Combined Electroweak Analysis

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Outline

Summary of precision electroweak measurements

Tests of the electroweak Standard Model

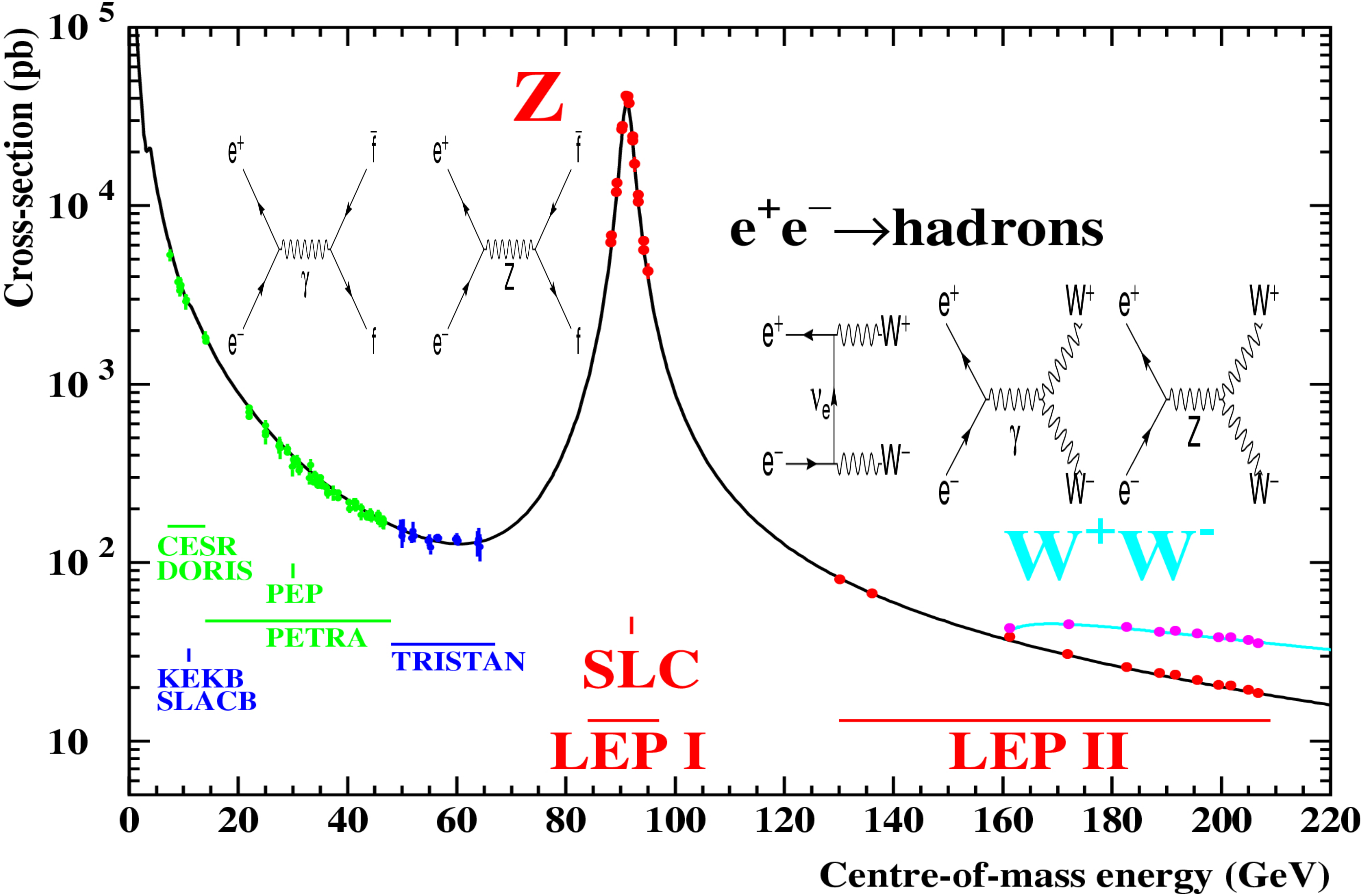
The Higgs Boson of the Standard Model

Outlook and 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

e^+e^- Interactions



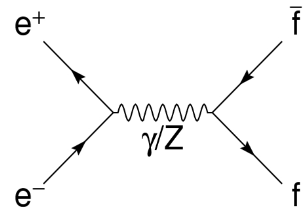
Z-Pole Physics

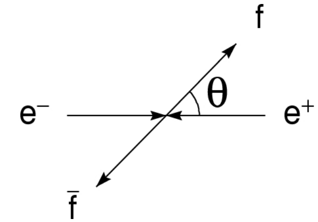
Cross sections:

$$M_Z = 91.1875 \pm 0.0021 \;\; GeV$$

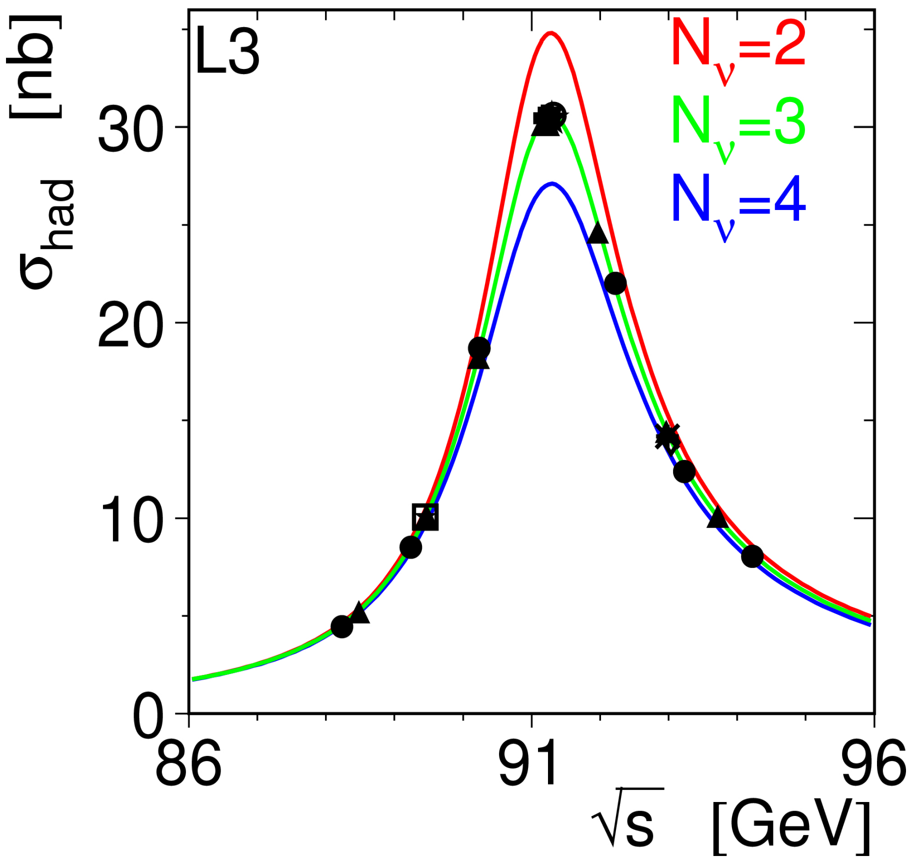
$$\Gamma_Z = 2.4952 \pm 0.0023 \;\; GeV$$

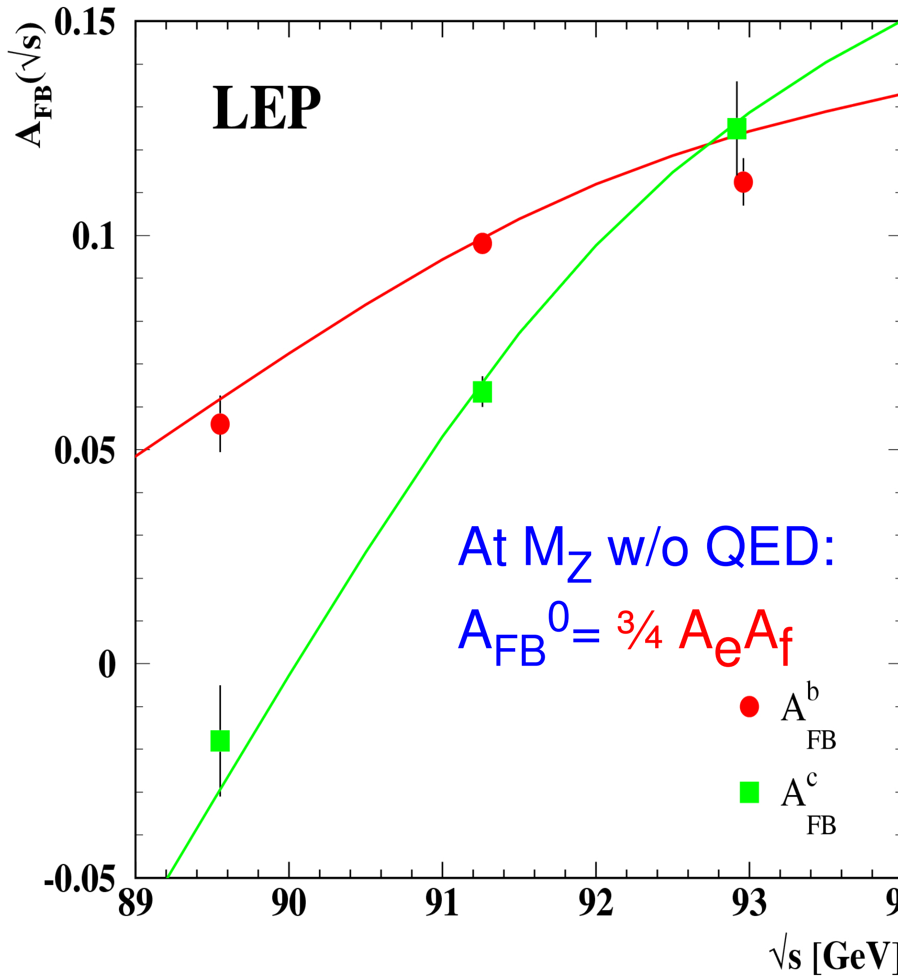
$$N_\nu = 2.9840 \pm 0.0082$$





$$A_{FB} = \frac{N_F - N_B}{N_F + N_B}$$





$$\Gamma(Z \to f\bar{f}) \propto g_{Vf}^2 + g_{Af}^2$$

$$A_f = 2\frac{g_{Vf}/g_{Af}}{1+(g_{Vf}/g_{Af})^2} \Leftrightarrow \sin^2\theta_{eff}$$

Comparison of all Z-Pole Asymmetries

Effective electroweak mixing angle:

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

$= 0.23153 \pm 0.00016$

$\chi^2/ndof = 11.8/5$ [3.7%]

Subsequent observation:

0.23113±0.00021 leptons

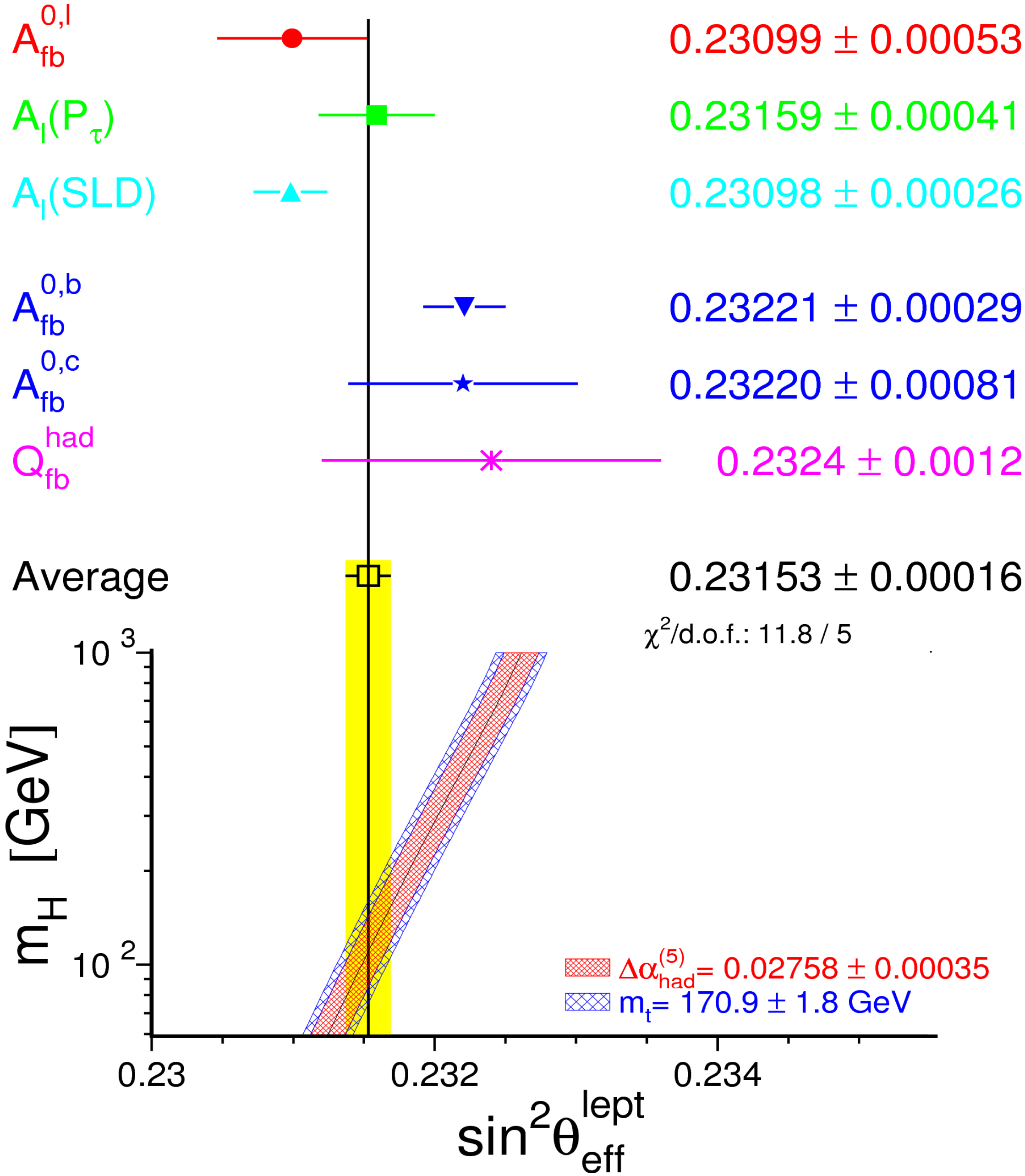
0.23222±0.00027 hadrons

3.2 σ difference

But is really:

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

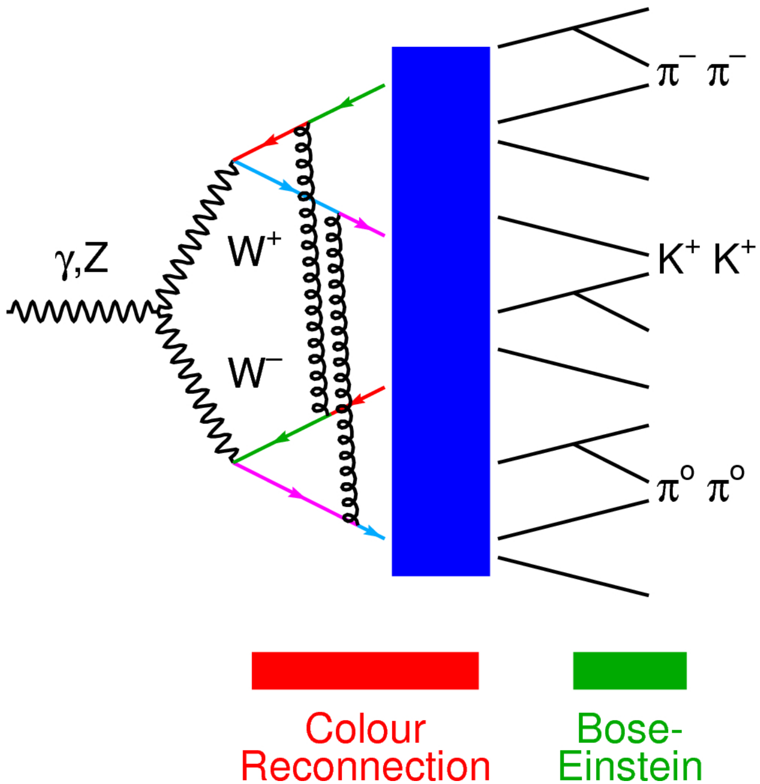
3.2 σ difference

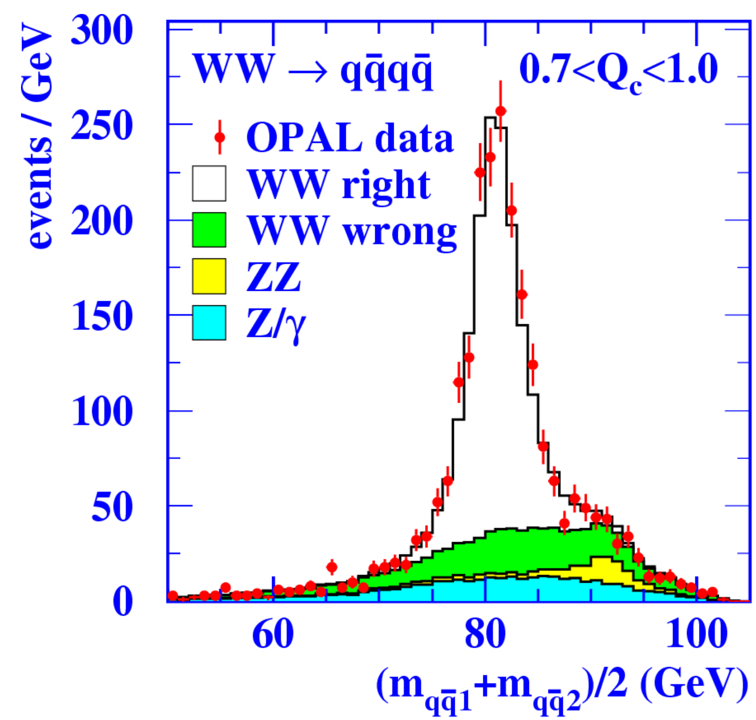


Low vs. high Higgs-boson mass

W Boson Mass at LEP-2

LEP-2: $e^+e^- \rightarrow W^+W^- \rightarrow$ qqqq, qqlν, lνlν   Invariant mass M_{inv}(ff)





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

M_W average dominated by qqlν channel (qqlν: 78%, qqqq: 22%)

FSI test: mass difference (calculated without FSI uncertainties):

$M_W(\mathrm{qqqq}) - M_W(\mathrm{qql\nu}) = -12 \pm 45$ MeV

Need final CR limit from dedicated studies to limit CR error on M_W

W Boson Mass at the Tevatron

Tevatron: $p\bar{p} \to WX$, $W \to e\nu, \mu\nu$

Transverse mass $M_T(l\nu)$

Run-I results (~ 100/pb):

CDF: 80433 ± 79 MeV

DO : 80483 ± 84 MeV

Preliminary Run-II:

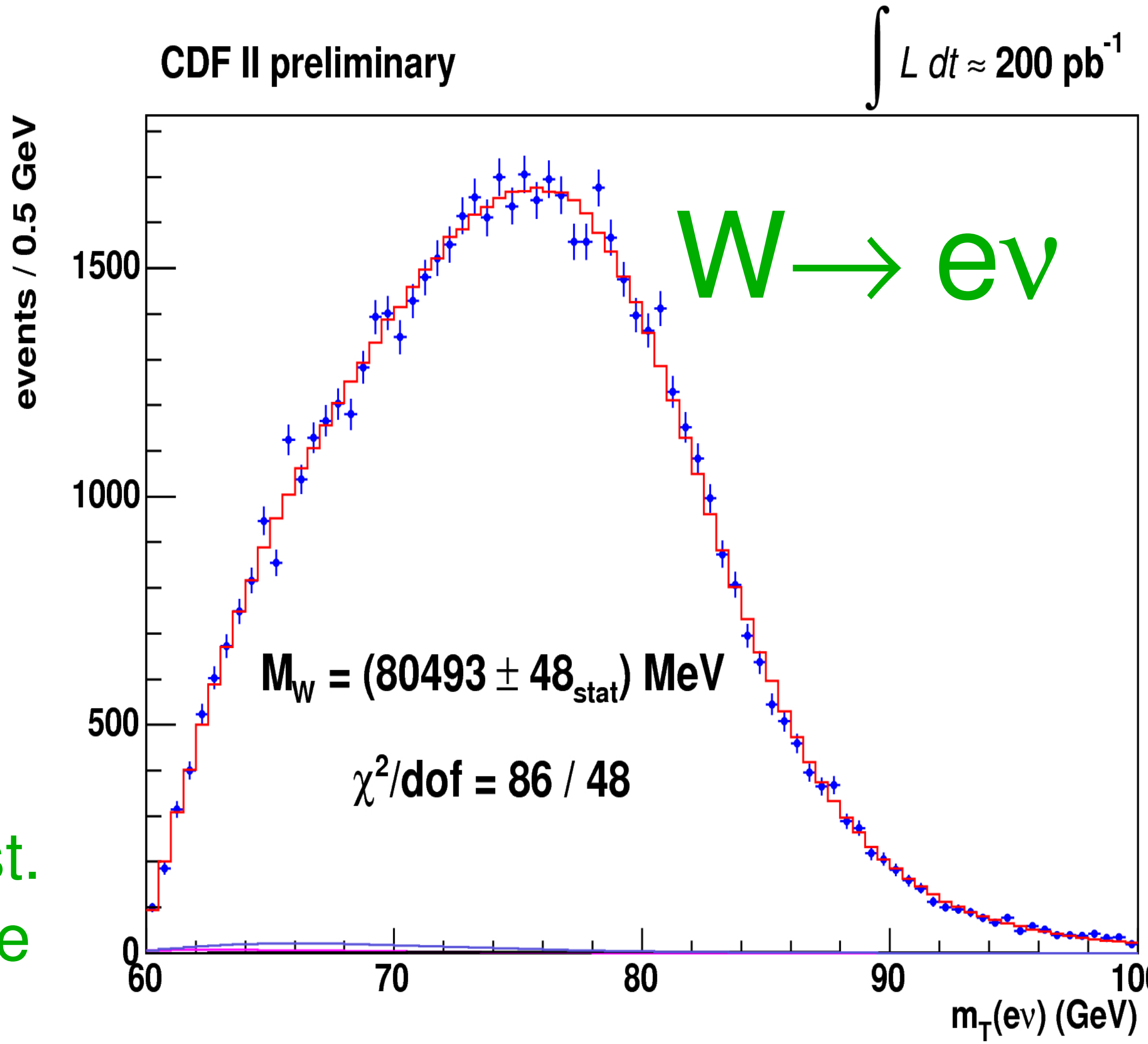
CDF: 80413 ± 48 MeV

Combined $e\nu + \mu\nu$

Uncertainties:

34 MeV stat., 34 MeV syst.

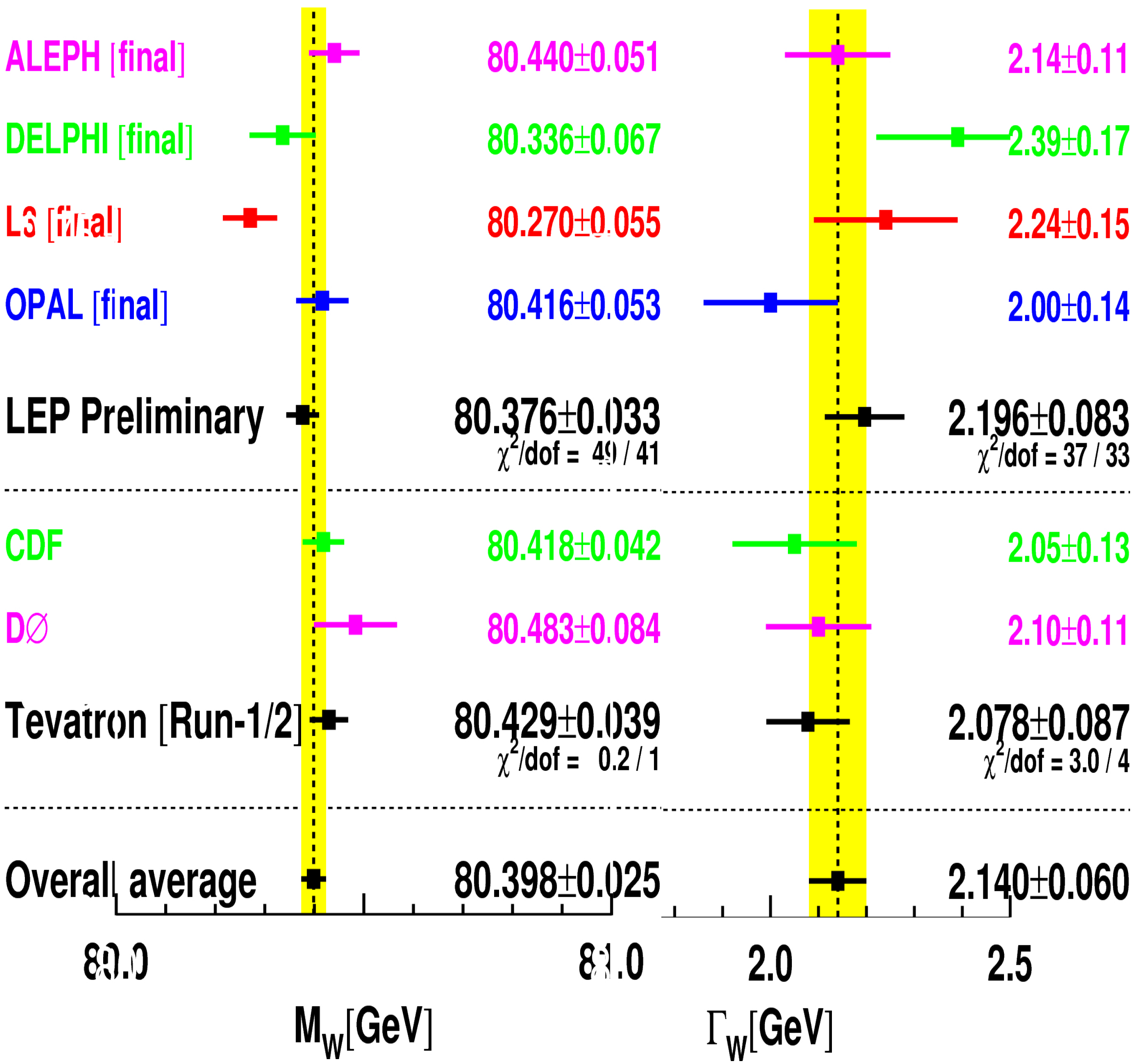
Syst.: Lepton energy scale

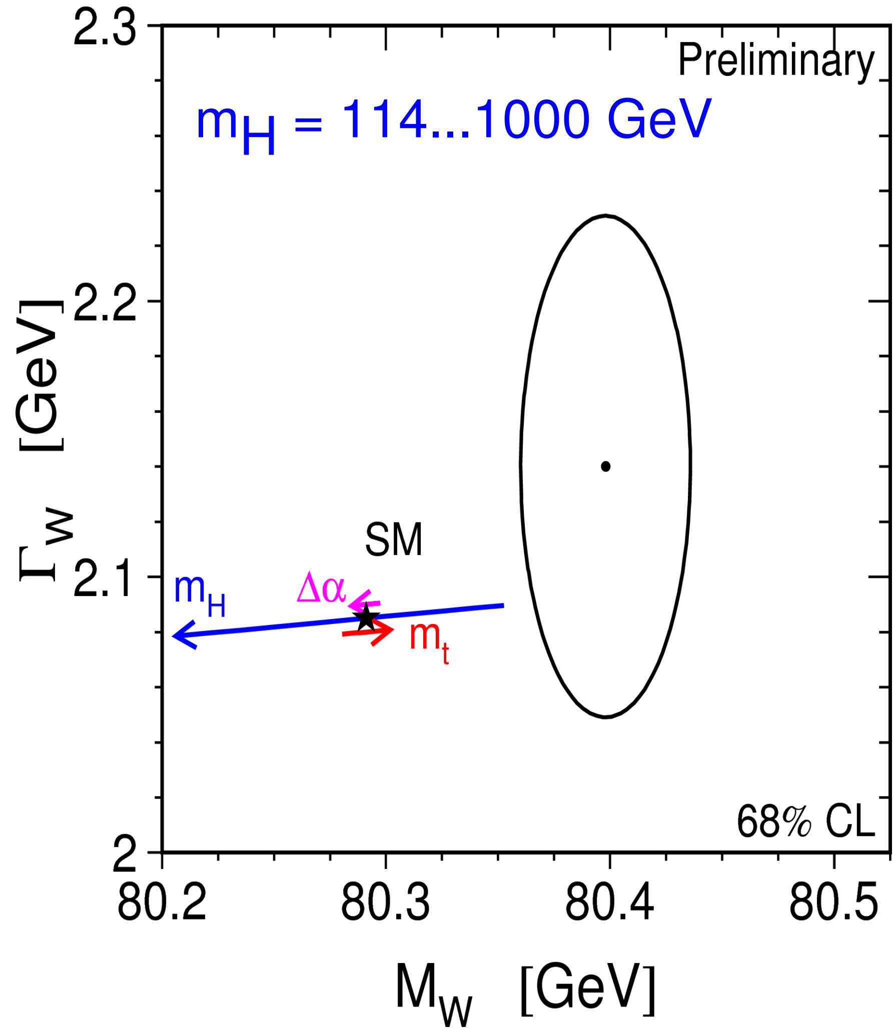


Uncertainty of ~25 MeV expected for 2/fb of data

W Boson - Mass and Width

Good agreement between all six experiments:





SM comparison:

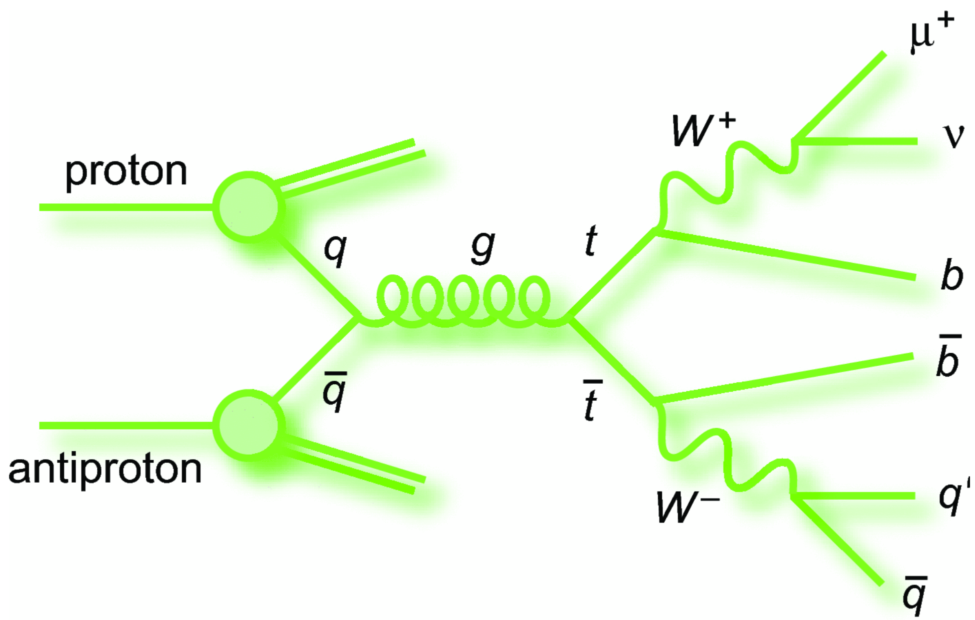
Small Higgs-boson mass

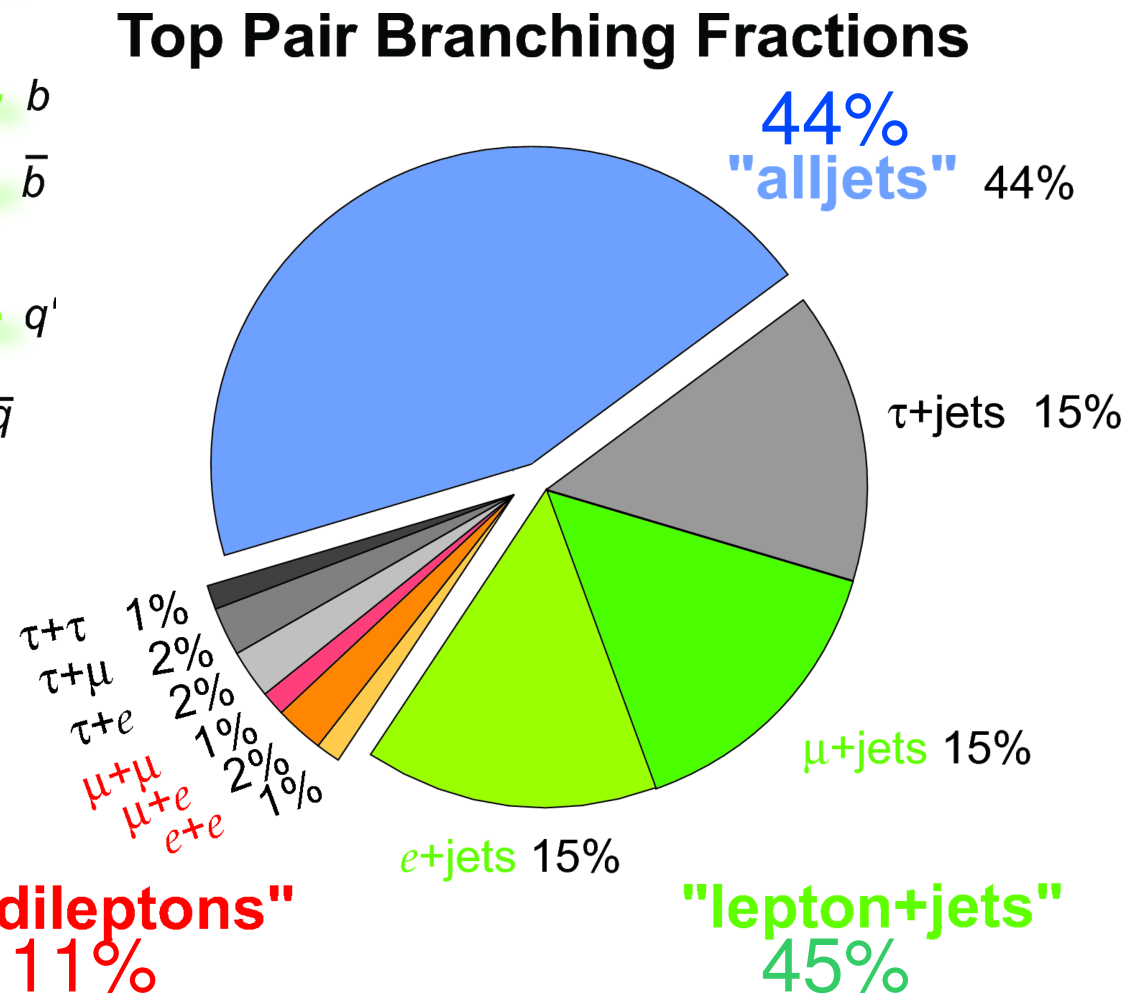
Top Physics

Tevatron: only source of top quarks in the world!

Mainly top-pair production

$$p\bar{p} \to t\bar{t}X, \quad t\bar{t} \to b\bar{b}W^+W^-$$
$$W^- \to q\bar{q}, l^-\bar{\nu}$$





Total cross section: ~7.5 pb

Event signature given by W-pair decay modes

Top-Quark Mass

Separate final states:

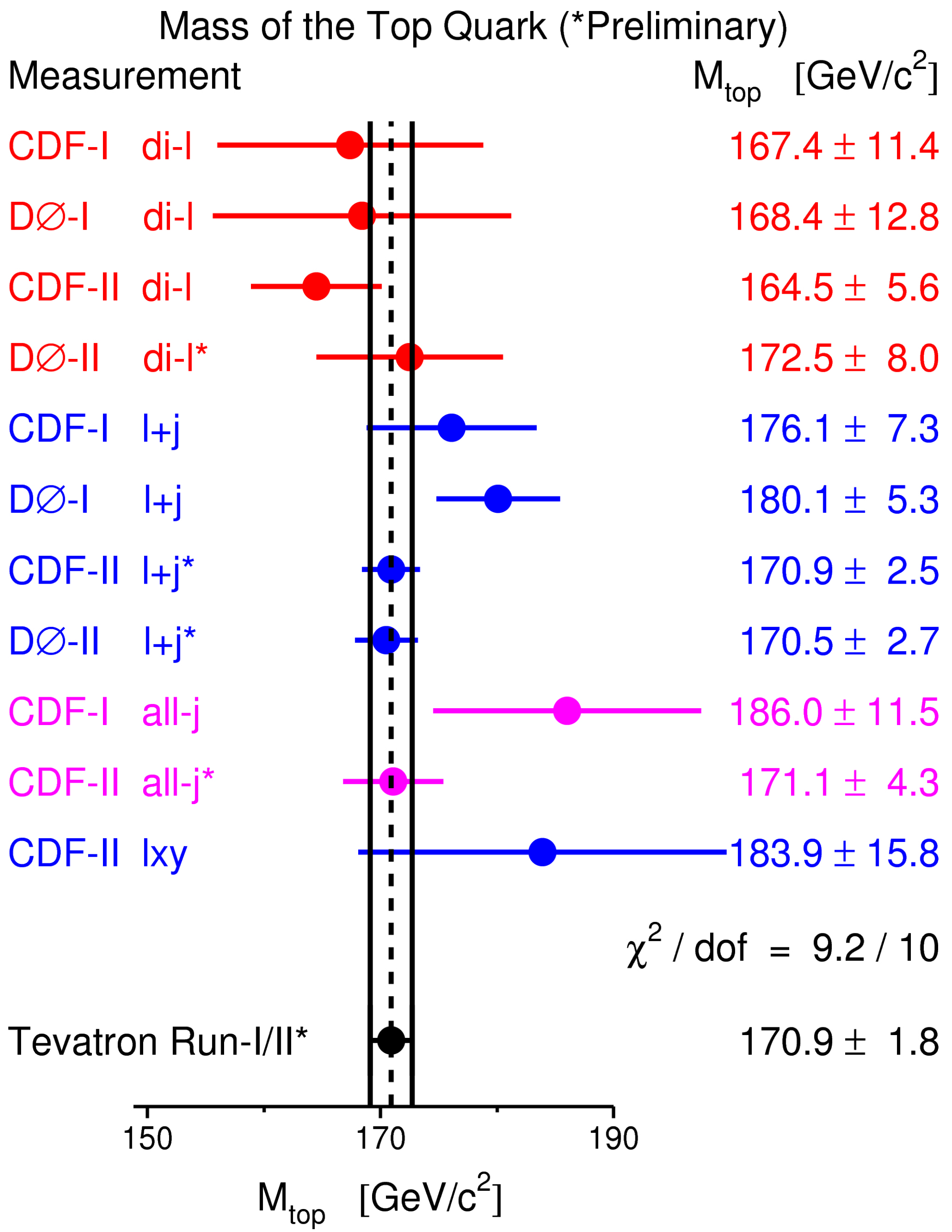
- 163.5 ± 4.5 GeV   di-leptons
- 171.2 ± 1.9 GeV   lepton+jets
- 172.2 ± 4.1 GeV   all-jets

Reduction of JES systematics:

- In-situ calibration
- using W-mass constraint

Systematic theory errors:

- Mass definition (in MC)
- Signal model
- Colour reconnection effects



Run-II prel.: M_{top} = 170.9 ± 1.1 (stat.) ± 1.5 (syst.) GeV   (1.1%!)

Standard Model Analysis

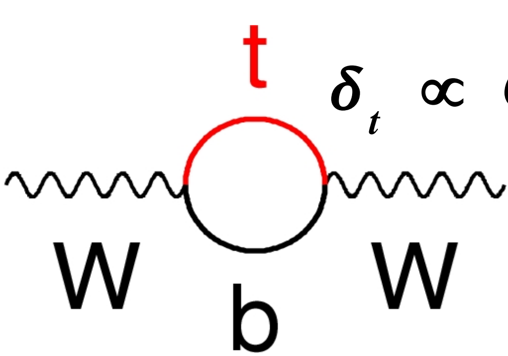
SM: Each electroweak observable calculated as a function of:

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

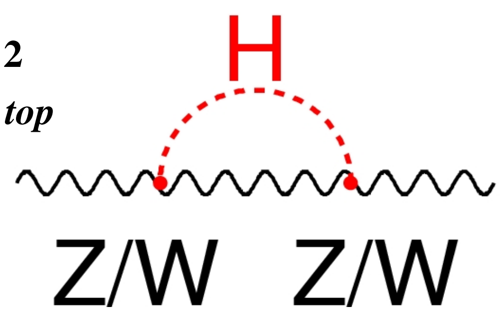
- $\Delta\alpha_{had}$: hadronic vacuum polarisation [0.02758±0.00035]
- $\alpha_s(M_Z)$: given by Γ_{had} and related observables
- M_Z: constrained by LEP-1 lineshape

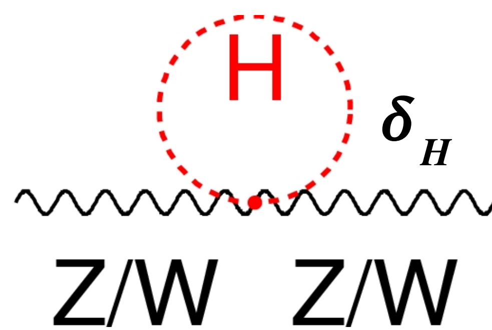
Precision requires 1st and 2nd order electroweak and mixed radiative correction calculations (QED to 3rd)

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



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





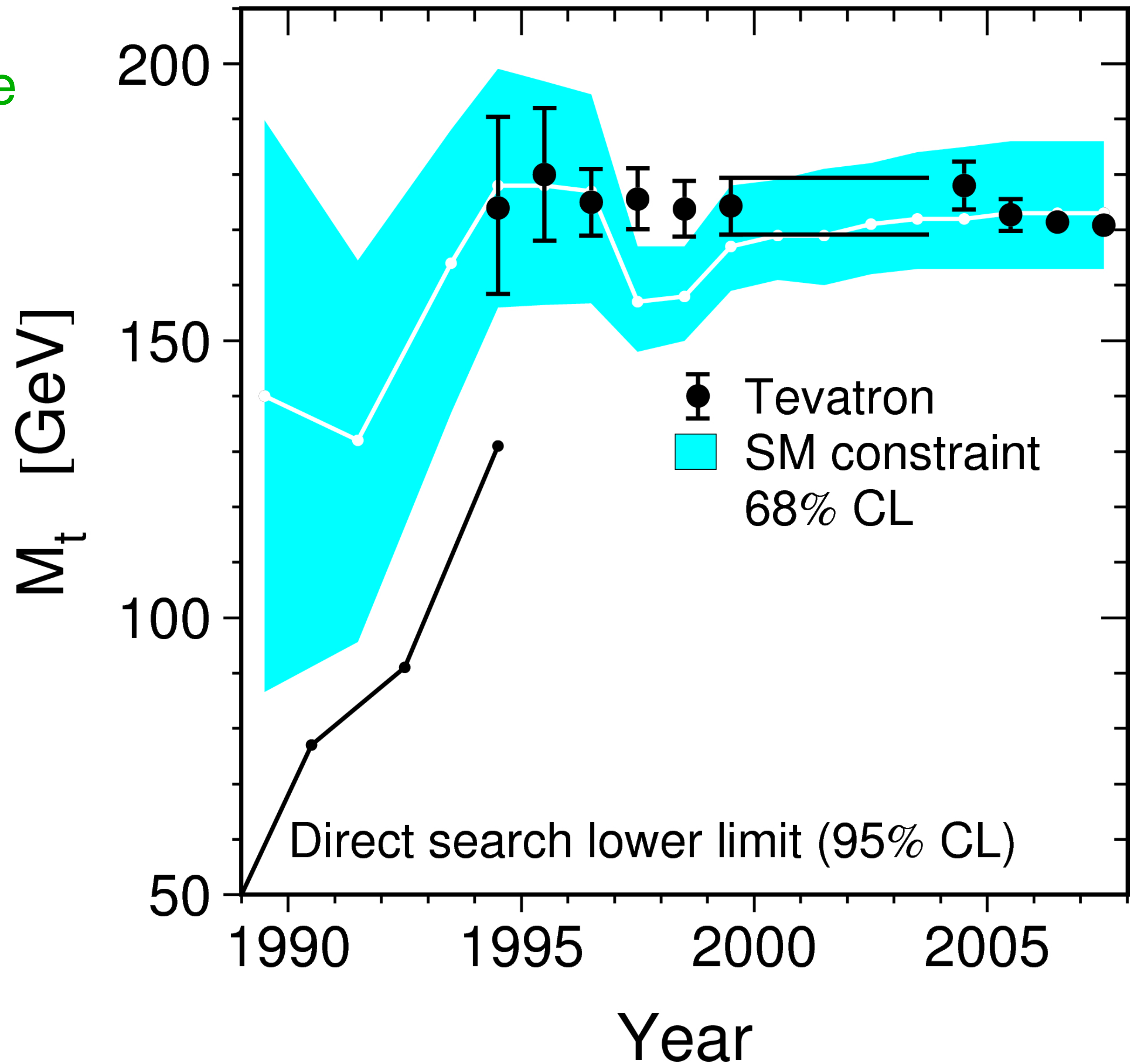
$$\delta_H \propto \ln \frac{M_{Higgs}}{M_W}$$

Calculations by programs TOPAZ0 and ZFITTER

The Top Quark

Since 1990:
Prediction of the top quark mass

1995: Discovery at the Tevatron CDF, DØ



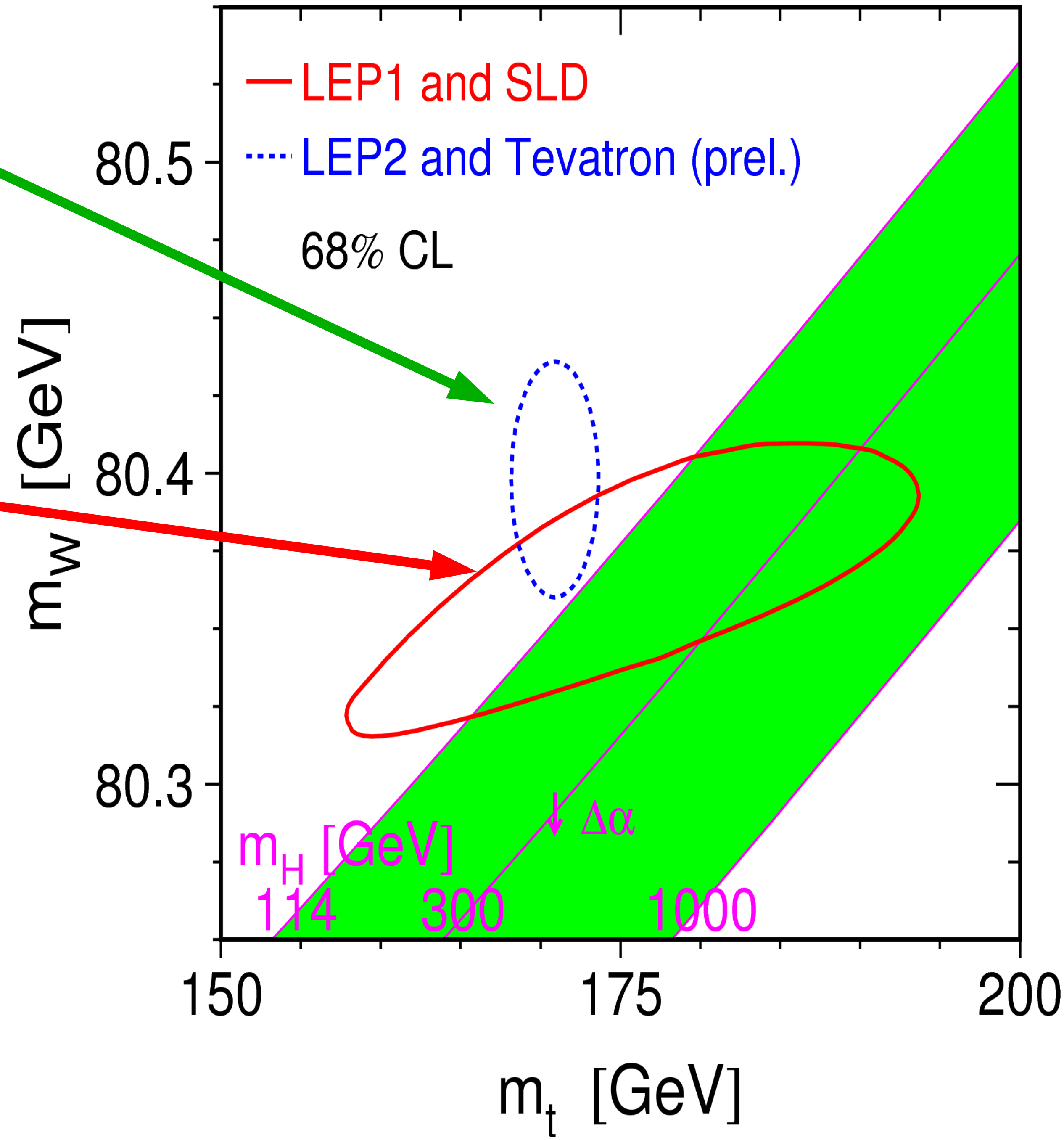
Heavy Particle Masses W and Top

Direct measurements:
  LEP2 and Tevatron

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

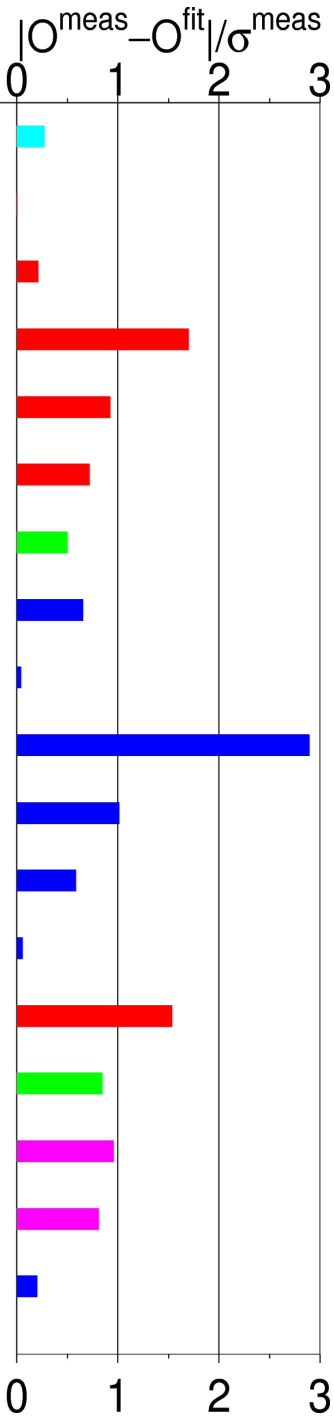
Good agreement:
  Successful SM test

Both data sets prefer a light Higgs boson



Standard Model Analysis

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1875
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957
σ_{had}^{0} [nb]	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21586
R_c	0.1721 ± 0.0030	0.1722
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.398 ± 0.025	80.374
Γ_W [GeV]	2.140 ± 0.060	2.091
m_t [GeV]	170.9 ± 1.8	171.3



Fit to 17 high-Q^2 observables plus $\Delta\alpha_{had}$:

χ^2/ndof = 18.2/13 (15.1%)

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: 2.9σ!

Standard Model Analysis

$M_H = 76^{+33}_{-24}$ GeV

Incl. theory uncertainty:

$M_H < 144$ GeV (95%CL)

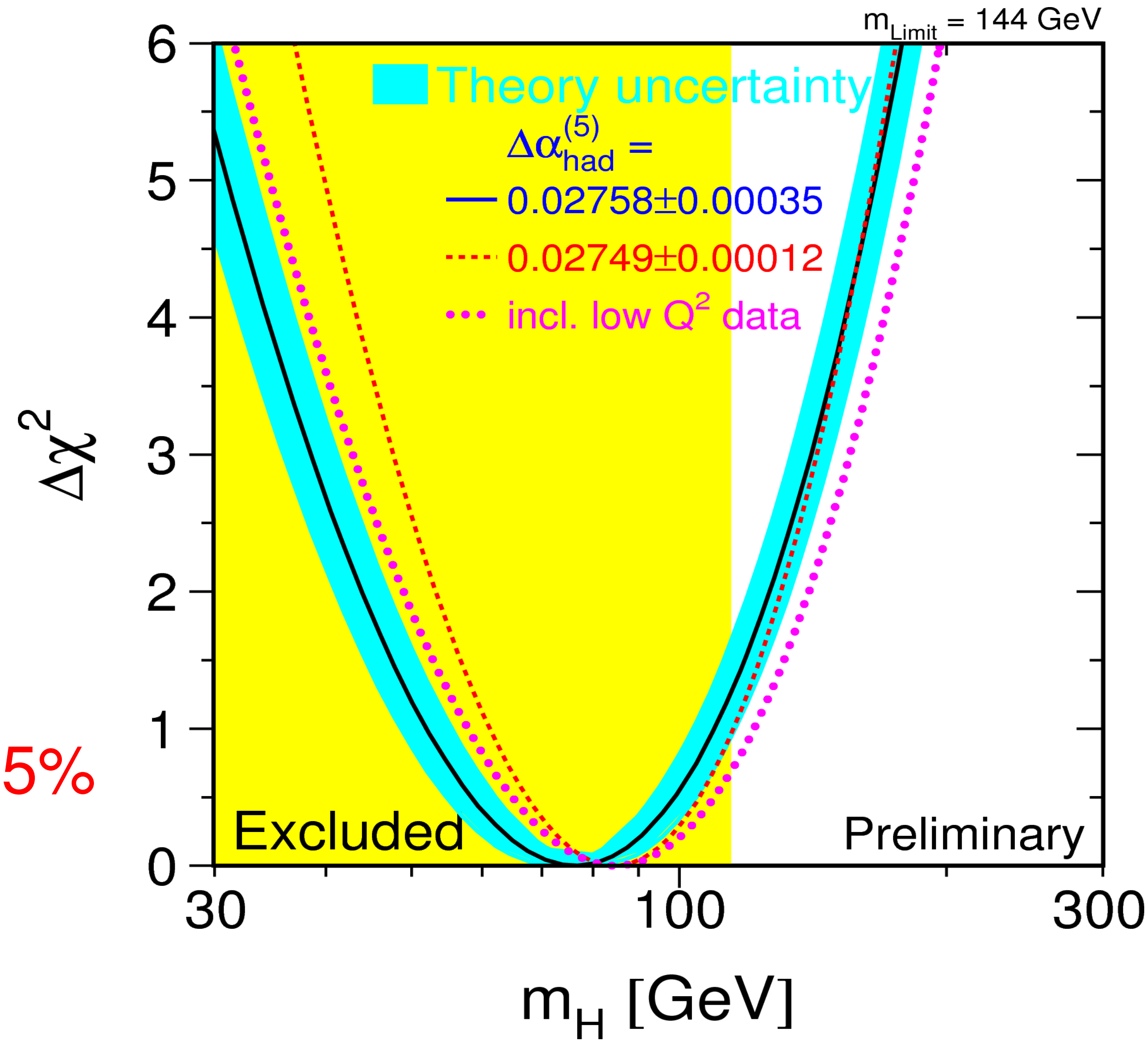
Direct search limit (LEP-2):

$M_H > 114$ GeV (95%CL)

Probability $M_H > 114$ GeV: 15%

Renormalise probability for $M_H > 114$ GeV to 100%:

$M_H < 182$ GeV (95%CL)



Theory uncertainty:

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

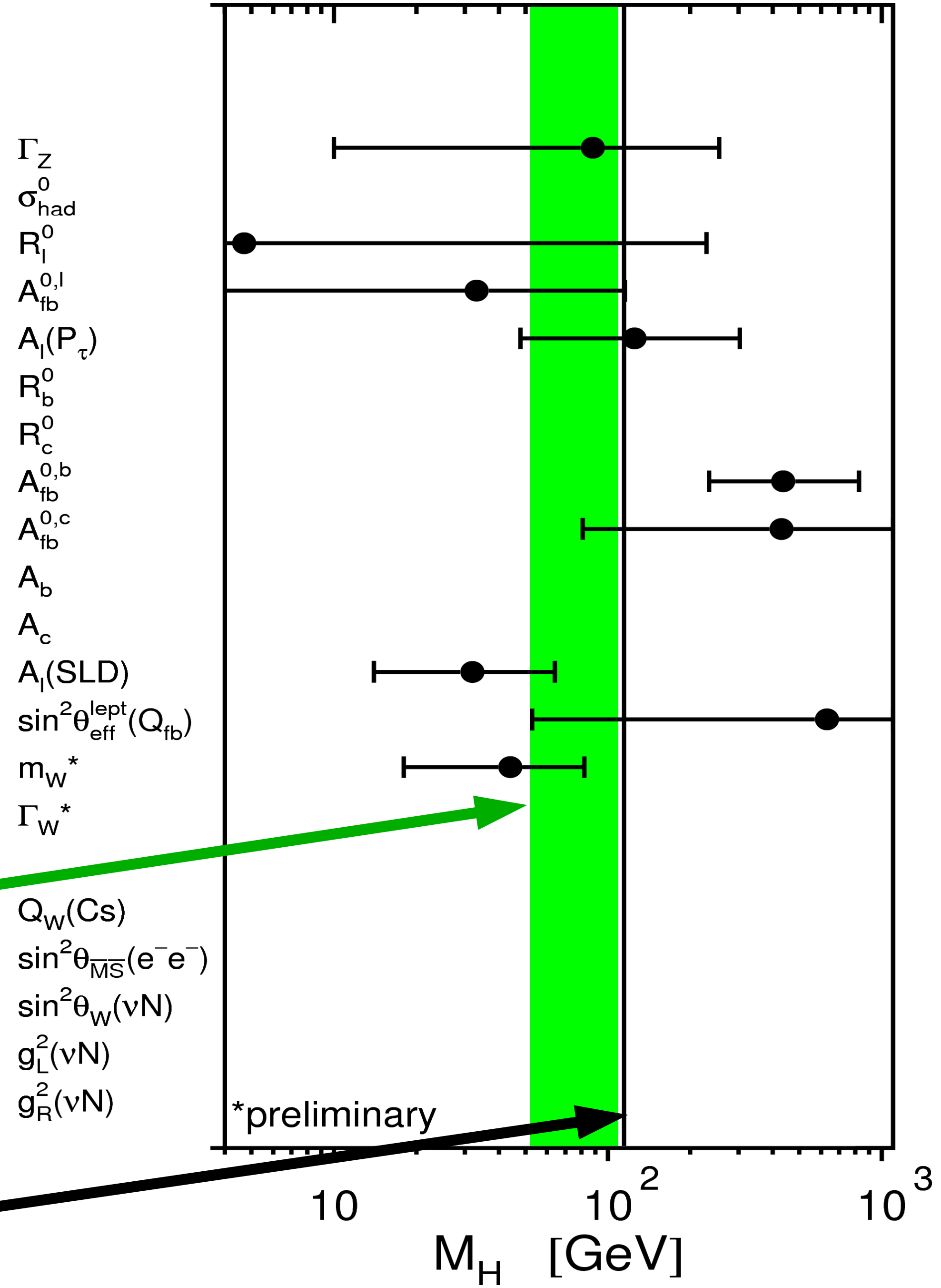
Higgs Constraints

Each observable yields a constraint on M_{Higgs}:

SM fit to observable, constraining the other 4 SM parameters:
$\Delta\alpha_{had}$, $\alpha_s(M_Z)$, M_Z, M_{top},
to their measured results

Result from global fit:
$M_{Higgs} = 76^{+33}_{-24}$ GeV

Lower limit from Higgs search:
$M_{Higgs} > 114$ GeV



Standard Model Analysis

Fit results:

$\Delta\alpha_{had}$	=	0.02768	$\pm$ 0.00034
$\alpha_s(M_Z)$	=	0.1185	$\pm$ 0.0026
M_Z	=	91.1875	$\pm$ 0.0021 GeV
M_{top}	=	171.3	$\pm$ 1.7 GeV
$\log_{10}M_H$	=	1.88	$\pm$ 0.16

$M_{Higgs} = 76^{+33}_{-24}$ GeV

$\Delta\alpha_{had}$ marginally improved

$\alpha_s(M_Z)$ one of the best

M_Z ~ unchanged

M_{top} marginally improved

Correlations:

0.03			
0.00	-0.02		
-0.01	0.03	-0.02	
-0.54	0.06	0.09	**0.39**

Strong correlations with:

fitted $\Delta\alpha_{had}$ - reduced to

-0.22 with pQCD $\Delta\alpha_{had}$

fitted M_{top} -

15 % shift in M_{Higgs} for

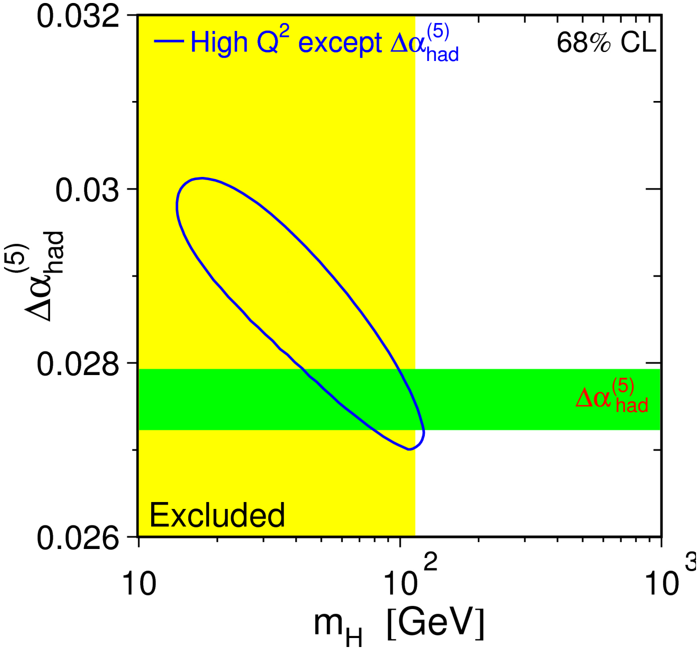
2 GeV shift in meas. M_{top}

M_{top} and $\Delta\alpha_{had}$ results crucial!

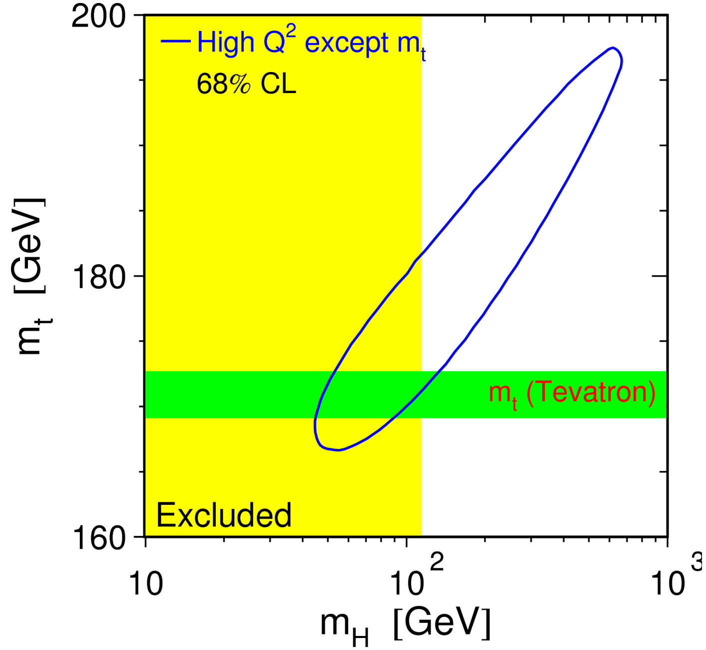
Crucial Observables

Fit to all measurements but excluding:

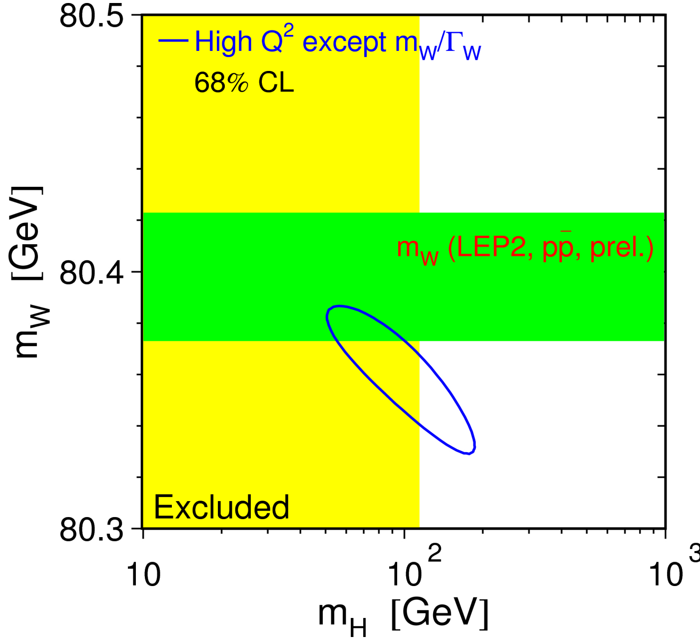
$\Delta\alpha_{had}(M_Z)$



M_{top}



M_W



Future constraints with increased precision:

Tevatron/LHC

ILC/GigaZ

Future Prospects

2007:

M_{Higgs} constrained to 37%

Tevatron/LHC:

M_W to 15 MeV

M_{top} to 1.0 GeV

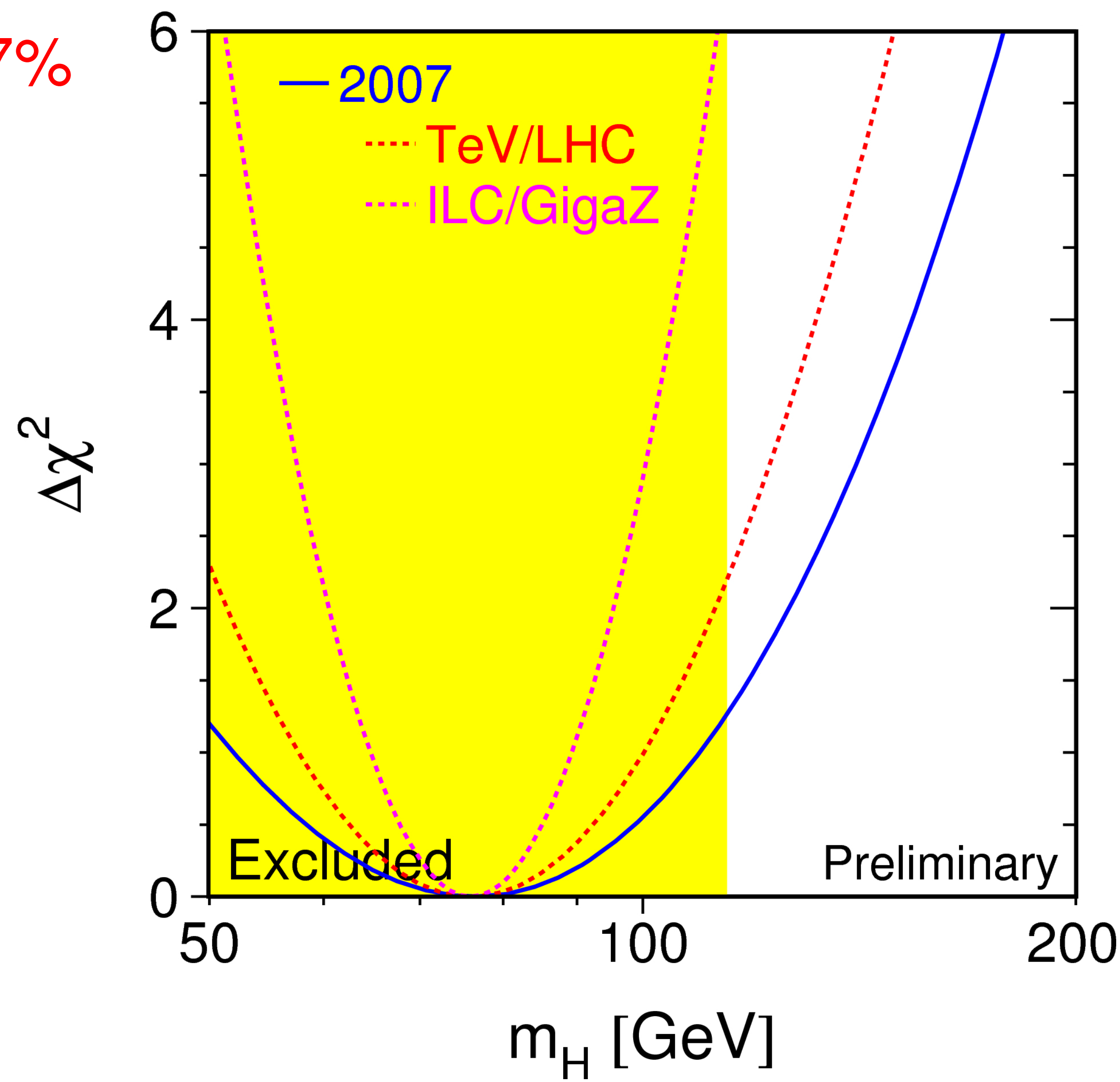
=> M_{Higgs} to 28%

ILC/GigaZ:

M_W to 7 MeV

M_{top} to 0.1 GeV

=> M_{Higgs} to 16%



Direct M_{Higgs} measurement at discovery: ~ 1% accuracy

Conclusions

Many high-precision electroweak measurements at colliders:

- Z-pole results (LEP-1, SLD) final, LEP-2 close to final!
- New exciting results from Tevatron's Run-II (W, top)

Most measurements agree well with SM expectations:

- Successful test of loop corrections
- SM Higgs boson should be light
- Theories beyond the SM tightly constrained

Future at Tevatron, LHC and ILC:

- Improved measurements in W boson and top quark physics
- Search and discovery of the Higgs boson
- Tests of the theory - mass of the Higgs boson

Backup

Heavy Flavour Results at the Z-Pole

Electroweak HF results:

$R_b = \Gamma_b/\Gamma_{had}$	0.21629 ± 0.00066
$R_c = \Gamma_c/\Gamma_{had}$	0.1721 ± 0.0030
$A_{fb}(b) = ¾ A_e A_b$	0.0992 ± 0.0016
$A_{fb}(c) = ¾ A_e A_c$	0.0707 ± 0.0035
A_b	0.923 ± 0.020
A_c	0.670 ± 0.027

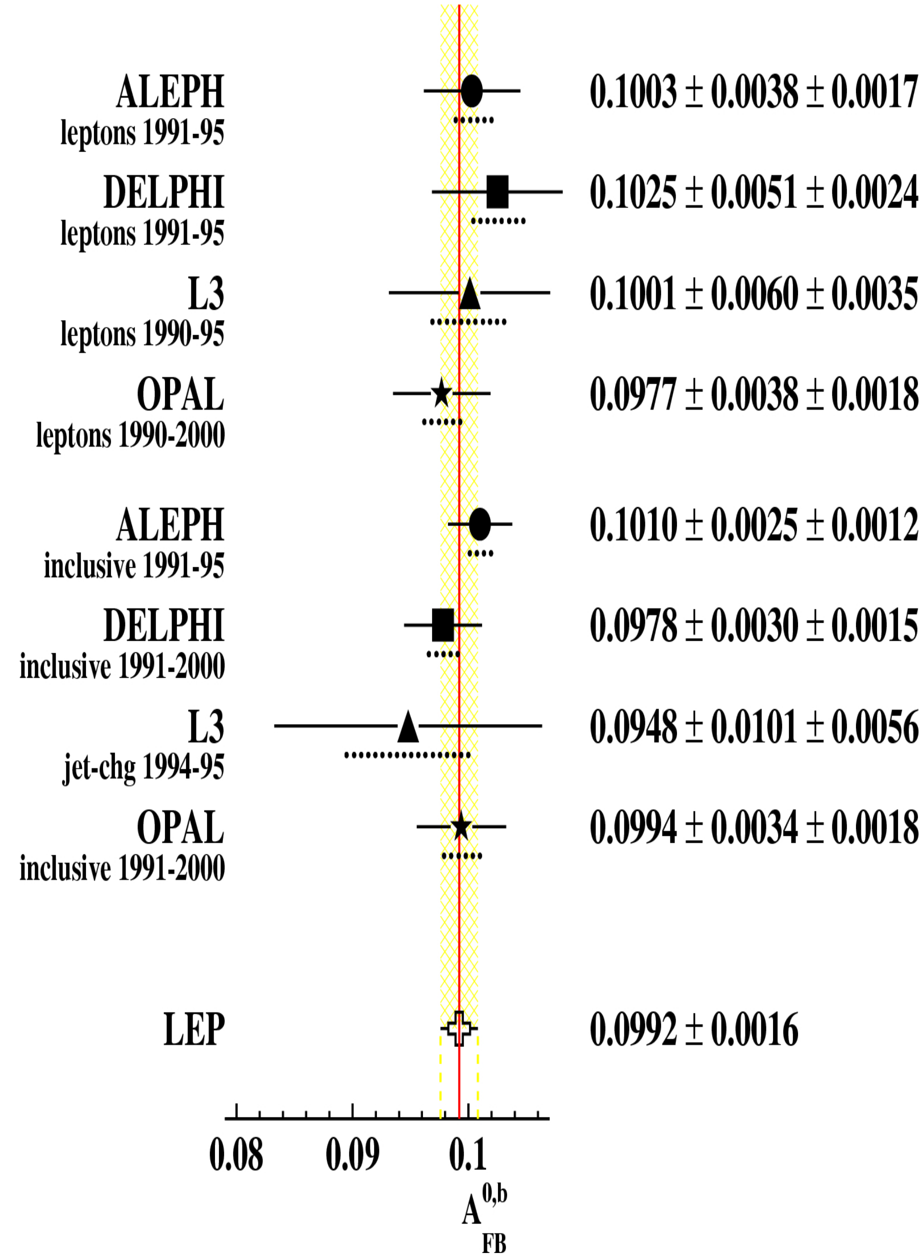
+ small correlations

Heavy-flavour combination:

χ^2/ndof = 53/(105-14) low!

Central values very consistent

Several systematic tests dominated by MC statistics

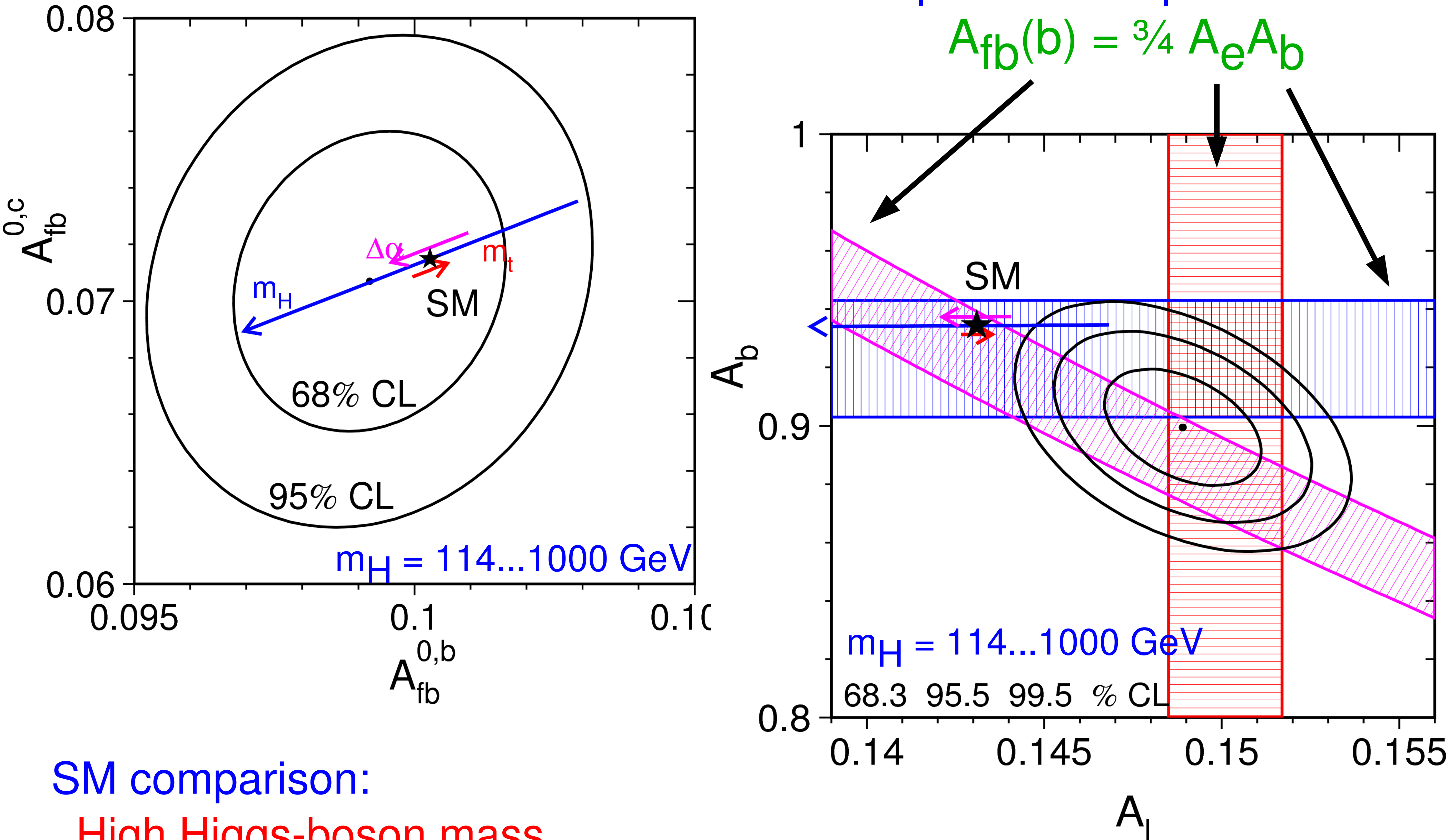


Asymmetries statistics dominated

Heavy Flavour Results at the Z-Pole

Compare with leptons:

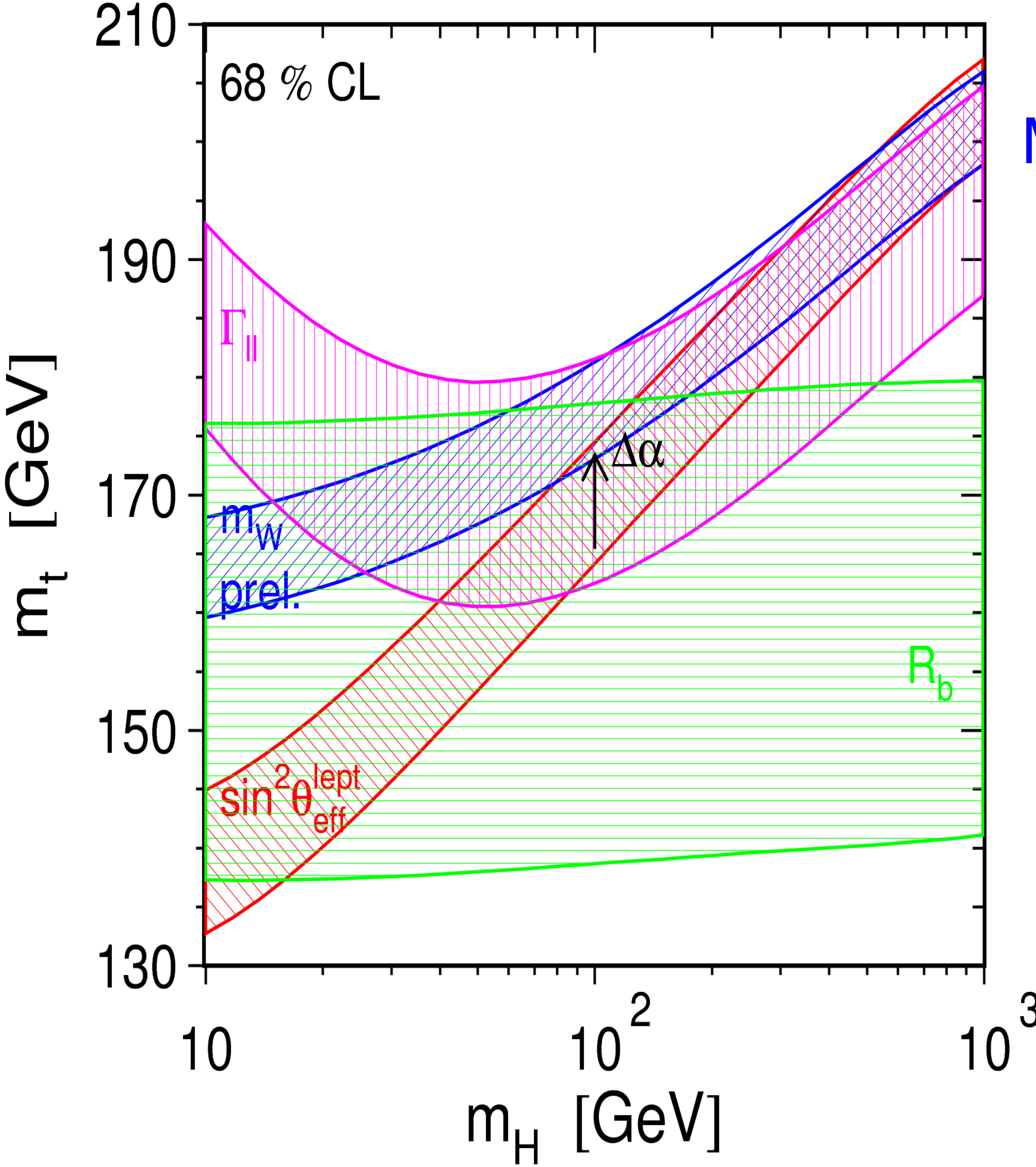
$A_{fb}(b) = \frac{3}{4} A_e A_b$



SM comparison:

High Higgs-boson mass

Top-Higgs Bands



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

Bands of ±1σ from:

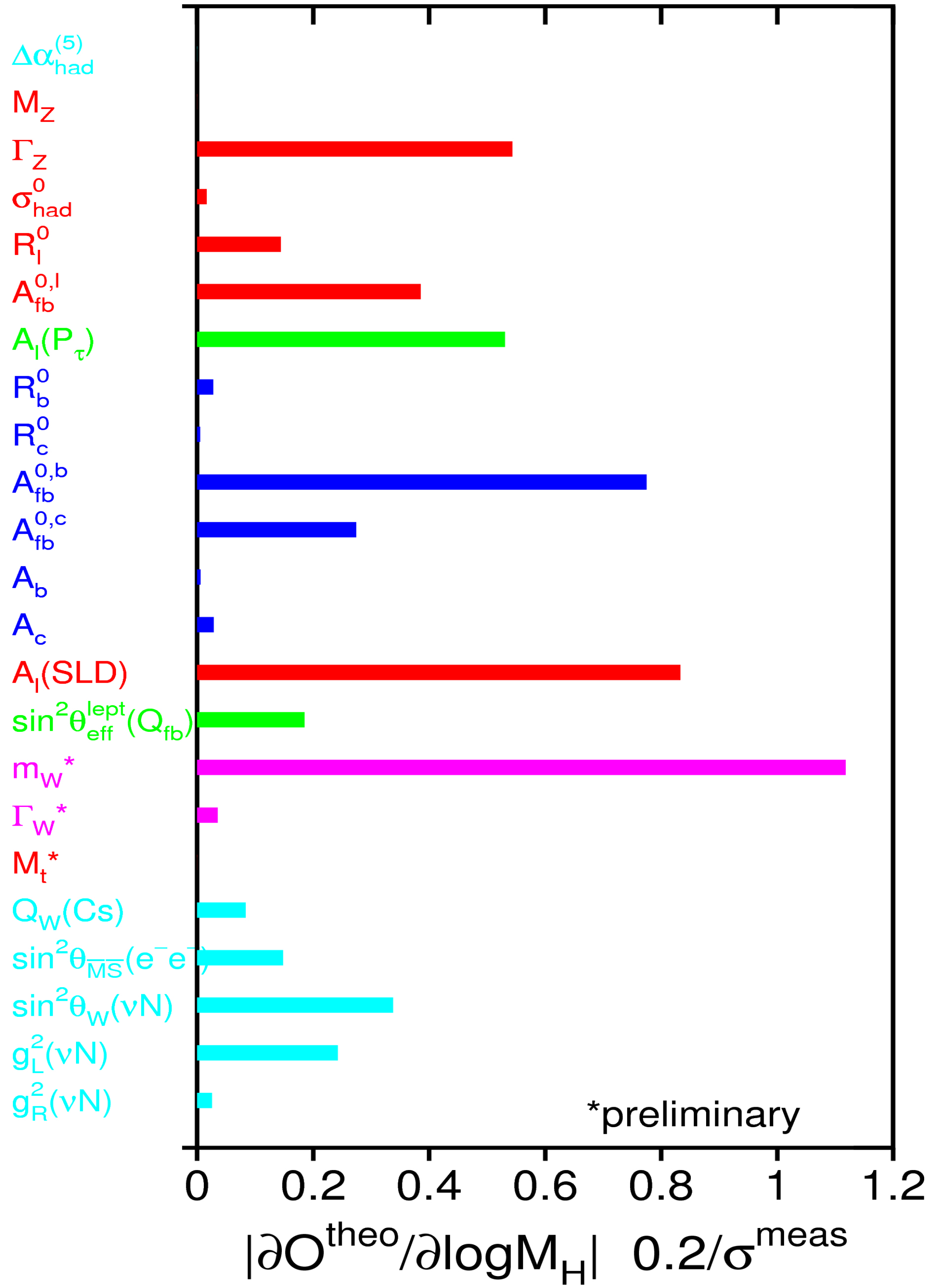
M_W = 80.398(25) GeV

$\sin^2\Theta_{eff}$ = 0.23153(16)

Γ_l = 83.984(86) MeV

R_b = 0.21629(66)

Higgs Sensitivities



Calculation of ew observables:

- In terms of 5 SM parameters
  - $\Delta\alpha_{had}$, $\alpha_s(M_Z)$,
  - M_Z, M_{top}, M_{Higgs}

Partial derivative w.r.t. M_{Higgs}:

- Scaled by measurement error

Relative importance of result in constraining M_{higgs}:

- Z-pole asymmetries ($\sin^2\Theta_{eff}$)
- and M_W

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)

$Q_W(Cs) = -72.74 \pm 0.46$ SM fit: -72.90 ± 0.03 ✔

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

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

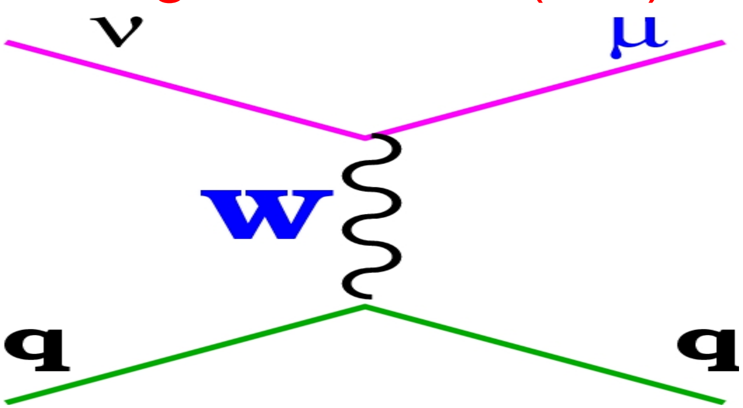
$A_{PV} = (\sigma_R-\sigma_L)/(\sigma_R+\sigma_L) \propto Q_W(e^-) = -4g_{Ae}g_{Ve}$ at $Q^2 \sim 0.03\ \mathrm{GeV}^2$

$\sin^2\Theta_{eff}(Q=M_Z) = 0.2333 \pm 0.0015$ SM fit: 0.2314 ± 0.0001 ✔

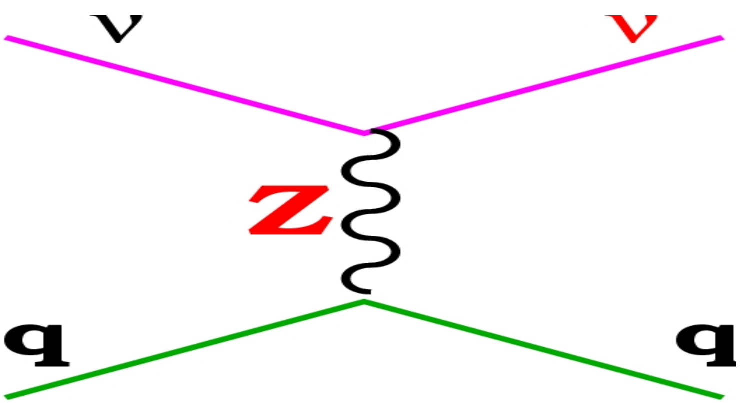
NuTeV Neutrino-Nucleon Scattering

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

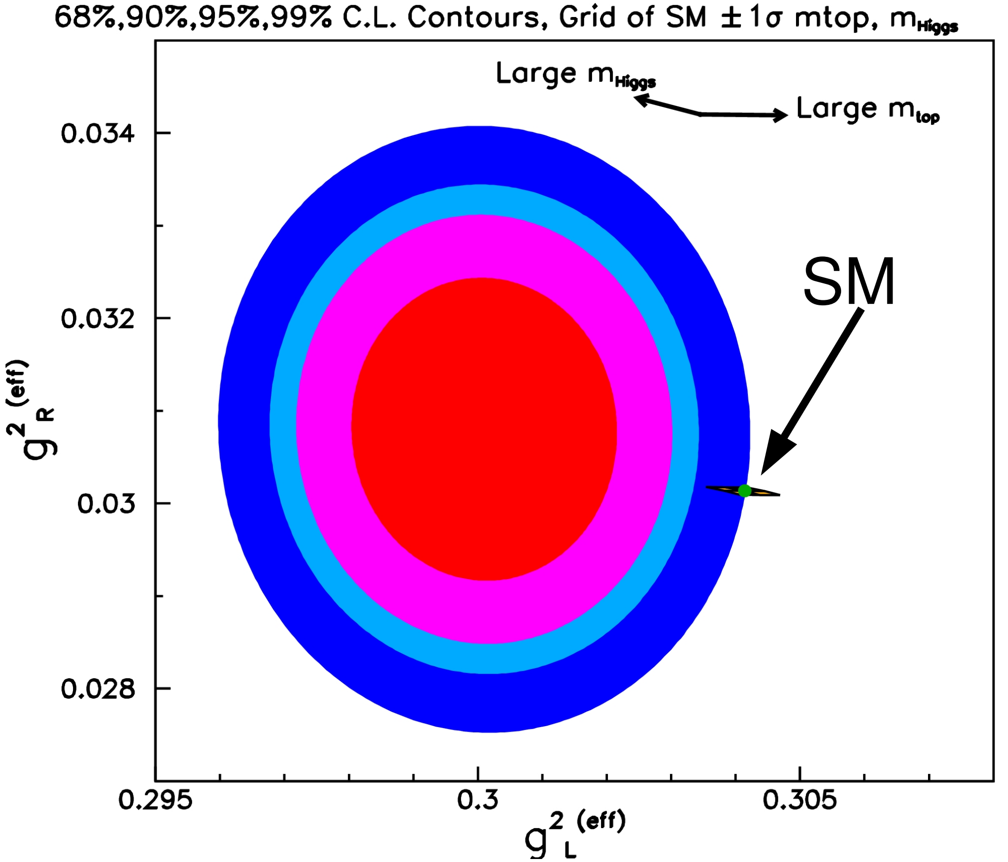
Effective couplings: g_L, g_R at $\langle Q^2 \rangle \sim 20\ \mathrm{GeV}^2$

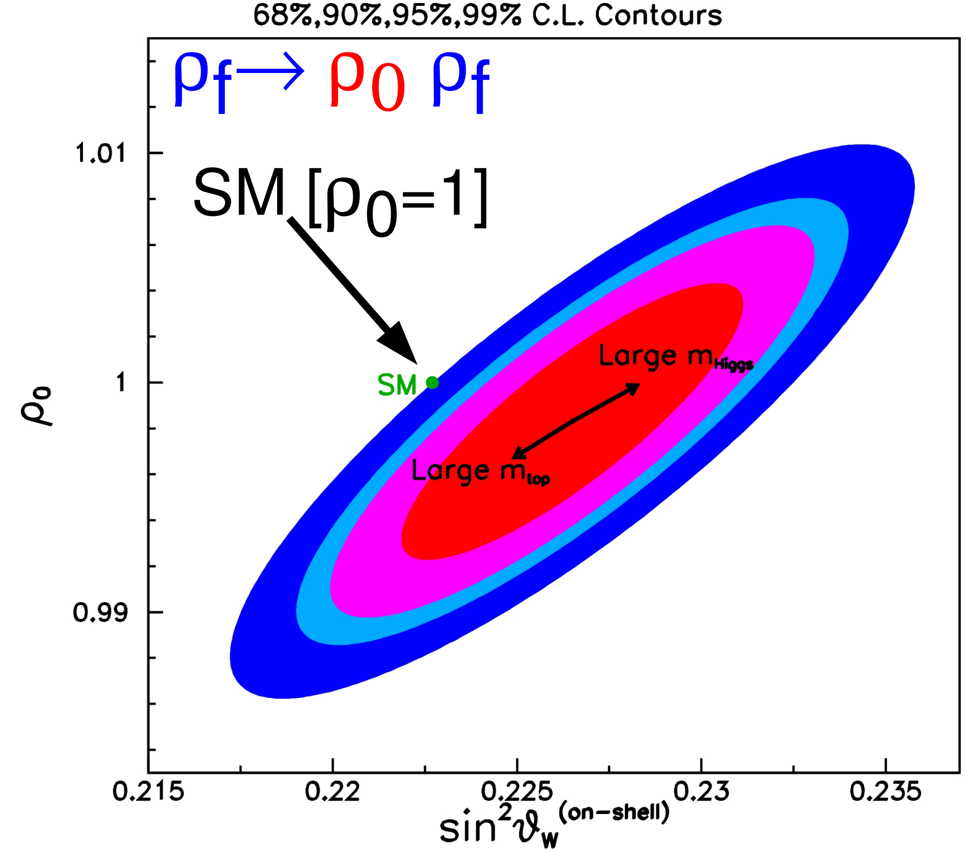
Historically result quoted in terms of: $\sin^2\Theta_W = 1-(M_W/M_Z)^2$

Factor two more precise than previous νN world average

NuTeV's Result

SM fit: Difference of ~3 σ in either $\sin^2\Theta_W$ or the ρ's!



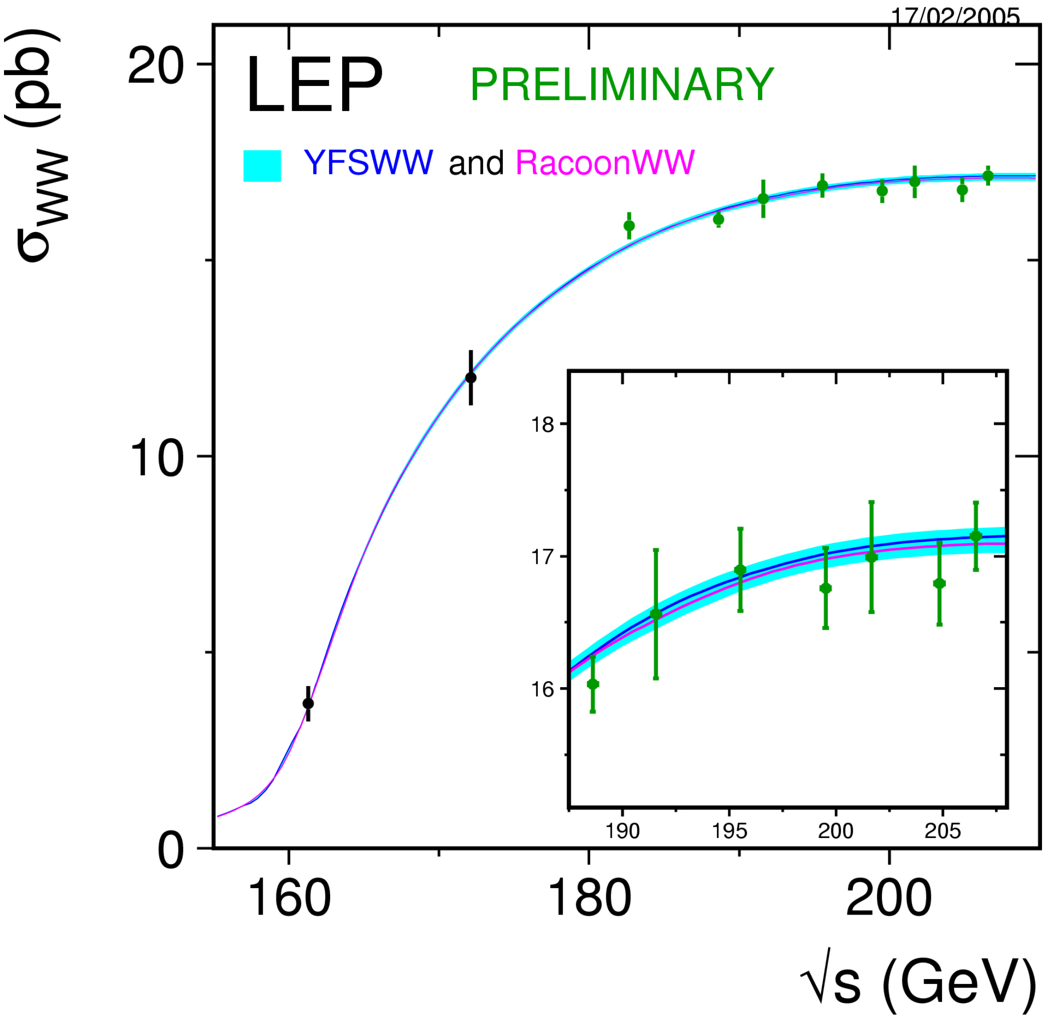


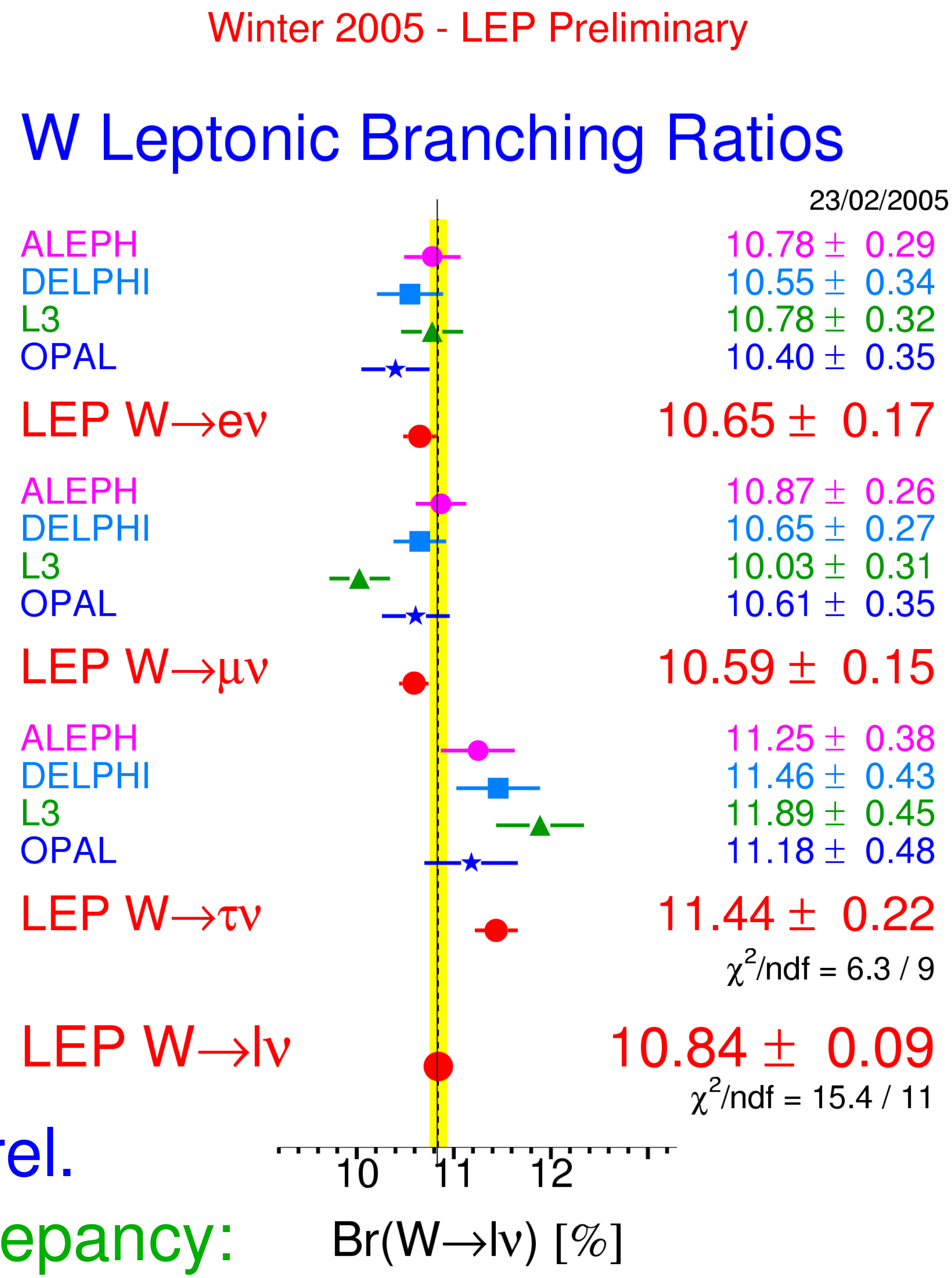
New physics: Z', contact interactions, lepto-quarks, new fermions, neutrino oscillations, . . .

But likely rather old physics: Theory uncertainty (QED, LO PDFs), isospin violating PDFs, sea asymmetry

Possible NOMAD measurement?

W-Pairs at LEP





ALEPH, DELPHI, L3 final, OPAL prel.

Subsequent maximisation of discrepancy:

W-tau branching fraction ~2.9σ above W-e/μ average

End