Precision Electroweak Measurements and Fits

Martin W. Grünewald

University College Dublin, Ireland

APS Denver, 3 May 2004

Outline

Overview on precision measurements

Tests of the electroweak Standard Model

The mass of the Higgs boson

Conclusions

Thanks to the members of the LEP electroweak working group, the Tevatron electroweak working group, and the D∅, CDF, SLD, OPAL, L3, DELPHI, ALEPH, E-158, NuTeV, ... experiments!

http://tevewwg.fnal.gov   http://www.cern.ch/LEPEWWG

Electroweak Precision Data

Very high Q^2 physics at LEP, SLC, and the Tevatron:

More than 1000 measurements with (correlated) uncertainties

Reduced to 17 precision electroweak observables

Top quark, W boson:

1 Top quark mass (Tevatron)

2 W boson mass and width (LEP-2, Tevatron)

Z boson (LEP-1,SLD):

5 Z lineshape and leptonic forward-backward asymmetries

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

6 Heavy flavour results (Z decays to b and c quarks)

1 Inclusive hadronic charge asymmetry

17

Global Standard Model Analysis

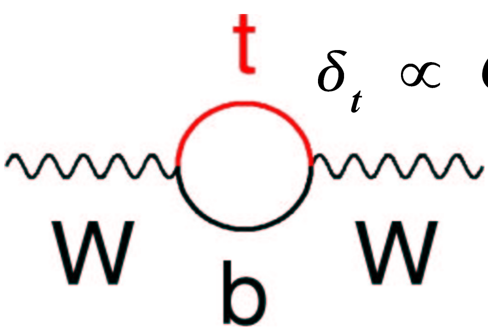
SM: Each observable calculated as a function of:

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

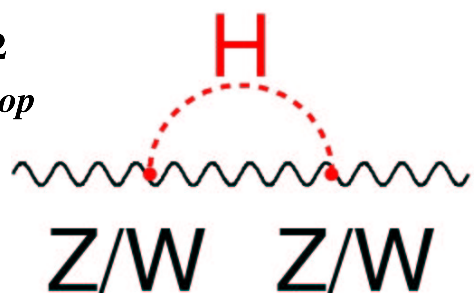
- $\Delta\alpha_{had}$: hadronic vacuum polarisation [0.02761±0.00036]
- $\alpha_s(M_Z)$: given by Γ_{had} and related observables
- M_Z: constrained by LEP-1 lineshape

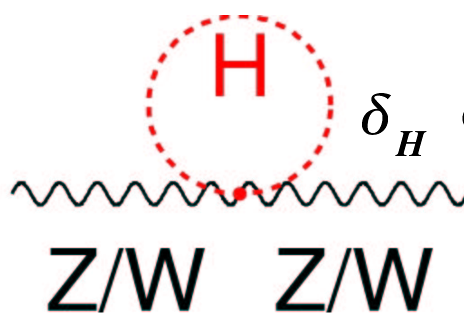
Precision requires 1st and 2nd order electroweak and mixed radiative correction calculations (QED to 3rd)

M_{top}, M_{Higgs} enter through electroweak corrections (~ 1%)!



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

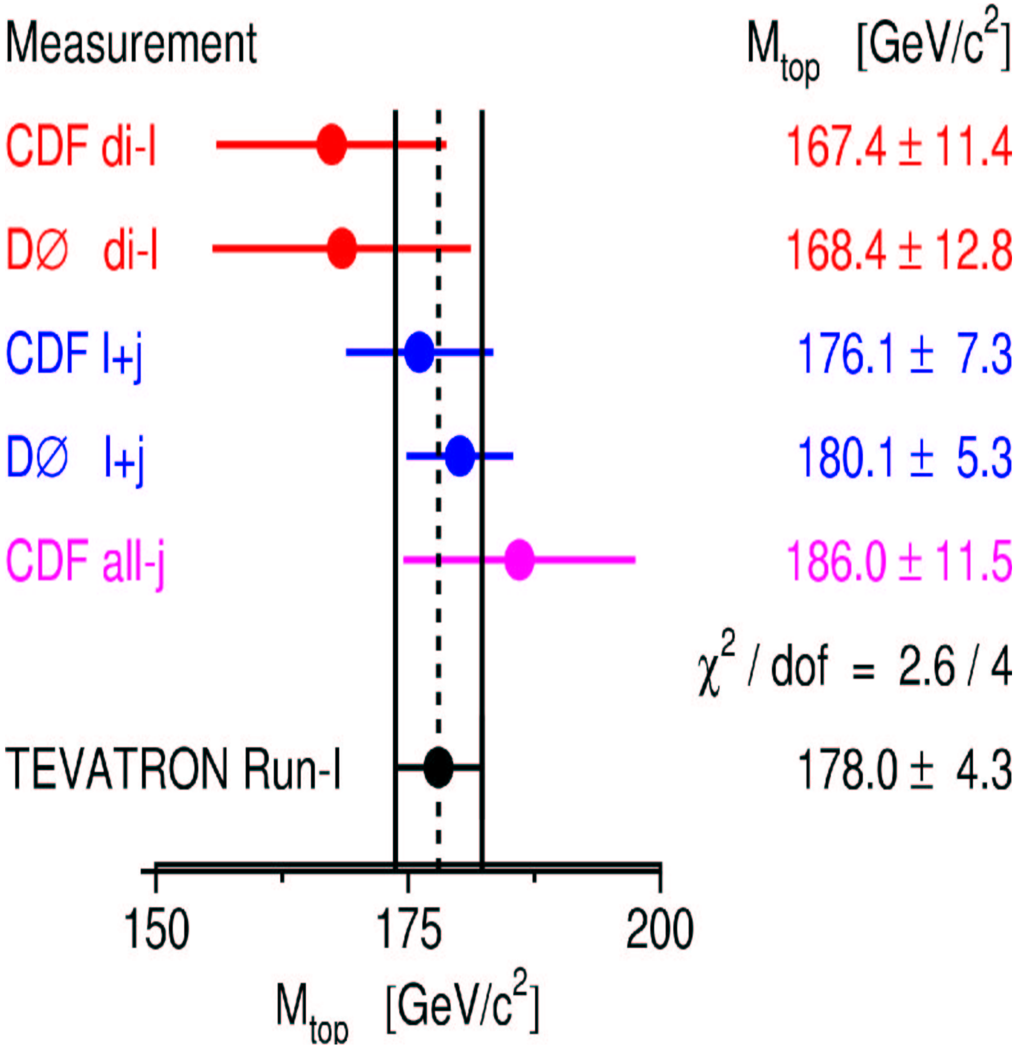




$$\delta_H \propto \ln \frac{M_{Higgs}}{M_W}$$

Calculations by programs TOPAZ0 and ZFITTER

Mass of the Top Quark



Tevatron (CDF, DØ):

$p\bar{p} \rightarrow ttX,\ \ tt \rightarrow b\bar{b}WW$

$W \rightarrow qq, l\nu$

New Run-I combination

Preliminary Run-II results

Systematic uncertainties dominated by:

- Jet energy scale (2-5 GeV) - will reduce with more data
- Signal model (1-3 GeV)
- Background model (~2 GeV)
- MEs, PDFs, MC generators

Run-I final: M_{top} = 178.0 ± 2.7 (stat.) ± 3.3 (syst.) GeV

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

W Boson Mass and Width

Tevatron (CDF, D∅): $p\bar{p} \rightarrow$ WX, W $\rightarrow e\nu, \mu\nu$

Transverse mass

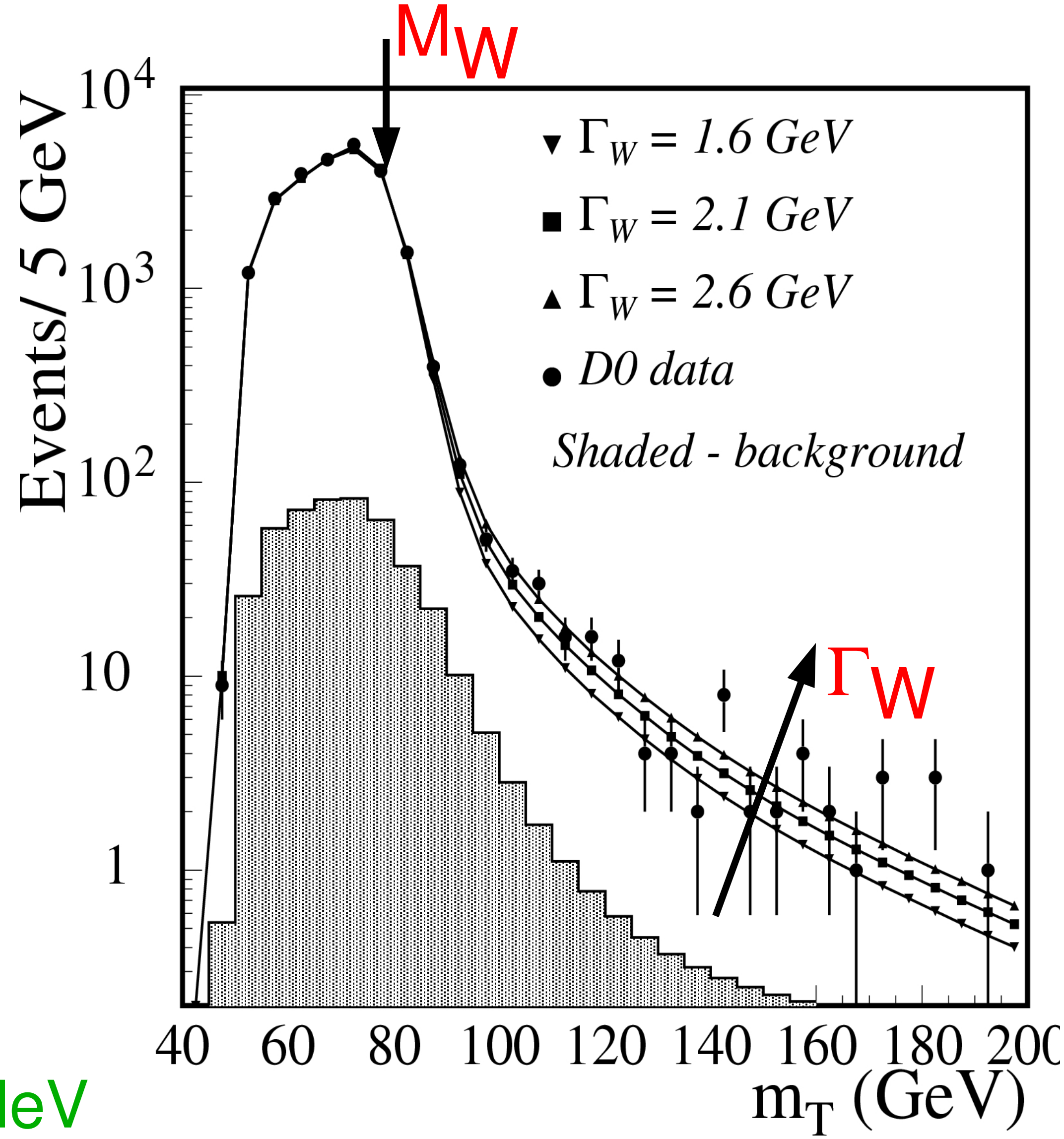
$$m_T^2 = 2E_T^e E_T^\nu \cos\phi(e,\nu)$$

Final Run-I combination

No Run-II results yet

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: δM_W < 25 MeV

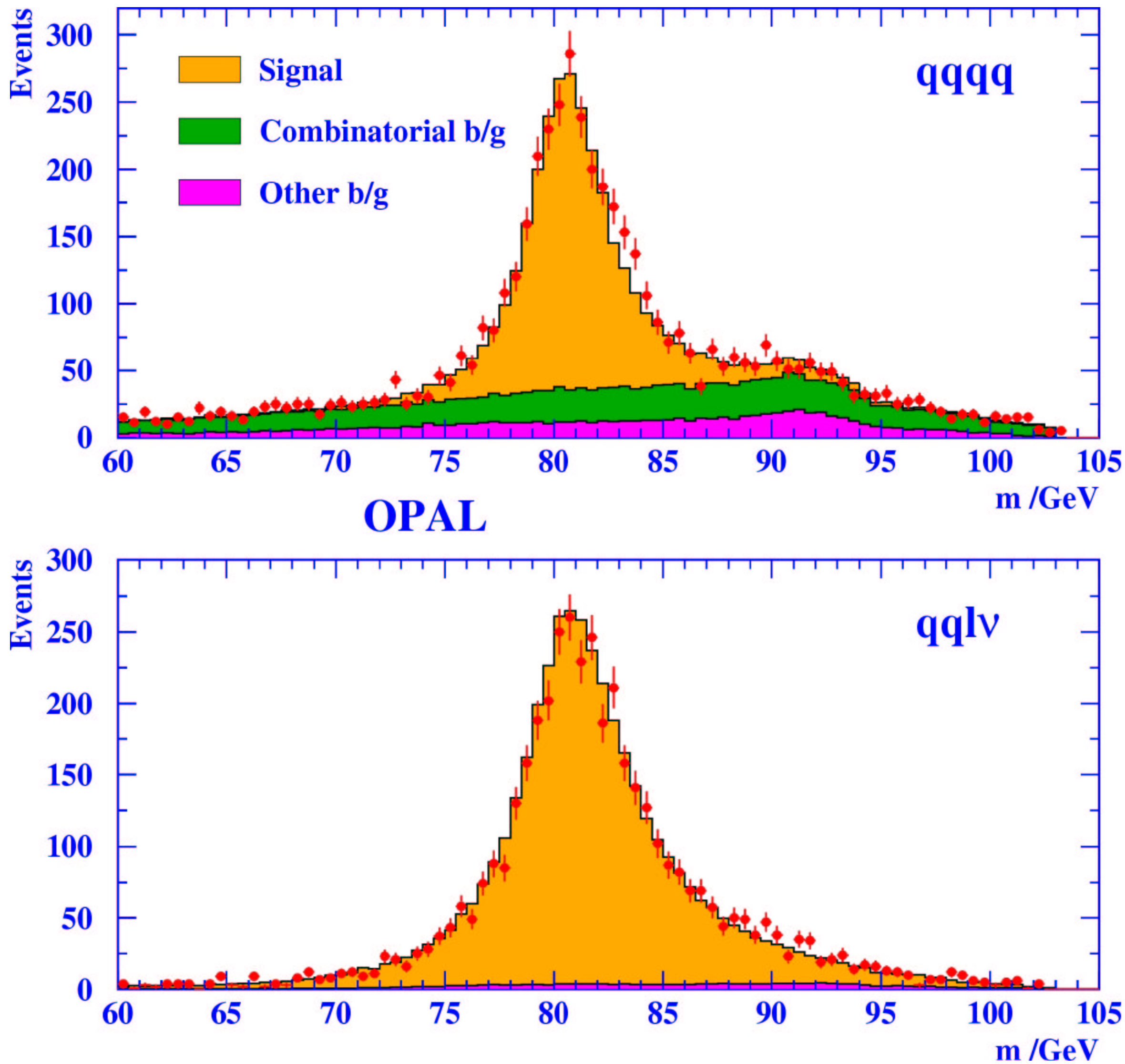
W Boson Mass and Width

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

$\rightarrow$ qqqq, qqlν, lνlν

Invariant mass M_{inv}

Preliminary results



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

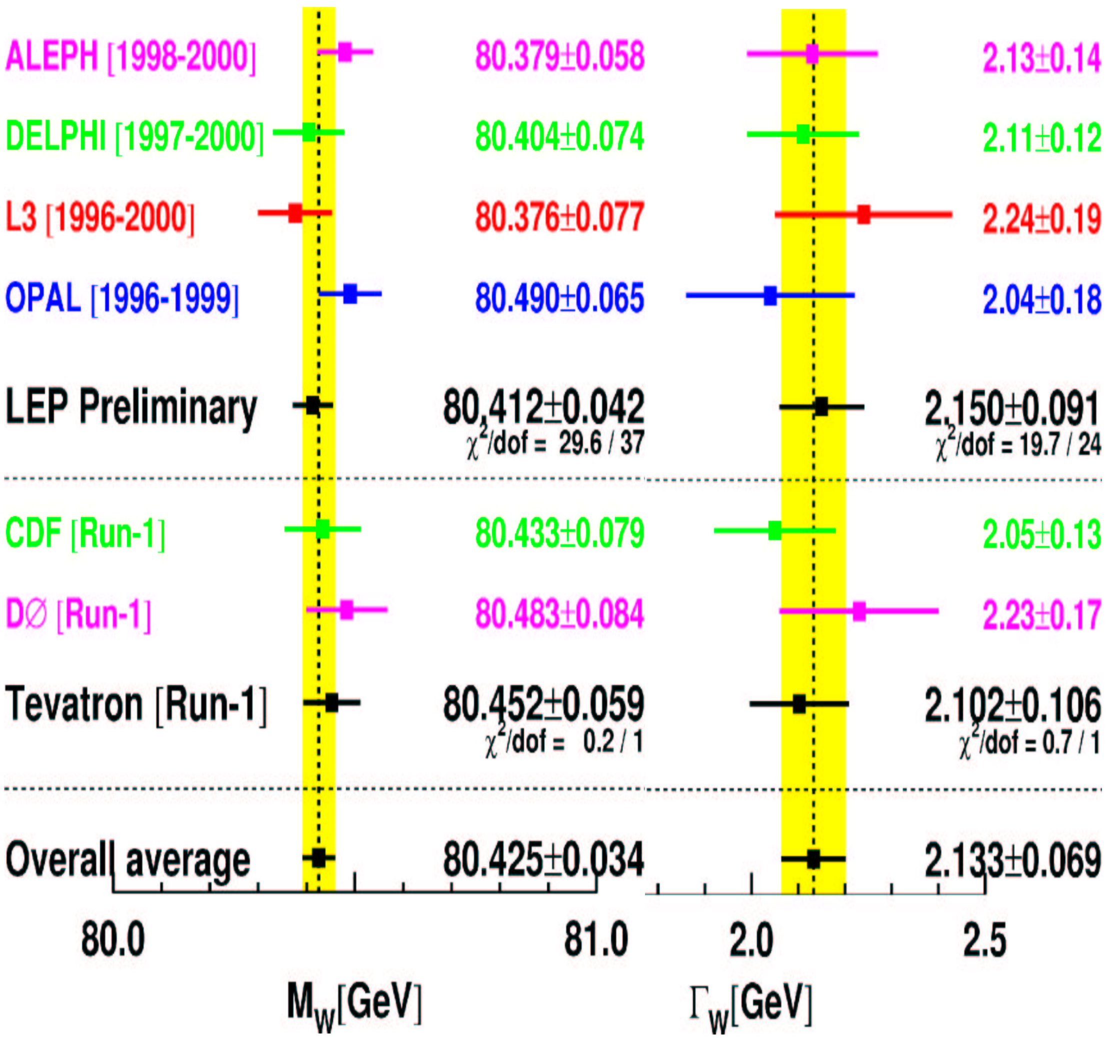
M_W average dominated by qqlν channel

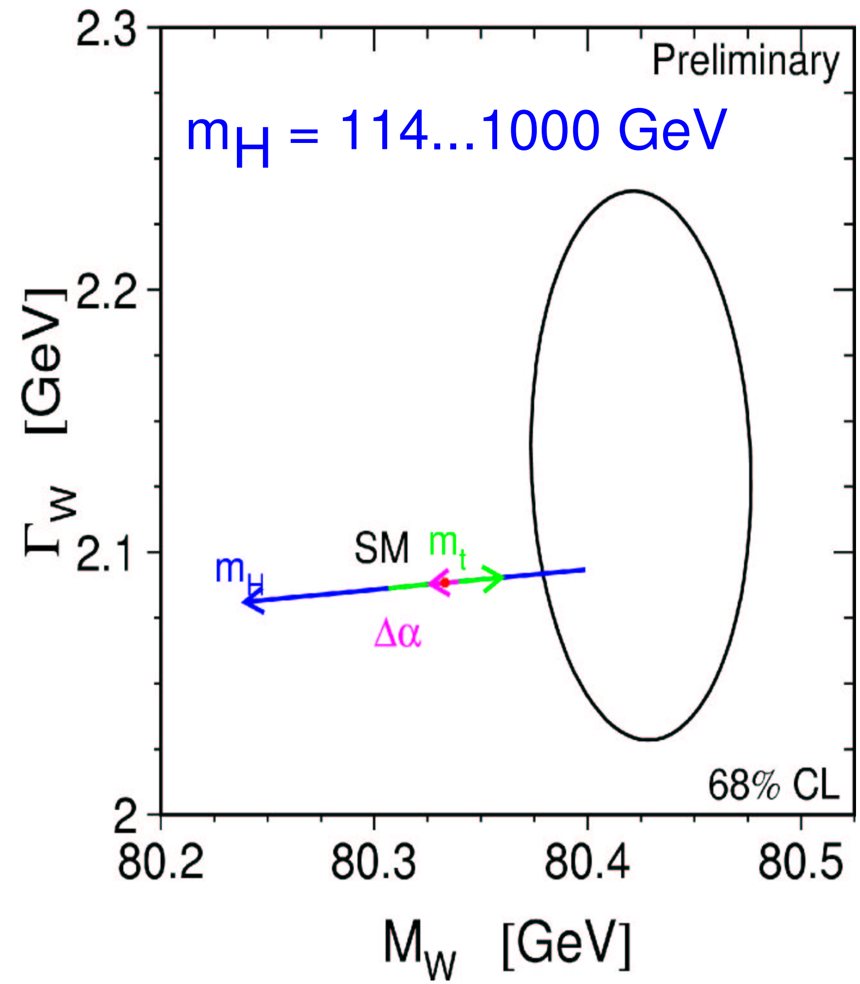
Mass difference (calculated without FSI errors):

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

W Boson Mass and Width

Very good agreement between all six experiments:



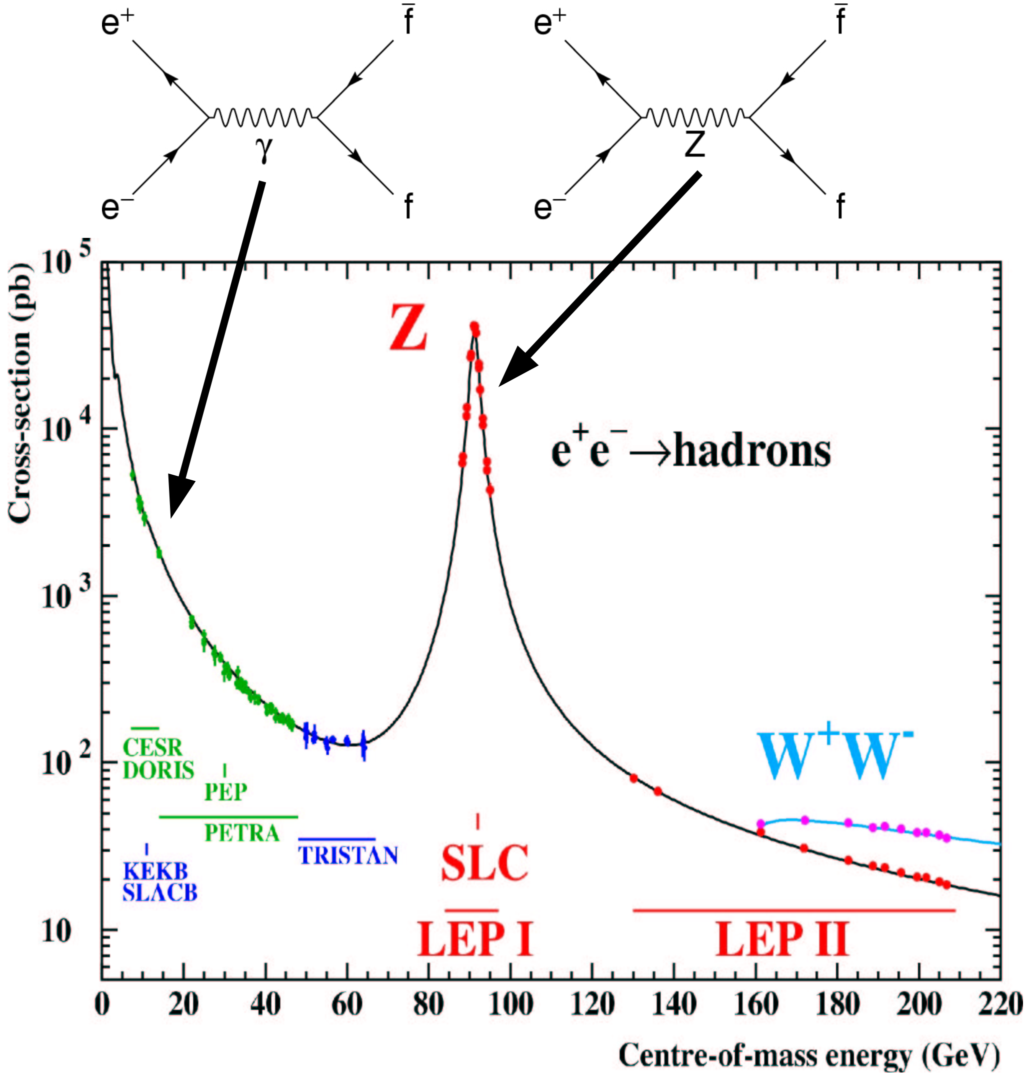


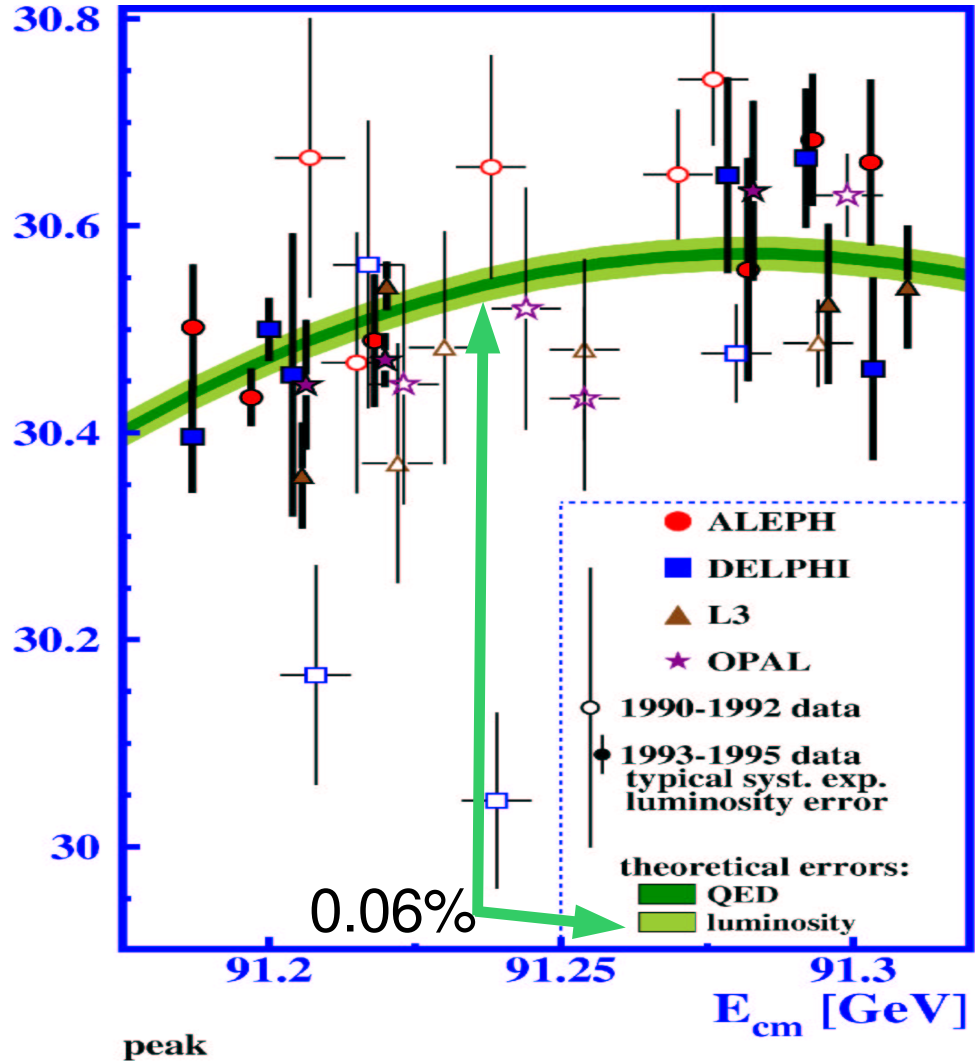
SM comparison:

Small Higgs-boson mass

Correlation M_W-Γ_W: -0.07

The Z Lineshape





M_Z = 91187.5 ± 2.1 MeV

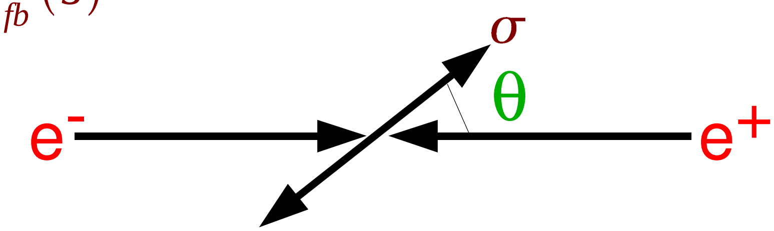
Γ_Z = 2495.2 ± 2.3 MeV

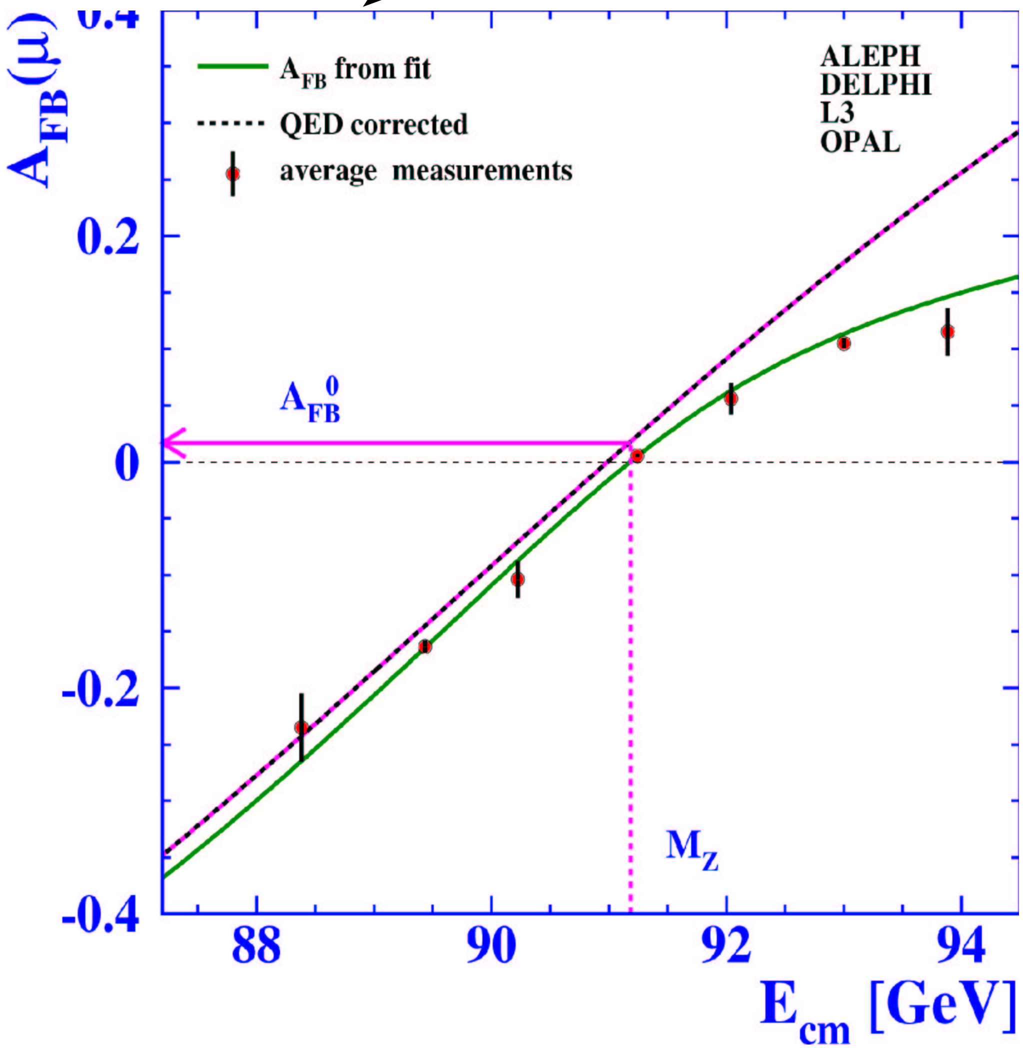
N_ν = 2.9841 ± 0.0083 [-1.9σ]

$R_l = \sigma_{had}/\sigma_l = \Gamma_{had}/\Gamma_l$

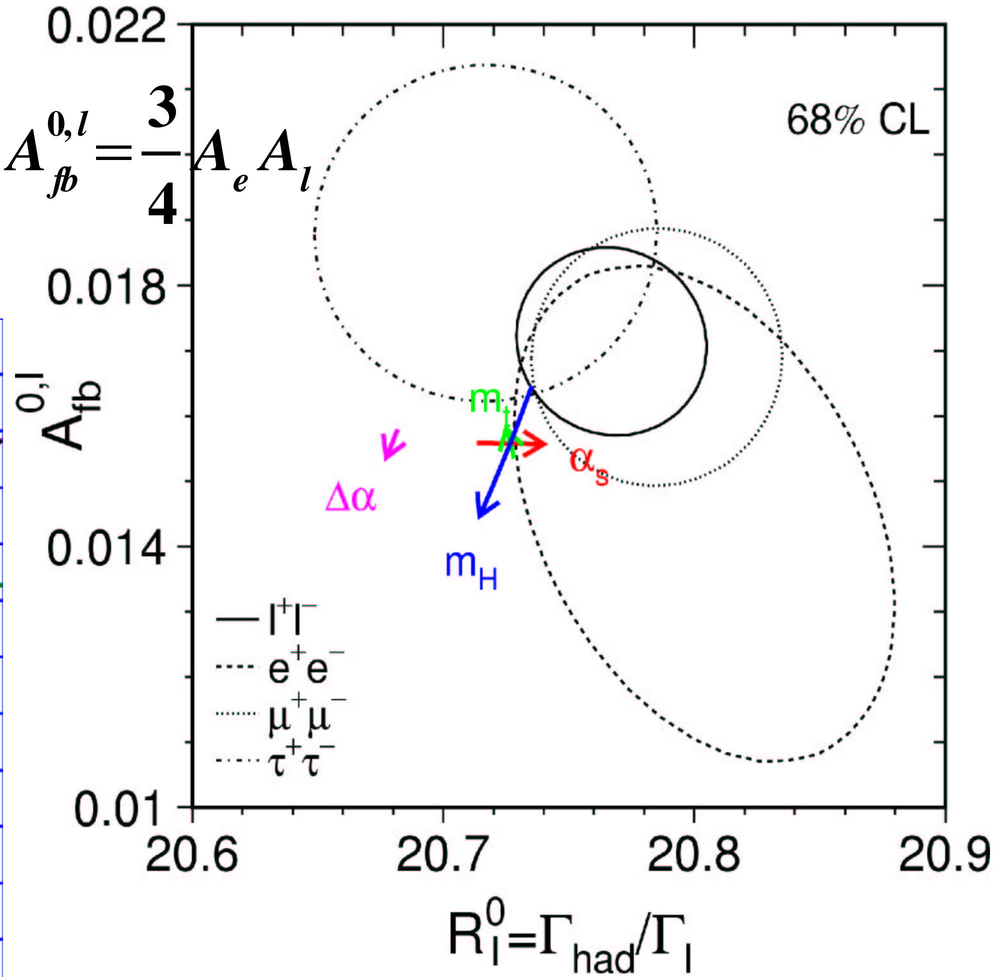
The Forward-Backward Asymmetry at the Z

$$A_{fb}(s) = \frac{\sigma(\cos\theta > 0) - \sigma(\cos\theta < 0)}{\sigma}$$





$$A_{fb}^{0,l} = \frac{3}{4} A_e A_l$$



SM prediction shown for:

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

$M_{top} = 178.0 \pm 4.3\, GeV$ $M_{Higgs} = 114...1000\, GeV$

Low Higgs mass preferred!

Polarised Leptonic Asymmetries at the Z

Asymmetry parameter:

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

LEP-1:

Leptonic f/b asymmetry

$A_l = 0.1512 \pm 0.0042$

Final state τ polarisation

$A_l = 0.1465 \pm 0.0033$

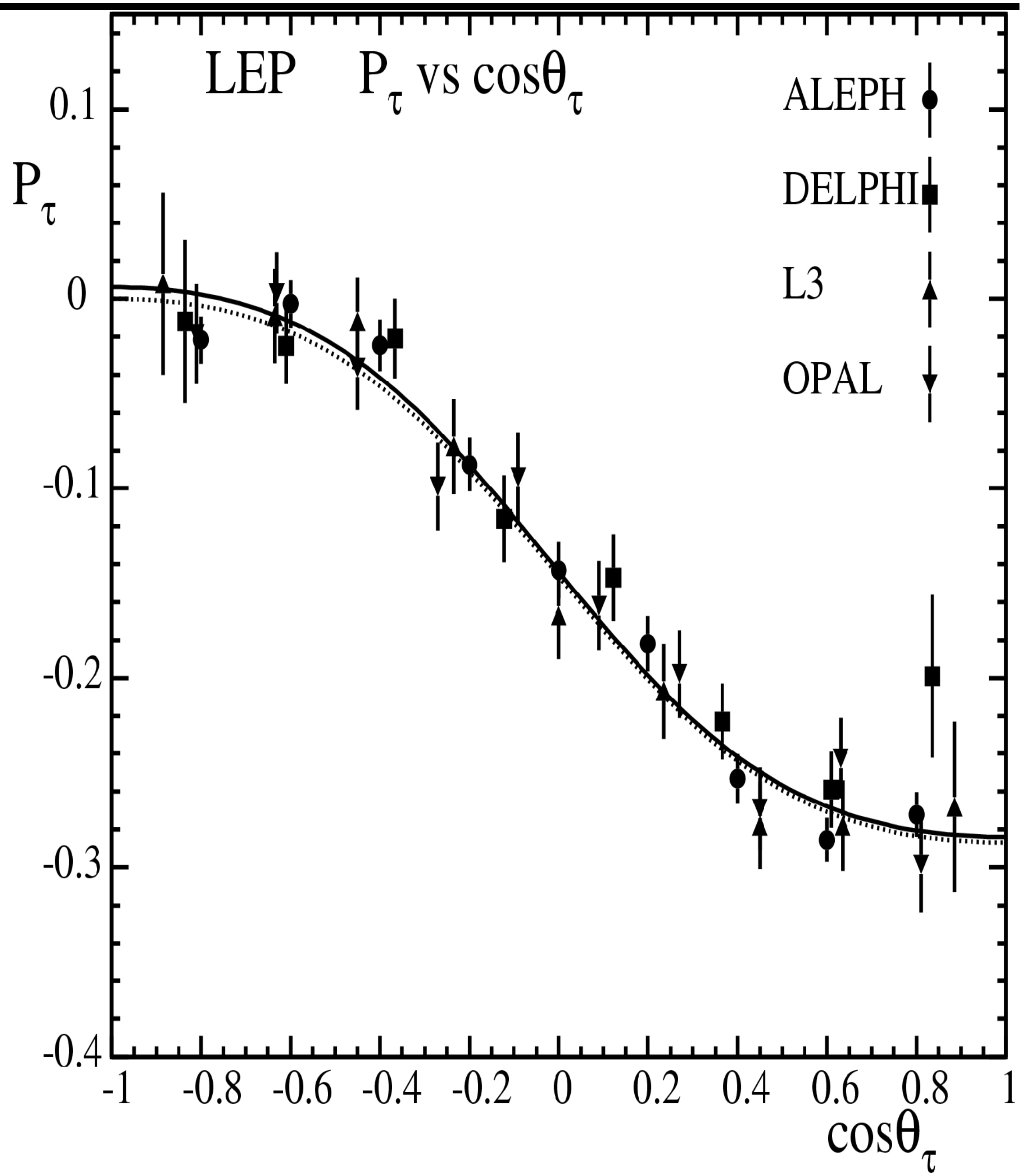
SLD:

Left/right (f/b) asymmetry

$A_l = 0.1513 \pm 0.0021$

Final SLD+LEP-1 result:

$A_l = 0.1501 \pm 0.0016$



Effective Leptonic Coupling Constants

$$g_{Vf} = \sqrt{\rho_f}\left(T_3^f - 2 q_f \sin^2\theta_{eff}^f\right)$$
$$g_{Af} = \sqrt{\rho_f}\, T_3^f \qquad at \quad Q^2 = M_Z^2$$

Z partial widths:

$$\Gamma_f \propto g_{Vf}^2 + g_{Af}^2$$

Asymmetry parameters:

$$A_f \rightarrow g_{Vf}/g_{Af} \rightarrow \sin^2\theta_{eff}^f$$

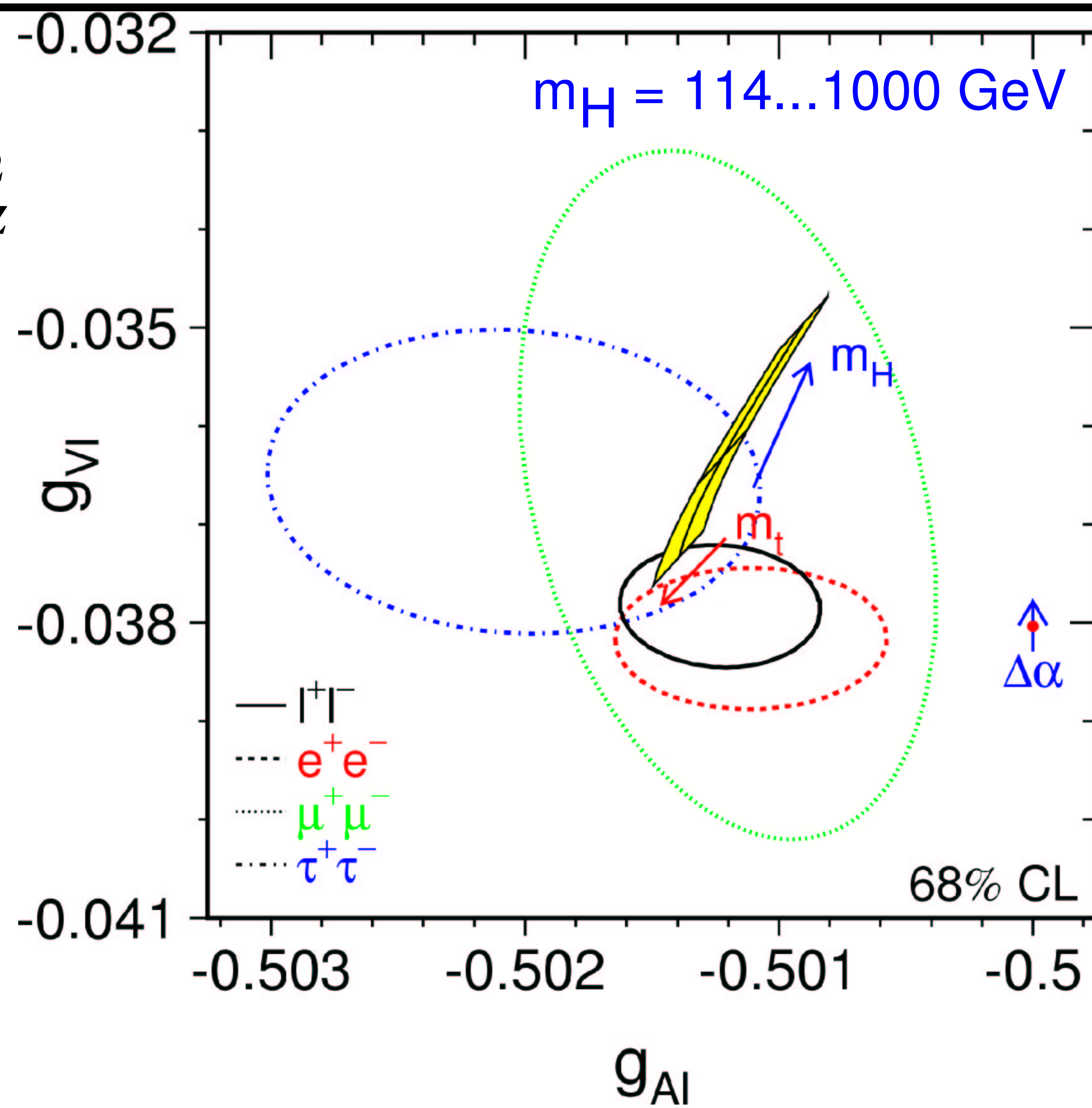
Lepton universality

Radiative corrections

Final SLD+LEP-1 result:

g_{Vl} = -0.03783 ± 0.00041

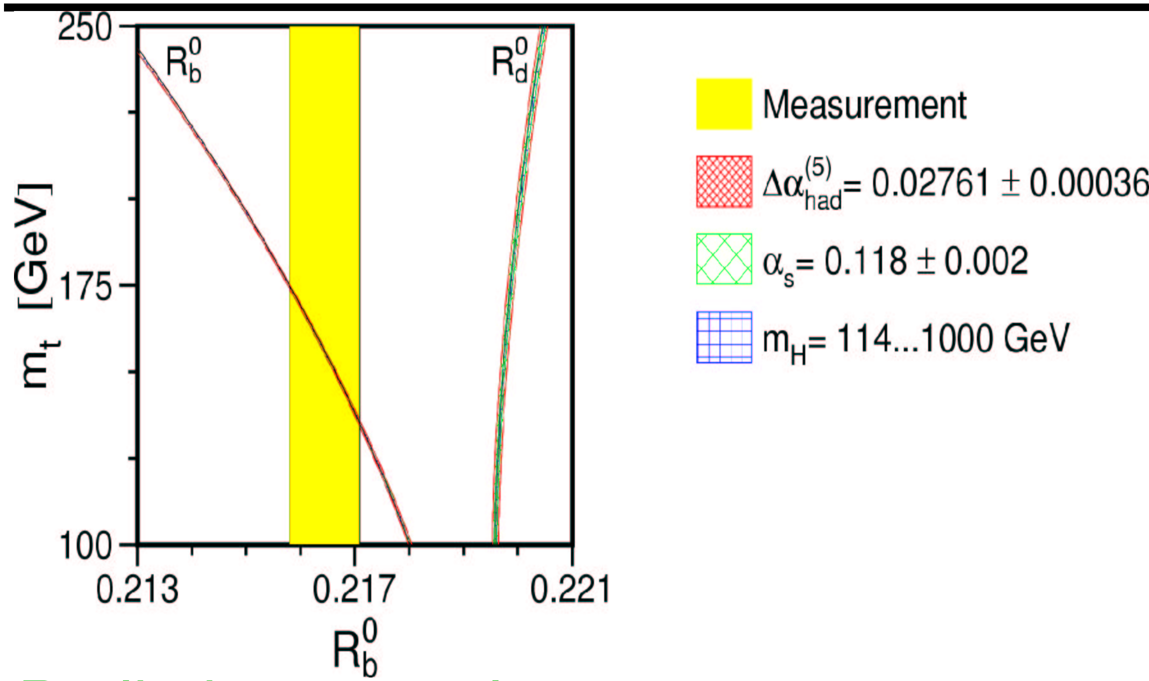
g_{Al} = -0.50123 ± 0.00026



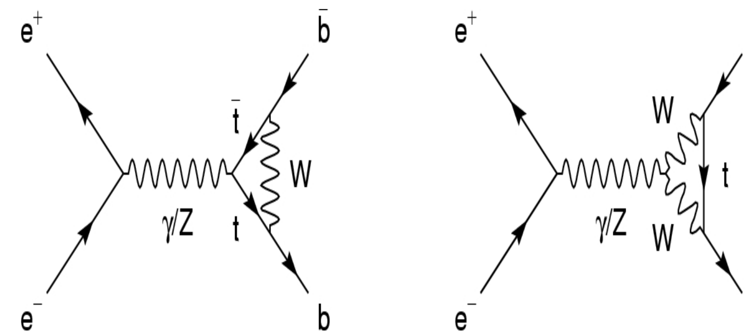
SM comparison:

Small Higgs-boson mass

Heavy Flavour Results at the Z



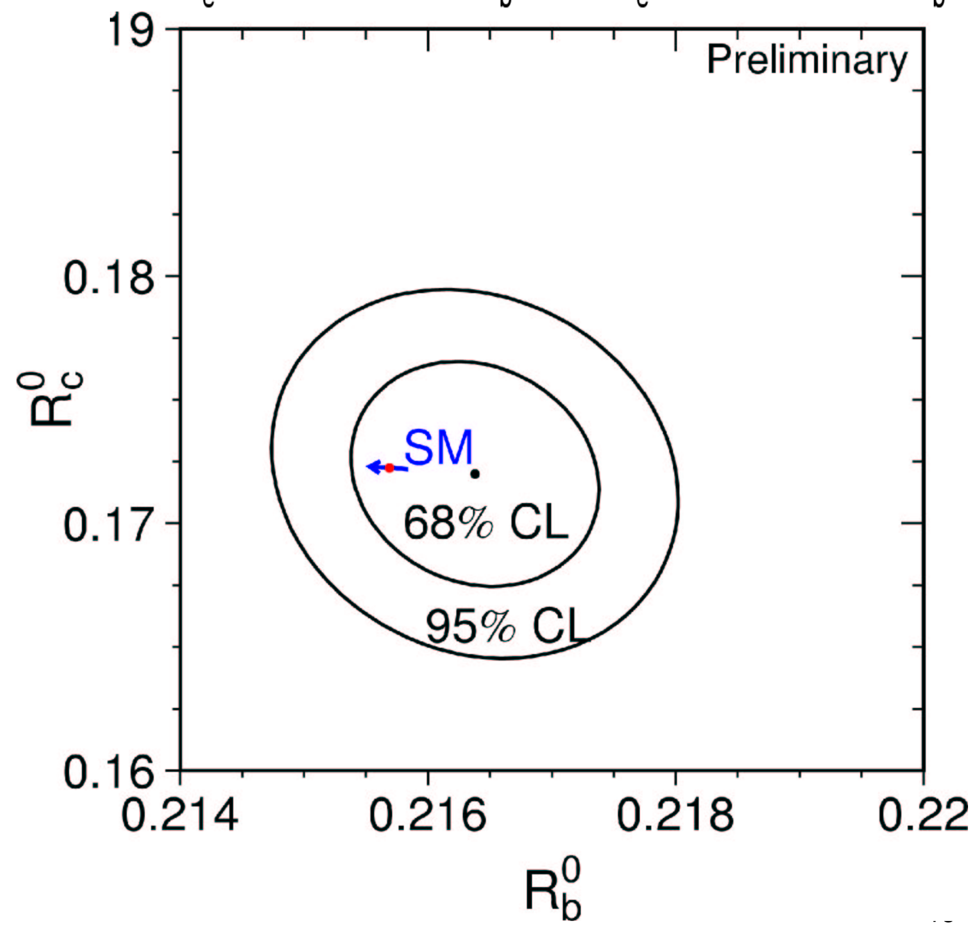
R_b is a M_{top} meter:



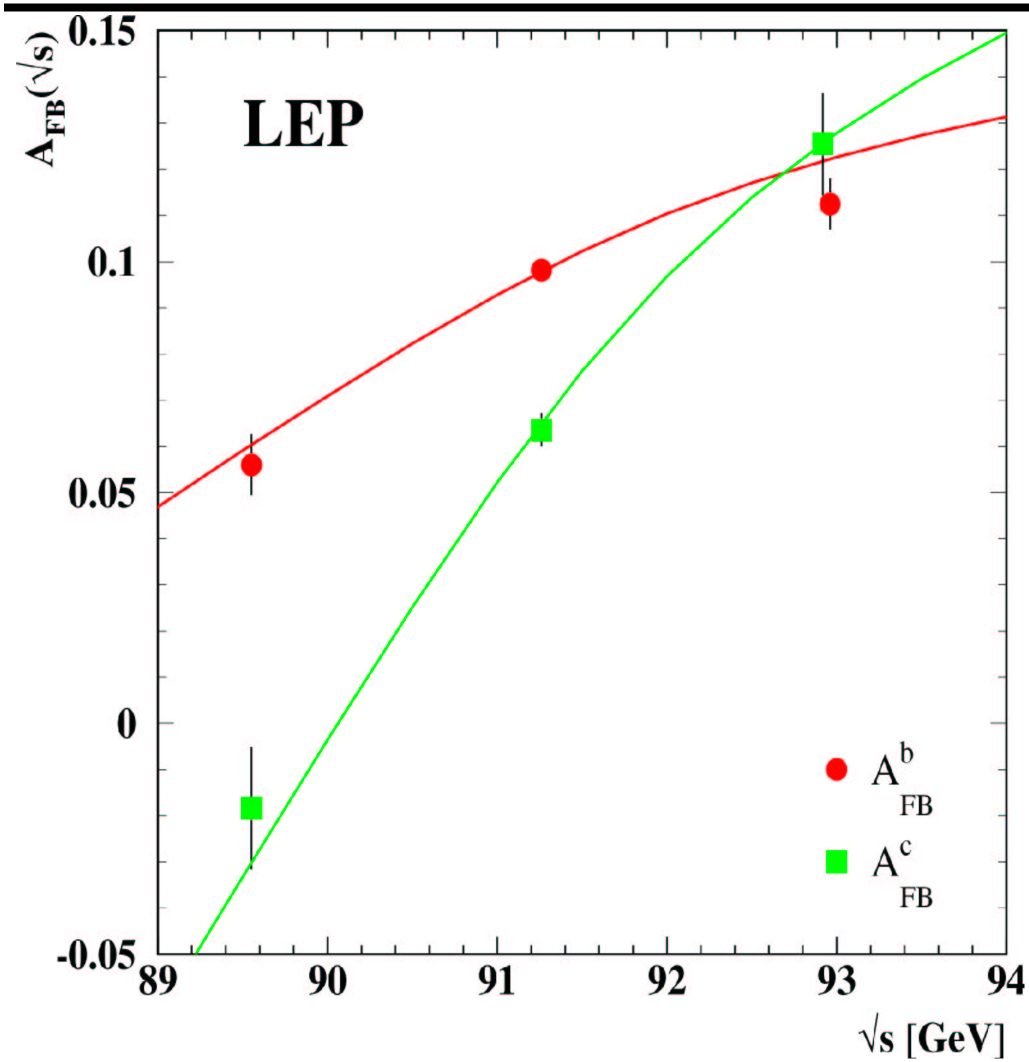
Preliminary results:

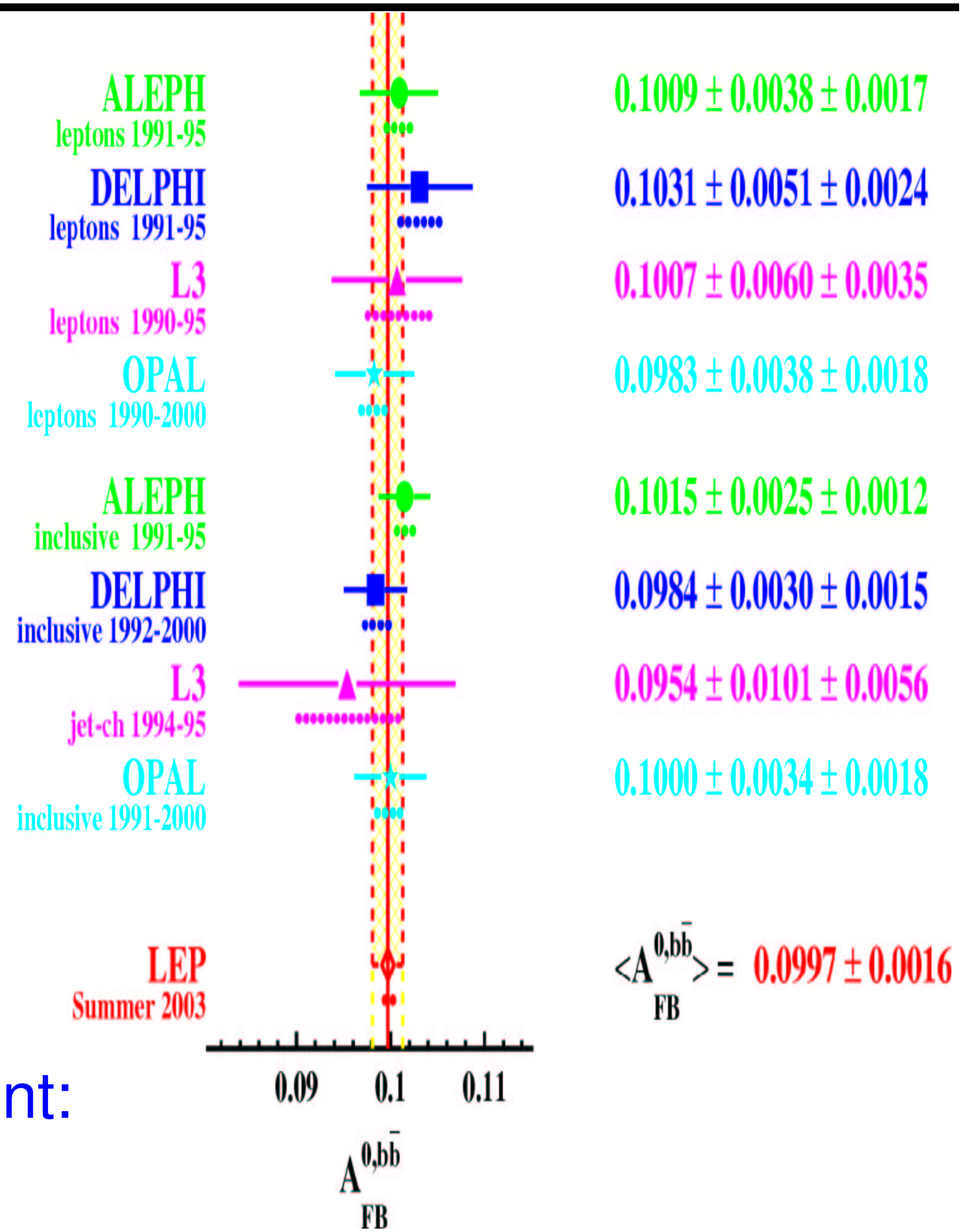
$R_b = \Gamma_b/\Gamma_{had}$	=	0.21638	$\pm$ 0.00066
$R_c = \Gamma_c/\Gamma_{had}$	=	0.1720	$\pm$ 0.0030
$A_{fb}(b) = ¾\, A_e A_b$	=	0.0997	$\pm$ 0.0016
$A_{fb}(c) = ¾\, A_e A_c$	=	0.0706	$\pm$ 0.0035
A_b	=	0.925	$\pm$ 0.020
A_c	=	0.670	$\pm$ 0.026

+ small correlations



Heavy Flavour Results at the Z



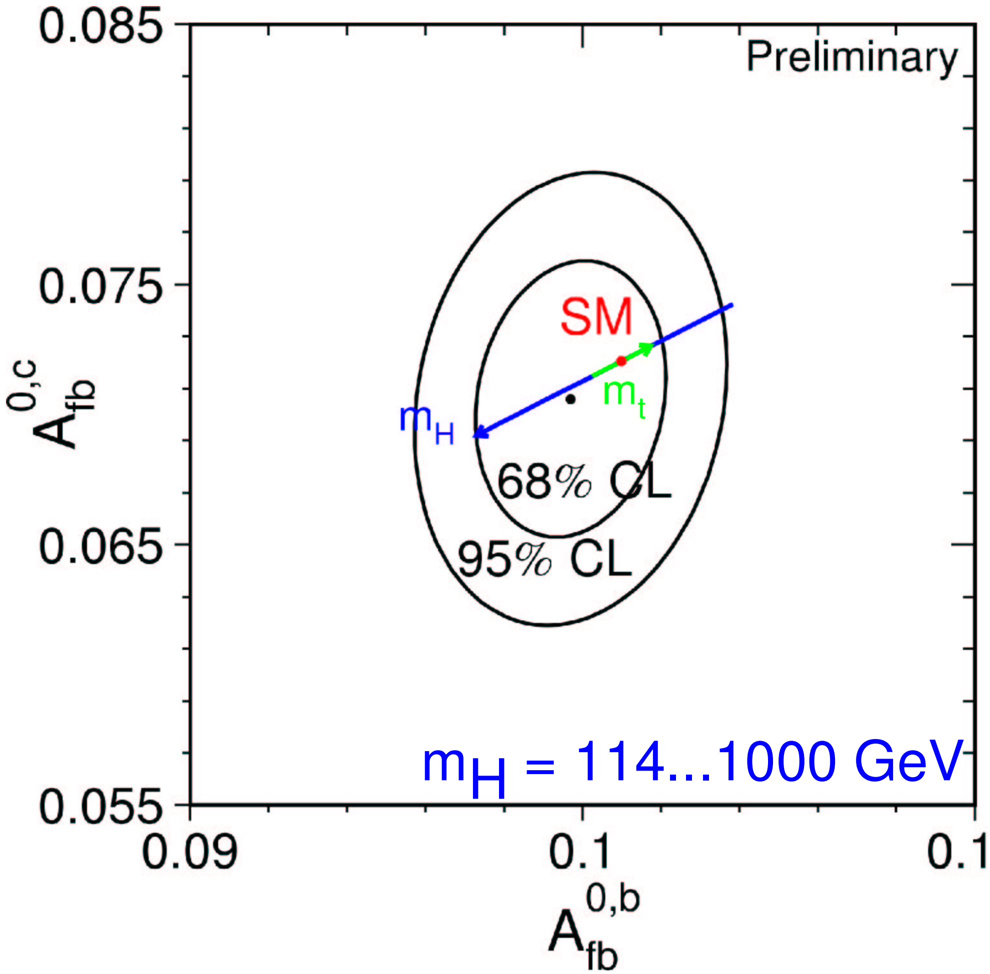


All HF measurements very consistent:

χ^2/ndof = 53/(105-14) low!

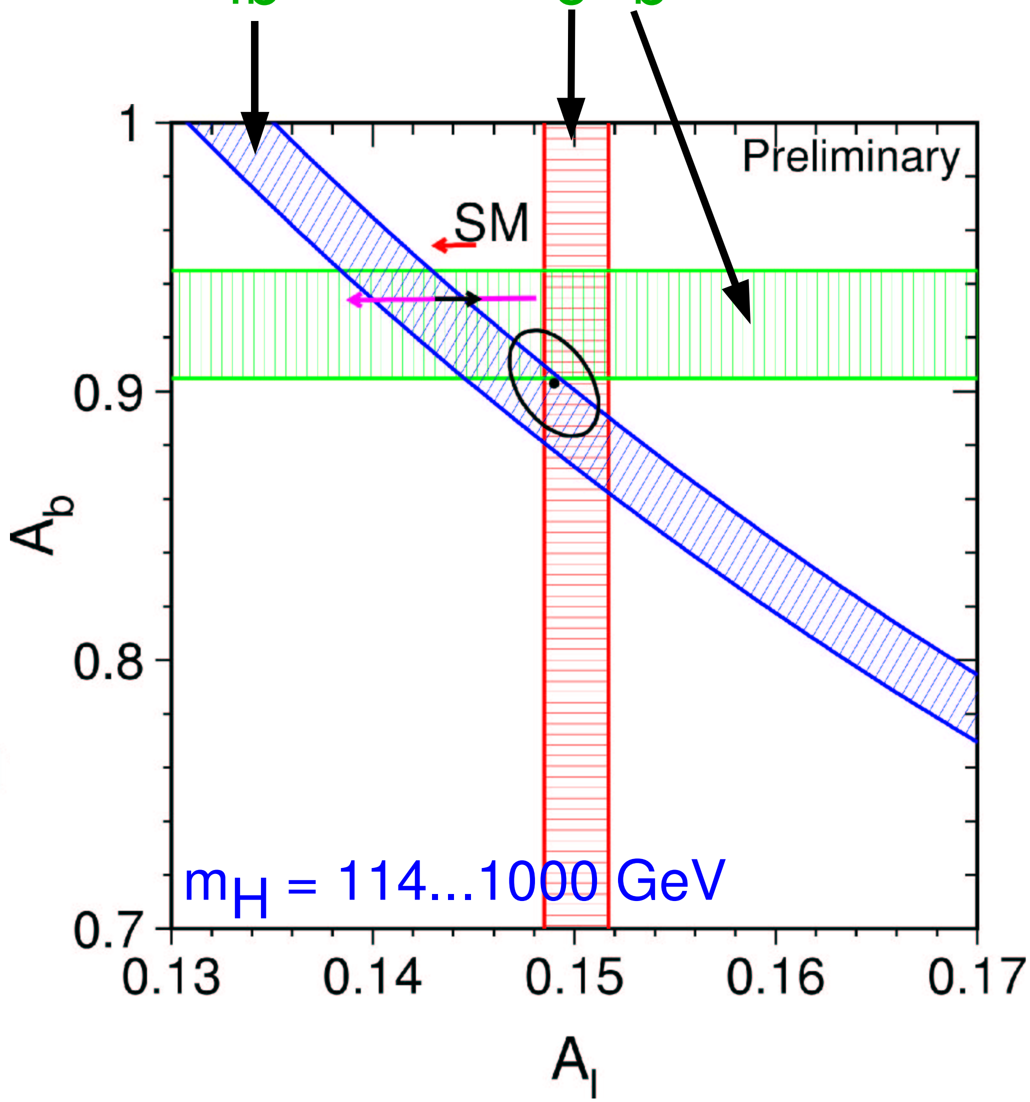
F/B asymmetries statistics dominated

Heavy Flavour Results at the Z



Compare with leptons:

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



SM comparison:

High Higgs-boson mass

Comparison of all Z-Pole Asymmetries

Effective electroweak mixing angle:

$\sin^2\Theta_{eff} = (1-g_{Vl}/g_{Al})/4$

$= 0.23150 \pm 0.00016$

$\chi^2/\text{ndof} = 10.5/5$ [6.2%]

A-posteriori observation:

0.23113±0.0021 leptons

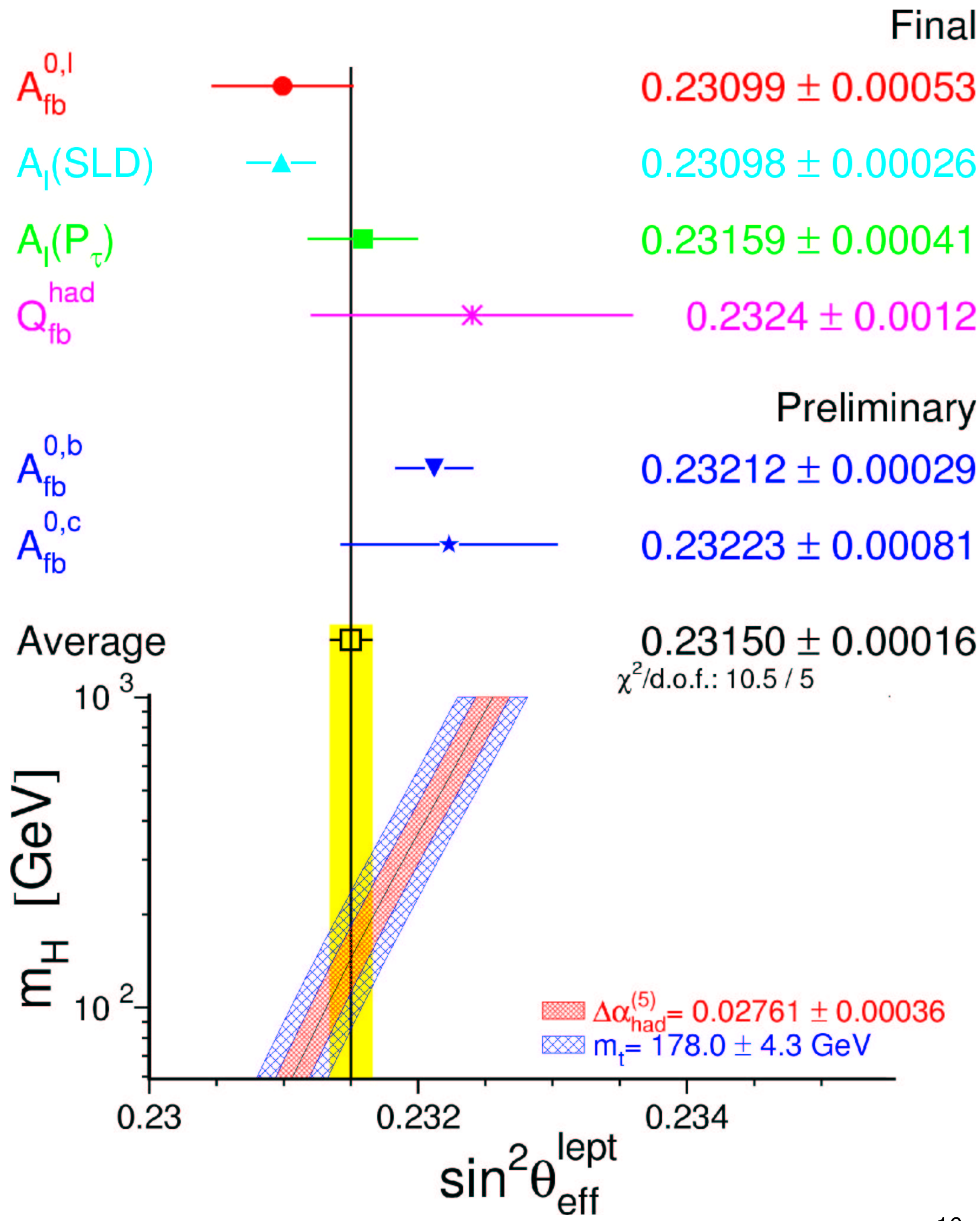
0.23214±0.0027 hadrons

3.0 σ difference

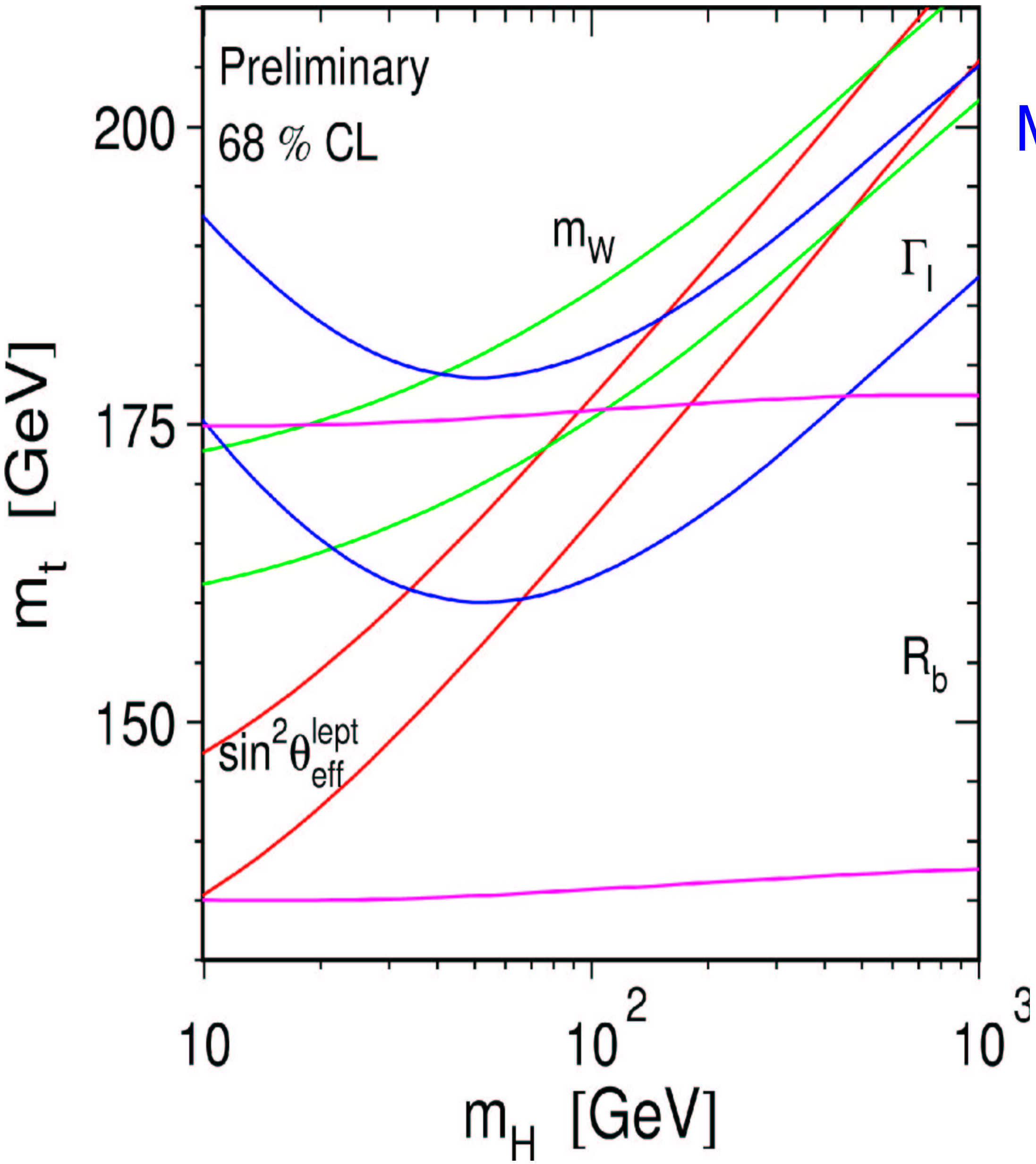
But is really:

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

2.9 σ difference



Top-Higgs Bands



Measurements in the M_{top} - M_{Higgs} plane:

Bands of $\pm 1\sigma$ from:

M_W = 80.425(34) GeV

$\sin^2\Theta_{eff}$ = 0.23150(16)

Γ_l = 83.984(86) MeV

R_b = 0.21638(66)

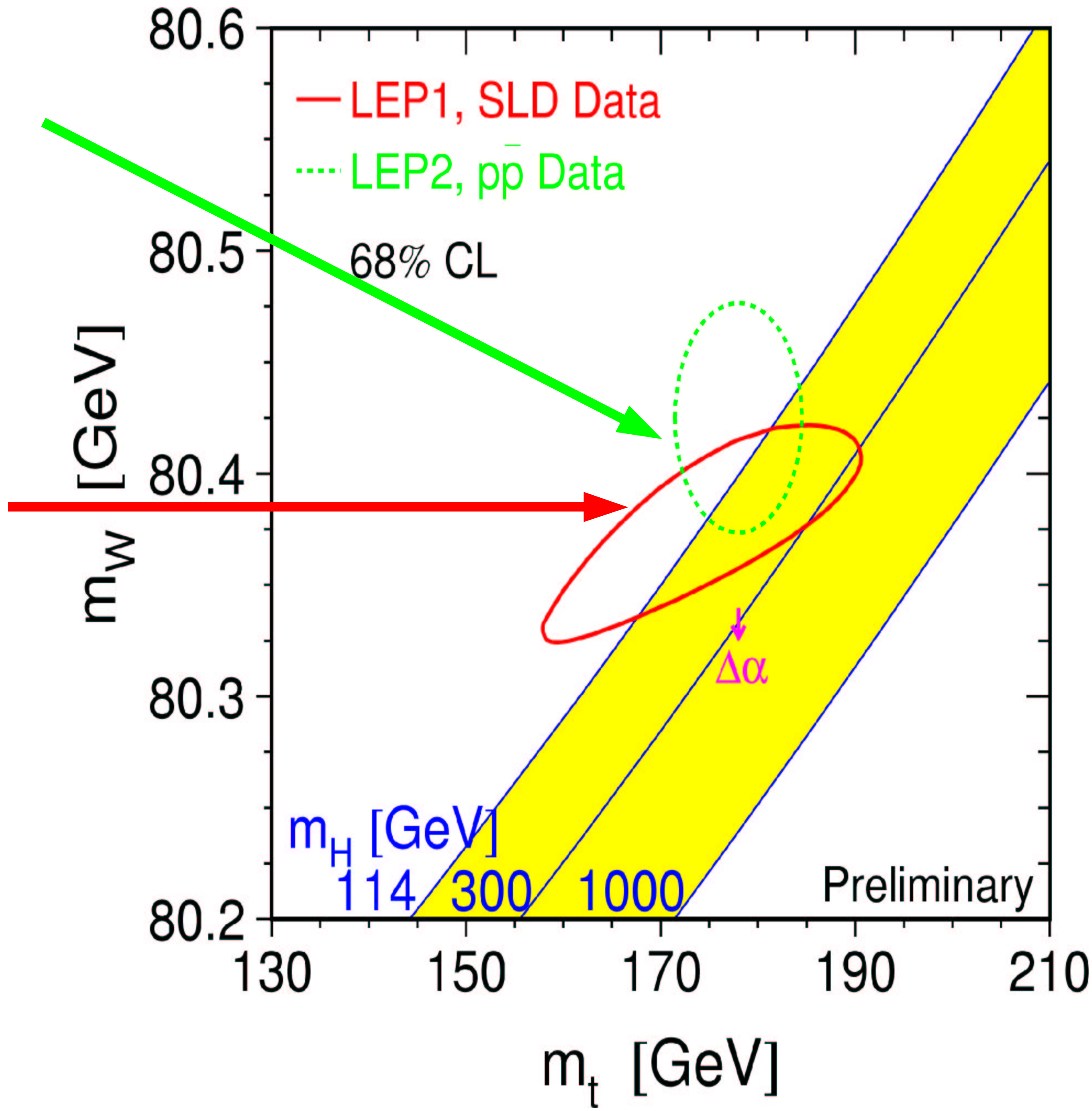
Heavy Particle Masses W and Top

Direct measurements:
TEVATRON and LEP2

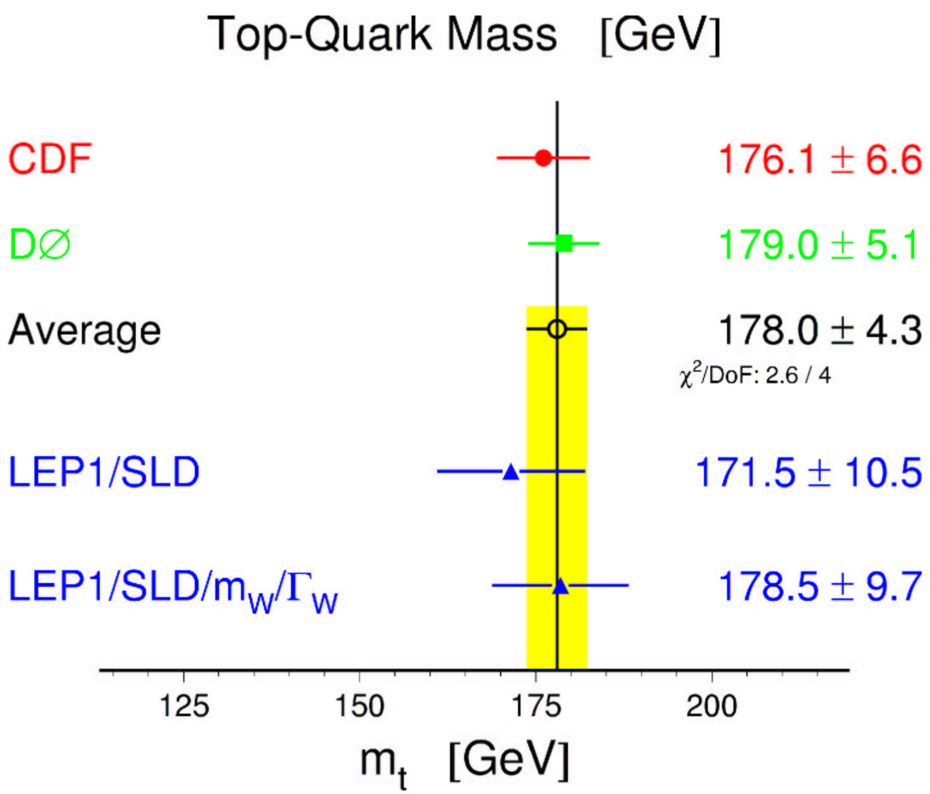
Z-Pole measurements:
Constrain electroweak radiative corrections
Allow to predict M_W and M_{top} within SM

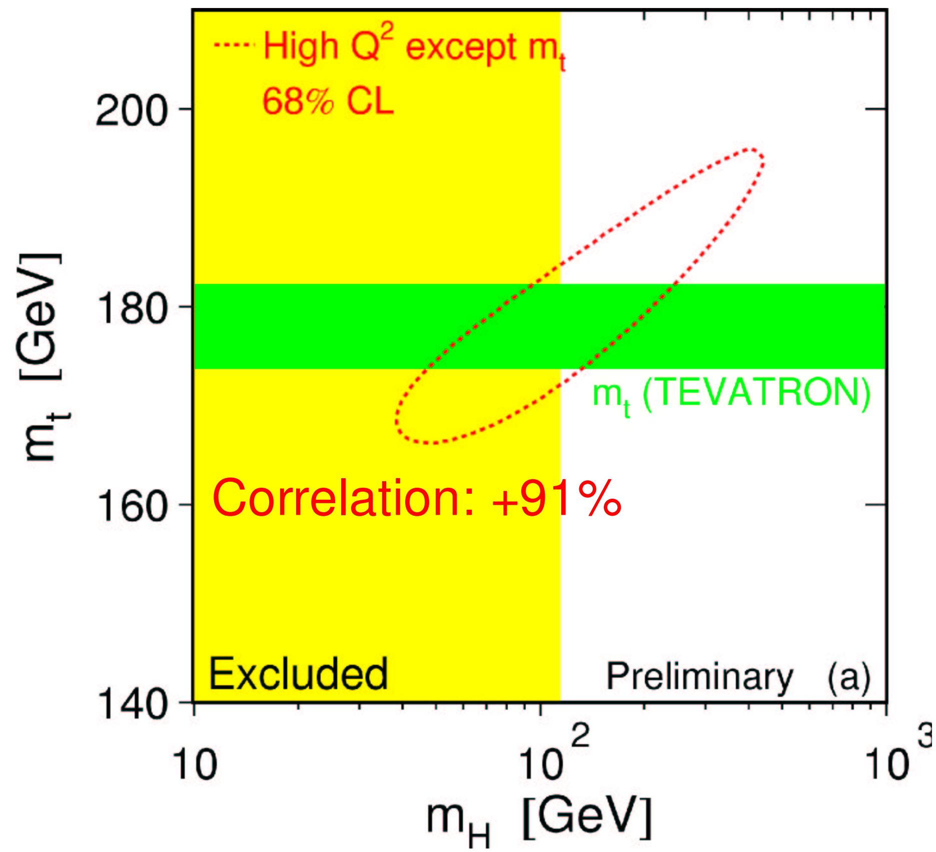
Good agreement:
Successful SM test

Both data sets prefer a light Higgs boson



Heavy Particle Masses: Top Quark

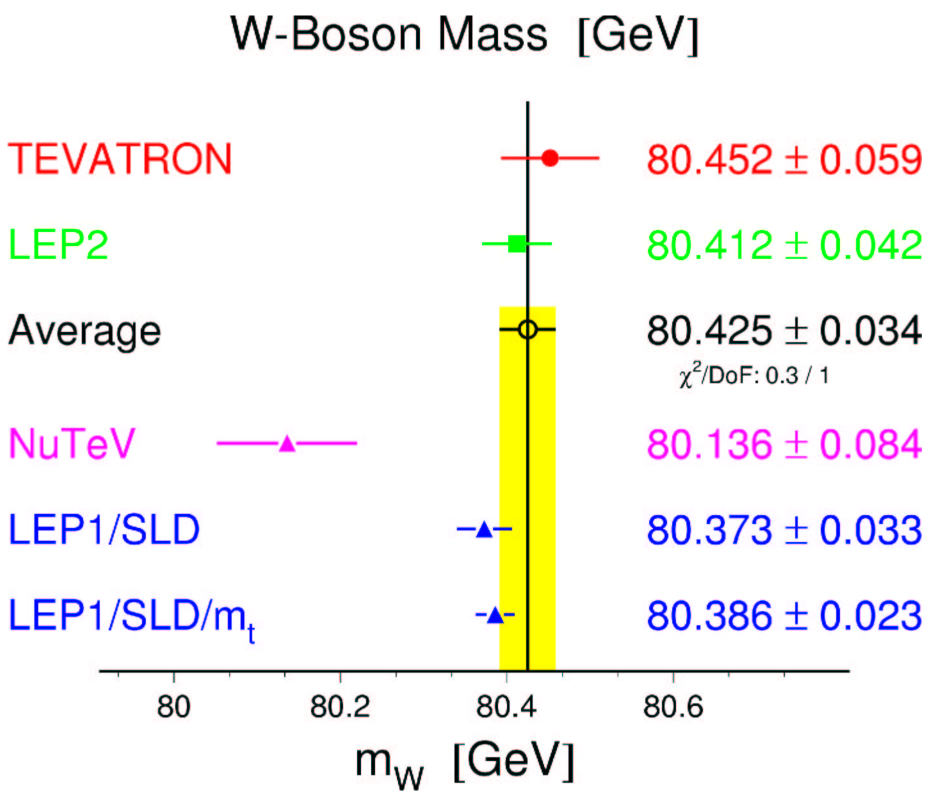


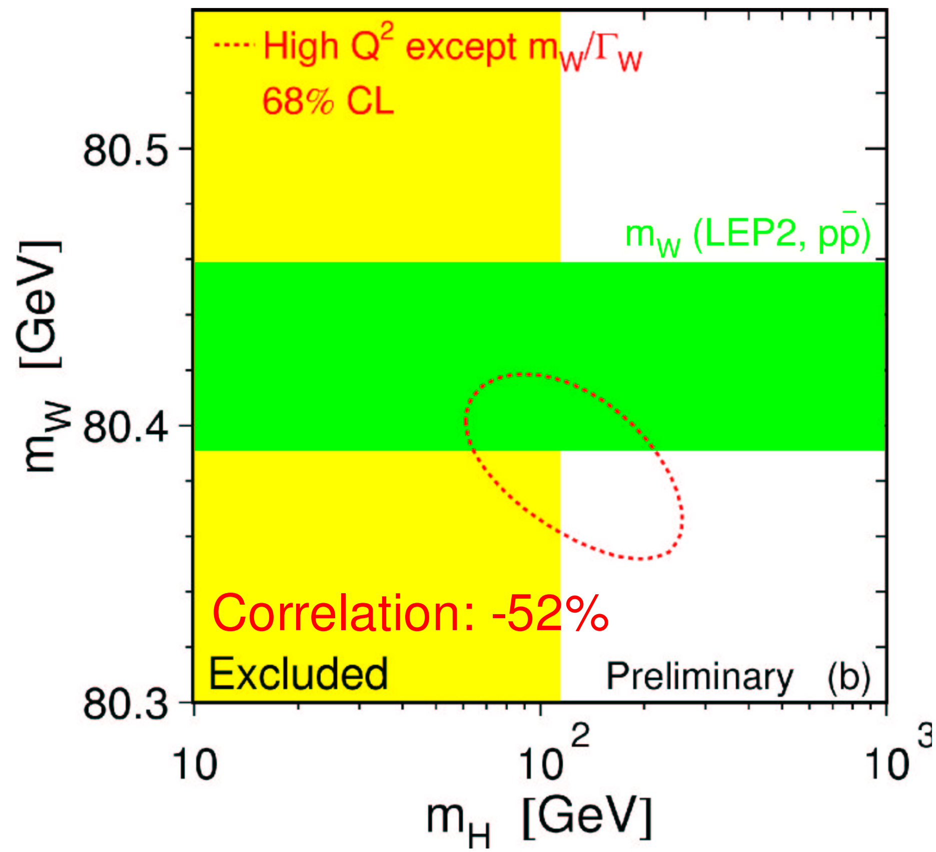


Predicted M_{top} in very good agreement with measurement

Measured M_{top} more than twice as precise as prediction

Heavy Particle Masses: W Boson





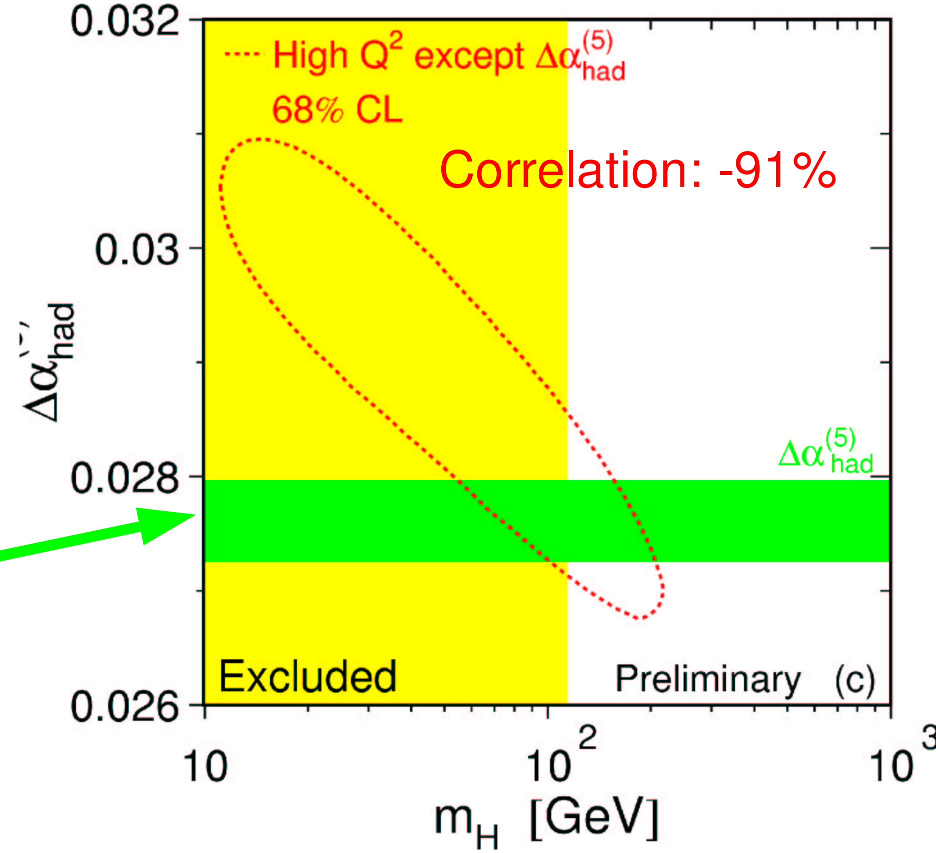
Predicted and measured M_W within ~1 σ

Measured M_W not yet as precise as prediction

Hadronic Vacuum Polarisation

Fermion loops cause running of α:

- Leptonic contribution calculated
- Hadronic contribution derived from
  - τ decays
  - hadronic cross section at low $\sqrt{s}$



Experimentally driven result:

$\Delta\alpha_{had}(M_Z) = 0.02761 \pm 0.00036$

Theory driven result (more pQCD):

$\Delta\alpha_{had}(M_Z) = 0.02747 \pm 0.00012$

Subject of ongoing experimental and theoretical work:

- New measurements by CMD-2, KLOE, BABAR/BELLE, CLEO-c
- Discrepancy between results derived from τ and e^+e^- data

Global Standard Model Analysis

Fit results:

$\Delta\alpha_{had}$ = 0.02768 ± 0.00035
$\alpha_s(M_Z)$ = 0.1186 ± 0.0027
M_Z = 91.1873 ± 0.0021 GeV
M_{top} = 178.1 ± 3.9 GeV
$\log_{10}M_H$ = 2.05 ± 0.20

M_{Higgs} = 113^{+62}_{-42} GeV

$\Delta\alpha_{had}$ marginally improved
$\alpha_s(M_Z)$ one of the best
M_Z ~ unchanged
M_{top} error improved by 10%

Correlations:

1.00				
-0.02	1.00			
-0.01	-0.02	1.00		
-0.06	0.10	-0.03	1.00	
-0.48	0.16	0.06	**0.67**	1.00

Strong correlations with:

fitted $\Delta\alpha_{had}$ - reduced to
-0.18 with pQCD $\Delta\alpha_{had}$

fitted M_{top} -
25% shift in M_{Higgs} for
4 GeV shift in meas. M_{top}

M_{top} measurement crucial!

Global Standard Model Analysis

$M_{Higgs} = 113^{+62}_{-42}$ GeV

Incl. theory uncertainty:

$M_{Higgs} < 237$ GeV (95%CL)

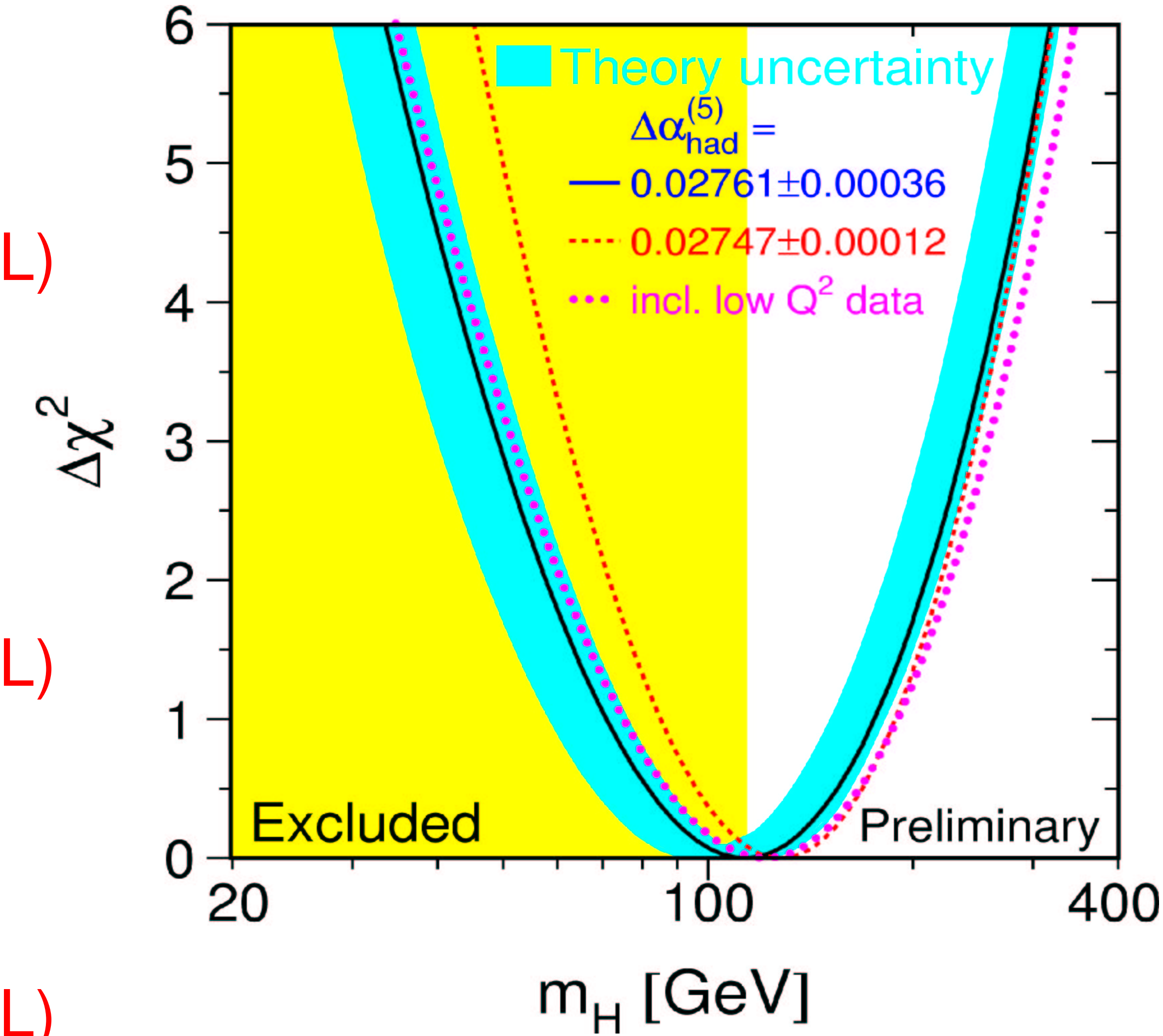
does not include:

Direct search limit (LEP-2):

$M_{Higgs} > 114$ GeV (95%CL)

Renormalise probability for $M_H > 113$ GeV to 100%:

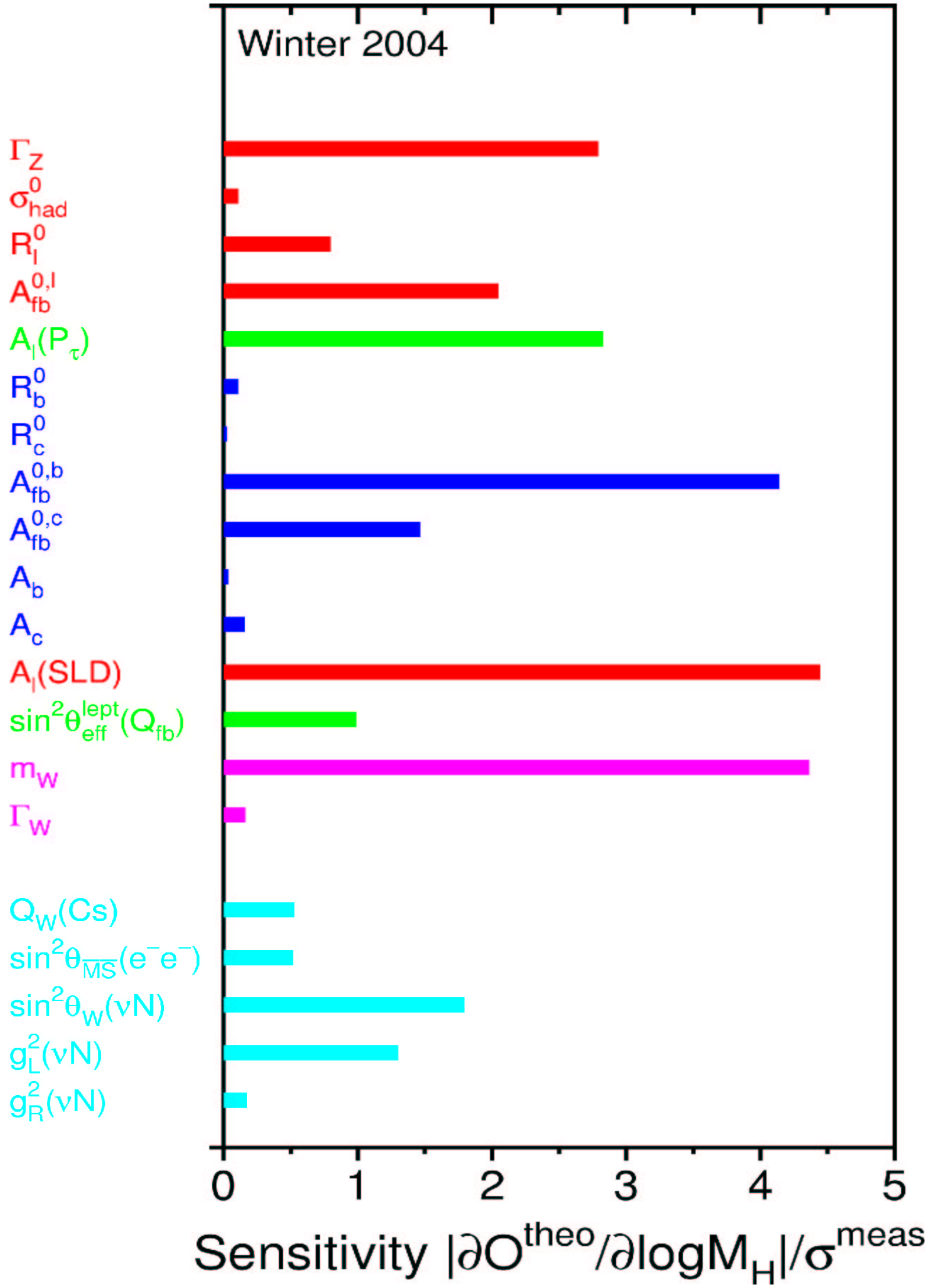
$M_{Higgs} < 269$ GeV (95%CL)

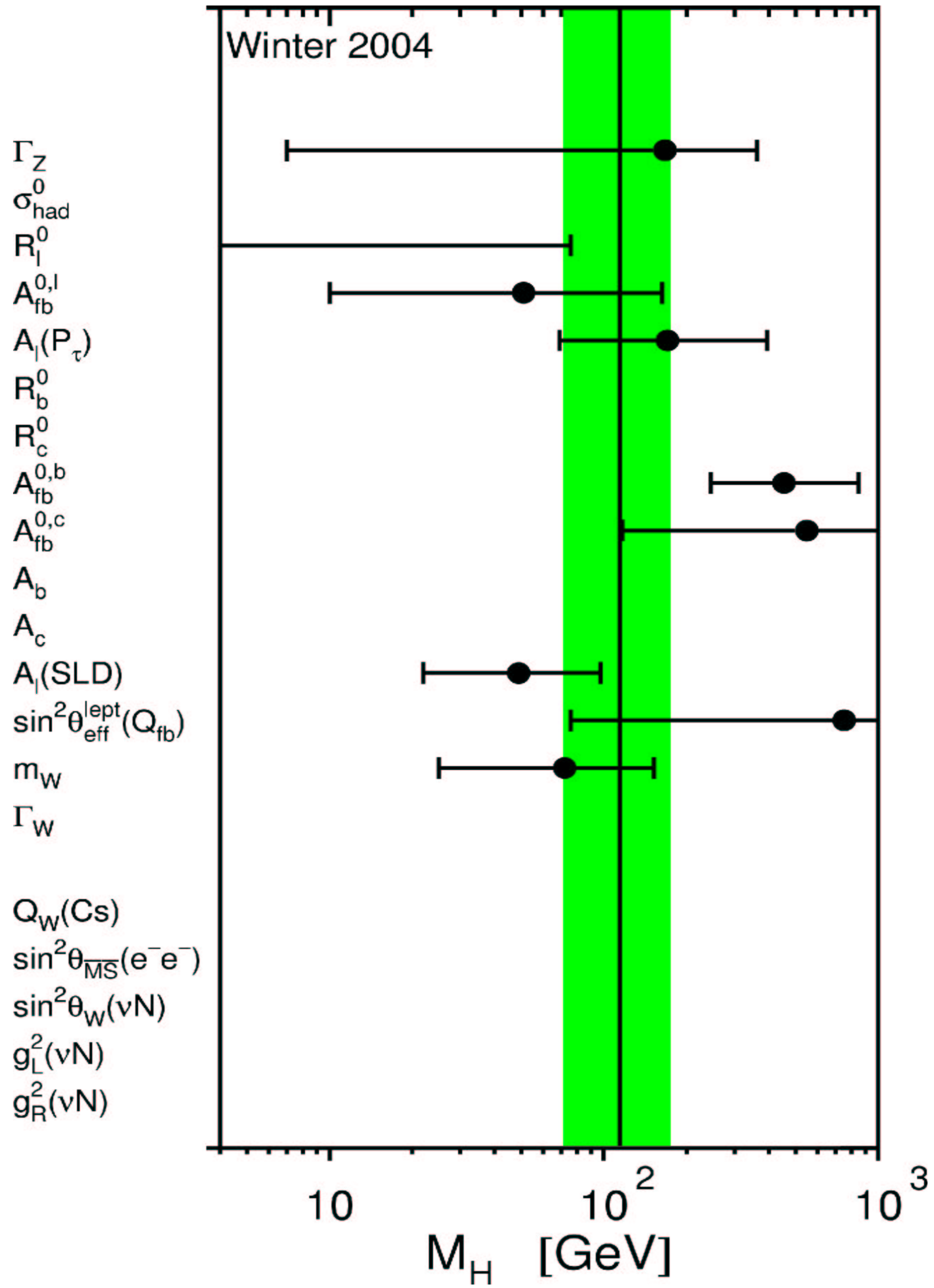


Theory uncertainty:

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

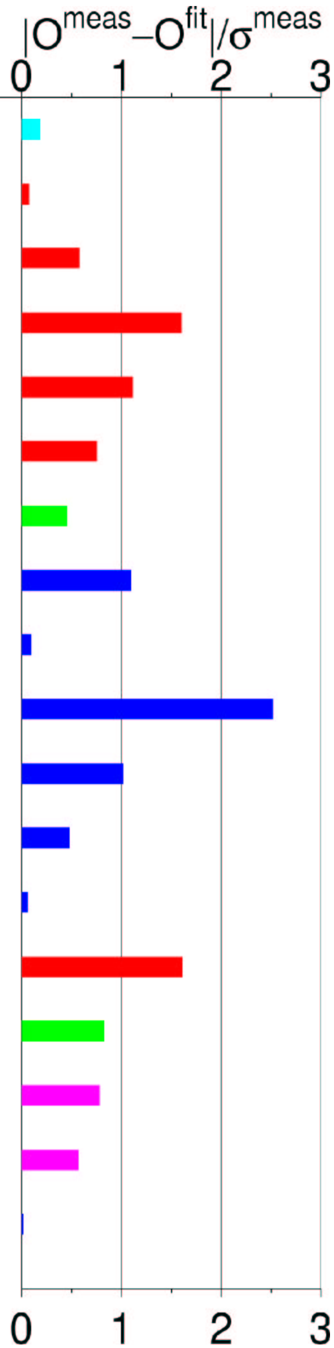
Higgs Sensitivities and Constraints





Global Standard Model Analysis

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02761 ± 0.00036	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1873
Γ_Z [GeV]	2.4952 ± 0.0023	2.4965
σ_{had}^0 [nb]	41.540 ± 0.037	41.481
R_l	20.767 ± 0.025	20.739
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01642
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21638 ± 0.00066	0.21566
R_c	0.1720 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0997 ± 0.0016	0.1037
$A_{fb}^{0,c}$	0.0706 ± 0.0035	0.0742
A_b	0.925 ± 0.020	0.935
A_c	0.670 ± 0.026	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1480
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.425 ± 0.034	80.398
Γ_W [GeV]	2.133 ± 0.069	2.094
m_t [GeV]	178.0 ± 4.3	178.1



Fit to all 17 observables
+ $\Delta\alpha_{had}$:

χ^2/ndof = 16.3/13 (23.3%)

Largest χ^2 contribution:

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

Decided in favour of "leptons" by M_W

Afb(b) has largest pull: 2.5

Predict observables measured in reactions with: $Q^2 \ll M_W^2$

Predictions for Low-Q^2 Measurements

Electron-nucleus atomic parity violation (APV) in atomic transitions:

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 $Q^2 \rightarrow 0$ (q=u,d)

$Q_W(Cs) = -72.84 \pm 0.49$ SM fit: -72.91 ± 0.04 ✔

Møller scattering (e^-e^-) with polarised e^- beam (E-158 experiment):

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

$A_{PV} = (\sigma_R-\sigma_L)/(\sigma_R+\sigma_L) \propto Q_W(e^-) = -4g_{Ae}g_{Ve}$ at $Q^2 \sim 0.03$ GeV^2

$\sin^2\Theta_{eff}(Q=M_Z) = 0.2296 \pm 0.0023$ SM fit: 0.2314 ± 0.0001 ✔

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 $\langle Q^2 \rangle \sim 20\ \mathrm{GeV}^2$

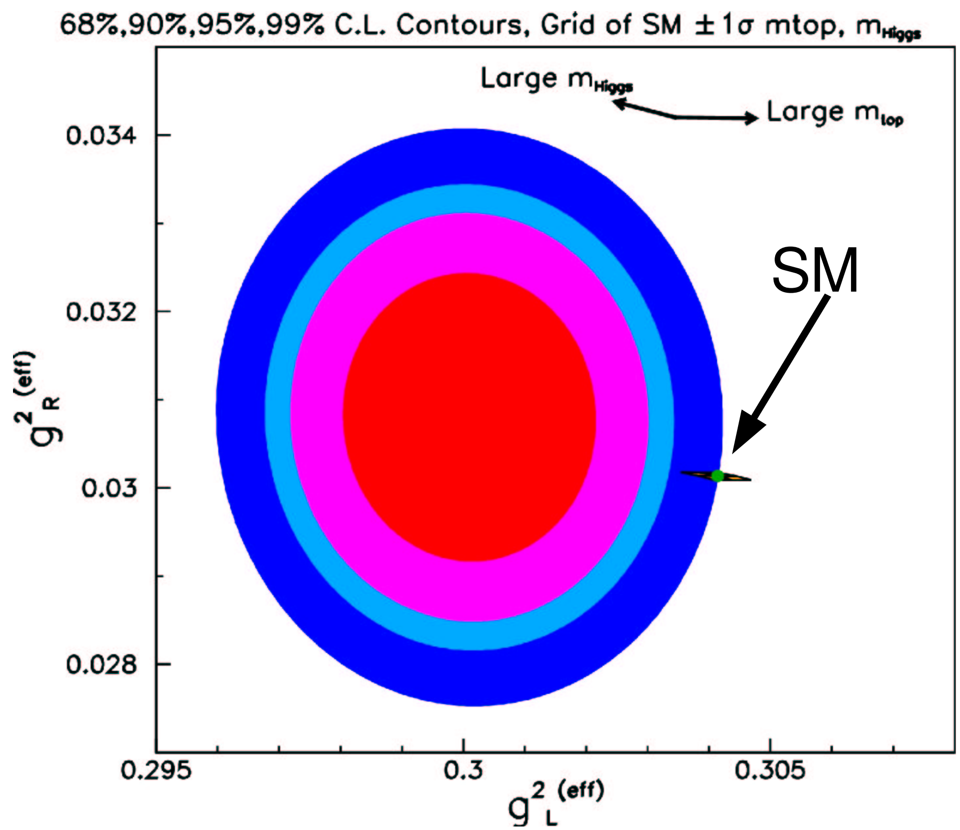
Historically result quoted in terms of: $\sin^2\Theta_W = 1-(M_W/M_Z)^2$

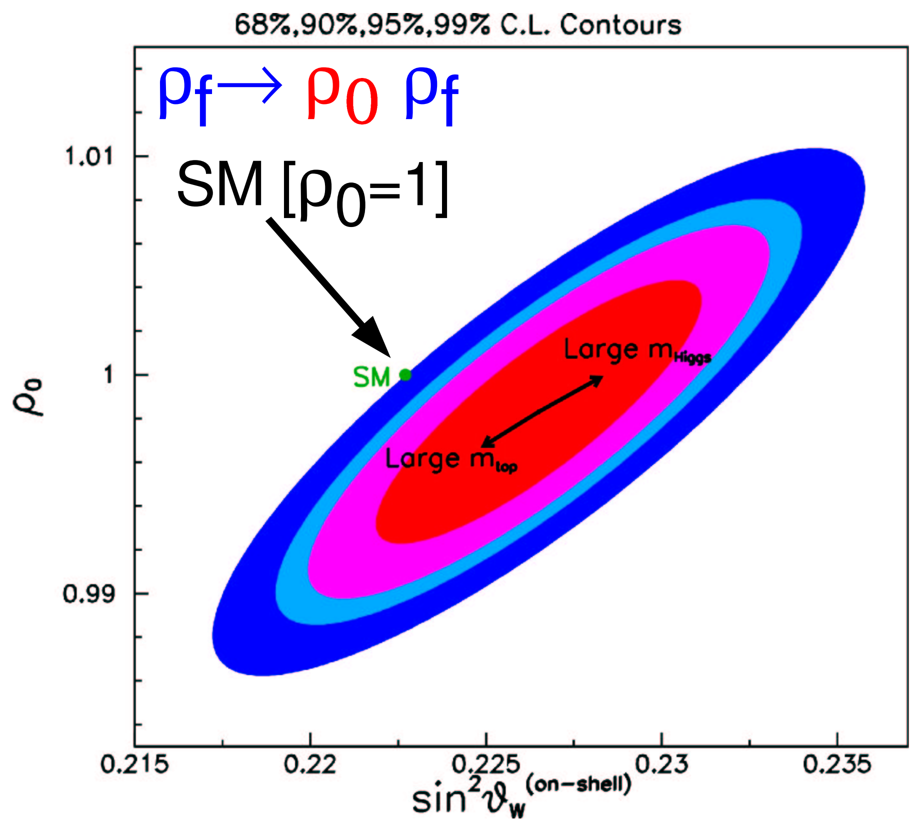
Factor two more precise than previous ν N world average

NuTeV's Result

$$\sin^2\theta_W = 1-\frac{M_W^2}{M_Z^2} = 0.2277 \pm 0.0016 - 0.00022\frac{M_{top}^2-(175\,GeV)^2}{(50\,GeV)^2} + 0.00032\ln\frac{M_{Higgs}}{150\,GeV} \qquad [\rho=\rho_{SM}]$$

SM fit: 0.2226 ± 0.0004   Difference of 3.1 σ!

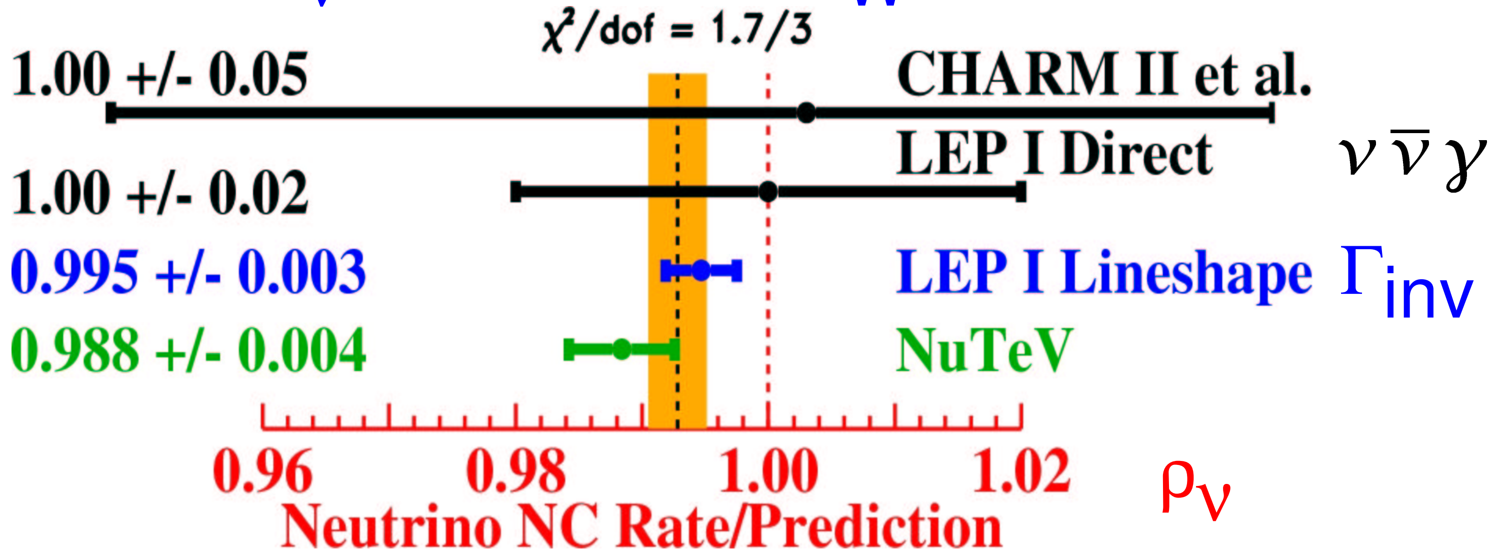




Quote result in terms of effective couplings, not $\sin^2\Theta_W$ nor M_W!

NuTeV's Result

Strength of ν coupling ρ_ν (assuming $\sin^2\Theta_W$ ok):



Various explanations:

New physics:

Z', contact interactions, lepto-quarks, new fermions, neutrino oscillations, . . .

But likely rather old physics:

Theory uncertainty (QED, LO PDFs)

Isospin violating PDFs, sea asymmetry

Conclusions

Wealth of high-precision measurements:

Many with high sensitivity to radiative corrections

Most measurements agree with expectations:

Successful test of SM loop corrections

Stringent constraints on new physics beyond the SM

But have two ~3-sigma effects:

Spread in $\sin^2\Theta_{eff}$ at the Z pole, and NuTeV's result

SM Higgs boson seems to be "around the corner - sort of"

Future:

Precise theoretical calculations - including theory uncertainties

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

Check Higgs-mass prediction!