The Electro-Weak Sector

- **Precision Experiments “before” LEP**
- **LEP Physics**
- **Probing the Standard Model**
- **Beyond the Standard Model**

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CERN, LEP Fest
11 October, 2000

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
- 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
- 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)

Results before the LEP era

- Global Analysis
  - more information than individual experiments
  - caveat: exp./theor. systematics, correlations
- model-independent fits
  - Unique νq, νe, eq
    - SM correct to first approximation
    - Contrived imitators out
- QCD evolved structure functions
- Radiative corrections necessary ($\sin^2\theta_W$ defns)
- $\sin^2\theta_W = .230 \pm 0.007$, $m_t < 200$ GeV
- Unique fermion reps. (wnc + wcc)
- t exists
- Grand unification
  - Ordinary SU_5 excluded; "consistent with SUSY GUTS and perhaps even the first harbinger of supersymmetry"
- Stringent limits on new physics
- Z', exotic fermions, exotic Higgs, leptoquarks, 4-F operators

The LEP 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; SLC (SLAC), 5×10^5, $P_{e^-} \sim 75$ %
- Z pole observables
  - lineshape: M_Z, Γ_Z, σ
  - branching ratios
    - $e^+e^-, \mu^+\mu^-, \tau^+\tau^-$
    - $q\bar{q}, c\bar{c}, b\bar{b}, s\bar{s}$
    - $\nu\bar{\nu} \Rightarrow N_\nu = 2.985 \pm 0.008$ if $m_\nu < M_Z/2$
  - asymmetries: FB, polarization, P_τ, mixed
  - lepton family universality
- 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); M_W, m_t (Tevatron)

The Z Lineshape

- $e^+e^- \longrightarrow f\bar{f}$ ($f = e, \mu, \tau, s, b, c,$ hadrons); $s = E_{CM}^2$

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

(plus initial state rad. corrections)

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

$$\begin{aligned} \Gamma(\text{inv}) &= \Gamma_Z - \Gamma(\text{had}) - \sum_i \Gamma(\ell_i \bar{\ell}_i) \\ &\equiv N_\nu \Gamma(\nu\bar{\nu}) \end{aligned}$$

$$R_{q_i} \equiv \frac{\Gamma(q_i\bar{q}_i)}{\Gamma(\text{had})}, \quad q_i = b, c, s$$

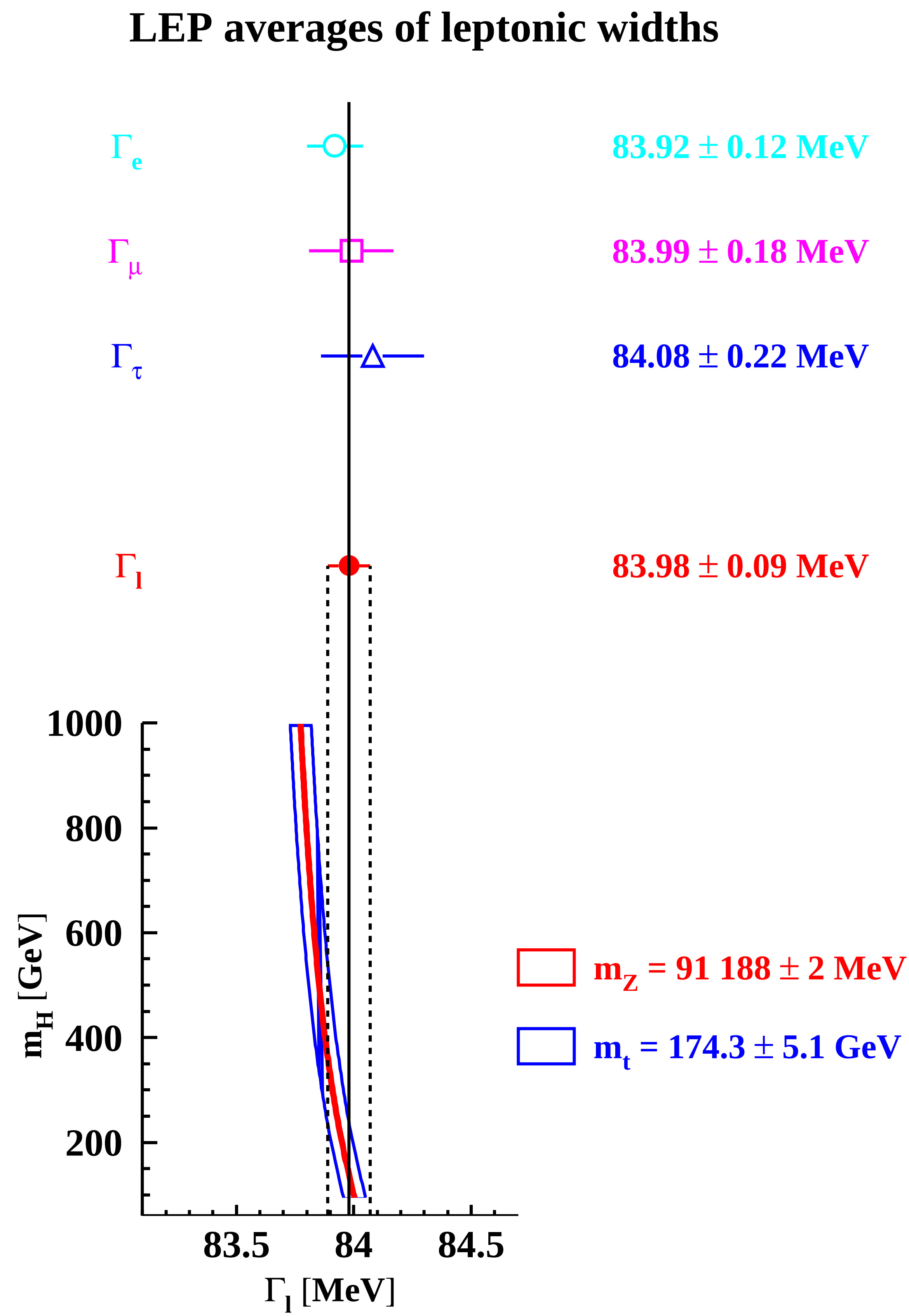
$$R_{\ell_i} \equiv \frac{\Gamma(\text{had})}{\Gamma(\ell_i\bar{\ell}_i)}, \quad \ell_i = e, \mu, \tau$$

($R_e = R_\mu = R_\tau \equiv R_\ell \longrightarrow$ lepton universality)

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

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

- $M_Z, \Gamma_Z, \sigma_{\text{had}}, R_\ell, R_b, R_c$ mainly weakly correlated


LEP averages of leptonic widths
Γe
83.92 ± 0.12 MeV
Γμ
83.99 ± 0.18 MeV
Γτ
84.08 ± 0.22 MeV
Γl
83.98 ± 0.09 MeV
1000
800
600
400
200
mH [GeV]
83.5
84
84.5
Γl [MeV]
mZ = 91 188 ± 2 MeV
mt = 174.3 ± 5.1 GeV

Z-Pole Asymmetries

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

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

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

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

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

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

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

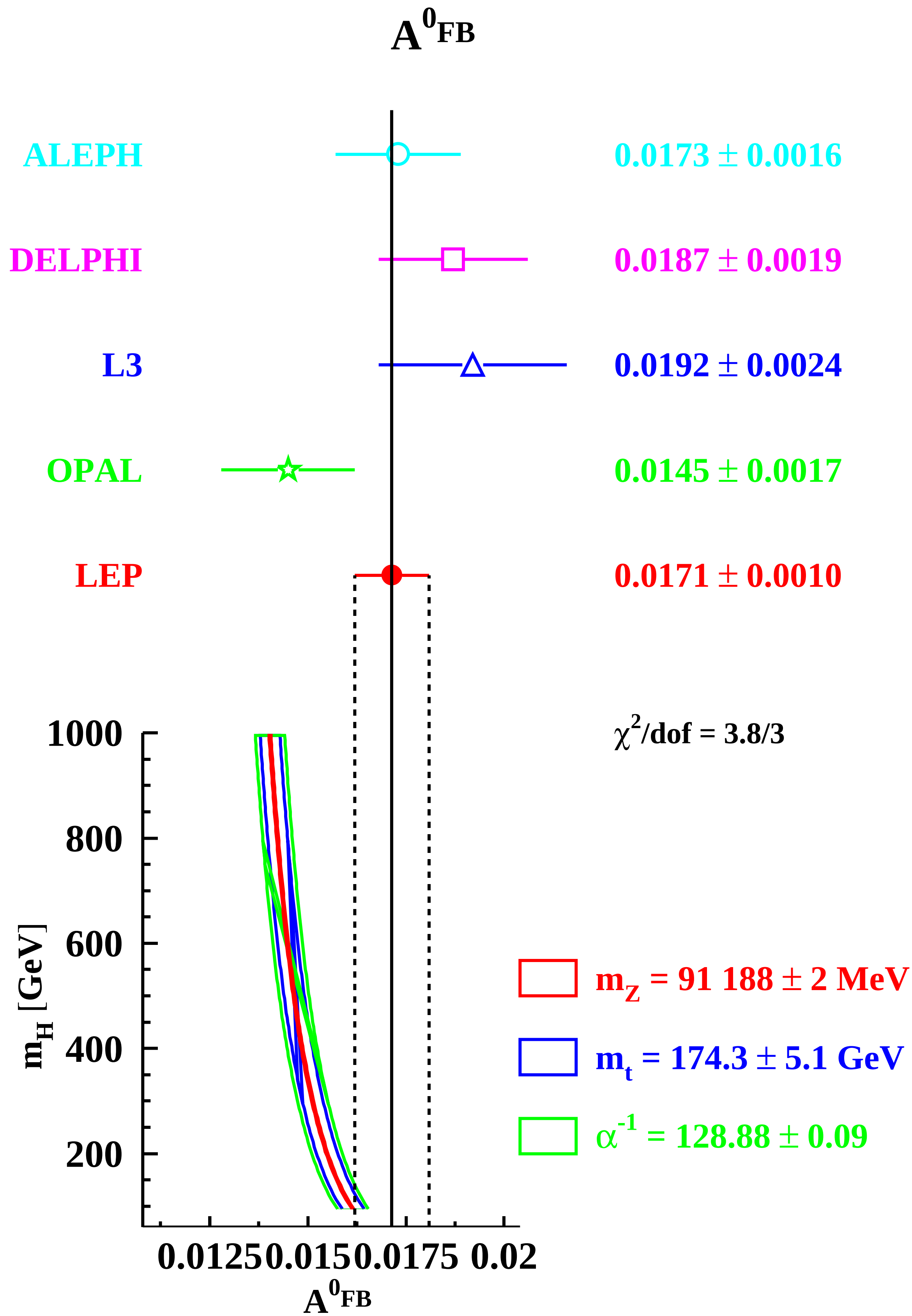
$$A_f \equiv \frac{2 \bar{g}_{VF} \bar{g}_{Af}}{\bar{g}_{VF}^2 + \bar{g}_{AF}^2}$$

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

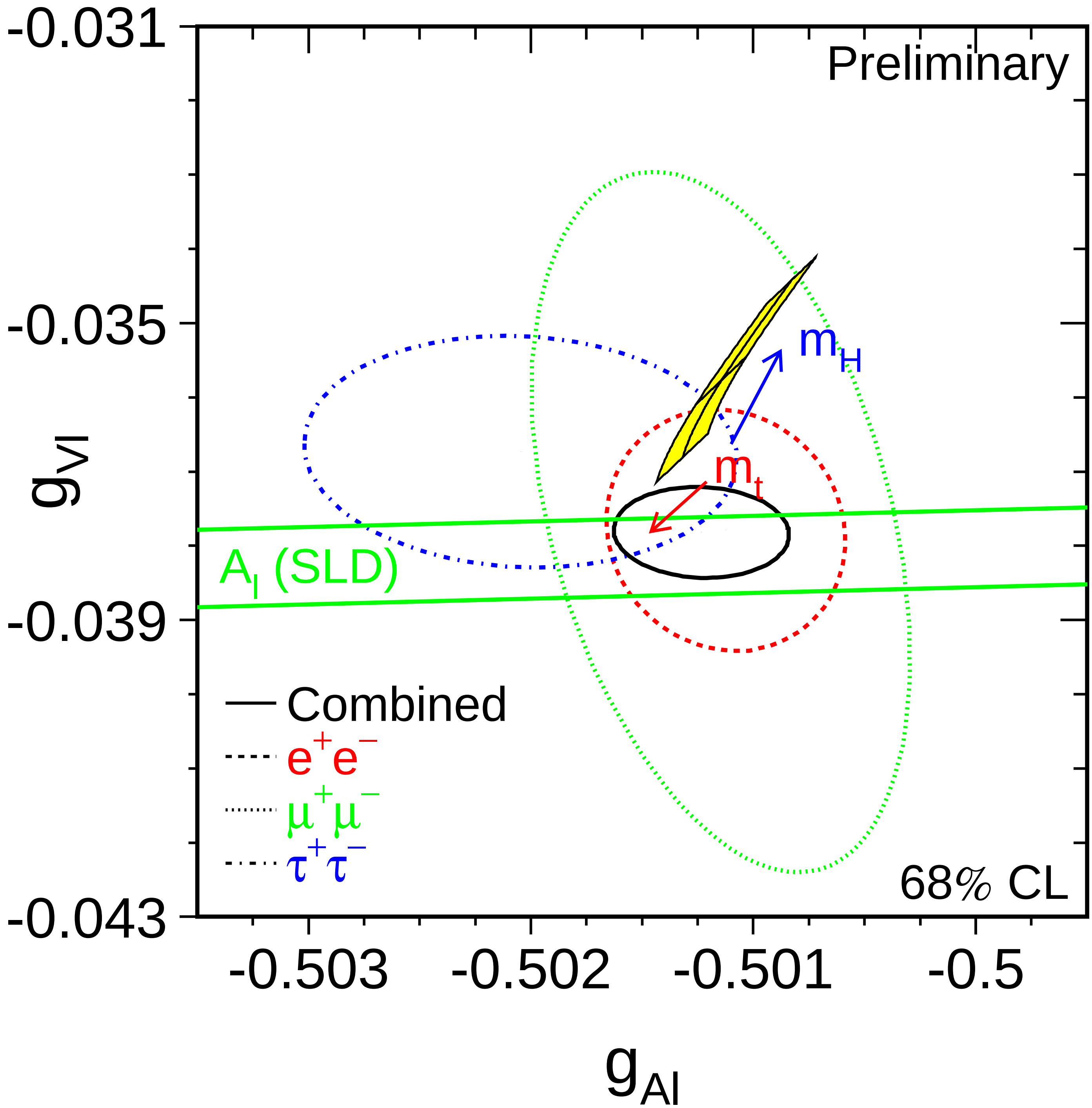
where $\bar{s}_f^2$ the effective weak angle,

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

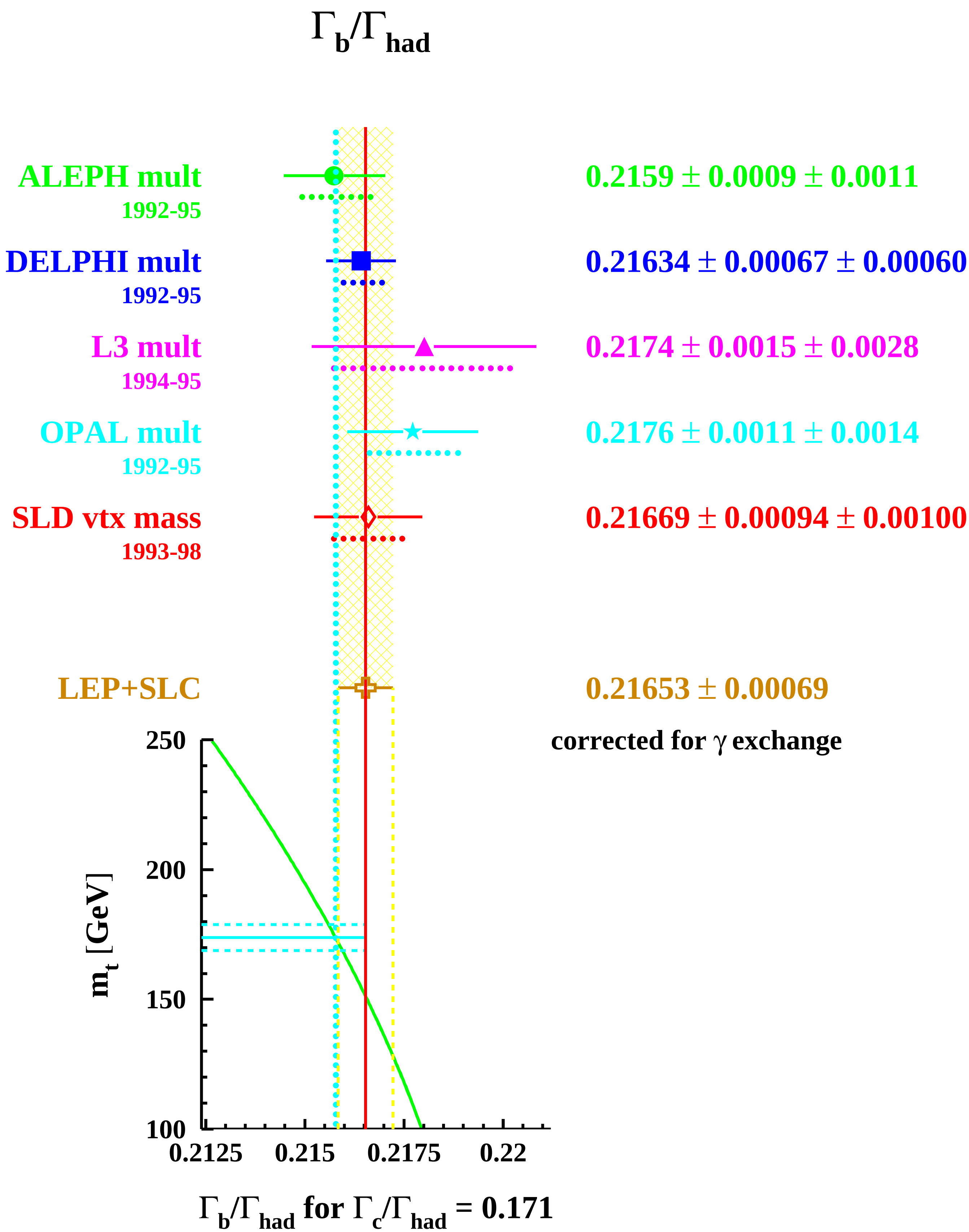
ρ_f, κ_f, and $\hat{\kappa}_f$ are electroweak corrections, q_f = electric charge, t_{3f} = weak isospin

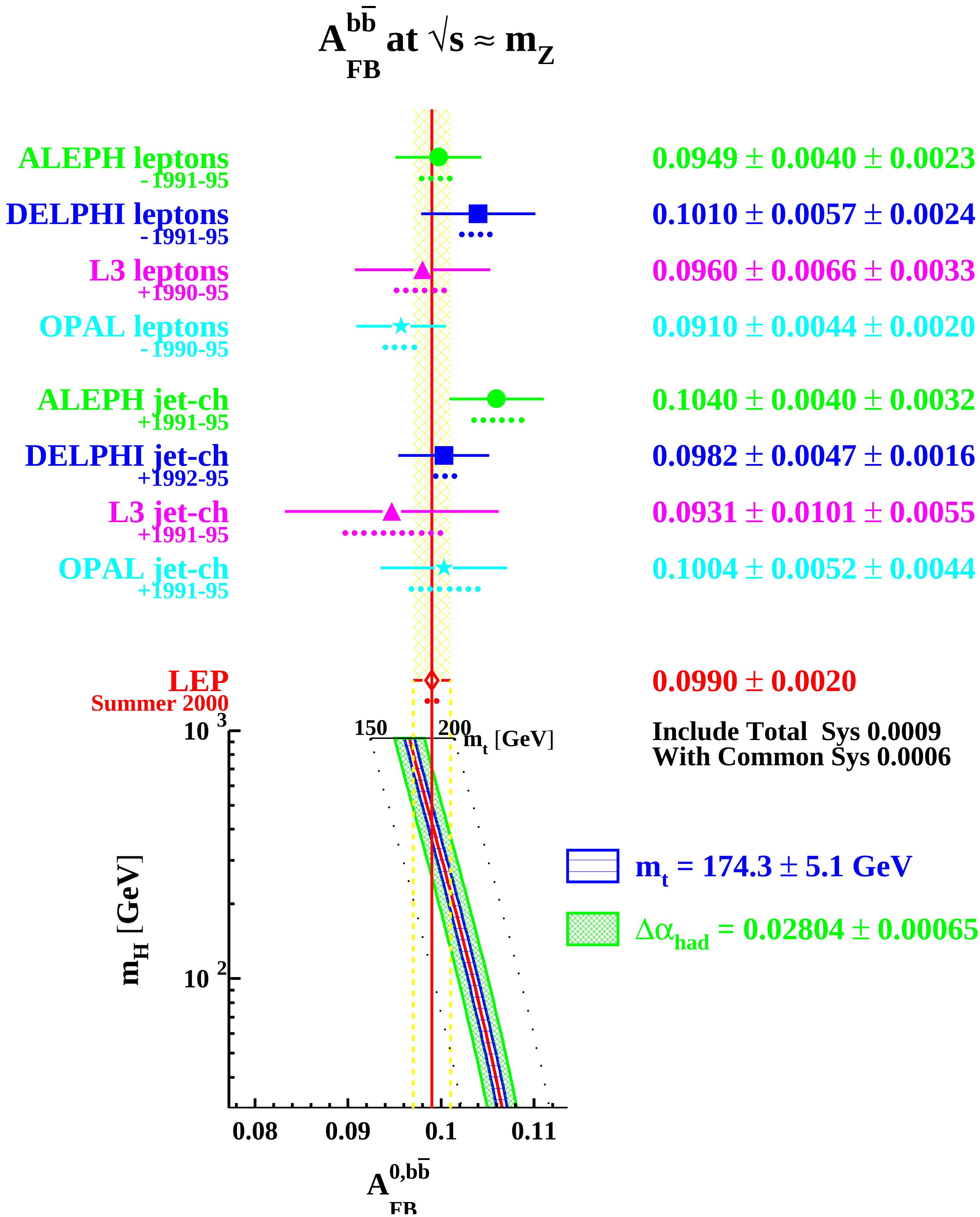


A^0_{FB}
ALEPH
0.0173 ± 0.0016
DELPHI
0.0187 ± 0.0019
L3
0.0192 ± 0.0024
OPAL
0.0145 ± 0.0017
LEP
0.0171 ± 0.0010
χ^2/dof = 3.8/3
1000
800
600
400
200
m_H [GeV]
m_Z = 91 188 ± 2 MeV
m_t = 174.3 ± 5.1 GeV
α^{-1} = 128.88 ± 0.09
0.0125
0.015
0.0175
0.02
A^0_{FB}



-0.031
-0.035
-0.039
-0.043
-0.503
-0.502
-0.501
-0.5
g_Vl
g_Al
Preliminary
m_H
m_t
A_l (SLD)
Combined
e+e−
μ+μ−
τ+τ−
68% CL

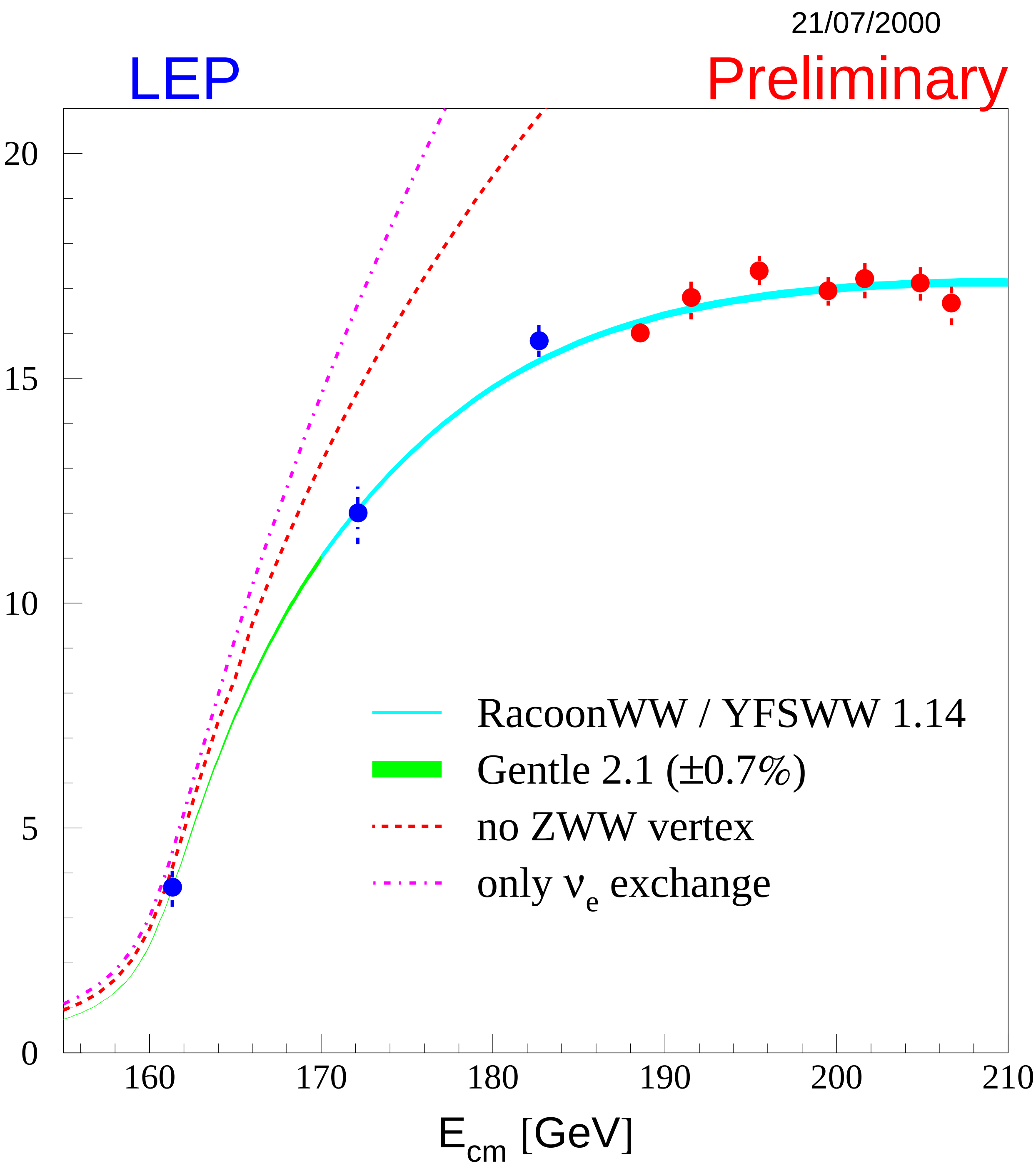

Γb/Γhad
ALEPH mult
1992-95
0.2159 ± 0.0009 ± 0.0011
DELPHI mult
1992-95
0.21634 ± 0.00067 ± 0.00060
L3 mult
1994-95
0.2174 ± 0.0015 ± 0.0028
OPAL mult
1992-95
0.2176 ± 0.0011 ± 0.0014
SLD vtx mass
1993-98
0.21669 ± 0.00094 ± 0.00100
LEP+SLC
0.21653 ± 0.00069
corrected for γ exchange
250
200
150
100
mt [GeV]
0.2125
0.215
0.2175
0.22
Γb/Γhad for Γc/Γhad = 0.171



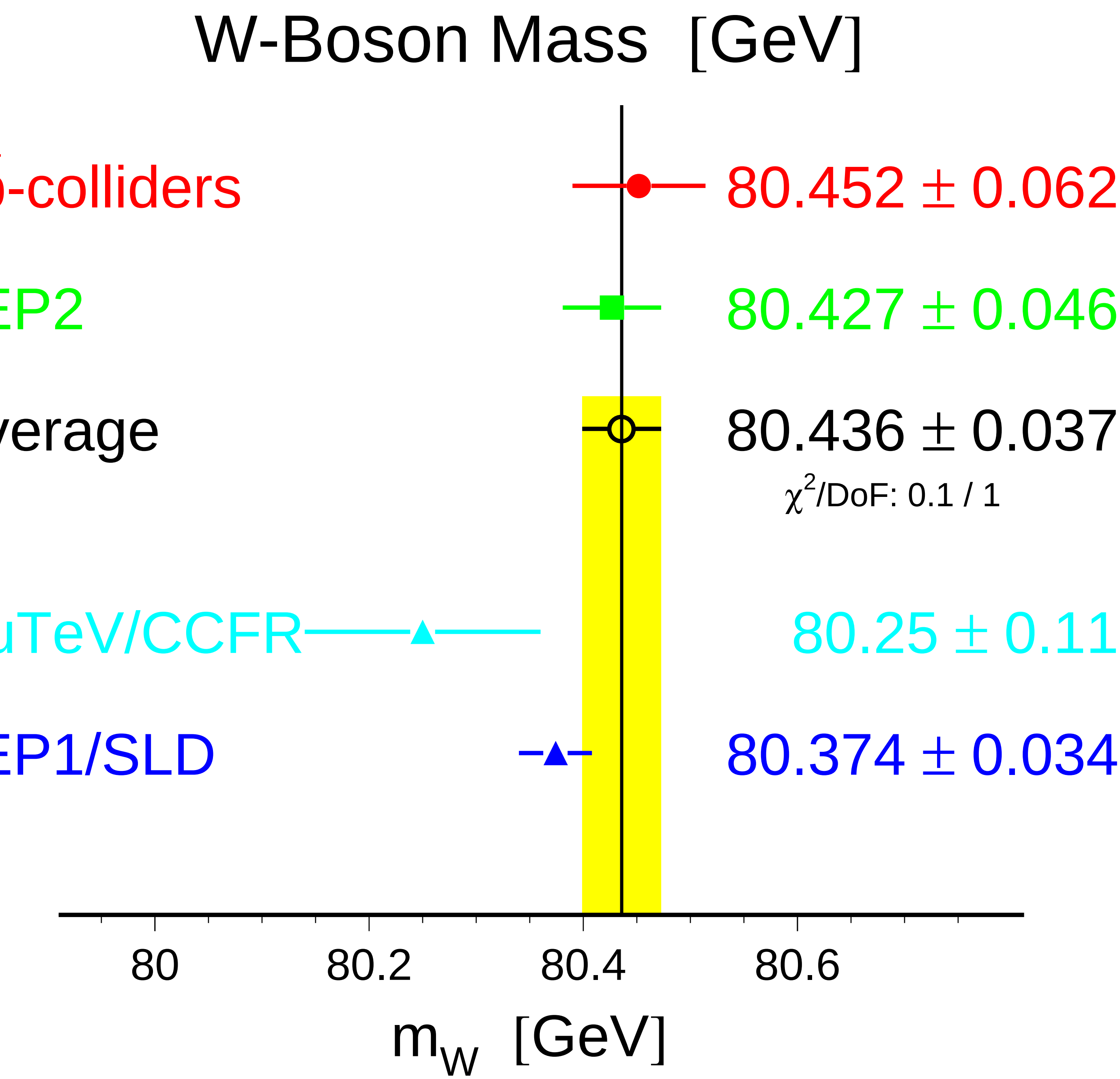
$A_{FB}^{b\bar{b}}$ at $\sqrt{s} \approx m_Z$
ALEPH leptons
-1991-95
0.0949 ± 0.0040 ± 0.0023
DELPHI leptons
-1991-95
0.1010 ± 0.0057 ± 0.0024
L3 leptons
+1990-95
0.0960 ± 0.0066 ± 0.0033
OPAL leptons
-1990-95
0.0910 ± 0.0044 ± 0.0020
ALEPH jet-ch
+1991-95
0.1040 ± 0.0040 ± 0.0032
DELPHI jet-ch
+1992-95
0.0982 ± 0.0047 ± 0.0016
L3 jet-ch
+1991-95
0.0931 ± 0.0101 ± 0.0055
OPAL jet-ch
+1991-95
0.1004 ± 0.0052 ± 0.0044
LEP
Summer 2000
0.0990 ± 0.0020
Include Total Sys 0.0009
With Common Sys 0.0006
150
200
m_t [GeV]
10^3
10^2
m_H [GeV]
m_t = 174.3 ± 5.1 GeV
$\Delta\alpha_{had}$ = 0.02804 ± 0.00065
0.08
0.09
0.1
0.11
$A_{FB}^{0,b\bar{b}}$

The Z Pole Observables: LEP and SLC

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	2.4963 ± 0.0016	−0.5
$\Gamma(\text{had})$ [GeV]	LEP	1.7444 ± 0.0020	1.7427 ± 0.0015	—
$\Gamma(\text{inv})$ [MeV]	LEP	499.0 ± 1.5	501.74 ± 0.15	—
$\Gamma(\ell^+\ell^-)$ [MeV]	LEP	83.984 ± 0.086	84.018 ± 0.028	—
σ_{had} [nb]	LEP	41.541 ± 0.037	41.479 ± 0.014	1.7
R_e	LEP	20.804 ± 0.050	20.743 ± 0.018	1.2
R_μ	LEP	20.785 ± 0.033	20.743 ± 0.018	1.3
R_τ	LEP	20.764 ± 0.045	20.788 ± 0.018	−0.5
$A_{FB}(e)$	LEP	0.0145 ± 0.0025	0.0165 ± 0.0003	−0.8
$A_{FB}(\mu)$	LEP	0.0169 ± 0.0013		0.3
$A_{FB}(\tau)$	LEP	0.0188 ± 0.0017		1.4
R_b	LEP + SLD	0.21653 ± 0.00069	0.21572 ± 0.00015	1.2
R_c	LEP + SLD	0.1709 ± 0.0034	0.1723 ± 0.0001	−0.4
$R_{s,d}/R_{(d+u+s)}$	OPAL	0.371 ± 0.023	0.3592 ± 0.0001	0.5
$A_{FB}(b)$	LEP	0.0990 ± 0.0020	0.1039 ± 0.0009	−2.5
$A_{FB}(c)$	LEP	0.0689 ± 0.0035	0.0743 ± 0.0007	−1.5
$A_{FB}(s)$	DELPHI,OPAL	0.0976 ± 0.0114	0.1040 ± 0.0009	−0.6
A_b	SLD	0.922 ± 0.023	0.9348 ± 0.0001	−0.6
A_c	SLD	0.631 ± 0.026	0.6683 ± 0.0005	−1.4
A_s	SLD	0.82 ± 0.13	0.9357 ± 0.0001	−0.4
A_{LR} (hadrons)	SLD	0.15138 ± 0.00216	0.1483 ± 0.0012	1.4
A_{LR} (leptons)	SLD	0.1544 ± 0.0060		1.0
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 ± 0.0042		−1.0
$A_e(\mathcal{P}_\tau)$	LEP	0.1498 ± 0.0048		0.3
$\bar{s}_\ell^2(Q_{FB})$	LEP	0.2321 ± 0.0010	0.23136 ± 0.00015	0.7



21/07/2000
LEP
Preliminary
20
15
10
5
0
160
170
180
190
200
210
RacoonWW / YFSWW 1.14
Gentle 2.1 (±0.7%)
no ZWW vertex
only ν_e exchange
E_{cm} [GeV]


W-Boson Mass [GeV]
-colliders
80.452 ± 0.062
EP2
80.427 ± 0.046
verage
80.436 ± 0.037
χ2/DoF: 0.1 / 1
uTeV/CCFR
80.25 ± 0.11
EP1/SLD
80.374 ± 0.034
80
80.2
80.4
80.6
mW [GeV]

Non-Z Pole Precision Observables: Tevatron, LEP 2, νN, APV

Quantity	Group(s)	Value	Standard Model	pull
m_t [GeV]	Tevatron	174.3 ± 5.1	174.2 ± 4.4	0.0
M_W [GeV]	LEP	80.427 ± 0.046	80.394 ± 0.019	0.7
M_W [GeV]	Tevatron,UA2	80.451 ± 0.061		0.9
R^-	NuTeV	$0.2277 \pm 0.0021 \pm 0.0007$	0.2301 ± 0.0002	-1.1
R^ν	CCFR	$0.5820 \pm 0.0027 \pm 0.0031$	0.5834 ± 0.0004	-0.3
R^ν	CDHS	$0.3096 \pm 0.0033 \pm 0.0028$	0.3093 ± 0.0002	0.1
R^ν	CHARM	$0.3021 \pm 0.0031 \pm 0.0026$		-1.8
$R^{\bar\nu}$	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	$0.365 \pm 0.015 \pm 0.007$	0.3817 ± 0.0002	-1.0
$g_V^{\nu e}$	CHARM II	-0.035 ± 0.017	-0.0399 ± 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	$-72.65 \pm 0.28 \pm 0.34$	-73.08 ± 0.04	1.0
$Q_W(\text{Tl})$	Oxford,Seattle	$-114.8 \pm 1.2 \pm 3.4$	-116.6 ± 0.1	0.5
$\frac{\Gamma(b\to s\gamma)}{\Gamma(b\to ce\nu)}$	CLEO	$3.26^{+0.75}_{-0.68} \times 10^{-3}$	$3.15^{+0.21}_{-0.20} \times 10^{-3}$	0.1

- **LEP remarkably successful (beyond anticipation)**
  - **Machine**
  - **Detectors: ALEPH, DELPHI, L3, OPAL (LEP); SLD (SLC)**
  - **Analysis: tides, water table/lake, trains**
  - **LEPEWWG critical**
  - **Theoretical inputs**
    - **precise QED, EW, QCD, mixed radiative corrections**
    - **$\sin^2\theta_W$ definitions**
    - **$\alpha_{\rm had}$ (running α)**
    - **Packages: ZFITTER, TOPAZ0, ALIBABA, BHLUMI, GAPP, (LEP2)**
    - **new physics parametrizations**
  - **Global analyses: LEPEWWG, PDG, $\cdots$**
  - **Polarization: SLC advantage; (Blondel scheme)**
- **Future: GigaZ ?**

Radiative Corrections

- Dominant two-loop electroweak ($\alpha^2 m_t^4,\ \alpha^2 m_t^2$)
- Dominant 3 loop QCD (4 loop estimate)
- Dominant 3 loop mixed QCD-EW ($\alpha\alpha_s$ vertex)
- Definitions of renormalized $\sin^2\theta_W$
  - On shell: $s_W^2 \equiv 1 - \frac{M_W^2}{M_Z^2}$
  - Z mass: $s_{M_Z}^2\left(1 - s_{M_Z}^2\right) \equiv \frac{\pi\alpha(M_Z)}{\sqrt{2}G_F M_Z^2}$
  - $\overline{\text{MS}}$: $\hat{s}_Z^2 \equiv \frac{\hat{g}'^2(M_Z)}{\hat{g}'^2(M_Z)+\hat{g}^2(M_Z)}$
  - Effective (Z-pole): $\bar{s}_f^2 \equiv \frac{1}{4}\left(1 - \frac{\bar{g}_{Vf}}{\bar{g}_{Af}}\right)$

$$M_W^2 = \frac{\left(\pi\alpha/\sqrt{2}G_F\right)}{s_W^2(1-\Delta r)} = \frac{\left(\pi\alpha/\sqrt{2}G_F\right)}{\hat{s}_Z^2(1-\Delta\hat{r}_W)}$$

$$M_Z^2 = \frac{M_W^2}{c_W^2} = \frac{M_W^2}{\hat{\rho}\hat{c}_Z^2}$$

$$\bar{s}_f^2 = \kappa_f s_W^2 = \hat{\kappa}_f \hat{s}_Z^2$$

$$\bar{s}_e^2 \sim \hat{s}_Z^2 + 0.00029$$

($\kappa_f, \hat{\kappa}_f$ depend on m_t, M_H)

$$\hat{\rho} \sim 1 + \frac{3G_F\hat{m}_t^2}{8\sqrt{2}\pi^2} + \cdots$$

$$\Delta\hat{r}_W \sim \Delta\alpha + \cdots \sim 0.066 + \cdots$$

Definitions of $\sin^2\theta_W$

On-shell : $s_W^2 = 1 - \frac{M_W^2}{M_Z^2} = 0.22272\,(38)$
+ most familiar + simple conceptually − large m_t, M_H dependence from Z-pole observables − depends on SSB mechanism − awkward for new physics
Z-mass : $s_{M_Z}^2 = 0.23105\,(8)$
+ most precise (no m_t, M_H dependence) + simple conceptually − m_t, M_H reenter when predicting other observables − depends on SSB mechanism − awkward for new physics
$\overline{MS}$: $\hat{s}_Z^2 = 0.23107\,(16)$
+ based on coupling constants + convenient for GUTs + usually insensitive to new physics + Z asymmetries ∼ independent of m_t, M_H − theorists definition; not simple conceptually − usually determined by global fit − some sensitivity to m_t, M_H − variant forms (m_t cannot be decoupled in all processes; $\hat{s}_{ND}^2$ larger by $0.0001 - 0.0002$)
effective : $\bar{s}_\ell^2 = 0.23136\,(15)$
+ simple + Z asymmetry independent of m_t + Z widths: m_t in ρ_f only − phenomenological; exact definition in computer code − different for each f − hard to relate to non Z-pole observables

Running of α

- Largest theory uncertainty in $M_Z - \hat{s}_Z^2$ (cf. $a_\mu^{\rm had}$)

$$\alpha(M_Z^2) = \frac{\alpha}{1 - \Delta\alpha}$$

$$\begin{aligned}\Delta\alpha &= \Delta\alpha_\ell + \Delta\alpha_t + \Delta\alpha_{\rm had}^{(5)} \\ &\sim 0.031497 - 0.000070 + \Delta\alpha_{\rm had}^{(5)}\end{aligned}$$

$$\alpha^{-1} \sim 137.036$$

$$\alpha^{-1}(M_Z) \sim \hat{\alpha}^{-1}(M_Z) + 0.99 \sim 129$$

$$M_Z^2 = \frac{\left(\pi\alpha/\sqrt{2}G_F\right)}{\hat{\rho}\hat{c}_Z^2\hat{s}_Z^2(1 - \Delta\hat{r}_W)}$$

$$\hat{\rho} \sim 1 + \frac{3G_F\hat{m}_t^2}{8\sqrt{2}\pi^2} + \cdots$$

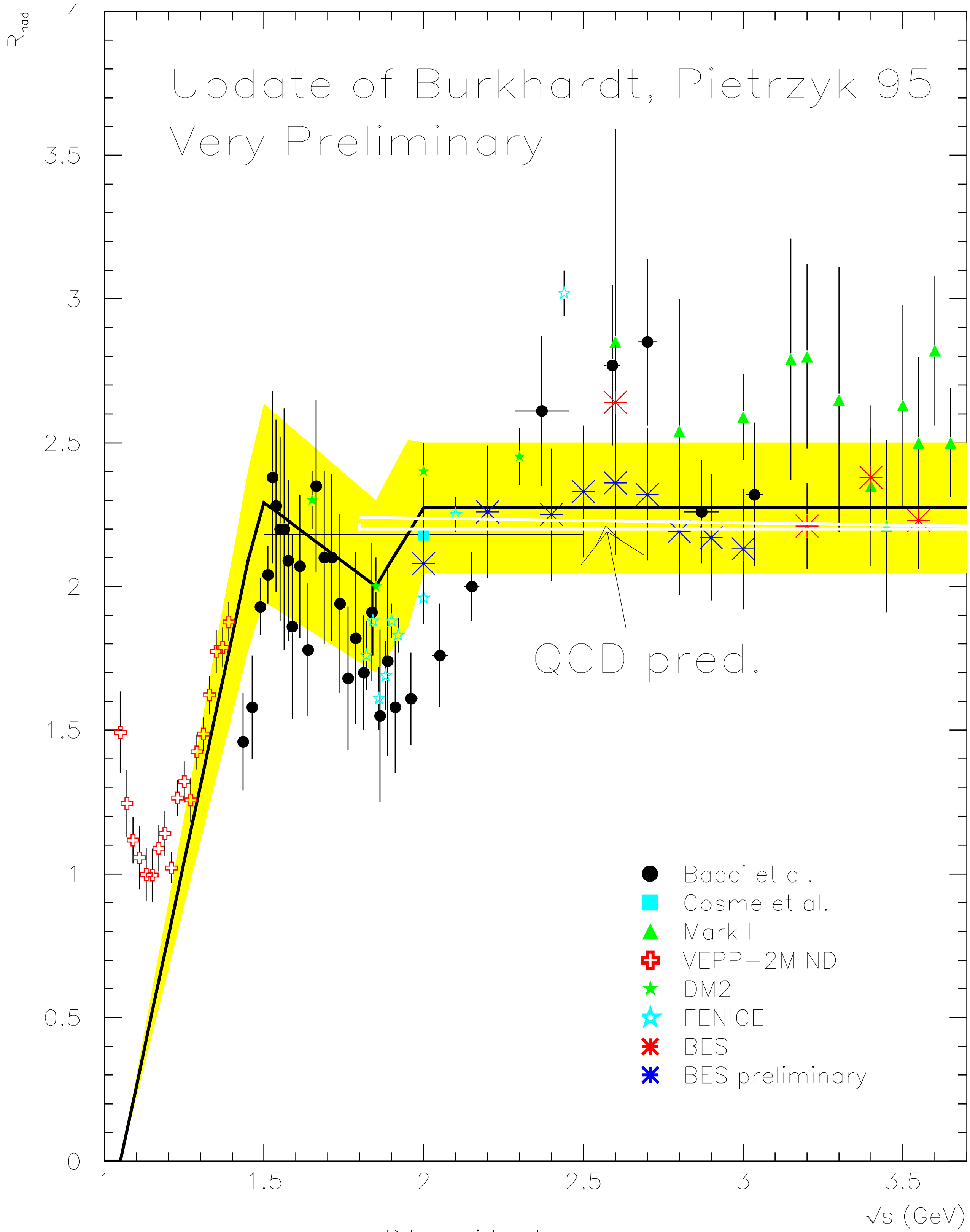
$$\Delta\hat{r}_W \sim \Delta\alpha + \cdots$$

- Calculation of $\Delta\alpha_{\rm had}^{(5)}$
  - Data driven: $R_{\rm had}$ up to $\sim$ 40 GeV; PQCD above
  - Theory driven: PQCD + NPQCD (OPE, sum rules) above $\sim$ 2 GeV $\longrightarrow$ smaller uncertainties
  - New BES-II data $\longrightarrow$ convergence
- Measurements of running α: TOPAZ ($e^+e^-\mu^+\mu^-$); VENUS, L3 (Bhabha), OPAL (high Q^2)

Recent evaluations of on-shell $\Delta\alpha_{\rm had}^{(5)}(M_Z)$

(Adjusted to fixed $\alpha_s(M_Z) = 0.120$)

Author(s)	Result	Comment
Martin & Zeppenfeld	0.02744 ± 0.00036	PQCD for $\sqrt{s} > 3$ GeV
Eidelman & Jegerlehner	0.02803 ± 0.00065	PQCD for $\sqrt{s} > 40$ GeV
Geshkenbein & Morgunov	0.02780 ± 0.00006	$\mathcal{O}(\alpha_s)$ resonance model
Burkhardt & Pietrzyk	0.0280 ± 0.0007	PQCD for $\sqrt{s} > 40$ GeV
Swartz	0.02754 ± 0.00046	use of fitting function
Alemany, Davier, Höcker	0.02816 ± 0.00062	includes τ decay data
Krasnikov & Rodenberg	0.02737 ± 0.00039	PQCD for $\sqrt{s} > 2.3$ GeV
Davier & Höcker	0.02784 ± 0.00022	PQCD for $\sqrt{s} > 1.8$ GeV
Kühn & Steinhauser	0.02778 ± 0.00016	complete $\mathcal{O}(\alpha_s^2)$
Erler	0.02779 ± 0.00020	converted from $\overline{\rm MS}$ scheme
Davier & Höcker	0.02770 ± 0.00015	use of QCD sum rules
Groote *et al.*	0.02787 ± 0.00032	use of QCD sum rules
Jegerlehner	0.02778 ± 0.00024	converted from MOM
Martin, Outhwaite, Ryskin	0.02741 ± 0.00019	includes new BES data
Pietrzyk	0.02755 ± 0.00046	details not published



R Exp without resonances

- Z pole + LEP 2 + WNC + Tevatron
  - SM tested at 0.1% level, including EW loops (gauge principle, group, representations, renorm. field theory)
  - $\sin^2\theta_W$; m_t, α_s (loops; agree with direct) determined; α_{had}, M_H constrained
  - $M_H \lesssim 194$ GeV (direct: $M_H > 112$ GeV) $\leftrightarrow$ SUSY
  - severe constraint on TeV physics
    - unification (decoupling): expect 0.1%
    - TeV compositeness: expect several %
  - precise gauge coupling constants (unification)

Global Electroweak Fits

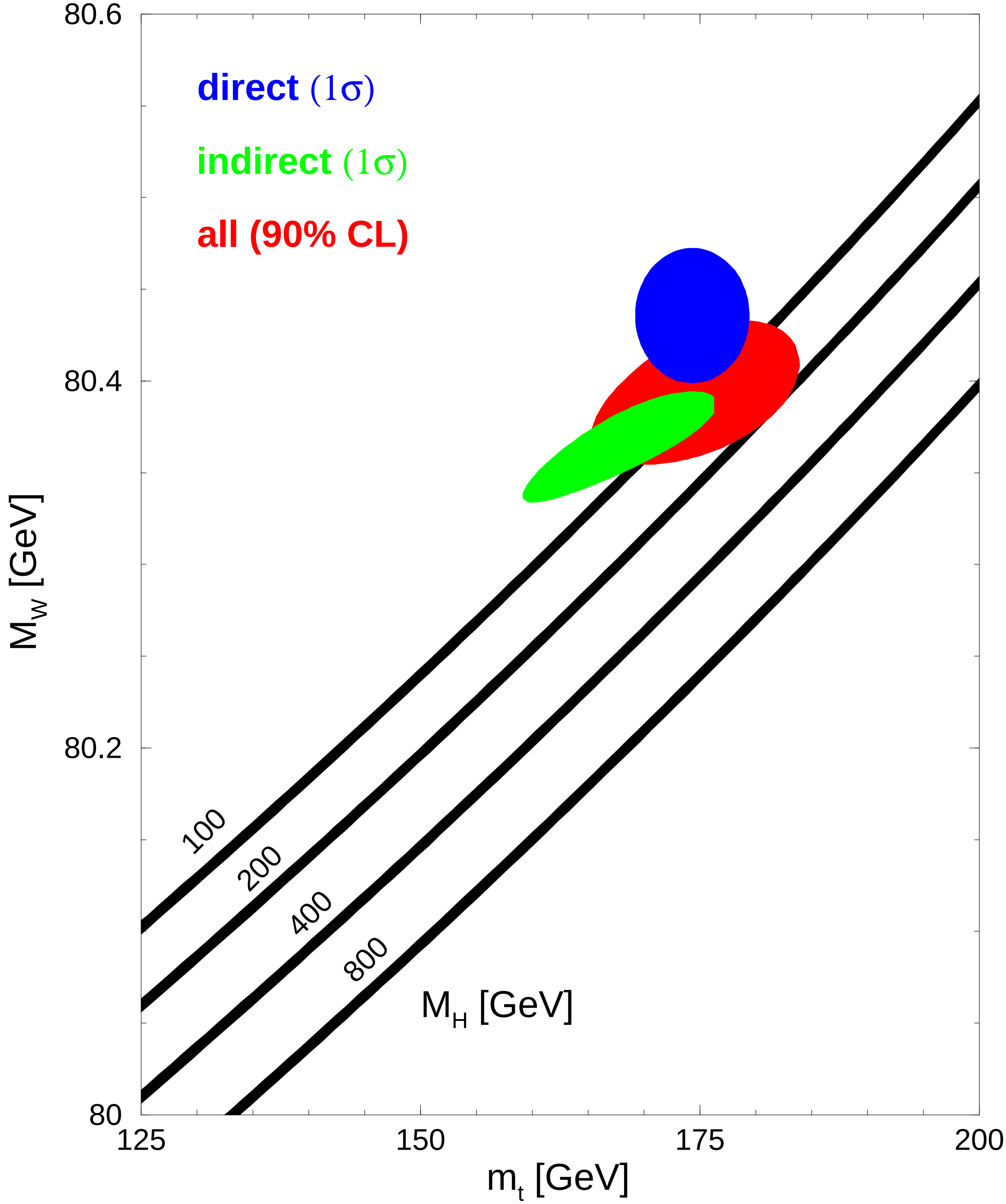
- much more information than individual experiments
- caveat: experimental/theoretical systematics, correlations
- PDG '00 review + summer (J. Erler and PL)
- Complete Z-pole and WNC (important beyond SM)
- New radiative correction program (Erler)
  - GAPP: Global Analysis of Particle Properties
  - Fully $\overline{\text{MS}}$ (ZFITTER on-shell)
- New $\Delta\alpha_{had}$, correlated with α_s
- Good agreement with LEPEWWG up to well-understood effects (WNC, HOT, $\Delta\alpha_{had}$) despite different renormalization schemes
- www.physics.upenn.edu/~erler/electroweak/

Fit Results (10/00) (Erler, PL)

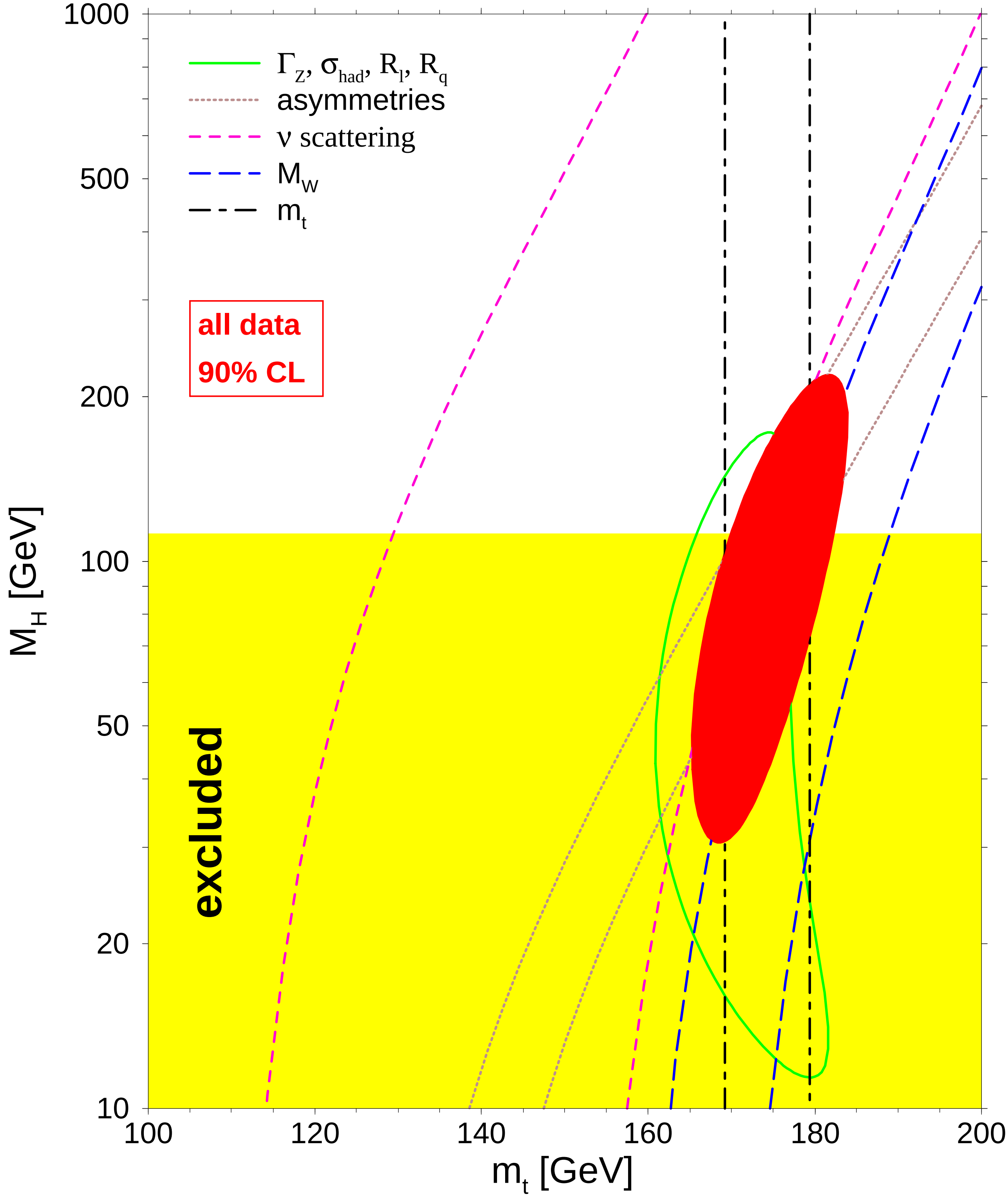
$$
\begin{aligned}
M_H &= 86^{+48}_{-32} \text{ GeV}, \\
m_t &= 174.2 \pm 4.4 \text{ GeV}, \\
\alpha_s &= 0.1195 \pm 0.0028, \\
\hat{s}^2_Z &= 0.23107 \pm 0.00016, \\
\bar{s}^2_\ell &= 0.23136 \pm 0.00015, \\
s^2_W &= 0.22272 \pm 0.00038 \\
s^2_{M_Z} &= 0.23105 \pm 0.00008 \\
\Delta\alpha^{(5)}_{\rm had}(M_Z) &= 0.02778 \pm 0.00020
\end{aligned}
$$

- Gurtu (Osaka): $M_H = 60^{+52}_{-29}$ GeV (88^{+60}_{-37} for new BES-II data for $\Delta\alpha^{(5)}_{\rm had}(M_Z)$)
- $\alpha_s = 0.1183 \pm 0.0027$
- $m_t = 174.3^{+4.4}_{-4.1}$ GeV
- $\bar{s}^2_\ell = 0.23140 \pm 0.00016$

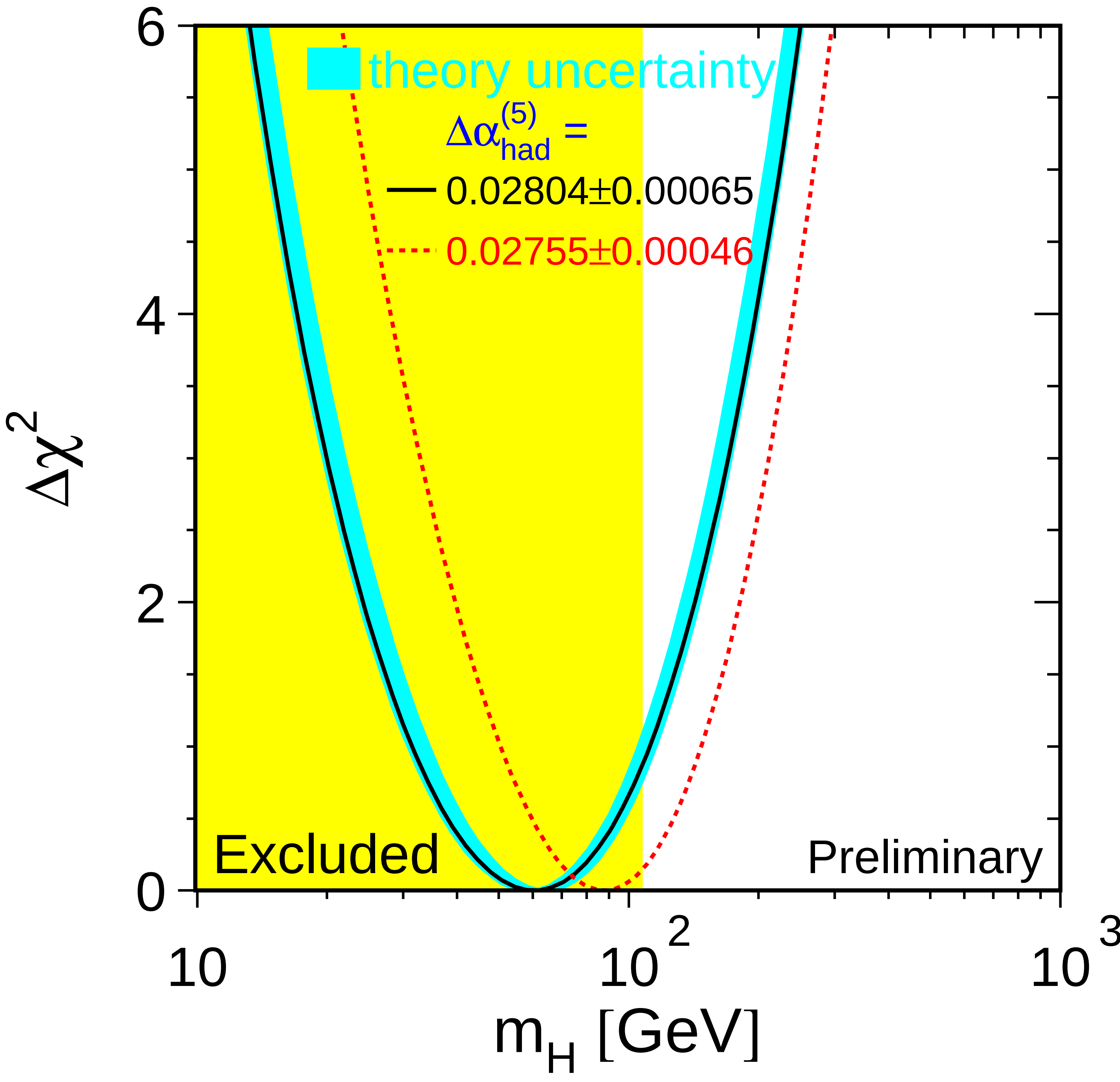
- $\Delta\alpha^{(5)}_{\rm had}(M_Z) = 0.02778 \pm 0.00020$
  - 0.02765 ± 0.00040 from indirect only (theory (Erler): 0.02779 ± 0.00020)
- $m_t = 174.2 \pm 4.4$ GeV
  - $174.1^{+7.6}_{-9.7}$ GeV from indirect (loops) only (direct: 174.3 ± 5.1)
- $\alpha_s = 0.1195 \pm 0.0028$ consistent w. other values (PDG: 0.1182 ± 0.0013 w/o lineshape)
- Higgs mass $M_H = 86^{+48}_{-32}$ GeV
  - direct limit (LEP 2): $M_H \gtrsim 112$ 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
    - ∗ $M_H < 194$ GeV at 95%, including direct



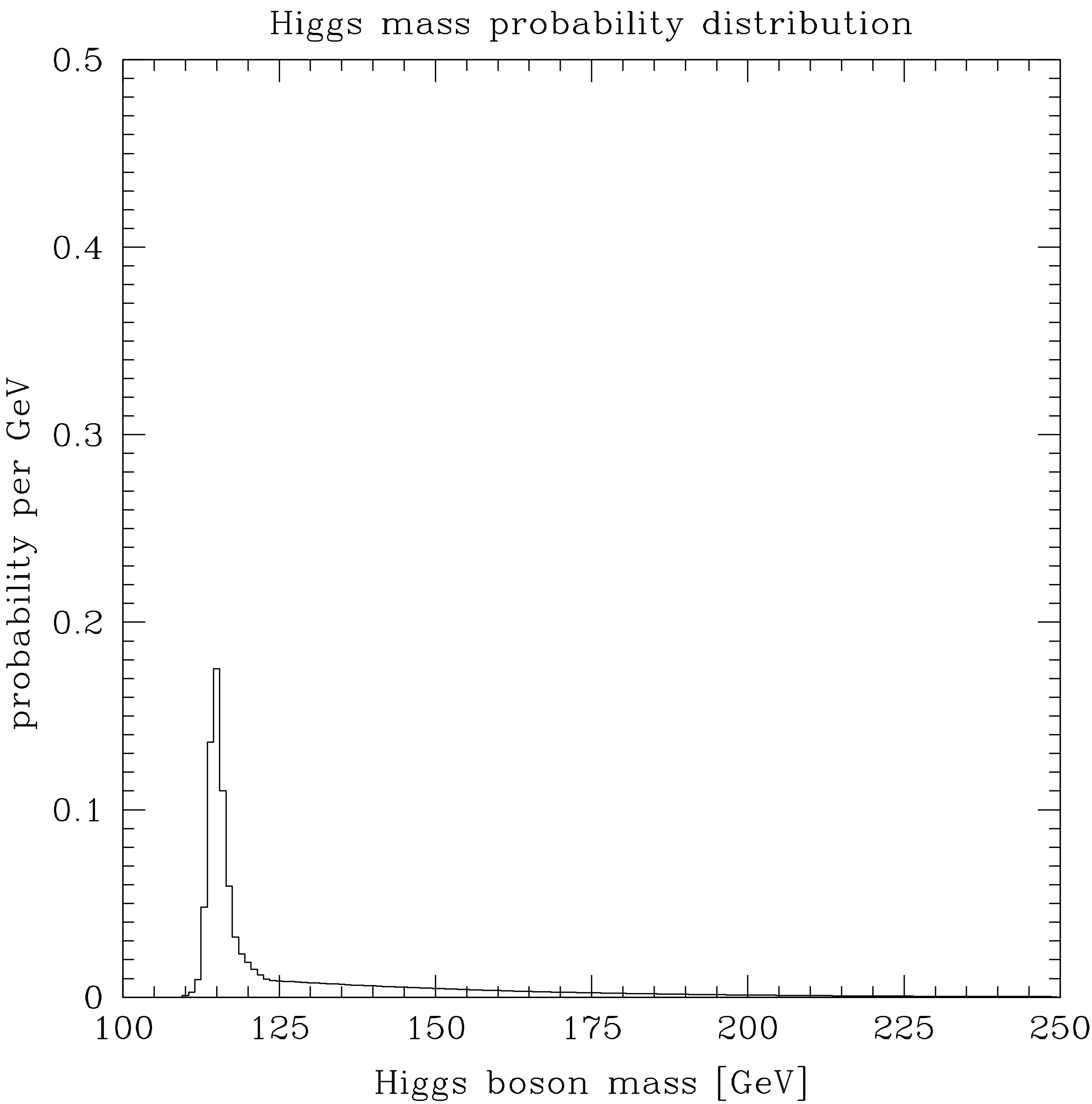
direct (1σ)
indirect (1σ)
all (90% CL)
80.6
80.4
80.2
80
125
150
175
200
M_W [GeV]
m_t [GeV]
100
200
400
800
M_H [GeV]



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



theory uncertainty
$\Delta\alpha^{(5)}_{had}$ =
0.02804±0.00065
0.02755±0.00046
Excluded
Preliminary
$\Delta\chi^2$
6
4
2
0
10
10^2
10^3
m_H [GeV]


Higgs mass probability distribution
probability per GeV
0.5
0.4
0.3
0.2
0.1
0
100
125
150
175
200
225
250
Higgs boson mass [GeV]

Skeletons in the Closet

Standard model ($SU_3 \times SU_2 \times U_1$ + general relativity) correct to 10^{-16} cm, *but* 21 free parameters (≥ 28 with $m_\nu \neq 0$).

- **Gauge Problem**
  - complicated gauge group with 3 couplings
  - charge quantization ($|q_e| = |q_p|$) unexplained
- **Fermion problem**
  - Fermion masses, mixings, families unexplained
- **Higgs/hierarchy problem**
  - Expect $M_H^2 = O(M_W^2)$
  - higher order corrections: $\delta M_H^2 / M_W^2 \sim 10^{34}$
- **Strong CP problem**
  - Can add $\frac{\theta}{32\pi^2} g_s^2 F\tilde{F}$ to QCD (breaks, P, T, CP)
  - $d_N \Rightarrow \theta < 10^{-9}$
  - but $\delta\theta|_{\text{weak}} \sim 10^{-3}$
- **Graviton problem**
  - gravity not unified
  - quantum gravity not renormalizable
  - cosmological constant: $\Lambda_{\text{SSB}} = 8\pi G_N \langle V \rangle > 10^{50} \Lambda_{\text{obs}}$

The Two Paths: Unification or Compositeness

- **The Bang**
  - unification of interactions
  - grand desert to unification (GUT) or Planck scale
  - elementary Higgs, supersymmetry (SUSY), GUTs, strings
  - possibility of probing to M_P and very early universe
  - hint from coupling constant unification
  - tests
    - light ($< 110 - 130$ GeV) Higgs (LEP 2, TeV, LHC)
    - *absence* of deviations in precision tests (usually)
    - supersymmetry (LHC)
    - possible: m_b, proton decay, ν mass, rare decays
    - SUSY-safe: Z'; seq/mirror/exotic fermions; singlets
- **The Whimper**
  - onion-like layers
  - composite fermions, scalars (dynamical sym. breaking)
  - *not* like to atom $\rightarrow$ nucleus $+e^- \rightarrow p+n \rightarrow$ quark
  - at most one more layer accessible (LHC)
  - rare decays (e.g., $K \rightarrow \mu e$)
    - severe problem
    - no realistic models
  - effects (typically, few %) expected at LEP & other precision observables (4-f ops; $Zb\bar{b}$; ρ_0; S, T, U)
  - anomalous VVV, new particles, future $WW \rightarrow WW$

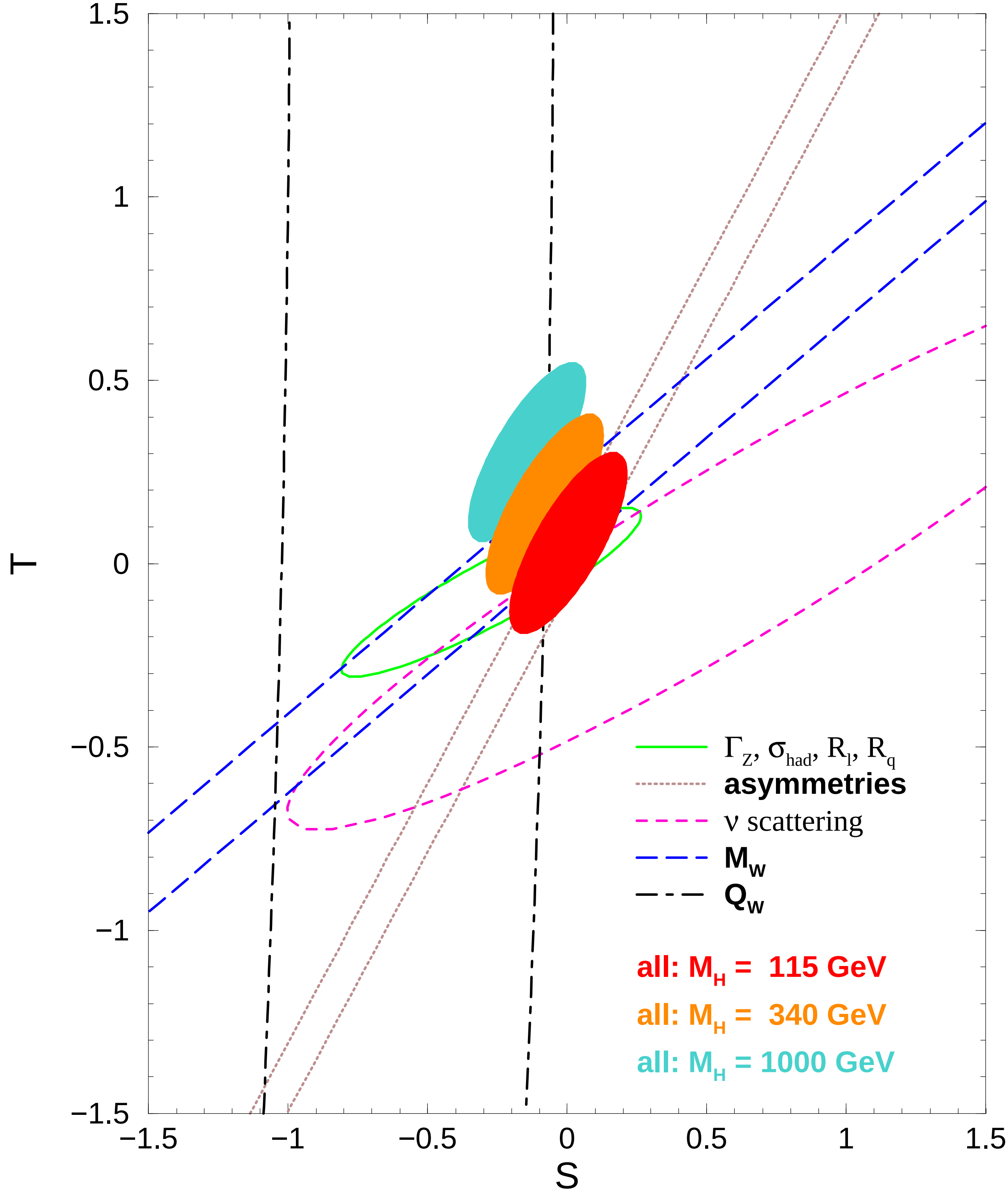
Beyond the standard model

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

$$S = -0.05 \pm 0.11(-0.09)$$
$$T = -0.03 \pm 0.13(+0.10)$$
$$U = 0.18 \pm 0.14(+0.01)$$

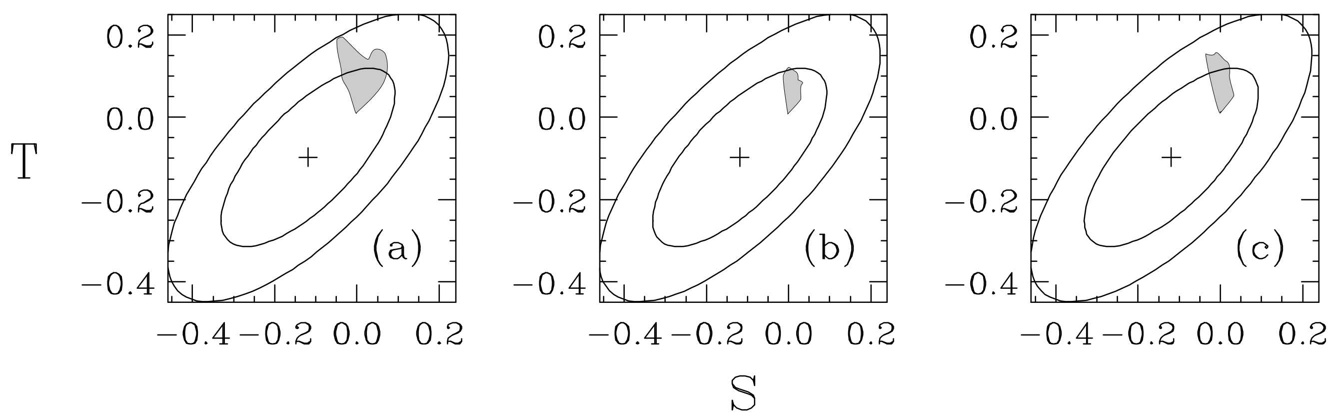
for $M_H = 115$ (340) GeV

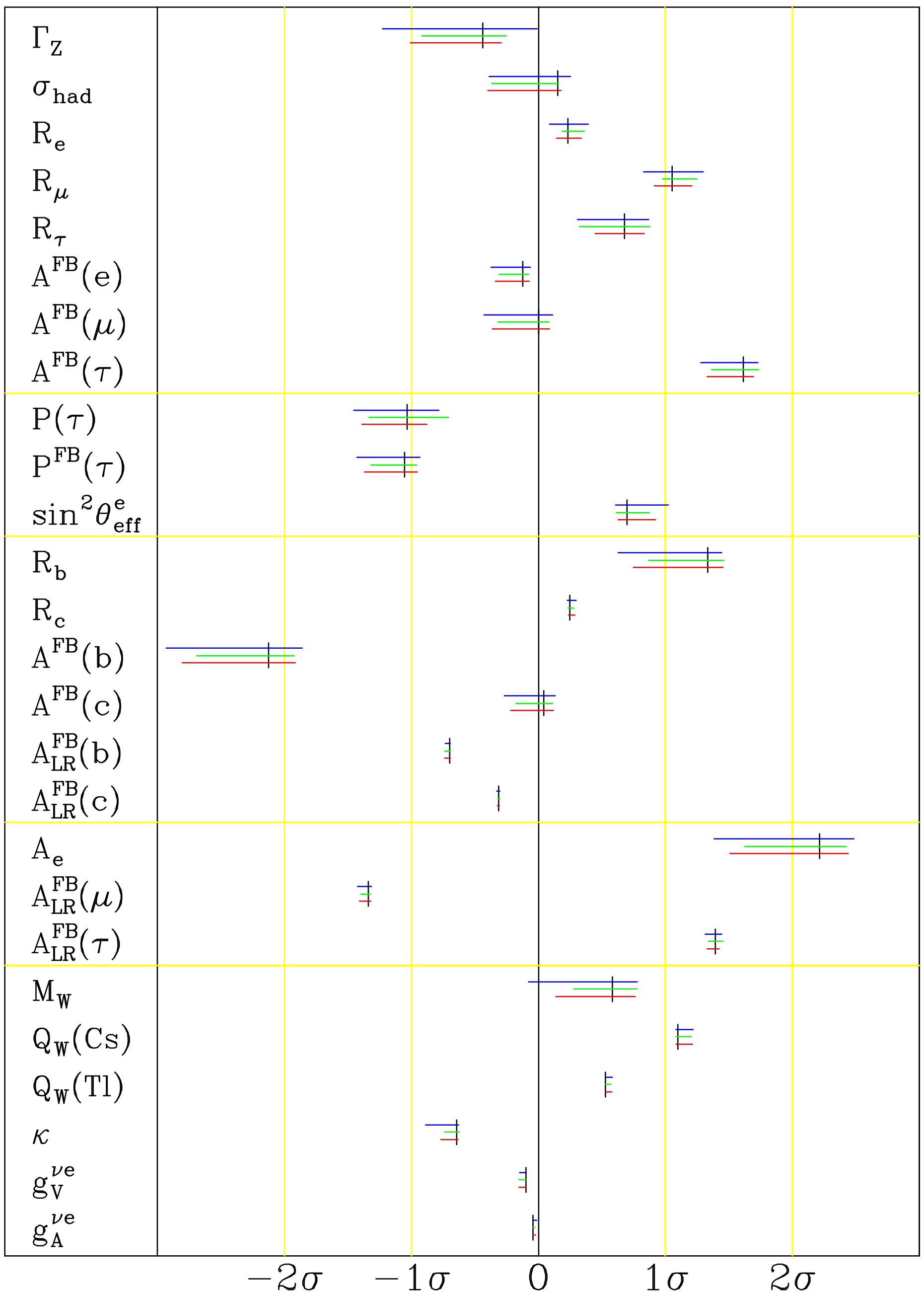
  – $\rho_0 =\sim 1 + \alpha T = 1.0004^{+0.0018}_{-0.0011}$ ($M_H = 113^{+310}_{-64}$ GeV)
  – $N_{\rm fam} = 2.84 \pm 0.30$ (cf. lineshape: $N_\nu = 2.985 \pm 0.008$)
  – Fourth family excluded at 99.92%



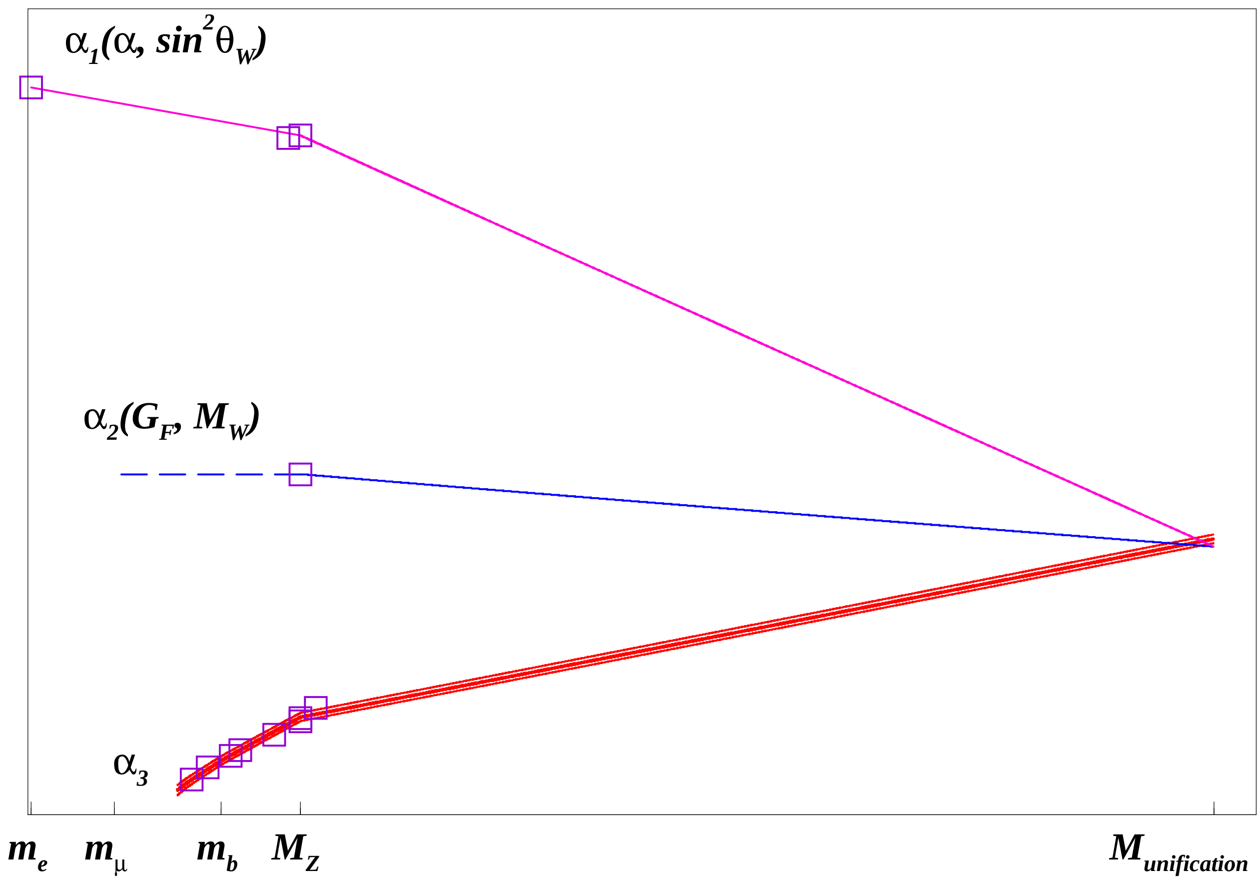
1.5
1
0.5
0
−0.5
−1
−1.5
T
−1.5
−1
−0.5
0
0.5
1
1.5
S
Γ_Z, σ_{had}, R_l, R_q
asymmetries
ν scattering
M_W
Q_W
all: M_H = 115 GeV
all: M_H = 340 GeV
all: M_H = 1000 GeV

- **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**
- **Heavy Z': GUTs, string theories**
  - **Typically $M_{Z'} > 500 - 800$ GeV (Tevatron, LEP 2, WNC), $|\theta_{Z-Z'}| <$ few $\times 10^{-3}$ (Z-pole)**
- **Gauge unification: GUTs, string theories**
  - $\alpha + \hat{s}_Z^2 \rightarrow \alpha_s = 0.130 \pm 0.010$
  - $M_G \sim 3 \times 10^{16}$ **GeV**
  - **Perturbative string: $\sim 5 \times 10^{17}$ GeV (10% in $\ln M_G$). Exotics: $O(1)$ corrections.**


T
S
0.2
0.0
−0.2
−0.4
−0.4 −0.2 0.0 0.2
(a)
(b)
(c)



Γ_Z
σ_{had}
R_e
R_μ
R_τ
$A^{FB}(e)$
$A^{FB}(\mu)$
$A^{FB}(\tau)$
$P(\tau)$
$P^{FB}(\tau)$
$\sin^2\theta^e_{eff}$
R_b
R_c
$A^{FB}(b)$
$A^{FB}(c)$
$A^{FB}_{LR}(b)$
$A^{FB}_{LR}(c)$
A_e
$A^{FB}_{LR}(\mu)$
$A^{FB}_{LR}(\tau)$
M_W
$Q_W(Cs)$
$Q_W(Tl)$
κ
$g_V^{\nu e}$
$g_A^{\nu e}$
-2σ
-1σ
0
1σ
2σ



$\alpha_1(\alpha, sin^2\theta_W)$
$\alpha_2(G_F, M_W)$
α_3
m_e
m_μ
m_b
M_Z
$M_{unification}$

Conclusions

- WNC, Z, W are primary predictions and test of electroweak unification
- 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)
- LEP has performed spectacularly well (accelerator, experiments, analysis (LEPEWWG), theoretical support)
- Watershed in physics: decoupling