LEP Results on Electroweak Phenomena

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Where are we now?

For example: the mass of the Z Boson

The overall conclusion is that at LEP the Z mass and width can be measured with relative ease down to $\delta m_Z = \delta\Gamma_{tot} = \pm 50$ MeV. A factor of 2-3 improvement can be reached with a determined effort...

Altarelli in "Physics at LEP", CERN 86-02

PDG 88:

$$92.4 \pm 1.8 \text{ GeV}$$

PDG 90:

$$91.161 \pm 0.031 \text{ GeV}$$

PDG 92:

$$91.173 \pm 0.020 \text{ GeV}$$

PDG 94:

$$91.187 \pm 0.007 \text{ GeV}$$

Hope for the future (1993 scan):

$$\pm 0.003 \text{ GeV}$$

LEP Data Samples

Most of the results presented here are based on the 1990-1992 data.

		ALEPH	DELPHI	L3	OPAL	LEP
		Number of events (10^3)				
$q\bar{q}$	'90-'91	451	365	423	454	1693
	'92	686	695	677	733	2791
	total	1137	1060	1100	1187	4484
$\ell^+\ell^-$	'90-'91	55	37	40	58	190
	'92	82	76	58	88	304
	total	137	113	98	146	494

'93 data sample $\approx$ '92.

$\Rightarrow$ now 7M hadrons, 700k leptons.

For '94 hope to get $\gtrsim$ '93 lumi $\Rightarrow \approx$ 4M more hadrons (if no scan).

So, by end of '94 we should have $\approx$ 2.5 times the statistics than presented here.

Z Parameters

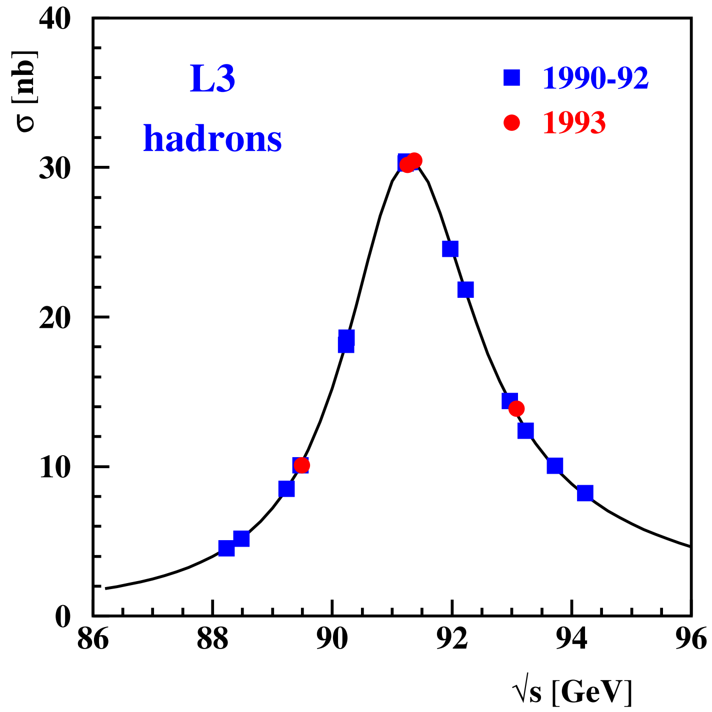
All LEP experiments measure the hadronic and leptonic cross sections as a function of energy.

QED radiative corrections are applied (radiation and vacuum polarization), and fits are made to obtain:

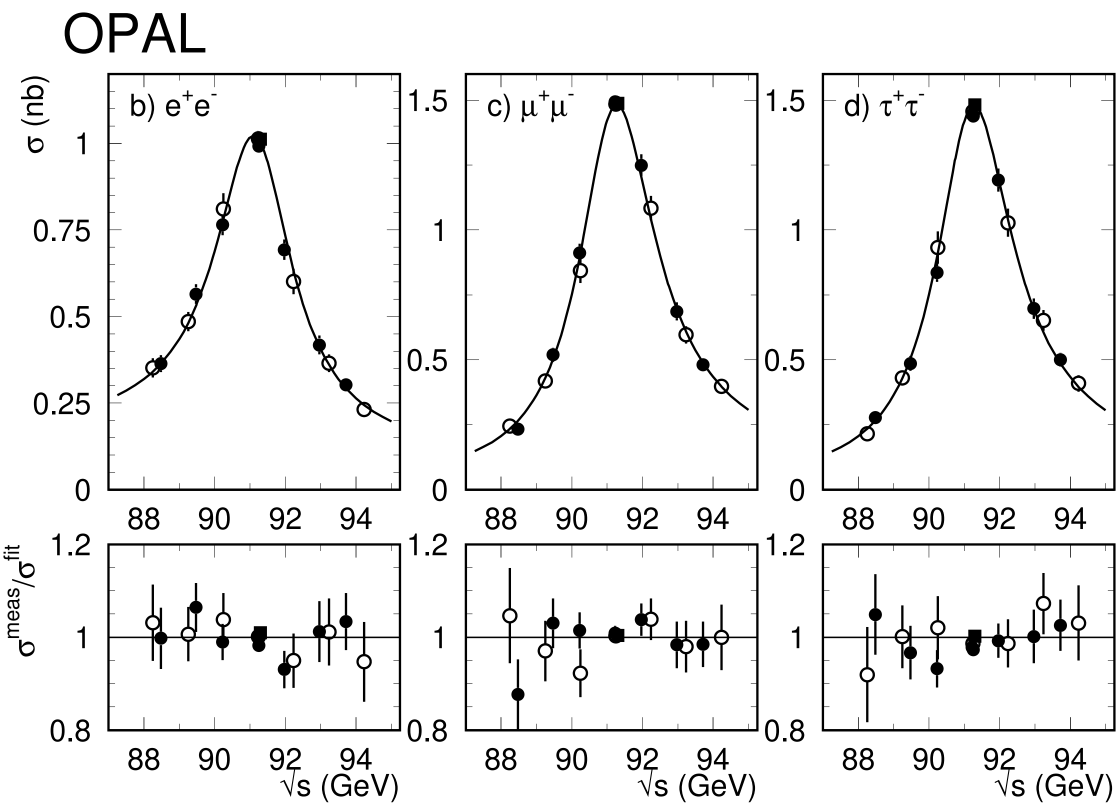
- $m_{\rm Z}$ **and** $\Gamma_{\rm Z}$
- $\sigma^0_{\rm had} \equiv \frac{12\pi}{m_{\rm Z}^2}\frac{\Gamma_{\rm ee}\Gamma_{\rm had}}{\Gamma_{\rm Z}^2}$ **("peak" cross section)**
- $R_f \equiv \Gamma_{ff}/\Gamma_{\rm had}$, **for** f **= e,** μ, τ

One can then derive other important parameters such as

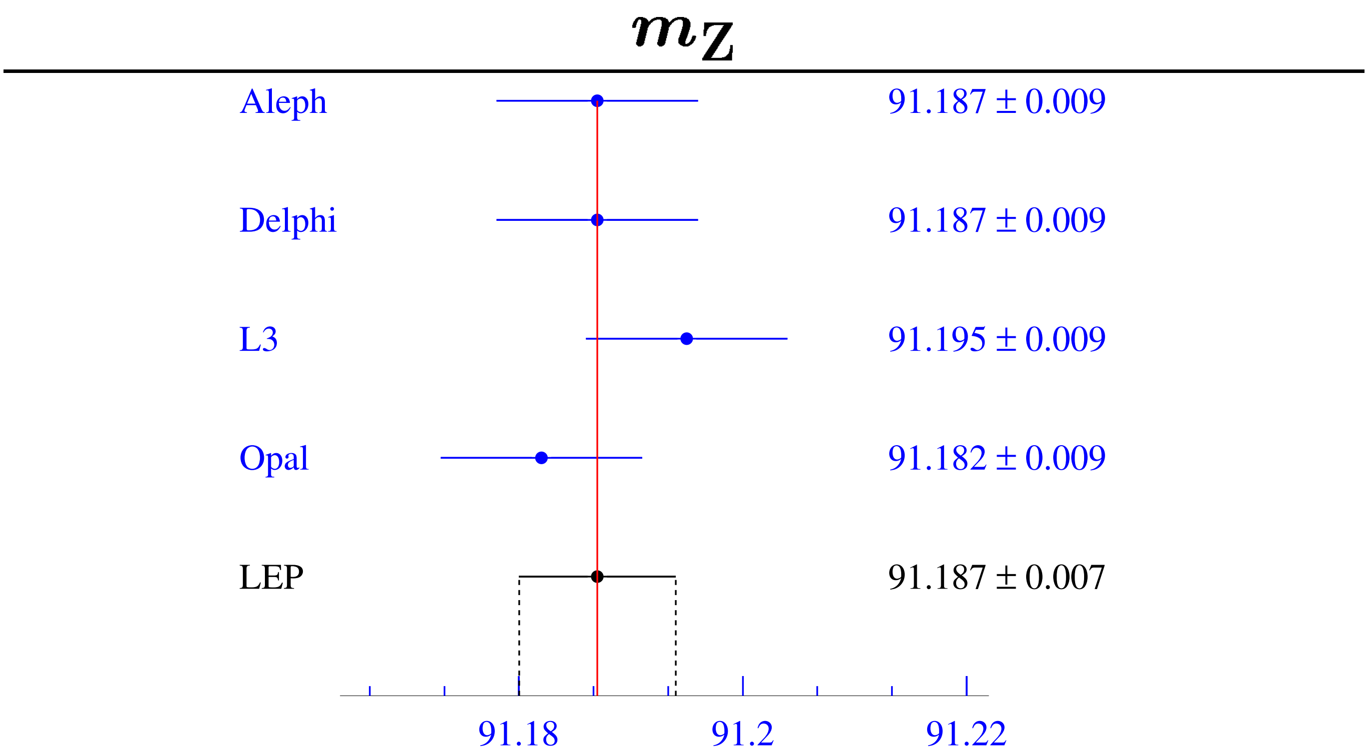
- $\alpha_{\rm s}$ **from QCD corrections to** $\Gamma_{\rm had}$.
- $\Gamma_{\ell\ell} \propto (g_{\rm V}^2 + g_{\rm A}^2)$
- $\Gamma_{\rm inv} = \Gamma_{\rm Z} - \Gamma_{\rm had} - 3\Gamma_{\ell\ell}$
- $N_\nu = \frac{\Gamma_{\rm inv}}{\Gamma_{\ell\ell}}\left(\frac{\Gamma_{\ell\ell}}{\Gamma_{\nu\nu}}\right)_{\rm SM}$ **(in the SM only!!)**



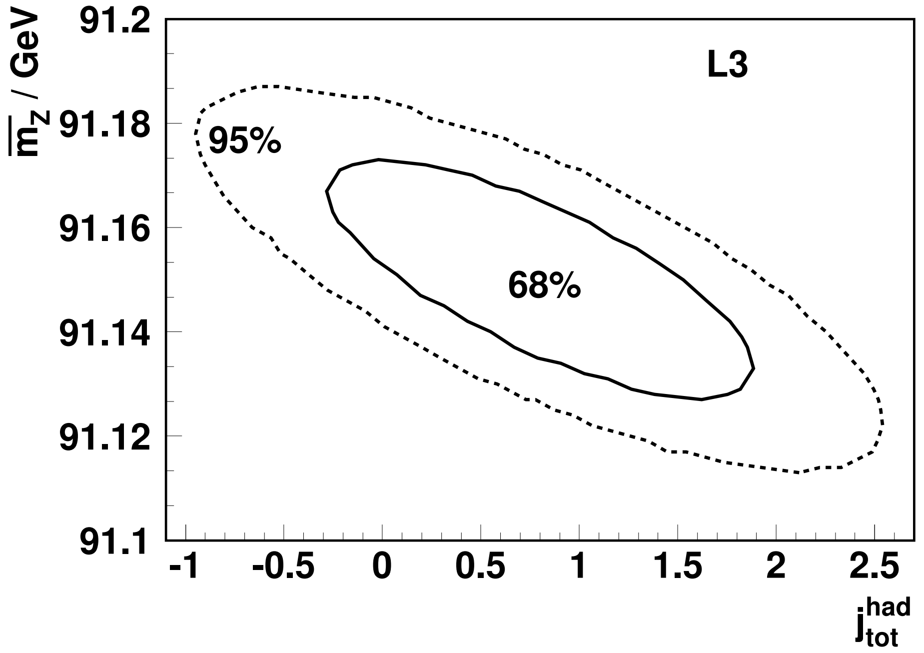
L3
hadrons
1990-92
1993
σ [nb]
40
30
20
10
0
86
88
90
92
94
96
√s [GeV]



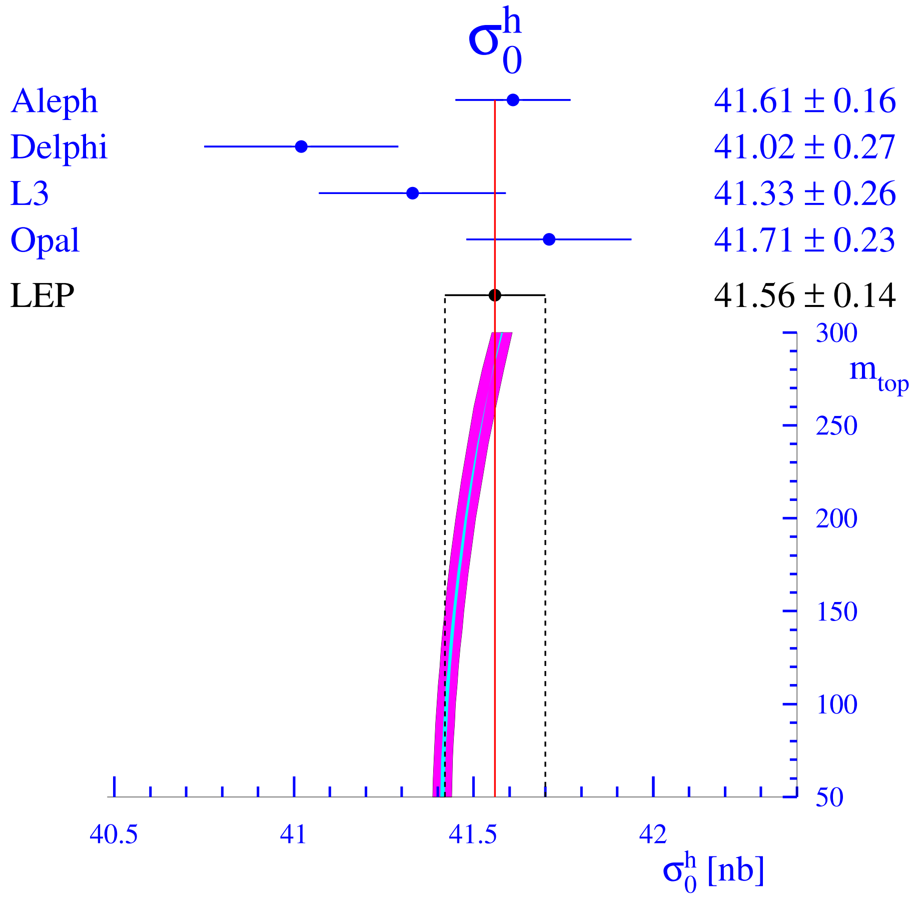
OPAL
b) e+e-
c) μ+μ-
d) τ+τ-
σ (nb)
σmeas/σfit
√s (GeV)



- **Breit-Wigner with energy-dependent width, not pole position in the S-Matrix**
- **The $Z\gamma$ interference term has been fixed to the SM value. Allowing it to be free increases the error on the mass:**



σ^0_{had}



Dominant errors:

- **Selection efficiencies: 0.15%-0.20% per experiment.**
- **Experimental luminosity systematics: $\approx$ 0.5% per experiment, except end '92 for Aleph: 0.15%!**
  L3 and Opal expect similar errors as of '93.
- **Theoretical lumi: 0.25%-0.30%, 100% correlated between experiments.**
  Needs new Bhabha cross section calculations (work in progress).

N_ν

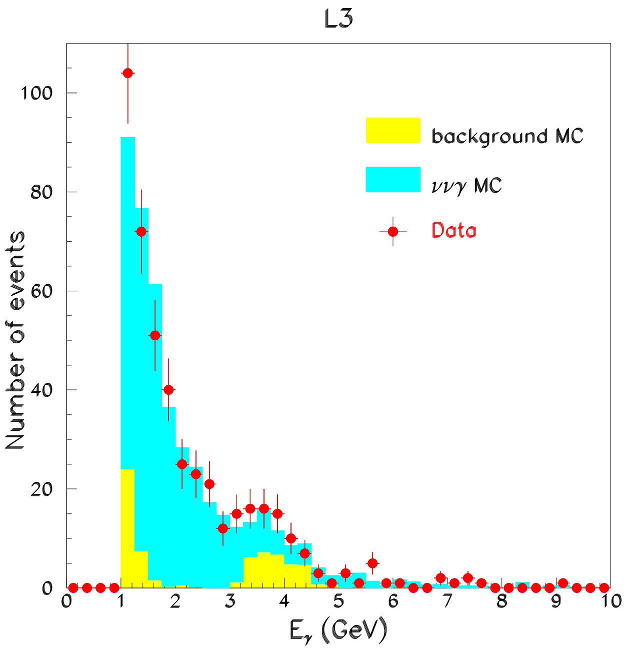
Using the lineshape results, one can derive

$$N_\nu = \left(\frac{\Gamma_{\text{inv}}}{\Gamma_{\ell\ell}}\right)\left(\frac{\Gamma_{\ell\ell}}{\Gamma_{\nu\nu}}\right)_{\text{SM}} = 2.980 \pm 0.027$$

An alternative method measures the width more directly by looking for the process:

$$e^+e^- \to \gamma + \textit{nothing}$$

Best done above the peak, but can also be done on the peak.



Rapidly falling spectrum
Need good trigger for low energy photons
Important to have hermiticity

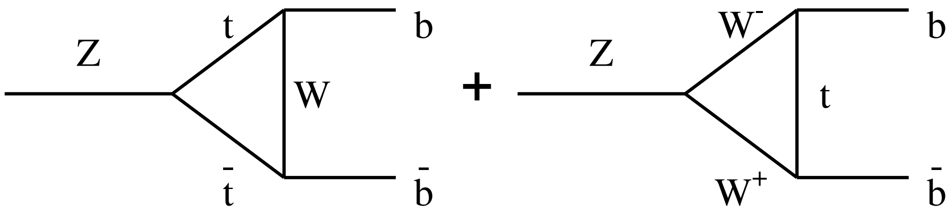
Small gap between lumi and endcap

Result: OPAL (90), Aleph(90-91), L3(90-92):

$$N_\nu = 3.00 \pm 0.13$$

$R_{b\bar{b}}$

$R_{b\bar{b}} = \Gamma_{b\bar{b}}/\Gamma_{had}$ provides an excellent measurement of the effects of the diagrams



Provides additional information on m_t

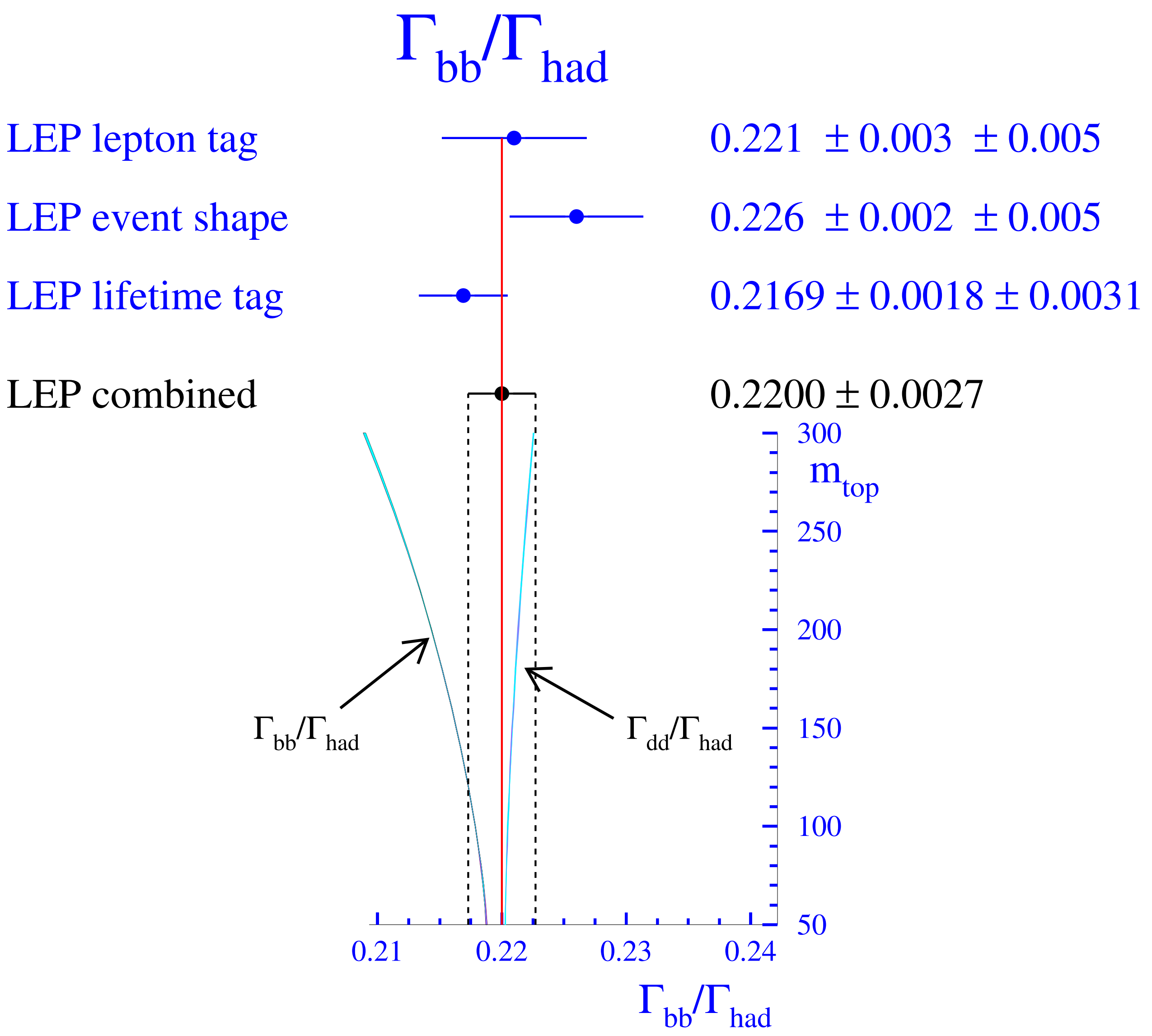
Tagging $b\bar{b}$ events:

- **Lepton tag: high purity; low efficiency**
- **Event shape tag: high efficiency; low purity**
- **Lifetime tag: high efficiency; high purity**

Dominant errors are semileptonic branching ratio, and decay models.

Use data with multiple tags to determine efficiency

$R_{b\bar{b}}$



1.2% **measurement! Can still improve with better understanding of models, and more use of multiple tags.**

Asymmetries

The charge asymmetries at the peak can be expressed as

$$A_{\mathrm{FB}}^{0,f} \equiv \frac{3}{4}\mathcal{A}_{\mathrm{e}}\mathcal{A}_{f},$$

where

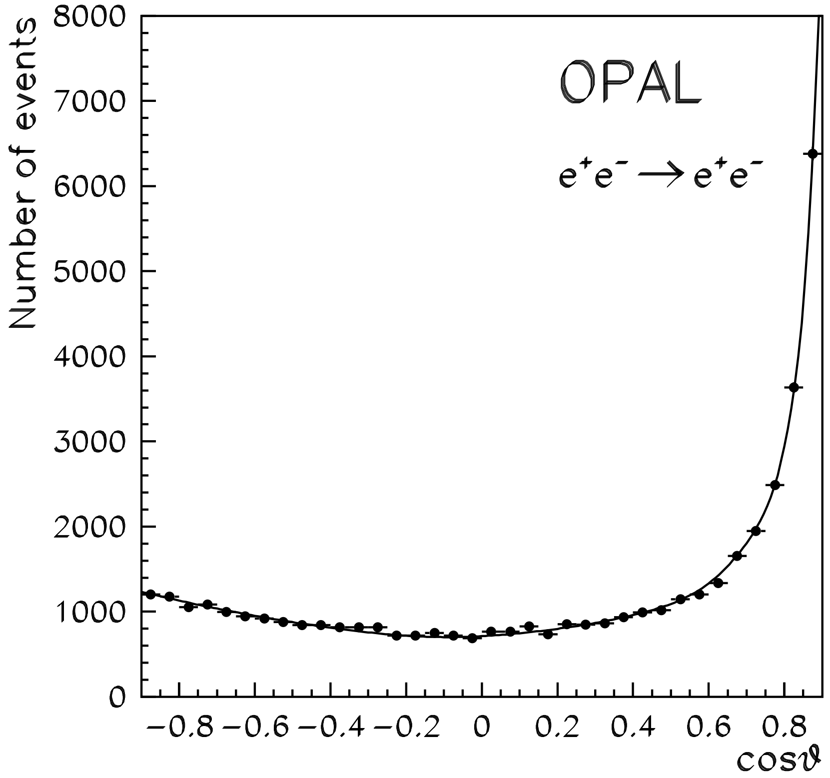
$$\mathcal{A}_{f} = \frac{2 g_{\mathrm{V}f} g_{\mathrm{A}f}}{g_{\mathrm{V}f}^2 + g_{\mathrm{A}f}^2}$$

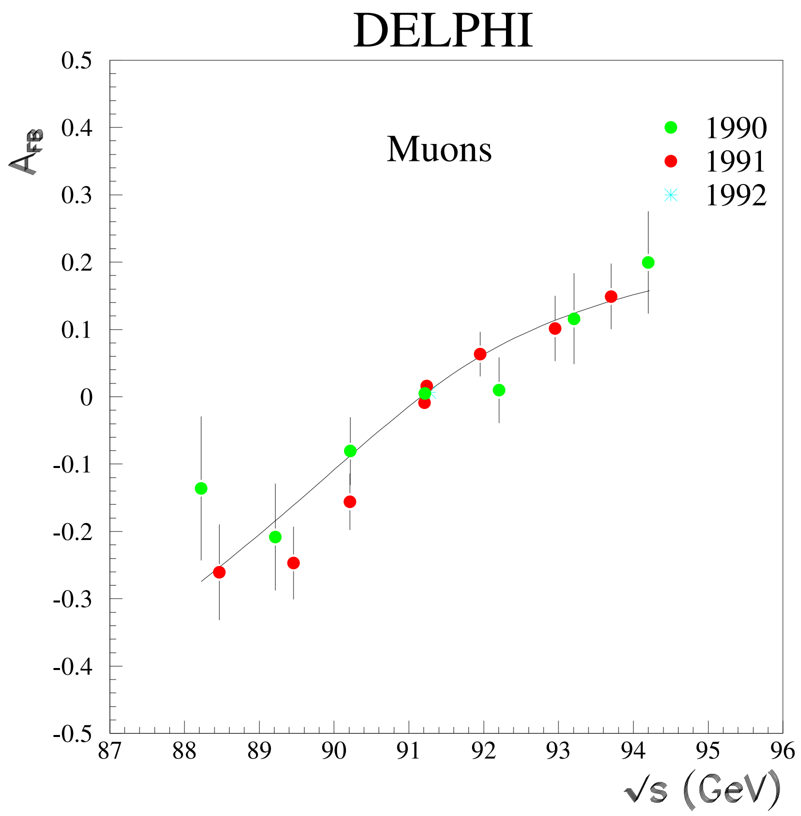
The asymmetries provide a direct measurement of

$$\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}} \equiv \frac{1}{4}(1 - g_{\mathrm{V}}/g_{\mathrm{A}})$$

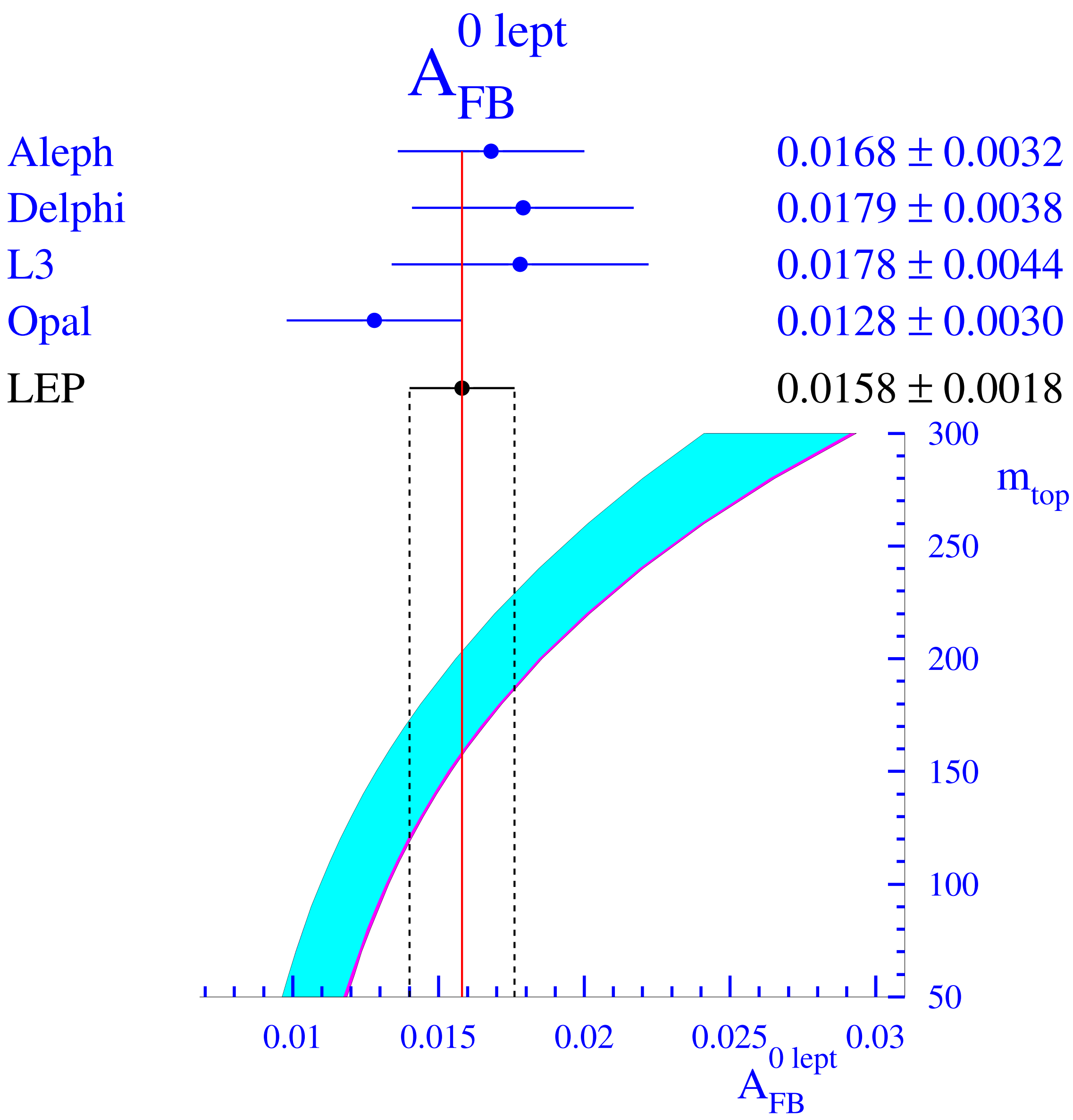
In combination with $\Gamma_{\ell\ell}$, the coupling constants g_{A} and g_{V} can be determined.

Data Examples





Lepton Asymmetries

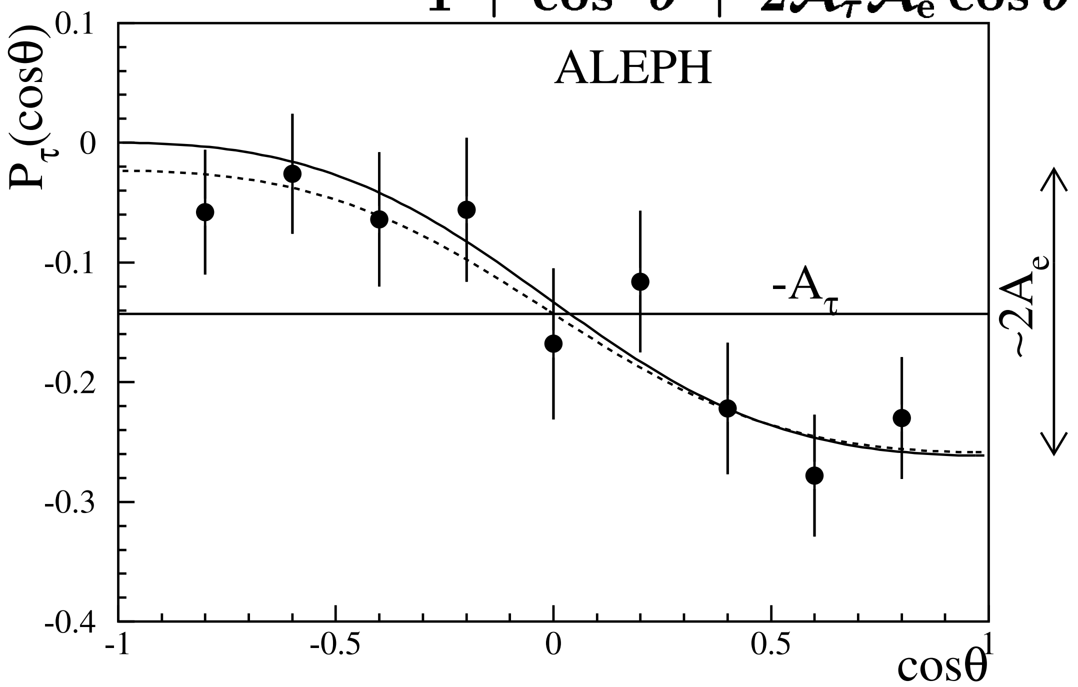


Still dominated by statistics, but theoretical error estimated to be 0.001 ⇒ will be important in the future.

Tau Polarization

Z decays produce polarized final states (A_{LR} in reverse). Only the $\tau^+\tau^-$ final state can be used as a polarimeter.

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



Averaged over θ,

$$\mathcal{P}_\tau = -\mathcal{A}_\tau,$$

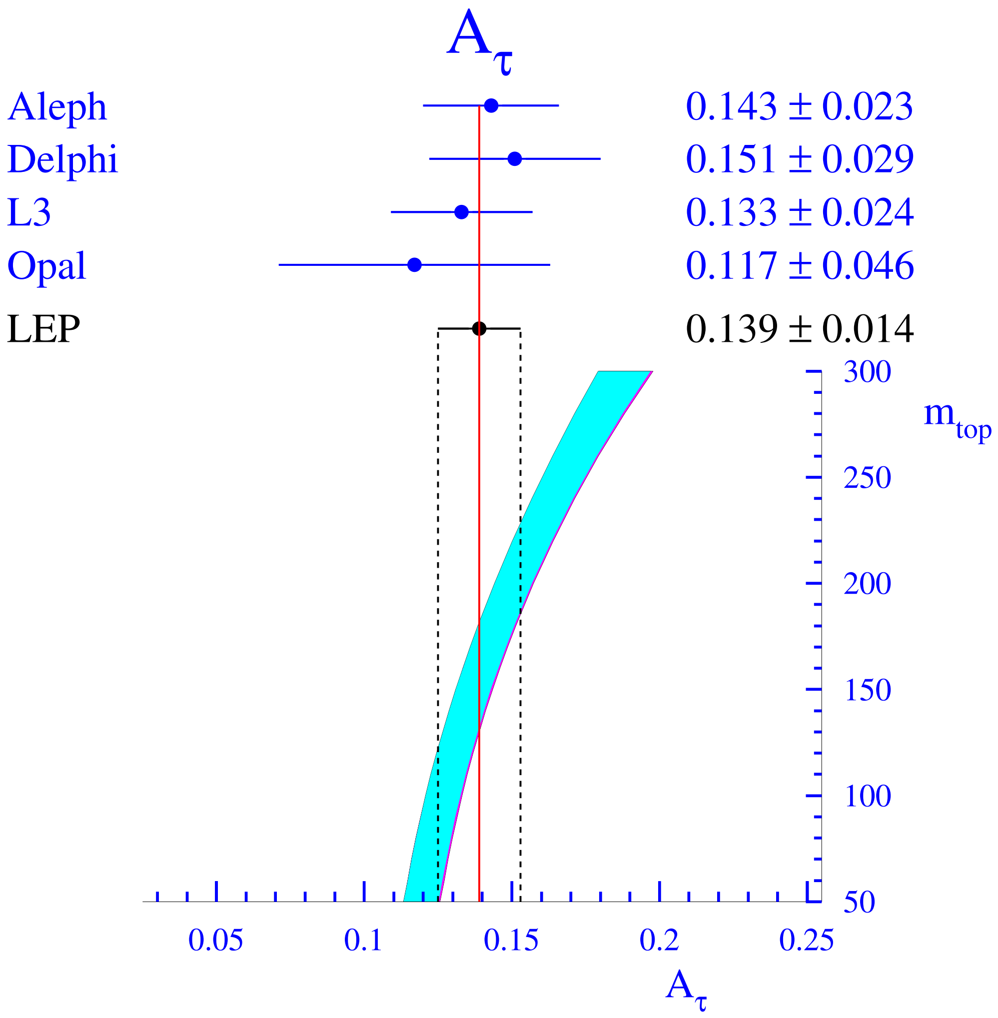
whereas the forward-backward polarization asymmetry is:

$$\mathcal{P}_\tau^{\mathrm{FB}} = -\frac{3}{4}\mathcal{A}_e$$

Tau polarization gives independent measurements of $\mathcal{A}_\tau$ and $\mathcal{A}_e$.

Since the measurement is linear in $\mathcal{A}_\tau$ and $\mathcal{A}_e$, the relative sign of g_A and g_V is also determined.

$\mathcal{P}_\tau$



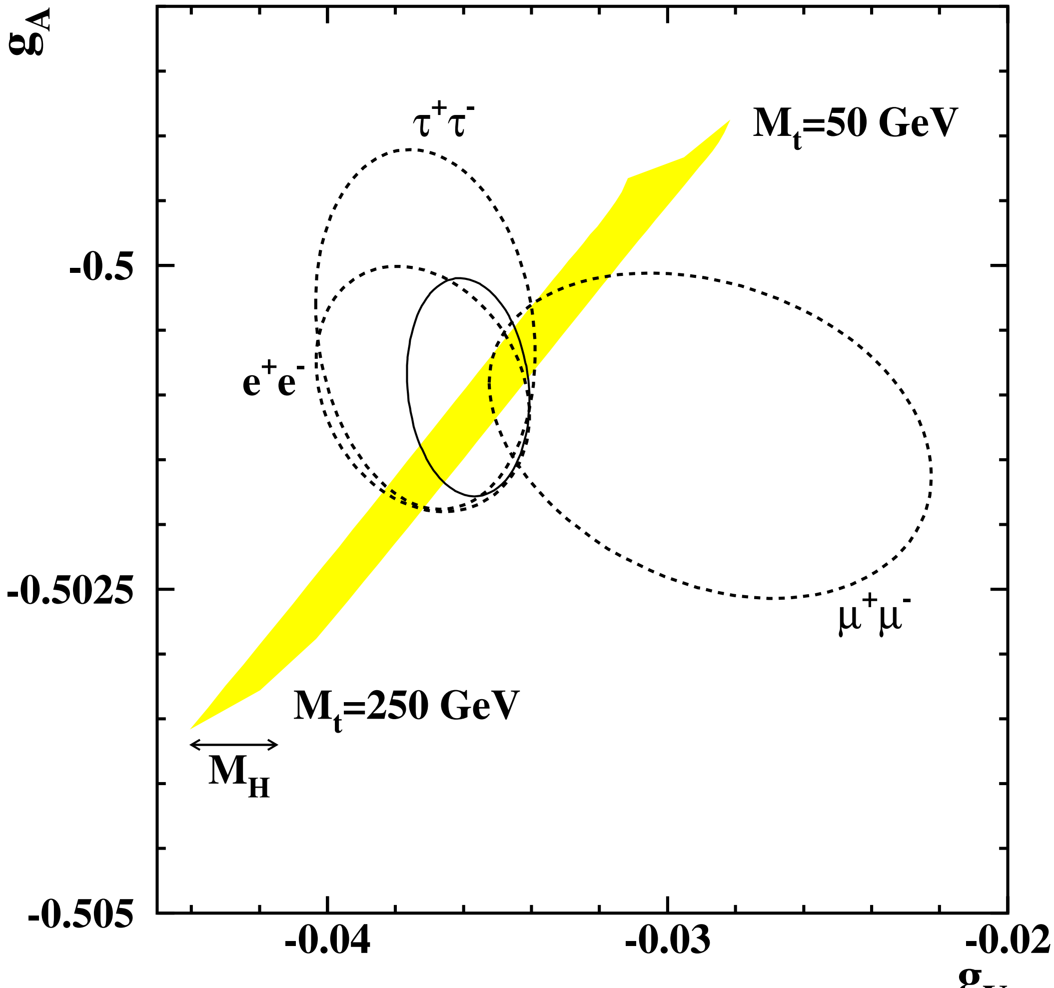
Error on $\mathcal{A}_\tau$ approximately equal contributions from statistics and detector calibrations.

$$\mathcal{A}_e = \mathbf{0.130 \pm 0.025} \textbf{ (Aleph and Opal only)}$$

and is dominated by statistics.

g_V and g_A

Combining all the lepton asymmetry measurements plus the $\Gamma_{\ell\ell}$ results determines the lepton g_V and g_A:



Assuming lepton universality

$$g_V = -0.0359 \pm 0.0018$$
$$g_A = -0.5009 \pm 0.0008$$

Heavy Quark Asymmetries

As for leptons, the $\mathrm{b\bar{b}}$ asymmetry on the peak is

$$A_{\mathrm{FB}}^{0,\,\mathrm{b}} = \frac{3}{4}\mathcal{A}_{\mathrm{e}}\mathcal{A}_{\mathrm{b}}.$$

However, as $g_{\mathrm{V}} \propto (1 - 4|Q|\sin^2\theta)$, $g_{\mathrm{V}_\mathrm{b}}$ is large and relatively constant $\Rightarrow$ $A_{\mathrm{FB}}^{0,\,\mathrm{b}}$ is mostly sensitive to $\mathcal{A}_{\mathrm{e}}$.

Events are tagged using

- **Leptons:** Direction and sign of the lepton determines the charge of the quark. High purity; low efficiency; needs mixing correction.
- **Lifetime:** High lifetime tags the event; the charge of the jet determines the charge of the quark.

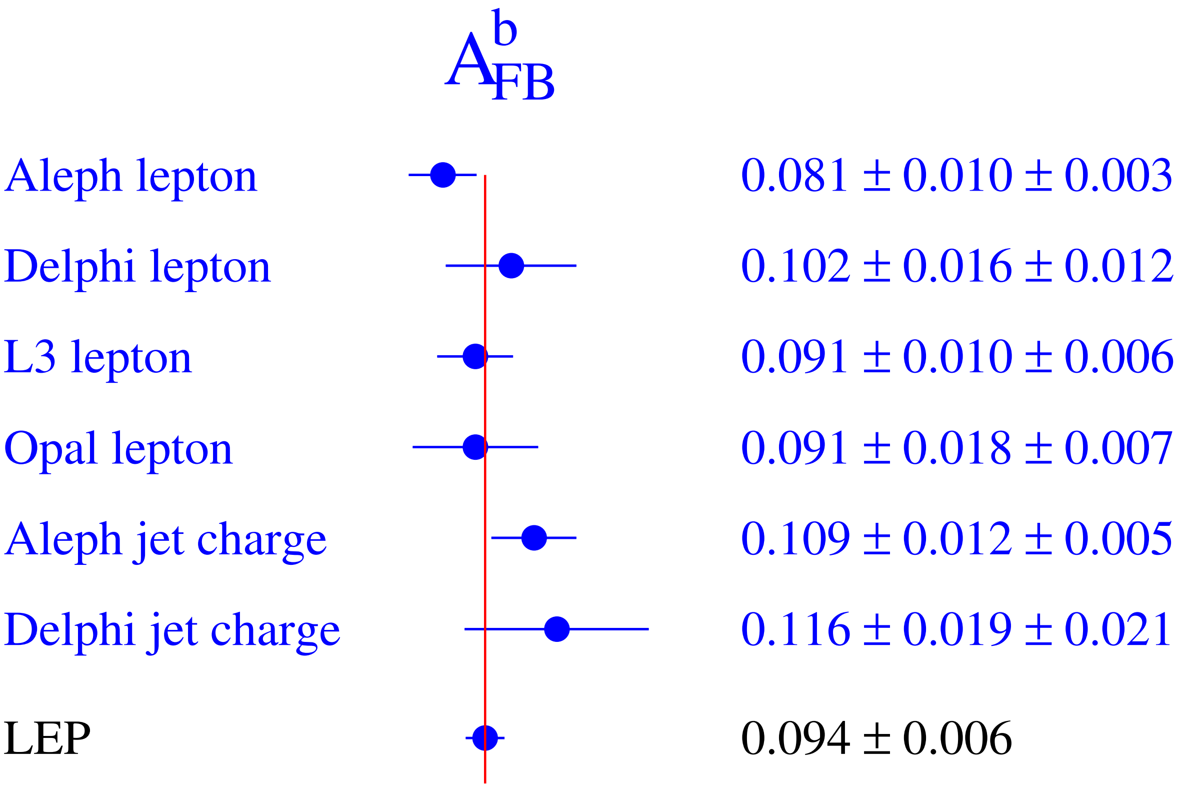
$$Q_{jet} = \frac{\Sigma Q p^{\kappa}}{\Sigma p^{\kappa}}$$

High efficiency; poor charge determination.

Both methods use the thrust axis to approximate the quark direction $\Rightarrow$ QCD corrections.

Heavy Quark Asymmetries

The LEP experiments report A_{FB}^{b} after only mixing corrections:



QED and QCD corrections modify the result to

$$A_{FB}^{0,b} = 0.099 \pm 0.006$$

Still dominated by statistics, but modelling is also important.

Quark Charge Asymmetry

The charge asymmetry averaged over all quark species can be used to measure $\sin^2\theta_{\rm eff}^{\rm lept}$.

In principle, the measurement is not quite as "model-independent" as other asymmetries, as knowledge of the relative fractions of quarks is necessary.

Jet charge is measured as in the b quark asymmetry.

Results are quoted in terms of $\sin^2\theta_{\rm eff}^{\rm lept}$:

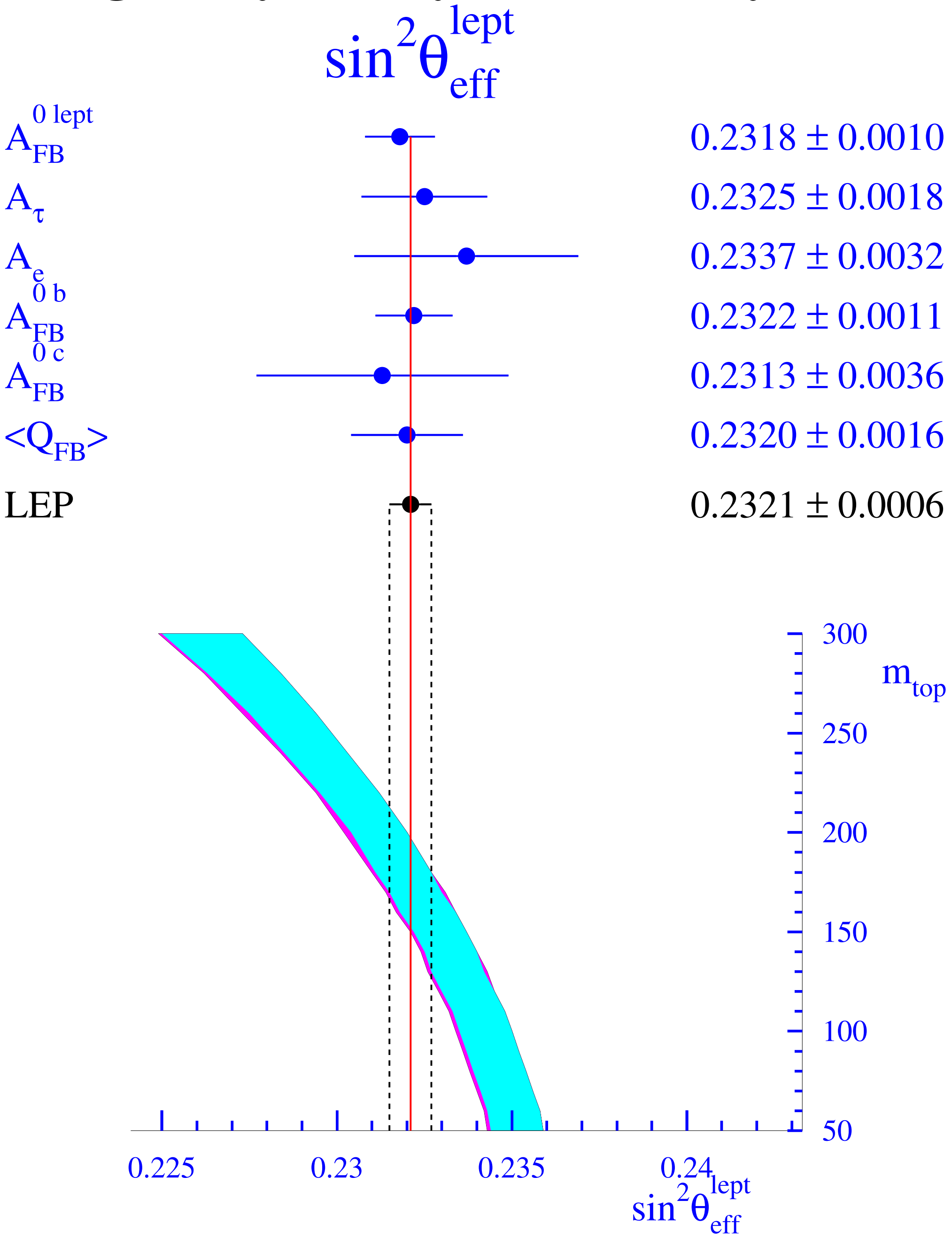
Exp.	data	$\sin^2\theta_{\rm eff}^{\rm lept}$
ALEPH	89-92 prel.	$0.2317 \pm 0.0013 \pm 0.0011$
DELPHI	90-91	$0.2345 \pm 0.0030 \pm 0.0027$
OPAL	90-91	$0.2321 \pm 0.0017 \pm 0.0028$
Average		$0.2320 \pm 0.0011 \pm 0.0011$

Dominant errors are fragmentation and knowledge of charge separation.

Aleph has reduced the latter by using the measured mean and b quark charge separations They also have rejected the Herwig model.

$\sin^2\theta_{\rm eff}^{\rm lept}$

Combining all asymmetry information yields:



Note that most of the measurements can still be improved with additional statistics.

Standard Model Fit

Within the Standard Model, all observables depend on the masses and couplings.

$\Rightarrow$ one can use current measurements to predict, *e.g.*, m_{W} and m_{t}.

Use all lineshape parameters (m_{Z}, Γ_{Z}, R_{ℓ}, $R_{\mathrm{b\bar{b}}}$, σ^0_{had}), and all asymmetries (lepton, τ polarization, $A_{\mathrm{FB}}^{0,\mathrm{b}}$, $A_{\mathrm{FB}}^{0,\mathrm{c}}$, $< Q_{\mathrm{FB}} >$) to obtain:

	LEP
m_{t} (GeV)	$166^{+17}_{-19}\,^{+19}_{-22}$
$\alpha_{\mathrm{s}}(m_{\mathrm{Z}})$	$0.120 \pm 0.006 \pm 0.002$
$\sin^2\theta^{\mathrm{lept}}_{\mathrm{eff}}$	$0.2324 \pm 0.0005\ ^{+0.0001}_{-0.0002}$
$\sin^2\theta_{\mathrm{W}}$	$0.2255 \pm 0.0019\ ^{+0.0005}_{-0.0003}$
m_{W} (GeV)	$80.25 \pm 0.10\ ^{+0.02}_{-0.03}$

- **No prediction on m_{H} (second error is $60\ \mathrm{GeV} < m_{\mathrm{H}} < 1000\ \mathrm{GeV}$).**
- **Almost no improvement by including $\mathrm{p\bar{p}}$ and ν data.**
- **Extrapolation of $\alpha = 1/137$ to $\alpha(m_{\mathrm{Z}}) \approx 1/128$ has an error due to light quark loops $\Rightarrow$ uncertainty on $\sin^2\theta^{\mathrm{lept}}_{\mathrm{eff}}$ of about 0.0003. New results from low-energy $\mathrm{e^+e^-}$ could be used to reduce this to 0.0002.**

Conclusions

The LEP experiments have tested the Standard Model to better than 1%. So far, it has come through with flying colors.

The quest for deviations continues with increasingly precise measurements.

We will need additional help from

- **our theory friends**
- **our SLC friends**
- **our $p\bar{p}$ friends**
- **our low energy friends**