$\sin^2\theta_{eff}^{lept}$ Determinations using the process $e^+e^- \to \ell^+\ell^-$ at LEP

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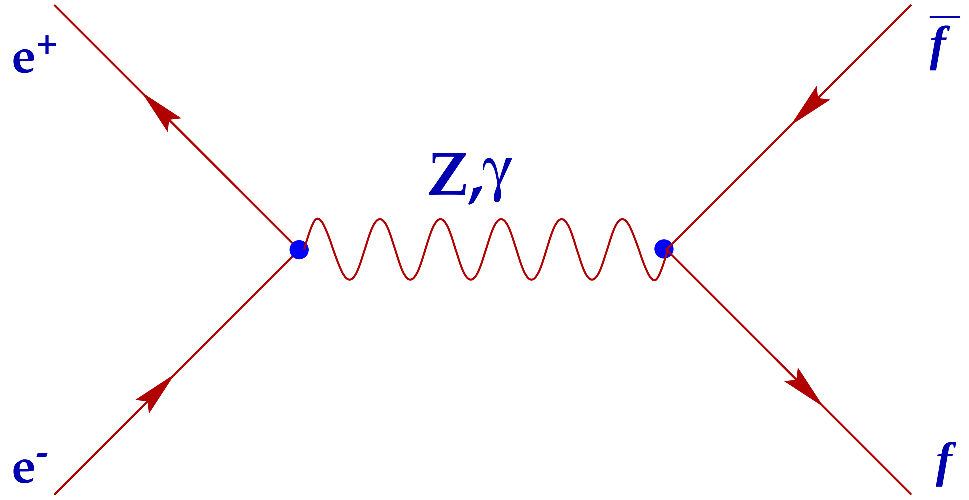
Introduction

Fermion Pair Production:



effective coupling constants used in improved Born approximation:

$$\bar{g}_V^f = \sqrt{\rho}\left(I_f^3 - 2Q_f \sin^2\theta_{eff}\right)$$
$$\bar{g}_A^f = \sqrt{\rho}\, I_f^3$$

Relevant Quantity:

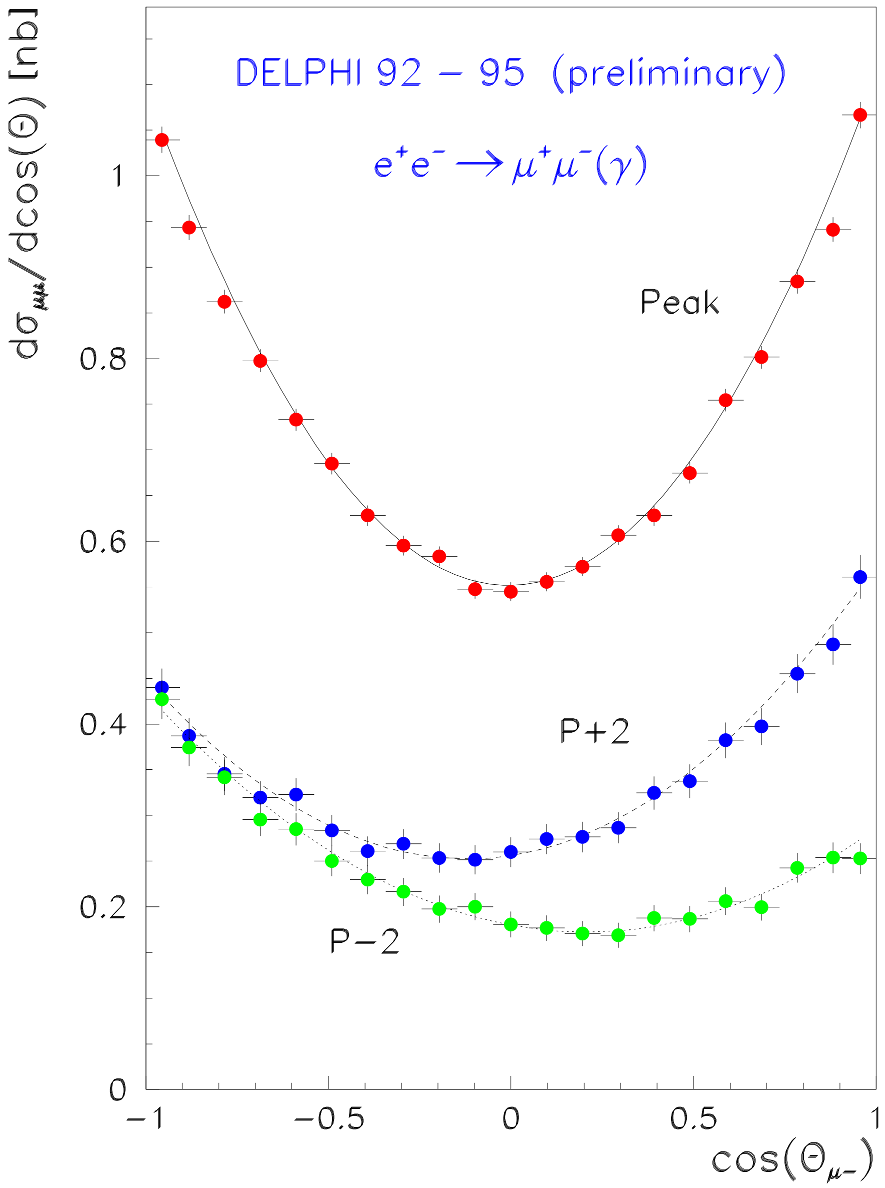
$$\mathcal{A}^\ell \equiv \frac{2\bar{g}_V^\ell \bar{g}_A^\ell}{(\bar{g}_V^\ell)^2 + (\bar{g}_A^\ell)^2} = \frac{2(1-4\sin^2\theta_{eff}^{\rm lept})}{1+(1-4\sin^2\theta_{eff}^{\rm lept})^2}$$

Forward-Backward Asymmetries

$$A_{FB}^{\ell^+\ell^-} \equiv \frac{\sigma^F(e^+e^- \to \ell^+\ell^-) - \sigma^B(e^+e^- \to \ell^+\ell^-)}{\sigma^F(e^+e^- \to \ell^+\ell^-) + \sigma^B(e^+e^- \to \ell^+\ell^-)}$$

At $\sqrt{s} = m_Z$, only Z exchange:

$$A_{FB,0}^{\ell^+\ell^-} = \frac{3}{4}\mathcal{A}^e\mathcal{A}^\ell$$



Forward-Backward Asymmetries

Extraction of $A_{\mathrm{FB}}^{\ell^+\ell^-}(\sqrt{s})$:

Counting: For $e^+e^- \to e^+e^-$ (t-channel).

$$A_{\mathrm{FB}} = \frac{N_{\mathrm{ev}}(\cos\theta > 0) - N_{\mathrm{ev}}(\cos\theta < 0)}{N_{\mathrm{ev}}(\cos\theta > 0) + N_{\mathrm{ev}}(\cos\theta < 0)}$$

Maximum-likelihood fit:

$$\frac{d\sigma}{d\cos\theta} \sim 1 + \cos^2\theta + \frac{8}{3} A_{\mathrm{FB}} \cos\theta$$

Systematic Uncertainties:

Experimental: Uncertainty on e^+e^- background in $\tau^+\tau^-$ channel (and *vice versa*); charge confusion

Theoretical: Uncertainty on t-channel and s–t interference contributions as calculated using ALIBABA: 0.1%–0.2% estimated from observed differences between ALIBABA and TOPAZ0

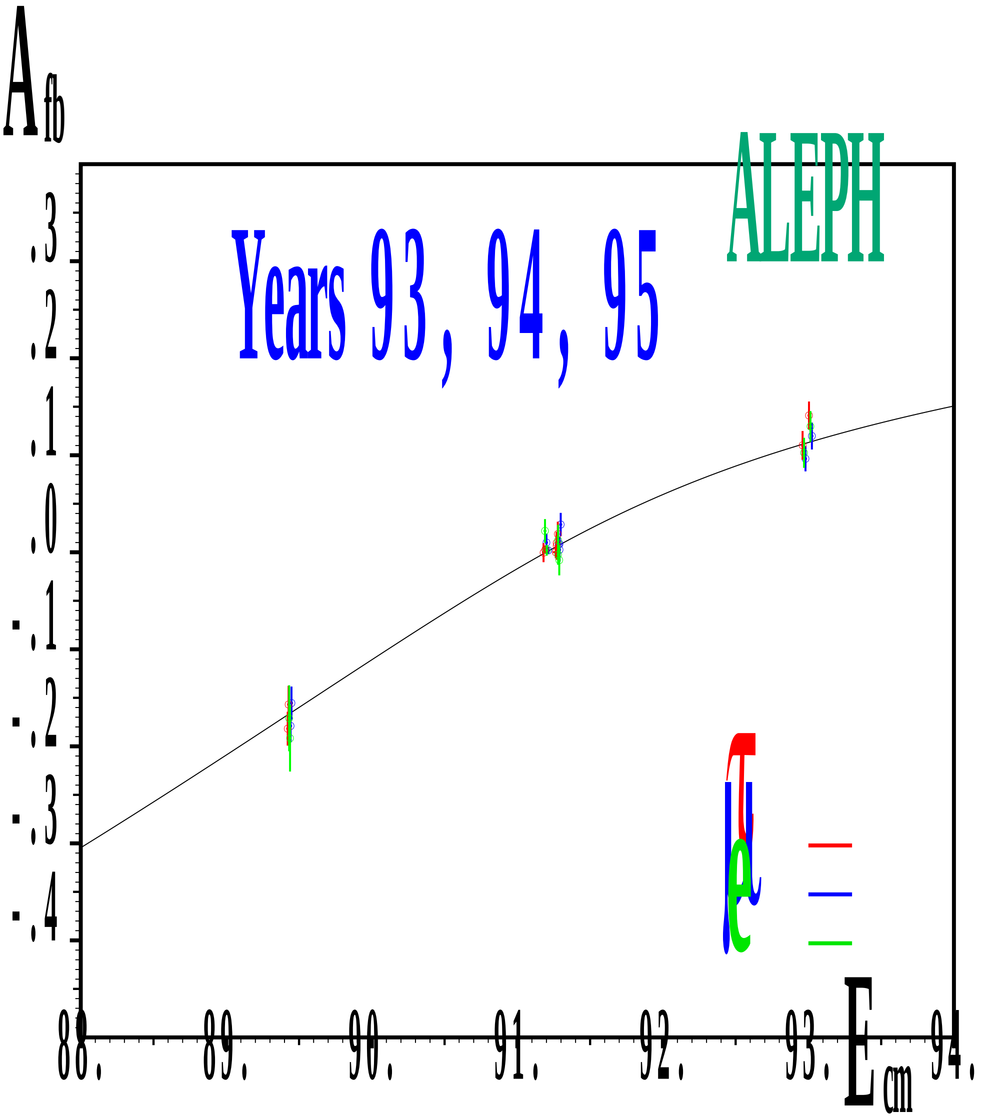
$e^+e^- \to \ell^+\ell^-$ Statistics ($\times 10^3$):

	ALEPH	DELPHI	L3	OPAL	Total
1990-1992	137	106	98	146	487
1993-1995*	348	276	219	308	1151
Total	485	382	317	454	1638

* Preliminary, waiting for final LEP energies…

Forward-Backward Asymmetries

Results:

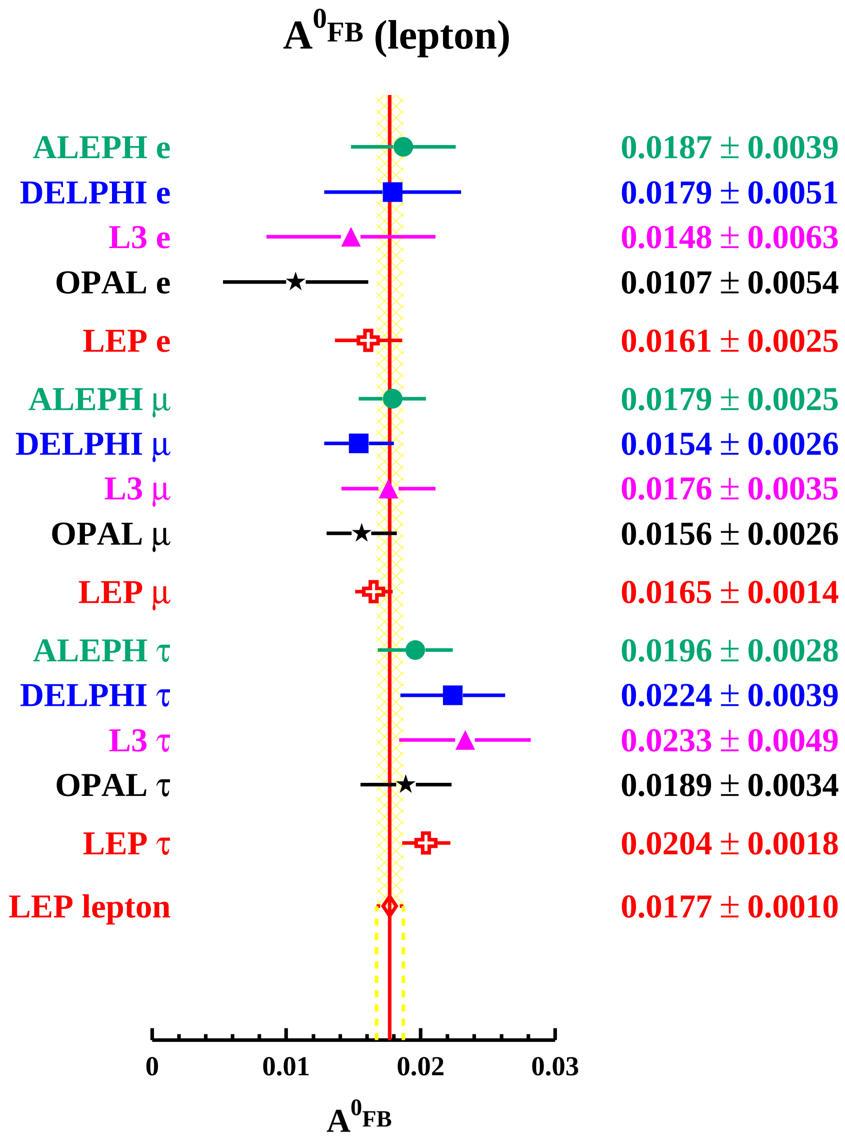


Fit $A_{\mathrm{FB},0}^{\ell^+\ell^-}$:

- For each channel, fit $A_{\mathrm{FB},0}^{\ell^+\ell^-}$ to asymmetry data fixing γ exchange and γZ interference terms to SM expectation
- Apply residual weak corrections (small)
- Apply QED corrections (NOT small!)

Forward-Backward Asymmetries

(Preliminary) Result:



NB: Currently the Bhabha *t*-channel and *s*–*t* interference uncertainty is not treated as a common systematic error!

Derive:

$$\sin^2\theta_{eff}^{\mathrm{lept}} = 0.23068 \pm 0.00055$$

Tau Polarization

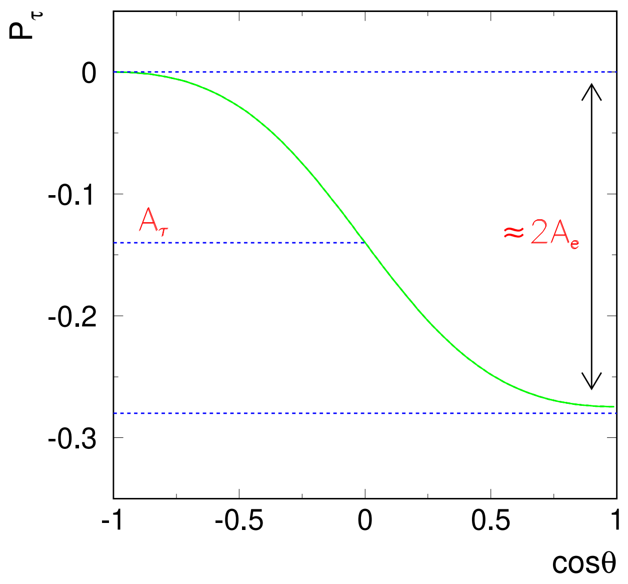
Helicity ($h = \pm 1/2$) dependence of angular distribution:

$$\frac{d\sigma(e^+e^- \to \tau^+\tau^-; h)}{d\cos\theta} \sim \left\{C_0(s)(1+\cos^2\theta) + 2C_1(s)\cos\theta\right\}$$
$$+2h \left\{D_0(s)(1+\cos^2\theta) + 2D_1(s)\cos\theta\right\}$$

- $C_0(s)$, $C_1(s)$, $D_0(s)$, $D_1(s)$ receive contributions from Z, γ and interference
- Neglect τ mass (helicity-flip terms are heavily suppressed)

Sensitivity to $\mathcal{A}_\tau$ and $\mathcal{A}_e$ separately:

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



Tau Polarization

Extraction of polarization:

- Selection: First select $\ell^+\ell^-$ final states, then reject non-τ and τ background
- Maximum-likelihood fit to polarization-sensitive variables
  - ALEPH, DELPHI, L3: Fit to each channel separately (account for polarization dependence of τ background)
  - OPAL: Combined fit to gain sensitivity

  Assume $V-A$ Charged Current structure
  (verified using measurements of Michel parameters)
- Initial- and final-state and interference radiation: accounted for by MC (KORALZ)
- Correct for, or weight, $\sqrt{s}$ dependence

Event samples:

Experiment	Period	Decays ($\times 10^3$)
ALEPH	1990–1992	52
DELPHI	1990–1994*	71
L3	1990–1994*	111
OPAL	1990–1994	123

* Preliminary

Relative weights: $\sim 7\%$ ($\ell\nu\bar{\nu}$), $\sim 37\%$ ($\pi\nu$, $\rho\nu$), $\sim 12\%$ ($a_1\nu$)

Tau Polarization

Hadronic decays:

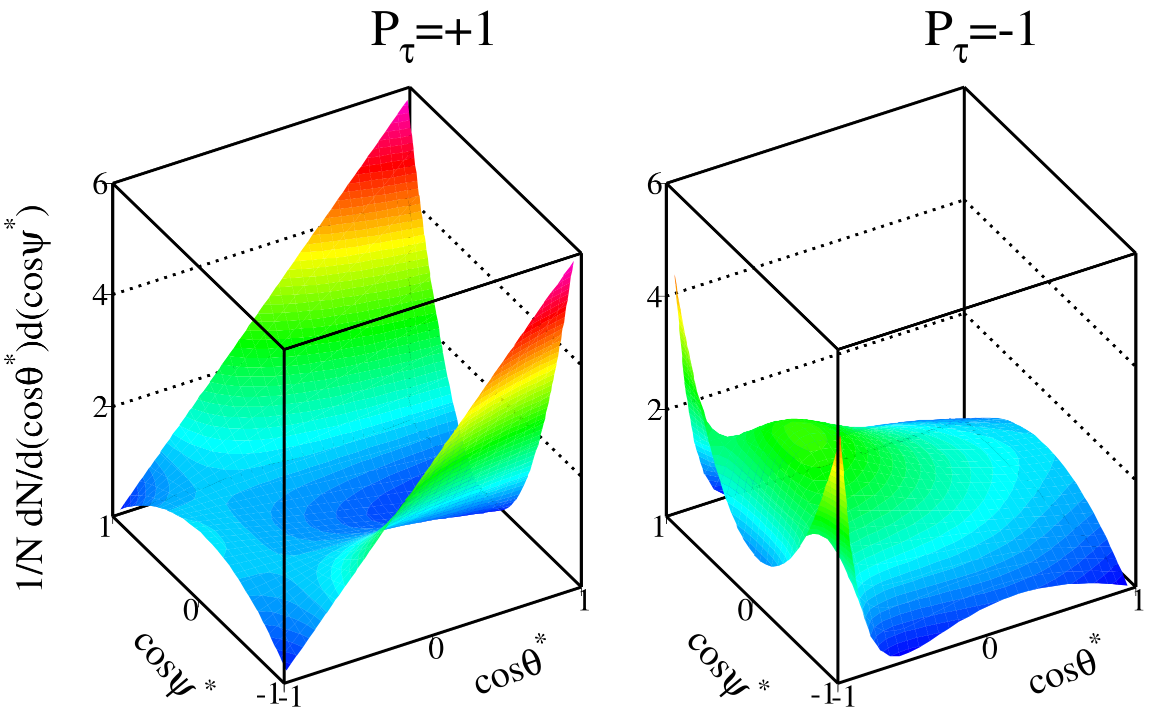
ρ, a_1 are spin-1 particles $\Rightarrow$ loss of sensitivity (2 spin states)
Recover this loss using spin analysis of ρ, a_1

- Analyse ρ channel using $\theta^* = \angle(\tau, \rho)$, $\psi^* = \angle(\rho, \pi)$ (L3,OPAL)

$$\cos\theta^* = \frac{2x - 1 - m_h^2/m_\tau^2}{1 - m_h^2/m_\tau^2}, \quad \cos\psi^* = \frac{E_\pi - E_{\pi^0}}{p_\rho\sqrt{1 - 2(m_\pi + m_{\pi^0})^2/m_\rho^2}}$$

- Consider moments of angular distributions in a_1 decay (DELPHI)
- Use 'Optimal Variable' ω to reduce 3-d (ρ) or 6-d (a_1) decay phase space $\vec{x}$ to 1 dimension

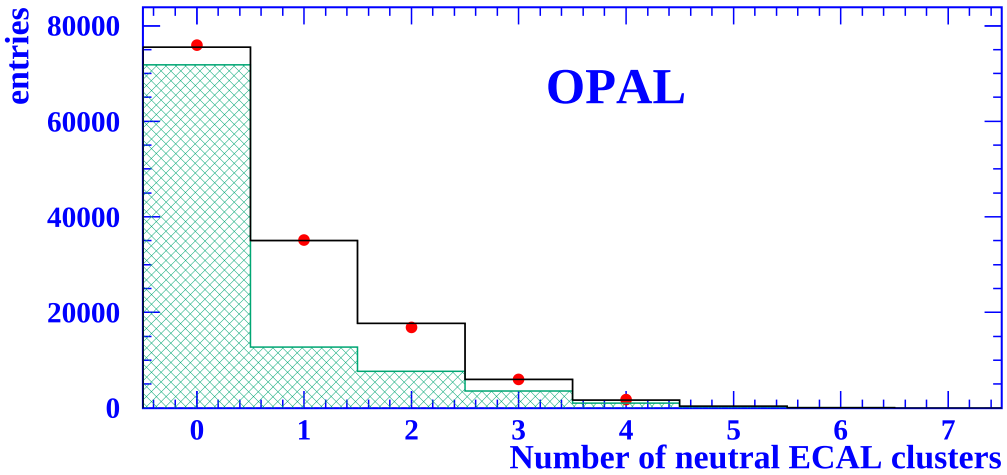
$$\omega = \frac{d\Gamma(\vec{x}; h = +1/2) - d\Gamma(\vec{x}; h = -1/2)}{d\Gamma(\vec{x}; h = +1/2) + d\Gamma(\vec{x}; h = -1/2)}$$

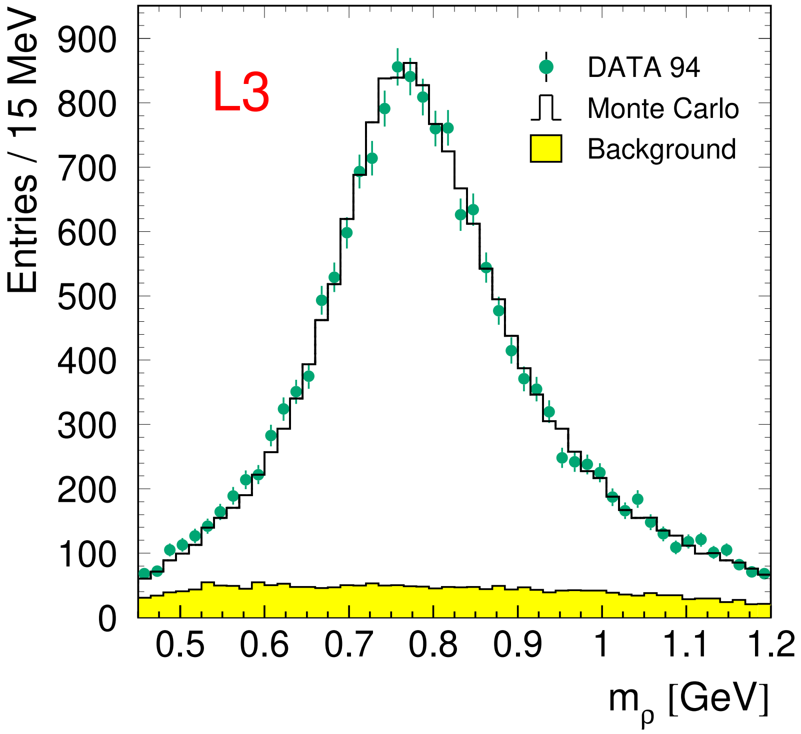


Tau Polarization

Experimental details:

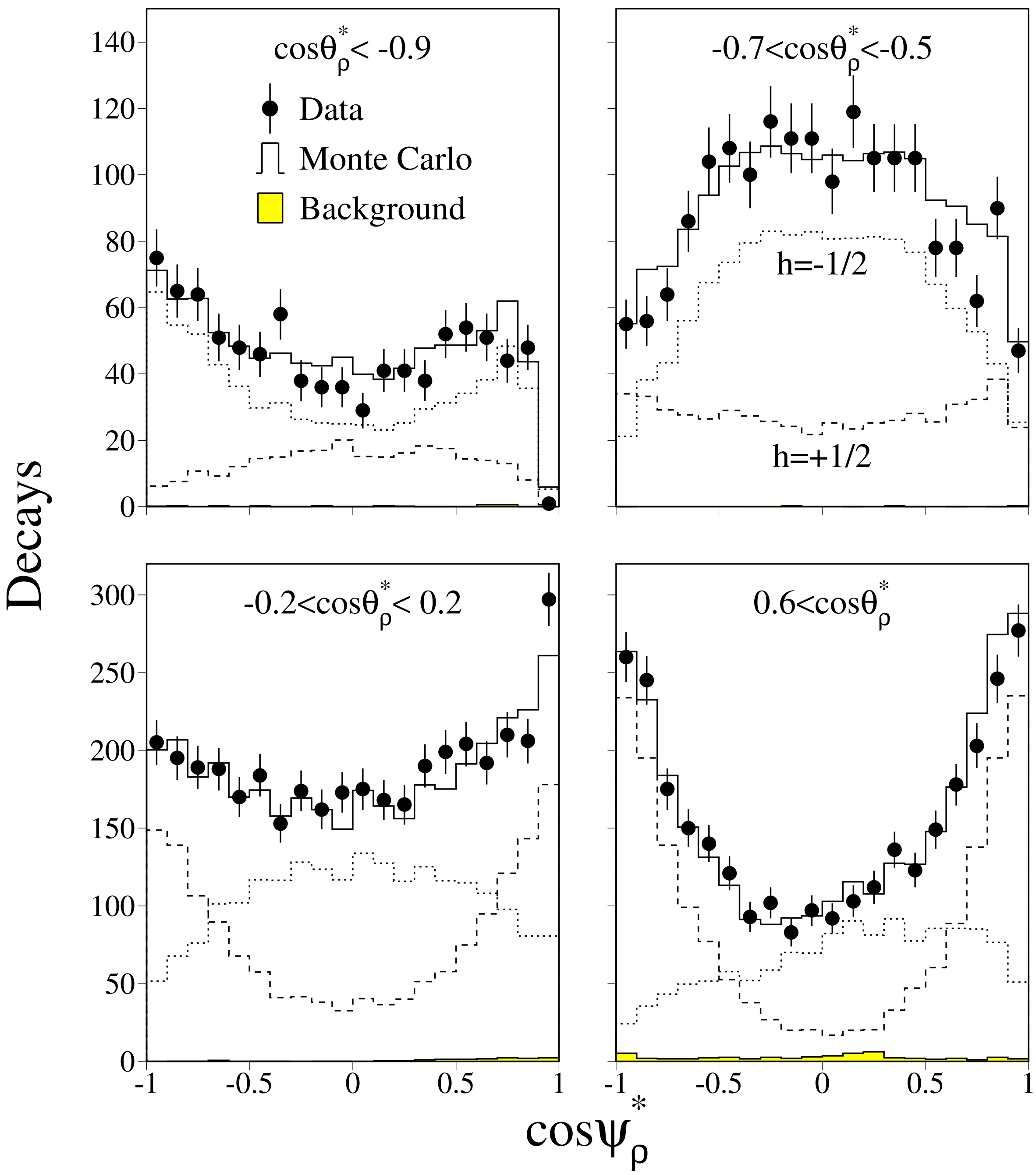
- $\pi^{\pm}$, π^0 from ρ decay very close (3°) together
- Requires good π^0 recognition $\Rightarrow$ No control samples!
- Additional complication: $\tau \rightarrow \rho\gamma, a_1\gamma$ decay rates not well known





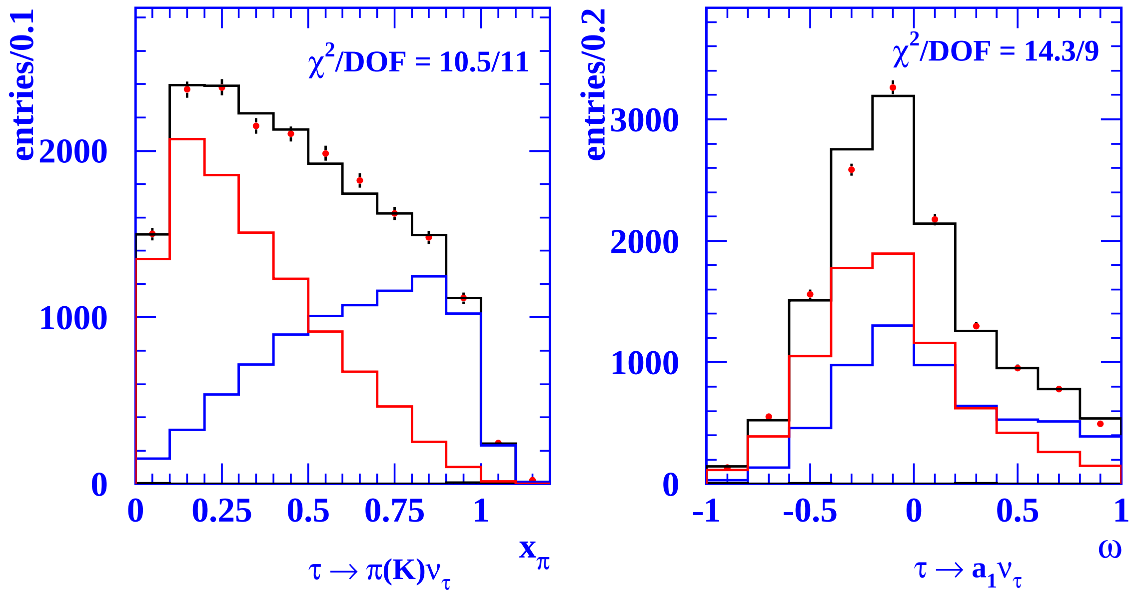
Tau Polarization

L3



Tau Polarization

OPAL



$\mathcal{A}_\tau$ Experimental systematics:

ALEPH ρ: π^0 ID (0.013); a_1: τ background (0.008)

DELPHI ρ: π^0 ID (0.015); a_1: τ background (0.030)

L3 ρ: Energy scale (0.014); a_1: τ Energy scale/τ background (0.020)

OPAL ρ: Energy scale/π^0 ID (0.005); a_1: τ Energy scale/τ background (0.020)

$\mathcal{A}_\tau$ Systematics due to a_1 modelling:

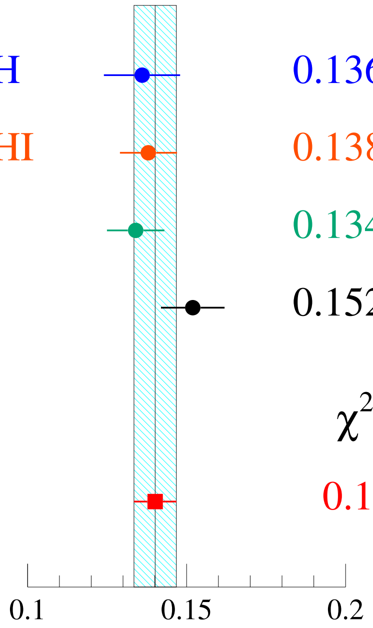
Uncertainties in a_1 channel: 0.012 (ALEPH) – 0.15 (DELPHI)
Estimated from difference between models assuming different structure functions (OPAL: none of models agree with data!)
OPAL: effect amplified in ρ channel (0.004).
$\Rightarrow$ not considered by other experiments!

$\mathcal{A}_\tau$ Systematics due to decay radiation:

Theorists suggest $\tau \to \pi\nu\gamma$ saturated by $\rho, a_1 \to \pi\gamma$
Expect smaller effect (~ 0.001) for ρ. Optimistic?

Tau Polarization

A_τ



ALEPH	$0.136 \pm 0.012 \pm 0.009$
DELPHI	$0.138 \pm 0.009 \pm 0.008$
OPAL	$0.134 \pm 0.009 \pm 0.010$
L3	$0.152 \pm 0.010 \pm 0.009$
	$\chi^2/\text{dof} = 1.1 / 3$
LEP	0.1401 ± 0.0067

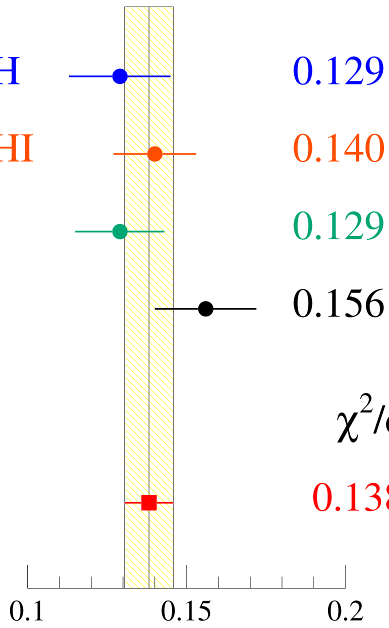
Combine:

$$\mathcal{A}_{e-\tau} = 0.1393 \pm 0.0050$$

Derive:

$$\sin^2\theta_{eff}^{lept} = 0.23251 \pm 0.00063$$

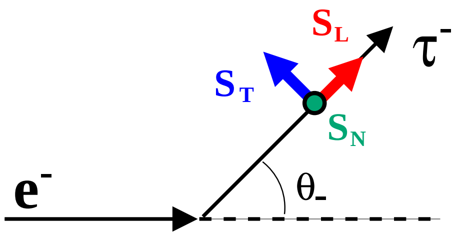
A_e



ALEPH	$0.129 \pm 0.016 \pm 0.005$
DELPHI	$0.140 \pm 0.013 \pm 0.003$
OPAL	$0.129 \pm 0.014 \pm 0.005$
L3	$0.156 \pm 0.016 \pm 0.005$
	$\chi^2/\text{dof} = 1.8 / 3$
LEP	0.1382 ± 0.0076

Spin Correlations

Full spin analysis of $e^+e^- \to \tau^+\tau^-$:



$$\frac{d\sigma(e^+e^- \to \tau^+\tau^-; \hat{s}_-, \hat{s}_+)}{d\cos\theta_-} \sim (1 - s_-^L s_+^L)\left\{C_0(s)(1+\cos^2\theta_-) + 2C_1(s)\cos\theta_-\right\}$$
$$-(s_-^L - s_+^L)\left\{D_0(s)(1+\cos^2\theta_-) + 2D_1(s)\cos\theta_-\right\}$$
$$+(s_-^N s_+^N - s_-^T s_+^T)C_2(s)\sin^2\theta_-$$
$$+(s_-^N s_+^T + s_-^T s_+^N)D_2(s)\sin^2\theta_-$$

Experimentally: access to

$$C_{TT} \equiv \frac{C_2(m_Z^2)}{C_0(m_Z^2)} = \frac{|\bar{g}_A^\tau|^2 - |\bar{g}_V^\tau|^2}{|\bar{g}_A^\tau|^2 + |\bar{g}_V^\tau|^2}$$
$$C_{TN} \equiv \frac{D_2(m_Z^2)}{C_0(m_Z^2)} = -\frac{2\mathrm{Im}(\bar{g}_A^\tau \bar{g}_V^{*\tau})}{|\bar{g}_A^\tau|^2 + |\bar{g}_V^\tau|^2} + \mathrm{Im}(\gamma Z\ \text{interference})$$

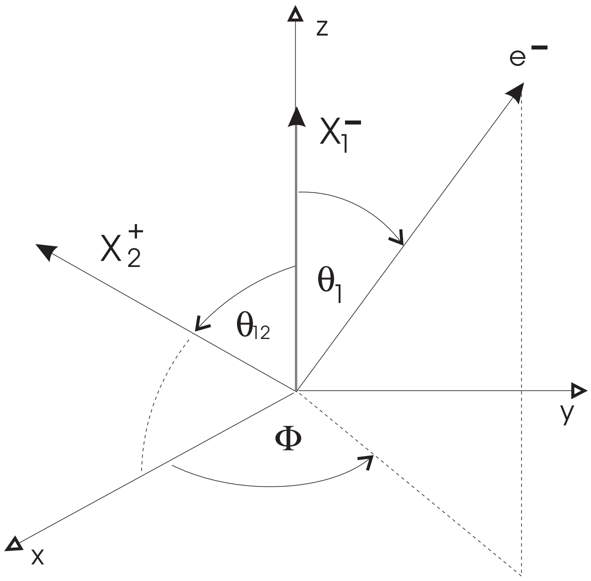
Standard Model prediction

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

- C_{TT} breaks symmetry $\bar{g}_V^f$–$\bar{g}_A^f$
- C_{TN} sensitive to CP-violating effects

Spin Correlations

$e^+e^- \to \tau^+\tau^- \to X_1^- X_2^+ \nu_\tau \bar{\nu}_\tau$ Measurements:



- $\theta_1 = \angle(X_-, e^-)$
- $\theta_{12} =$ collinearity(X_-, X_+)
- $\Phi =$ aplanarity(e^-, X_+)

Largest sensitivity from Φ distribution:

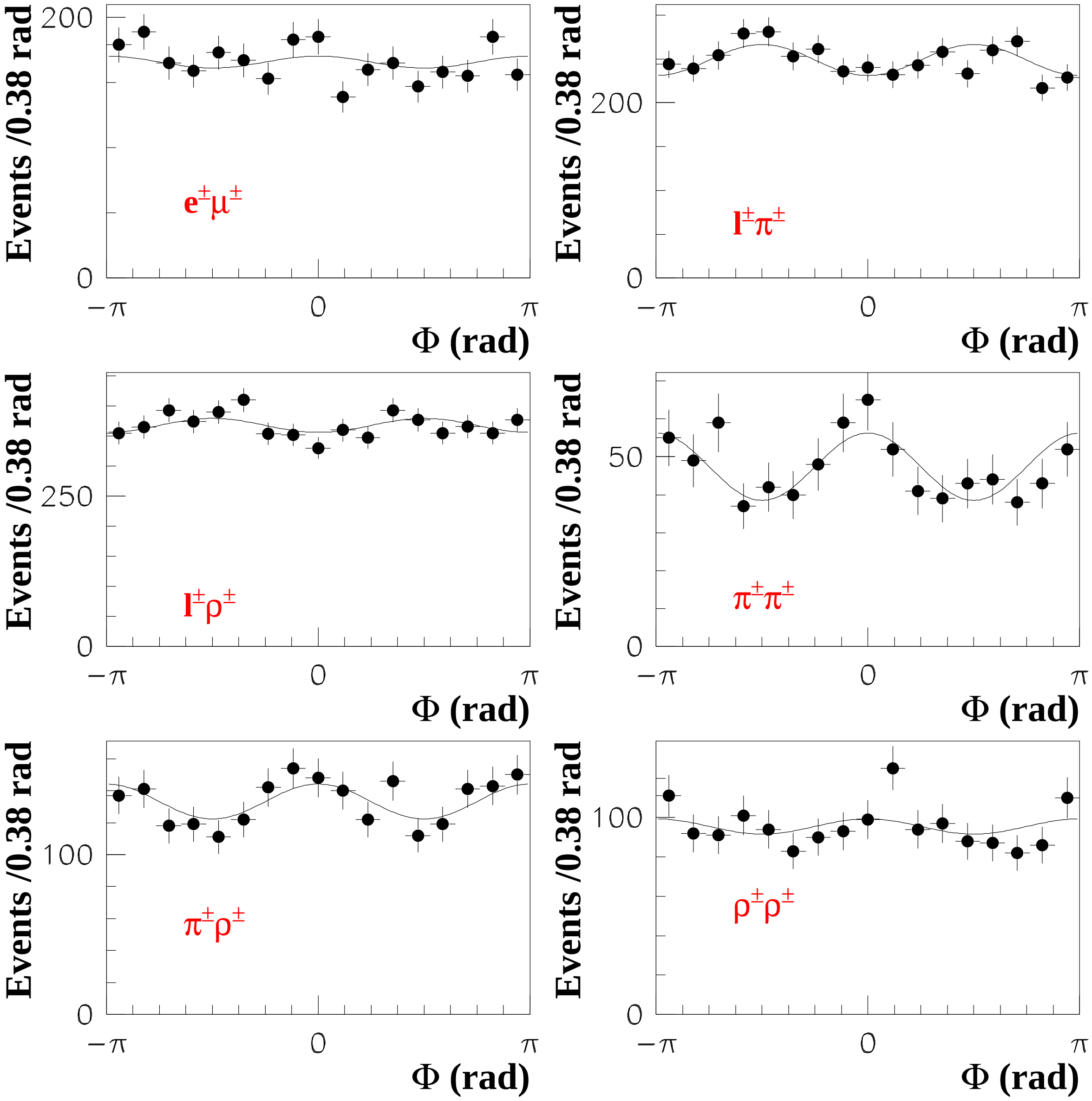
$$\frac{d\sigma}{d\Phi} \sim \alpha_+\alpha_-(C_{TT}\cos 2\Phi + C_{TT}\sin 2\Phi) + C$$

- Sign difference leptons (ℓ) and hadrons (h): $\alpha_\ell < 0$, $\alpha_h > 0$
- Need good background knowledge: ISR in $Z \to e^+e^-, \mu^+\mu^-$
- ALEPH 1992–1994: 3-d likelihood
- L3 1994*: 1-d
- DELPHI 1992–1994: 1-d inclusive ℓh, hh

* Preliminary

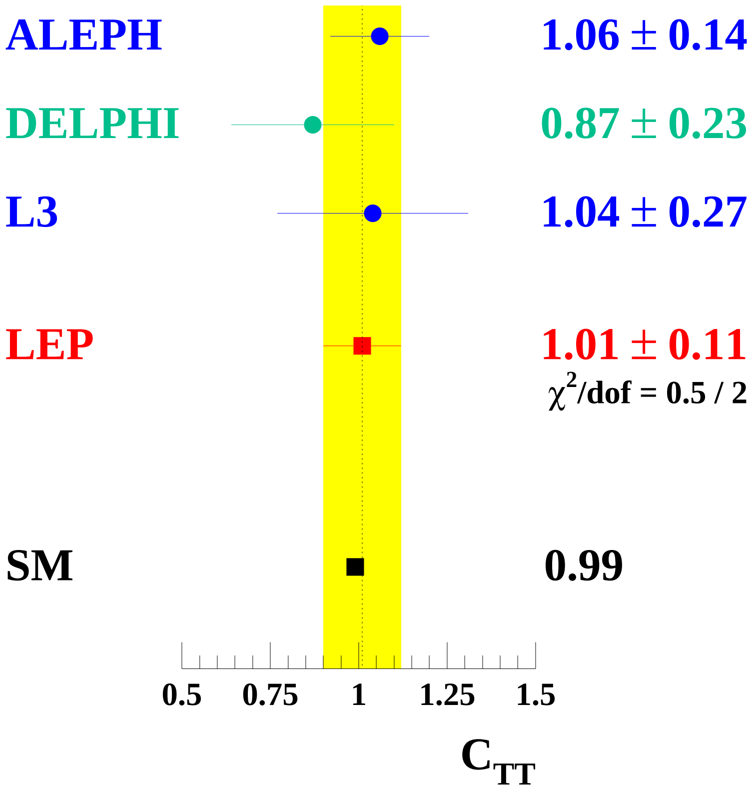
Spin Correlations

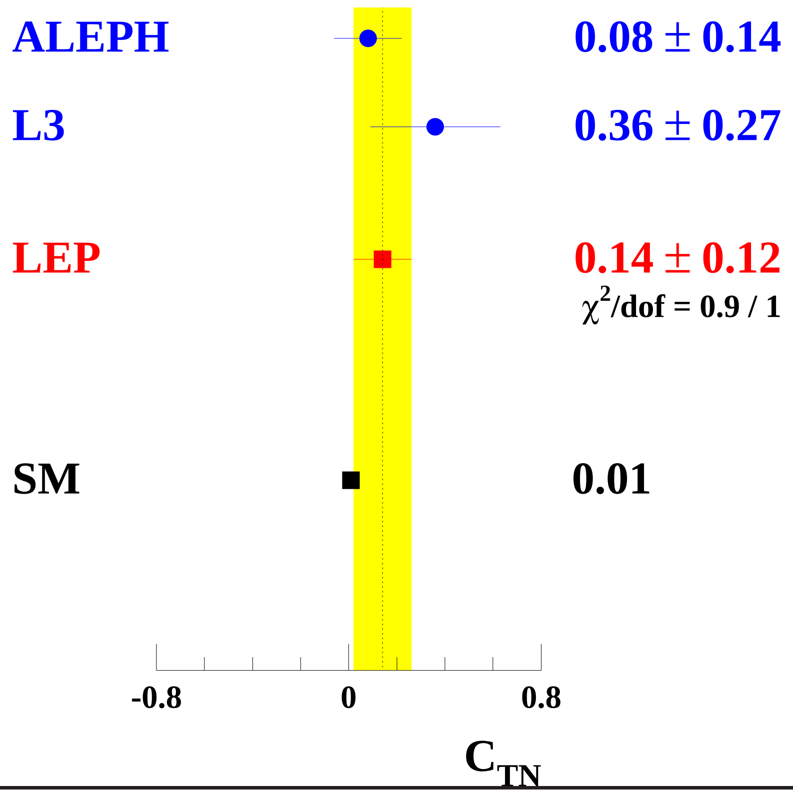
ALEPH



Note the sign difference in ℓh channels compared to $\ell\ell$, hh!

Spin Correlations





Conclusions

- Two precise measurements of $\sin^2\theta_{eff}^{\mathrm{lept}}$:

$$\sin^2\theta_{eff}^{\mathrm{lept}} = \begin{cases} 0.23068 \pm 0.00055 & \text{from } A_{\mathrm{FB}} \\ 0.23251 \pm 0.00063 & \text{from } \tau \text{ polarization} \end{cases}$$

- Eagerly awaiting final high-precision results…
- Full τ spin structure now investigated: agreement with SM
- Common systematics to be better accounted for:

  A_{FB}:

  – t-channel, interference contributions for Bhabhas

  τ polarization:

  – Effects of decay radiation

  – a_1 modelling uncertainties