Electroweak Precision Data
Global Higgs Analysis

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Outline

Overview on precision measurements

Tests of the electroweak Standard Model

Caveat: Low Higgs Masses

Conclusions

Thanks to the members of the LEPEWWG and the CDF, D∅, SLD, OPAL, L3, DELPHI, ALEPH and NuTeV experiments!

Visit http://www.cern.ch/LEPEWWG

Electroweak Precision Data

More than 1000 measurements with (correlated) uncertainties:

Reduced to 20 precision pseudo-observables:

Z-pole (SLD, LEP-1):

5 Z lineshape and leptonic forward-backward asymmetries

2 Polarised lepton asymmtries P_τ, $A_{LR(FB)}$

6 Heavy flavour results (b,c)

1 Hadronic charge asymmetry

Other:

2 W mass and width (Tevatron, LEP-2) (New LEP-2 M_W)

1 Top-quark mass (Tevatron)

1 Neutrino-nucleon scattering (NuTeV)

1 Atomic parity violation (Caesium) (New corrections)

1 Hadronic vacuum polarisation (Z-pole / g-2?)

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20 plus "constants" such as the Fermi constant G_F

Atomic Parity Violation

Electron-nucleus interaction:

Parity-violating t-channel contribution due to γ/Z interference

Weak charge Q_W of the nucleus (Z protons, N neutrons)

$$Q_W(Z,N) = -2\,[\,(2Z+N)C_{1u} + (Z+2N)C_{1d}\,]$$

with $C_{1q} = 2g_{Ae}g_{Vq}$ at $Q^2 \to 0$ (q=u,d)

Most precise measurement for Caesium (Z=55, N=78)

Progress in theoretical corrections applied to measurements:

QED self-energy and vertex radiative corrections $Z\alpha^2$ and $Z^2\alpha^3$

hep-ph/0204134, 0206124, 0208196, 0208227

$Q_W(Cs) = -72.18 \pm 0.29$ (exp.) ± 0.36 (theo.)

$\to -72.83 \pm 0.29$ (exp.) ± 0.39 (theo.)

Now perfect agreement with SM expectation!

NuTeV Neutrino-Nucleon Scattering

Muon-(anti-)neutrino quark scattering:

charged current (CC) neutral current (NC)

Paschos-Wolfenstein relation (iso-scalar target):

$$R_{-} = \frac{\sigma_{NC}(\nu) - \sigma_{NC}(\bar{\nu})}{\sigma_{CC}(\nu) - \sigma_{CC}(\bar{\nu})} = 4g_{L\nu}^2 \sum_{q_\nu} \left[g_{Lq}^2 - g_{Rq}^2 \right] = \rho_\nu \rho_{ud} \left[\frac{1}{2} - \sin^2\theta_W^{(on-shell)} \right]$$

+ electroweak radiative corrections

Effective couplings: g_L, g_R at $\langle Q^2 \rangle \sim 20$ GeV^2

Historically result quoted in terms of: $\sin^2\Theta_W = 1-(M_W/M_Z)^2$

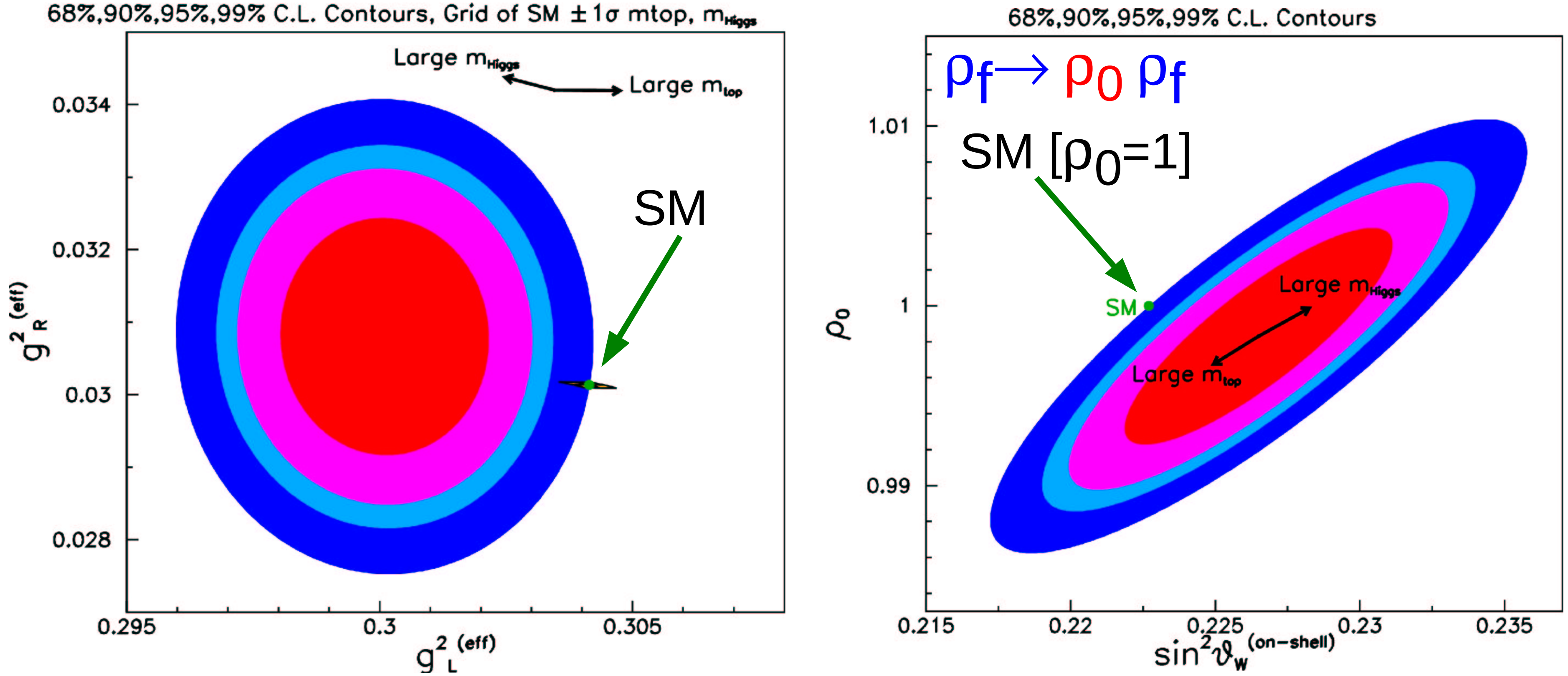
Factor two more precise than previous νN world average

NuTeV's Result

$$\sin^2\theta_W^{(on-shell)} = 1 - \frac{M_W^2}{M_Z^2} = 0.2277 \pm 0.0013(stat.) \pm 0.0009(syst.)$$

$$-\ 0.00022\frac{M_{top}^2 - (175\,GeV)^2}{(50\,GeV)^2} + 0.00032\ln\frac{M_{Higgs}}{150\,GeV} \qquad [\rho = \rho_{SM}]$$

Global SM analysis predicts: 0.2229(4) Difference of 2.9 σ!



Quote result in terms of effective couplings, not $\sin^2\Theta_W$ nor M_W!

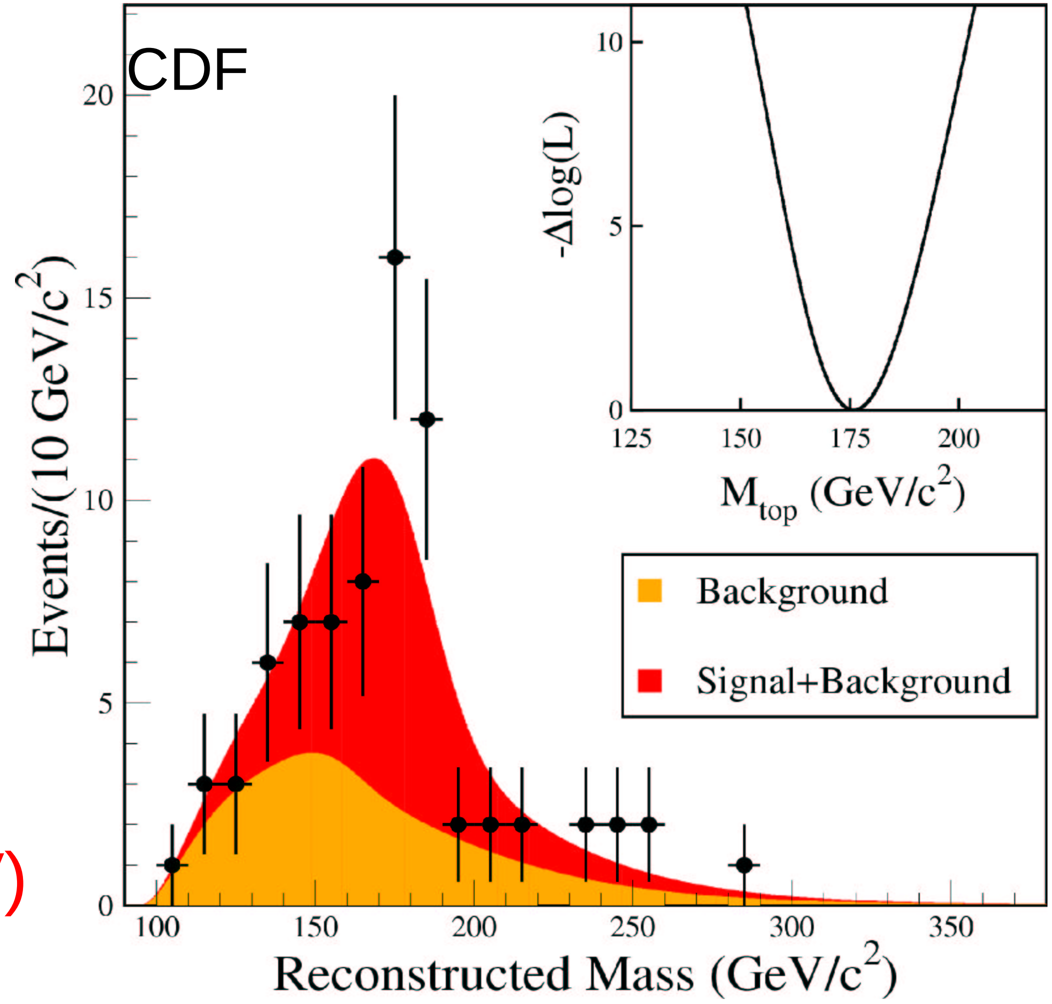
Mass of the Top Quark

Tevatron (CDF, D∅):

$p\bar{p} \rightarrow t\bar{t}X, \; t\bar{t} \rightarrow b\bar{b}WW$

No results from Run-II yet

Final Run-I results in RPP



Systematic uncertainties dominated by:

- Jet energy scale (2-5 GeV)
  - will reduce with more data
- Signal model (2-3 GeV)
- Background model (~2 GeV)
- MEs, PDFs, MC generators

Run-I result: M_{top} = 174.3 ± 3.2 (stat.) ± 4.0 (syst.) GeV

Run-II expectation: δM_{top} < 2.5 GeV

W Boson - Mass and Width

Tevatron (CDF, DØ):

$p\bar{p} \rightarrow WX$, $W \rightarrow e\nu, \mu\nu$

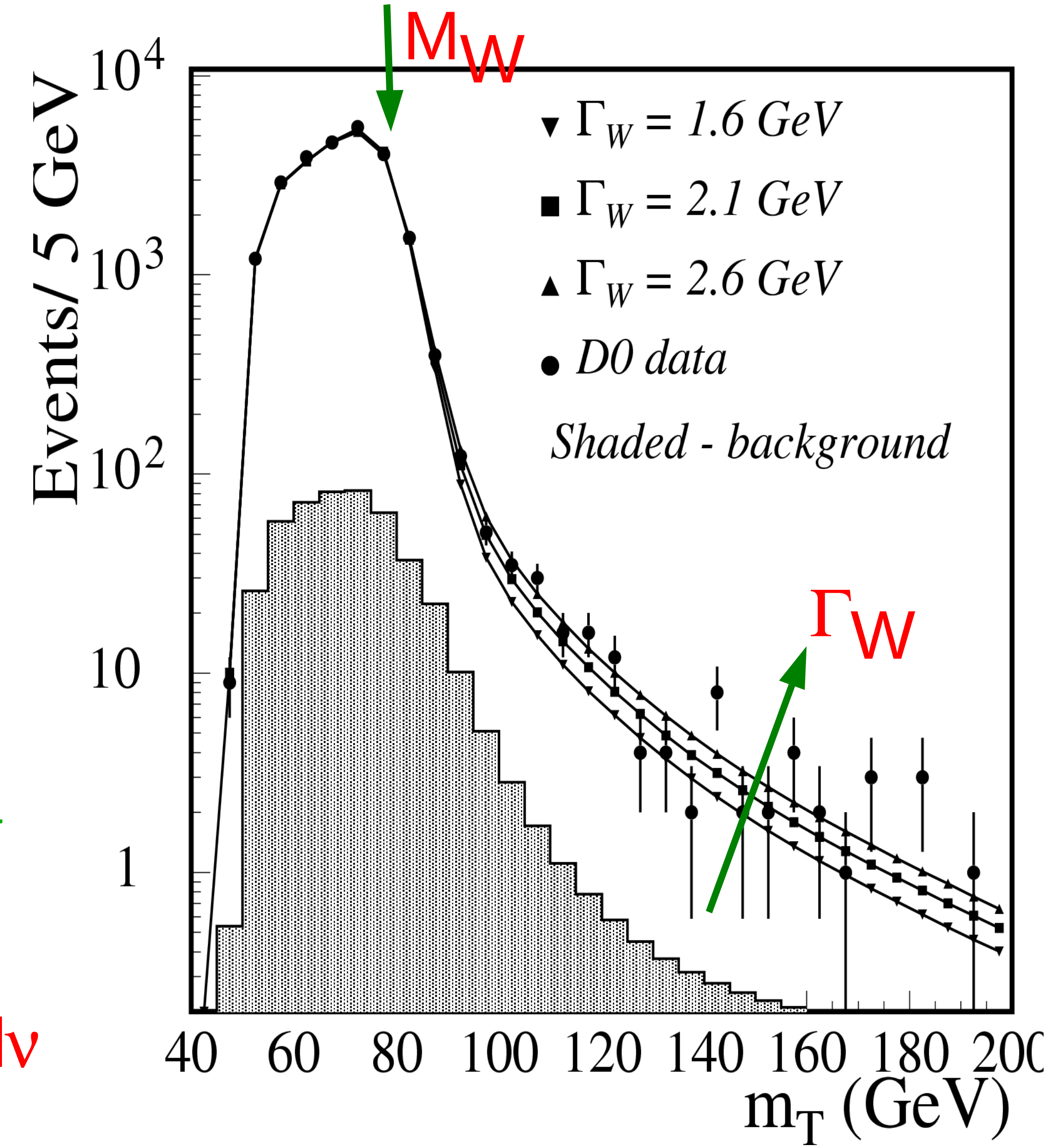
Transverse mass M_T

No results from Run-II yet

Final Run-I results

Uncertainties dominated by:

- Statistics
- Lepton energy scale
  - will reduce with more data
- Then: Signal model
  - PDFs, gluon radiation
  - QED corrections in $W \rightarrow l\nu$



Run-II expectation: $\delta M_W < 25$ MeV

W Boson - Mass and Width

LEP-2: $e^+e^- \rightarrow W^+W^-$

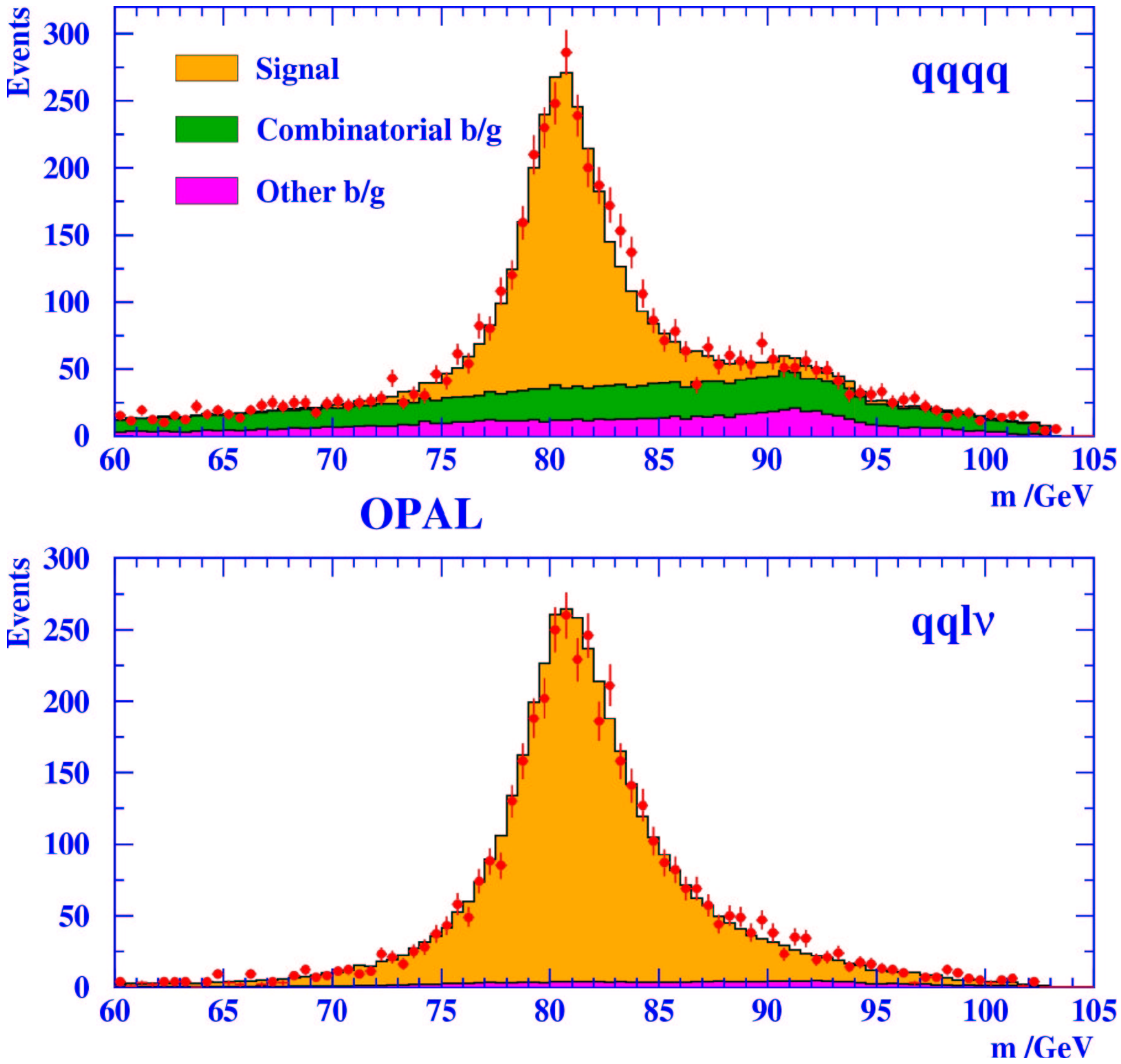
$\rightarrow$ qqqq, qqlν, lνlν

Invariant mass M_{inv}

Preliminary results

Currently large FSI systematics (BE,CR) in the qqqq channel:

Average dominated by $M_W(qql\nu)$



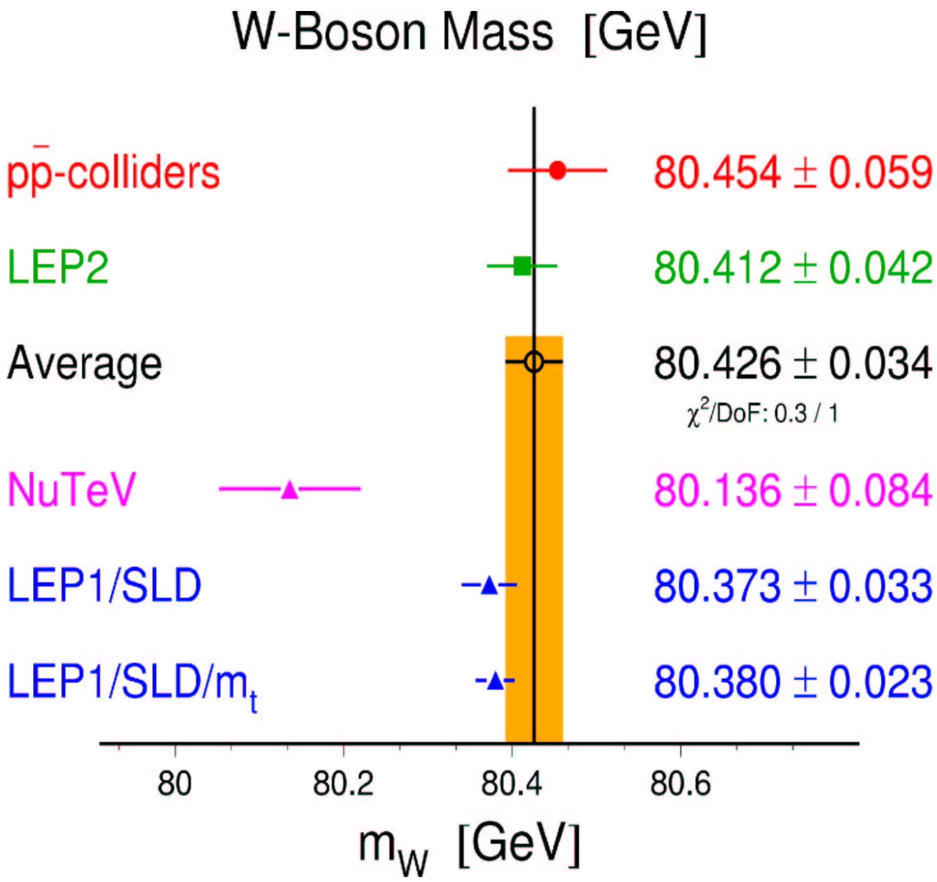
Mass difference (calculated without FSI errors):

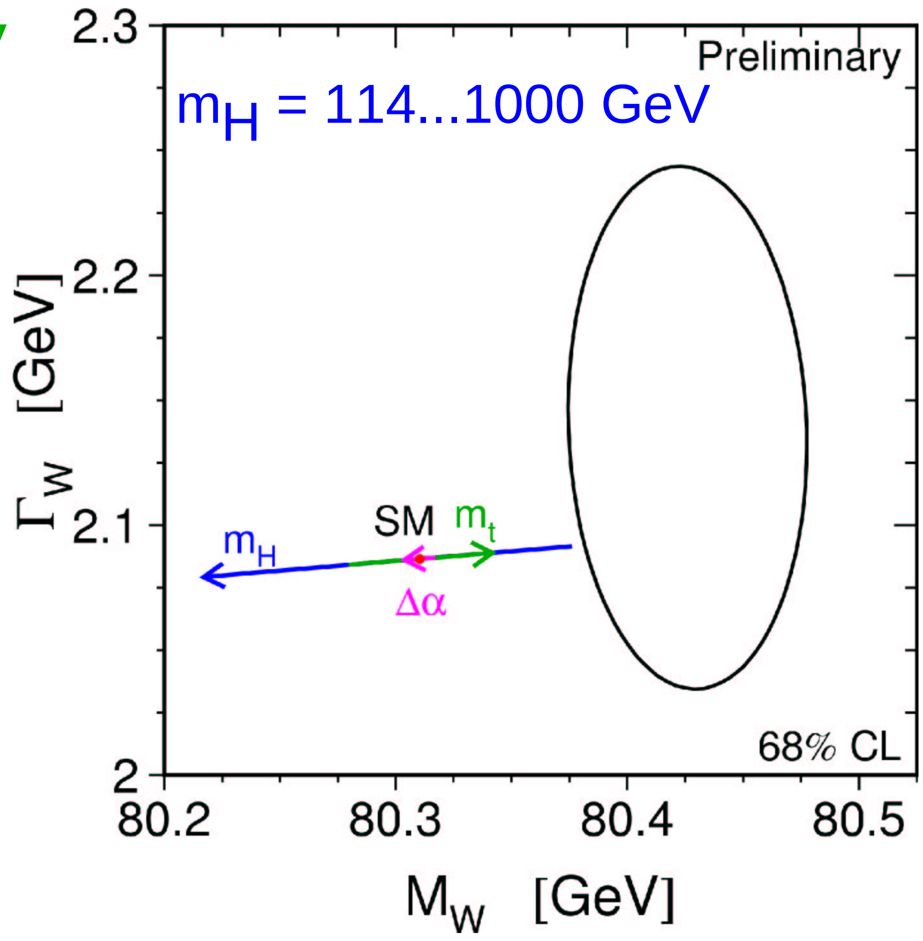
$M_W(qqqq) - M_W(qql\nu) = 22 \pm 43$ MeV

W Boson - Mass and Width

Very good agreement between the experiments

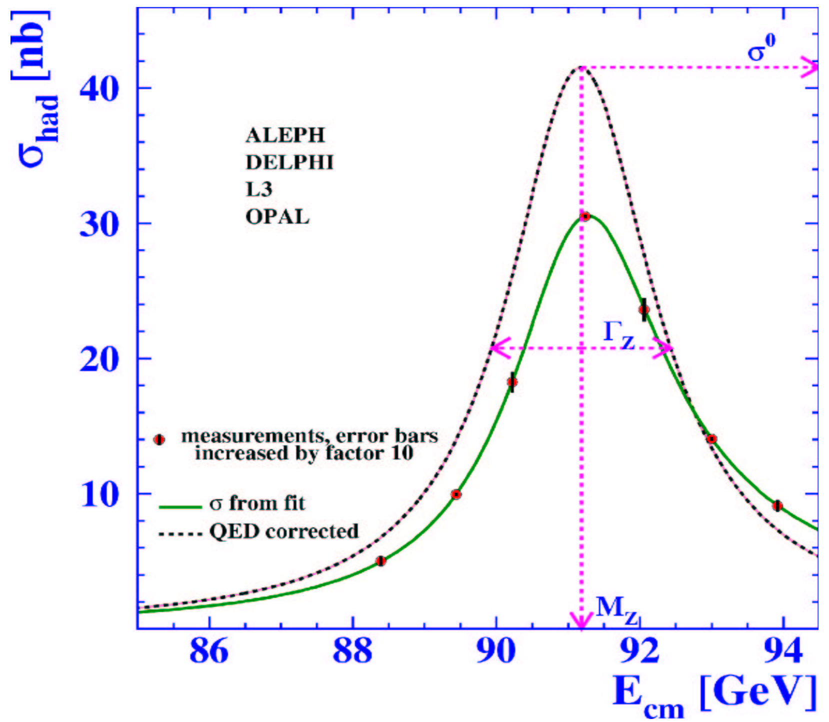
M_W (LEP-2) reduced by 35 MeV

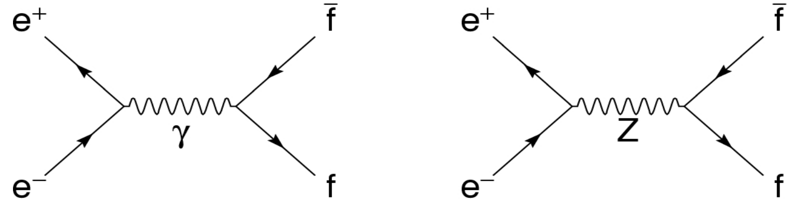


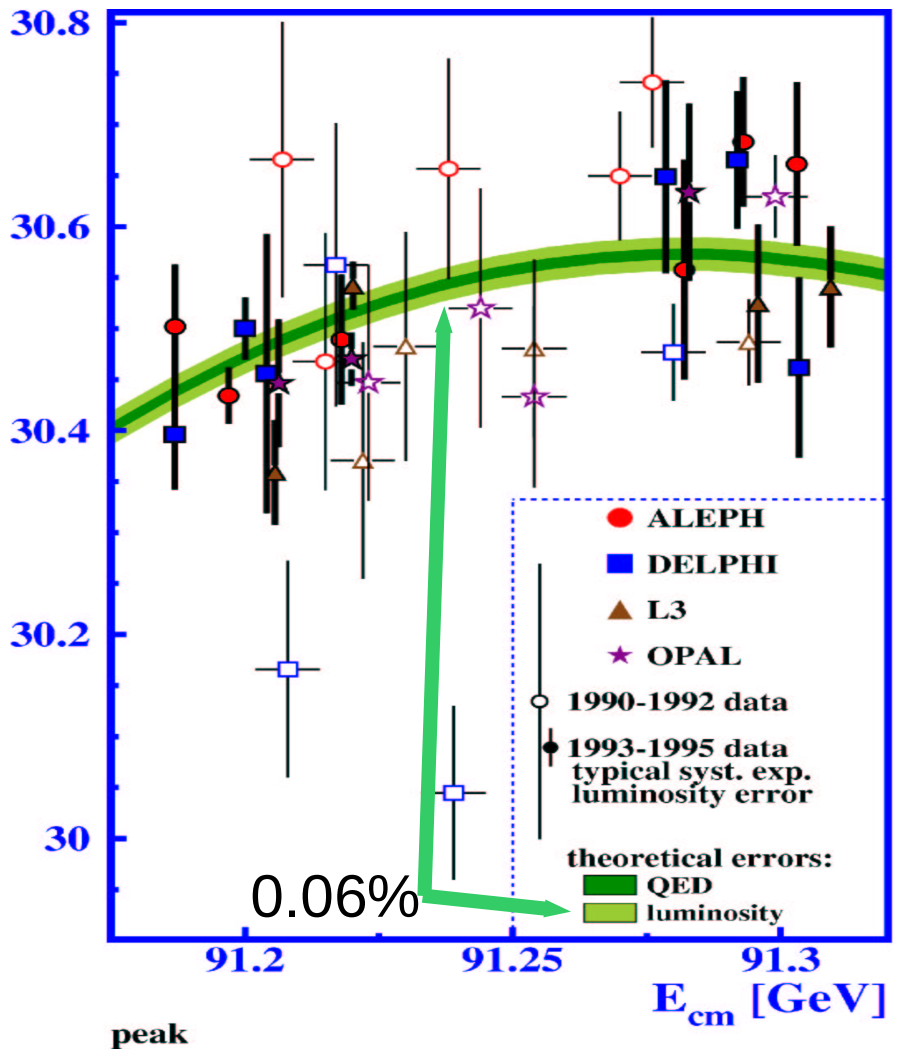


SM comparison:
Small Higgs-boson mass

Z Lineshape and Leptonic F/B Asymmetries







χ^2/dof:

ALEPH:	169 / 176
DELPHI:	177 / 168
L3:	158 / 166
OPAL:	155 / 194
LEP:	36.5 / 31 (23%)

Z Lineshape and Leptonic F/B Asymmetries

Final LEP-1 results: hep-ex/0101027

M_Z = 91.1875 (21) GeV

Γ_Z = 2.4952 (23) GeV

LEP beam energy:

1.7 MeV on mass

1.2 MeV on width

N_ν = 2.9841 (83)

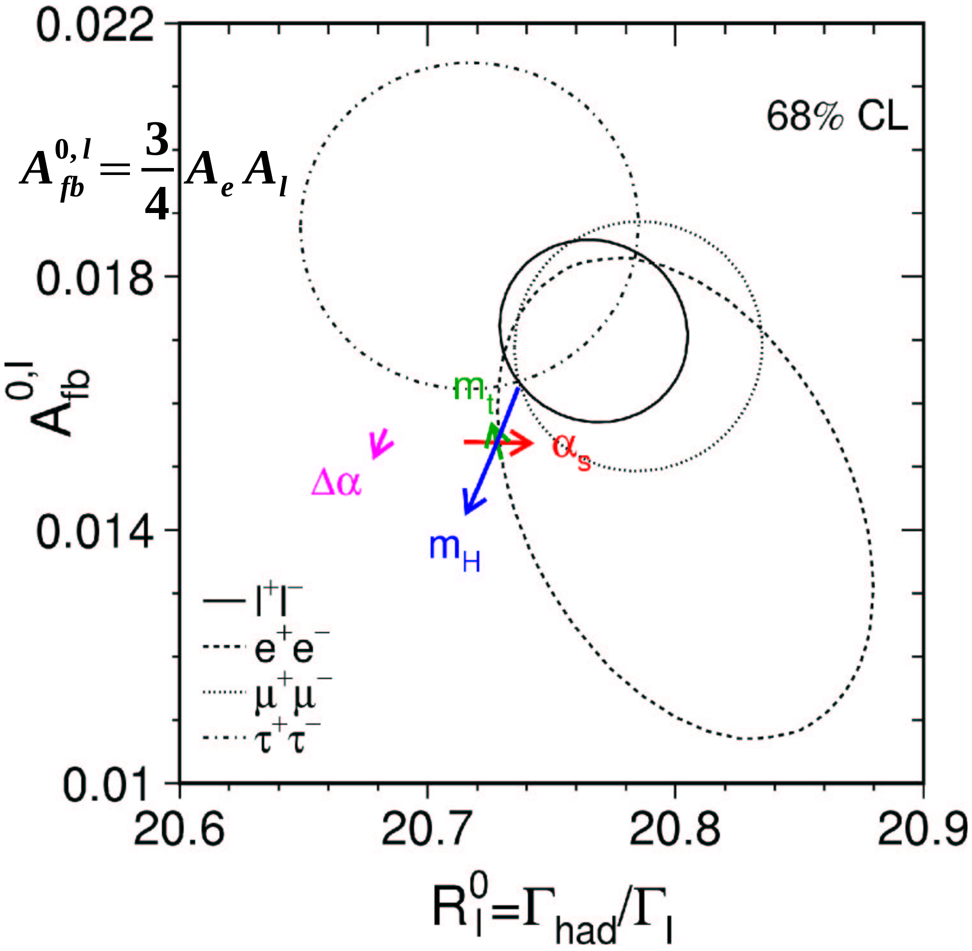
$$\delta N_\nu = 10.5 \frac{\delta N_{had}}{N_{had}} \oplus 3.0 \frac{\delta N_{lep}}{N_{lep}} \oplus 7.5 \frac{\delta L}{L}$$

Luminosity: ±0.0046 on N_ν

Lepton universality:

R_l = 20.767 (25)

$A_{fb}(l)$ = 0.0171 (10)



MSM prediction shown for:

$\alpha_s = 0.118 \pm 0.002$ $\Delta\alpha_{had} = 0.02761 \pm 0.0036$

$M_{top} = 174.3 \pm 5.1\, GeV$ $M_{Higgs} = 114...1000\, GeV$

Low Higgs mass preferred!

Polarised Lepton Asymmetries

Asymmetry parameter:

$$A_f = 2\frac{g_{Vf}/g_{Af}}{1+\left(g_{Vf}/g_{Af}\right)^2}$$

LEP-1:

Leptonic f/b asymmetry

$A_l = 0.1512\ (42)$

Final state τ polarisation

$A_l = 0.1465\ (33)$

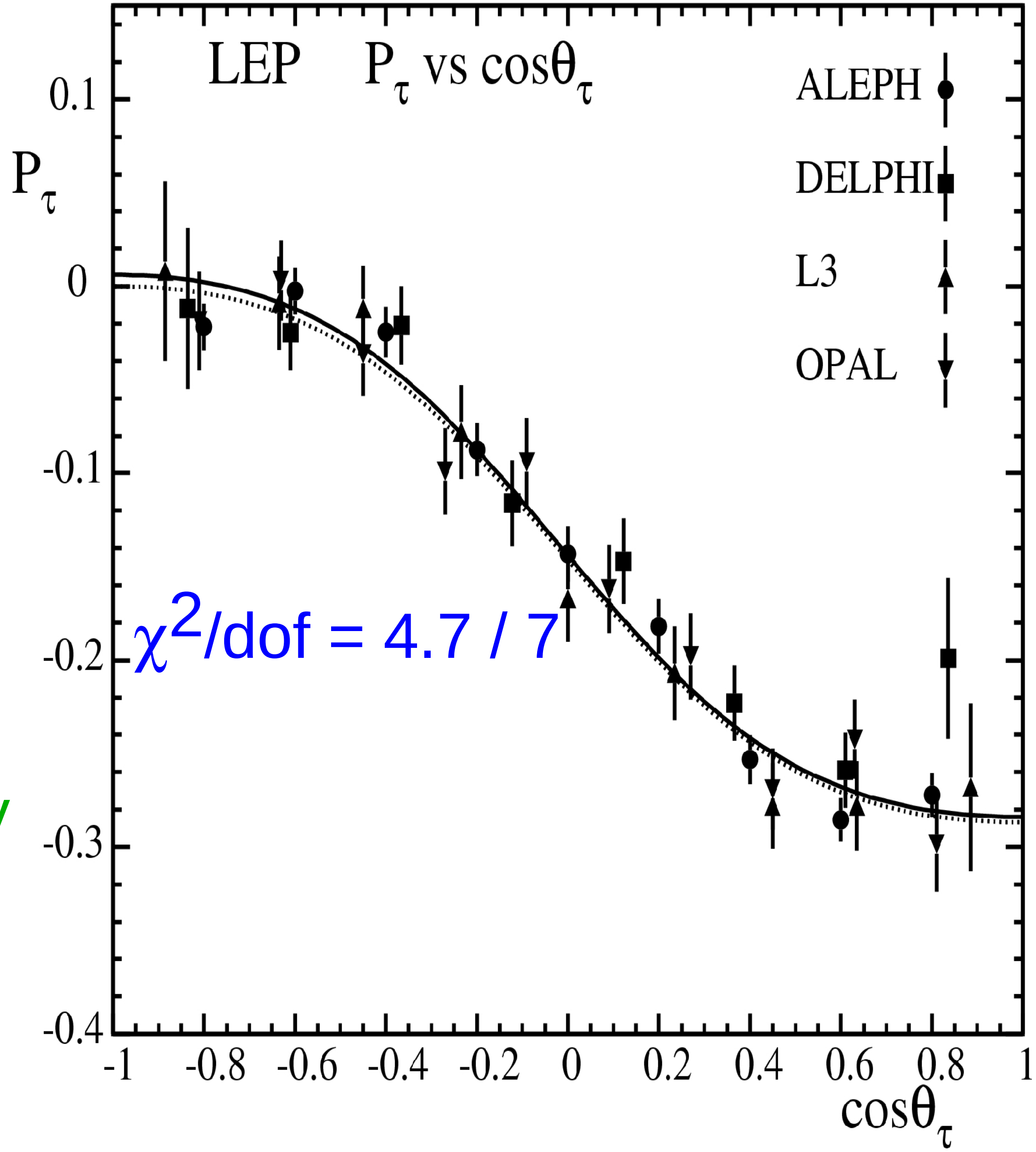
SLD:

Left/right (f/b) asymmetry

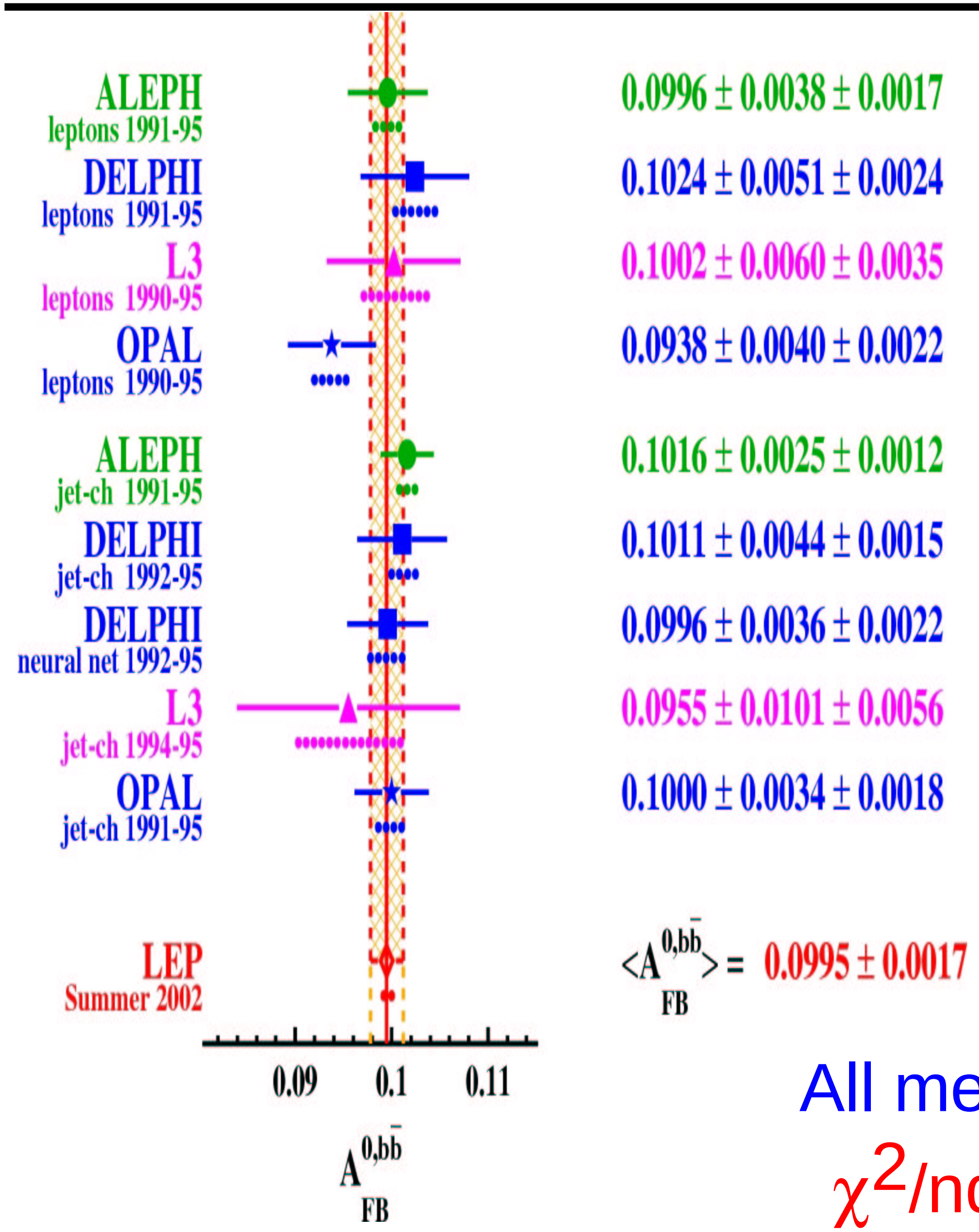
$A_l = 0.1513\ (21)$

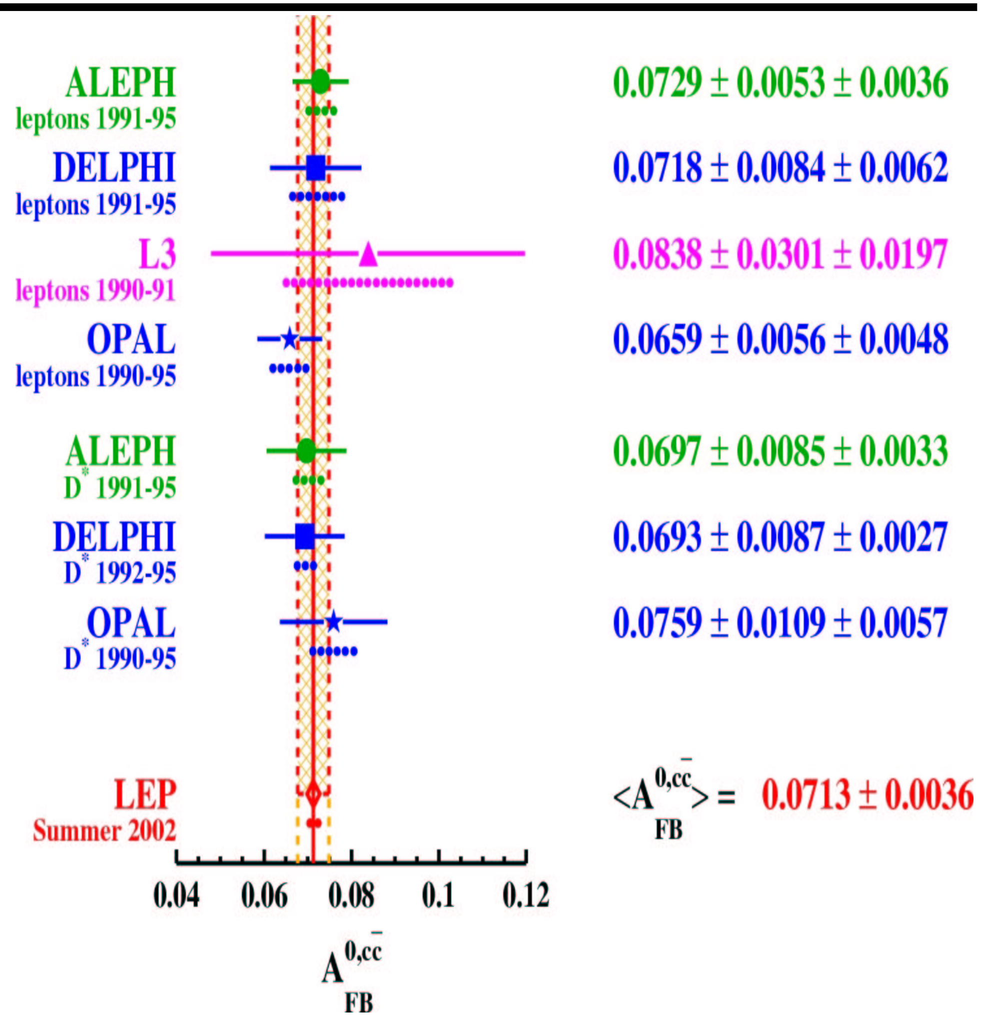
Final SLD+LEP-1 result:

$A_l = 0.1501\ (16)$



Heavy Flavour Results at the Z Pole



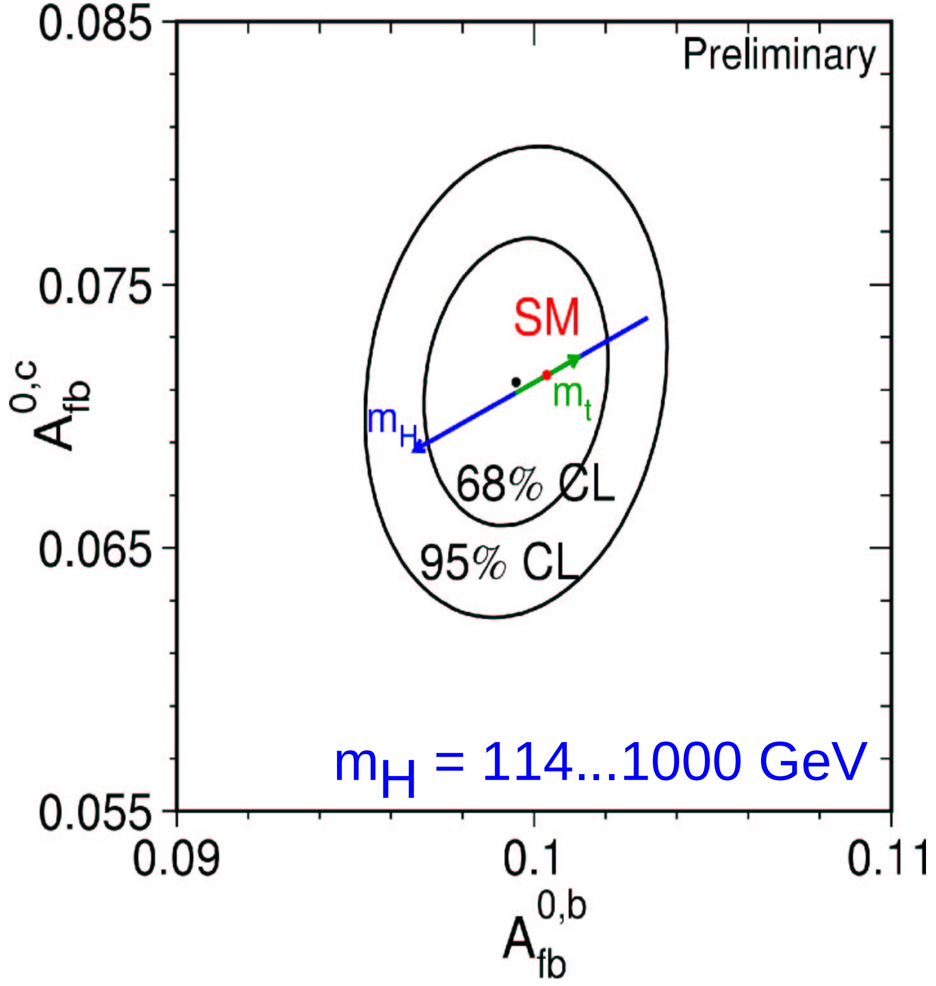


All measurements very consistent:

χ^2/ndof = 47.6/(105-14) low!

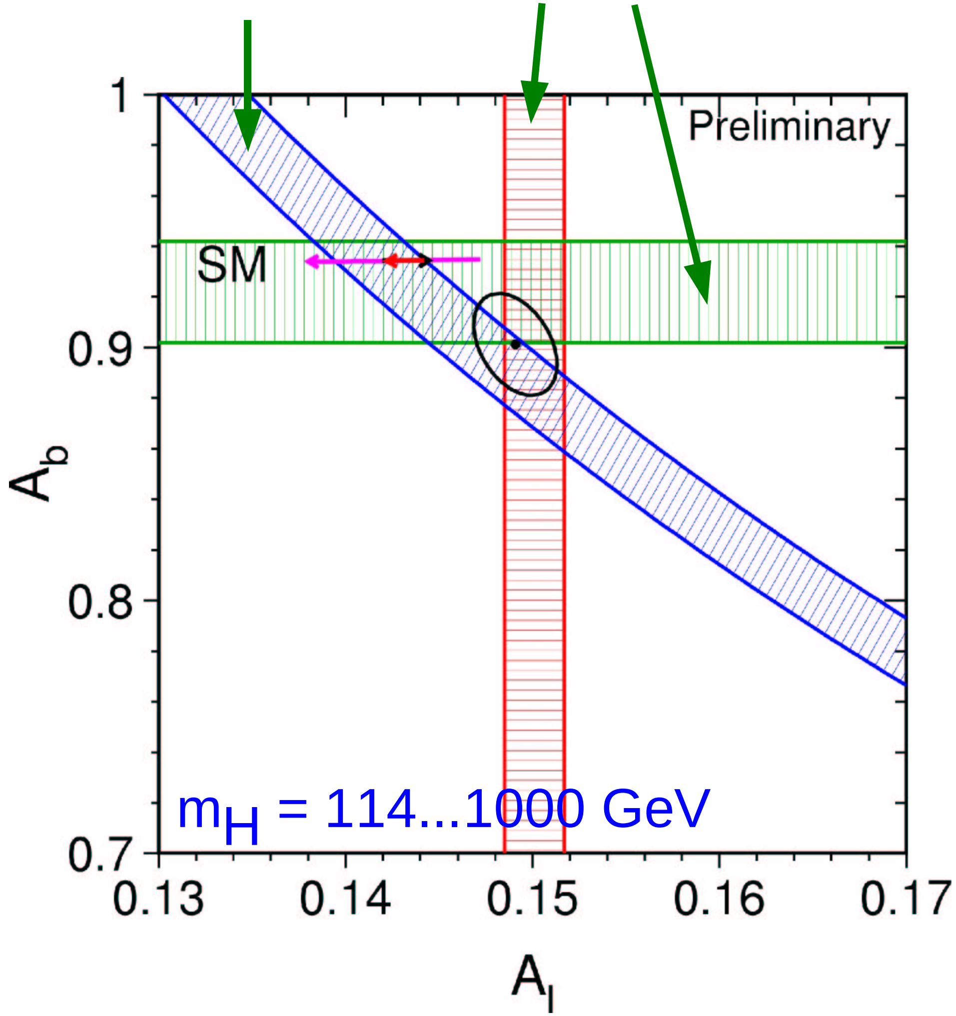
F/B asymmetries statistics dominated

Heavy Flavour Results at the Z Pole



Compare with leptons:

$A_{fb}(b) = \frac{3}{4} A_e A_b$



SM comparison:

Higher Higgs-boson mass

Comparison of all Z-Pole Asymmetries

Effective electroweak mixing angle:

$\sin^2\Theta_{eff} = 0.23148\ (17)$

$\chi^2/ndof = 10.2/5\ \ [7.0\%]$

A-posteriori observation:

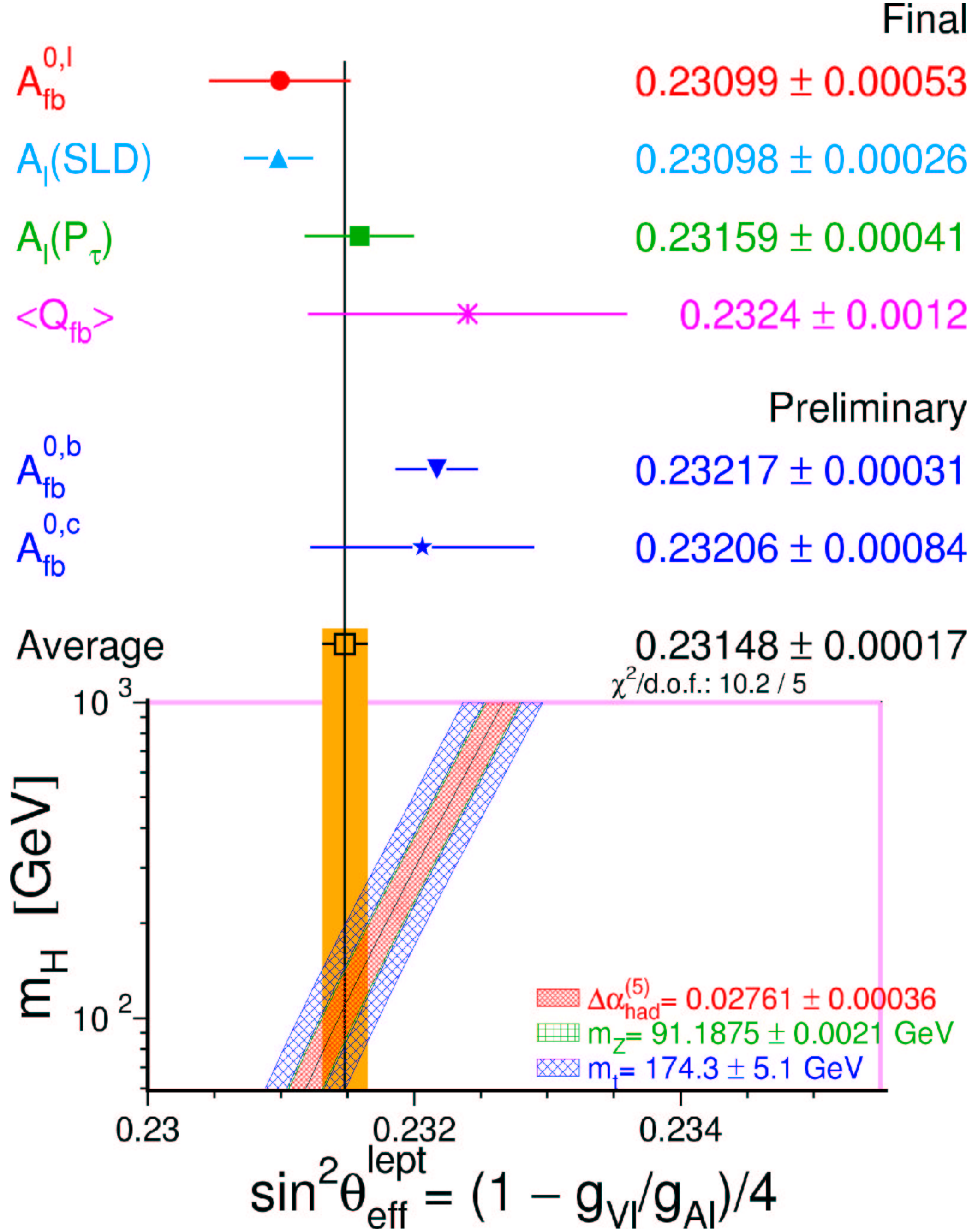
0.23113 (21) leptons

0.23217 (29) hadrons

But is really:

$A_l(SLD)$ vs. $A_{fb}b(LEP)$

Both: 2.9 σ difference



Global Standard-Model Analysis

SM: Each observable calculated as a function of:

$\Delta\alpha_{had}$, $\alpha_s(M_Z)$, M_Z, M_{top}, M_{Higgs} (and G_F)

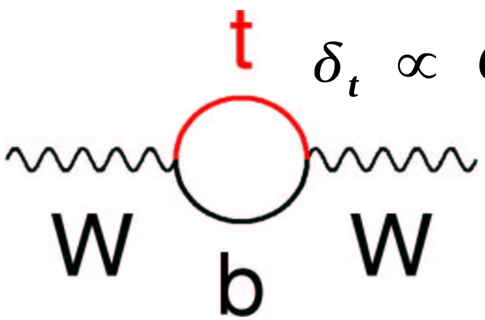
$\Delta\alpha_{had}$: hadronic vacuum polarisation [0.02761(36)]

$\alpha_s(M_Z)$: given by Γ_{had} and related observables

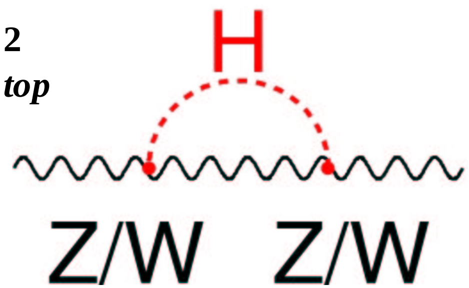
M_Z: constrained by LEP-1 lineshape

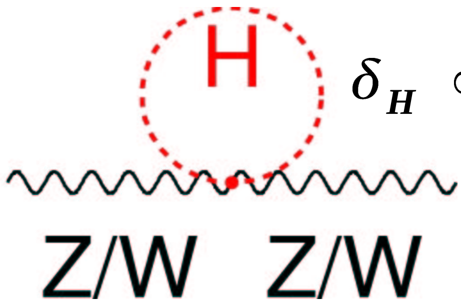
Precision requires 1st and 2nd order electroweak and mixed radiative correction calculations (QED to 3rd)

M_{top}, M_{Higgs} enter through electroweak corrections!



$\delta_t \propto G_F M_{top}^2$





$\delta_H \propto \ln \frac{M_{Higgs}}{M_W}$

Calculations by programs TOPAZ0 and ZFITTER

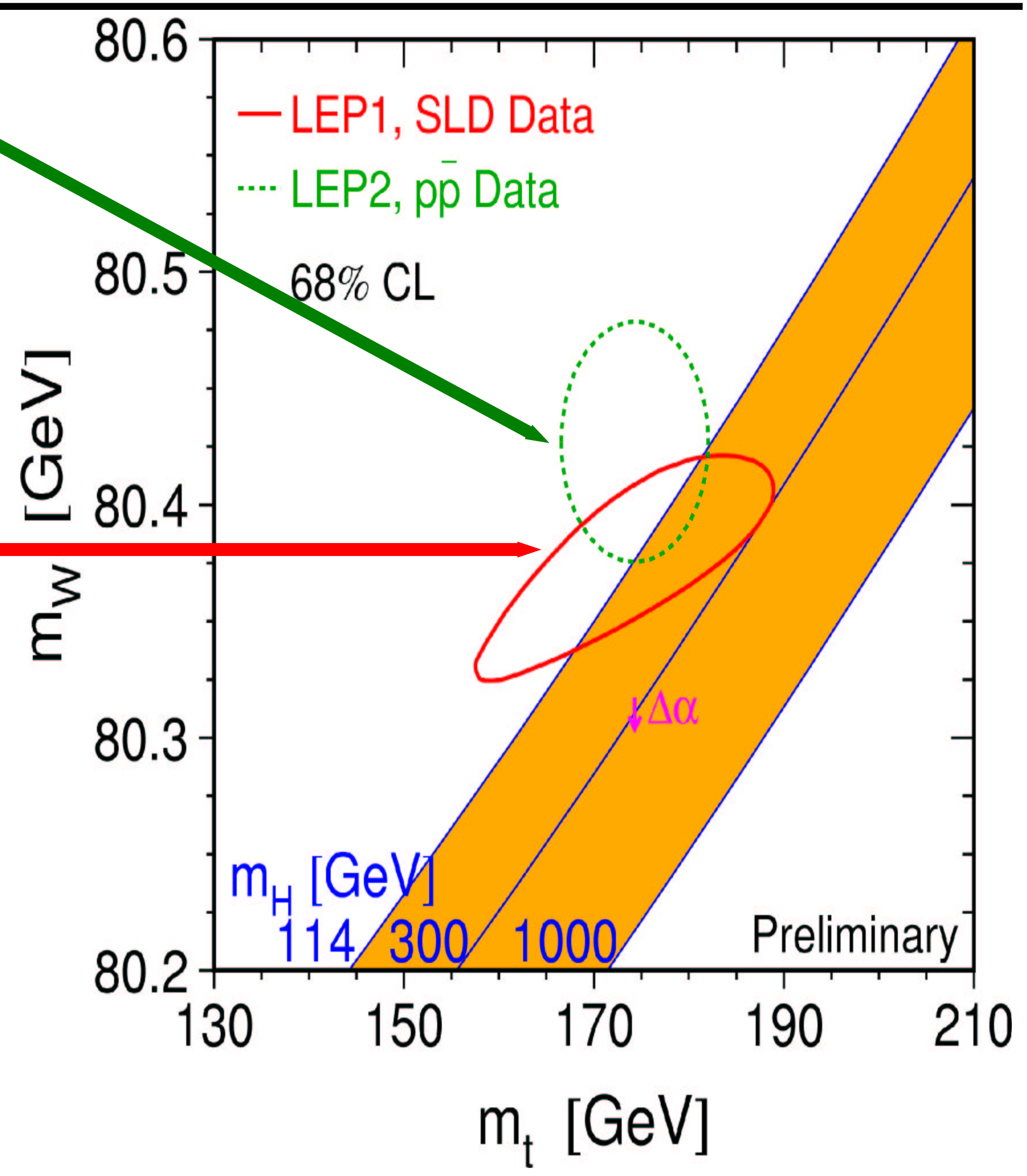
Heavy Particle Masses W and Top

Direct measurements:
TEVATRON and LEP2

Z-Pole measurements:
Constrain electroweak radiative corrections
Allows to predict M_W and M_{top} within SM

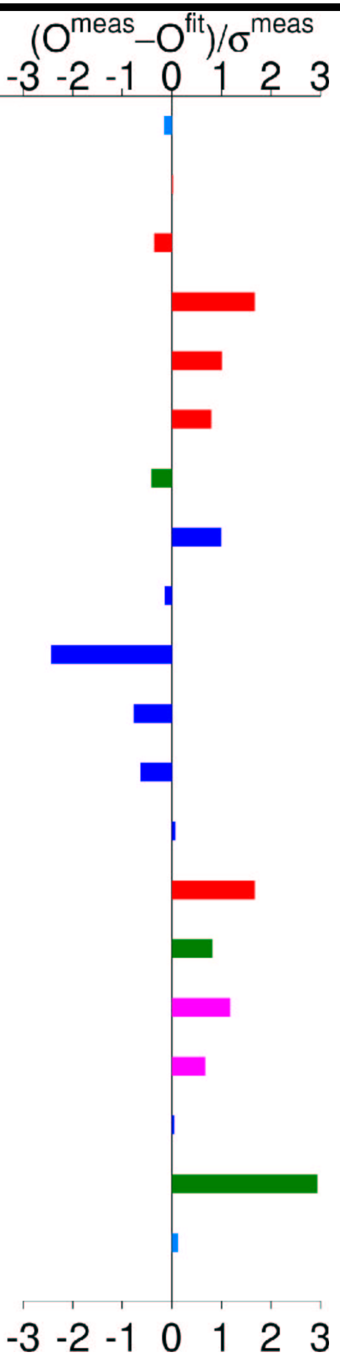
Now good agreement
Successful SM test

Both data sets prefer a light Higgs boson



Global Standard-Model Analysis

	Measurement	Pull
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	-0.16
m_Z [GeV]	91.1875 ± 0.0021	0.02
Γ_Z [GeV]	2.4952 ± 0.0023	-0.36
σ^0_{had} [nb]	41.540 ± 0.037	1.67
R_l	20.767 ± 0.025	1.01
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.79
$A_l(P_\tau)$	0.1465 ± 0.0032	-0.42
R_b	0.21644 ± 0.00065	0.99
R_c	0.1718 ± 0.0031	-0.15
$A^{0,b}_{fb}$	0.0995 ± 0.0017	-2.43
$A^{0,c}_{fb}$	0.0713 ± 0.0036	-0.78
A_b	0.922 ± 0.020	-0.64
A_c	0.670 ± 0.026	0.07
A_l(SLD)	0.1513 ± 0.0021	1.67
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.82
m_W [GeV]	80.426 ± 0.034	1.17
Γ_W [GeV]	2.139 ± 0.069	0.67
m_t [GeV]	174.3 ± 5.1	0.05
$\sin^2\theta_W(\nu N)$	0.2277 ± 0.0016	2.94
Q_W(Cs)	-72.83 ± 0.49	0.12



Fit to all data:

χ^2/ndof = 25.5/15 (4.4%)

Largest χ^2 contribution:

$\sin^2\Theta_W$(NuTeV, $\rho=\rho_{SM}$)

Spread of $\sin^2\Theta_{eff} \rightarrow$ Afb(b)

Fit without NuTeV:

χ^2/ndof = 16.7/14 (27.3%)

Fit result is robust:

Fitted parameters almost unchanged!

Constraints on the SM Higgs-Boson Mass

$M_{Higgs} = 91^{+58}_{-37}$ GeV

Incl. theory uncertainty:

$M_{Higgs} < 211$ GeV (95%CL)

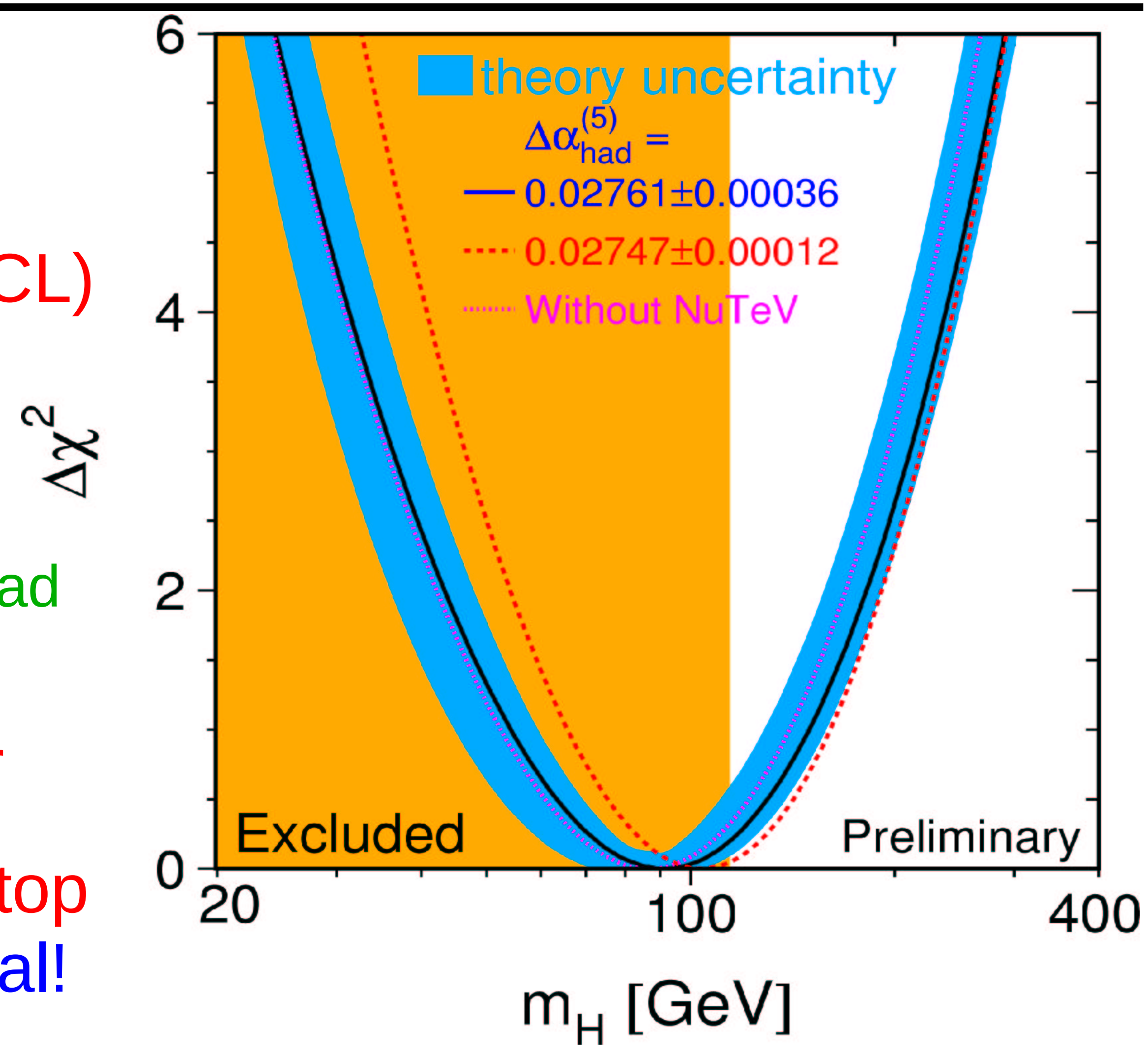
Strongly correlated:

- -0.5 (-0.2) with fitted $\Delta\alpha_{had}$
- +0.7 with fitted M_{top}
  - 35% shift in M_{Higgs} for
  - 5 GeV shift in meas. M_{top}

M_{top} measurement crucial!

Direct Higgs search limit:

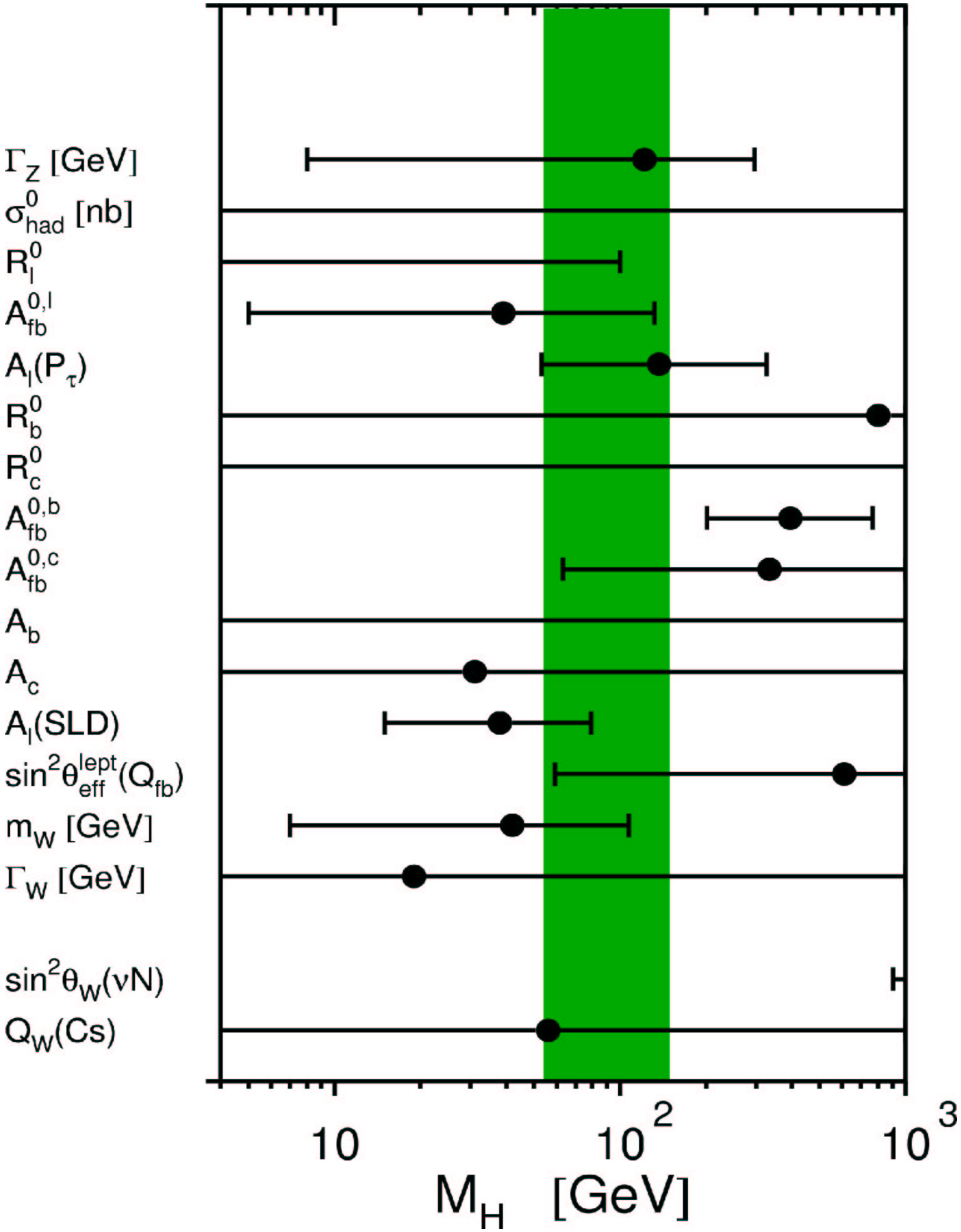
No contradiction!



Theory uncertainty:

Need two-loop calculations for $\sin^2\Theta_{eff}$

Higgs Mass from each Observable



For each observable:

Fit for M_{Higgs} with the constraints:

$\Delta\alpha_{had}$ = 0.02761(36)

$\alpha_s(M_Z)$ = 0.118(2)

M_Z = 91187.5(2.1) MeV

M_{top} = 174.3(5.1) GeV

Meaningful?

Caveats

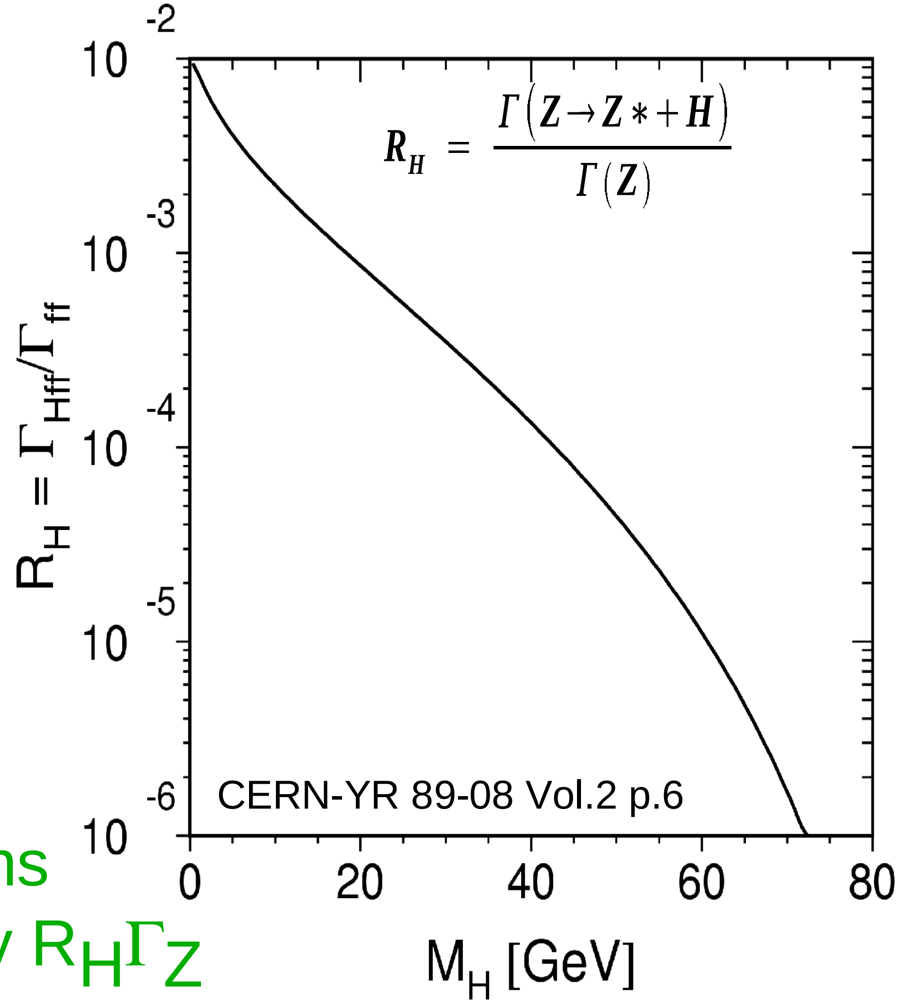
Real Higgs-Strahlung (Z*+H) not taken into account:

Experimental analyses:

- Higgs-mass dependent effects in cross sections and asymmetries

Calculation of predictions:

- Total Z decay width increases
- Cross sections and asymmetries change (2f vs. 4f)



Simple considerations at the Z-pole:

- All Z*+H decays selected as hadrons
- Measured Γ_Z and Γ_{had} increase by $R_H \Gamma_Z$
- Increase of fitted α_S in SM fit neglecting Z*+H
- $\Delta\alpha_S = 4R_H$ | $\Delta\alpha_S < 0.1\delta\alpha_S$ => $M_H > 22$ GeV is required

Caveats

What about heavy-flavour widths and f/b asymmetries?

- Maximal effect if all Z*H decays are tagged as b-production
- Γ_b increased by the same amount as Γ_{had}, Afb(b) changed
- $\Delta R_b = 1.1 R_H$ | $\Delta R_b < 0.1 \delta R_b$ => $M_H > 47$ GeV is required

W mass reconstruction probably not affected

Z*+H also dependent on centre-of-mass energy!

SM global fit ok for M_H central value and upper errors

- Quantitative statements in low Higgs-mass regime dubious

Correct treatment requires experimental efficiencies and corrections for Z*+H as a function of M_H

- Not available!
- But have limit from direct search M_H>114.4 GeV (95% CL)

Conclusions

Wealth of high-precision measurements:

Many with high sensitivity to radiative corrections

Most measurements agree with expectations:

Successful test of SM loop corrections

But have two ~3-sigma effects:

Spread in $\sin^2\Theta_{eff} \rightarrow A_{fb}(b)$, and NuTeV's R_{-} result

Validity of any pseudo-observable analysis: Real Higgs production or non-MSM final states must be negligible

Future:

Precise theoretical calculations - incl. theor. uncertainties

Improved measurements of top, W, $\Delta\alpha_{had}$, $\sin^2\Theta_{eff}$

Check Higgs-mass prediction