MSSM Higgs Physics: Theoretical Developments

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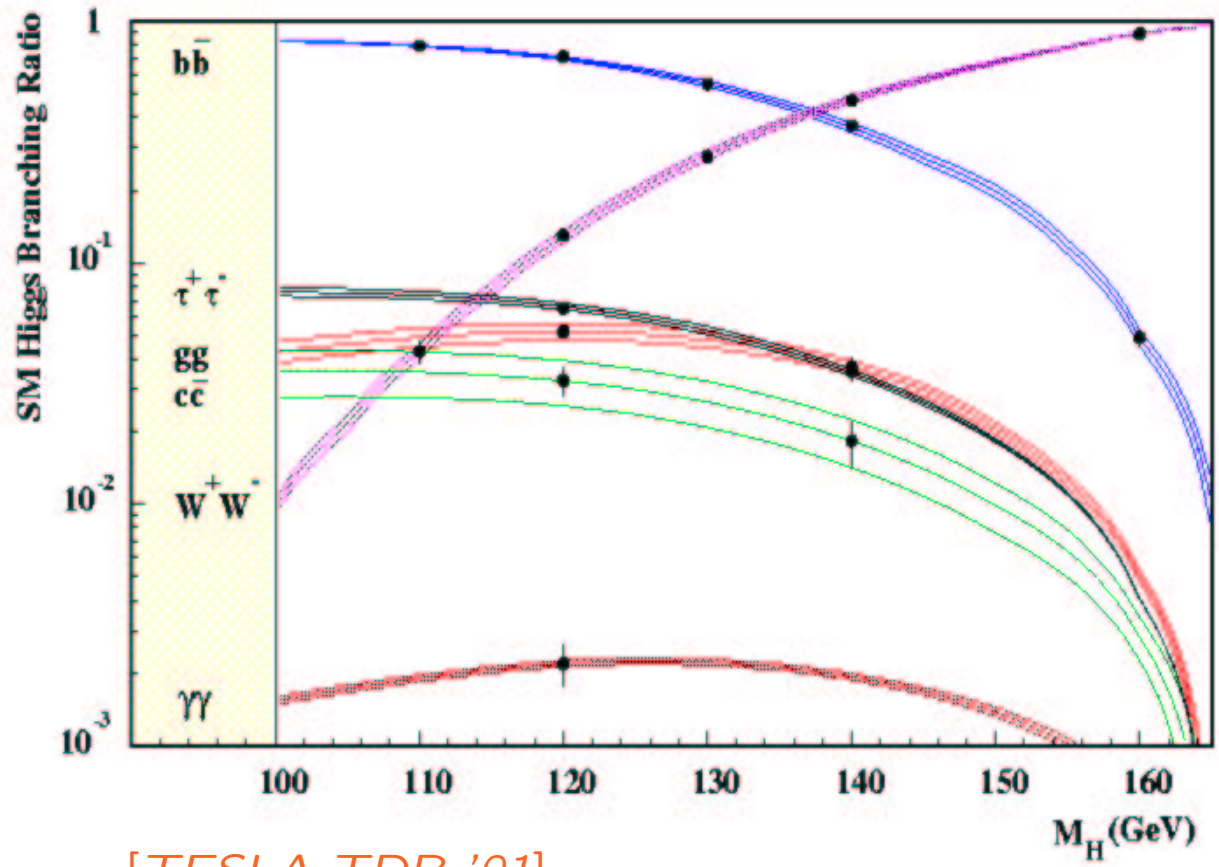
1. Motivation
2. Recent calculations in the MSSM Higgs sector
3. Theoretical uncertainty of m_h
4. The code *FeynHiggs*2.1
5. Conclusions

1. Motivation

SM Higgs @ LC:
Precise measurement of:

1. Higgs boson mass, $\delta M_H \approx 50$ MeV
2. Higgs boson width (direct/indirect)
3. Higgs boson couplings, $\mathcal{O}$ (few%) $\Rightarrow$
4. Higgs boson quantum numbers: spin, ...



[*TESLA TDR '01*]

MSSM: similar precision expected (possible problems from loop corrections)

Q: Can this precision be utilized in the MSSM Higgs sector?

The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles

$$\left[u, d, c, s, t, b\right]_{L,R} \quad \left[e, \mu, \tau\right]_{L,R} \quad \left[\nu_{e,\mu,\tau}\right]_{L} \qquad \text{Spin } \tfrac{1}{2}$$

$$\left[\tilde{u}, \tilde{d}, \tilde{c}, \tilde{s}, \tilde{t}, \tilde{b}\right]_{L,R} \quad \left[\tilde{e}, \tilde{\mu}, \tilde{\tau}\right]_{L,R} \quad \left[\tilde{\nu}_{e,\mu,\tau}\right]_{L} \qquad \text{Spin } 0$$

$$g \quad \underbrace{W^{\pm}, H^{\pm}} \quad \underbrace{\gamma, Z, H_1^0, H_2^0} \qquad \text{Spin } 1 \text{ / Spin } 0$$

$$\tilde{g} \quad \tilde{\chi}_{1,2}^{\pm} \quad \tilde{\chi}_{1,2,3,4}^{0} \qquad \text{Spin } \frac{1}{2}$$

Enlarged Higgs sector: Two Higgs doublets

Problem in the MSSM: many scales

Enlarged Higgs sector: Two Higgs doublets

$$H_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix}$$

$$H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix}$$

$$V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.})$$

$$+ \underbrace{\frac{g'^2 + g^2}{8}}_{\text{gauge couplings, in contrast to SM}} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}}_{} |H_1 \bar{H}_2|^2$$

physical states: $h^0, H^0, A^0, H^\pm$

Goldstone bosons: $G^0, G^\pm$

Input parameters:

$$\tan\beta = \frac{v_2}{v_1}, \qquad M_A^2 = -m_{12}^2 (\tan\beta + \cot\beta)$$

Contrary to the SM:

m_h is not a free parameter

MSSM tree-level bound: $m_h < M_Z$, excluded by LEP Higgs searches

Large radiative corrections:

Dominant one-loop corrections:

$$\Delta m_h^2 \sim G_\mu m_t^4 \ln\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right)$$

The MSSM Higgs sector is connected to all other sector via loop corrections (especially to the scalar top sector)

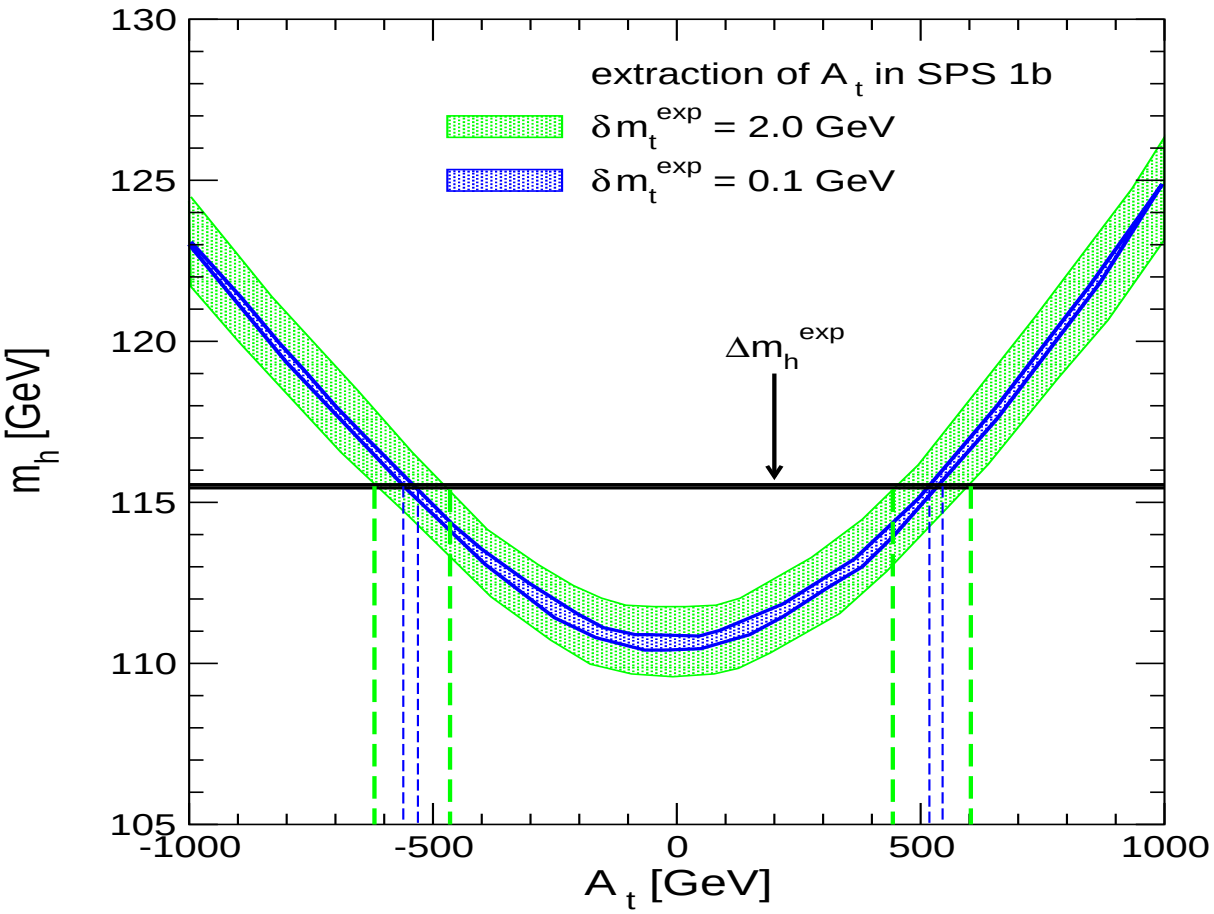
Measurement of m_h, Higgs couplings $\Rightarrow$ test of the theory

LC: $\Delta m_h \approx 0.05$ GeV

$\Rightarrow m_h$ will be (the best?) electroweak precision observable

Example of application: m_h prediction as a function of A_t

[*S.H., S. Kraml, W. Porod, G. Weiglein '02*]



SPS1b:

$m_{\tilde{t}_1}, m_{\tilde{t}_2}, m_{\tilde{b}_1}, m_{\tilde{b}_2}$ known,

A_t unknown

$\tan\beta, M_A$ known,

realistic parametric errors assumed

(incl. SUSY exp. errors)

$\Rightarrow$ extraction of A_t possible

Theory error neglected

$\Rightarrow$ m_h is crucial input for SUSY fit programs (Fittino, Sfitter)

(see talk by P. Wienemann in the SUSY session)

Experimental situation:

LC will provide high accuracy measurements !

Theory situation:

measured observables have to be compared with theoretical predictions (in the MSSM)

Measured data is only meaningful if it is matched with theoretical calculations (masses, couplings) at the same level of accuracy

Theoretical calculations should be viewed as an essential part of all future High Energy Physics programs

$\Rightarrow$ concentrate on Higgs masses and couplings here

2. Recent calculations in the MSSM Higgs sector

Many people worked on better theory predictions in the MSSM Higgs sector:

More recently done (this millennium):

- subleading (non)-log $\mathcal{O}\left(\alpha_t^2\right)$ terms
  $\Rightarrow \delta m_h \lesssim 1 - 4$ GeV
  [*A. Brignole, G. Degrassi, P. Slavich, F. Zwirner '01*] [*J. Espinosa, R. Zhang '01*]
- "Δm_b" effects $\Rightarrow$ leading $\mathcal{O}\left(\alpha_b \alpha_s\right)$ terms
  $\Rightarrow \delta m_h$ for large $\tan\beta$
  [*M. Carena, D. Garcia, U. Nierste, C. Wagner '00*]
- Remaining $\mathcal{O}\left(\alpha_b \alpha_s\right)$ corrections
  $\Rightarrow \delta m_h \lesssim 0 - 3$ GeV for very large μ, $\tan\beta$
  [*A. Brignole, G. Degrassi, P. Slavich, F. Zwirner '01*]
  [*S.H., W. Hollik, H. Rzehak, G. Weiglein '04*]
- Leading $\mathcal{O}\left(\alpha_t \alpha_b, \alpha_b^2\right)$ corrections
  $\Rightarrow \delta m_h \lesssim 0 - 3$ GeV for "extreme" parameters
  [*A. Dedes, G. Degrassi, P. Slavich '03*]
- "Full" 2-loop EP (not for OS calculation)
  [*S. Martin '02, '03*]

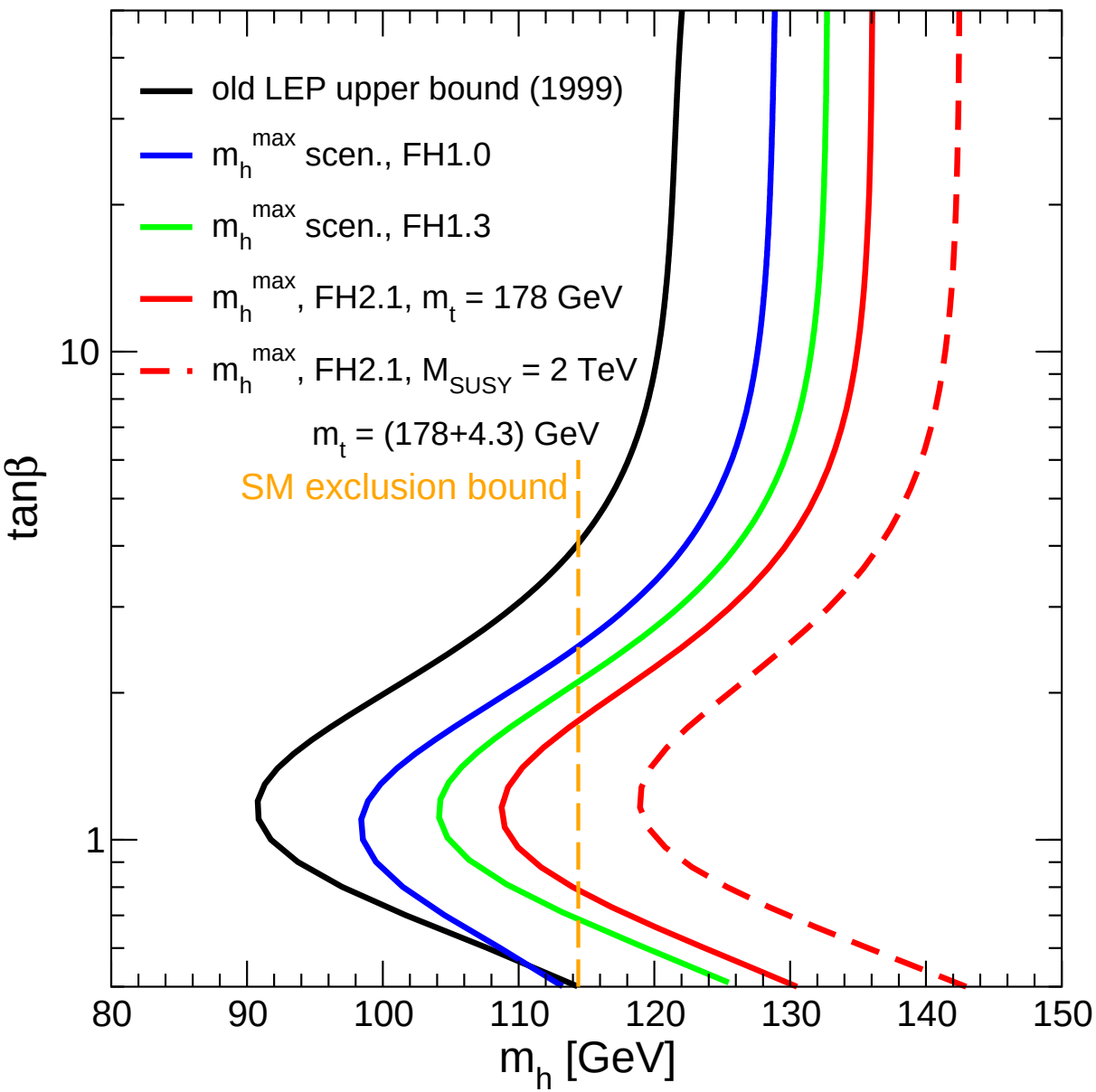
More recently done (cont.'):

- evaluation of the Higgs sector of the cMSSM:
  full 1-loop, $q^2 \neq 0 \Rightarrow \delta m_h \lesssim 1 - 7$ GeV
  [*M. Frank, S.H., W. Hollik, G. Weiglein '02*]
- full 1-loop corrections for charged Higgs sector
  [*M. Frank, S.H., W. Hollik, G. Weiglein '02*]
- New renormalization ($\overline{\text{MS}}$/OS)
  for 1-loop result $\Rightarrow \delta m_h \approx 1 - 2$ GeV
  [*M. Frank, S.H., W. Hollik, G. Weiglein '02*]
- Renormalization at $\mathcal{O}(\alpha_b \alpha_s)$
  $\Rightarrow \delta m_h \lesssim 1 - 3$ GeV for very large μ, $\tan\beta$
  [*S.H., W. Hollik, H. Rzehak, G. Weiglein '04*]

Missing:

- full 2-loop (incl. full renormalization)
- leading 3-loop ($\rightarrow$ possible, but technical difficulties ...)

Example: effect on $\tan\beta$ exclusion:



compare:

old evaluation, until 1999

$m_h^{\max}$ scenario, *FeynHiggs*1.0

$m_h^{\max}$ scenario, *FeynHiggs*1.3

$m_h^{\max}$ scenario, *FeynHiggs*2.1, $m_t = 178$ GeV

$\Rightarrow$ $\tan\beta$ bound considerably weakened

even worse:

$m_h^{\max}$ scenario with $m_t = 178 + 4.3$ GeV, $M_{\mathrm{SUSY}} = 2$ TeV

3. Theoretical uncertainty in m_h

3A: Intrisic uncertainties (unknown higher-order corrections)

2-loop momentum independent:

remaining 2-loop, $q^2 = 0$: $\Delta m_h \lesssim 1.5$ GeV

- subleading $\mathcal{O}(\alpha_t \alpha_s)$
- subleading $\mathcal{O}\left(\alpha_t^2\right)$
- $\mathcal{O}\left(\alpha_\tau^2\right)$
- 2-loop gaugino contributions

$\rightarrow$ T

2-loop momentum dependent:

Formally of $\mathcal{O}\left(\alpha_s \alpha_t m_t^2 m_h^2 / M_{\mathrm{W}}^2\right)$
(i.e. like the "remaining 2-loop" corrections)

1-loop: $\Delta m_h \lesssim 2$ GeV

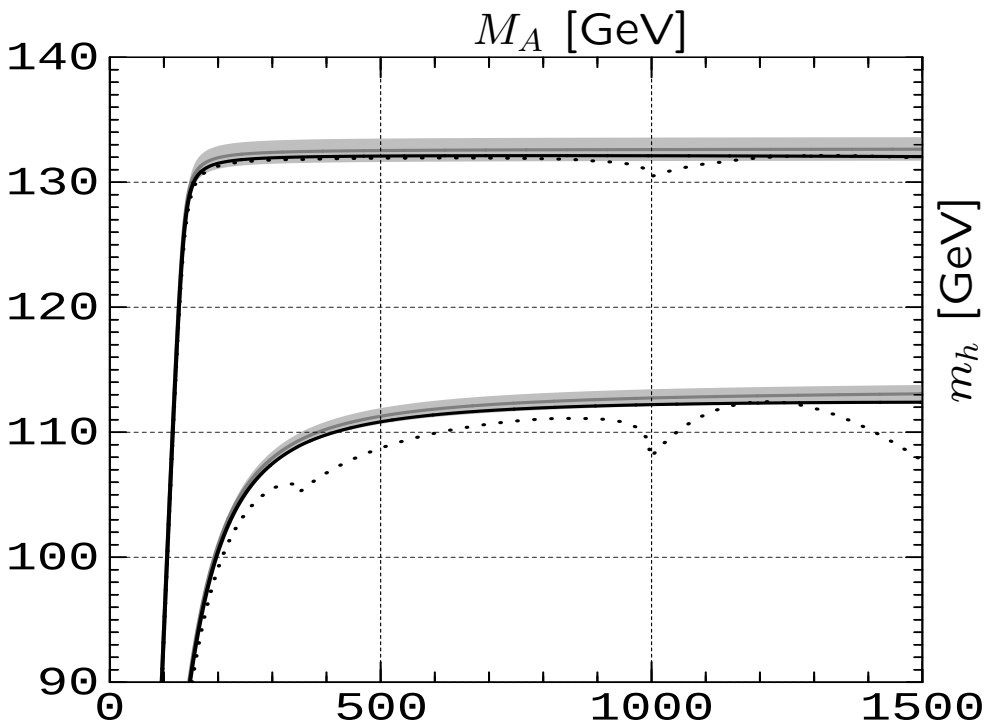
2-loop: $\Delta m_h \lesssim 1$ GeV

Variation of $\overline{\text{MS}}$ renormalization constant:

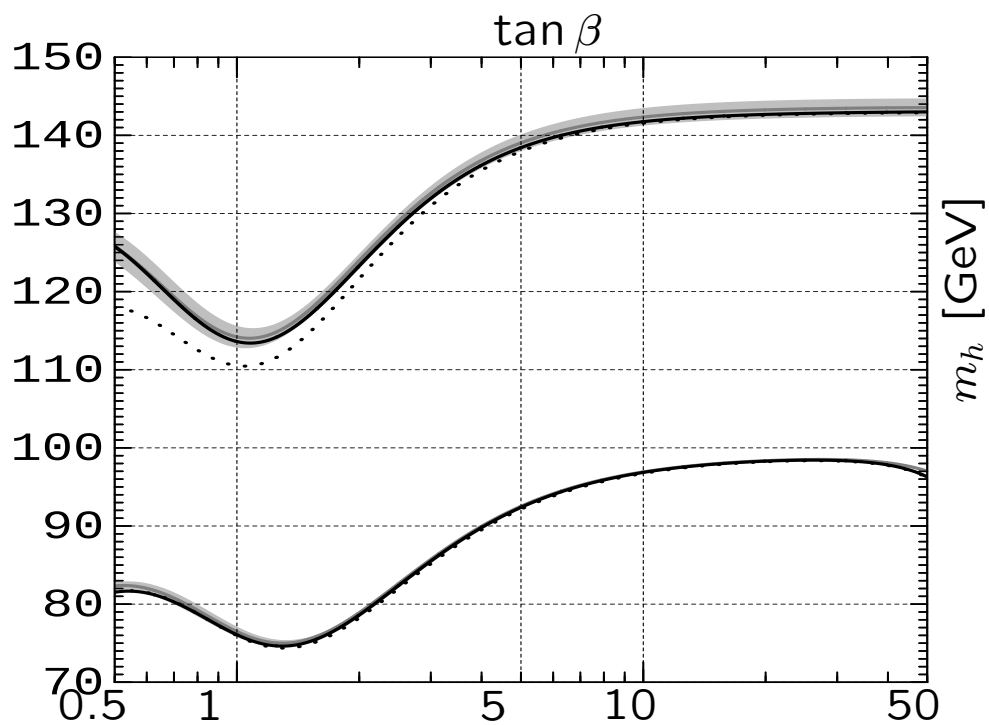
m_h^{max} scenario, $\mu_{\text{dim}} = 0.5\, m_t \ldots 2\, m_t$

[*M. Frank, S.H., W. Hollik, G. Weiglein '02*]

$\tan\beta = 2, 20$



$M_A = 100, 500$ GeV



$t/\tilde{t}$: 3-loop, 4-loop, ... :

1) changing renormalization of m_t at 2-loop: $\rightarrow$ T
   $\Rightarrow \Delta m_h \lesssim 1.5$ GeV from leading 3-loop corrections

2) explicit formula for simplified case:

$$\Delta m_h^2 = \frac{3\alpha_t \overline{m}_t^2}{\pi^3} \log^3\left(\frac{M_{\text{SUSY}}^2}{m_t^2}\right)\left[\frac{23}{6}\alpha_s^2 - \frac{5}{4}\alpha_s\alpha_t - \frac{33}{64}\alpha_t^2\right]$$

$(M_A = m_{\tilde{g}} = m_{\tilde{t}_1} = m_{\tilde{t}_2} \equiv M_{\text{SUSY}},\ \tan\beta \rightarrow \infty) \Rightarrow \Delta m_h \lesssim 1.5$ GeV

3) iterative numerical solution of RGEs: [*A. Hoang '97*] $\Rightarrow \Delta m_h \lesssim 1.5$ GeV

$b/\tilde{b}$: 3-loop, 4-loop, ... :

changing the renormalization scheme $\rightarrow$ T
$\Rightarrow \Delta m_h \lesssim 0 - 3$ GeV (depending on parameter space)

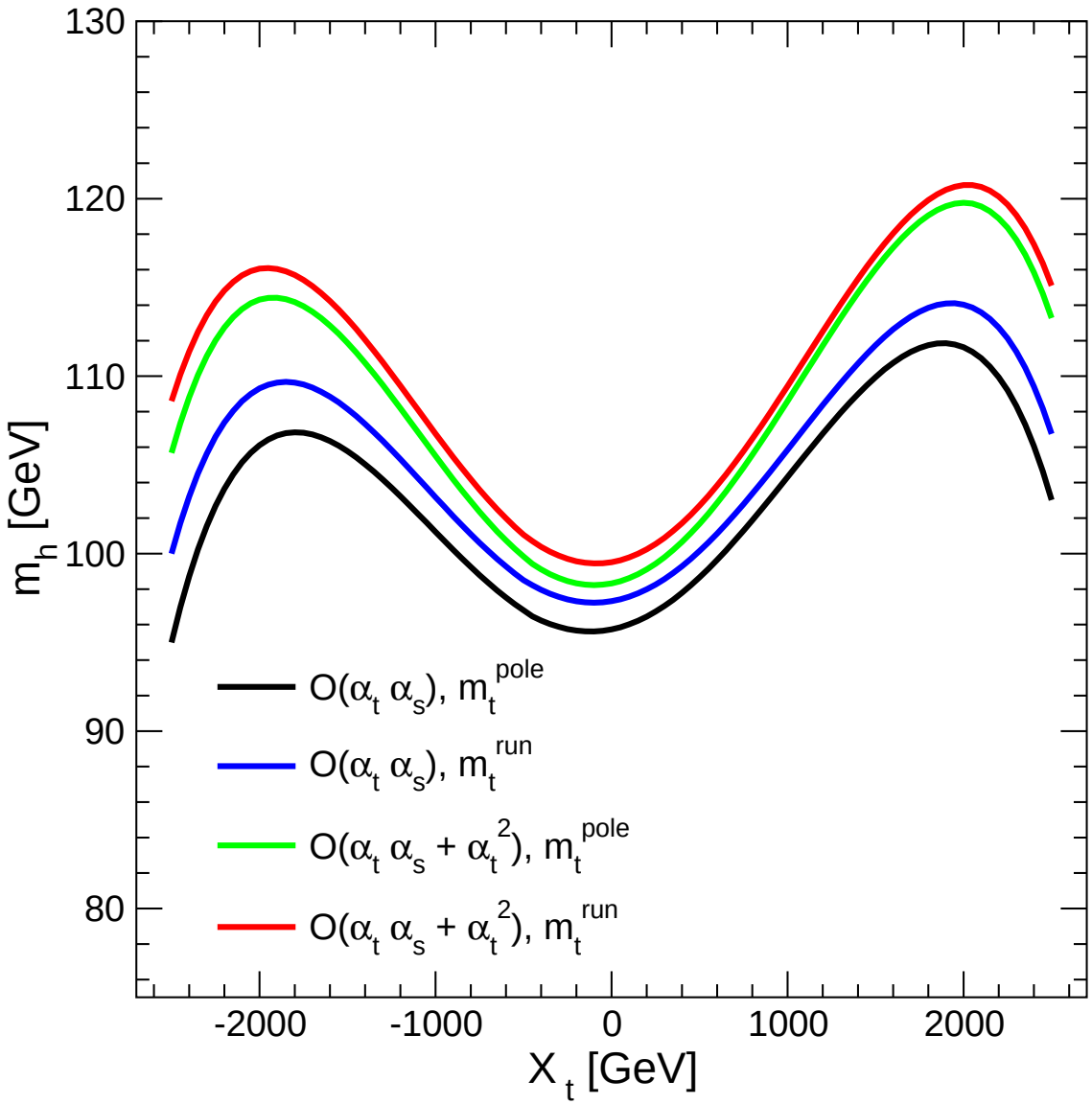
full intrinsic error: (from unknown higher-order corrections)

today: $\Delta m_h^{\text{intr}} \approx 3$ GeV

needed for future: $\Delta m_h^{\text{intr}} \lesssim 0.5 - 0.1$ GeV ... possible:
needed: full two-loop (incl. renormalization), leading three-loop

$t/\tilde{t}$: 3-loop, 4-loop, ... : changing renormalization of m_t at 2-loop:

[*G. Degrassi, S.H., W. Hollik, P. Slavich, G. Weiglein '02*]



Parameter:

$M_A = M_{\text{SUSY}} = 1$ TeV,

$\tan\beta = 3$

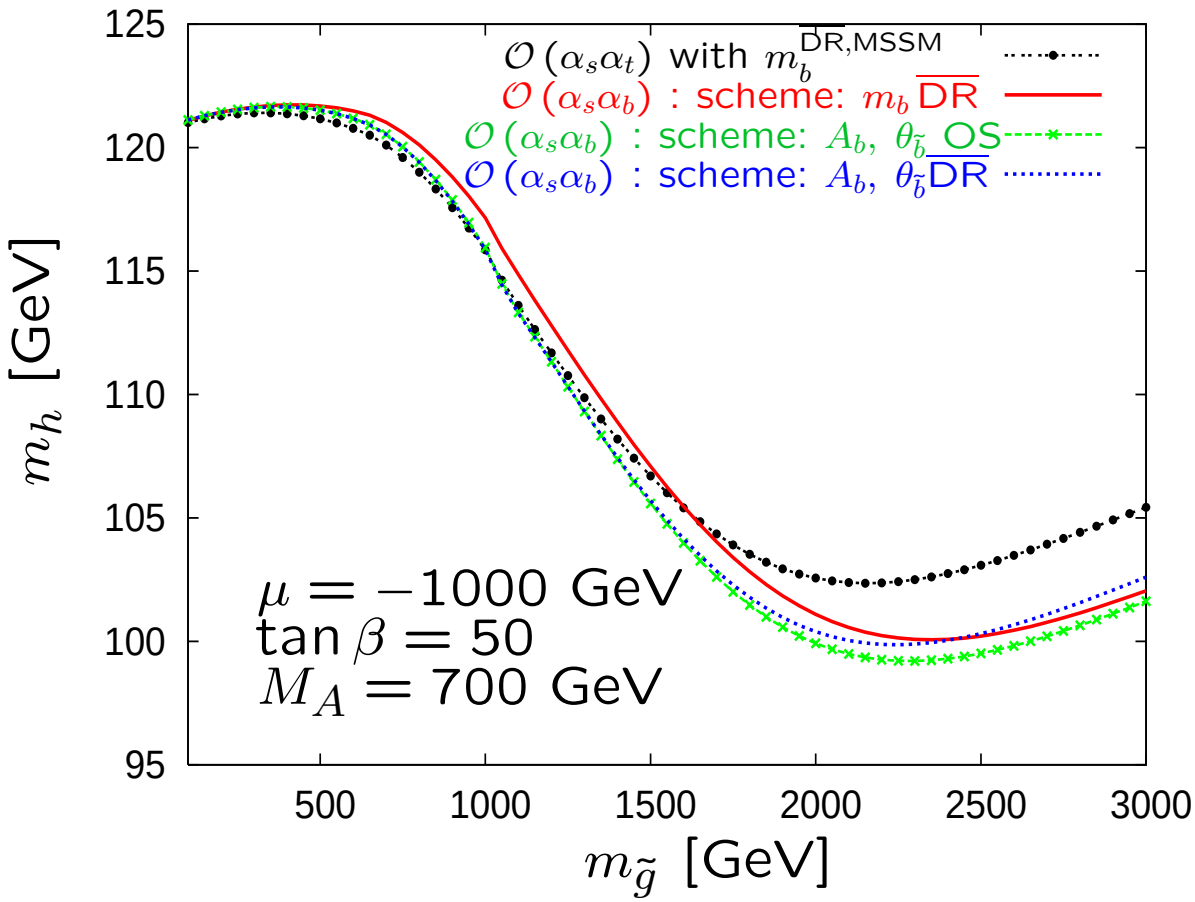
compare: m_t^{pole} vs. m_t^{run}

$\Rightarrow \Delta m_h \lesssim 1.5$ GeV

from leading 3-loop corrections

$b/\tilde{b}$: 3-loop, 4-loop, ... : changing renormalization of $b/\tilde{b}$ sector at 2-loop:

[*S.H., W. Hollik, H. Rzehak, G. Weiglein '04*]



Parameter:

$M_{\text{SUSY}} = 1$ TeV,

$A_t = A_b = 2$ TeV

compare: 3 schemes

$\Rightarrow \Delta m_h \lesssim 0 - 3$ GeV

from leading 3-loop corrections

depending on parameter space!

3B: Parametric uncertainties:

m_t:

today: $\delta m_t^{\text{Tevatron}} \approx 4$ GeV $\Rightarrow \Delta m_h^{m_t} \approx 4$ GeV

future: $\delta m_t^{\text{LC}} \approx 100$ MeV $\Rightarrow \Delta m_h^{m_t} \approx 100$ MeV

m_b: $\delta m_b \lesssim 100$ MeV $\Rightarrow$ negligible

M_{W}:

today: $\delta M_{\text{W}} = 34$ MeV $\Rightarrow \Delta m_h^{M_{\text{W}}} \approx 100$ MeV

future: $\delta M_{\text{W}}^{\text{GigaZ}} \approx 7$ MeV negligible

α_s:

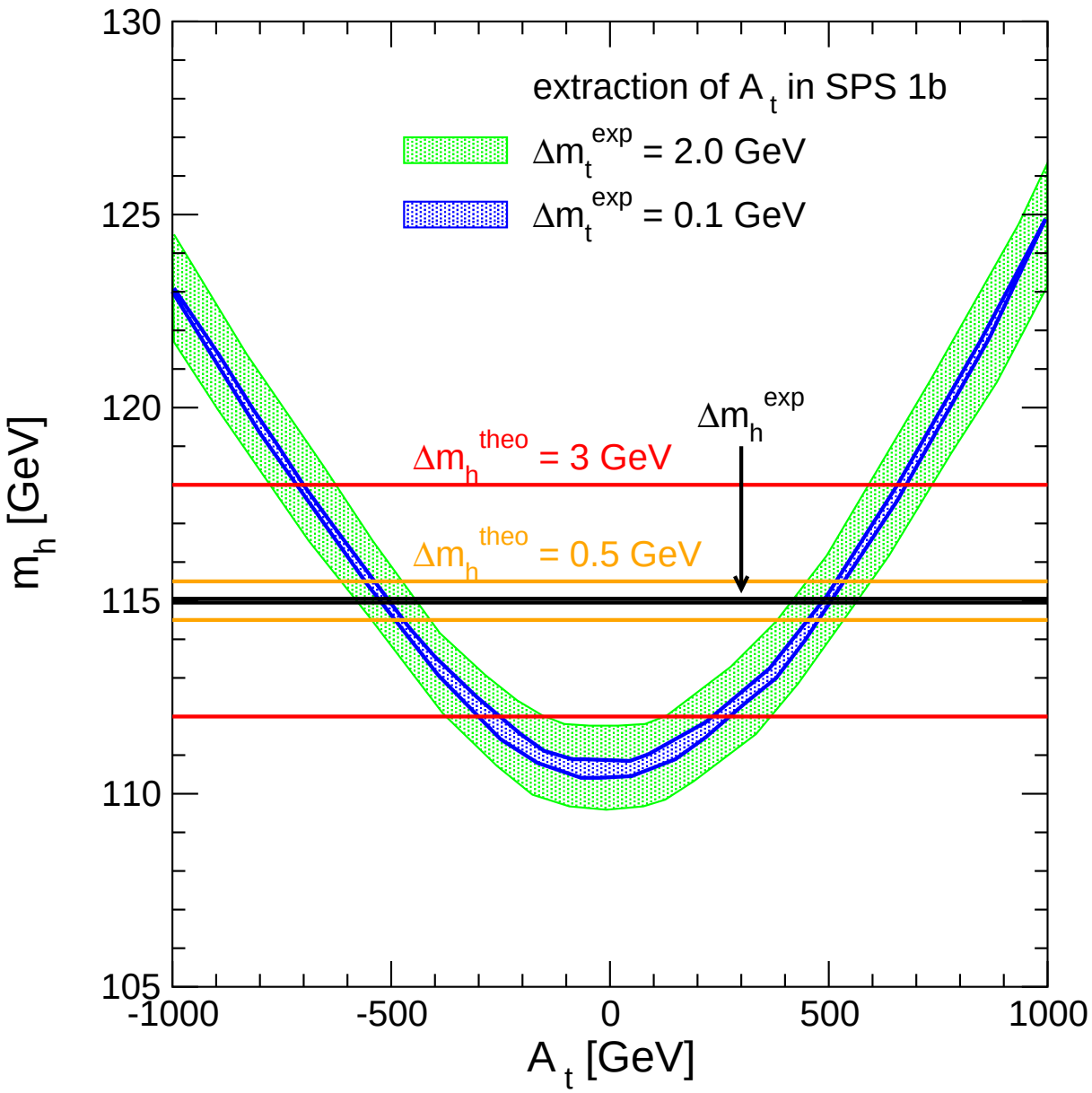
today: $\delta\alpha_s(M_Z) \approx 0.002 \Rightarrow \Delta m_h^{\alpha_s} \approx 0.3$ GeV

future: $\delta\alpha_s(M_Z) \lesssim 0.001 \Rightarrow \Delta m_h^{\alpha_s} \approx 0.1 - 0.2$ GeV

Experimental uncertainties:

$\Delta m_h^{\text{exp,LC}} \approx 50$ MeV $\Rightarrow$ very difficult to match

Example of effects: m_h prediction as a function of A_t



SPS1b:

$m_{\tilde{t}_1}, m_{\tilde{t}_2}, m_{\tilde{b}_1}, m_{\tilde{b}_2}$ known,

A_t unknown

$\tan\beta, M_A$ known,

realistic parametric errors assumed

(incl. SUSY exp. errors)

$\Rightarrow$ extraction of A_t possible

$\Rightarrow$ Δm_h^{theo} has to be under control

4. The code FeynHiggs2.1

[*M. Frank, T. Hahn, S. H., W. Hollik, G. Weiglein '03*]

Latest version: (04/04) $\Rightarrow$ contains all above described results

Included in *FeynHiggs*2.1 (I):

Evaluation of all Higgs boson masses and mixing angles (cMSSM/rMSSM)

- $m_{h_1}, m_{h_2}, m_{h_3}, M_{H^\pm}$, α_{eff}, u_{ij}, $\ldots$

Evaluation of all neutral Higgs boson decay channels (cMSSM/rMSSM)

- total decay width Γ_{tot}
- BR($h_i \to f\bar{f}$): decay to SM fermions
- BR($h_i \to \gamma\gamma, ZZ, WW, gg$): decay to SM gauge bosons
- BR($h_i \to h_1 Z, h_1 h_1$): decay to gauge and Higgs bosons
- BR($h_i \to \tilde{f}_i \tilde{f}_j$): decay to sfermions
- BR($h_i \to \tilde{\chi}_i^\pm \tilde{\chi}_j^\pm, \tilde{\chi}_i^0 \tilde{\chi}_j^0$): decay to charginos, neutralinos

Included in *FeynHiggs*2.1 (II):

Evaluation for the SM Higgs (same masses as the three MSSM Higgses)

- total decay width $\Gamma_{\rm tot}^{\rm SM}$
- BR($h_i^{\rm SM} \to f\bar{f}$): decay to SM fermions
- BR($h_i^{\rm SM} \to \gamma\gamma, ZZ, WW, gg$): decay to SM gauge bosons

Evaluation of all charged Higgs boson decay channels (cMSSM/rMSSM)

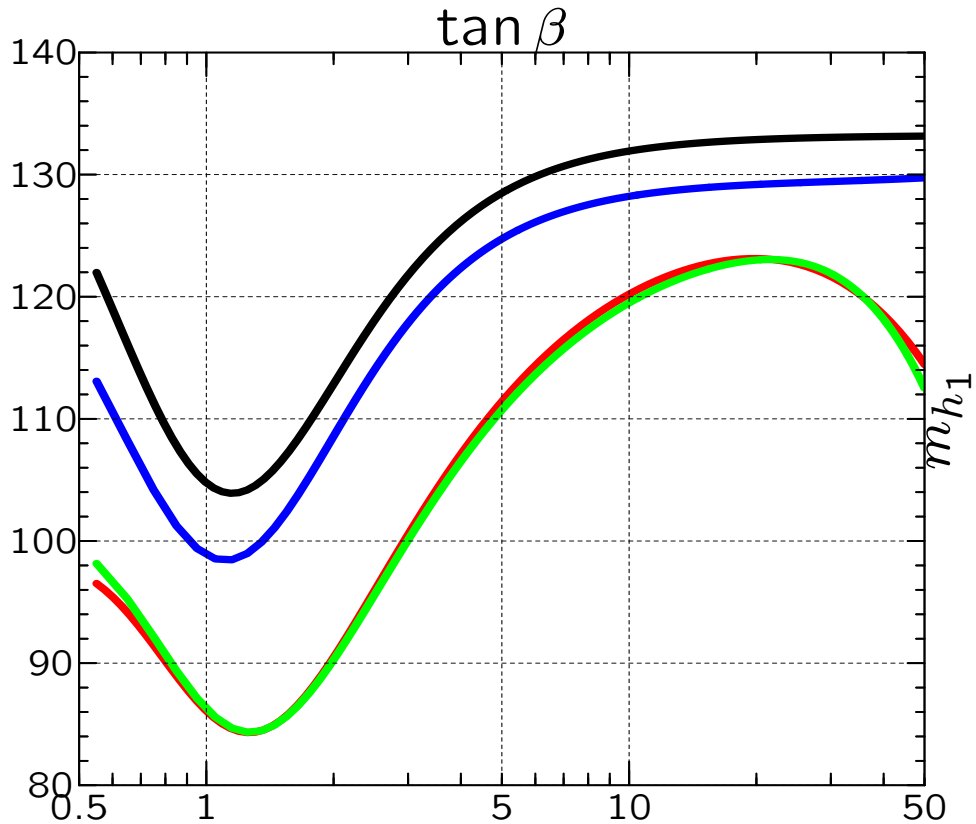
- total decay width $\Gamma_{\rm tot}$
- BR($H^+ \to f\bar{f}'$): decay to SM fermions
- BR($H^+ \to h_i W^+$): decay to gauge and Higgs bosons
- BR($H^+ \to \tilde{f}_i \tilde{f}'_j, \tilde{\chi}_i^0 \tilde{\chi}_j^+$): decay to sfermions, charginos and neutralinos

Evaluation of additional couplings:

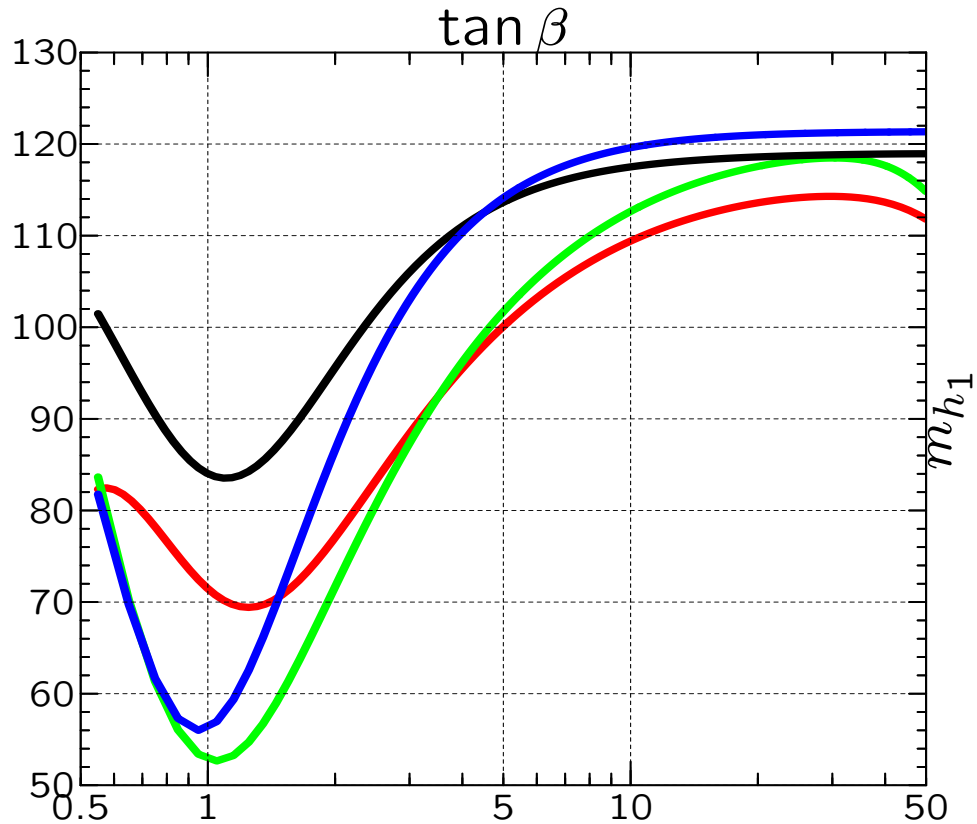
- $g(V \to V h_i, h_i h_j)$: coupling of gauge and Higgs bosons
- $g(h_i h_j h_k)$: all Higgs self couplings (including charged Higgs)

Compare *FeynHiggs* with Hdecay/CPsH : m_{h_1} in two scenarios:

$m_h^{\max}$ scenario



gluophobic Higgs scenario



FeynHiggs, $M_{H^\pm} = 150$ GeV , CPsH, $M_{H^\pm} = 150$ GeV

FeynHiggs, $M_{H^\pm} = 500$ GeV , CPsH, $M_{H^\pm} = 500$ GeV

$\Rightarrow$ large differences, understood: new corrections only in *FeynHiggs*

How does it work?

1. Go to www.feynhiggs.de
2. Download the latest version (possibly also *LoopTools*)
3. type `./configure`, `make`
   ⇒ library `libFH.a` is created
4. 3 possible ways to use *FeynHiggs*:

   A) as a stand alone program

   B) called from a Fortran/C++ code (as a subroutine)

   C) called within Mathematica

   processing of Les Houches Accord data possible
5. Detailed instructions and help are provided in the man pages

Example of application: *FeynHiggs* is used for

– final evaluations of LEP Higgs WG for $\mathcal{CP}$V scenario (together with CPH)
[*P. Bechtle, K. Desch, priv. comm.*]

– ATLAS Higgs analyses [*M. Schumacher, priv. comm.*]

– CMS Higgs analyses [*S. Nikitenko, priv. comm.*]

5. Conclusinos

- The LC will provide high precision results for a light (MSSM) Higgs
- MSSM Higgs masses and couplings are connected via radiative corrections to all other sectors
- m_h is (the best?) electroweak precision observable
  (m_h is crucial input for MSSM Fit programs)
- Many corrections to MSSM Higgs sector in this millennium in r/cMSSM
  $\Rightarrow \delta m_h \lesssim 7$ GeV
- Current theory uncertainty: $\delta m_h^{\text{theo,today}} \approx 3$ GeV
  Future theory uncertainty: $\delta m_h^{\text{theo,future}} \lesssim 0.5$ GeV necessary/possible
  Future parametric uncertainty: $\delta m_h^{\text{para,future}} = \mathcal{O}(0.2 \text{ GeV})$ $(m_t,\ \alpha_s)$
- All corrections included in *FeynHiggs* (www.feynhiggs.de)
  $\Rightarrow$ High precision tool for MSSM Higgs physics at the LHC/LC