The Charged Higgs Boson: Codes and Tools

Sven Heinemeyer, IFCA (CSIC, Santander)

Uppsala, 09/2008

1. Motivation
2. Classification of codes and tools
3. Examples for higher-order corrections
4. Conclusions

1. Motivation

Higgs mechanism in the SM case:

$$\mathcal{L}_{\rm SM} = \underbrace{m_d \bar{Q}_L \Phi d_R}_{\text{d-quark mass}} + \underbrace{m_u \bar{Q}_L \Phi_c u_R}_{\text{u-quark mass}}$$

$$Q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L, \quad \Phi_c = i\sigma_2 \Phi^\dagger, \quad \Phi \to \begin{pmatrix} 0 \\ v \end{pmatrix}, \quad \Phi_c \to \begin{pmatrix} v \\ 0 \end{pmatrix}$$

In SUSY: term $\bar{Q}_L \Phi^\dagger$ not allowed

Superpotential is holomorphic function of chiral superfields, i.e. depends only on φ_i, not on φ_i^*

$\Rightarrow$ $H_d (\equiv H_1)$ and $H_u (\equiv H_2)$ needed to give masses to down- and up-type fermions

In general: two Higgs doublets appear ‘more natural’ than only one

Models with charged Higgs bosons:

1. Two Higgs Doublet Model (THDM)
   $\longrightarrow$ no code(s) available

2. Minimal Supersymmetric Standard Model (MSSM)
   $\longrightarrow$ code(s) exist

3. MSSM with extra singlet (NMSSM)
   $\longrightarrow$ code(s) exist

4. MSSM with more extra singlets
   $\longrightarrow$ no code(s) available

5. SM/MSSM with Higgs triplets
   $\longrightarrow$ no code(s) available

6. ...

"code exists" = working computer code publicly available

THDM: Enlarged Higgs sector: Two Higgs doublets

$$V = \frac{\lambda_1}{2}\left(H_1^\dagger H_1\right)^2 + \frac{\lambda_2}{2}\left(H_2^\dagger H_2\right)^2 + \lambda_3\left(H_1^\dagger H_1\right)\left(H_2^\dagger H_2\right) + \lambda_4\left(H_1^\dagger H_2\right)\left(H_2^\dagger H_1\right)$$

$$+ \left[\frac{\lambda_5}{2}\left(H_1^\dagger H_2\right)\left(H_1^\dagger H_2\right) + \lambda_6\left(H_1^\dagger H_1\right)\left(H_1^\dagger H_2\right) + \lambda_7\left(H_2^\dagger H_2\right)\left(H_1^\dagger H_2\right)\right] + \text{h.c.}$$

$$- \frac{1}{2}m_1^2\left(H_1^\dagger H_1\right) - \frac{1}{2}m_2^2\left(H_2^\dagger H_2\right) - \frac{1}{2}m_{12}^2\left(H_1^\dagger H_2\right) + \text{h.c.}$$

$\lambda_{1,2,3,4}$, m_1^2, m_2^2: real parameters

$\lambda_{5,6,7}$, m_{12}^2: complex parameters

14 parameters $\Rightarrow$ 11 independent

$\Rightarrow M_{H^\pm}$ can be chosen as free parameter

only very few restrictions in the THDM

MSSM: Enlarged Higgs sector: Two Higgs doublets

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

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

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

$$+ \underbrace{\frac{g'^2 + g^2}{8}} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}} |H_1 \bar{H}_2|^2$$

gauge couplings, in contrast to SM

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

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

Input parameters: (to be determined experimentally)

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

MSSM: Enlarged Higgs sector: Two Higgs doublets with $\mathcal{CP}$ violation

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

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

$$V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.})$$
$$+ \underbrace{\frac{g'^2 + g^2}{8}}(H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}} |H_1 \bar{H}_2|^2$$

gauge couplings, in contrast to SM

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

2 $\mathcal{CP}$-violating phases: ξ, arg(m_{12}) $\Rightarrow$ can be set/rotated to zero

Input parameters: (to be determined experimentally)

$$\tan\beta = \frac{v_2}{v_1}, \qquad M_{H^\pm}^2$$

In lowest order:

Input parameters: (to be determined experimentally)

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

$\Rightarrow$ m_h, m_H, mixing angle α, $m_{\mathrm{H}^\pm}$: no free parameters, can be predicted

In lowest order:

$$m_{\mathrm{H}^\pm}^2 = M_A^2 + M_W^2$$

Keep in mind: higher-order corrections

$\Rightarrow$ Test of the model!

Necessary:

– discover the charged Higgs at the LHC or at the ILC

– measure its mass/characteristics at the LHC or at the ILC

– compare with theory prediction for $M_{H^\pm}$/other characteristics

2. Classification of codes and tools

THDM: no codes for charged Higgs boson in THDM found . . .

MSSM: many codes, detailed list follows . . .

NMSSM: NMSSMTools [*U. Ellwanger, C. Hugonie*]
contains NMSpec, NMHdecay, . . .

$M_{H^\pm}$: one-loop corrections

charged Higgs couplings, decay widths:
leading logarithmic corrections to top- and bottom Yukawa couplings included

→ concentrate on MSSM from now on

Charged Higgs boson codes in the MSSM (I):

- RGE codes: SoftSUSY, Suspect, Spheno, Isasusy, . . .

  $\longrightarrow$ corrections to $M_{H^\pm}$: one-loop
  $\longrightarrow$ $H^\pm$ decays: effective couplings
  $\longrightarrow$ their strength: provide tree-level parameters at EW scale
  link to other codes via SLHA(2)

- Mass calculators, decay packages: FeynHiggs, CPSuperH, Hdecay, . . .

  $\longrightarrow$ corrections to $M_{H^\pm}$: one- or two-loop
  (FeynHiggs, Hdecay only; CPSuperH has $M_{H^\pm}$ as input)
  $\longrightarrow$ $H^\pm$ decays: effective couplings, Δ_b corrections
  $\Rightarrow$ more details below

- Charged Higgs LHC production cross sections: [*O. Brein*] [*T. Plehn*]

  $\longrightarrow$ not really public yet (still waiting . . .)

  $\Rightarrow$ more in the next talk?

Charged Higgs boson codes in the MSSM (II):

- Event generators: Pythia, Herwig, Sherpa, . . .

  only few corrections for $M_{H^\pm}$, $\Gamma_{H^\pm}$
  $\longrightarrow$ link to mass calculators, decay packages via SLHA(2)

- Indirect constraints via B-physics observables, . . . :
  SuperIso, Isidori/Paradisi (genuine BPO codes)
  Micromegas, CPSuperH, FeynHiggs, . . . (BPO as additional check)

Comparison of mass calculators:

FeynHiggs: [*T. Hahn, S.H., W. Hollik, H. Rzehak, G. Weiglein*]

rMSSM: full one-loop, $\mathcal{O}(\alpha_t\alpha_s)$ two-loop, Δ_b corrections
cMSSM: $M_{H^\pm}$ is input, corrections go to $M_{h_1}, M_{h_2}, M_{h_3}$

Hdecay: [*M. Spira, A. Djouadi, J. Kalinowski, M. Mühlleitner*]

rMSSM: link to other codes

CPSuperH: [*J. Lee, M. Pilaftsis, S. Choi, M. Carena, M. Drees, J. Ellis, C. Wagner*]
cMSSM: $M_{H^\pm}$ is input, corrections go to $M_{h_1}, M_{h_2}, M_{h_3}$
many one-loop, RGE improved for two-loop, Δ_b corrections

$\Rightarrow$ Examples for two-loop and Δ_b in the next section

Comparison of decay calculations (I):

Hdecay:

main correction: SM QCD + $\Delta_{b,\text{real}}$ for bottom Yukawa coupling

- total decay width Γ_{tot}
- BR($H^+ \to f^{(*)}\bar{f}'$): decay to SM fermions
- BR($H^+ \to h_i W^{+(*)}$): decay to gauge and Higgs bosons
- BR($H^+ \to \tilde{f}_i \tilde{f}'_j$): decay to sfermions
- BR($H^+ \to \tilde{\chi}^0_i \tilde{\chi}^+_j$): decay to charginos and neutralinos
- BR($t \to H^+ \bar{b}$) for $M_{H^\pm} \le m_t$ ($H^\pm$ production at Tevatron/LHC)

Comparison of decay calculations (II):

CPSuperH:

main correction: SM QCD + $\Delta_{b,\text{complex}}$ for bottom Yukawa coupling

- total decay width Γ_{tot}
- $\text{BR}(H^+ \to f^{(*)} \bar{f}')$: decay to SM fermions
- $\text{BR}(H^+ \to h_i W^{+(*)})$: decay to gauge and Higgs bosons
- $\text{BR}(H^+ \to \tilde{f}_i \tilde{f}'_j)$: decay to sfermions
- $\text{BR}(H^+ \to \tilde{\chi}^0_i \tilde{\chi}^+_j)$: decay to charginos and neutralinos
- Higgs triple/quartic self-couplings (for $H^\pm H^\mp$, incl. corr.)

Comparison of decay calculations (III):

FeynHiggs:

main correction: SM QCD + $\Delta_{b,\text{complex}}$ for bottom Yukawa coupling

- total decay width Γ_{tot}
- $\text{BR}(H^+ \to f^{(*)} \bar{f}')$: decay to SM fermions
- $\text{BR}(H^+ \to h_i W^{+(*)})$: decay to gauge and Higgs bosons
- $\text{BR}(H^+ \to \tilde{f}_i \tilde{f}'_j)$: decay to sfermions
- $\text{BR}(H^+ \to \tilde{\chi}^0_i \tilde{\chi}^+_j)$: decay to charginos and neutralinos
- Higgs triple self-couplings (for $H^\pm H^\mp$, incl. corr.)
- H^+ production cross sections at LHC: [*T. Plehn et al.*] $\otimes$ Δ_b corr.
- $\text{BR}(t \to H^+ \bar{b})$ for $M_{H^\pm} \leq m_t$ ($H^\pm$ production at Tevatron/LHC)

3. Examples for higher-order corrections

MSSM: input: M_A and $\tan\beta$

output: neutral and charged Higgs masses, . . .

Tree-level:

$$m_{H^\pm}^2 = M_A^2 + M_W^2$$

Higher-order: $M_{H^\pm}^2$ is solution of

$$p^2 - m_{H^\pm}^2 + \hat{\Sigma}_{H^+H^-}(p^2) = 0$$

with

$$\hat{\Sigma}_{H^+H^-}(p^2) = \Sigma_{H^+H^-}(p^2) + \delta Z_{H^+H^-}(p^2 - m_{H^\pm}^2) - \delta m_{H^\pm}^2$$

The following results are based on/taken from

[M. Frank, T. Hahn, S.H., W. Hollik, H. Rzehak, G. Weiglein '08]*

(* hopefully)

$\tilde{t}/\tilde{b}$ sector of the MSSM: (scalar partner of the top/bottom quark)

Stop, sbottom mass matrices ($X_t = A_t - \mu^*/\tan\beta$, $X_b = A_b - \mu^* \tan\beta$):

$$\mathcal{M}^2_{\tilde{t}} = \begin{pmatrix} M^2_{\tilde{t}_L} + m_t^2 + DT_{t_1} & m_t X_t^* \\ m_t X_t & M^2_{\tilde{t}_R} + m_t^2 + DT_{t_2} \end{pmatrix} \xrightarrow{\theta_{\tilde{t}}} \begin{pmatrix} m^2_{\tilde{t}_1} & 0 \\ 0 & m^2_{\tilde{t}_2} \end{pmatrix}$$

$$\mathcal{M}^2_{\tilde{b}} = \begin{pmatrix} M^2_{\tilde{b}_L} + m_b^2 + DT_{b_1} & m_b X_b^* \\ m_b X_b & M^2_{\tilde{b}_R} + m_b^2 + DT_{b_2} \end{pmatrix} \xrightarrow{\theta_{\tilde{b}}} \begin{pmatrix} m^2_{\tilde{b}_1} & 0 \\ 0 & m^2_{\tilde{b}_2} \end{pmatrix}$$

mixing important in stop sector (also in sbottom sector for large $\tan\beta$)

soft SUSY-breaking parameters A_t, A_b also appear in ϕ-$\tilde{t}/\tilde{b}$ couplings

$SU(2)$ relation $\Rightarrow M_{\tilde{t}_L} = M_{\tilde{b}_L}$

$\Rightarrow$ relation between $m_{\tilde{t}_1}, m_{\tilde{t}_2}, \theta_{\tilde{t}}, m_{\tilde{b}_1}, m_{\tilde{b}_2}, \theta_{\tilde{b}}$

One-loop (complete):

$$\hat{\Sigma}^{(1)}_{H^+H^-}(p^2) = \Sigma^{(1)}_{H^+H^-}(p^2) + \delta Z^{(1)}_{H^+H^-}(p^2 - m^2_{H^\pm}) - \delta m^{(1)2}_{H^\pm}$$

with

$$\delta Z^{(1)}_{H^+H^-}(p^2) = \sin^2\beta\,\delta Z_{\mathcal{H}_1} + \cos^2\beta\,\delta Z_{\mathcal{H}_2}$$

$$\delta Z_{\mathcal{H}_1} = \delta Z^{\overline{\mathrm{DR}}}_{\mathcal{H}_1} = -\left[\mathrm{Re}\Sigma'_{HH|\alpha=0}\right]^{\mathrm{div}}$$

$$\delta Z_{\mathcal{H}_2} = \delta Z^{\overline{\mathrm{DR}}}_{\mathcal{H}_2} = -\left[\mathrm{Re}\Sigma'_{hh|\alpha=0}\right]^{\mathrm{div}}$$

$$\delta m^{(1)2}_{H^\pm} = \delta M^{(1)2}_W + \delta M^{(1)2}_A$$

$$\delta M^{(1)2}_A = \Sigma^{(1)}_{AA}(M^2_A)$$

Furthermore:

$$m_b \to \frac{\overline{m}_b}{1 + \Delta_b}$$

$$\Delta_b = \frac{2\alpha_s}{3\,\pi}\, m_{\tilde{g}}\,\mu\,\tan\beta \times I(m_{\tilde{b}_1}, m_{\tilde{b}_2}, m_{\tilde{g}}) + \frac{\alpha_t}{4\,\pi}\, A_t\,\mu\,\tan\beta \times I(m_{\tilde{t}_1}, m_{\tilde{t}_2}, \mu)$$

One-loop (complete):

$$\hat{\Sigma}^{(1)}_{H^+H^-}(p^2) = \Sigma^{(1)}_{H^+H^-}(p^2) + \delta Z^{(1)}_{H^+H^-}(p^2 - m^2_{H^\pm}) - \delta m^{(1)2}_{H^\pm}$$

with

$$\delta Z^{(1)}_{H^+H^-}(p^2) = \sin^2\beta\, \delta Z_{\mathcal{H}_1} + \cos^2\beta\, \delta Z_{\mathcal{H}_2}$$

$$\delta Z_{\mathcal{H}_1} = \delta Z^{\overline{\rm DR}}_{\mathcal{H}_1} = -\left[\mathrm{Re}\Sigma'_{HH|\alpha=0}\right]^{\rm div}$$

$$\delta Z_{\mathcal{H}_2} = \delta Z^{\overline{\rm DR}}_{\mathcal{H}_2} = -\left[\mathrm{Re}\Sigma'_{hh|\alpha=0}\right]^{\rm div}$$

$$\delta m^{(1)2}_{H^\pm} = \delta M^{(1)2}_{W} + \delta M^{(1)2}_{A}$$

$$\delta M^{(1)2}_{A} = \Sigma^{(1)}_{AA}(M^2_A)$$

Furthermore:

$$m_b \;\to\; \frac{\overline{m}_b}{1 + \Delta_b}$$

$\Rightarrow$ also main higher-order effect in $H^\pm tb$ coupling

Two-loop:

leading $\mathcal{O}(\alpha_t \alpha_s)$

- only y_t^2 contributions
- $g, g' \to 0$
- external momentum $\to 0$

$$\hat{\Sigma}^{(2)}_{H^+H^-}(0) = \Sigma^{(2)}_{H^+H^-}(0) - \delta m^{(2)2}_{H^\pm}$$

with

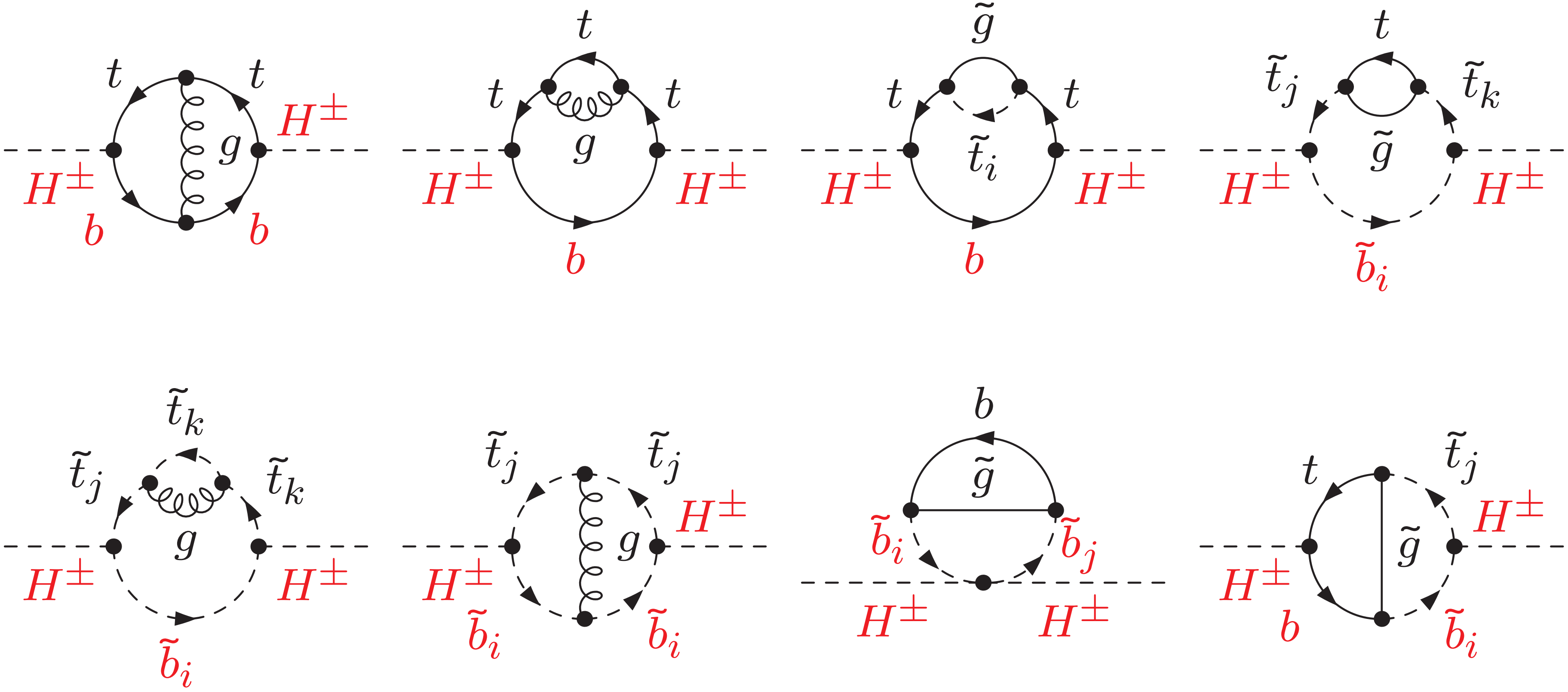
$$\delta Z^{(2)}_{H^+H^-} = 0$$

$$\delta M^{(2)2}_W = 0$$

$$\delta m^{(2)2}_{H^\pm} = \delta M^{(2)2}_A = \Sigma^{(2)}_{AA}(0)$$

Contributions to the 2-loop self-energy:

2-loop self-energy diagrams:



new: $H^\pm$ as external Higgs

$\Rightarrow b/\tilde{b}$ enter (even diagrams without $t/\tilde{t}$: $H^+H^-\tilde{b}_i\tilde{b}_j \sim y_t^2$)

$\Rightarrow$ renormalization of $b/\tilde{b}$ sector necessary

$\mathcal{O}(\alpha_t \alpha_s)$ corrections in the FD approach

– only y_t^2 contributions

– $g, g' \to 0$

– external momentum $\to 0$

$\Rightarrow$ Two-loop diagrams

new: $H^\pm$ as external Higgs
$\Rightarrow b/\tilde{b}$ enter (even diagrams without $t/\tilde{t}$)

$\mathcal{O}(\alpha_t \alpha_s)$ corrections in the FD approach

– only y_t^2 contributions

– $g, g' \to 0$

– external momentum $\to 0$

$\Rightarrow$ Two-loop diagrams

new: $H^\pm$ as external Higgs
$\Rightarrow b/\tilde{b}$ enter (even diagrams without $t/\tilde{t}$)

Differences to neutral case:

$\Rightarrow b/\tilde{b}$ enter

$\Rightarrow$ many more scales

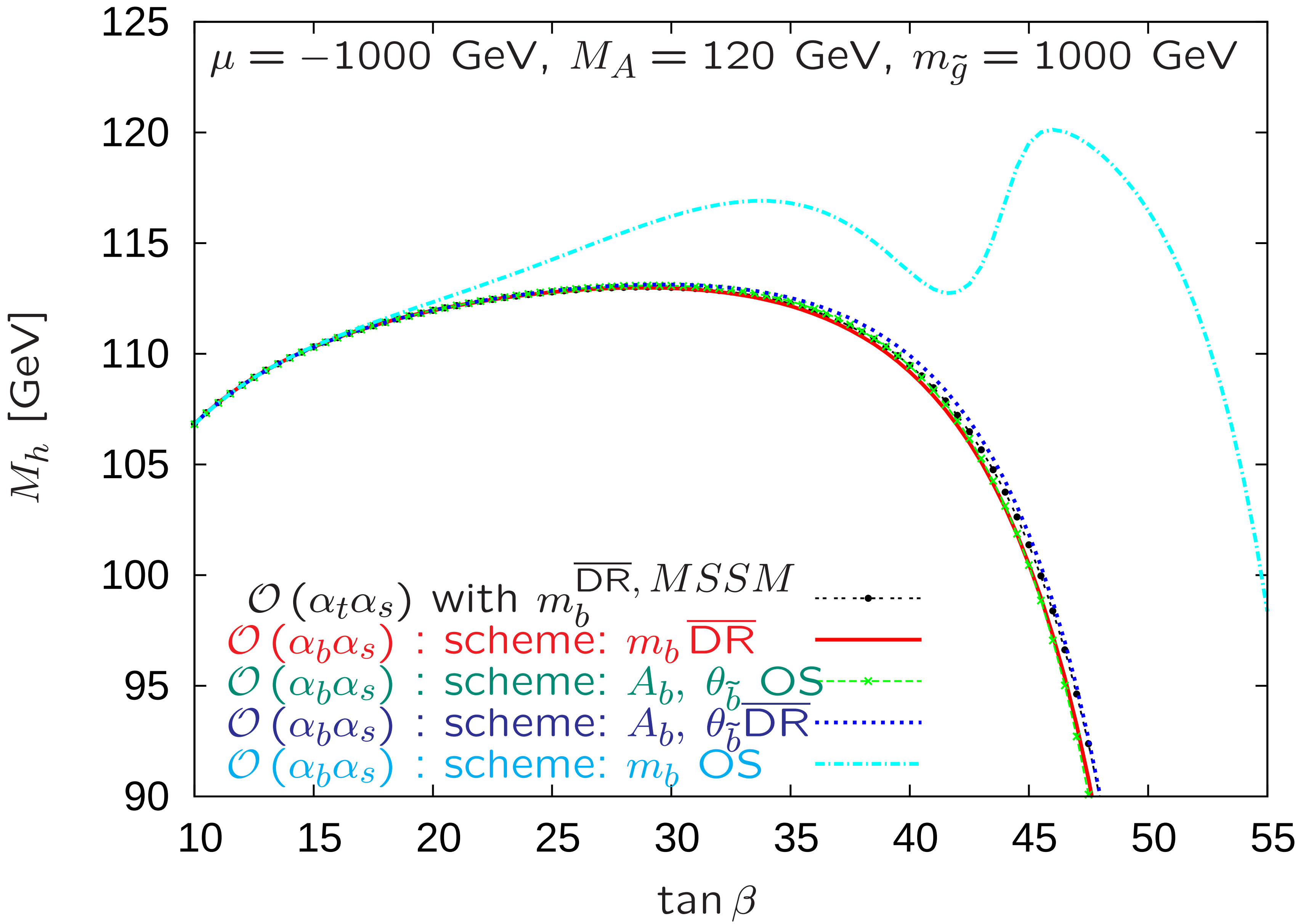
but not as many parameters ($SU(2)$)

$\Rightarrow$ Renormalization . . .

. . . especially involved for $b/\tilde{b}$ sector: bad choice can lead to completely unreliable results *[S.H., W. Hollik, H. Rzehak, G. Weiglein '04]*

Old example: M_h as a function of $\tan\beta$, $\mu < 0$:

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



Numerical results:

$\rightarrow$ no-mixing scenario, with variation of

- M_A : tree-level parameter
- $\tan\beta$: tree-level parameter
- μ : enters via Δ_b

($m_h^{\rm max}$ scenario similar, slightly smaller corrections)

Experimental resolution:

$M_{H^\pm} = 200$ GeV:

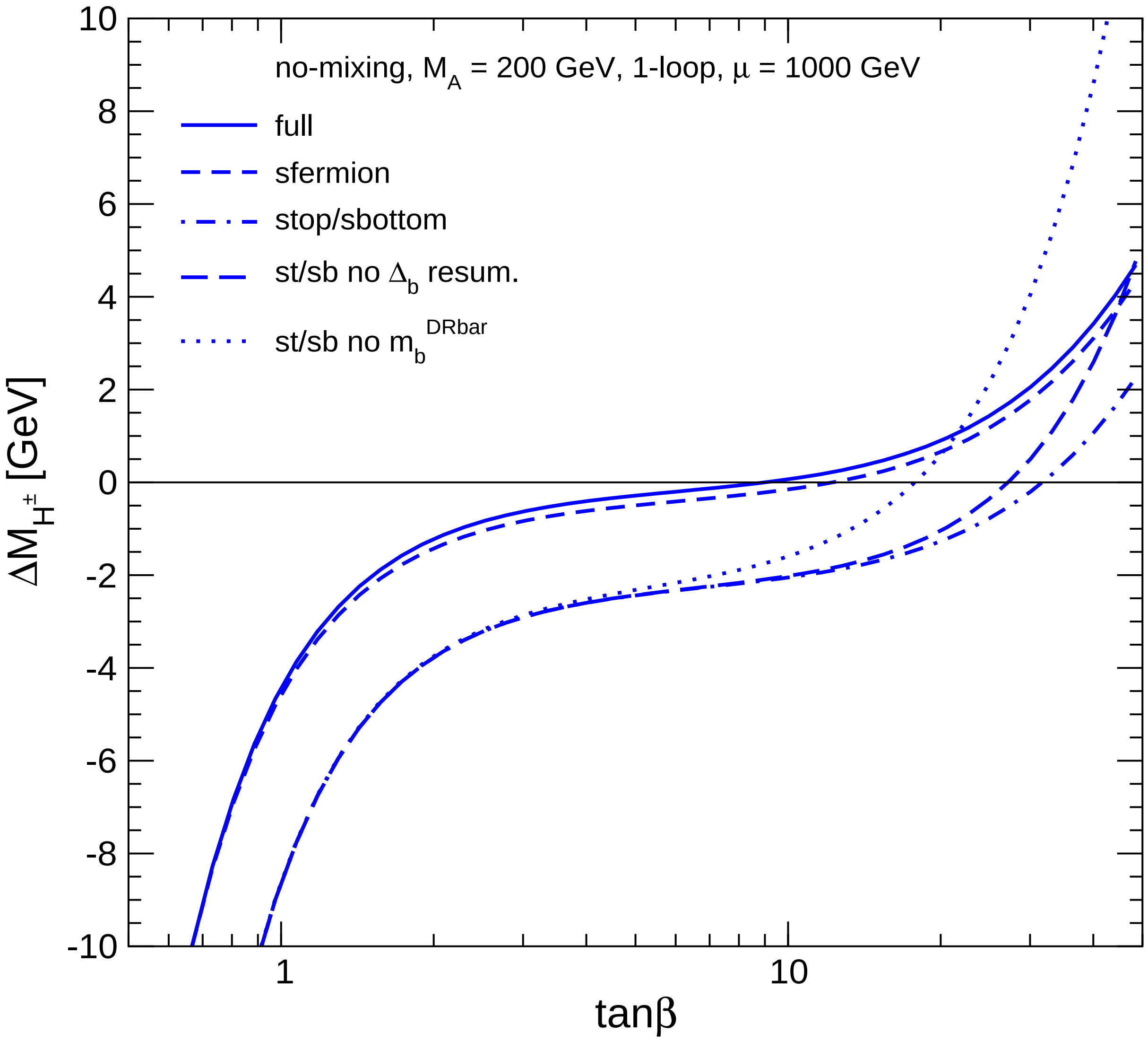
$$\text{LHC}: \Rightarrow \delta M_{H^\pm} \approx 1.5 \text{ GeV}$$

$$\text{ILC}: \Rightarrow \delta M_{H^\pm} \approx 0.5 \text{ GeV}$$

Higher masses:

$$\text{LHC}: \Rightarrow \delta M_{H^\pm} \approx 1 - 2\%$$

1-loop, tan β varied:



$t/\tilde{t}/b/\tilde{b}$ important

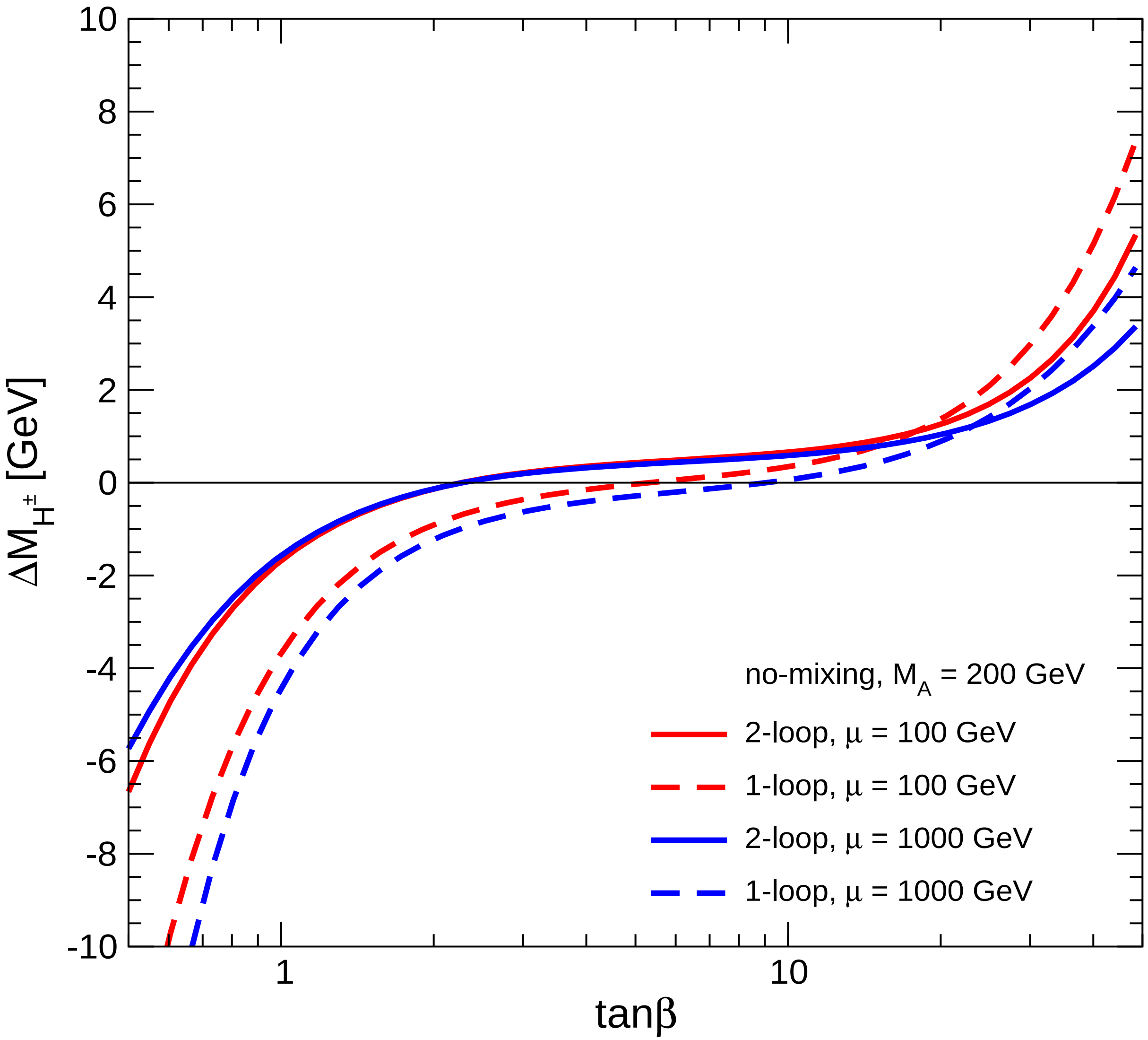
$\overline{m}_b$ important

Δ_b important

non-$t/\tilde{t}/b/\tilde{b}$
$\sim \log(M_{\text{SUSY}}/M_W)$
relevant

non-sfermion
corrections small

2-loop, tan β varied:



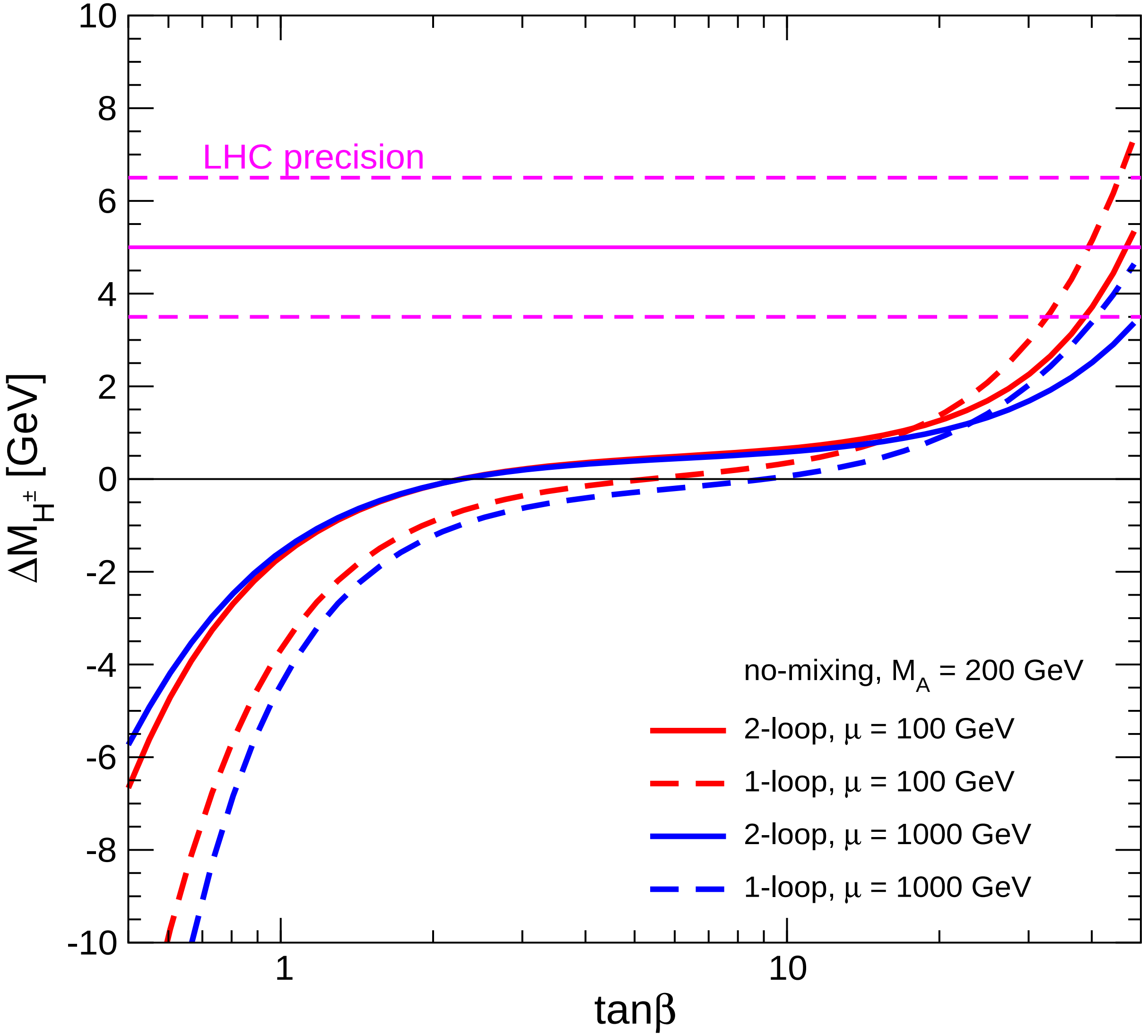
small tan β:

$\Delta M_{H^\pm} \gtrsim 4$ GeV

large tan β:

$\Delta M_{H^\pm} \sim 2$ GeV

2-loop, tan β varied:



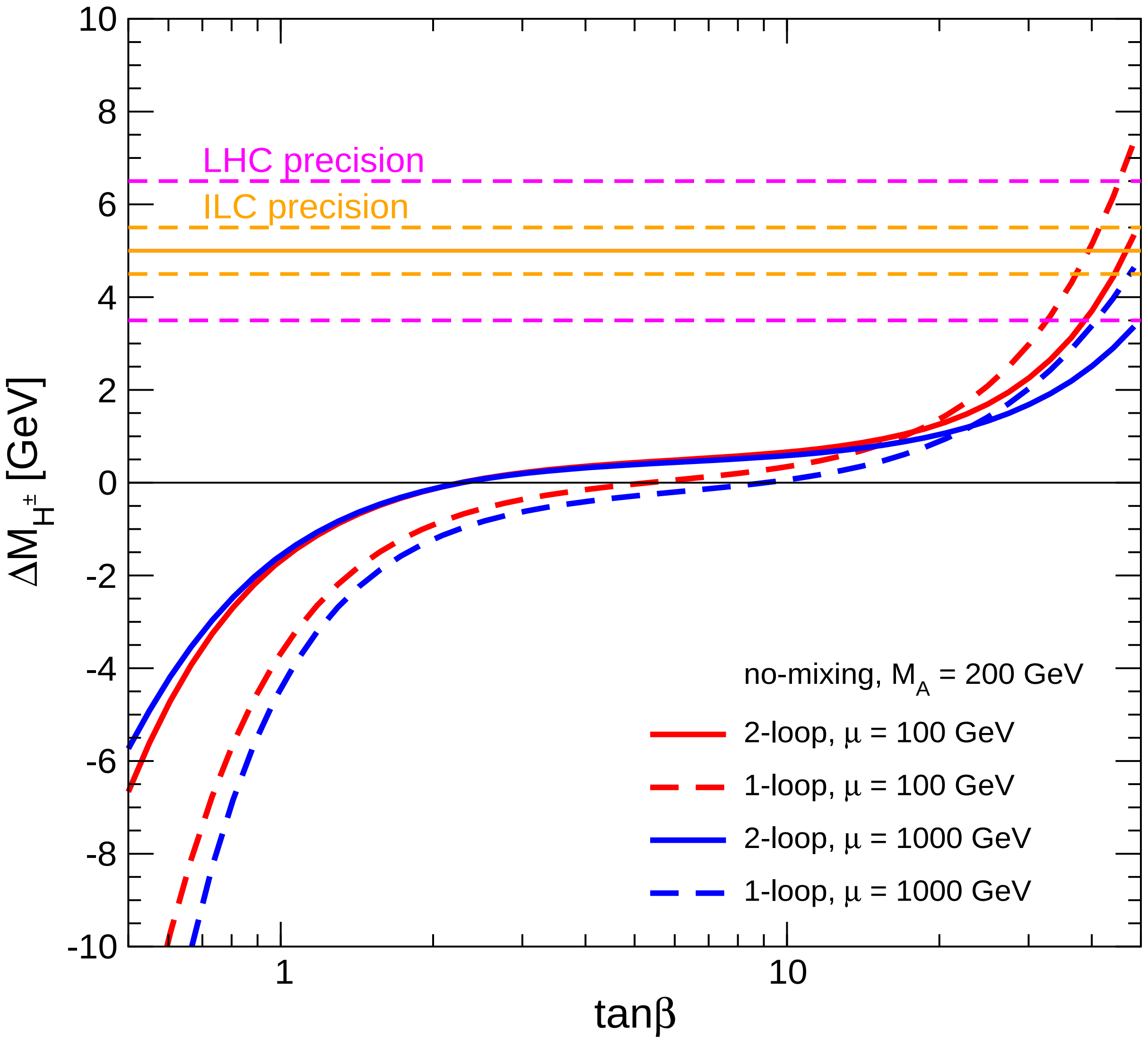
small tan β:

$\Delta M_{H^\pm} \gtrsim 4$ GeV

large tan β:

$\Delta M_{H^\pm} \sim 2$ GeV

2-loop, $\tan\beta$ varied:



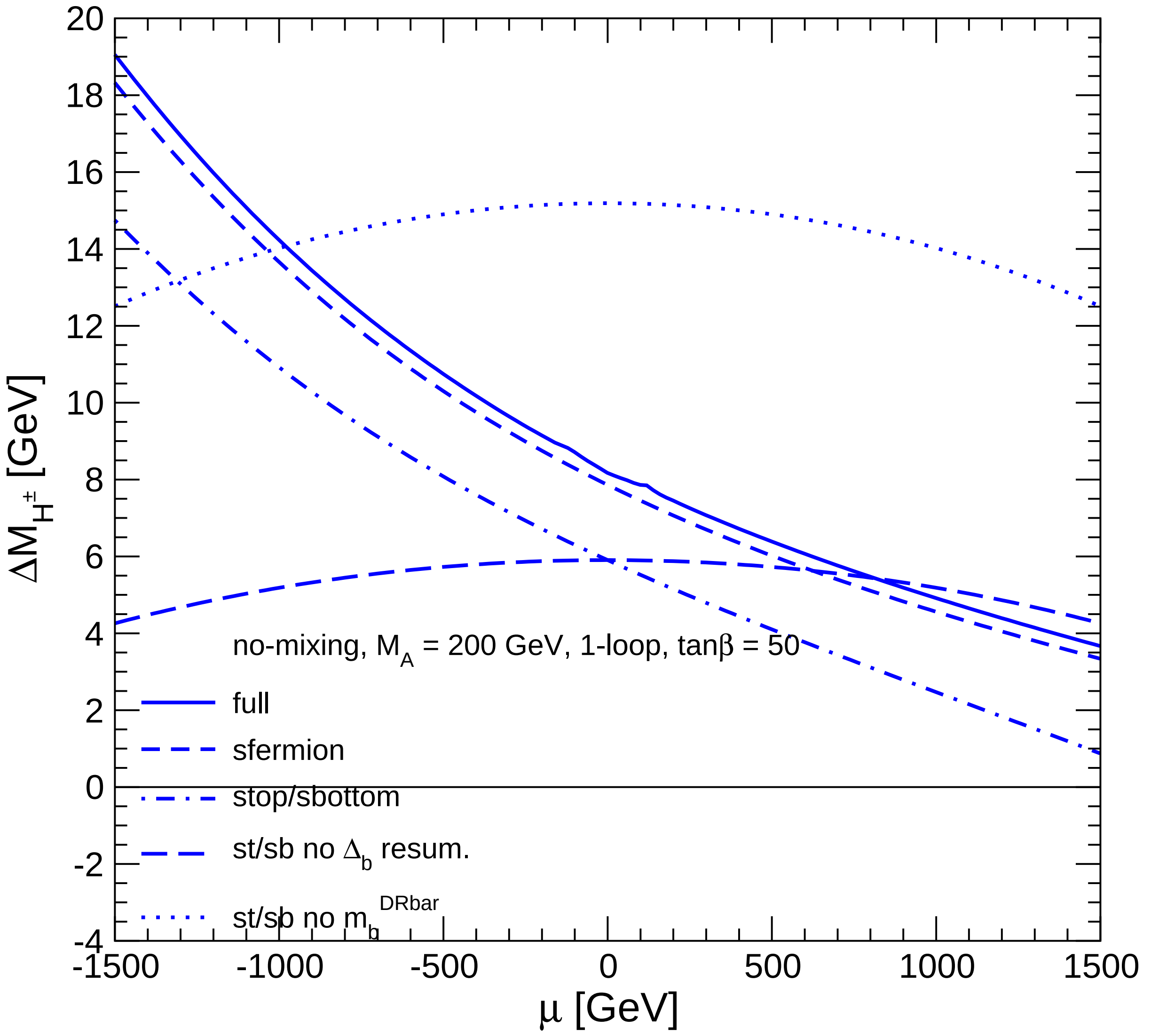
small $\tan\beta$:

$\Delta M_{H^\pm} \gtrsim 4$ GeV

large $\tan\beta$:

$\Delta M_{H^\pm} \sim 2$ GeV

1-loop, μ varied:



$t/\tilde{t}/b/\tilde{b}$ important

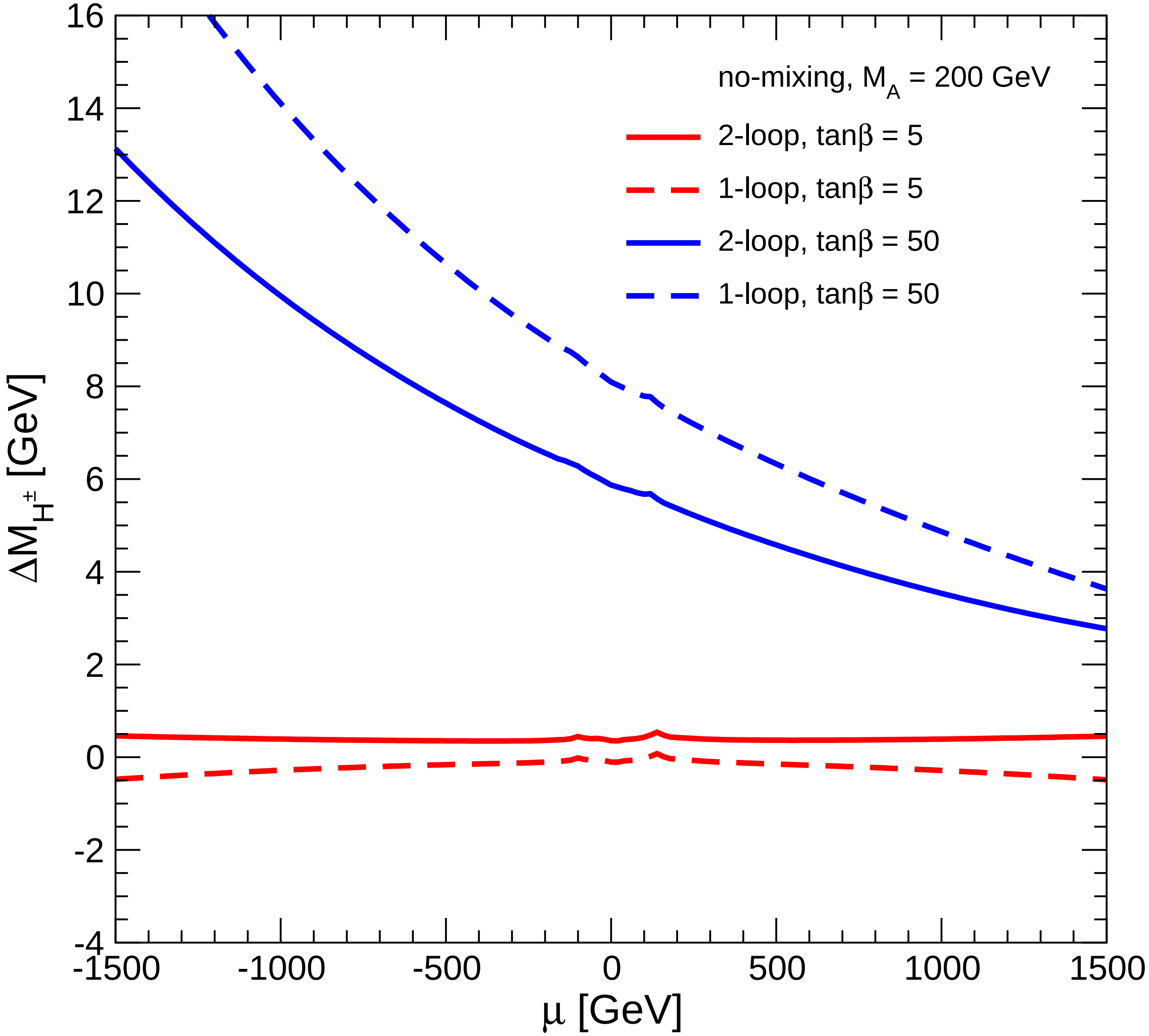
$\overline{m}_b$ important

Δ_b important

non-$t/\tilde{t}/b/\tilde{b}$
$\sim \log(M_{\text{SUSY}}/M_W)$
relevant

non-sfermion
corrections small

2-loop, μ varied:



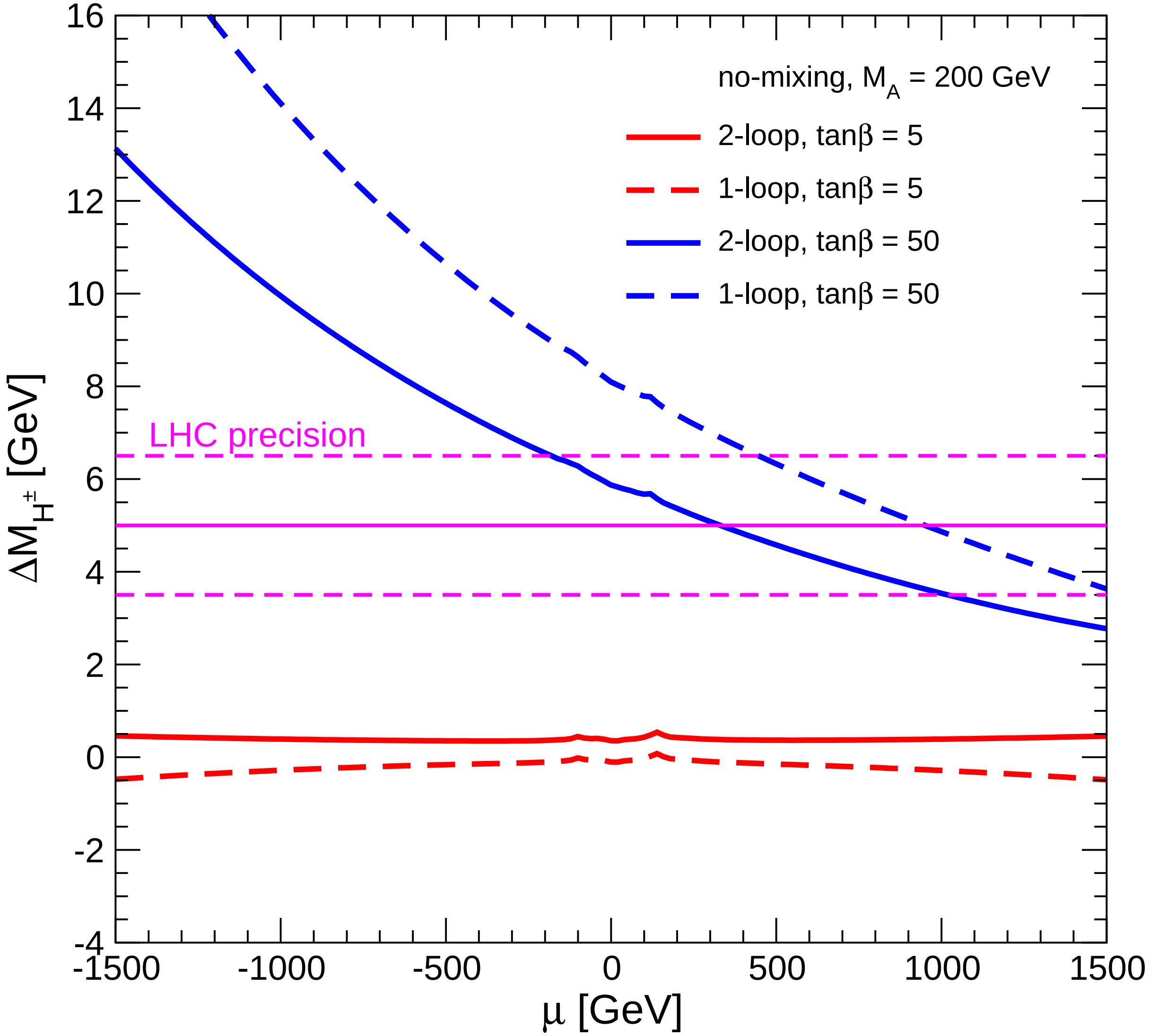
negative μ:

$\Delta M_{H^\pm} = 2 - 5$ GeV

positive μ:

$\Delta M_{H^\pm} = 0.5 - 2$ GeV

2-loop, μ varied:



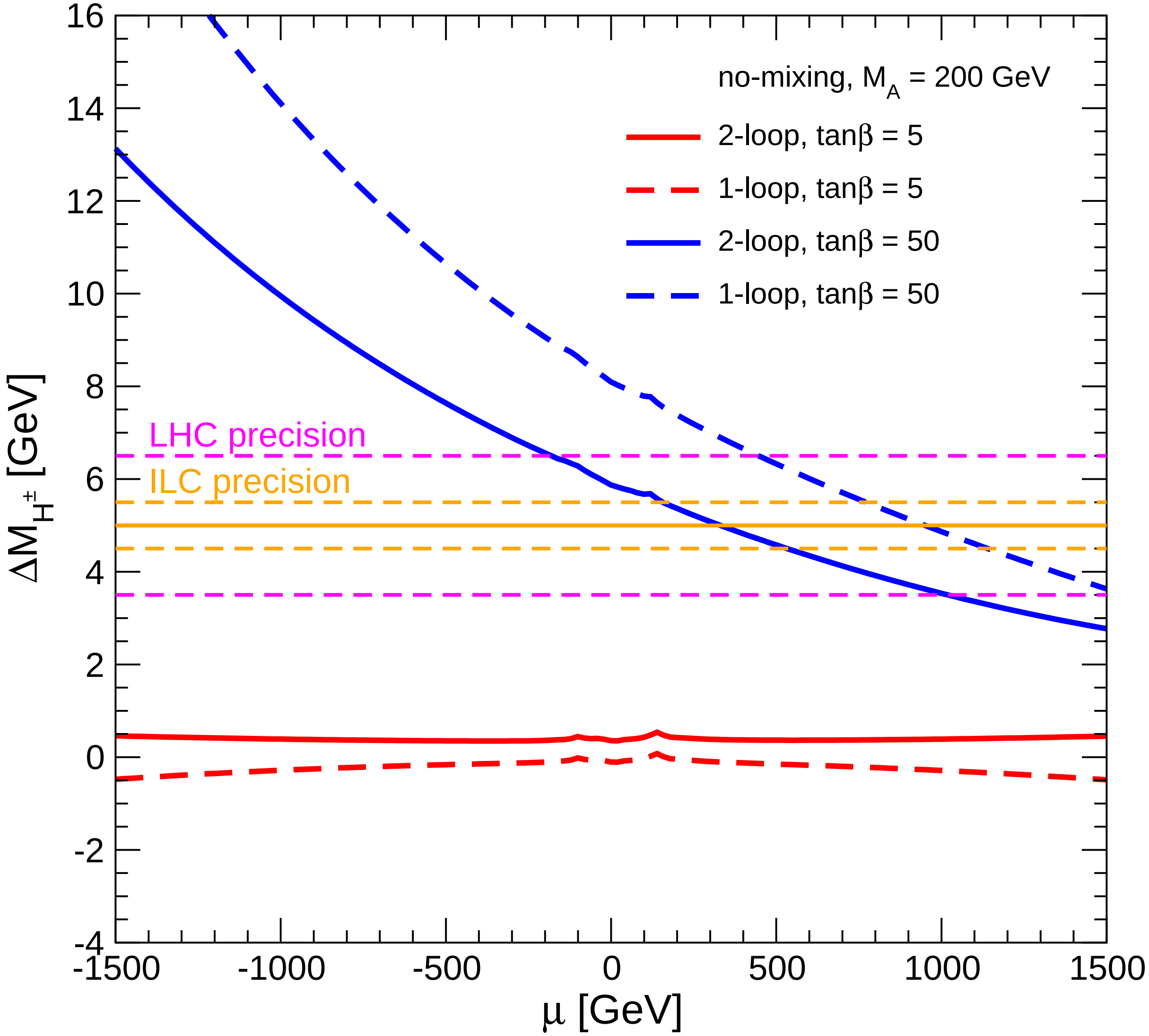
negative μ:

$\Delta M_{H^\pm} = 2 - 5$ GeV

positive μ:

$\Delta M_{H^\pm} = 0.5 - 2$ GeV

2-loop, μ varied:



negative μ:

$\Delta M_{H^\pm} = 2 - 5$ GeV

positive μ:

$\Delta M_{H^\pm} = 0.5 - 2$ GeV

4. Conclusinos (concentrate on MSSM)

- Charged MSSM Higgs boson:

  mass and couplings predicted in terms of other model parameters
  $\Rightarrow$ test of the model, parameter determination
  $\Rightarrow$ needed for reliable prediction of phenomenology

- Many codes exist for RGEs, masses, decays, production XS, event generators, indirect constraints

- Main mass/decay codes: FeynHiggs, Hdecay, CPSuperH
  – some differences in mass calculations
  – some differences in decays and other features

- Higher-order corrections to $M_{H^\pm}$:
  – 1L: all sectors relevant $\Rightarrow$ full 1L necessary
  Δ_b corrections crucial
  – 2L $\mathcal{O}(\alpha_t\alpha_s)$: $\Delta M_{H^\pm} = 0.5 - 5$ GeV
  important for LHC/ILC precision


MSSM Higgs Physics at the LHC
Theory meets Experiment
in Santander (Spain)
07.-10. October 2008
contact: Sven.Heinemeyer@cern.ch
http://www.ifca.unican.es/MHPaL
IFCA
Instituto de Física de Cantabria
CSIC
UC
UNIVERSIDAD DE CANTABRIA