Two-Loop Results for Electroweak Precision Observables in the SM and the MSSM

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1. Introduction

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1. Introduction

Electroweak precision measurements:

M_Z[GeV]	=	91.1875 ± 0.0021	0.002%
G_μ[GeV^{-2}]	=	$1.16637(1)\,10^{-5}$	0.0009%
m_t[GeV]	=	174.3 ± 5.1	2.9%
M_W[GeV]	=	80.450 ± 0.034	0.04%
$\sin^2\theta_{\rm eff}^{\rm lept}$	=	0.23148 ± 0.00017	0.07%
Γ_Z[GeV]	=	2.4952 ± 0.0023	0.09%
...			

Quantum effects of the theory:

Loop corrections: $\sim \mathcal{O}(1\%)$

SM:

M_H is free parameter

precise measurement of M_W, $\sin^2\theta_{\rm eff}$, ...

$\Rightarrow$ constraints on M_H

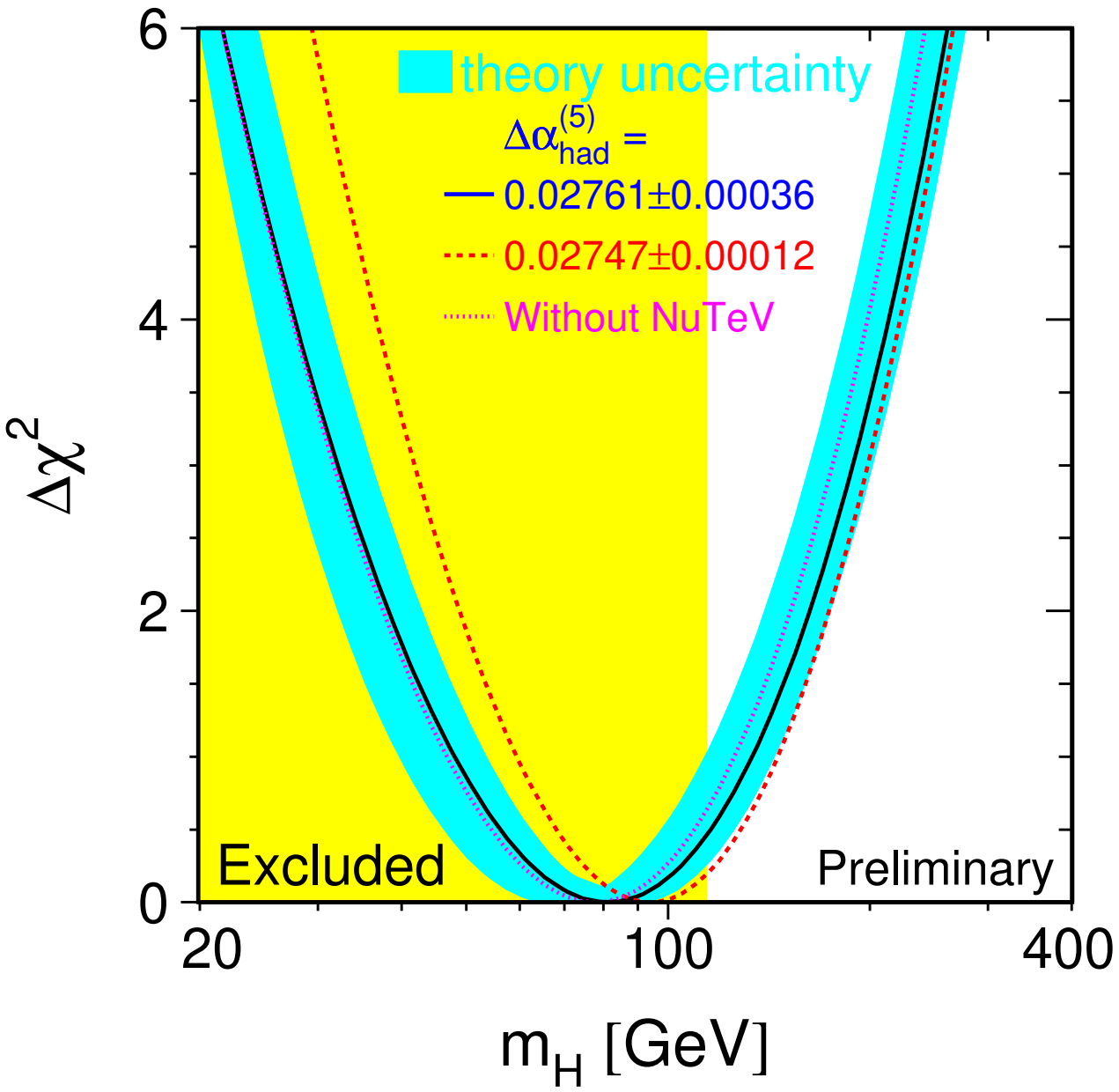
MSSM:

m_h is predicted

precise measurement of M_W, $\sin^2\theta_{\rm eff}$, m_h, ...

$\Rightarrow$ constraints on $m_{\tilde t}$, $\theta_{\tilde t}$, $m_{\tilde b}$, $\theta_{\tilde b}$, ...

Global fit to all data in the SM:
[*LEPEWWG '02*]



$$\Rightarrow M_H = 81^{+52}_{-33}\ \text{GeV}$$

$$M_H < 193\ \text{GeV, 95\% C.L.}$$

Theoretical uncertainties:

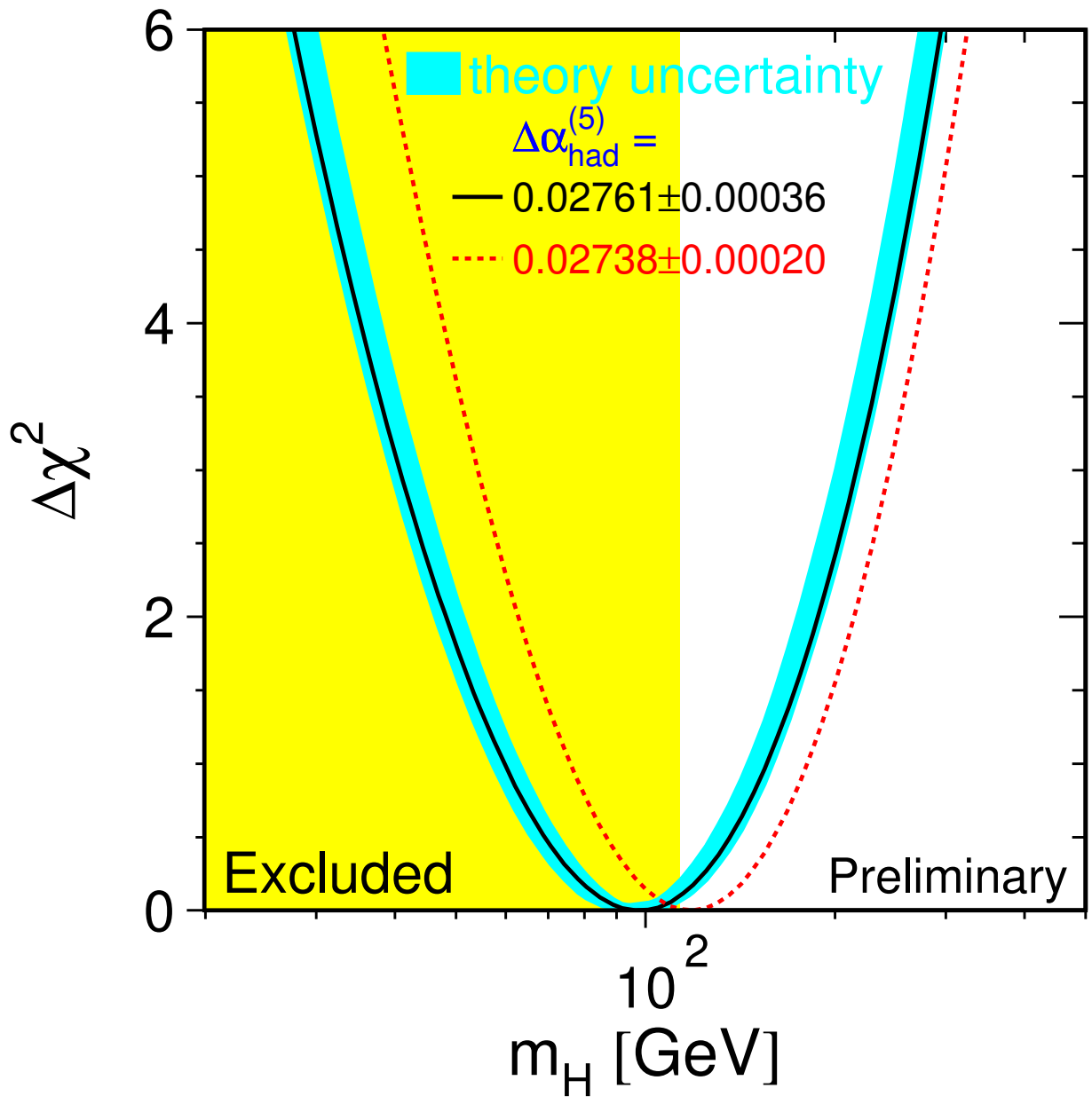
– unknown higher-order corrections ($\Rightarrow$ "blue band")

– exp. error of input parameters: m_t, $\Delta\alpha_{had}$, ...

Uncertainties from unknown higher-order corrections:

Comparison: global fit results one year ago
[*LEPEWWG '01*]

[*Moriond '01*]



$$\Rightarrow M_H = 98^{+58}_{-38} \text{ GeV}$$

$$M_H < 212 \text{ GeV, } 95\% \text{ C.L.}$$

$\Rightarrow$ "Blue band" has widened w.r.t. one year ago

"Blue band":

Estimate of unknown higher-order corrections
by varying different options in

ZFITTER [*D. Bardin et al.*]

TOPAZ0 [*G. Passarino*]

Different renormalization schemes,
different resummations of non-leading terms

$\Rightarrow$ differ by higher-order corrections

Error estimate for blue band plot up to Moriond '01:

$$\begin{aligned} \Delta M_{\mathrm{W}}^{\mathrm{theo}} &\approx \pm 3 \text{ MeV} \\ \Delta \sin^2 \theta_{\mathrm{eff}}^{\mathrm{theo}} &\approx \pm 3 \times 10^{-5} \end{aligned}$$

Comparison: estimate of higher-order uncertainties

[*G. Degrassi et al. '00*]

[*U. Baur et al. '01*]

$$\Delta \sin^2 \theta_{\mathrm{eff}}^{\mathrm{theo}} \approx \pm 6 - 7 \times 10^{-5}$$

Theoretical prediction for M_{W} in the SM:

Definition of Fermi constant G_μ via muon lifetime:

$$\tau_\mu^{-1} = \frac{G_\mu^2 m_\mu^5}{192\pi^3} F\left(\frac{m_{\mathrm{e}}^2}{m_\mu^2}\right)\left(1+\frac{3}{5}\frac{m_\mu^2}{M_{\mathrm{W}}^2}\right)(1+\Delta q)$$

Δq: QED corrections in Fermi Model,
included in definition

[*R. Behrends, R. Finkelstein, A. Sirlin '56*]

[*T. van Ritbergen, R. Stuart '99*]

[*M. Steinhauser, T. Seidensticker '99*]

Comparison with SM prediction for muon decay:

$$\Rightarrow \quad M_{\mathrm{W}}^2\left(1-\frac{M_{\mathrm{W}}^2}{M_{\mathrm{Z}}^2}\right) = \frac{\pi\alpha}{\sqrt{2}G_\mu}(1+\Delta r)\,,$$

$$\Updownarrow$$

loop corrections

$\Rightarrow$ Theoretical prediction for M_{W} in terms of M_{Z}, α, G_μ

Higher-order results for $M_{\rm W}$ in the SM:

Resummation of leading 1-loop contributions:

$$1 + \Delta r \to \frac{1}{(1 - \Delta\alpha)\left(1 + \frac{c_{\rm W}^2}{s_{\rm W}^2}\Delta\rho\right) - \Delta r_{\rm rem}}$$

$\Rightarrow$ $(\Delta\alpha)^2$, $(\Delta\rho)^2$, $(\Delta\alpha\Delta\rho)$, $(\Delta\alpha\Delta r_{\rm rem})$ terms correct at 2-loop order

[*W. Marciano '79*], [*A. Sirlin '84*]

[*M. Consoli, W. Hollik, F. Jegerlehner '89*]

QCD corrections:

Results in $\mathcal{O}(\alpha\alpha_{\rm s})$ and $\mathcal{O}(\alpha\alpha_{\rm s}^2)$ known

[*A. Djouadi, C. Verzegnassi '87*], [*A. Djouadi '89*]

[*B.A. Kniehl '90*], [*F. Halzen, B.A. Kniehl '91*]

[*L. Avdeev, J. Fleischer, S.M. Mikhailov, O. Tarasov '94*]

[*K. Chetyrkin, J. Kühn, M. Steinhauser '95*]

EW 2-loop corrections:

Expansion for asymptotically large m_t:

Leading m_t^4/M_W^4 terms:

[*J. van der Bij, F. Hoogeveen '87*]

[*R. Barbieri, M. Beccaria, P. Ciafaloni, G. Curci, A. Vicere '92*]

[*J. Fleischer, O.V. Tarasov, F. Jegerlehner '93*]

Next-to-leading m_t^2/M_W^2 terms:

expansions:

$$M_W, M_Z, M_H \ll m_t$$

$$M_W, M_Z \ll m_t, M_H$$

$$+ \text{ interpolation}$$

[*G. Degrassi, P. Gambino, A. Vicini '96*]

[*G. Degrassi, P. Gambino, A. Sirlin '97*]

$\rightarrow$ Same order of magnitude as m_t^4/M_W^4 terms, same sign

$\Rightarrow$ Exact evaluation of EW 2-loop contributions desirable (no expansion in masses)

Expansion for asymptotically large M_{H}:

Leading $M_{\mathrm{H}}^2/M_{\mathrm{W}}^2$ terms:

expansion: $M_{\mathrm{W}}, M_{\mathrm{Z}}, m_{\mathrm{t}} \ll M_{\mathrm{H}}$

[*J. van der Bij, M. Veltman '84*], [*J. van der Bij '84*]

Exact result for Higgs-mass dependence of fermionic contributions:

$M_{\mathrm{W,subtr}}(M_{\mathrm{H}}) = M_{\mathrm{W}}(M_{\mathrm{H}}) - M_{\mathrm{W}}(M_{\mathrm{H}} = 65\,\mathrm{GeV})$

[*S. Bauberger, G.W. '98*]

Pure bosonic two-loop contributions to on-shell counterterms for M_{W} and M_{Z}:

expansion in $\sin^2\theta_{\mathrm{W}}$, $M_{\mathrm{Z}}^2/M_{\mathrm{H}}^2$

[*F. Jegerlehner, M. Kalmykov, O. Veretin '01*]

Leading EW corrections beyond 2-loop:

Pure fermion-loop contributions up to 4-loop order

[*A. Stremplat '98*], [*G.W. '98*]

Leading 3-loop corrections to $\Delta\rho$:

$\mathcal{O}(G_\mu^3 m_{\mathrm{t}}^6)$, $\mathcal{O}(G_\mu^2 \alpha_{\mathrm{s}} m_{\mathrm{t}}^4)$ terms

limit: $M_{\mathrm{H}} = 0$

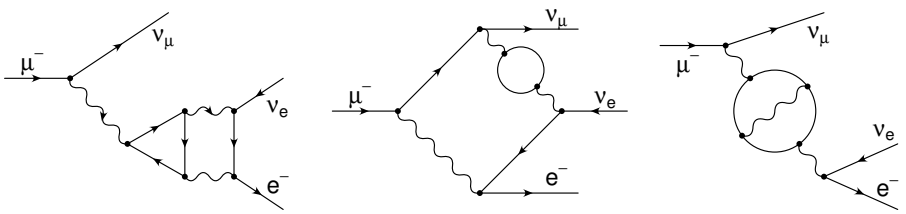
[*J. van der Bij, K. Chetyrkin, M. Faisst, G. Jikia, T. Seidensticker '01*]

2. Prediction for M_W in the SM: Complete fermionic two-loop results and Higgs-mass dependence of bosonic contributions

Complete fermionic two-loop results:

Exact result for all two-loop diagrams containing at least one fermion loop

[*A. Freitas, W. Hollik, W. Walter, G.W. '00, '02*]



⇒ full dependence on m_t, complete light fermion contributions at two-loop order

Method of calculation:

– Algebraic evaluation:

FeynArts [*J. Küblbeck, A. Denner, M. Böhm '90*] [*H. Eck '95*], [*T. Hahn '99*]

⇒ Feynman amplitudes and counterterms

TwoCalc [*G. W. '92*], [*G. W., R. Scharf, M. Böhm '94*]

⇒ tensor integral reduction, etc.
standard scalar integrals

– General R_ξ gauge

– Regularisation:

DREG [*G. 't Hooft, M. Veltman '72*]

Careful treatment of γ_5 necessary
[*P. Breitenlohner, D. Maison '77*]

– Two-loop renormalization:

On-shell scheme (physical parameters)

Renormalization in gauge-fixing and ghost sector

Mass renormalization of unstable particles
$\Rightarrow$ determines physical meaning of M_{W}, M_{Z}

– Numerical evaluation:

One-dimensional integral representations with elementary functions
[*S. Bauberger, F. Berends, M. Böhm, M. Buza '95*]
[*S. Bauberger, M. Böhm '95*]

$\Rightarrow$ Exact evaluation of 2-loop 2-point functions

Mass renormalization of unstable particles

From 2-loop order on:

real part of complex pole $\mathcal{M}^2 = \overline{M}^2 - i\overline{M}\,\overline{\Gamma}$ $\neq$ pole of real part $\widetilde{M}^2$

$$\delta\overline{M}^2_{(2)} = \delta\widetilde{M}^2_{(2)} + \underbrace{\mathrm{Im}\left\{\Sigma'_{\mathrm{T},(1)}(M^2)\right\}\,\mathrm{Im}\left\{\Sigma_{\mathrm{T},(1)}(M^2)\right\}}_{\text{gauge-parameter dependent!}}$$

S-matrix theory

[*A. Sirlin '91*], [*R.G. Stuart '91*], [*H. Veltman '94*]

[*P. Gambino, P.A. Grassi '99*]

Explicit 2-loop calculation in general R_ξ-gauge:

[*A. Freitas, W. Hollik, W. Walter, G.W. '00*]

$\Rightarrow$ Only complex pole gauge-invariant

Comparison theory prediction – experimental result:

Definition via real part of complex pole:

$$\Rightarrow \sigma(s) \sim \frac{s}{(s - \overline{M}^2)^2 + \overline{M}^2\overline{\Gamma}^2}$$

$\Rightarrow$ Breit–Wigner shape with constant width

Experimental determinations at LEP/Tevatron use:

$$\sigma(s) \sim \frac{s}{(s - M^2)^2 + s^2\Gamma^2/M^2}$$

$\Rightarrow$ Breit–Wigner shape with running width

Relation:

$$M^2 = \overline{M}^2 + \overline{\Gamma}^2 \quad \Rightarrow \underbrace{\Delta M_{\mathrm{W}} \approx 27\,\mathrm{MeV}}$$

formally a 2-loop effect!

$\Rightarrow$ For theoretical prediction of M_{W}:
need prediction for $\overline{\Gamma}$

$\Rightarrow$ (Slightly) larger theoretical uncertainty for M_{W} than for $\overline{M}_{\mathrm{W}}$

$\Rightarrow$ Using $\overline{M}_{\mathrm{W}}$ instead of M_{W} as experimental value would be preferable

Numerical results and estimate of remaining theory uncertainty:

Checks of the calculation:

UV-, IR-finiteness, general R_ξ-gauge

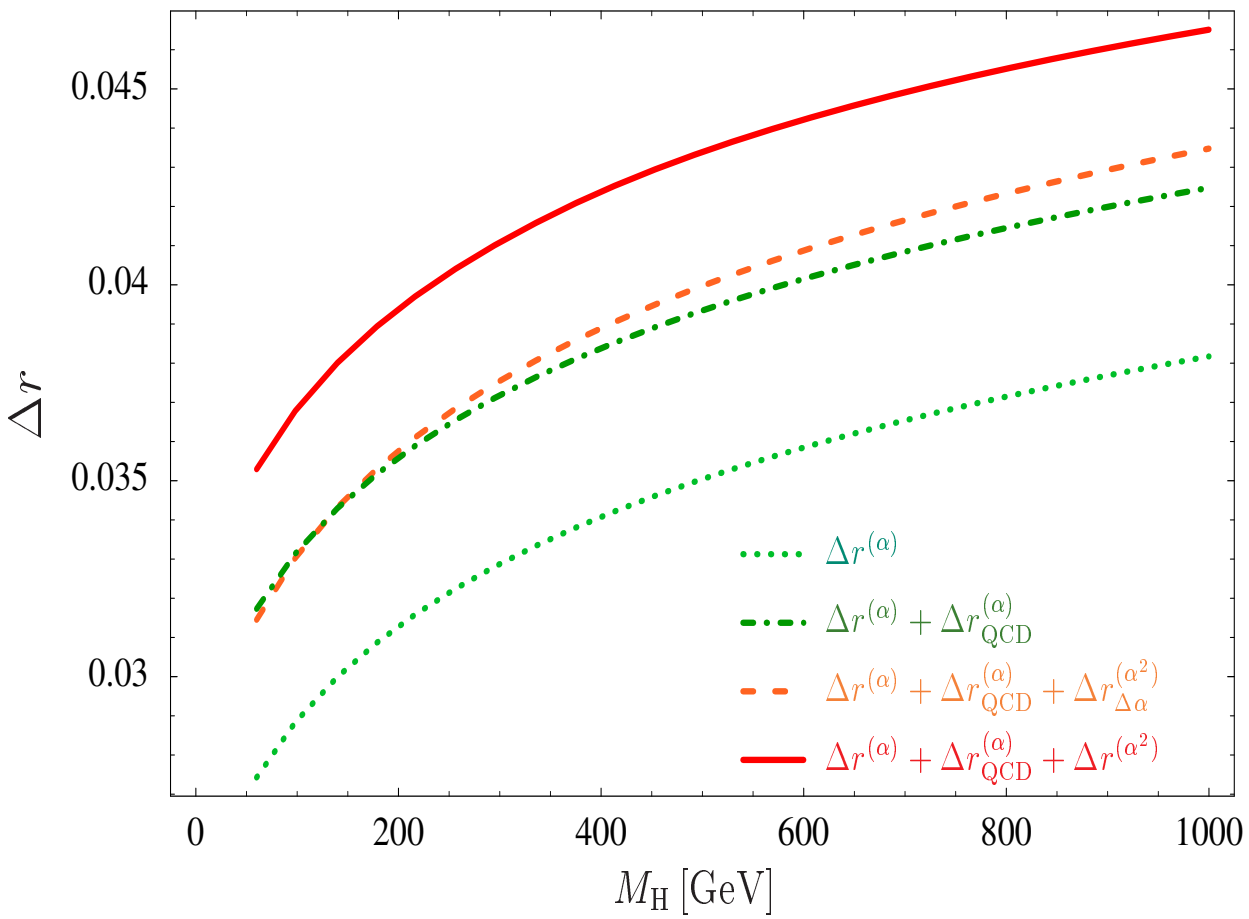
$\Rightarrow$ gauge-parameter independence at algebraic level

Higgs-mass dependence agrees with existing result
[*S. Bauberger, G.W. '98*]

1-loop, QCD and ew 2-loop contributions to Δr:

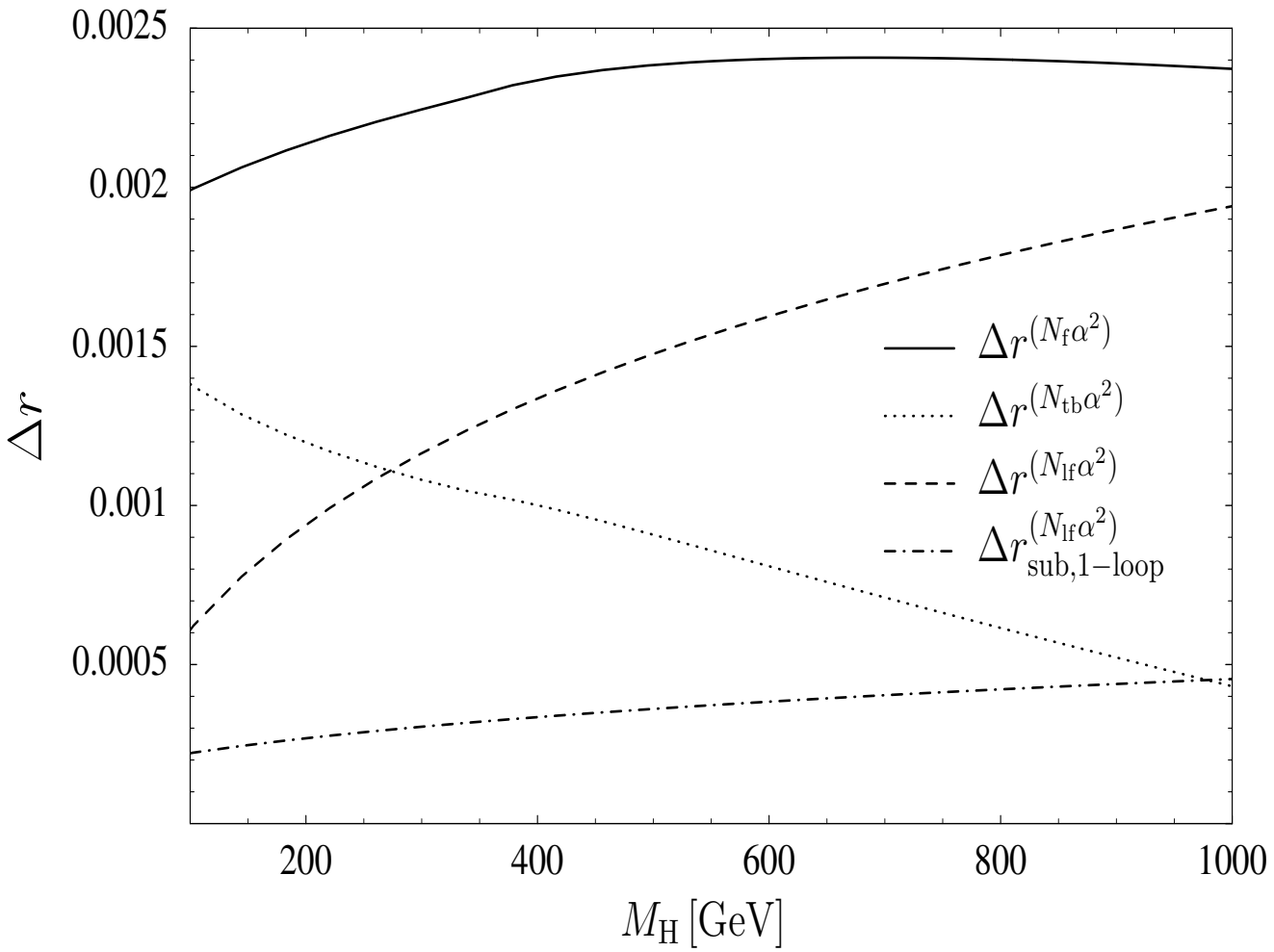
$$\Delta r = \Delta r^{(\alpha)} + \Delta r^{(\alpha\alpha_s)} + \Delta r^{(\alpha\alpha_s^2)} + \Delta r^{(N_f\alpha^2)} + \Delta r^{(N_f^2\alpha^2)}$$

fully expanded, no resummation needed



Comparison of contributions from top/bottom doublet and from light fermions:

[*A. Freitas, W. Hollik, W. Walter, G.W. '02*]



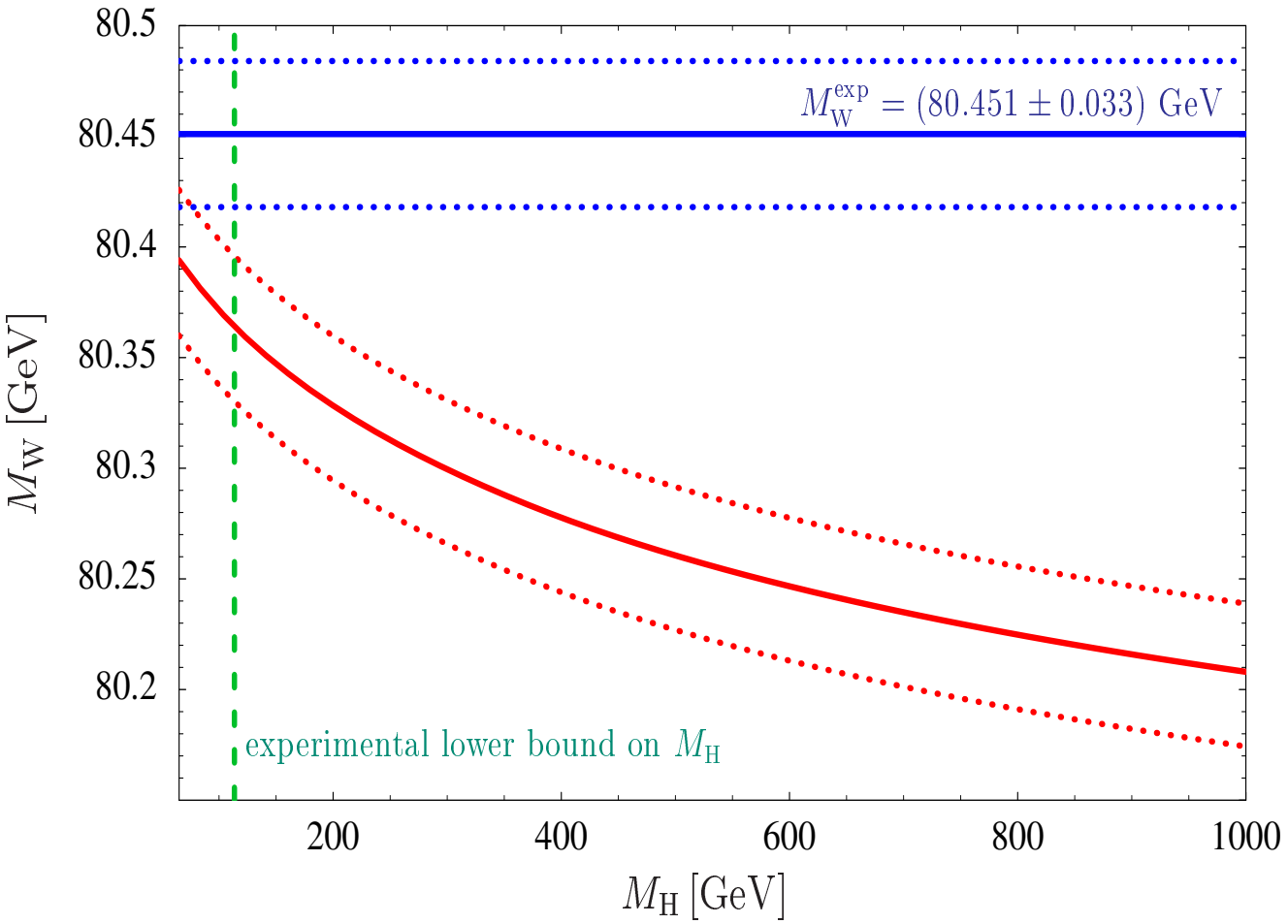
$$\Delta r^{(N_{\rm lf}\alpha^2)}_{\rm sub,1-loop} = \Delta r^{(N_{\rm lf}\alpha^2)} - 2\Delta\alpha\Delta r^{(\alpha)}_{\rm bos}$$

$\Rightarrow$ genuine two-loop light fermion contributions lead to shift in $M_{\rm W}$ of up to 5 MeV

smaller than top/bottom corrections for $M_{\rm H} \lesssim 1$ TeV

SM prediction for M_W vs. experimental result:

[*A. Freitas, W. Hollik, W. Walter, G.W. '00, '02*]



$\Rightarrow$ Light Higgs preferred

$M_W^{exp} = 80.450 \pm 0.034$ GeV, $m_t^{exp} = 174.3 \pm 5.1$ GeV

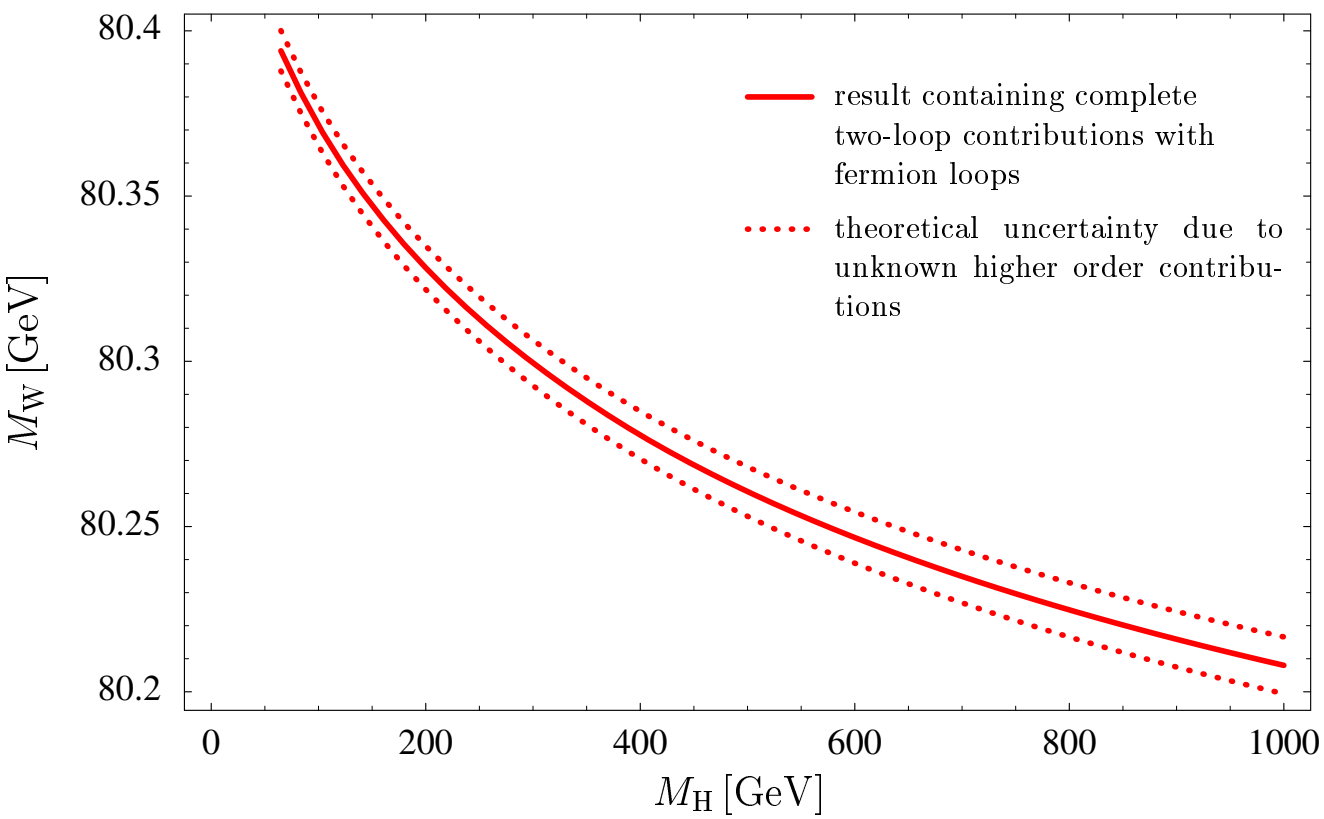
$M_H > 114.4$ GeV, 95% C.L.

$\Rightarrow$ 1σ regions do not overlap

Uncertainty from experimental error of input parameters: $\Delta m_t = \pm 5.1$ GeV $\Rightarrow \Delta M_W \approx \pm 31$ MeV

Estimate of theoretical uncertainty from unknown higher-order corrections:

- Purely bosonic $\mathcal{O}(\alpha^2)$ ew corr.: $\Delta M_W \lesssim 2$ MeV
- Higher-order ew corr., $\mathcal{O}(\alpha^3)$: $\Delta M_W \lesssim 3.5$ MeV
- Higher-order QCD corr., $\mathcal{O}(\alpha\alpha_s^3)$, $\mathcal{O}(\alpha^2\alpha_s)$: $\Delta M_W \lesssim 4$ MeV



For light Higgs masses:

$$\Delta M_W^{\text{theo}} \approx \pm 6\,\text{MeV}$$

Simple parameterization of full result:

$$\begin{aligned} M_\mathrm{W} &= M_\mathrm{W}^0 - c_1\,\mathrm{dH} - c_2\,\mathrm{dH}^2 + c_3\,\mathrm{dH}^4 \\ &\quad - c_4\,\mathrm{d}\alpha + c_5\,\mathrm{dt} - c_6\,\mathrm{dt}^2 \\ &\quad - c_7\,\mathrm{dH}\,\mathrm{dt} - c_8\,\mathrm{d}\alpha_\mathrm{s} + c_9\,\mathrm{dz} \end{aligned}$$

where

$$\mathrm{dH} = \ln\left(\frac{M_\mathrm{H}}{100\ \mathrm{GeV}}\right), \quad \mathrm{dt} = \left(\frac{m_\mathrm{t}}{174.3\ \mathrm{GeV}}\right)^2 - 1,$$

$$\mathrm{d}\alpha = \frac{\Delta\alpha}{0.05924} - 1, \quad \mathrm{d}\alpha_\mathrm{s} = \frac{\alpha_\mathrm{s}(M_\mathrm{Z})}{0.119} - 1,$$

$$\mathrm{dz} = M_\mathrm{Z} - 91.1875\ \mathrm{GeV}$$

$\Rightarrow$ approximates full result within 0.3 MeV
for 65 GeV $\leq M_\mathrm{H} \leq$ 1 TeV, 2σ variations
[*A. Freitas, W. Hollik, W. Walter, G.W. '02*]

Result now implemented in *ZFITTER*
[*D. Bardin '01*]

Comparison with previous result for M_{W} (for $M_{\mathrm{H}} = 100$ GeV):

$\Rightarrow$ Downward shift of $M_{\mathrm{W}}^{\mathrm{theo}}$ by $\delta M_{\mathrm{W}}^{\mathrm{theo}} \approx 4.3$ MeV

$\Rightarrow$ Tendency towards light Higgs sharpened

Theoretical uncertainty of $\sin^2\theta_{\mathrm{eff}}$:

$$\sin^2\theta_{\mathrm{eff}} = \left(1 - \frac{M_{\mathrm{W}}^2}{M_{\mathrm{Z}}^2}\right)\kappa(M_{\mathrm{W}}^2)$$

New contribution (complete fermionic two-loop result) for κ not yet known

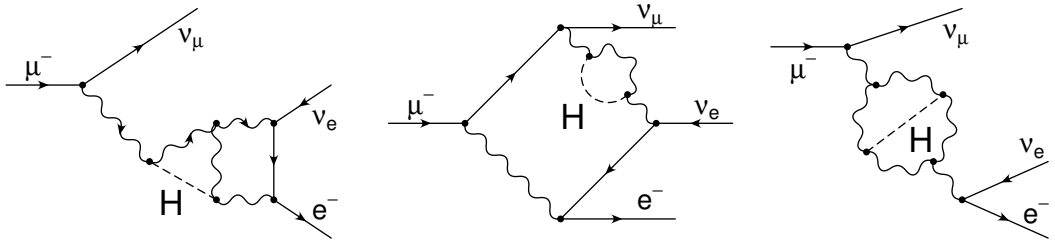
$\Rightarrow$ Effect of $\delta M_{\mathrm{W}}^{\mathrm{theo}}$ (non-leading electroweak two-loop corrections) in $\sin^2\theta_{\mathrm{eff}}$ yields estimate of uncertainty

Upward shift in $\sin^2\theta_{\mathrm{eff}}$ caused by $\delta M_{\mathrm{W}}^{\mathrm{theo}}$:

$$\delta \sin^2\theta_{\mathrm{eff}}^{\mathrm{theo}} \approx 8.2 \times 10^{-5} \text{ for } M_{\mathrm{H}} = 100 \text{ GeV}$$

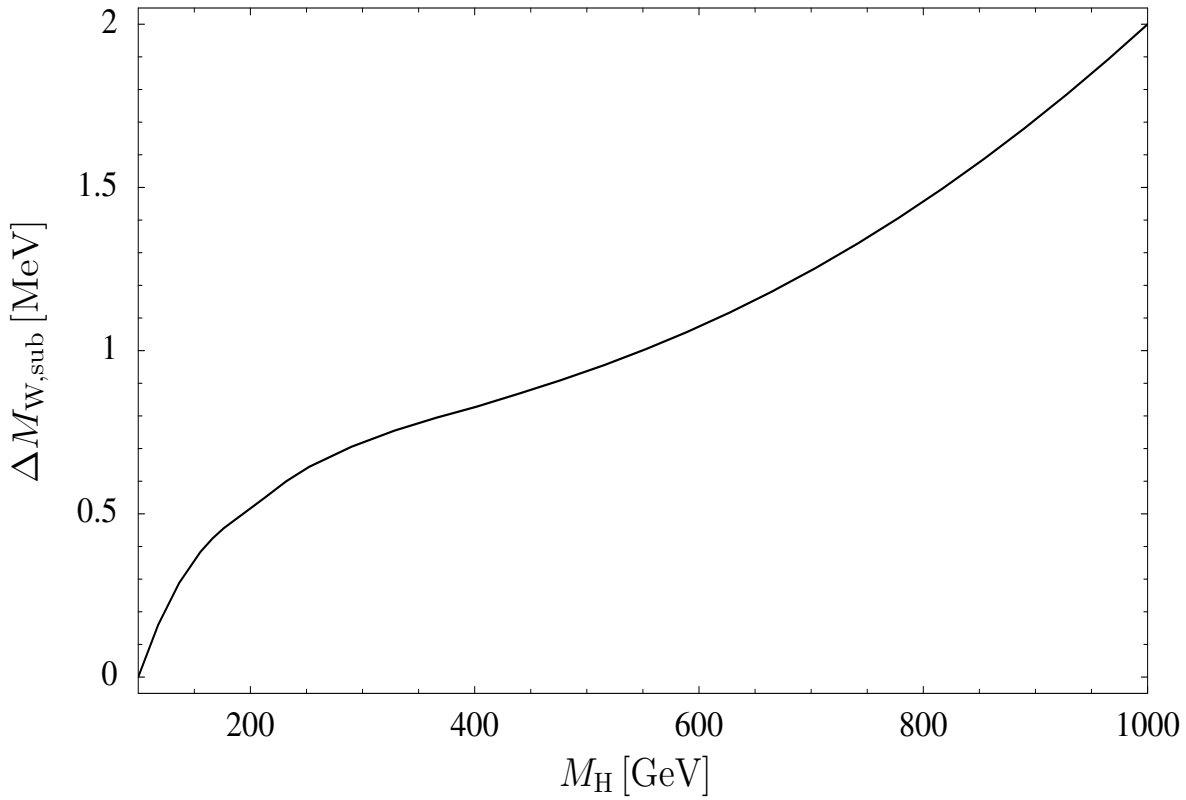
$\Rightarrow$ Used as estimate of higher-order uncertainty in new "blue band"

Higgs-mass dependence of purely bosonic two-loop contributions:



Shift in M_{W}:

[*A. Freitas, W. Hollik, W. Walter, G.W. '02*]



$\Rightarrow \Delta M_{\mathrm{W}} \leq 2$ MeV

$\Rightarrow$ Only missing piece of complete two-loop result for M_{W} in the SM:
M_{H}-independent constant

$\longrightarrow$ see talks by M. Czakon, O. Veretin

Remaining theoretical uncertainties:

[*A. Freitas, W. Hollik, W. Walter, G.W. '00, '02*]

[*S. Heinemeyer, W. Hollik, G.W. '00*]

[*S. Heinemeyer, G.W. '01*]

[*U. Baur, R. Clare, J. Erler, S. Heinemeyer, D. Wackeroth, G. W., D. Wood '01*]

- from experimental errors of input parameters:

  $\delta m_{\rm t} = \pm 5.1$ GeV

  $\Rightarrow \delta M_{\rm W} \approx \pm 31$ MeV, $\delta \sin^2\theta_{\rm eff} \approx \pm 16 \times 10^{-5}$

  $\delta m_{\rm h}^{\rm MSSM} \approx \pm 5$ GeV

  $\delta \alpha_{\rm had} = \pm 3.6 \times 10^{-4}$

  $\Rightarrow \delta M_{\rm W} \approx \pm 6.5$ MeV, $\delta \sin^2\theta_{\rm eff} \approx \pm 13 \times 10^{-5}$

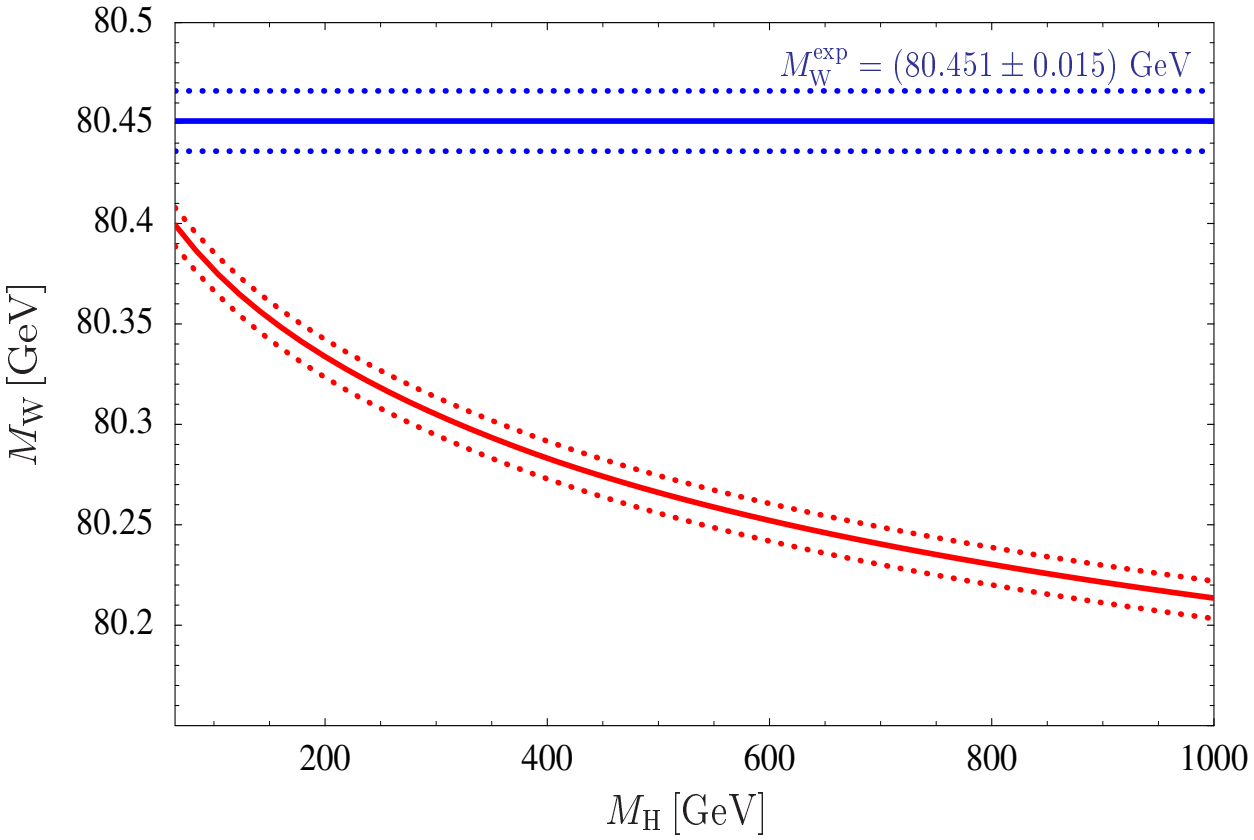
- from unknown higher-order corrections:

  $\delta m_{\rm h}^{\rm MSSM} \approx \pm 3$ GeV

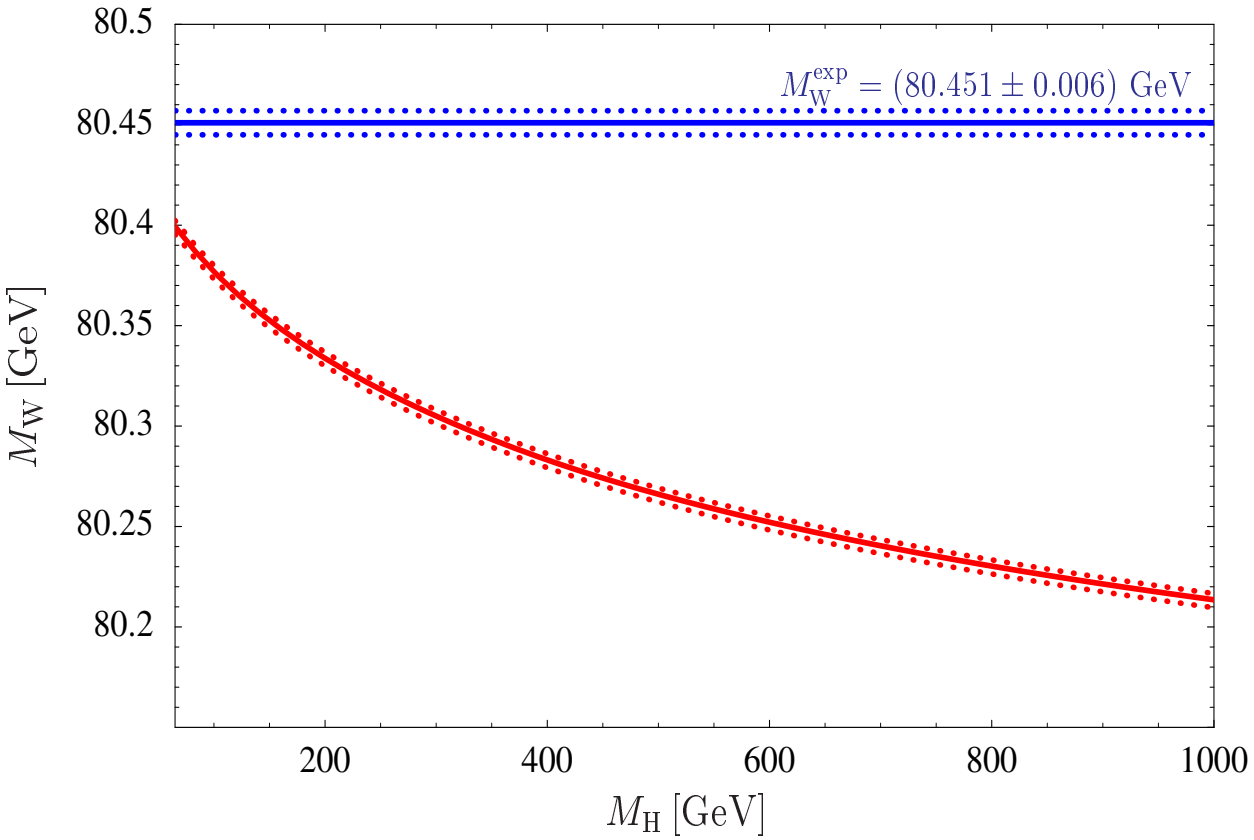
  $\delta M_{\rm W}^{\rm SM} \approx \pm 5$ MeV, $\delta \sin^2\theta_{\rm eff}^{\rm SM} \approx \pm 7 \times 10^{-5}$

  $\delta M_{\rm W}^{\rm MSSM} \gg \delta M_{\rm W}^{\rm SM}$, $\delta \sin^2\theta_{\rm eff}^{\rm MSSM} \gg \delta \sin^2\theta_{\rm eff}^{\rm SM}$

Prospects for Tevatron Run II, LHC:



LC with high luminosity in low-energy mode: GigaZ



3. Leading electroweak two-loop corrections to $\Delta\rho$ in the MSSM

Prediction for M_W, $\sin^2\theta_{\rm eff}$ in the MSSM:

Complete one-loop results

[*P. Chankowski, A. Dabelstein, W. Hollik, W. Mösle, S. Pokorski, J. Rosiek '94*]

[*D. Garcia, J. Solà '94*]

[*D. Garcia, R. Jiménez, J. Solà '95*]

[*A. Dabelstein, W. Hollik, W. Mösle '95*]

[*P. Chankowski, S. Pokorski '96*]

Leading two-loop $\mathcal{O}(\alpha\alpha_s)$ corrections

[*A. Djouadi, P. Gambino, S. Heinemeyer, W. Hollik, C. Jünger, G. W. '97*]

[*S. Heinemeyer, W. Hollik, G. W. '98*]

Leading contributions to M_W, $\sin^2\theta_{\rm eff}$, ... from mass splitting between isospin doublet fields enter via

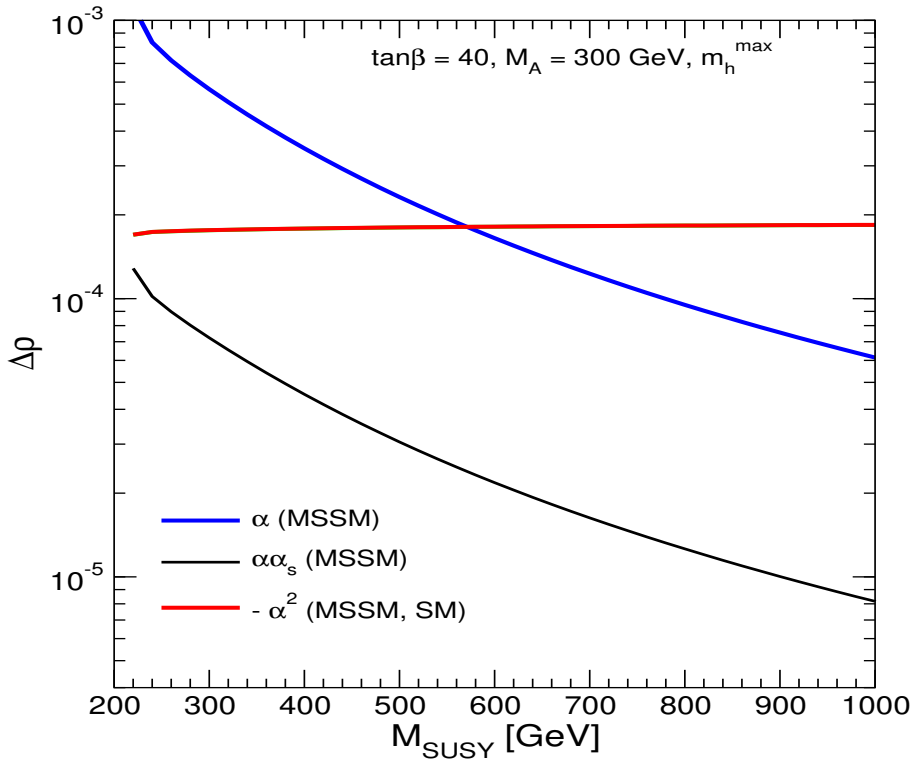
$$\Delta\rho = \frac{\Sigma_Z(0)}{M_Z^2} - \frac{\Sigma_W(0)}{M_W^2},$$

$$\Delta M_W \approx \frac{M_W}{2}\frac{c_W^2}{c_W^2 - s_W^2}\Delta\rho, \qquad \Delta\sin^2\theta_{\rm eff} \approx -\frac{c_W^2 s_W^2}{c_W^2 - s_W^2}\Delta\rho$$

Leading $\mathcal{O}(\alpha_t^2)$, $\mathcal{O}(\alpha_t\alpha_b)$, $\mathcal{O}(\alpha_b^2)$ corrections to $\Delta\rho$

For $M_{\rm SUSY} \to \infty$: SUSY loop contributions decouple

E.g.: $\Delta\rho^{\rm SUSY}_{\alpha}$, $\Delta\rho^{\rm SUSY}_{\alpha\alpha_s}$ vs. $\Delta\rho^{\rm SM}_{\alpha_t^2}$



$\Rightarrow$ For $M_{\rm SUSY} \gtrsim 200$ GeV: $\Delta\rho^{\rm SM}_{\alpha_t^2} > \Delta\rho^{\rm SUSY}_{\alpha\alpha_s}$

$\Rightarrow$ Leading 2-loop contributions for large $M_{\rm SUSY}$: Higgs-exchange, 2HDM with MSSM restrictions

Result in limit $m_h \to 0$, $m_b \to 0$:
[*S. Heinemeyer, G. W. '01*]

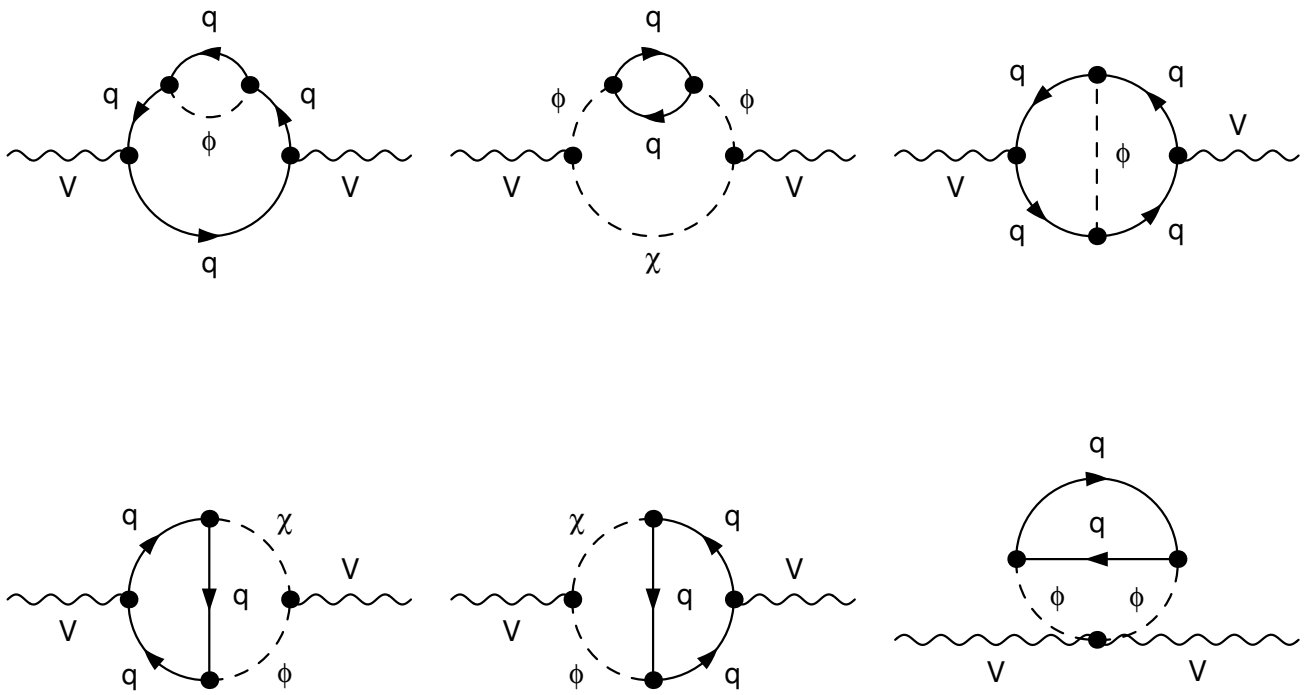
$\Rightarrow$ small corrections:

$\Delta M_W \lesssim 2$ MeV, $\Delta \sin^2\theta_{\rm eff} \lesssim 1 \times 10^{-5}$

but in SM case:
much larger corrections for $M_H = \mathcal{O}(100$ GeV$)$

Evaluation of leading $\mathcal{O}(\alpha_t^2)$, $\mathcal{O}(\alpha_t\alpha_b)$, $\mathcal{O}(\alpha_b^2)$ contributions to $\Delta\rho$ for arbitrary m_h:

Generic types of two-loop diagrams:

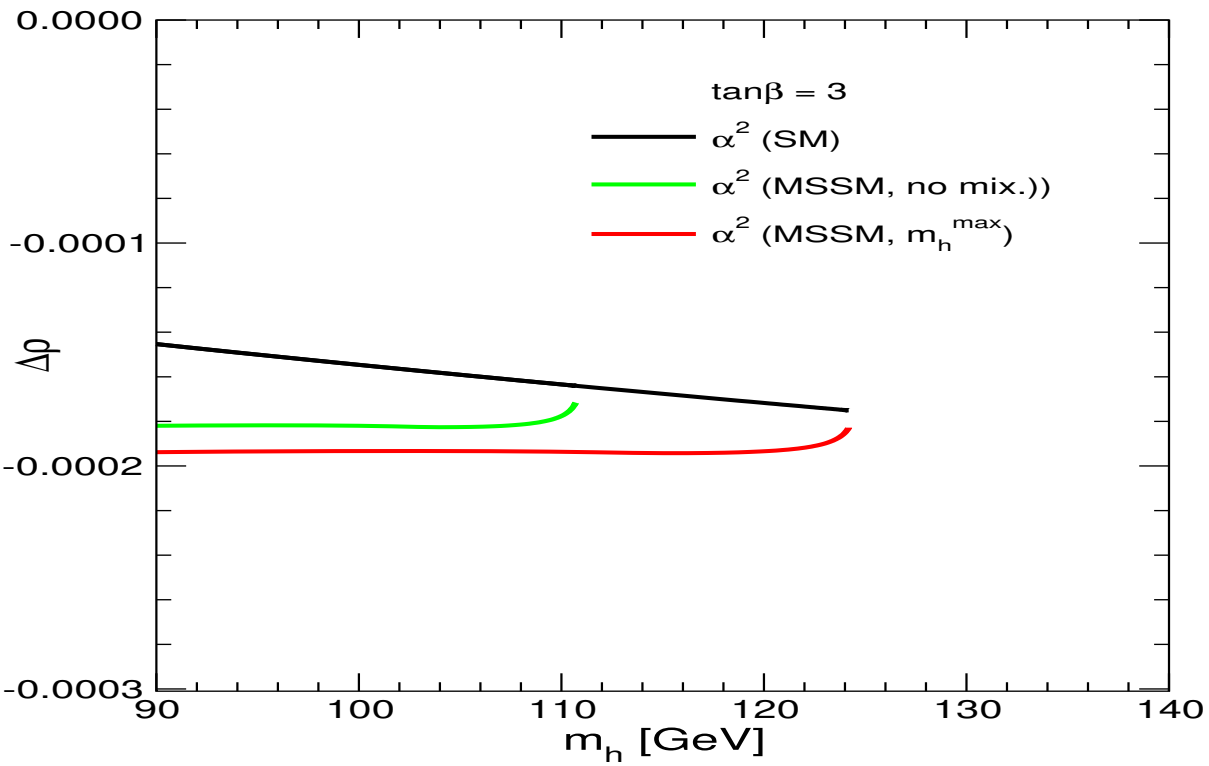


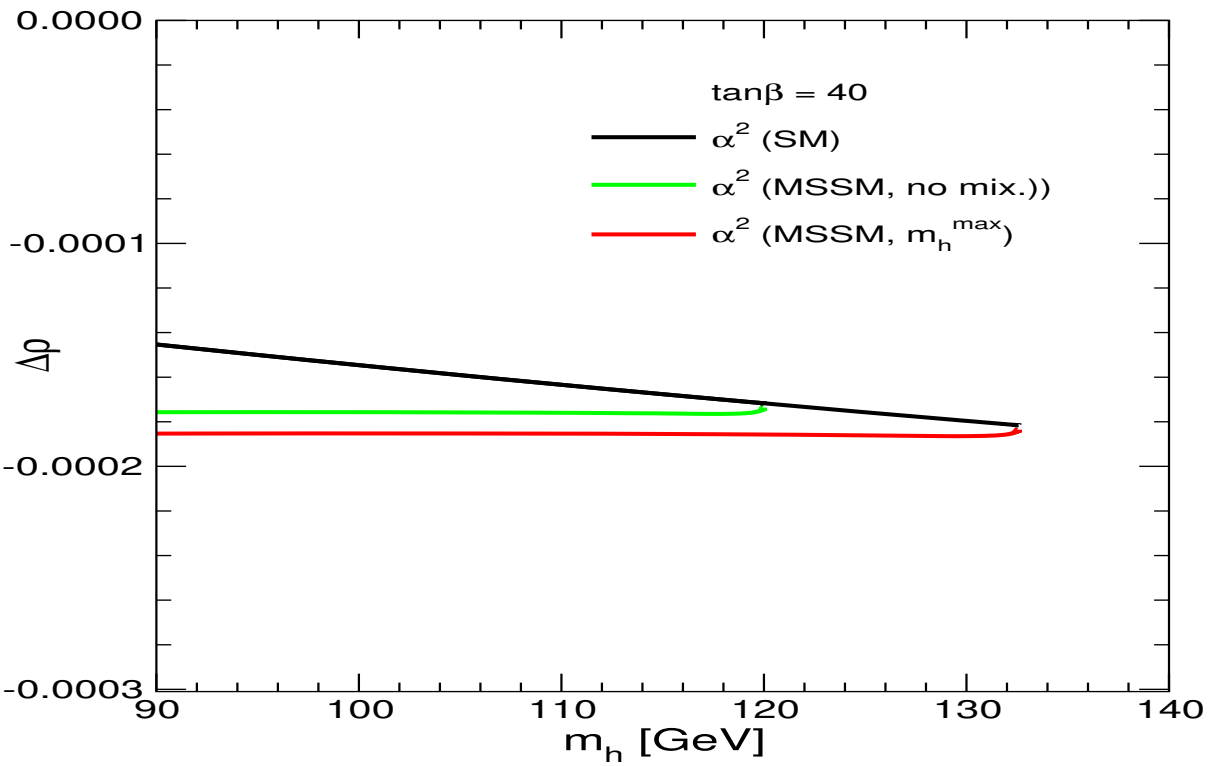
$$
\begin{aligned}
V &= Z, W^{\pm} \\
q &= t, b \\
\phi, \chi &= h^0, H^0, A^0, H^{\pm}, G^0, G^{\pm}
\end{aligned}
$$

Numerical results for $\Delta\rho$:

Comparison SM vs. MSSM as function of m_{h} (M_{A} varied), $\tan\beta = 3, 40$:

[*S. Heinemeyer, G. W. '02*]





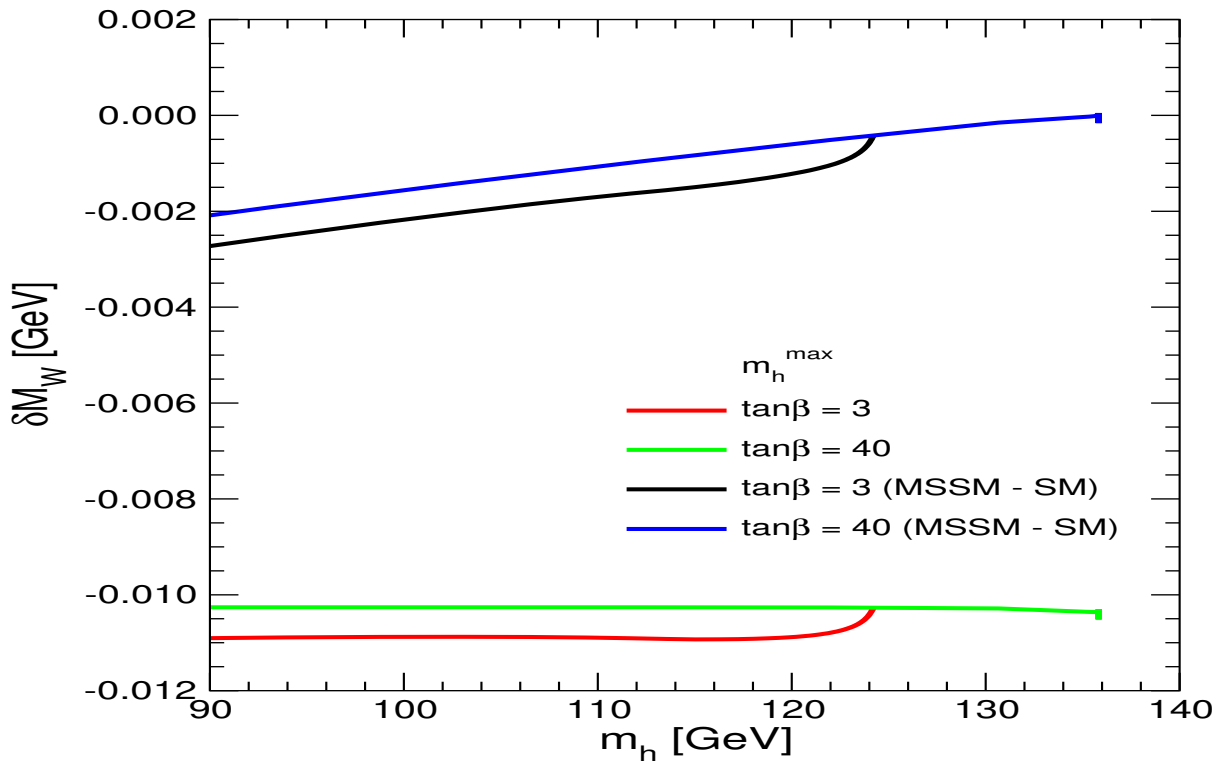
$\Rightarrow$ Correction in MSSM always larger than in SM

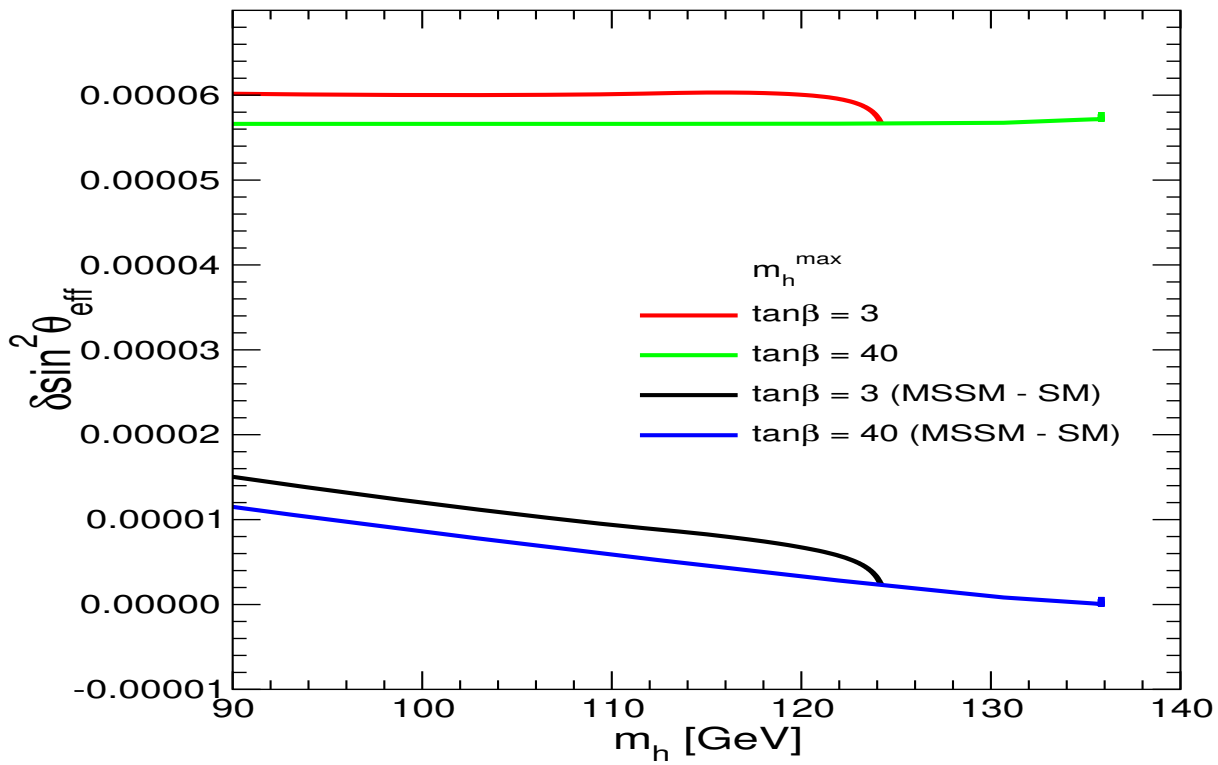
$\Delta\rho^{\mathrm{MSSM}} \to \Delta\rho^{\mathrm{SM}}$ for $M_{\mathrm{A}} \to \infty$

Corrections to M_W and $\sin^2\theta_{\rm eff}$:

Contribution from $\Delta\rho^{\rm MSSM}_{\alpha_t^2}$ and comparison with SM contrib. as fct. of m_h (M_A varied), $\tan\beta = 3, 40$:

[*S. Heinemeyer, G. W. '02*]





Corrections to M_W, $\sin^2\theta_{\rm eff}$ up to -12 MeV, 6×10^{-5}

$|\delta M_W^{\rm MSSM-SM}| \lesssim 3$ MeV, $\delta\sin^2\theta_{\rm eff}^{\rm MSSM-SM} \lesssim 3\times10^{-5}$

Electroweak precision tests yield constraints on Yukawa coupling y_t:

SM with $M_H = 114$ GeV, $y_t = x\, y_t^{SM}$:

Predictions for M_W, $\sin^2\theta_{eff}$ vs. experimental result

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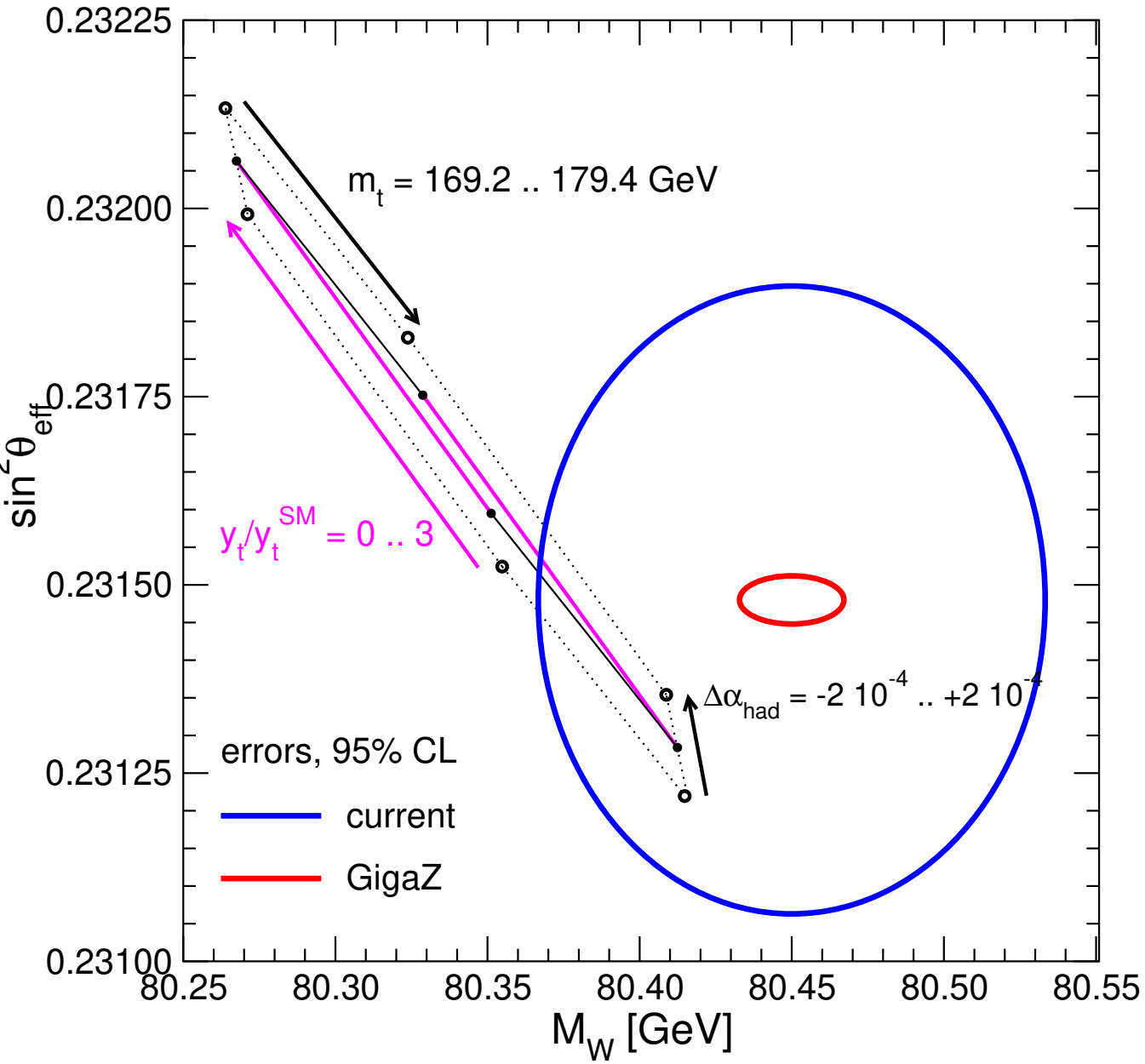

$\Rightarrow$ For $m_t = 174.3$ GeV: $y_t < 1.3\, y_t^{SM}$ at 95% C.L.

$\Rightarrow$ For $m_t = 179.4$ GeV: $y_t < 2.2\, y_t^{SM}$ at 95% C.L.

MSSM with $y_t = x\, y_t^{MSSM}$:

Predictions for M_W, $\sin^2\theta_{eff}$ vs. experimental result,
$M_A = 175$ GeV, $\tan\beta = 3$, $M_{SUSY} = 500$ GeV,
$X_t = 1000$ GeV ($\Rightarrow m_h \approx 114$ GeV)

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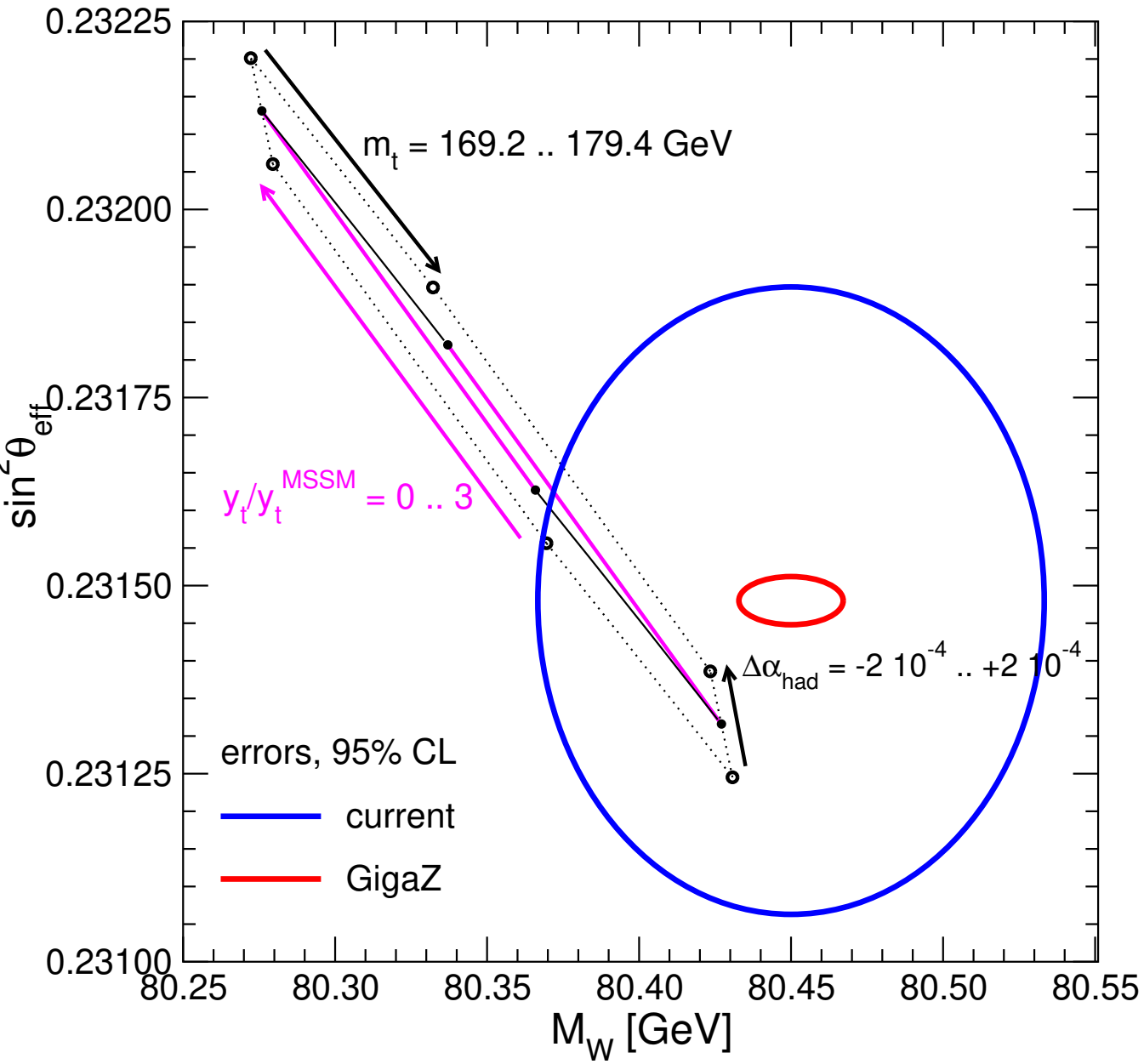

$\Rightarrow$ For $m_t = 174.3$ GeV: $y_t < 1.7\, y_t^{MSSM}$ at 95% C.L.

$\Rightarrow$ For $m_t = 179.4$ GeV: $y_t < 2.5\, y_t^{MSSM}$ at 95% C.L.

4. Conclusions

- Results for M_{W} in the electroweak SM:
  - Complete fermionic two-loop corrections
  - Higgs dependence of bosonic corrections

- Estimate of theoretical uncertainties from unknown higher orders:
  $\delta M_{\mathrm{W}} \approx \pm 5,\ \pm 6$ MeV
  with / without new result for M_{H}-indep. constant

- New estimate of theoretical uncertainties
  $\Rightarrow$ "Blue band" has widened

- Leading $\mathcal{O}(\alpha_{\mathrm{t}}^2)$, $\mathcal{O}(\alpha_{\mathrm{t}}\alpha_{\mathrm{b}})$, $\mathcal{O}(\alpha_{\mathrm{b}}^2)$ contributions to $\Delta\rho$ in MSSM for large M_{SUSY}:
  Higgs-exchange, 2HDM with MSSM restrictions

- Result for arbitrary m_{h}:
  Correction in MSSM always larger than in SM
  Corrections to M_{W}, $\sin^2\theta_{\mathrm{eff}}$ up to
  $\Delta M_{\mathrm{W}} = -12$ MeV, $\Delta \sin^2\theta_{\mathrm{eff}} = 6 \times 10^{-5}$

- Electroweak precision tests yield constraints on Yukawa coupling y_{t}:
  SM with $m_{\mathrm{t}} = 174.3$ GeV, $y_{\mathrm{t}} \neq y_{\mathrm{t}}^{\mathrm{SM}}$:
  $\Rightarrow y_{\mathrm{t}} < 1.3\, y_{\mathrm{t}}^{\mathrm{SM}}$, 95% C.L.