Electroweak Physics

- The Standard Model
- Parameters and Global Fit
- Deviations
- Teaser: Z' and Supersymmetry
- Low Energy and New Physics
- Weak Mixing Angle at Low Energies
- Conclusions

Standard Model milestones

- CERN: weak neutral currents found
- SLAC eD-DIS: SM favored
- UA1 and UA2: W and Z bosons found
- ν-DIS & APV: SM correct at tree level
- LEP & SLC: SM correct at loop level
- Tevatron: top quark found
- Super-Kamiokande: $\boldsymbol{\nu}$-mass

Features

- SM Lagrangian $\mathcal{L}$ is the most general consistent with gauge symmetry and renormalizability.
- Renormalizability not fundamental: $\mathcal{L}$ is leading order in an expansion E^2/M^2_{new}
- $\mathcal{L}$ = SU(3) X SU(2) X U(1) gauge interactions + quartic scalar Higgs potential + trilinear Yukawa couplings.
- Only dimensionful parameter: $M^2_H < 0$.

Parameters

- α: $g_e - 2$ or quantum Hall effect
- α(M_Z): QED + data
- α_s: inclusive observables, $E \gg \Lambda_{QCD}$
- M_Z: Lineshape
- $\langle 0|H|0\rangle = \frac{2^{-1/4}}{\sqrt{G_F}} \sim \frac{M_W}{g}$: μ lifetime
- M_H: M_W and Z-pole asymmetries

$M_W \Leftrightarrow M_Z \Leftrightarrow \sin^2\theta_W$

$\mu - \text{decay} \Rightarrow G_F = 1.16637(1)10^{-5}\,\text{GeV}^2$

v. Ritbergen, Stuart

$$\Rightarrow A^2 = \frac{\pi\alpha}{\sqrt{2}G_F} = (37.28\,\text{GeV})^2$$

$$\sin^2\hat{\theta}_W = \frac{A^2}{M_W^2(1-\Delta\widehat{r_W})} \qquad \sin^2\hat{\theta}_W\cos^2\hat{\theta}_W = \frac{A^2}{M_Z^2(1-\Delta\widehat{r_Z})}$$

$[\overline{\text{MS}}-\text{scheme}]$

Degrassi, Fanchiotti, Sirlin

$$\Delta\widehat{r_Z} = \frac{\alpha}{\pi}\widehat{\Delta_\gamma} + F_1(m_t^2, M_H, \ldots) \qquad \Delta\widehat{r_W} = \frac{\alpha}{\pi}\widehat{\Delta_\gamma} + F_2(\log m_t, M_H, \ldots)$$

$\Rightarrow$ correlations between $\widehat{\Delta_\gamma}, M_H, g_\mu - 2, \sin^2\theta_W(0)$

EW radiative corrections

enhanced 2-loop: complete

van der Bij; Barbieri et al.; Fleischer, Tarasov, Jegerlehner; Degrassi, Gambino, Sirlin, Vicini

M_W

2-loop fermionic: complete

Freitas, Hollik, Walter, Weiglein

2-loop bosonic: complete

Awramik, Czakon; Onishenko, Veretin

$\sin^2\theta_W^{\text{eff}}$

2-loop fermionic: complete

Awramik, Czakon, Freitas, Weiglein

enhanced 3-loop: partially

Global fit results

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

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

$m_t = 172.4^{+9.8}_{-6.9}\,\mathrm{GeV}\ [\mathrm{indirect}]$

$m_t = 177.9 \pm 4.4\,\mathrm{GeV}\ [\mathrm{direct}]$

CDF I+II, DØ

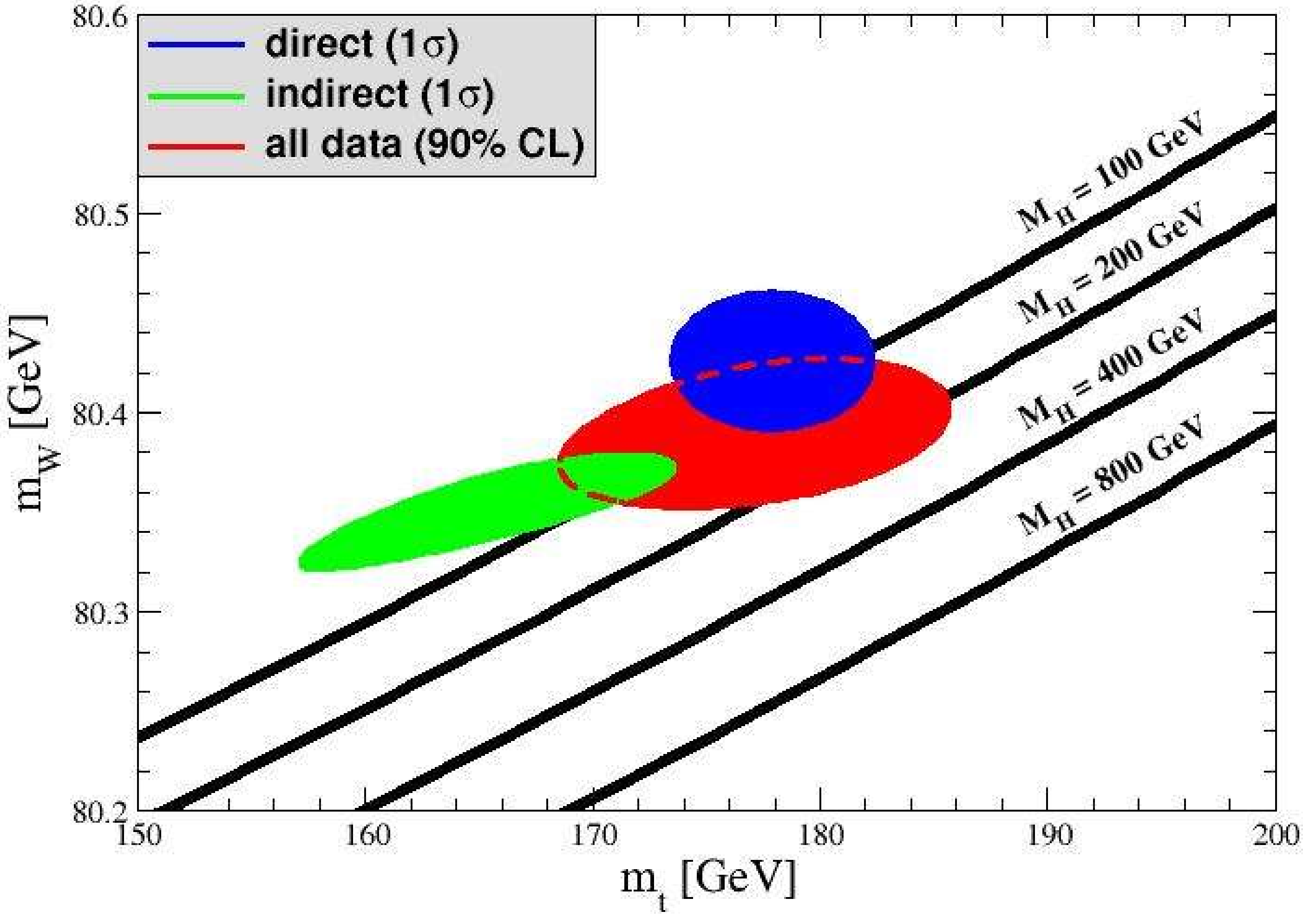
$\widehat{\alpha_s}(M_Z) = 0.1213 \pm 0.0018$

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

$\sin^2\widehat{\theta_W}(M_Z) = 0.23120 \pm 0.00015$

$\chi^2/\mathrm{d.o.f.} = 45.5/45 \quad (45\%)$

Fermilab plot



Strong coupling

$\hat{\alpha}_s(M_Z) = 0.1197 \pm 0.0028$ [Z−lineshape]

$\hat{\alpha}_s(M_Z) = 0.1221^{+0.0026}_{-0.0023}$ [τ_τ]

perfect agreement with [not included]:

$\hat{\alpha}_s(M_Z) = 0.1202 \pm 0.0049$ [LEP jet event shapes]

$\hat{\alpha}_s(M_Z) = 0.121 \pm 0.003$ [lattice Υ spectroscopy]

LEP 1 deviations

$A^0_{FB}(b) = 0.0977 \pm 0.0016$

$A^0_{FB}(b) = 0.1032 \pm 0.0008 \ [SM] \quad (-2.2\sigma)$

$A^0_{LR} = 0.1513 \pm 0.0021$

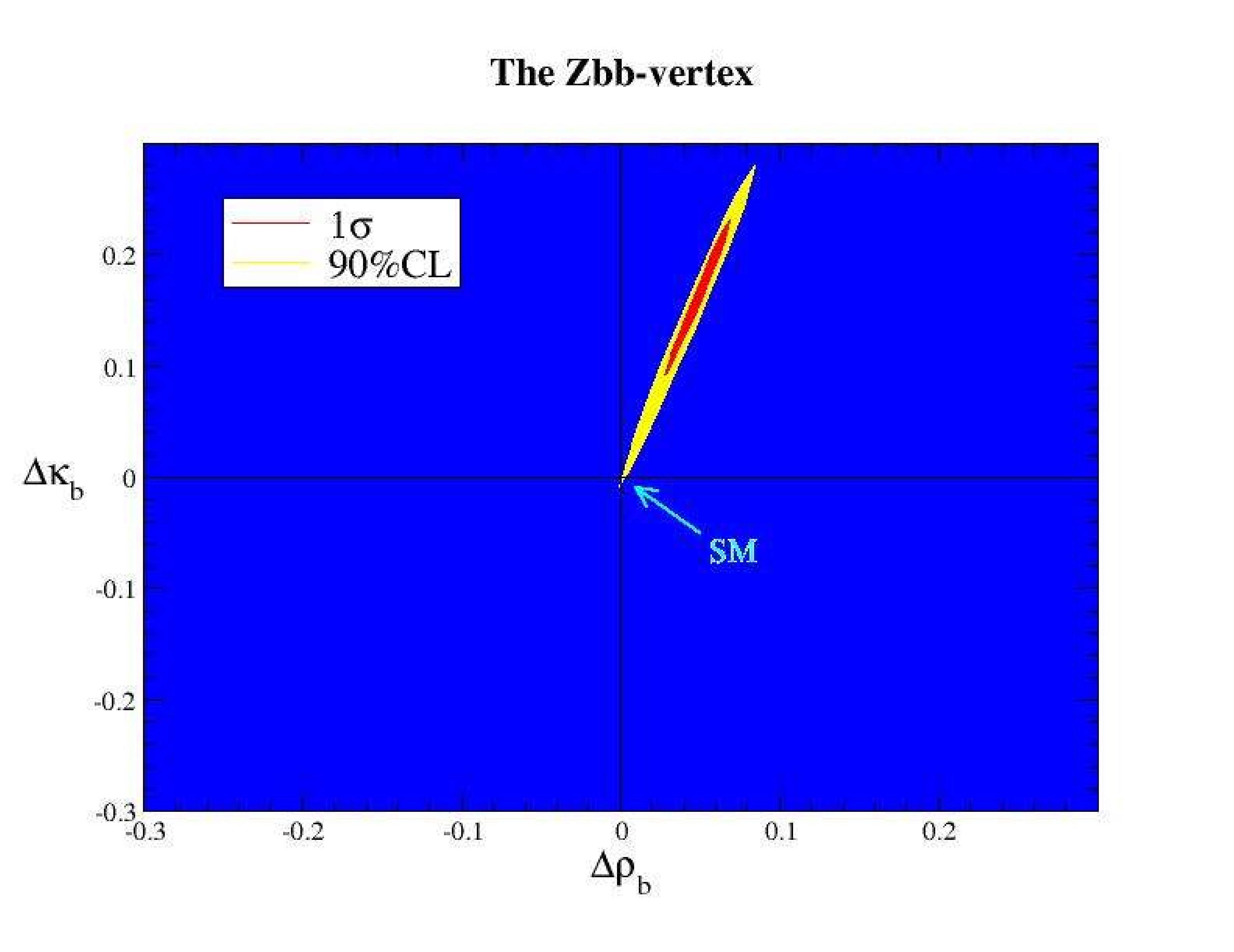
$A^0_{LR} = 0.1472 \pm 0.0011 \ [SM] \quad (1.9\sigma)$

$\sigma^0_{had} = 41.541 \pm 0.0037 \quad \Rightarrow \quad N_\nu = 2.986 \pm 0.007$

$\sigma^0_{had} = 41.472 \pm 0.0009 \ [SM] \quad (1.9\sigma)$

ALEPH, DELPHI, L3, OPAL

Zbb-vertex



Other deviations

$g_L^2 = 0.30005 \pm 0.00137$ NuTeV

$g_L^2 = 0.30397 \pm 0.00023$ [SM] (-2.9σ)

$\frac{1}{2}(g_\mu - 2 - \frac{\alpha}{\pi}) = 4511.07 \pm 0.80$ BNL E-821

$\frac{1}{2}(g_\mu - 2 - \frac{\alpha}{\pi}) = 4509.32 \pm 0.10$ [SM] (2.2σ)

LEP 2[not included]: ALEPH, DELPHI, L3, OPAL

σ_{had}: 1.7σ R_b: -2.1σ $A_{FB}(b)$: -1.6σ

M_H

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

$M_H(\text{LEP 2}) > 114.4\,\text{GeV}$ (95% CL)

ALEPH, DELPHI, L3, OPAL

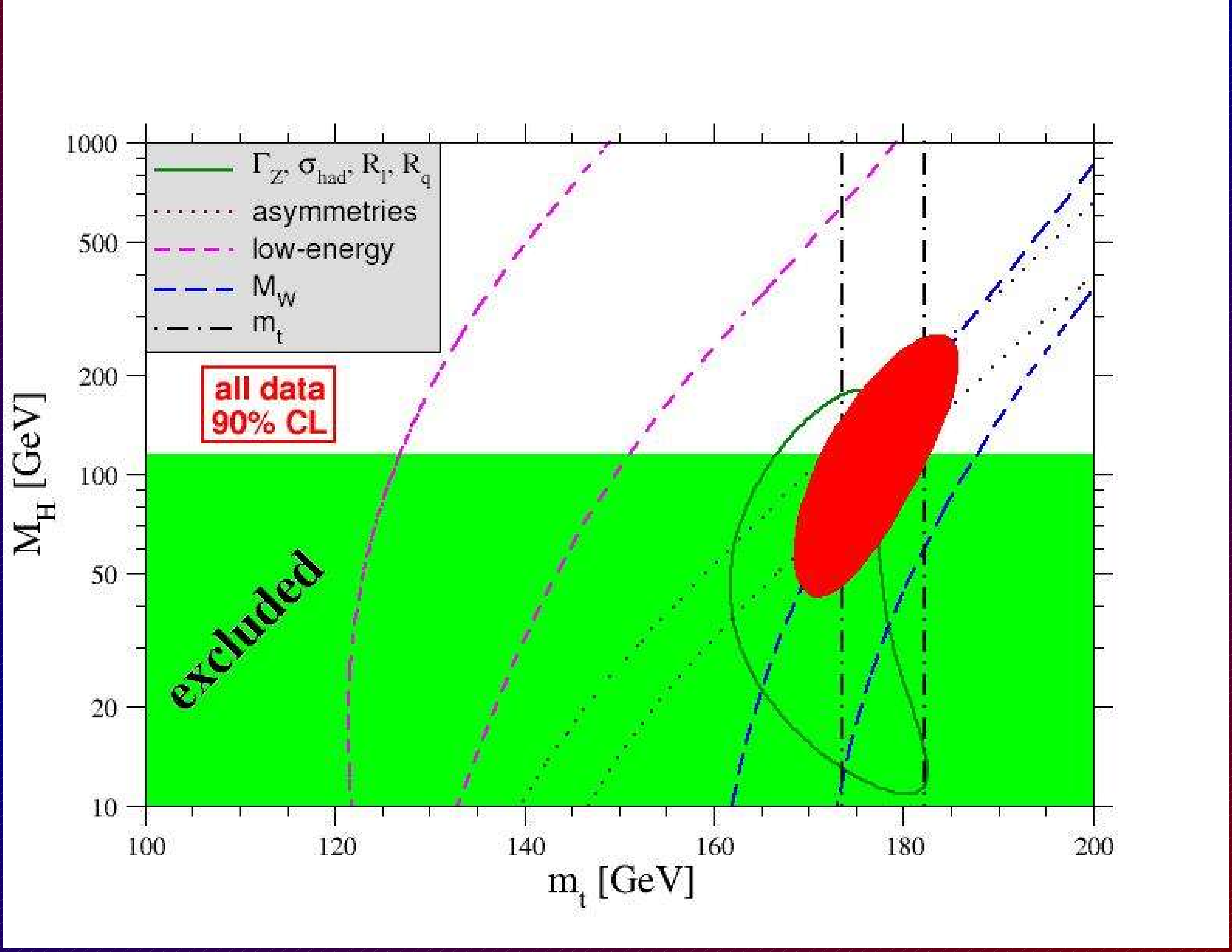
90% central confidence interval:

$53\,\text{GeV} < M_H < 213\,\text{GeV}$

Including direct searches:

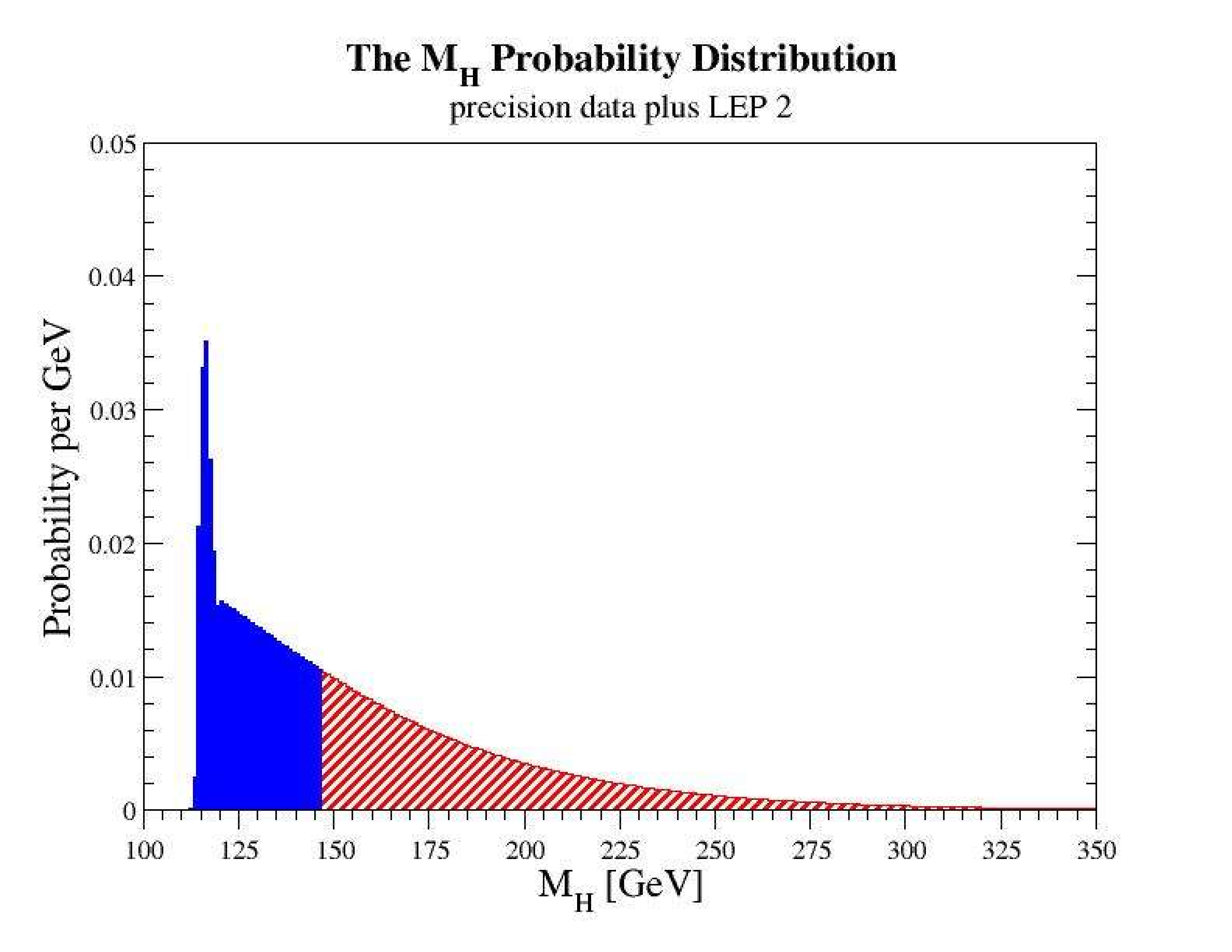
$M_H < 246\ (217, 311)\,\text{GeV}$ 95 (90, 99)% CL

Higgs mass



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

Higgs mass distribution



SM issues

A very successful prediction:

$$\tau_p \sim \tau_\mu \frac{m_\mu^5}{m_p^5} \frac{M_{Planck}^4}{M_W^4} \geqslant \mathcal{O}(10^{47}\,a)$$

Less successful predictions:

$$m_H^2 = \mathcal{O}(M_{Planck}^2) \qquad \Lambda_C = \mathcal{O}(M_{Planck}^4)$$

Gauge group and representations ad hoc

Supersymmetry – The Good

- Fundamental symmety ↔ Strings
- Non-ren theorems ↔ Stable hierarchy
- MSSM ↔ Gauge coupling unification
- Weak coupling ↔ Precision Tests
- Heavy top ↔ Radiative breaking
- $\lambda = T_3 \sqrt{g^2 + g'^2}$ ↔ $M_H \leqslant 150\,\mathrm{GeV}$

Supersymmetry – The Bad

- SUSY breaking
- μ - problem
- Little hierarchy problem
- Flavor and CP problems
- $\Lambda_C = \mathcal{O}(M^4_{SUSY})$

Supersymmetry – The Ugly

$$L_Y^{SUSY} = \lambda \bar{E}_L E_L e_R + \lambda' \bar{Q}_L E_L d_R + \lambda'' \bar{u}_R \bar{d}_R \bar{d}_r + \mu' \bar{E}_L H_u$$

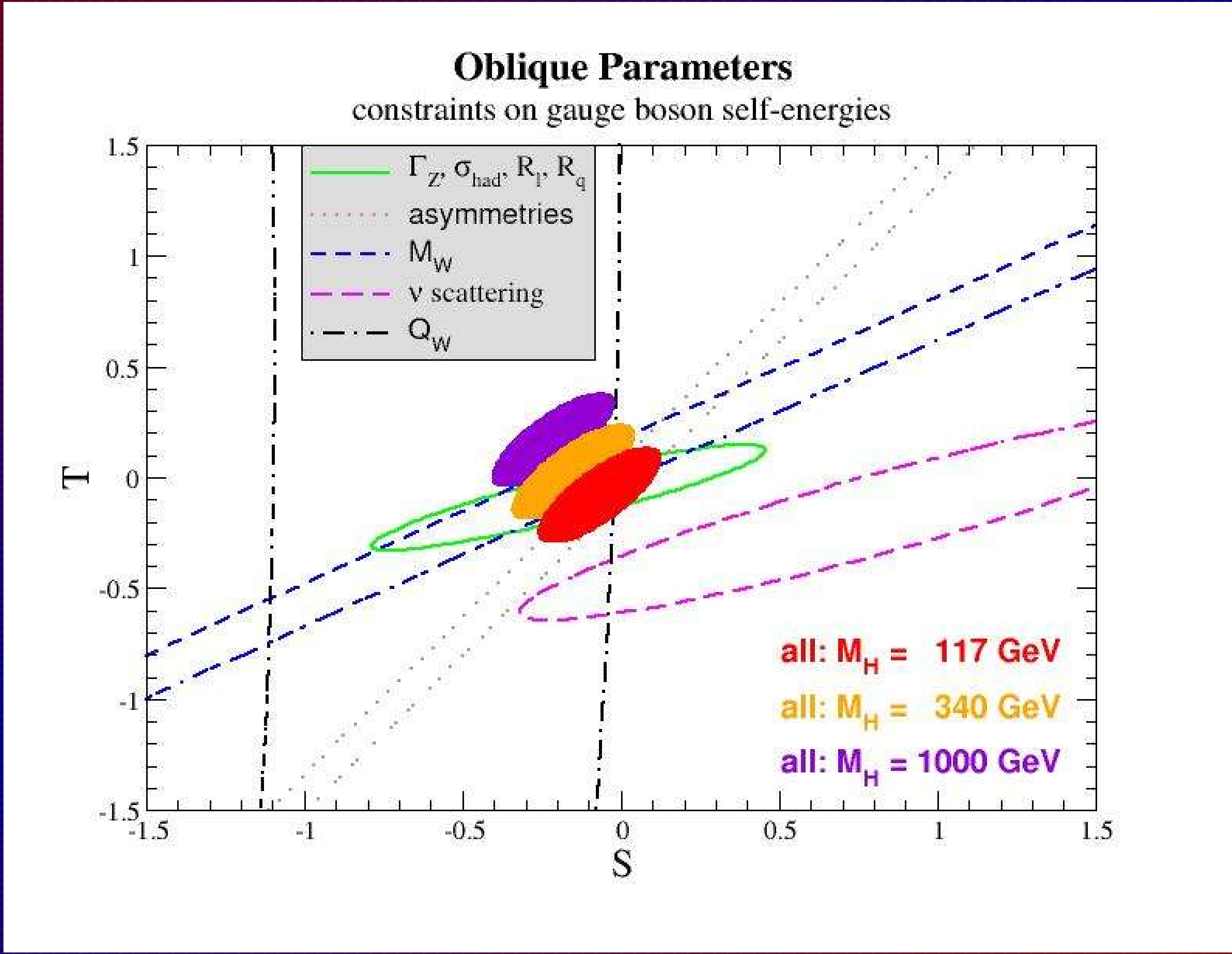
$$\tau_p \sim \tau_\mu \left(C_1 |\lambda|^2 + C_2 |\lambda'|^2 \right) |\lambda''|^2 \frac{m_\mu^5}{m_p^5} \frac{M_{SUSY}^4}{M_W^4} \sim \tau_\mu$$

R-parity?

A fifth force?

- Gauge coupling unification preserved
- Naturalness (most general Lagrangian)
- Anomaly cancellation
- Chirality
- $S H_u H_d \Rightarrow \langle S \rangle H_d H_u = \mu_{eff} H_d H_u$
- τ_p predicted in half of the models
- E_6-like charges
- Precision data (S-parameter)

Oblique parameters



A SEARCH FOR NEW PHYSICS

Qweak

$$A_{LR}=\frac{\sigma_L-\sigma_R}{\sigma_L+\sigma_R}=\frac{-G_F Q^2}{4\sqrt{2}\pi\alpha}\left[Q_W^p+F^p(Q^2,\theta)\right]$$

Musolf et al. (1994)

$$F^p(Q^2,\theta)=Q^2 B(Q^2)$$

$B(Q^2)$ depends on nucleon, EM, and strangeness form factors

SAMPLE, HAPPEX, A4, G0

$Q_W^p(0)$ protected by current conservation against large strong interaction corrections

$$\frac{\Delta Q_W^p}{Q_W^p}=0.04\Rightarrow\frac{\Lambda}{g}\approx\frac{1}{\sqrt{\sqrt{2}G_F\left|\Delta Q_W^p\right|}}\approx 4.6\,TeV$$

Qweak radiative corrections

$$Q_W^p = [\rho_{NC} + \Delta_e][1 - 4\sin^2\theta_W(0) + \Delta_e'] + B_{WW} + B_{ZZ} + B_{\gamma Z}$$

$$\Delta_e = \frac{-\alpha}{2\pi}$$

$$\Delta_e' = \frac{-\alpha}{3\pi}(1 - 4\sin^2\hat{\theta}_W(M_Z))[\ln(\frac{M_Z^2}{m_e^2}) + \frac{1}{6}$$

$$B_{WW} = \frac{\hat{\alpha}}{4\pi\hat{s}^2}\left[2 + 5\left(1 - \frac{\alpha_s(M_W)}{\pi}\right)\right]$$

Adler, Tung; Beg;
Marciano, Sirlin;
Musolf, Holstein, J.E.

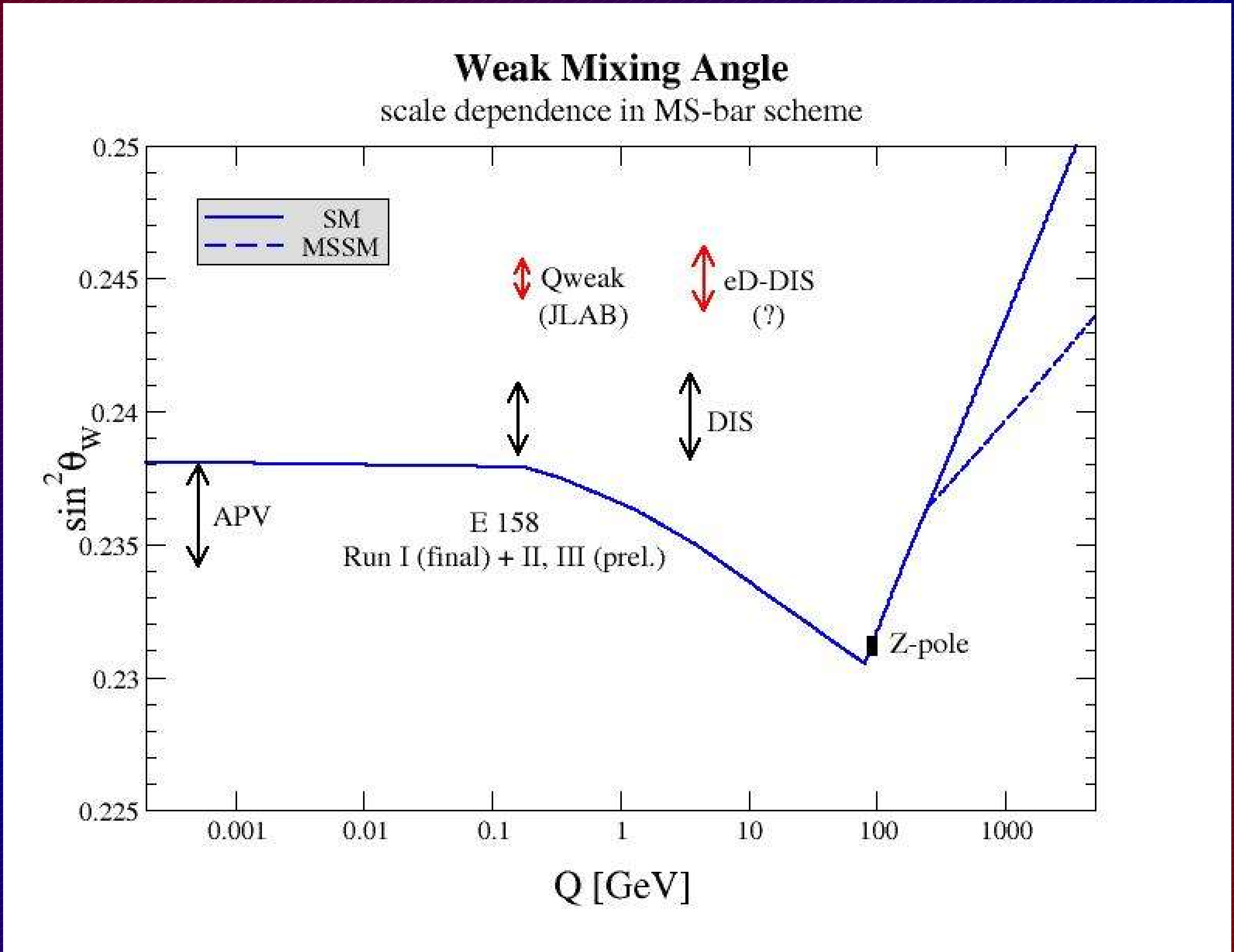
$$B_{ZZ} \rightarrow B_{ZZ}\left[1 - \frac{\alpha_s(M_Z)}{\pi}\right]$$

(28 +- 0.2%)

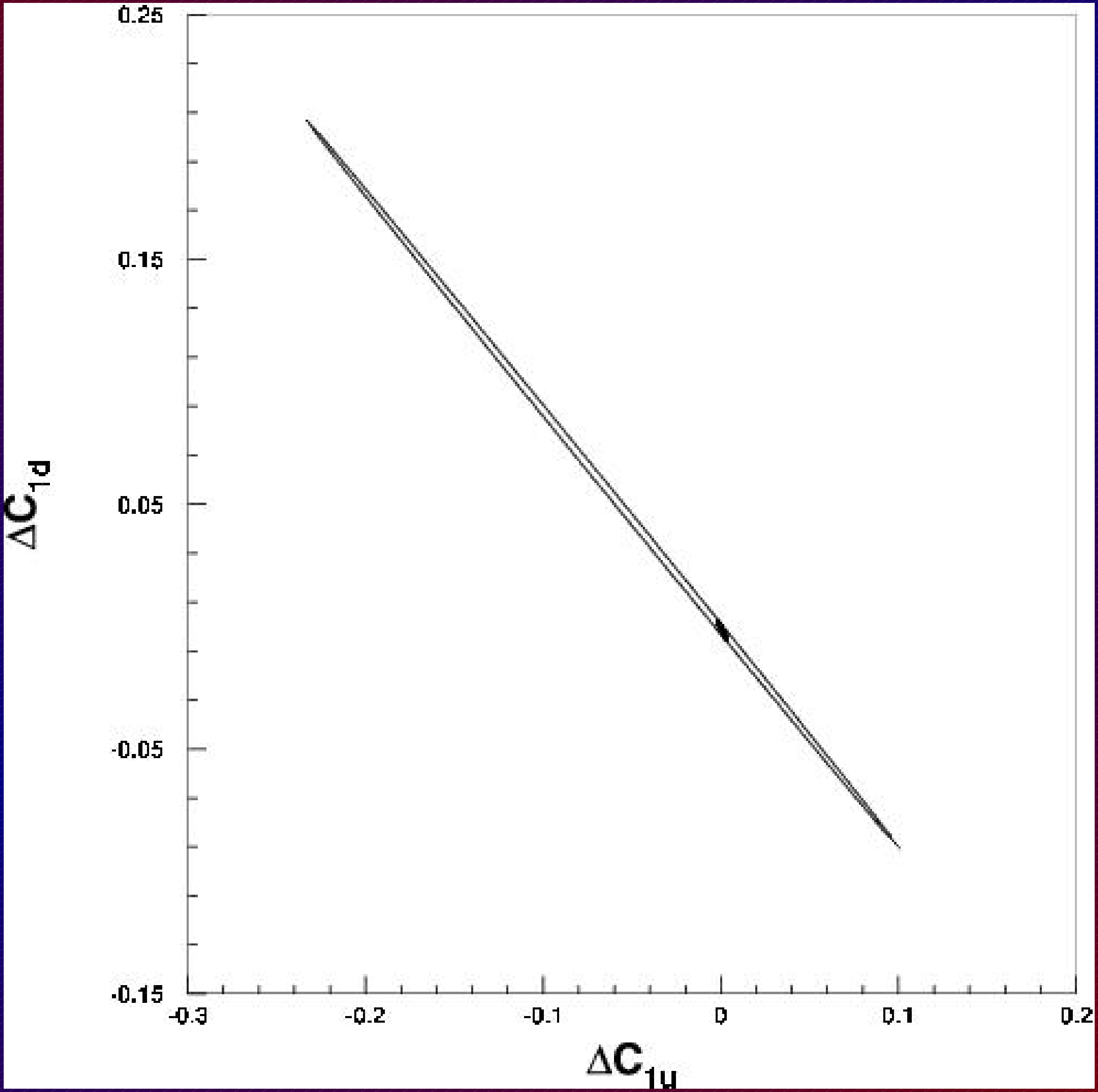
$$B_{\gamma Z} = \frac{5\hat{\alpha}}{2\pi}(1 - 4\hat{s}^2)\left[\ln\left(\frac{M_Z^2}{\Lambda^2}\right) + C_{\gamma Z}(\Lambda)\right]$$

(7 +- 0.7%)

Weak mixing angle



Effective couplings



Conclusions

- SM still in perfect shape
- $M_H = 113^{+56}_{-40}\,\mathrm{GeV}$ $\quad M_H < 246\,\mathrm{GeV}$ (95% CL)
- $\alpha_s = 0.1213 \pm 0.0018 (Z - \mathrm{lineshape} + \tau_\tau)$
- Off Z-peak information important
- SUSY looking good with a Z'