Global Fits to Precision Electroweak Data

- **Precision Experiments: Historical Perspective**
- **LEP/SLC Physics**
- **Probing the Standard Model**
- **Beyond the Standard Model**

The Z, the W, and the Weak Neutral Current

- Primary prediction and test of electroweak unification
- WNC discovered 1973 (Gargamelle, HPW)
- 70's, 80's: weak neutral current experiments (few %)
  - Pure weak: νN, νe scattering
  - Weak-elm interference in eD, e^+e^-, atomic parity violation
  - $SU(2) \times U(1)$ group/representations; t and ν_τ exist; hint for SUSY unification; limits on TeV scale physics
- W, Z discovered directly 1983 (UA1, UA2)

- 90's: Z pole (LEP, SLD), 0.1%; lineshape, modes, asymmetries
- LEP 2: M_W, Higgs, gauge self-interactions
- Tevatron: m_t, M_W
- 4th generation weak neutral current experiments
- Implications
  - SM correct and unique to zeroth approx. (gauge principle, group, representations)
  - SM correct at loop level (renorm gauge theory; m_t, α_s, M_H)
  - TeV physics severely constrained (unification vs compositeness)
  - Precise gauge couplings (gauge unification)

The LEP/SLC Era

- Z Pole: $e^+e^- \to Z \to \ell^+\ell^-, \quad q\bar{q}, \quad \nu\bar{\nu}$
  - LEP (CERN), $2 \times 10^7 Z's$, unpolarized (ALEPH, DELPHI, L3, OPAL); SLC (SLAC), 5×10^5, $P_{e^-} \sim$ 75 % (SLD)

- Z pole observables
  - lineshape: M_Z, Γ_Z, σ
  - branching ratios
    * $e^+e^-, \mu^+\mu^-, \tau^+\tau^-$
    * $q\bar{q}, c\bar{c}, b\bar{b}, s\bar{s}$
    * $\nu\bar{\nu} \Rightarrow N_\nu = 2.983 \pm 0.009$ if $m_\nu < M_Z/2$
  - asymmetries: FB, polarization, P_τ, mixed
  - lepton family universality

The Z Lineshape

Basic Observables: $e^+e^- \to f\bar{f}$ ($f = e, \mu, \tau, s, b, c,$ **hadrons**) ($s = E_{CM}^2$)

$$\sigma_f(s) \sim \sigma_f \frac{s\Gamma_Z^2}{(s - M_Z^2)^2 + \frac{s^2\Gamma_Z^2}{M_Z^2}}$$

(plus initial state rad. corrections)

Peak Cross Section:

$$\sigma_f = \frac{12\pi}{M_Z^2} \frac{\Gamma(e^+e^-)\Gamma(f\bar{f})}{\Gamma_Z^2}$$

Partial Widths:

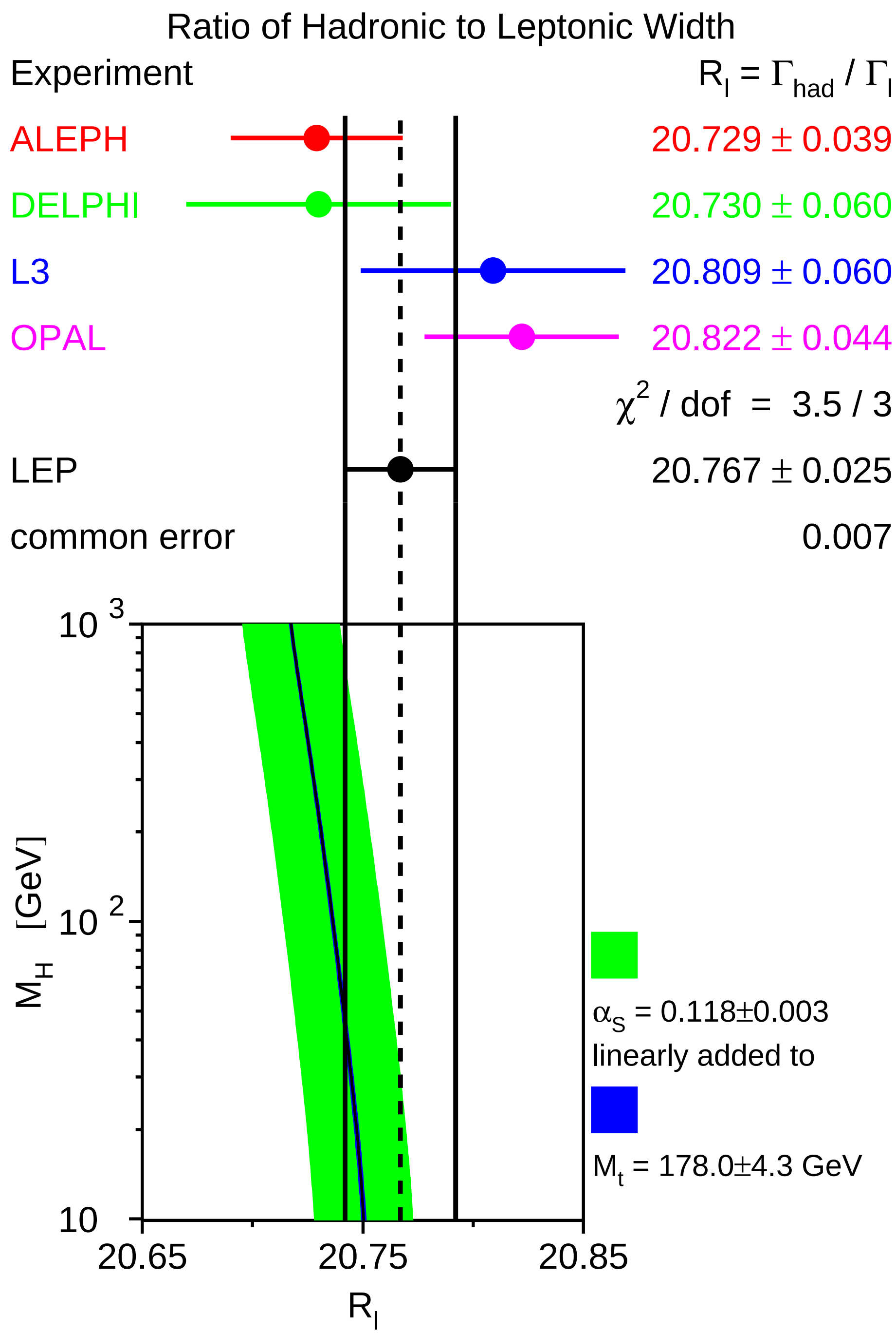
$$\Gamma(f\bar{f}) \sim \frac{C_f G_F M_Z^3}{6\sqrt{2}\pi}\left[|\bar{g}_{Vf}|^2 + |\bar{g}_{Af}|^2\right]$$

(plus mass, QED, QCD corrections; $C_\ell = 1,\ C_q = 3;\quad \bar{g}_{V,Af} =$ effective coupling (includes ew)).

At tree level:

$$\bar{g}_{Af} = \pm\frac{1}{2}, \quad \bar{g}_{Vf} = \pm\frac{1}{2} - 2\sin^2\theta_W\, q_f$$

where $\sin^2\theta_W \equiv 1 - \frac{M_W^2}{M_Z^2}$ is the weak angle, $\pm\frac{1}{2}$ is the weak isospin ($+$ for (u,ν), $-$ for (d,e^-)), and q_f is the electric charge



Ratio of Hadronic to Leptonic Width
Experiment
$R_l = \Gamma_{had} / \Gamma_l$
ALEPH
20.729 ± 0.039
DELPHI
20.730 ± 0.060
L3
20.809 ± 0.060
OPAL
20.822 ± 0.044
χ^2 / dof = 3.5 / 3
LEP
20.767 ± 0.025
common error
0.007
10^3
10^2
10
M_H [GeV]
20.65
20.75
20.85
R_l
α_S = 0.118±0.003
linearly added to
M_t = 178.0±4.3 GeV

Z-Pole Asymmetries

- Effective axial and vector couplings of Z to fermion f

$$\bar{g}_{Af} = \sqrt{\rho_f} t_{3f}$$
$$\bar{g}_{Vf} = \sqrt{\rho_f} \left[t_{3f} - 2\bar{s}_f^2 q_f \right]$$

where $\bar{s}_f^2$ the effective weak angle,

$$\bar{s}_f^2 = \kappa_f s_W^2 \quad (\text{on} - \text{shell})$$
$$= \hat{\kappa}_f \hat{s}_Z^2 \sim \hat{s}_Z^2 + 0.00029 \quad (f = e) \quad (\overline{\text{MS}}),$$

ρ_f, κ_f, and $\hat{\kappa}_f$ are electroweak corrections, q_f = electric charge, t_{3f} = weak isospin

- $A^0 =$ **Born asymmetry** (after removing γ, off-pole, box (small), P_{e^-})

$$\text{forward} - \text{backward}: \; A_{FB}^{0f} \simeq \frac{3}{4} A_e A_f$$

$(A_{FB}^{0e} = A_{FB}^{0\mu} = A_{FB}^{0\tau} \equiv A_{FB}^{0\ell} \longrightarrow$ universality)

$$\tau \;\; \text{polarization}: \; P_\tau^0 = -\frac{A_\tau + A_e \frac{2z}{1+z^2}}{1 + A_\tau A_e \frac{2z}{1+z^2}}$$

$(z = \cos\theta, \quad \theta =$ scattering angle)

$$e^- \text{polarization} \;\; (\text{SLD}): \; A_{LR}^0 = A_e$$

$$\text{mixed} \;\; (\text{SLD}): \; A_{LR}^{0FB} = \frac{3}{4} A_f$$

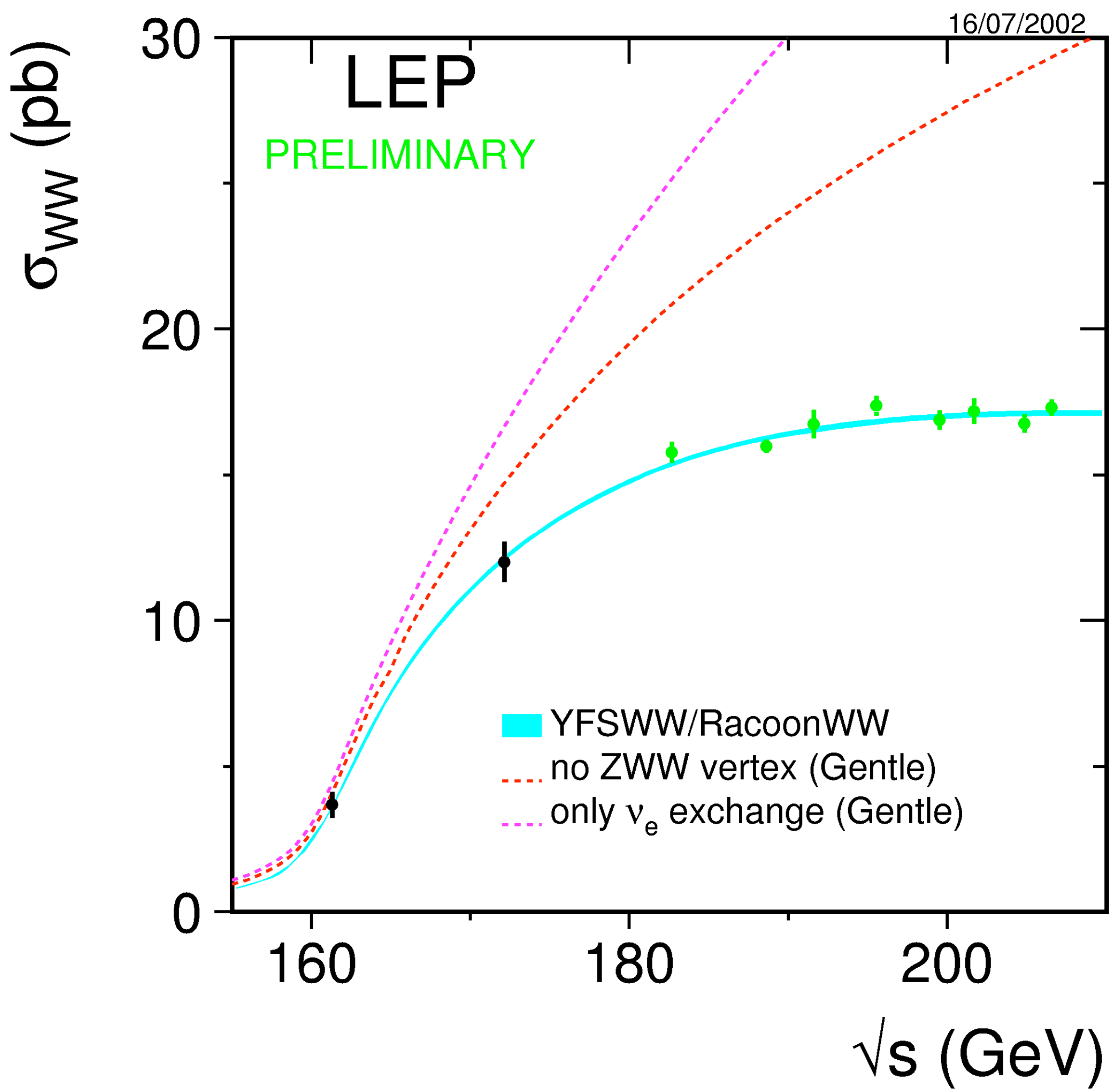
$$A_f \equiv \frac{2 \bar{g}_{VF} \bar{g}_{Af}}{\bar{g}_{VF}^2 + \bar{g}_{AF}^2}$$

The Z Pole Observables: LEP and SLC (01/03)

Quantity	Group(s)	Value	Standard Model	pull
M_Z [GeV]	LEP	91.1876 ± 0.0021	91.1874 ± 0.0021	0.1
Γ_Z [GeV]	LEP	2.4952 ± 0.0023	2.4972 ± 0.0011	-0.9
$\Gamma(\text{had})$ [GeV]	LEP	1.7444 ± 0.0020	1.7436 ± 0.0011	—
$\Gamma(\text{inv})$ [MeV]	LEP	499.0 ± 1.5	501.74 ± 0.15	—
$\Gamma(\ell^+\ell^-)$ [MeV]	LEP	83.984 ± 0.086	84.015 ± 0.027	—
σ_{had} [nb]	LEP	41.541 ± 0.037	41.470 ± 0.010	1.9
R_e	LEP	20.804 ± 0.050	20.753 ± 0.012	1.0
R_μ	LEP	20.785 ± 0.033	20.753 ± 0.012	1.0
R_τ	LEP	20.764 ± 0.045	20.799 ± 0.012	-0.8
$A_{FB}(e)$	LEP	0.0145 ± 0.0025	0.01639 ± 0.00026	-0.8
$A_{FB}(\mu)$	LEP	0.0169 ± 0.0013		0.4
$A_{FB}(\tau)$	LEP	0.0188 ± 0.0017		1.4

Quantity	Group(s)	Value	Standard Model	pull
R_b	LEP/SLD	0.21664 ± 0.00065	0.21572 ± 0.00015	1.1
R_c	LEP/SLD	0.1718 ± 0.0031	0.17231 ± 0.00006	-0.2
$R_{s,d}/R_{(d+u+s)}$	OPAL	0.371 ± 0.023	0.35918 ± 0.00004	0.5
$A_{FB}(b)$	LEP	0.0995 ± 0.0017	0.1036 ± 0.0008	-2.4
$A_{FB}(c)$	LEP	0.0713 ± 0.0036	0.0741 ± 0.0007	-0.8
$A_{FB}(s)$	DELPHI/OPAL	0.0976 ± 0.0114	0.1037 ± 0.0008	-0.5
A_b	SLD	0.922 ± 0.020	0.93476 ± 0.00012	-0.6
A_c	SLD	0.670 ± 0.026	0.6681 ± 0.0005	0.1
A_s	SLD	0.895 ± 0.091	0.93571 ± 0.00010	-0.4
A_{LR} (hadrons)	SLD	0.15138 ± 0.00216	0.1478 ± 0.0012	1.7
A_{LR} (leptons)	SLD	0.1544 ± 0.0060		1.1
A_μ	SLD	0.142 ± 0.015		-0.4
A_τ	SLD	0.136 ± 0.015		-0.8
$A_e(Q_{LR})$	SLD	0.162 ± 0.043		0.3
$A_\tau(\mathcal{P}_\tau)$	LEP	0.1439 ± 0.0043		-0.9
$A_e(\mathcal{P}_\tau)$	LEP	0.1498 ± 0.0048		0.4
Q_{FB}	LEP	0.0403 ± 0.0026	0.0424 ± 0.0003	-0.8

- **LEP 2**
  - M_W, Γ_W, B **(also hadron colliders)**
  - M_H **limits (hint?)**
  - WW **production (triple gauge vertex)**
  - **Quartic vertex**
  - **SUSY/exotics searches**


16/07/2002
LEP
PRELIMINARY
σWW (pb)
√s (GeV)
30
20
10
0
160
180
200
YFSWW/RacoonWW
no ZWW vertex (Gentle)
only νe exchange (Gentle)

- **Other: atomic parity (Boulder); νe; νN (NuTeV); polarized Møller asymmetry (SLAC E158); M_W, m_t (Tevatron)**

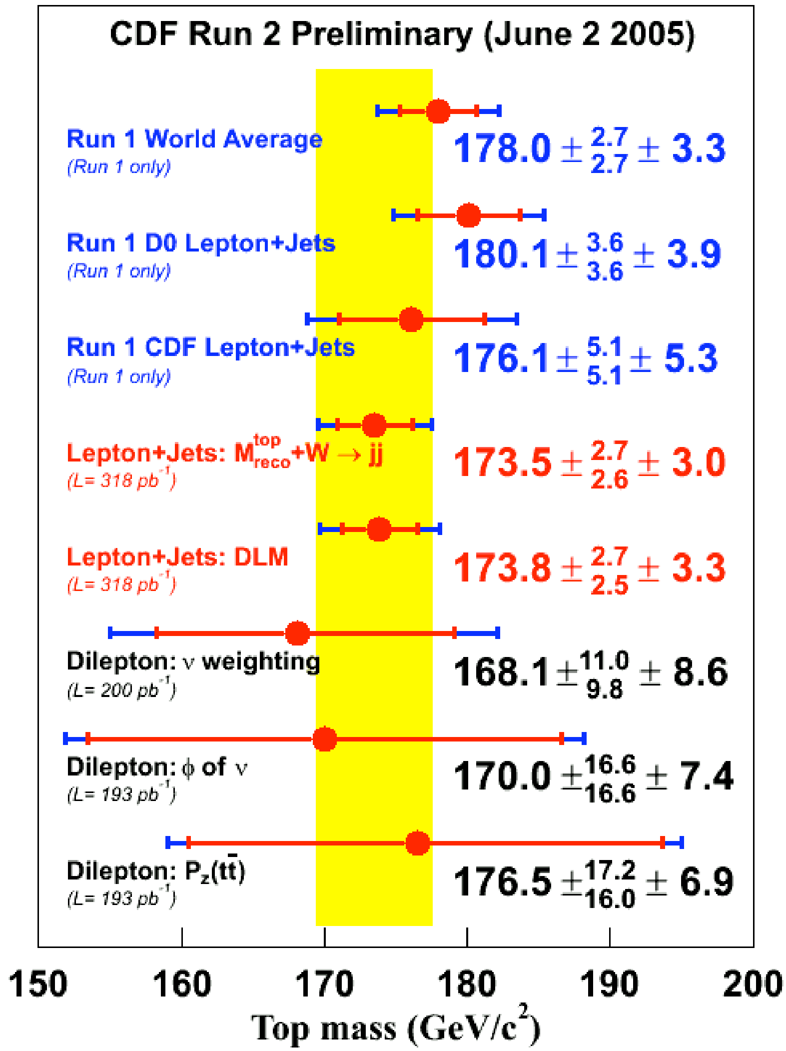
Non-Z Pole Precision Observables (1/03)

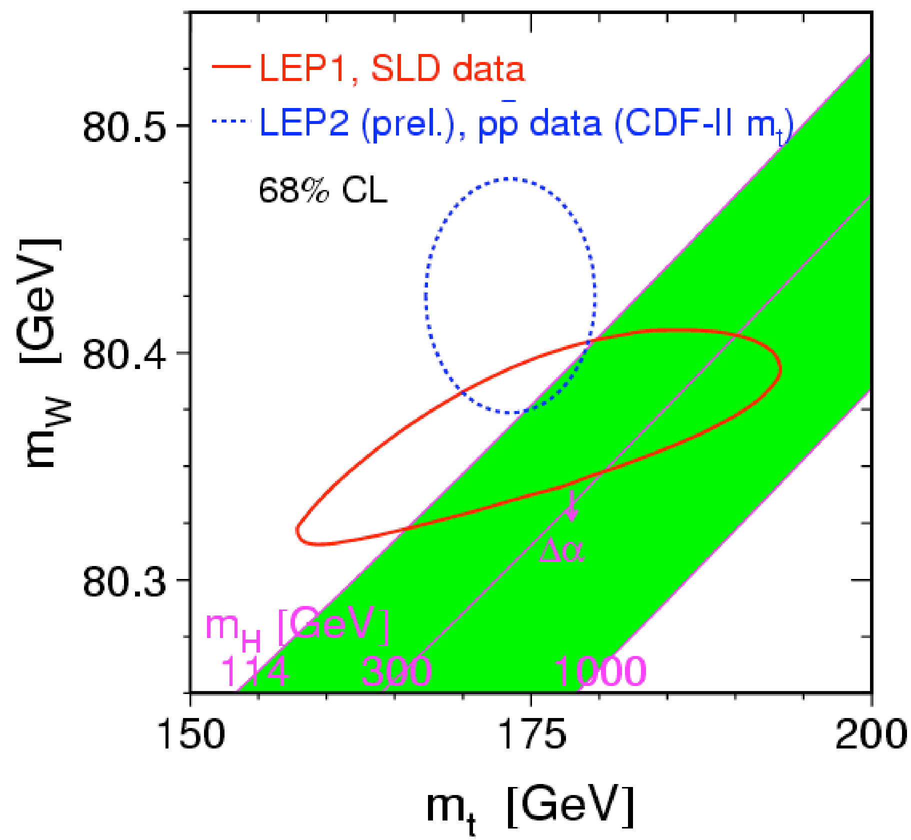
Quantity	Group(s)	Value	Standard Model	pull
m_t [GeV]	Tevatron	174.3 ± 5.1	174.4 ± 4.4	0.0
M_W [GeV]	LEP	80.447 ± 0.042	80.391 ± 0.018	1.3
M_W [GeV]	Tevatron /UA2	80.454 ± 0.059		1.1
g_L^2	NuTeV	0.30005 ± 0.00137	0.30396 ± 0.00023	-2.9
g_R^2	NuTeV	0.03076 ± 0.00110	0.03005 ± 0.00004	0.6
R^ν	CCFR	$0.5820 \pm 0.0027 \pm 0.0031$	0.5833 ± 0.0004	-0.3
R^ν	CDHS	$0.3096 \pm 0.0033 \pm 0.0028$	0.3092 ± 0.0002	0.1
R^ν	CHARM	$0.3021 \pm 0.0031 \pm 0.0026$		-1.7
$R^{\bar{\nu}}$	CDHS	$0.384 \pm 0.016 \pm 0.007$	0.3862 ± 0.0002	-0.1
$R^{\bar{\nu}}$	CHARM	$0.403 \pm 0.014 \pm 0.007$		1.0
$R^{\bar{\nu}}$	CDHS 1979	$0.365 \pm 0.015 \pm 0.007$	0.3816 ± 0.0002	-1.0

Quantity	Group(s)	Value	Standard Model	pull
$g_V^{\nu e}$	CHARM II	-0.035 ± 0.017	-0.0398 ± 0.0003	—
$g_V^{\nu e}$	all	-0.041 ± 0.015		-0.1
$g_A^{\nu e}$	CHARM II	-0.503 ± 0.017	-0.5065 ± 0.0001	—
$g_A^{\nu e}$	all	-0.507 ± 0.014		0.0
$Q_W(\mathrm{Cs})$	Boulder	-72.69 ± 0.44	-73.10 ± 0.04	0.8
$Q_W(\mathrm{Tl})$	Oxford/Seattle	-116.6 ± 3.7	-116.7 ± 0.1	0.0
$10^3\ \frac{\Gamma(b \to s\gamma)}{\Gamma_{SL}}$	BaBar/Belle/CLEO	$3.48^{+0.65}_{-0.54}$	3.20 ± 0.09	0.5
τ_τ [fs]	direct/$\mathcal{B}_e$/$\mathcal{B}_\mu$	$290.96 \pm 0.59 \pm 5.66$	291.90 ± 1.81	-0.4
$10^4\ \Delta\alpha^{(3)}_{\rm had}$	e^+e^-/τ decays	$56.53 \pm 0.83 \pm 0.64$	57.52 ± 1.31	-0.9
$10^9\ (a_\mu - \frac{\alpha}{2\pi})$	BNL/CERN	$4510.64 \pm 0.79 \pm 0.51$	4508.30 ± 0.33	2.5

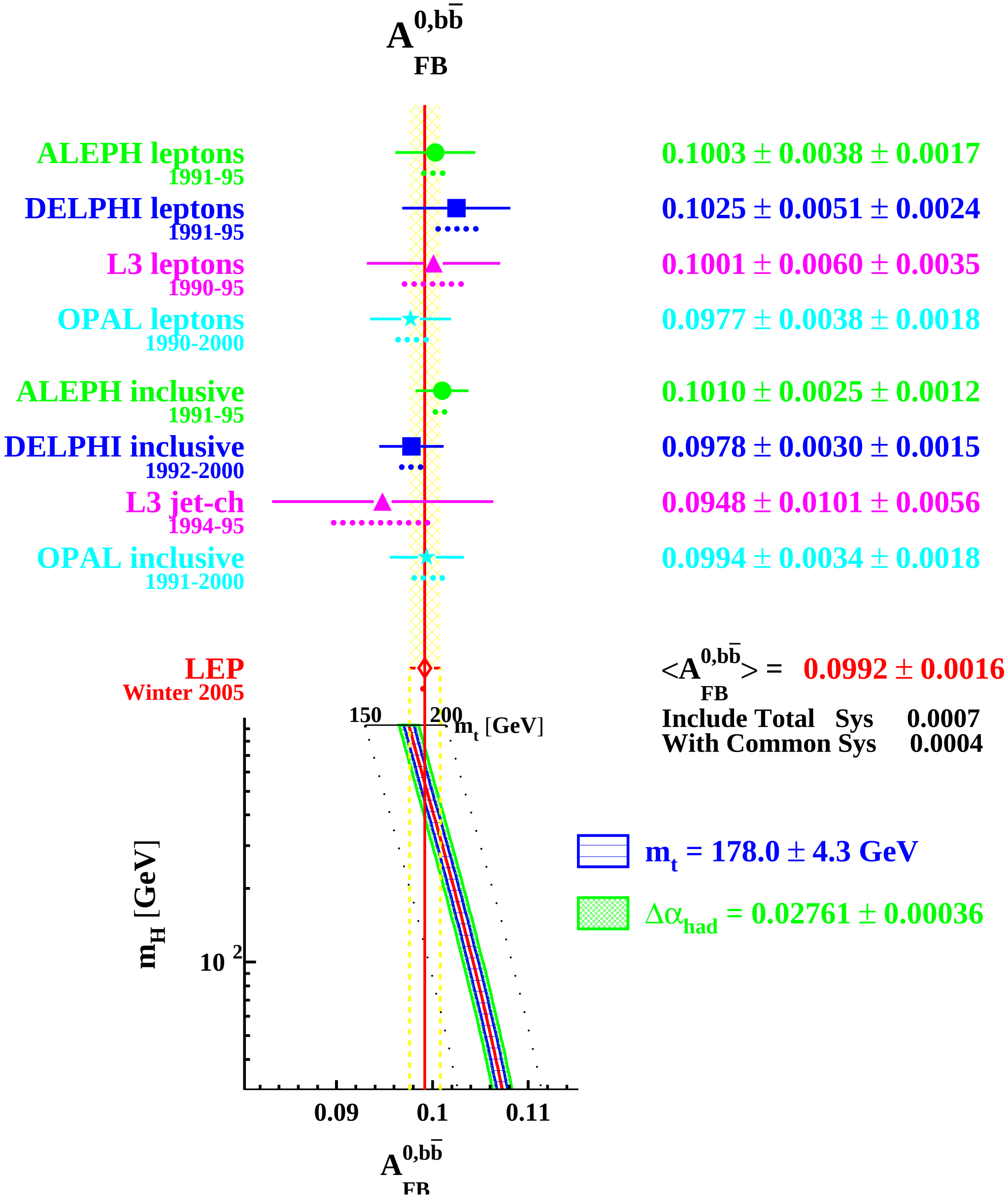
New Inputs, Anomalies, Things to Watch

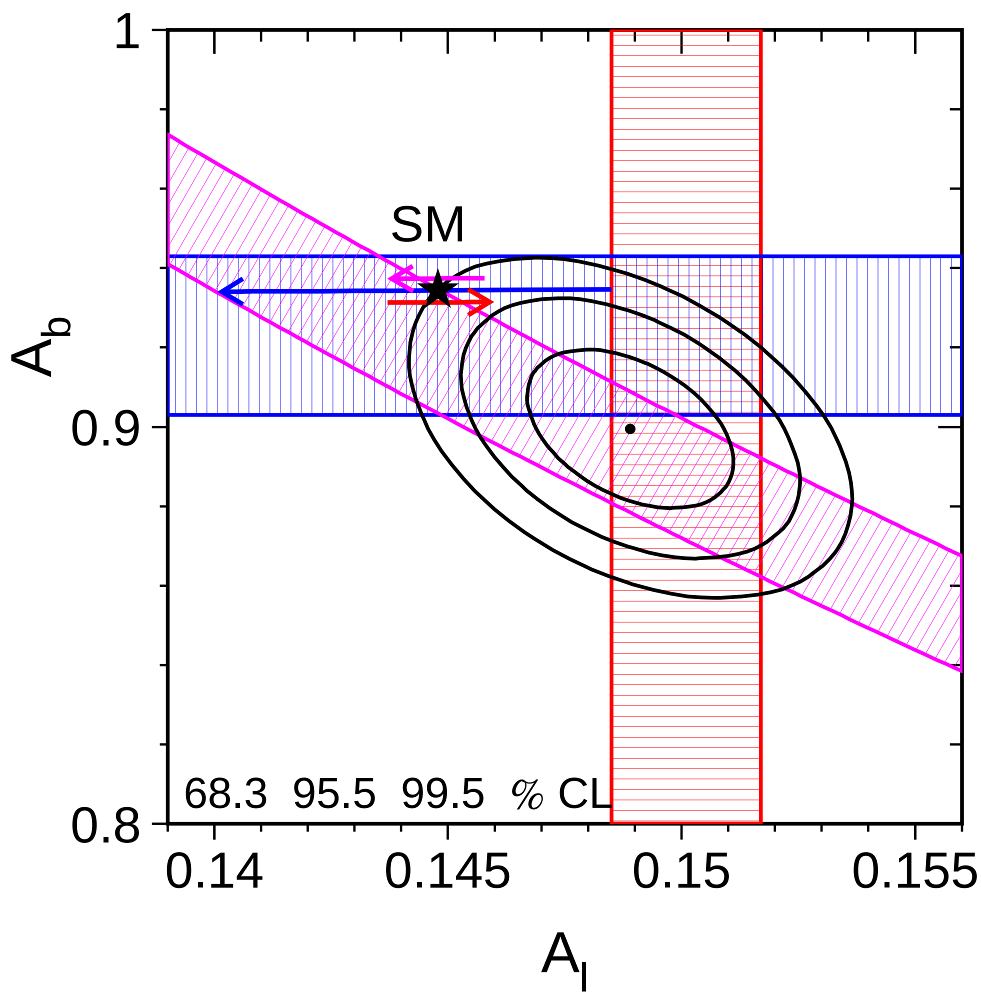
- New CDF m_t from Run II (lepton + jets)
  - $m_t = 173.5^{+4.1}_{-4.0}$ GeV, lower than previous Tevatron average 178.0 ± 4.3 GeV (dominated by reanalysis of D ∅ Run)
  - More precise than previous average
  - Will lower the M_H prediction


CDF Run 2 Preliminary (June 2 2005)
Run 1 World Average
(Run 1 only)
178.0 ± 2.7 2.7 ± 3.3
Run 1 D0 Lepton+Jets
(Run 1 only)
180.1 ± 3.6 3.6 ± 3.9
Run 1 CDF Lepton+Jets
(Run 1 only)
176.1 ± 5.1 5.1 ± 5.3
Lepton+Jets: M top reco +W → jj
(L= 318 pb-1)
173.5 ± 2.7 2.6 ± 3.0
Lepton+Jets: DLM
(L= 318 pb-1)
173.8 ± 2.7 2.5 ± 3.3
Dilepton: ν weighting
(L= 200 pb-1)
168.1 ± 11.0 9.8 ± 8.6
Dilepton: φ of ν
(L= 193 pb-1)
170.0 ± 16.6 16.6 ± 7.4
Dilepton: Pz(tt̄)
(L= 193 pb-1)
176.5 ± 17.2 16.0 ± 6.9
150
160
170
180
190
200
Top mass (GeV/c2)

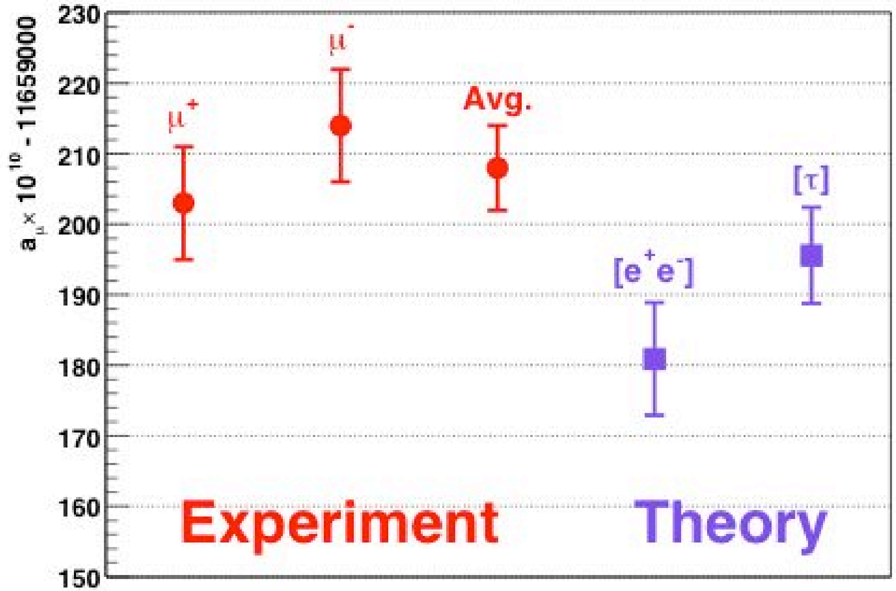

LEP1, SLD data
LEP2 (prel.), pp̄ data (CDF-II mt)
68% CL
80.5
80.4
80.3
mW [GeV]
Δα
mH [GeV]
114
300
1000
150
175
200
mt [GeV]

- $A^b_{FB} = 0.0995(17)$ is 2.4σ below expectation of $0.1032(8)$ for M_H= 114 GeV
  - Favors large M_H. New physics *or* fluctuation/systematics lead to smaller M_H
  - $A^b_{FB} = \frac{3}{4} A_l A_b$; A_b agrees with SM, A_l (SLC) is 1.9σ high
  - New physics in A^b_{FB} would require compensation of L and R couplings (to preserve R_b)
  - 5% effect, but $\sim$ 25% in $\kappa \longrightarrow$ probably tree level affecting third family
  - New physics possibilities include Z' with non-universal couplings, or b_R mixing with B_R in doublet with charge $-4/3$


$A_{FB}^{0,b\bar{b}}$
ALEPH leptons 1991-95
0.1003 ± 0.0038 ± 0.0017
DELPHI leptons 1991-95
0.1025 ± 0.0051 ± 0.0024
L3 leptons 1990-95
0.1001 ± 0.0060 ± 0.0035
OPAL leptons 1990-2000
0.0977 ± 0.0038 ± 0.0018
ALEPH inclusive 1991-95
0.1010 ± 0.0025 ± 0.0012
DELPHI inclusive 1992-2000
0.0978 ± 0.0030 ± 0.0015
L3 jet-ch 1994-95
0.0948 ± 0.0101 ± 0.0056
OPAL inclusive 1991-2000
0.0994 ± 0.0034 ± 0.0018
LEP Winter 2005
$\langle A_{FB}^{0,b\bar{b}} \rangle$ = 0.0992 ± 0.0016
Include Total Sys 0.0007
With Common Sys 0.0004
150
200
m_t [GeV]
m_H [GeV]
10^2
m_t = 178.0 ± 4.3 GeV
$\Delta\alpha_{had}$ = 0.02761 ± 0.00036
0.09
0.1
0.11
$A_{FB}^{0,b\bar{b}}$

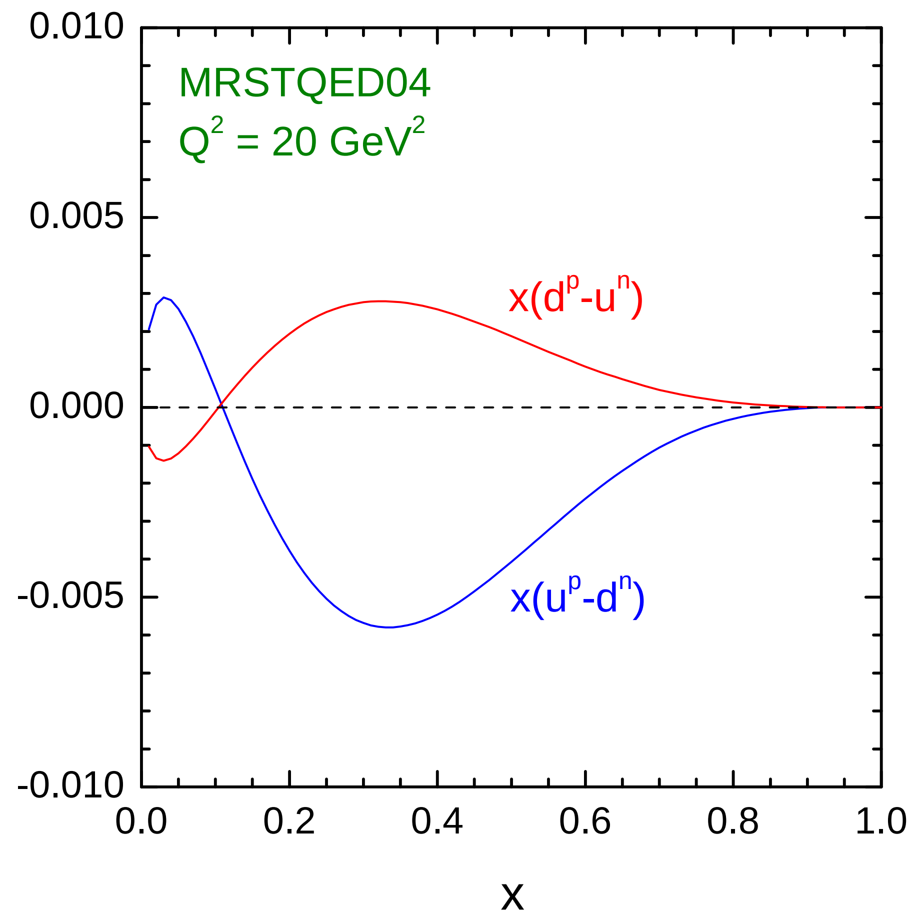

1
0.9
0.8
SM
68.3 95.5 99.5 % CL
0.14
0.145
0.15
0.155
A_b
A_l

- $a_\mu = (g_\mu - 2)/2$
  - More sensitive than a_e to new physics
  - BNL (2004) + other: $a_\mu^{\rm exp} = 11659208(6)\times 10^{-10}$
  - Hadronic light by light has settled down, but considerable uncertaintly from $a_\mu^{\rm Had}$
  - $a_\mu^{\rm exp} - a_\mu^{\rm SM} = (24 \pm 10)\times 10^{-10}$ (2.4σ) (using e^+e^- data for $a_\mu^{\rm Had}$) $\rightarrow 0.9\sigma$ (using τ decay data. Theory uncertainties?)
  - New physics? Supersymmetry: $(\tilde{m} \sim 70 \text{ GeV} \sqrt{\tan\beta})$

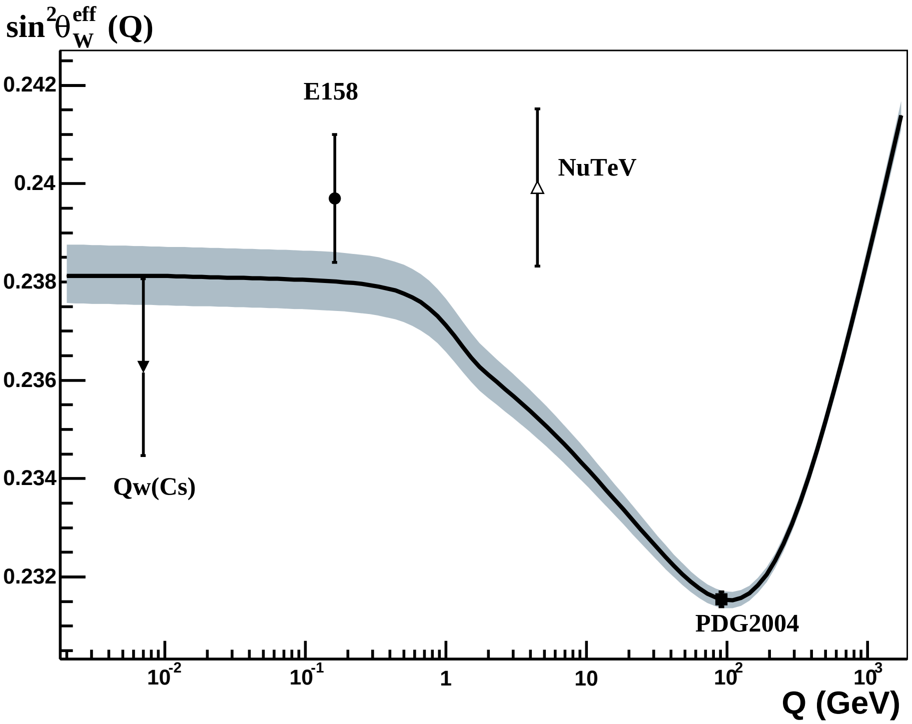


- **NuTeV**

$$\frac{\overset{(-)}{\nu}_\mu N \to \overset{(-)}{\nu}_\mu X}{\overset{(-)}{\nu}_\mu N \to \mu^\mp X}$$



- Little c threshold uncertaintly
- $s^2_W = 0.2277(16)$, 3.0σ above SM value 0.2228(4)
- Possible QCD effects: large $\bar{s} - s$ asymmetry (CTEQ); large isospin breaking in sea (MRST; Glück, Jimenez-Delgado, Reya)
- Need new analysis
- Future NOMAD



- **SLAC E158 Polarized Møller Asymmetry**
  - e^-e^- asymmetry, $P \sim 90\%$
  - $\sin^2\theta_W^{eff}(Q) = 0.2397 \pm 0.0013$ at $Q^2 = 0.026$ GeV^2

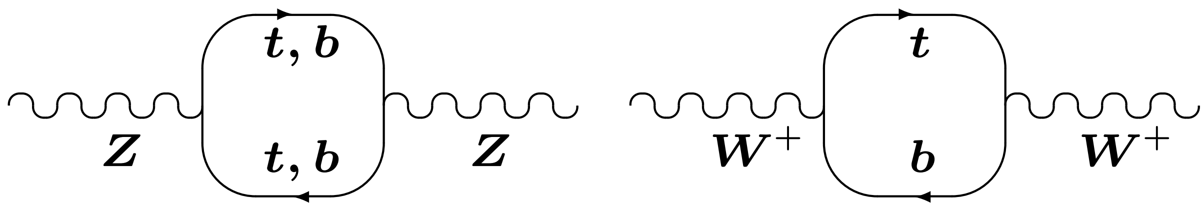
- **Atomic Parity Violation**
  - Very precise measurement (0.4%) in cesium (single electron outside tightly bound core)
  - Previous hint (2.2σ) of discrepancy, but theory-dominated error
  - Surprisingly large (O(1%)) radiative corrections: Breit, vacuum polarization, vertex, self-energy have now stabilized
  - Now excellent agreement: $Q_W(\mathrm{Cs}) = -72.69(48)$ (SM: $-73.19(3)$)
- **CKM Unitarity**
  - Expect $\Delta \equiv 1 - |V_{ud}|^2 - |V_{us}|^2 - |V_{ub}|^2 = 0$
  - PDG 2002: $\Delta = 0.0042 \pm 0.0019$
  - Superallowed ($0^+ \rightarrow 0^+$): $|V_{ud}| = 0.9740(5)$ under control
  - Recent BNL865 K^+, KTEV K_L, KLOE, NA48 give higher $|V_{us}|$, consistent with unitarity

Global Standard Model Fit Results

- PDG 2004 (12/93) (Erler, PL)
  - Fully $\overline{MS}$
  - Good agreement with LEPEWWG up to known effects
  - Update for PDG 2006 in progress

$$
\begin{aligned}
M_H &= 113^{+56}_{-40}\ \text{GeV}, \\
m_t &= 176.9 \pm 4.0\ \text{GeV}, \\
\alpha_s &= 0.1213 \pm 0.0018, \\
\hat{\alpha}(M_Z)^{-1} &= 127.906 \pm 0.019 \\
\hat{s}^2_Z &= 0.23120 \pm 0.00015, \\
s^2_W &= 0.22280 \pm 0.00035 \\
\Delta\alpha^{(5)}_{\rm had}(M_Z) &= 0.02801 \pm 0.00015
\end{aligned}
$$

- $m_t = 176.9 \pm 4.0$ GeV
  - $172.4^{+9.8}_{-7.3}$ GeV from indirect (loops) only (direct: 178.0 ± 4.3)
  - New CDF Run II, $m_t = 173.5^{+4.1}_{-4.0}$ GeV, *not* included

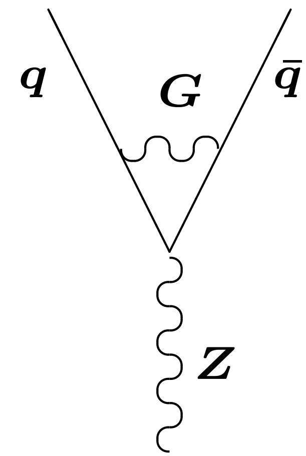


- $\alpha_s = 0.1213 \pm 0.0018$

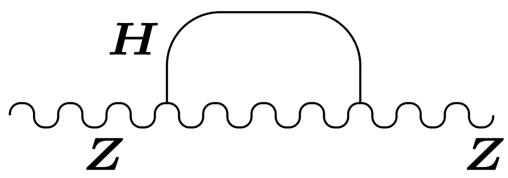
  - Higher than $\alpha_s = 0.1187(20)$ (Hinchliffe (PDG) 2004), because of τ lifetime

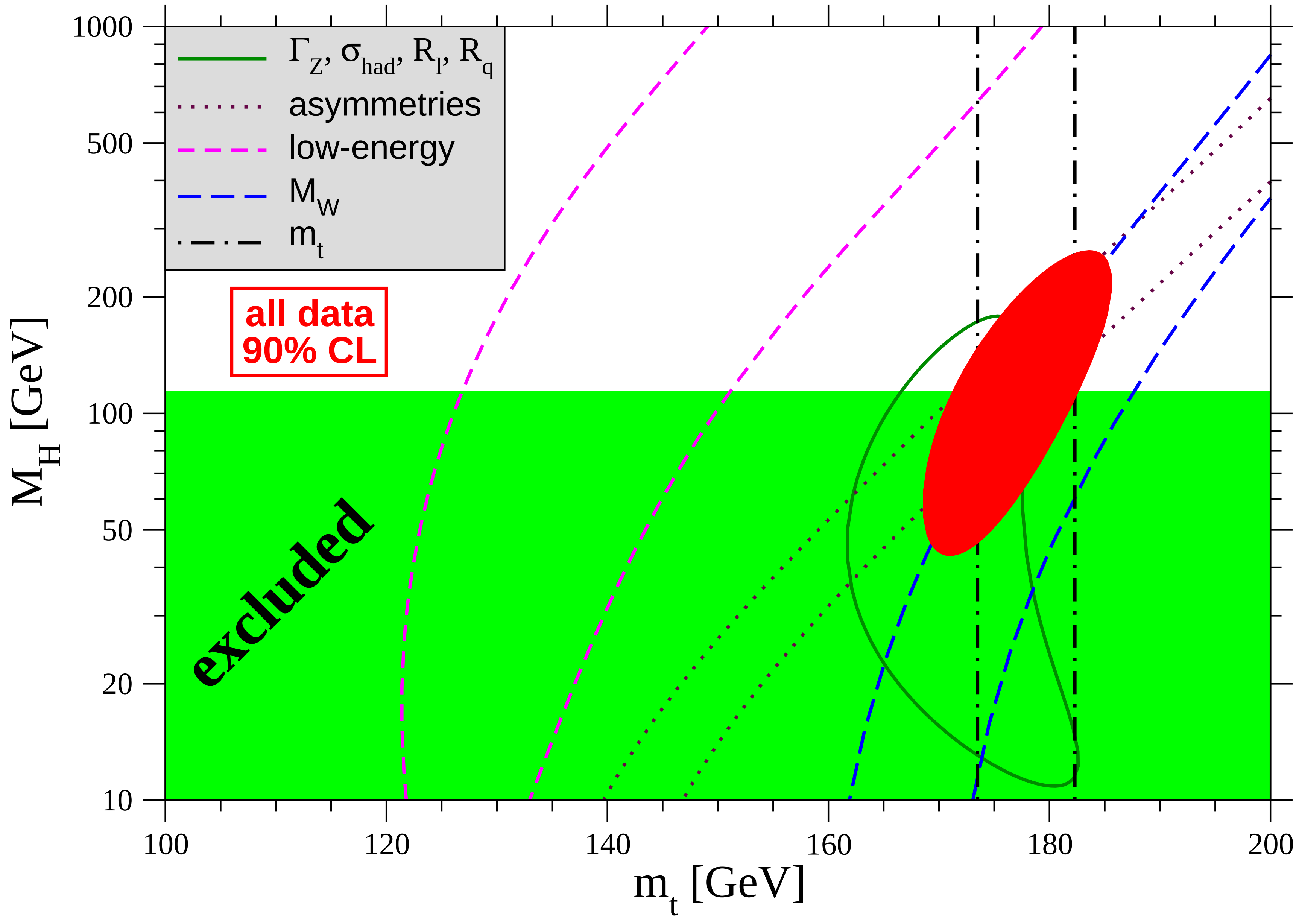
  - insensitive to oblique new physics

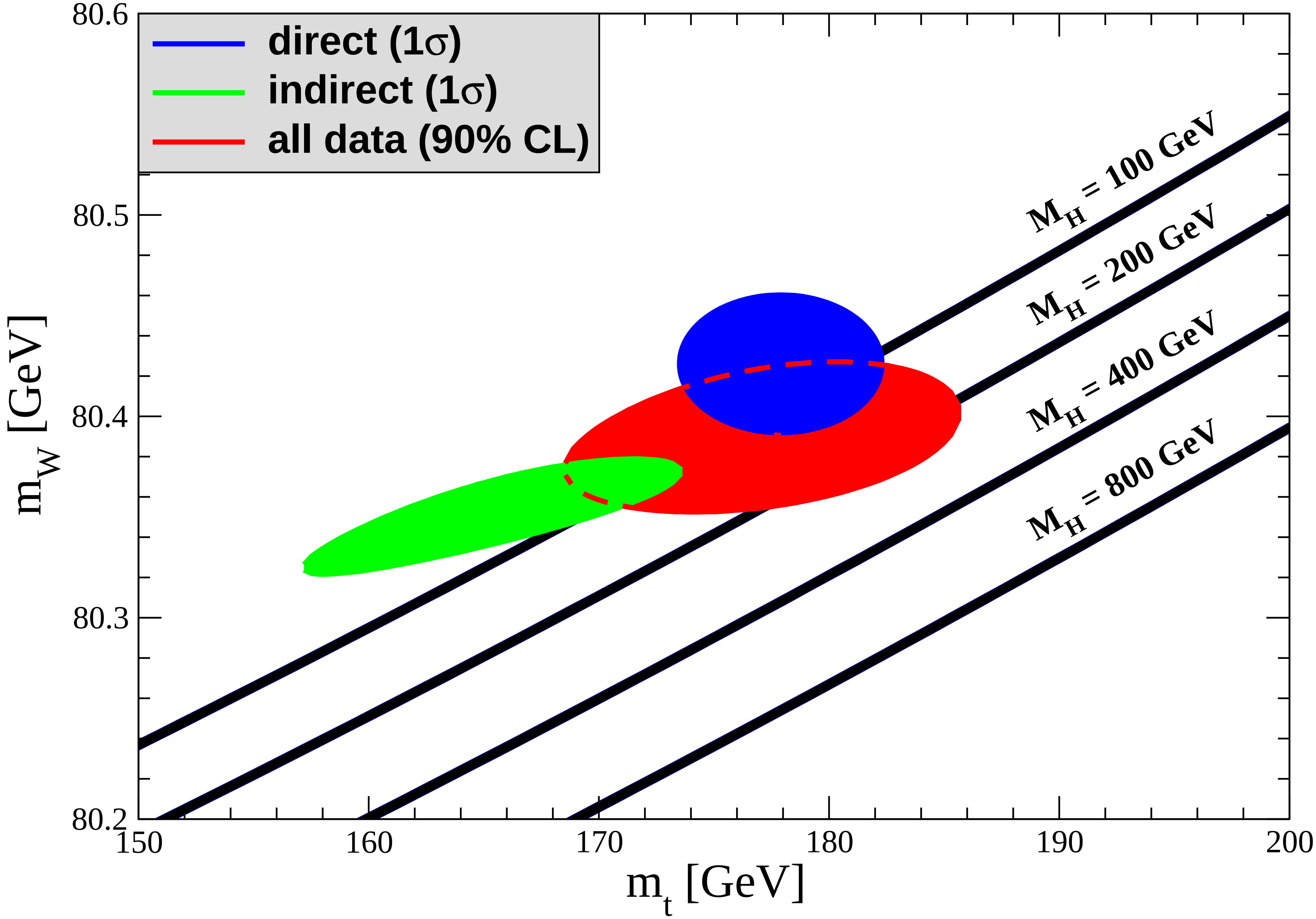
  - very sensitive to non-universal new physics (e.g., $Zb\bar{b}$ vertex)

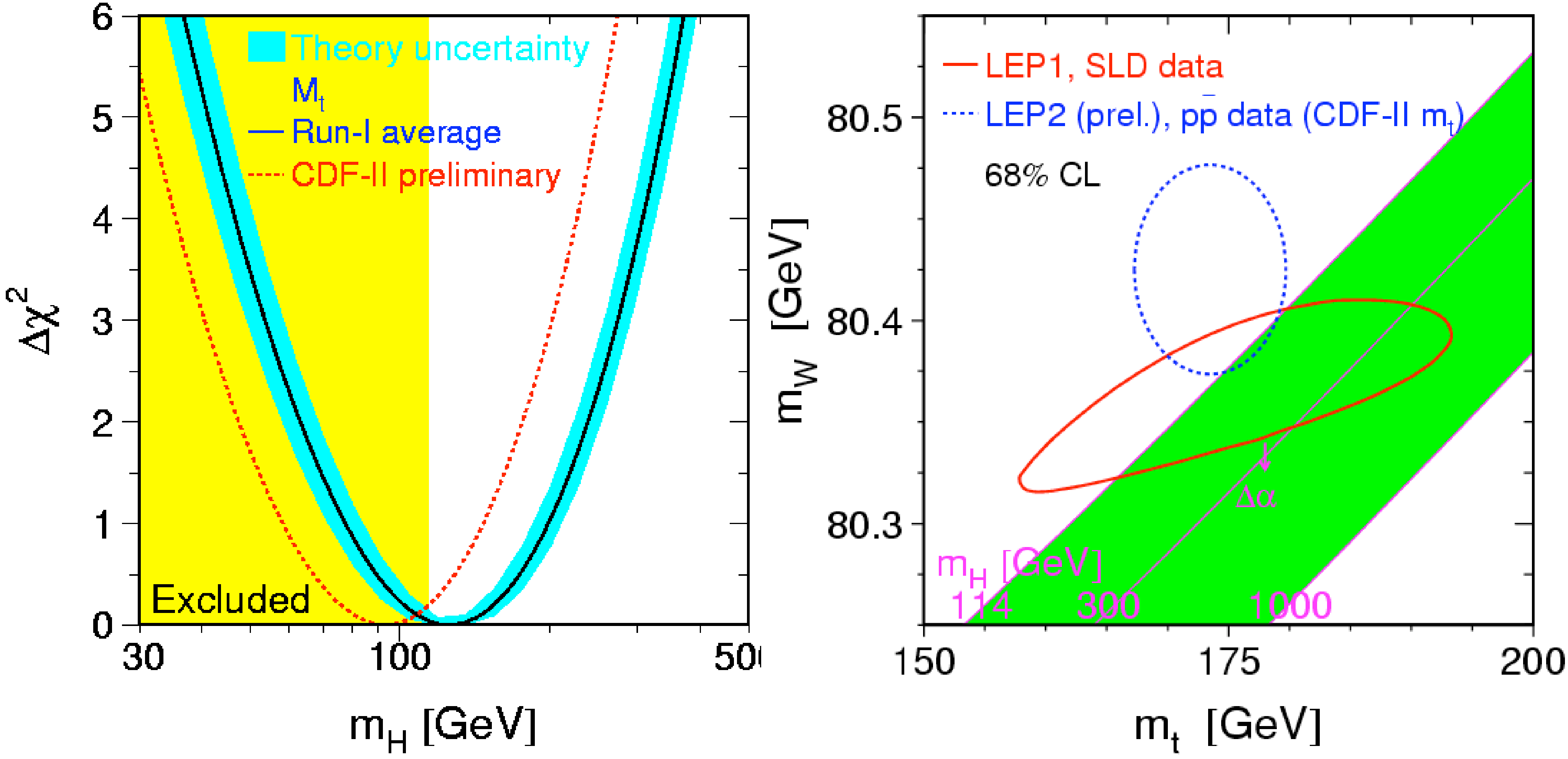


- Higgs mass $M_H = 113^{+56}_{-40}$ GeV
  - LEPEWWG (12/94): 114^{+69}_{-45}
  - direct limit (LEP 2): $M_H \gtrsim 114.4$ (95%) GeV
  - SM: 115 (vac. stab.) $\lesssim M_H \lesssim$ 750 (triviality)
  - MSSM: $M_H \lesssim 130$ GeV (150 in extensions)
  - indirect: $\ln M_H$ but significant
    - fairly robust to new physics (except $S < 0$, $T > 0$)
    - however, strong $A_{FB}(b)$ effect
    - $M_H < 246$ GeV at 95%, including direct




Γ_Z, σ_{had}, R_l, R_q
asymmetries
low-energy
M_W
m_t
all data
90% CL
excluded
1000
500
200
100
50
20
10
M_H [GeV]
100
120
140
160
180
200
m_t [GeV]


direct (1σ)
indirect (1σ)
all data (90% CL)
M_H = 100 GeV
M_H = 200 GeV
M_H = 400 GeV
M_H = 800 GeV
80.6
80.5
80.4
80.3
80.2
150
160
170
180
190
200
m_W [GeV]
m_t [GeV]


Theory uncertainty
M_t
Run-I average
CDF-II preliminary
Excluded
$\Delta\chi^2$
m_H [GeV]
LEP1, SLD data
LEP2 (prel.), $p\bar{p}$ data (CDF-II m_t)
68% CL
$\Delta\alpha$
m_H [GeV]
114
300
1000
m_W [GeV]
m_t [GeV]

Beyond the standard model

- ρ_0; S, T, U: Higgs triplets, nondegenerate fermions or scalars; chiral families (ETC)

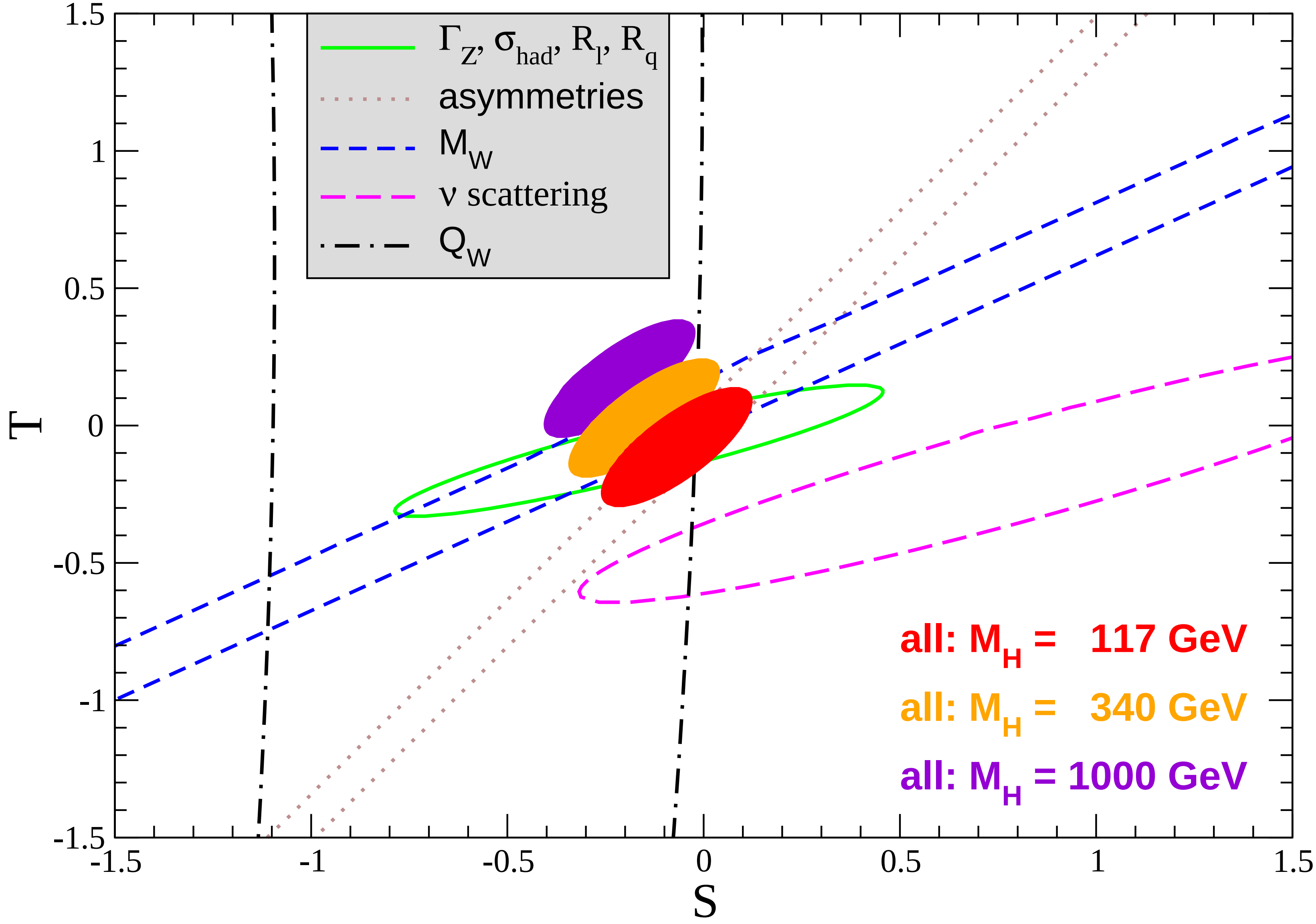
$$\begin{aligned} S &= -0.13 \pm 0.10(-0.08) \\ T &= -0.17 \pm 0.12(+0.09) \\ U &= 0.22 \pm 0.13(+0.01) \end{aligned}$$

for $M_H = 117\ (300)$ GeV

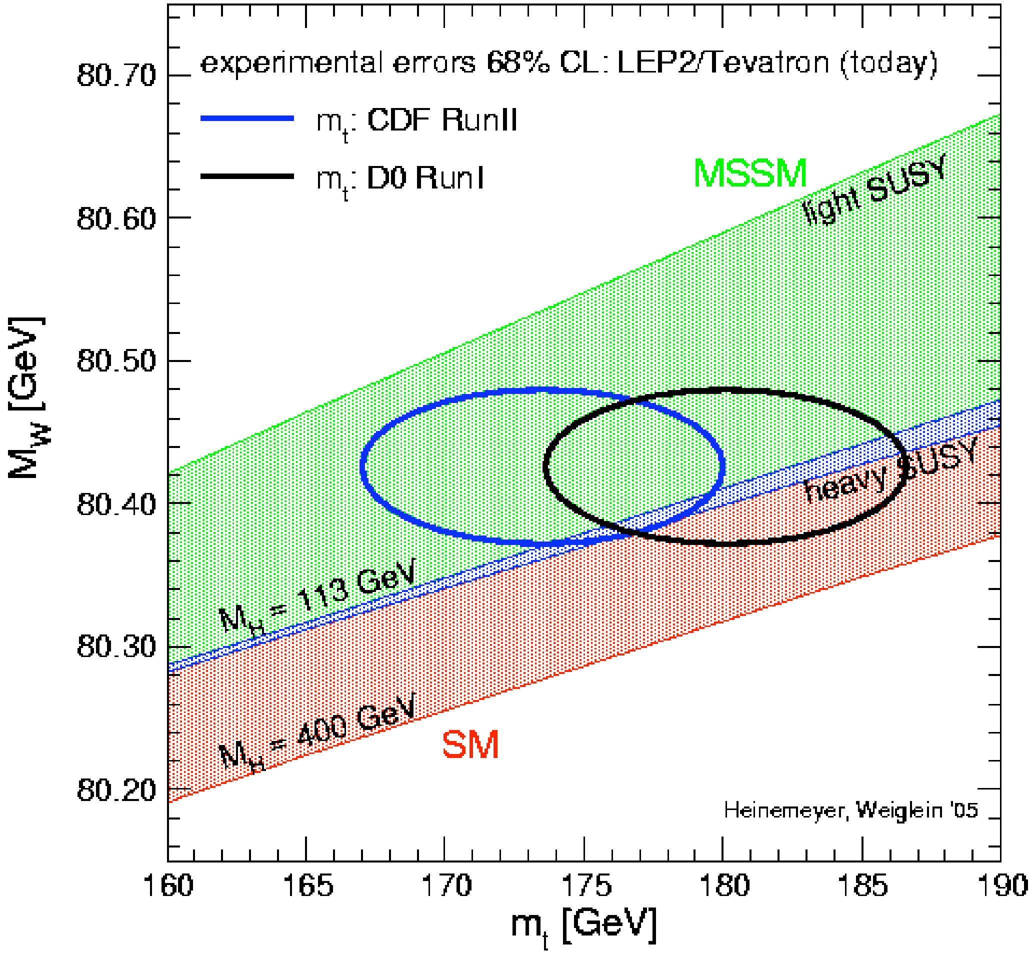
  - $\rho_0 =\sim 1 + \alpha T = 0.9998^{+0.0008}_{-0.0005}$ and 114.4 GeV $< M_H <$ 193 GeV (for $S = U = 0$)
  - Can evade Higgs mass limit for $S < 0,\ T > 0$ (Higgs doublet/triplet loops, Majorana fermions)

Oblique Parameters

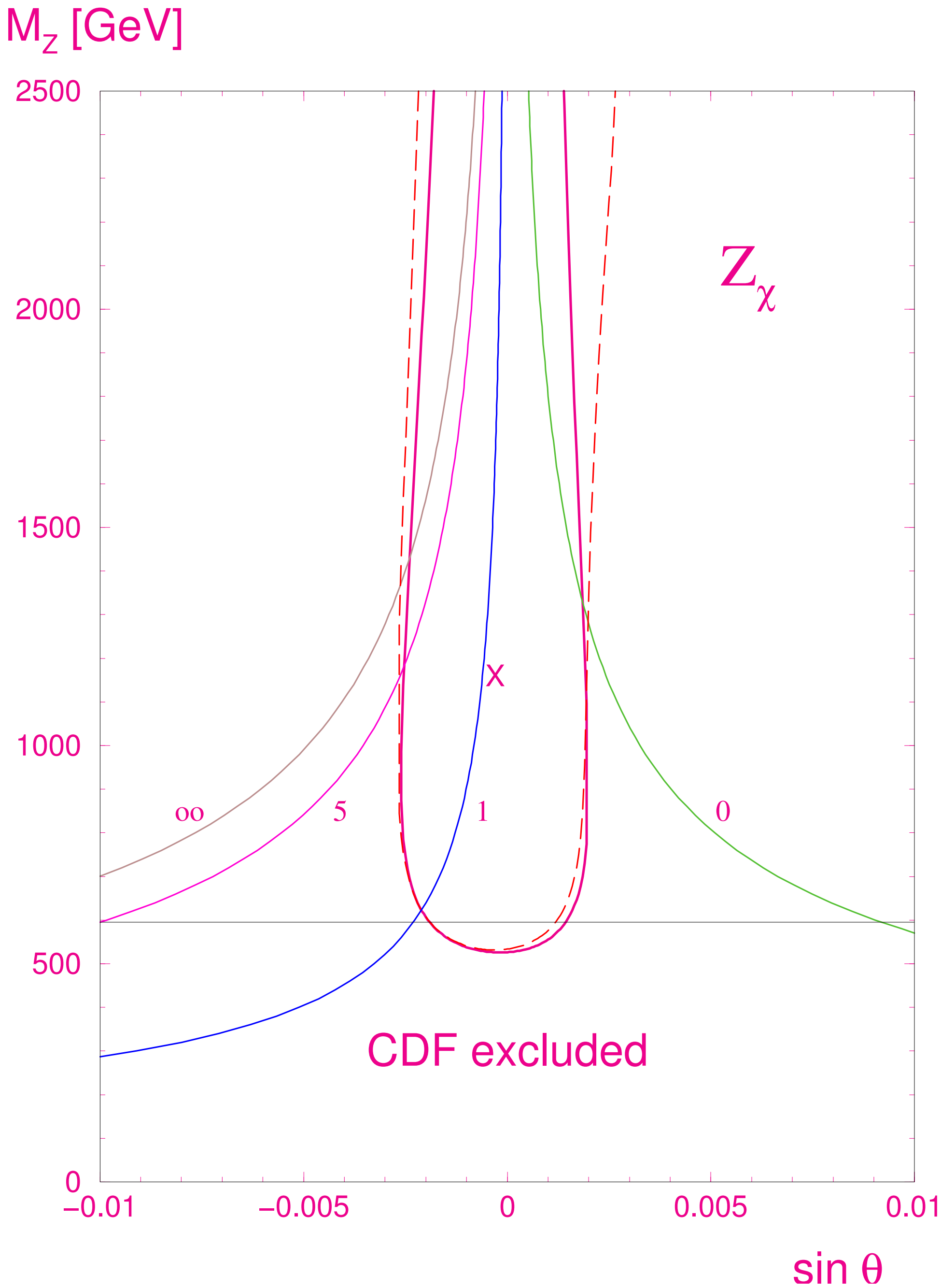
constraints on gauge boson self-energies



- **Supersymmetry**
  - **decoupling limit ($M_{new} \gtrsim 200-300$ GeV): only precision effect is light SM-like Higgs**
  - **little improvement on SM fit**
  - **SUSY parameters constrained**



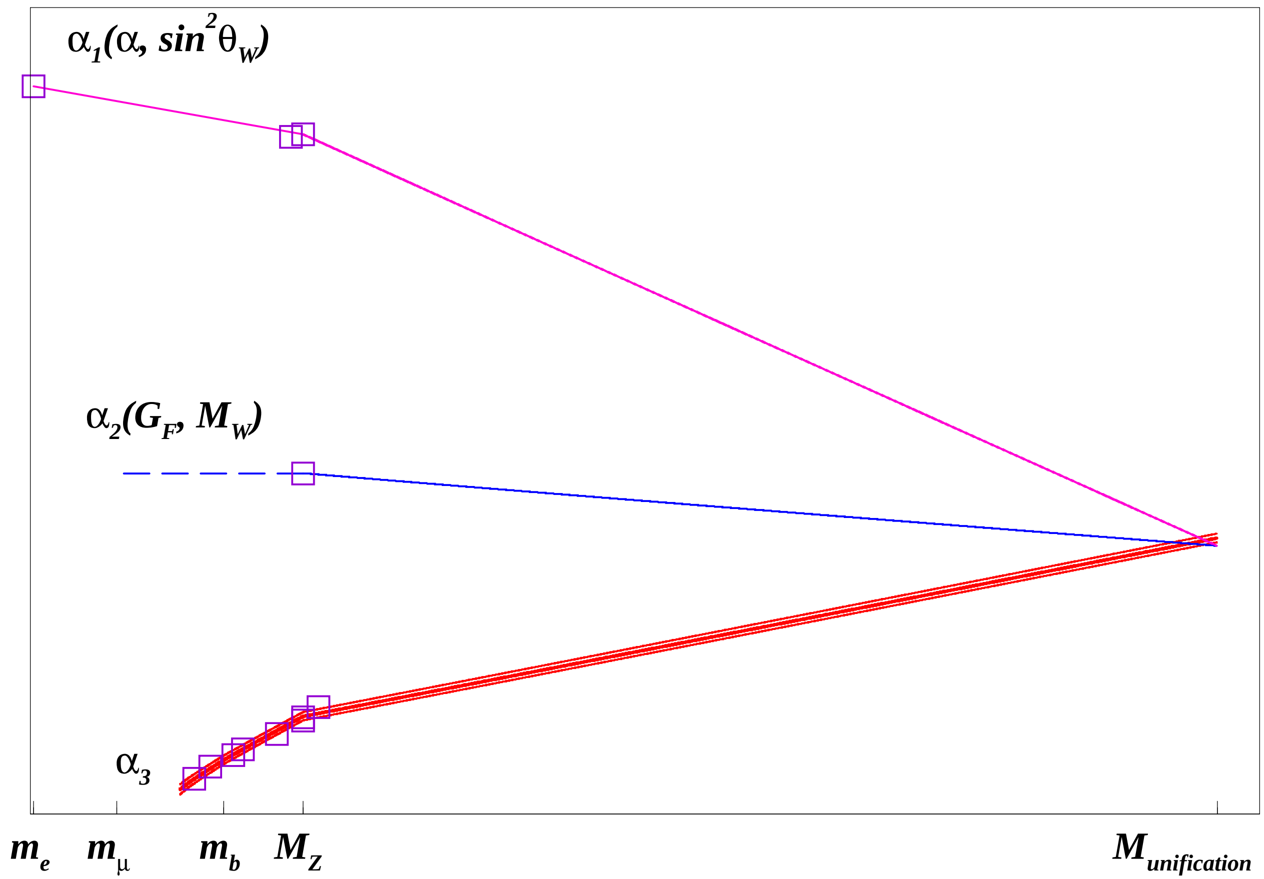
- A TeV scale Z'?
  - Expected in many string theories, grand unification, dynamical symmetry breaking, little Higgs
  - Natural solution to μ problem
  - Implications
    * Exotics
    * FCNC (especially in string models)
    * Non-standard Higgs masses, couplings (doublet-singlet mixing)
    * Non-standard sparticle spectrum
    * Neutrino mass, BBN, structure
    * Enhanced possibility of EW baryogenesis
  - Typically $M_{Z'} > 500 - 800$ GeV (Tevatron, LEP 2, WNC), $|\theta_{Z-Z'}| < \text{few} \times 10^{-3}$ (Z-pole)



M_Z [GeV]
2500
2000
1500
1000
500
0
−0.01
−0.005
0
0.005
0.01
sin θ
Z_χ
X
oo
5
1
0
CDF excluded

- Other
  - Exotic fermion mixings
  - Large extra dimensions
  - New four-fermi operator
  - Leptoquark bosons

- Gauge unification: GUTs, string theories
  - $\alpha + \hat{s}_Z^2 \to \alpha_s = 0.130 \pm 0.010$
  - $M_G \sim 3 \times 10^{16}$ GeV
  - Perturbative string: $\sim 5 \times 10^{17}$ GeV (10% in $\ln M_G$). Exotics: $O(1)$ corrections.



α1(α, sin²θW)
α2(GF, MW)
α3
me
mμ
mb
MZ
Munification

Conclusions

- WNC, Z, W are primary predictions and test of electroweak unification

- SM correct and unique to first approx. (gauge principle, group, representations)

- SM correct at loop level (renorm gauge theory; m_t, α_s, M_H)

- Watershed: TeV physics severely constrained (unification vs compositeness)
  - unification (decoupling): expect 0.1%
  - TeV compositeness: expect several % unless decoupling

- Precise gauge couplings (gauge unification)