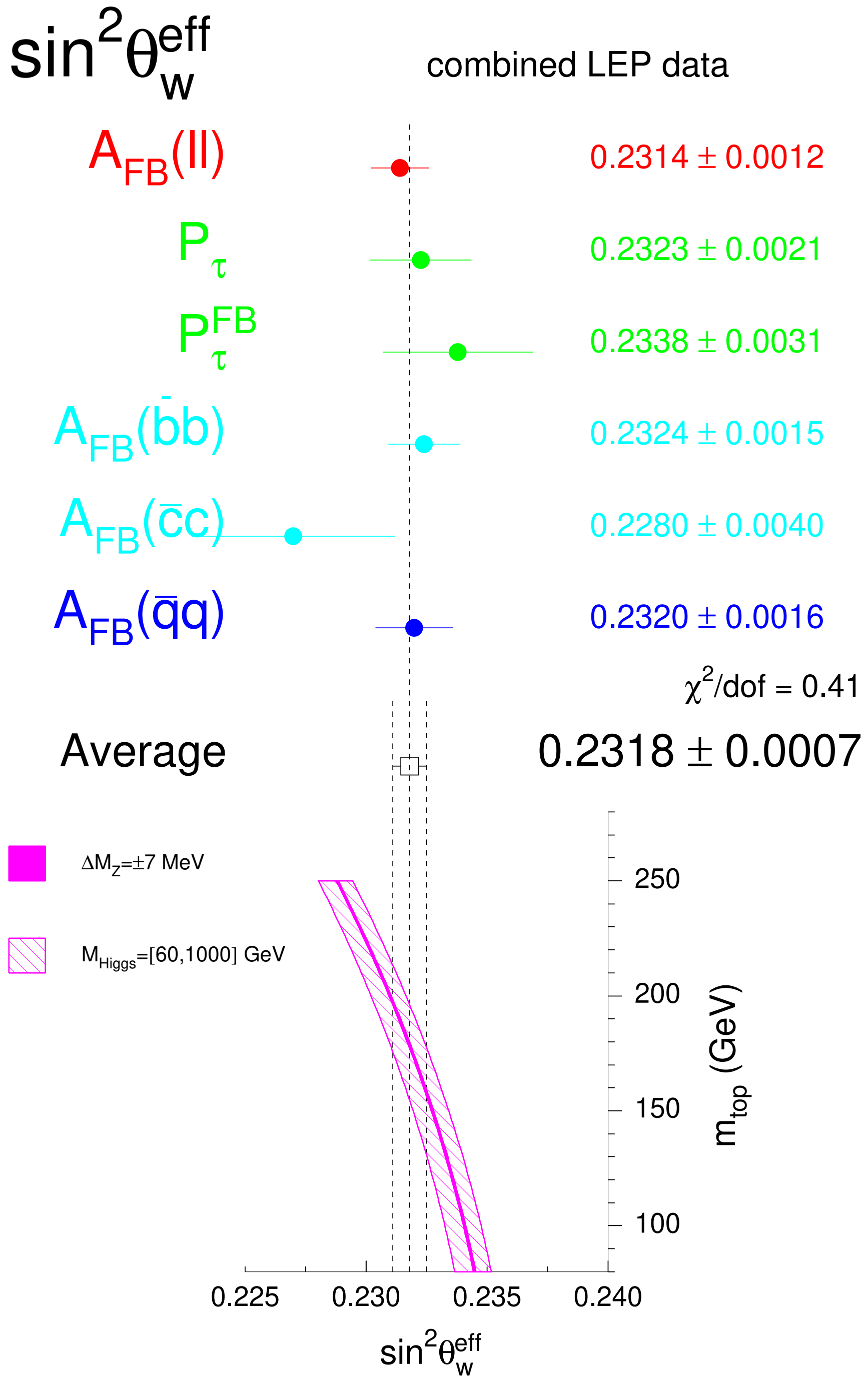
- Γ_l, A^0_{fb} include 1992 results, if they are available
- fit to $\sigma_{tot} \Rightarrow \Gamma_l$
- fit to σ_{tot}, $A_{fb} \Rightarrow A^0_{fb}$
- Γ_l, A^0_{fb} are weakly correlated

$$\begin{aligned} v_\tau &= 0.0389 \pm 0.0037 \qquad & a_\tau &= 0.4999 \pm 0.0015 \\ v_e &= 0.0349 \pm 0.0039 \qquad & a_e &= 0.5009 \pm 0.0010 \end{aligned}$$

$$\Downarrow$$

$$\begin{aligned} \sin^2\theta_W^{\text{eff}}(\tau^+\tau^-) &= 0.2306 \pm 0.0019 \\ \sin^2\theta_W^{\text{eff}}(e^+e^-) &= 0.2326 \pm 0.0019 \end{aligned}$$

$\sin^2 \theta_W^{eff}$ at LEP



S – Matrix

Ref: T. Riemann, Phys. Lett. **B293** (1992) 451.

- truly model independent approach to the lineshape and asymmetries

$$M^i = \frac{R_\gamma}{s} + \frac{r_z^i}{s - s_z} + F(s)$$

$$s_z = M_z^2 + iM_z\Gamma_z$$

R_γ – residual of the photon
r_z^i – residuals of the Z-Boson

$$\begin{aligned} r_z^0 &= r_z(e_L^- e_R^+ \longrightarrow \tau_L^- \tau_R^+) \\ r_z^1 &= r_z(e_L^- e_R^+ \longrightarrow \tau_R^- \tau_L^+) \\ r_z^2 &= r_z(e_R^- e_L^+ \longrightarrow \tau_R^- \tau_L^+) \\ r_z^3 &= r_z(e_R^- e_L^+ \longrightarrow \tau_L^- \tau_R^+) \end{aligned}$$

- the cross section is given by:

$$\sigma_A(s) = \sum_{i=1}^{4} (\pm)\sigma^i(s) = \frac{1}{4}\sum_{i=1}^{4} s \mid M^i(s) \mid^2$$

$$A = tot, fb, pol, fbpol$$

S – Matrix

L3 Results (preliminary)

- one needs σ_{tot} and three asymmetries to get r_Z^{0-3}
- A_{pol}^{fb} not measured at L3 up to now

$\Rightarrow$ Lepton universality

$\Rightarrow r_Z^1 = r_Z^3$

- all lepton data used

$$r_Z^0 = +0.429 \pm 0.012$$
$$r_Z^1 = -0.370 \pm 0.003$$
$$r_Z^2 = +0.323 \pm 0.016$$
$$\Downarrow$$

$$\begin{aligned} \sin^2\theta_W^{\text{eff}} &= +0.2285 \pm 0.0036 \\ v &= -0.0430 \pm 0.0100 \\ a &= -0.4994 \pm 0.0019 \end{aligned}$$

Conclusion

- The operation of LEP has given 136 K $\tau^+\tau^-$ events
- Parity violation is confirmed in the neutral current

$$\begin{aligned} A_\tau^{LEP} &= 0.142 \pm 0.017 \\ A_e^{LEP} &= 0.130 \pm 0.025 \end{aligned}$$

- Lepton universality holds

$$A_e^{LEP}/A_\tau^{LEP} = 0.92 \pm 0.21$$

- an amplitude analysis was performed for the first time

$$\begin{aligned} r_Z^0 &= +0.429 \pm 0.012 \\ r_Z^1 &= -0.370 \pm 0.003 \\ r_Z^2 &= +0.323 \pm 0.016 \end{aligned}$$

- $\tau^+\tau^-$ is the channel with the highest sensitivity to the couplings

$$\begin{aligned} v_\tau^{LEP} &= 0.0389 \pm 0.0037 \\ a_\tau^{LEP} &= 0.4999 \pm 0.0015 \end{aligned}$$

$$\sin^2\theta_W^{\mathrm{eff}}(\tau^+\tau^-) = 0.2306 \pm 0.0019$$