Electroweak Physics

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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 boson physics (LEP-1,SLD):

5 Z lineshape and leptonic forward-backward asymmetries

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

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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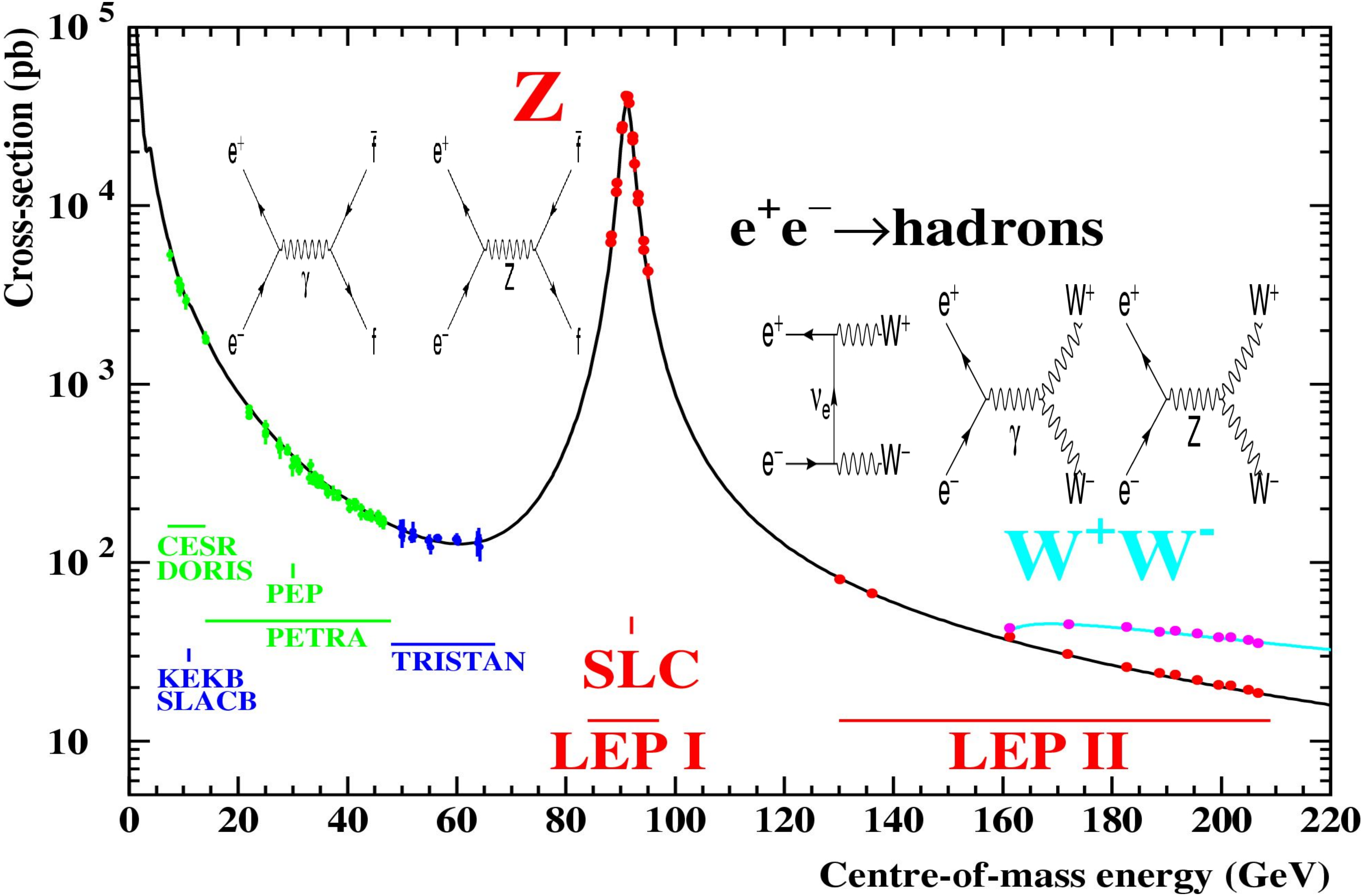
17

e^+e Interactions



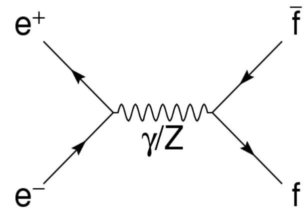
Z Physics

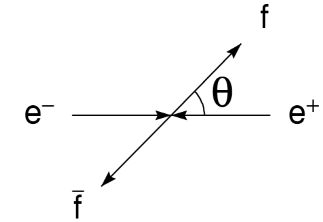
Cross sections:

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

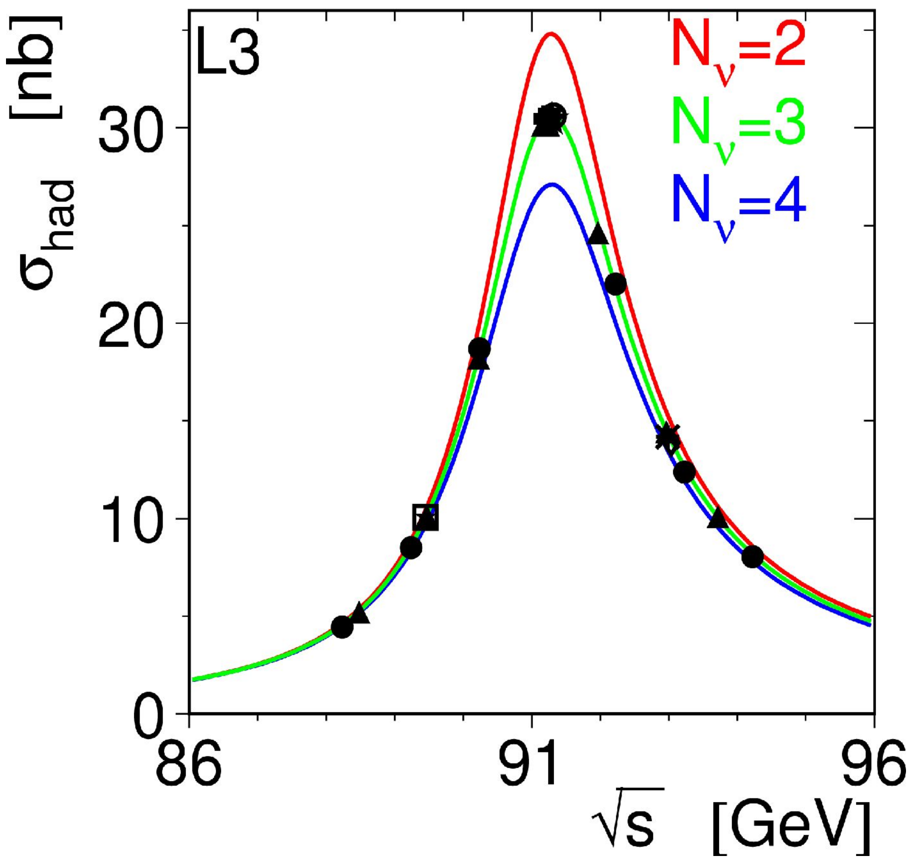
$$\Gamma_Z = 2.4952 \pm 0.0023 \ GeV$$

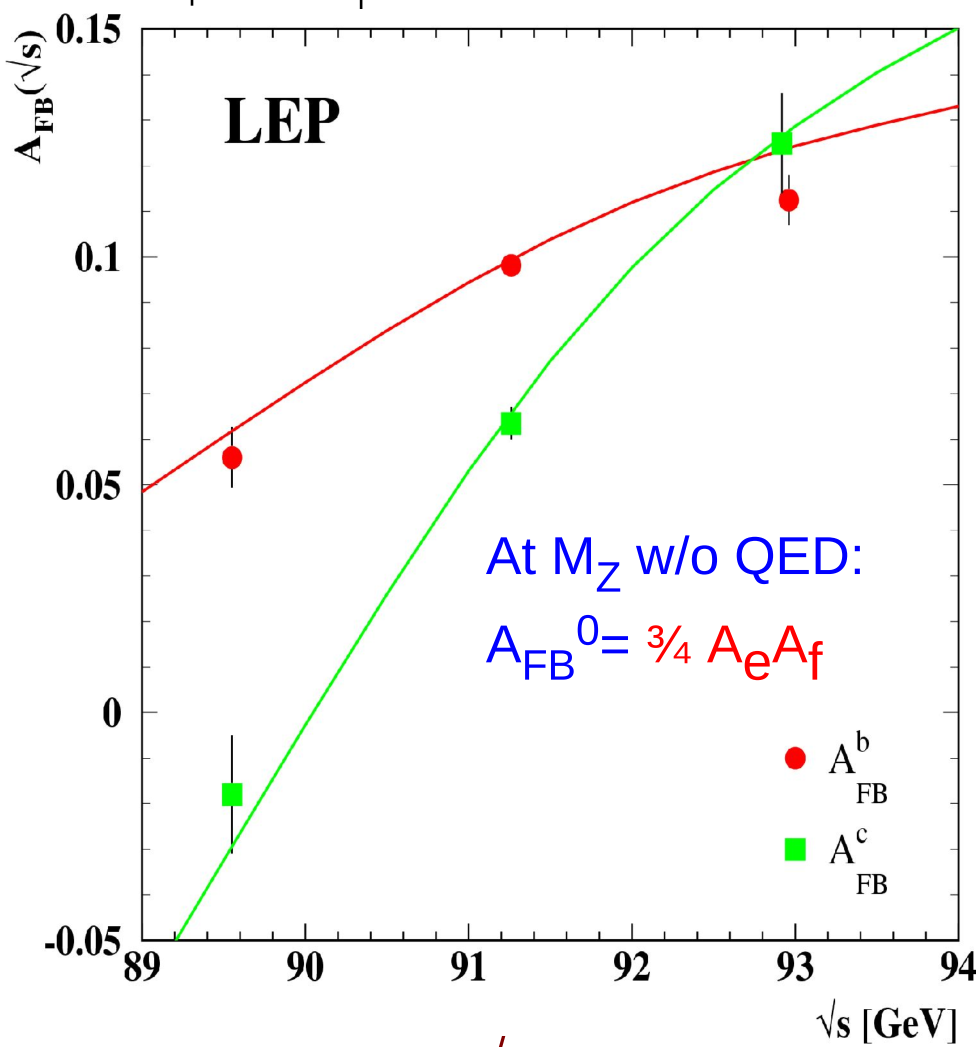
$$N_\nu = 2.9840 \pm 0.0082$$





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





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

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

Heavy Flavour Results at the Z

Finally: final HF results available

$R_b = \Gamma_b/\Gamma_{had}$	0.21630	± 0.00066
$R_c = \Gamma_c/\Gamma_{had}$	0.1723	± 0.0031
$A_{fb}(b) = ¾ A_e A_b$	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

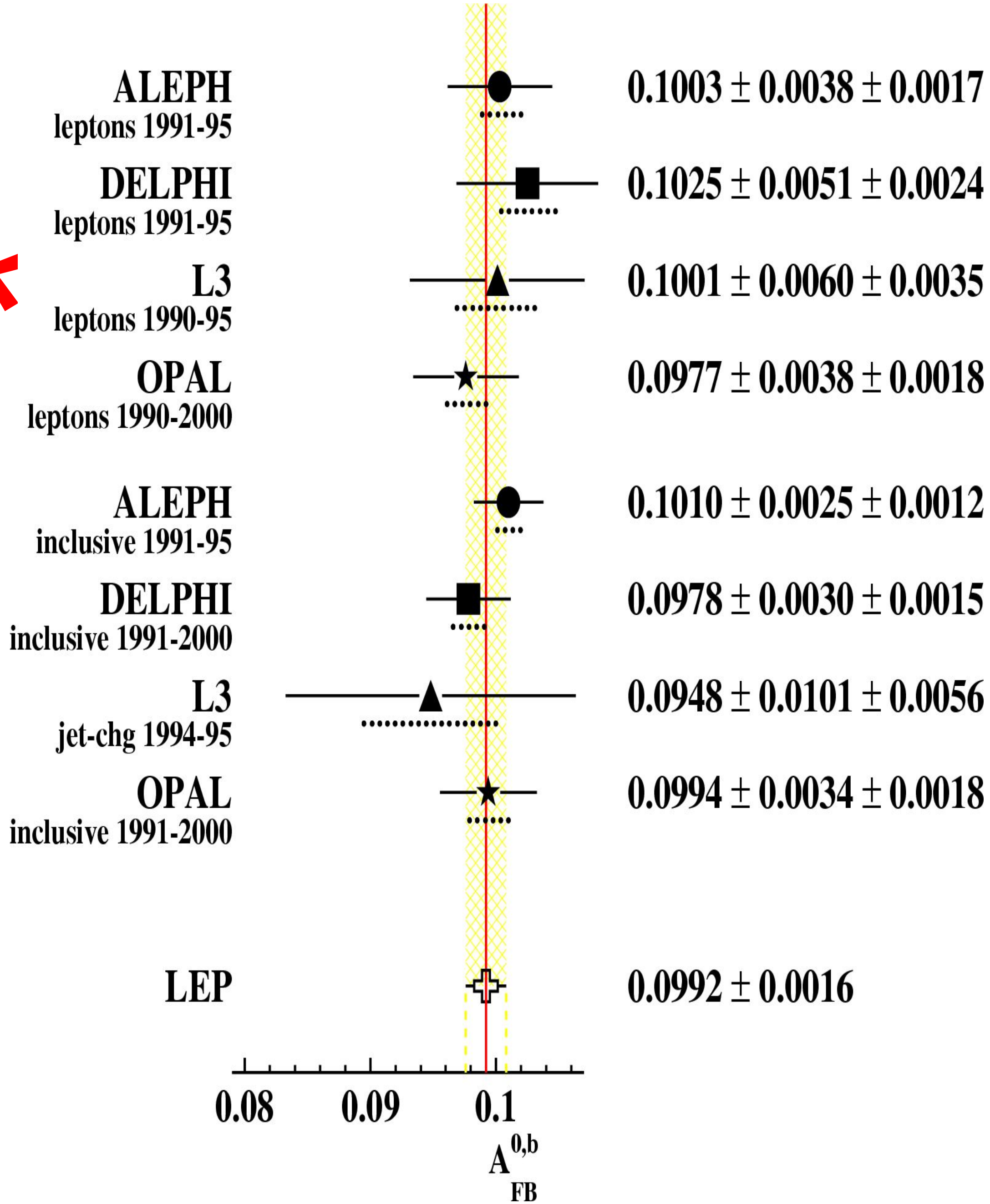
+ small correlations

Heavy-flavour combination:

χ^2/ndof = 53/(105-14) low!

Central values very consistent

Several systematic tests dominated by MC statistics

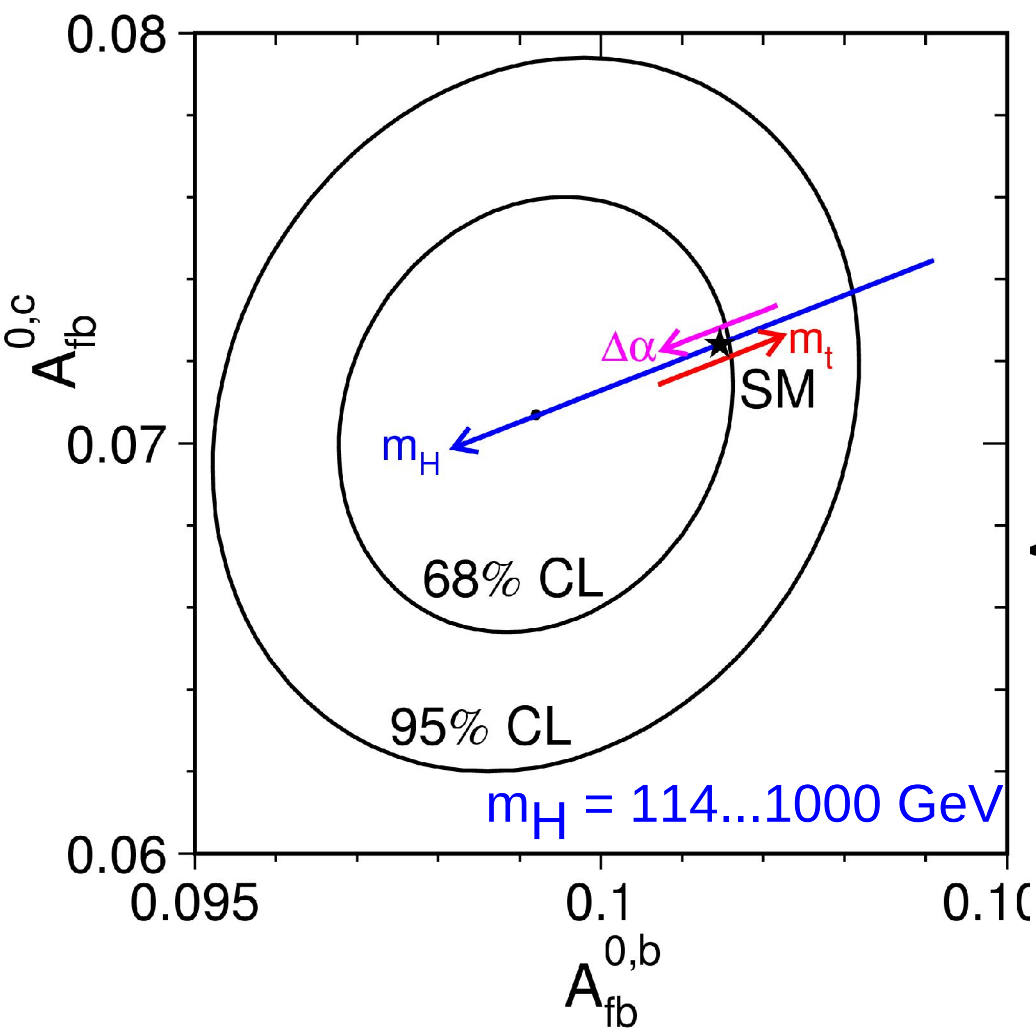


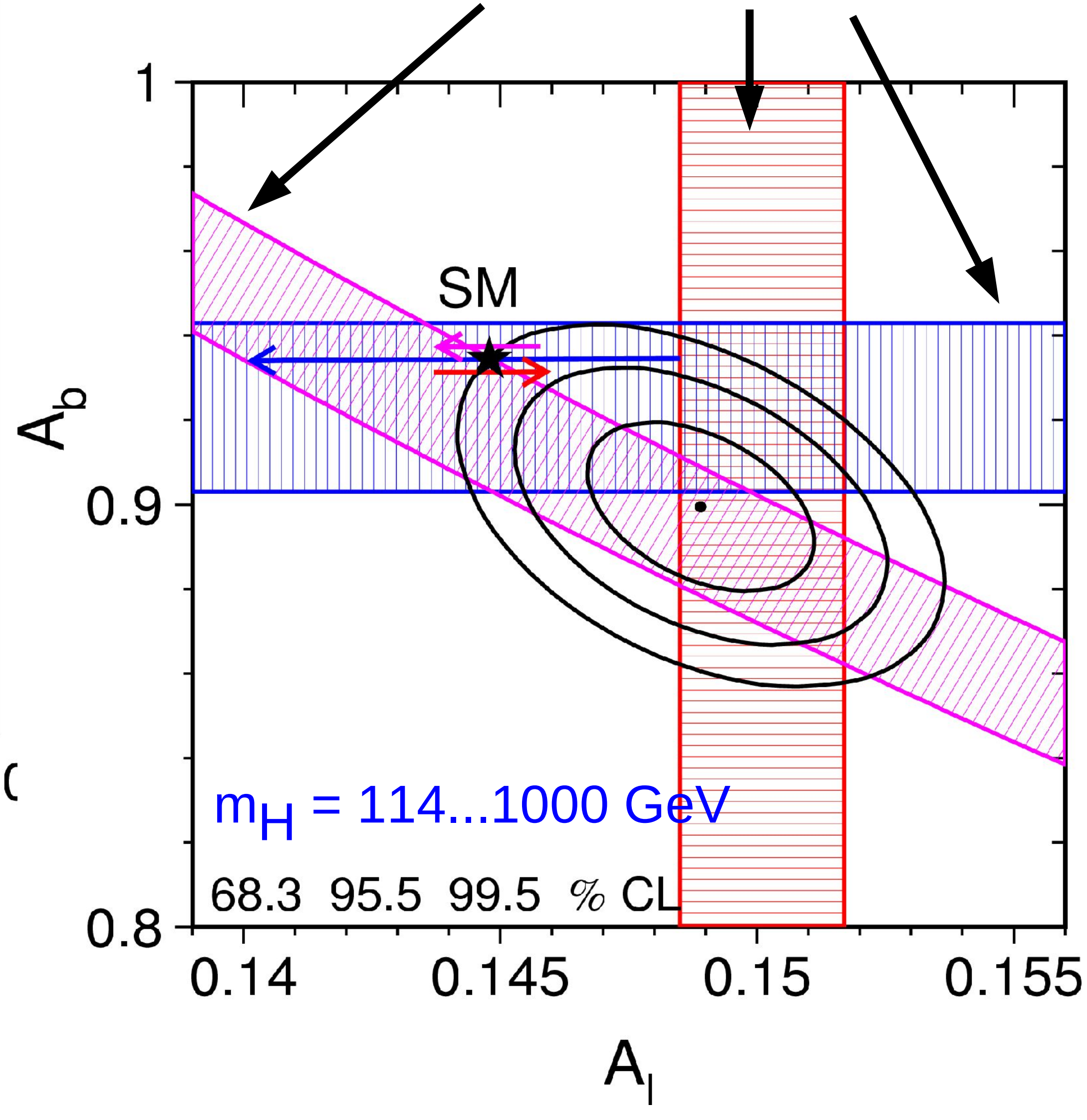
Asymmetries statistics dominated

Heavy Flavour Results at the Z

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:

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

$= 0.23153 \pm 0.00016$

$\chi^2/\mathrm{ndof} = 11.8/5$ [3.8%]

Subsequent observation:

0.23113±0.00021 leptons

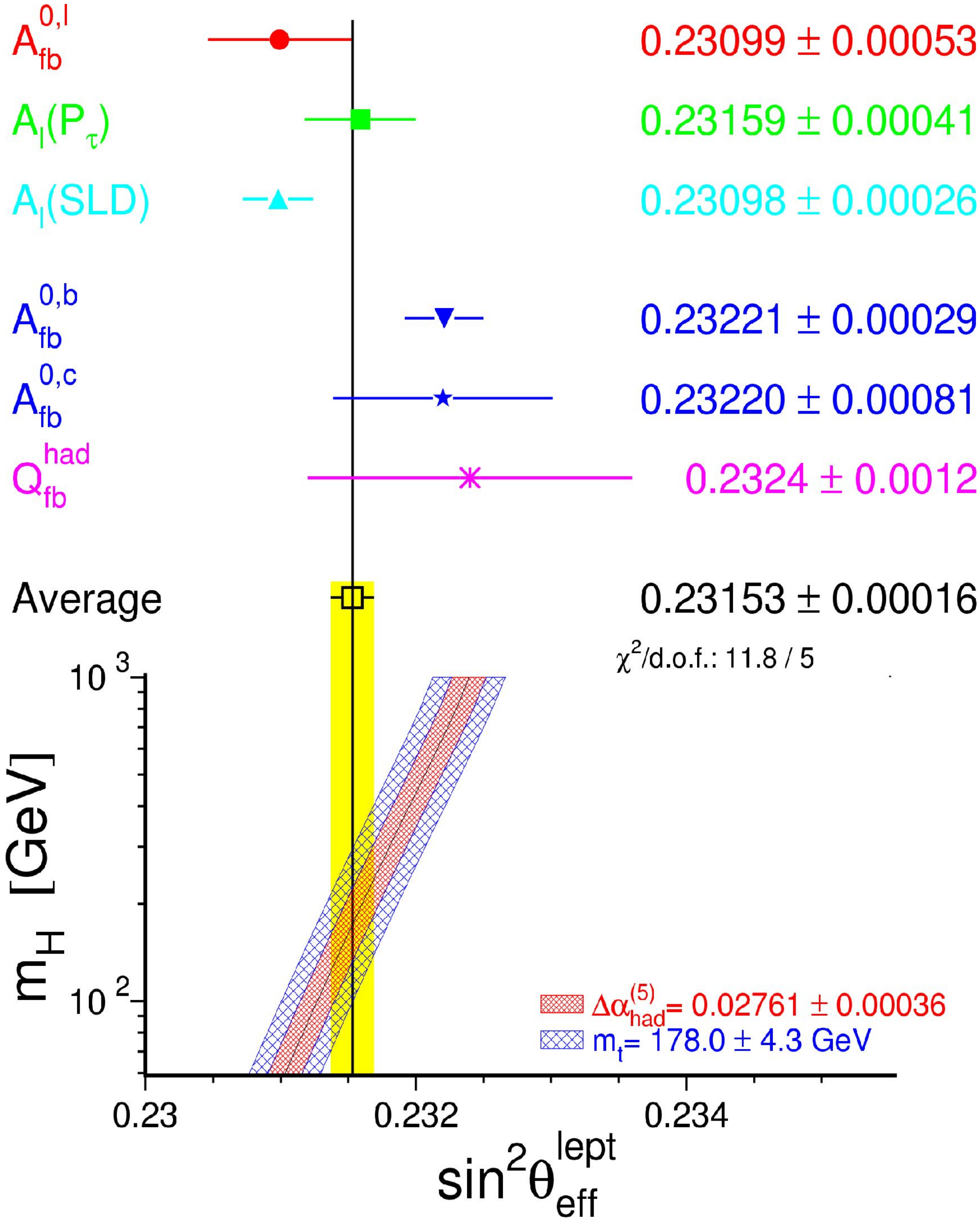
0.23222±0.00027 hadrons

3.2 σ difference

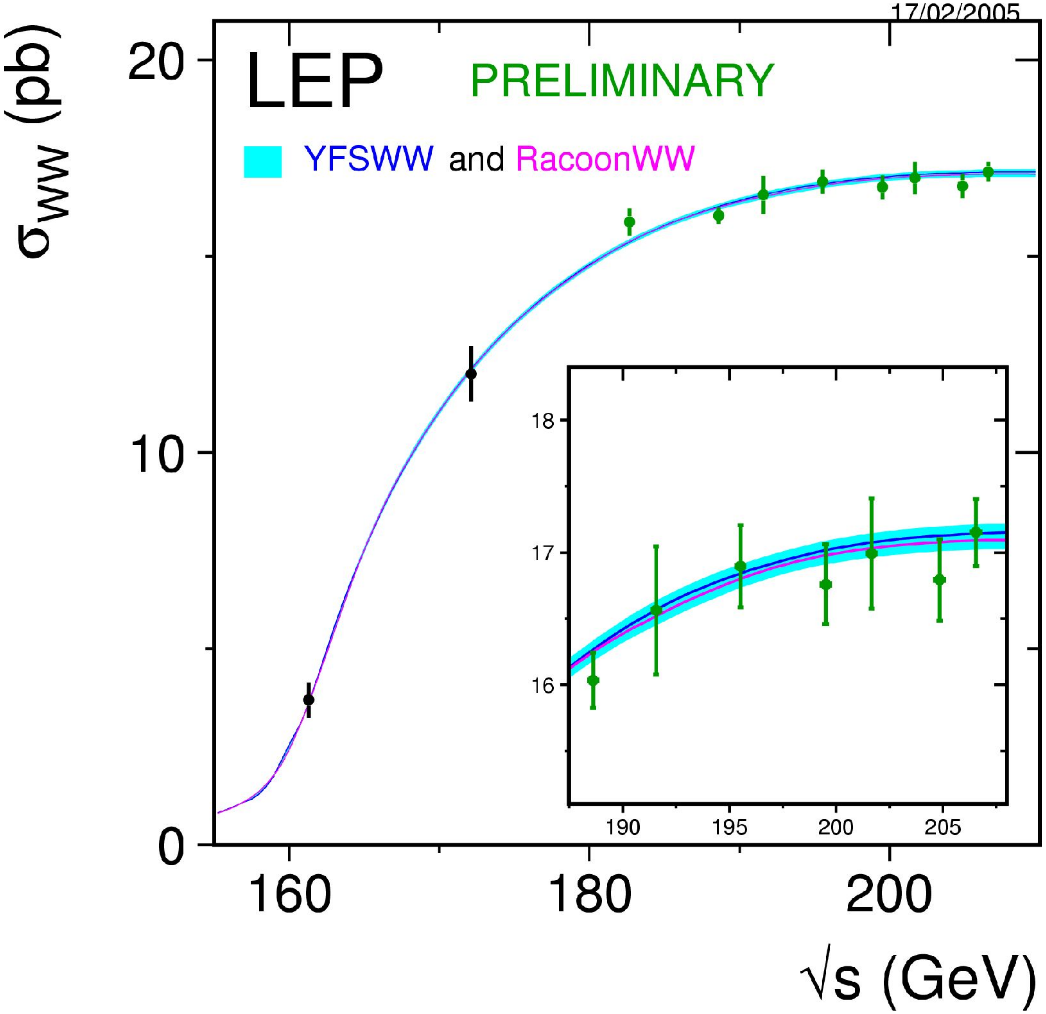
But is really:

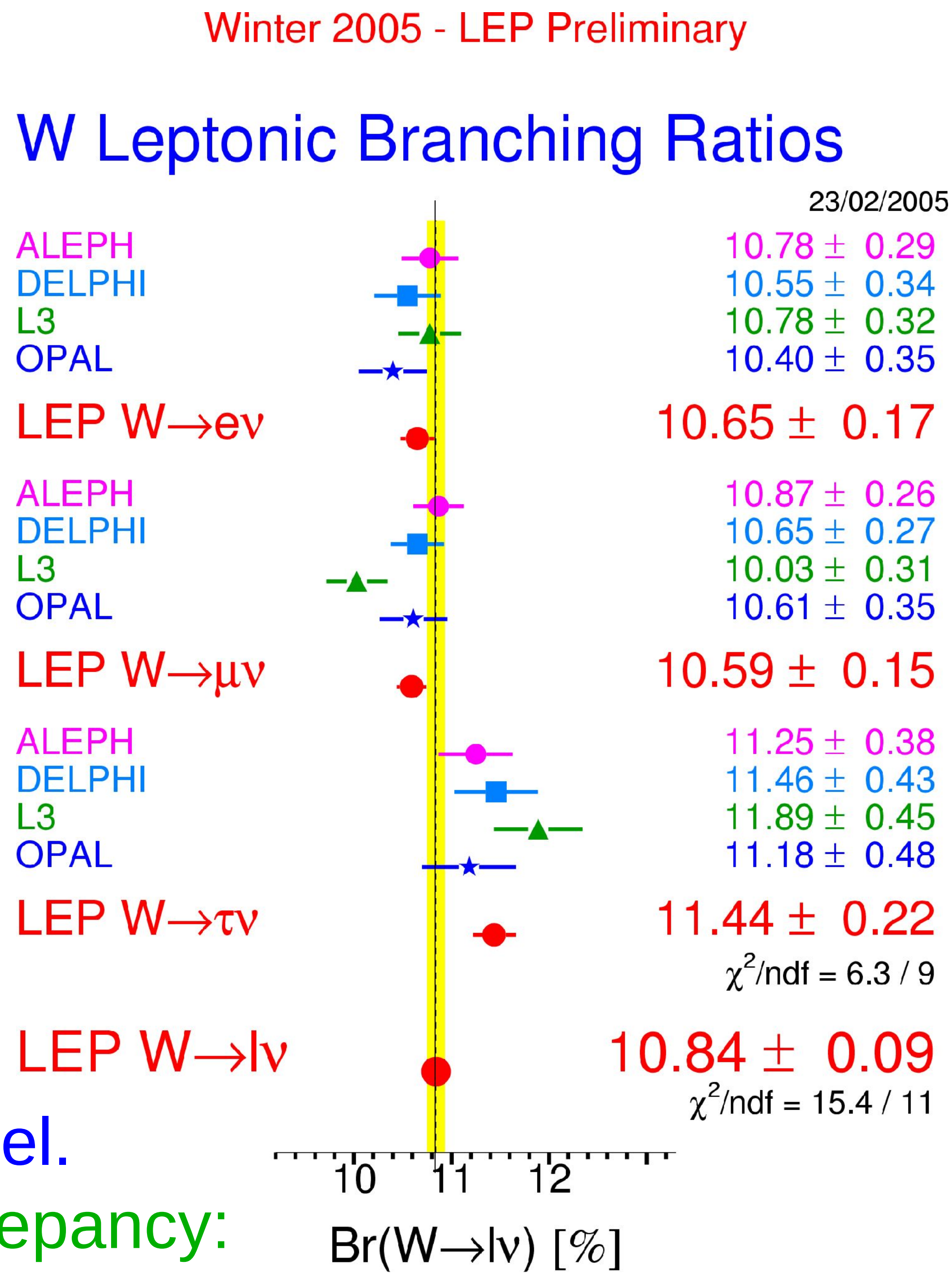
A_l(SLD) vs. A_{fb}b(LEP)

3.2 σ difference



W-Pairs at LEP





ALEPH, DELPHI, L3 final, OPAL prel.

Subsequent maximisation of discrepancy:

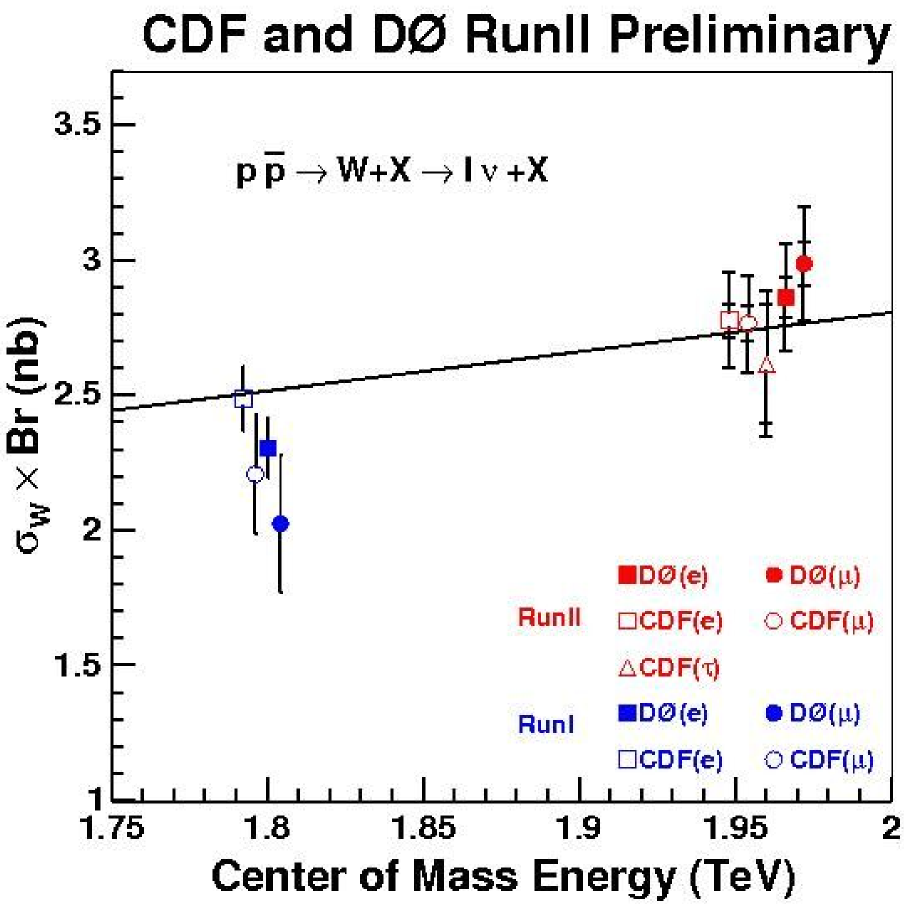
W-tau branching fraction ~2.9σ above W-e/μ average

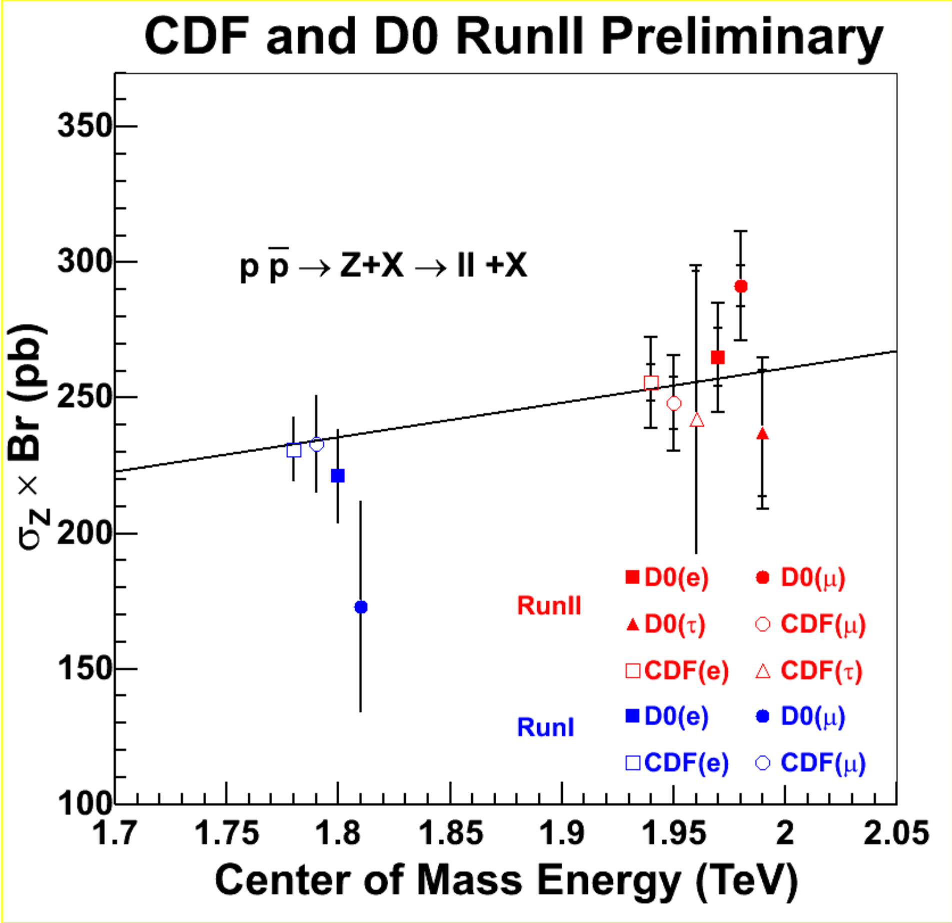
W/Z Physics at the Tevatron

Leptonic decay modes of W and Z (including tau leptons!):

4,000-14,000 Z's per e/μ

40,000-120,000 W per e/μ





Largest uncertainties:

Luminosity (~6%)

Lepton id efficiencies and PDFs (1-1.5% each)

Forward-backward asymmetries in W and Z:

W^+ boosted in p direction

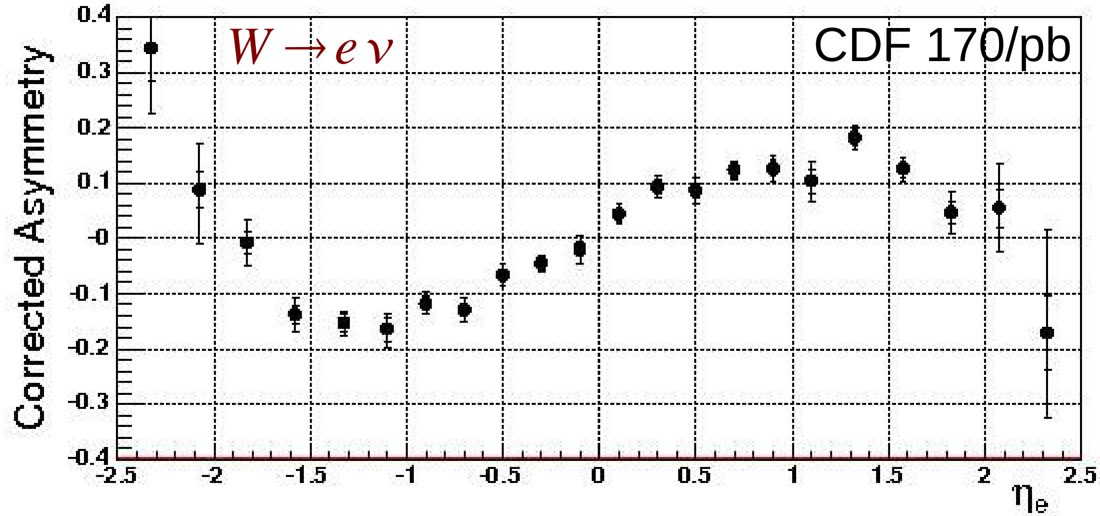
Constrains PDFs

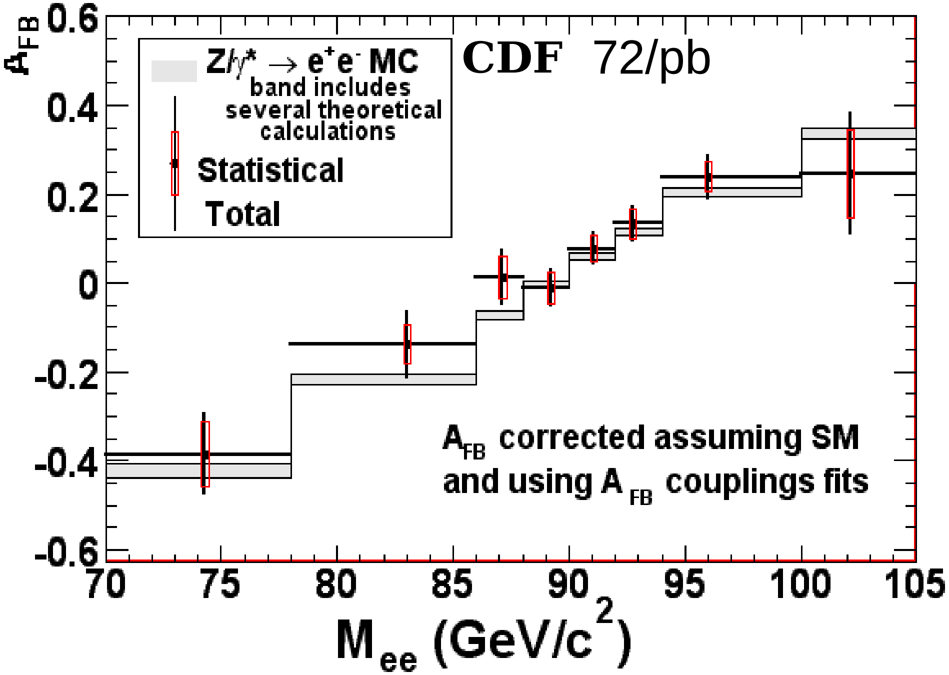
Z f/b asymmetry:

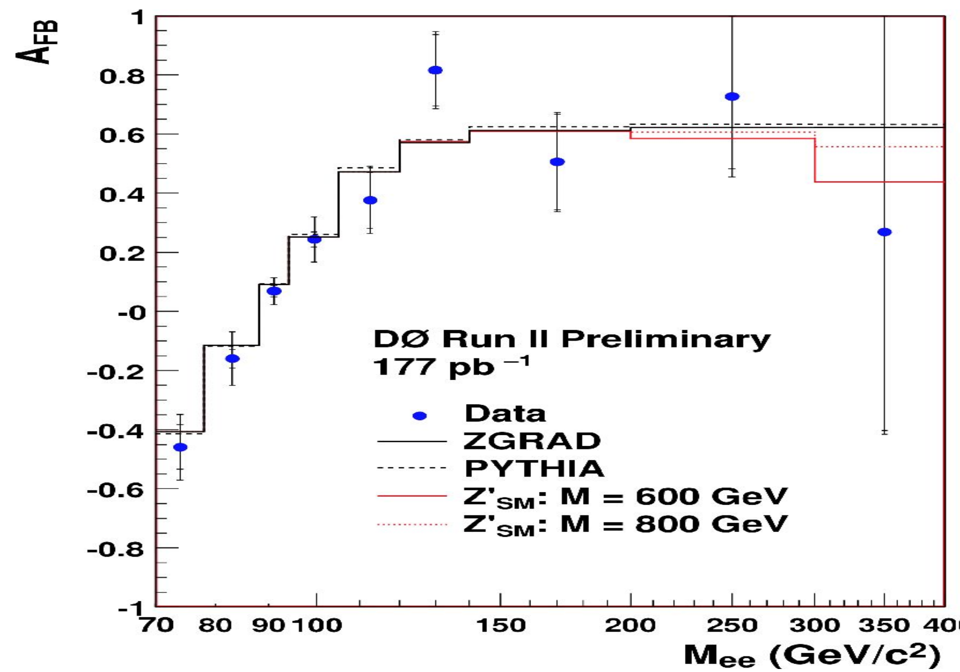
Needs PDFs to measure

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

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







W Boson - Mass and Width

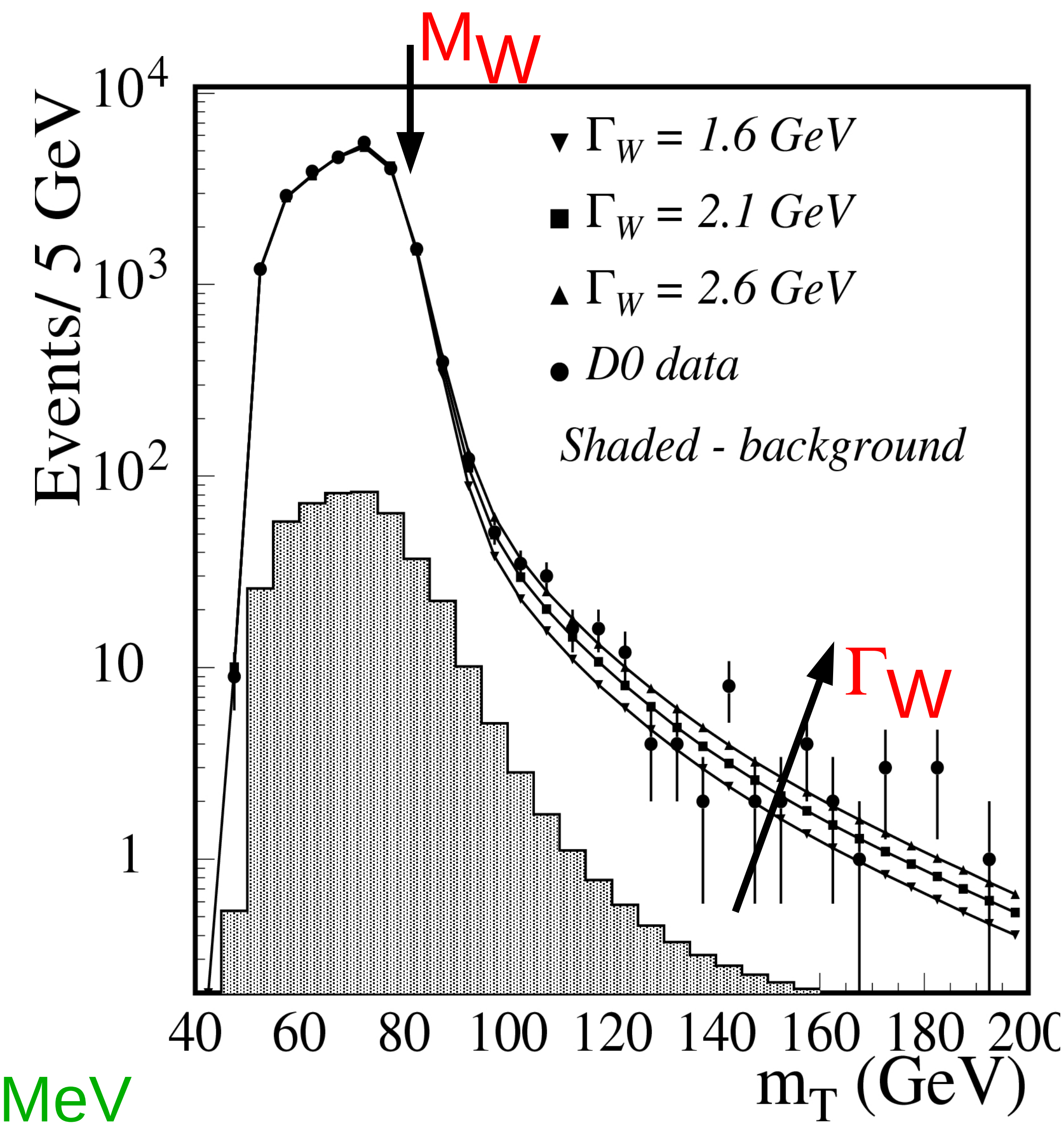
Tevatron (CDF, D∅): $p\bar{p} \to$ WX, W $\to$ eν, μν

Transverse mass

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

Final Run-I combination

Awaiting Run-II results!



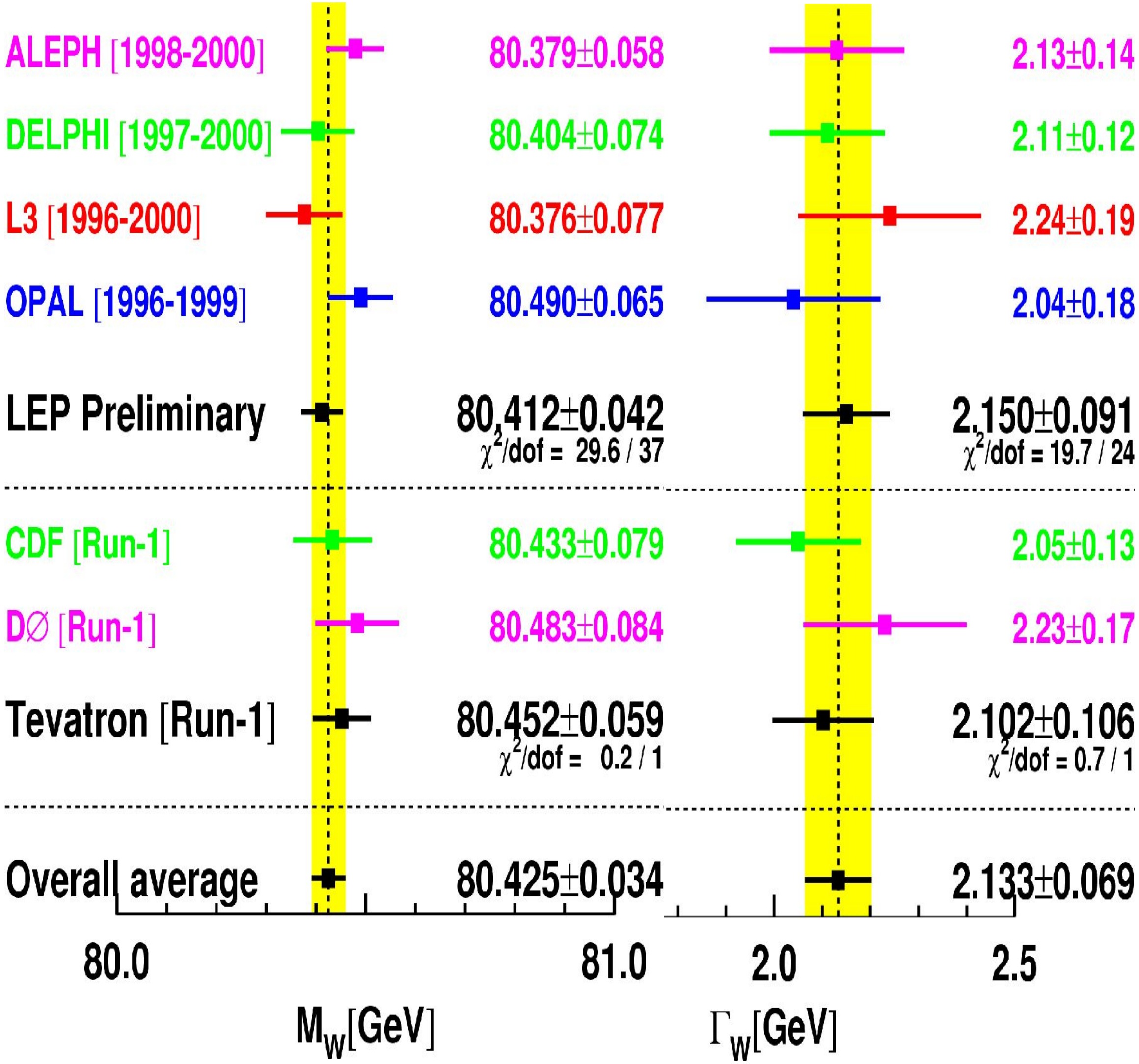
Uncertainties dominated by:

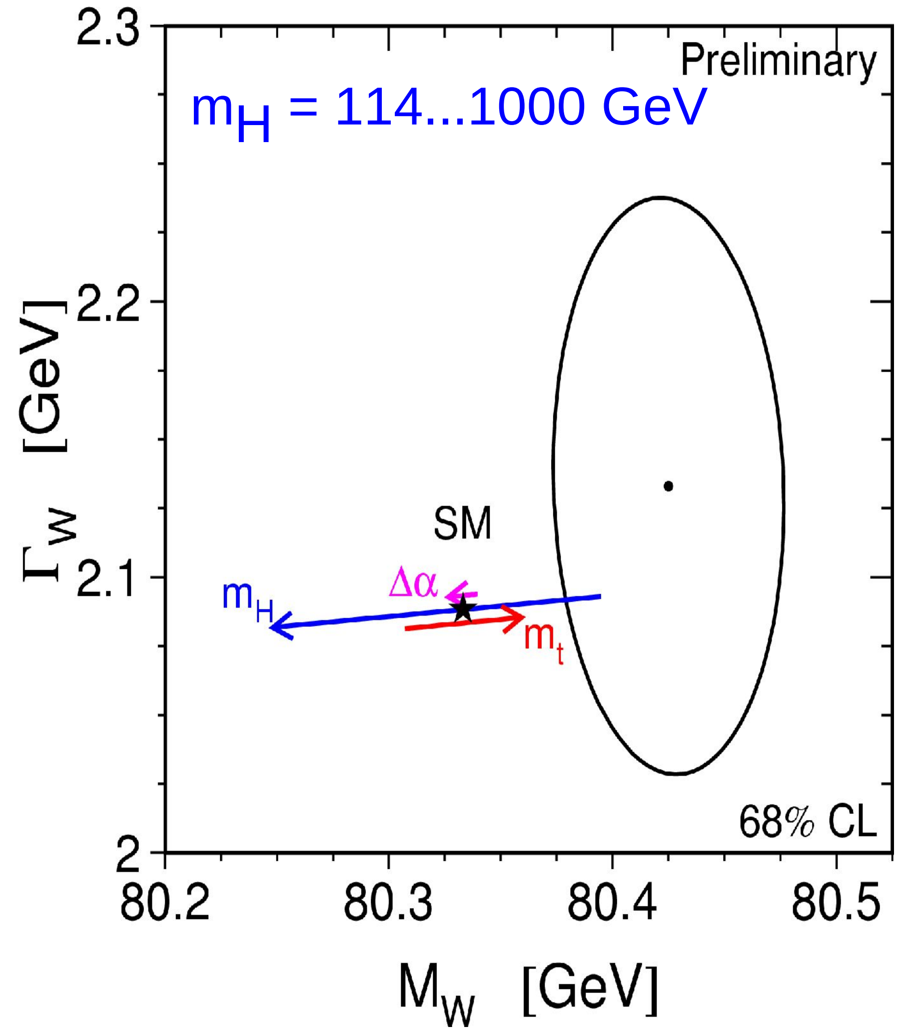
- Statistics
- Lepton energy scale -
  - will reduce with more data
- Then: Signal model
  - PDFs, gluon radiation
  - QED corrections in $W \to l\nu$

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

W Boson - Mass and Width

Very good agreement between all six experiments:





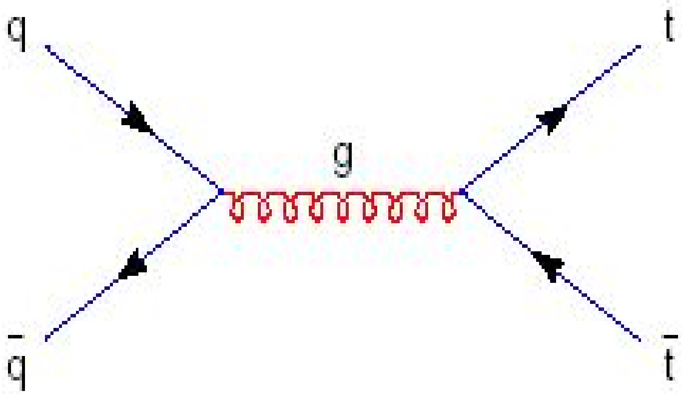
SM comparison:
Small Higgs-boson mass

Correlation M_W-Γ_W: -0.07

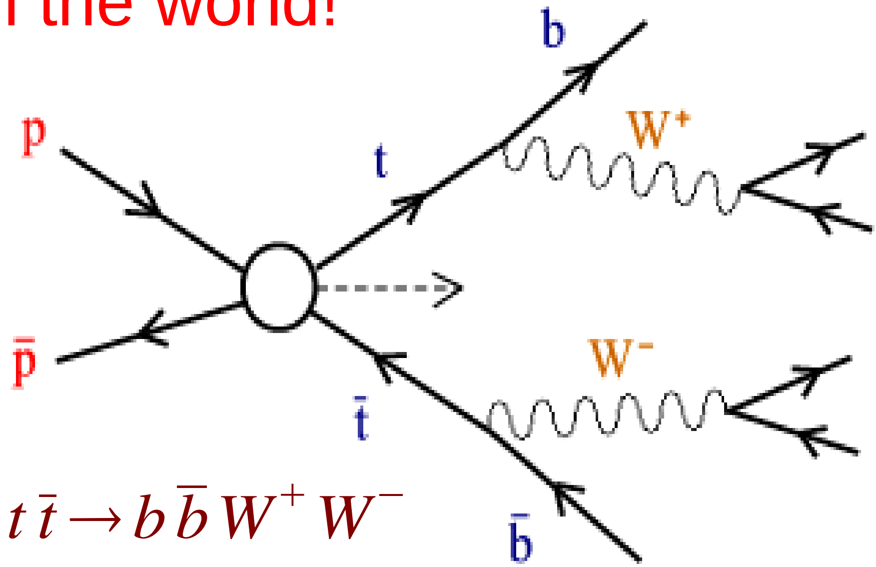
Top Physics

Tevatron: only source of top quarks in the world!

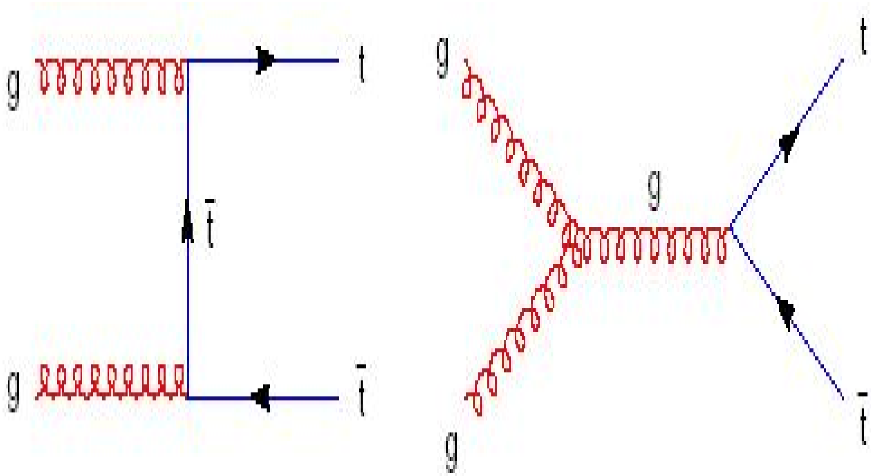
Primarily top-pair production



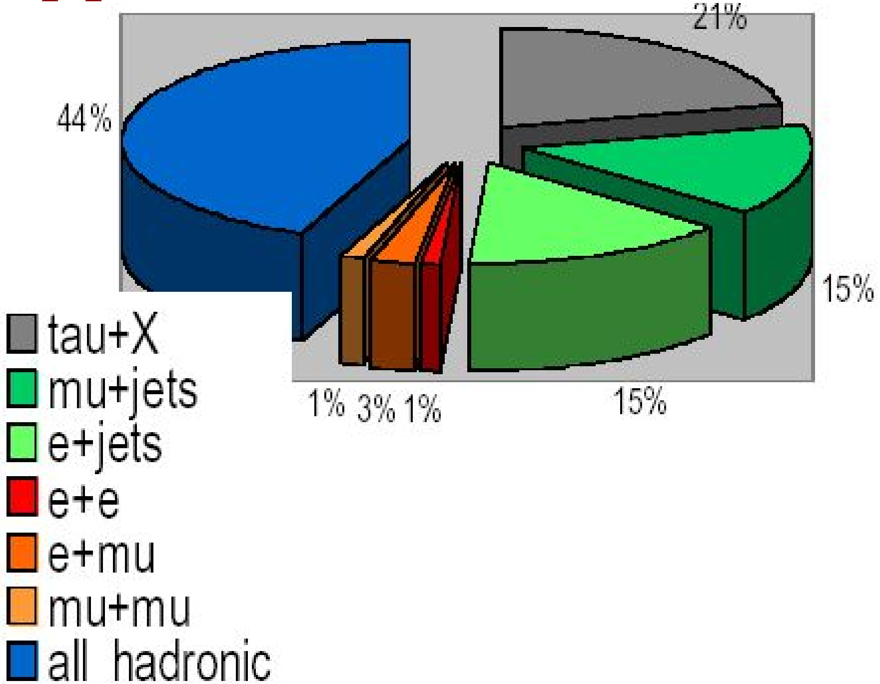
$q\bar{q}$ annihilation (85%)



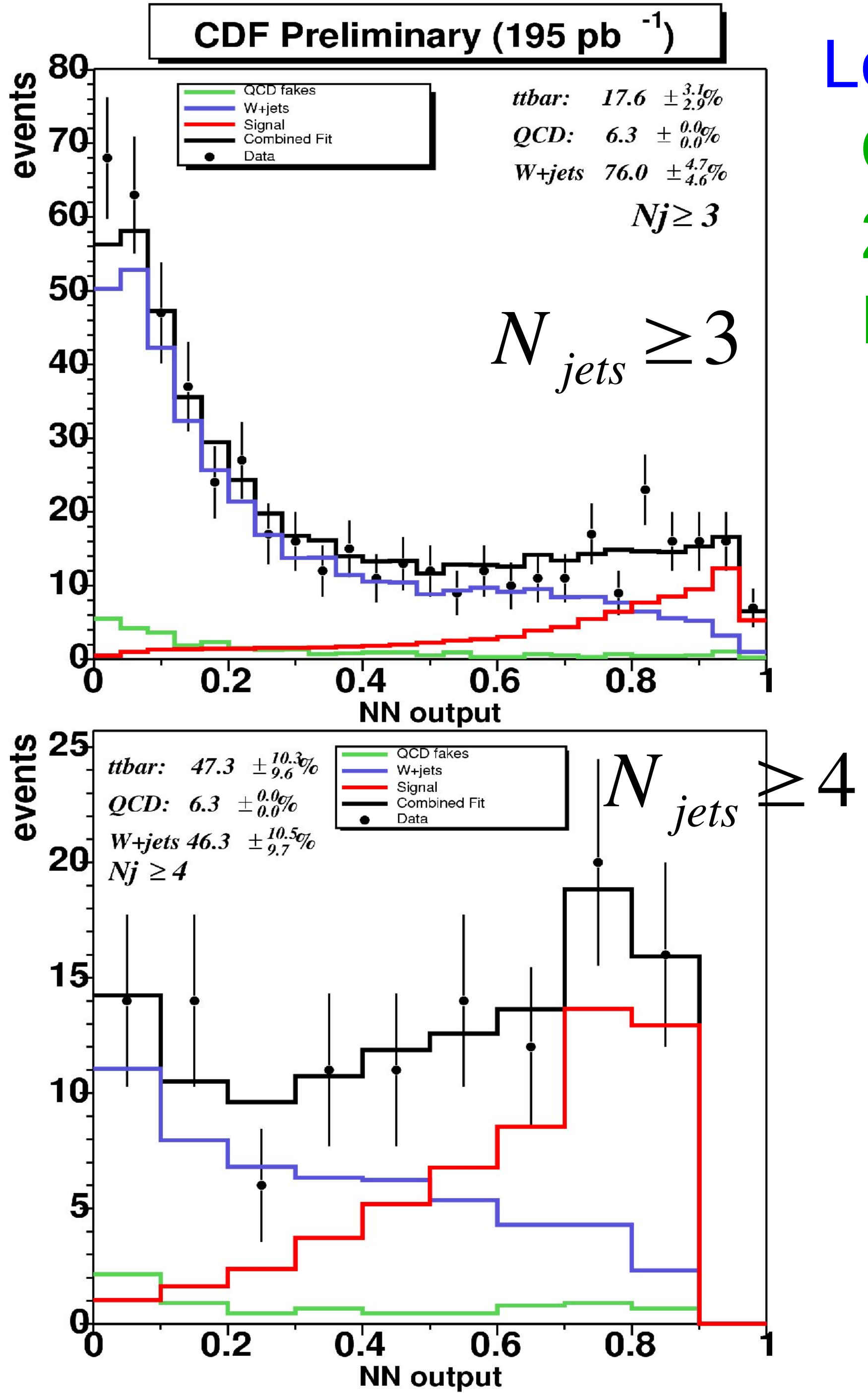
$$p\bar{p}\to t\bar{t}X,\quad t\bar{t}\to b\bar{b}W^{+}W^{-}$$
$$W^{-}\to q\bar{q},l^{-}\bar{\nu}$$



gluon fusion (15%)

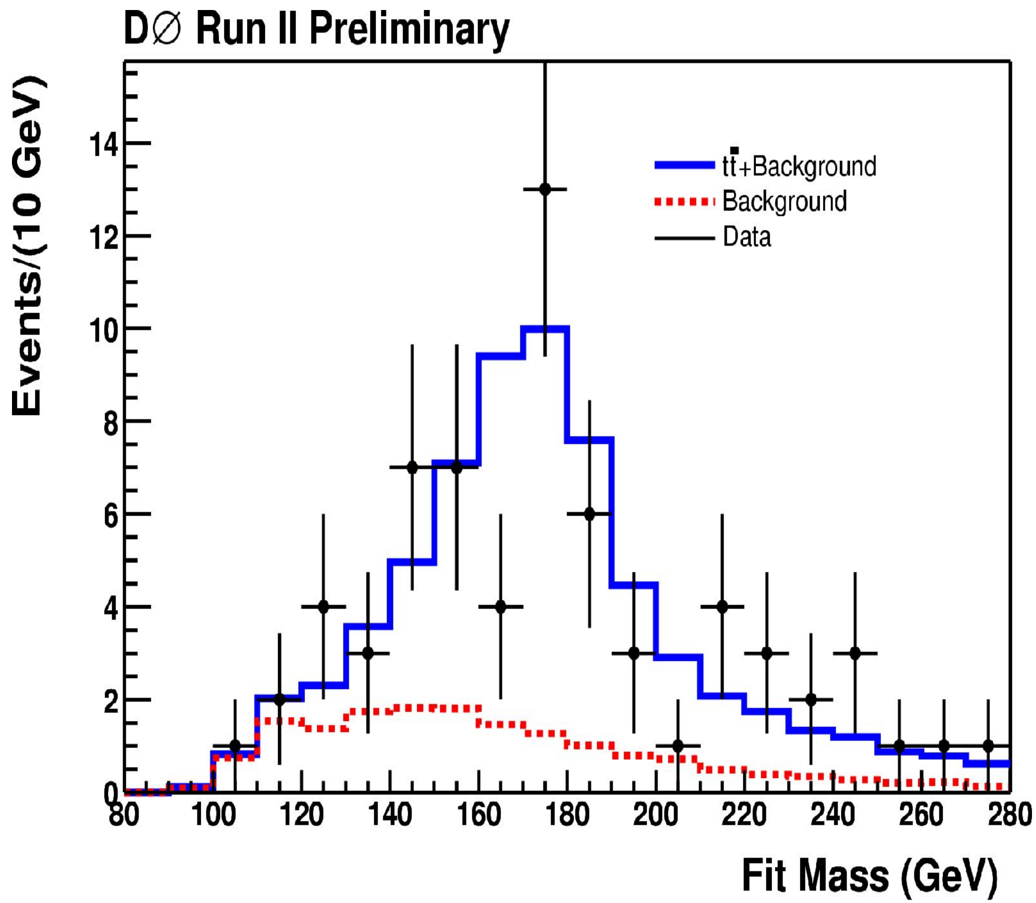


Top Production

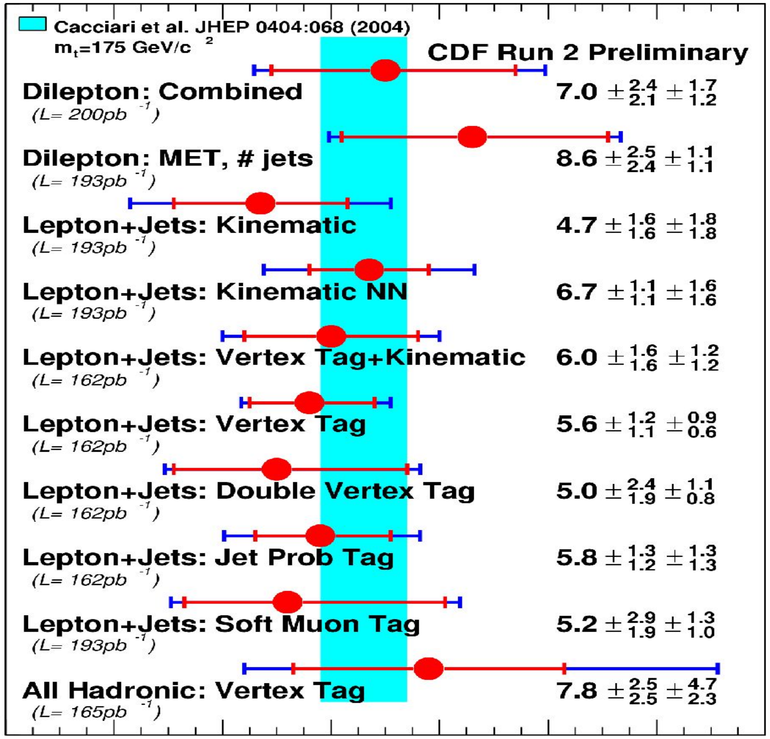


Lepton+jets most promising channel:

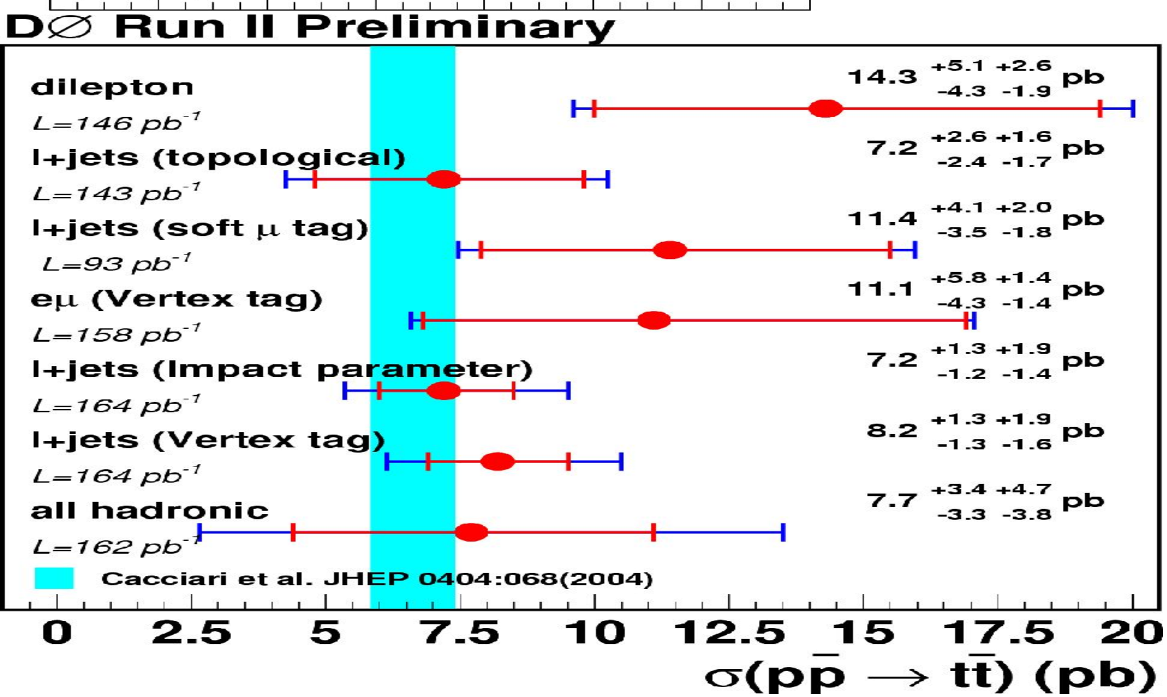
- Charged lepton, 2 b-quark jets
- 2 other jets, only 1 neutrino
- Invariant mass M(top) = M(Wb)

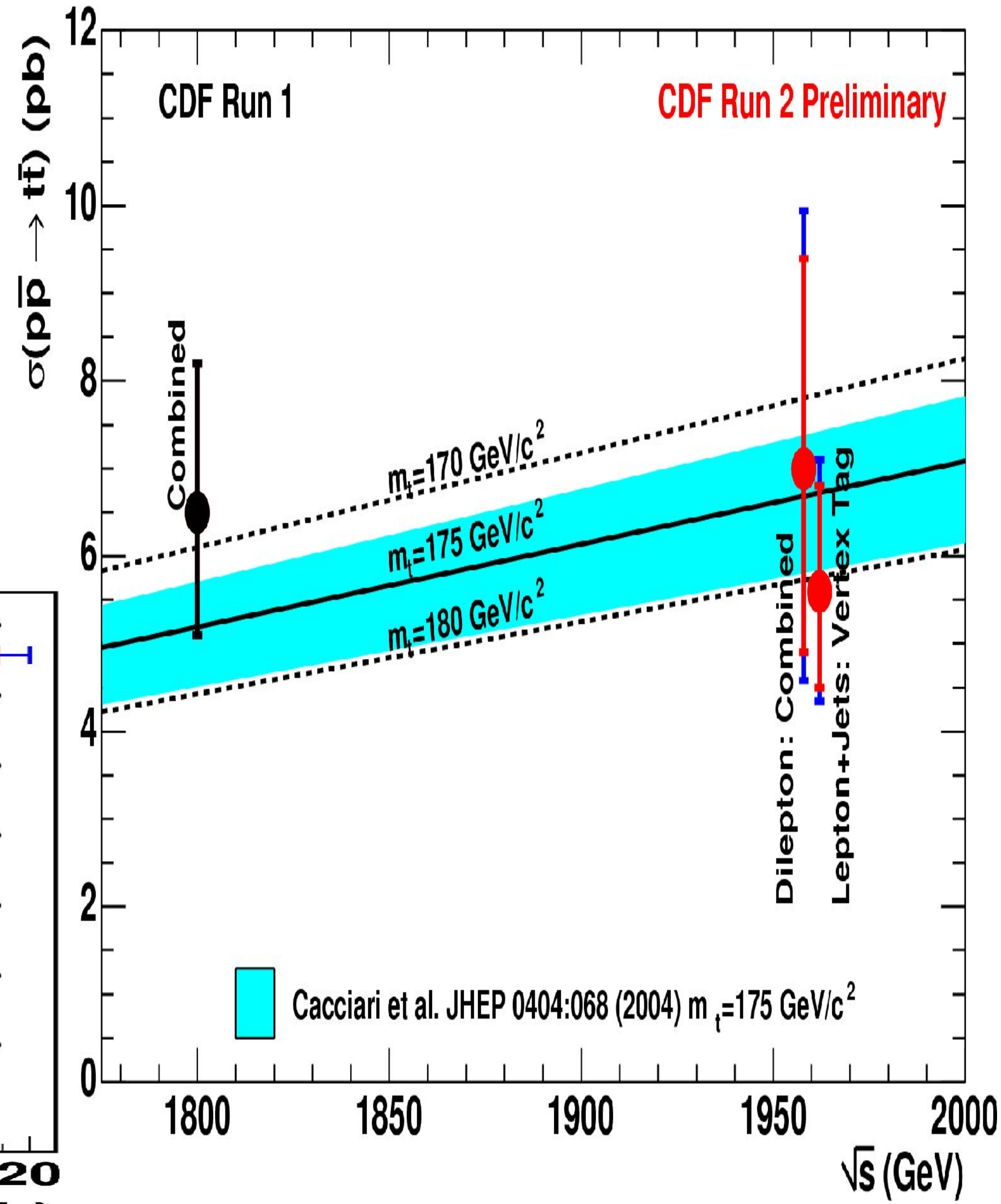


Top-Pair Cross Section



CDF: 160-200 pb^{-1} DØ: 90-160 pb^{-1}

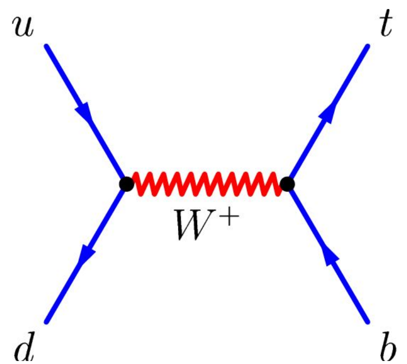




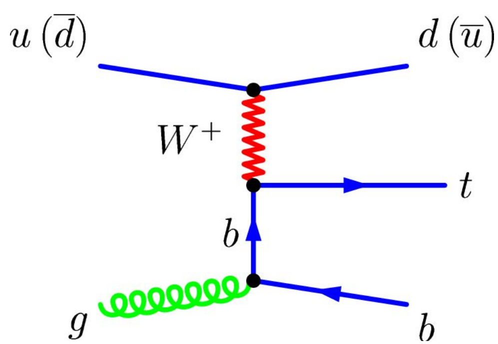
Single-top Production

Electroweak top production:

$|V_{tb}|$ and new physics



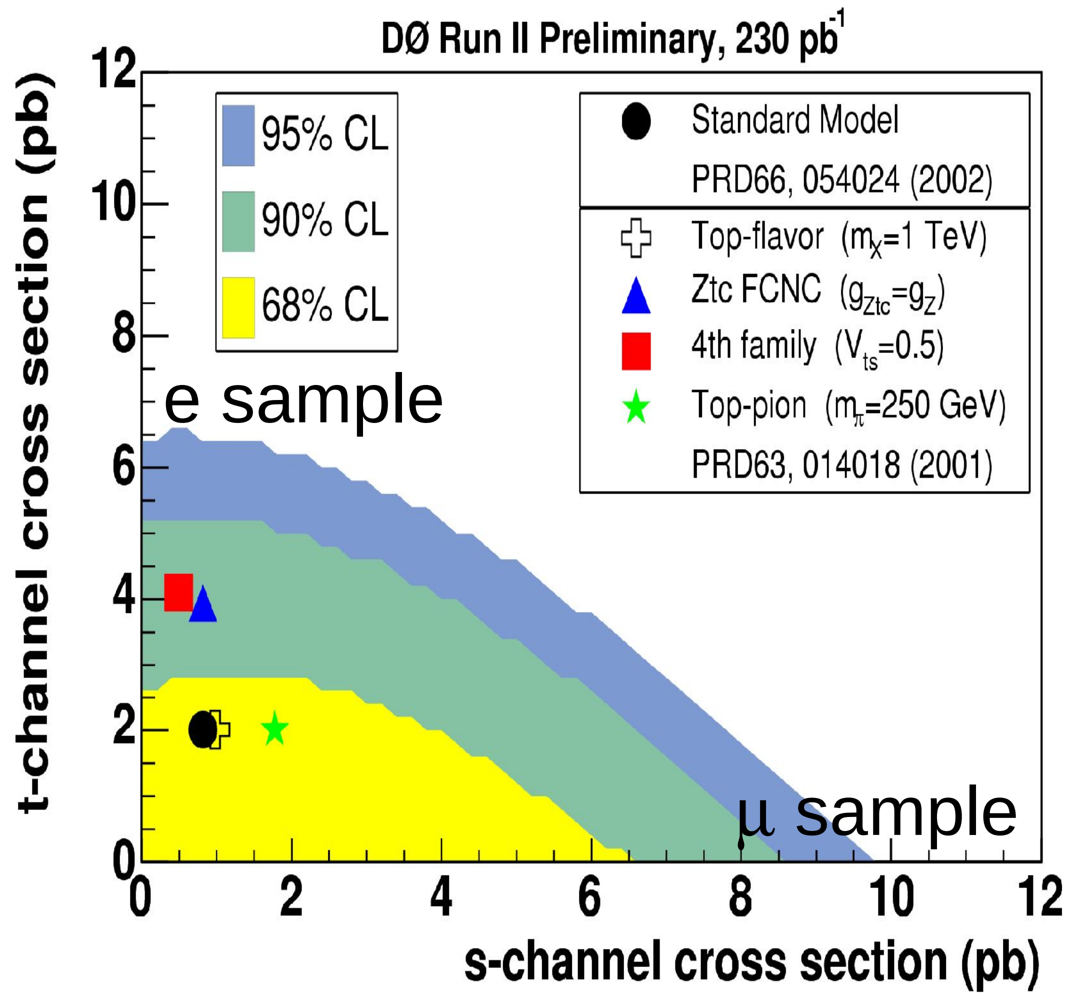
s-channel: tb->lνbb final state



t-channel: tbq->lνbbq final state

None observed yet!

Background dominated by top-pairs and W+jets



95% CL upper limits on s / t cross sections:

CDF publ. 162 pb^{-1}: $\sigma <$ 13.6 / 10.1 pb

D∅ prel. 230 pb^{-1}: $\sigma <$ 6.4 / 5.0 pb

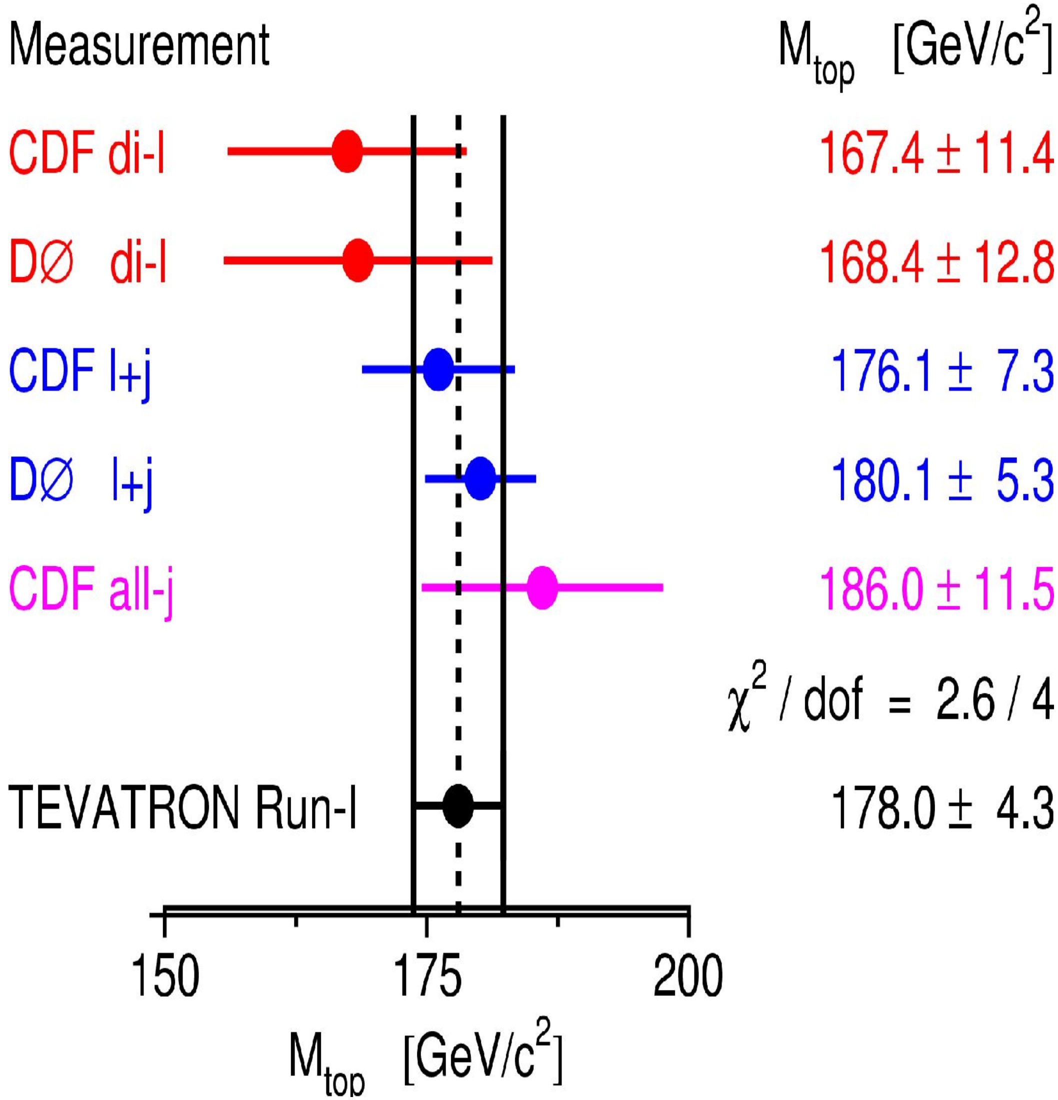
Top-Quark Mass - Run-I

Tevatron (CDF, D∅):

Final Run-I combination

Systematic uncertainties dominated by:

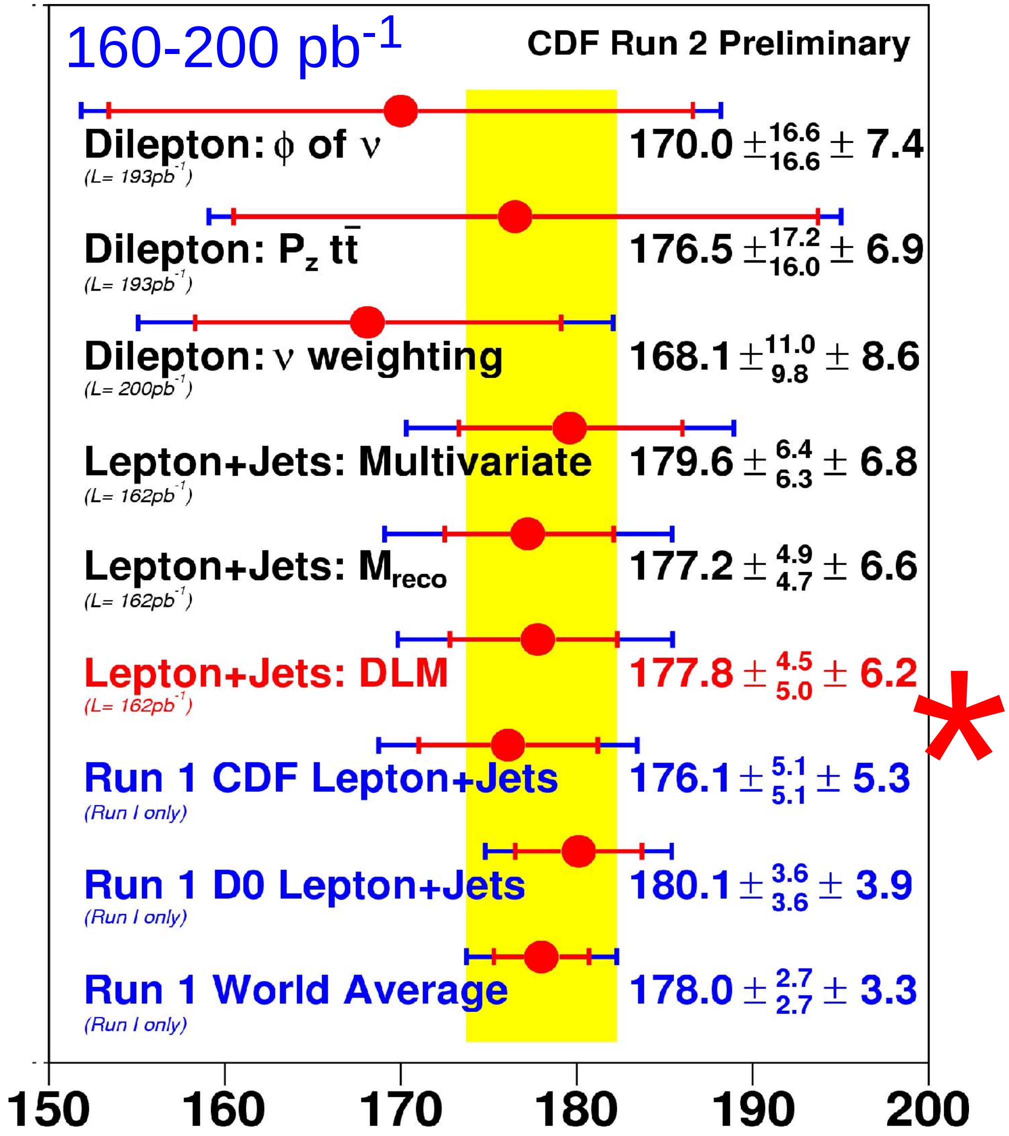
- Jet energy scale (2-5 GeV) -
  will reduce with more data
- Signal model (1-3 GeV)
- Background model (~2 GeV)
- MEs, PDFs, MC generators

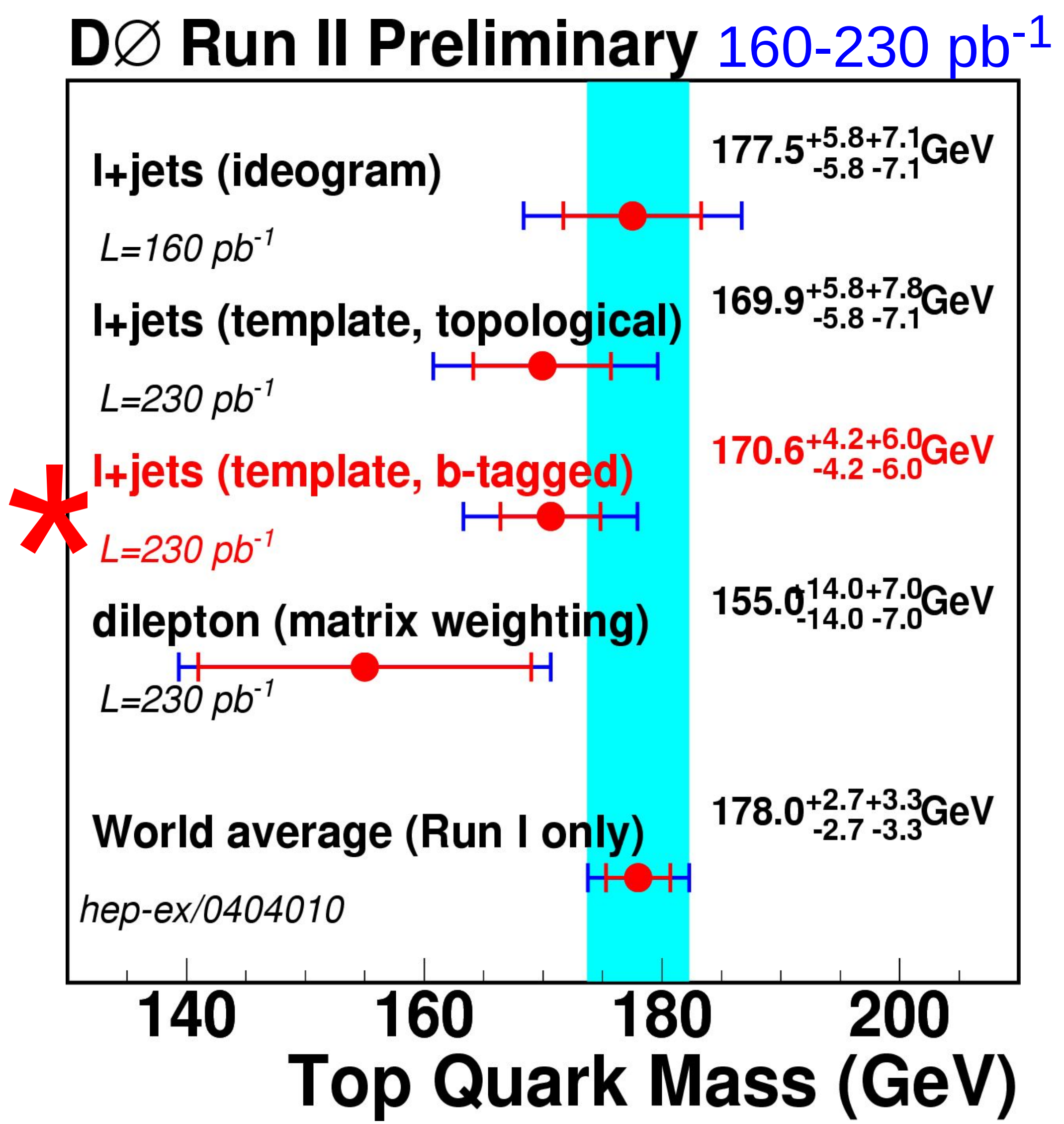


Run-I final: M_{top} = 178.0 ± 2.7 (stat.) ± 3.3 (syst.) GeV

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

Top-Quark Mass - Run-II





Systematics (prel.):
Jet energy scale (~5 GeV)

In 2005: each experiment better than Run-I average!

Standard Model Analysis

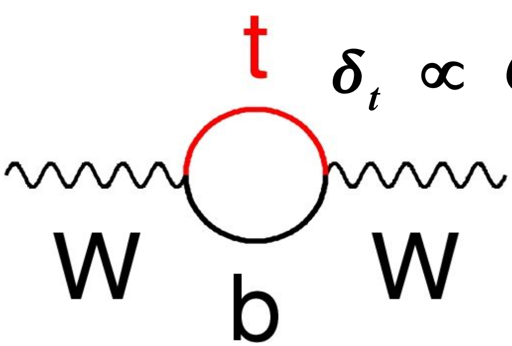
SM: Each observable calculated as a function of:

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

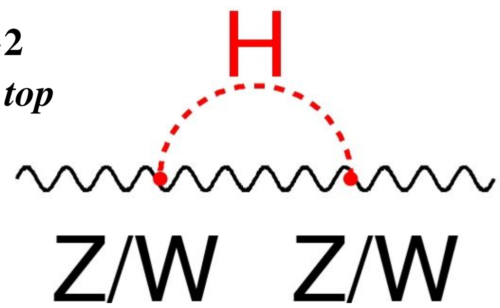
- $\Delta\alpha_{had}$: hadronic vacuum polarisation [0.02761±0.00036]
- $\alpha_s(M_Z)$: given by Γ_{had} and related observables
- M_Z: constrained by LEP-1 lineshape

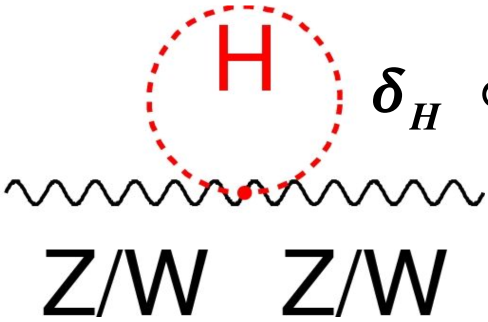
Precision requires 1st and 2nd order electroweak and mixed radiative correction calculations (QED to 3rd)

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

Heavy Particle Masses W and Top

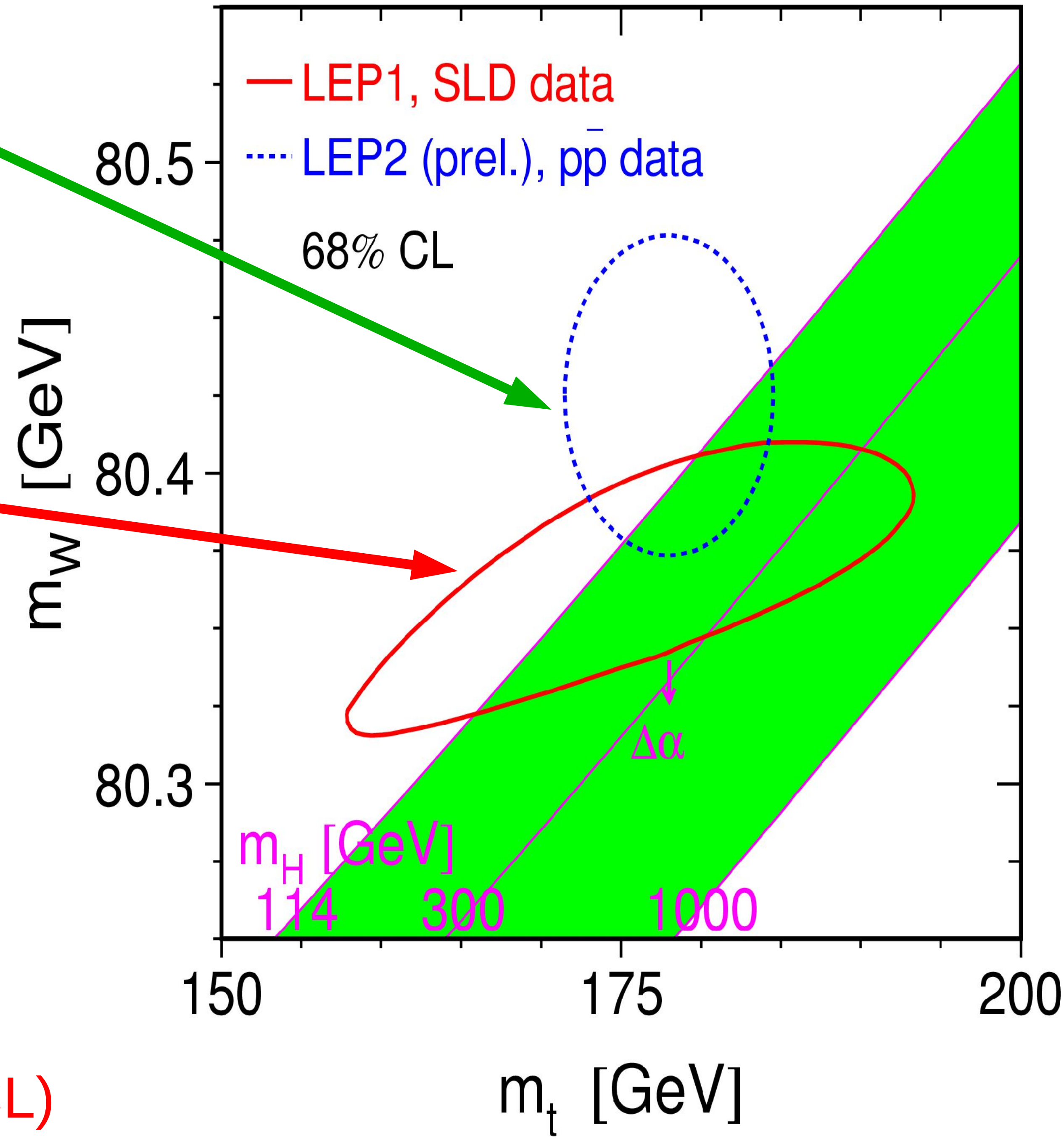
Direct measurements:
  Tevatron and LEP2

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

M_{Higgs} < 280 GeV (95%CL)



Standard Model Analysis

Fit results:

$\Delta\alpha_{had}$ = 0.02770 ± 0.00035
$\alpha_s(M_Z)$ = 0.1188 ± 0.0027
M_Z = 91.1874 ± 0.0021 GeV
M_{top} = 178.4 ± 3.9 GeV
$\log_{10}M_H$ = 2.10 ± 0.20

$M_{Higgs} = 126^{+73}_{-48}$ GeV

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

Correlations:

-0.02			
-0.01	-0.02		
-0.05	0.11	-0.03	
-0.47	0.18	0.06	**0.67**

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!

Standard Model Analysis

$M_{Higgs} = 126^{+73}_{-48}$ GeV

Incl. theory uncertainty:

$M_{Higgs} < 280$ GeV (95%CL)

does not include:

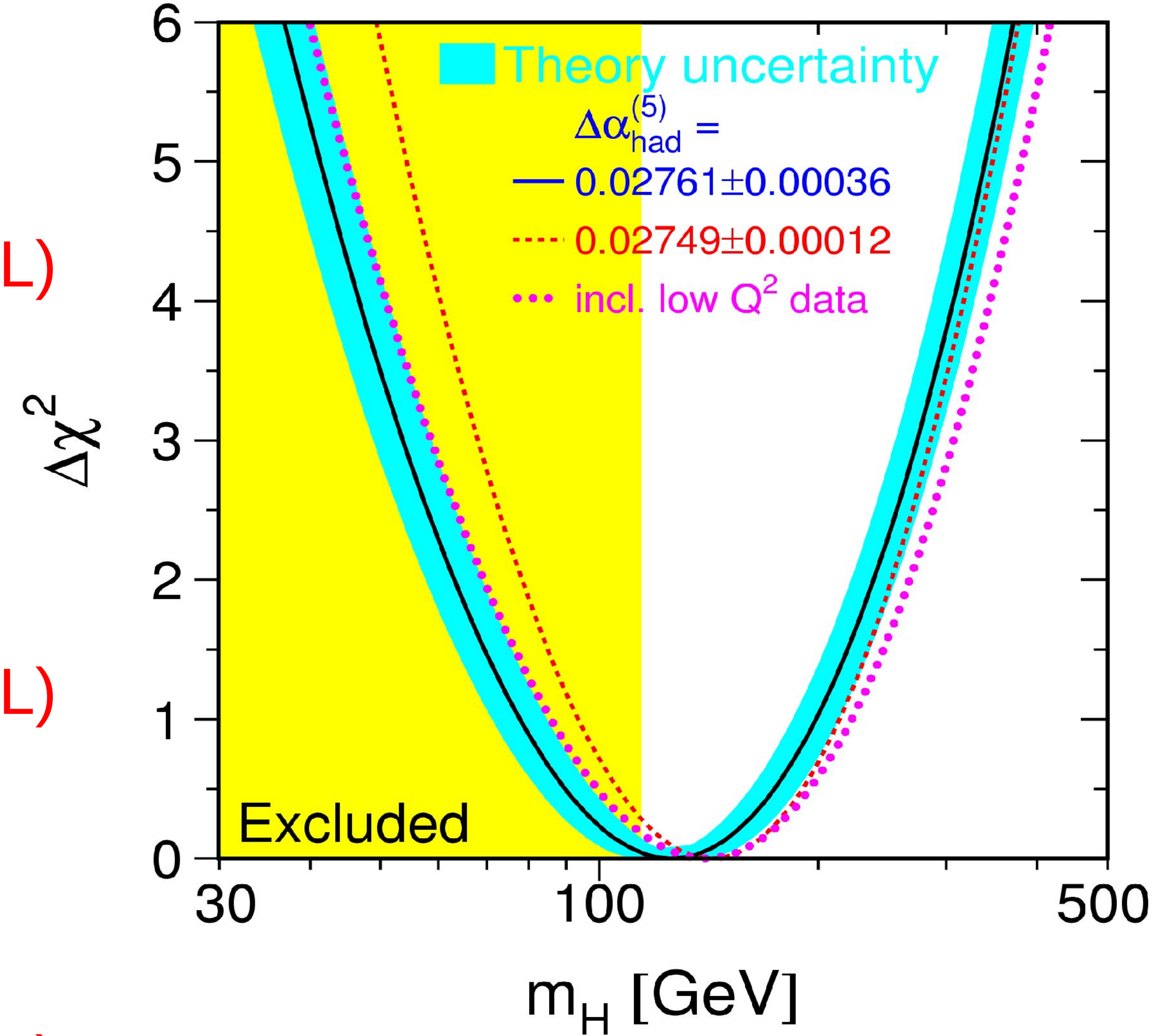
Direct search limit (LEP-2):

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

Renormalise probability

for M_H>114 GeV to 100%:

$M_{Higgs} < 300$ GeV (95%CL)



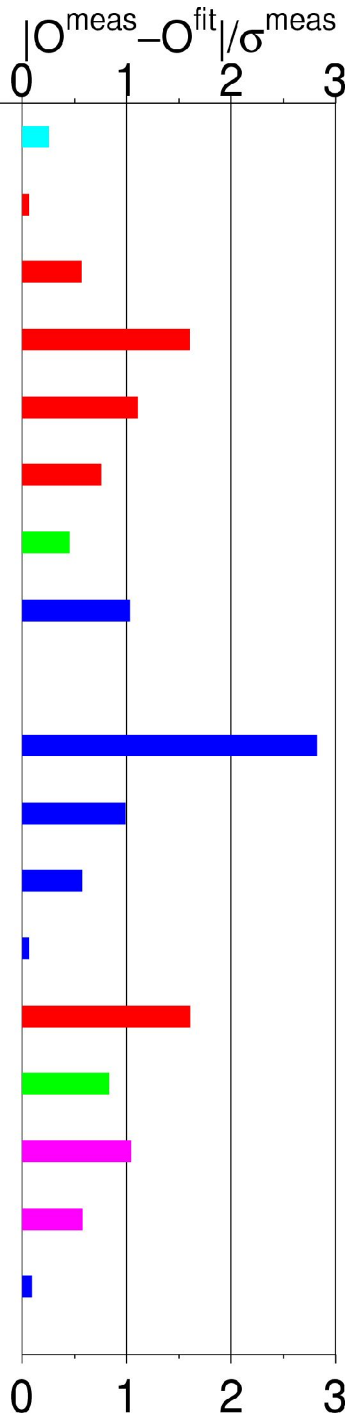
Theory uncertainty:

Dominated by two-loop

calculations for $\sin^2\Theta_{eff}$

Standard Model Analysis

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02761 ± 0.00036	0.02770
m_Z [GeV]	91.1875 ± 0.0021	91.1874
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	0.21630 ± 0.00066	0.21562
R_c	0.1723 ± 0.0031	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1037
$A_{fb}^{0,c}$	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]	80.425 ± 0.034	80.390
Γ_W [GeV]	2.133 ± 0.069	2.093
m_t [GeV]	178.0 ± 4.3	178.4



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

χ^2/ndof = 18.3/13 (14.7%)

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: 2.8

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 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: -72.94 ± 0.04 ✔

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

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

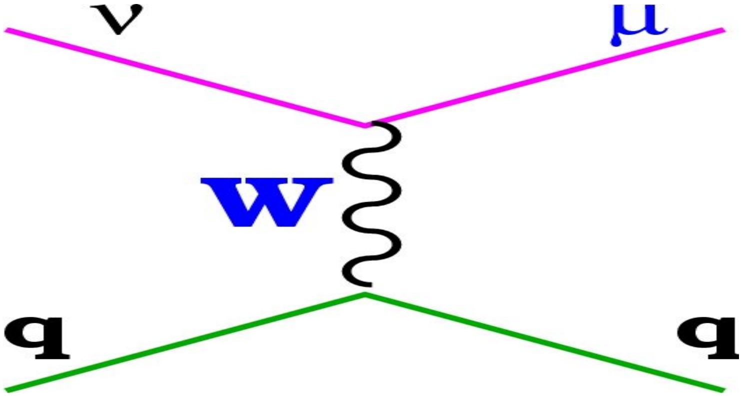
$A_{PV} = (\sigma_R-\sigma_L)/(\sigma_R+\sigma_L) \propto Q_W(e^-) = -4g_{Ae}g_{Ve}$ at Q^2~0.03 GeV^2

$\sin^2\Theta_{eff}(Q=M_Z) = 0.2333 \pm 0.0016$ SM fit: 0.2314 ± 0.0001 ✔

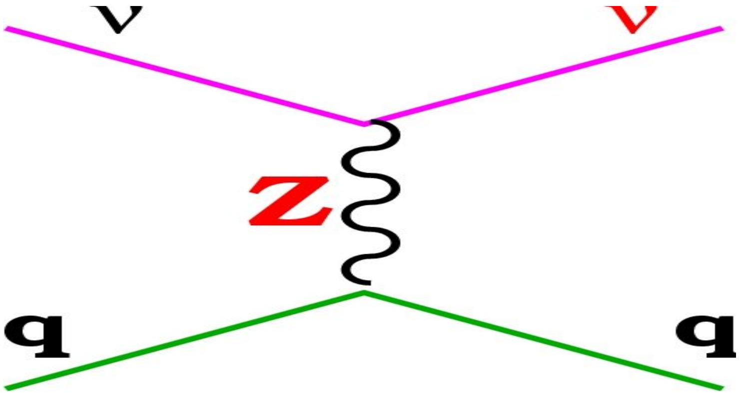
NuTeV Neutrino-Nucleon Scattering

Muon-(anti-)neutrino quark scattering:

charged current (CC)



neutral current (NC)



Paschos-Wolfenstein relation (iso-scalar target):

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

+ electroweak radiative corrections

Effective couplings: g_L, g_R at $<Q^2>$ ~ 20 GeV^2

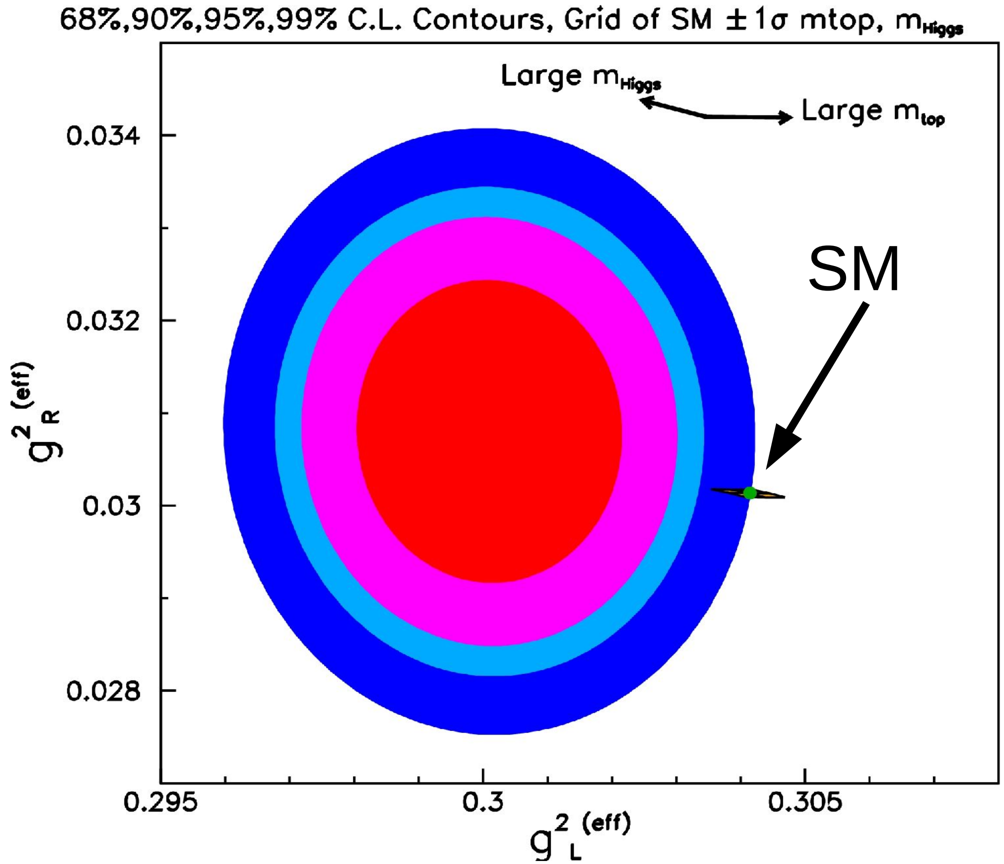
Historically result quoted in terms of: $\sin^2\Theta_W = 1-(M_W/M_Z)^2$

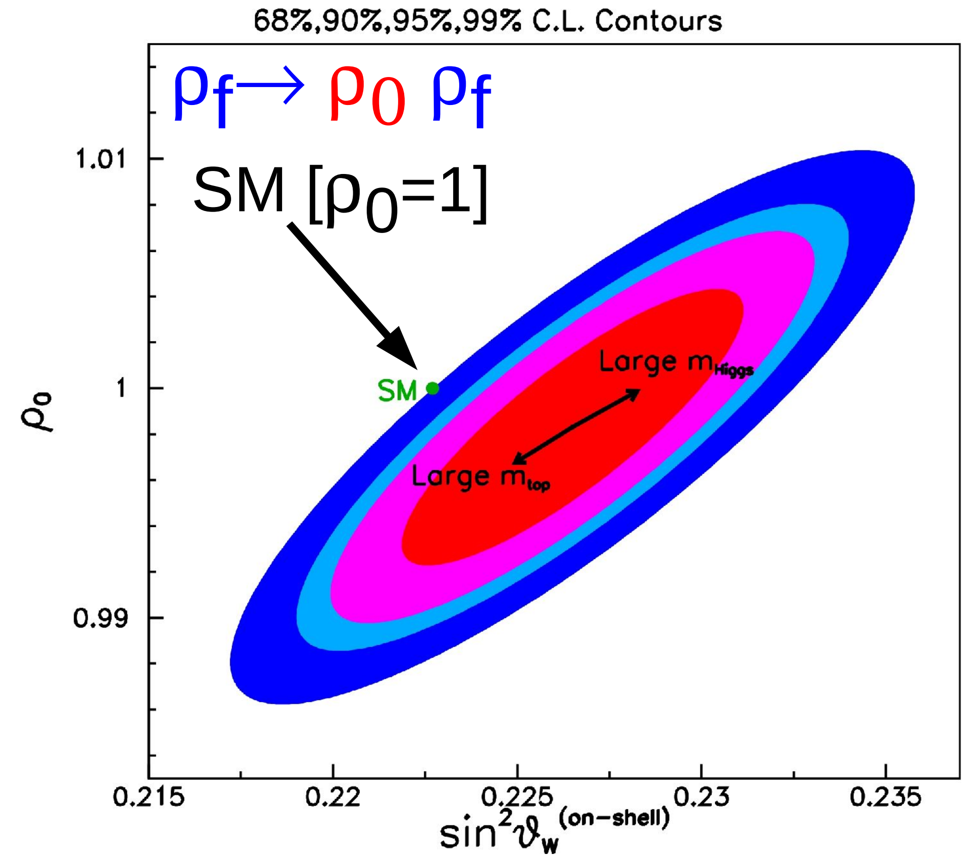
Factor two more precise than previous νN world average

NuTeV's Result

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

SM fit: 0.2228 ± 0.0004   Difference of 3.0 σ!

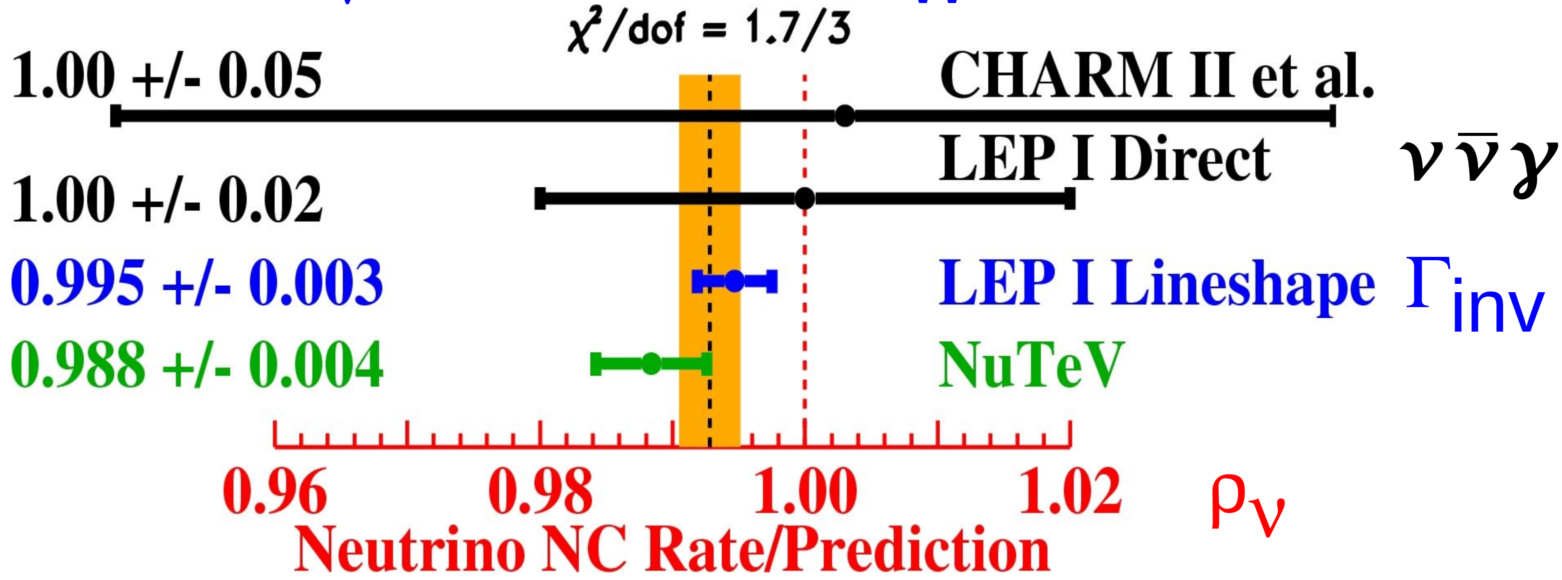




Quote result in terms of effective couplings, not $\sin^2\Theta_W$ nor M_W!

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, . . .

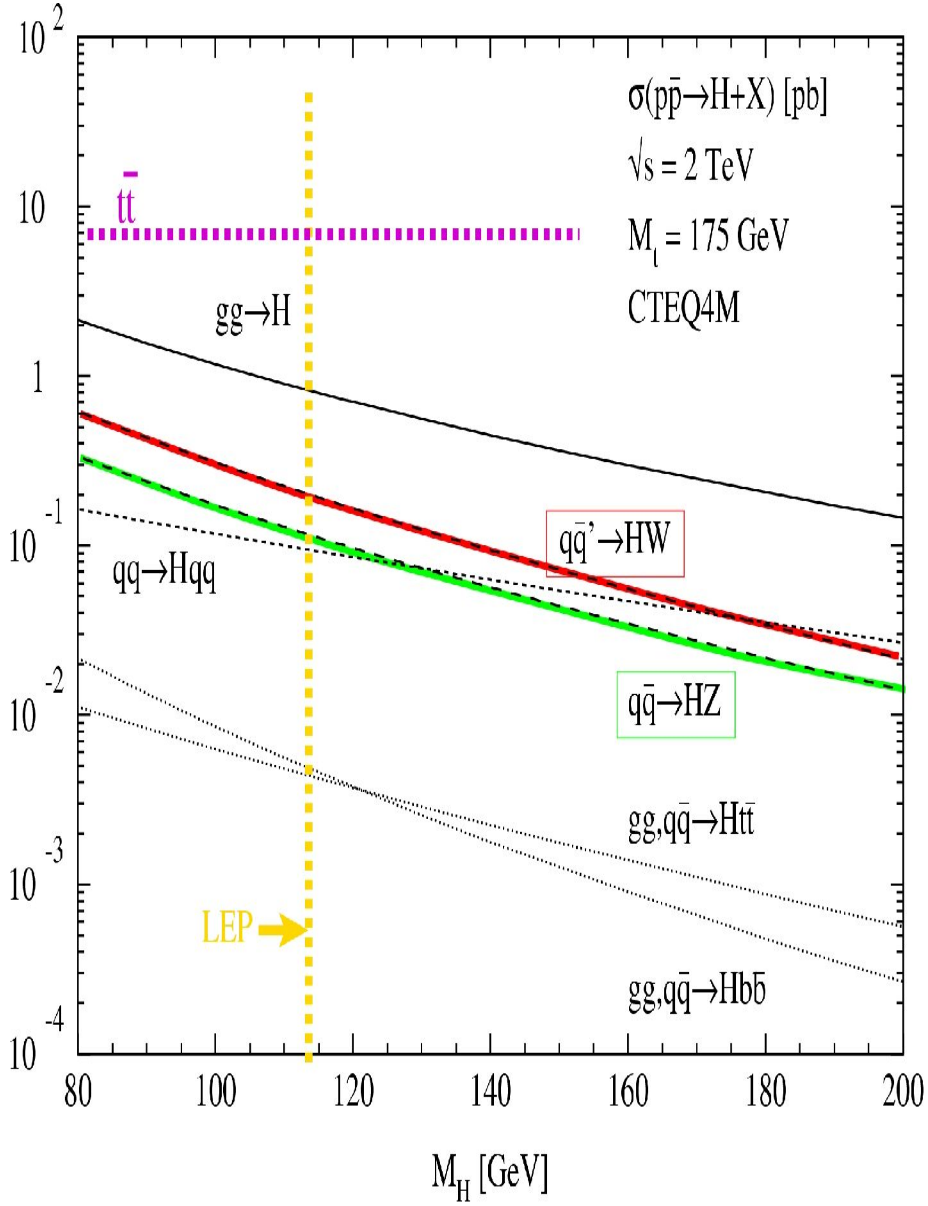
But likely rather old physics:

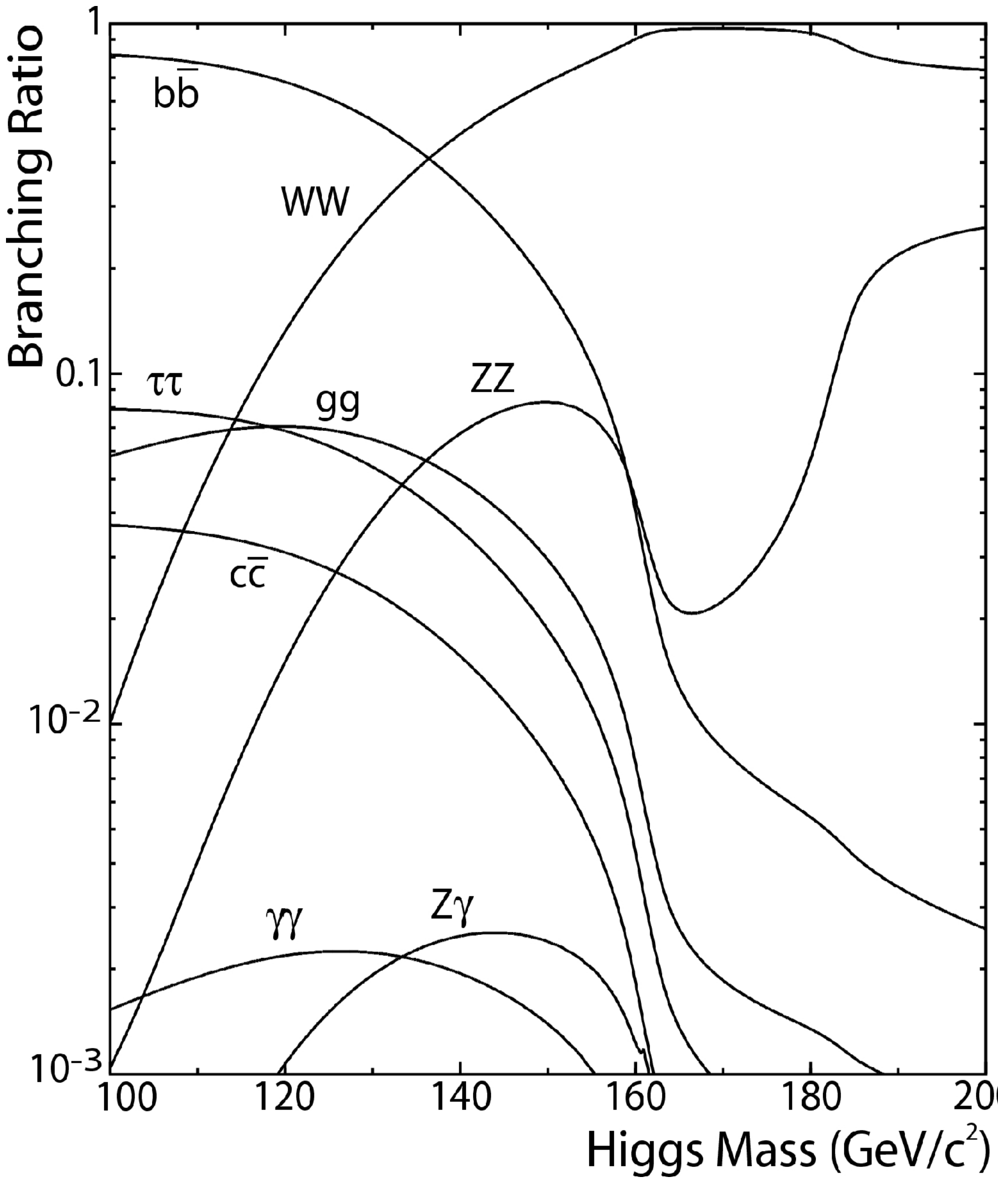
Theory uncertainty (QED, LO PDFs)

Isospin violating PDFs, sea asymmetry

Standard Model Higgs Search

Negative direct search at LEP-2: $M_H > 114.4$ GeV @ 95%CL



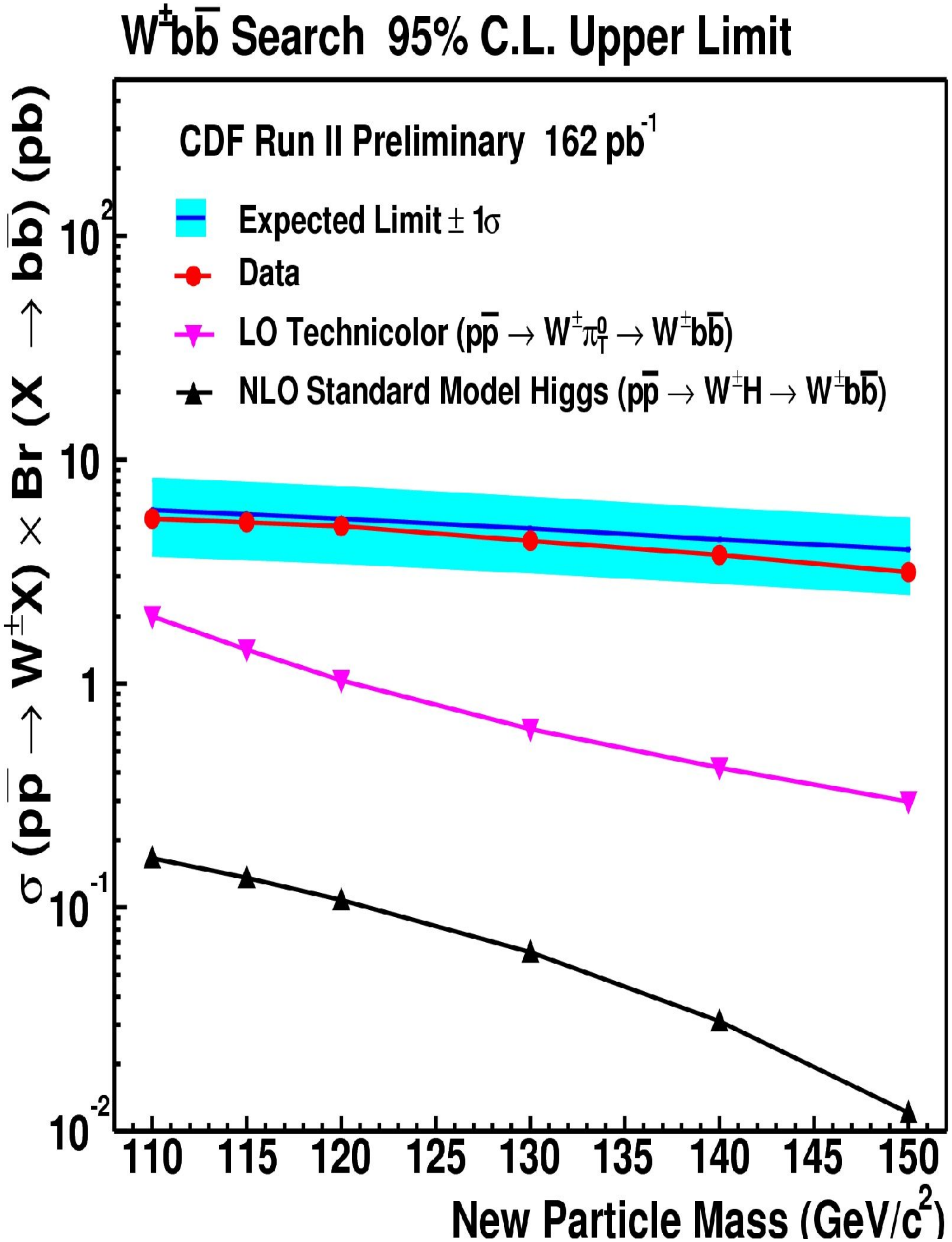


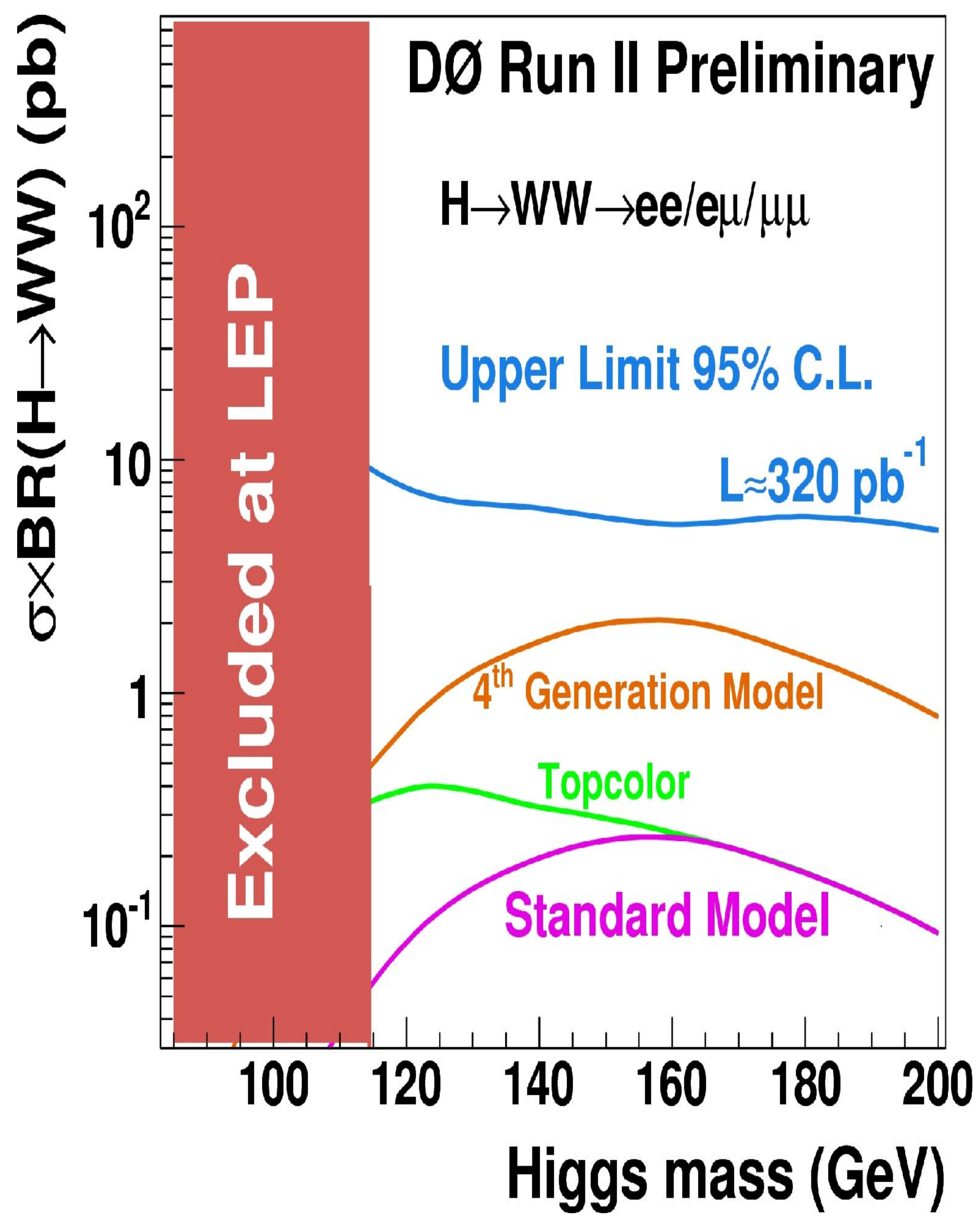
Production cross section at the Tevatron

Higgs decays

Standard Model Higgs Search

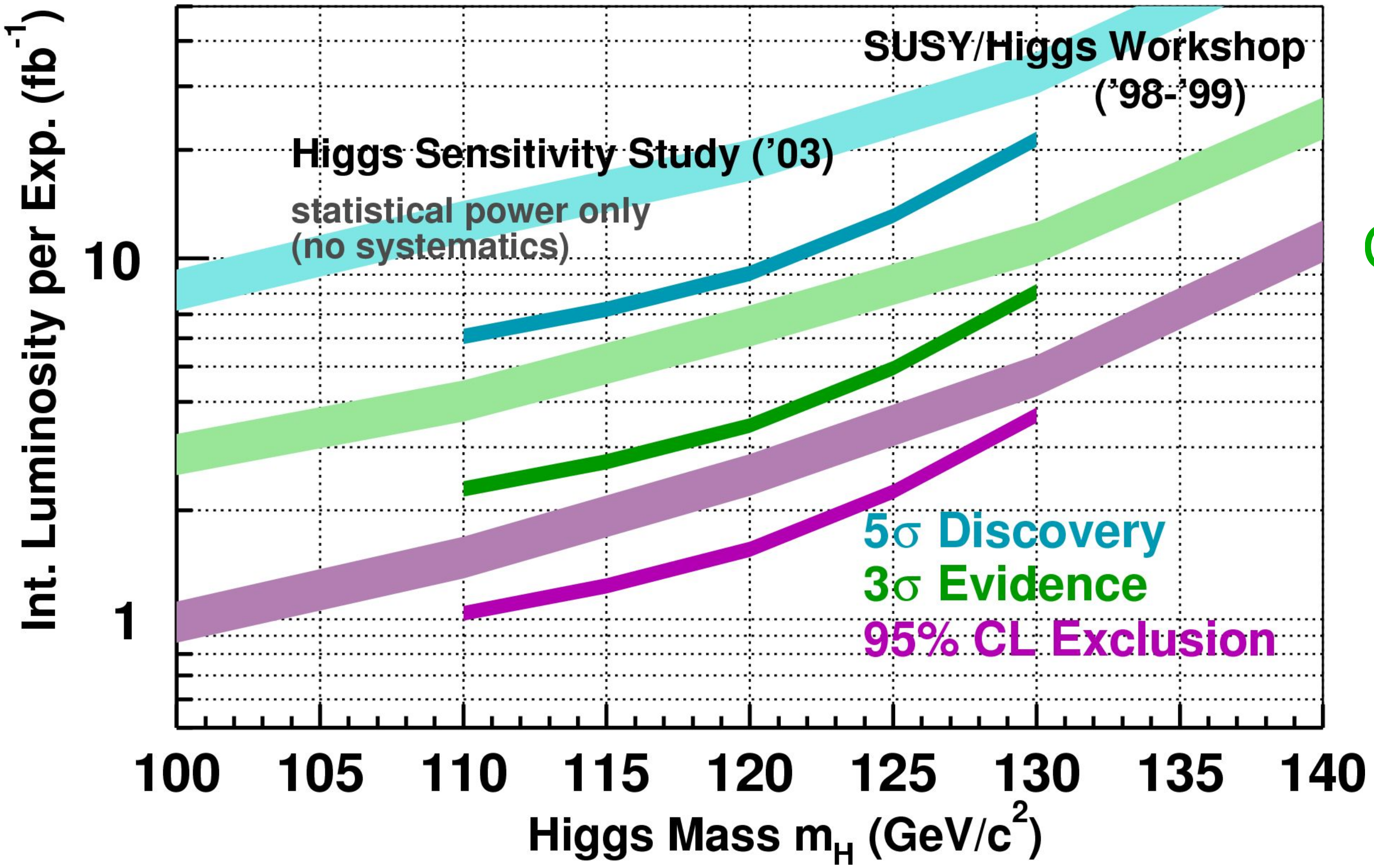
Selection: Missing transverse energy, lepton+b-jets / lepton-pairs





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: 0.5/fb on tape

Conclusions

Wealth of high-precision electroweak measurements:

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

Need combination of top-quark mass results!

Most measurements agree with expectations:

Successful test of loop corrections, constraints on new physics

SM Higgs boson should be "light"

Three ~3-sigma effects:

Spread in $\sin^2\Theta_{eff}$ at the Z pole, W branching fractions, 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?

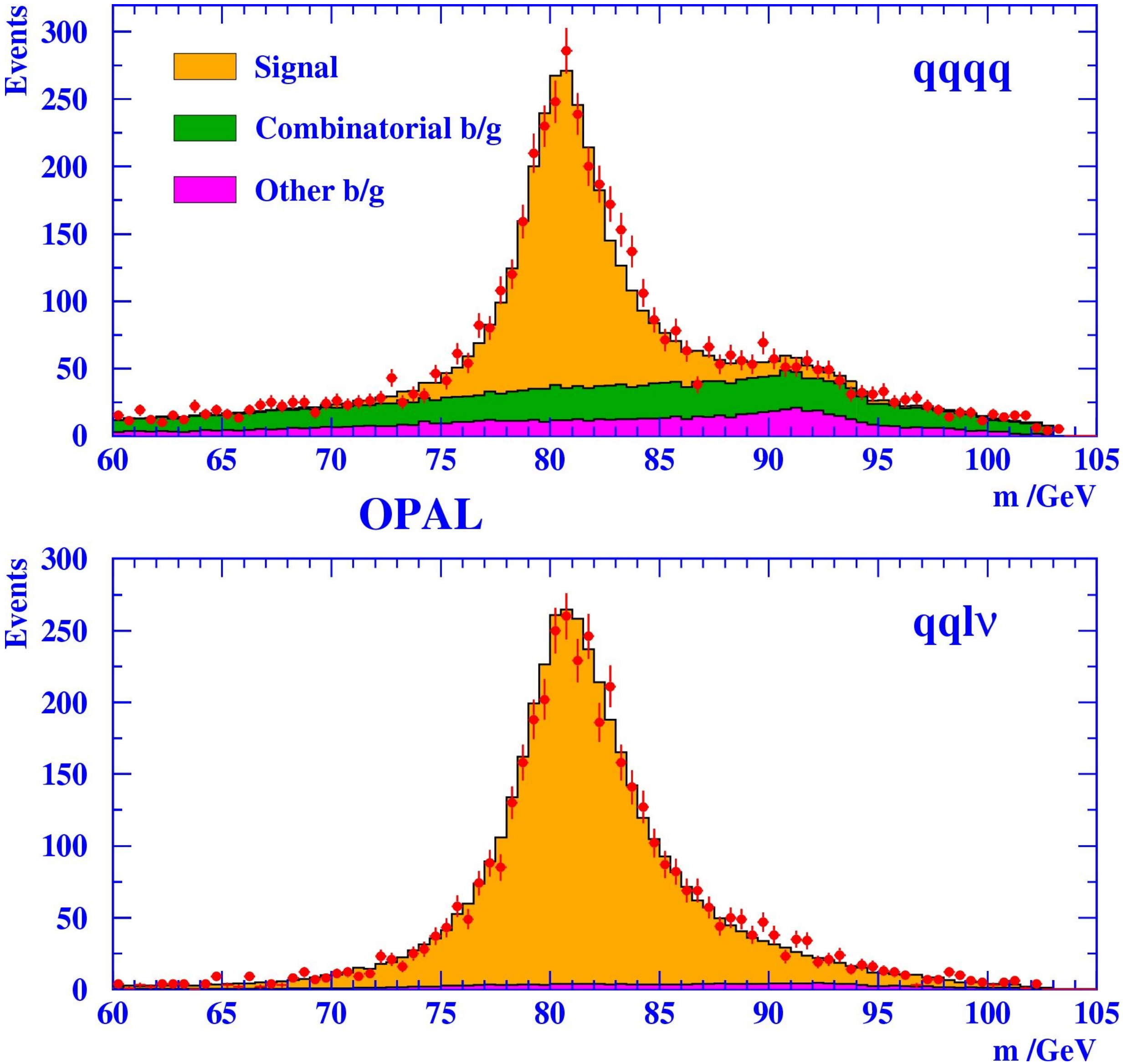
W Boson - Mass and Width

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

$\to$ qqqq, qqlν, lνlν

Invariant mass M_{inv}

Preliminary results



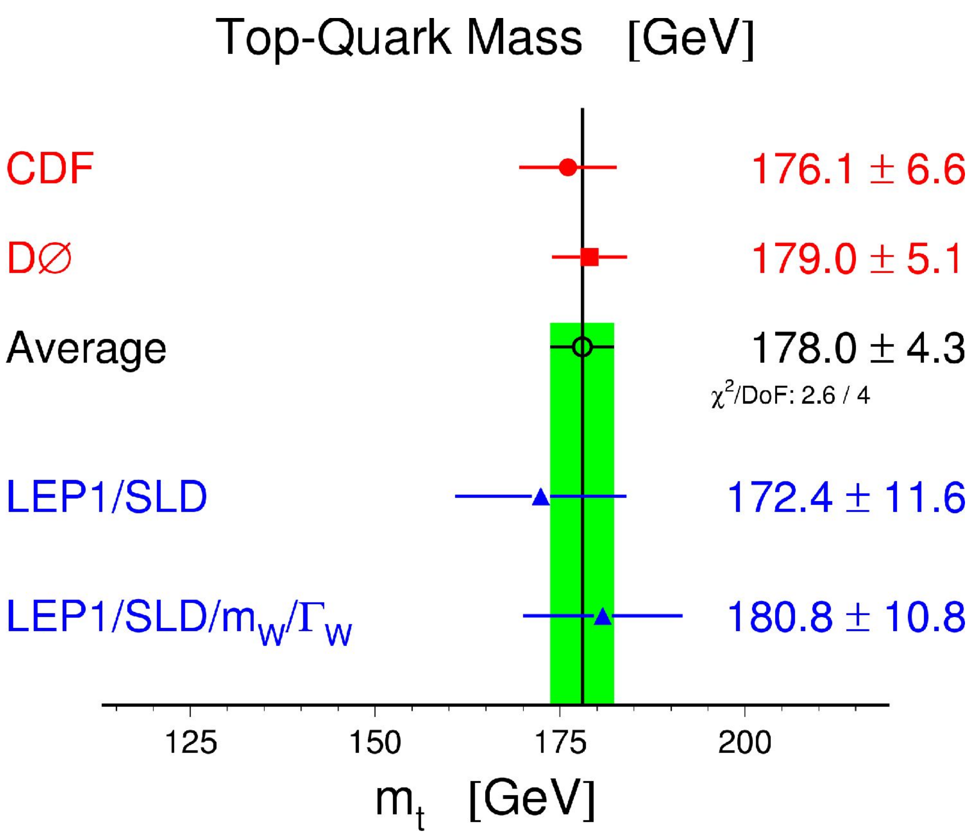
Potentially large FSI systematics (BE,CR) in the qqqq channel:

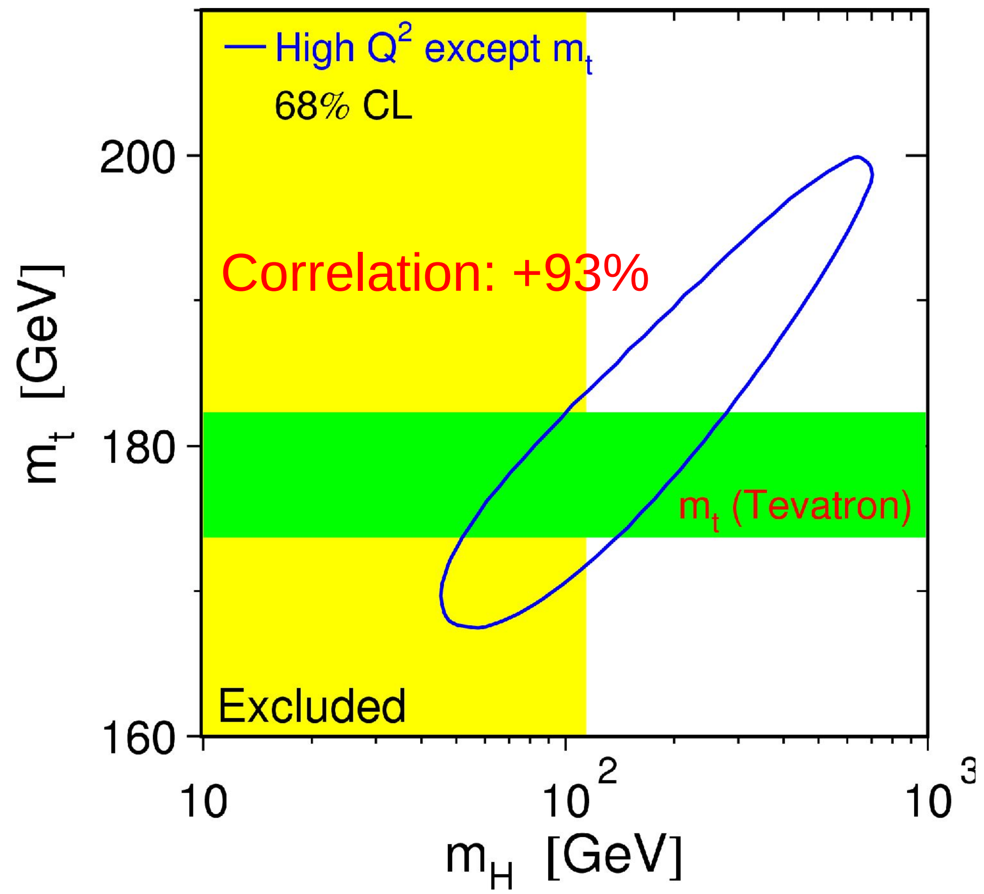
M_W average dominated by qqlν channel

Mass difference (calculated without FSI errors):

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

Heavy Particle Masses: Top Quark

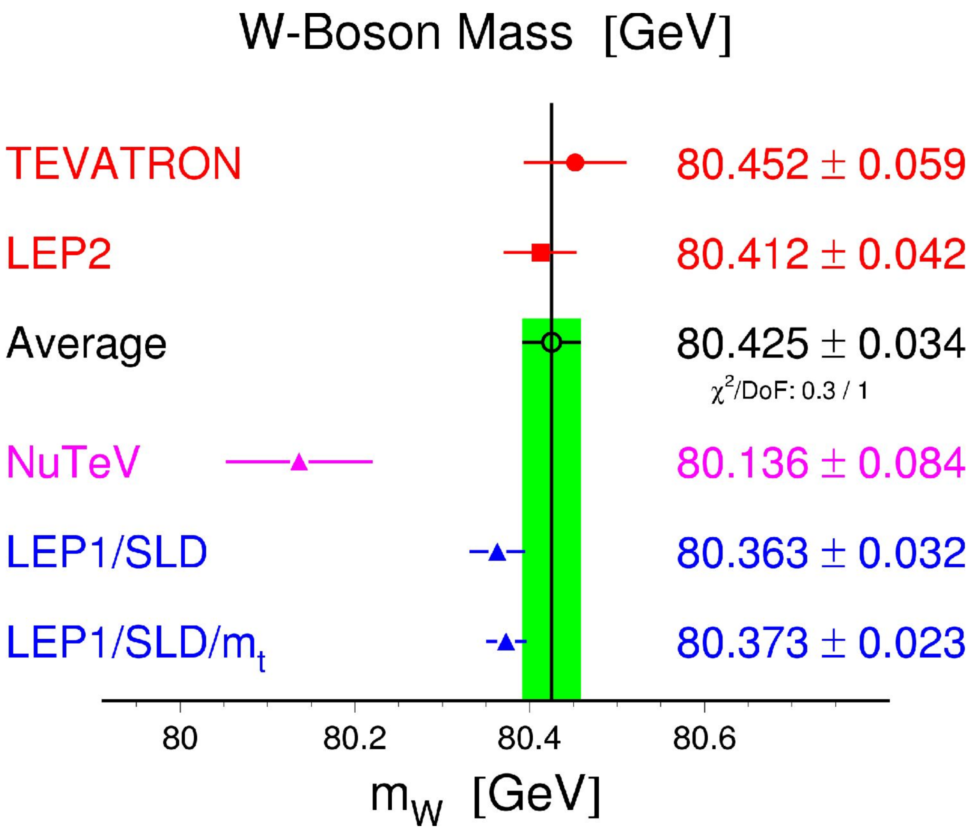


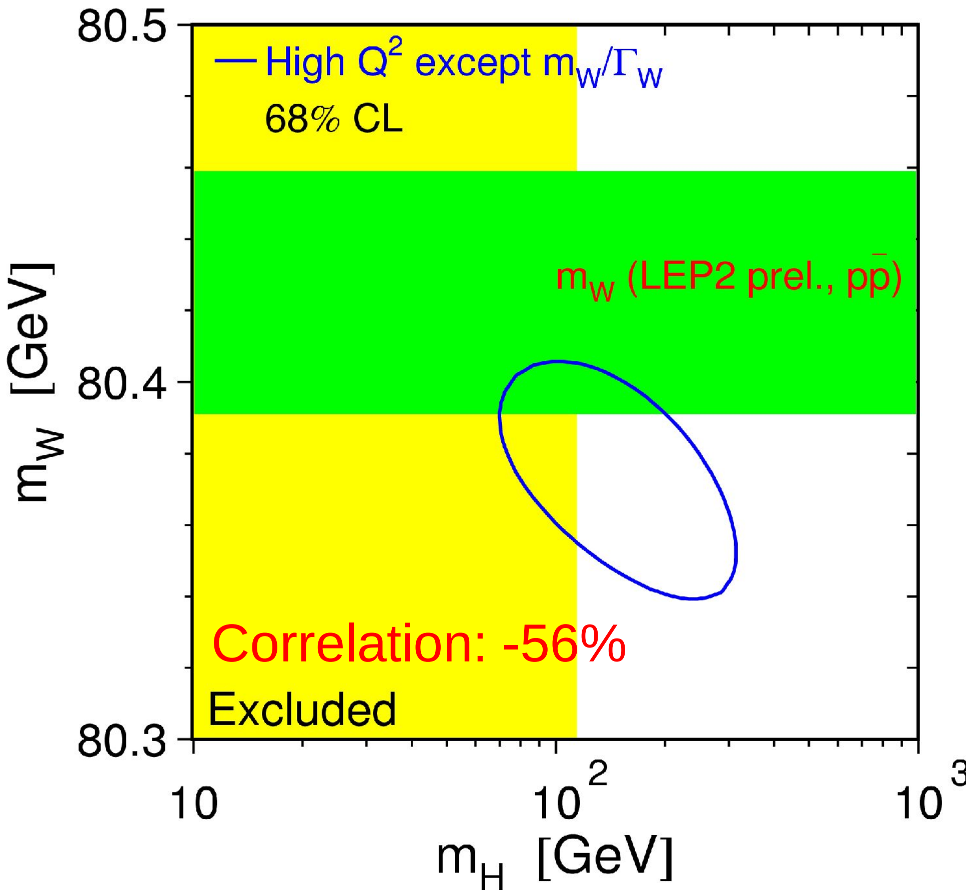


Predicted M_{top} in very good agreement with measurement

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

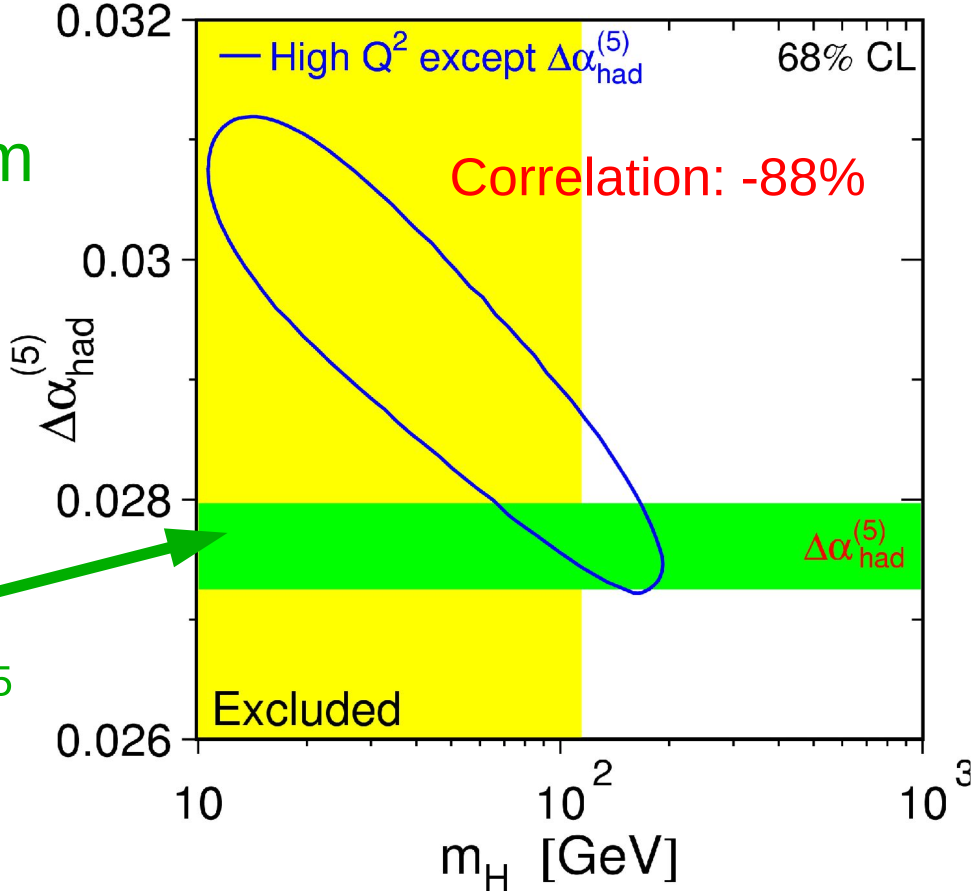
Fermion loops cause running of α:

Leptonic contribution calculated

Hadronic contribution derived from

τ decays

hadronic cross section at low $\sqrt{s}$



Experimentally driven result:

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

*Update with new CMD-2/KLOE data: 0.02758±0.00035

Theory driven result (more pQCD):

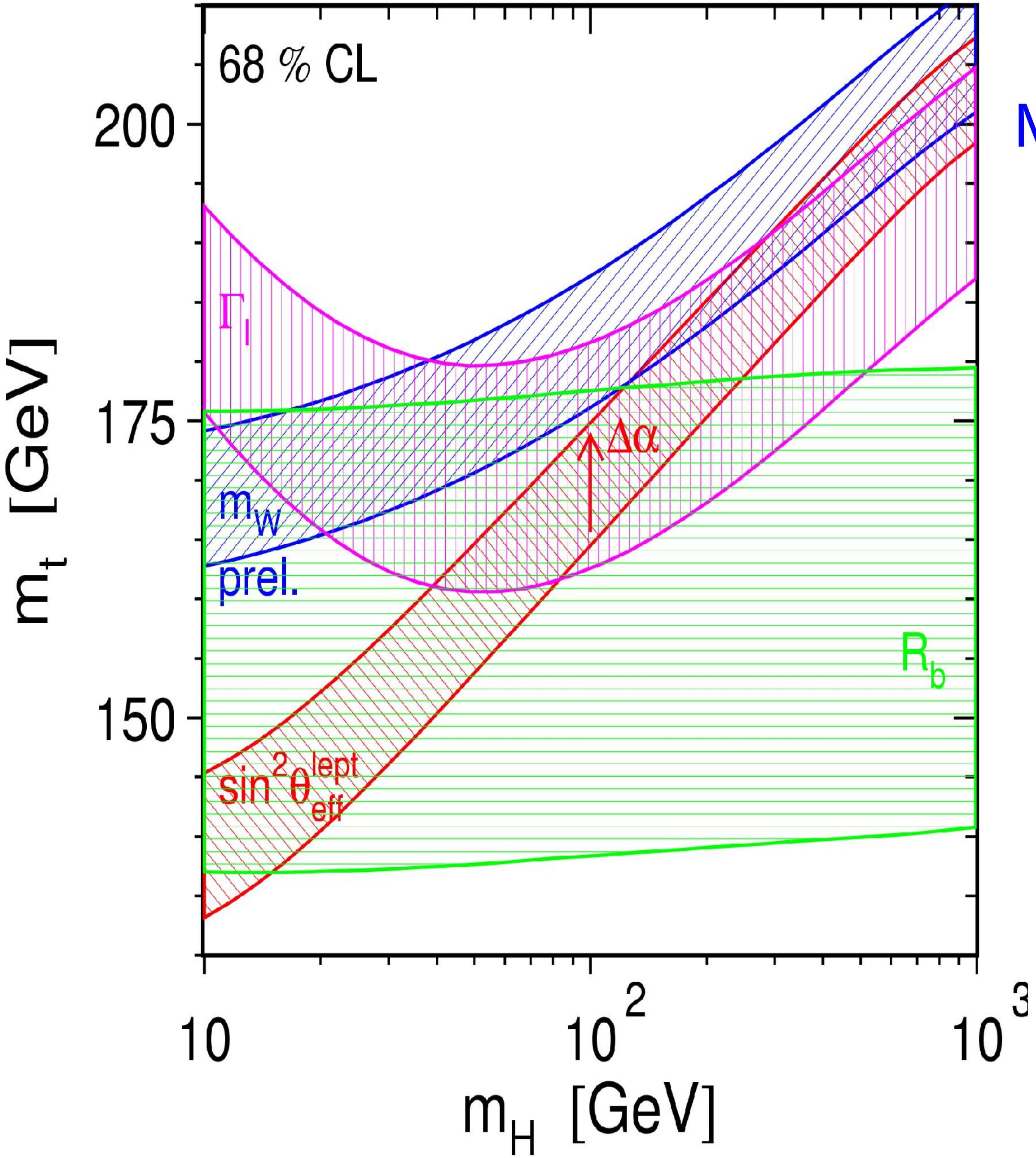
$\Delta\alpha_{had}(M_Z) = 0.02749 \pm 0.00012$

Subject of ongoing experimental and theoretical work:

New measurements by CMD-2, KLOE, BABAR/BELLE, CLEO-c

Discrepancy between results derived from τ and e^+e^- data

Top-Higgs Bands



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

Bands of ±1σ from:

M_W = 80.425(34) GeV

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

Γ_l = 83.984(86) MeV

R_b = 0.21630(66)

Higgs Sensitivities and Constraints