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: **ν**-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

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

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

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

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

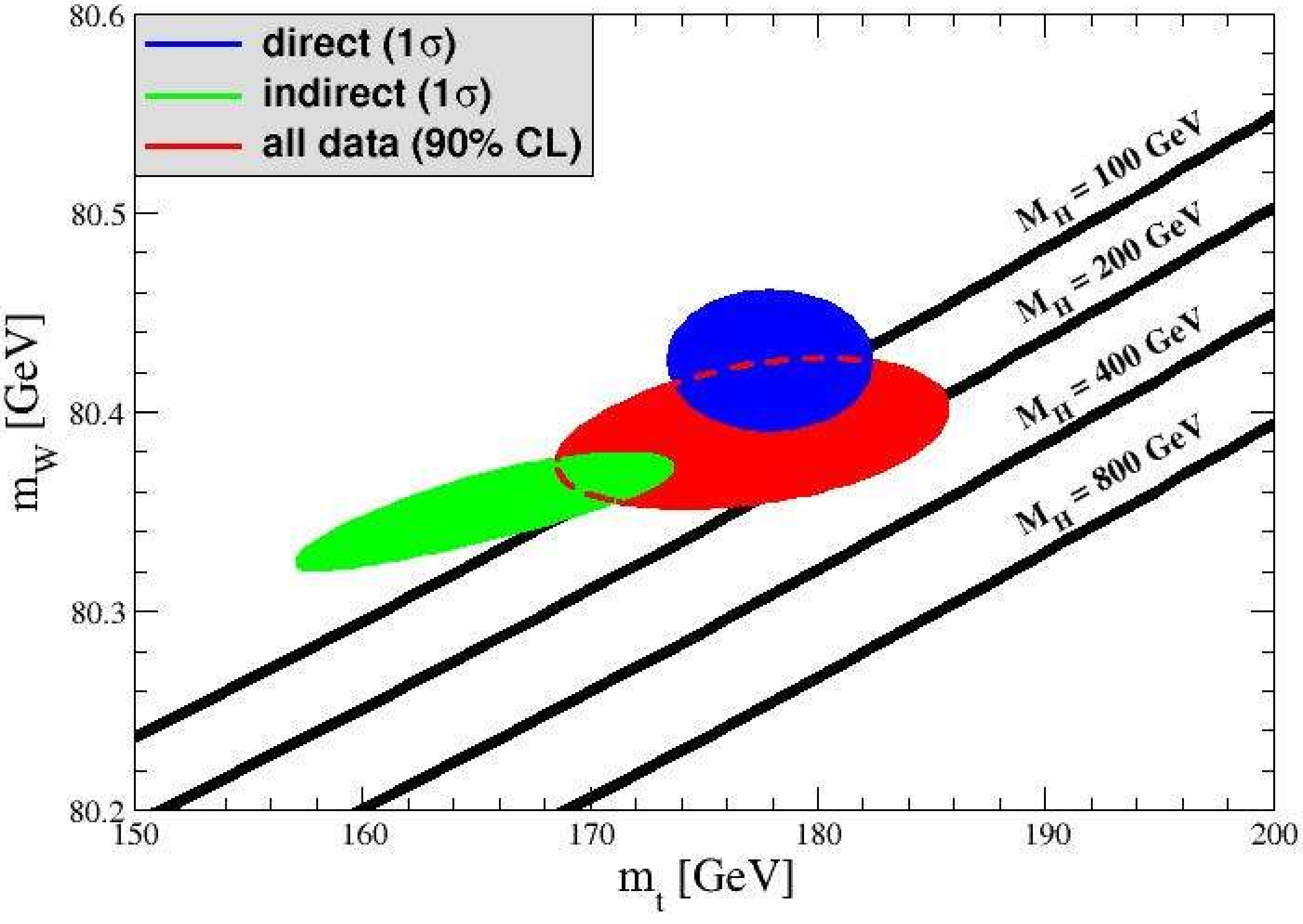
CDF I+II, DØ

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

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

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

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



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]

Strong coupling

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

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

perfect agreement with [not included]:

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

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

LEP 1 deviations

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

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

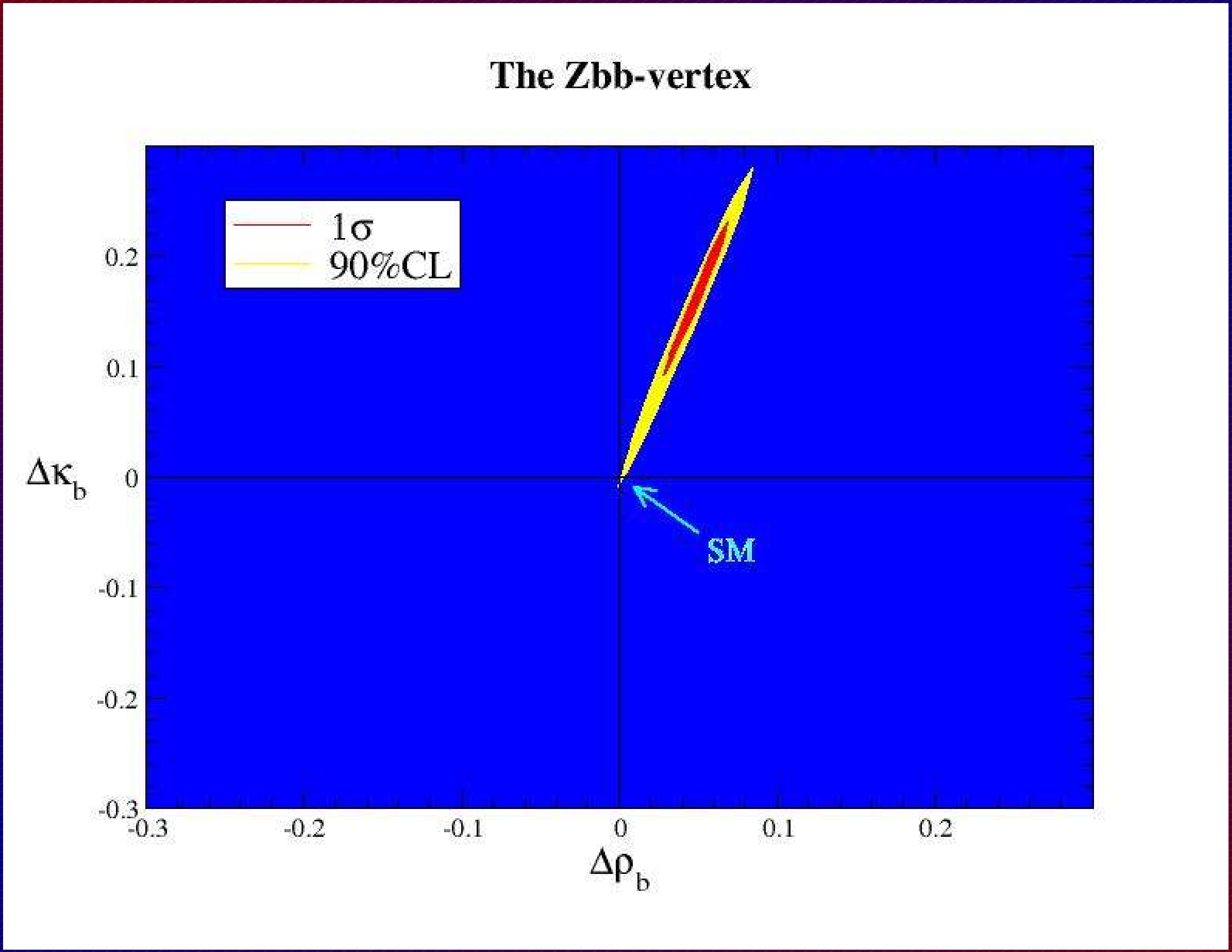
$A_{LR}^{0} = 0.1513 \pm 0.0021$

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

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

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

ALEPH, DELPHI, L3, OPAL


The Zbb-vertex
1σ
90%CL
SM
Δκb
Δρb
0.2
0.1
0
-0.1
-0.2
-0.3
-0.3
-0.2
-0.1
0
0.1
0.2

Other deviations

$g_L^2 = 0.30005 \pm 0.00137$ NuTeV

$g_L^2 = 0.30397 \pm 0.00023 \; [\mathrm{SM}] \quad (-2.9\sigma)$

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

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

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

$\sigma_{\mathrm{had}}: \; 1.7\sigma \qquad R_b: \; -2.1\sigma \qquad A_{FB}(b): \; -1.6\sigma$

M_H

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

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

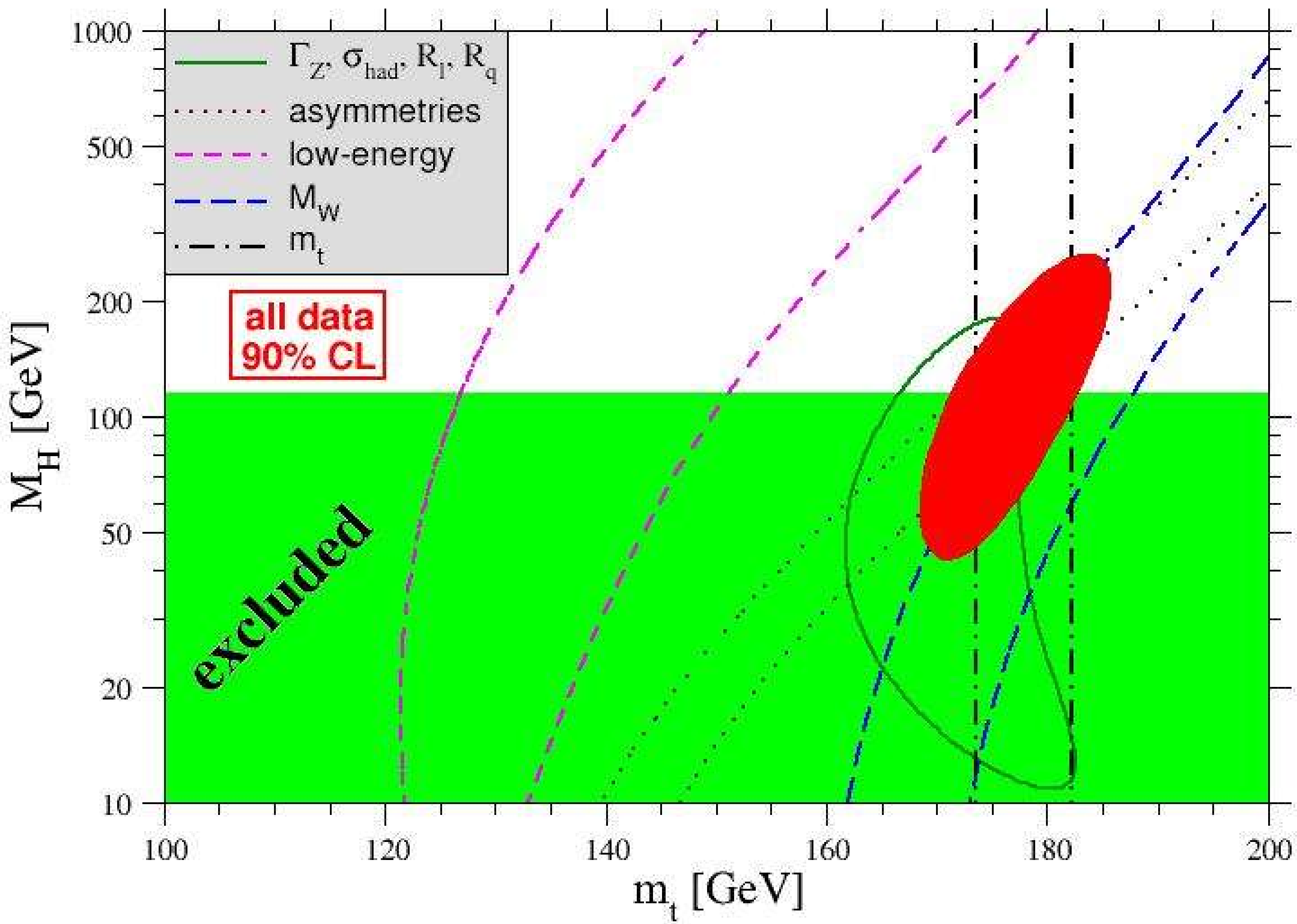
ALEPH, DELPHI, L3, OPAL

90% central confidence interval:

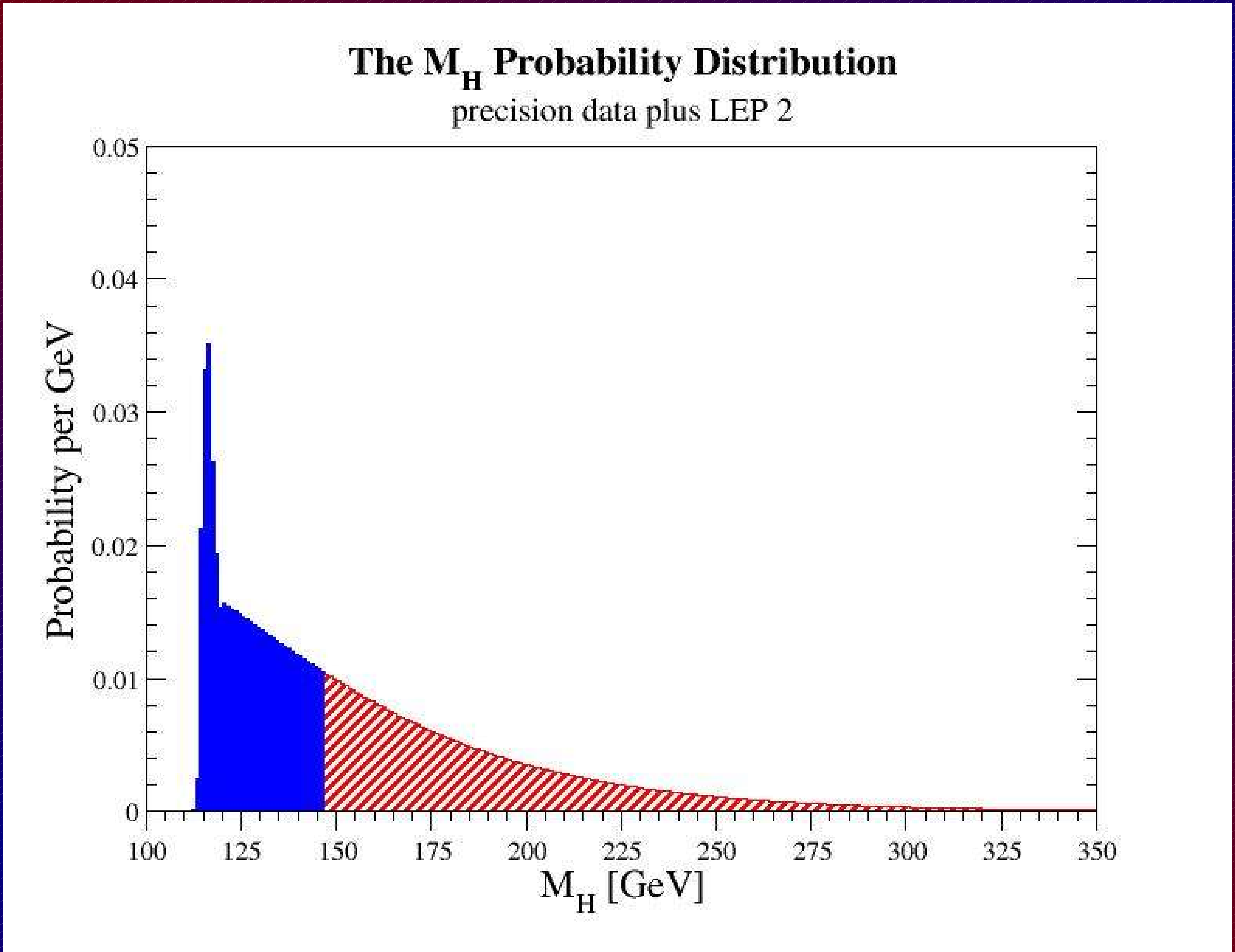
$53\,\mathrm{GeV} < M_H < 213\,\mathrm{GeV}$

Including direct searches:

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



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]
1000
500
200
100
50
20
10
100
120
140
160
180
200


The M_H Probability Distribution
precision data plus LEP 2
Probability per GeV
0.05
0.04
0.03
0.02
0.01
0
100
125
150
175
200
225
250
275
300
325
350
M_H [GeV]

SM issues

A very successful prediction:

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

Less successful predictions:

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

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
- $\lambda = T_3 \sqrt{g^2 + g'^2}$ ↔ $M_H \leqslant 150\,\mathrm{GeV}$

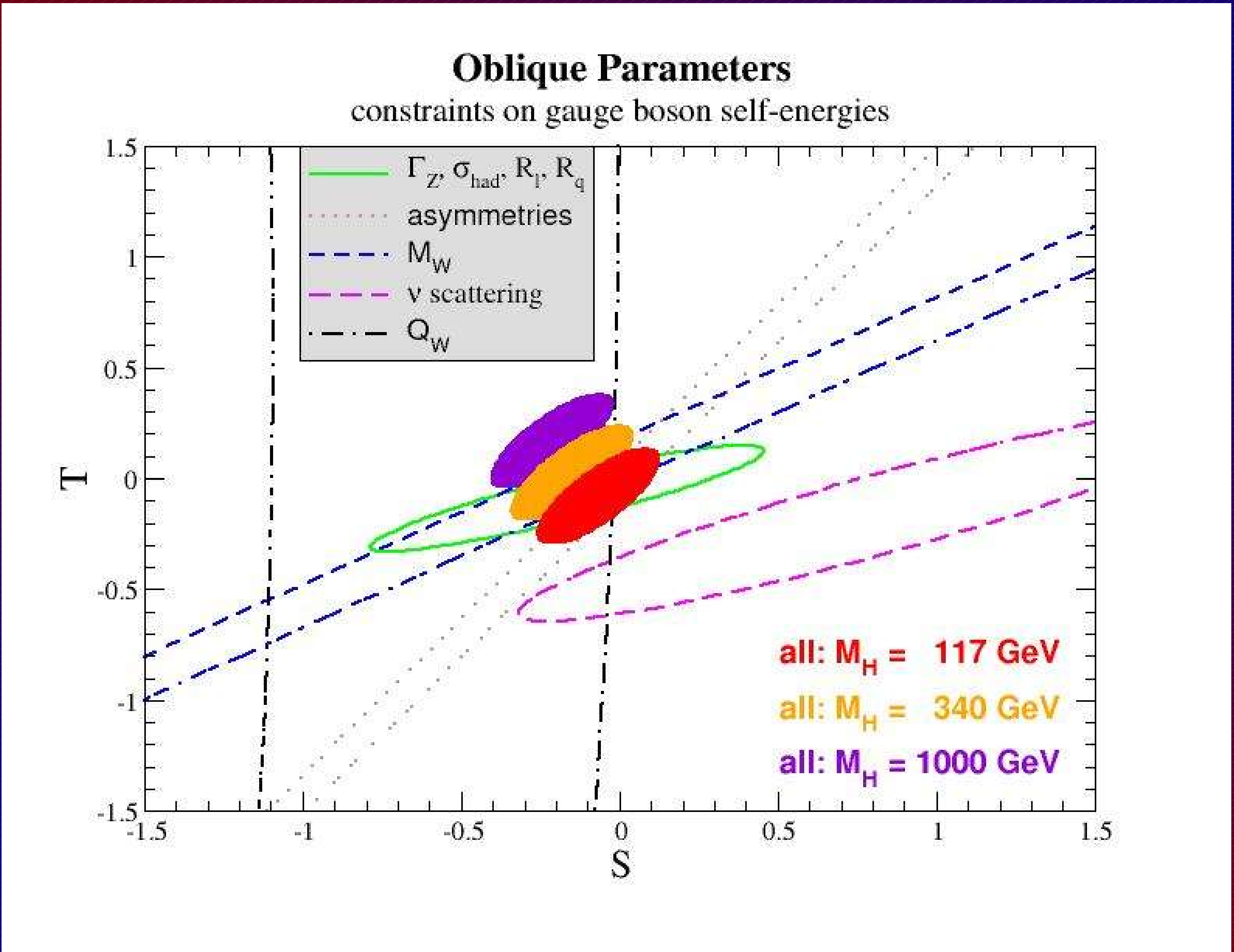
Supersymmetry – The Bad

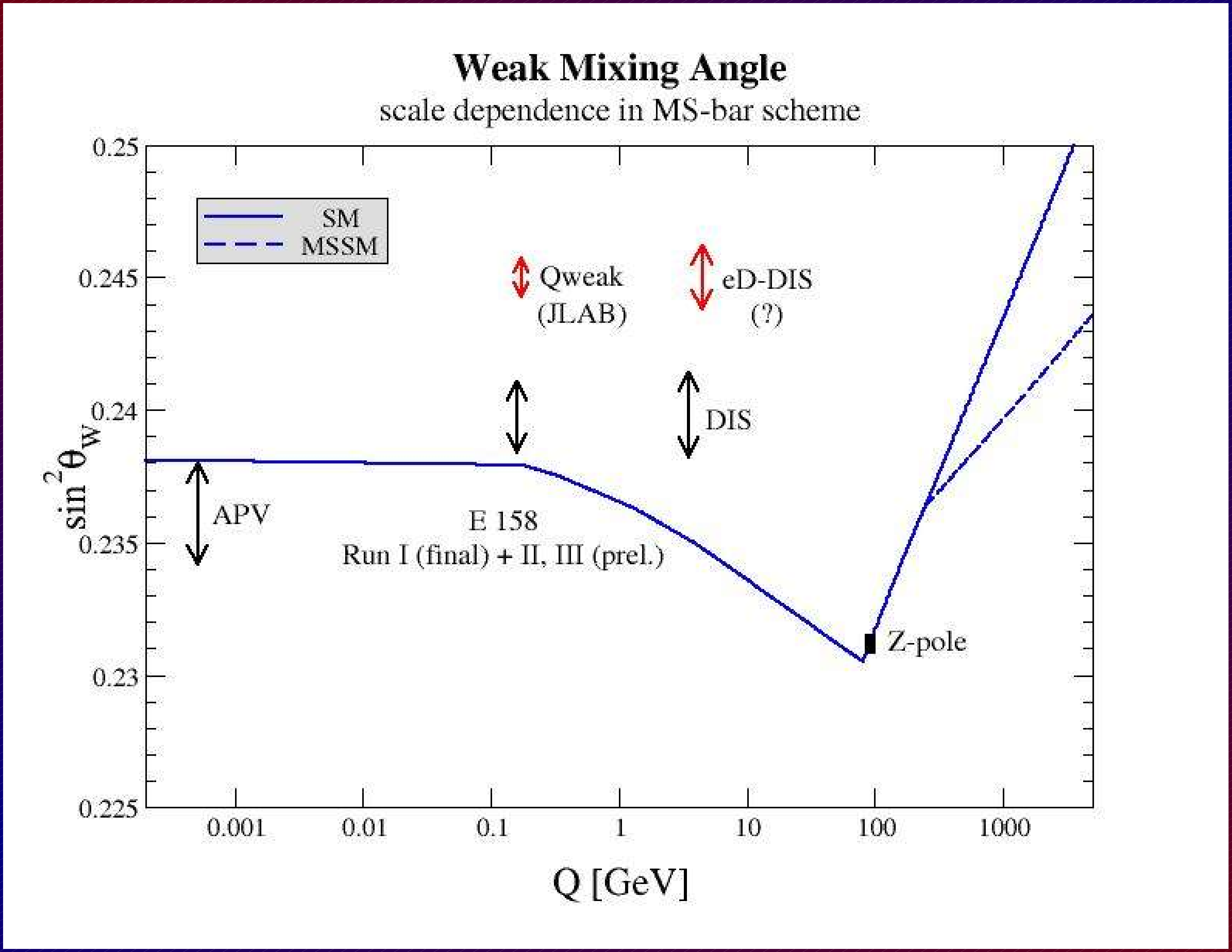
- SUSY breaking
- μ - problem
- Little hierarchy problem
- Flavor and CP problems
- $\Lambda_C = \mathcal{O}(M^4_{SUSY})$

Supersymmetry – The Ugly

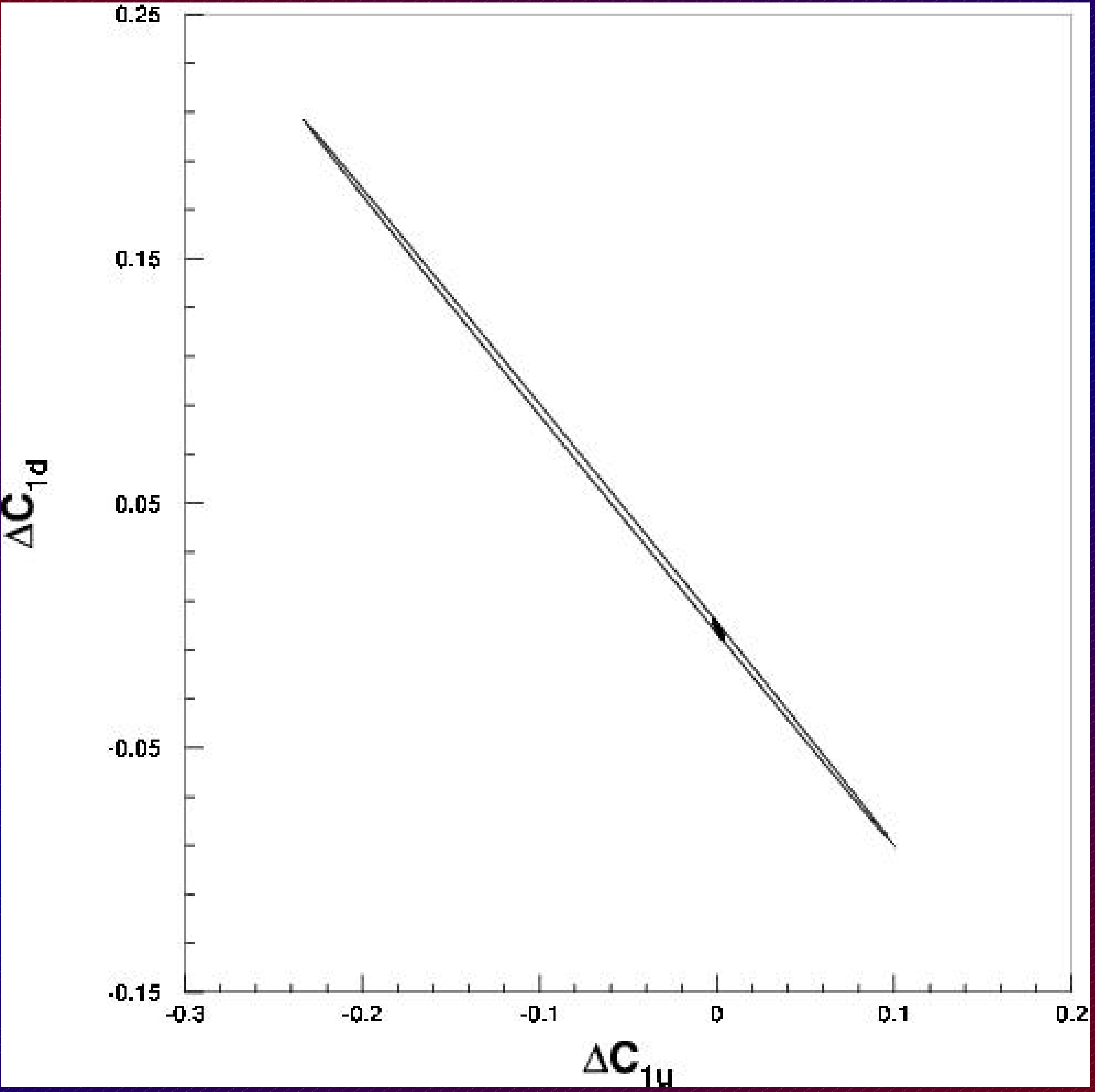
$$L_Y^{SUSY} = \lambda \bar{E}_L E_L e_R + \lambda' \bar{Q}_L E_L d_R + \lambda'' \bar{u}_R \bar{d}_R \bar{d}_r + \mu' \bar{E}_L H_u$$

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


Oblique Parameters
constraints on gauge boson self-energies
Γ_Z, σ_had, R_l, R_q
asymmetries
M_W
ν scattering
Q_W
all: M_H = 117 GeV
all: M_H = 340 GeV
all: M_H = 1000 GeV
T
S
1.5
1
0.5
0
-0.5
-1
-1.5
-1.5
-1
-0.5
0
0.5
1
1.5



Weak Mixing Angle
scale dependence in MS-bar scheme
SM
MSSM
Qweak
(JLAB)
eD-DIS
(?)
DIS
APV
E 158
Run I (final) + II, III (prel.)
Z-pole
sin²θ_W
Q [GeV]
0.25
0.245
0.24
0.235
0.23
0.225
0.001
0.01
0.1
1
10
100
1000


0.25
0.15
0.05
-0.05
-0.15
-0.3
-0.2
-0.1
0
0.1
0.2
ΔC_{1d}
ΔC_{1u}