ELECTROWEAK PHYSICS

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on behalf of the
LEP **E**lectro**W**eak **W**orking **G**roup

CERN, LEPC, 15th September 1998

NEW since last LEPC:

- study of errors from LEP I energy on LS parameters
- theoretical improvements
- new LEP results and Post-Vancouver status
- the latest Standard Model fits
- plans for the near future

Results from sub-group on line shape combination

$\rightarrow$LEPEWWG/ LS 98-01, May 1998

Standard procedure: average Line Shape ("LS") and asymmetry ("A_{FB}") at parameter level

for energy related errors:

- Ansatz: covariance matrix of each experiment is composed as $\mathbf{V} = \mathbf{V}_{\mathrm{Energy}} + \mathbf{V}_{\mathrm{exp.}}$
- compare with second fit, where $\mathbf{V}_{\mathrm{exp.}}$ is scaled by factor f
- solve analytically for $\mathbf{V}_{\mathrm{Energy}}$

Energy related errors constitute the largest and most complicated common error among the experiments.

$\Longrightarrow$ Check using the 4×7 hadronic cross sections 1993 – 1995 and covariance matrices.

Thanks to the experiments for providing preliminary numbers!

Findings:

- combination procedure was validated but
- there is a small shift of 0.3 MeV in M_Z, can be avoided by additional input from each experiment (not done for now!)

common Errors due to LEP energy:

M_Z [GeV]	$\mathbf{0.0017^2}$		
Γ_Z [GeV]	-0.0005^2	$\mathbf{0.0013^2}$	
σ_h^0 [nb]	-0.0025^2	-0.0027^2	$\mathbf{0.011^2}$

$A_{FB}^{0,e}$	0.00023^2		
$A_{FB}^{0,\mu}$	-0.00018^2	0.00021^2	
$A_{FB}^{0,\tau}$	-0.00018^2	0.00021^2	0.00021^2

Note: error on M_Z can come down to 1.6 MeV once we take care of the small shift

t-channel in Bhabhas

Theoretical error on **t-channel** contribution to Bhabha cross section now evaluated W. Beenakker, G. Passarino, hep-ph 97 10376

t-channel uncertainty assumed to be fully correlated among energy points and between cross sections and asymmetries.

Implications on fitted parameters R_{e} and $\mathrm{A}_{\mathrm{FB}}^{0,\mathrm{e}}$ studied by (most) experiments. More work is still needed!

For now, take smallest errors as common:

R_{e}	$\mathbf{0.025}^2$	
$\mathrm{A}_{\mathrm{FB}}^{0,\mathrm{e}}$	-0.0057^2	$\mathbf{0.0013}^2$

- $\sim$50 % of combined error on R_{e} and $\mathrm{A}_{\mathrm{FB}}^{0,\mathrm{e}}$
- gives rise to 44 % correlation between R_{e} and $\mathrm{A}_{\mathrm{FB}}^{0,\mathrm{e}}$
- with lepton universality: effect reduced to $< \frac{1}{3}$ for R_{ℓ}, $\mathrm{A}_{\mathrm{FB}}^{0,\ell}$

Improved $O(\alpha^3)$ radiative corrections

hard $O(\alpha^3)$ QED radiative corrections very recently implemented in ZFITTER, in addition to exponentiation of the soft part

Montagna et al., PLB406 (1997) 243
+ earlier work by Jadach et al., PL B257 (1991) 173

has quite significant effects

- $\Delta M_Z = +0.5$ MeV
- $\Delta\Gamma_Z = +0.6$ MeV
- $\Delta\sigma_h^o = +0.05$ %

Not yet used by experiments in fits to σ and A_{FB}

$\Rightarrow$ take shifts as errors for now

Plan: compare with YFS scheme, where 3rd order is known to be small, in order to evaluate **final common errors**

(won't be zero, but smaller than numbers in list above)

Improved error on small angle Bhabha cross section

The theoretical error on $\frac{\Delta L}{L}$ was reported at ICHEP 98 to come down from 0.11 % to 0.06 %

B. Ward et al., ICHEP 98

Publication expected soon!

The above improvements will require new fits to the measured cross sections and asymmetries from all experiments

LS and Afb

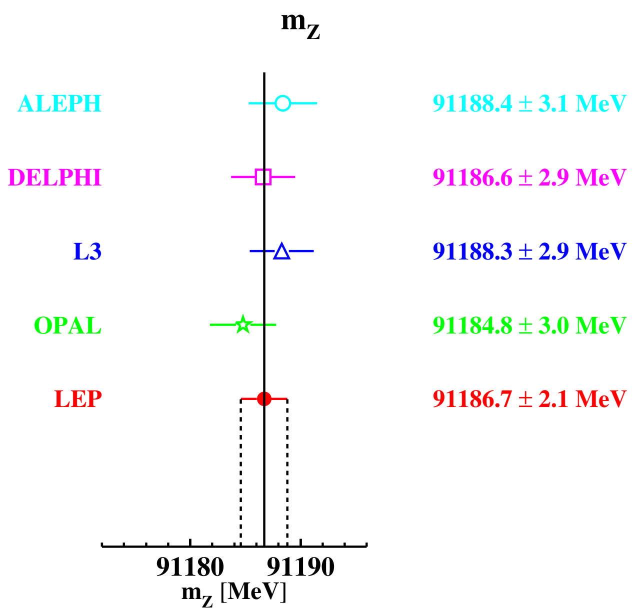
new results:

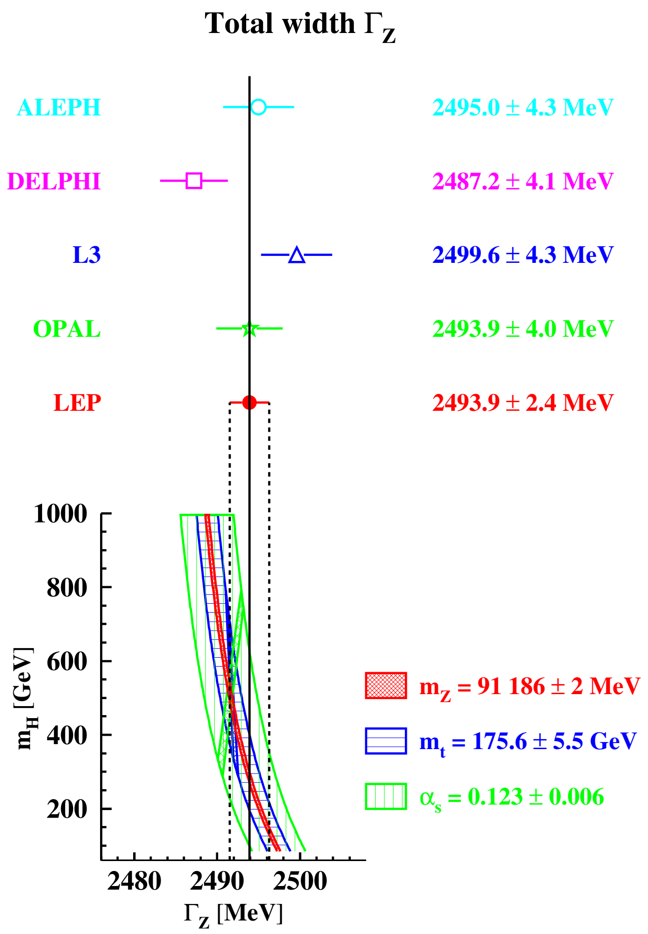
- ALEPH, DELPHI and OPAL updated, use final energy calibration
- L3 corrected to final energy calibration (+0.3 MeVon M_Z and Γ_Z)

Results of combination:

χ^2/DoF = 28/27 (42 % prob.) without lepton universality

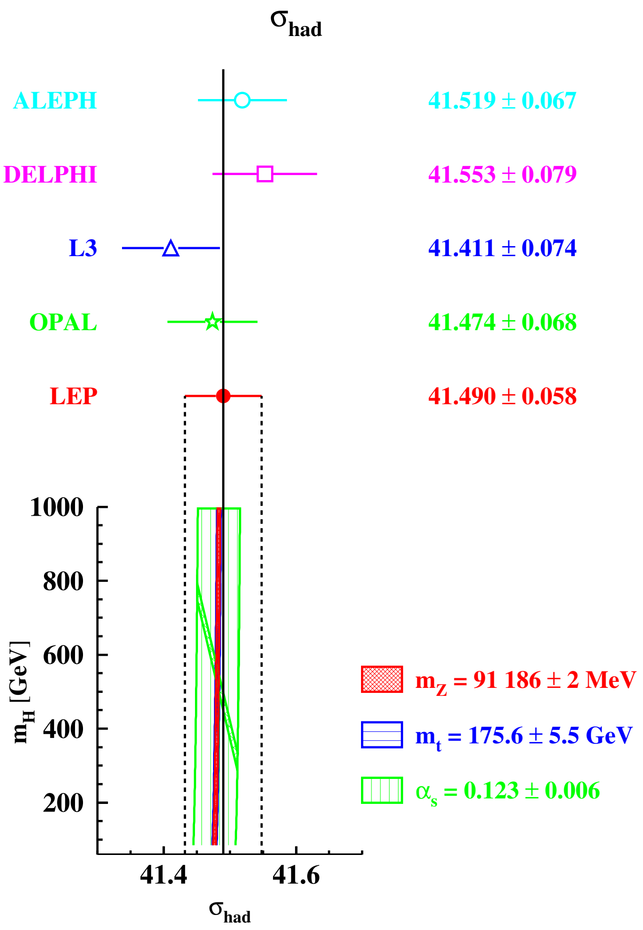
χ^2/DoF = 31/31 (47 % prob.) with lepton universality

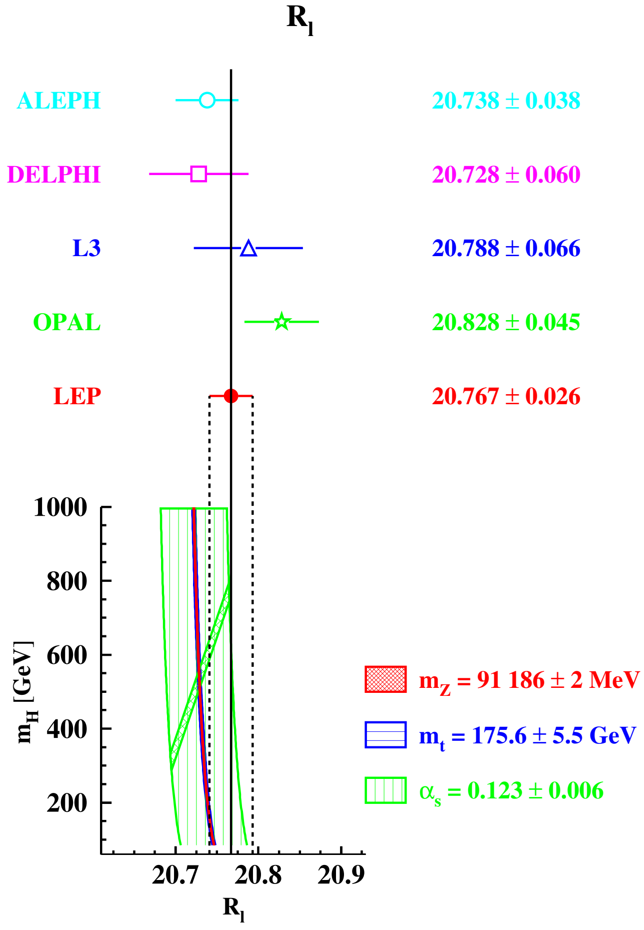




$M_Z = 91.1867 \pm 0.0021$ GeV essentially unchanged

$\Gamma_Z = 2.4939 \pm 0.0024$ GeV central value lower by 0.9 MeV





$\sigma_{\mathrm{h}}^{o} = 41.490 \pm 0.058\ \mathrm{nb}$, error 10 % larger than before

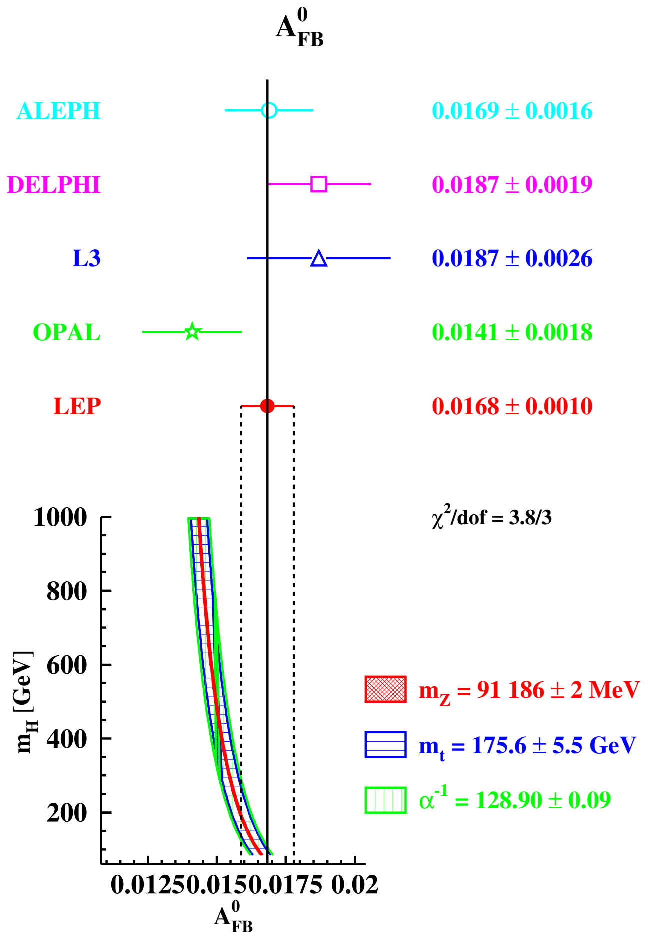
$R_{\mathrm{e}} = 20.783 \pm 0.052$, $R_{\mu} = 20.789 \pm 0.034$,

$R_{\tau} = 20.764 \pm 0.045$, $R_{\ell} = 20.767 \pm 0.026$.

errors 10 % smaller than before

α_s from R_ℓ: $0.124 \pm 0.004_{\mathrm{exp.}} \pm 0.002_{\mathrm{Higgs}}$.

Note: $M_{\mathrm{H}} = 300^{+700}_{-210}$ GeV here and in what follows



$A_{FB}^{0,e} = 0.0153 \pm 0.0025$, $\quad A_{FB}^{0,\mu} = 0.0164 \pm 0.0013$,

$A_{FB}^{0,\tau} = 0.0183 \pm 0.0017$, $\quad A_{FB}^{0,\ell} = 0.0168 \pm 0.0010$

averages essentially unchanged

Some derived quantities

	without	with
	lepton universality	
Γ_{had} [MeV]	1743.0±2.9	1742.3±2.3
Γ_{inv} [MeV]	499.5±2.5	500.1±1.8
$\Gamma_{inv}/\Gamma_{\ell\ell}$	-	5.961±0.023
$\Gamma_{\ell\ell}$ [MeV]	-	83.90±0.10
Γ_{ee} [MeV]	83.87 ±0.14	-
$\Gamma_{\mu\mu}$ [MeV]	83.84 ±0.18	-
$\Gamma_{\tau\tau}$ [MeV]	83.94 ±0.22	-

Number of neutrino generations

$$N_\nu = \frac{\Gamma_{inv}}{\Gamma_{\ell\ell}} \Big/ \left(\frac{\Gamma_{\nu\nu}}{\Gamma_{\ell\ell}}\right)_{SM} = 2.994 \pm 0.011$$

Limit on invisible width not from neutrinos

include a term $\Delta\Gamma^x_{inv}$ in Standard Model fit to all e.w. data $\Rightarrow$

$$\Delta\Gamma^x_{inv} < 2.8\,\mathrm{MeV}\ @\ 95\%\ \mathrm{C.L.}$$

conservatively, limit was derived allowing only positive values of $\Delta\Gamma_{inv}$.

Note: This will be affected most by the improvements in the near future described previously ($O(\alpha^3)$ QED and error on $\Delta L/L$)

Lepton couplings - include τ polarization:

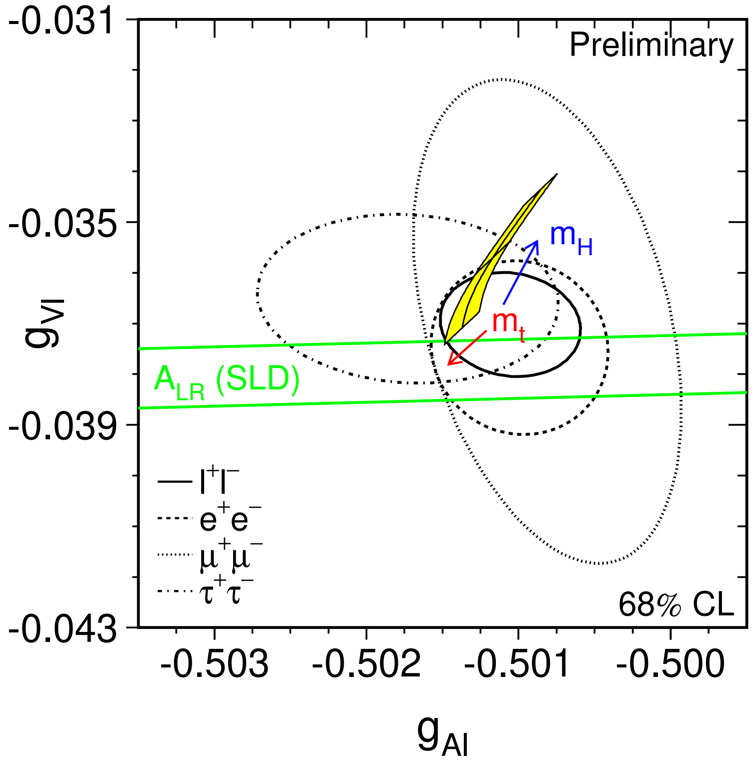
new results:

- ALEPH: 90 - 92 data reanalysed, new 93-95 data
- DELPHI updated

LEP average: $\mathcal{A}_\tau = 0.1431 \pm 0.0045$

$\mathcal{A}_e = 0.1479 \pm 0.0051$

errors factor $\sim$1.4 smaller than before



ratios of couplings

LEP only

$g^v_\mu / g^v_e = 0.984 \pm 0.098$
$g^v_\tau / g^v_e = 0.974 \pm 0.043$
$g^a_\mu / g^a_e = 0.9996 \pm 0.0014$
$g^a_\tau / g^a_e = 1.0015 \pm 0.0015$

LEP + SLC

$g^v_\mu / g^v_e = 0.967 \pm 0.082$
$g^v_\tau / g^v_e = 0.965 \pm 0.032$
$g^a_\mu / g^a_e = 0.9997 \pm 0.0014$
$g^a_\tau / g^a_e = 1.0015 \pm 0.0015$

Note: SLD and LEP now closer than ever, see comparison of $\sin^2\theta_{eff}$ later

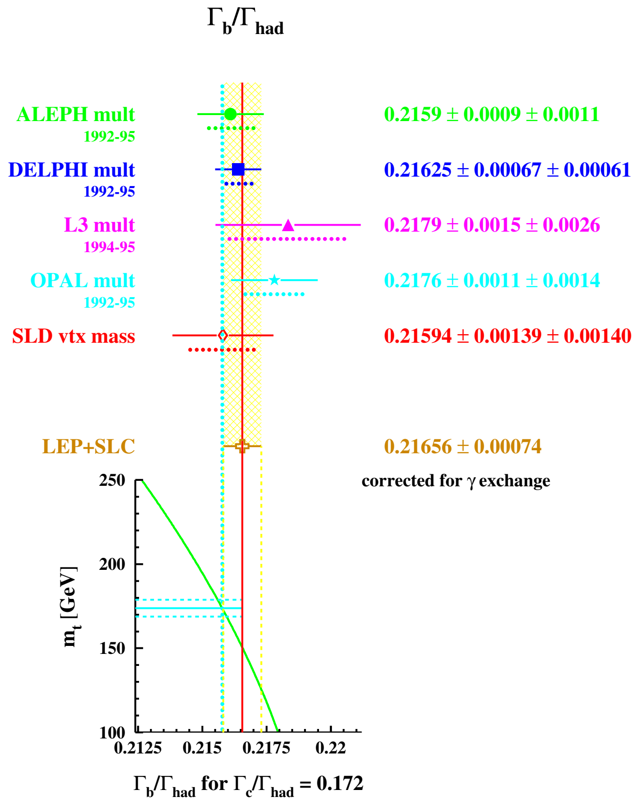
lepton universality $\surd$

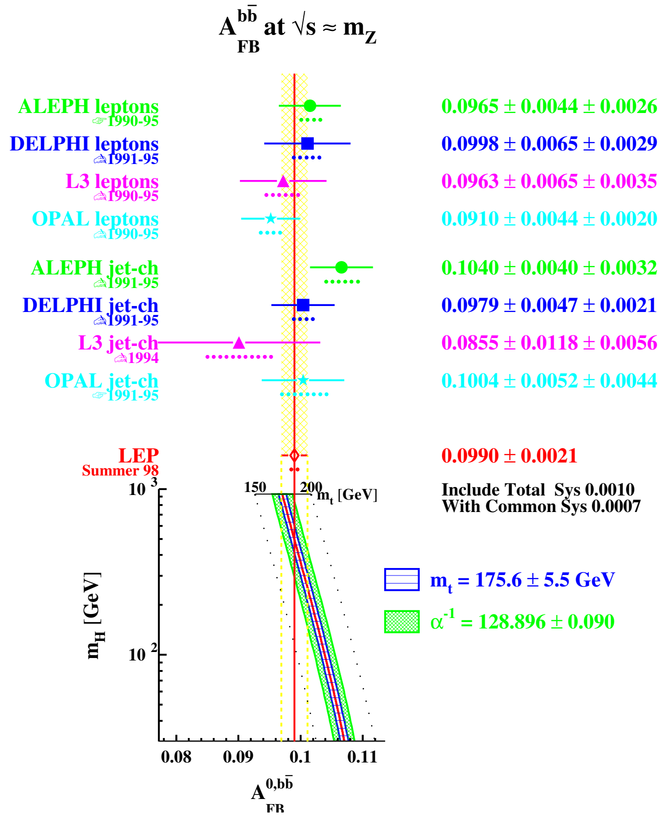
heavy flavours

new results:

- OPAL, multiple tags R_b
- DELPHI, multiple tags R_b
- DELPHI, $A_{FB}^{0,b}$ lepton and jet-charge

essentially all data up to 1995 now analysed





Most complicated combination procedure, depends on many properties of heavy quarks

recommendations for input parameters revised

$\longrightarrow$ LEPHF/98-01, Sept. 1998

NEW:

- PDG 98 values where possible (charmed hadron decay fractions, lifetimes, exclusive branching ratios)
- b decay multiplicities from LEP (DELPHI, L3, OPAL)
- gluon splitting to $\mathrm{b\bar{b}}$ from LEP (ALEPH and DELPHI)
- $\mathrm{BR}(\mathrm{b} \to \bar{\mathrm{c}} \to \ell^-)$ from measurements (CLEO and ALEPH)

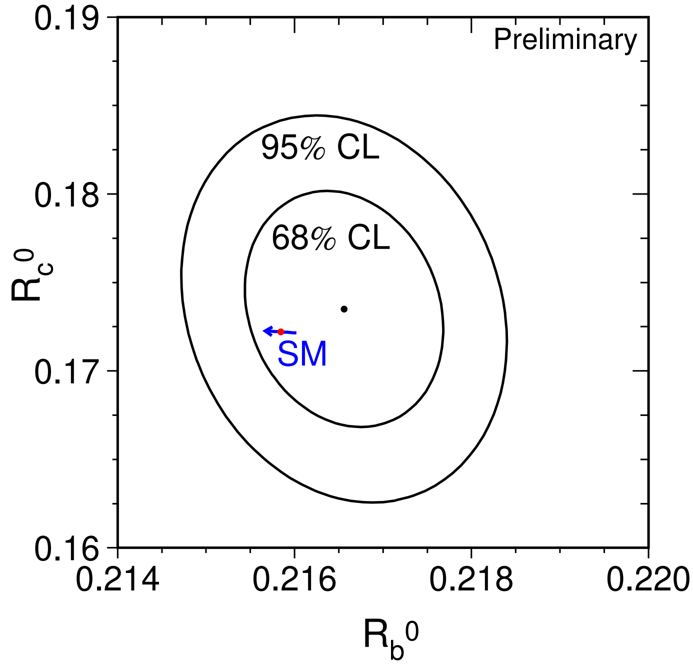
Use these in fits to LEP only [and LEP+SLC] data

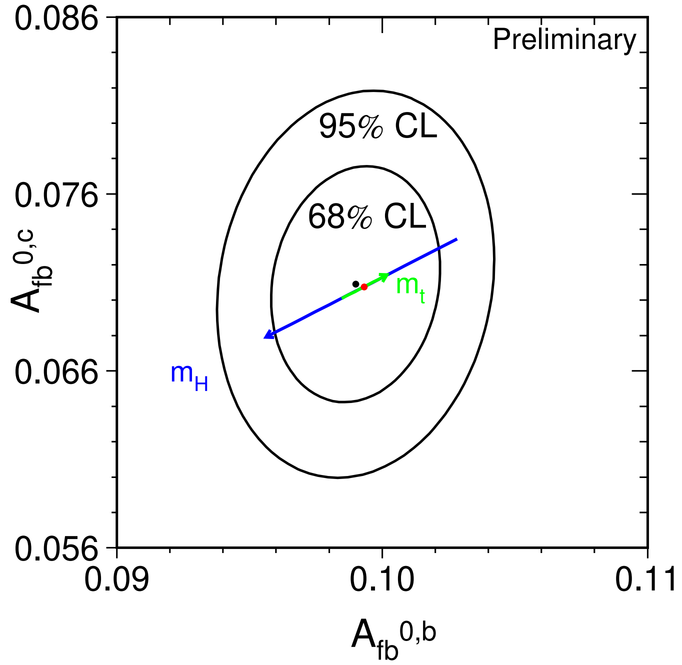
R_b, R_c, $A_{\mathrm{FB}}^{0,\mathrm{b}}$, $A_{\mathrm{FB}}^{0,\mathrm{c}}$ [,$\mathcal{A}_\mathrm{b}$, $\mathcal{A}_\mathrm{c}$]

correlations are important

Rb and *Rc*: $-17\,\%$

$A_{FB}^{0,b}$ and $A_{FB}^{0,c}$: $+13\,\%$ $\quad\Rightarrow\quad$ contour plots





LEP:

$R_b = 0.21664 \pm 0.00076$, $\quad R_c = 0.1724 \pm 0.0048$,

$A_{FB}^{0,b} = 0.0991 \pm 0.0021$, $\quad A_{FB}^{0,c} = 0.0712 \pm 0.0045$,

error on R_b factor $\sim$1.2 smaller than before

LEP + SLD combination:

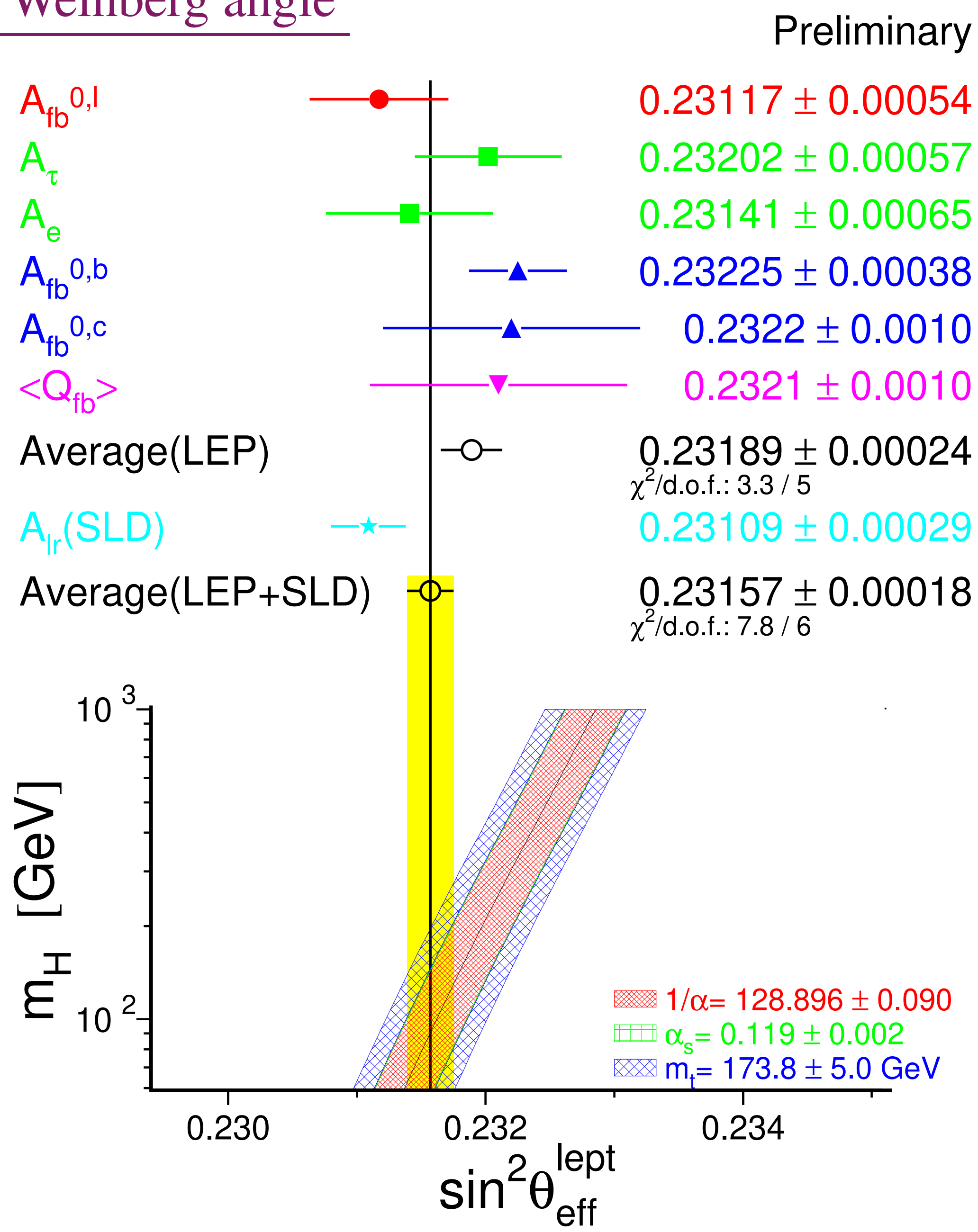
$R_b = 0.21656 \pm 0.00074$, $\quad R_c = 0.1735 \pm 0.0044$,

$A_{FB}^{0,b} = 0.0990 \pm 0.0021$, $\quad A_{FB}^{0,c} = 0.0709 \pm 0.0044$,

$\mathcal{A}_b = 0.867 \pm 0.035$, $\quad \mathcal{A}_c = 0.647 \pm 0.040$.

+ correlations

Effective Weinberg angle



worst disagreement: the two most precise measurements,
A_{LR} from SLD and $A_{FB}^{0,b}$ from LEP, disagree by about $2\frac{1}{2}$ σ

overall χ^2 of the average of 7.8/6 per DoF quite acceptable
χ^2-probability now: 25 % (was only 5 % last year!)

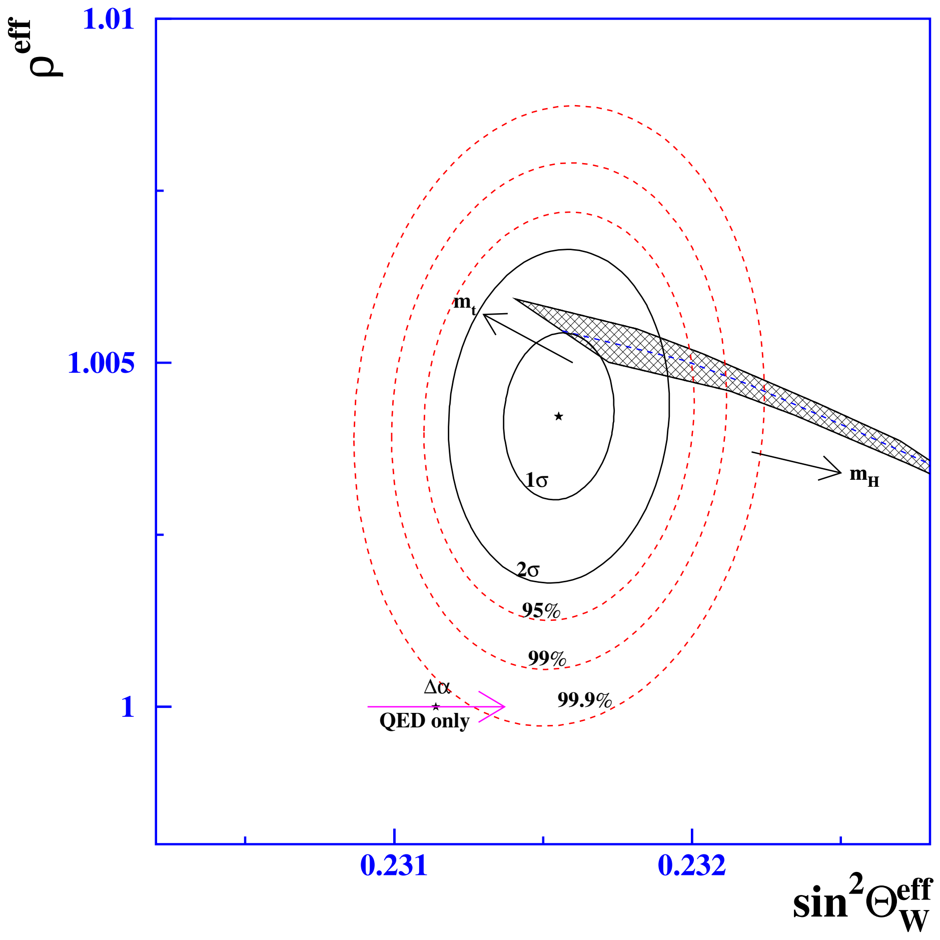
agreement has constantly improved over the years

No more reason to worry?

$$\text{look at } \rho_{eff}^{\text{lept}} \text{ vs. } \sin^2\theta_{eff}^{\text{lept}}$$

$$\Gamma_{\ell\ell} \propto \rho = \frac{1}{1-\Delta\rho}$$

$$\rho_{eff}^{\text{lept}} = 1.0042 \pm 0.0012$$



pure QED corrected point ("*" on plot) given by

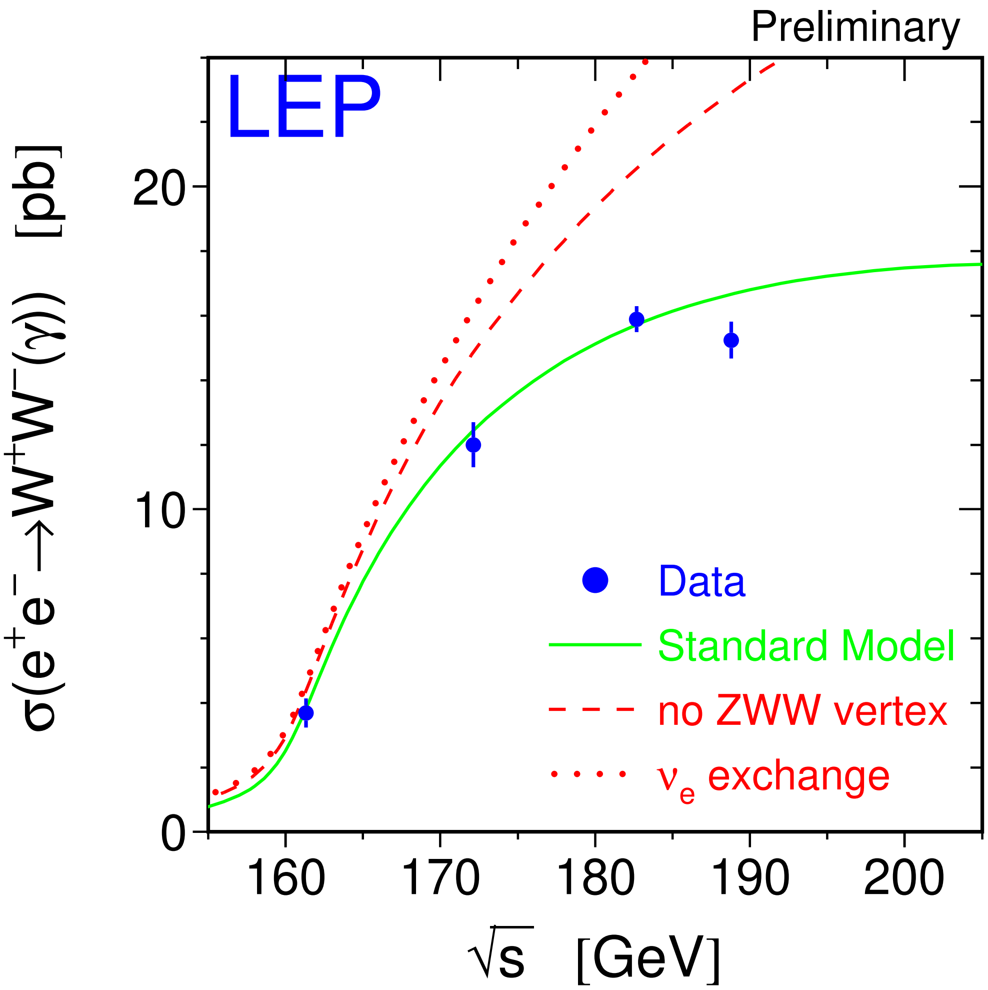
$$(\sin^2\theta_W)^0\,(\cos^2\theta_W)^0 = \frac{\pi\alpha(M_Z)}{\sqrt{2}G_F M_Z^2}$$

- presence of genuine electroweak corrections with >99 % C.L. (mainly due to $\Delta\rho$) !

W Physics (data up to 1997)

- only cross sections updated with fraction of 1998 data

WW cross section (includes $\sim$36 pb^{-1} of 1998 data)

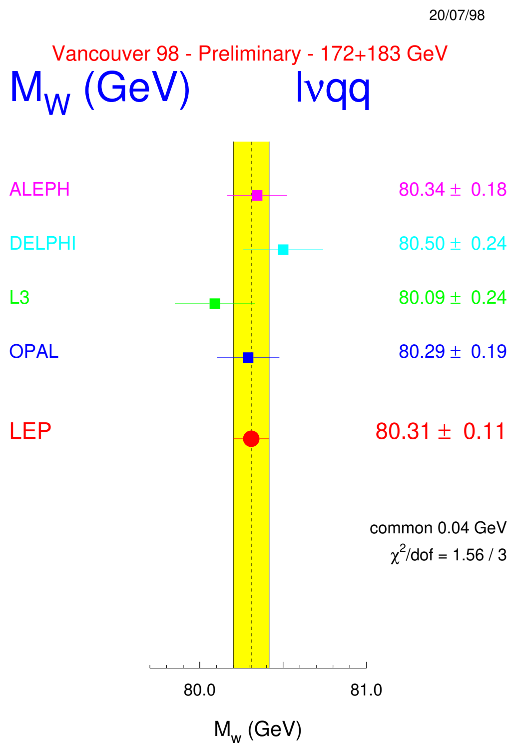


189 GeV point very preliminary, only fraction of '98 data used

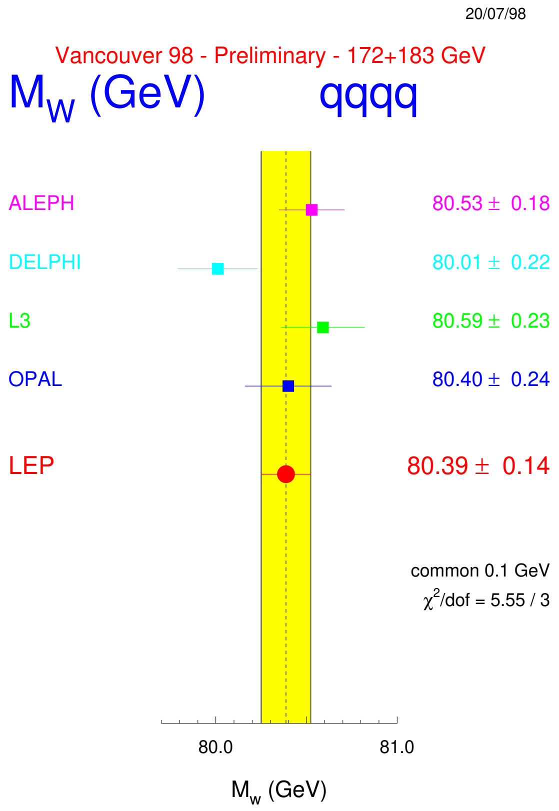
W boson mass

- 1998 data not included
- minor changes only to ALEPH analysis since Moriond
- Final-state interactions dominate error on hadronic mass

  now reduced to ±50 MeV(ALEPH), others still use 100 MeV



common errors: ±40 MeV±20 MeV$_{energy}$



common errors: ±40 MeV±90 MeV$_{FSI}$±20 MeV$_{energy}$

- each experiment averages masses from qqqq and νlqq

  better control of experimental systematic errors

average from direct reconstruction: $M_W = 80.36 \pm 0.09$ GeV

combine with σ_{WW} from threshold: $M_W = 80.40 \pm 0.22$ GeV

$\Rightarrow$ LEP combined: $M_W = 80.37 \pm 0.09$ GeV

W mass - non-LEP

W mass from CDF/D0:	$M_{\mathrm{W}_{\mathrm{p\bar{p}}}} = 80.41 \pm 0.09$ GeV
$\Rightarrow$ world average:	$M_{\mathrm{W}} = 80.39 \pm 0.06$ GeV

Measurement of the neutral-to-charged current ratio in neutrino scattering from **NuTeV** can best be compared if also expressed in terms of the W mass.

Measured quantity is

$$\sin^2\theta_{\mathrm{W}} = 1 - M_{\mathrm{W}}^2/M_{\mathrm{Z}}^2$$

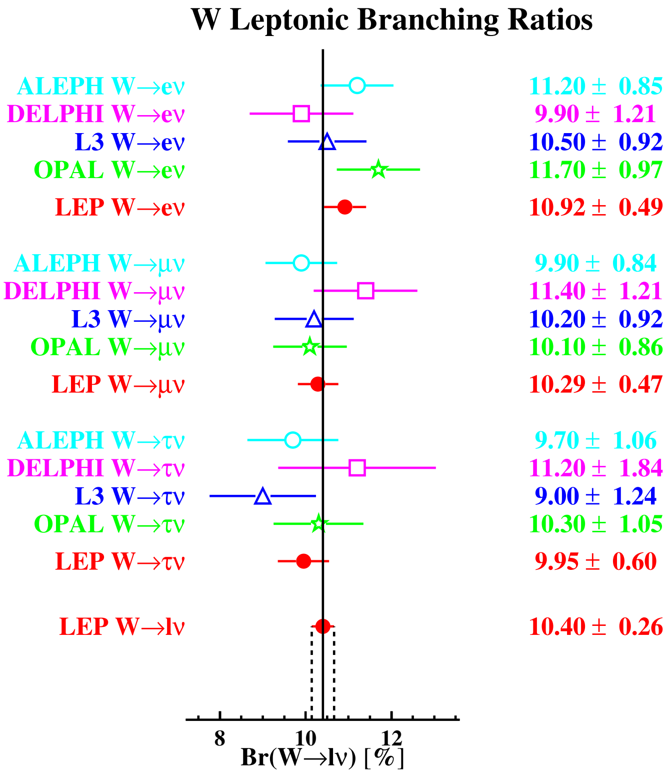
with small Top and Higgs dependent corrections!

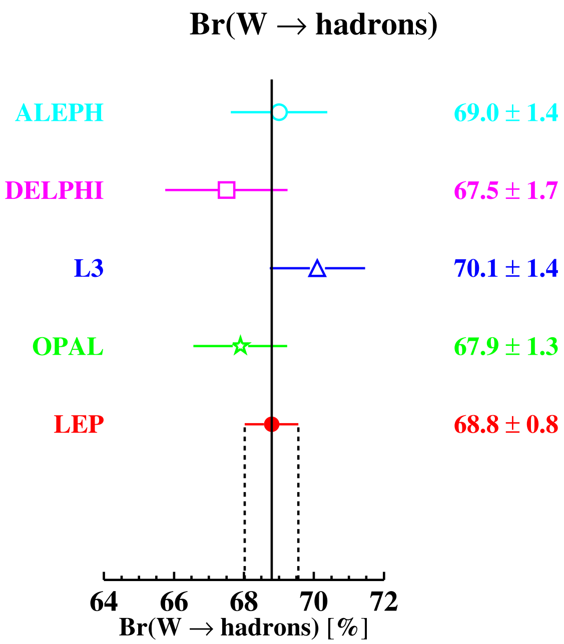
with **LEP** M_{Z}:

from NuTeV ν scattering: $M'_{\mathrm{W}} = 80.25 \pm 0.11$ GeV

M_{t}, M_{H} dependence now parameterized in Standard Model fits !

W branching fraction (data up to 1997)





$\mathrm{Br}(\mathrm{W} \to \mathrm{leptons}) = 3\times(10.40\pm0.26\,\%)$

$\mathrm{Br}(\mathrm{W} \to \mathrm{hadrons}) = 68.79\pm0.77\,\%$

From this, can derive least-well known CKM element V_{cs}:

$$\frac{\mathrm{Br(hadrons)}}{\mathrm{Br(leptons)}} = \sum |V_{ij}|^2 \left(1 + \frac{\alpha_s}{\pi}\right)$$

solve for $|V_{cs}| = 1.04\pm0.04$

compare with direct LEP measuremetents with charm tag:

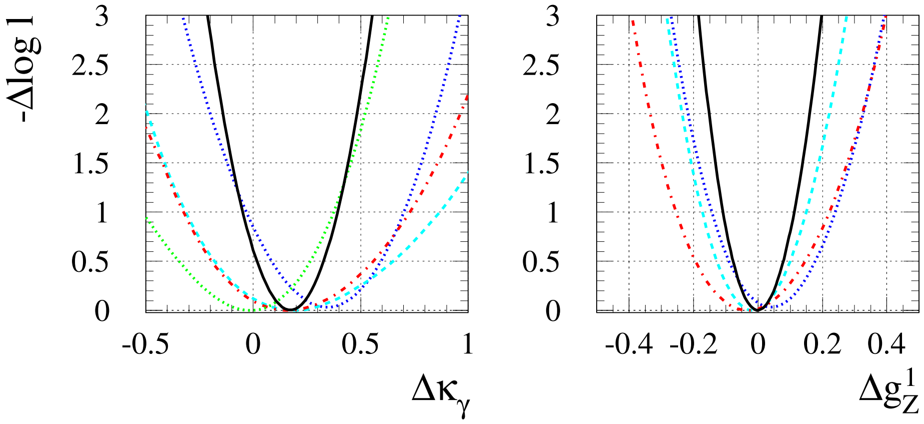
$|V_{cs}|=0.99\pm0.11$

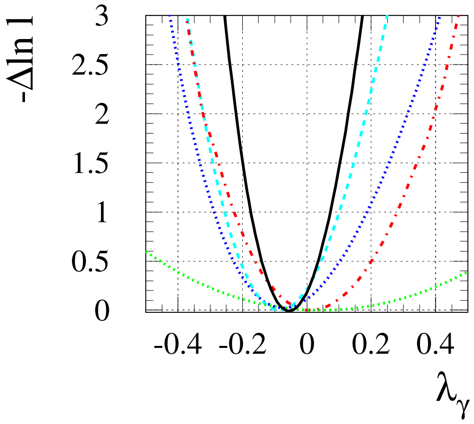
Anomalous couplings - no 1998 data yet

parameterisation now available in terms of $\Delta\kappa_\gamma$, Δg_1^Z and λ_γ

used to be
$$\begin{aligned} \alpha_{W\Phi} &= \Delta g_1^Z \cos^2\theta_W \\ \alpha_W &= \lambda_\gamma \\ \alpha_{B\Phi} &= \Delta\kappa_\gamma - \Delta g_1^Z \cos^2\theta_W \end{aligned}$$

ALEPH+ DELPHI+ L3 + OPAL





$\Delta\kappa_\gamma = 0.17 \begin{smallmatrix} +0.16 \\ -0.16 \end{smallmatrix}$

$\Delta g_1^Z = 0.00 \begin{smallmatrix} +0.08 \\ -0.08 \end{smallmatrix}$

$\lambda_\gamma = -0.05 \begin{smallmatrix} +0.08 \\ -0.09 \end{smallmatrix}$

Including D0 results:

$\Delta\kappa_\gamma = 0.13 \pm 0.14$, $\Delta g_1^Z = 0.00 \pm 0.08$, $\lambda_\gamma = -0.03 \pm 0.07$.

Note: Excludes Kaluza/Klein-type theories (5-dim spacetime), which would require $\Delta\kappa_\gamma = -3$ (L. Maiani and P.M. Zerwas in memo to LEP EWWG)

After ICHPEP98: correction to $\alpha(M_Z)$

now use our own value for $\alpha(M_Z) = \frac{\alpha(0)}{1-\Delta\alpha}$

still based on experimentally motivated value by Jegerlehner *et al.*,

but

- remove top contribution from $\alpha \Rightarrow \alpha \to \alpha^{(5)}$
  take top contribution from SM codes instead
  $(\Delta\alpha(\mathrm{Top}) \simeq -0.0000573514)$
- include three-loop leptonic contribution by Steinhauser,
  hep-ph/9803313, $(\Delta\alpha(\mathrm{lept}) = 0.031498)$
  changes $1/\alpha$ from 128.896 to 128.886

$\Rightarrow$ use $1/\alpha^{(5)}(M_Z) = 128.878 \pm 0.090$ as input to fits.

Note: no change to the error!

There was some reduction in the error driven by theory (QCD)
Davier et al., Erler, Groote et al., Kühn et al., Krasnikov et al.

Evaluations are consistent for central value, but vary by factor $\sim$**2** in the error estimates. Use as an illustration for the effects on SM fits the value by Davier *et al.*:

$$1/\alpha^{(5)}(M_Z) = 128.905 \pm 0.036$$

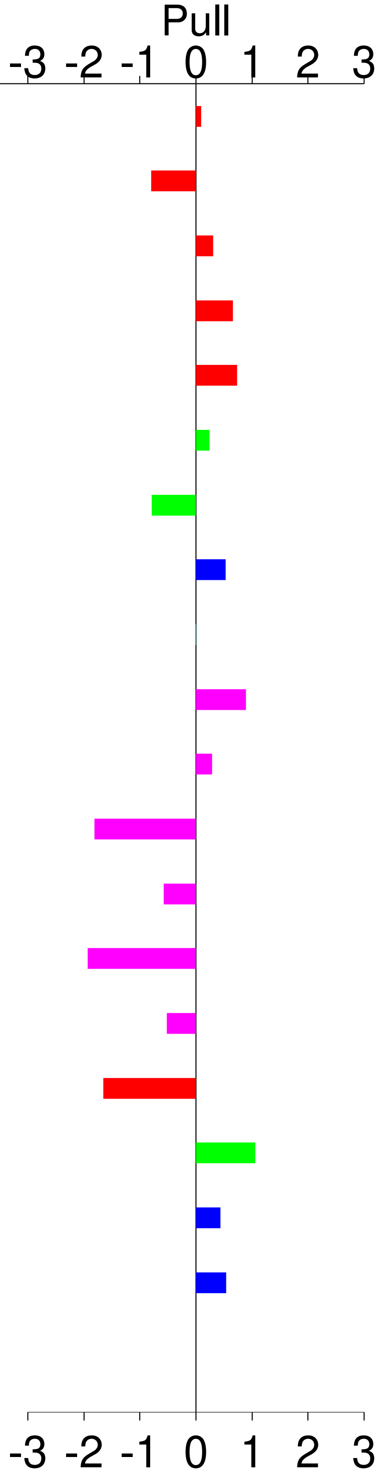
Comparison with data from one year ago

	summer 1997	summer 1998
M_Z [GeV] (LEP)	91.1867 ± 0.0020	91.1867 ± 0.0021
Γ_Z [GeV]	2.4948 ± 0.0025	2.4939 ± 0.0024
σ_h^o [nb]	41.486 ± 0.053	41.491 ± 0.058
R_ℓ	20.775 ± 0.027	20.765 ± 0.026
$A_{FB}^{0,\ell}$	0.0171 ± 0.0010	0.01683 ± 0.00096
$\mathcal{A}_e$	0.1399 ± 0.0073	0.1479 ± 0.0051
$\mathcal{A}_\tau$	0.1411 ± 0.0064	0.1431 ± 0.0044
R_b (LEP+SLC)	0.2170 ± 0.0009	0.21656 ± 0.00074
R_c (LEP+SLC)	0.1734 ± 0.0048	0.1735 ± 0.0044
$A_{FB}^{0,b}$	0.0984 ± 0.0024	0.0990 ± 0.0021
$A_{FB}^{0,c}$	0.0741 ± 0.0048	0.0709 ± 0.0044
$\sin^2\theta_{eff}^{lept}$ fr. $Q_{FB}(q\bar{q})$	0.2322 ± 0.0010	0.2321 ± 0.0010
M_W [GeV]	80.48 ± 0.14	80.37 ± 0.09
$\sin^2\theta_{eff}^{lept}$ fr. $\mathcal{A}_{lr}$ (SLC)	0.23055 ± 0.00041	0.23109 ± 0.00029
$\mathcal{A}_b$	0.900 ± 0.050	0.867 ± 0.035
$\mathcal{A}_c$	0.650 ± 0.058	0.647 ± 0.040
M_W [GeV] (CDF/D0)	80.41 ± 0.09	80.41 ± 0.09
M_t [GeV]	175.6 ± 5.5	173.8 ± 5.0
$1 - M_W^2/M_Z^2(\nu N)$	0.2254 ± 0.0037	0.2255 ± 0.0021
$1/\alpha(M_Z)$	$1/\alpha=128.896 \pm 0.090$	$1/\alpha^{(5)}=128.878 \pm 0.090$ (=128.905 ±0.036)

Overview of precision measurements vs. SM

Vancouver 1998

	Measurement	Pull
m_Z [GeV]	91.1867 ± 0.0021	.09
Γ_Z [GeV]	2.4939 ± 0.0024	-.80
σ^0_{hadr} [nb]	41.491 ± 0.058	.31
R_e	20.765 ± 0.026	.66
$A^{0,e}_{fb}$	0.01683 ± 0.00096	.73
A_e	0.1479 ± 0.0051	.25
A_τ	0.1431 ± 0.0045	-.79
$\sin^2\theta^{lept}_{eff}$	0.2321 ± 0.0010	.53
m_W [GeV]	80.37 ± 0.09	-.01
R_b	0.21656 ± 0.00074	.90
R_c	0.1735 ± 0.0044	.29
$A^{0,b}_{fb}$	0.0990 ± 0.0021	-1.81
$A^{0,c}_{fb}$	0.0709 ± 0.0044	-.58
A_b	0.867 ± 0.035	-1.93
A_c	0.647 ± 0.040	-.52
$\sin^2\theta^{lept}_{eff}$	0.23109 ± 0.00029	-1.65
$\sin^2\theta_W$	0.2255 ± 0.0021	1.06
m_W [GeV]	80.41 ± 0.09	.43
m_t [GeV]	173.8 ± 5.0	.54
$1/\alpha^{(5)}(m_Z)$	128.878 ± 0.090	.00



(Pull is from full SM fit, see later)

Standard Model fits

LEP only

fit with ZFITTER 5.12

$\chi^2/N_{df} = 4.1/9$, prob.=90%

M_t [GeV]	$160\ ^{+13}_{-9}$
M_H [GeV]	$60\ ^{+130}_{-35}$
α_s	0.1205 ± 0.0029
derived:	
$\sin^2\theta^{lept}_{eff}$	0.23182 ± 0.00023
M_W [GeV]	80.31 ± 0.04

All data

fit with ZFITTER 5.12

$\chi^2/N_{df} = 14.9/15$, **prob.=46%**

M_t [GeV]	$171.1\ \pm 4.9$
M_H [GeV]	$76\ ^{+85}_{-47}$
α_s	0.1194 ± 0.0029
derived:	
$\sin^2\theta^{lept}_{eff}$	0.23157 ± 0.00019
M_W [GeV]	80.371 ± 0.027

Strong coupling constant

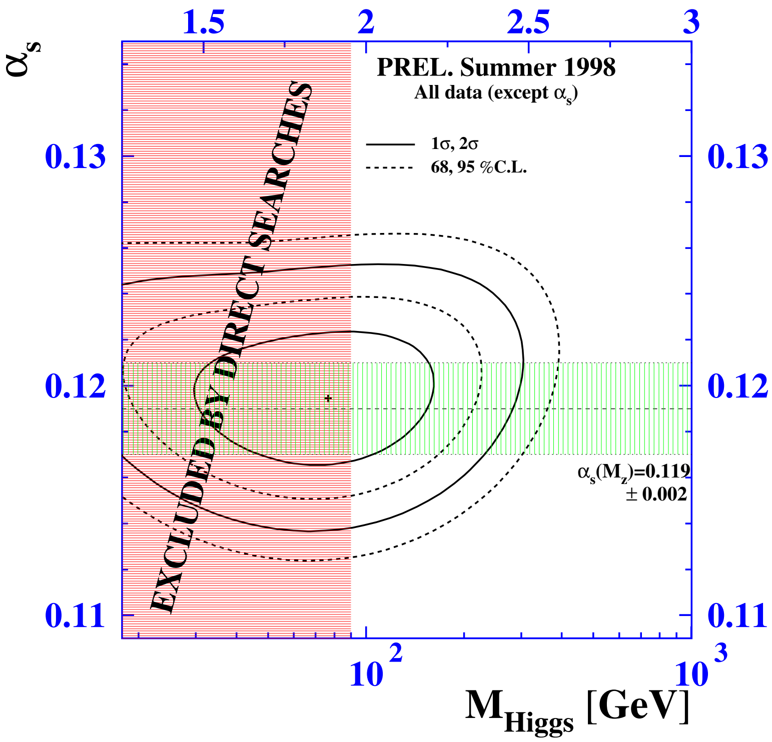
Information on α_s comes exclusively from LEP *i.e.*

R_ℓ, Γ_Z and σ_h^o (+ correlations!)

α_s from R_ℓ only
$\alpha_s = 0.124 \pm 0.004 \pm 0.002_{(M_H)}$
for $M_H = 300^{+700}_{-210}$ GeV
α_s from full SM fit
$\alpha_s = 0.1194 \pm 0.0029$

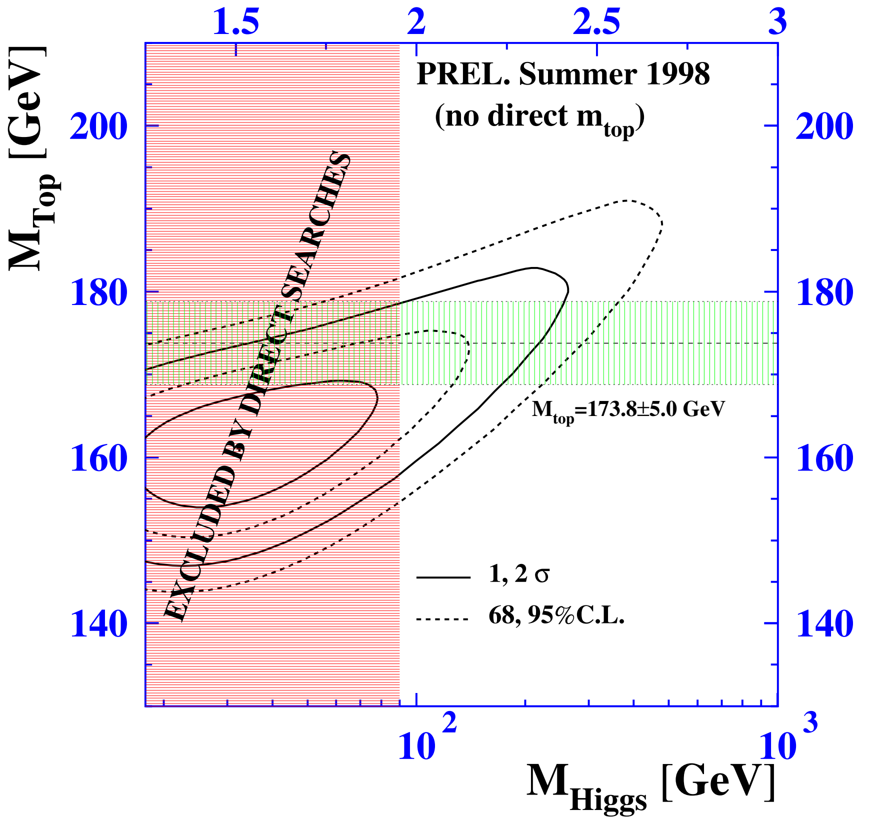
note that a syst. QCD error of $\sim$0.002 still has to be added

this value agrees well with present world average from PDG! $\surd$



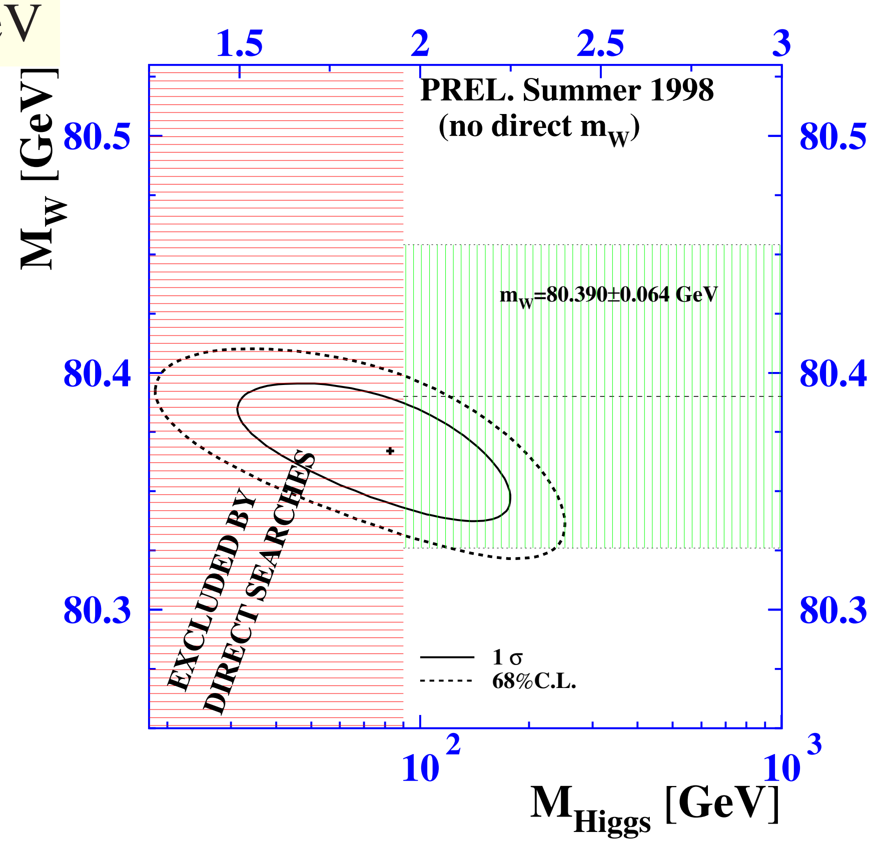
Indirect M_t Use **all** precision data except direct M_t

$M_t = 161^{+8}_{-7}$ GeV



Indirect M_W all precision data except direct M_W

$M_W = 83.367 \pm 0.029$ GeV



The Higgs boson

New theoretical calulations incorporated for Moriond '98:

– Four loop QCD effects

Larin et al., PLB 400(1997) 379, PLB405 (1997) 327, Chetyrkin et al., PRL79 (1997) 2184, hep-ph-9708255

– Nonfactorizable QCD/EW effects

Czarnecki et al. PRL77 (1996) 3955, Harlander et al. PLB426(1998) 125

– Two-loop sub-leading corrections $O(\alpha^2 M_t^2/M_W^2)$

Degrassi et al., PLB383 (1996) 219, PLB394 (1997) 188, PLB418 (1998) 209

Now: also have evaluation of theoretical errors

compared different running options in SM calculations as implemented in

– ZFITTER vers. 5.12

– TOPAZ0 vers. 4.1

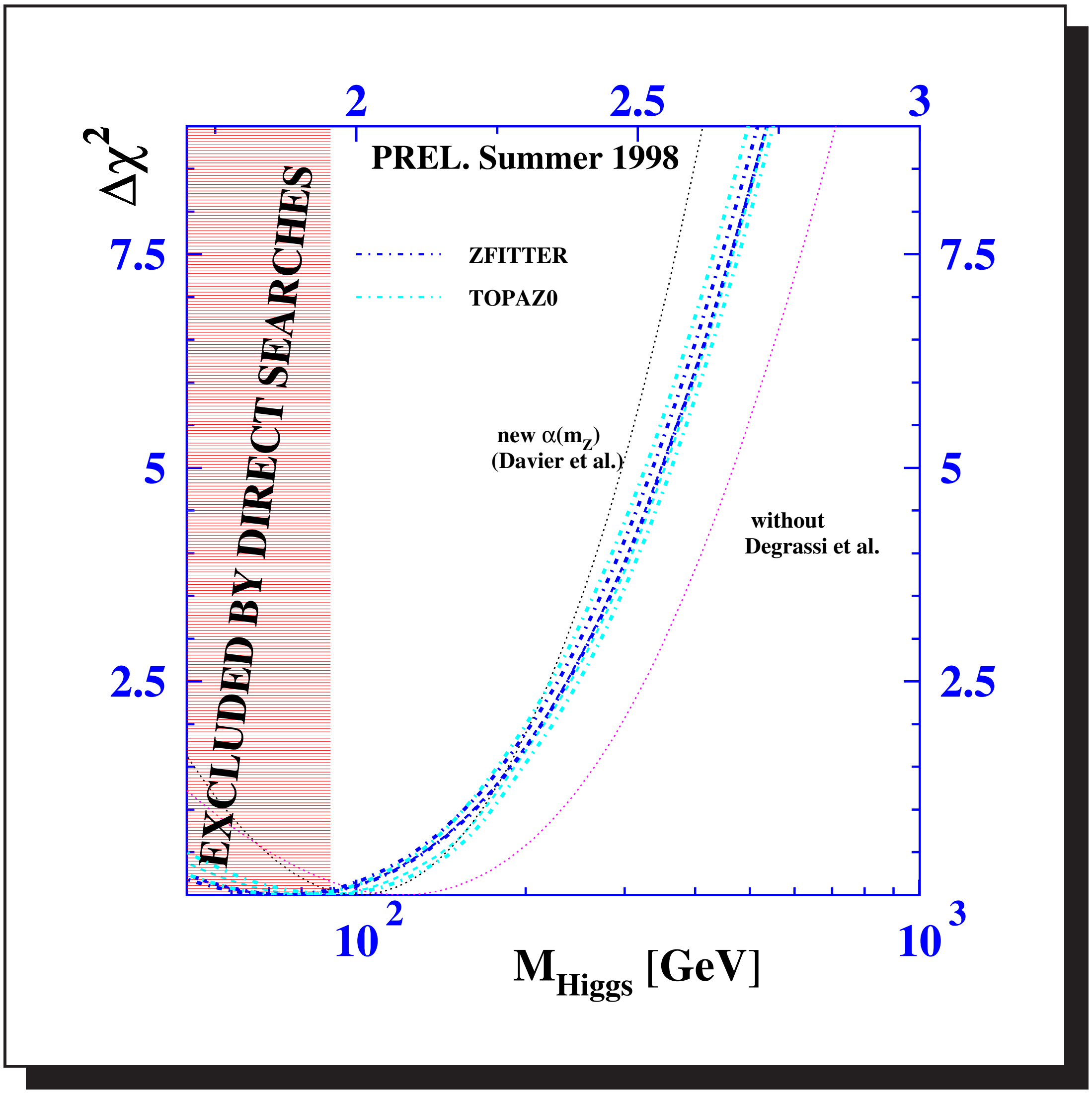
many thanks to: D. Bardin, G. Passarino

$\Rightarrow$ error on $\log_{10}(M_H[\mathrm{GeV}])$ $\sim \pm 0.05$

$\sim$half of what it was last summer

$$\log_{10}(M_H[\mathrm{GeV}]) = 1.88^{+0.33}_{-0.41} \pm 0.05$$

$$M_H = 76\,^{+85}_{-47} \pm 10\ \mathrm{GeV}$$



limit on Higgs mass:

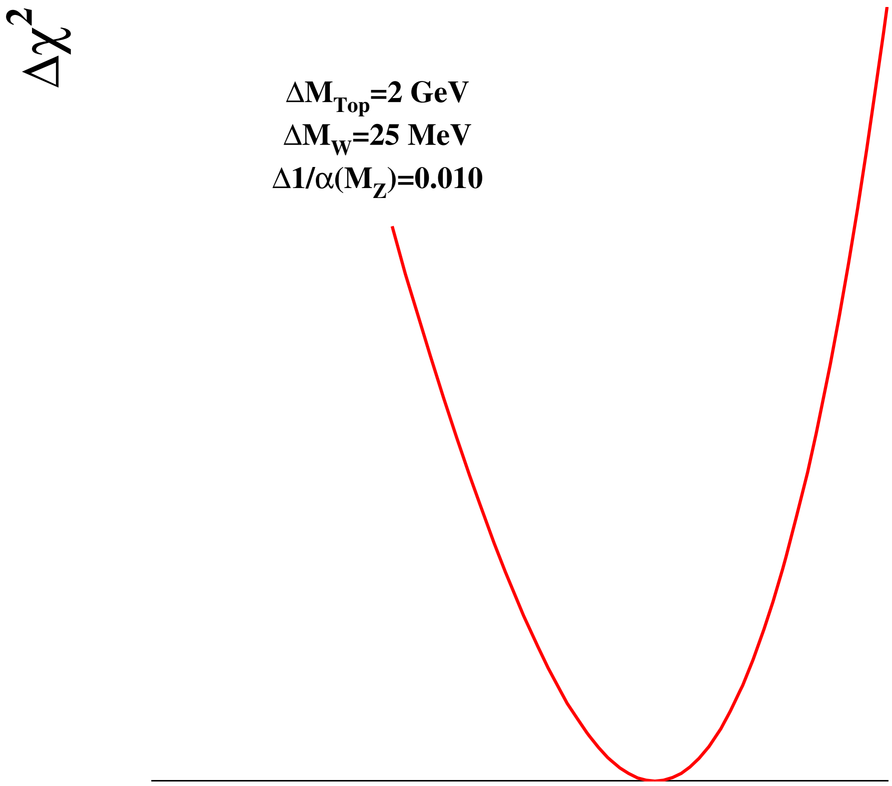
take 1.64 σ from minimum of most pessimistic blue curve $\Rightarrow$

$$M_\mathrm{H} < 260\,\mathrm{GeV} \;\; @ \;\; 95\% \text{ C.L.}$$

Notes:

- most significant changes in M_H from theoretical improvements
- further improvement from $\alpha(M_Z)$, at present also theory driven
  experimental confimation from measurements of σ_had at $\sqrt{s} = 1 \rightarrow 7$ GeV possible

The ultimate dream ...



Conclusions

- complete LEP I data set analysed, many results still preliminary
- reduced discrepancy in measurements of $\sin^2\theta_{eff}$, χ^2prob. 25 % now
- much improvement to SM codes (TOPAZ0 and ZFITTER); incorporate the most recent theoretical results

Standard Model is in better shape than ever!

Future Plans

- annual EP note based on summer 98 results
- after publications of LEP experiments, perform and publish combination of **final** LEP I LS and Afb results
- continue as usual ...