Bounds on the Higgs boson mass from M_W (and s^2_{eff})

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Torino – April 13, 2004

“Incontri di Fisica delle Alte Energie”

General consensus: The SM gives a very good description of a multitude of phenomena . . .

Why the Higgs boson is so important?
→ It is the most "obvious" problem of the SM!

It has NOT been found experimentally (yet?)

The support for the SM Higgs comes from the theory

- ⋆ Higgs mechanism → masses for Z and W
- ⋆ Yukawa couplings → masses for fermions

⇒ Only *indirectly* from the experiments!

We have no DIRECT measurement of the Higgs mass, only direct evidence of a lower bound (95% C.L.)

$$M_H > 114.4 \text{ GeV}$$

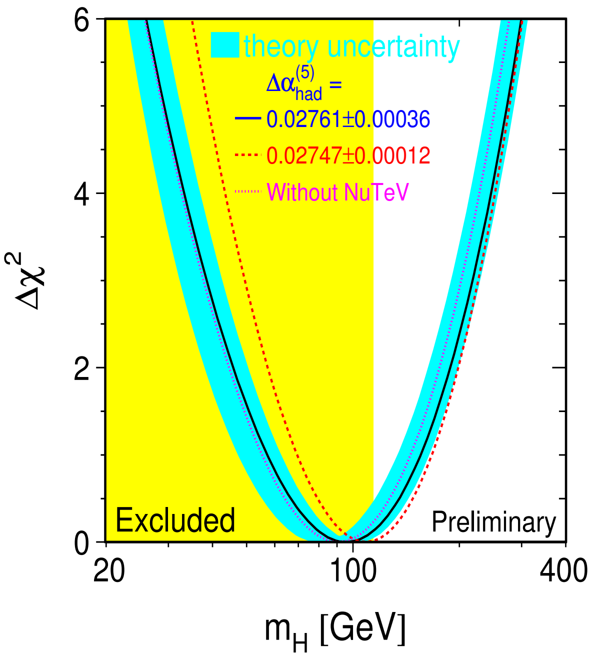
All the information on M_H is INDIRECT

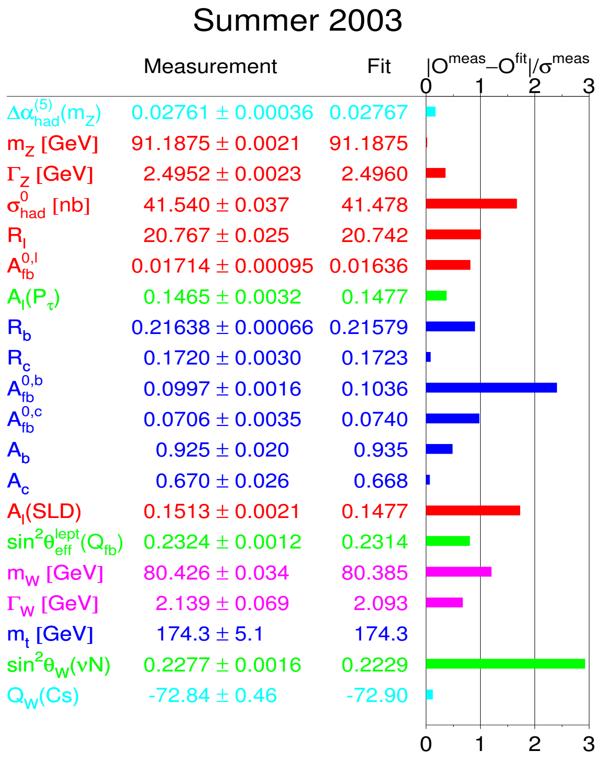
- ⋆ Theoretical predictions that depends on M_H via radiative corrections
- ⋆ Experimental data

Problem: Logarithmic dependence on M_H

Global Analysis → based on a $\Delta\chi^2$-analysis!

$$M_H = 96^{+60}_{-38}\,\text{GeV}\,; \quad M_H^{95} = 219\,\text{GeV} \qquad \text{(Summer 2003)}$$



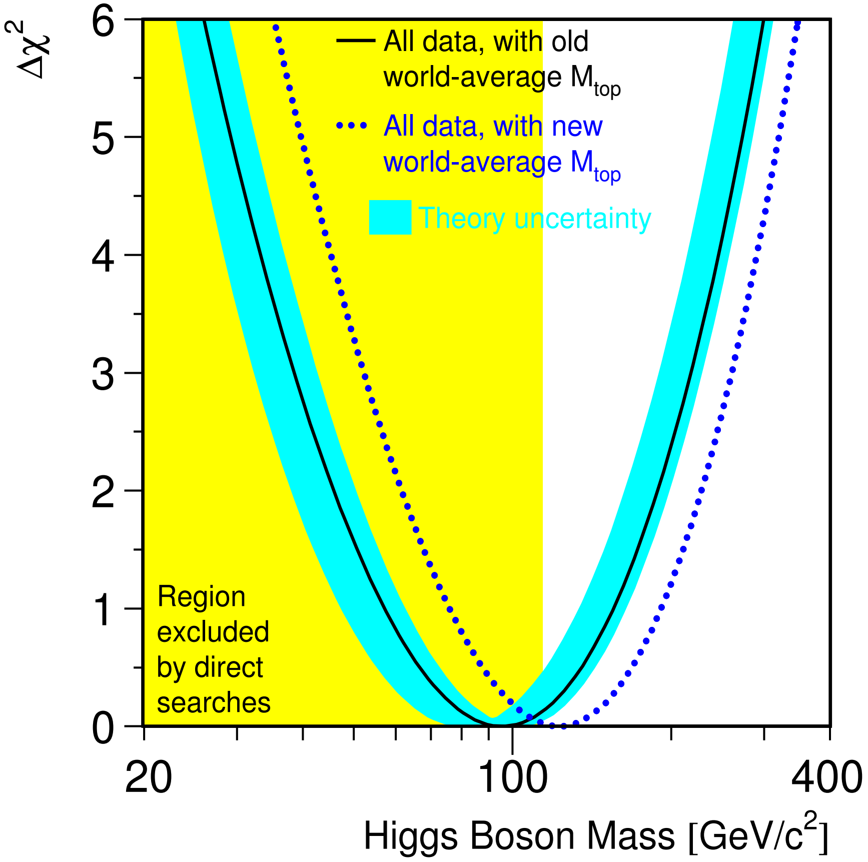


Summer 2003

	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1875
Γ_Z [GeV]	2.4952 ± 0.0023	2.4960
σ^0_{had} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01636
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1477
R_b	0.21638 ± 0.00066	0.21579
R_c	0.1720 ± 0.0030	0.1723
$A^{0,b}_{fb}$	0.0997 ± 0.0016	0.1036
$A^{0,c}_{fb}$	0.0706 ± 0.0035	0.0740
A_b	0.925 ± 0.020	0.935
A_c	0.670 ± 0.026	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1477
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.426 ± 0.034	80.385
Γ_W [GeV]	2.139 ± 0.069	2.093
m_t [GeV]	174.3 ± 5.1	174.3
$\sin^2\theta_W(\nu N)$	0.2277 ± 0.0016	0.2229
Q_W(Cs)	-72.84 ± 0.46	-72.90

Global Analysis with NEW $m_t = 178.0 \pm 4.3$ GeV

$$M_H = 117^{+67}_{-45}\,\mathrm{GeV}\,; \quad M_H^{95} = 251\,\mathrm{GeV} \quad \text{(April 2004)}$$



→ The “most likely” value is ABOVE 114.4 GeV !!

The Global Analysis, by itself, could be misleading!

⋆ Striking discrepancies and inconsistencies may be blurred (Marciano, Chanowitz, Sirlin).

⋆ Relative improvements are more important then overall χ^2 (Erler).

⋆ Aside from the Global Fit, we need to look at the observables most sensitive to M_H.

$$\Longrightarrow \quad M_W \quad \sin^2\theta^{lept}_{eff}$$

M_W

There are several factors that single out the M_W determination as particularly important:

- The LEP2 and Tevatron experimental measurements of M_W are in excellent agreement;

D0/CDF(Tevatron)	80.454 ± 0.059 GeV
LEP2	80.412 ± 0.042 GeV

- It places sharp restrictions on M_H;
- The relevant electroweak correction Δr has been fully evaluated at the two-loop level.

“The Toolbox” – Simple formulae for M_W

$$M_W = M_W^0 - d_1 A_1 - d_5 {A_1}^2 - d_2 A_2 + d_3 A_3 - d_4 A_4,$$

$$A_1 \equiv \ln\left(M_H/100\,\mathrm{GeV}\right)\,, \qquad A_2 \equiv \left[\Delta\alpha_h^{(5)}/0.02761\right] - 1\,,$$

$$A_3 \equiv \left(M_t/174.3\,\mathrm{GeV}\right)^2 - 1\,, \qquad A_4 \equiv \left[\alpha_s(M_Z)/0.118\right] - 1\,.$$

Scheme	M_W^0	$10^2\, d_1$	$10\, d_2$	$10\, d_3$	$10^2\, d_4$	$10^3\, d_5$
$\overline{MS}$	80.3868	5.719	5.07	5.42	8.5	8.98
OSI	80.3849	5.667	5.08	5.40	8.5	8.85
$OSII$	80.3847	5.738	5.08	5.37	8.5	8.92
EFF	80.3862	5.730	5.08	5.42	8.5	8.98

A. Ferroglia, G.O., M. Passera and A. Sirlin – hep-ph/0203224

G. Degrassi, P. Gambino, M. Passera and A. Sirlin – hep-ph/9708311

Effective renormalization scheme (EFF)

Weak mixing angle → $\sin^2\theta_{eff}^{lept}$

- Good convergence properties of the $\overline{MS}$ scheme
- Strictly scale independent at finite order in perturbation theory

A. Ferroglia, G.O., and A. Sirlin – hep-ph/0103001 and hep-ph/0106094

A. Ferroglia, G.O., M. Passera, and A. Sirlin – hep-ph/0203224

Effective renormalization scheme (EFF) – more details

We obtain directly $\sin^2\theta_{eff}^{lept}$ using the equation:

$$s_{eff}^2 c_{eff}^2 = \frac{A^2}{M_Z^2\,(1-\Delta r_{eff})}$$

where Δr_{eff}:

- is a function of the **effective angle** s_{eff}^2
- depends on the input parameters:

$$\alpha, G_\mu, M_Z, m_f, M_t, M_h$$

- contains all the one loop corrections and the two-loop corrections inhanced by

$$\left(\frac{M_t^2}{M_Z^2}\right)^n, n = 1,2$$

Input Parameters

$$
\begin{aligned}
M_Z &= 91.1875\,\mathrm{GeV} \\
\alpha &= 1/137.03599976 \\
G_\mu &= 1.16637 \times 10^{-5}\,\mathrm{GeV}^{-2}
\end{aligned}
$$

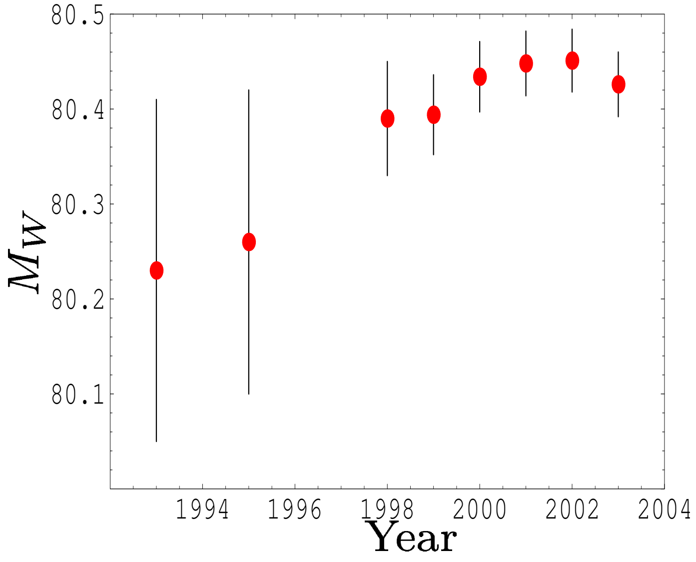
$$
\begin{aligned}
\Delta\alpha_h^{(5)} &= 0.02761 \pm 0.00036 \\
(M_t)_{OLD} &= 174.3 \pm 5.1\,\mathrm{GeV} \\
(M_t)_{NEW} &= 178.0 \pm 4.3\,\mathrm{GeV} \\
\alpha_s\,(M_Z) &= 0.118 \pm 0.002
\end{aligned}
$$

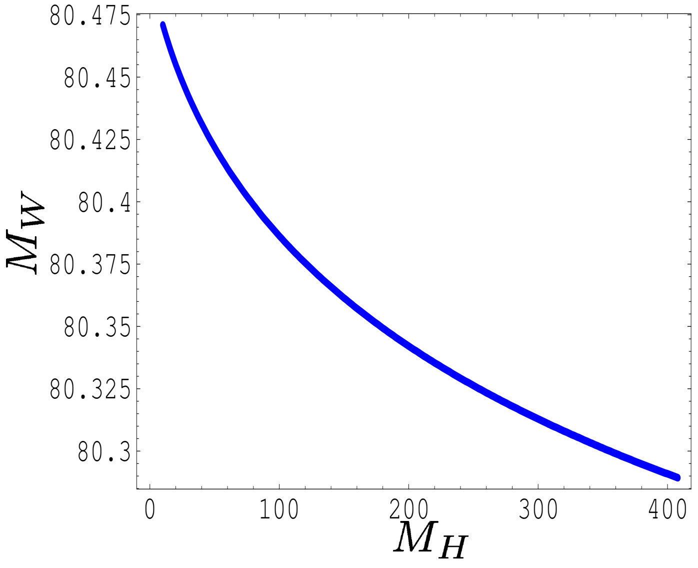
Summer 2002:

$$M_H = 23^{+49}_{-23}\,\text{GeV}\,; \quad M_H^{95} = 122\,\text{GeV}$$

Winter 2003:

$$M_H = 45^{+69}_{-36}\,\text{GeV}\,; \quad M_H^{95} = 184\,\text{GeV}$$





⋆ Let’s not forget that M_{top} plays a big role!

Sources of theoretical error

Main parametric errors:

$$\Delta\alpha_h^{(5)} \pm 0.00036 \begin{cases} \Delta s^2_{eff} & \simeq & 1 \times 10^{-4} \\ \Delta M_W & \simeq & 6 \text{ MeV} \end{cases}$$

$$m_t \pm 5\text{GeV} \begin{cases} \Delta s^2_{eff} & \simeq & 1.5 \times 10^{-4} \\ \Delta M_W & \simeq & 30 \text{ MeV} \end{cases}$$

Truncation error:

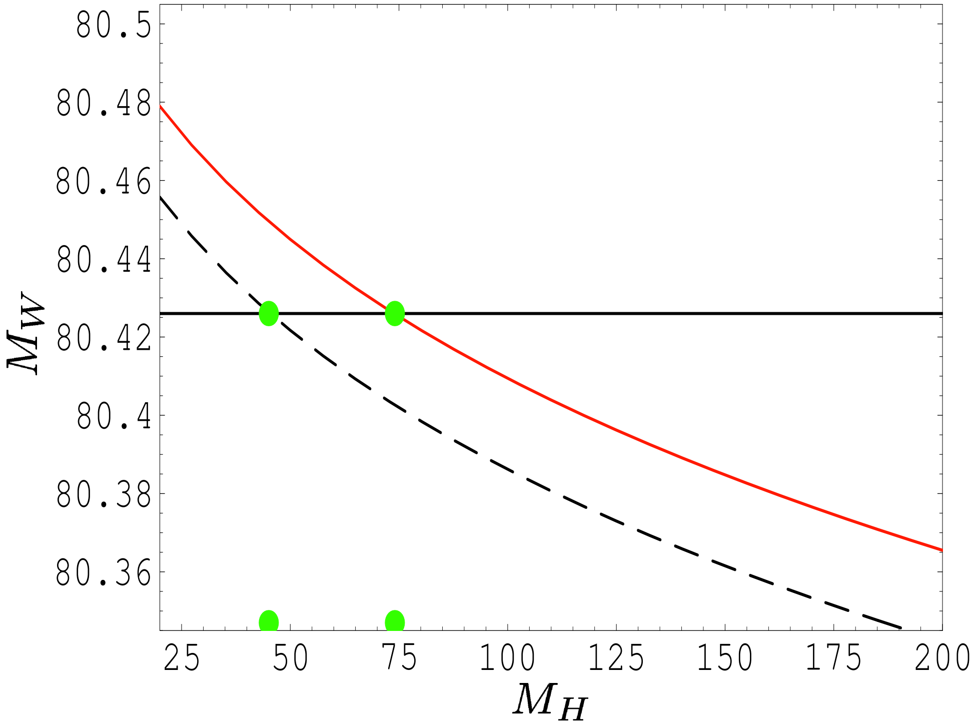
$$\begin{aligned} \Delta s^2_{eff} &\simeq 6 \times 10^{-5} \\ \Delta M_W &\simeq 7 \text{ MeV} (4 \text{ MeV}) \end{aligned}$$

m_t and its error-bar are crucial!

March 2004: using the NEW value for m_t

$$m_t = 178.0 \pm 4.3\,\text{GeV}$$

we increase the theoretical prediction for M_W by ≈ 20 MeV!!



and obtain: $M_H = 74^{+83}_{-47}\,\text{GeV}\,;\quad M_H^{95} = 238\,\text{GeV}$

We compared our results with a recent formula incorporating the two-loop complete calculation of Δr.

M. Awramik, M. Czakon, A. Freitas and G. Weiglein – hep-ph/0311148

⇒More restrictive results

$$M_H = 36^{+65}_{-33}\,\mathrm{GeV}\,; \quad M_H^{95} = 168\,\mathrm{GeV}\ \text{(Winter 2003)}$$

$$M_H = 62^{+78}_{-43}\,\mathrm{GeV}\,; \quad M_H^{95} = 216\,\mathrm{GeV}\ \text{(April 2004)}$$

Calculation of Δr

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

α: Marciano, Sirlin, 1980.

$\alpha\alpha_s$: Kniehl, Sirlin, Djouadi, Verzegnassi, Gambino, 1992.

$\alpha^2 m_t^4/M_Z^4$: Barbieri et al., 1992.

$\alpha\alpha_s^2$: Chetyrkin, Kuhn, Steinhauser, 1995.

$\alpha^2 m_t^2/M_Z^2$: Degrassi, Gambino, Vicini, 1996.

α^2 (ferm.): Freitas, Hollik, Walter, Weiglein, 2000.

α^2: Awramik, Czakon, Onishchenko, Veretin, 2002.

$\alpha^2\alpha_s^2 m_t^4/M_Z^4$, $\alpha^3 m_t^6/M_Z^6$: Faisst, Kuhn, Seidensticker, Veretin, 2003.

$\sin^2\theta_{eff}^{lept}$

$$(\sin^2\theta_{eff}^{lept})_{exp} = 0.23150 \pm 0.00016$$

Using this value (and the new m_t):

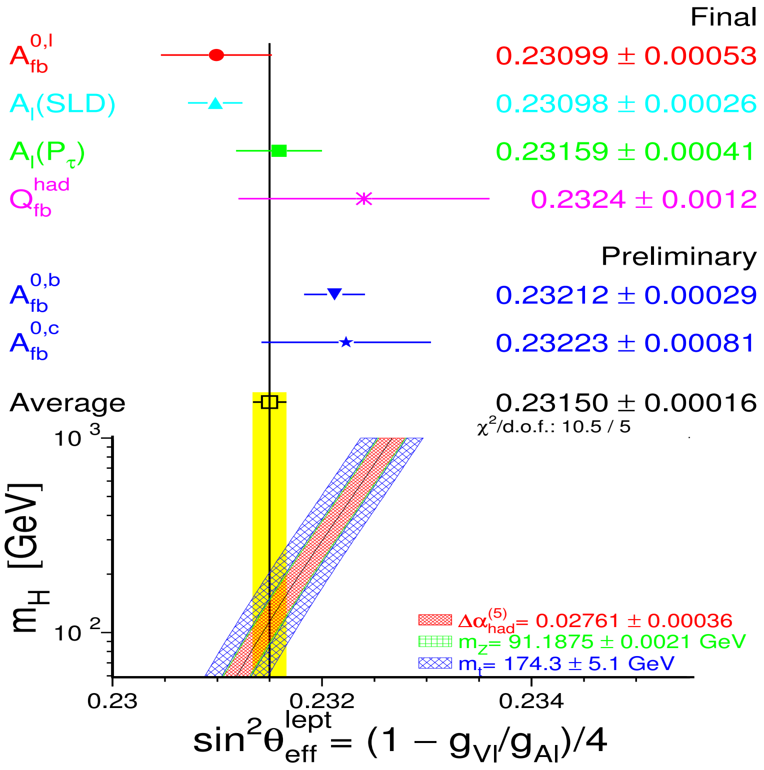
$$M_H = 159^{+92}_{-61}\,\mathrm{GeV}\,; \quad M_H^{95} = 332\,\mathrm{GeV}\,;$$

and combining with M_W:

$$M_H = 138^{+76}_{-51}\,\mathrm{GeV}\,; \quad M_H^{95} = 280\,\mathrm{GeV}\,.$$

This looks good, if we forget that:

- Data coming from different experiments are NOT in good agreement: ($\chi^2/\mathrm{Dof} = 10.5/5$)



$$(\sin^2\theta_{eff}^{lept})_{(l)} = 0.23113 \pm 0.00021$$

$$(\sin^2\theta_{eff}^{lept})_{(h)} = 0.23214 \pm 0.00027$$

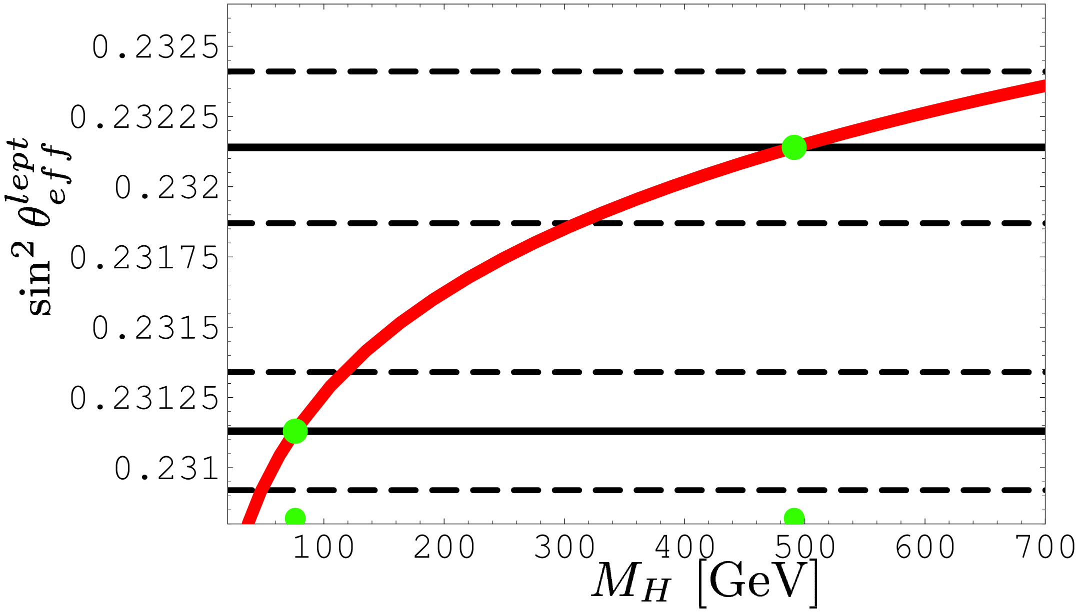
→ the difference is almost 3 σ!

$(\sin^2\theta^{lept}_{eff})_{(h)} \to$ heavy Higgs!

$$M_H = 491^{+342}_{-210}\,\mathrm{GeV}\,; \quad M_H^{95} = 1150\,\mathrm{GeV}\,.$$

$(\sin^2\theta^{lept}_{eff})_{(l)} \to$ light Higgs, but very good agreement with M_W!

$$M_H = 76^{+58}_{-35}\,\mathrm{GeV}\,; \quad M_H^{95} = 190\,\mathrm{GeV}\,,$$



M_W and $(\sin^2\theta^{lept}_{eff})_{(l)}$ are in perfect agreement!

From M_W:

$$M_H = 74^{+83}_{-47}\,\mathrm{GeV}\,; \quad M_H^{95} = 238\,\mathrm{GeV}$$

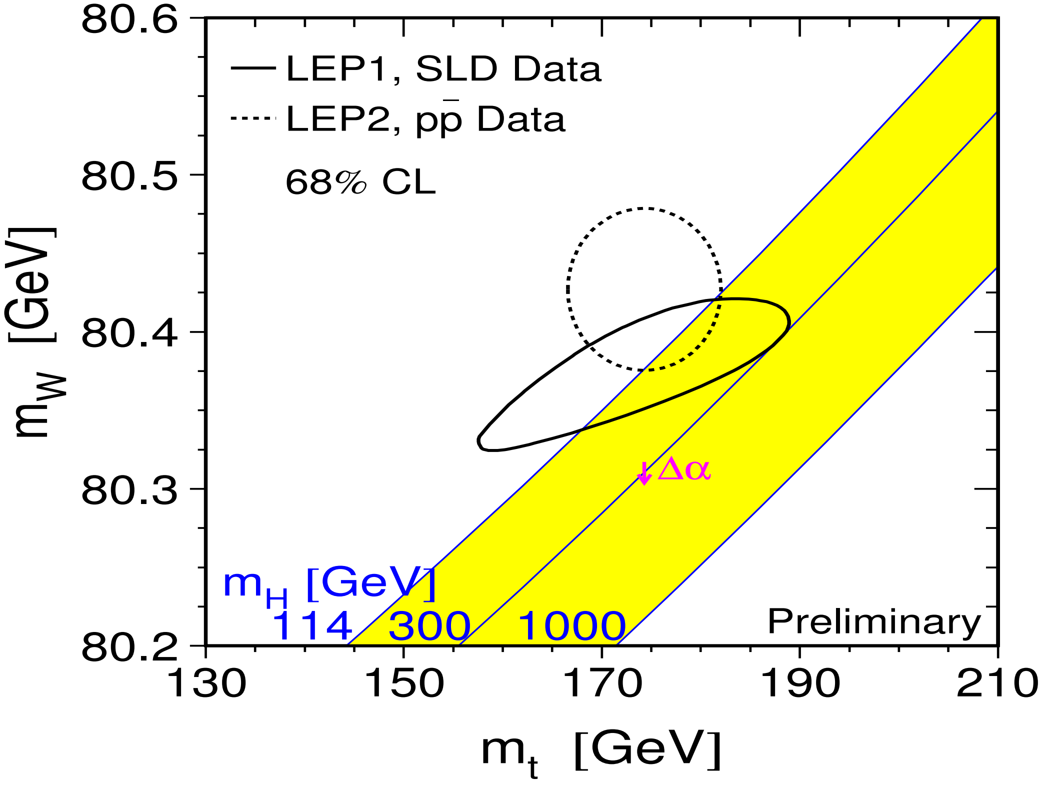
From $(\sin^2\theta^{lept}_{eff})_{(l)}$:

$$M_H = 76^{+58}_{-35}\,\mathrm{GeV}\,; \quad M_H^{95} = 190\,\mathrm{GeV}$$

Combining them:

$$M_H = 76^{+47}_{-32}\,\mathrm{GeV}\,; \quad M_H^{95} = 166\,\mathrm{GeV}$$

We can perform a different analysis:



⋆ New results on M_H before LHC? Maybe...

⋆ Most likely better new data on M_W and m_t!

Compare at various C.L. the experimental values for M_W and m_t with the theoretical function $M_W = M_W(M_H, m_t)$:

- Assume the validity of the SM
- Take $M_H \geq 114.4$ GeV as a sharp cutoff

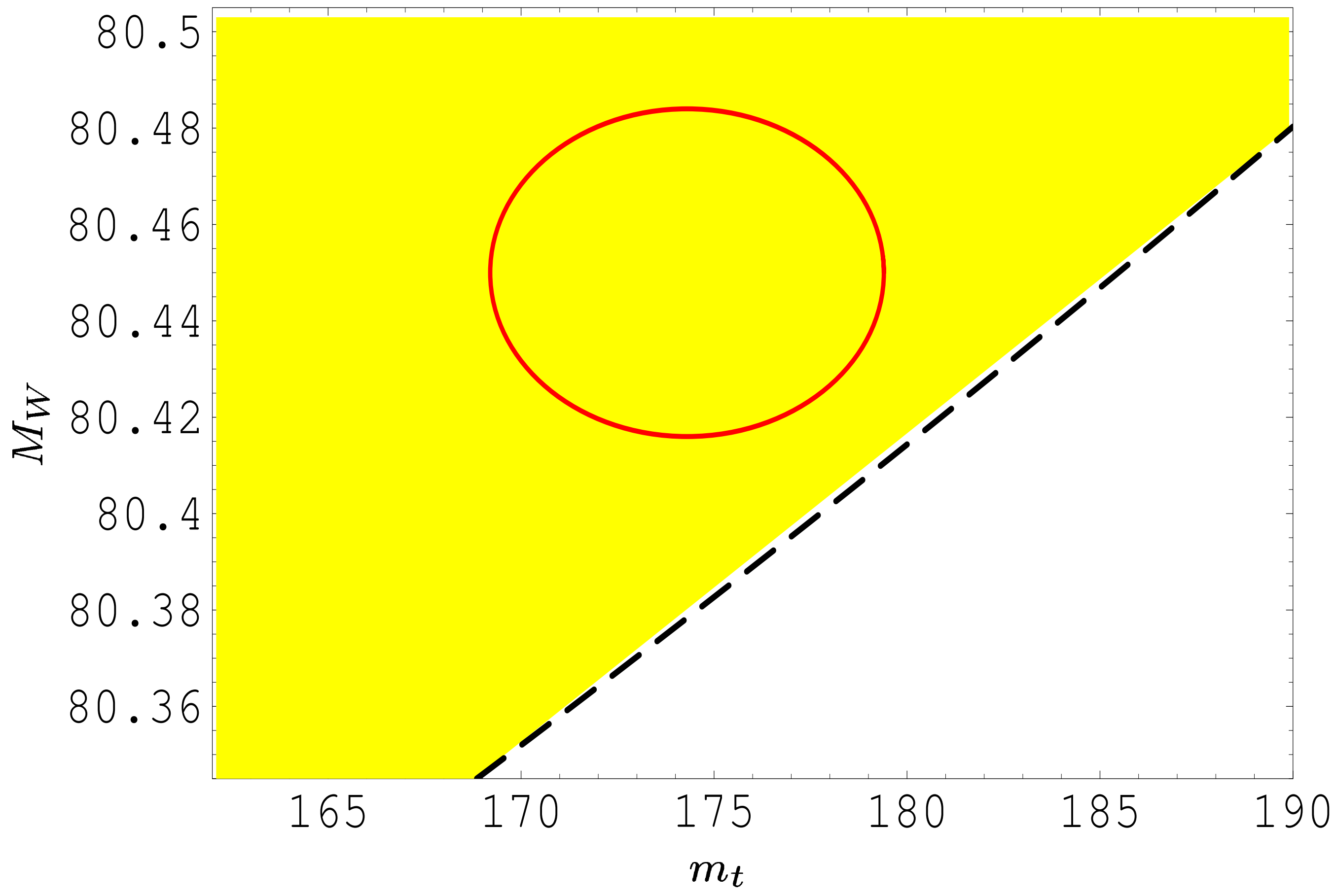
⇒ We obtain allowed regions for M_W and m_t

⇒ Sharp bounds on these parameters

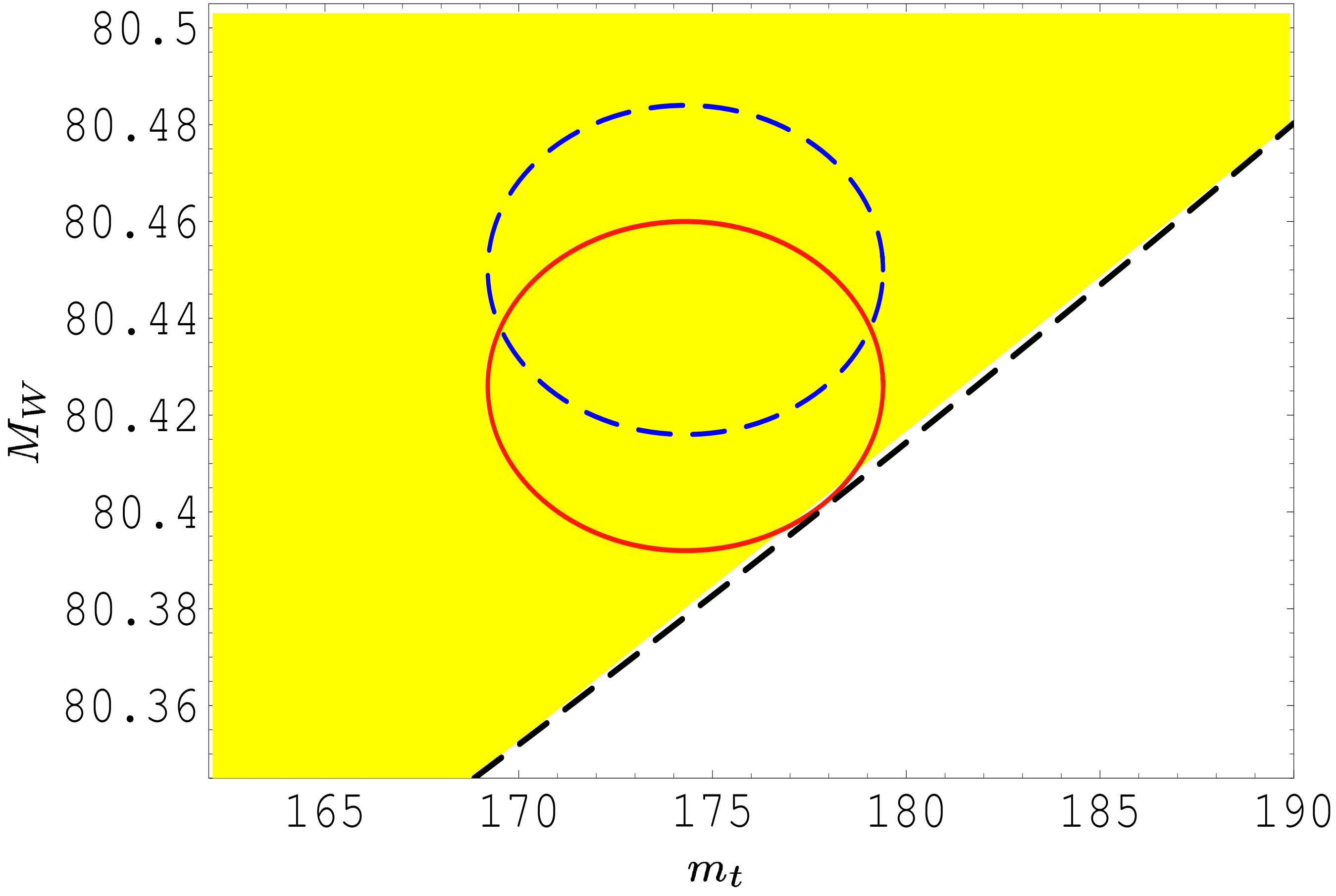
- The same can be done for $\sin^2\theta_{eff}^{lept}$

A. Ferroglia, G.O., and A. Sirlin – hep-ph/0401196, to appear in EJPC

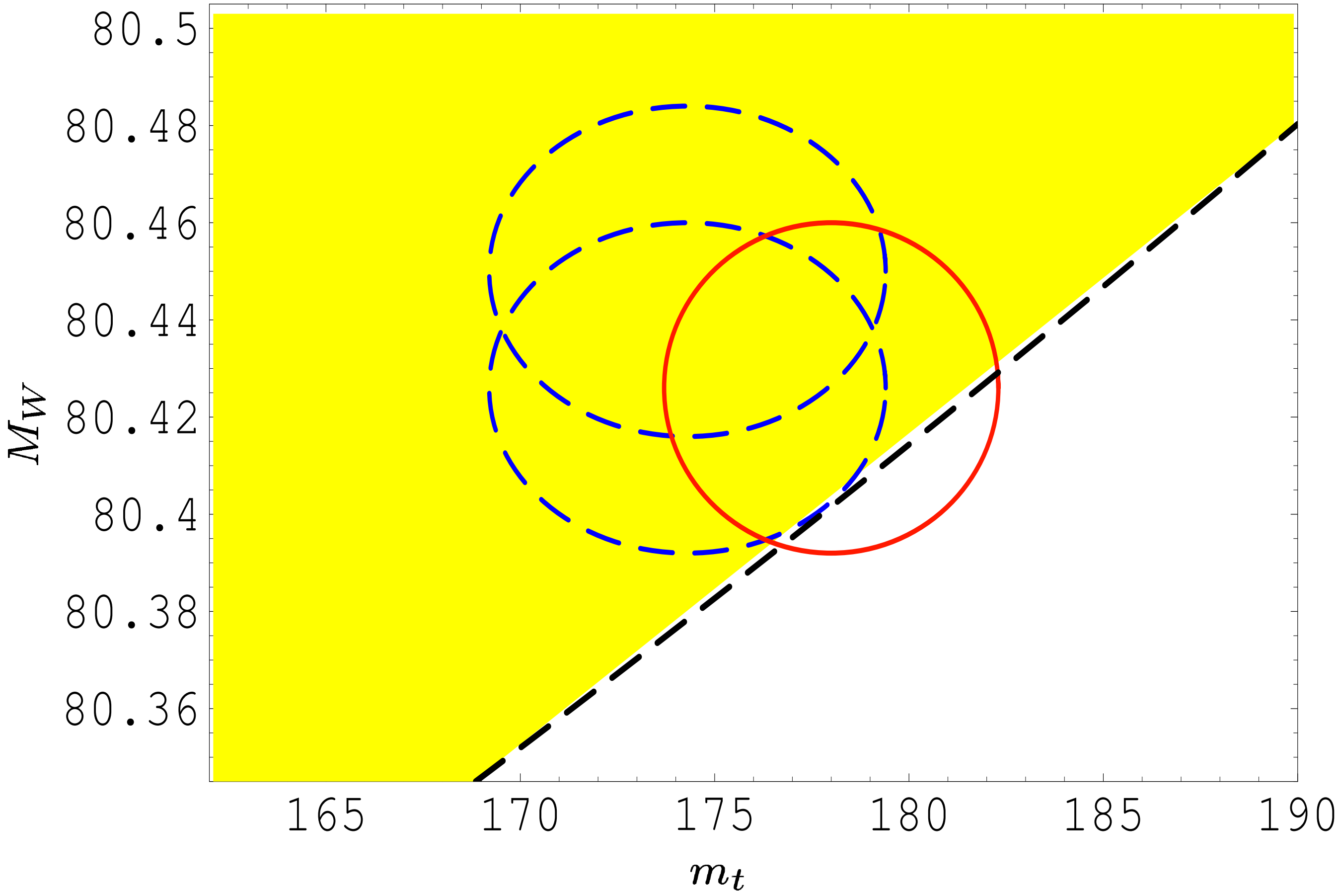
Summer 2002 – 68% C.L.



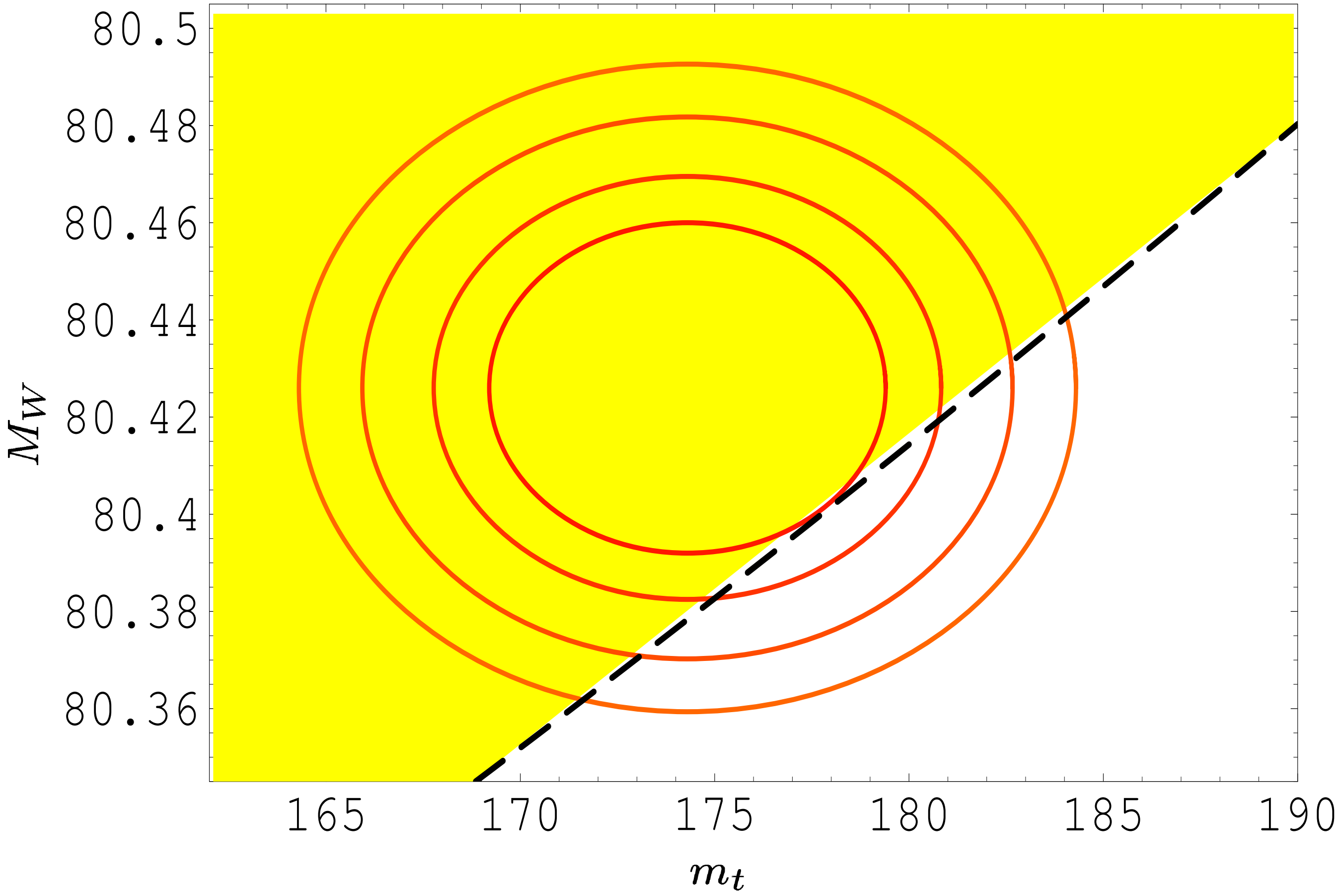
Summer 2002 and Winter 2003 – 68% C.L.



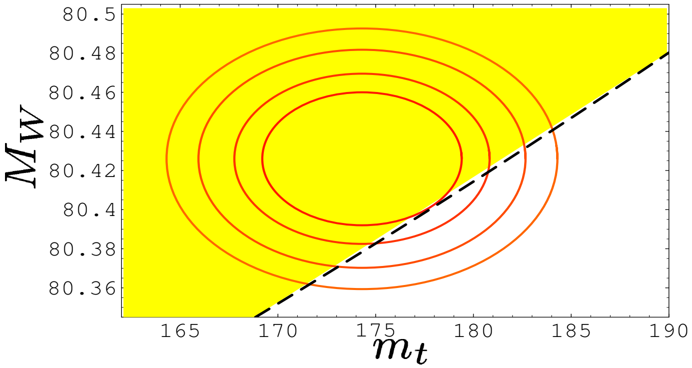
Summer 2002, Winter 2003 and April 2004 – 68% C.L.



Winter 2003 – 68% C.L., 80% C.L., 90% C.L., 95% C.L.



Using the data of Winter 2003, we derived ranges for m_t and M_W

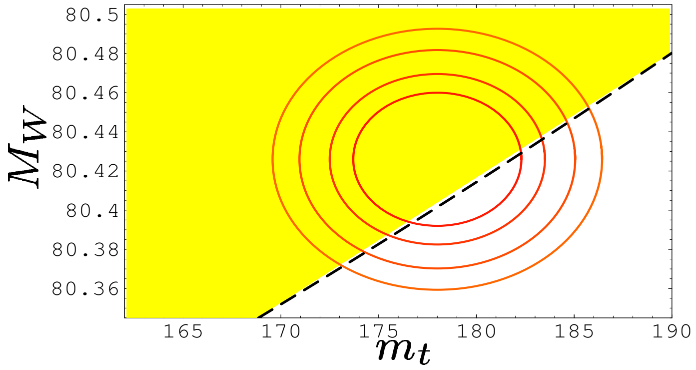


EFF / $\Delta\alpha_h^{(5)} = 0.02761$	range M_W [GeV]	range M_t [GeV]
80% C.L.	80.401 ± 0.018	177.9 ± 2.9
90% C.L.	80.401 ± 0.030	177.9 ± 4.8
95% C.L.	80.401 ± 0.040	177.9 ± 6.3

$\Rightarrow$ Benchmark Scenario: $M_W = 80.401$ GeV , $m_t = 177.9$ GeV

(mid-points independent of the C.L.)

We can redo the same analysis using the data of April 2004



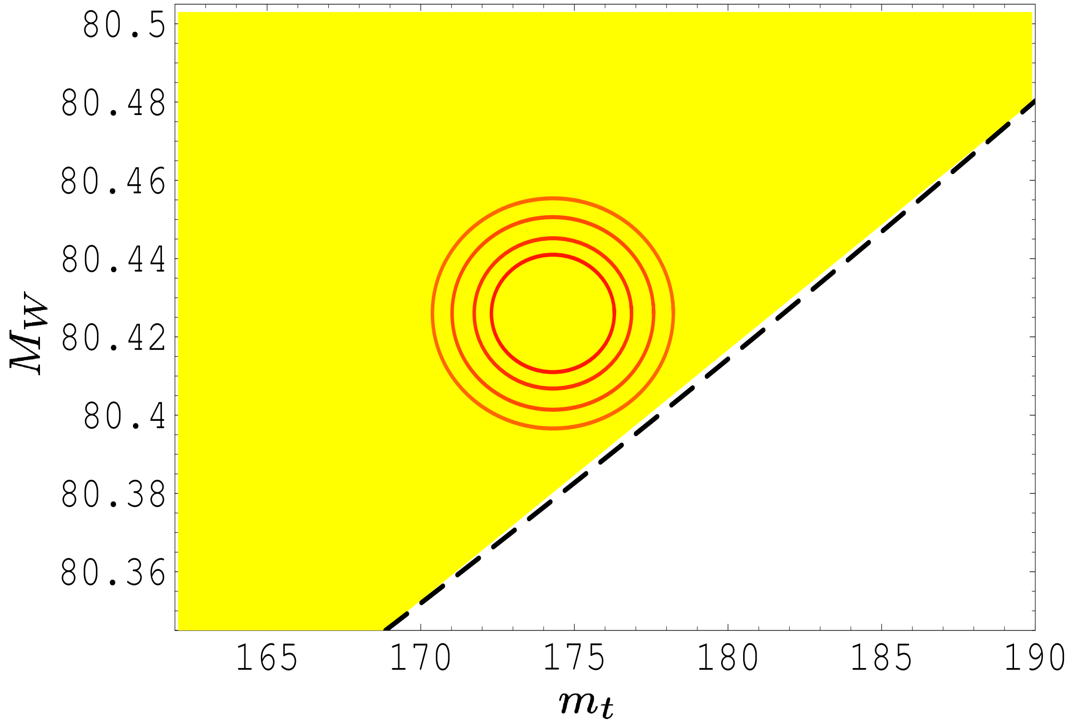
EFF / $\Delta\alpha_h^{(5)} = 0.02761$	range M_W [GeV]	range M_t [GeV]
68% C.L.	80.412 ± 0.018	179.5 ± 2.8
80% C.L.	80.412 ± 0.025	179.5 ± 3.9
90% C.L.	80.412 ± 0.034	179.5 ± 5.2
95% C.L.	80.412 ± 0.041	179.5 ± 6.3

⇒ NEW Benchmark Scenario:

$M_W = 80.412$ GeV , $m_t = 179.5$ GeV

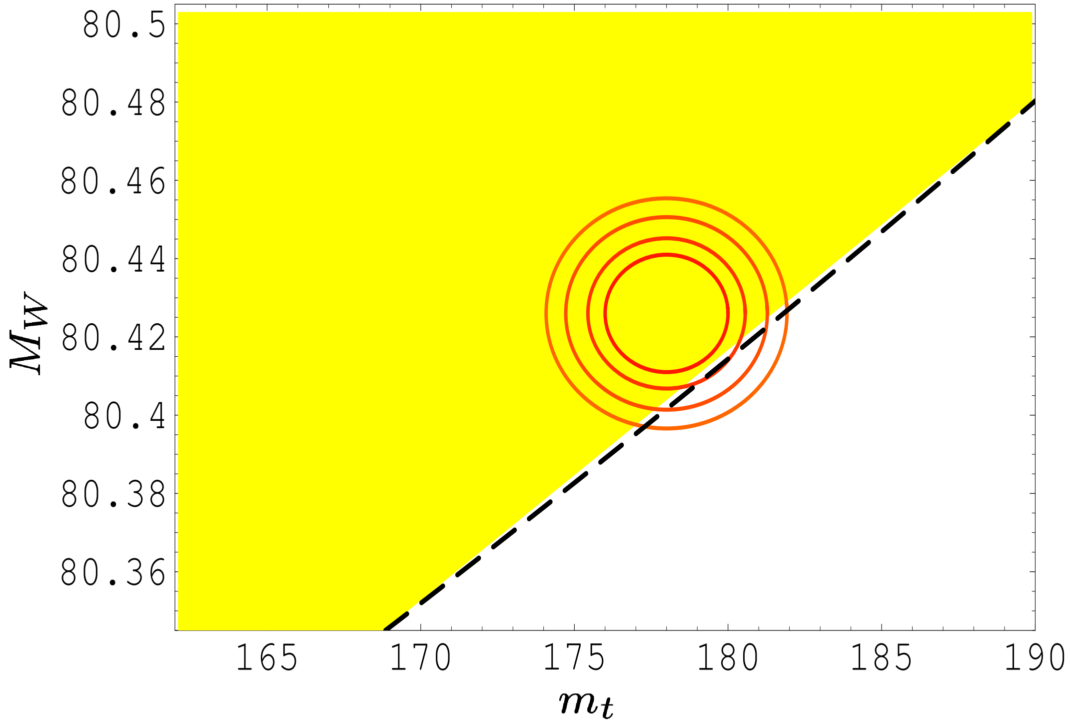
(mid-points independent of the C.L.)

Using $M_W = 80.426$ GeV and $(m_t)_{old} = 174.3$ GeV
with the error-bars for the near future (Tevatron/LHC)
$\delta m_t = 2$ GeV , $\delta M_W = 15$ MeV



(Winter 2003)
⇒ NO overlap at 95% C.L.

Using $M_W = 80.426$ GeV and $(m_t)_{NEW} = 178.0$ GeV
with the error-bars for the near future (Tevatron/LHC)
$\delta m_t = 2$ GeV , $\delta M_W = 15$ MeV



(April 2004)

⇒ NO problems in the near future

What if we really find the Higgs? (at LHC)

$\Rightarrow$ No more free parameters to play with

$\Rightarrow$ M_W depends logarithmically on M_H!

$$M_H = 150 \pm 10\,\mathrm{GeV} \Longrightarrow \delta_{M_W} = 4\,\mathrm{Mev}$$

This means, for example, that if

$$\left\{ \begin{array}{l} m_t = 175 \pm 2\,\mathrm{GeV} \\ M_H = 150 \pm 10\,\mathrm{GeV} \end{array} \right. \Longrightarrow M_W = 80.362 \underbrace{\pm 0.004}_{M_H} \underbrace{\pm 0.010}_{m_t}$$

Conclusions (as of April 1st, 2004)

How is the SM doing? Is there need for “New Physics” beyond the SM ?

Now, there is no compelling evidence for it.

In the future, maybe not, but

- ⋆ This analysis is very sensitive to M_W and m_t
  (Be careful, error-bars will shrink)
- ⋆ We should give an answer to the $\sin^2\theta_{eff}^{lept}$ anomaly
- ⋆ The discovery of the Higgs boson will change the game...