

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:** $e^+e^- \rightarrow Z \rightarrow \ell^+\ell^-, q\bar{q}, \nu\bar{\nu}$
 - 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: $e^+e^- \rightarrow f\bar{f}$ ($f = e, \mu, \tau, s, b, c, \text{ hadrons}$) ($s = E_{CM}^2$)

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

(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:

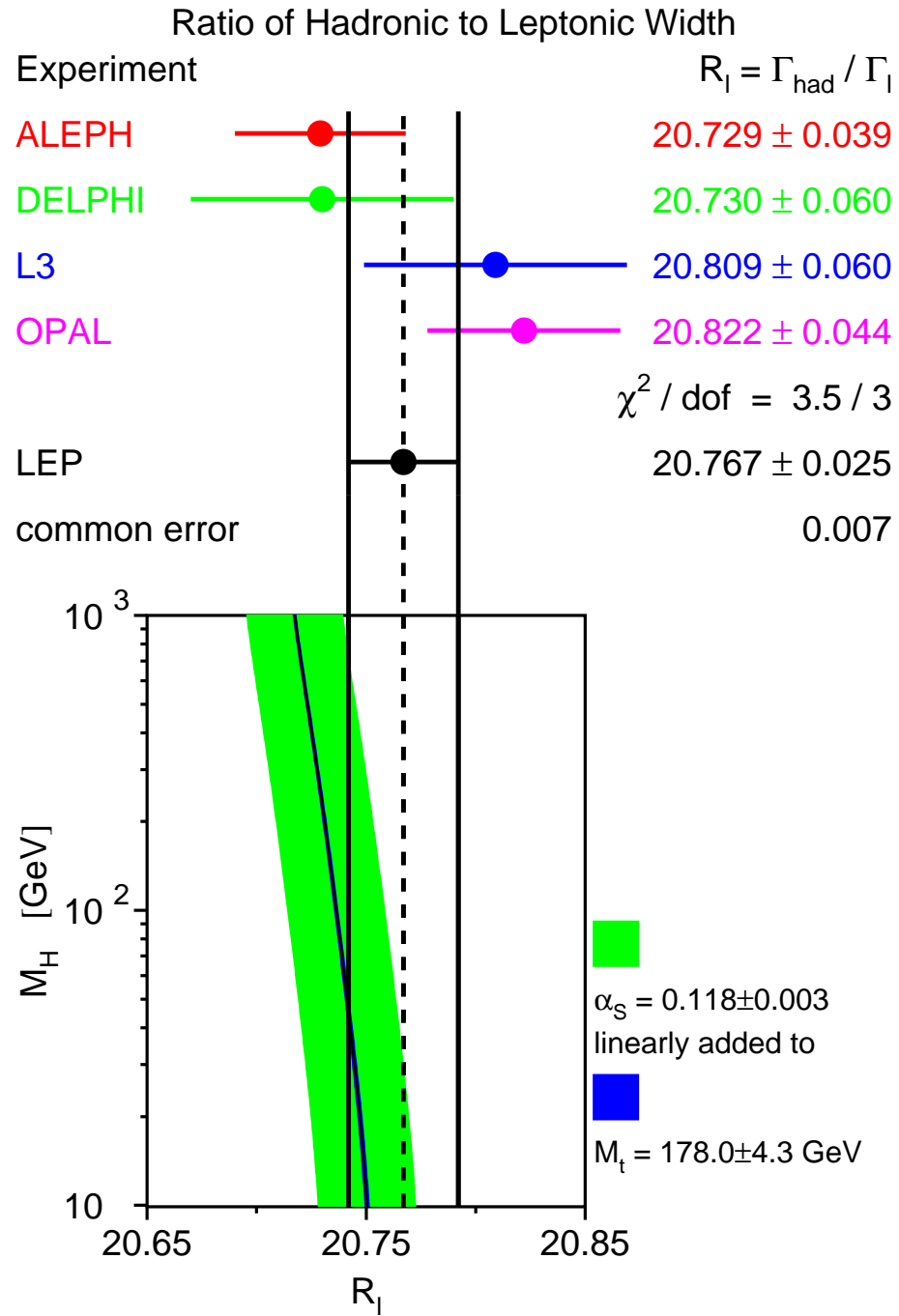
$$\Gamma(f\bar{f}) \sim \frac{C_f G_F M_Z^3}{6\sqrt{2}\pi} [|\bar{g}_{Vf}|^2 + |\bar{g}_{Af}|^2]$$

(plus mass, QED, QCD corrections; $C_\ell = 1$, $C_q = 3$; $\bar{g}_{V,Af} =$ 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



Z-Pole Asymmetries

- Effective axial and vector couplings of Z to fermion f

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

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

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

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

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

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

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

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

($z = \cos \theta$, $\theta = \text{scattering angle}$)

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

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

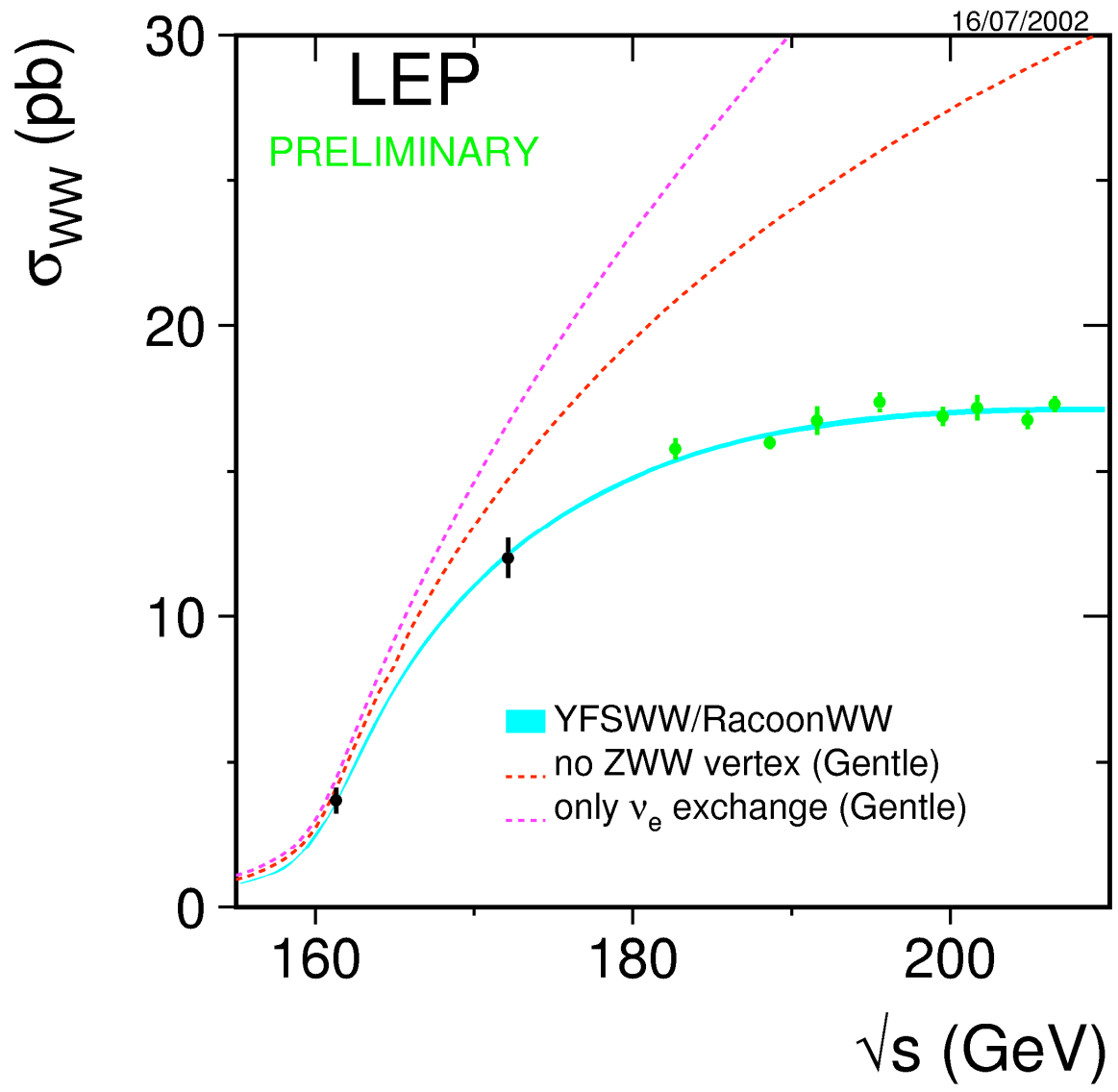
$$A_f \equiv \frac{2\bar{g}_{VF}\bar{g}_{Af}}{\bar{g}_{VF}^2 + \bar{g}_{AF}^2}$$

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



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

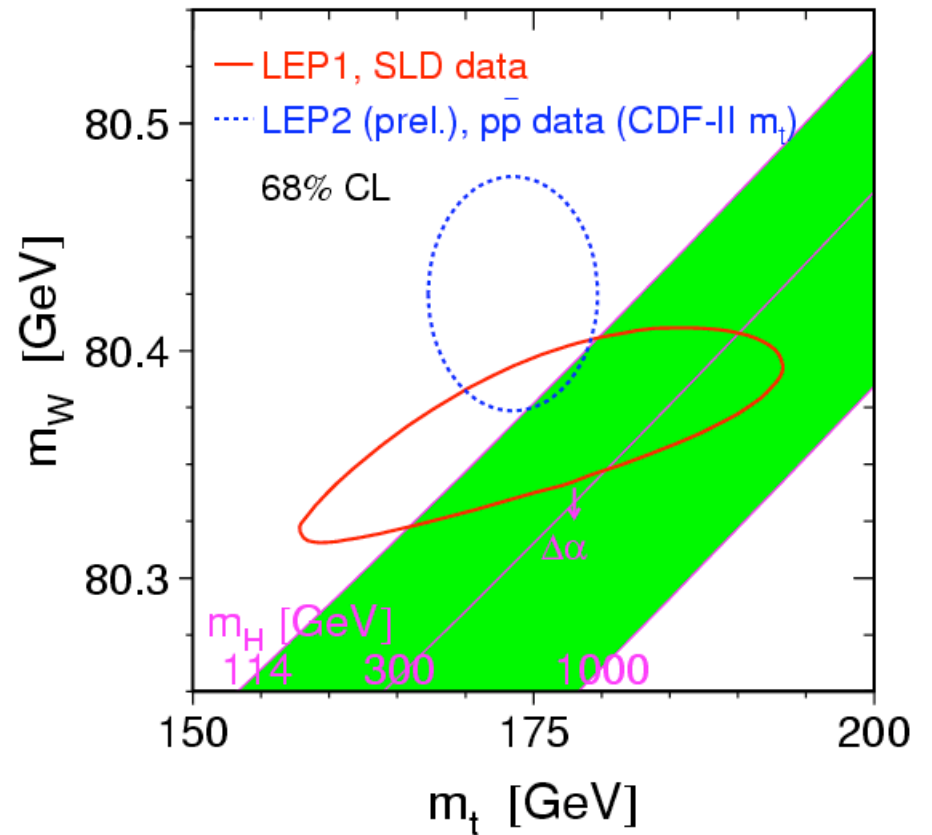
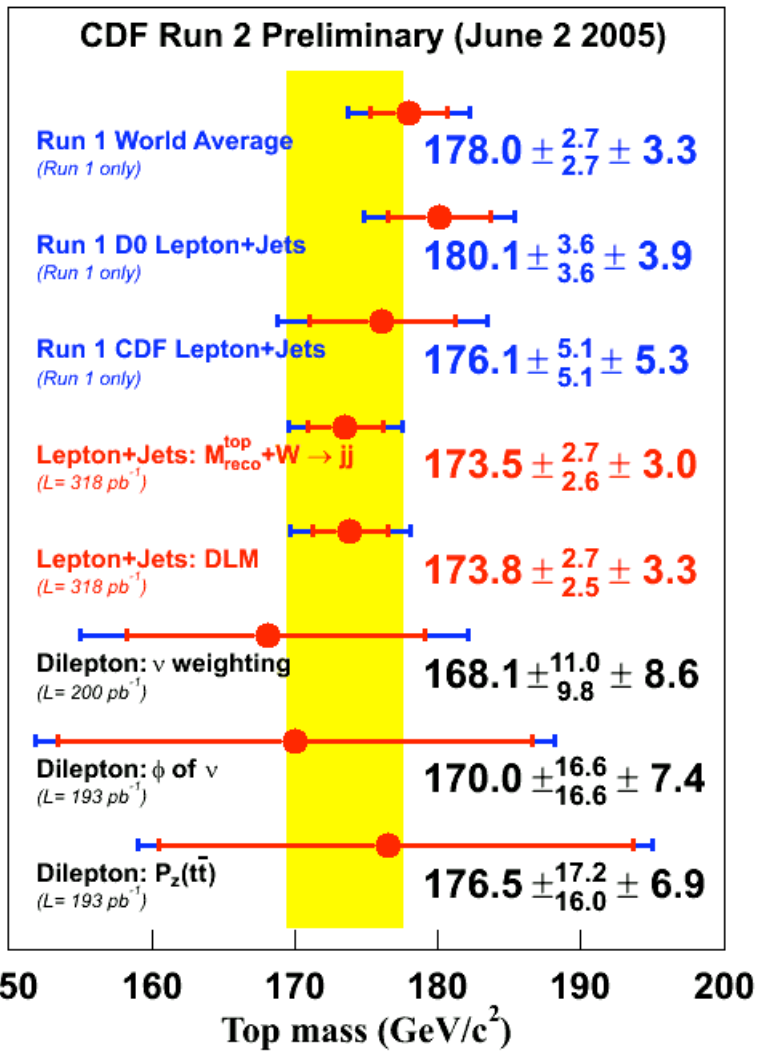
Non- Z Pole Precision Observables (1/03)

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

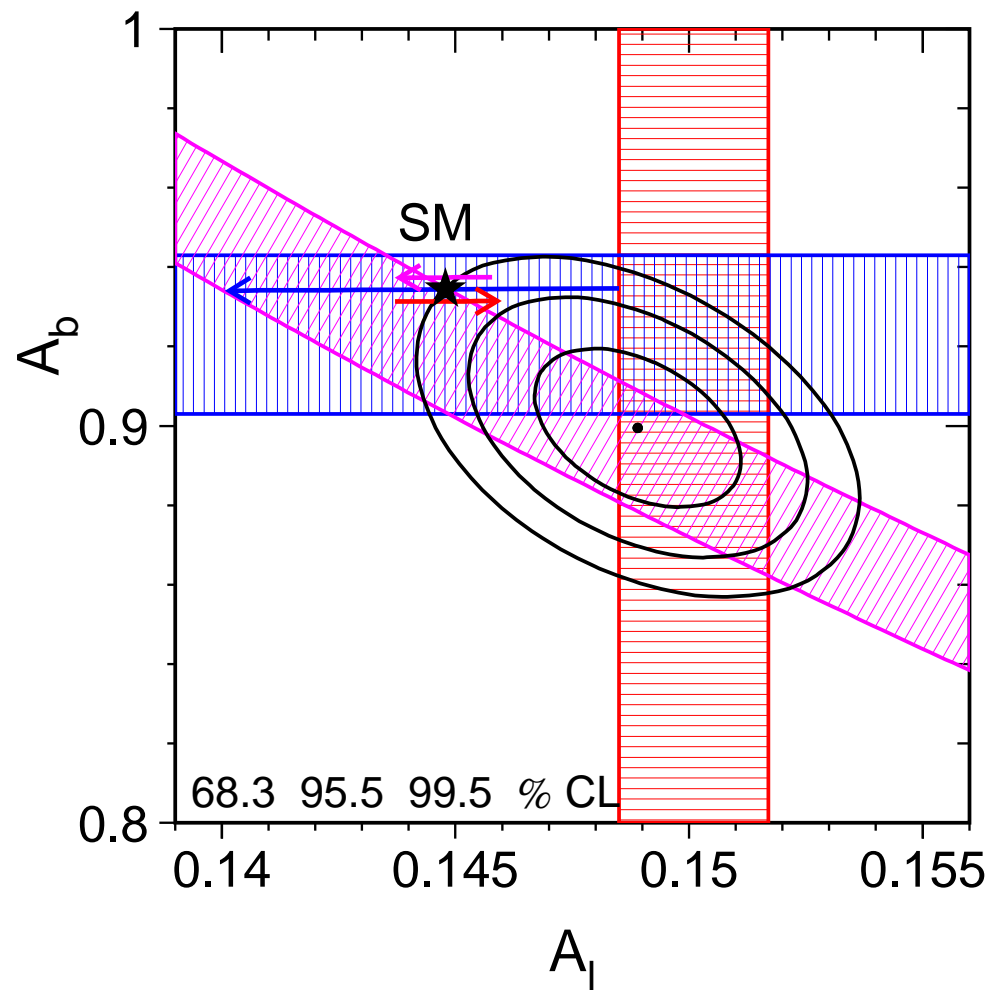
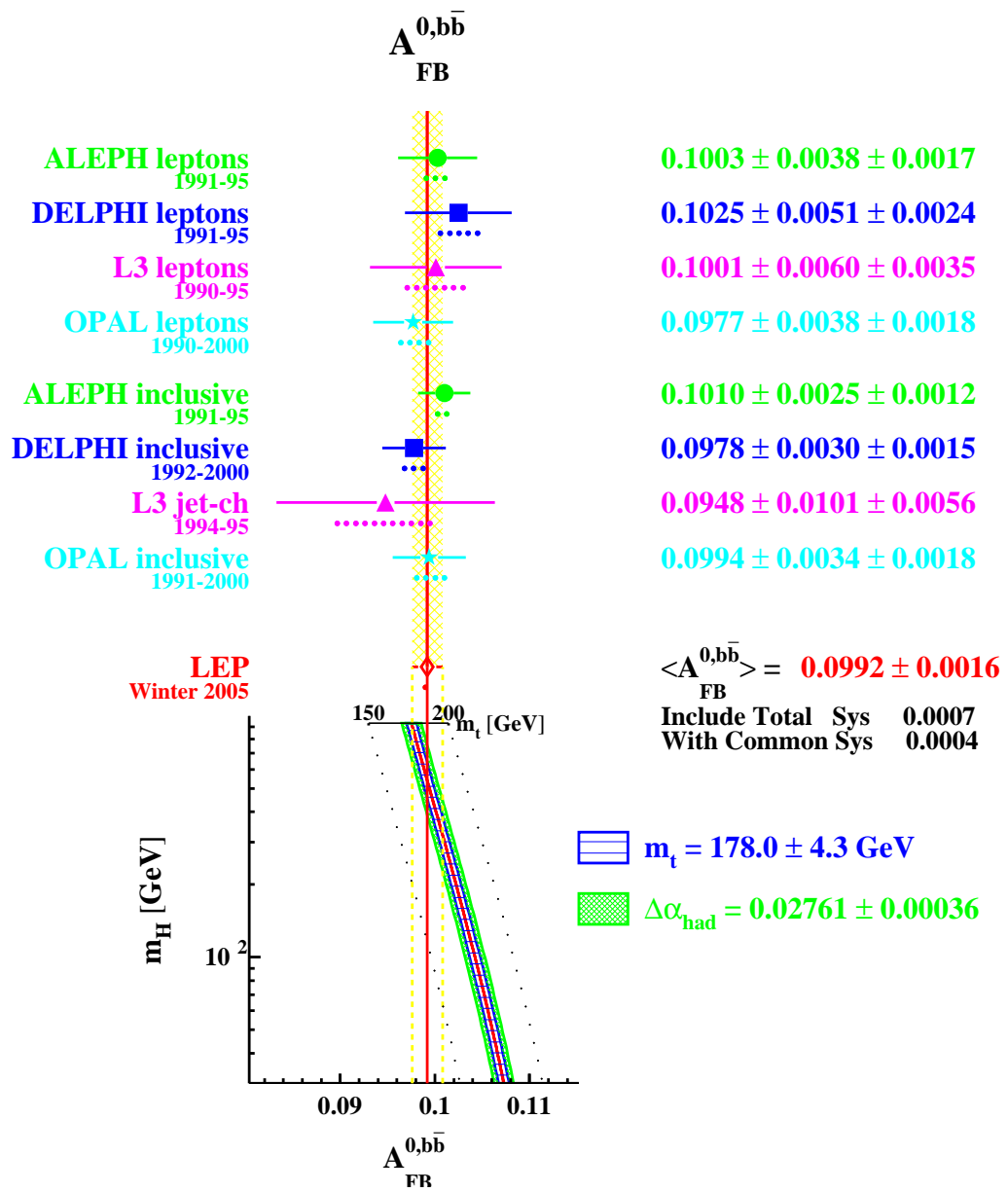
Quantity	Group(s)	Value	Standard Model	pull
$g_V^{\nu e}$	CHARM II	-0.035 ± 0.017	-0.0398 ± 0.0003	—
$g_V^{\nu e}$	all	-0.041 ± 0.015		-0.1
$g_A^{\nu e}$	CHARM II	-0.503 ± 0.017	-0.5065 ± 0.0001	—
$g_A^{\nu e}$	all	-0.507 ± 0.014		0.0
$Q_W(\text{Cs})$	Boulder	-72.69 ± 0.44	-73.10 ± 0.04	0.8
$Q_W(\text{Tl})$	Oxford/Seattle	-116.6 ± 3.7	-116.7 ± 0.1	0.0
$10^3 \frac{\Gamma(b \rightarrow s\gamma)}{\Gamma_{SL}}$	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
$10^4 \Delta\alpha_{\text{had}}^{(3)}$	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

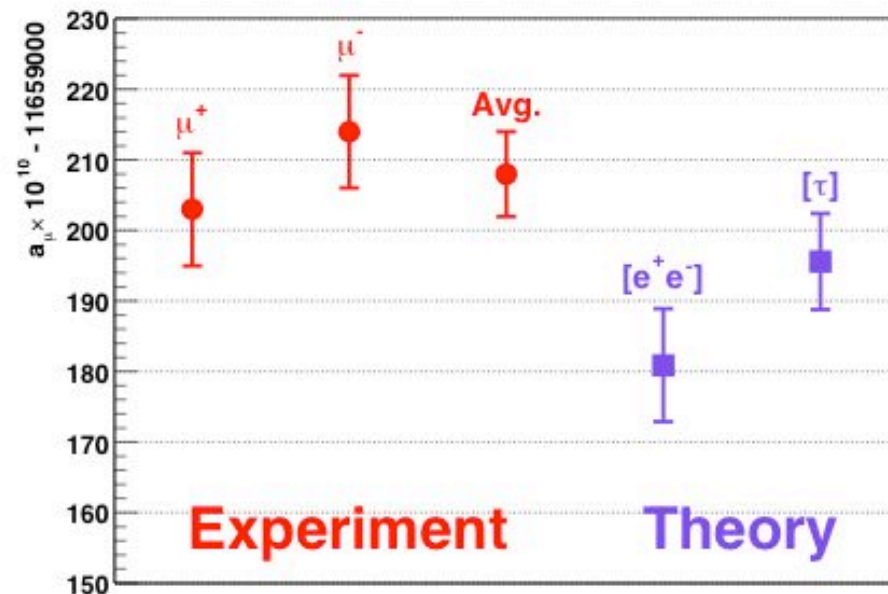
- New CDF m_t from Run II (lepton + jets)
 - $m_t = 173.5_{-4.0}^{+4.1}$ GeV, lower than previous Tevatron average 178.0 ± 4.3 GeV (dominated by reanalysis of D \emptyset Run)
 - More precise than previous average
 - Will lower the M_H prediction



- $A_{FB}^b = 0.0995(17)$ 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
 - $A_{FB}^b = \frac{3}{4}A_l A_b$; A_b agrees with SM, A_l (SLC) is 1.9σ high
 - New physics in A_{FB}^b would require compensation of L and R couplings (to preserve R_b)
 - 5% effect, but $\sim 25\%$ in $\kappa \rightarrow$ 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 $-4/3$



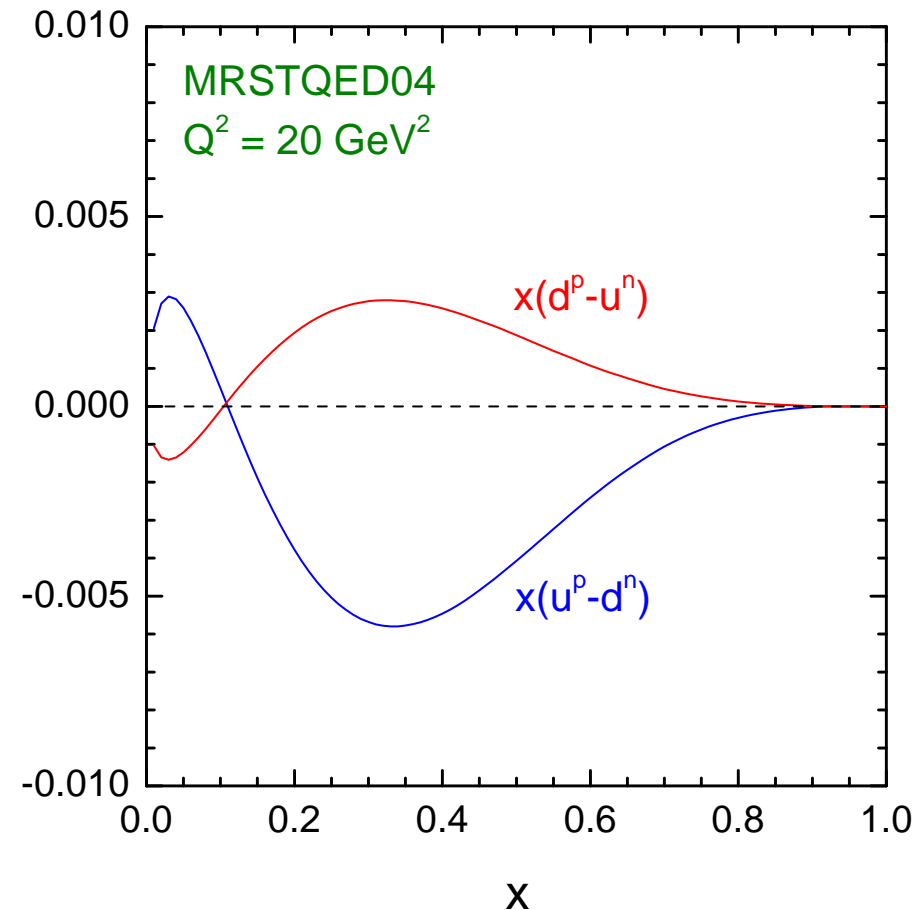
- $a_\mu = (g_\mu - 2)/2$
 - More sensitive than a_e to new physics
 - BNL (2004) + other: $a_\mu^{\text{exp}} = 11659208(6) \times 10^{-10}$
 - Hadronic light by light has settled down, but considerable uncertainty from a_μ^{Had}
 - $a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (24 \pm 10) \times 10^{-10}$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

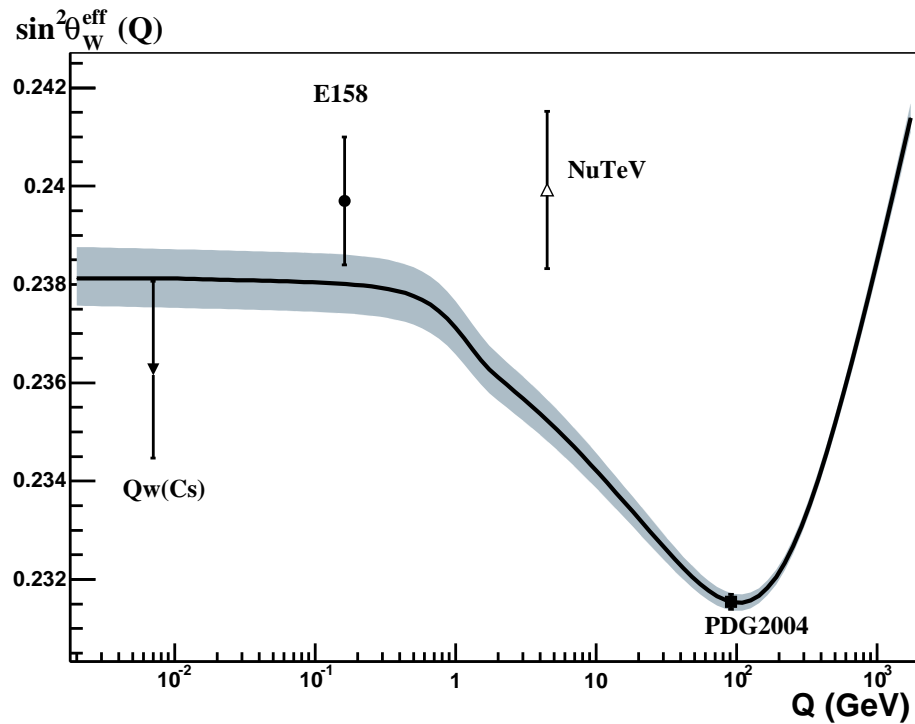


- NuTeV

$$\frac{\langle \bar{\nu} \rangle_{\mu} N \rightarrow \langle \bar{\nu} \rangle_{\mu} X}{\langle \bar{\nu} \rangle_{\mu} N \rightarrow \mu^{\mp} X}$$

- Little c threshold uncertainty
- $s_W^2 = 0.2277(16)$, 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 $Q^2 = 0.026 \text{ GeV}^2$

- 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:
 $Q_W(\text{Cs}) = -72.69(48)$ (SM: $-73.19(3)$)

- CKM Unitarity

- Expect $\Delta \equiv 1 - |V_{ud}|^2 - |V_{us}|^2 - |V_{ub}|^2 = 0$
- PDG 2002: $\Delta = 0.0042 \pm 0.0019$
- Superaligned ($0^+ \rightarrow 0^+$): $|V_{ud}| = 0.9740(5)$ 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

$$M_H = 113_{-40}^{+56} \text{ GeV},$$

$$m_t = 176.9 \pm 4.0 \text{ GeV},$$

$$\alpha_s = 0.1213 \pm 0.0018,$$

$$\hat{\alpha}(M_Z)^{-1} = 127.906 \pm 0.019$$

$$\hat{s}_Z^2 = 0.23120 \pm 0.00015,$$

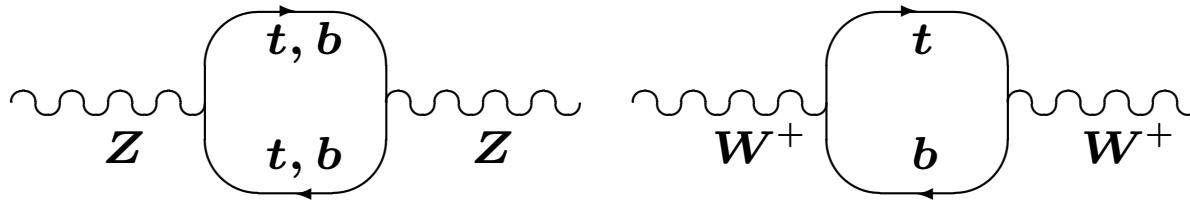
$$s_W^2 = 0.22280 \pm 0.00035$$

$$\Delta\alpha_{\text{had}}^{(5)}(M_Z) = 0.02801 \pm 0.00015$$

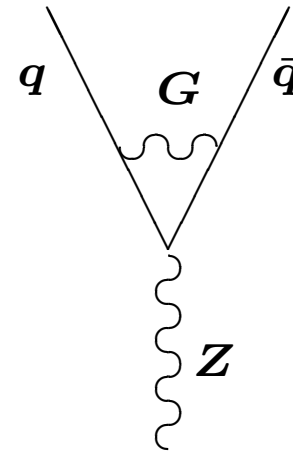
- $m_t = 176.9 \pm 4.0$ GeV

- $172.4_{-7.3}^{+9.8}$ GeV from indirect (loops) only (direct: 178.0 ± 4.3)

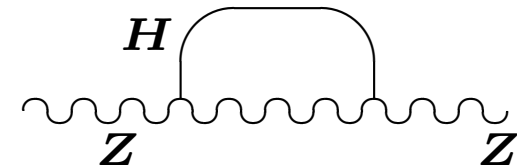
- New CDF Run II, $m_t = 173.5_{-4.0}^{+4.1}$ GeV, *not included*

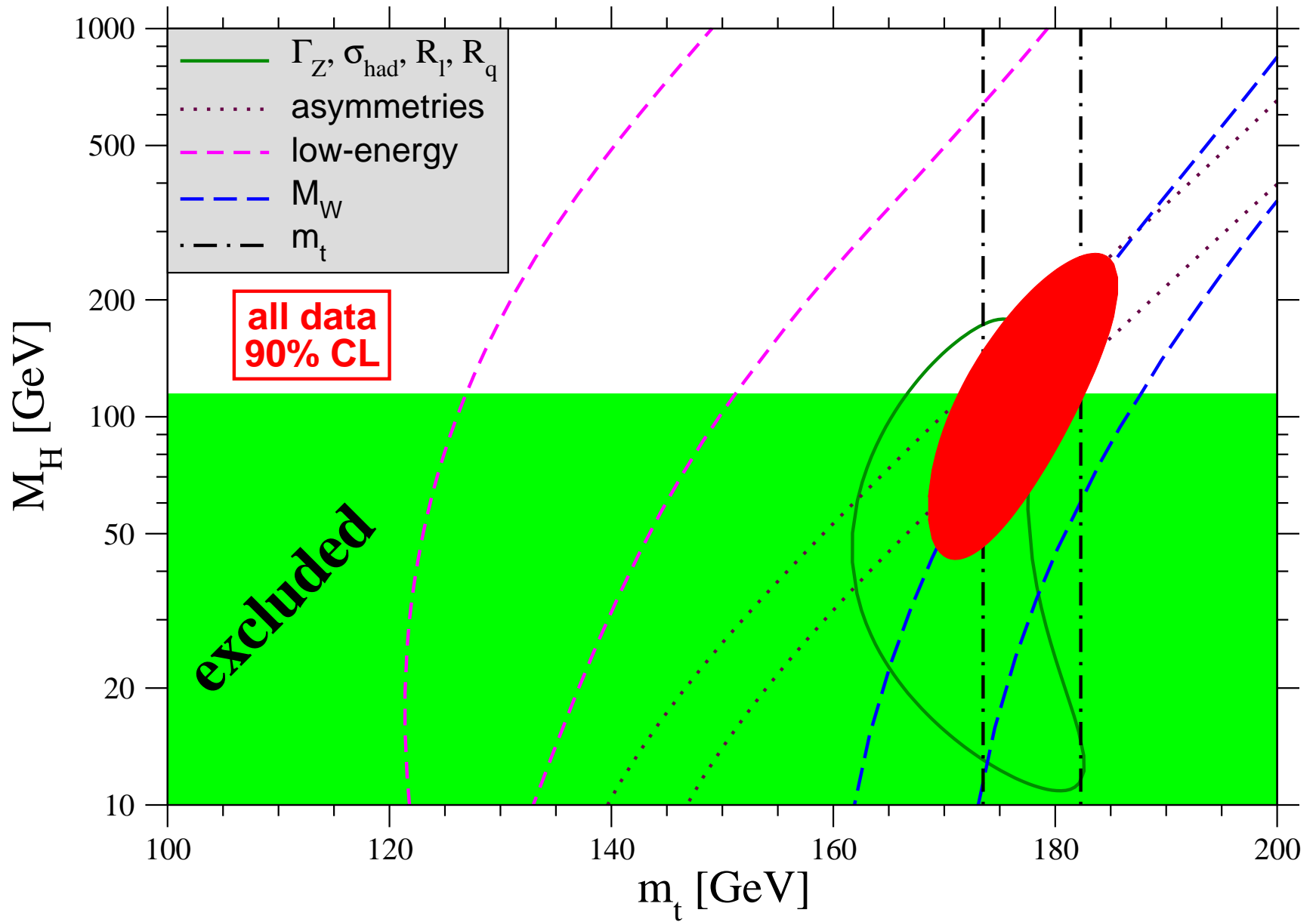


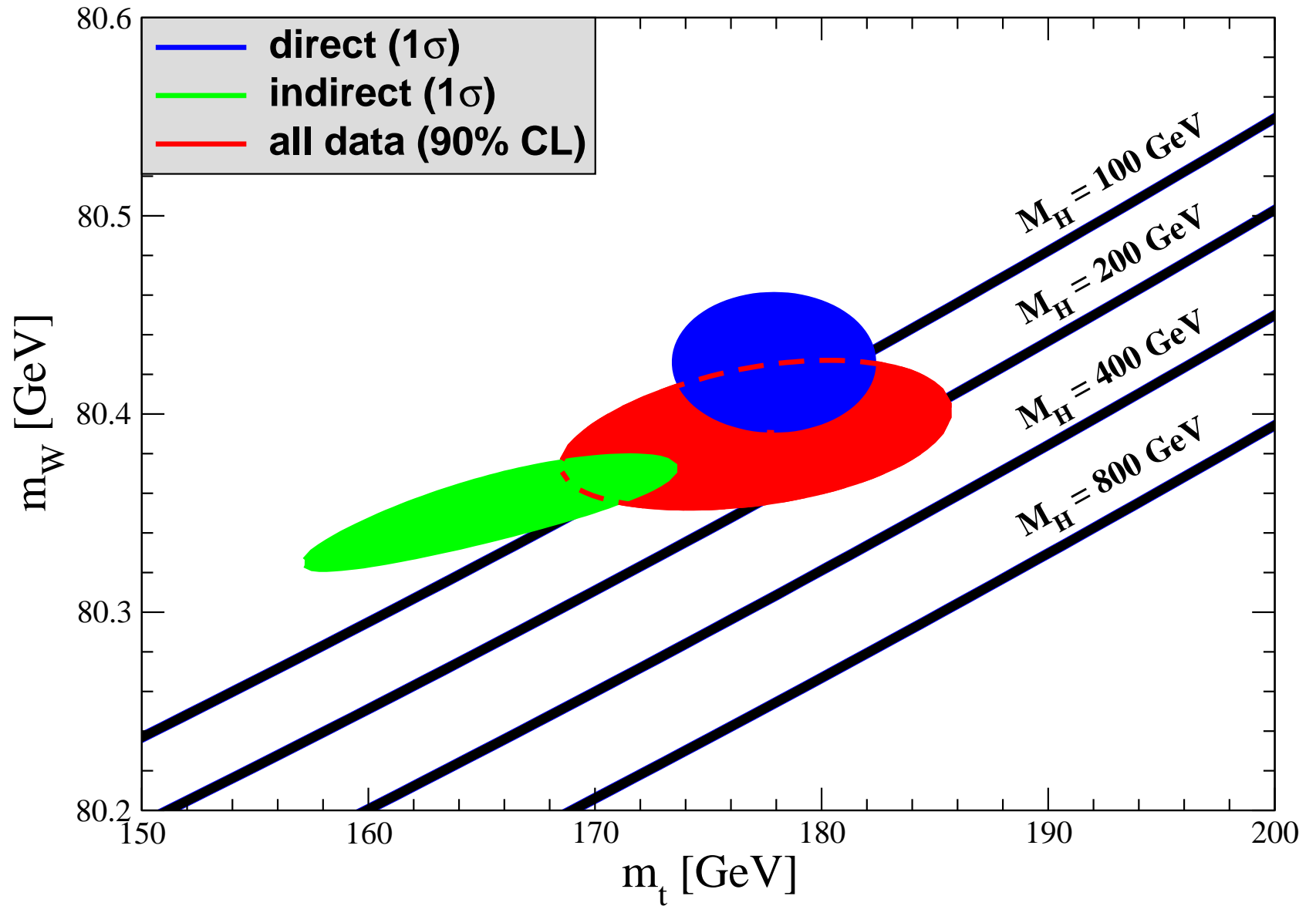
- $\alpha_s = 0.1213 \pm 0.0018$
 - Higher than $\alpha_s = 0.1187(20)$ (Hinchliffe (PDG) 2004), because of τ lifetime
 - insensitive to oblique new physics
 - very sensitive to non-universal new physics (e.g., $Zb\bar{b}$ vertex)

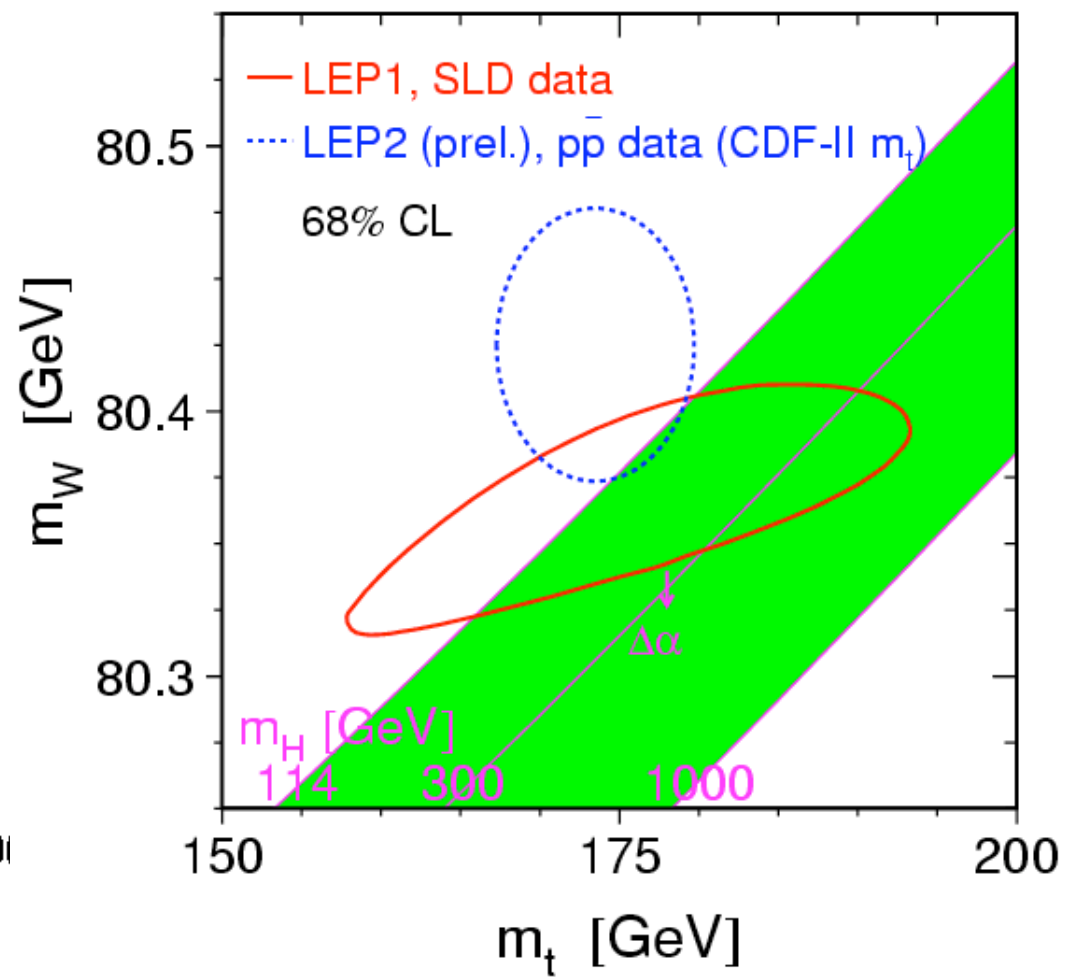
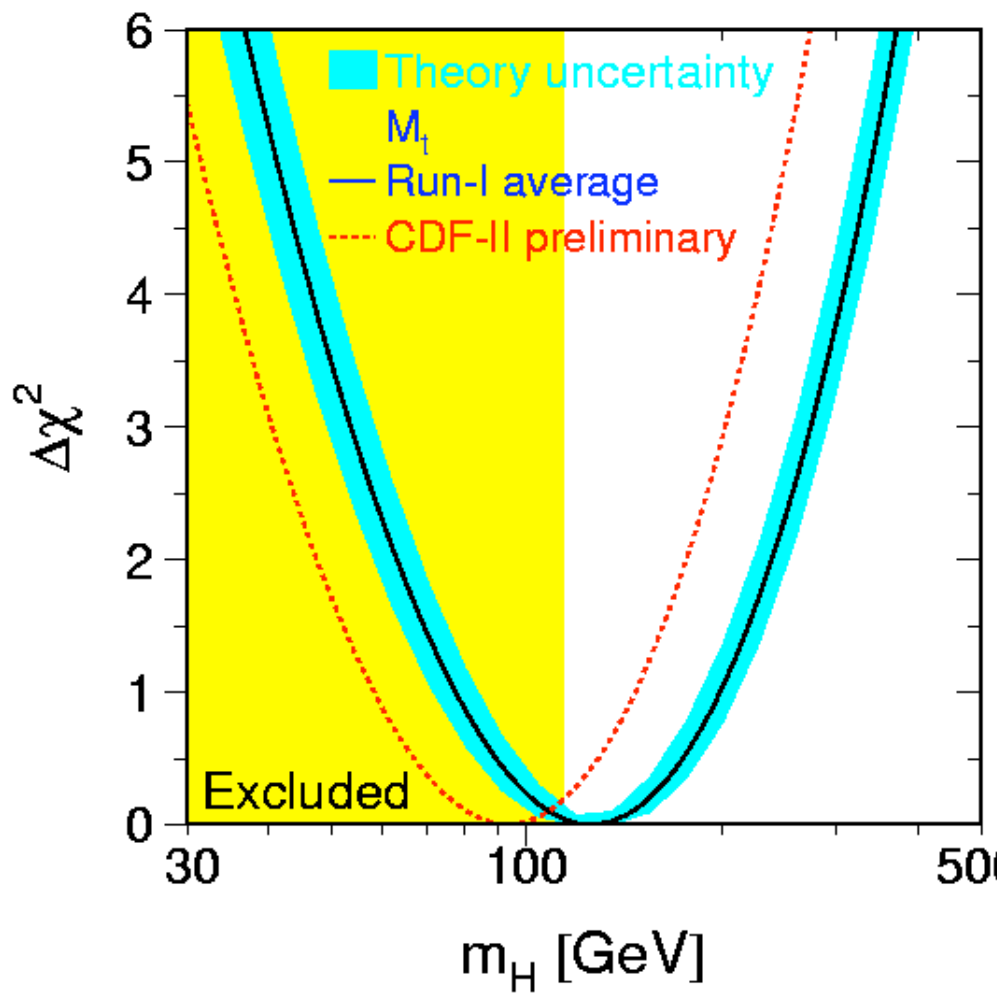


- Higgs mass $M_H = 113_{-40}^{+56}$ GeV
 - LEPWWG (12/94): 114_{-45}^{+69}
 - direct limit (LEP 2): $M_H \gtrsim 114.4$ (95%) GeV
 - SM: 115 (vac. stab.) $\lesssim M_H \lesssim 750$ (triviality)
 - MSSM: $M_H \lesssim 130$ GeV (150 in extensions)
 - indirect: $\ln M_H$ but significant
 - * fairly robust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









Beyond the standard model

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

$$S = -0.13 \pm 0.10(-0.08)$$

$$T = -0.17 \pm 0.12(+0.09)$$

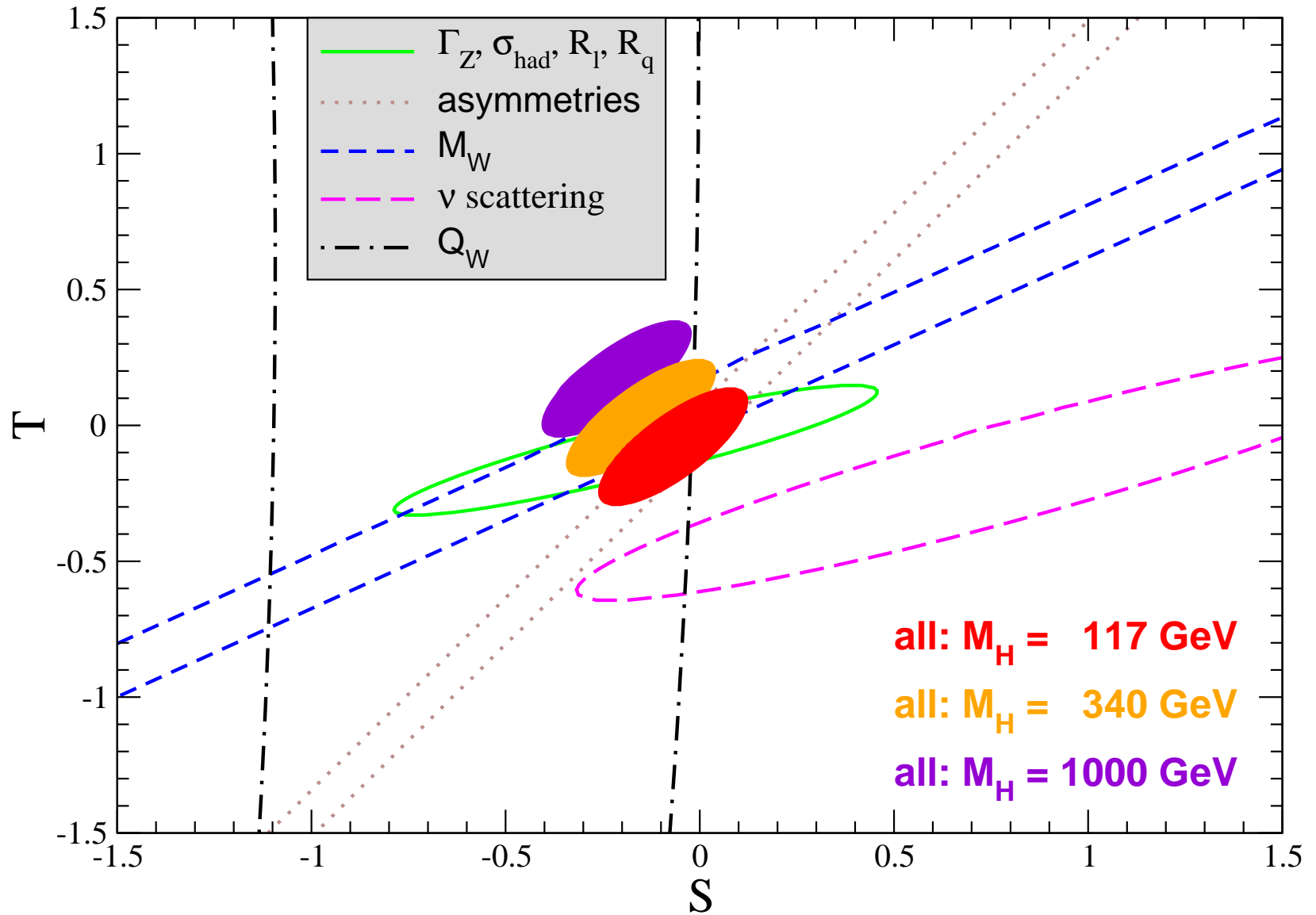
$$U = 0.22 \pm 0.13(+0.01)$$

for $M_H = 117$ (300) GeV

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

Oblique Parameters

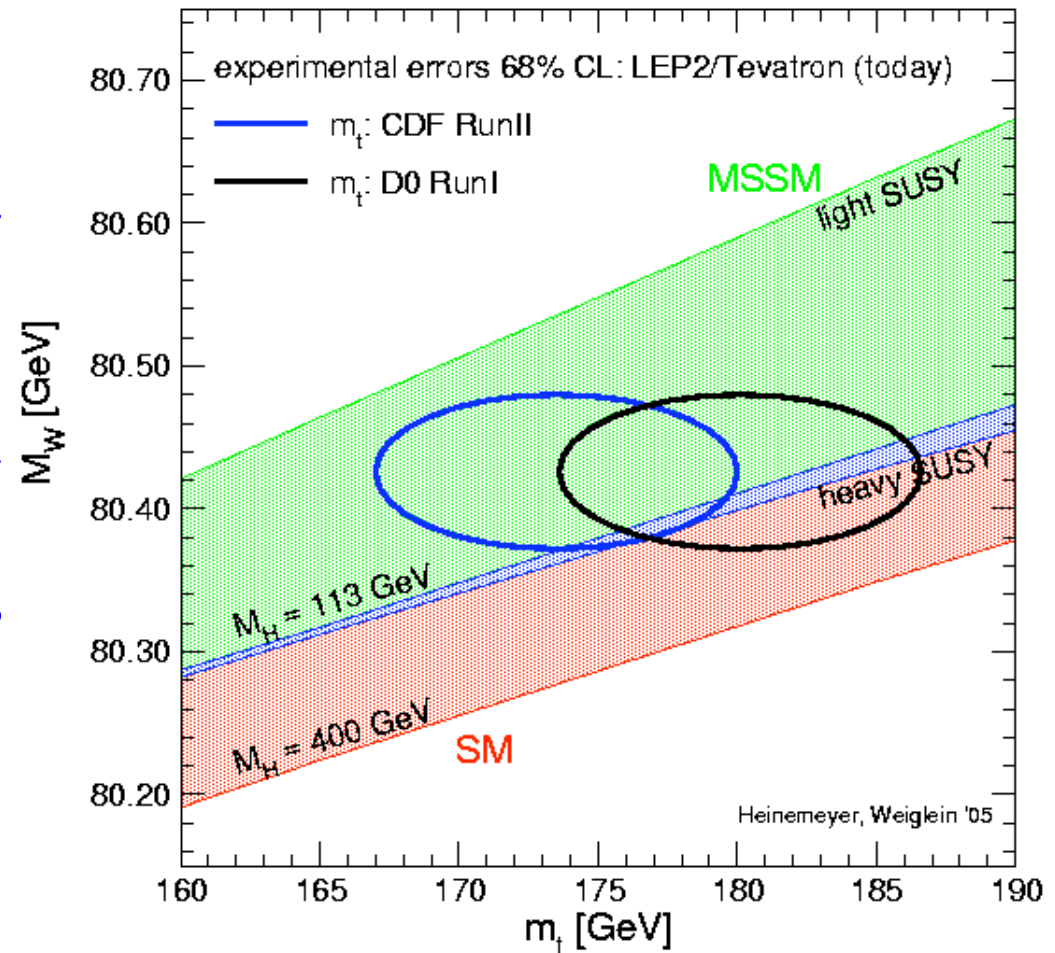
constraints on gauge boson self-energies



- **Supersymmetry**

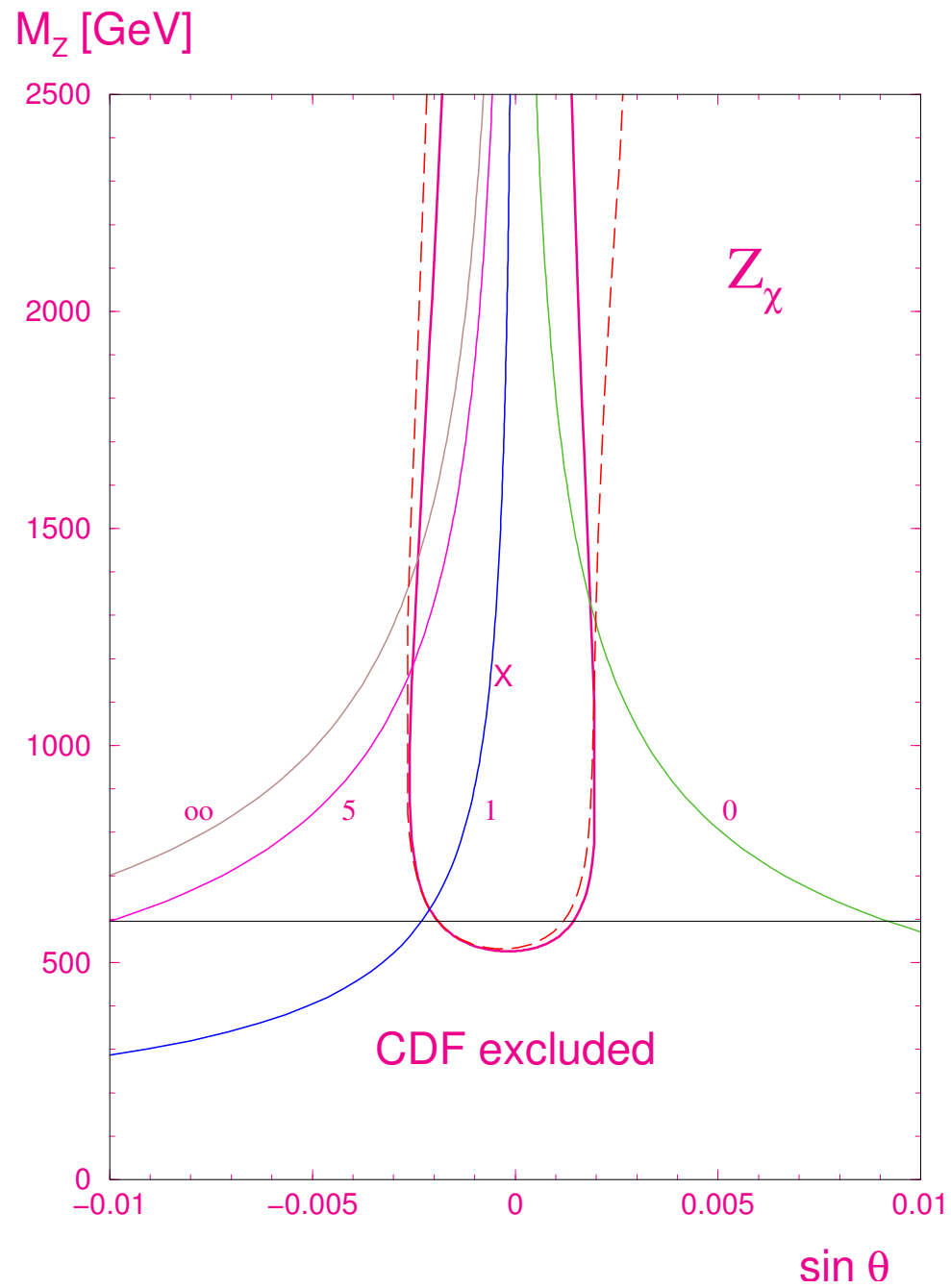
- decoupling limit ($M_{new} \gtrsim 200 - 300 \text{ GeV}$): only precision effect is light SM-like Higgs
- little improvement on SM fit
- SUSY parameters constrained

parameters



- 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)

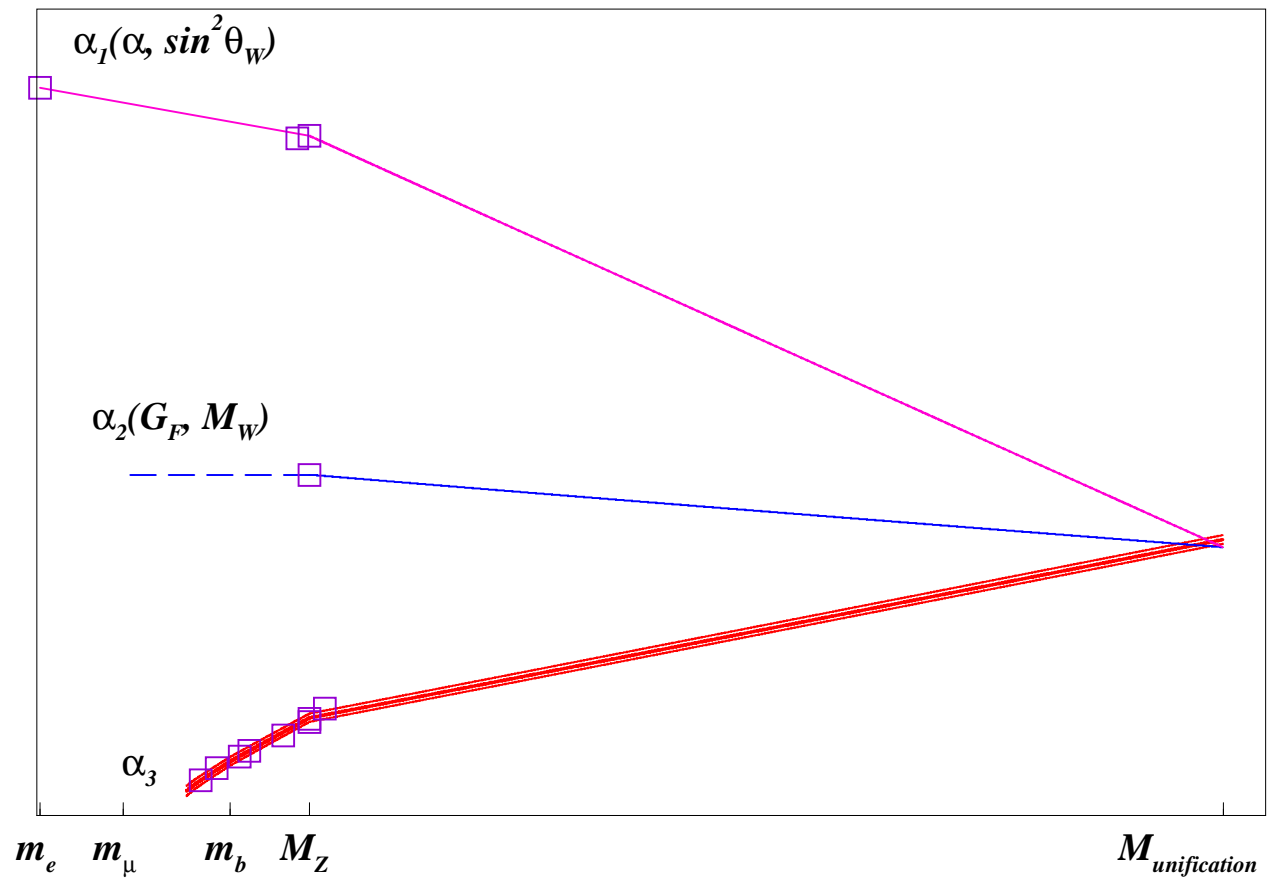


- Other

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

- Gauge unification: GUTs, string theories

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



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)