united nations educational, scientific and cultural organization

international atomic energy agency

the
abdus salam
international centre for theoretical physics

SMR.1317 - 3

SUMMER SCHOOL ON PARTICLE PHYSICS

18 June - 6 July 2001

STANDARD MODEL AND HIGGS PHYSICS

Lecture II

J. ELLIS
CERN, Geneva, SWITZERLAND

Please note: These are preliminary notes intended for internal distribution only.

strada costiera, 11 - 34014 trieste italy - tel. +39 0402240111 fax +39 040224163 - sci_info@ictp.trieste.it - www.ictp.trieste.it

2 - Precision Electroweak Physics

2.1 - Higher orders

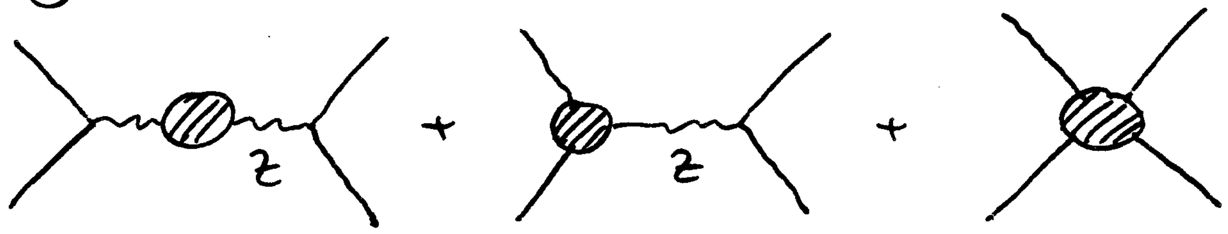
2.2 - Sensitivity to unseen particles

2.3 - Standard Model fit to electroweak data

2.4 - Possible physics with GigaZ

1.1 - Higher Orders

(CERN 95-03



propagator vertex box

\+ multi-photon emission, ...

(pseudo-)observables

$$\underbrace{m_Z, m_W}_{\text{complex poles}}, \underset{\uparrow}{\sigma_h}, \Gamma_Z, \Gamma_i, \Gamma_{inv}, A_{FB}, A_{LR}, P^\tau, \ldots$$

complex poles ISR soft γ, ... to be deconvoluted

e.g. $\sigma_h = \dfrac{12\pi\Gamma_e\Gamma_h}{m_Z^2\Gamma_Z^2}$ removes boxes, γ, ISR, ...

@ Born level: $g_a^f = I_3^f$, $g_v^f = I_3^f - 2Q^f \sin^2\theta$

in general:

Z pol^n vector

$$\mathcal{M}_{eff}^{Z\bar{f}f} = \bar{u}_f \gamma_\alpha \left[\mathcal{G}_v^f(m_Z^2) - \mathcal{G}_a^f(m_Z^2)\gamma_5 \right] v_f \epsilon_Z^\alpha$$

S-matrix element $\ni \mathcal{G}_i^e(m_Z^2)\,\mathcal{G}_j^f(m_Z^2)$ @ $t=0$

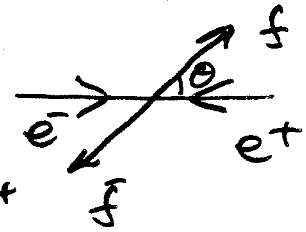
define: $\boxed{g_{V,A}^f \equiv \mathrm{Re}\,\mathcal{G}_{V,A}^f(m_Z^2)}$, $\mathcal{A}^f \equiv \dfrac{2 g_V^f g_A^f}{(g_V^f)^2 + (g_A^f)^2}$

then $A_{FB}^f = \frac{3}{4}\mathcal{A}^e\mathcal{A}^f$, $A_{LR} = \mathcal{A}^e$, $P^\tau = -\mathcal{A}^\tau$, ...

Asymmetries

forward-backward $\quad A^f_{FB} \equiv \dfrac{\int_0^1 d\cos\theta - \int_{-1}^0 d\cos\theta}{+}$

$$A^f_{FB} = \frac{3}{4} A^e A^f$$



left-right $\quad A_{LR} \equiv \dfrac{\sigma_{e^-_L e^+} - \sigma_{e^-_R e^+}}{+}$

$$A_{LR} = A^e$$

τ polarization

$$P^\tau = -A^\tau$$

where $\quad A^f \equiv \dfrac{2 g^f_V g^f_A}{(g^f_V)^2 + (g^f_A)^2}$

with $\quad g^f_a = I^f_3$

$\qquad\; g^f_v = I^f_3 - 2Q^f \sin^2\theta \qquad$ @ tree level

radiative corrections $\rightarrow$ next lecture

Renormalization Schemes

to calculate observable

physical input parameters:

$$\boxed{G_\mu \,,\; M_Z \,,\; \alpha_{em}} \leftarrow \text{best measured}$$

$G_\mu = 1{\cdot}16639(2) \times 10^{-5}\,\text{GeV}^{-2}$

$M_Z = 91{\cdot}1875(21)$ GeV

$\alpha_{em} = 1/137{\cdot}0359895(61)$

in practice effectively replaced by $\bar{\alpha} \equiv \alpha_{em}(M_Z)$
↳ later

different schemes used:

on-shell	G_μ	*	$\overline{MS}$
$\sin^2\theta_W = 1 - M_W^2/M_Z^2$			like QCD
(BHM/WOH, ZFITTER)			(TOPAZ0)

many common features:

QED, QCD, $\alpha\alpha_s$ in

some 2-loop: $G_\mu^2 m_t^4$, $\alpha_s G_\mu m_t^2$, $\alpha\alpha_s^2$, ...

some differences:

higher-order electroweak: 2-loop , $\alpha^2 m_\mu^2$, ..

resummation of 1-loop

On-shell Schemes

(BHM, WOH, ZFITTER ...

$$G_\mu = \frac{\pi}{\sqrt{2}} \frac{\alpha}{s_W^2 c_W^2 m_Z^2 \rho_c}$$

$\Delta\alpha$, W propagator vertex, box

include 1+2-loop effects:

dominant

$$\frac{1}{\tau_\mu} = \frac{G_\mu^2 m_\mu^5}{192\pi^3}\left(1 - \frac{8m_e^2}{m_\mu^2}\right)\left[1 + \frac{\alpha}{2\pi}\left(1 + \frac{2\alpha}{3\pi}\ln\frac{m_\mu}{m_e}\right)\left(\frac{25}{4} - \pi^2\right)\right]$$

$$\rho_c = 1/1-\Delta r$$

use Δr to calculate $\theta_W \Rightarrow$ predict m_W

$$m_W = \frac{m_Z}{\sqrt{2}}\sqrt{1 + \sqrt{1 - \frac{4\pi\alpha}{\sqrt{2}G_\mu m_Z^2[1-\Delta r(m_W)]}}}$$

different codes use different gauges, field ren^n, ...

$\overline{\text{MS}}$ Schemes

(TOPAZ0, ...

fit α, G_μ, m_Z using bare parameters

$$g^0, m_W^0, \sin^2\theta_0 = f_i(\alpha, G_\mu, m_Z, \Delta) \qquad \Delta \equiv \frac{-2}{n-4} + \gamma_E - \ln\pi$$

e.g. leading-order approximation to $\sin^2\theta_0$

$$\hat{s}^2 = \frac{1}{2}\left[1 - \sqrt{1 - \frac{4\pi\alpha(m_Z)}{\sqrt{2}G_\mu m_Z^2 \rho_Z^R}}\right] \quad \left(\text{solves } G_\mu = \frac{\pi\hat{\alpha}}{\sqrt{2}m_Z^2\hat{s}^2\hat{c}^2\rho_Z^R}\right)$$

where $$(\rho_Z^R)^{-1} = 1 + \frac{G_\mu m_Z^2}{2\sqrt{2}\pi^2}\left[\text{UV-finite combination of 2-point functions}\right]$$

How an electroweak code works

(CERN 95-03

FLOWCHART OF ZFITTER/BHM/WOH

Select minimal set of parameters in the MSM Lagrangian: $\alpha_0, M_{W0}, M_{Z0}, M_{H0}, m_{f0}$ (including m_{t0}); note that α_{W0}, α_{Z0} and VEV η are not among these.

Define renormalization Z-factors for each bare parameter and each field (Z-matrices for Z$-\gamma$ and fermion mixing — for ZFITTER only). Fix Z-factors on mass shell. Use dimensional regularization $(1/\epsilon, \mu)$.

Lagrangian now depends only on physical fields, couplings and masses, and on counterterms (Z-factors).

Expand Z-factors; $Z_i = 1 + \alpha f_i$, where $\alpha = \alpha(0)$ and f_i's are functions of physical input M_W, M_Z, M_H, m_f and $1/\epsilon$ and μ.

Calculate one–loop electroweak amplitudes with graphs, including loops and counterterms; $1/\epsilon$ and μ drop out.

Improve one-loop results by RG-techniques and by proper resummation of the higher-order e.w. terms. Define improved Born approximation.

Select experimental inputs: $\alpha(0)$, M_Z, G_μ (τ_μ).

Get M_W from $G_\mu = (\pi/\sqrt{2})\,(\alpha/s_W^2\, c_W^2\, M_Z^2)\,\rho_c$, where ρ_c depends on m_t, M_H, $\alpha(0)$, M_W, M_Z and $s_W^2 = 1 - M_W^2/M_Z^2$.

Calculate Z^0 decay observables, with m_t and M_H free, in terms of G_μ, $\alpha(0)$, M_Z.

Introduce gluonic corrections into quark loops and QED + QCD final state interactions in terms of $\bar{\alpha}$, $\hat{\alpha}_s(M_Z)$, $m_b\,(M_Z)$, m_t.

Compare the results with electroweak experimental data, exhibit M_Z, m_t, M_H, and $\hat{\alpha}_s(M_Z)$ dependence.

Figure 8: BHM/WOH ZFITTER flowchart.

Running of α_{em}: $0 \to m_Z$

$$\alpha_{em}(m_Z) \equiv \bar{\alpha} = \frac{\alpha}{1-\Delta\alpha}$$

with leptonic, hadronic contributions

$$\Delta\alpha_l = \frac{\alpha}{3\pi}\sum_l\left[-\frac{5}{3} - 4\frac{m_l^2}{m_Z^2} + \beta_l\left(1+2\frac{m_l^2}{m_Z^2}\right)\ln\frac{\beta_l+1}{\beta_l-1}\right]$$

$$= 0.0314129 \qquad \text{where } \beta_l \equiv \sqrt{1-\frac{4m_l^2}{m_Z^2}}$$

hadronic contribution:

$$\Delta\alpha_h = \frac{\alpha m_Z^2}{3\pi}\,\mathrm{Re}\int_{4m_\pi^2}^{\infty} ds\,\frac{R(s)}{s(m_Z^2 - i\epsilon - s)}$$

where $R(s)$ is hadronic cross section $e^+e^- \to$ hadron

$$R(s) \equiv \sigma_{e^+e^-}(s)/\sigma_0(s) \quad : \quad \sigma_0(s) = \frac{4}{3\pi}\frac{\alpha^2}{s}$$

estimate using data: low E, thresholds

theory: QCD in high-E continuum

Recent estimate:

$$\Delta\alpha_h = 0.02761 \pm 0.00036$$

(Burkhardt + Pietrzyk: 0

other recent calculations:

(Davier + Höcker, Martin + Outhwaite + Ryskin, Erler)

Ingredients in estimate of $\Delta\alpha_h$

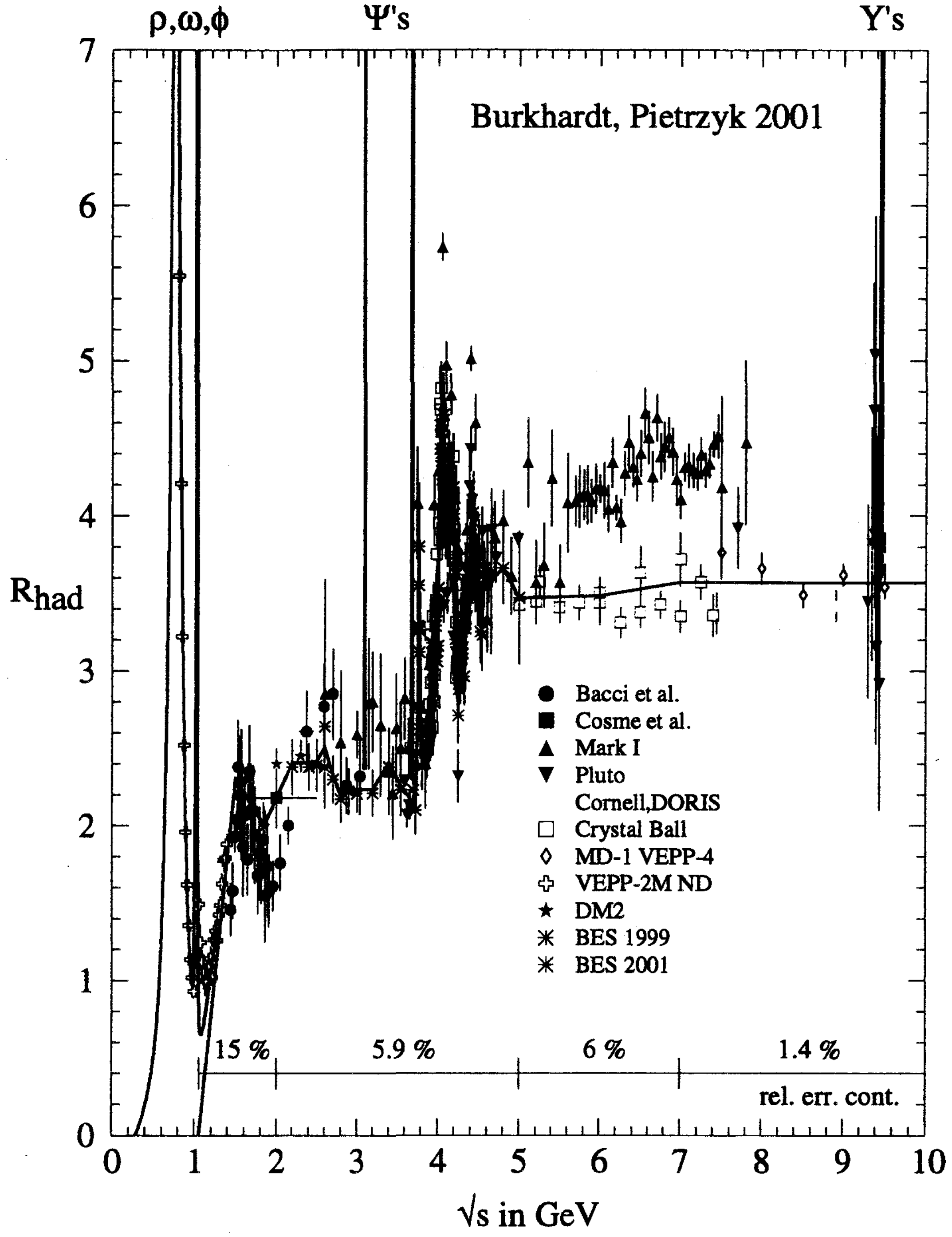


Fig. 1. $R_{\rm had}$ including resonances. Measurements are shown with statistical errors. In addition there are overall systematic errors (up to 20% in case of Mark I). The relative uncertainty assigned to our parametrization is shown as band and given with numbers at the bottom.

(Burkhardt + Pietrzyk 01

Relative contributions to $\Delta\alpha_h$

contributions at m_Z $\boxed{\text{Burkhardt, Pietrzyk 2001}}$

dominant in $g_\mu - 2$.

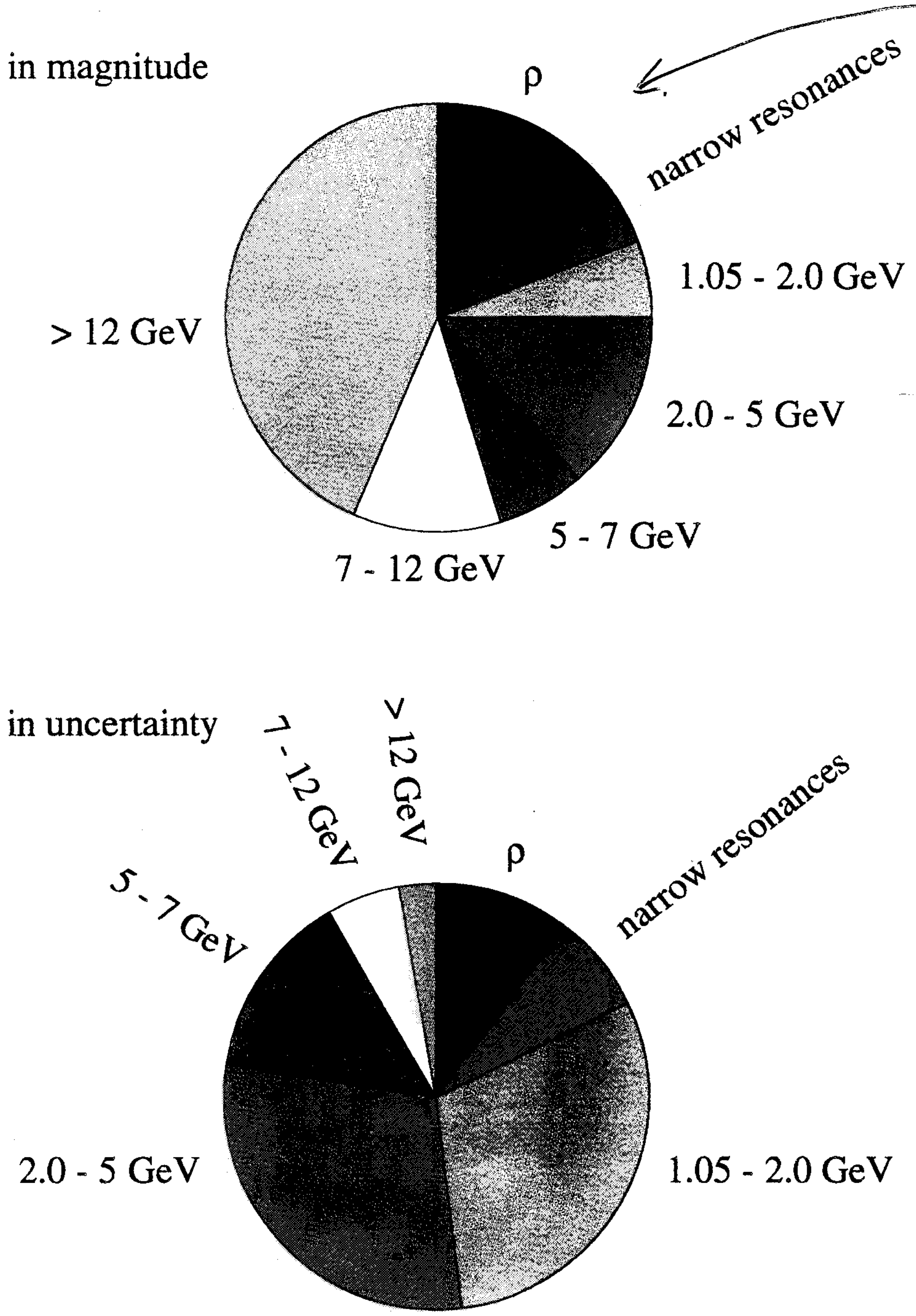


Fig. 2. Relative contributions to $\Delta\alpha^{(5)}_{\text{had}}(m_Z^2)$ in magnitude and uncertainty.

9

Recent determinations of $\Delta\alpha_h$

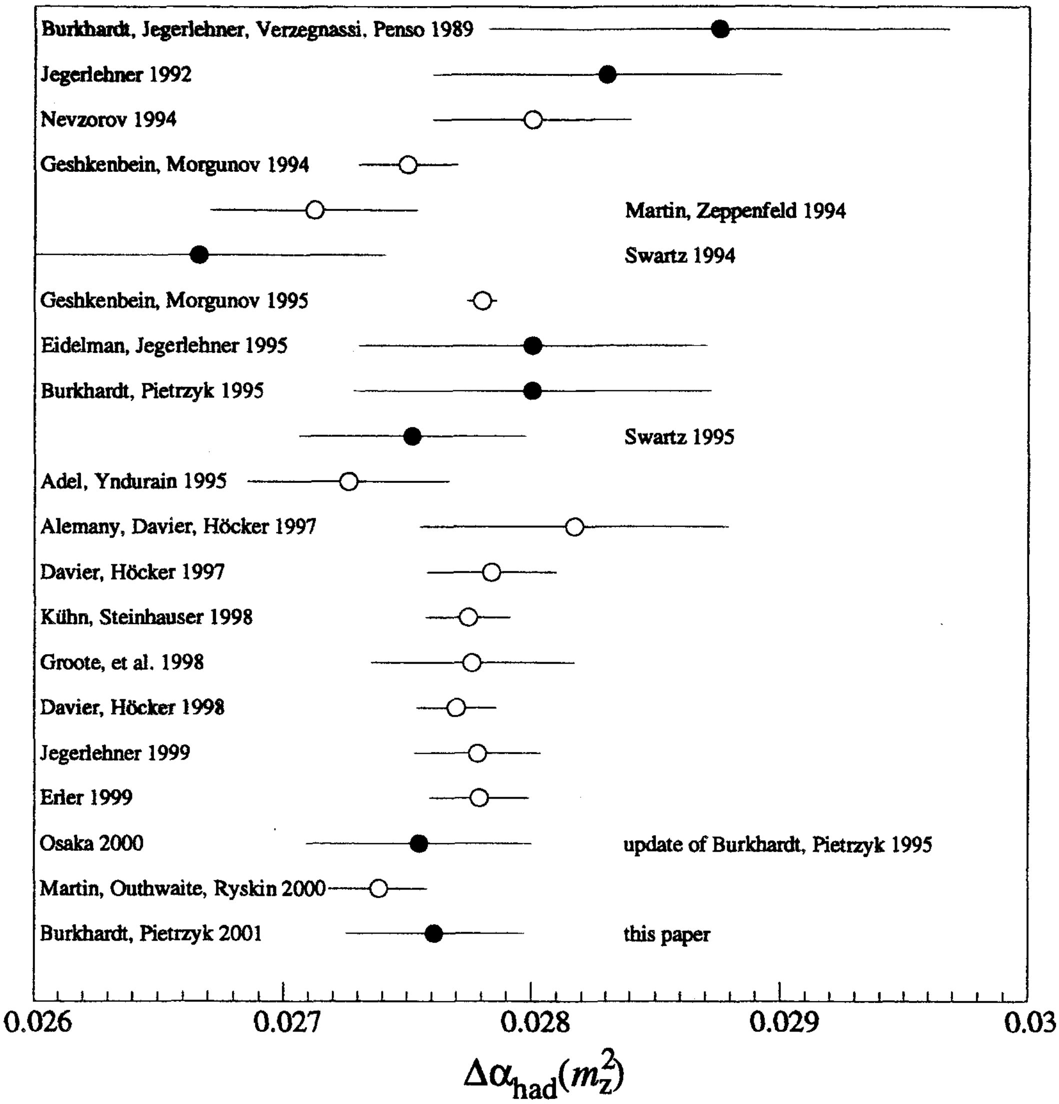


Fig. 4. Comparison of recent estimates of $\Delta\alpha^{(5)}_{\rm had}(m_Z^2)$. Estimates based on dispersion integration of the experimental data are shown with solid dots and estimates relying on additional theoretical assumptions shown as open circles.

$\longrightarrow$ lower m_H

(Burkhardt+Pietrzyk: 01

11

2- Sensitivity to unseen particles

at one loop (Veltman)

$$M_W^2 \sin^2\theta_W = m_Z^2 \cos^2\theta_W \sin^2\theta_W = \frac{\pi\alpha}{\sqrt{2}\,G_\mu}(1+\Delta r)$$

top quark

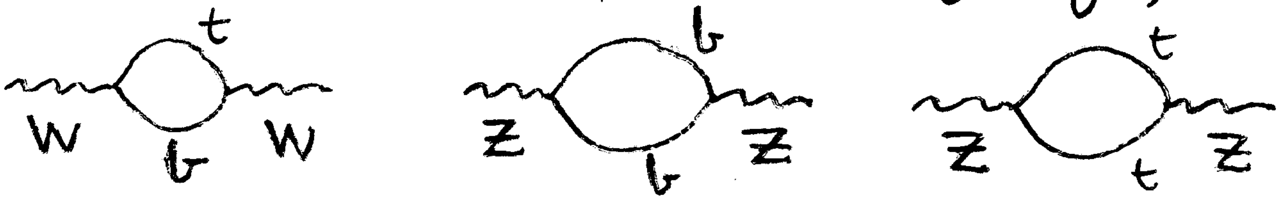
not renormalizable !!!

without it, gauge structure lost $\begin{pmatrix} t \\ b \end{pmatrix}$

measure of electroweak isospin breaking

$$\propto (m_t^2 - m_b^2)$$

seen via vacuum polarization (oblique) diagrams

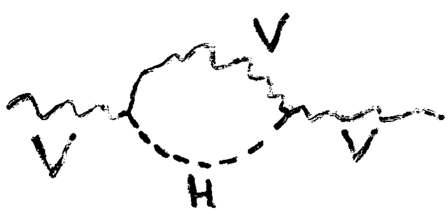


$$\Delta r \ni \frac{3G_\mu}{8\pi^2\sqrt{2}}\, m_t^2 \qquad \text{for } m_t \gg m_b$$

Higgs boson

theory $\begin{cases}\text{with} \\ \text{without}\end{cases}$ spontaneous symmetry breaking
both renormalizable @1 loop

Veltman screening theorem



physical H

$$\Delta \sim \ln\left(m_H^2 / m_Z^2\right)$$

unphysical "eaten" H

$$\Delta r \ni \frac{\sqrt{2}\,G_\mu}{16\pi^2} M_W^2 \left\{ \frac{11}{3} \ln m_H^2 / m_W^2 - \cdots \right\}$$

for $m_H \gg m_W$

Phenomenology of Z Decays (CERN 95-03

$$\Gamma_f = \Gamma(Z \to \bar{f}f) = 4 N_c^f \left[(g_V^f)^2 R_V^f + (g_A^f)^2 R_A^f \right]$$

N_c^f = # of colours = 1 or 3

R_V^f, R_A^f: QED, QCD, m_f radiation factors

simple for leptons:

$$\Gamma_l = 4 \left(\frac{G_\mu M_Z^3}{24\sqrt{2}\pi} \right) \left[(g_V^l)^2 \left(1 + \frac{3}{4\pi}\bar{\alpha}\right) + (g_A^l)^2 \left(1 - 6\frac{m_l^2}{M_Z^2} + \frac{3}{4\pi}\bar{\alpha}\right) \right]$$

$$\Gamma_\nu = 8 . \Gamma_0 . (g^\nu)^2 \quad : g^\nu = g_V^\nu = g_A^\nu$$

($\Gamma_0 \equiv \frac{G_\mu M_Z^3}{24\sqrt{2}\pi}$)

more complicated for quarks:

$$R_V^q(s) = 1 + \left(\frac{3}{4} Q_q^2 \frac{\alpha(s)}{\pi} + \frac{\alpha_s}{\pi} - \frac{1}{4} Q_q^2 \frac{\alpha}{\pi} \frac{\alpha_s}{\pi} \right)$$

$$+ \left(1.40923 + \left(\frac{44}{675} - \frac{2}{135} \ln \frac{s}{m_t^2}\right)\frac{s}{m_t^2}\right)\left(\frac{\alpha_s}{\pi}\right)^2$$

$$- 12.76706 \left(\frac{\alpha_s}{\pi}\right)^3 + 12 \frac{\bar{m}_q^2(s)}{s}\left(\frac{\alpha_s}{\pi}\right)\left(1 + 8.7\frac{\alpha_s}{\pi} + \ldots\right.$$

$$R_A^q(s) = R_V^q(s) - 2 I_3^q \left(\frac{\alpha_s}{\pi}\right)^2 \left(-\frac{37}{12} + \ln\frac{s}{m_t^2} + \frac{7}{81}\frac{s}{m_t^2} + 0.0132\left(\frac{s}{m_t^2}\right)^2 \right.$$

$$- (\text{more complicated})\left(\frac{\alpha_s}{\pi}\right)^3 + \left(\text{different } \frac{m^2}{s}\right)$$

- where running light quark mass

$$m_{pole} = \bar{m}(m)\left[1 + \frac{4}{3}\alpha_s(m) + K(\alpha_s(m))^2\right]$$

- pole mass for top quark
- ambiguity in $O(\alpha_s^2)$

Electroweak Corrections

in on-shell schemes:

$$4(g_A^f)^2 \equiv \rho_f = \frac{1}{1-\delta\rho_f}$$

$$g_V^f/g_A^f = 1 - 4|Q_f|\sin^2\theta_W \kappa_f \; : \; \kappa_f = 1+\delta\kappa_f$$

so $$\Gamma_f = \Gamma_0 N_c^f \rho_f \left[4(I_3^f - 2Q_f s_w^2 \kappa_f)^2 + 1\right]$$

μ decay: $$\rho_c = \frac{1}{1-\Delta r} = \frac{1}{(1-\Delta\alpha)\left(1+\frac{c_W^2}{s_W^2}\Delta\rho_X\right) - \Delta r_{rem}}$$

and $$\rho_f = \frac{1}{1-\Delta\rho - \Delta\rho_{f,rem}}$$

universal

same

$$\kappa_f = (1+\Delta\kappa_{f,rem})\left(1+\frac{c_W^2}{s_W^2}\Delta\rho_X\right)$$

where

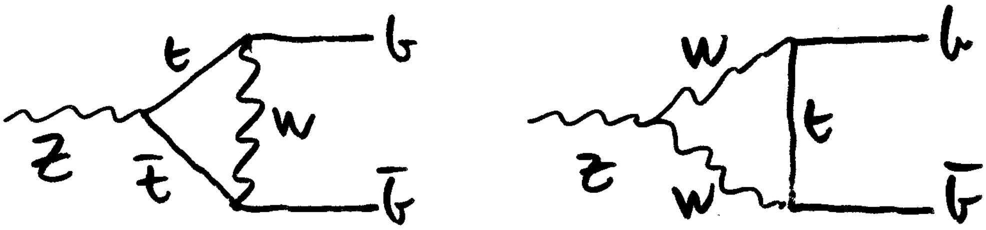
$$\Delta\rho_X = N_c \underbrace{x_t}_{\frac{G_\mu m_t^2}{8\sqrt{2}\pi^2}}\left[1 + x_t \underbrace{\Delta\rho^{(2)}\left(\frac{m_t^2}{m_H^2}\right)}_{2\text{-loop}} + \underbrace{c_1\left(\frac{\alpha_s}{\pi}\right) + c_2\left(\frac{\alpha_s}{\pi}\right)^2}_{\text{known}} + \cdots\right]$$

$$\Delta\rho = \Delta\rho_X - \cdots$$

$$\left.\begin{aligned}\Delta r_{rem} &\ni \cot^2\theta_W \Delta\bar\rho_X \\ \Delta\rho_{f,rem} &\ni -\Delta\bar\rho \\ \Delta\kappa_{f,rem} &\ni -\cot^2\theta_W \Delta\bar\rho_X\end{aligned}\right\} \quad \begin{aligned}&\Delta\bar\rho_X = \Delta\bar\rho + \cdots \\ &\Delta\bar\rho = \frac{3\alpha}{16\pi s_W^2 c_W^2}\frac{m_t^2}{m_Z^2}\times \\ &\left[1 - \frac{2}{3}\left(1+\frac{\pi^2}{3}\right)\frac{\alpha_s}{\pi}\right]\end{aligned}$$

$Z \to \bar{b}b$ Decay

additional top exchange diagrams:



@ 1 loop: $\Delta\bar{\rho}_b = \frac{\alpha}{8\pi s_W^2}\frac{m_t^2}{M_W^2}$

2-loop QCD and electroweak:

$$\rho_b \to \rho_b(1+\tau_b)^2 \quad , \quad \kappa_b \to \frac{\kappa_b}{1+\tau_b}$$

$$\tau_b = -2x_t\left[1 - \frac{\pi}{3}\alpha_s(m_t) + x_t\tau^{(2)}\left(\frac{m_t^2}{M_H^2}\right)\right]$$

known 2-loop

Two-loop calculations

$$\Delta\rho \ni 3\left(\frac{G_\mu m_t^2}{8\pi^2\sqrt{2}}\right)^2 (19-2\pi^2)$$

(van der Bij + Hoogeveen : 87

$$\Delta\rho \ni 3\left(\frac{G_\mu m_t^2}{8\pi^2\sqrt{2}}\right)\left(1-\frac{26}{9}\frac{\alpha_s}{\pi}\right)$$

(Djouadi + Verzegnassi : 87

$\Delta\rho$ for $m_H \gg m_t \gg m_W$ (Barbieri + Beccaria + Ciafaloni + Curci + Vicere : 92

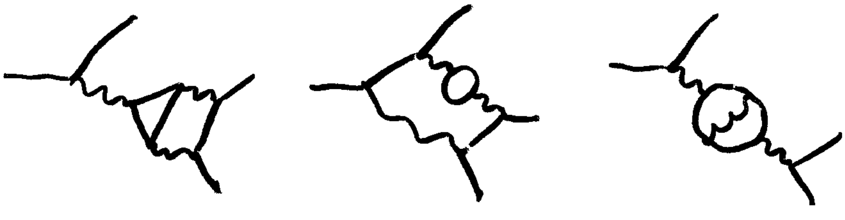
$$\ni 3\left(\frac{G_\mu m_t^2}{8\pi^2\sqrt{2}}\right)^2\Big[\frac{49}{4}+\pi^2+\frac{27}{2}\ln R+\frac{3}{2}\ln^2 R+\frac{1}{3}R\left(2-12\pi^2+12\ln R-27\ln^2 R\right)+\frac{1}{48}R^2\left(1613-240\pi^2-1500\ln R-720\ln^2 R\right)\Big]$$

also Γ_b

$$\Delta\Gamma_Z/\Gamma_Z = 0.53\times10^{-4}\left(\frac{m_H}{1\,\text{TeV}}\right)^2$$

(Barbieri + Ciafaloni + Strumia : 93

$$\Delta m_W = -0.05613\ln\left(m_H/100\,\text{GeV}\right)-0.00936\left(\ln m_H/100\,\text{GeV}\right)^2$$
$$+0.000546\left(\ln m_H/100\,\text{GeV}\right)^4-1.081\left(\frac{\Delta\alpha}{0.05924}-1\right)$$
$$+0.5235\left(\left(\frac{m_t}{174.3\,\text{GeV}}\right)^2-1\right)-0.0763\left(\frac{\alpha_s(m_Z)}{0.119}-1\right)$$



(Freitas + Hollik + Walter + Weiglein : 00

Impact of 2-loop calculations

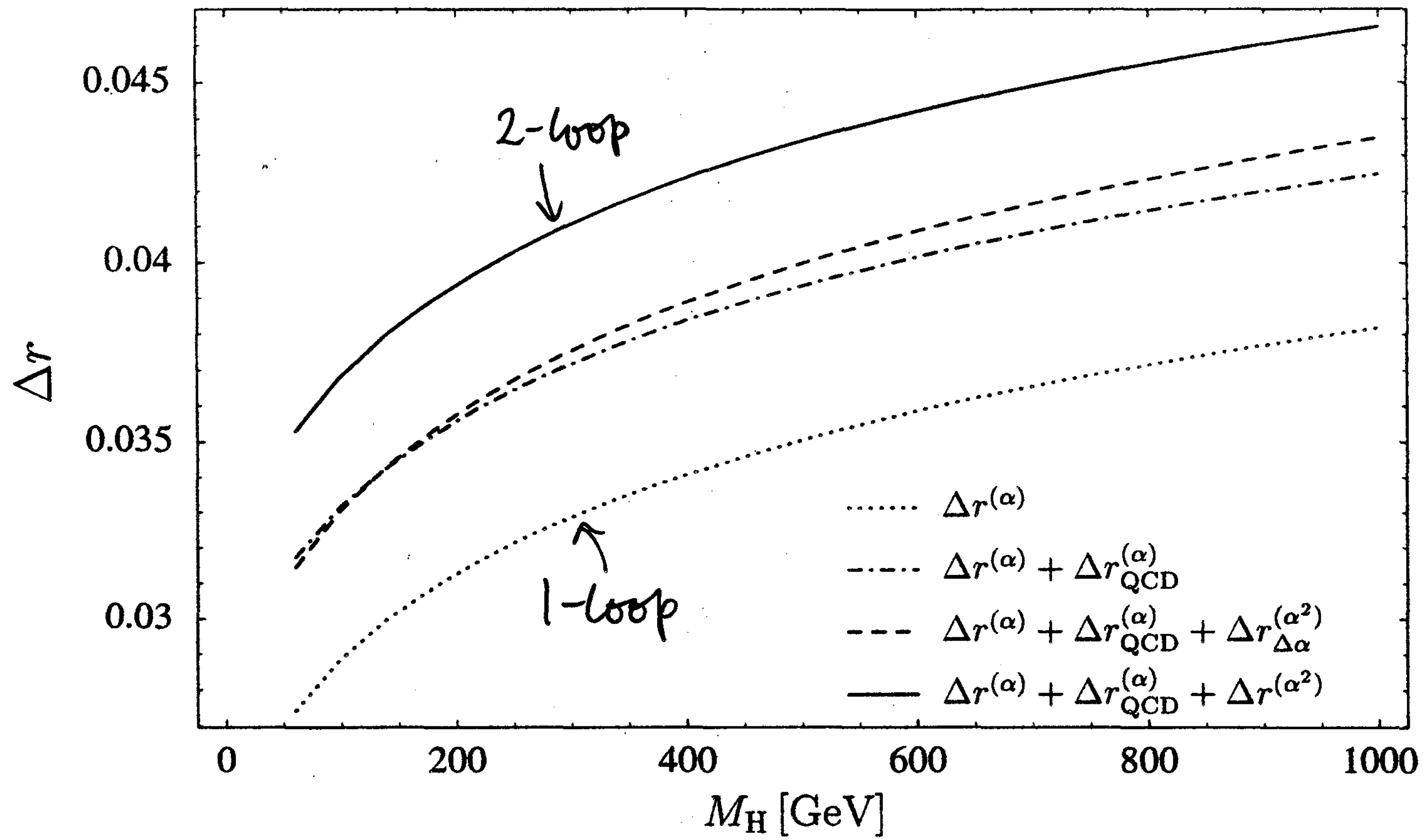


Figure 3: Different contributions to Δr as a function of M_{H}. The one-loop contribution, $\Delta r^{(\alpha)}$, is supplemented by the two-loop and three-loop QCD corrections, $\Delta r^{(\alpha)}_{\mathrm{QCD}} \equiv \Delta r^{(\alpha\alpha_s)} + \Delta r^{(\alpha\alpha_s^2)}$, and the fermionic electroweak two-loop contributions, $\Delta r^{(\alpha^2)} \equiv \Delta r^{(N_f\alpha^2)} + \Delta r^{(N_f^2\alpha^2)}$. For comparison, the effect of the two-loop corrections induced by a resummation of $\Delta\alpha$, $\Delta r^{(\alpha^2)}_{\Delta\alpha}$, is shown separately.

(Freitas + Hollik + Walter + Weiglein: 00

Theoretical Uncertainties

(CERN 95-03

- Factorization of QCD corrections

  ignorance of $O(\alpha\alpha_s)$, etc.

  how accurate to shrink electroweak blob to a point before QCD correction?

- Weak uncertainties

  leading remainder splitting:

$$\frac{1}{1-\Delta r} = \frac{1}{1-\Delta r_L - \Delta r_{rem}} \stackrel{?}{=} \frac{1}{1-\Delta r_L}\left(1 + \frac{\Delta r_{rem}}{1-\Delta r_L}\right) \simeq \ldots$$

- Scale in vertex corrections

  $\alpha(0)$ vs $\alpha(m_Z)$, $\alpha_s(m_Z)$ vs $\alpha_s(m_t)$, ...

- Linearization, resummation, ...

Typical values

$$\left.\begin{aligned} \Delta\Gamma_Z &= 0.3 \text{ MeV} \\ \Delta\sigma_0^h &= 0.01 \text{ nb} \\ \Delta R_\ell &= 0.002 \\ \sin^2\theta_{eff}^\ell &= 0.00005 \end{aligned}\right\}$$

spreads between different codes with same inputs

Figures

Pseudo-observables in different electroweak codes

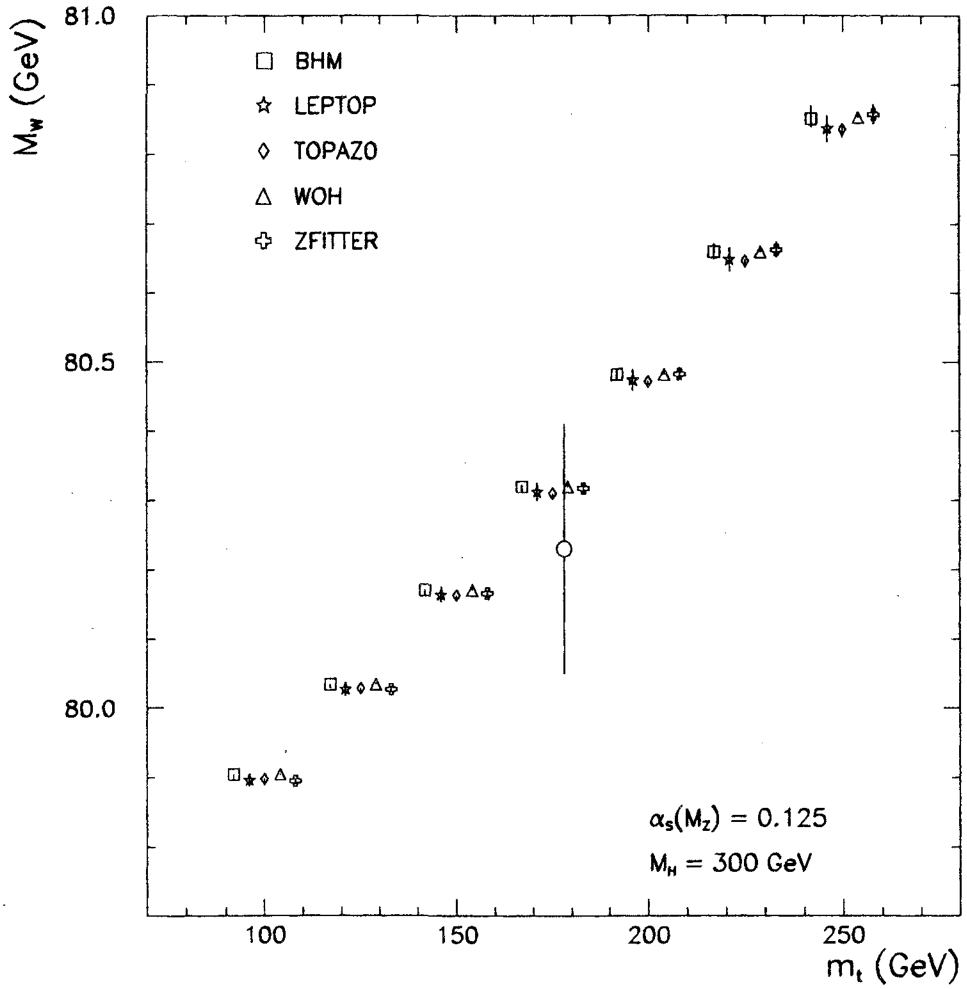


Figure 11: The BHM, LEPTOP, TOPAZO, ZFITTER, WOH predictions for M_W, including an estimate of the theoretical error as a function of m_t, for $M_H = 300\,\mathrm{GeV}$ and $\hat{\alpha_s} = 0.125$.

Comparison between electroweak codes

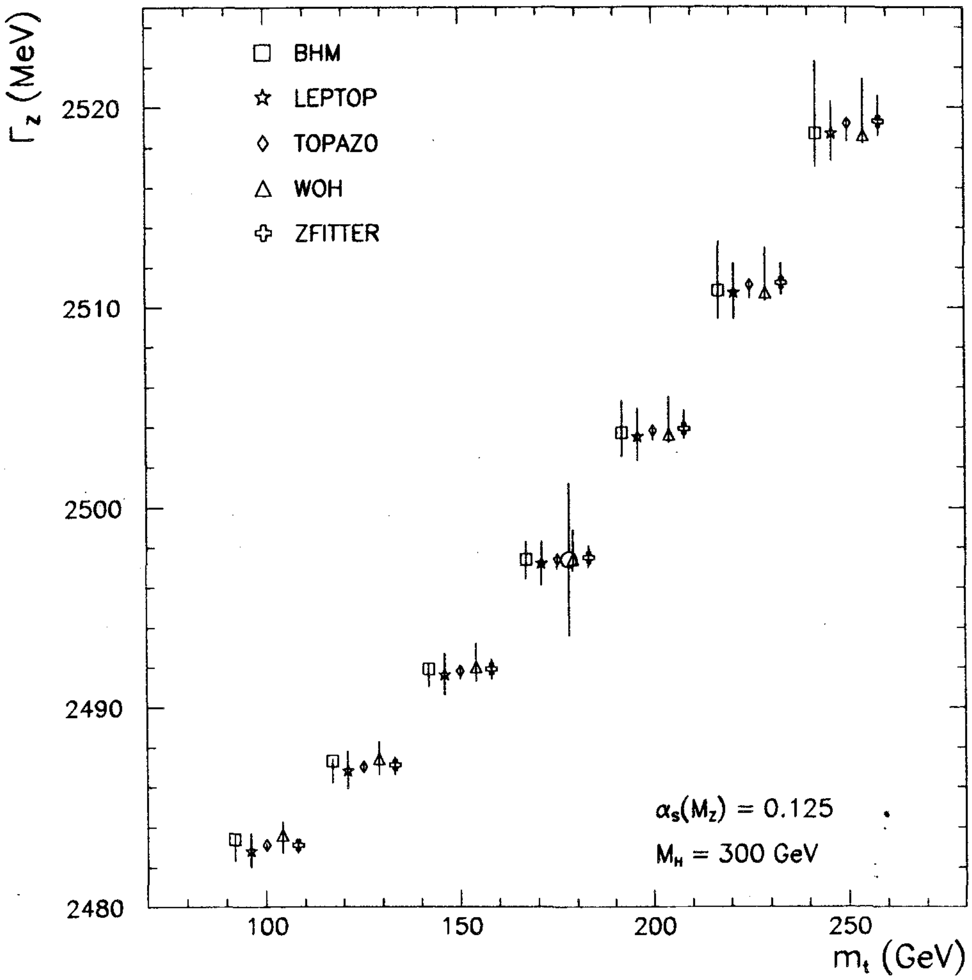


Figure 13: The BHM, LEPTOP, TOPAZO, ZFITTER, WOH predictions for Γ_z, including an estimate of the theoretical error as a function of m_t, for $M_H = 300\,\text{GeV}$ and $\hat{\alpha_s} = 0.125$.

(CERN 95-03

113

Comparison between electroweak codes

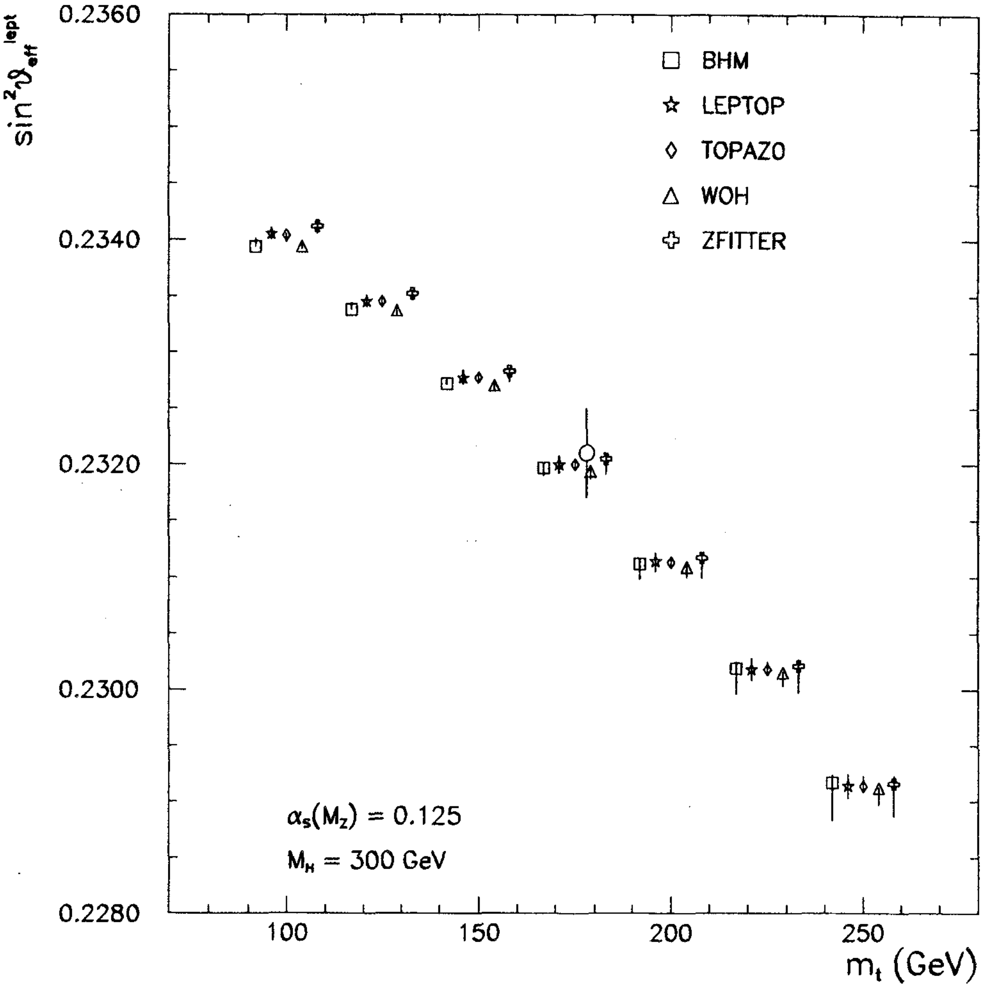
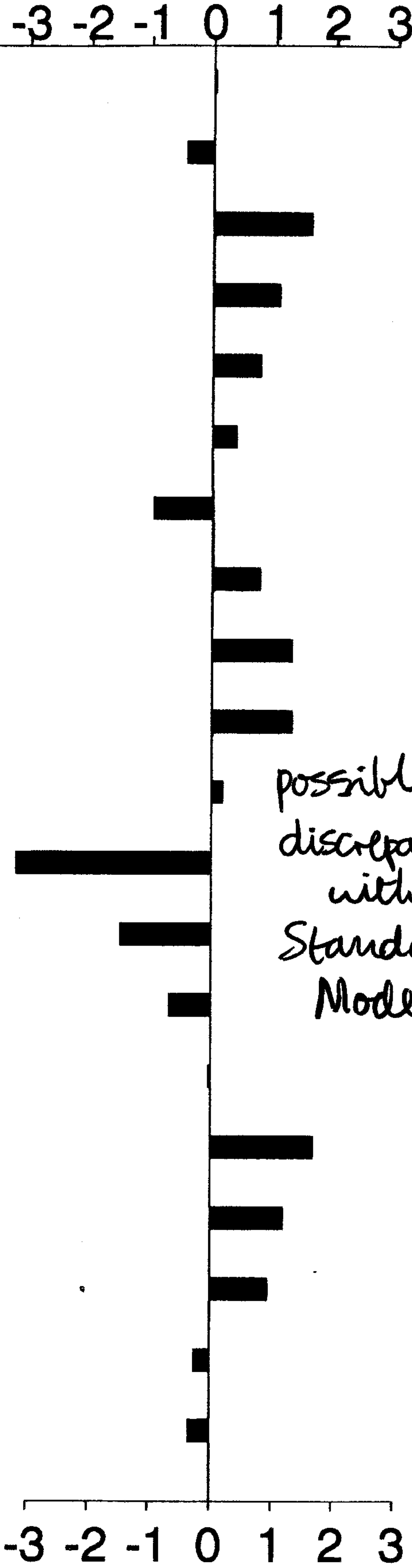


Figure 17: The BHM, LEPTOP, TOPAZ0, ZFITTER, WOH predictions for $\sin^2\theta^l_{\rm eff}$, including an estimate of the theoretical error as a function of m_t, for $M_H = 300$ GeV and $\hat{\alpha_s} = 0.125$.

(CERN 95-03

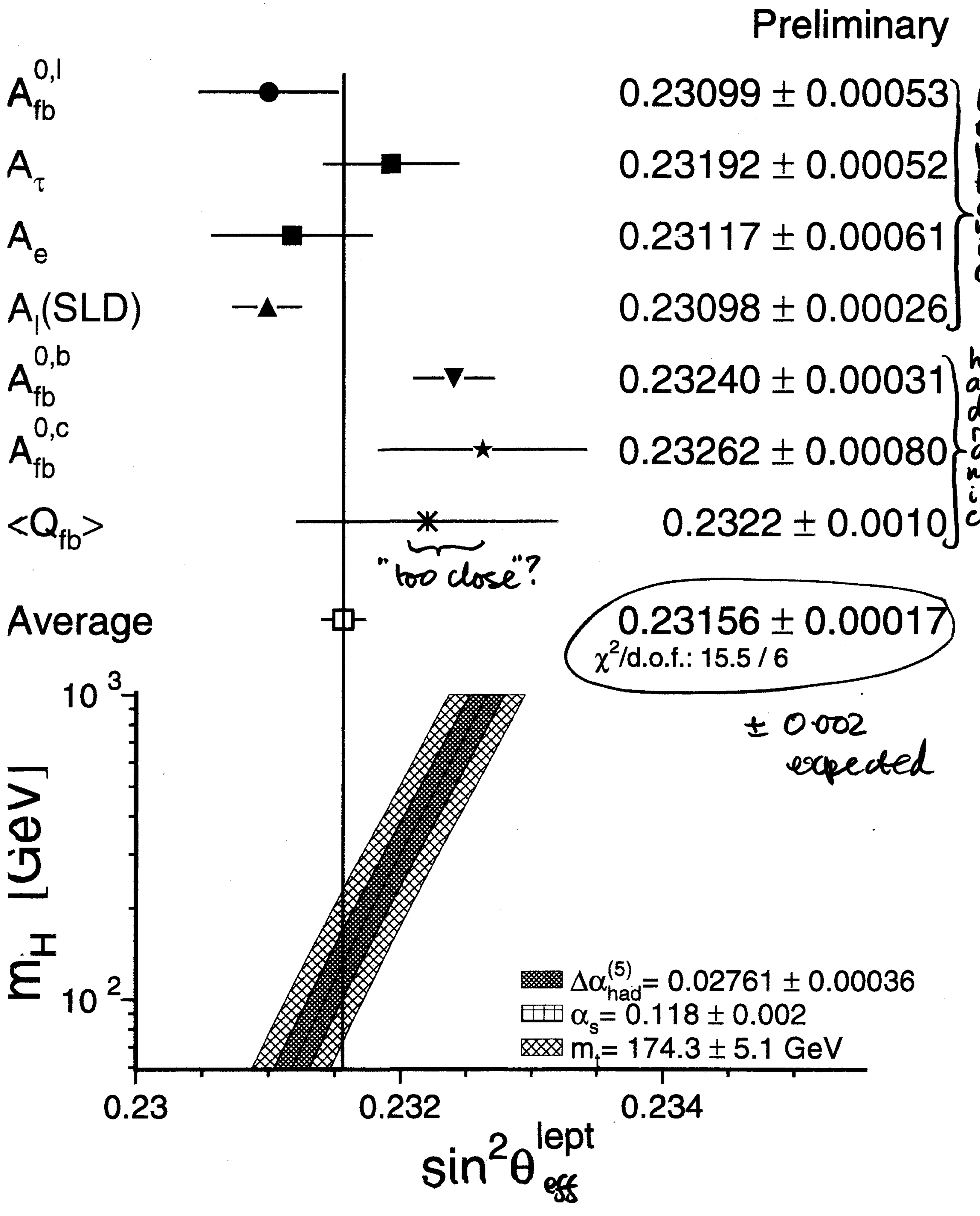
117

m_Z [GeV]	91.1875 ± 0.0021	.04
Γ_Z [GeV]	2.4952 ± 0.0023	-.46
σ^0_{hadr} [nb]	41.540 ± 0.037	1.62
R_l	20.767 ± 0.025	1.09
$A^{0,l}_{fb}$	0.01714 ± 0.00095	.79
A_e	0.1498 ± 0.0048	.41
A_τ	0.1439 ± 0.0041	-.96
$\sin^2\theta^{lept}_{eff}$	0.2322 ± 0.0010	.78
m_W [GeV]	80.446 ± 0.040	1.32
R_b	0.21664 ± 0.00068	1.32
R_c	0.1729 ± 0.0032	.20
$A^{0,b}_{fb}$	0.0982 ± 0.0017	-3.20
$A^{0,c}_{fb}$	0.0689 ± 0.0035	-1.48
A_b	0.921 ± 0.020	-.68
A_c	0.667 ± 0.026	-.05
A_l	0.1513 ± 0.0021	1.68
$\sin^2\theta_W$	0.2255 ± 0.0021	1.20
m_W [GeV]	80.452 ± 0.062	.95
m_t [GeV]	174.3 ± 5.1	-.27
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	-.36



possible discrepancy with Standard Model?

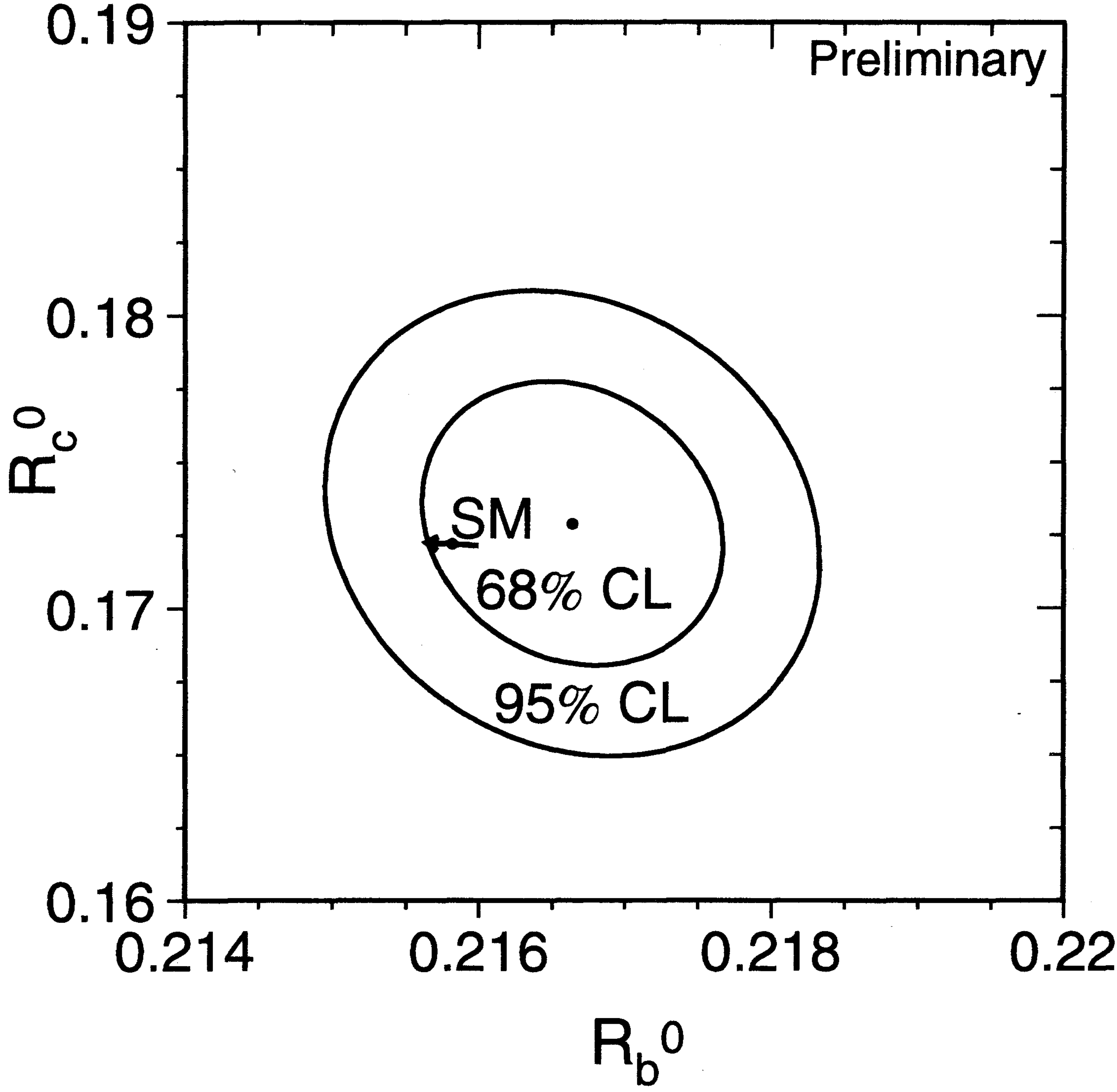
2.3 - Standard Model fit to electroweak data



Preliminary
$A_{fb}^{0,l}$ 0.23099 ± 0.00053
A_τ 0.23192 ± 0.00052
A_e 0.23117 ± 0.00061
A_l(SLD) 0.23098 ± 0.00026
leptonic
$A_{fb}^{0,b}$ 0.23240 ± 0.00031
$A_{fb}^{0,c}$ 0.23262 ± 0.00080
<Q_{fb}> 0.2322 ± 0.0010
hadronic
"too close"?
Average 0.23156 ± 0.00017
χ^2/d.o.f.: 15.5 / 6
± 0.002 expected
10^3
10^2
m_H [GeV]
$\Delta\alpha_{had}^{(5)}$= 0.02761 ± 0.00036
α_s= 0.118 ± 0.002
m_t= 174.3 ± 5.1 GeV
0.23
0.232
0.234
$\sin^2\theta^{lept}_{eff}$

Measurements of $\Gamma(Z \to \bar{b}b, \bar{c}c)$

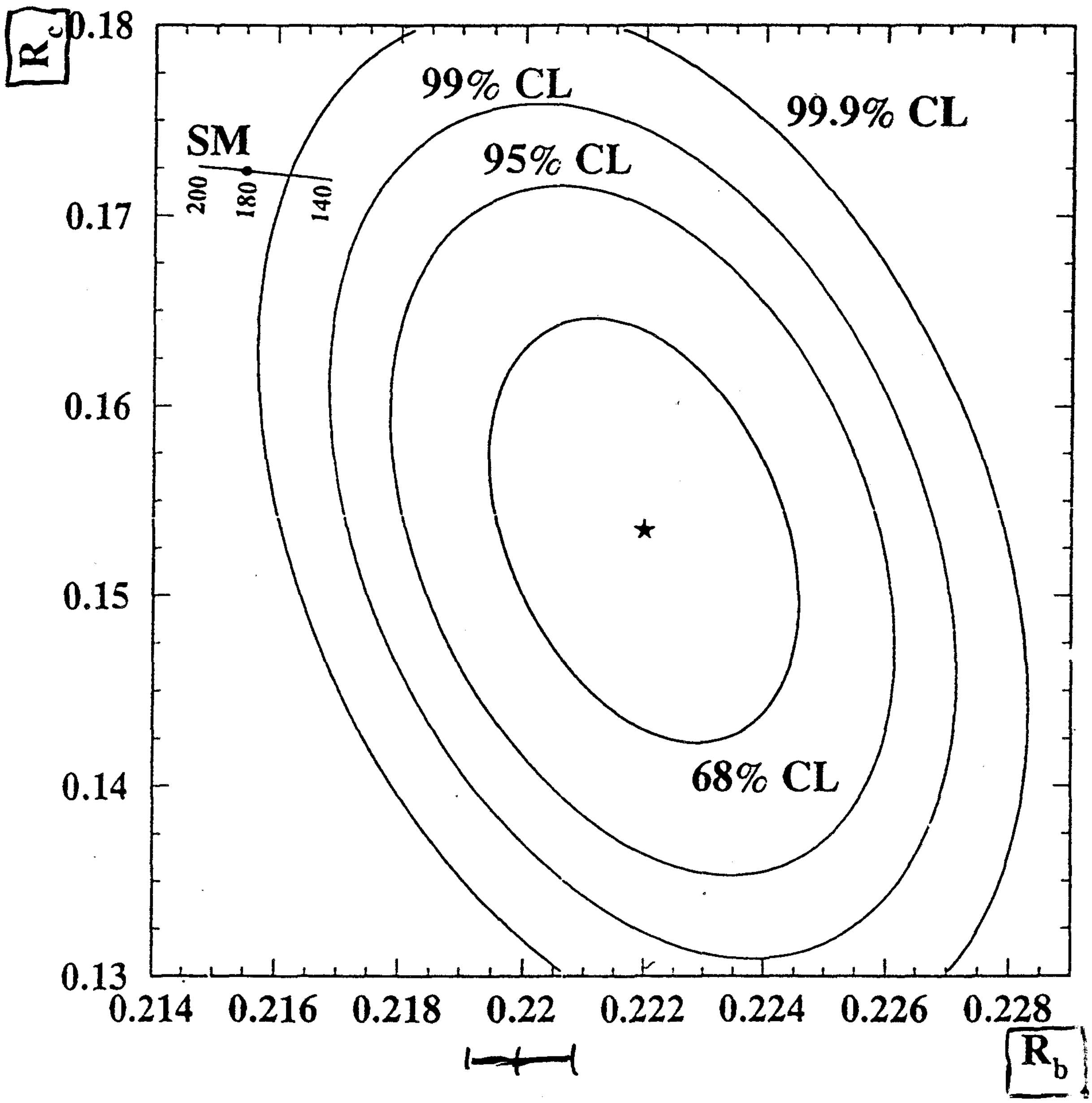
consistent with Standard Model



R_b and Supersymmetry?

Z Decay Rates into $\bar{b}b$, $\bar{c}c$

(summer 1995)



$\Delta\chi^2$ between best fit with Standard Model R_b and R_c ($m_{\mathrm{top}} = 180$ GeV, $R_b = 0.2155, R_c = 0.172$), and best overall fit, is 16.0

a hint to be ignored ...!

Upper limits on supersymmetric contributions to R_b

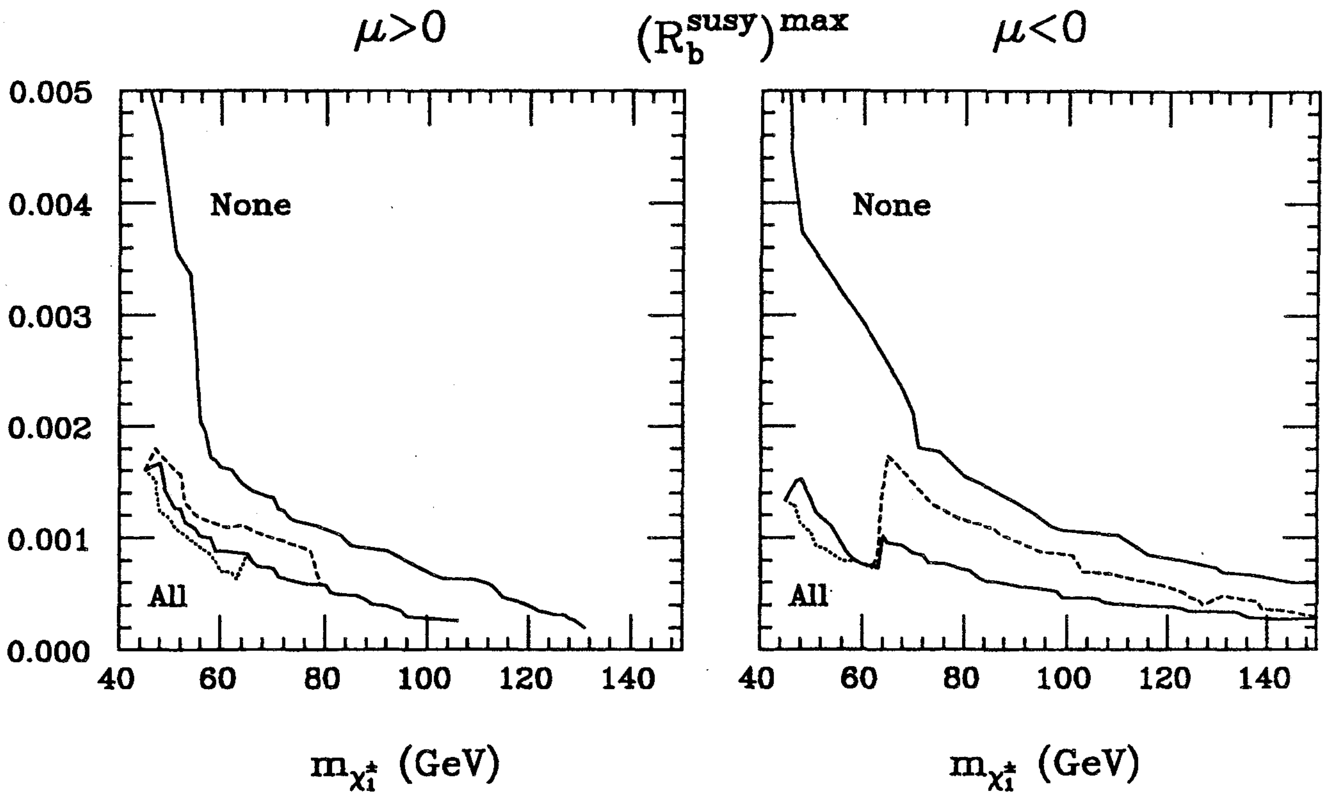
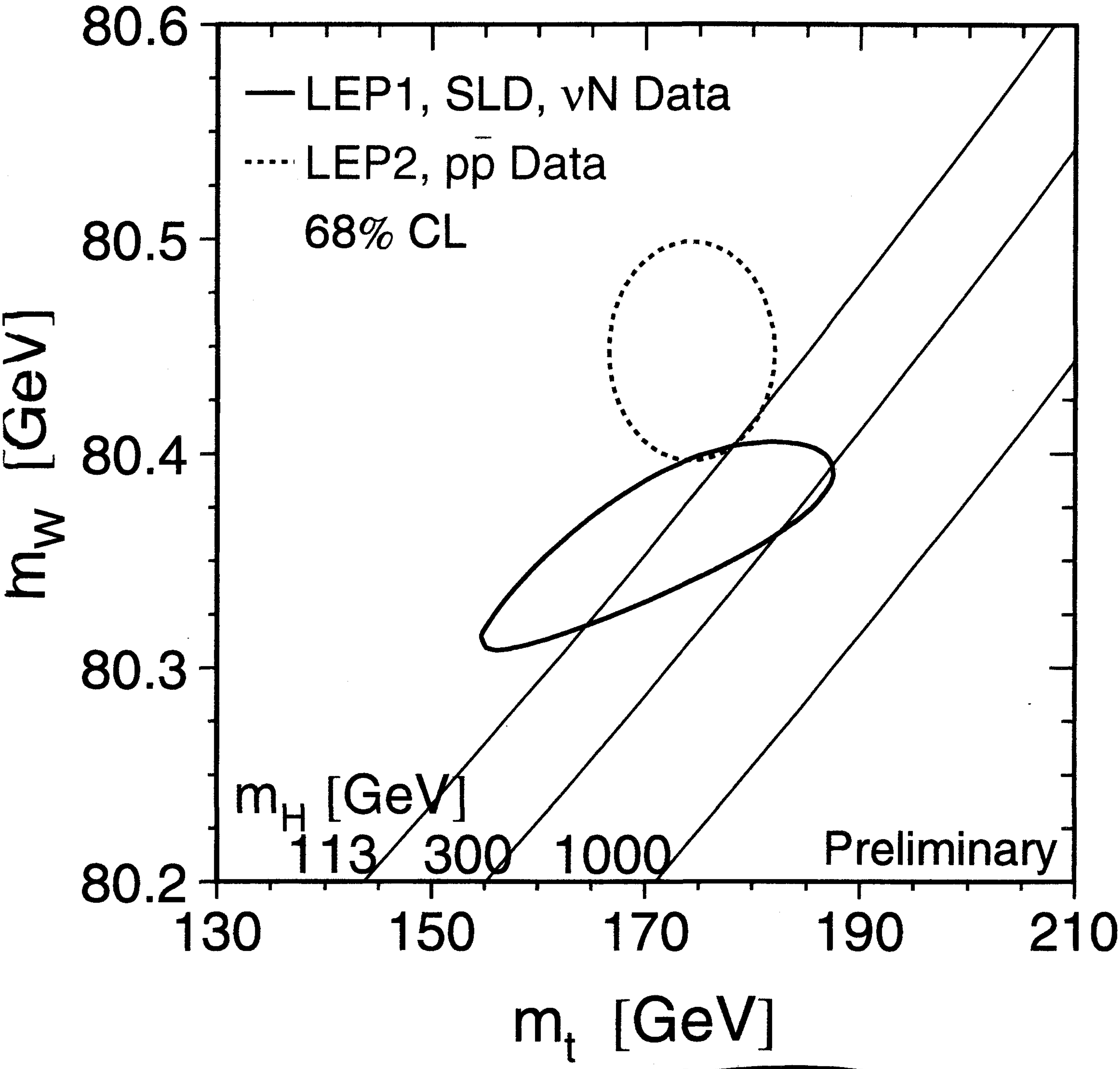


Figure 1: The maximum attainable value of $R_b^{\rm susy}$ versus the chargino mass for both signs of μ, when no constraint has been applied ("None") and when all the constraints described in the text have been applied ("All"). The dashed lines indicate the effect of not enforcing the Higgs-mass constraints, and the dotted lines indicate the possible further restriction should future LEP 1.5 searches exclude a chargino-neutralino mass down to about 5 GeV.

(J.E. + Nanopoulos + Lopez: hep-ph/9612376

Measurements of m_t, m_W

favour light Higgs boson



predict $\boxed{m_t = 168^{+12}_{-9}\ \text{GeV}}$

The Nobel Prize in Physics 1999

BACK

The Royal Swedish Academy of Sciences has awarded the 1999 Nobel Prize in Physics jointly to

Professor **Gerardus 't Hooft**
and
Professor Emeritus **Martinus J.G. Veltman**

for "elucidating the quantum structure of electroweak interactions in physics."

Martinus Veltman
Professor Emeritus at the University of Michigan, Ann Arbor, USA, formerly at the University of Utrecht, Utrecht, the Netherlands.

Gerardus 't Hooft
Professor at the University of Utrecht, Utrecht, the Netherlands.

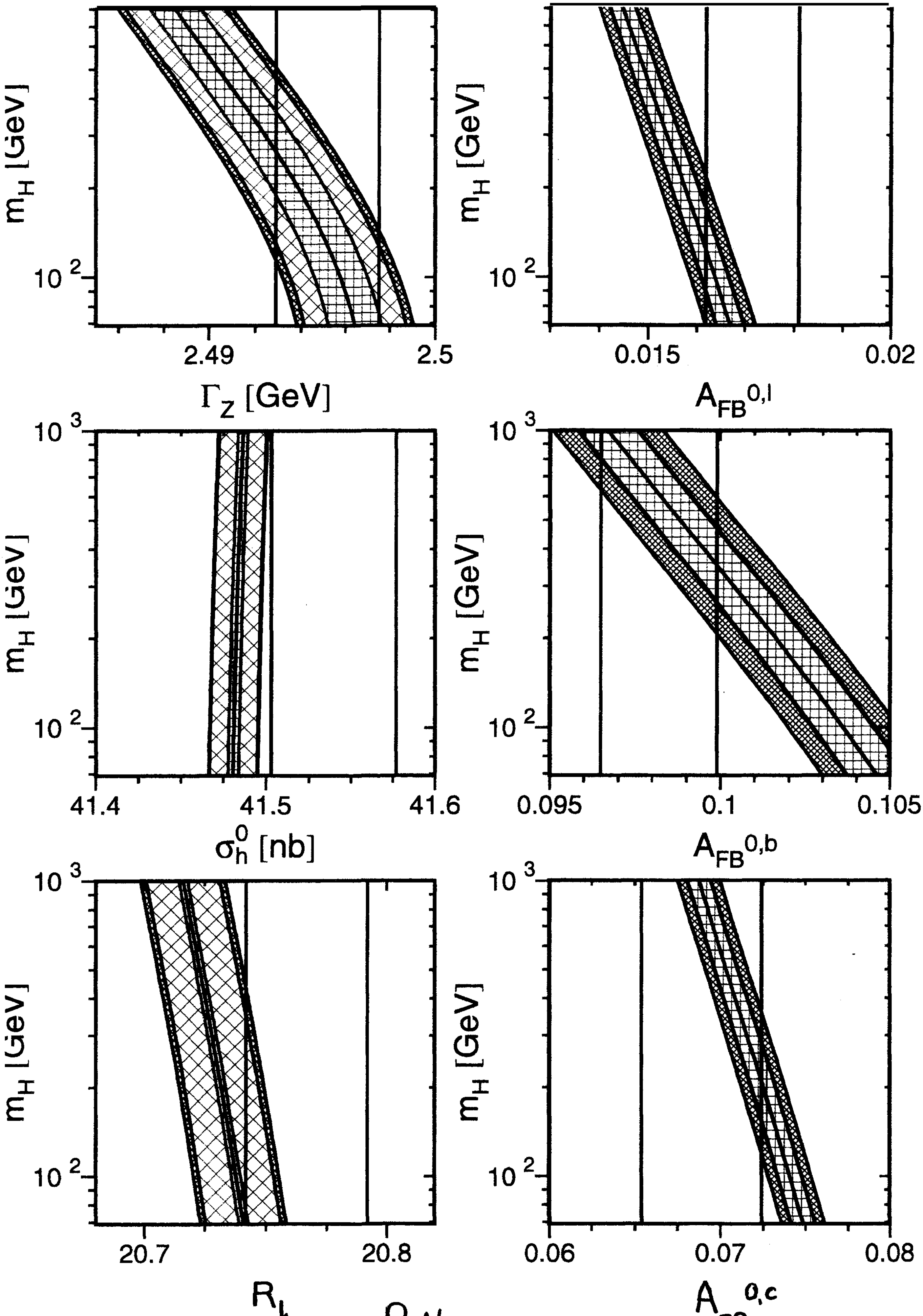
A theory to reckon with

The structure of particle physics is described using the Standard Model. In this model electromagnetic and weak interactions are unified and together called electroweak interactions. It is theoretical studies of these interactions that have been rewarded with the 1999 Nobel Prize in Physics.

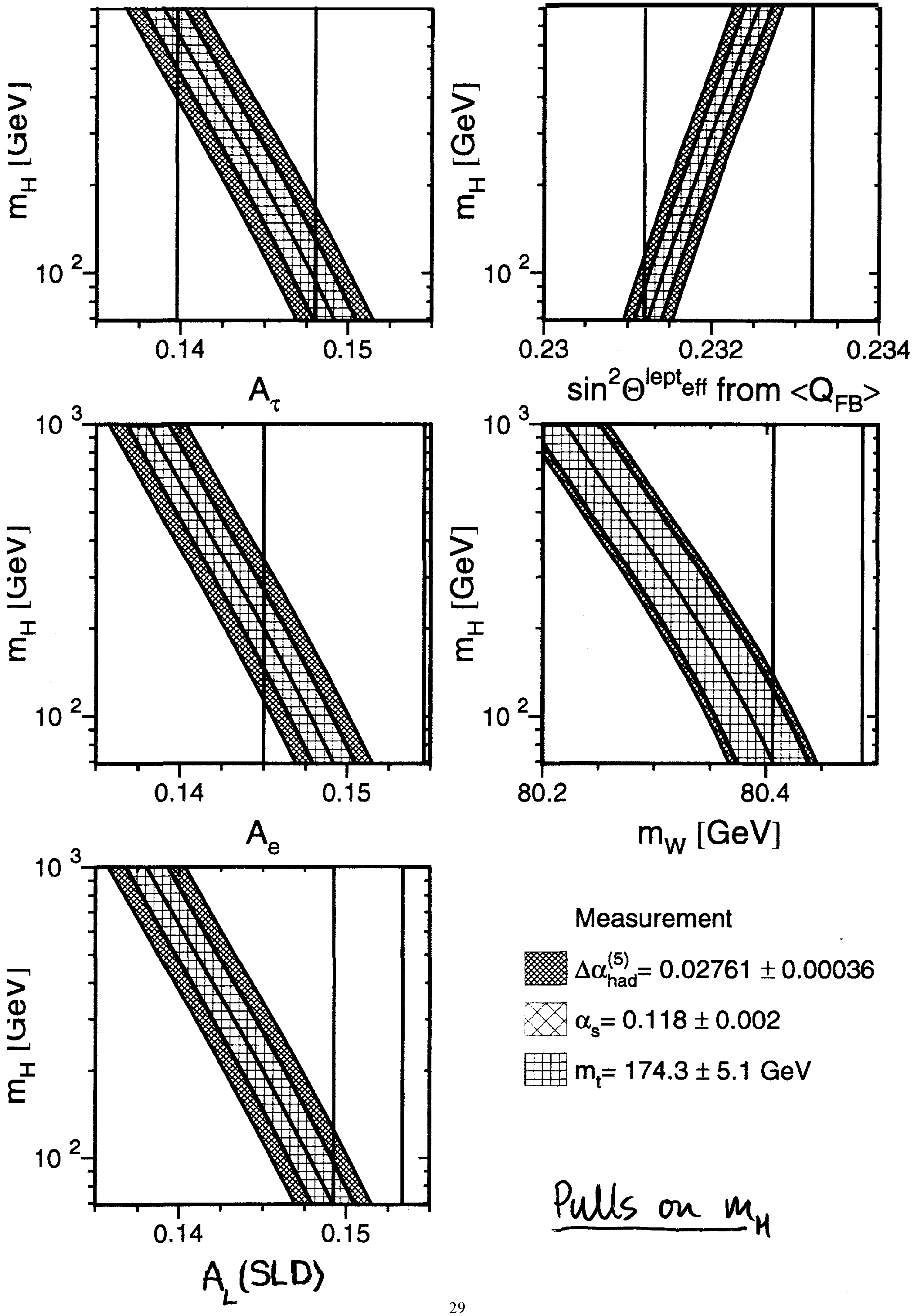
Contents:

BACK

Based on materials from the 1999 Nobel Poster for Physics.


m_H [GeV]
10 2
2.49
2.5
Γ_Z [GeV]
0.015
0.02
A_FB^0,l
10 3
41.4
41.5
41.6
σ_h^0 [nb]
0.095
0.1
0.105
A_FB^0,b
20.7
20.8
R_l
0.06
0.07
0.08
A_FB^0,c

Pulls on m_H

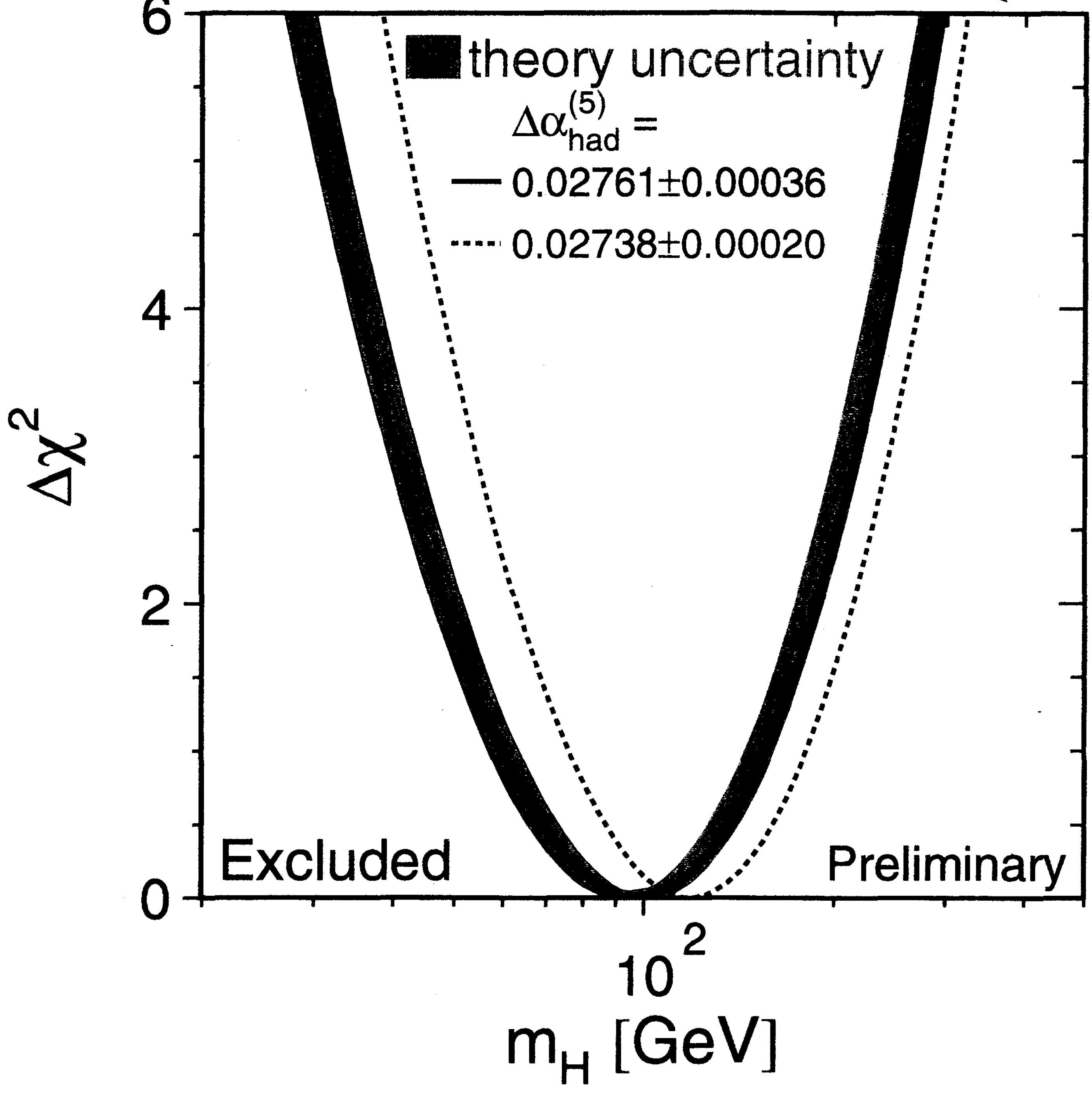

m_H [GeV]
10^2
10^3
0.14
0.15
A_τ
0.23
0.232
0.234
sin^2Θ^lept_eff from <Q_FB>
A_e
80.2
80.4
m_W [GeV]
A_L (SLD)
Measurement
Δα^(5)_had = 0.02761 ± 0.00036
α_s = 0.118 ± 0.002
m_t = 174.3 ± 5.1 GeV

Pulls on m_H

Electroweak fit for m_H

predicts $\boxed{m_H = 98^{+58}_{-38}\ \text{GeV}}$

(LEPEWWG:



Anticorelation: $m_H \Leftrightarrow \alpha_h$

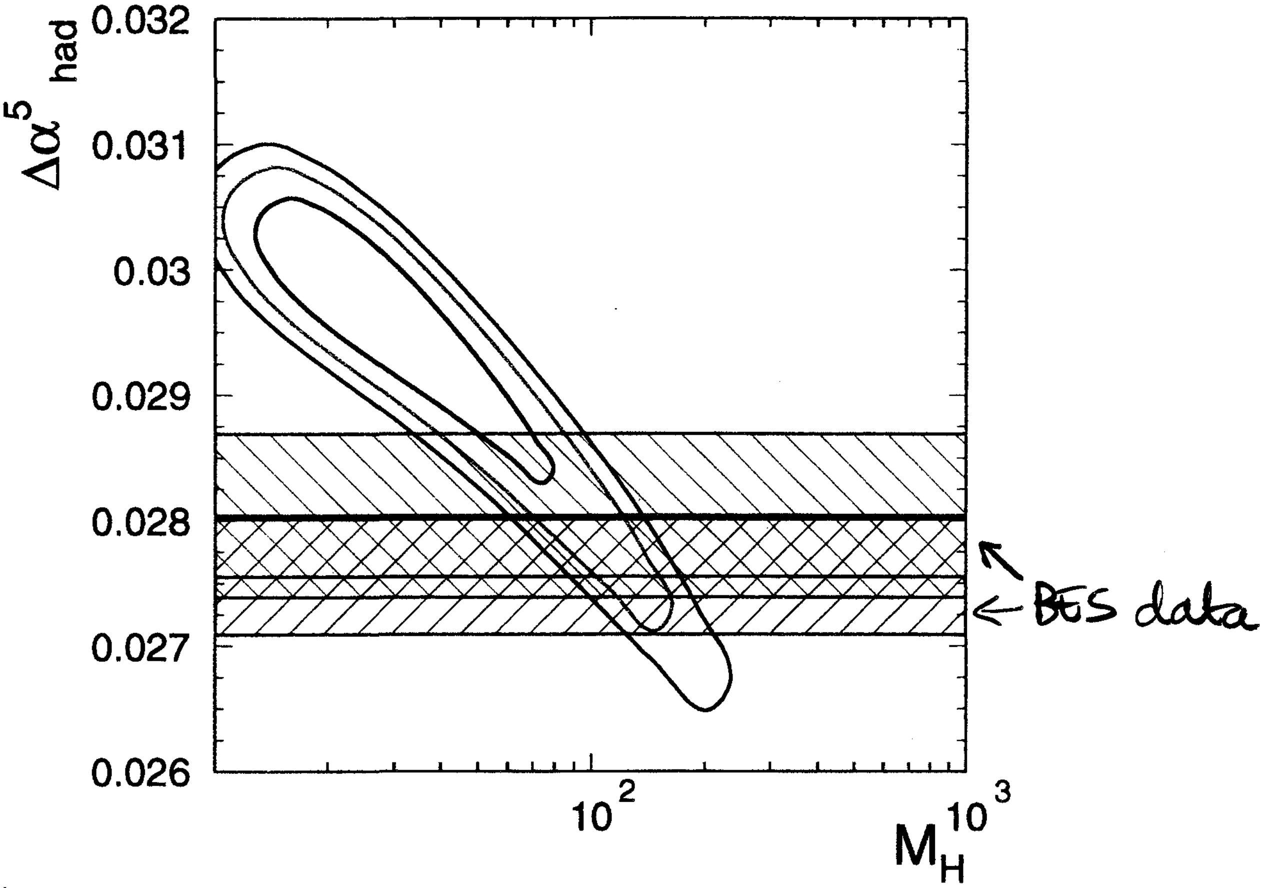


Figure 4: The contours show the 1 σ (47% C.L.), 2 σ (91% C.L.) and 3σ (99.5% C.L.) limits in the $\Delta\alpha^5_{\rm had}(m_Z{}^2)$-$m_{\rm h}$ plane, for a data similar, but not indentical to that of Table 1[36]. The upper bands show the value from $\Delta\alpha^5_{\rm had}(m_Z{}^2)$-$m_{\rm h}$ from Reference [41] and the lower band shows preliminary results using the new preliminary BES data from Reference [50]

Is there an A_{FB}^b crisis?

$$A_{FB}^b = 0.0982 \pm 0.0017$$

- 3.2σ from Standard Model fit (prob. = 0.021

  but no effect in A_{FBLR}^b

  remember R_b!

- if there is underestimated systematic error then should drop from global fit
- but other determinations of $\sin^2\theta_{eff}^l$ prefer very light Higgs boson

  $m_H < 113$ GeV @ 95 to 97% c.l.

recall: $A_{FB}^b = \frac{3}{4} A_e A_b$ ← insensitive to $m_H, m_t, \alpha(m_Z)$

without A_{FB}, high c.l. for global fit:

$$\chi^2/_{dof} = 15.8/14 \Rightarrow \text{c.l.} = 0.33$$

with A_{FB}, low c.l. for global fit

$$\chi^2/_{dof} = 26/_{15} \Rightarrow \text{c.l.} = 0.038$$

damned if you drop it m_H predicted too low

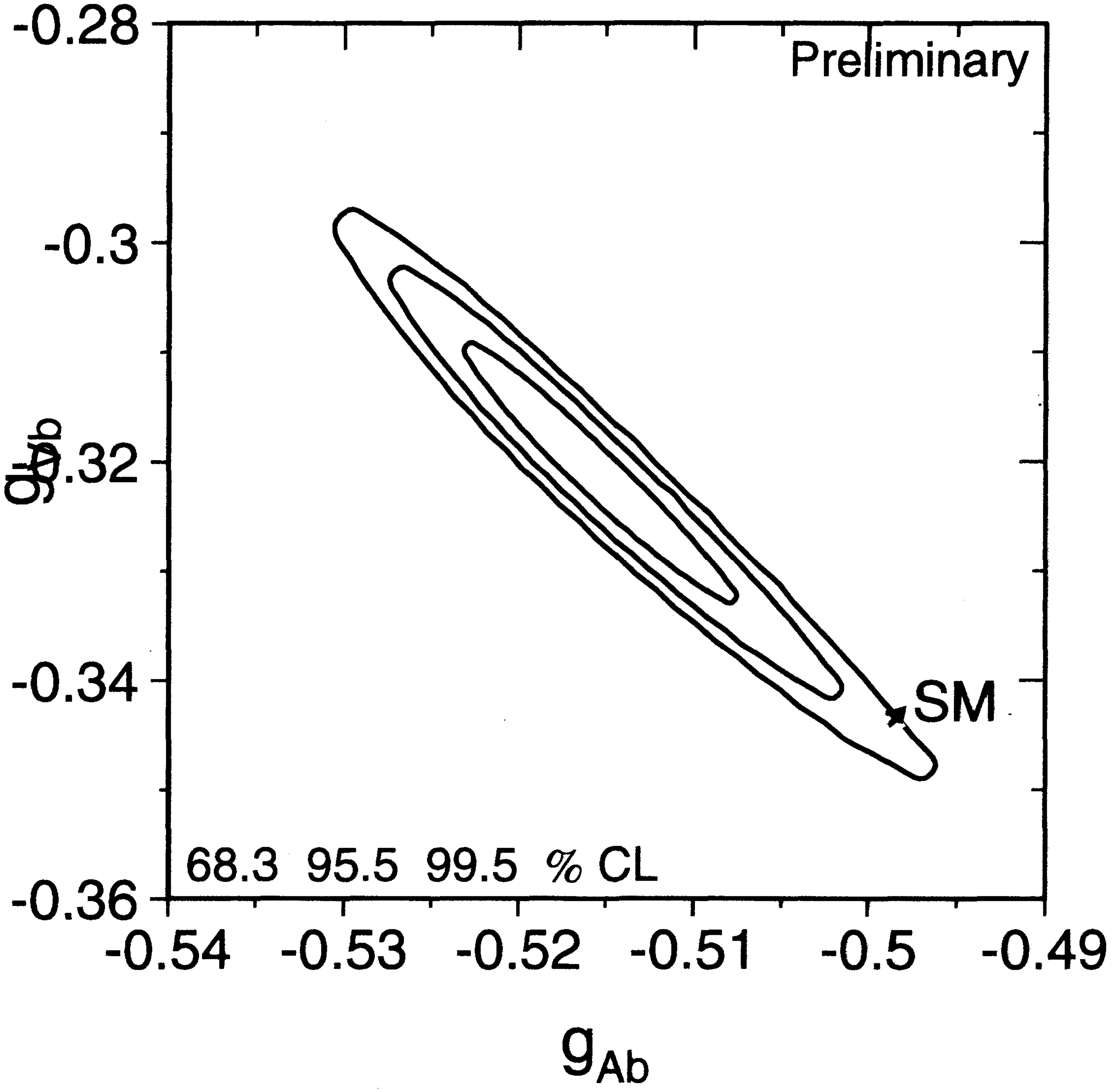
Chanowitz) you keep it low confidence level

Measurements of b electroweak couplings

$R_b \sim$ Standard Model

$A_{FB}^b \neq$ Standard Model

$\Rightarrow$ correlated deviations



χ^2 function for m_H

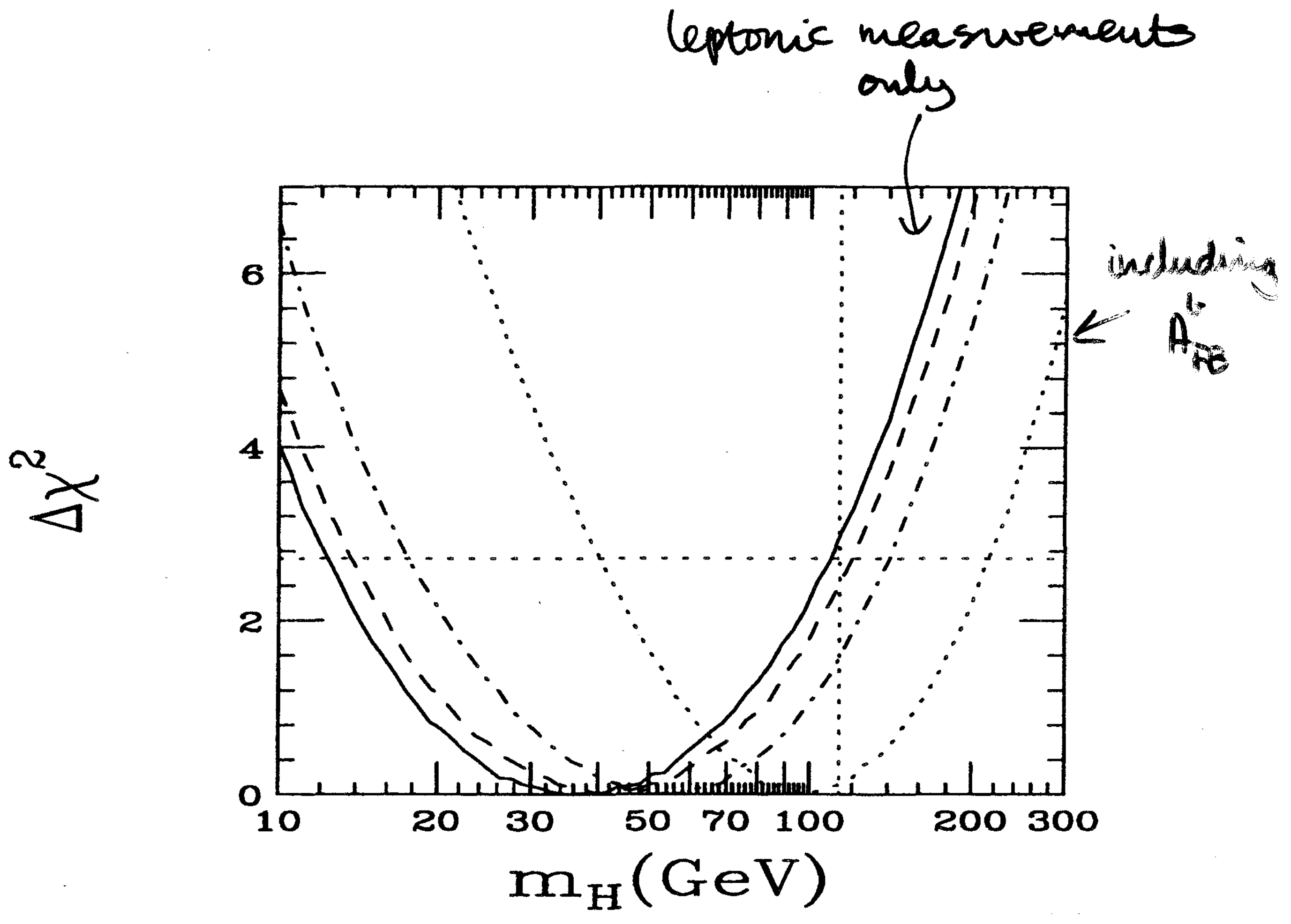


Figure 2: χ^2 distributions as in figure 1. The lines correspond to fits of m_W, Γ_Z, and R_l, combined incrementally, as in table 2, with the four leptonic asymmetry measurements (solid), plus Q_{FB} (dashes), plus A_{FB}^c (dot-dashes), plus A_{FB}^b (dots).

Chanowitz

Suggested Resolution

- drop A^b_{FB} from global fit (Altarelli + Caravaglios + Giudice + Gambino + Ridolfi '01)

  underestimated (undiscovered) systematic?

- look for new physics capable of reconciliation with direct Higgs limit

- example in supersymmetry

$$m_{\tilde{\nu}} \simeq 55 \text{ to } 80 \text{ GeV}$$

and hence also other light sparticles:

$$m^2_{\tilde{e}_L} = m^2_{\tilde{\nu}} + m^2_W |\cos 2\beta|$$

must break scalar mass universality,

otherwise $m^2_{\tilde{e}_L} - m^2_{\tilde{e}_R} = 0.56 M_2^2 + m_Z^2(1 - 4\sin^2\theta_W)|\cos 2\beta|$

$\Rightarrow$ too low

even so: $m^2_{\tilde{\nu}} = m_0^2 + 0.78 M_2^2 - \frac{m_Z^2}{2}|\cos 2\beta|$

$$\Rightarrow \quad M_2 < 116 \text{ GeV if } m_0^2 > 0$$

$$\Rightarrow \quad \text{light charginos}$$

Standard Model in crisis?

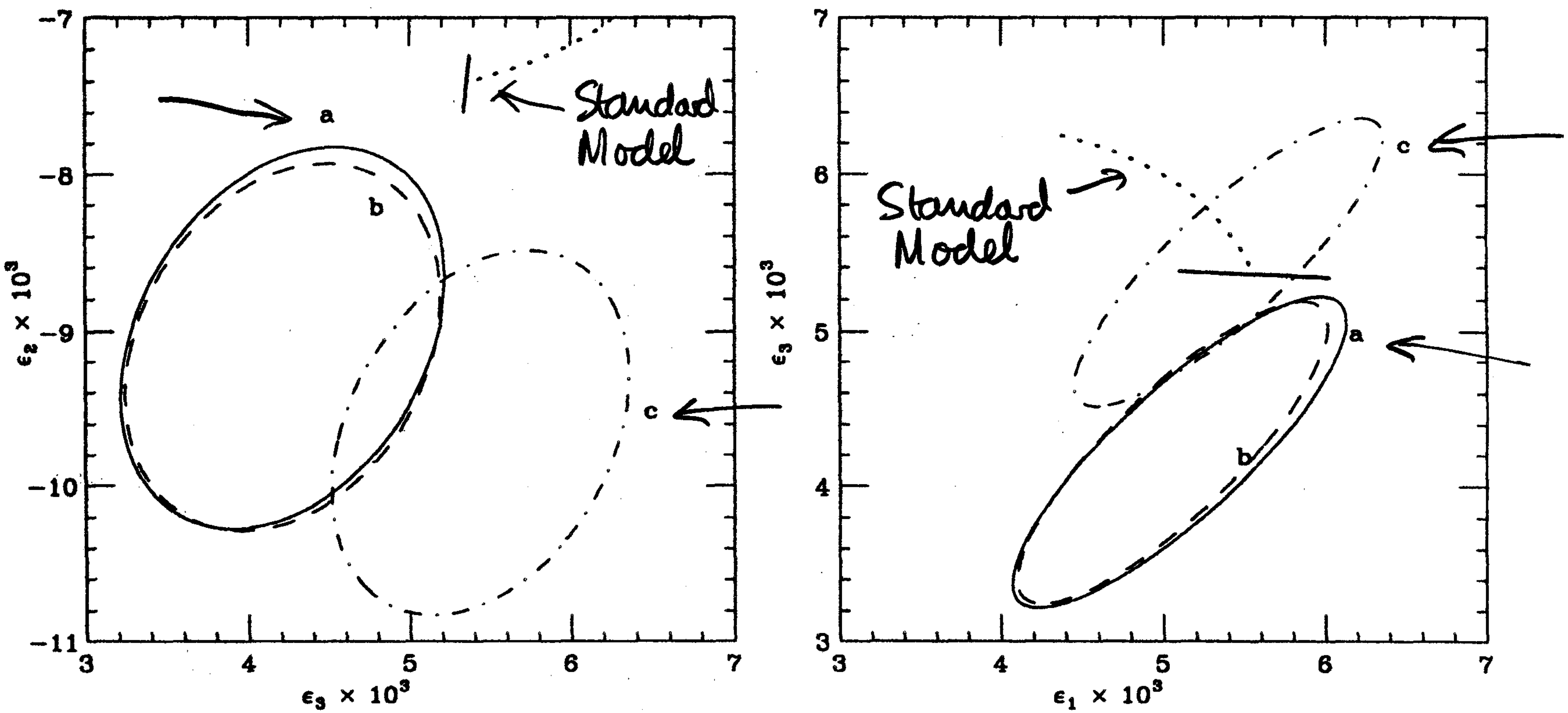


Figure 1: *One-sigma ellipses in the* $\epsilon_3 - \epsilon_2$ *(left) and in the* $\epsilon_1 - \epsilon_3$ *(right) planes obtained from:* a. m_W*,* Γ_ℓ*,* $\sin^2\theta_{\text{eff}}$ *from all leptonic asymmetries and* R_b*;* b. *the same observables, plus the hadronic partial widths derived from* Γ_Z*,* σ_h *and* R_ℓ*;* c. *as in* b.*, but with* $\sin^2\theta_{\text{eff}}$ *also including the hadronic asymmetry results. The solid straight lines represent the SM predictions for* $m_H = 113$ GeV *and* m_t *in the range* 174.3 ± 5.1 GeV*. The dotted curves represent the SM predictions for* $m_t = 174.3$ GeV *and* m_H *in the range* 113 *to* 500 GeV.

(Altarelli + Caravaglios + Giudice + Gambino + Ridolfi : 01

36

Including MSSM loop corrections

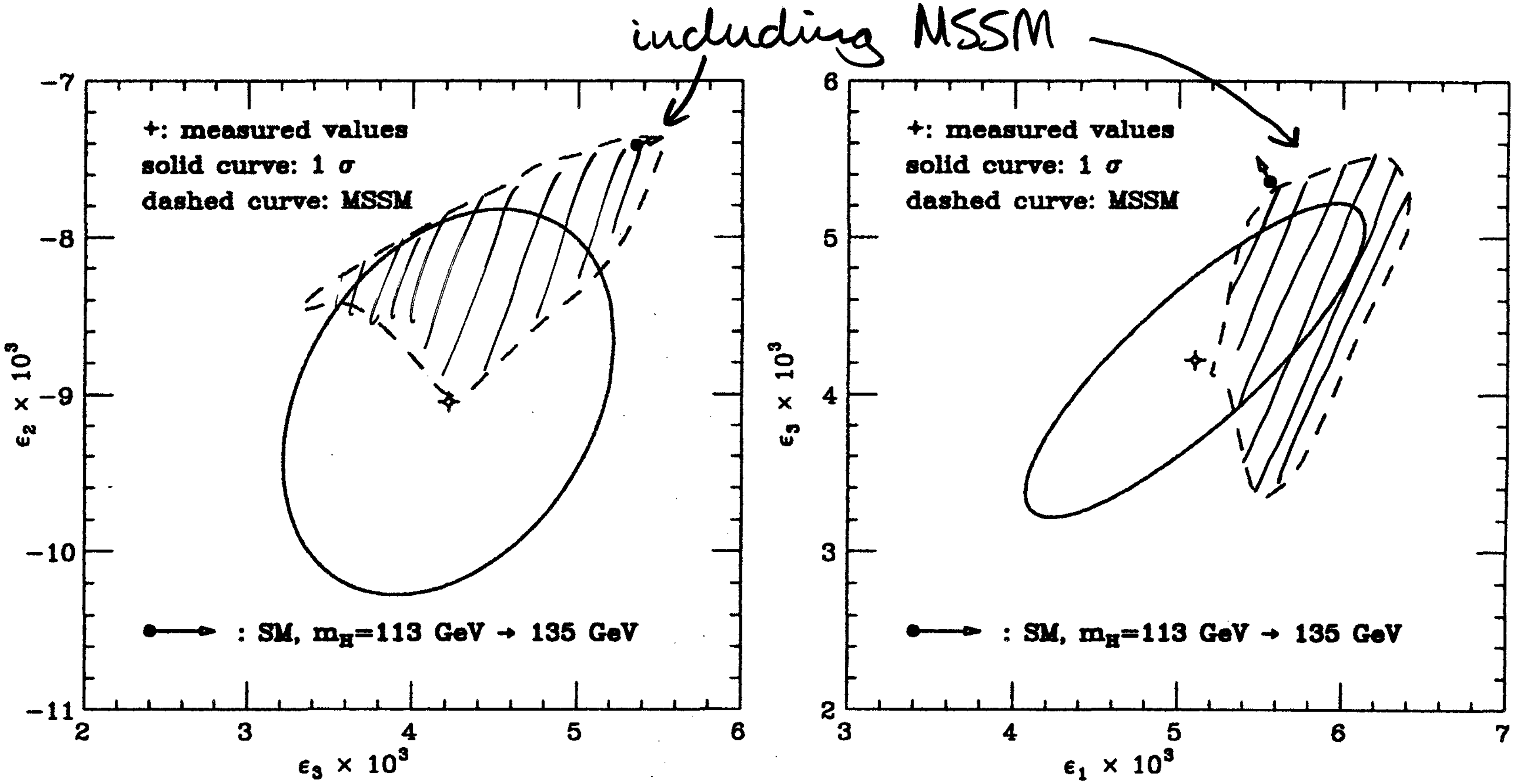


Figure 2: *Measured values (cross) of ϵ_3 and ϵ_2 (left) and of ϵ_1 and ϵ_3 (right), with their* 1 σ *region (solid ellipses), corresponding to case* a *of fig. 1. The area inside the dashed curves represents the MSSM prediction for $m_{\tilde{e}_L}$ between 96 and 300* GeV, *m_{χ^+} between 105 and 300* GeV, -1000 GeV $< \mu < 1000$ GeV, $\tan\beta = 10$, $m_{\tilde{e}_L} = 1$ TeV. *and $m_A = 1$* TeV. (ACGGR: 01

4 - Possible Physics with GigaZ

10^9 Z @ linear collider (TESLA

- new level of precision

$$\delta(\sin^2\theta_{eff}) = 1 \times 10^{-5}$$

(Erler + Heinemeyer + Hollik + Weiglein + Zerwas: 00

$$\delta m_W = 6\,\text{MeV}, \quad \delta m_t = 0.13\,\text{GeV}$$

- comparable to theoretical errors

$$\delta(\sin^2\theta_{eff}) = 3 \times 10^{-5} \leftarrow \text{including } \delta(\Delta\alpha)$$

$$\delta m_W = 3\,\text{MeV}$$

also $\delta m_Z = 2.1\,\text{MeV} \Rightarrow \delta m_W = 2.5\,\text{MeV}, \ \delta(\sin^2\theta_{eff}) = 1.4 \times 10^{-5}$

$\delta m_t = 0.13\,\text{GeV}$ $\quad 0.8\,\text{MeV}, \quad 0.4 \times 10^{-5}$

- precision estimate of Higgs mass

$$\Delta r \ni \frac{G_F m_W^2}{8\pi^2\sqrt{2}} \frac{11}{3} \ln m_H^2/m_W^2 + \cdots$$

$$\Rightarrow \quad \delta m_H/m_H = 0.07$$

also constrain supersymmetry, ...

Prospective improved accuracy with GigaZ

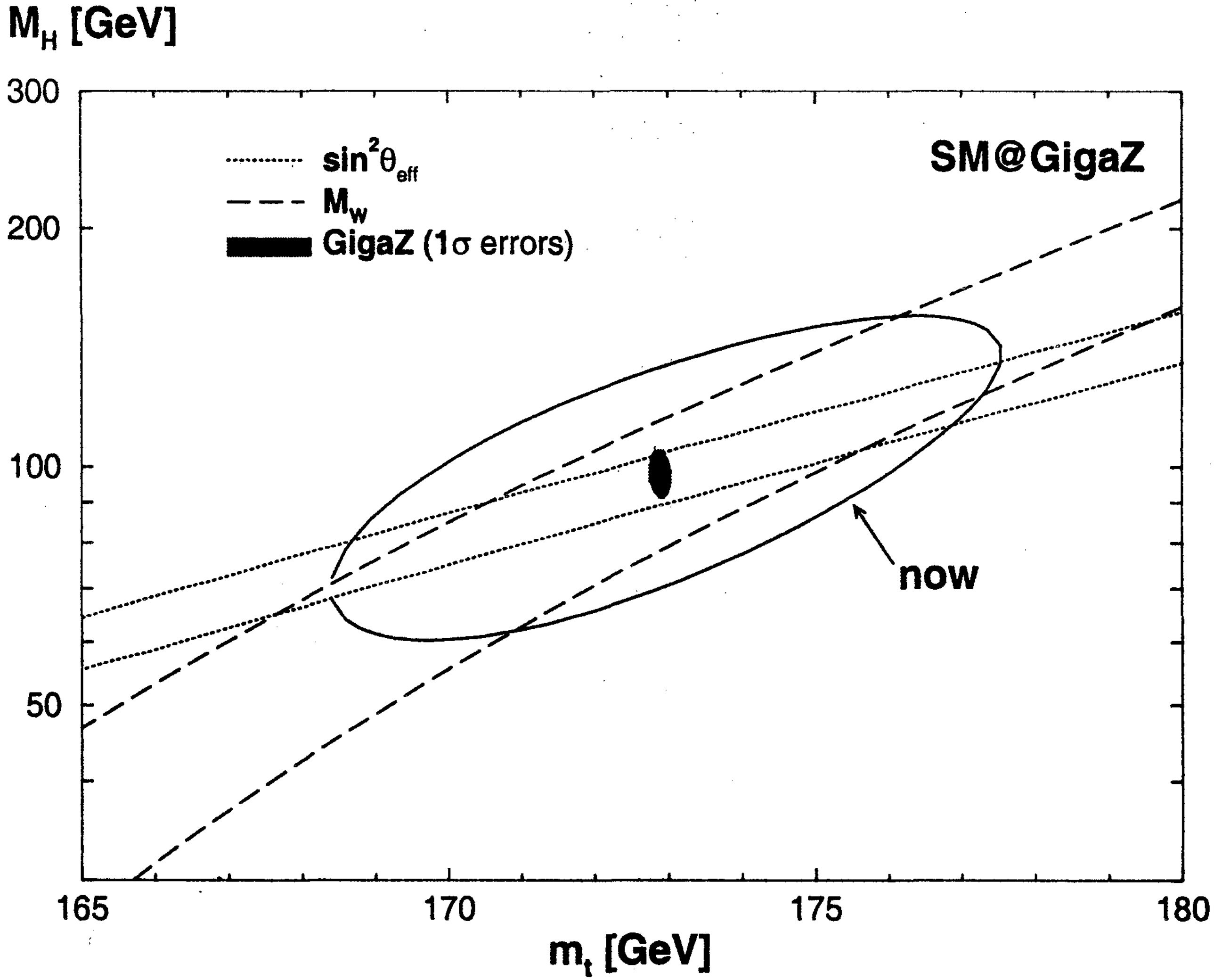


Figure 1: 1σ *allowed regions in the* m_t-M_H *plane taking into account the anticipated GigaZ precisions for* $\sin^2\theta_{\text{eff}}, M_W, \Gamma_Z, R_l, R_q$ *and* m_t *(see text). The presently allowed region (full curve labeled 'now') is shown for comparison.*

(Erler + Heinemeyer + Hollik + Weiglein + Zerwas: 00

39