# Precision Tests of the Standard Model

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# Outline

Overview on precision measurements

Tests of the electroweak Standard Model

The Standard Model 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

Combined to 17 precision electroweak observables

Z-pole physics (LEP-1,SLD):

5 Z lineshape and leptonic forward-backward asymmetries

2 Polarised leptonic asymmetries $P_\tau$, $A_{LR(FB)}$

1 Inclusive hadronic charge asymmetry

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

W boson & top quark physics – ongoing at Tevatron's Run-II:

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

1 Top quark mass (Tevatron)

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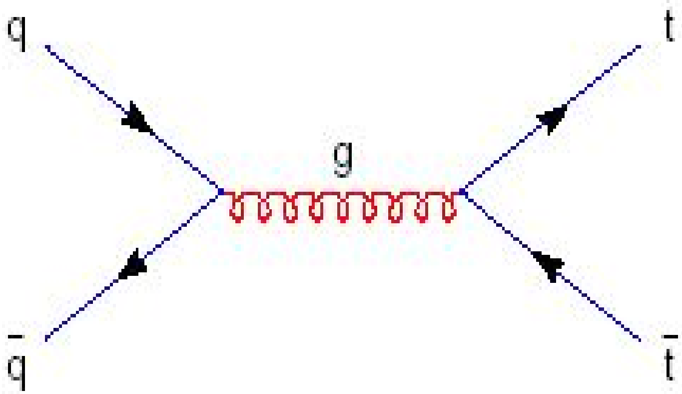
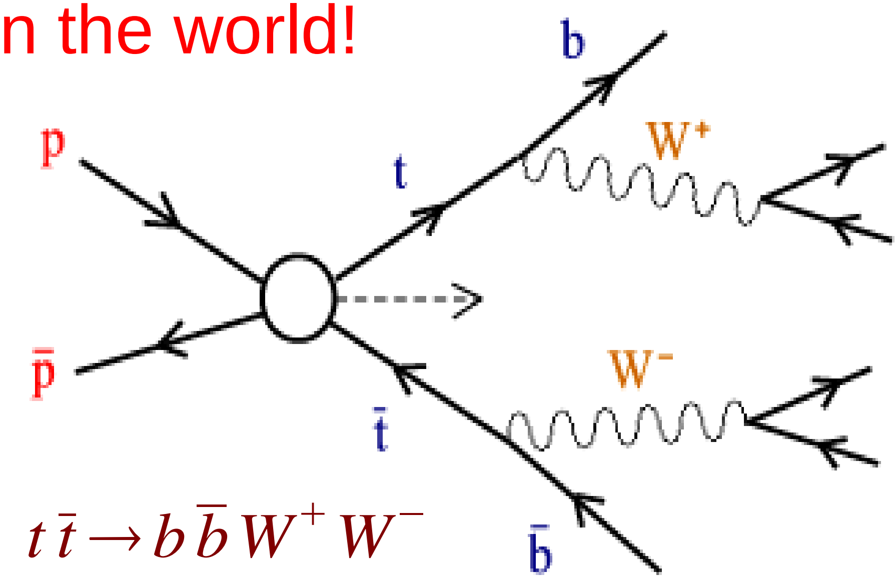
# Top Physics

Tevatron: only source of top quarks in the world!

Primarily top-pair production

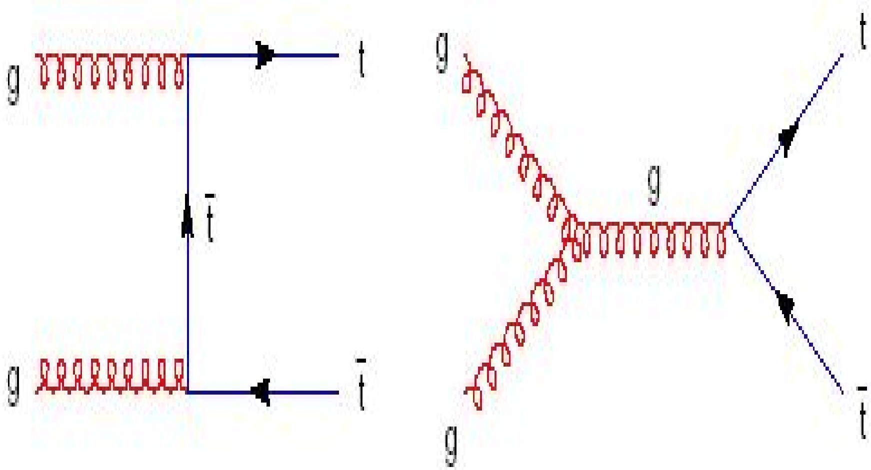



qq̄ annihilation (85%)

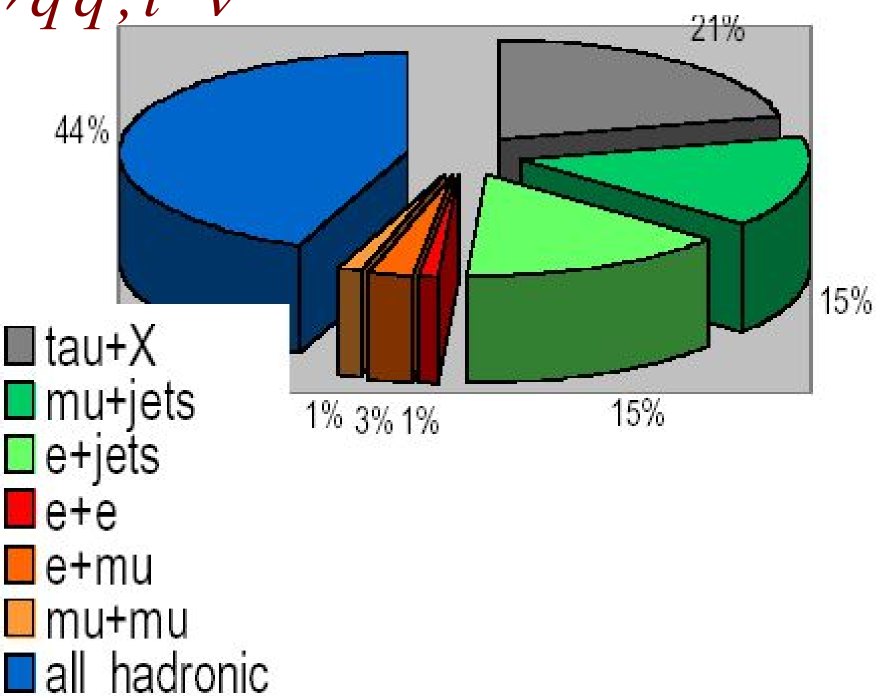



$$p\bar{p}\to t\bar{t}X,\quad t\bar{t}\to b\bar{b}W^{+}W^{-}$$

$$W^{-}\to q\bar{q},l^{-}\bar{\nu}$$




gluon fusion (15%)



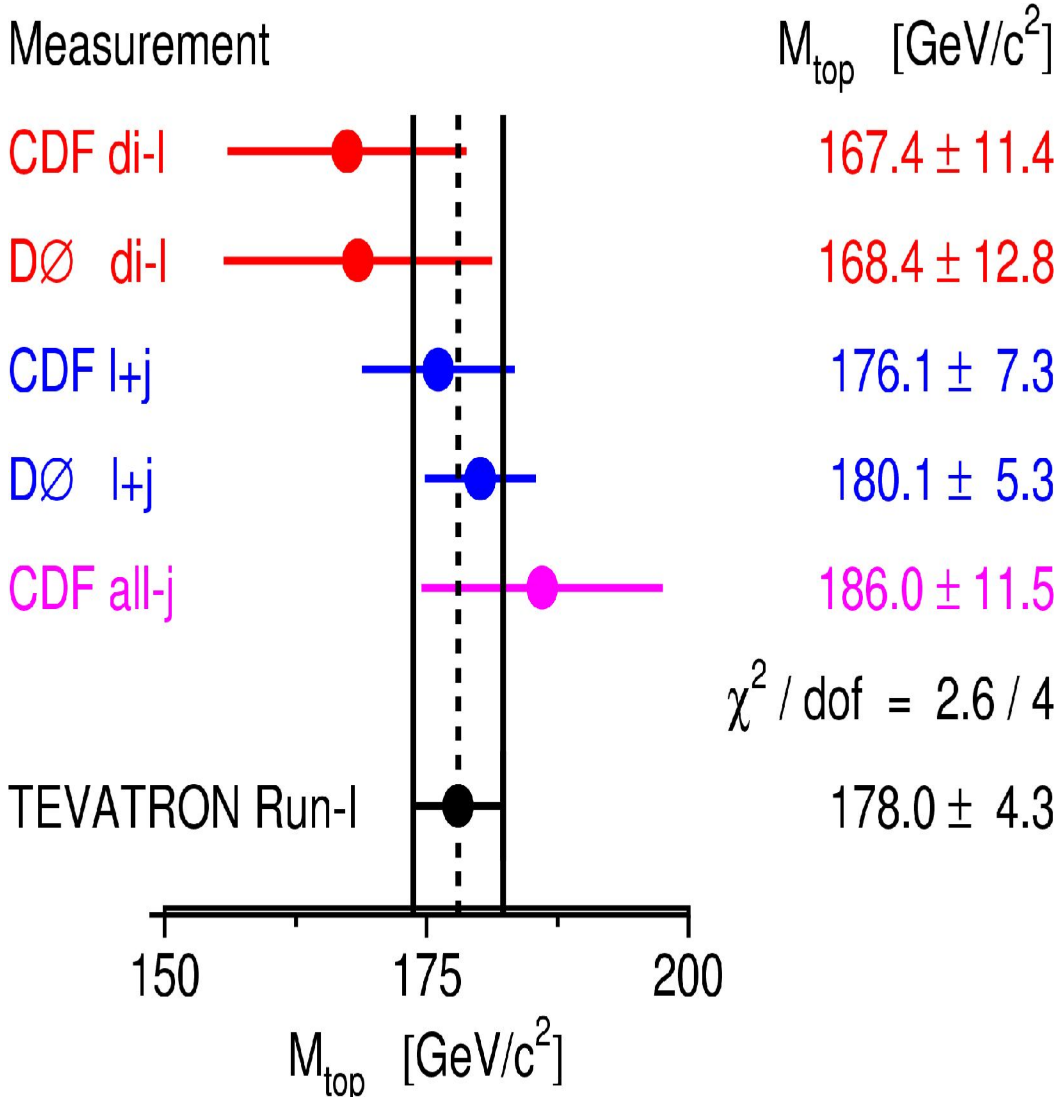
# Top-Quark Mass - Run-I

Tevatron (CDF, DØ):

- Final Run-I combination

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: $\delta M_{top}$ < 2.5 GeV

# Top-Quark Mass - Run-II

Reduction of JES systematics:

In-situ calibration
using W-mass constraint

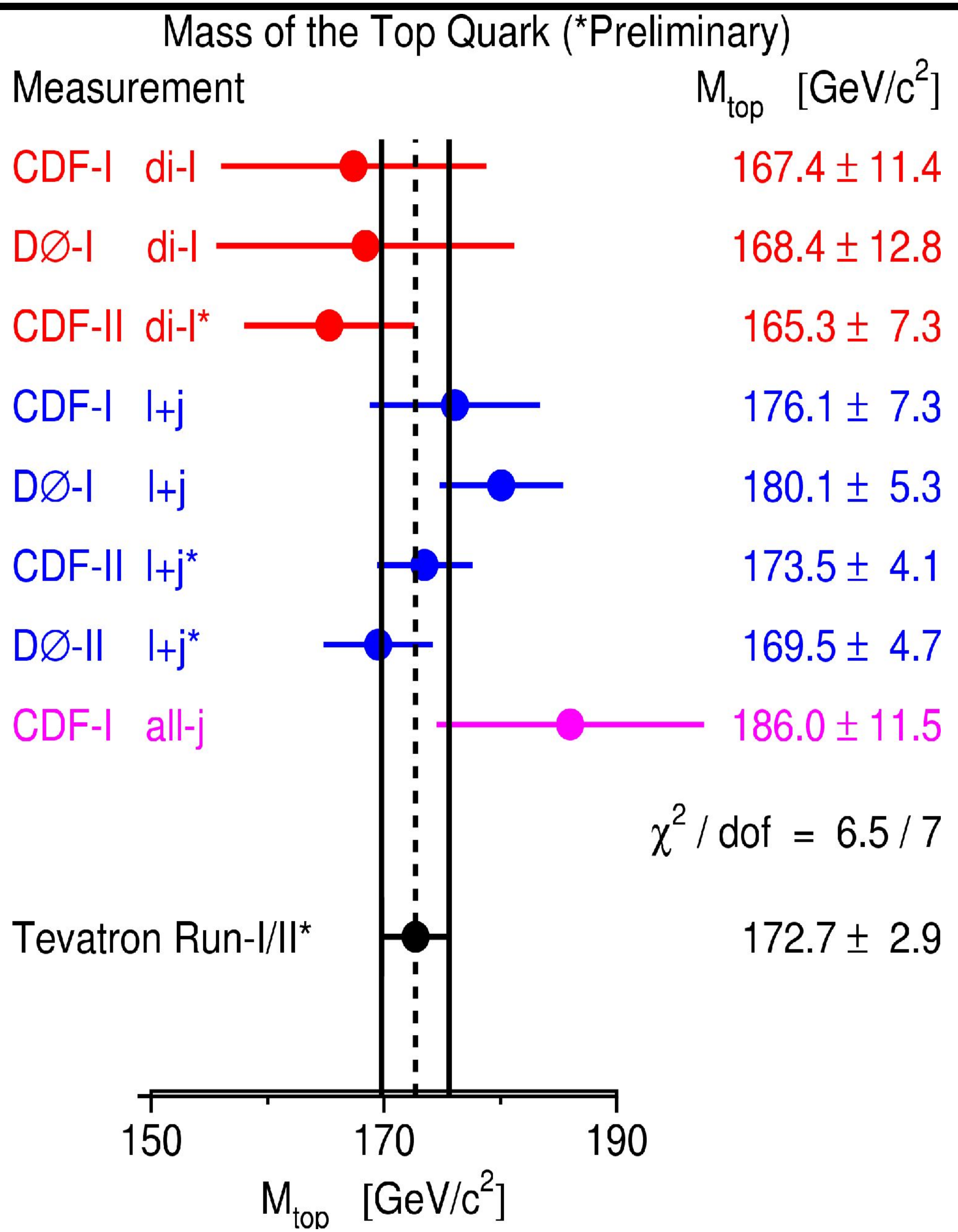
In 2005:

Each experiment (will be)
better than the Run-I average!

Separate final states:

| | | |
|---|---|---|
| 165.0± | 5.8 GeV | di-leptons |
| 173.5± | 3.0 GeV | lepton+jets |
| 185.0± | 10.9 GeV | all-jets |

Final state interactions (CR)?



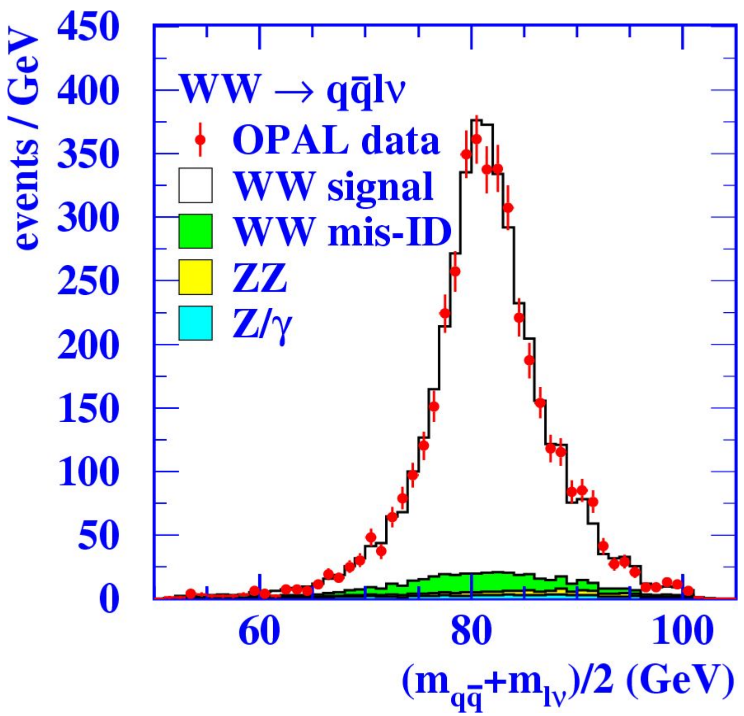

Run-II prel.: $M_{top}$ = 172.7 ± 1.7 (stat.) ± 2.4 (syst.) GeV

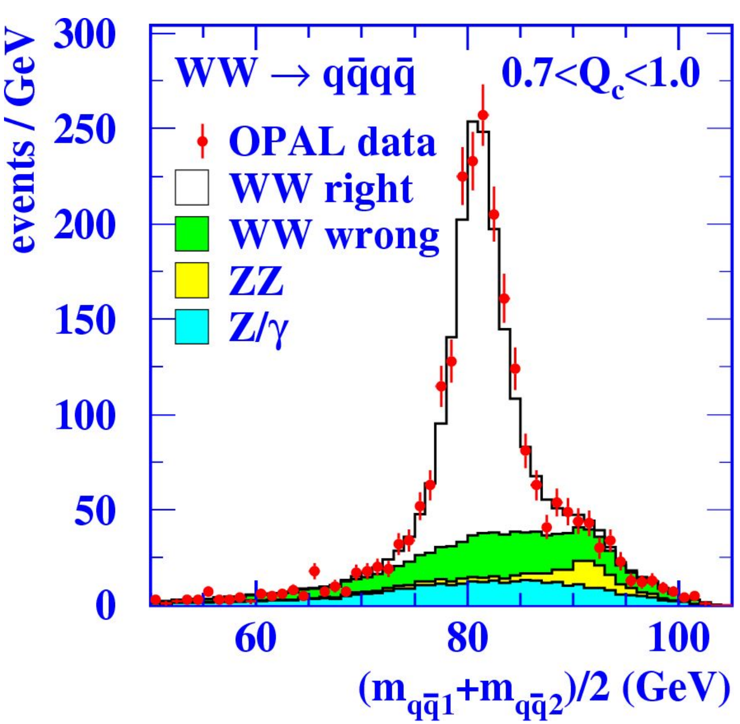
# W Boson - Mass and Width

LEP-2: $e^+e^- \to W^+W^- \to$ qqqq, qqlν, lνlν

Invariant mass $M_{inv}$

Final OPAL results in combination




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

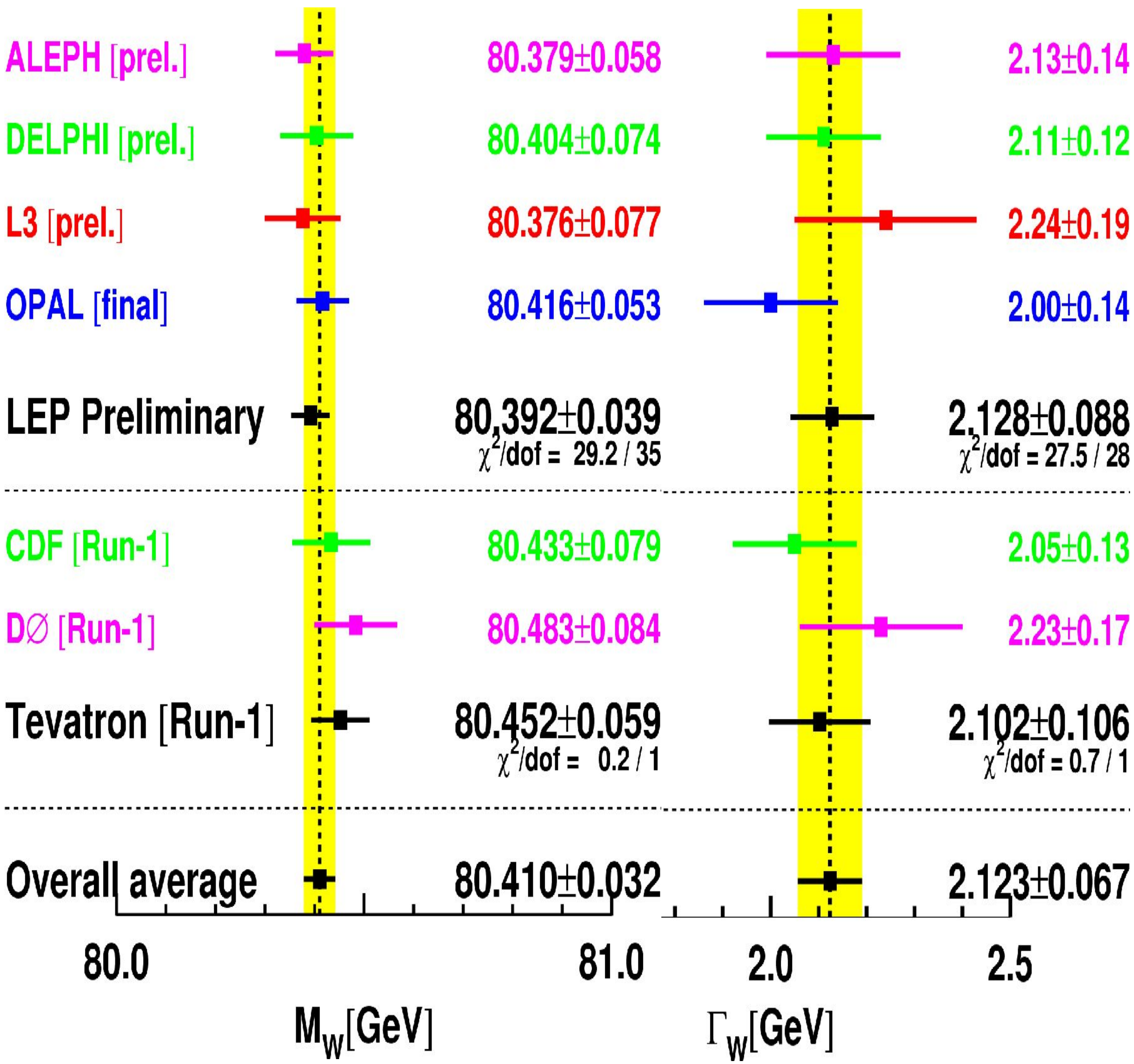
$M_W$ average dominated by qqlν channel (qqqq: 9.5% → 16%)

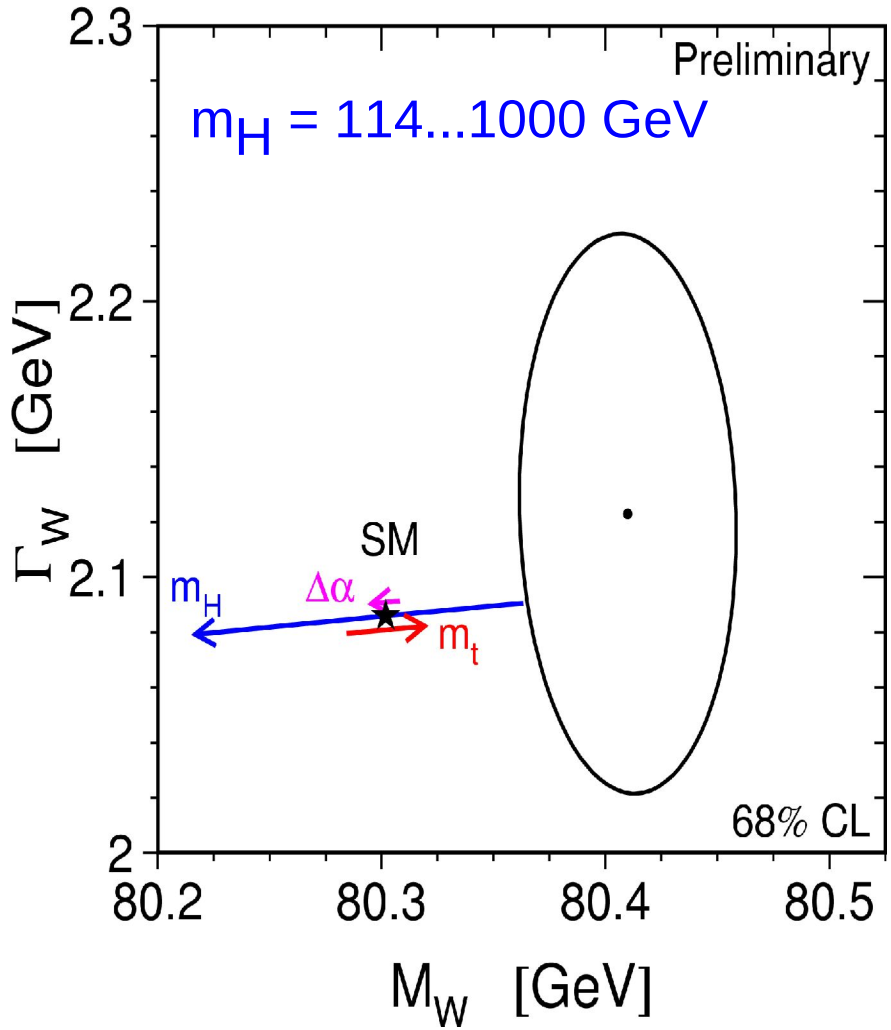
Mass difference (calculated without FSI errors):

$M_W$(qqqq) – $M_W$(qqlν) = 21 ± 42 MeV

# W Boson - Mass and Width

Good agreement between all six experiments:




SM comparison:

Small Higgs-boson mass

Correlation $M_W$-$\Gamma_W$: -0.06

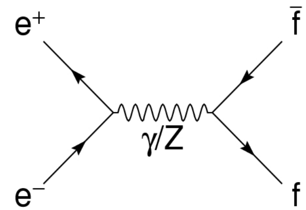
# Z-Pole Physics

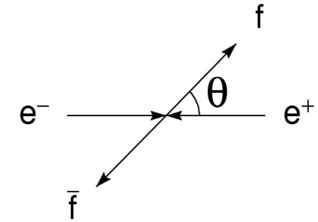
## Cross sections:

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

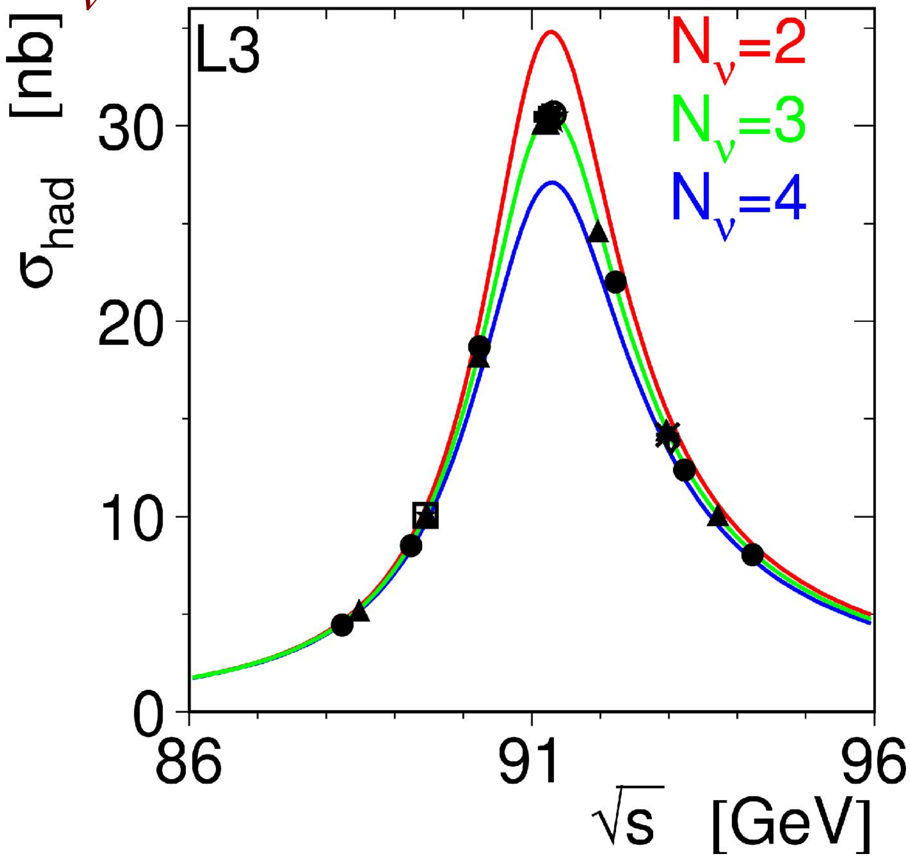
$$\Gamma_Z = 2.4952 \pm 0.0023 \ \ GeV$$

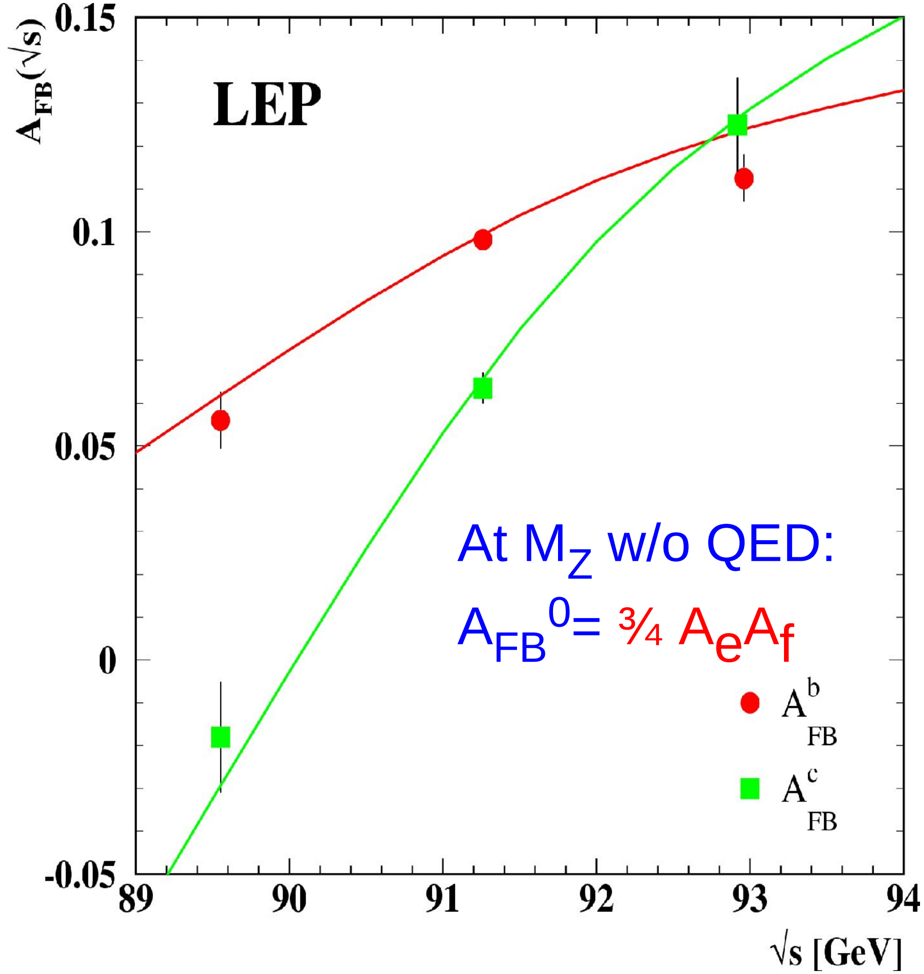
$$N_\nu = 2.9840 \pm 0.0082$$




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




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

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

# Heavy Flavour Results at the Z-Pole

Finally: really final HF results available

$R_b = \Gamma_b/\Gamma_{had}$  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

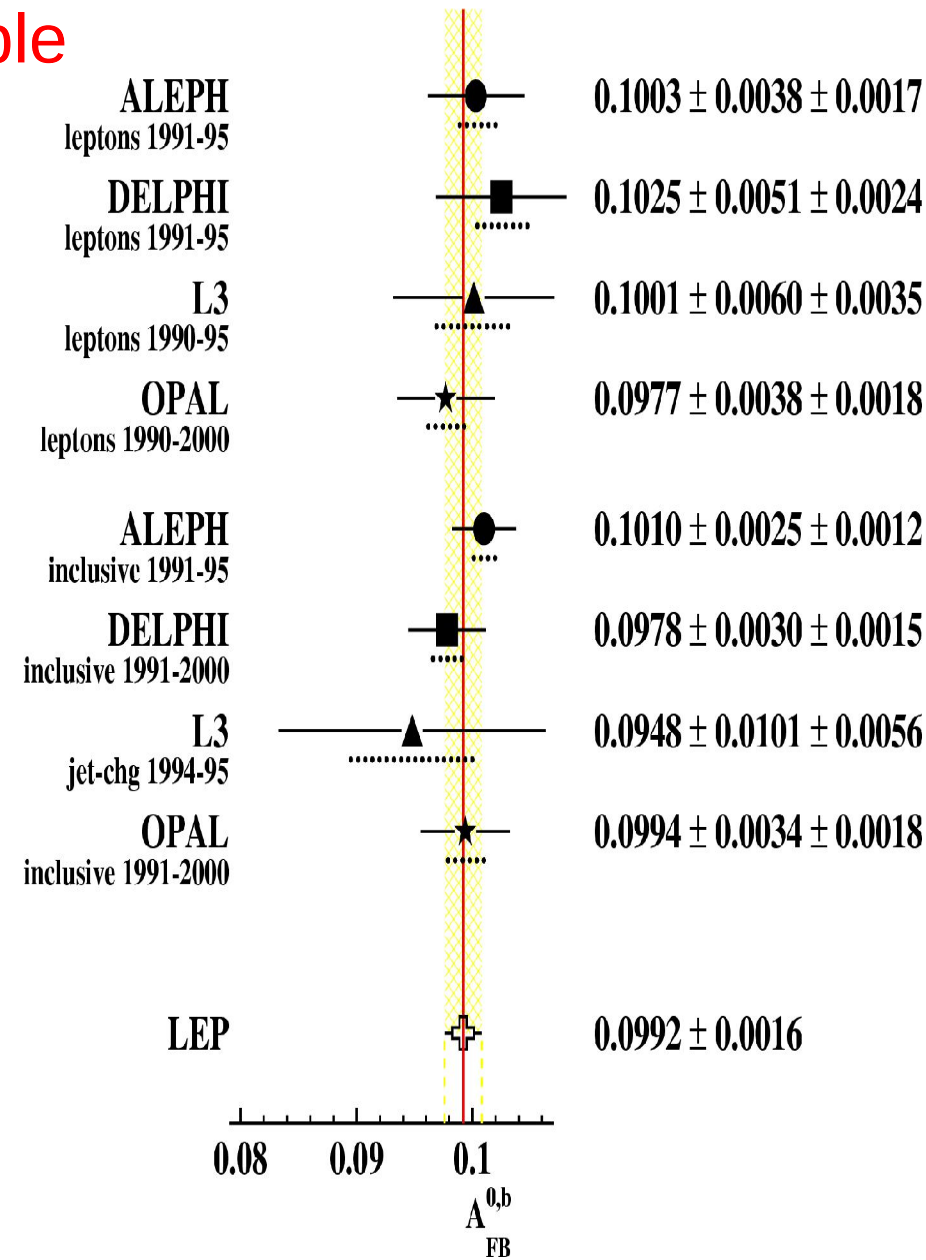
+ small correlations

Heavy-flavour combination:

$\chi^2$/ndof = 53/(105-14) low!

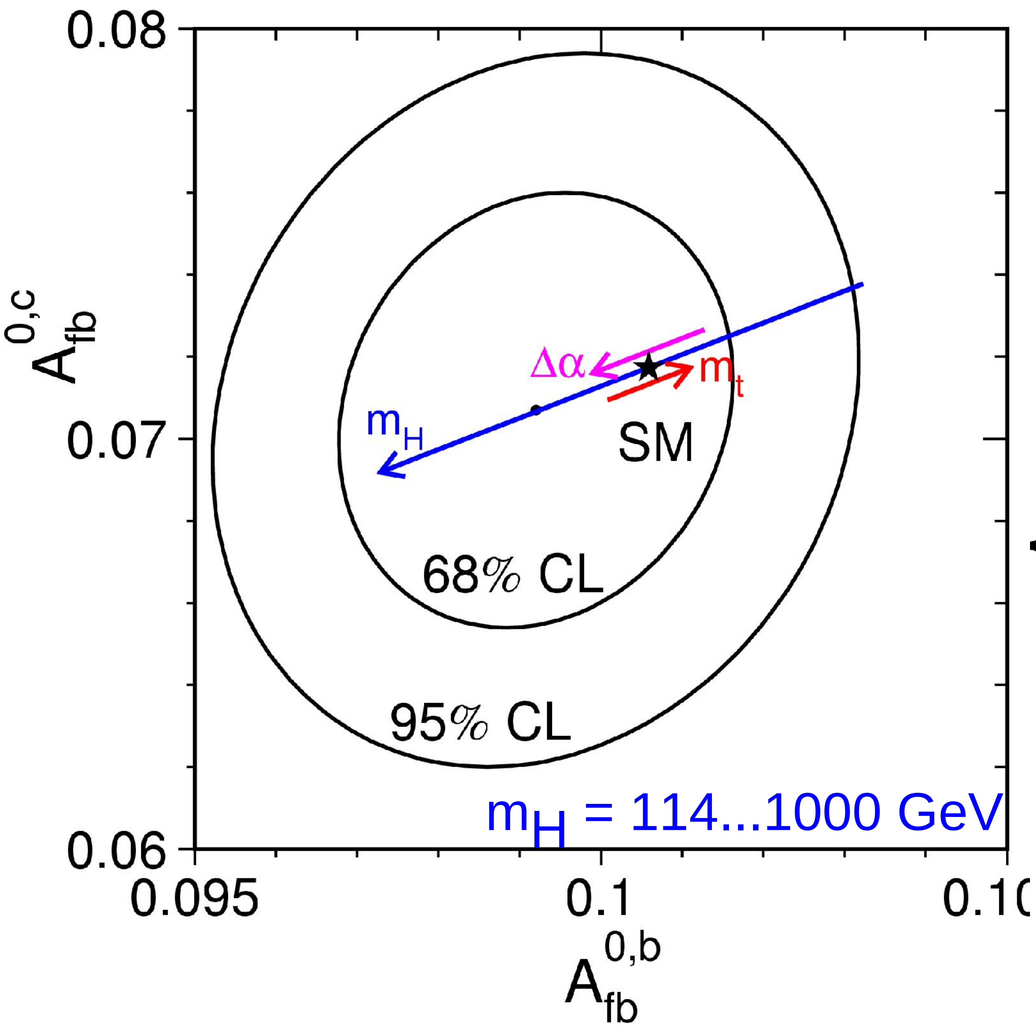
Central values very consistent

Several systematic tests dominated by MC statistics



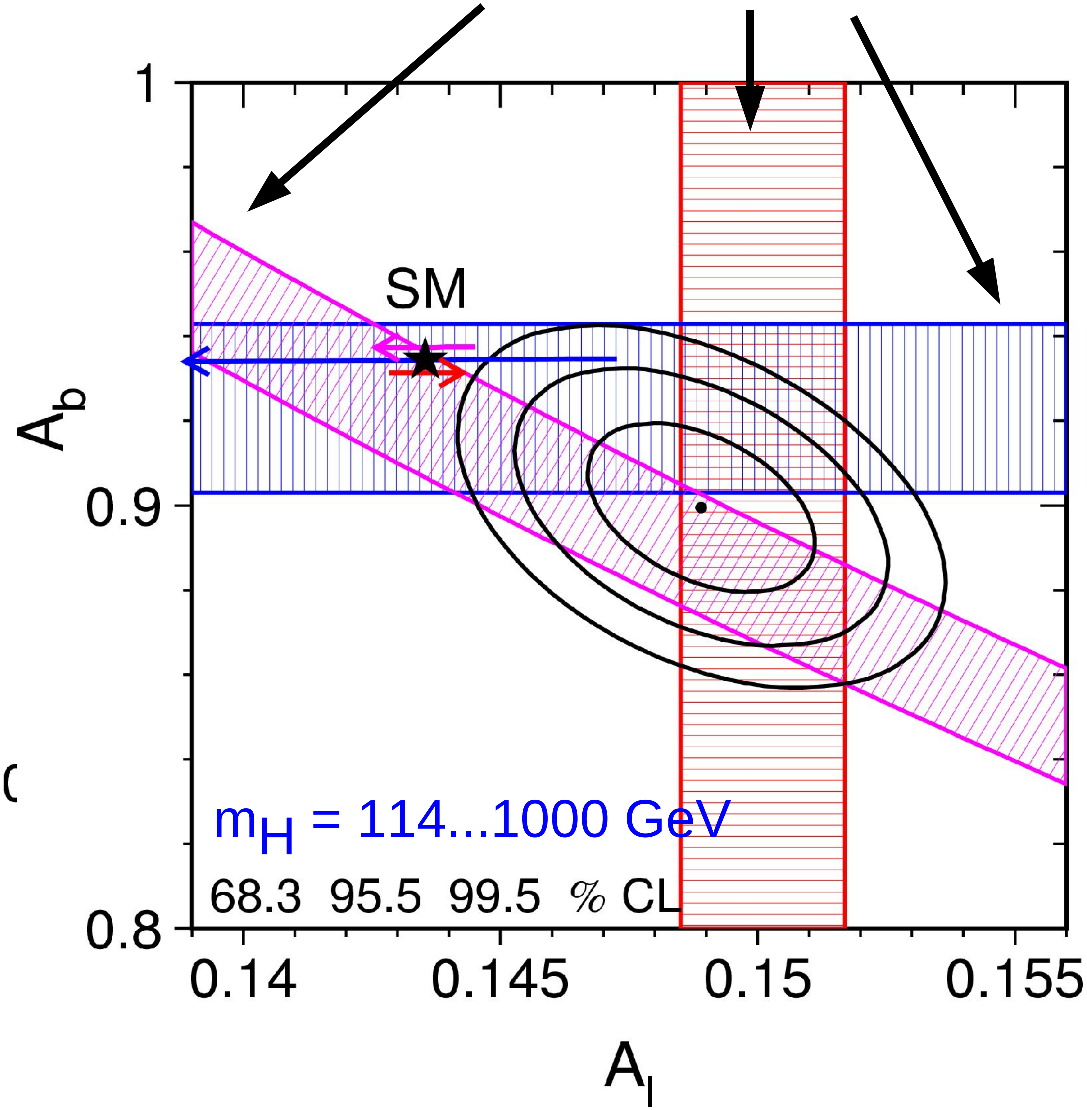

Asymmetries statistics dominated

# 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

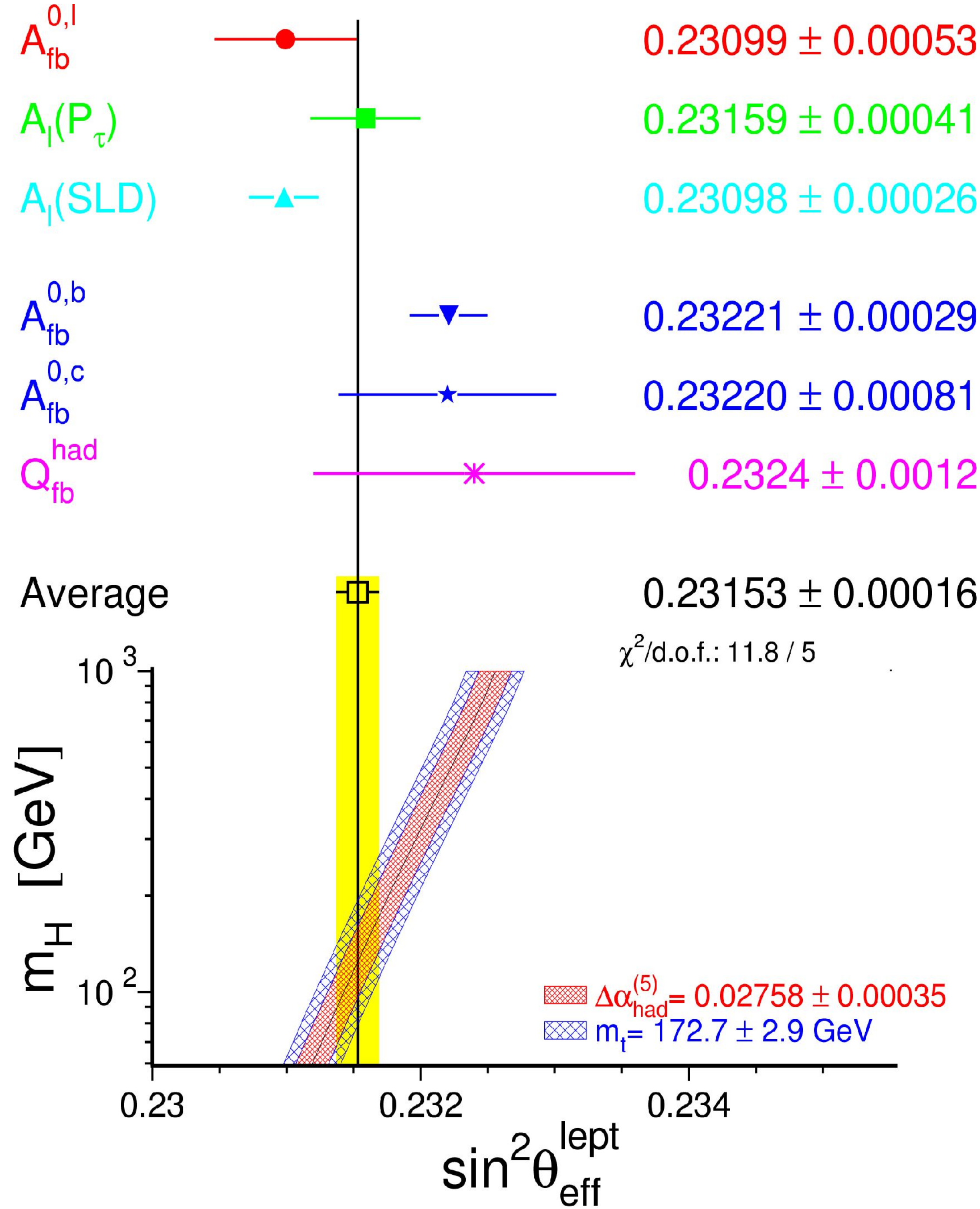
# Comparison of all Z-Pole Asymmetries

Effective electroweak mixing angle:

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

$= 0.23153 \pm 0.00016$

$\chi^2/\mathrm{ndof} = 11.8/5$ [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

# Standard Model Analysis

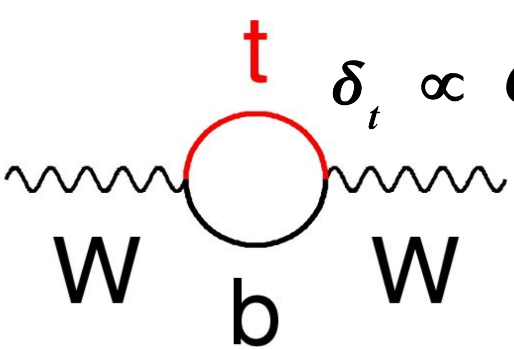
SM: Each observable calculated as a function of:

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

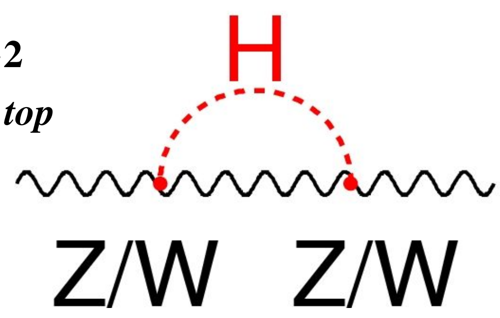
- $\Delta\alpha_{had}$: hadronic vacuum polarisation [0.02758±0.00035]
- $\alpha_s(M_Z)$: given by $\Gamma_{had}$ and related observables
- $M_Z$: constrained by LEP-1 lineshape

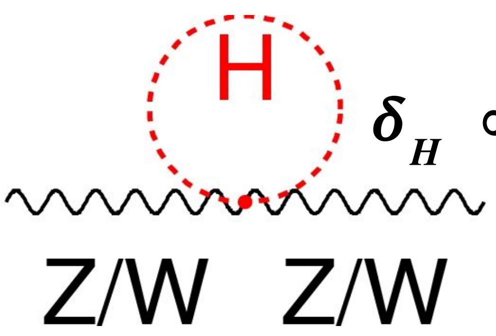
Precision requires 1st and 2nd order electroweak and mixed radiative correction calculations (QED to 3rd)

$M_{top}$, $M_{Higgs}$ 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

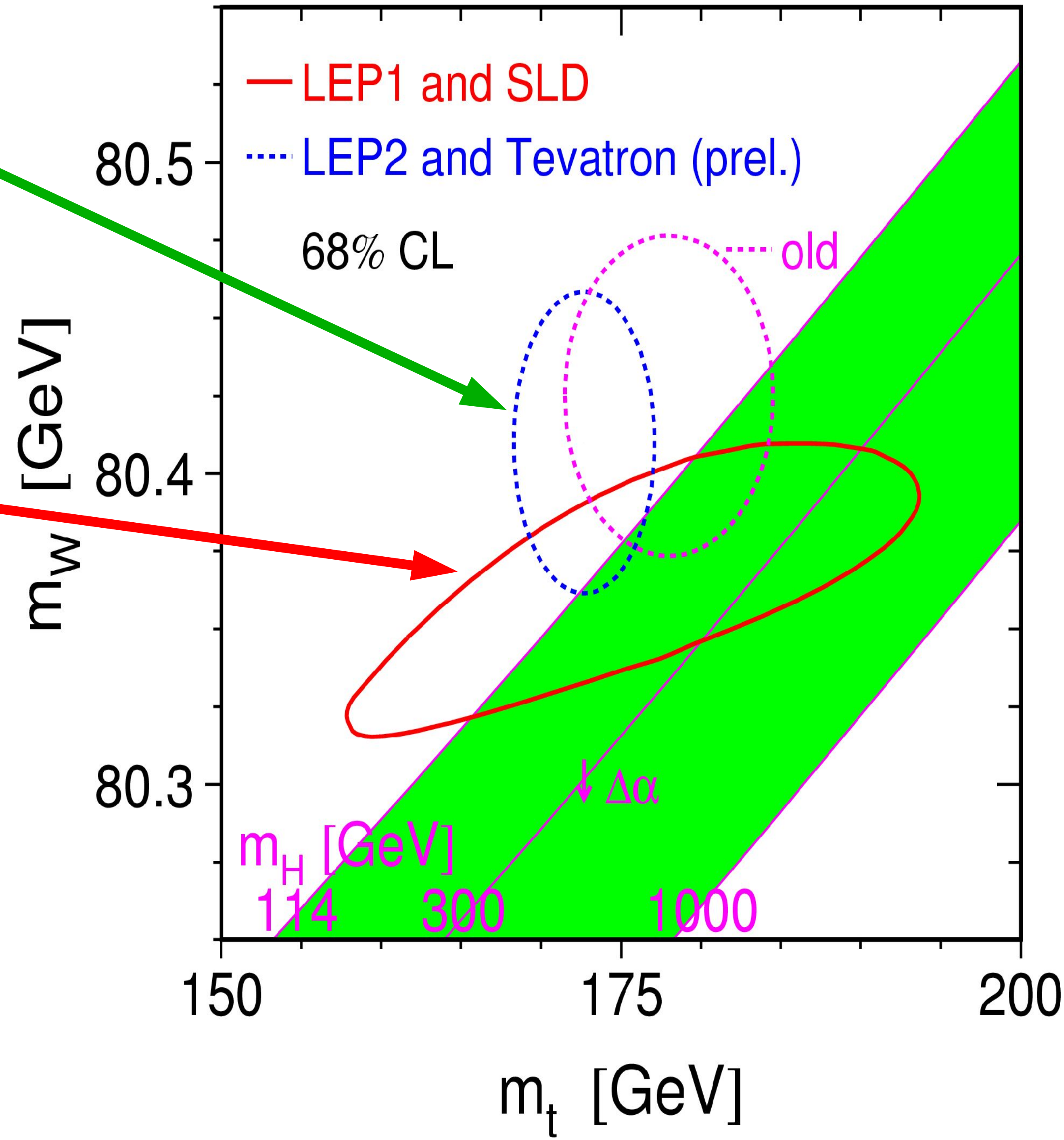
# Heavy Particle Masses W and Top

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

**Fit results:**

$\Delta\alpha_{had}$ = 0.02767 ± 0.00034

$\alpha_s(M_Z)$ = 0.1186 ± 0.0027

$M_Z$ = 91.1874 ± 0.0021 GeV

$M_{top}$ = 173.3 ± 2.7 GeV

$\log_{10}M_H$ = 1.96 ± 0.18

$M_{Higgs} = 91^{+45}_{-32}$ GeV

$\Delta\alpha_{had}$ marginally improved

$\alpha_s(M_Z)$ one of the best

$M_Z$ ~ unchanged

$M_{top}$ error improved by few %

**Correlations:**

| | | | |
|---|---|---|---|
| 0.01 | | | |
| -0.01 | -0.02 | | |
| -0.02 | 0.05 | -0.03 | |
| **-0.51** | 0.11 | 0.07 | **0.52** |

**Strong correlations with:**

fitted $\Delta\alpha_{had}$ - reduced to -0.20 with pQCD $\Delta\alpha_{had}$

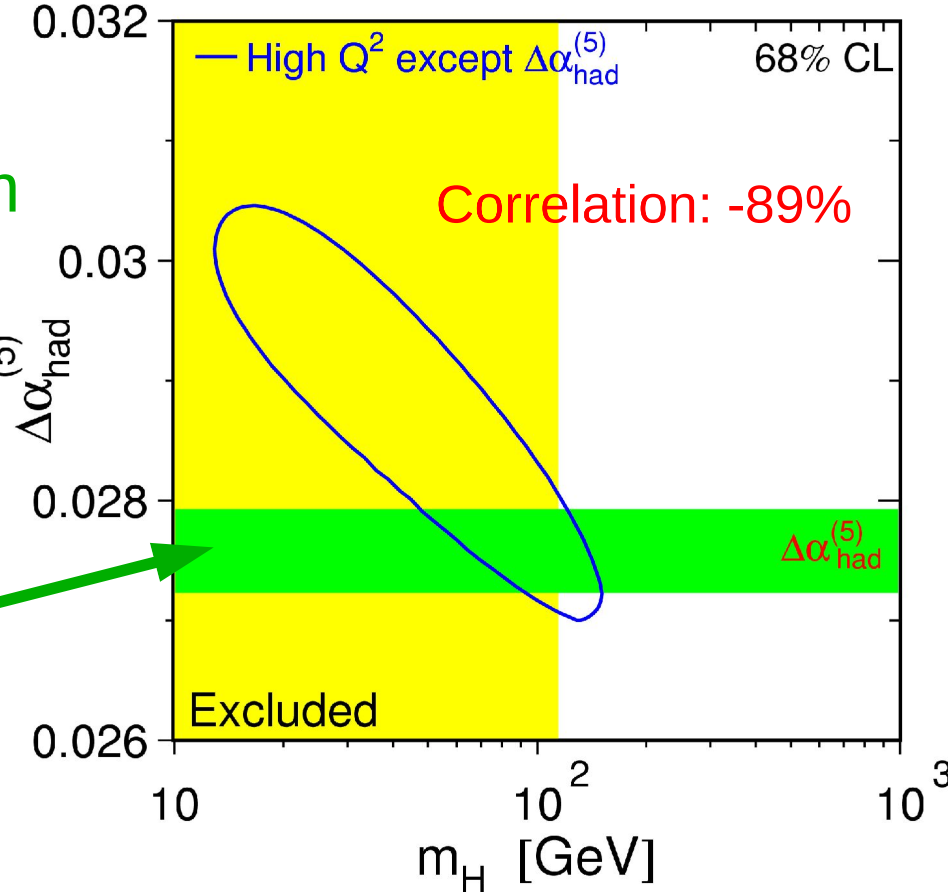
fitted $M_{top}$ - 20 % shift in $M_{Higgs}$ for 3 GeV shift in meas. $M_{top}$

**$M_{top}$ measurement crucial!**

# Hadronic Vacuum Polarisation

Fermion loops cause running of $\alpha$:

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




Experimentally driven result:

$\Delta\alpha_{had}(M_Z) = 0.02758 \pm 0.00035$*

*Update with new CMD-2/KLOE data

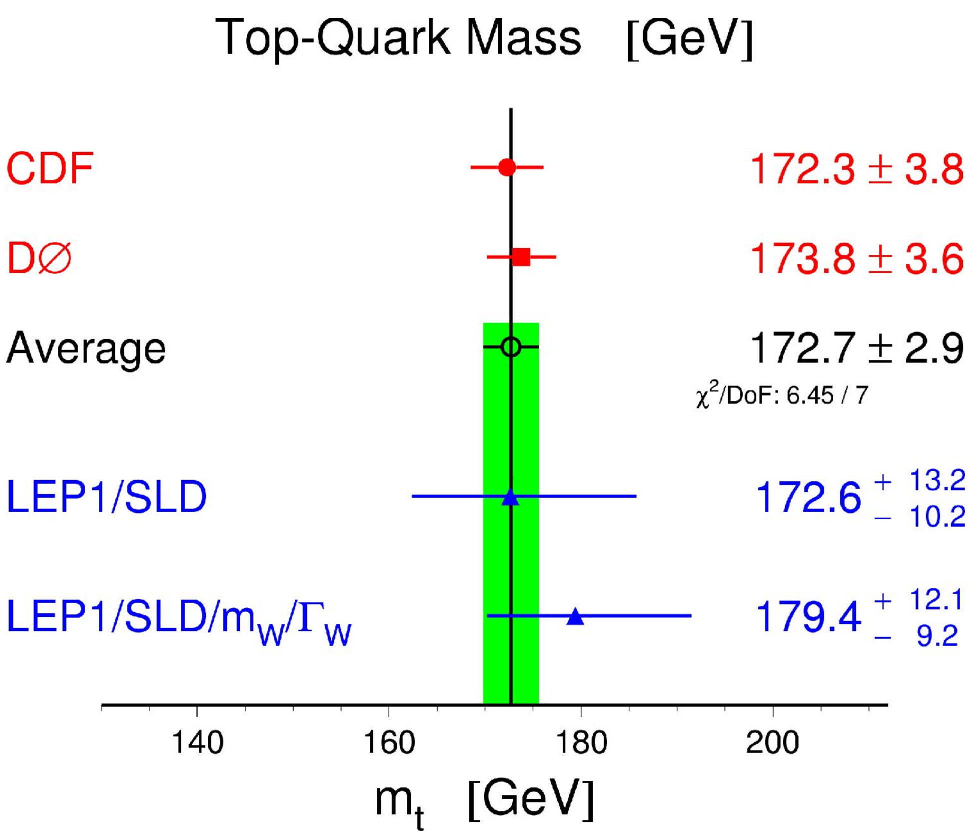
Theory driven result (more pQCD):

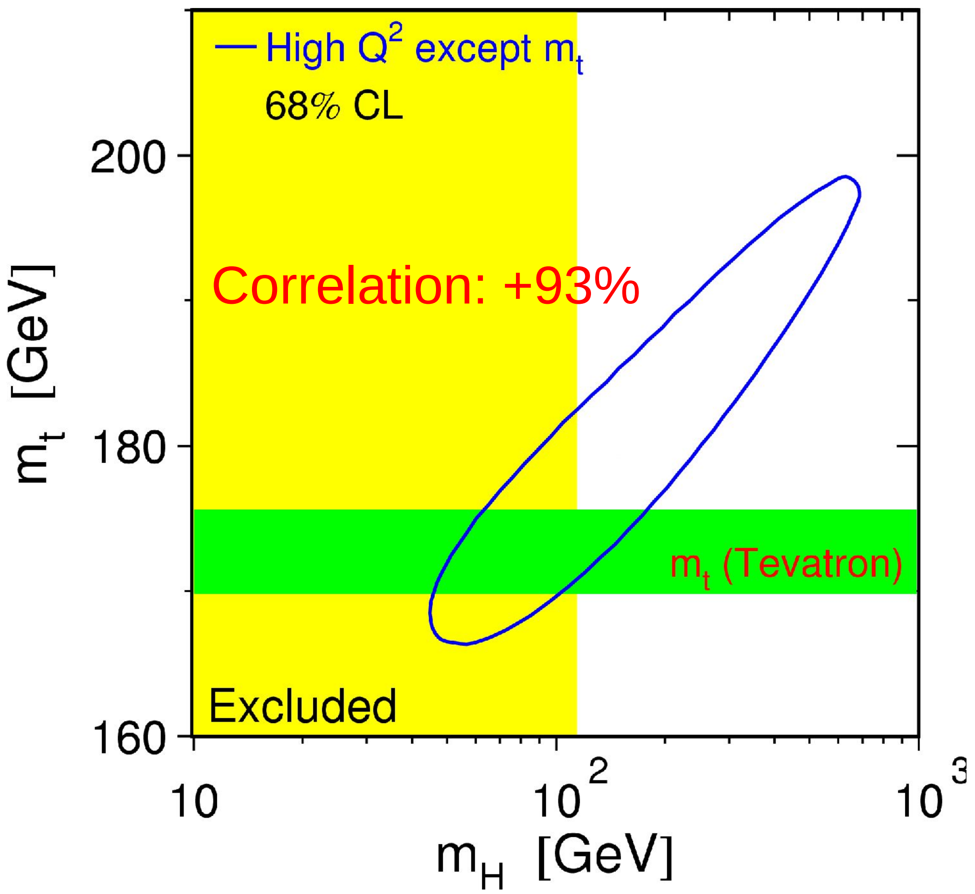
$\Delta\alpha_{had}(M_Z) = 0.02749 \pm 0.00012$

Subject of ongoing experimental and theoretical work:

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

# Heavy Particle Masses: Top Quark

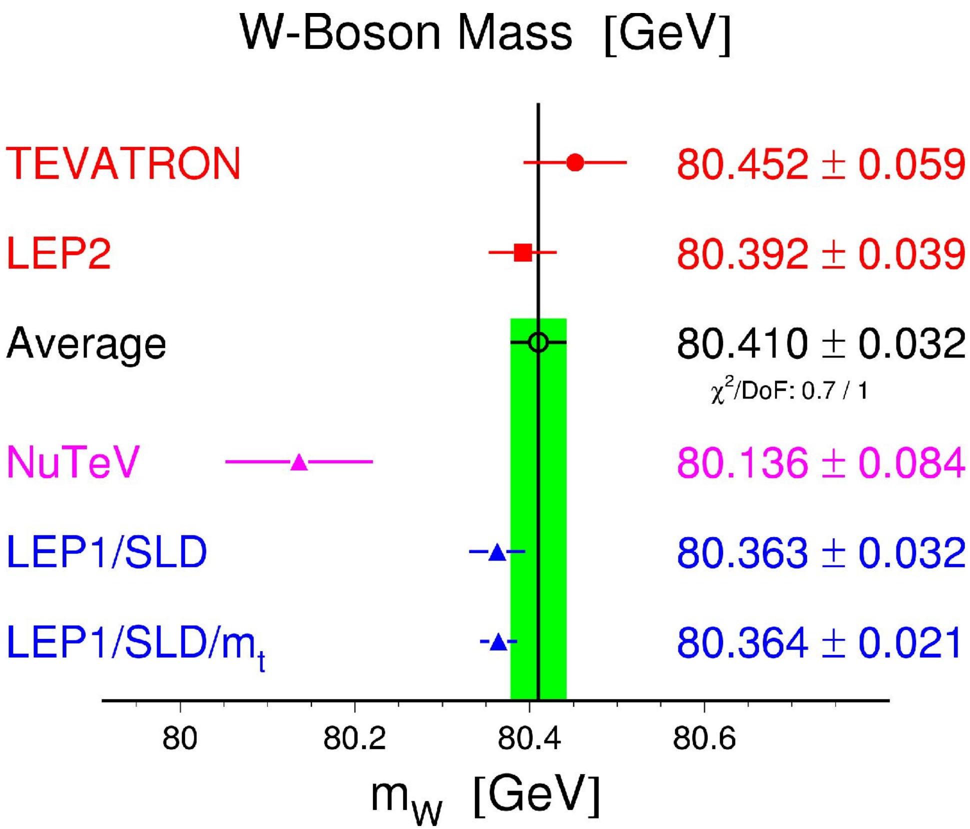


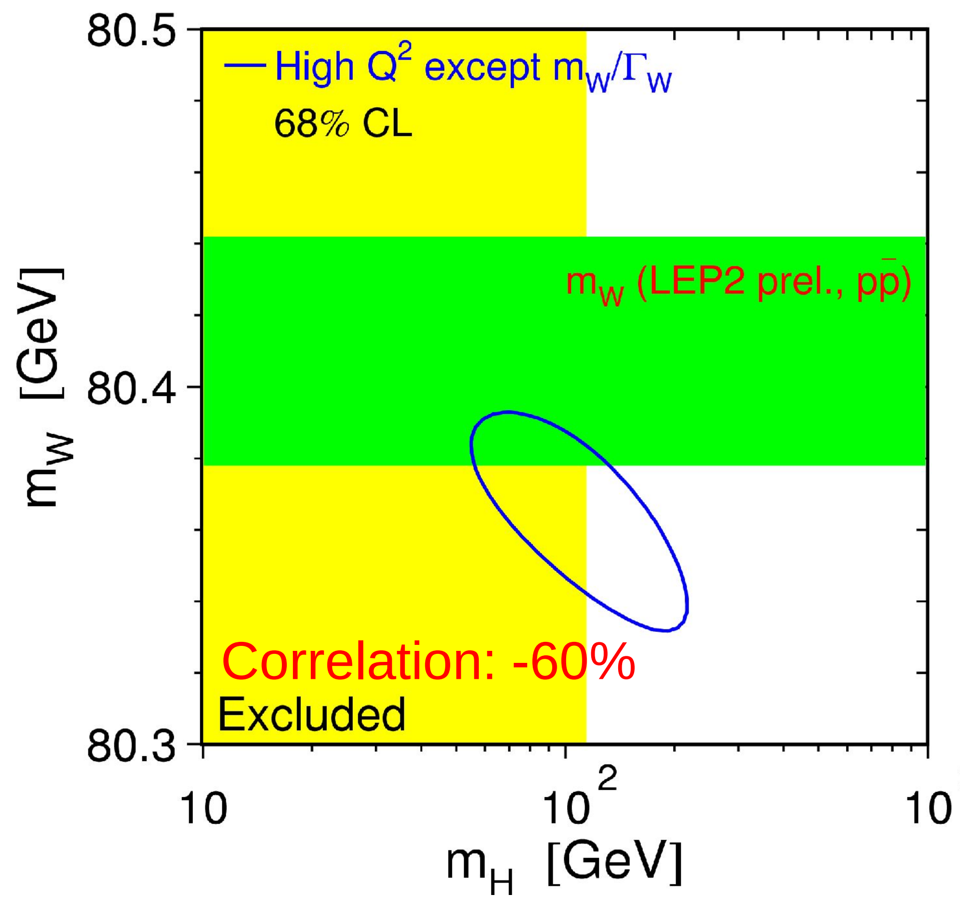




Predicted $M_{top}$ in very good agreement with measurement

Measured $M_{top}$ more than 3 times as precise as prediction

# Heavy Particle Masses: W Boson




Predicted and measured $M_W$ within ~1 $\sigma$

Measured $M_W$ not yet as precise as prediction incl. $M_{top}$

# Standard Model Analysis

$M_{Higgs} = 91^{+45}_{-32}$ GeV

Incl. theory uncertainty:

$M_{Higgs} < 186$ GeV (95%CL)

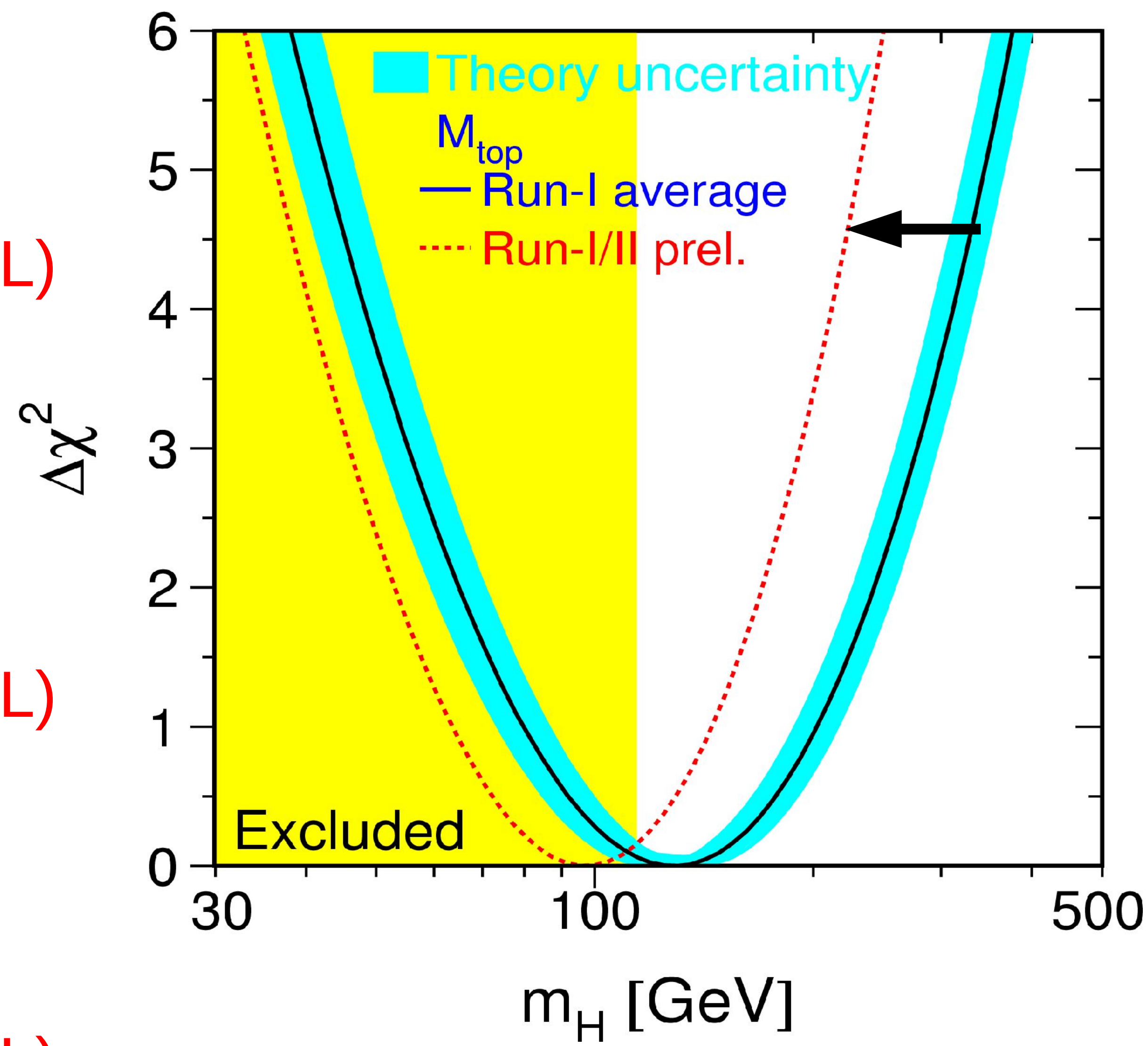
does not include:

Direct search limit (LEP-2):

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

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

$M_{Higgs} < 219$ GeV (95%CL)

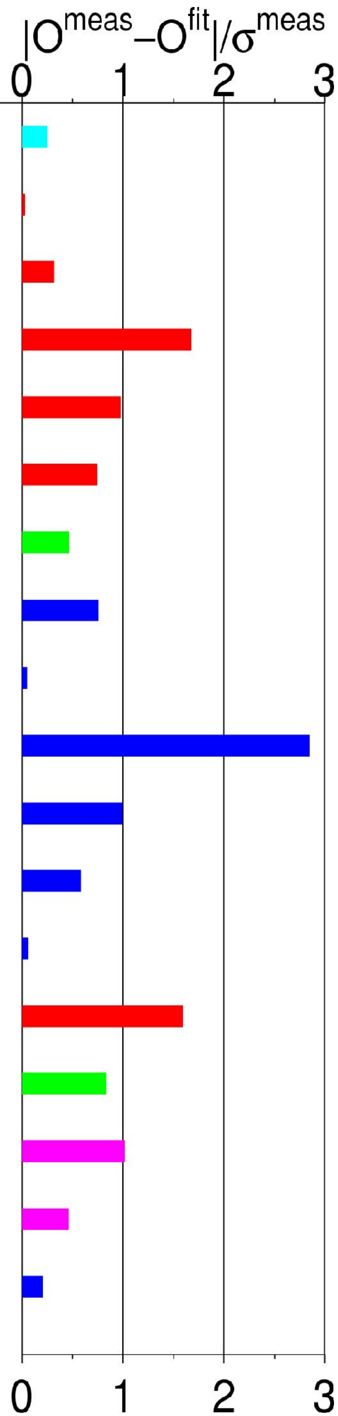



Theory uncertainty:

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

# Standard Model Analysis

| | Measurement | Fit |
|---|---|---|
| $\Delta\alpha_{had}^{(5)}(m_Z)$ | 0.02758 ± 0.00035 | 0.02767 |
| $m_Z$ [GeV] | 91.1875 ± 0.0021 | 91.1874 |
| $\Gamma_Z$ [GeV] | 2.4952 ± 0.0023 | 2.4959 |
| $\sigma_{had}^0$ [nb] | 41.540 ± 0.037 | 41.478 |
| $R_l$ | 20.767 ± 0.025 | 20.742 |
| $A_{fb}^{0,l}$ | 0.01714 ± 0.00095 | 0.01643 |
| $A_l(P_\tau)$ | 0.1465 ± 0.0032 | 0.1480 |
| $R_b$ | 0.21629 ± 0.00066 | 0.21579 |
| $R_c$ | 0.1721 ± 0.0030 | 0.1723 |
| $A_{fb}^{0,b}$ | 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 | 0.1480 |
| $\sin^2\theta_{eff}^{lept}(Q_{fb})$ | 0.2324 ± 0.0012 | 0.2314 |
| $m_W$ [GeV] | 80.410 ± 0.032 | 80.377 |
| $\Gamma_W$ [GeV] | 2.123 ± 0.067 | 2.092 |
| $m_t$ [GeV] | 172.7 ± 2.9 | 173.3 |




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

$\chi^2$/ndof = 18.6/13 (13.6%)

Largest $\chi^2$ contribution:

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

Decided in favour of leptons by $M_W$

Afb(b) has largest pull: 2.8!

Predict observables measured in reactions with low-$Q^2$:

$$Q^2 \ll M_W^2$$

# Predictions for Low-$Q^2$ Measurements

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

Parity-violating t-channel contribution due to $\gamma/Z$ 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)

$Q_W(Cs) = -72.74 \pm 0.46$ SM fit: $-72.91 \pm 0.03$ ✔

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

Parity-violating t-channel contribution due to $\gamma/Z$ interference

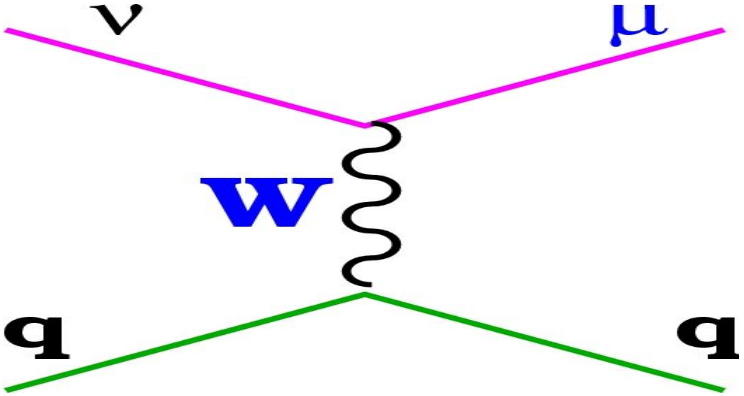
$A_{PV} = (\sigma_R - \sigma_L)/(\sigma_R + \sigma_L) \propto Q_W(e^-) = -4g_{Ae}g_{Ve}$ at $Q^2 \sim 0.03\ \mathrm{GeV}^2$

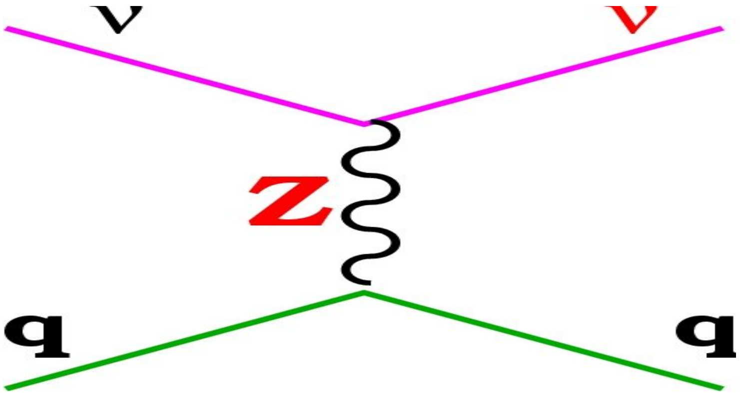
$\sin^2\Theta_{eff}(Q=M_Z) = 0.2333 \pm 0.0015$ SM fit: $0.2314 \pm 0.0001$ ✔

# NuTeV Neutrino-Nucleon Scattering

Muon-(anti-)neutrino quark scattering:

charged current (CC) neutral current (NC)




Paschos-Wolfenstein relation (iso-scalar target):

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

+ electroweak radiative corrections

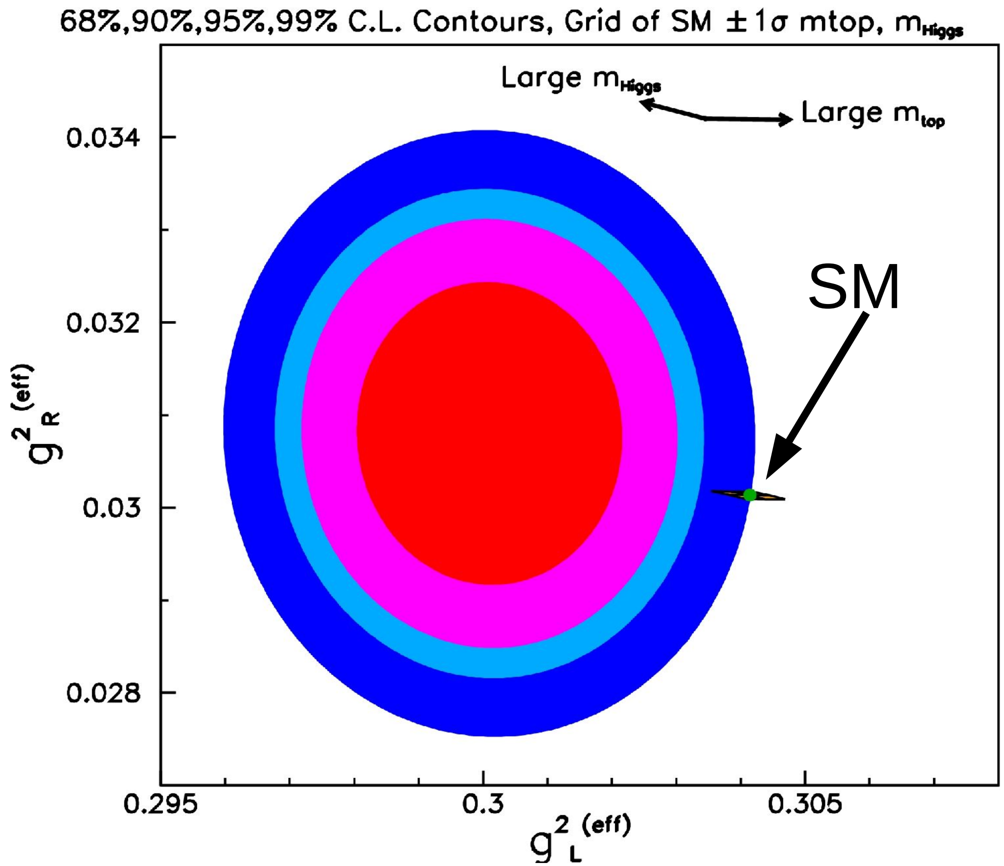
Effective couplings: $g_L$, $g_R$ at $\langle Q^2\rangle \sim 20\ \mathrm{GeV}^2$

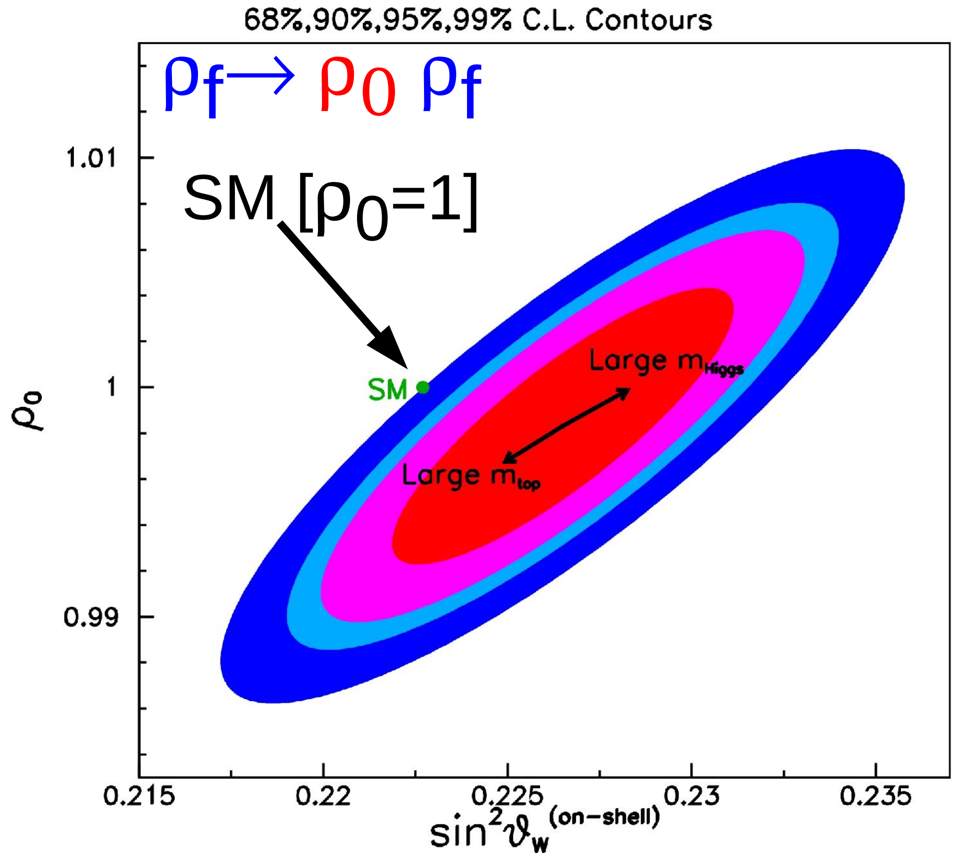
Historically result quoted in terms of: $\sin^2\Theta_W = 1-(M_W/M_Z)^2$

Factor two more precise than previous νN world average

# NuTeV's Result

SM fit: Difference of ~3 $\sigma$ in either $\sin^2\Theta_W$ or the $\rho$'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?

# Conclusions

Wealth of high-precision electroweak measurements:

New results from Tevatron's Run-II, surpassing Run-I

All Z-pole results (LEP-1, SLD) now final!

Most measurements agree with expectations:

Successful test of loop corrections, constraints on new physics

SM Higgs boson should be light

Some 3-sigma effects:

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

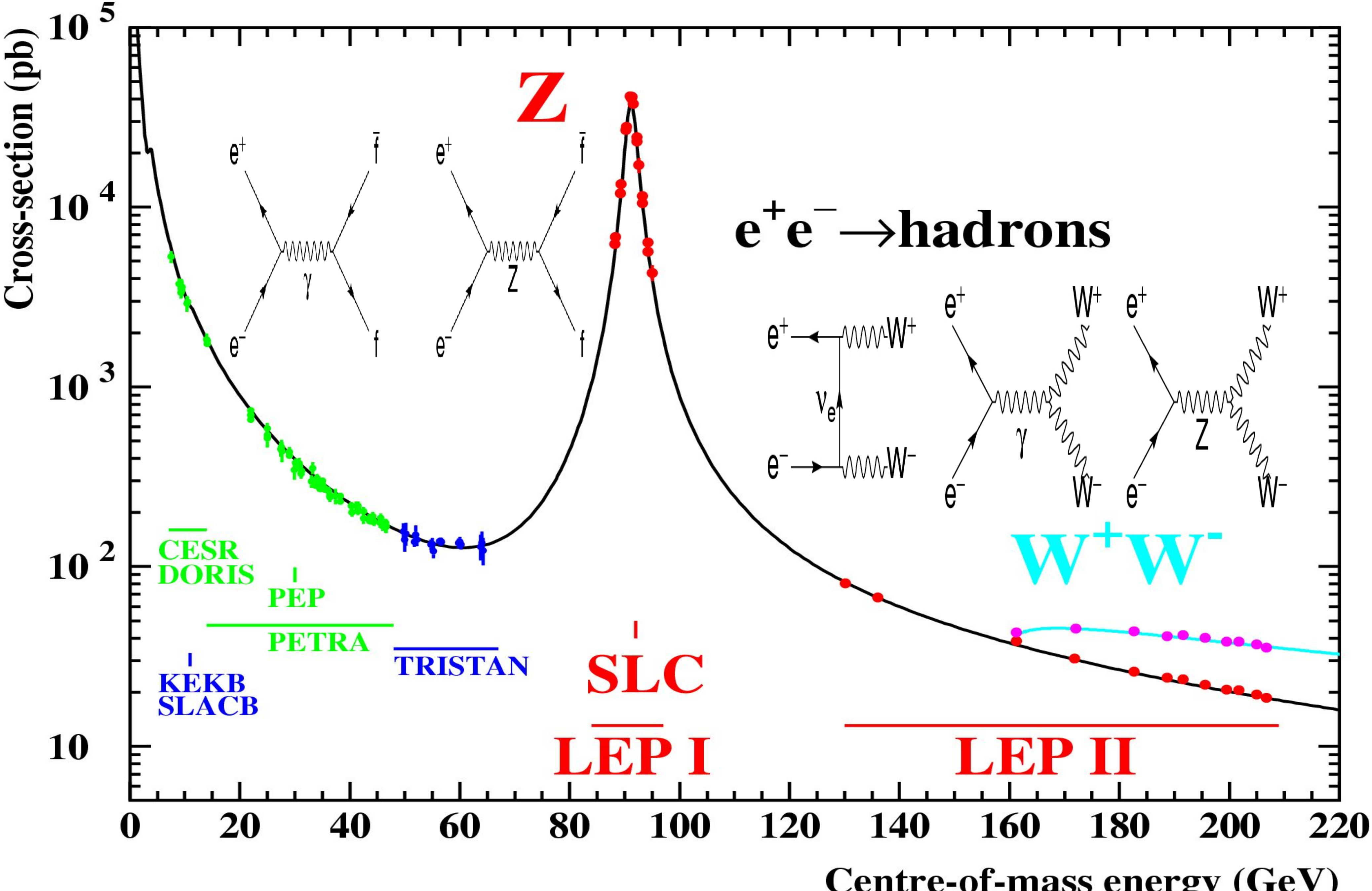
Future at TEVATRON, LHC and ILC:

Precise theoretical calculations - including theory uncertainties

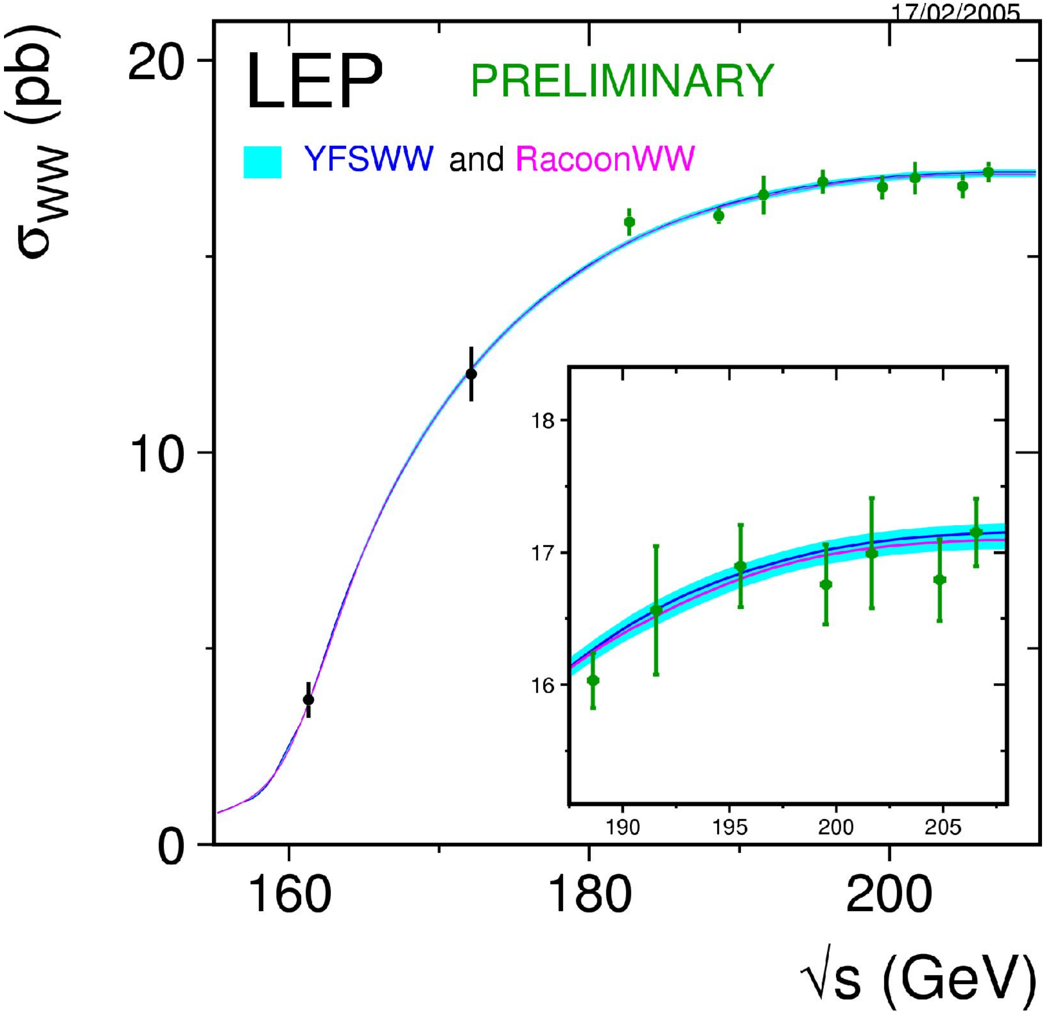
Improved measurements in W boson and top quark physics

Check Higgs-mass prediction! Find new physics?

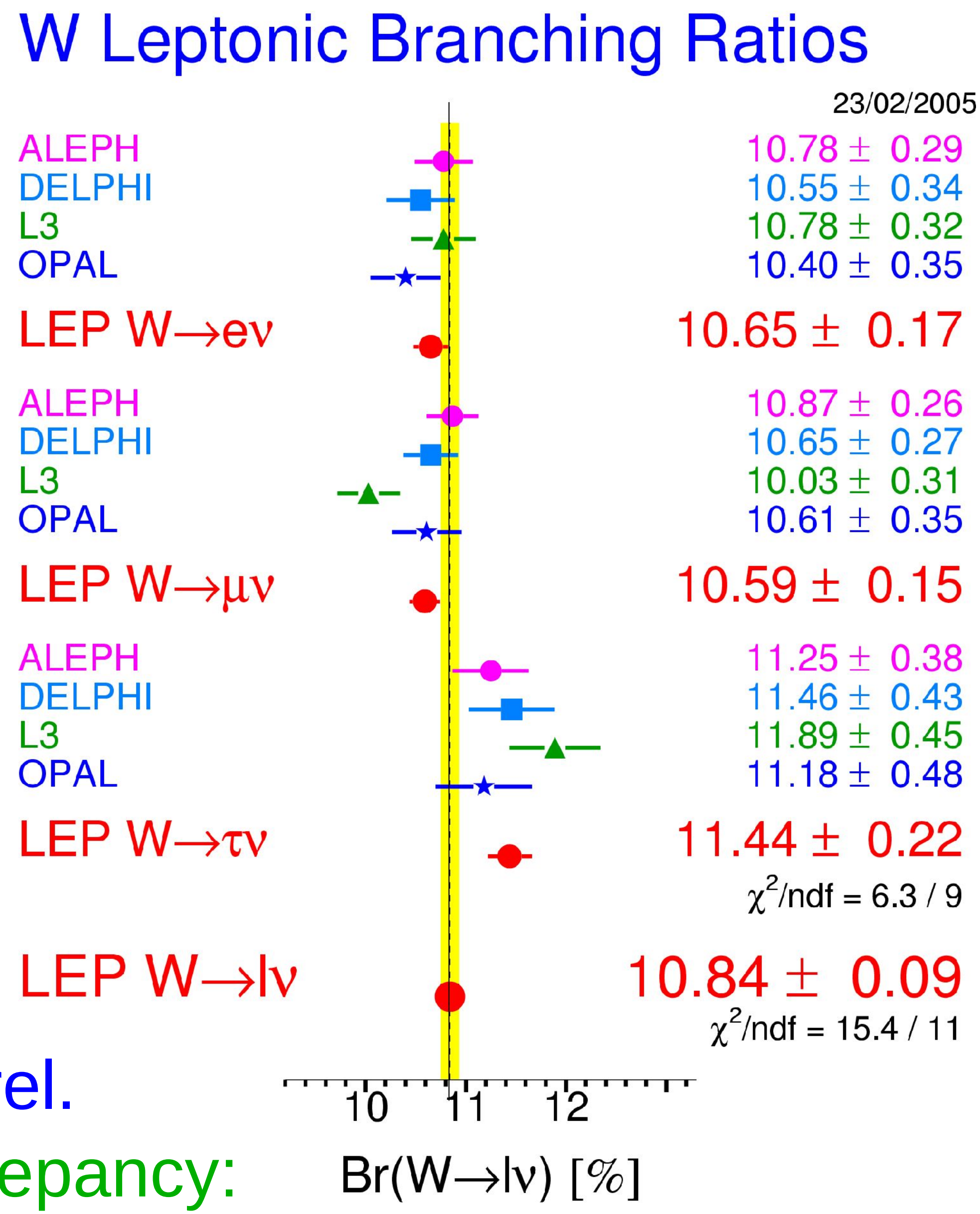
# $e^+e^-$ Interactions



# W-Pairs at LEP




Winter 2005 - LEP Preliminary




ALEPH, DELPHI, L3 final, OPAL prel.

Subsequent maximisation of discrepancy:

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

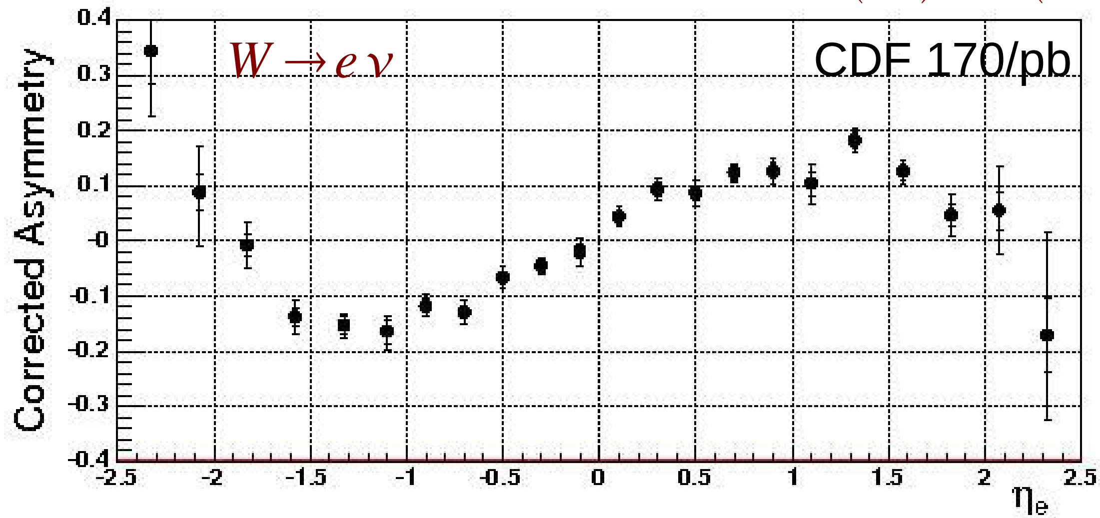
# W/Z Physics at the Tevatron

Forward-backward asymmetries in W and Z:

$W^+$ boosted in p direction

Constrains PDFs

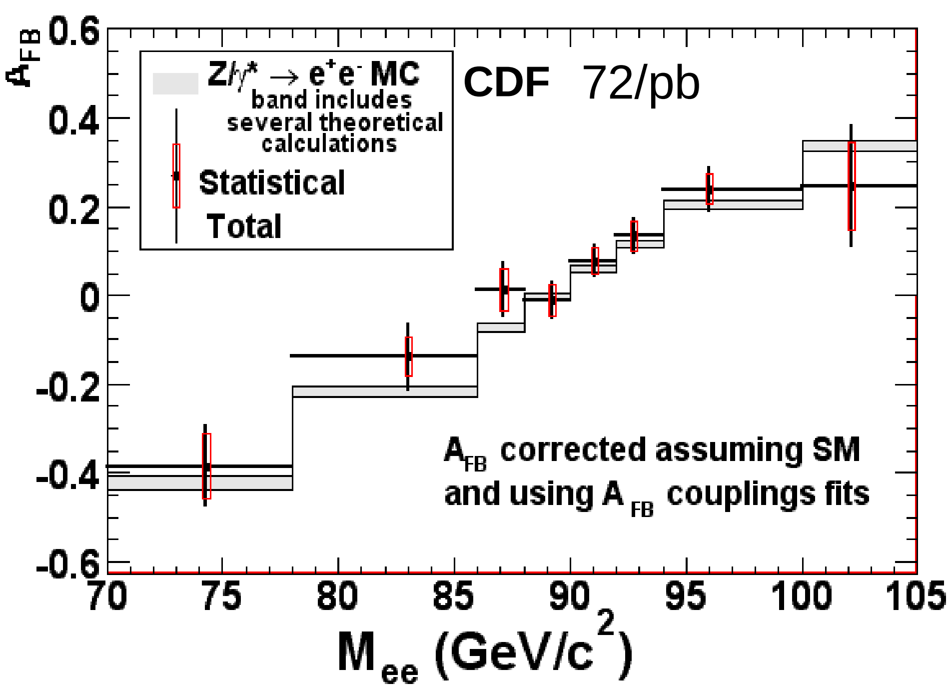
$$A_{charge}(\eta_e) = \frac{N(e^+)-N(e^-)}{N(e^+)+N(e^-)}$$

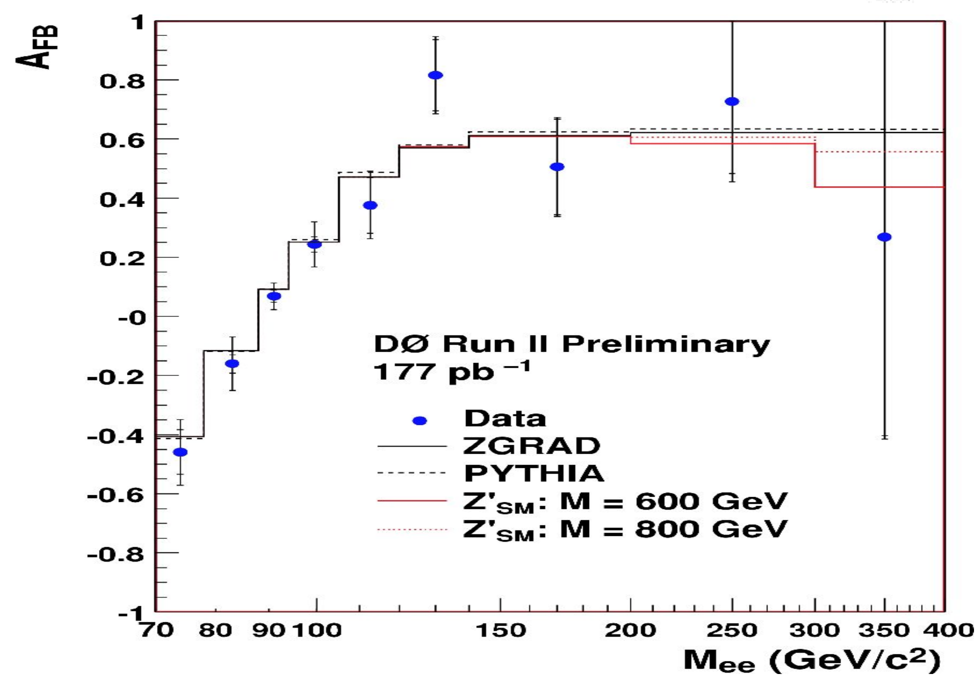



Z f/b asymmetry:

Needs PDFs to measure

$\sin^2\Theta_{eff}$ =0.2238(40)(30)



# W Boson - Mass and Width

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

Transverse mass

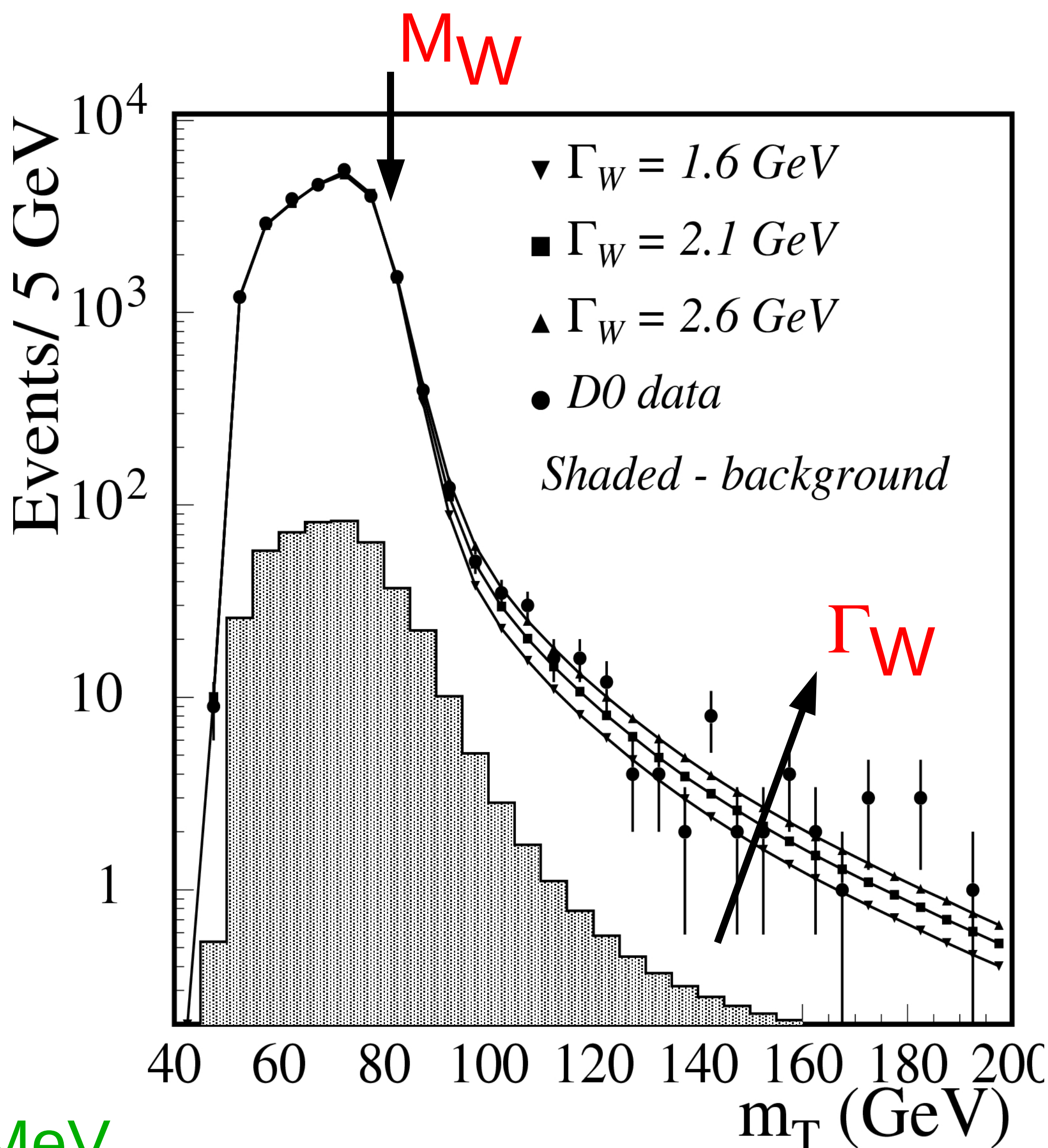
$$m_T^2 = 2E_T^e E_T^\nu \cos\phi(e,\nu)$$

Final Run-I combination

Awaiting Run-II results!

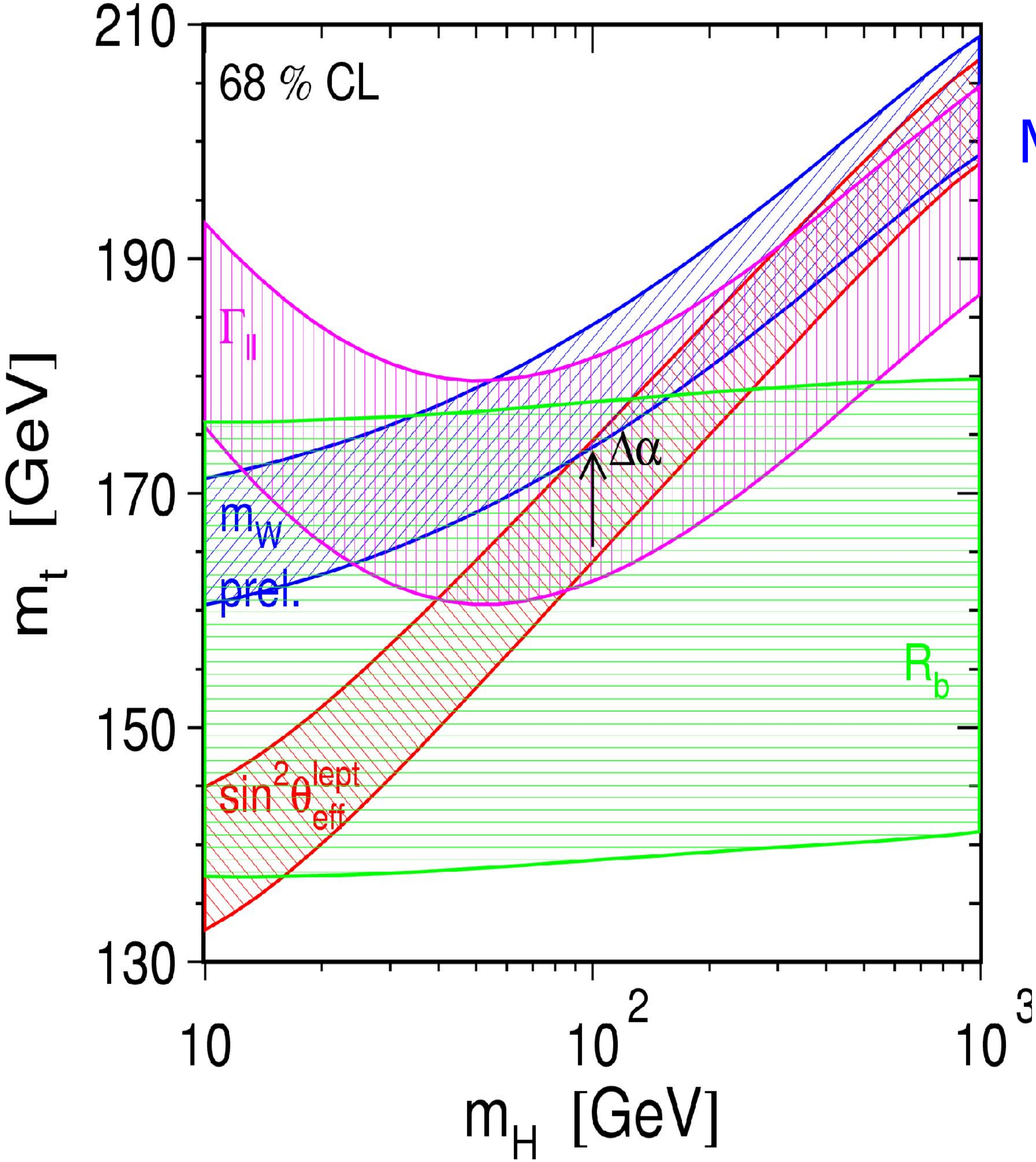
Uncertainties dominated by:

- 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

# Top-Higgs Bands




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

Bands of ±1σ from:

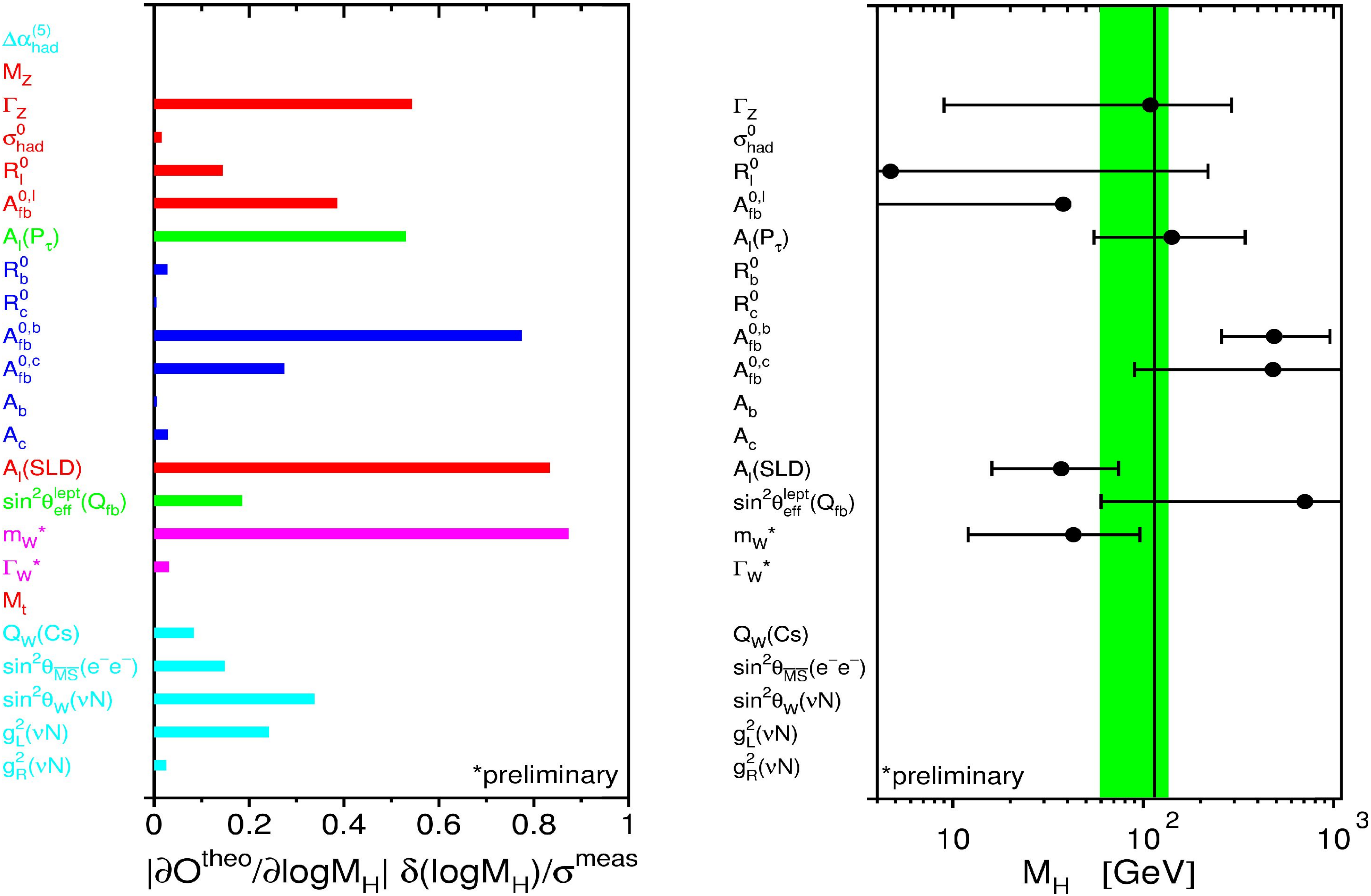
$M_W$ = 80.410(32) GeV

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

$\Gamma_l$ = 83.984(86) MeV

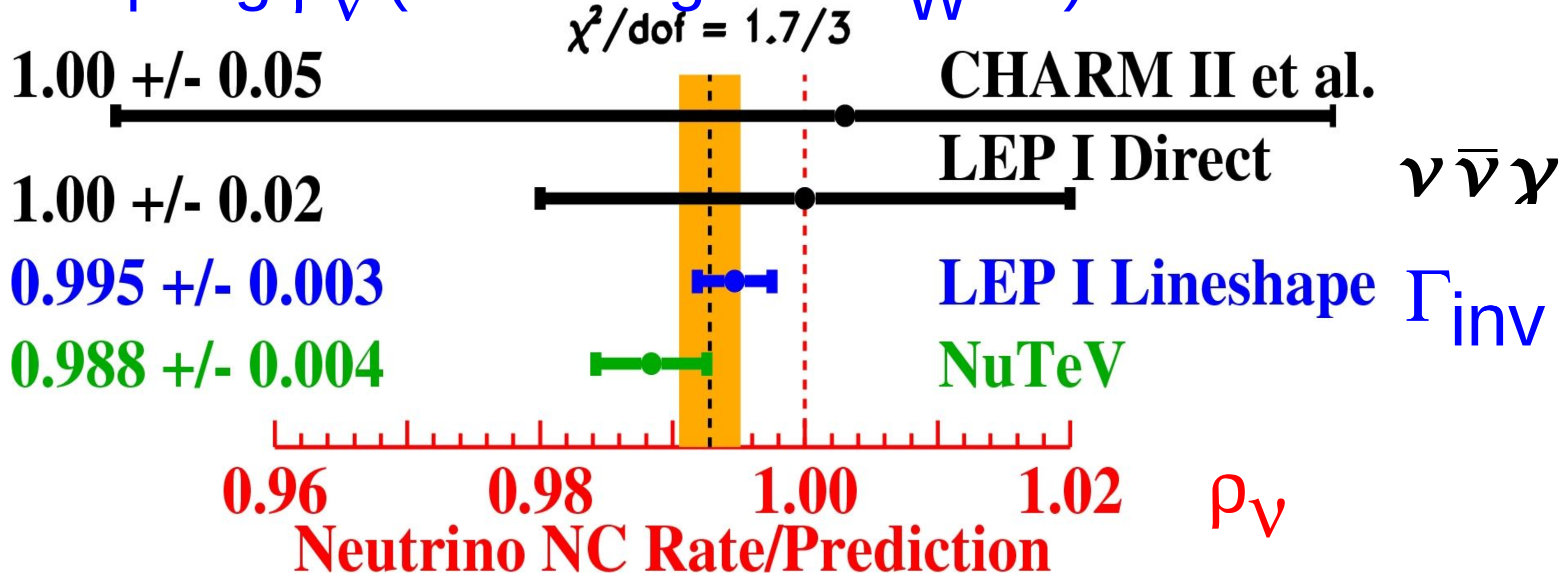
$R_b$ = 0.21629(66)

# Higgs Sensitivities and Constraints



# NuTeV's Result

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

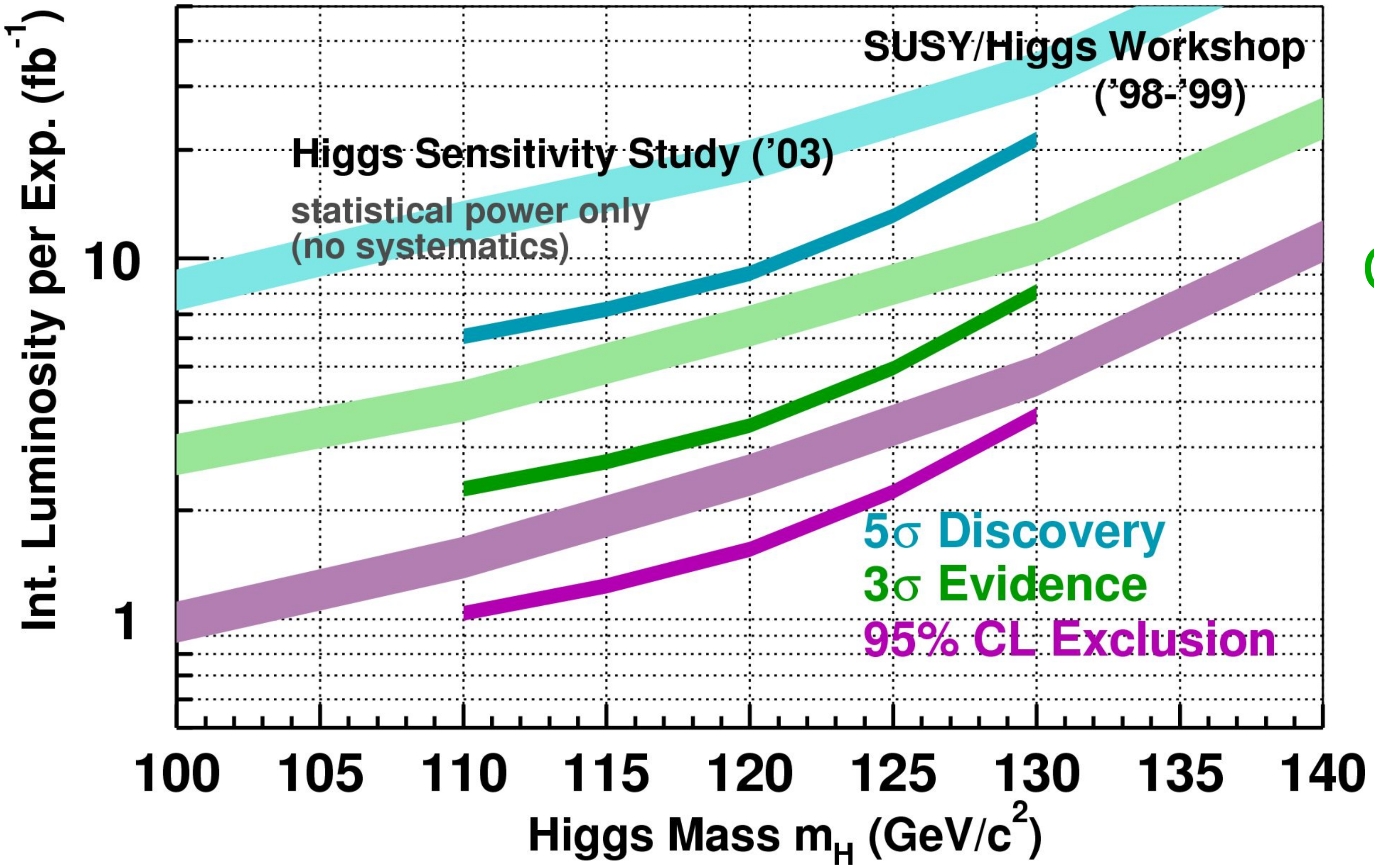



Various explanations:

- 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

# Standard Model Higgs Search

Combining production and decay channels and experiments:




Combined
CDF+DØ
Sensitivity

Expectations:

With 2/fb exclusion up to 123 GeV

With 10/fb discovery up to 121 GeV

Currently: ~1/fb on tape