LEP Electroweak Results

(and Global SM Fits)

Robert Clare
MIT

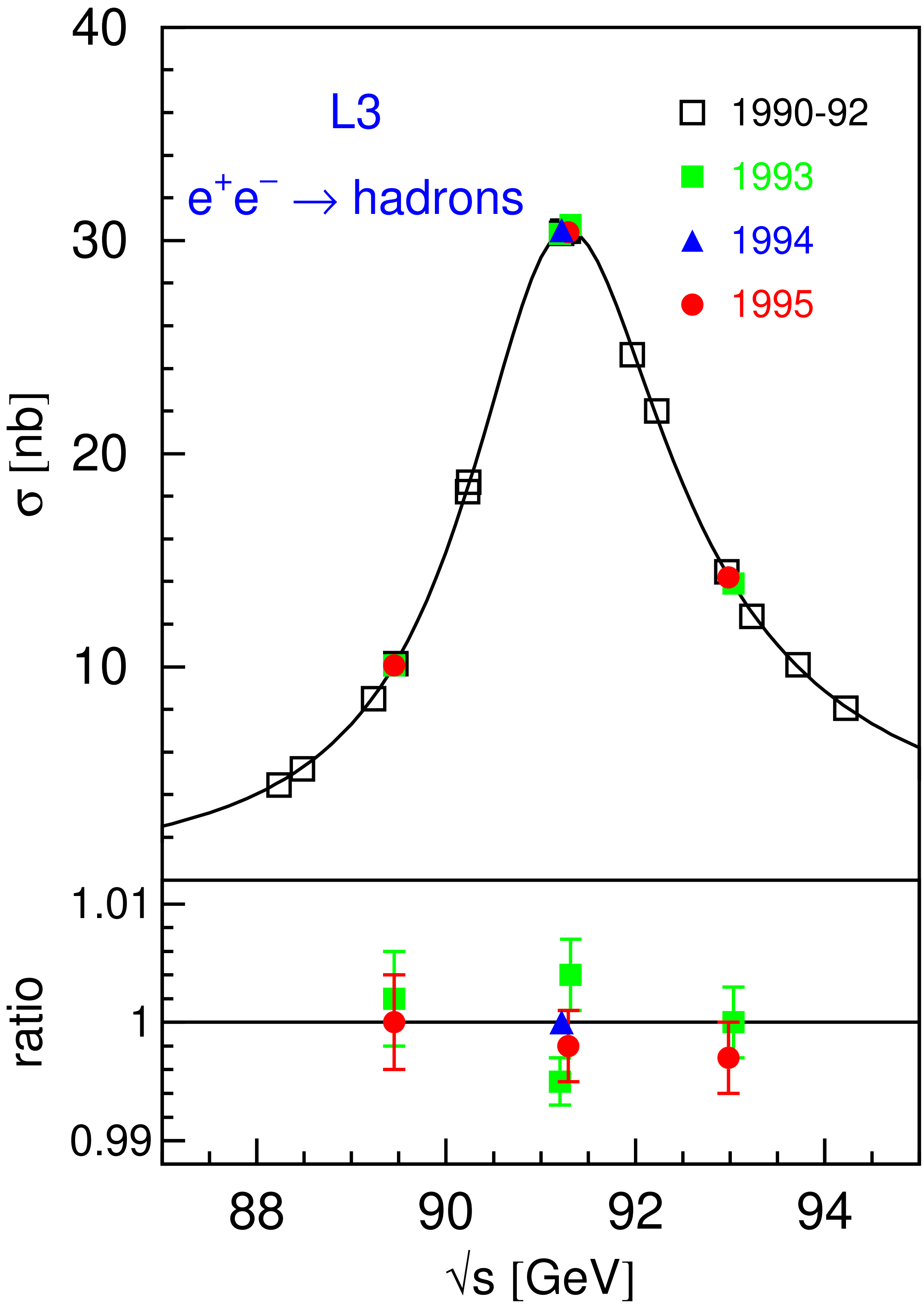
25 Mar 1999

- Z's
- W's
- H's

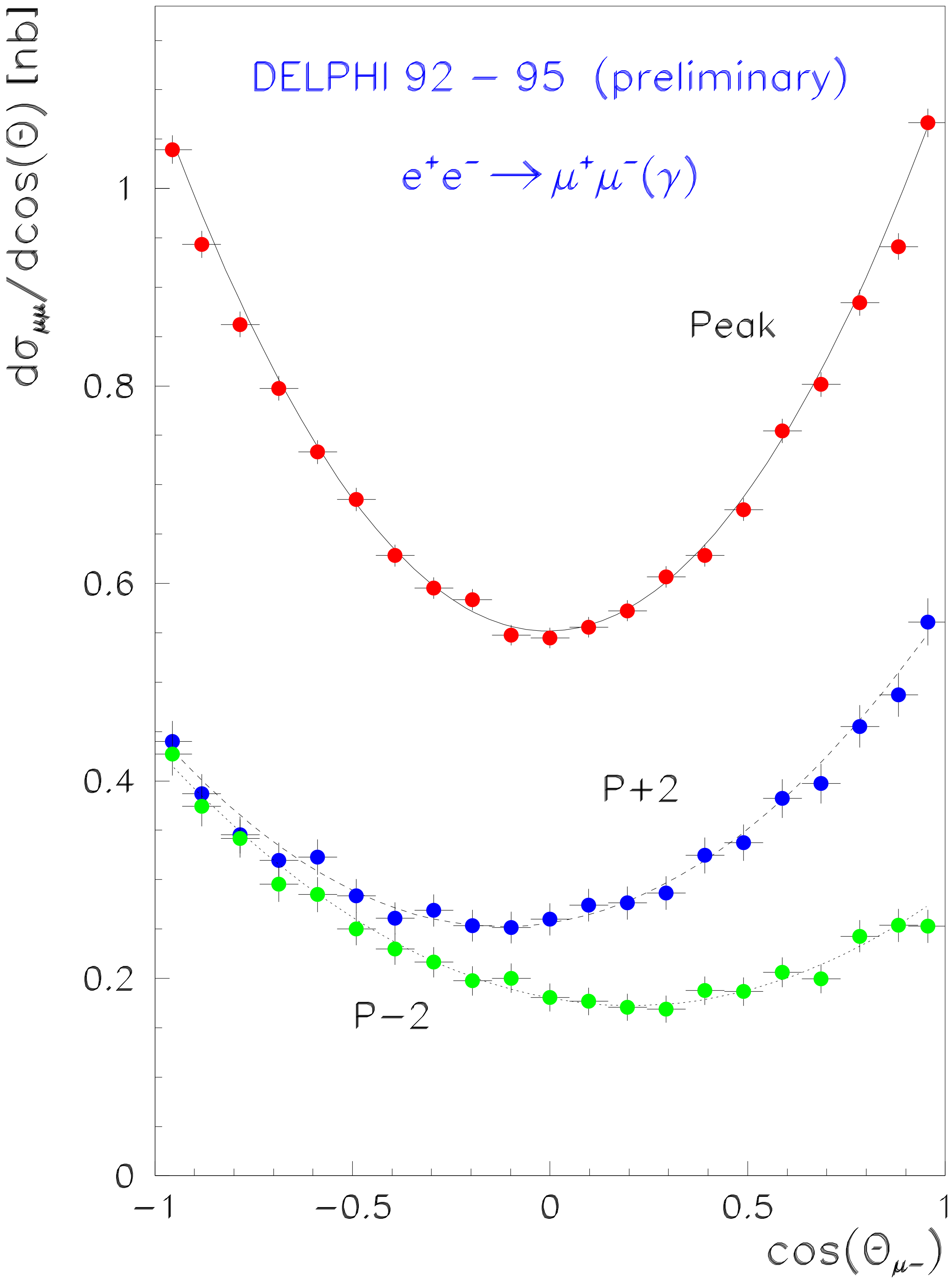
Many thanks to my colleagues in the LEP EW Working Group
and in the experiments
and many theorists working actively with us

Almost all results are still preliminary.

The Z “Lineshape”



Z asymmetries

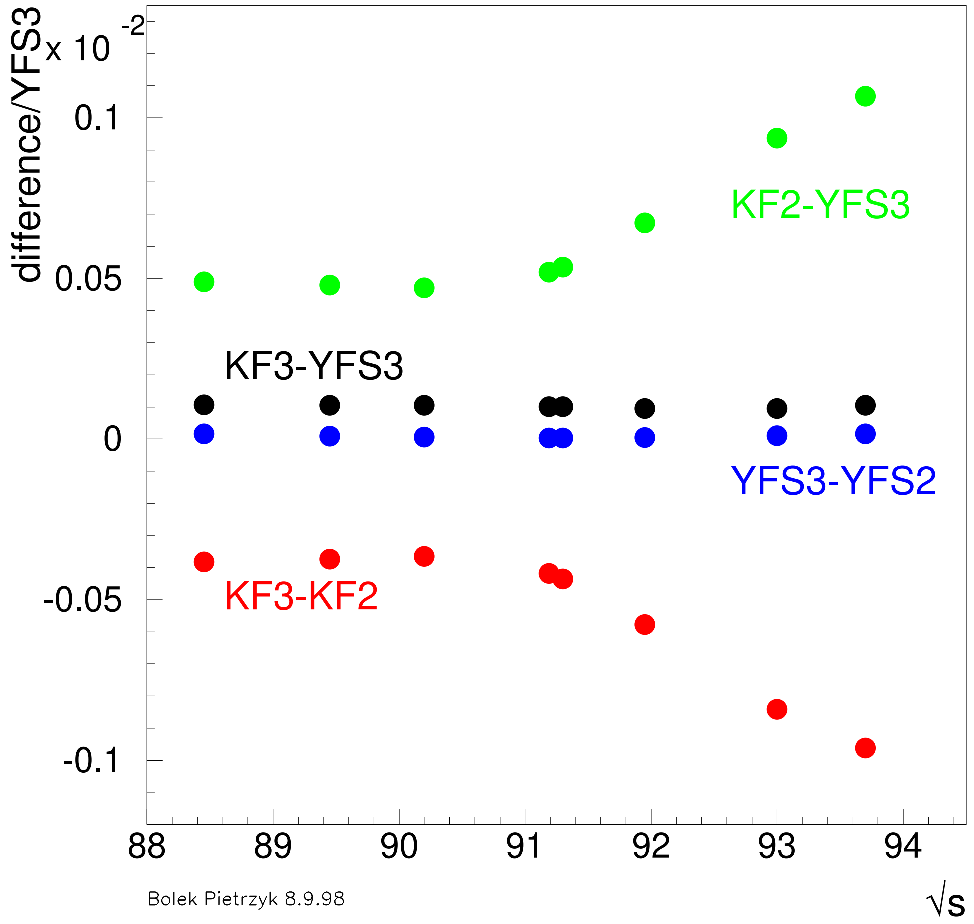


Recent developments

QED radiative corrections:

Current fits use second-order hard corrections. Recently 3rd order have been implemented.

Jadach, *et al.*, PLB 257(91)173;
Skrzypek, A.P. Polon. B23(92)135;
Montagna, *et al.*, PLB406(97)243.



Affects:

- $\Delta m_Z = +0.5$ MeV
- $\Delta \Gamma_Z = +0.6$ MeV
- $\Delta \sigma^0_{had} = +0.05\%$

Currently treated as additional errors; in next round of fits will be handled correctly.

Recent developments

Small Angle Bhabha:

At ICHEP98 theoretical lumi error reduced from 0.11% to 0.06%. Ward, *et al.*, UTHEP-98-0501, hep-ph/9811245.

Will also be used in next round. Will improve error on, *e.g.*, σ^0_{had} and N_ν.

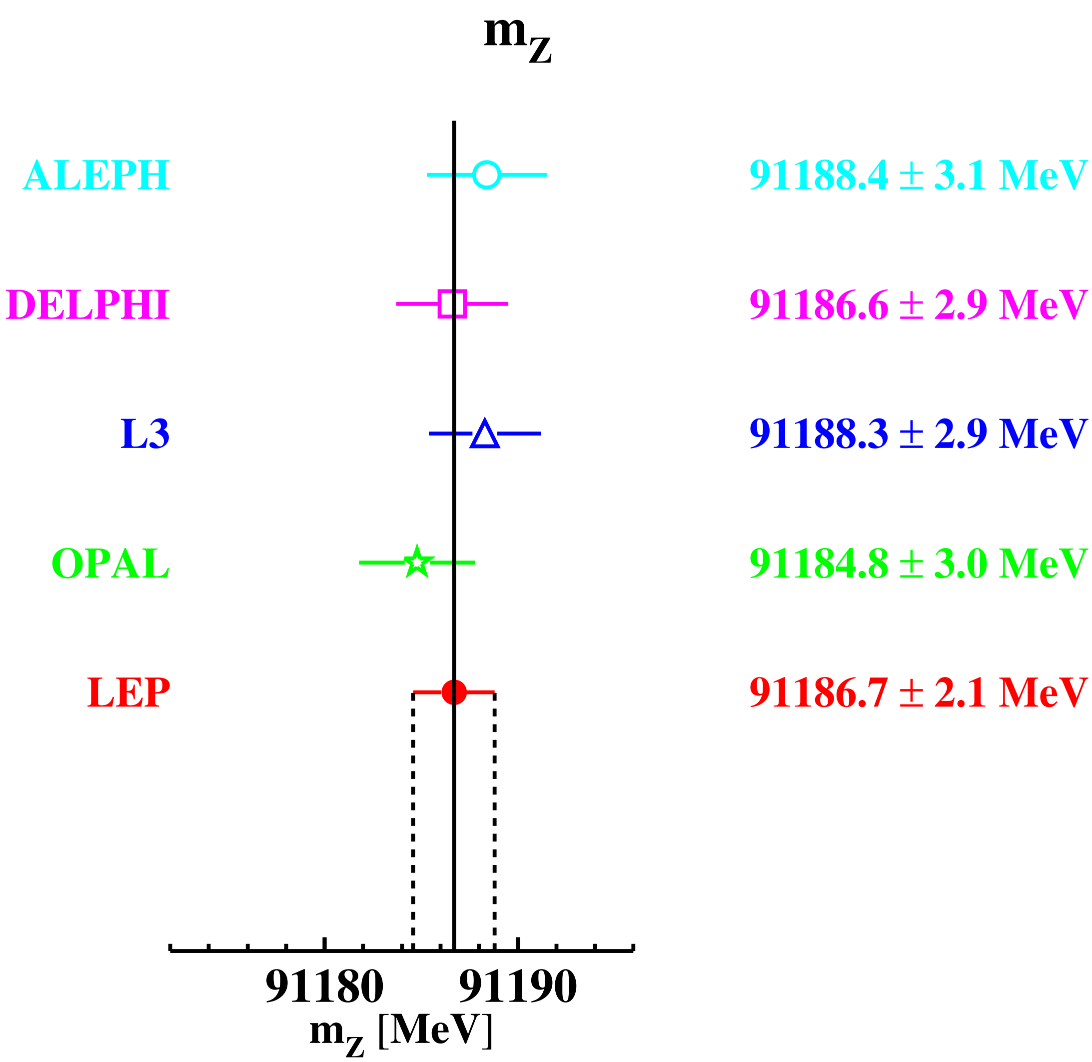
Improved treatment of t channel for e^+e^- final states:

Theoretical error in t channel subtraction now evaluated.

Beenakker & Passarino, PLB425(98)199-207.

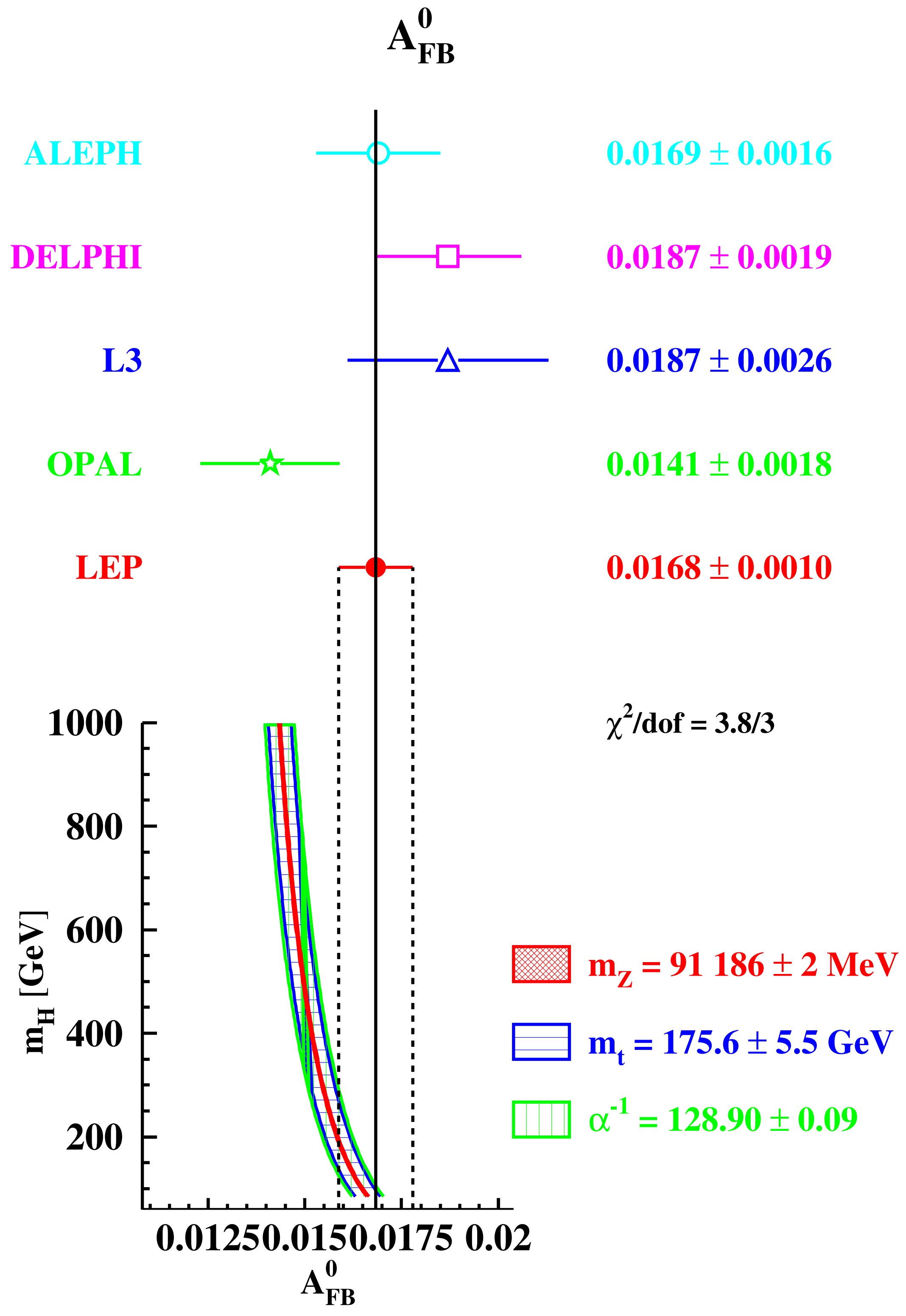
This error source was already considered by the experiments. New is the treatment as common systematic as well consideration of correlations between R_e and $A^{0,e}_{\mathrm{FB}}$.

Result of Lineshape fits



Note: E_{cms} differs by up to 20 MeV between experiments

Result of Lineshape fits



Result of Lineshape fits

Based on 15.2M hadronic events and 1.7M leptonic events:

$$\begin{array}{lll} m_Z & 91.1867 \pm 0.0021 & \text{GeV} \\ \Gamma_Z & 2.4939 \pm 0.0024 & \text{GeV} \\ & & \\ \sigma^0_{\text{had}} & 41.491 \pm 0.058 & \text{nb} \\ R_\ell & 20.765 \pm 0.026 & \\ & & \\ A^{0,\ell}_{\text{FB}} & 0.01683 \pm 0.00096 & \end{array}$$

Partial widths:

$$\begin{aligned} \Gamma_{\text{had}} &= 1742.3 \pm 2.3 \text{ MeV} \\ \Gamma_{\ell\ell} &= 83.90 \pm 0.10 \text{ MeV} \\ \\ \Gamma_{\text{inv}} &= 500.1 \pm 1.9 \text{ MeV} \\ N_\nu &= 2.994 \pm 0.011 \\ &\text{or} \\ \Delta\Gamma &< 2.8 \text{ MeV at 95\% CL} \end{aligned}$$

Effective Couplings

The asymmetry at the Z peak can be expressed as

$$A_{FB}^{0,f} \equiv \frac{3}{4}\mathcal{A}_e\mathcal{A}_f,$$

where

$$\mathcal{A}_f = \frac{2g_{Vf}g_{Af}}{g_{Vf}^2 + g_{Af}^2}$$

The asymmetries provide a direct measurement of

$$\sin^2\theta_{eff}^{lept} \equiv \frac{1}{4}(1 - g_V/g_A)$$

The partial widths of the Z can be expressed as

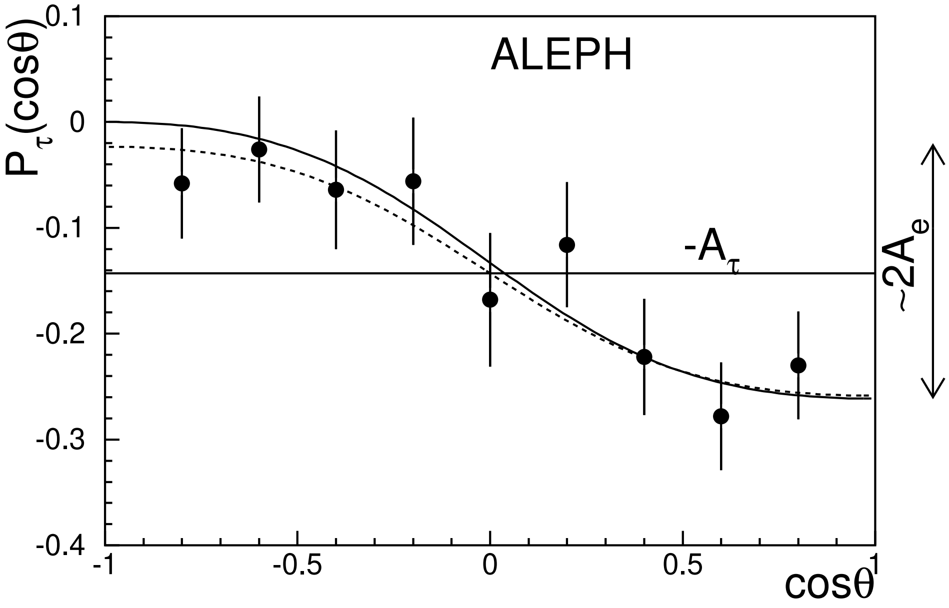
$$\Gamma_{\ell\ell} = \frac{G_F m_Z^3}{6\pi\sqrt{2}}(g_V^2 + g_A^2)(1 + \frac{3\alpha}{4\pi})$$

The asymmetries and widths can thus be used to determine g_A and g_V.

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.

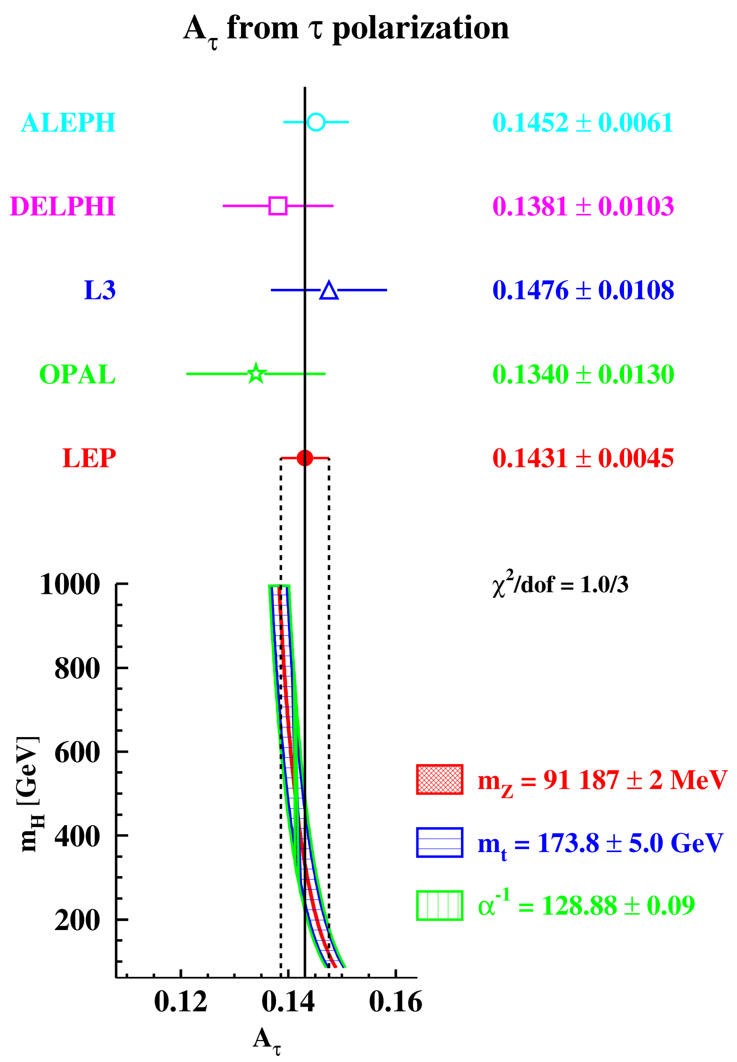
$$\mathcal{P}_\tau(\cos\theta) = -\frac{\mathcal{A}_\tau(1+\cos^2\theta) + 2\mathcal{A}_e\cos\theta}{1+\cos^2\theta + 2\mathcal{A}_\tau\mathcal{A}_e\cos\theta}$$

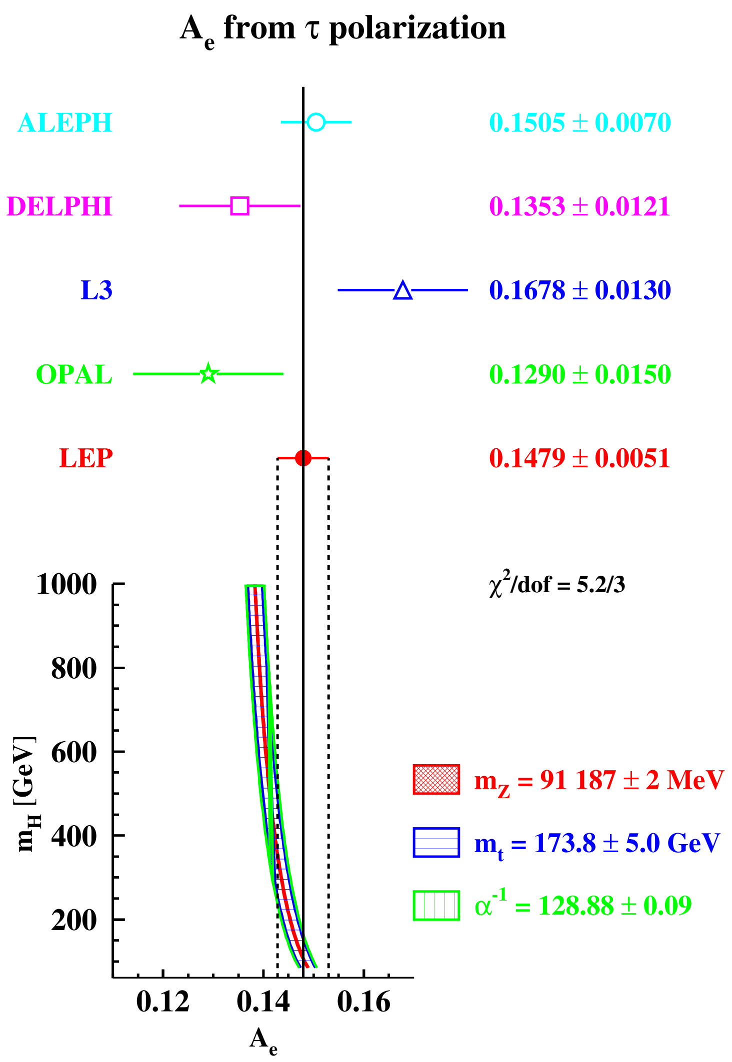


Tau polarization gives independent measurements of $\mathcal{A}_\tau$ and $\mathcal{A}_e$.

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.

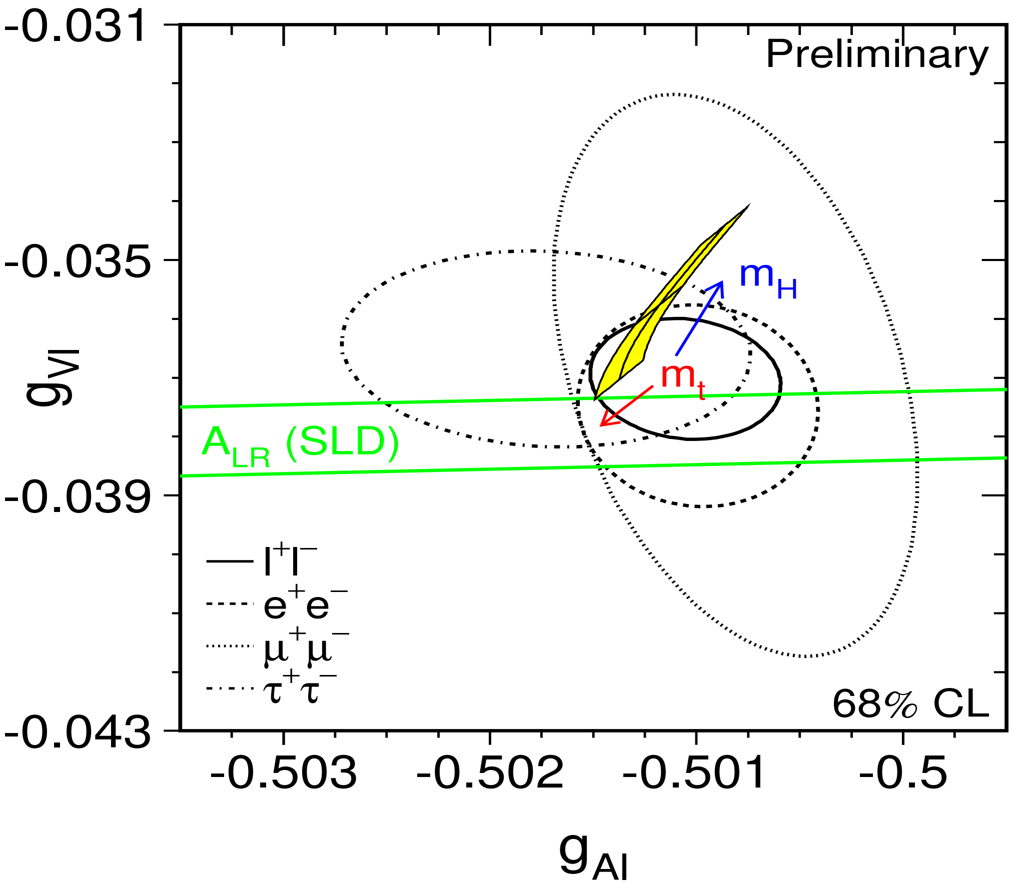
Tau Polarization





g_V and g_A

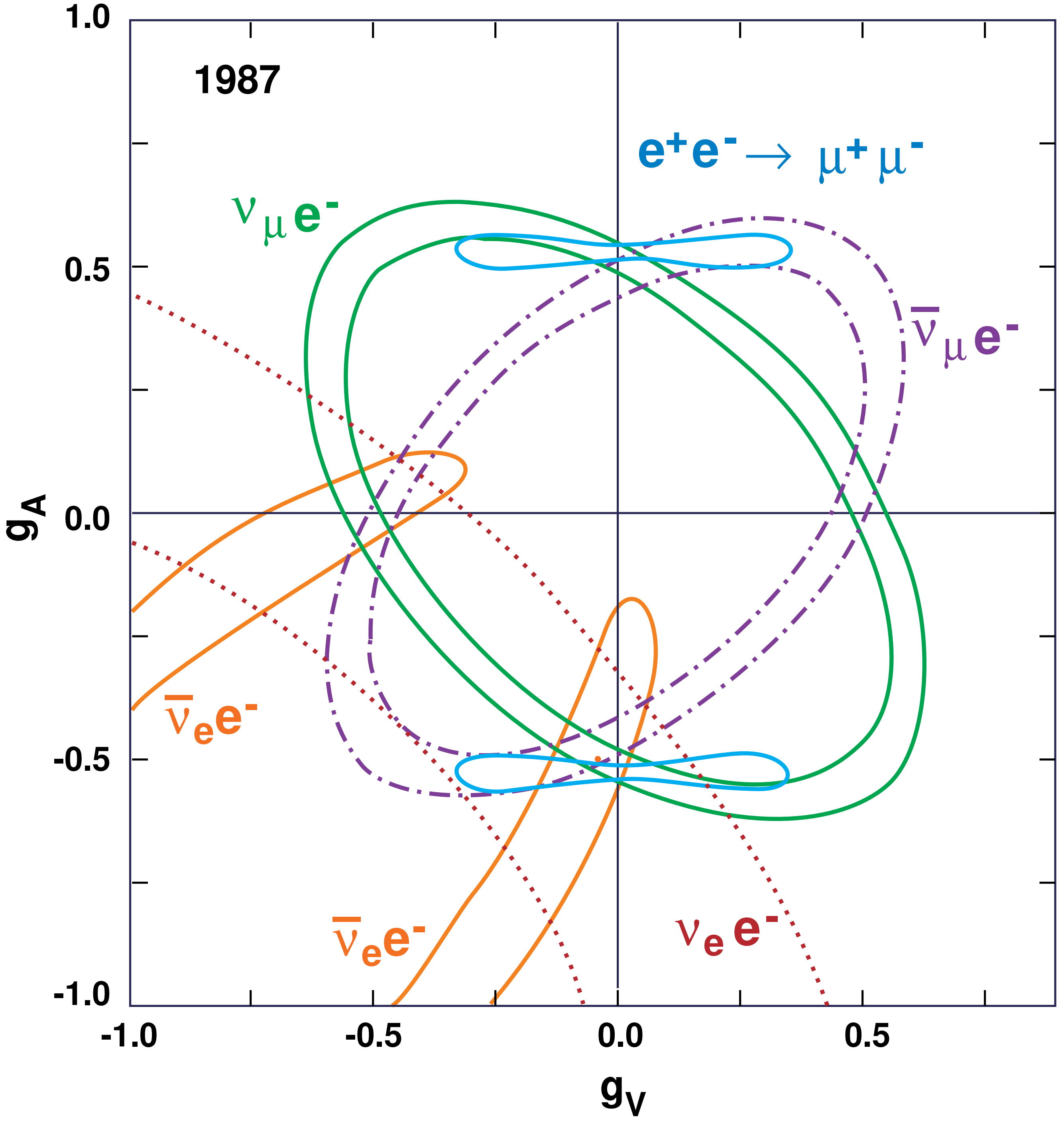
Combining the lepton asymmetry measurements, the τ polarization, the $\Gamma_{\ell\ell}$ and the SLD A_{LR} results determines the lepton g_V and g_A:



Assuming lepton universality

$$g_{V\ell} = -0.03753 \pm 0.00044$$
$$g_{A\ell} = -0.50102 \pm 0.00030$$

g_V and g_A 12 years ago



Heavy Flavor EW Physics

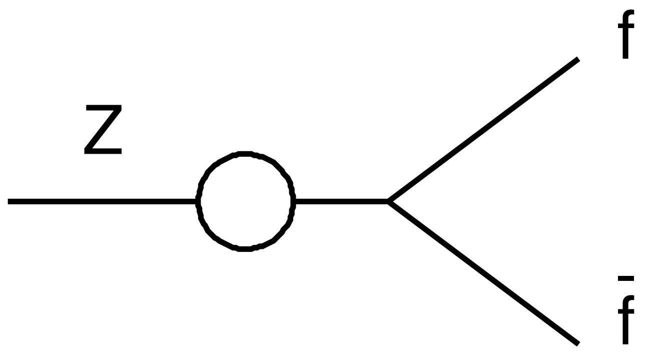
Using the properties of heavy quarks, one can isolate samples of $b\bar{b}$ and $c\bar{c}$ events.

These can be used to extract:

- $\Gamma_{b\bar{b}}$ and $\Gamma_{c\bar{c}}$
- A^{b}_{FB} and A^{c}_{FB}

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

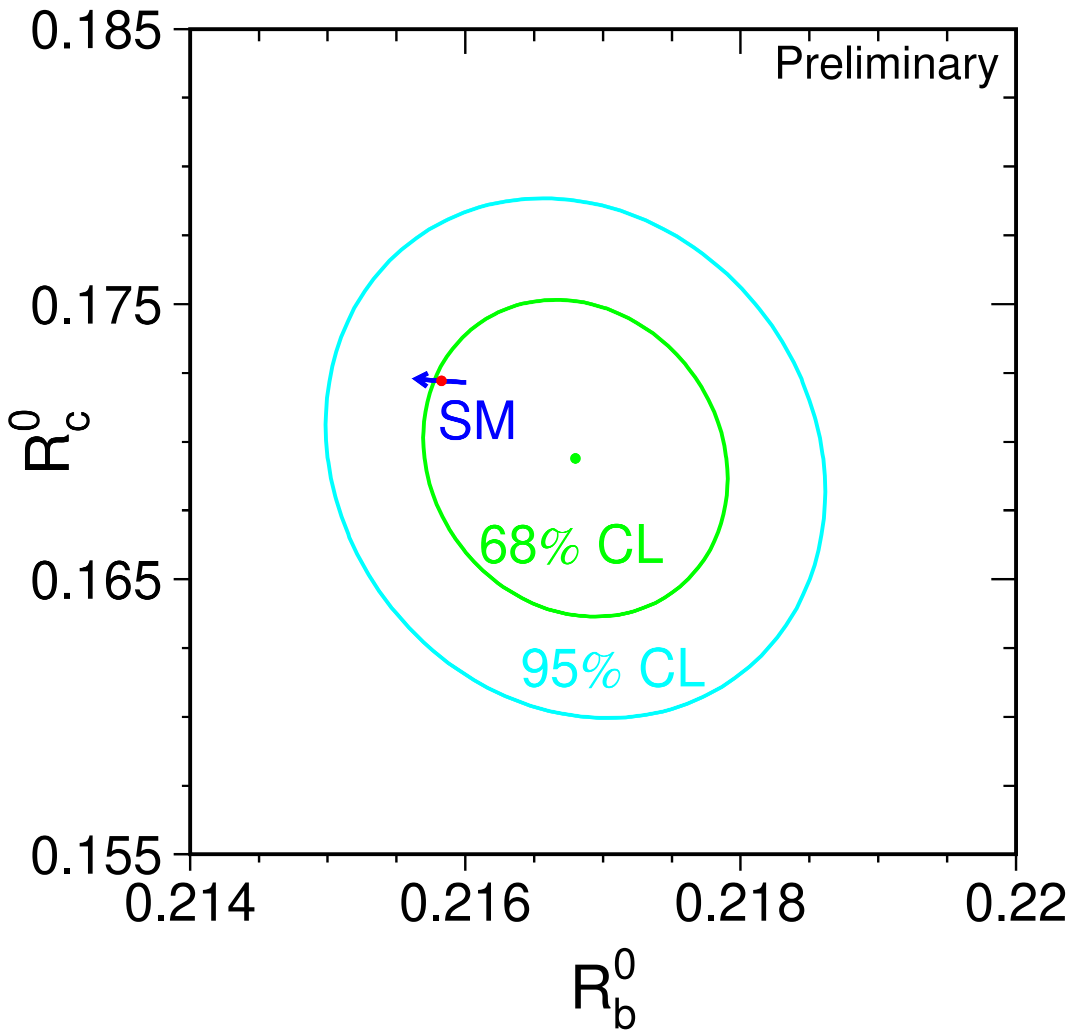
All Z decays have radiative corrections of the form



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

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

Heavy Flavor Crises?



Changes:

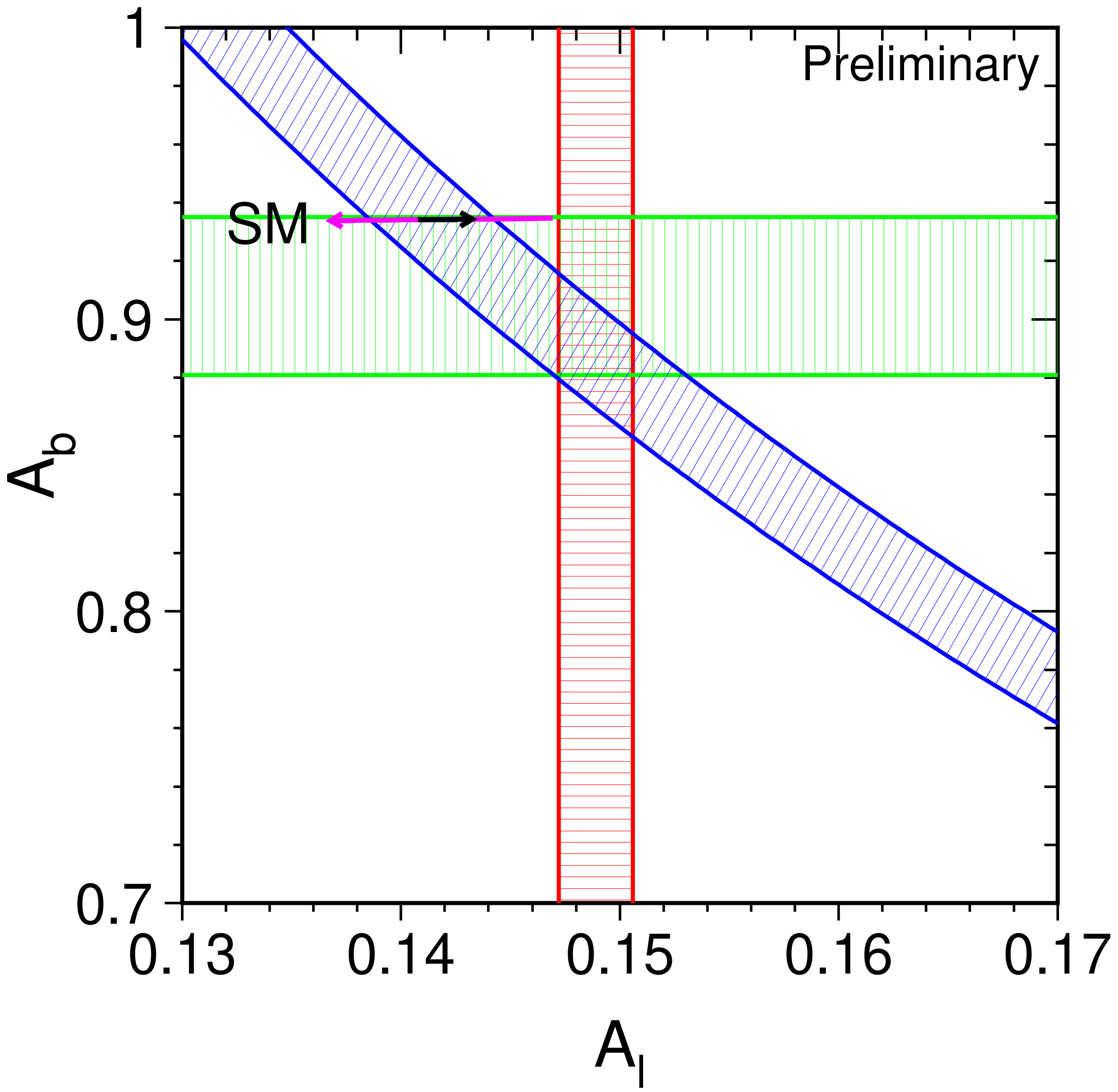
– a lot of new data analysed

– analysis techniques improved

– new measurements of some input parameters, *eg*: branching ratios; gluon splitting; hemisphere correlations

Heavy Flavor Crises?

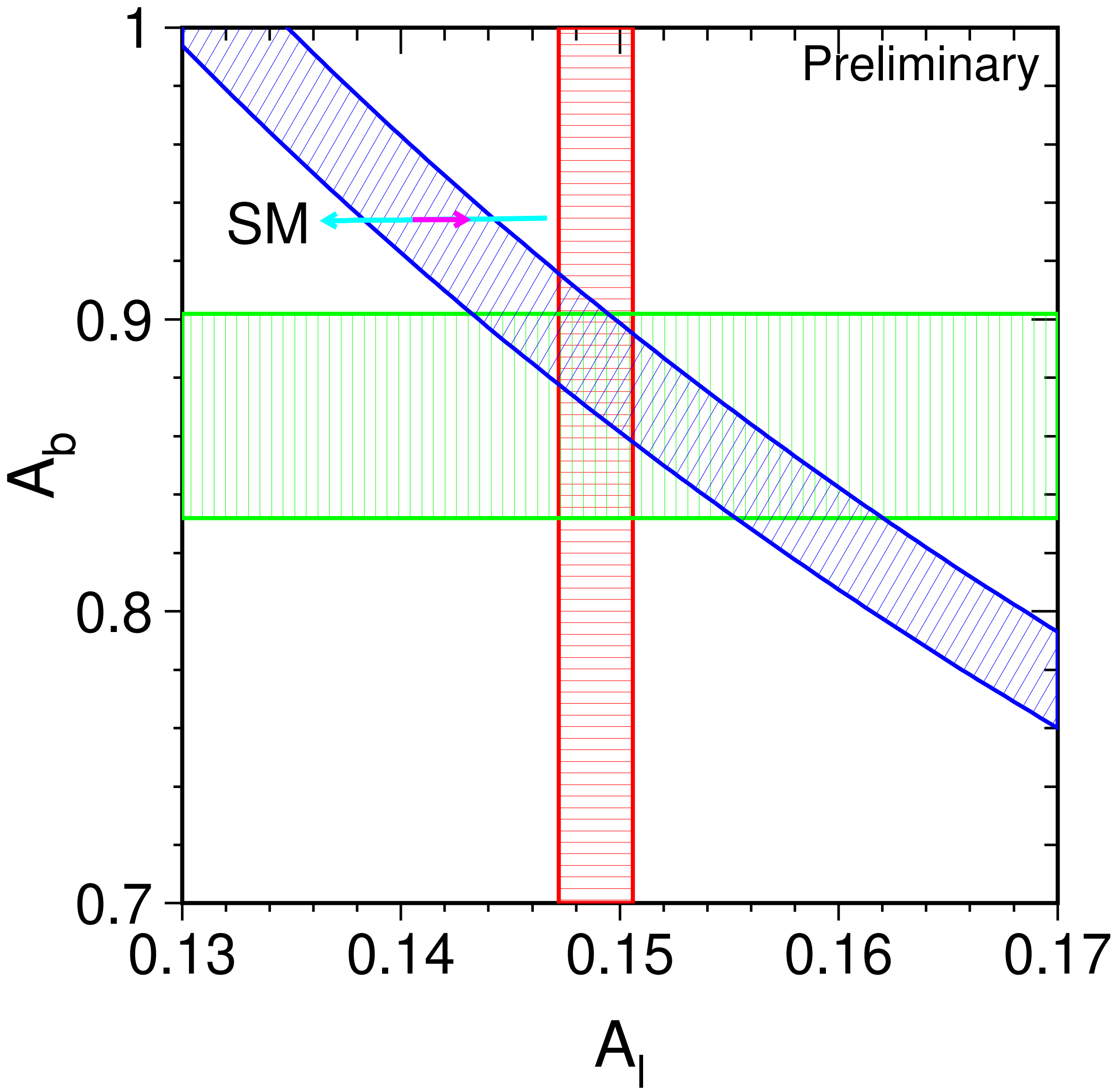
Winter 99:



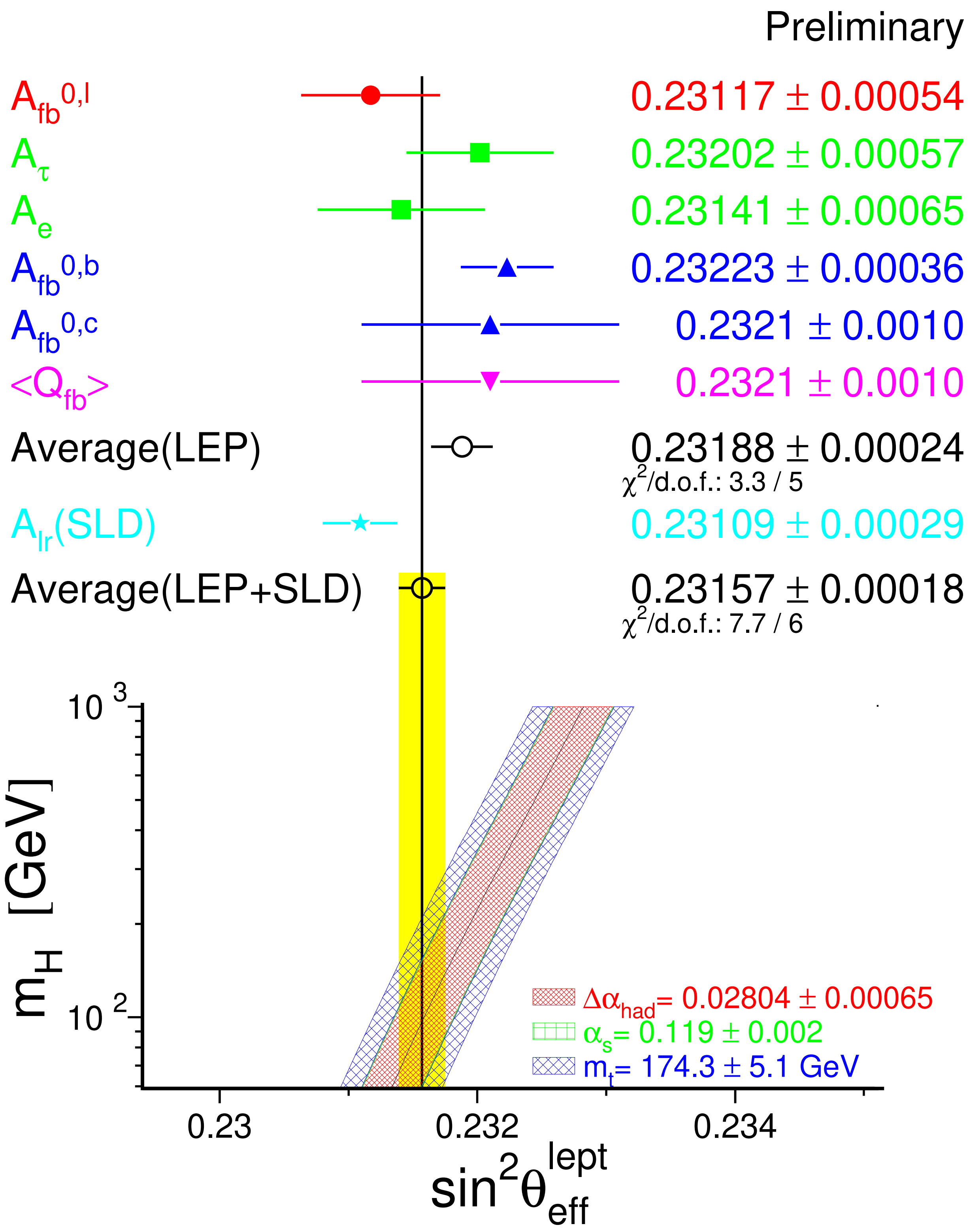
Combined LEP+SLD $\mathcal{A}_b$ 2.3σ off SM.

Heavy Flavor Crises?

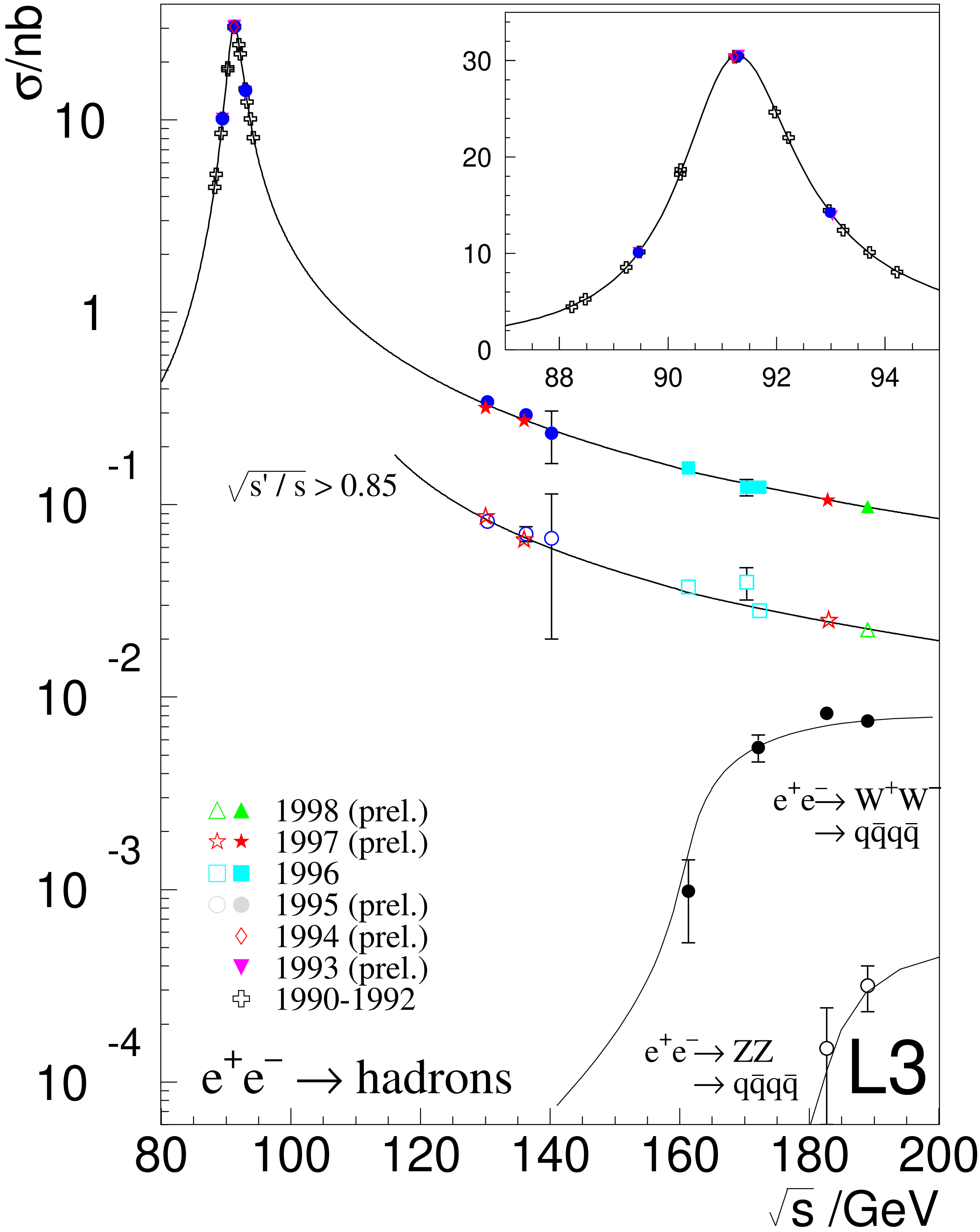
Summer 98:



Summary of $\sin^2\theta_{eff}^{lept}$



LEP II



σ/nb
√s /GeV
√(s'/s) > 0.85
1998 (prel.)
1997 (prel.)
1996
1995 (prel.)
1994 (prel.)
1993 (prel.)
1990-1992
e+e− → hadrons
e+e− → W+W− → qq̄qq̄
e+e− → ZZ → qq̄qq̄
L3

LEP II Overview

Expected total LEP-2 luminosity:

$\mathcal{L} \simeq 500\ \mathrm{pb}^{-1}$ / experiment

LEP-2 center-of-mass energies:

$$\begin{aligned}
\text{June 1996:} &\quad \sqrt{s} = 161\ \text{GeV} \quad (10\ \text{pb}^{-1}) \\
\text{October 1996:} &\quad \sqrt{s} = 172\ \text{GeV} \quad (10\ \text{pb}^{-1}) \\
\text{1997:} &\quad \sqrt{s} = 183\ \text{GeV} \quad (55\ \text{pb}^{-1}) \\
\text{1998:} &\quad \sqrt{s} = 189\ \text{GeV} \quad (175\ \text{pb}^{-1}) \\
\text{1999:} &\quad 192\ \text{GeV} \leq \sqrt{s} \leq 200\ \text{GeV} \\
\text{2000:} &\quad \text{maybe... maybe even} > 200\ \text{GeV ...}
\end{aligned}$$

Total cross-section after radiative corrections:

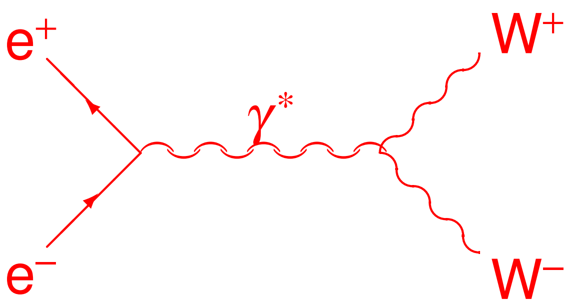
$\sigma(e^+e^- \to W^-W^+(\gamma);\ 192\ \text{GeV}) \simeq 17$ pb

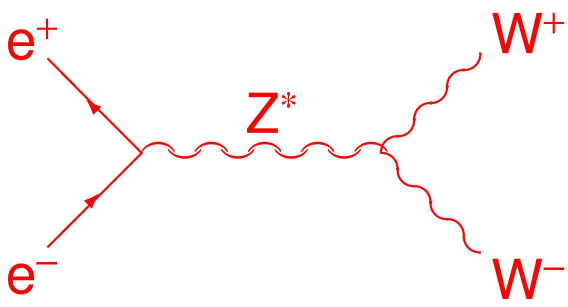
Currently about 3500 W^+W^- events / experiment

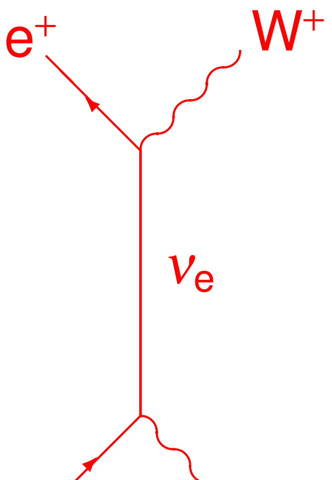
LEP II Overview

Higher energies $\rightarrow$ new physics:

$\sqrt{s} > 2m_W$: pair production of W^+W^- bosons



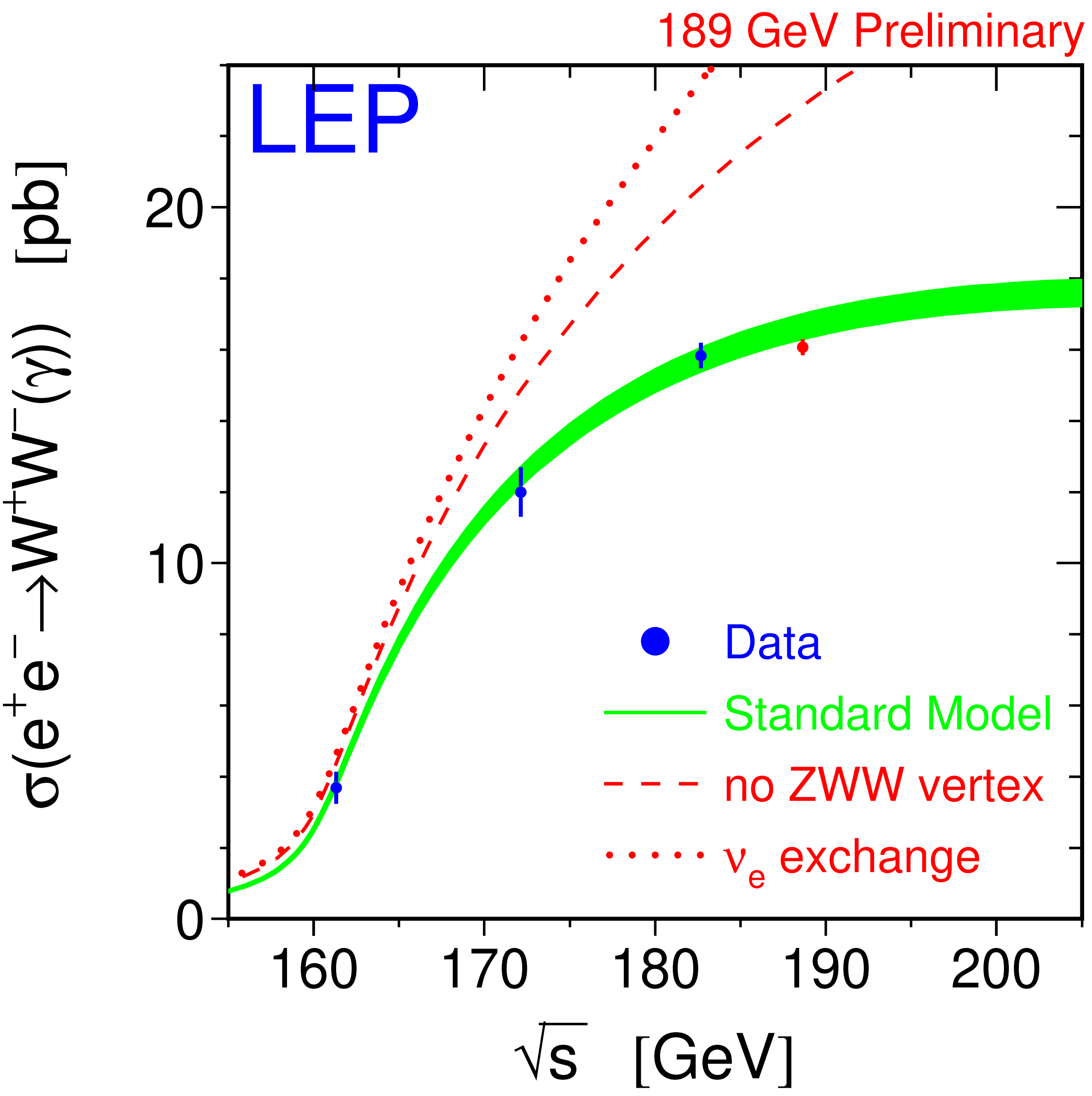




$W \rightarrow f\bar{f}'$

$e^+e^- \rightarrow W^+W^- \rightarrow f_1\bar{f}_2 f_3\bar{f}_4$

W Pair Production Cross-section



W Branching Ratios

The branching ratios are extracted from the total and partial cross-sections.

The 3 leptonic branching ratios are determined to be:

- Br(W$\rightarrow e\nu$) = 10.52±0.26%
- Br(W$\rightarrow \mu\nu$) = 10.56±0.25%
- Br(W$\rightarrow \tau\nu$) = 10.91±0.34%

Assuming Lepton Universality:

- Br(W$\rightarrow \ell\nu$) = 10.64±0.13%, $\ell = \mathrm{e}/\mu/\tau$
- Br(W$\rightarrow q\overline{q'}$) = 68.07±0.42%

Which can be compared with the Standard Model expectations of:

- B(W$\rightarrow \ell\,\overline{\nu}$) = 10.8%
- B(W$\rightarrow q\overline{q'}$) = 67.6%

Measurement of Triple-Boson Couplings

Normalisation:

$$
\begin{aligned}
g_{\gamma \mathrm{WW}} &= 1 \\
g_{\mathrm{ZWW}} &= \cot\theta_{\mathrm{W}}
\end{aligned}
$$

Most general triple-boson vertex function:

$$
\begin{aligned}
\Gamma_V^{\alpha\beta\mu} = \; & f_V^1 (q-\bar{q})^\mu g^{\alpha\beta} \\
- \; & f_V^2 (q-\bar{q})^\mu p^\alpha p^\beta / m_{\mathrm{W}}^2 \\
+ \; & f_V^3 (p^\alpha g^{\mu\beta} - p^\beta g^{\mu\alpha}) \\
+ \; & f_V^4 i (p^\alpha g^{\mu\beta} + p^\beta g^{\mu\alpha}) \\
+ \; & f_V^5 i \varepsilon^{\mu\alpha\beta\rho} (q-\bar{q})_\rho \\
- \; & f_V^6 \varepsilon^{\mu\alpha\beta\rho} p_\rho \\
- \; & f_V^7 (q-\bar{q})^\mu \varepsilon^{\alpha\beta\rho\sigma} p_\rho (q-\bar{q})_\sigma / m_{\mathrm{W}}^2
\end{aligned}
$$

2×7 complex couplings (FF) f_V^i $(V = \gamma, \mathrm{Z})$

Invariance under C, P and CP:

$$
\begin{aligned}
\mathrm{C:} \quad & f_V^4 = f_V^5 = 0 \\
\mathrm{P:} \quad & f_V^5 = f_V^6 = f_V^7 = 0 \\
\mathrm{CP:} \quad & f_V^4 = f_V^6 = f_V^7 = 0
\end{aligned}
$$

Measurement of Triple-Boson Couplings

Parameter transformation:

$$f_V^1 = g_1^V + \frac{s}{2m_W^2}\lambda_V$$
$$f_V^2 = \lambda_V$$
$$f_V^3 = g_1^V + \kappa_V + \lambda_V$$

Static properties of the W boson:

Magnetic dipole moment:

$$\mu_W = \frac{e}{2m_W}(g_1^\gamma + \kappa_\gamma + \lambda_\gamma)$$

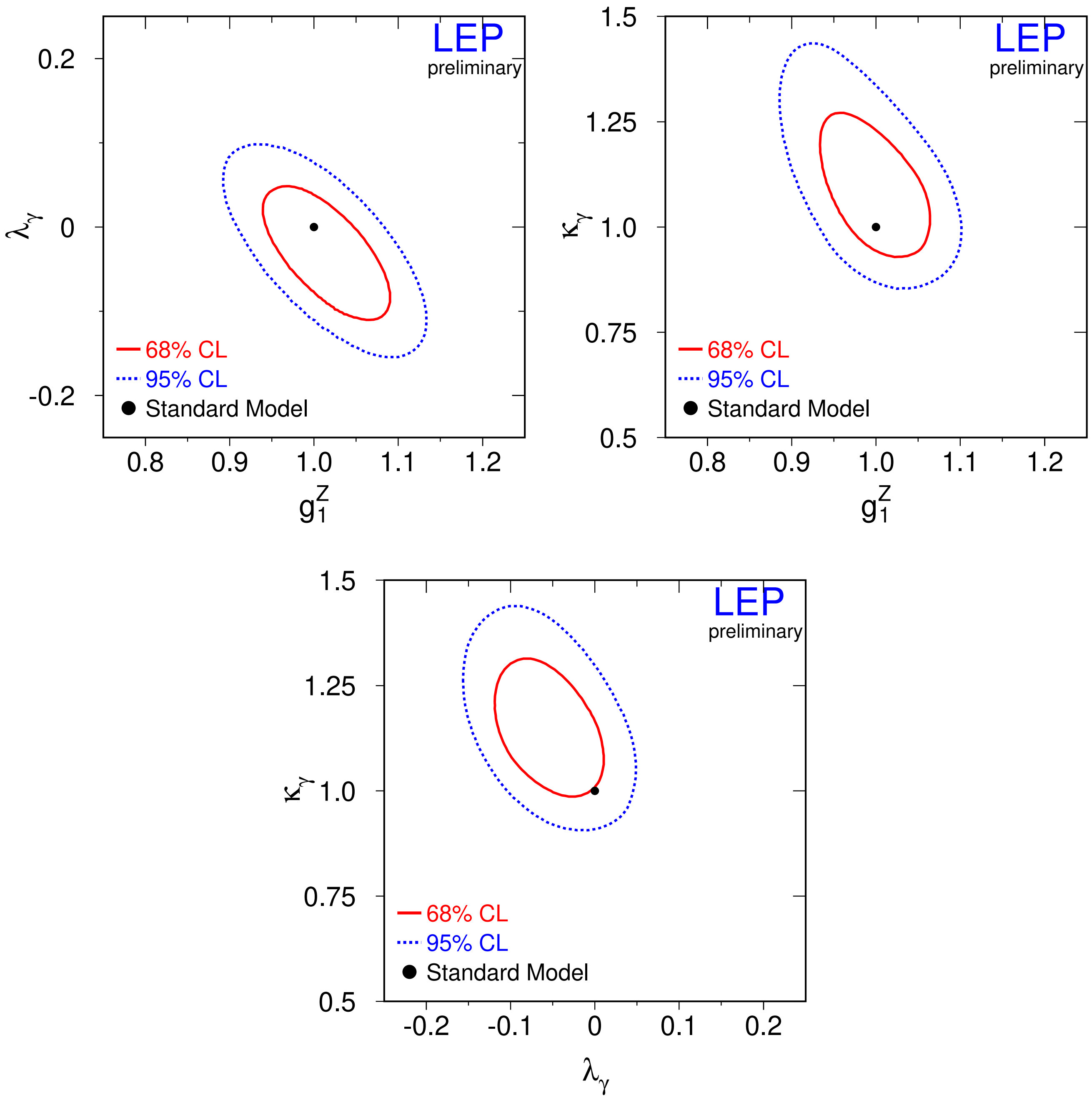
Electric quadrupole moment:

$$Q_W = -\frac{e}{m_W^2}(\kappa_\gamma - \lambda_\gamma)$$

Standard Model:

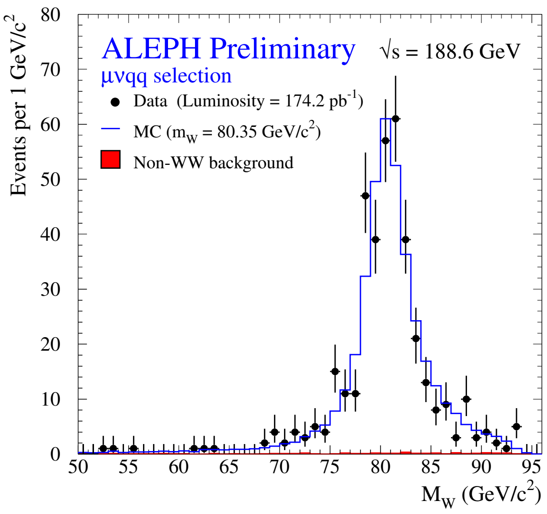
$$g_1^\gamma = g_1^Z = 1$$
$$\kappa_\gamma = \kappa_Z = 1$$
$$\lambda_\gamma = \lambda_Z = 0$$
$$f_\gamma^{4,5,6,7} = f_Z^{4,5,6,7} = 0$$

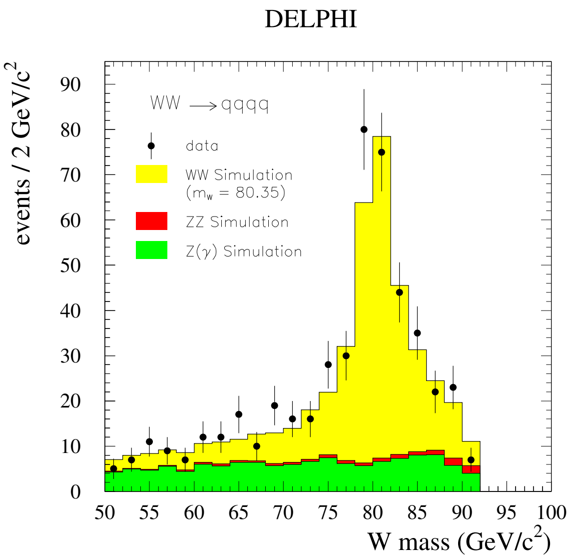
Measurement of Triple-Boson Couplings

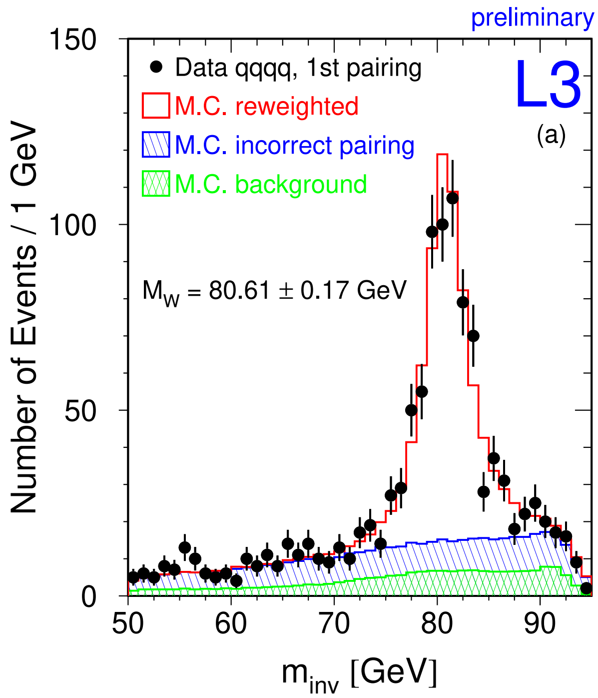


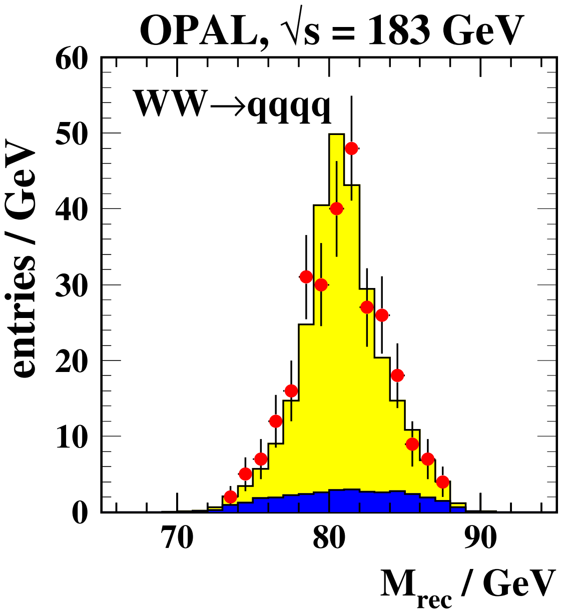
$$\left(\begin{array}{c} \text{The original Kaluza-Klein Model (1938) predicted} \\ \kappa_\gamma = -2 \end{array} \right)$$

W mass at LEP

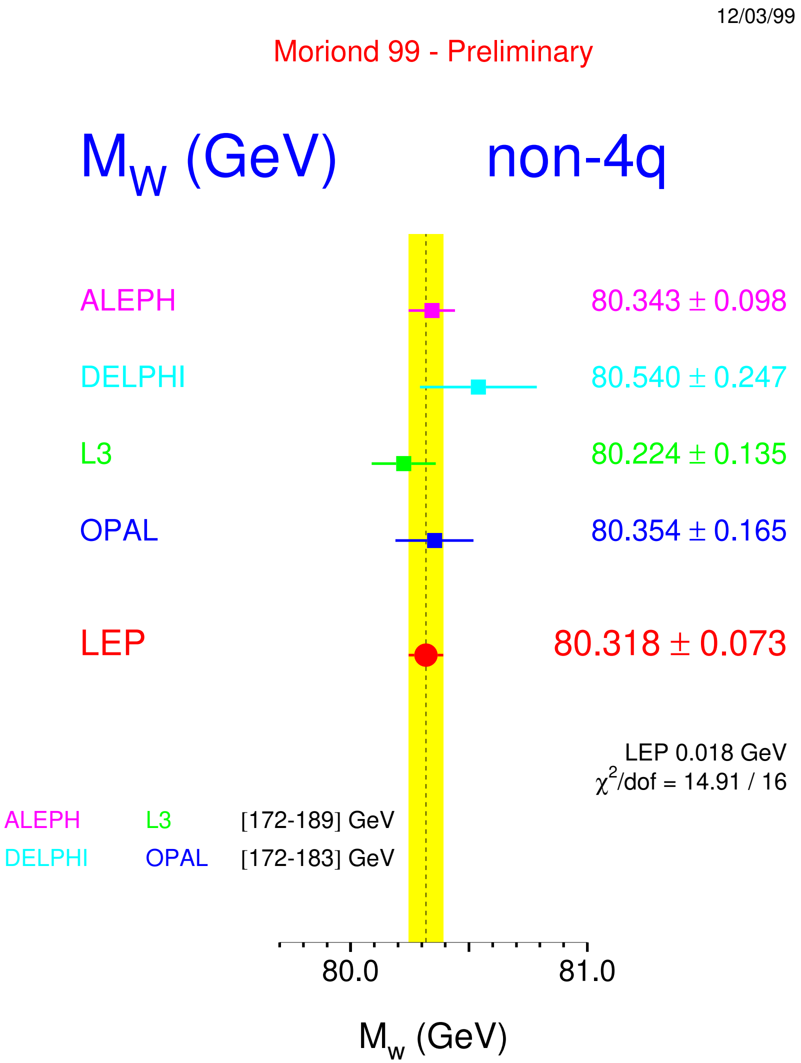

ALEPH Preliminary
√s = 188.6 GeV
μνqq selection
Data (Luminosity = 174.2 pb^{-1})
MC (m_W = 80.35 GeV/c^2)
Non-WW background
Events per 1 GeV/c^2
M_W (GeV/c^2)

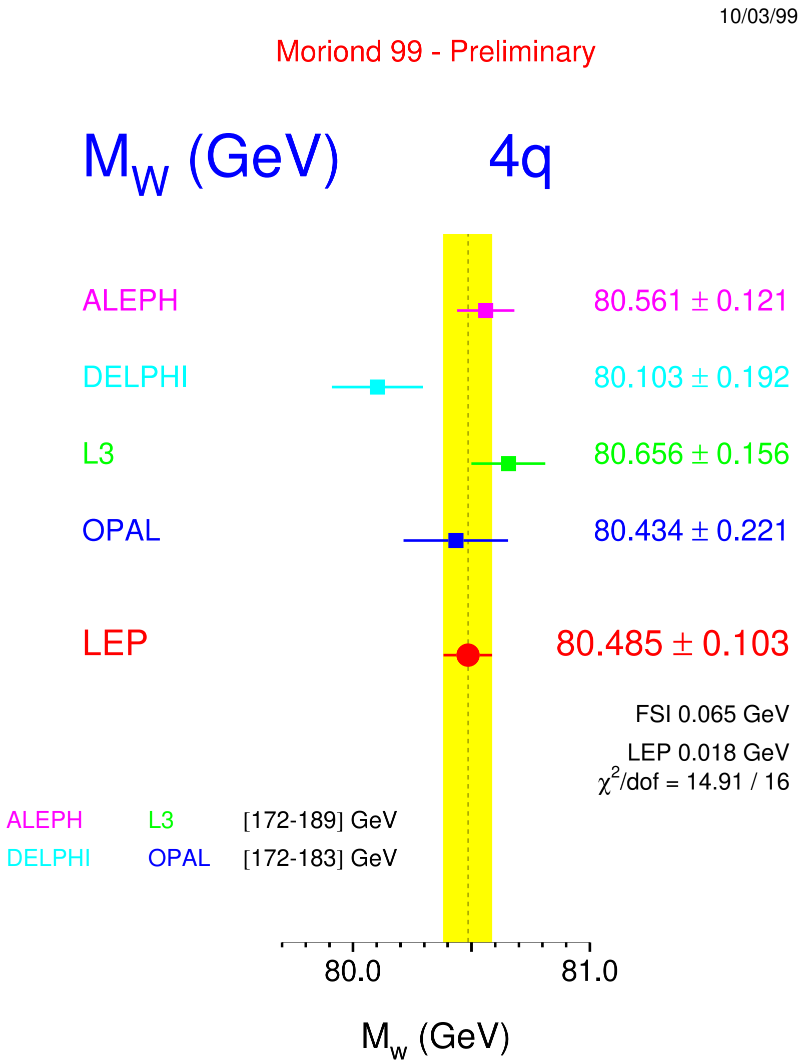

DELPHI
WW → qqqq
data
WW Simulation
(m_w = 80.35)
ZZ Simulation
Z(γ) Simulation
events / 2 GeV/c^2
W mass (GeV/c^2)


preliminary
L3
(a)
Data qqqq, 1st pairing
M.C. reweighted
M.C. incorrect pairing
M.C. background
M_W = 80.61 ± 0.17 GeV
Number of Events / 1 GeV
m_{inv} [GeV]


OPAL, √s = 183 GeV
WW→qqqq
entries / GeV
M_{rec} / GeV

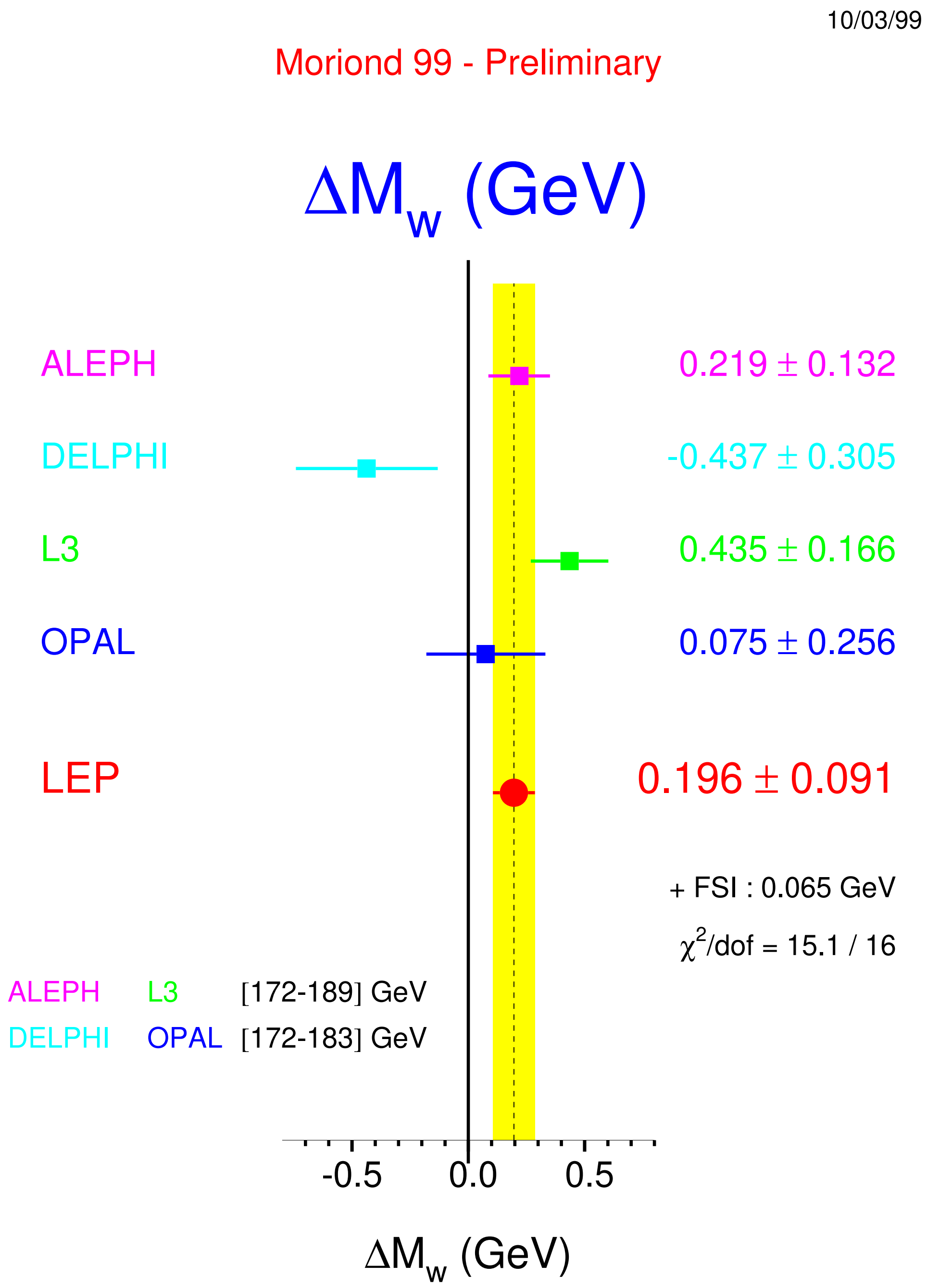
LEP m_W results





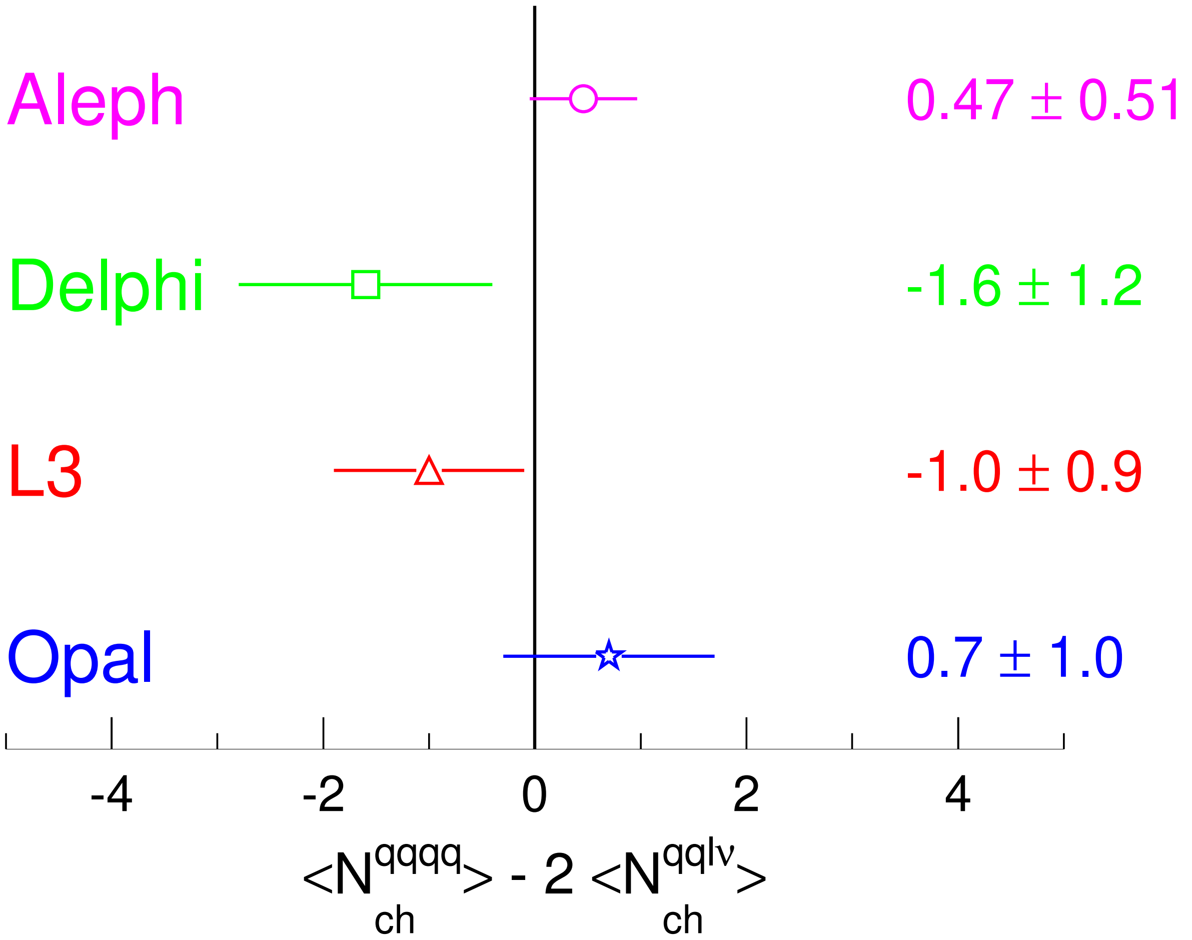
LEP m_W results

Difference between hadronic and semileptonic masses?



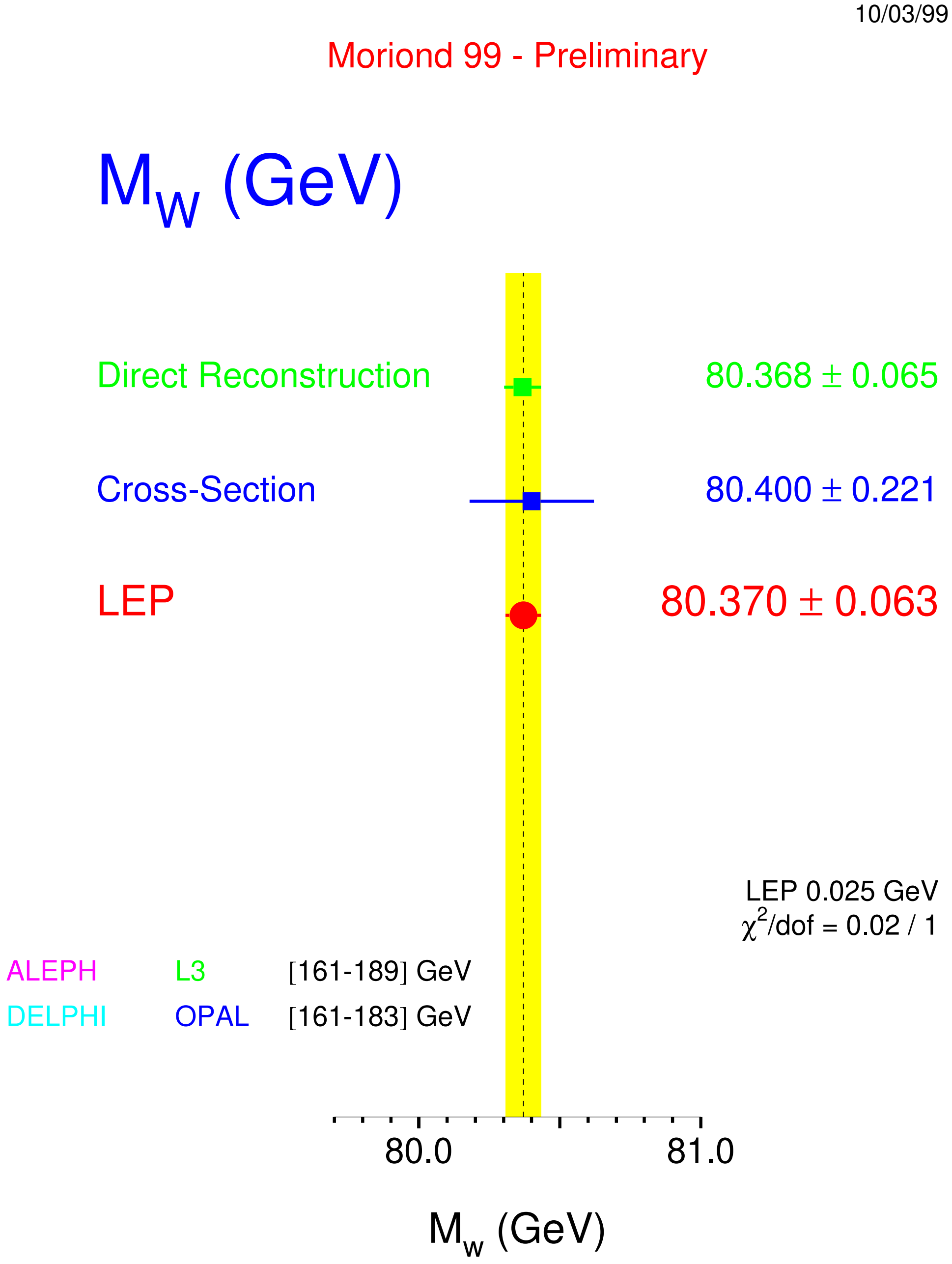
LEP m_W results

On the other hand:



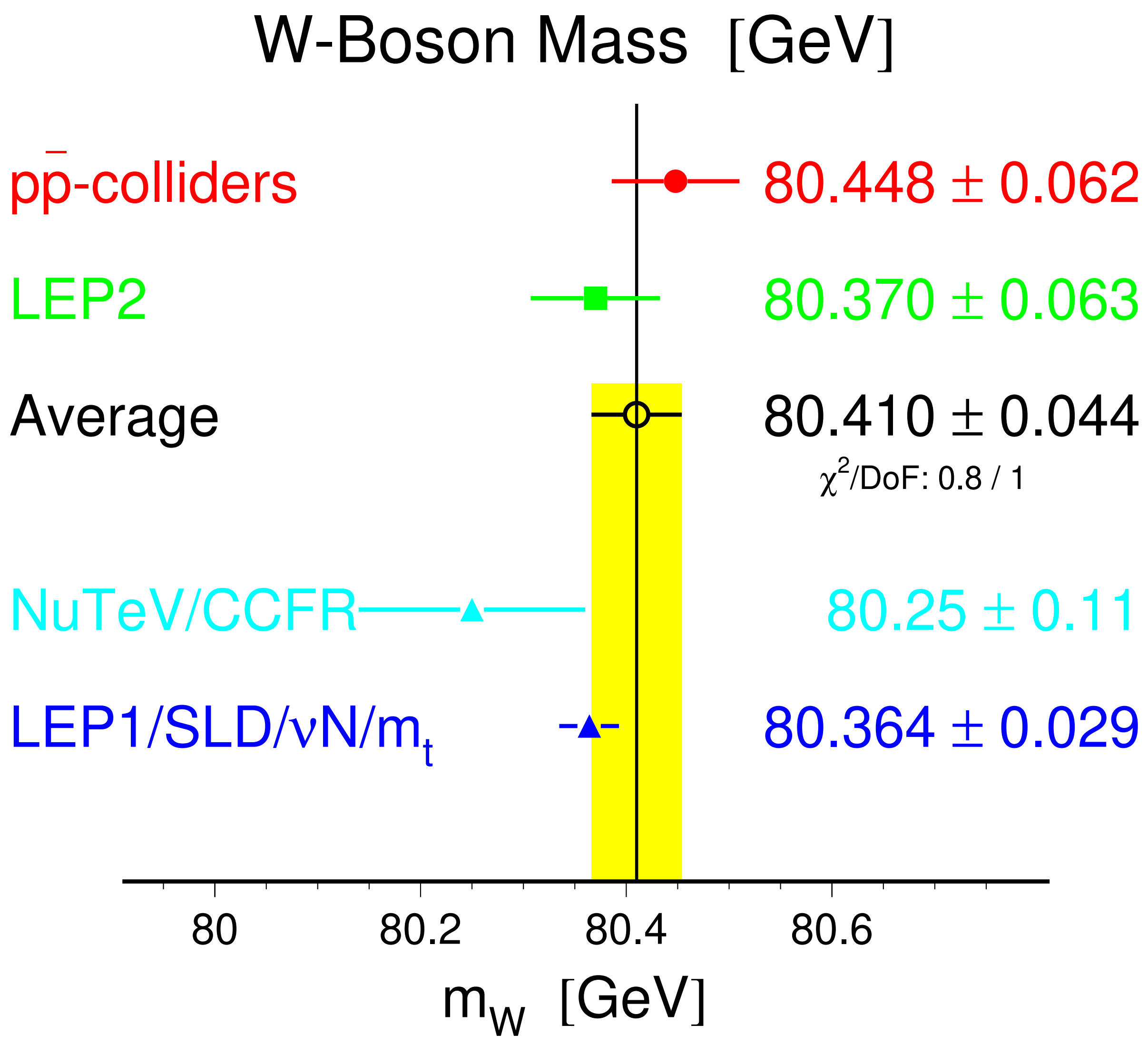
Most models that predict large mass differences also predict multiplicity differences...

m_W at LEP 2



10/03/99
Moriond 99 - Preliminary
M_W (GeV)
Direct Reconstruction
80.368 ± 0.065
Cross-Section
80.400 ± 0.221
LEP
80.370 ± 0.063
LEP 0.025 GeV
χ²/dof = 0.02 / 1
ALEPH
L3
[161-189] GeV
DELPHI
OPAL
[161-183] GeV
80.0
81.0
M_w (GeV)

m_W in the World



And finally, Higgses

At LEP and SLD:

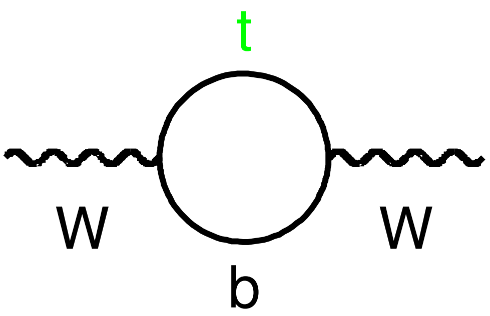
top–quark and Higgs–Boson not directly produced

sensitivity only via higher order terms

$\rightarrow$ radiative corrections

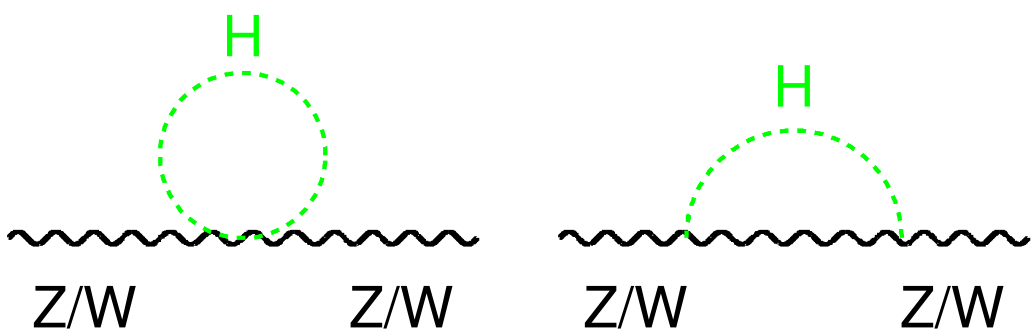
Important radiative corrections for m_t:

$\propto m_t^2$



Important radiative corrections for m_H:

$\propto log \left(\frac{m_H}{m_W}\right)$



Summary of data

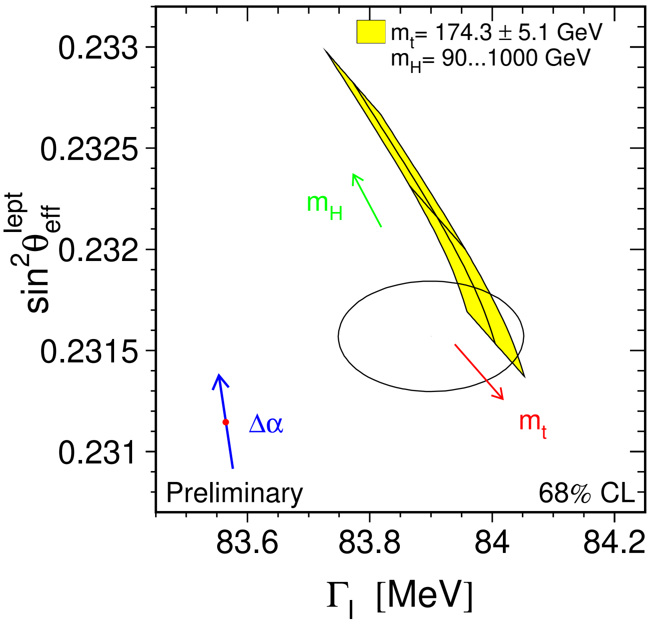
Data:

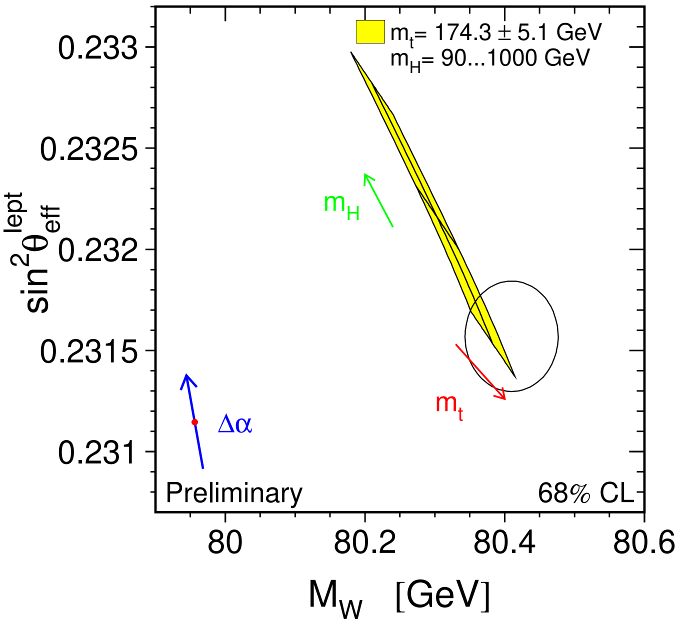
	99	Summer 98
$G_F [10^{-5}\ \mathrm{GeV}^{-2}]$	1.16637 ± 0.00001	1.16639 ± 0.00002
$\alpha(m_Z^2)^{-1}$	128.878 ± 0.090	128.878 ± 0.090
m_Z [GeV]	91.1867 ± 0.0021	91.1867 ± 0.0021
Γ_Z [GeV]	2.4939 ± 0.0024	2.4939 ± 0.0024
σ^0_{had} [nb]	41.491 ± 0.058	41.491 ± 0.058
R_ℓ	20.765 ± 0.026	20.765 ± 0.026
$A_{\mathrm{FB}}^{0,\ell}$	0.01683 ± 0.00096	0.01683 ± 0.00096
$\mathcal{A}_\tau$	0.1431 ± 0.0045	0.1431 ± 0.0045
$\mathcal{A}_e$	0.1479 ± 0.0051	0.1479 ± 0.0051
$\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$ $(\langle Q_{\mathrm{FB}}\rangle)$	0.2321 ± 0.0010	0.2321 ± 0.0010
m_W [GeV]	**80.370 ± 0.063**	80.37 ± 0.09
$\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$ (A_{LR})	0.23109 ± 0.00029	0.23109 ± 0.00029
$R^0_{\mathrm{b\bar{b}}}$	0.21680 ± 0.00073	0.21656 ± 0.00074
$R^0_{\mathrm{c\bar{c}}}$	**0.1694 ± 0.0038**	0.1735 ± 0.0044
$A_{\mathrm{FB}}^{0,b}$	0.0991 ± 0.0020	0.0990 ± 0.0021
$A_{\mathrm{FB}}^{0,c}$	0.0712 ± 0.0043	0.0709 ± 0.0044
$\mathcal{A}_b$	**0.908 ± 0.027**	0.867 ± 0.035
$\mathcal{A}_c$	**0.651 ± 0.030**	0.647 ± 0.040
$\sin^2\theta_W(\nu N)$	0.2255 ± 0.0021	0.2255 ± 0.0021
m_W [GeV] $(p\bar{p})$	**80.448 ± 0.062**	80.40 ± 0.09
m_t [GeV] $(p\bar{p})$	174.3 ± 5.1	173.8 ± 5.0

Sensitivity to radiative corrections

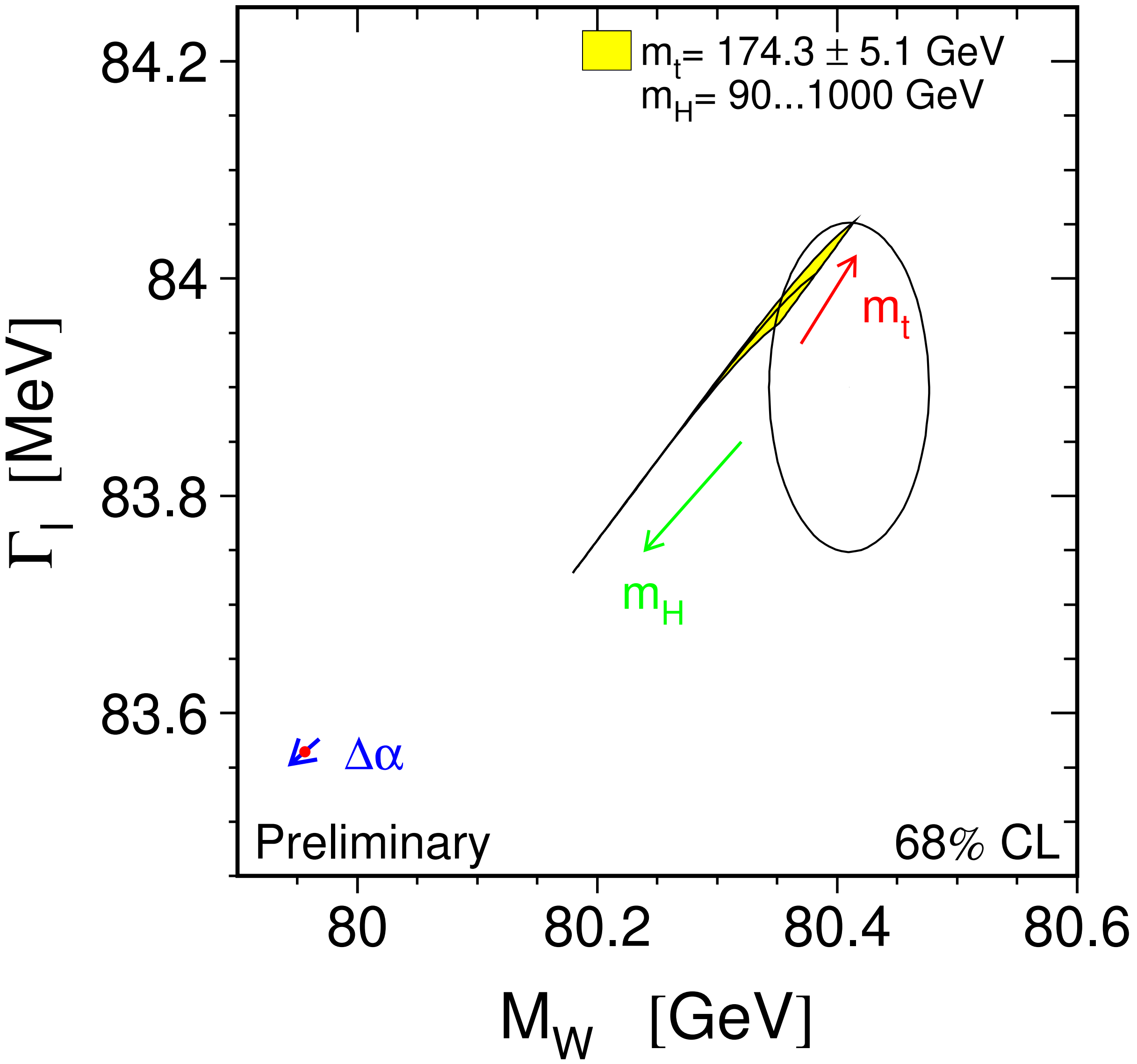
Using:

$$
\begin{aligned}
\alpha &= \alpha(m_Z^2) \\
\sin^2\theta_W &= 1 - \frac{m_W^2}{m_Z^2} \\
\sin^2\theta_W \cos^2\theta_W &= \frac{\pi\alpha}{\sqrt{2}G_F} \\
\Gamma_{\ell\ell} &= \frac{G_F m_Z^3}{6\pi\sqrt{2}}(g_V^2 + g_A^2)(1 + \frac{3\alpha}{4\pi}) \\
g_A &= -0.5 \\
g_V &= -0.5 + 2\sin^2\theta_W
\end{aligned}
$$





Sensitivity to radiative corrections



$\alpha(m_Z^2)$

Vacuum polarization results in

$$\alpha(m_Z^2) = \frac{\alpha}{1-\Delta\alpha}$$

$\Delta\alpha_{\mathrm{leptons}}$ is easy to calculate. To three loops

(Steinhauser, PLB 429 (98) 158)

$$\Delta\alpha_{\mathrm{leptons}} = 0.031498$$

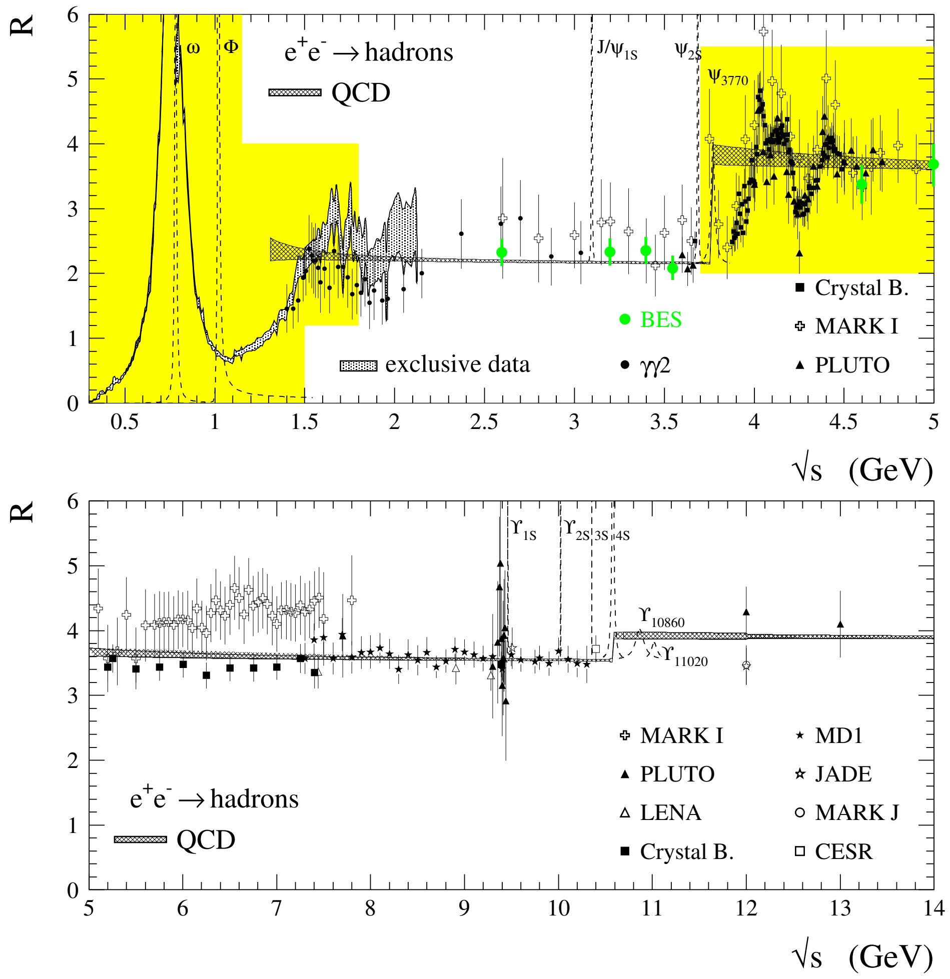
$\Delta\alpha_{\mathrm{had}}$ is not so easy, since one needs QCD to very low energy.

Dispersion relations + optical theorem relates $\Delta\alpha$had to $e^+e^- \to$ hadrons:

$$\Delta\alpha_{\mathrm{had}}(m_Z^2) = -\frac{\alpha m_Z^2}{3\pi}\int_{4m_\pi^2}^{\infty} ds \frac{R(s)}{s(s-m_Z^2-i\varepsilon)}$$

Two choices for R: data or theory.

$\alpha(m_Z^2)$



Two examples:

Using data:

Jegerlehner, *et al.* (95): $1/(128.878 \pm 0.090)$

Using theory:

Davier, *et al.* (97): $1/(128.905 \pm 0.036)$

For the moment, the LEPEWWG prefers to stay with the more model-independent Jegerlehner evaluation, although the effects of using Davier are also shown.

Results

	all data except m_t and m_W	all data
m_t [GeV]	157^{+9}_{-8}	171.7 ± 4.9
m_H [GeV]	33^{+40}_{-15}	71^{+75}_{-42}
$\log(m_H/\,\mathrm{GeV})$	$1.52^{+0.34}_{-0.27}$	$1.85^{+0.31}_{-0.39}$
$\alpha_s(m_Z^2)$	0.120 ± 0.003	0.119 ± 0.003
χ^2/d.o.f.	10/12	15/15

Derive:

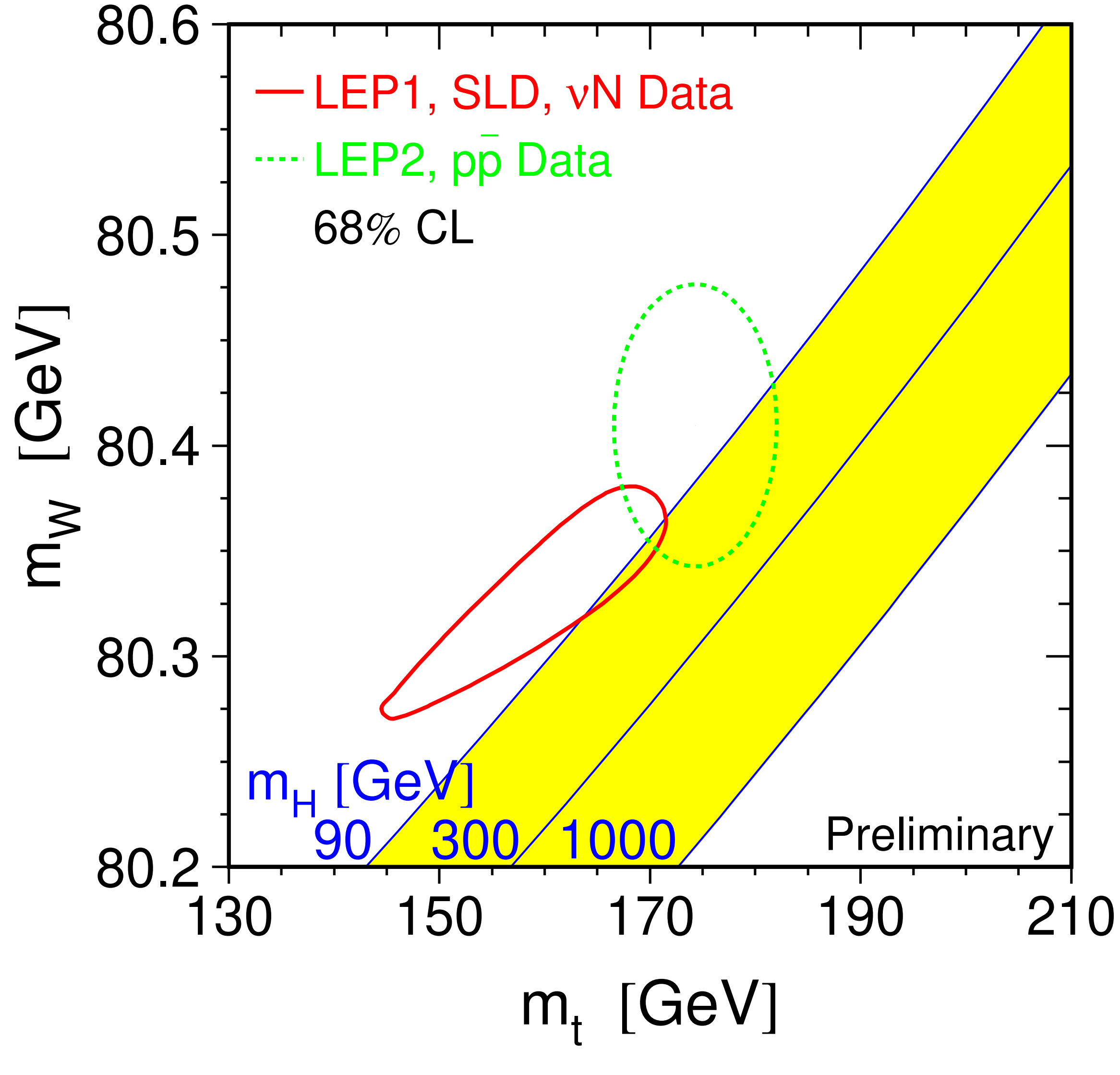
m_W [GeV]	80.326 ± 0.037	80.378 ± 0.023

- indirect m_t and m_W agrees well with direct measurements (174.3 ± 5.1 GeV and 80.410 ± 0.044 GeV)
- $\alpha_s(m_Z^2)$ agrees well with PDG value (0.119 ± 0.002)

Test Radiative Corrections

Compare:

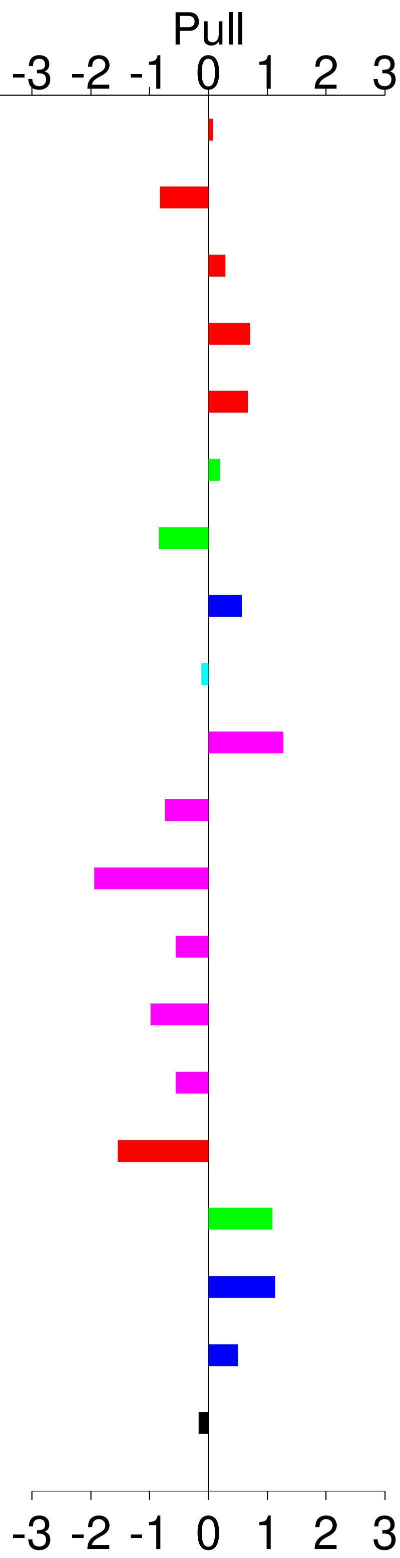
- m_W, m_t from radiative corrections
- direct measurement (TEVATRON, LEP2)



How is the fit?

Moriond 1999

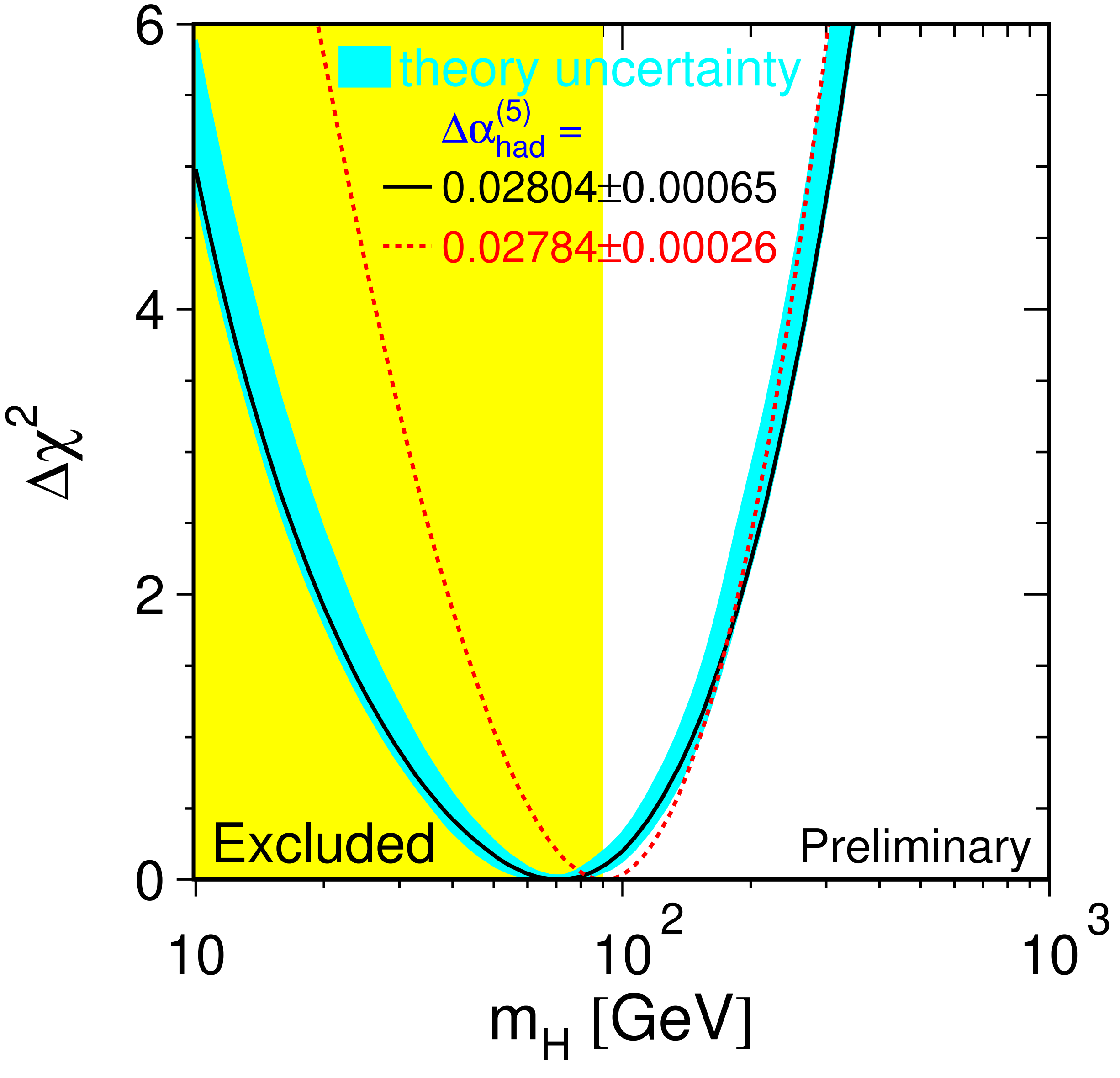
	Measurement	Pull
m_Z [GeV]	91.1867 ± 0.0021	.08
Γ_Z [GeV]	2.4939 ± 0.0024	-.83
σ^0_{hadr} [nb]	41.491 ± 0.058	.29
R_e	20.765 ± 0.026	.70
$A^{0,e}_{fb}$	0.01683 ± 0.00096	.67
A_e	0.1479 ± 0.0051	.20
A_τ	0.1431 ± 0.0045	-.84
$\sin^2\theta^{lept}_{eff}$	0.2321 ± 0.0010	.56
m_W [GeV]	80.370 ± 0.063	-.12
R_b	0.21680 ± 0.00073	1.27
R_c	0.1694 ± 0.0038	-.75
$A^{0,b}_{fb}$	0.0991 ± 0.0020	-1.94
$A^{0,c}_{fb}$	0.0712 ± 0.0043	-.55
A_b	0.908 ± 0.027	-.99
A_c	0.651 ± 0.030	-.56
$\sin^2\theta^{lept}_{eff}$	0.23109 ± 0.00029	-1.54
$\sin^2\theta_W$	0.2255 ± 0.0021	1.08
m_W [GeV]	80.448 ± 0.062	1.14
m_t [GeV]	174.3 ± 5.1	.50
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02804 ± 0.00065	-.17



Upper Limit on Higgs–Boson Mass?

Upper limit at 95% CL:

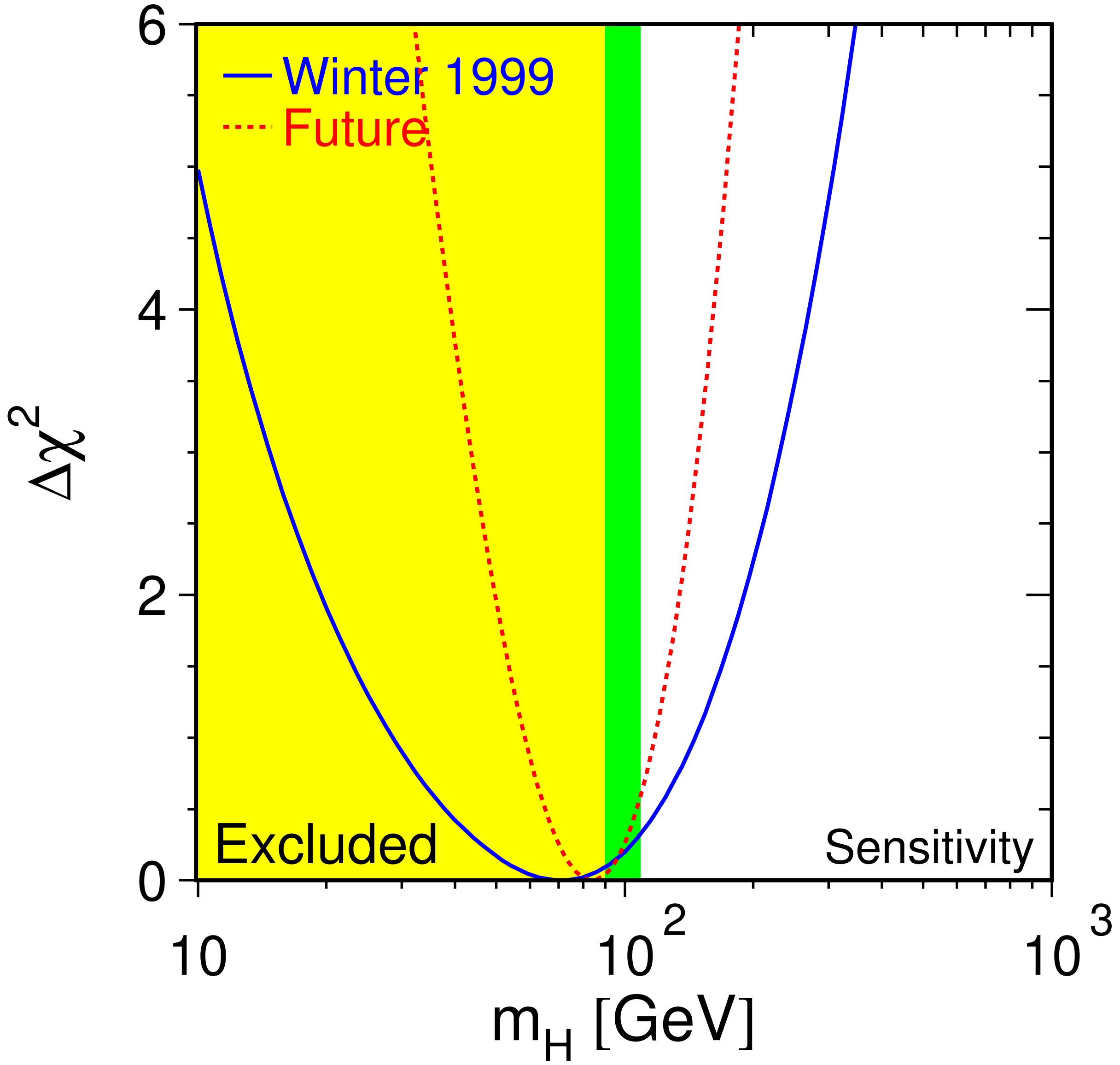
$m_H < 220$ GeV



NB: the famous blue band is now about half the size compared to a year ago. Many thanks to our theoretical colleagues!

Outlook for constraints on m_H

Possible improvements:



Assumes:

- $\Delta\alpha(m_Z^2) = 0.01$
- $\Delta m_t = 2$ GeV
- $\Delta m_W = 30$ MeV

Conclusions

- LEP I, along with SLC, have made an enormous contribution to our understanding of electroweak physics. Of course, Tevatron helped with the top quark...
- The LEP I era is over. Many results are now very close to being finalized. Some improvements will still come ($\mathcal{P}_\tau$ and HF).
- SLD has made very important contributions. It would be really good if the SLD extension gets funding!
- LEP and Tevatron seem to be keeping step in improvements on the W mass measurements. Let's see what the situation is like this summer!
- We have tantalizing hints of a low mass Higgs.

- so maybe we can still find it at LEP!

Final State and Bose-Einstein