EWK precision measurements

[present and future]

W. Hollik
14/4/99

Higgs: only unknown of SM

Higgs and **top** affect relations between high precision EW observables through **quantum effects**

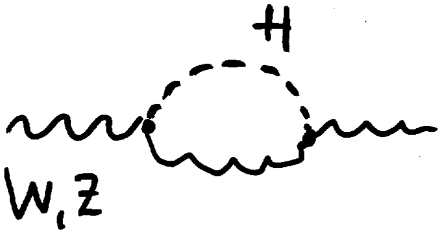
$$O_i = f_i(M_W, M_Z, \mathbf{M_H}, \mathbf{m_t} \ldots)$$

→ constraints on M_H

confronted with direct measurements

- tests of consistency
- signals for "new physics"

Higgs → precision observables



Higgs - gauge coupling

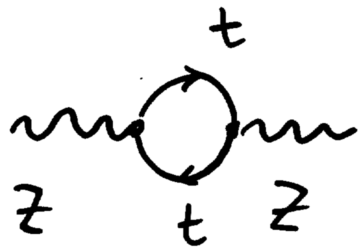
at 2-loop level:

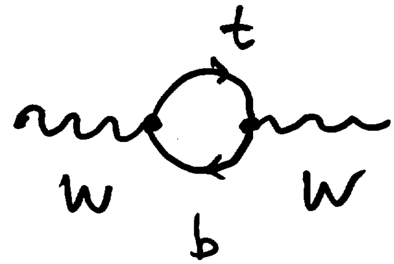
Higgs - Yukawa interaction

Higgs - self interaction

top $\longrightarrow$ precision observables

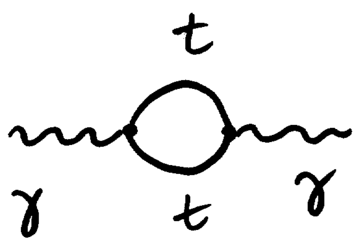
(1)





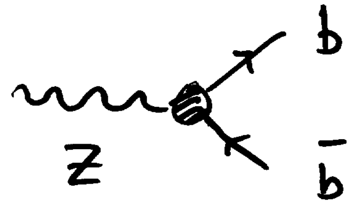
$\Longrightarrow$ ρ-parameter, Δr, g_V^f, g_A^f

[

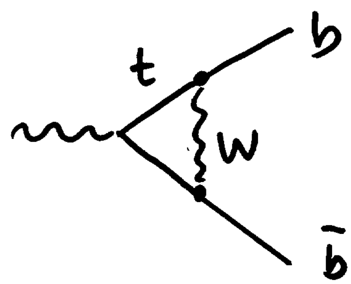


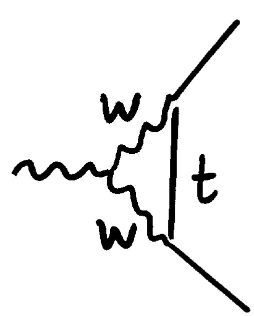
$\sim Q_t^2 \dfrac{M_Z^2}{m_t^2}$ (small)]

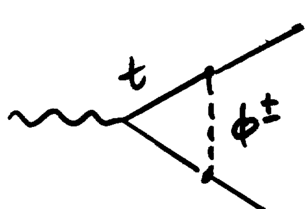
(2)

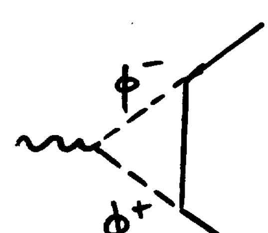


$\Rightarrow R_b \quad [A_b, A_{FB}^b$









$\sim m_t^2$

Electroweak parameters

- $$G_\mu = \frac{\pi}{\sqrt{2}} \cdot \frac{\alpha}{M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)} \left[1 + \underbrace{\Delta\alpha - \frac{c_W^2}{s_W^2}\Delta\rho + \dots}_{=\ \Delta r} \right.$$

$$s_W^2 = 1 - \frac{M_W^2}{M_Z^2}, \qquad c_W^2 = \frac{M_W^2}{M_Z^2}$$

- $$\sin^2\theta^{\ell}_{\mathrm{eff}}(M_Z) = s_W^2 + c_W^2\,\Delta\rho + \cdots$$

- NC coupling (Zff), overall normalization

$$\left(\sqrt{2}\, M_Z^2\, G_\mu\right)^{1/2} \left[1 + \tfrac{1}{2}\Delta\rho + \cdots \right]$$

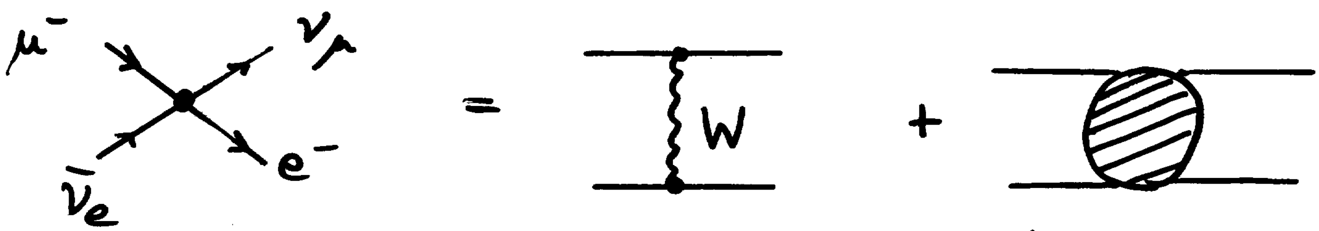
Vector boson masses

correlated by μ-lifetime $\leftrightarrow G_\mu$

$$\frac{1}{\tau_\mu} = \frac{G_\mu^2 m_\mu^5}{192\pi^3}\left(1-\frac{8m_e^2}{m_\mu^2}\right)\left\{1 - 1.81\frac{\alpha}{\pi} + 6.70\left(\frac{\alpha}{\pi}\right)\right.$$

Sirlin et al. — van Ritberg Stuart

$$\boxed{G_\mu = 1.16637(1)\cdot 10^{-5}\,\mathrm{GeV}^{-2}}$$

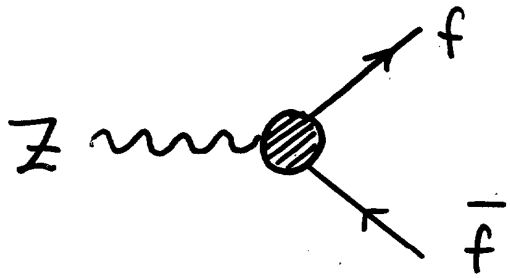


higher order

$$G_\mu = \frac{\pi\alpha}{\sqrt{2}}\cdot\frac{1}{M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)}\left(1 + \Delta r + \cdots\right)$$

$$\Delta r = \underset{\substack{\uparrow\\ 6\%}}{\Delta\alpha} \underbrace{- \frac{c_W^2}{s_W^2}\Delta\rho}_{\sim 4\%} + \underset{\sim 1\%}{(\Delta r)_{\mathrm{rem}}(m_t, M_H}$$

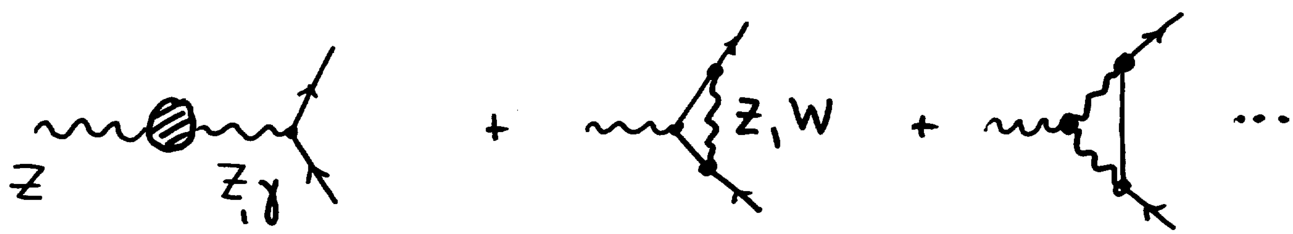
resum: $\alpha(1+\Delta\alpha+\cdots) \rightarrow \dfrac{\alpha}{1-\Delta\alpha} = \alpha(M_Z)$ L.L.-resu



$$\boxed{\begin{aligned} g_A^f &= \sqrt{\rho_f}\; I_3^f \\ g_V^f &= \sqrt{\rho_f}\,\left(I_3^f - 2\,Q_f \sin^2\Theta_f \right) \end{aligned}}$$

$$\rho_f(m_t, M_H, \alpha_s) = \frac{1}{1-\Delta\rho} + \ldots$$

$$\sin^2\Theta_f(m_t, M_H, \alpha_s) = s_W^2 + \Delta\rho \cdot c_W^2 + \ldots$$



non-universal

<u>higher order EW</u> (2-loop):

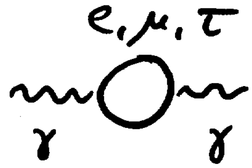
$$A\, G_\mu^2\, m_t^4 + B\, G_\mu^2 M_Z^2\, m_t^2 + (\text{unknown})$$

$\uparrow$ $\qquad\qquad$ $\uparrow$

$\Delta\rho \quad \Delta\rho^2$ $\qquad$ Degrassi et al.

(i)

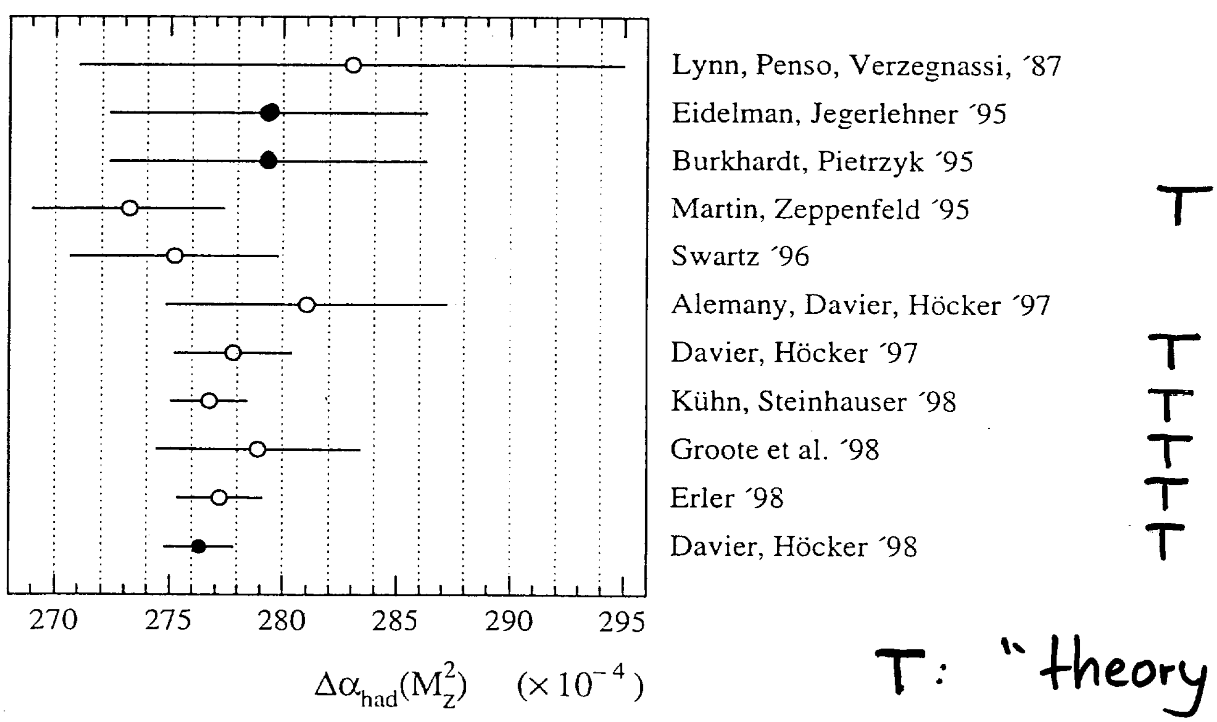
$$\Delta\alpha = (\Delta\alpha)_{lep} + (\Delta\alpha)^{(5)}_{had} + (\Delta\alpha)_{top}$$

$$(\Delta\alpha)_{lept} = \sum$$  +  + 

Källén, Sabry (1955) Steinhauser (1998)

$$(\Delta\alpha)^{(5)}_{had} = -\frac{M_Z^2}{4\pi^2\alpha}\,\mathrm{Re}\int_{4m_\pi^2}^{\infty} ds\, \frac{\boxed{\sigma(e^+e^- \to had)}}{s - M_Z^2 - i\varepsilon}$$

$$\boxed{\alpha(M_Z) = \frac{\alpha}{1-\Delta\alpha}} = \alpha\left[1 + \Delta\alpha + \Delta\alpha^2 + \cdots\right.$$



T: "theory driven

$$(\Delta\alpha)_{lept} = 0.0315$$

$$(\Delta\alpha)_{had} = 0.0280 \pm 0.0007$$ Eidelman, Jegerlehner ('95)

$$0.027782 \pm 0.000254$$ Jegerlehner ('99

$$0.02763 \pm 0.00016$$ Davier, Höcker ('9

$$0.02777 \pm 0.00017$$ Kühn, Steinhauser ('98)

(ii) ρ-parameter (heavy top)

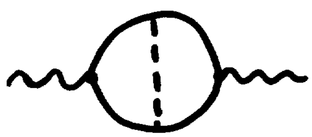
$m_t \gg m_b$

Veltman

$$(\Delta\rho)^{\text{top}}_{\text{1-loop}} = 3\,x_t\,, \qquad x_t = \frac{G_\mu m_t^2}{8\pi^2\sqrt{2}}$$

Higher order:

$$\Delta\rho = 3\,x_t\left[1 + \rho^{(2)} x_t + \delta\rho_{QCD}\right]$$



2-loop EW

van der Bij, Hoogeveen

Barbieri et al.

Fleischer, Jegerlehner, Tarasov

QCD

2- and 3-loop

Djouadi, Verzegnassi
Kniehl, Sirlin
Bardin et al.
Djouadi, Gambino
(2-loop)

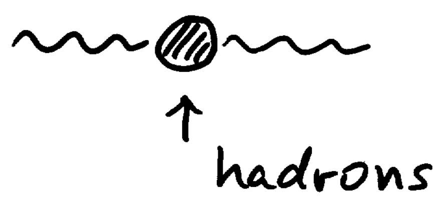
Avdeev, Fleischer,
Mikhailov, Tarasov

Chetyrkin, Kühn,
Steinhauser

(3-loop)

Uncertainties of predictions

- $\delta(\Delta\alpha)$



$\delta \sin^2\theta = 0.00024$ Eidelman, Jegerlehner

$\downarrow$

$5 \cdot 10^{-5}$ Davier, Höcker
Kühn, Steinhauser

- QCD uncertainty

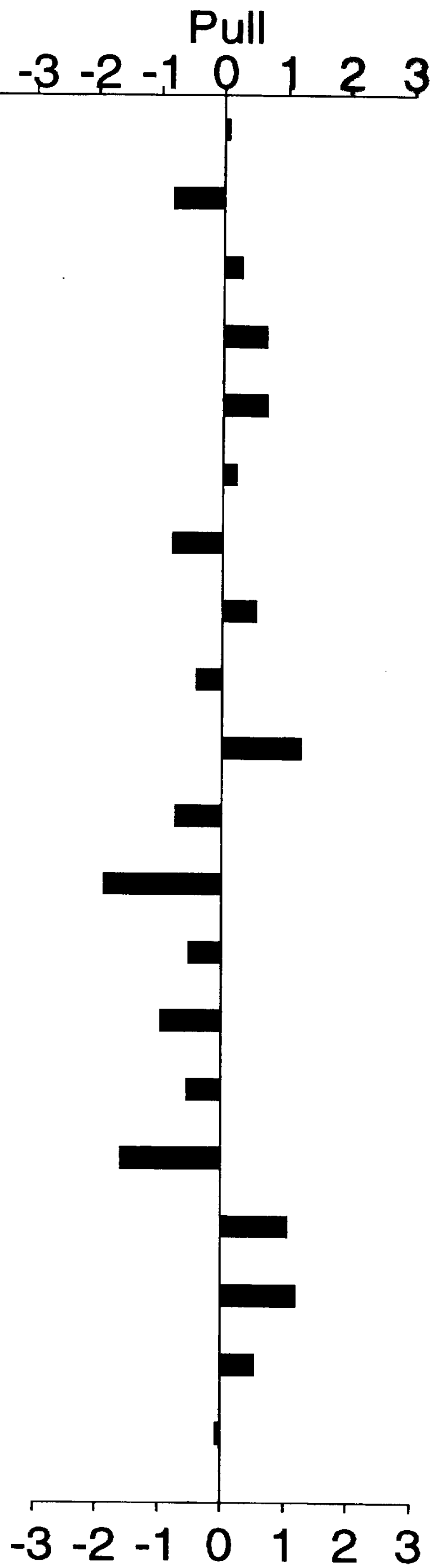
$\left.\begin{array}{l} \delta\alpha_s \text{ exp.} \\ \text{scale uncertainty} \\ m_b \text{ uncertainty} \end{array}\right\}$ small
$\delta \sin^2\theta_\ell \simeq 3 \cdot 10^{-5}$
$\delta(\Delta\rho) \simeq 1 \cdot 10^{-4}$

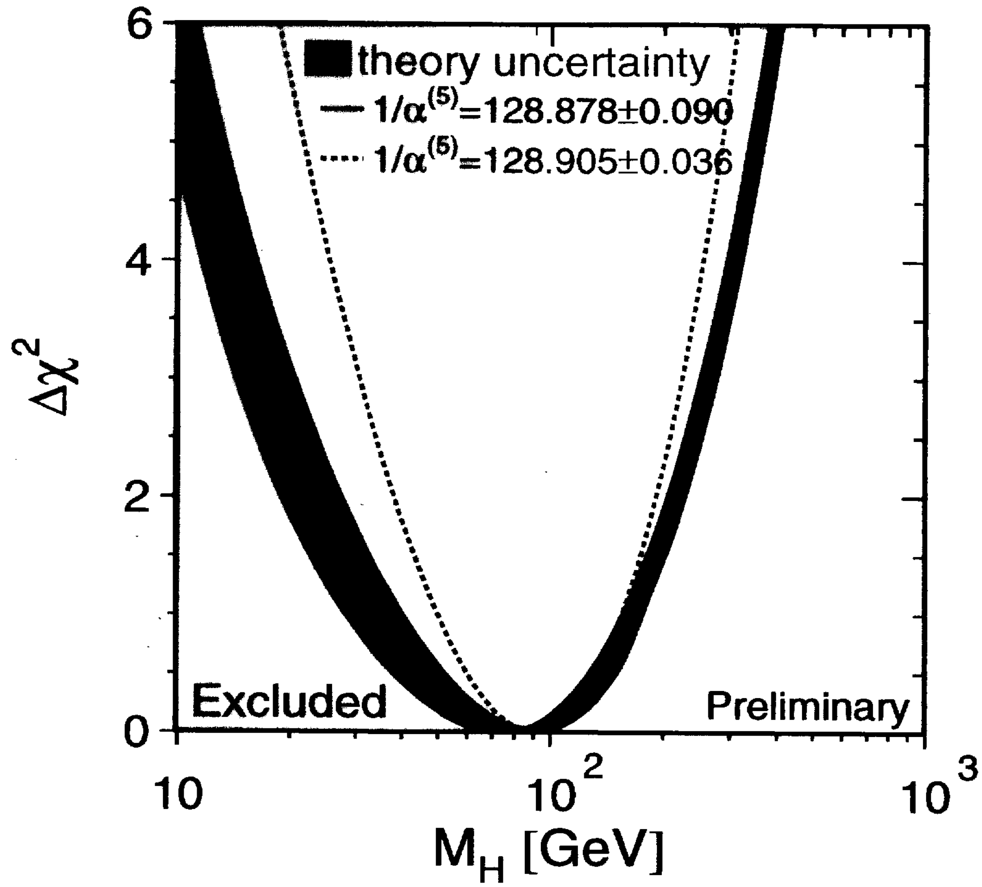
- uncertainties from unknown higher order EW contributions
  - different schemes
  - different options for uncontrolled higher order terms

CERN 95-03 (eds. Bardin, WH, Passarino)
Bardin, Grünewald, Passarino, hep-ph/9702452

Moriond 1999

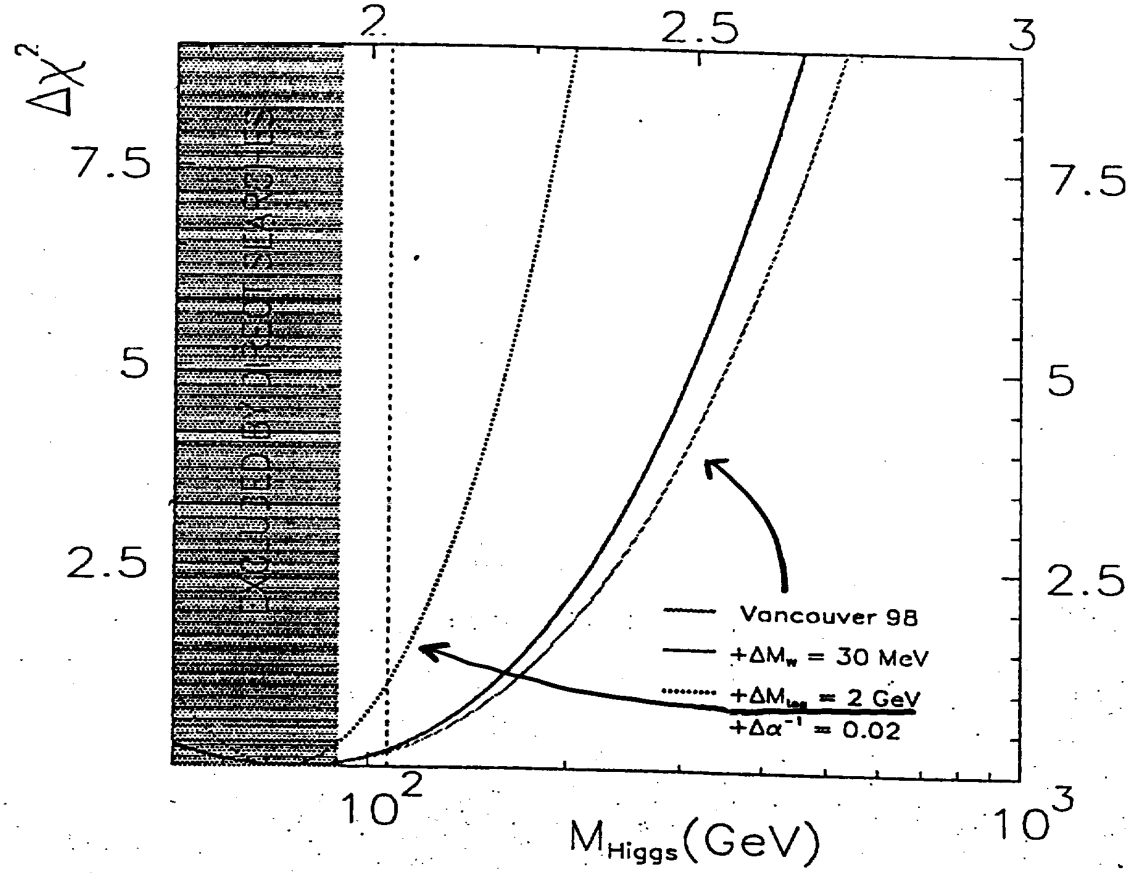
	Measurement	Pull
m_Z [GeV]	91.1867 ± 0.0021	.08
Γ_Z [GeV]	2.4939 ± 0.0024	-.81
σ^0_{hadr} [nb]	41.491 ± 0.058	.30
R_e	20.765 ± 0.026	.69
$A^{0,e}_{fb}$	0.01683 ± 0.00096	.71
A_e	0.1479 ± 0.0051	.23
A_τ	0.1431 ± 0.0045	-.81
$\sin^2\theta^{lept}_{eff}$	0.2321 ± 0.0010	.54
m_W [GeV]	80.350 ± 0.056	-.43
R_b	0.21680 ± 0.00073	1.26
R_c	0.1694 ± 0.0038	-.75
$A^{0,b}_{fb}$	0.0991 ± 0.0020	-1.88
$A^{0,c}_{fb}$	0.0712 ± 0.0043	-.53
A_b	0.908 ± 0.027	-.99
A_c	0.651 ± 0.030	-.56
$\sin^2\theta^{lept}_{eff}$	0.23109 ± 0.00029	-1.61
$\sin^2\theta_W$	0.2255 ± 0.0021	1.07
m_W [GeV]	80.448 ± 0.062	1.20
m_t [GeV]	174.3 ± 5.1	.54
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02804 ± 0.00065	-.08





$M_H < 262$ GeV @ 95% C.L.

Teubert
RADCOR '98



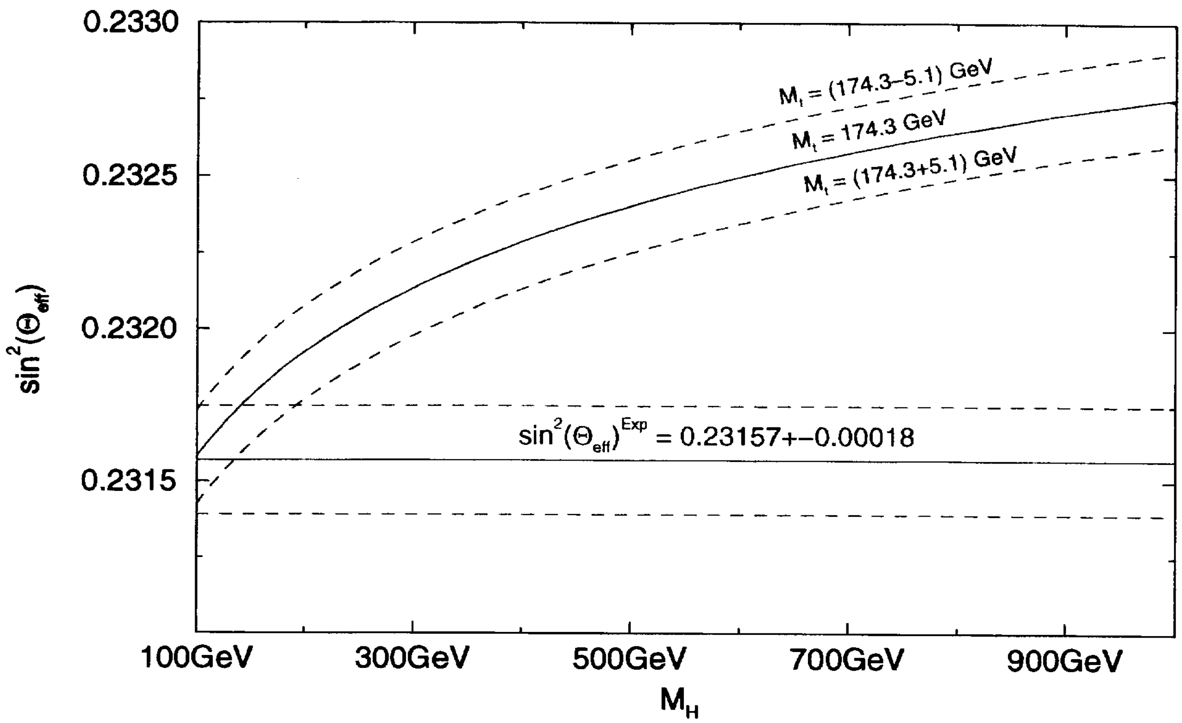
Exp. accuracy [present and expected]

	LEP2/TeV	LHC
M_W	40 MeV	15 - 20 MeV
$\sin^2\theta_\ell$	0.00018	0.00018
m_t	5 GeV	2 GeV

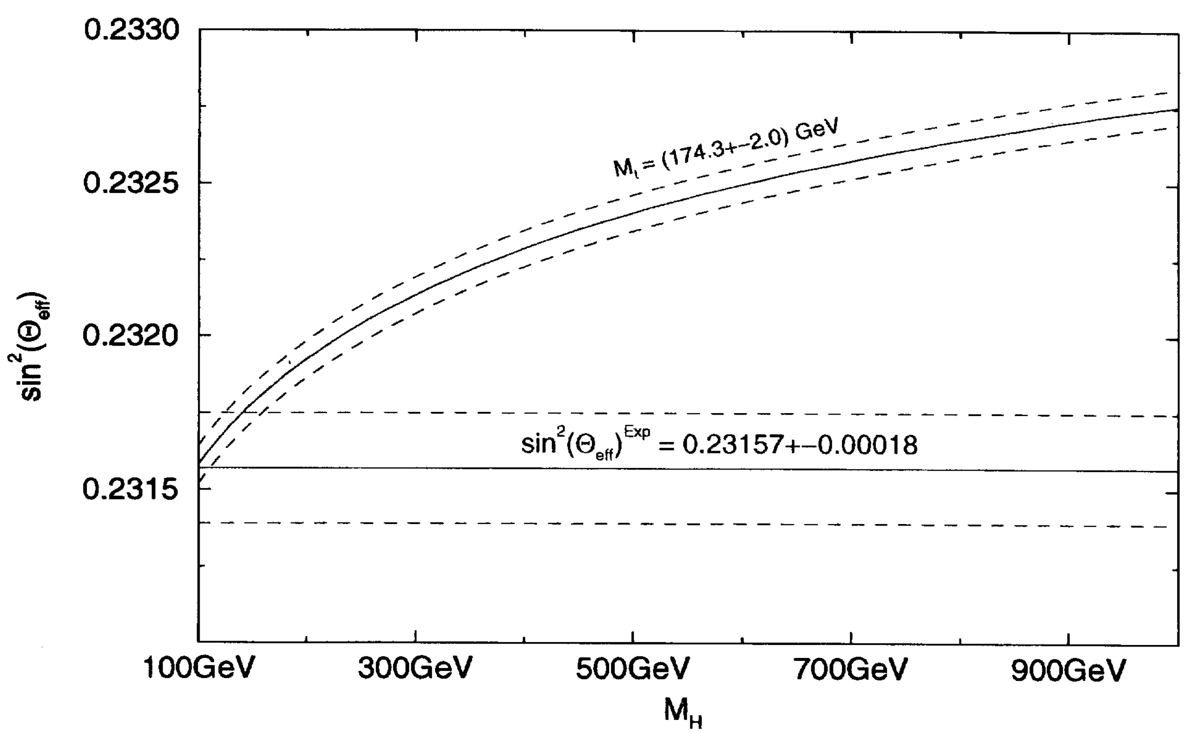
work done with
S. Heinemeyer, G. Weiglein

Higgs-mass dependence of $\sin^2\theta_{\text{eff}}$ in the SM

Current experimental precision:

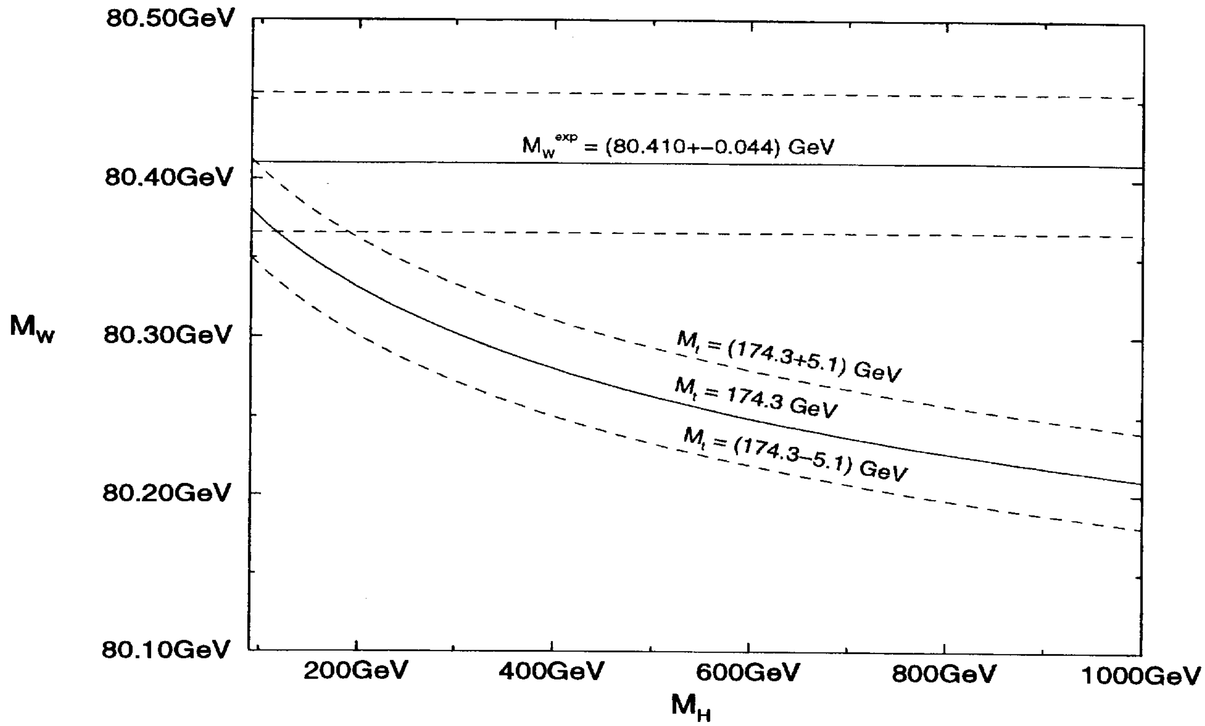


Experimental precision at LHC:

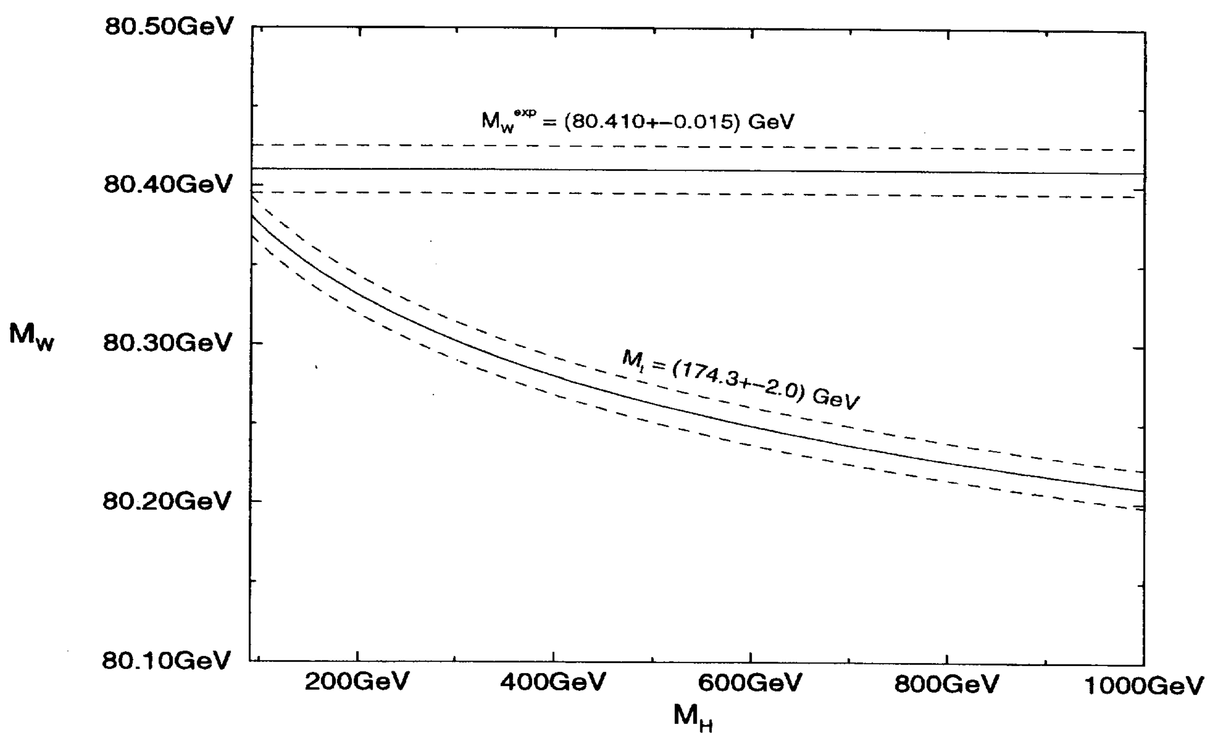


Higgs-mass dependence of M_W in the SM

Current experimental precision:



Experimental precision at LHC:



	M_H = 120	M_H = 150	M_H = 180	$\delta m_t = 2$ GeV	$\delta\alpha_h$ *)	δ_{ho}
M_W	80.363	80.349	80.337	0.012	0.013 0.005 0.003	0.004
$\sin^2\theta_\ell$	0.23167	0.23179	0.23188	0.00006	0.00023 0.00008 0.00005	0.00004
ρ_ℓ	1.0051	1.0050	1.0048	0.0002		0.00005
R_b	0.2158			0.0001		

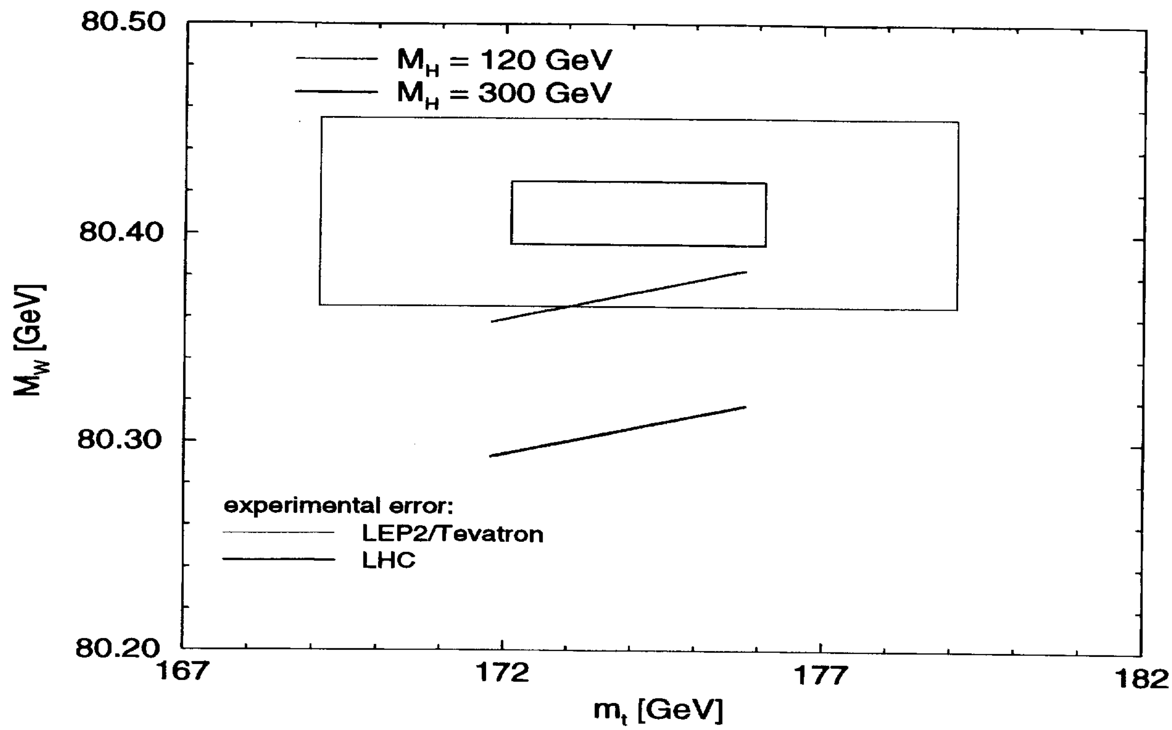
$\delta\rho_\ell^{exp} = 0.0012$

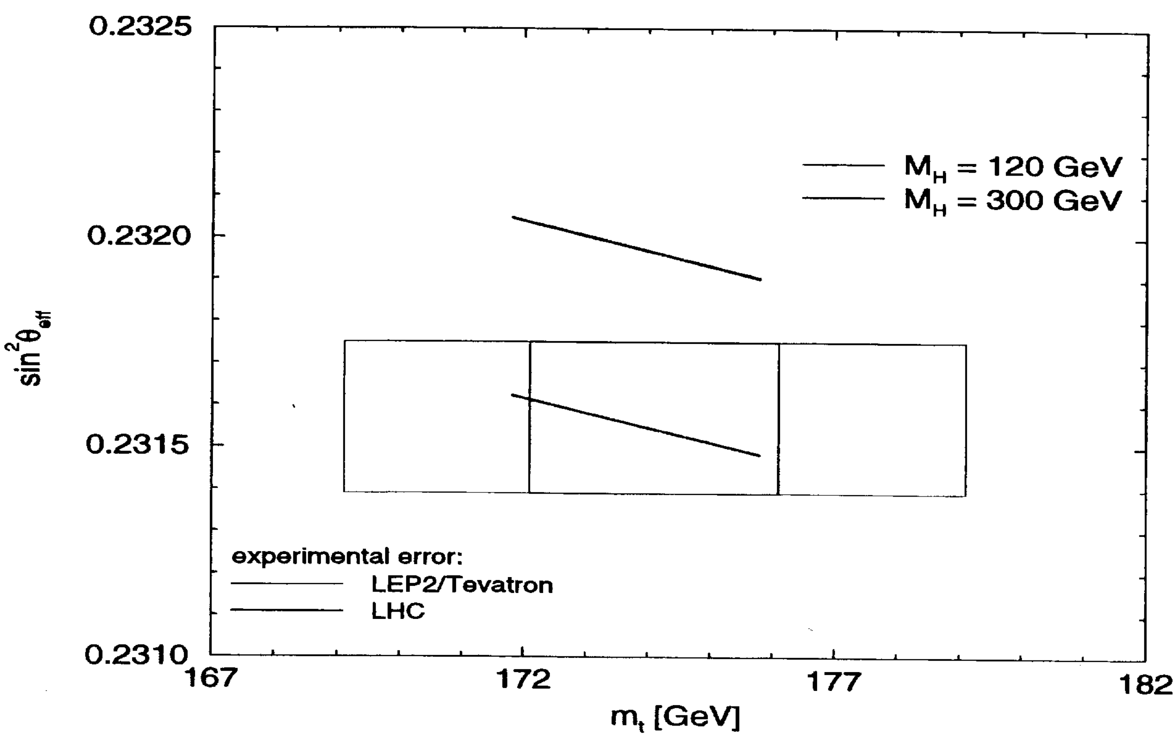
$\delta R_b^{exp} = 0.00074$

$$* \ \delta(\Delta\alpha) = 0.0007 \\ = 0.000254 \\ = 0.00017$$

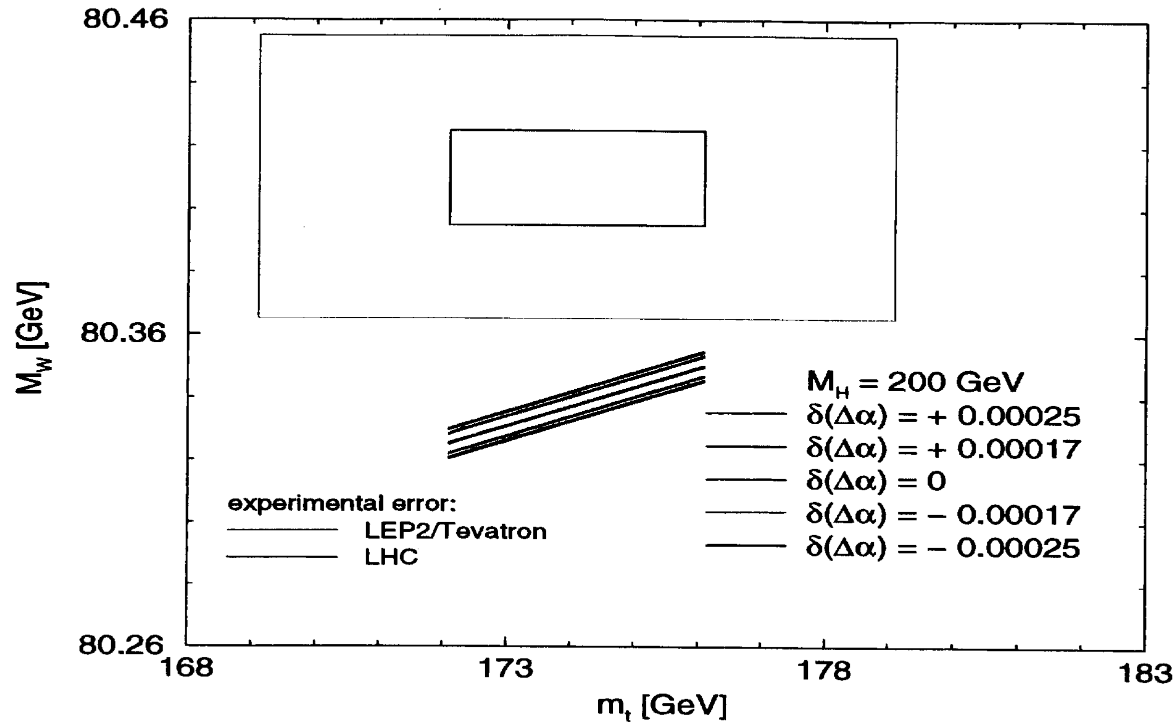
Prediction for $M_{\rm W}$, $\sin^2\theta_{\rm eff}$ in the SM,
experimental precision: LEP2/Tev., LHC

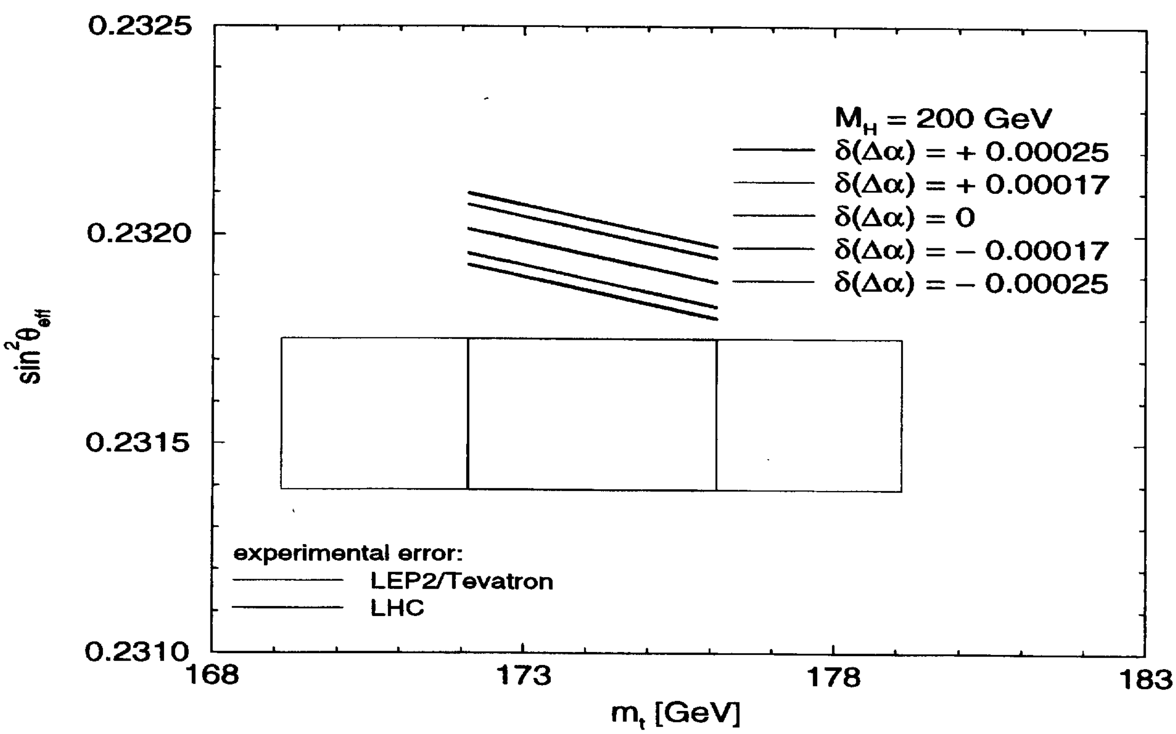
Sensitivity to variation of $m_{\rm h}$:





Prediction for M_W, $\sin^2\theta_{\mathrm{eff}}$ in the SM
Effect of uncertainty in $\Delta\alpha$:





determination of M_H:

$$M_W = f_W(M_H, m_t, \dots)$$

$$\sin^2\theta_\ell = f_s(M_H, m_t, \dots)$$

invert:

$$M_H = f_W^{-1}(M_W, m_t, \dots)$$

$$M_H = f_s^{-1}(\sin^2\theta_\ell, m_t, \dots)$$

	M_W	$\sin^2\theta_\ell$
LEP2/Tevatron	62 %	39 %
LHC *)	32 %	38 %

*) $\delta m_t = 2\,\text{GeV}$, $\delta M_W = 15\,\text{MeV}$, $\delta\alpha_h = 0.00017$

non-standard physics (virtual)

- new physics contributions to ρ
  e.g. new generation(s) of fermion:
  extra Higgses (doublet, triplet, ..
  new dynamics (strongly int. sector

  $\Rightarrow$ weaker bound on M_H

- new physics to $\Delta\rho = \varepsilon_1, \varepsilon_2, \varepsilon_3$ (T, U, S

  bounds on M_H disappear

  $M_H = 390^{+690}_{-310}$ GeV J. Erler ('99)

  $m_t = 172.9 \pm 4.8$ GeV

- Specific models : supersymmetry

  MSSM $\Rightarrow$ precision calculations of EW observables

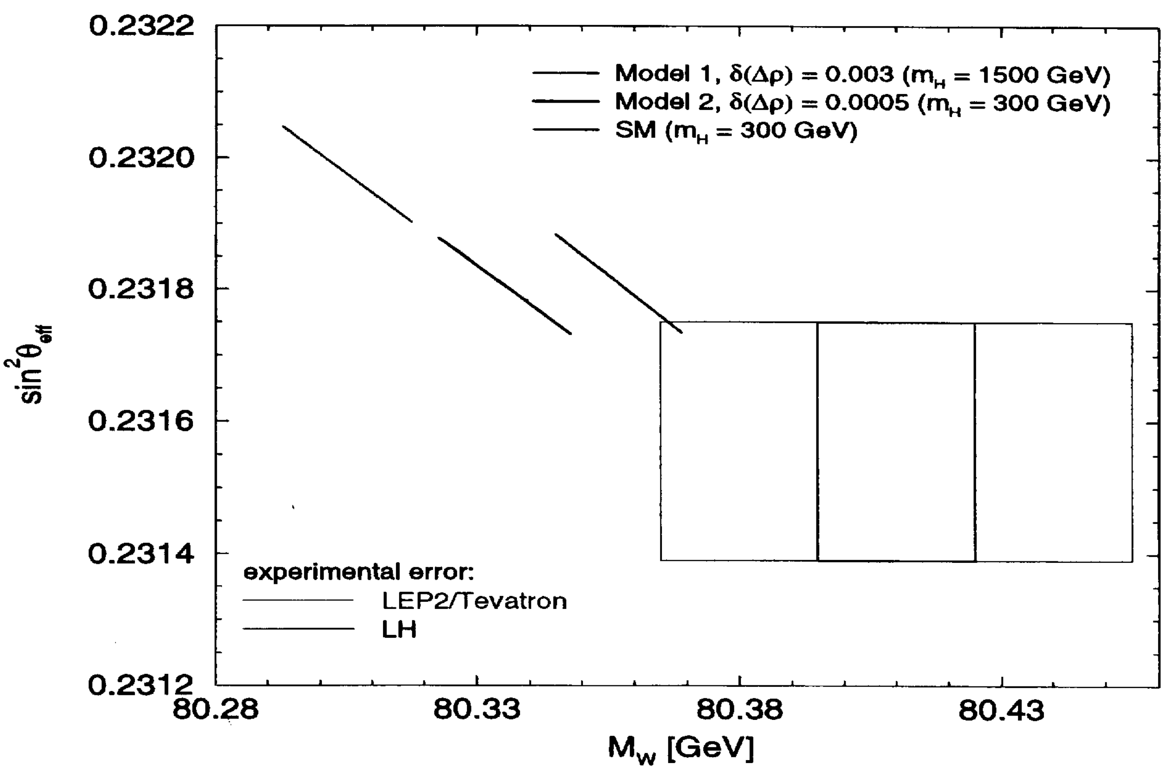
Test of extended models via extra contribution to $\Delta\rho$:

Sensitivity at LEP/Tevatron, LHC

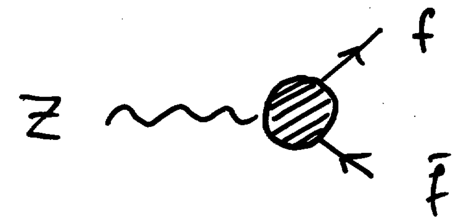
Two examples:

Model 1: Strong interacting Higgs bosons
$\to M_{\mathrm{H}} \gtrsim 900$ GeV (plot: $M_{\mathrm{H}} = 1500$ GeV)
$\Delta\rho^{extra} = \mathcal{O}(3 \times 10^{-3})$

Model 2: Extra dimensions at low energies
[*M. Masip, A. Pomarol '99*]
$\Delta\rho^{extra} = \mathcal{O}(5 \times 10^{-4})$



- **Effective Z boson couplings:**



$$\boxed{\begin{aligned} g_A^f &= \sqrt{\rho_f}\; I_3^f \\ g_V^f &= \sqrt{\rho_f}\left(I_3^f - 2\,Q_f \sin^2\theta_f\right) \end{aligned}}$$

$\rho_f\,(m_t, \alpha_s, M_A, \tan\beta,$ SUSY-parameter.

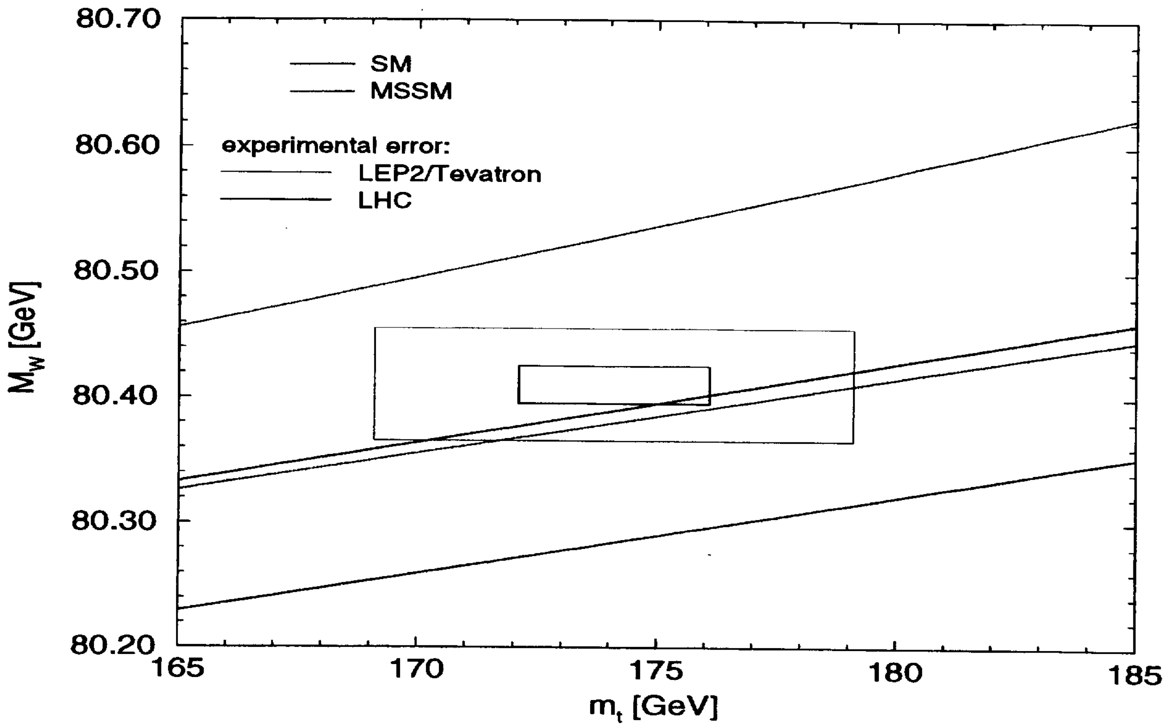
$\sin^2\theta_f\,(m_t, \alpha_s, M_A, \tan\beta,$ SUSY-parameters)

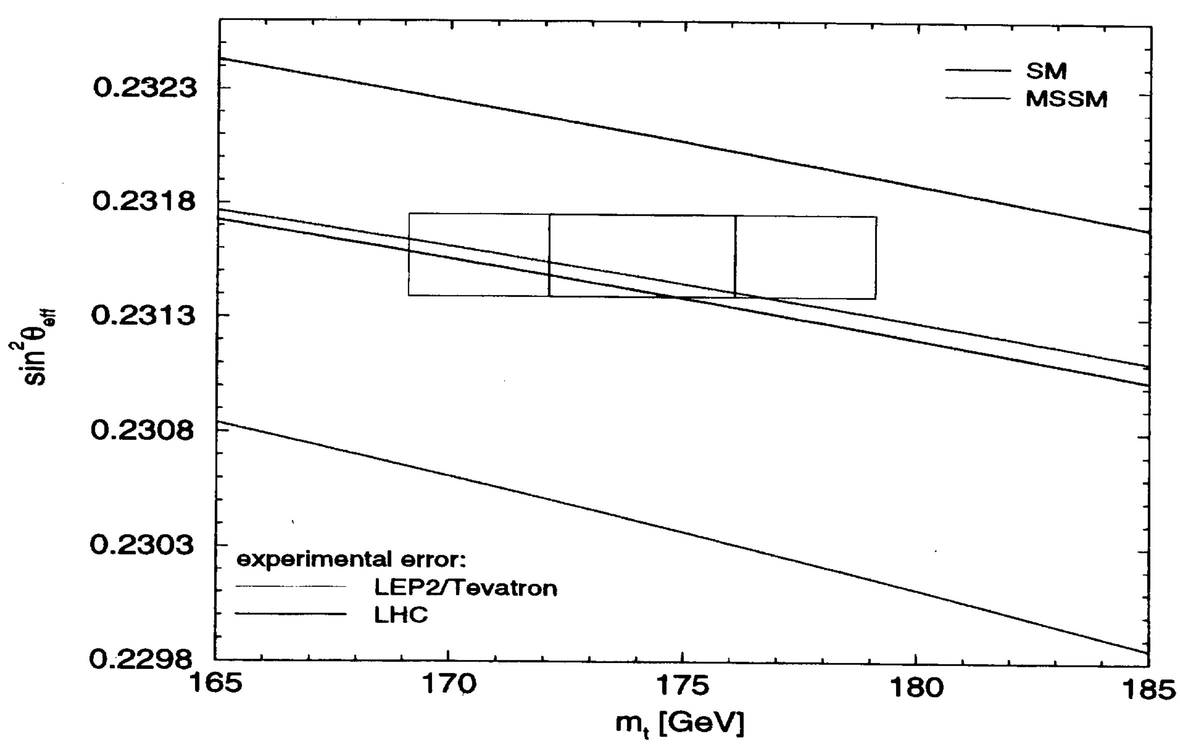
- **$M_W - M_Z$ correlation:**

$$\boxed{M_W^2\left(1 - \frac{M_W^2}{M_Z^2}\right) = \frac{\pi\alpha}{\sqrt{2}\,G_\mu}\cdot\frac{1}{1-\Delta r}}$$

$\Delta r = \Delta r\,(m_t, \alpha_s, M_A, \tan\beta,$ SUSY-par.)

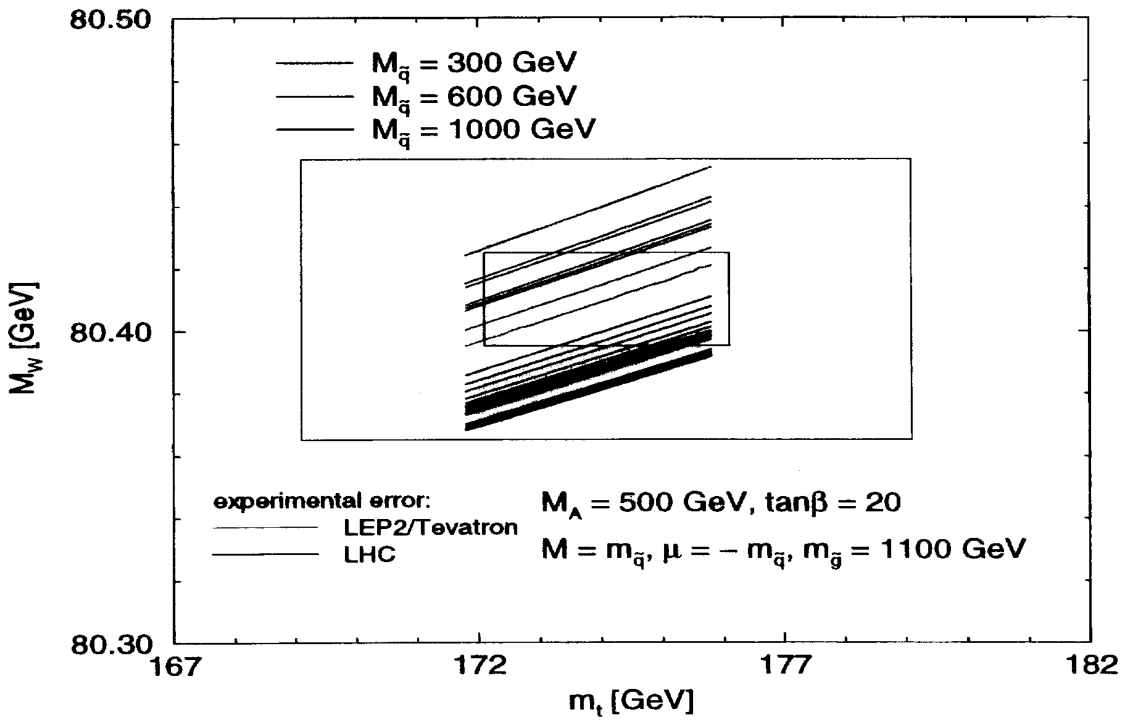
Prediction for M_W, $\sin^2\theta_{\rm eff}$ in SM and MSSM, experimental precision: LEP2/Tev., LHC

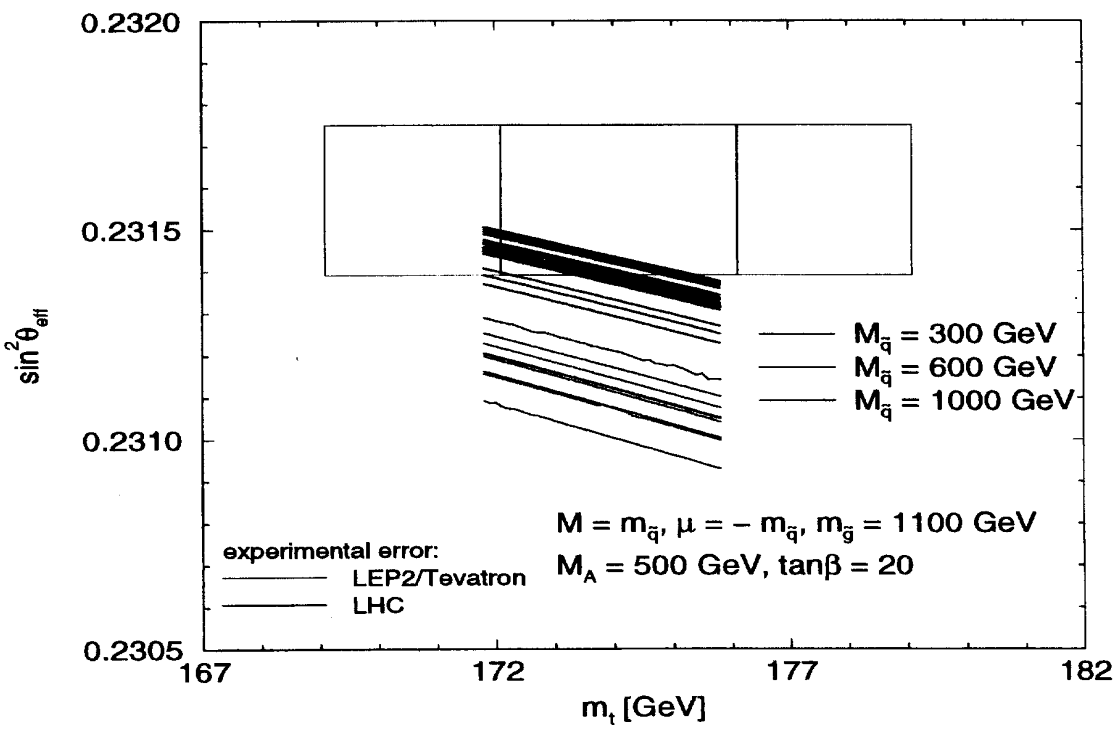




Prediction for M_W, $\sin^2\theta_{\text{eff}}$ in the MSSM, experimental precision: LEP2/Tev., LHC

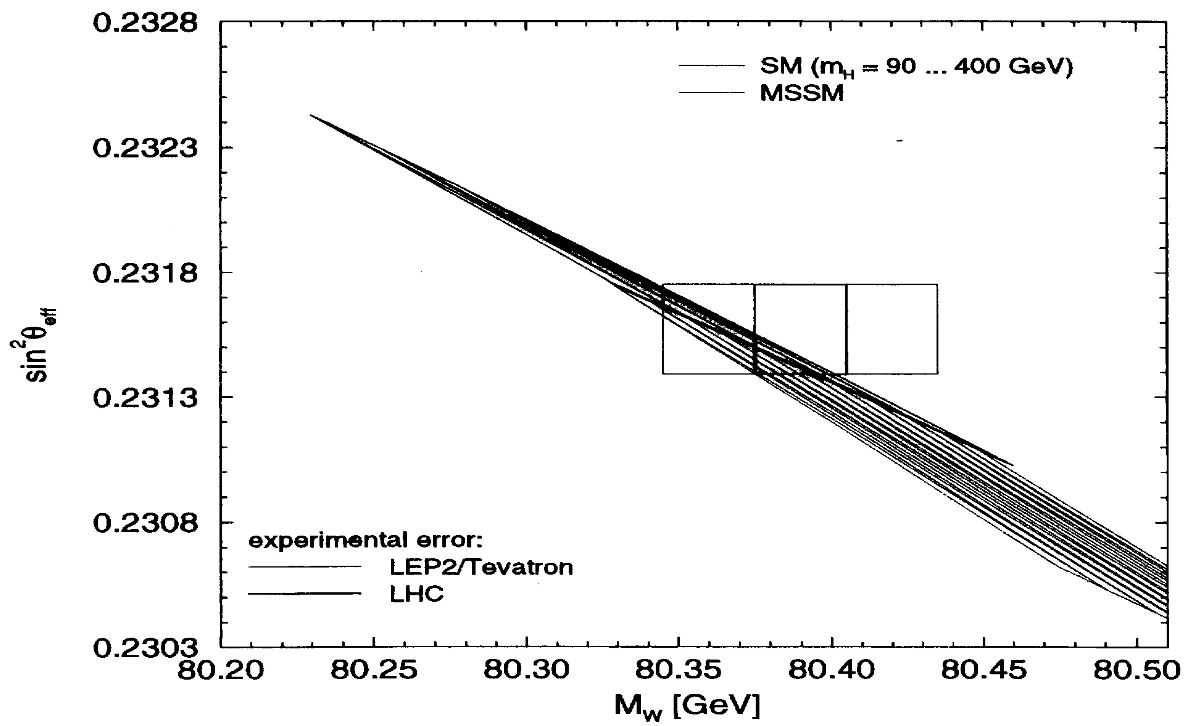
Sensitivity to variation of $m_{\tilde{q}}$ by $\pm 10\%$ and of mixing in $\tilde{t}$-sector:





Prediction for M_{W}, $\sin^2\theta_{\text{eff}}$ in SM and MSSM, experimental precision: LEP2/Tev., LHC

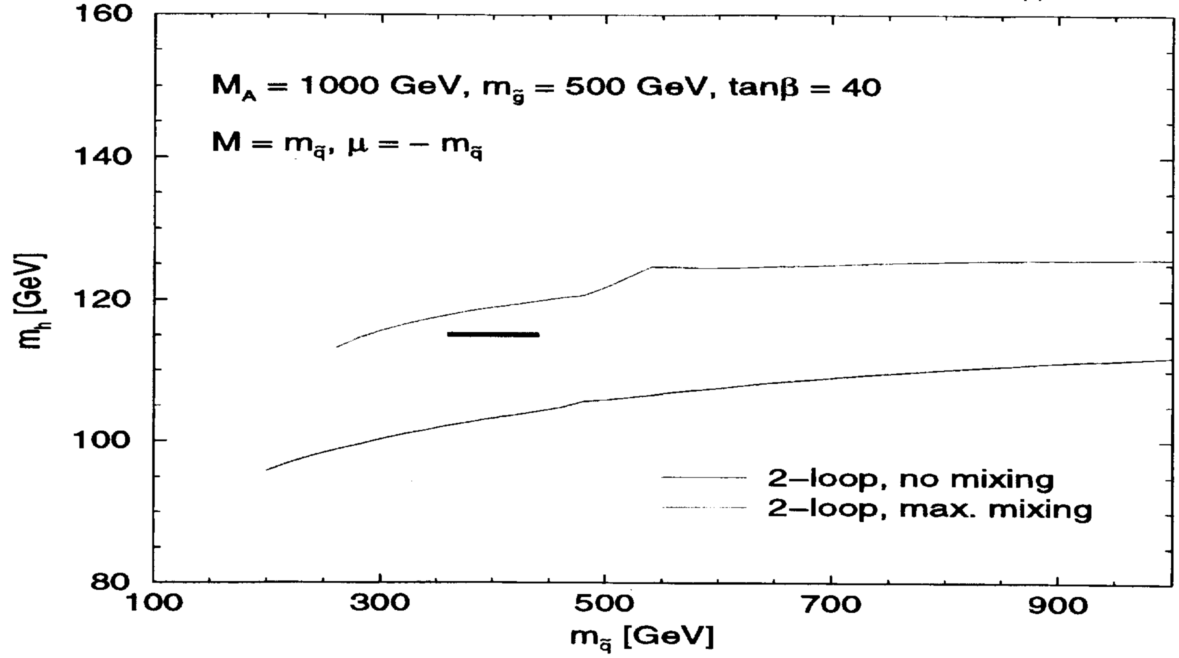
SM: 90 GeV $\leq m_{\text{h}} \leq$ 400 GeV, m_{t} ~~fixed~~ 165 – 185
MSSM: $m_{\tilde{q}}$, mixing in $\tilde{t}$-sector varied



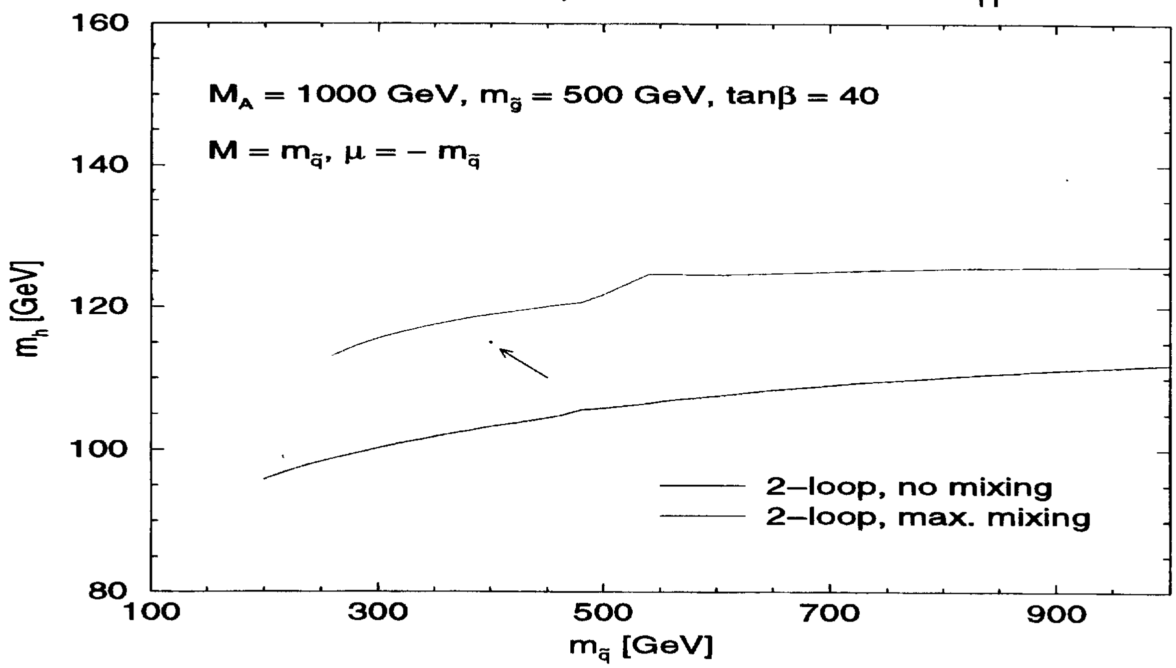
LHC/LC: Experimental information on $m_{\rm h}$, $M_{\rm SUSY}$

Assume: $m_{\rm h}^{\rm exp} = 115$ GeV, $M_{\rm SUSY}^{\rm exp} = 400$ GeV

LHC results vs. MSSM prediction for $m_{\rm h}$:

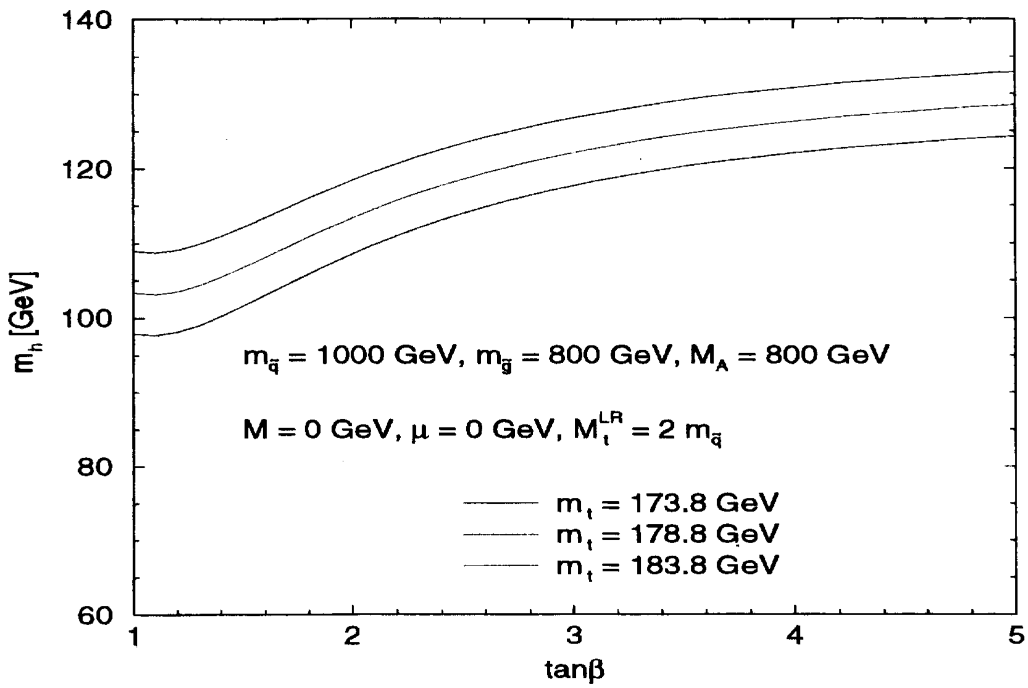


LC results vs. MSSM prediction for $m_{\rm h}$:



$\Rightarrow$ Stringent test of MSSM

Maximal m_{h}-value in scenario with small $\tan\beta$, $m_{\tilde{q}} = 1000$ GeV for different values of m_{t}: $m_{\mathrm{t}} = m_{\mathrm{t}}^{\mathrm{exp}}$, $m_{\mathrm{t}}^{\mathrm{exp}} + 1\sigma$, $m_{\mathrm{t}}^{\mathrm{exp}} + 2\sigma$



Values increase by 3–4 GeV for $m_{\tilde{q}} = 2000$ GeV

LEP2 exclusion limit: $\approx$ 107 GeV

$\Rightarrow m_{\mathrm{h}}^{\mathrm{max}}$ for $\tan\beta = 1.6$ is at the edge of LEP2 reach

$\tan\beta$ reach: $\tan\beta = 1.9$ for $m_{\mathrm{t}} = 173.8$ GeV
$\tan\beta = 1.5$ for $m_{\mathrm{t}} = 178.8$ GeV
for $m_{\tilde{q}} = 1000$ GeV