Precision Results on the Z

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Many thanks to J. Mnich, Ch. Paus and and my colleagues in the LEP EW Working Group

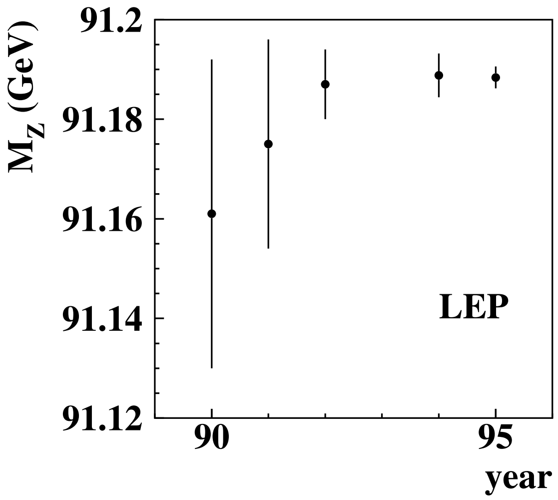
See also Sessions J7 and J14 tomorrow morning

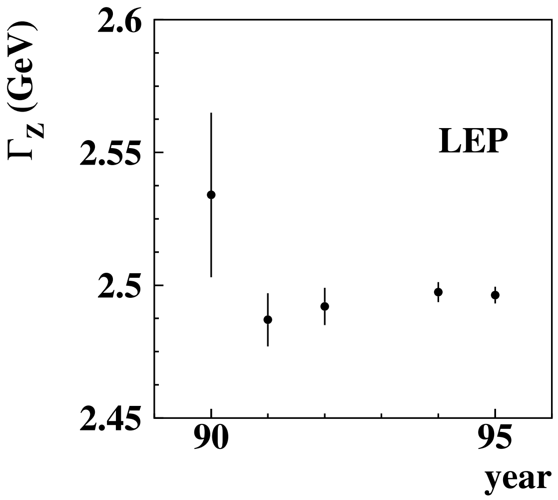
Precision Results

For example: the mass and width 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





Currently (Brussels 95, Moriond 96):

$$m_Z = 91.1884 \pm 0.0022 \text{ GeV}$$
$$\Gamma_Z = 2.4964 \pm 0.0032 \text{ GeV}$$

Due to

- LEP energy calibration
- Statistics
- Cross-section systematics

LEP Energy Determination

The most accurate method: resonant depolarization

Advantage:

- **precise to 0.2 MeV**

Disadvantages:

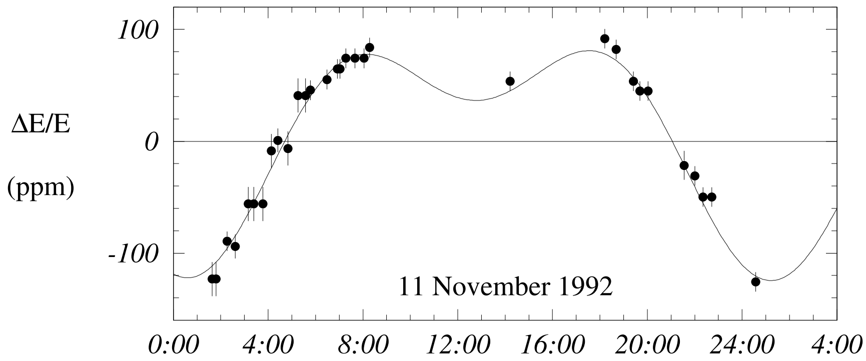
- **can not be done during "physics"**
- **takes about 2 hours per measurement**

⇒ not done very often.

But LEP is a big machine; the conditions are changing continuously ⇒ energy is changing (≈ 1 MeV/hr).

⇒ a model is needed to track the energy.

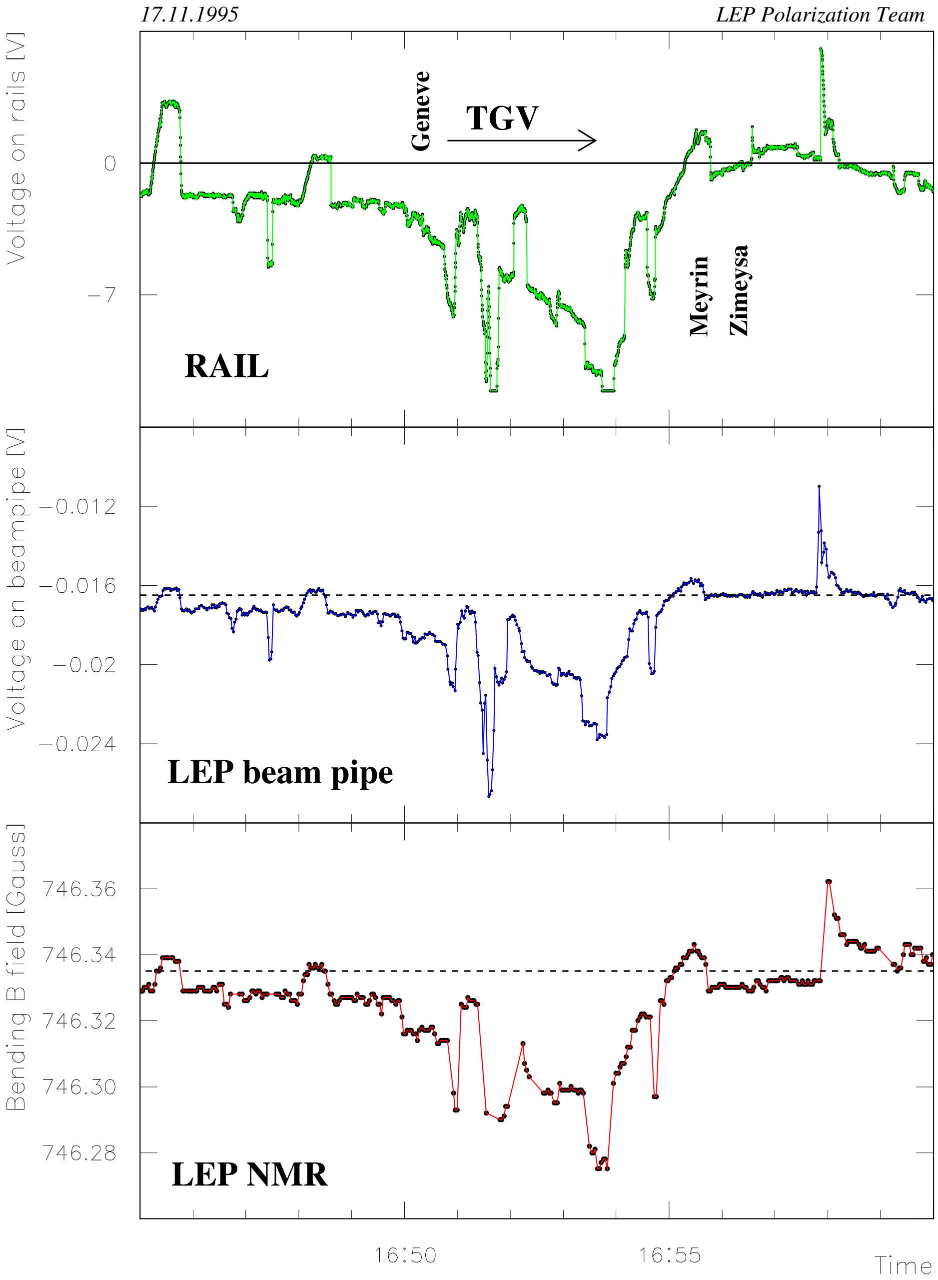
- **Magnet field strength**
- **RF status**
- **Size of ring (tides, *etc.*)**



- **Anything else . . .**

LEP Energy Determination

Anything else: electric trains!



Before this effect was discovered, the LEP energy error was 1.5 MeV on m_Z and 2.0 MeV on Γ_Z.

This effect is still under study. More news in the summer...

LEP Data Samples

The results presented here are based on the 1990-1994 + some 1995 data.

		ALEPH	DELPHI	L3	OPAL	LEP
		Number of events (10^3)				
$q\bar{q}$	'90-'91	451	365	416	454	1677
	'92	680	697	678	733	2788
	'93	640	677	654	646	2617
	'94	1281	1144	1362	1524	5311
	total	3052	2874	3110	3357	12393
$\ell^+\ell^-$	'90-'91	55	37	40	58	190
	'92	82	69	58	88	297
	'93	78	71	61	82	292
	'94	155	124	123	184	586
	'95	55	22	-	-	77
	total	425	323	282	412	1442

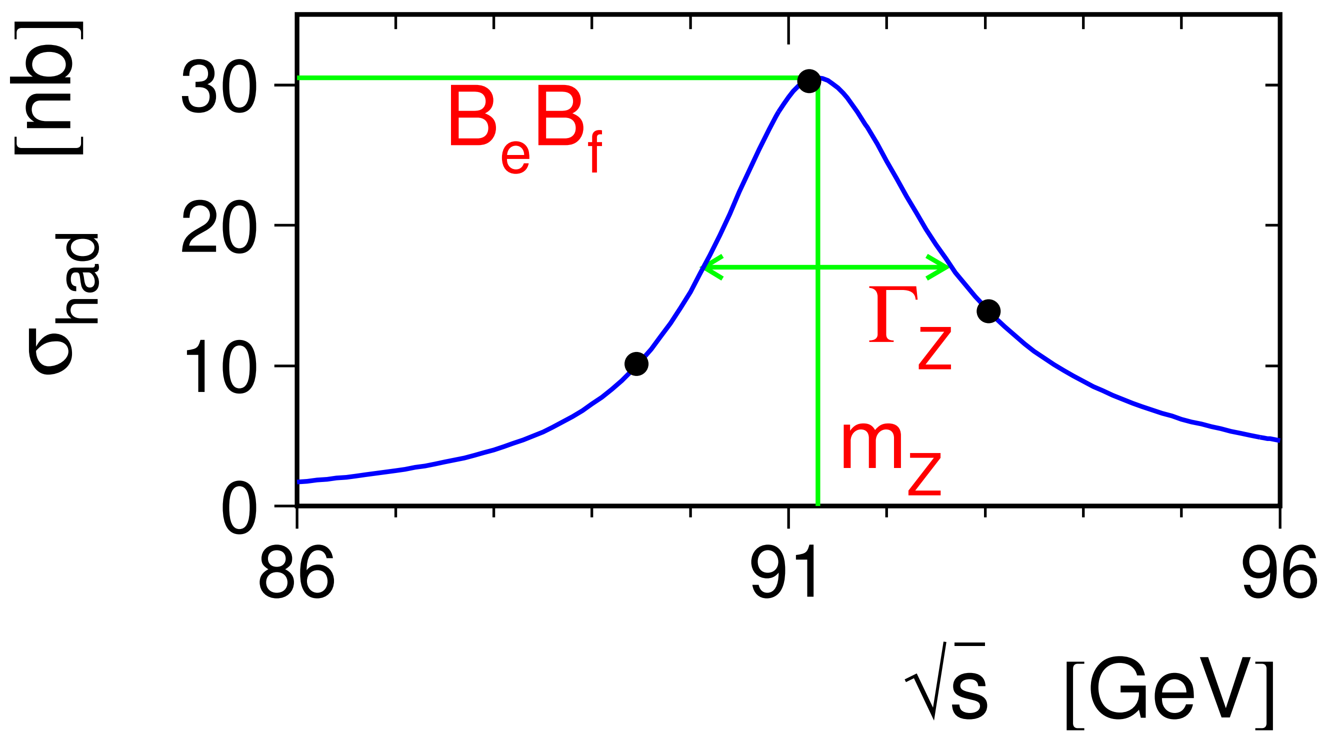
1995 sample is similar to 1993 (both lumi and energy scan).

$\Rightarrow$ final total LEP I sample will be

$\approx 15M$ **hadrons;**

$\approx 1.7M$ **leptons.**

Excitation Curve of the Z Boson



Properties of the Z boson:

Peak position: m_Z

Peak width: Γ_Z

Peak height: $B_e B_f = \Gamma_{ee}\Gamma_{ff}/\Gamma_Z^2$

QED corrections included by convolution:

$$\sigma(s) = \int_0^1 dz R(z,s)\sigma^0(zs)$$

Peak cross section reduced by ~ 25 %

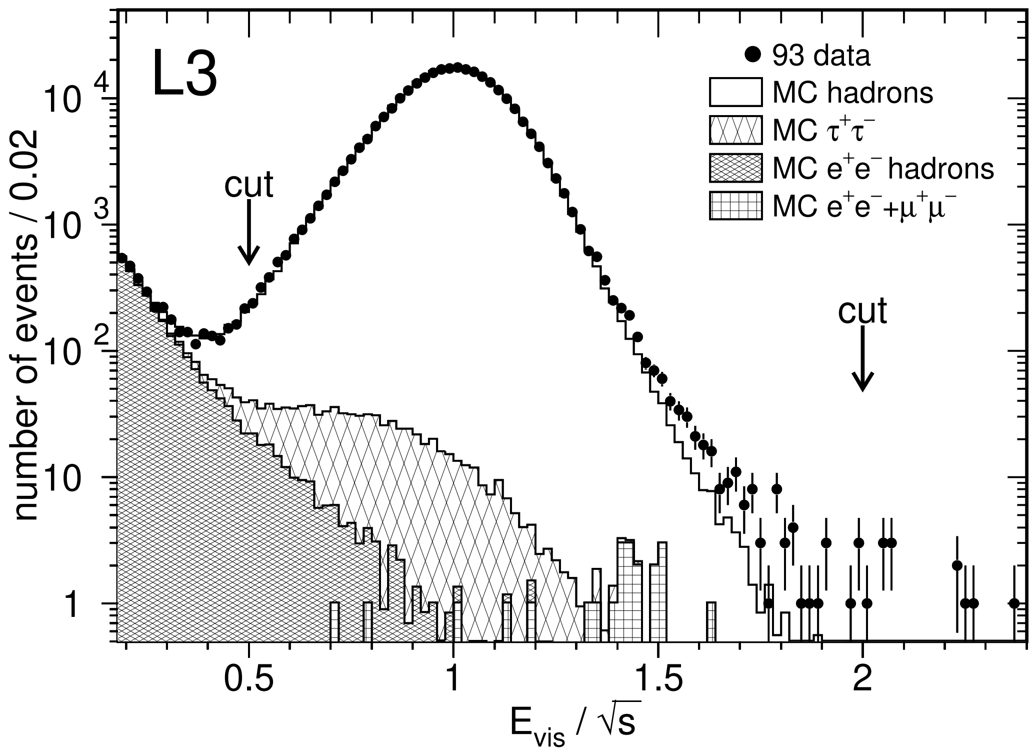
Precision in Cross-sections

Knowledge of the absolute cross-section is extremely important:

$$\Delta\sigma_{\mathrm{had}}[\mathrm{peak} - \mathrm{offpeak}] = 15\mathrm{pb}\ (0.05\%)$$

$$\Rightarrow \Delta\Gamma_Z = 2\ \mathrm{MeV}$$

$\Rightarrow$ need to know non-resonant background very well!



Typical systematic error on σ_{had} is $\approx 0.15\%$, almost entirely scale uncertainty.

Fitting procedure

Fit measured cross sections to:

- m_{Z}
- Γ_{Z}
- $\sigma^0_{\mathrm{had}} \equiv \dfrac{12\pi}{m_{\mathrm{Z}}^2}\dfrac{\Gamma_{\mathrm{ee}}\Gamma_{\mathrm{had}}}{\Gamma_{\mathrm{Z}}^2}$ **(“peak” cross section)**
- $R_\ell \equiv \Gamma_{\mathrm{had}}/\Gamma_{\ell\ell}$, **for** ℓ **= e,** μ, τ

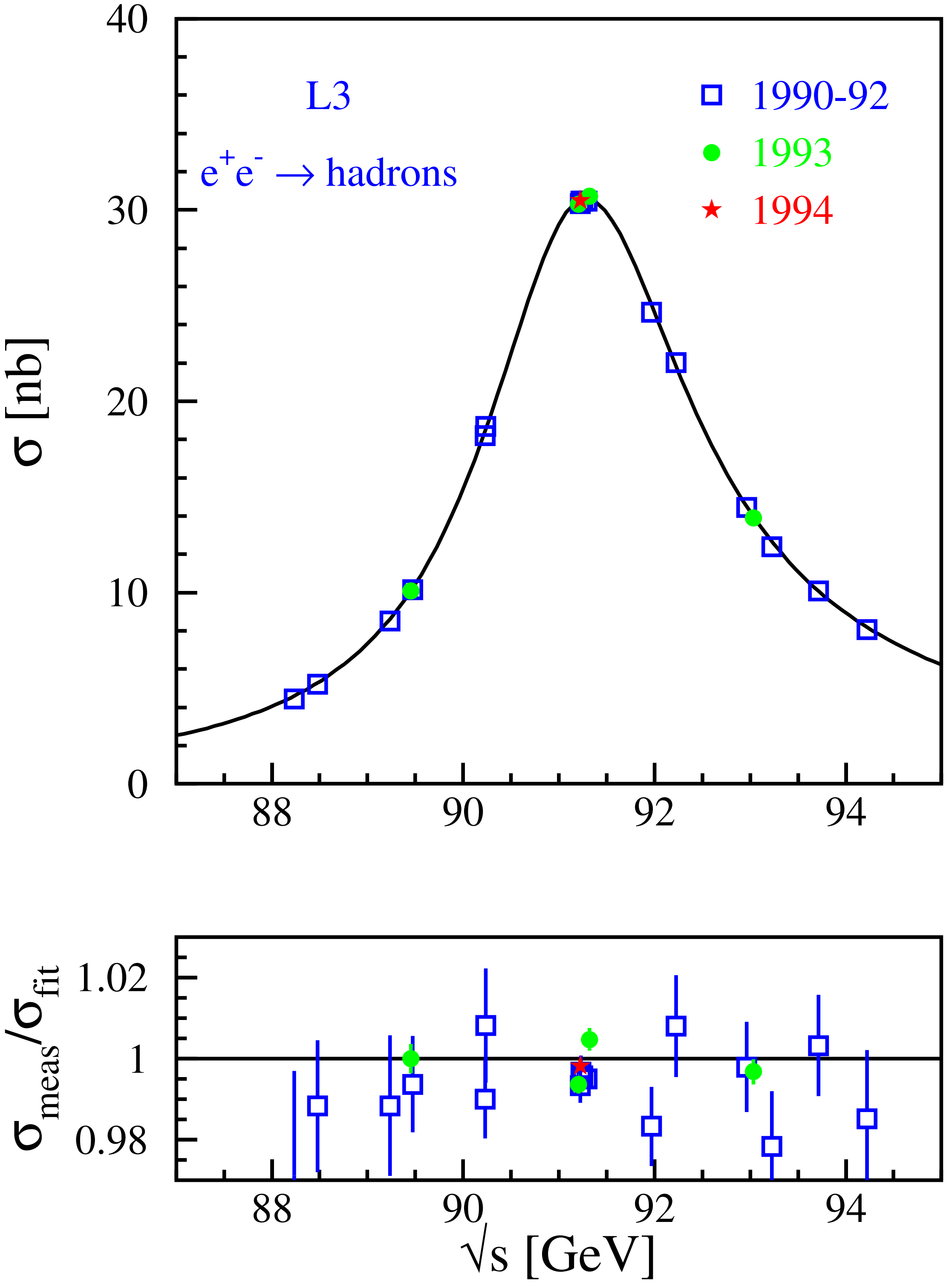
These quantities were chosen to reduce the correlations between the parameters.

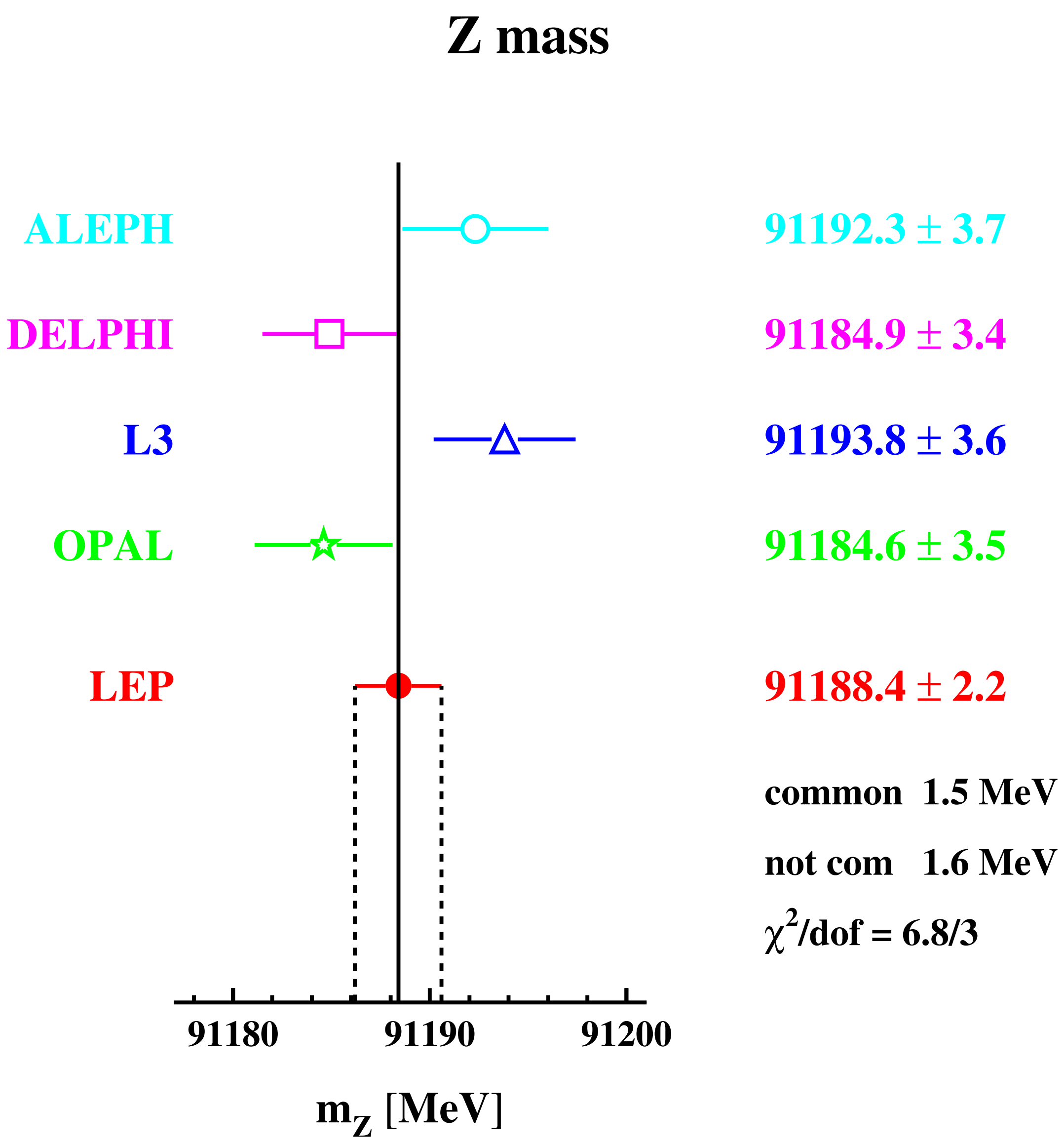
“Model independent,” *i.e.*, **no assumptions on** m_{t}, *etc.*

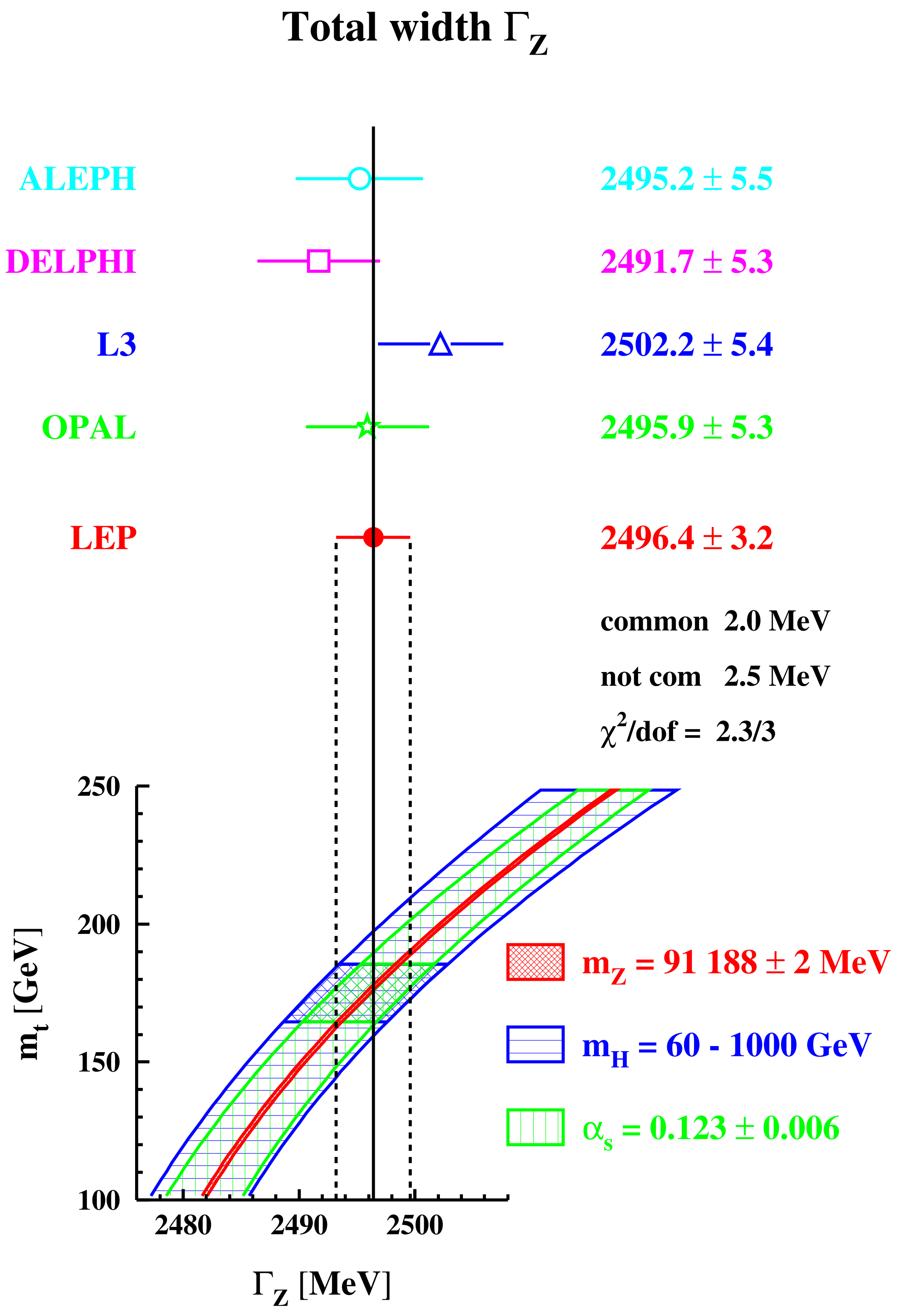
One can then derive other important parameters such as

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

Data Example




Z mass
ALEPH
DELPHI
L3
OPAL
LEP
91192.3 ± 3.7
91184.9 ± 3.4
91193.8 ± 3.6
91184.6 ± 3.5
91188.4 ± 2.2
common 1.5 MeV
not com 1.6 MeV
χ^2/dof = 6.8/3
91180
91190
91200
m_Z [MeV]


Total width Γ_Z
ALEPH
2495.2 ± 5.5
DELPHI
2491.7 ± 5.3
L3
2502.2 ± 5.4
OPAL
2495.9 ± 5.3
LEP
2496.4 ± 3.2
common 2.0 MeV
not com 2.5 MeV
χ^2/dof = 2.3/3
250
200
150
100
m_t [GeV]
2480
2490
2500
Γ_Z [MeV]
m_Z = 91 188 ± 2 MeV
m_H = 60 - 1000 GeV
α_s = 0.123 ± 0.006

Result of Lineshape fits

"Breit-Wigner" fit:

$$\begin{array}{lll} m_Z & 91.1884 \pm 0.0022 & \text{GeV} \\ \Gamma_Z & 2.4964 \pm 0.0032 & \text{GeV} \end{array}$$

$$\begin{array}{lll} \sigma^0_{\text{had}} & 41.490 \pm 0.078 & \text{nb} \\ R_\ell & 20.789 \pm 0.032 & \end{array}$$

$$\left(\begin{array}{ll} R_e & 20.801 \pm 0.058 \\ R_\mu & 20.795 \pm 0.043 \\ R_\tau & 20.815 \pm 0.061 \end{array} \right)$$

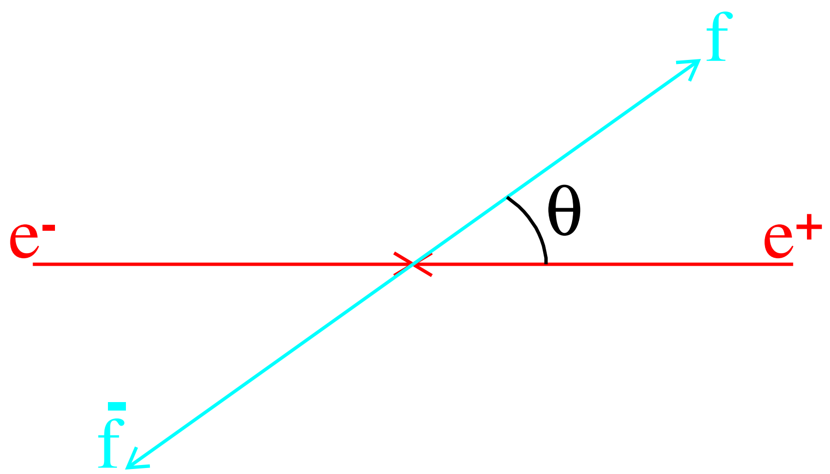
Partial widths:

$$\begin{aligned} \Gamma_{\text{had}} &= 1745.0 \pm 3.0 \text{ MeV} \\ \Gamma_{\ell\ell} &= 83.94 \pm 0.14 \text{ MeV} \end{aligned}$$

$$\Gamma_{\text{inv}} = 499.7 \pm 2.5 \text{ MeV}$$

$$N_\nu = 2.991 \pm 0.016$$

Asymmetries



$$\mathcal{A}_{\mathrm{FB}} = \frac{\sigma_F - \sigma_B}{\sigma_{\mathrm{tot}}}$$

Angular dependence:

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta} = \frac{3}{8}(1+\cos^2\theta) + \mathcal{A}_{\mathrm{FB}}\cos\theta$$

The asymmetry at the Z peak can be expressed as

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

where

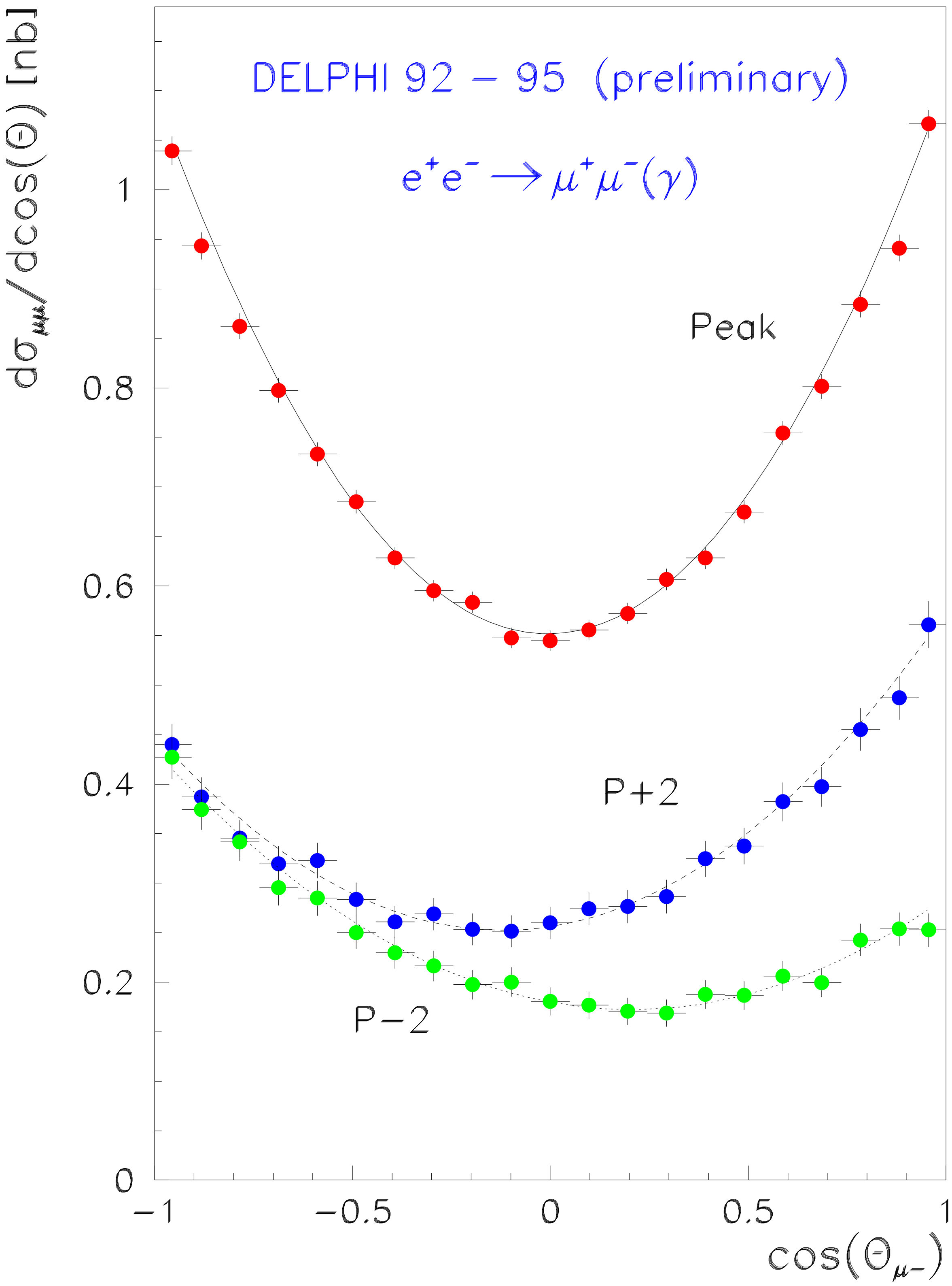
$$\mathcal{A}_{\mathrm{f}} = \frac{2g_{\mathrm{Vf}}g_{\mathrm{Af}}}{g_{\mathrm{Vf}}^2 + g_{\mathrm{Af}}^2}$$

The asymmetries provide a direct measurement of

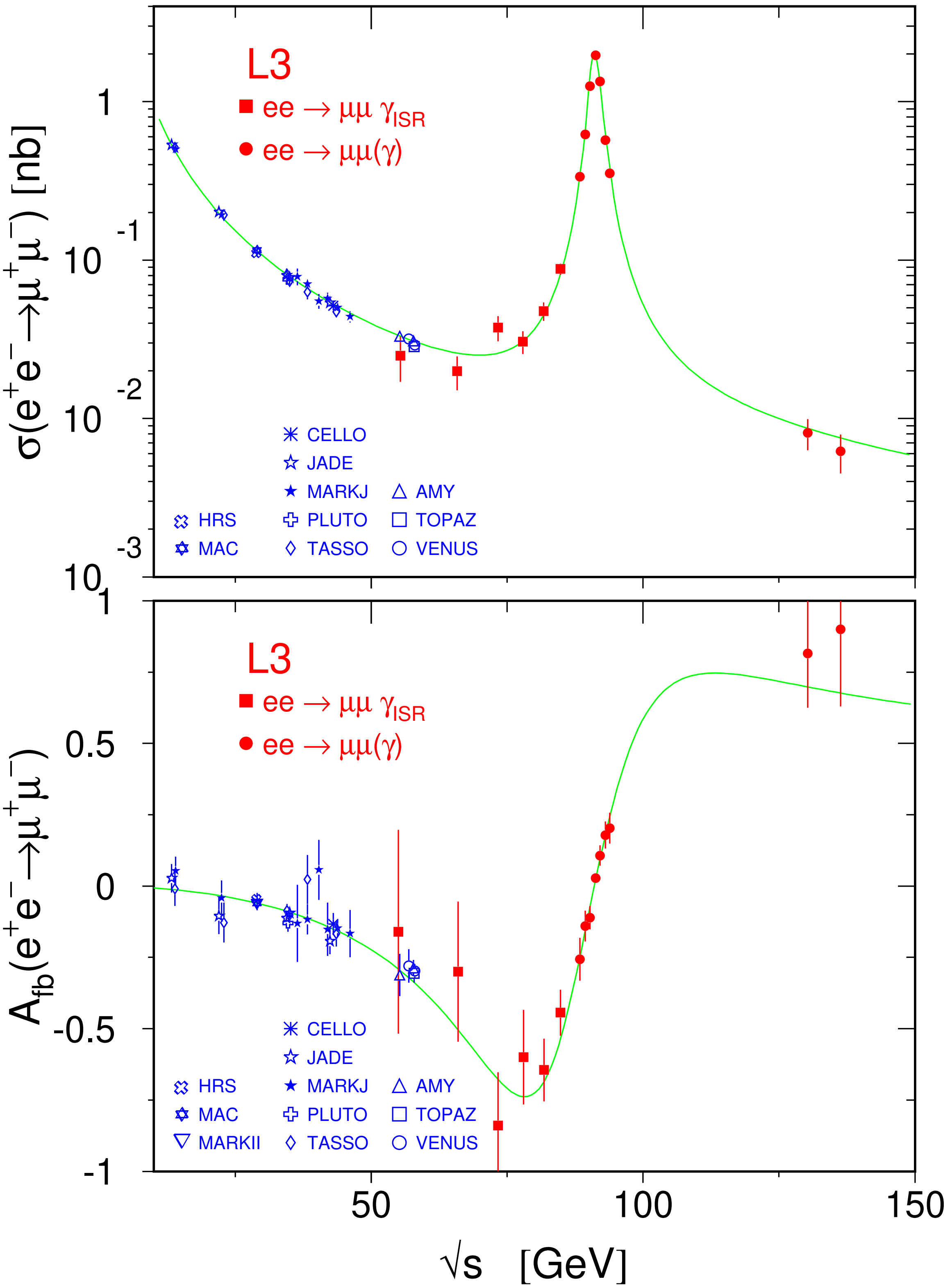
$$\sin^2\theta^{\mathrm{lept}}_{\mathrm{eff}} \equiv \frac{1}{4}(1 - g_{\mathrm{V}}/g_{\mathrm{A}})$$

In combination with $\Gamma_{\ell\ell}$, the coupling constants g_{A} and g_{V} can be determined. Note: these are effective couplings.

Data Examples



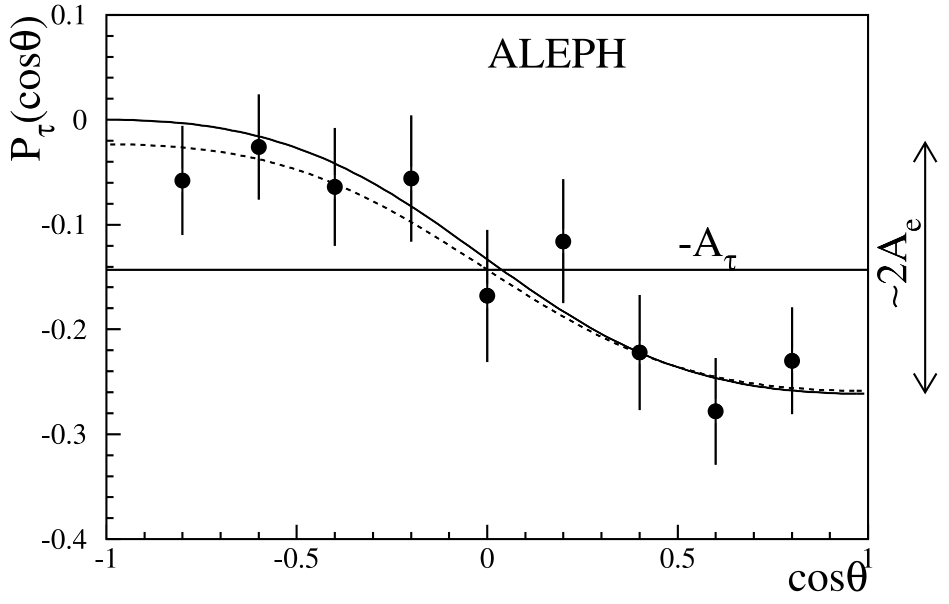
Data Examples



Tau Polarization

Parity violation in Z production and decay produces polarized final states.
At LEP only the $\tau^+\tau^-$ final state can be used as a polarimeter.

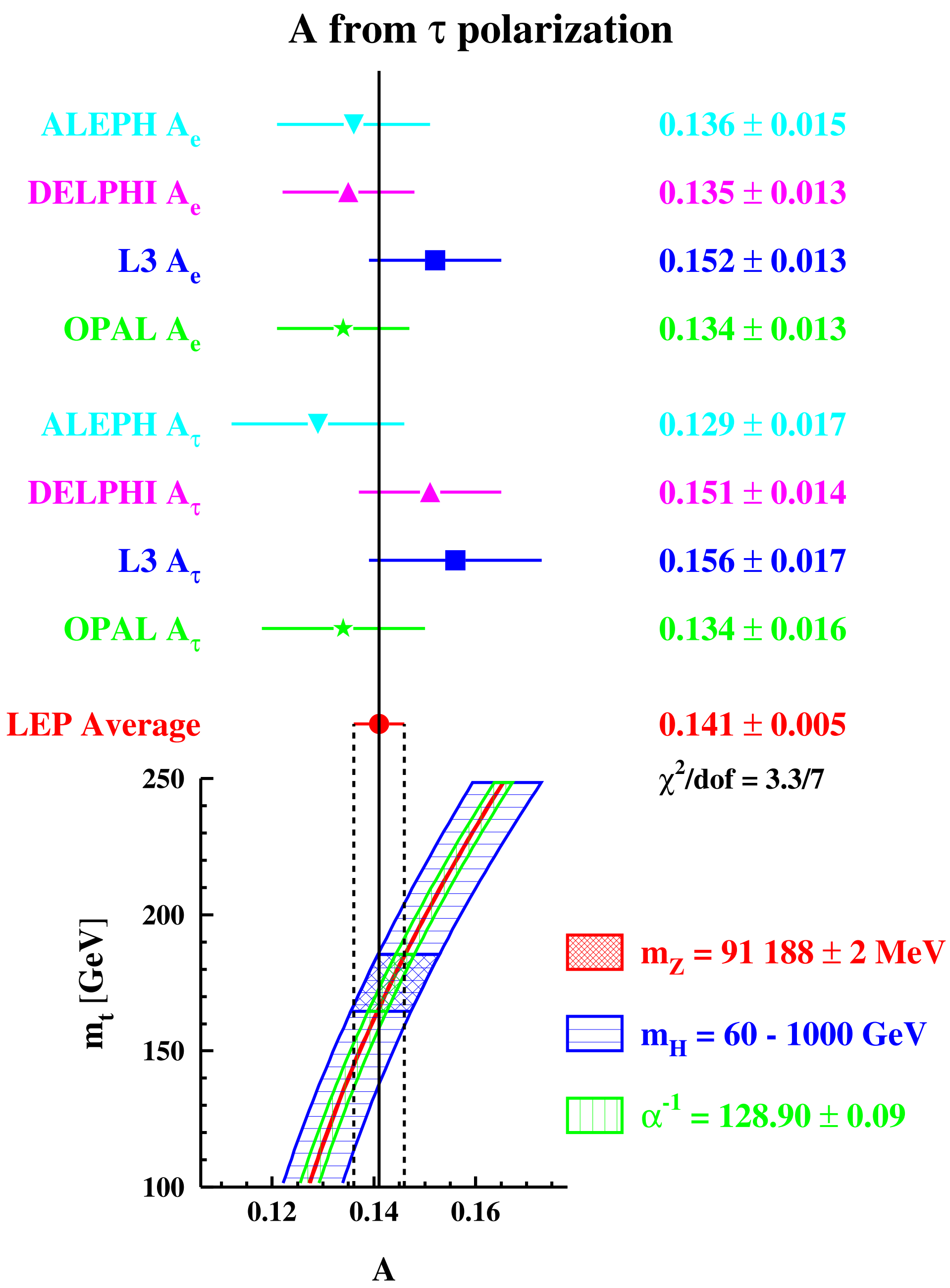
$$\mathcal{P}_\tau(\cos\theta) = -\frac{\mathcal{A}_\tau(1+\cos^2\theta) + 2\mathcal{A}_e\cos\theta}{1+\cos^2\theta + 2\mathcal{A}_\tau\mathcal{A}_e\cos\theta}$$



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.

Tau Polarization



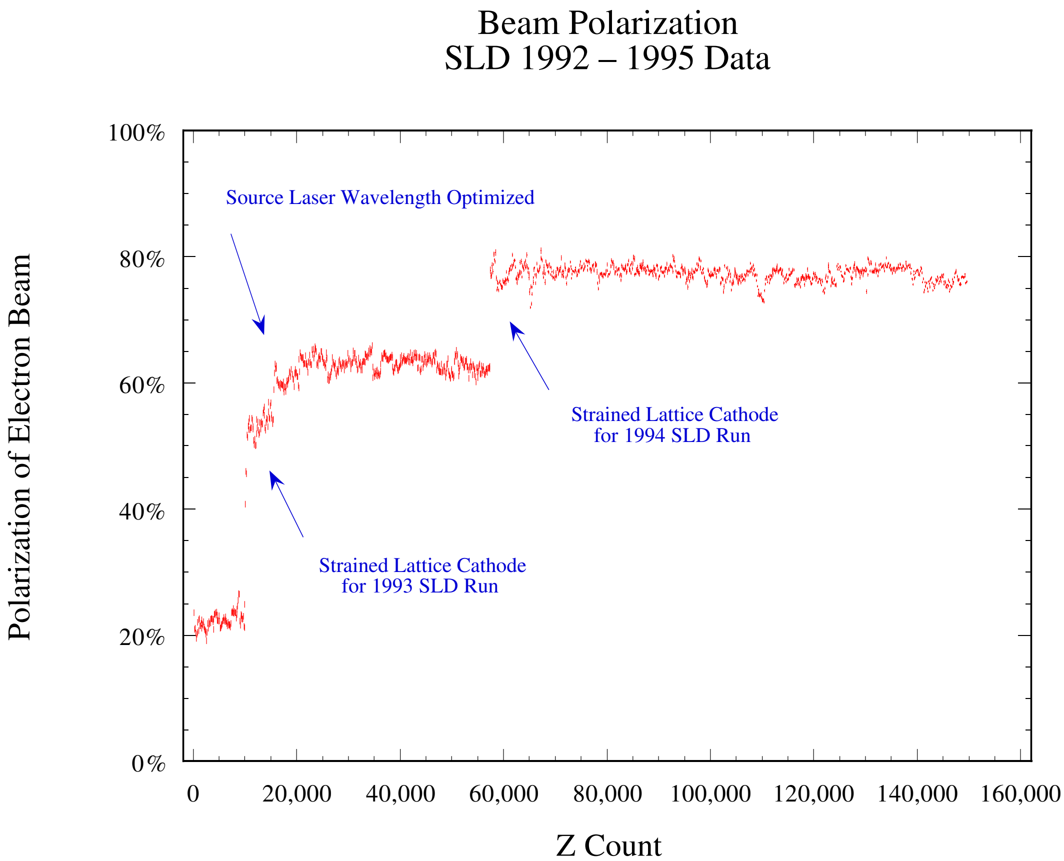
$$\mathcal{A}_e = 0.143 \pm 0.008$$
$$\mathcal{A}_\tau = 0.139 \pm 0.007$$

$\Rightarrow$

$$\mathcal{A}_\ell = 0.141 \pm 0.005$$

Polarized Asymmetries at SLD

At SLC, the electron beam is highly polarized.

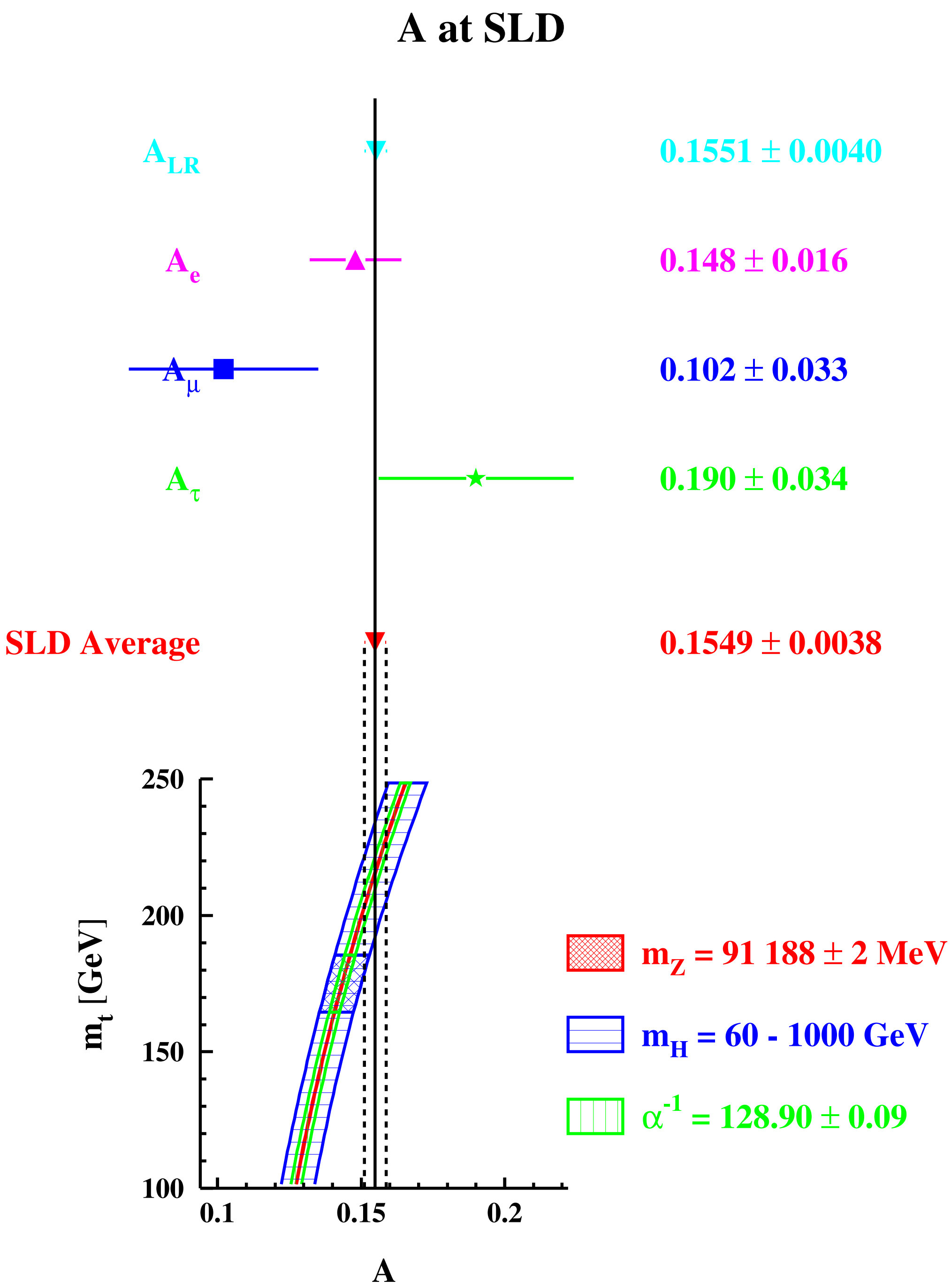


A straight-forward measurement of the hadronic cross-section for left and right polarized electrons gives a precise determination of $\mathcal{A}_e$:

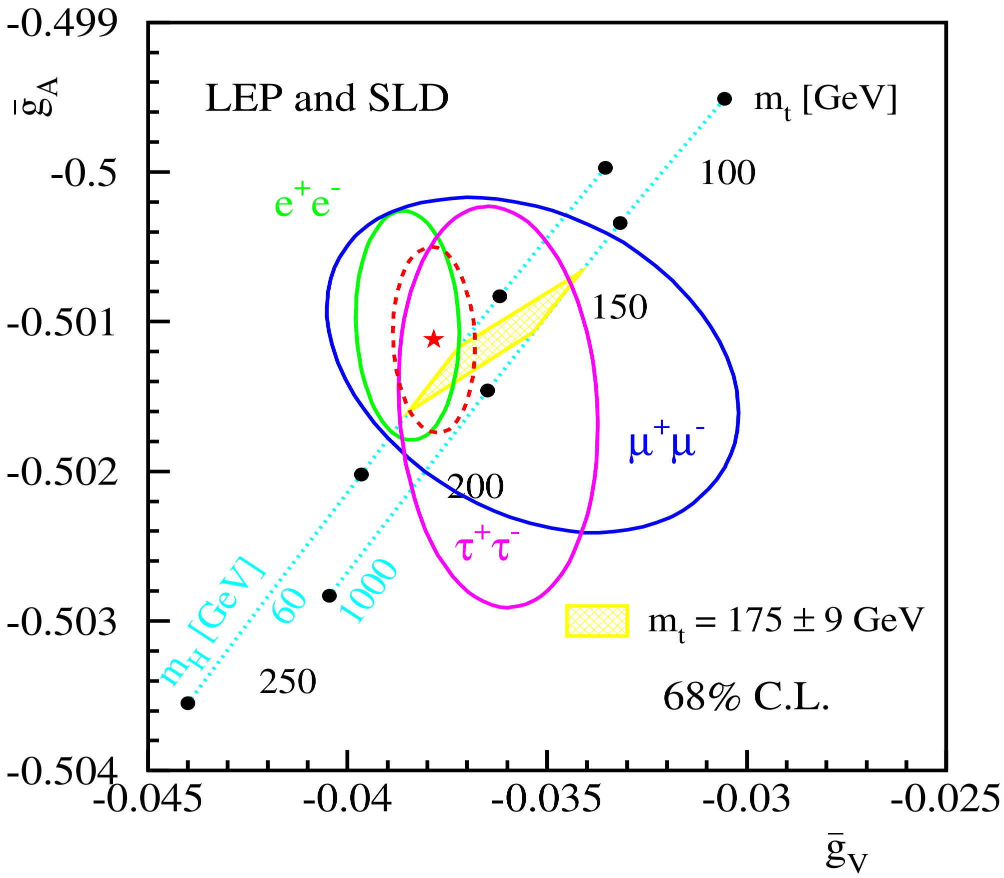
$$A_{LR} = \frac{1}{\mathcal{P}} \frac{\sigma_L - \sigma_R}{\sigma_{tot}} = \mathcal{A}_e$$

$\mathcal{P}_\tau$ in reverse, BUT 77% polarization of the electron beam, compared to 14% for $\mathcal{P}_\tau$

Polarized Asymmetries at SLD



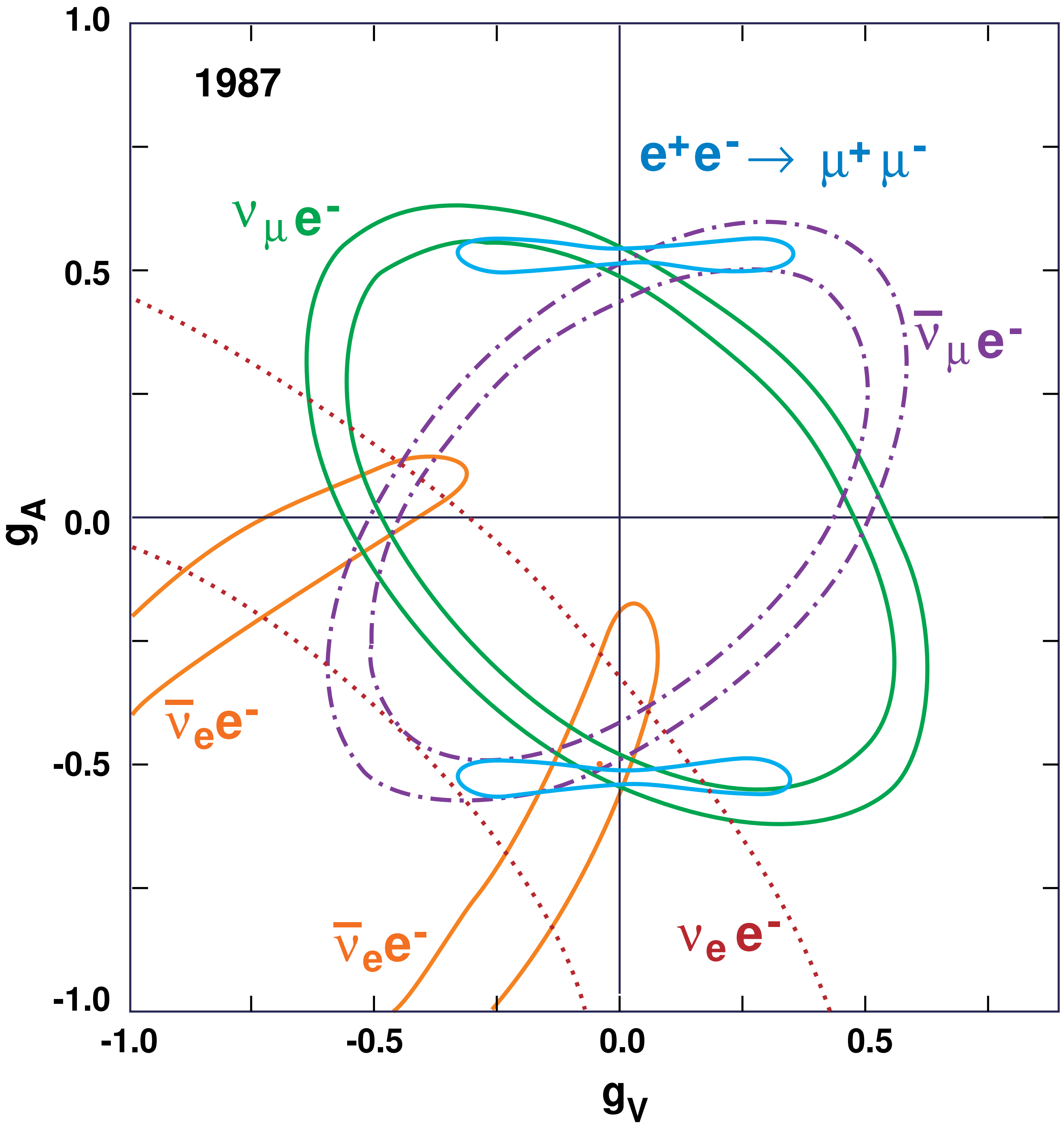
Combining the lepton asymmetry measurements, the τ polarization, the $\Gamma_{\ell\ell}$ and the SLD A_{LR} results determines the lepton g_V and g_A:



Assuming lepton universality

$$g_{V\ell} = -0.03785 \pm 0.00068$$
$$g_{A\ell} = -0.50112 \pm 0.00041$$

Progress!



1.0
0.5
0.0
-0.5
-1.0
g_A
1987
$e^+e^- \rightarrow \mu^+\mu^-$
$\nu_\mu e^-$
$\bar{\nu}_\mu e^-$
$\bar{\nu}_e e^-$
$\bar{\nu}_e e^-$
$\nu_e e^-$
-1.0
-0.5
0.0
0.5
g_V

Heavy Flavor EW Physics

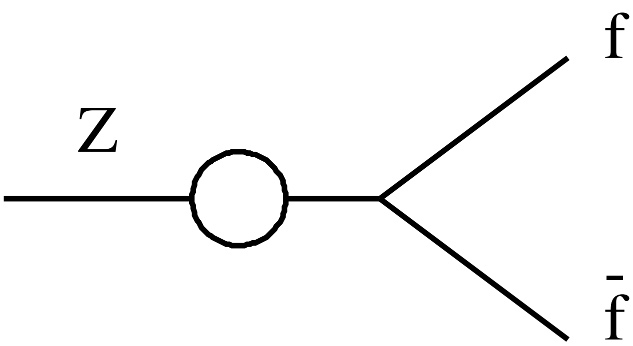
Using the properties of heavy quarks, one can isolate samples of $\mathrm{b\bar{b}}$ and $\mathrm{c\bar{c}}$ events.

These can be used to extract:

- $\Gamma_{\mathrm{b\bar{b}}}$ **and** $\Gamma_{\mathrm{c\bar{c}}}$
- $A_{\mathrm{FB}}^{\mathrm{b}}$ **and** $A_{\mathrm{FB}}^{\mathrm{c}}$

$\Gamma_{\mathrm{b\bar{b}}}$ **is especially interesting:**

All Z decays have radiative corrections of the form

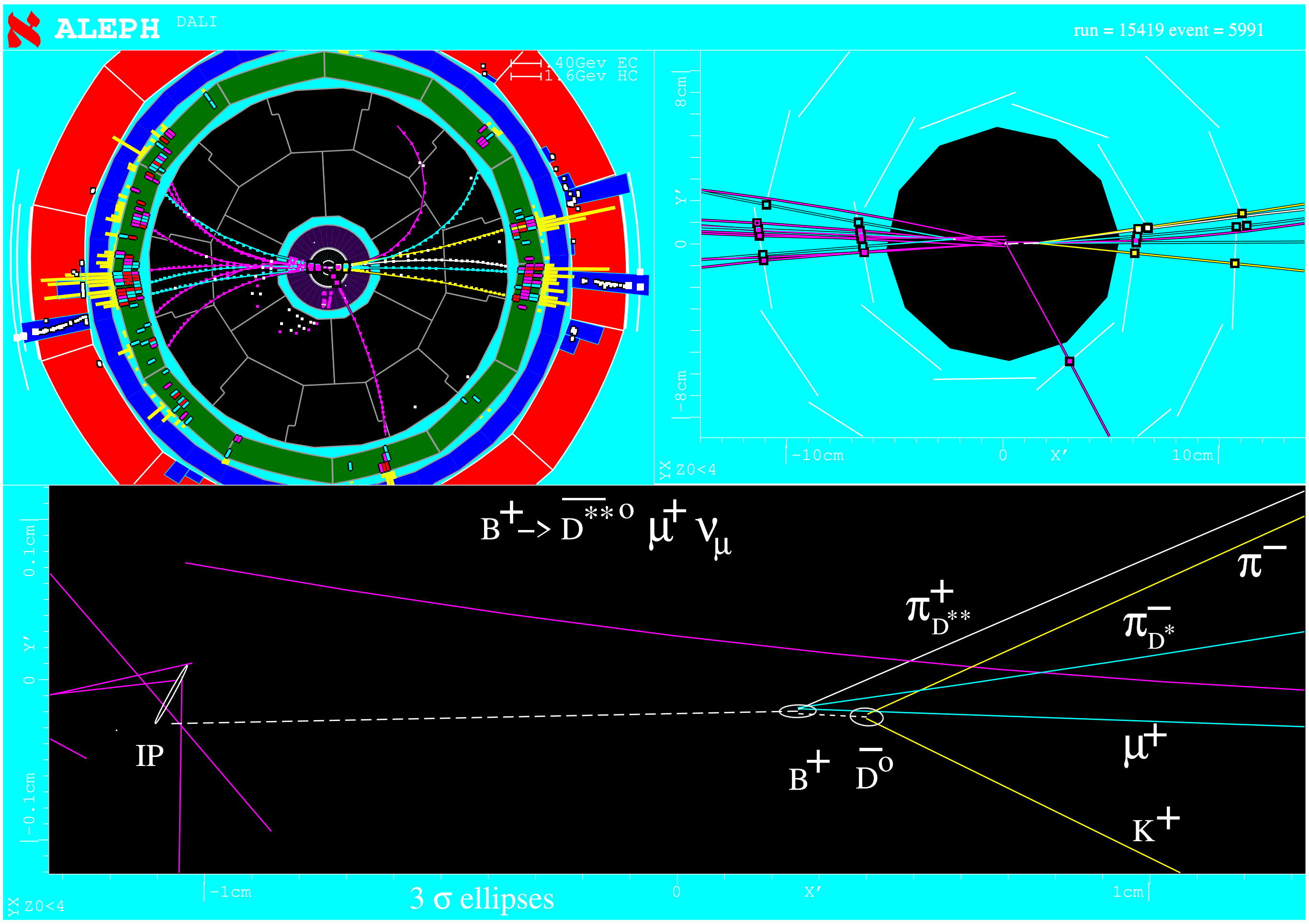


$\mathrm{Z} \rightarrow \mathrm{b\bar{b}}$ receives additional contributions from

The ratio $R_{\mathrm{b\bar{b}}} = \Gamma_{\mathrm{b\bar{b}}}/\Gamma_{\mathrm{had}}$ has a different sensitivity to m_{t} (and m_{H}) than other quantities.

Heavy Flavor EW Physics

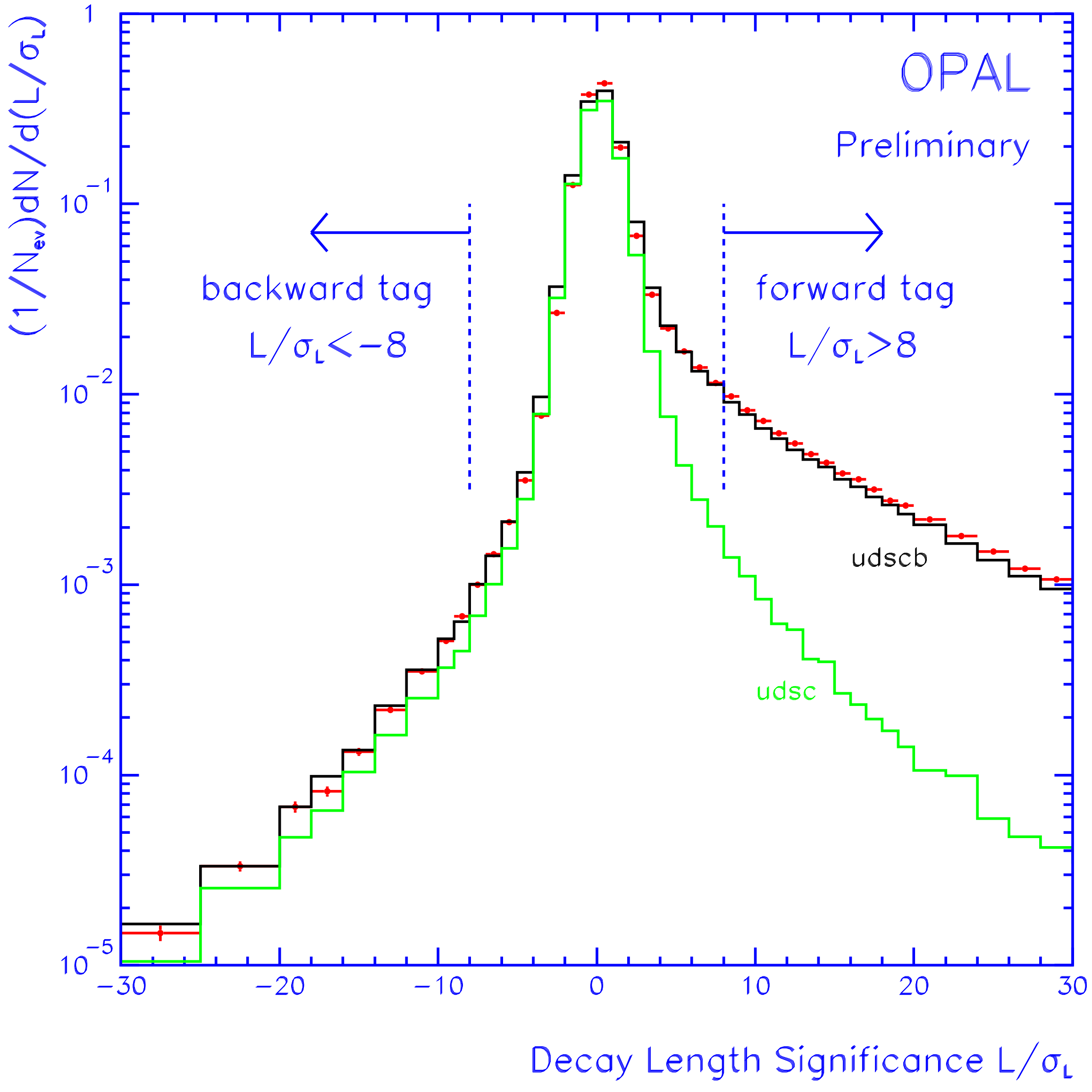
Summary of heavy flavor tags with a “typical”! event:



- **Long** lifetimes
- **Charmed** final states
- **Leptonic** final states
- **Broad** (massive) jets

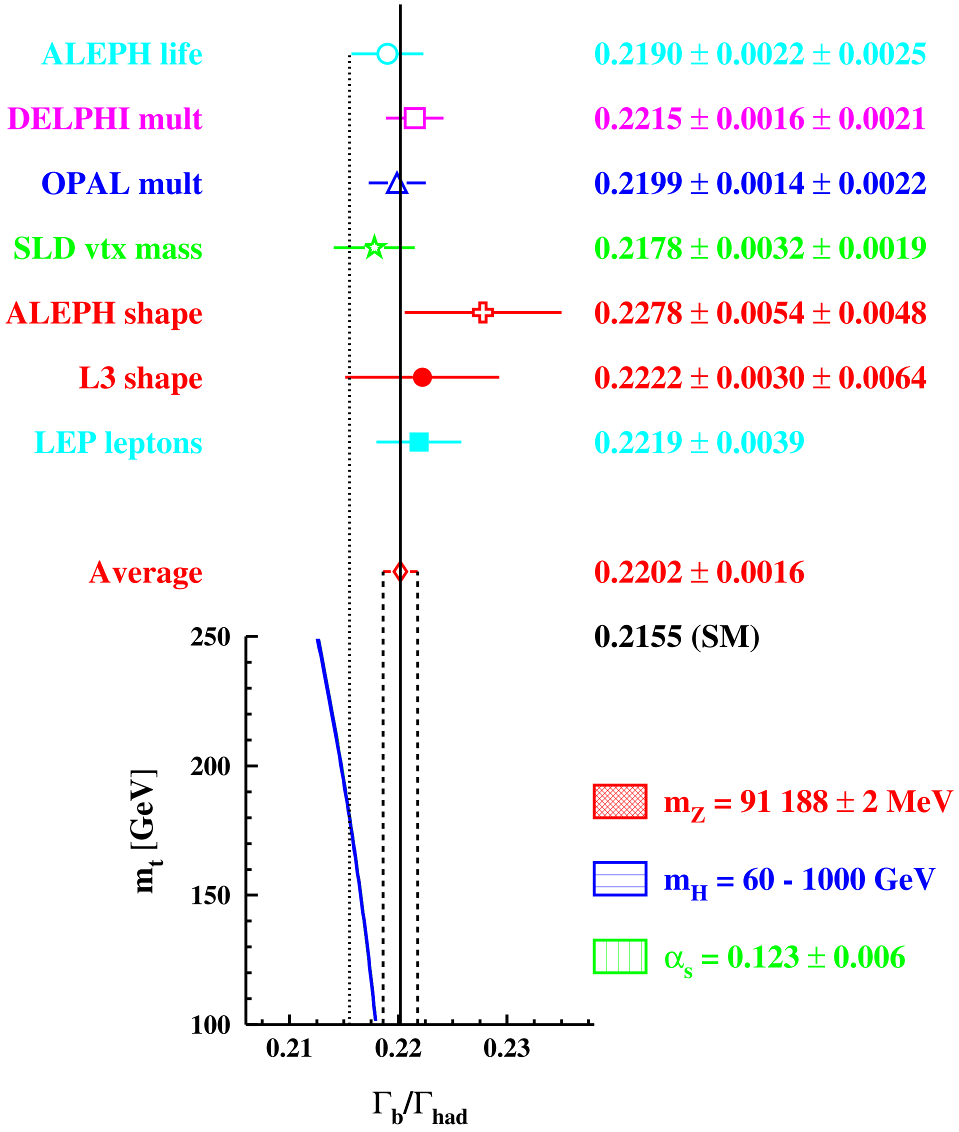
Heavy Flavor EW Physics

An example of decay length from secondary vertices:



- **Resolution determined from data**
- **Efficiency determined from data (multiple tags)**
- **Backgrounds and correlations determined from MC**

$R_{b\bar{b}}$



Note:

- **For $R_{c\bar{c}}$ fixed at SM**
- **Best results from multi-tag analyses**
- **Most analyses are systematics dominated (but watch SLD [36% eff. for 97.2% purity!])**

Heavy Flavor Results

Complete results:

$$
\begin{aligned}
R^0_{\mathrm{b\bar{b}}} &= 0.2211 \pm 0.0017 \\
R^0_{\mathrm{c\bar{c}}} &= 0.1598 \pm 0.0069 \\
A^{0,\,\mathrm{b}}_{\mathrm{FB}} &= 0.1002 \pm 0.0028 \\
A^{0,\,\mathrm{c}}_{\mathrm{FB}} &= 0.0759 \pm 0.0051
\end{aligned}
$$

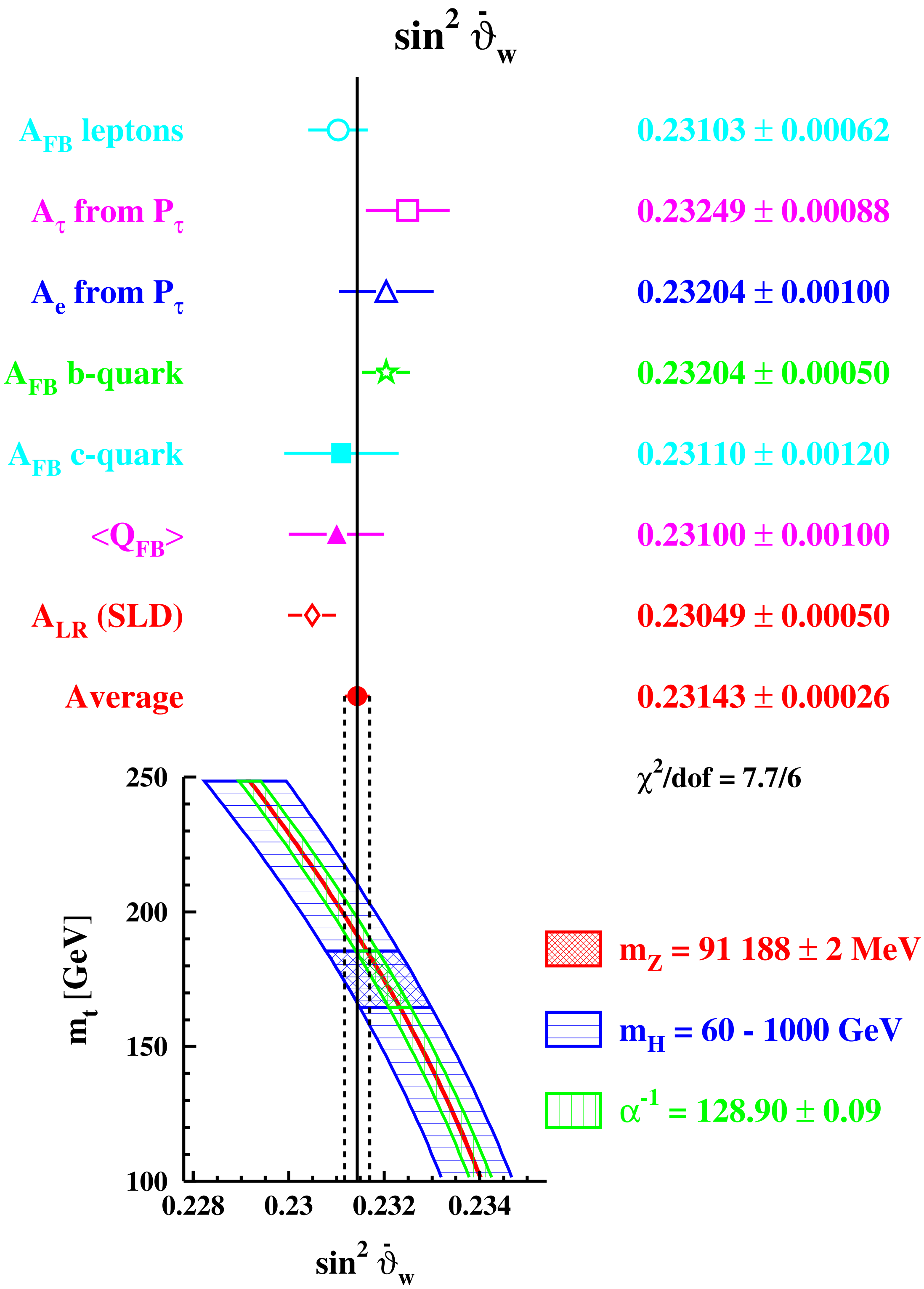
Note:

Correlation between $R_{\mathrm{b\bar{b}}}$ and $R_{\mathrm{c\bar{c}}}$: -0.30

Fixing $R^0_{\mathrm{c\bar{c}}}$ to SM (0.171) yields

$$R^0_{\mathrm{b\bar{b}}} = 0.2202 \pm 0.0016.$$

Tying it all together



Summary of Measurements

	Measurement
LEP	
m_Z [GeV]	91.1884 ± 0.0022
Γ_Z [GeV]	2.4964 ± 0.0032
σ^0_{had} [nb]	41.490 ± 0.078
R_ℓ	20.788 ± 0.032
$A_{\mathrm{FB}}^{0,\,\ell}$	0.0171 ± 0.0011
+ correlation matrix	
$\mathcal{A}_\tau$	0.1394 ± 0.0069
$\mathcal{A}_\mathrm{e}$	0.1429 ± 0.0079
$R_{\mathrm{b\bar{b}}}$	0.2215 ± 0.0017
$R_{\mathrm{c\bar{c}}}$	0.1596 ± 0.0070
$A_{\mathrm{FB}}^{0,\,\mathrm{b}}$	0.1002 ± 0.0028
$A_{\mathrm{FB}}^{0,\,\mathrm{c}}$	0.0756 ± 0.0051
+ correlation matrix	
$\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$ $(\langle Q_{\mathrm{FB}}\rangle)$	0.2320 ± 0.0010
SLD	
$\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$ (A_{LR})	0.23049 ± 0.00050
$R_{\mathrm{b\bar{b}}}$	0.2176 ± 0.0039
$\mathcal{A}_\mathrm{b}$	0.842 ± 0.052
$\mathcal{A}_\mathrm{c}$	0.618 ± 0.091

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}.

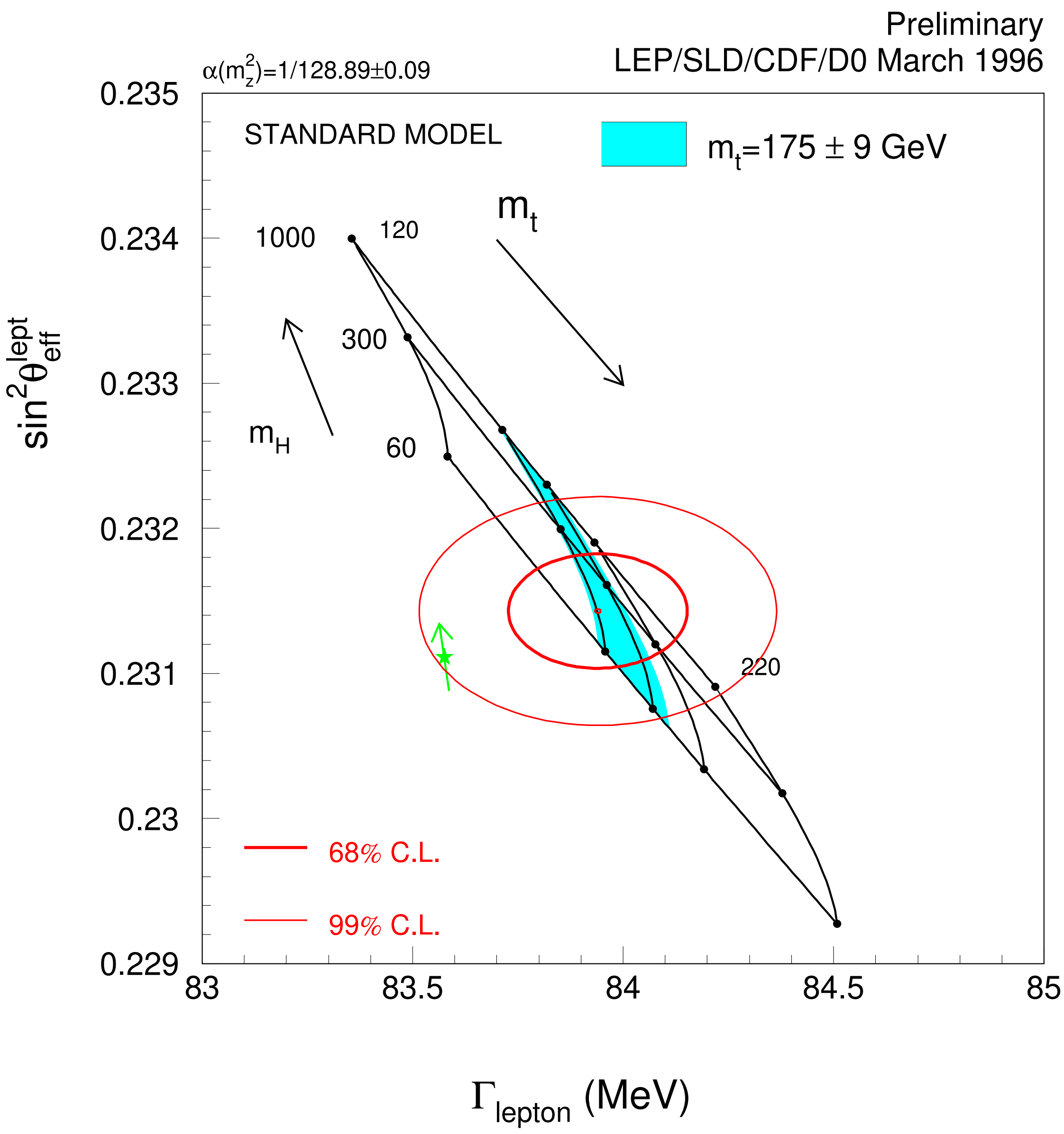
Use all all measurements plus $1/\alpha(m_{\mathrm{Z}}) = 128.896 \pm 0.0090$ and G_F.

Result:

	LEP+SLD
$m_{\mathrm{t}}[\ \mathrm{GeV}]$	$180\ ^{+8}_{-9}\ ^{+18}_{-20}$
$\alpha_s(m_{\mathrm{Z}})$	$0.123 \pm 0.004\ \pm 0.002$
$\sin^2\theta^{\mathrm{lept}}_{\mathrm{eff}}$	$0.23163 \pm 0.00024\ ^{+0.00006}_{-0.00012}$
$\sin^2\theta_{\mathrm{W}}$	$0.2235 \pm 0.0008\ ^{+0.0005}_{-0.0004}$
$m_{\mathrm{W}}[\ \mathrm{GeV}]$	$80.357 \pm 0.046\ ^{+0.017}_{-0.029}$

- Second error is $m_{\mathrm{H}} = 300^{+700}_{-240}$ GeV.
- Error on $\alpha(m_{\mathrm{Z}})$ contributes to $\Delta \sin^2\theta^{\mathrm{lept}}_{\mathrm{eff}}$ = 0.00023, and Δm_{t} = 4 GeV.
- m_{t} and m_{W} is in **very good** agreement with CDF/D0 values of $m_{\mathrm{t}} = 175 \pm 9$ GeV, and $m_{\mathrm{W}} = 80.33 \pm 0.15$.

SM *vs.* the Leptonic Sector

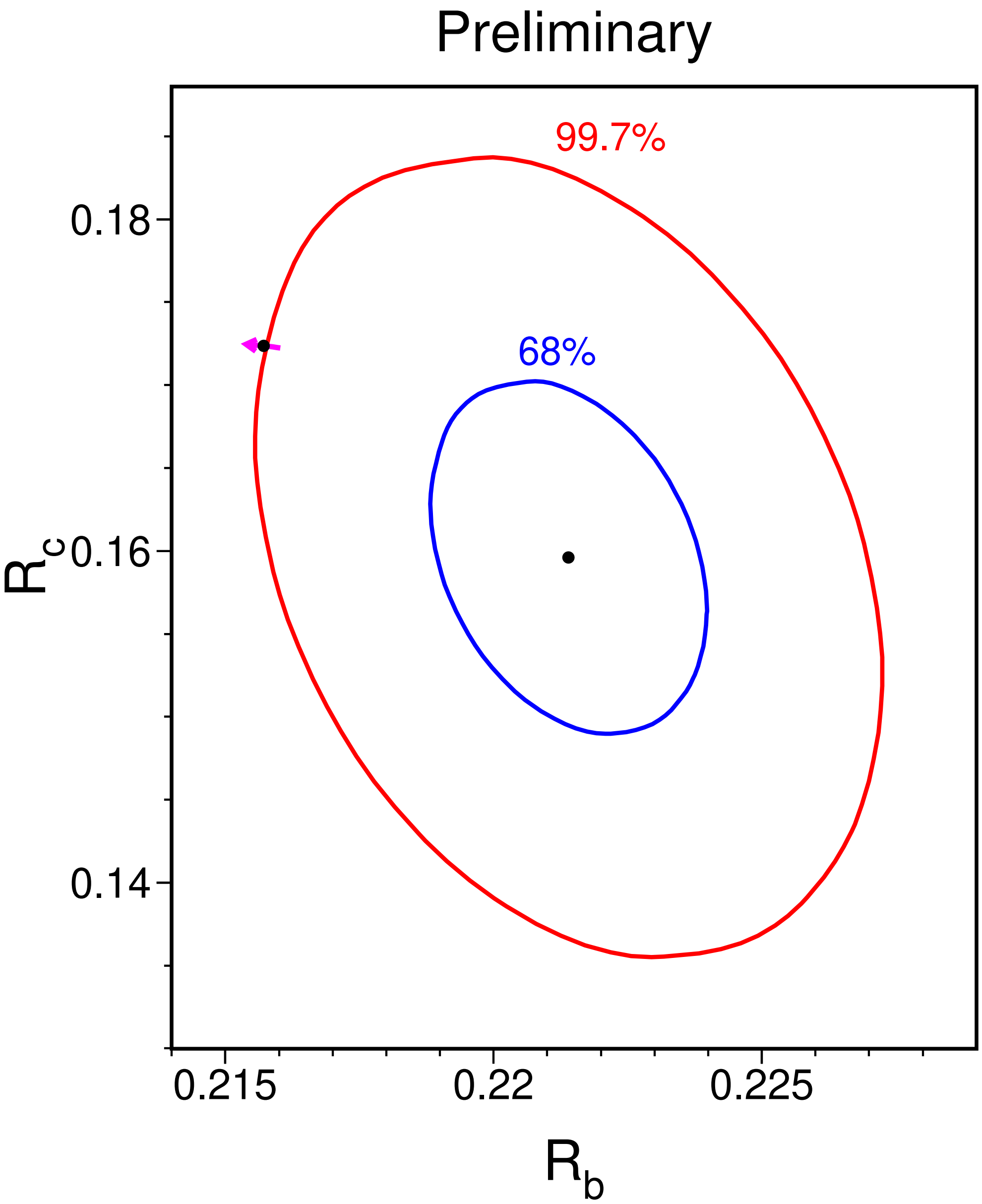


The star shows SM with just the running of α included.

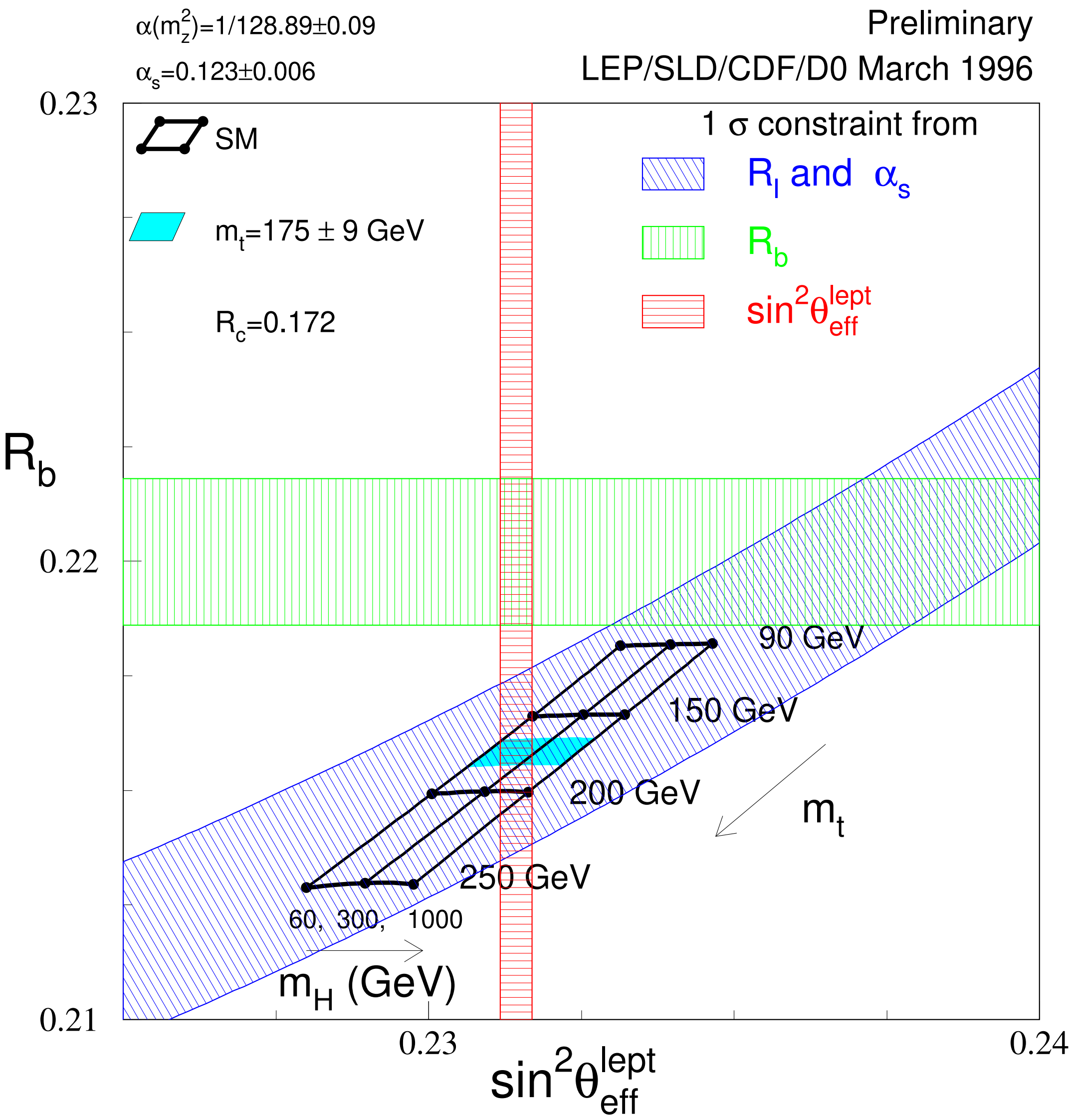
$\Rightarrow$ truely electroweak corrections are seen.

But...

$R_{b\bar{b}}$ and $R_{c\bar{c}}$ do not agree well with the SM prediction:



However...



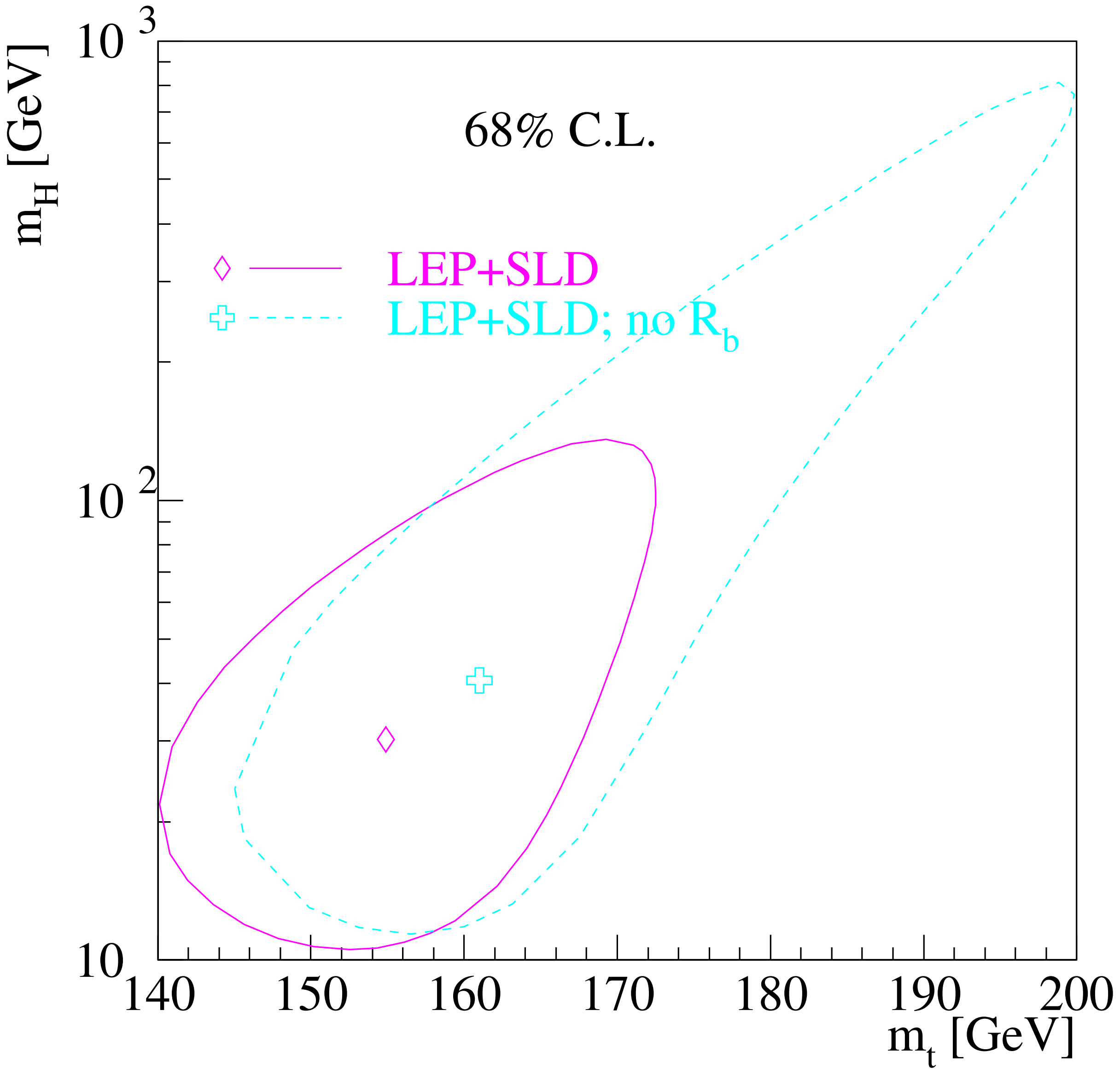
Lowering α_s raises the $R_\ell \equiv \Gamma_{\rm had}/\Gamma_{\ell\ell}$ band, but not the SM prediction!

Need more data and/or smart theorists and/or clever experimentalists...

Can we say anything about m_{H}?

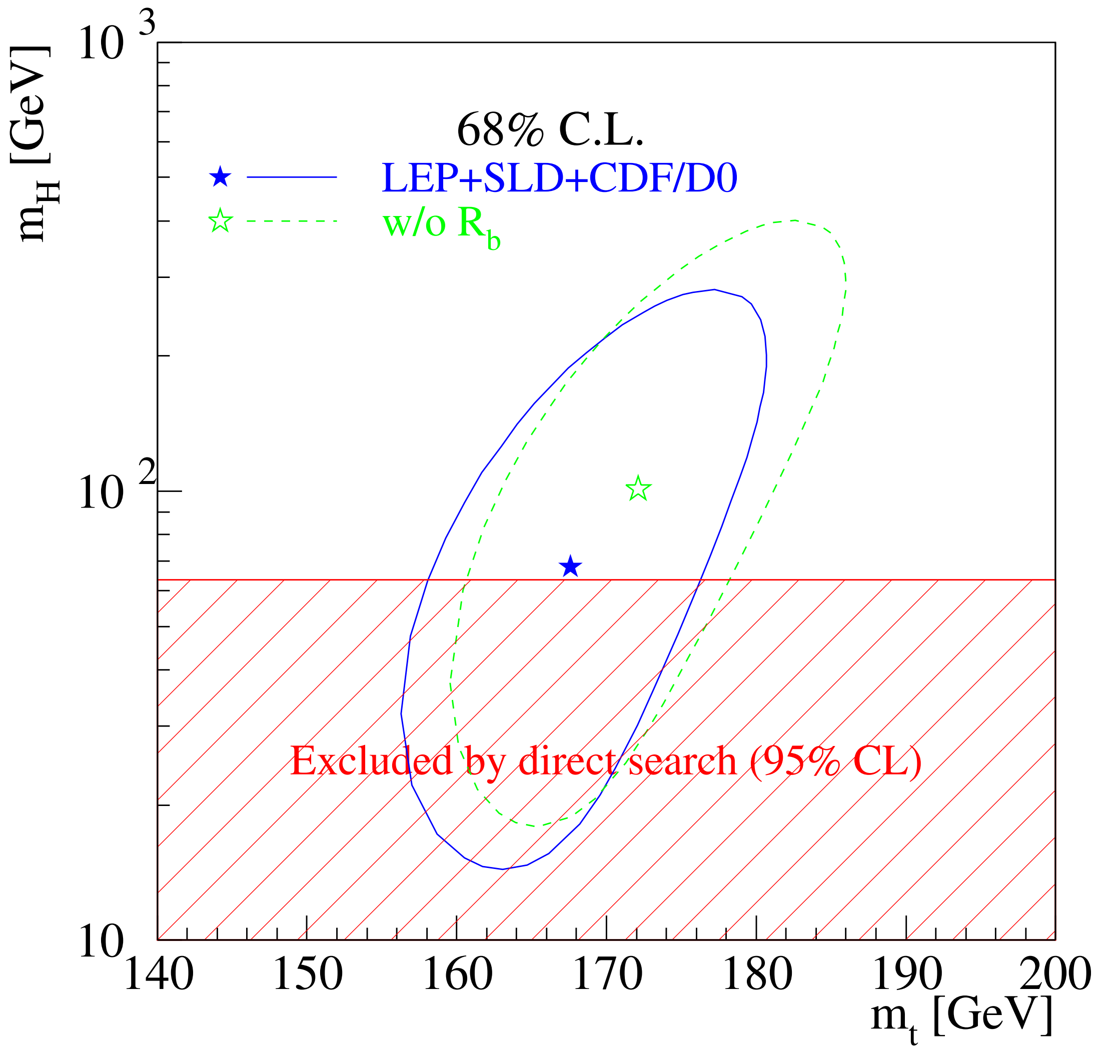
Most LEP/SLC measurements are sensitive to $\Delta\rho$, which to leading order contains terms $\propto m_t^2$ and $\log(m_{\mathrm{H}})$.

A notable exception, of course, is $R_{b\bar{b}}$.



Can we say anything about $m_{\rm H}$?

With an independent determination of m_t from CDF/D0 , this changes to:



- $m_{\rm H} < 310$ GeV (95% CL)
- $m_{\rm H} < 450$ GeV (95% CL) excluding $R_{b\bar{b}}$ and $R_{c\bar{c}}$.

Conclusion

After 7 years at LEP, progress has been impressive. In many cases, the results have exceeded expectations, both in statistics as well as in systematics.

The large discrepancy between $R_{b\bar{b}}$ and $R_{c\bar{c}}$ and the SM may be a sign of first crack in the SM armor, but be careful: these measurements are systematics dominated.

With the m_t constraints from CDF/D0 the limits on m_H are becoming interesting.

Still to come:

- analysis of 95 data
- more data from SLD
- Confrontation: LEPII *vs.* LEPI + SLD + Tevatron