New Higher-Order Corrections
in the MSSM Higgs Sector
with Real and Complex Parameters

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Sondershausen, 04/2008

1. The Grand Scheme

2. Two-loop corrections to the charged Higgs boson mass in the rMSSM

3. Decay into cMSSM Higgs bosons

4. Conclusions

1. The Grand Scheme

The LHC is coming . . .
first collisions by the end of this year?

The ILC is still coming . . .
. . . a bit later than anticipated

⇒ New Physics is certainly around the corner

⇒ Time to get ready

The big question:

Which Lagrangian describes the world?

My guess:

It is a supersymmetric one

$\Rightarrow$ concentrate on the MSSM from now on

(other people $\Rightarrow$ other guesses $\Rightarrow$ other priorities . . .)

In any case:

$\Rightarrow$ we have to measure as many observables as possible

– masses
– branching ratios
– angular distributions
– cross sections
– . . .

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In any case:

$\Rightarrow$ we have to measure as many observables as possible

- masses
- branching ratios
- angular distributions
- cross sections
- . . .

$\Rightarrow$ compare with theory calculations at the same level of accuracy

The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles

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

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

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

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

Enlarged Higgs sector: Two Higgs doublets $\Leftarrow$ focus here!

Problem in the MSSM: many scales

Problem in the MSSM: complex phases

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)

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

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)

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

Where are we? (a selection!)

1. Neutral Higgs boson masses
   - $\mathcal{O}(\alpha_t\alpha_s)$ in the cMSSM *[S.H., W. Hollik, H. Rzehak, G. Weiglein '07]*
   - $\mathcal{O}\left(\alpha_t\alpha_s^2\right)$, $\mathcal{O}\left(\alpha_t^2\alpha_s\right)$, rMSSM *[S. Martin '07]*
   - $\mathcal{O}\left(\alpha_t\alpha_s^2\right)$, rMSSM (incl. fin. terms) *[Harlander, Kant, Mihaila, Steinhauser '08]*
2. Charged Higgs mass
   - full 1-loop *[M. Frank, T. Hahn, S.H., W. Hollik, H. Rzehak, G. Weiglein '06]*
3. Production cross sections at the LHC
   - $gg \to h$ at 2-loop *[C. Anastasiou et al. '08][M. Mühlleitner et al. '08][. . .]*
   - WBF at 1-loop *[M. Ciccolini et al. '07][W. Hollik et al. '08][. . .]*
   - $bb \to h$ *[S. Dittmaier et al. '06][S. Dawson et al. '06]*
   - Z-factors at 2-loop *[M. Frank, T. Hahn, S.H., W. Hollik, H. Rzehak, G. Weiglein '06]*
4. Higgs decays
   - full 1-loop *[. . .]*
   - Z-factors at 2-loop *[M. Frank, T. Hahn, S.H., W. Hollik, H. Rzehak, G. Weiglein '06]*
5. Decays to Higgs bosons
   - (partial) 1-loop, rMSSM *[. . .]*
   - tree-level, cMSSM *[A. Bartl et al. '03][. . .]*

What is missing? (a selection!)

1. Neutral Higgs boson masses
   - full 2-loop
   - more 3-loop
   - leading 4-loop

2. Charged Higgs boson mass
   - leading 2-loop

3. Higgs decays
   - full 1-loop in the cMSSM
   - leading 2-loop

4. Decays to Higgs bosons
   - full 1-loop in the rMSSM
   - full 1-loop in the cMSSM

$\Rightarrow$ provide corresponding codes

What is missing? (a selection!)

1. Neutral Higgs boson masses
   - full 2-loop
   - more 3-loop
   - leading 4-loop

2. Charged Higgs boson mass
   - leading 2-loop $\Leftarrow$ this talk

3. Higgs decays
   - full 1-loop in the cMSSM $\Leftarrow$ Georg's talk
   - leading 2-loop

4. Decays to Higgs bosons
   - full 1-loop in the rMSSM
   - full 1-loop in the cMSSM $\Leftarrow$ this talk, Georg's talk

$\Rightarrow$ provide corresponding codes: FeynHiggs $\Leftarrow$ Thomas' talk

Generic problems for SUSY loop calculations:

- SUSY has to be preserved in the calculation
- Many different mass scales
- Many more mass scales than free parameters
- Even more parameters: mixing angles, complex phases
- Renormalization is much more involved than in the SM
  - much less explored than in the SM
  - has to preserve/respect mass relations
  - depend on mass scales realized in Nature
  - sometimes no really good solution exist (e.g. $\tan\beta$)
  - many sectors enter at the same time

2. Two-loop corrections to the rMSSM charged Higgs boson mass

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

rMSSM: 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

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

One-loop:

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

with

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

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

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

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

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

Furthermore:

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

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

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

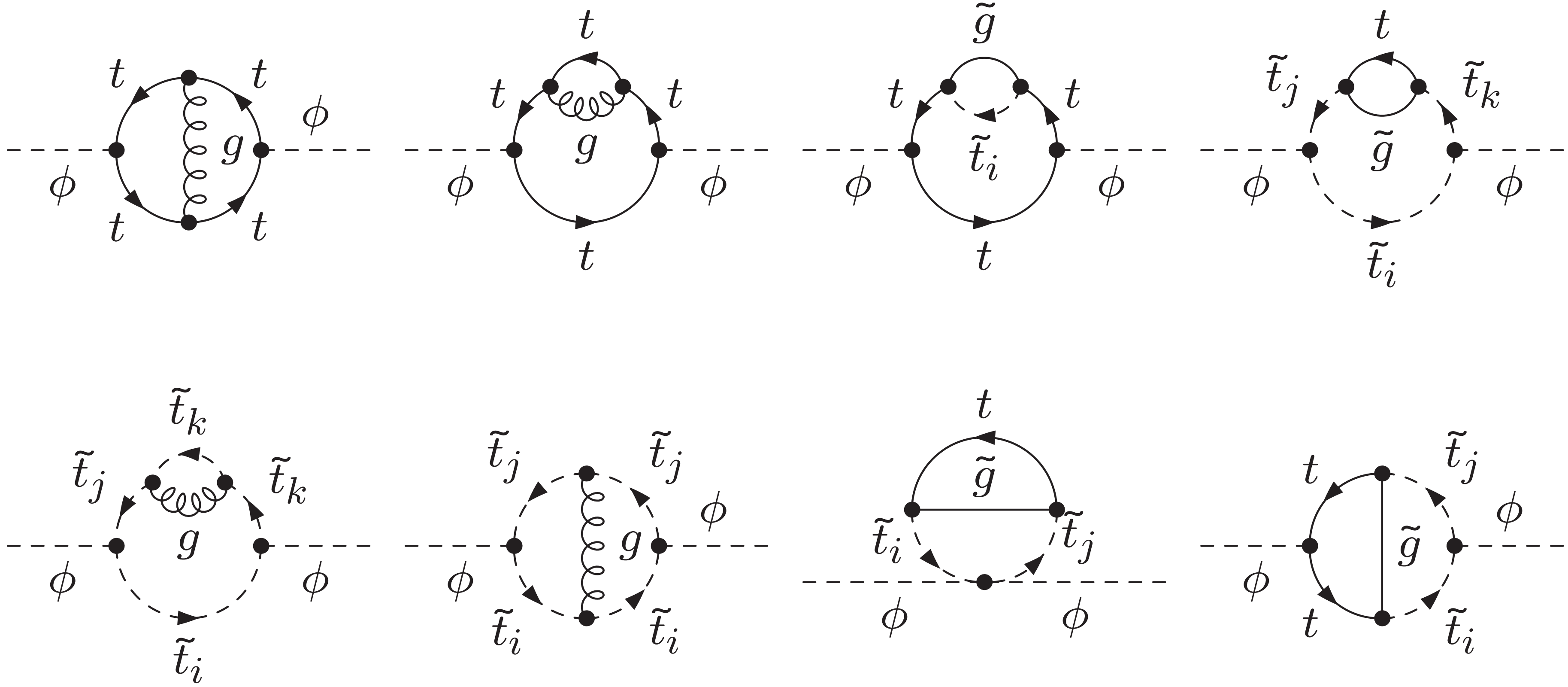
$$\delta Z^{(2)}_{H^+H^-} = 0$$

$$\delta M_W^{(2)2} = 0$$

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

Contributions to the 2-loop self-energy:

2-loop self-energy diagrams:



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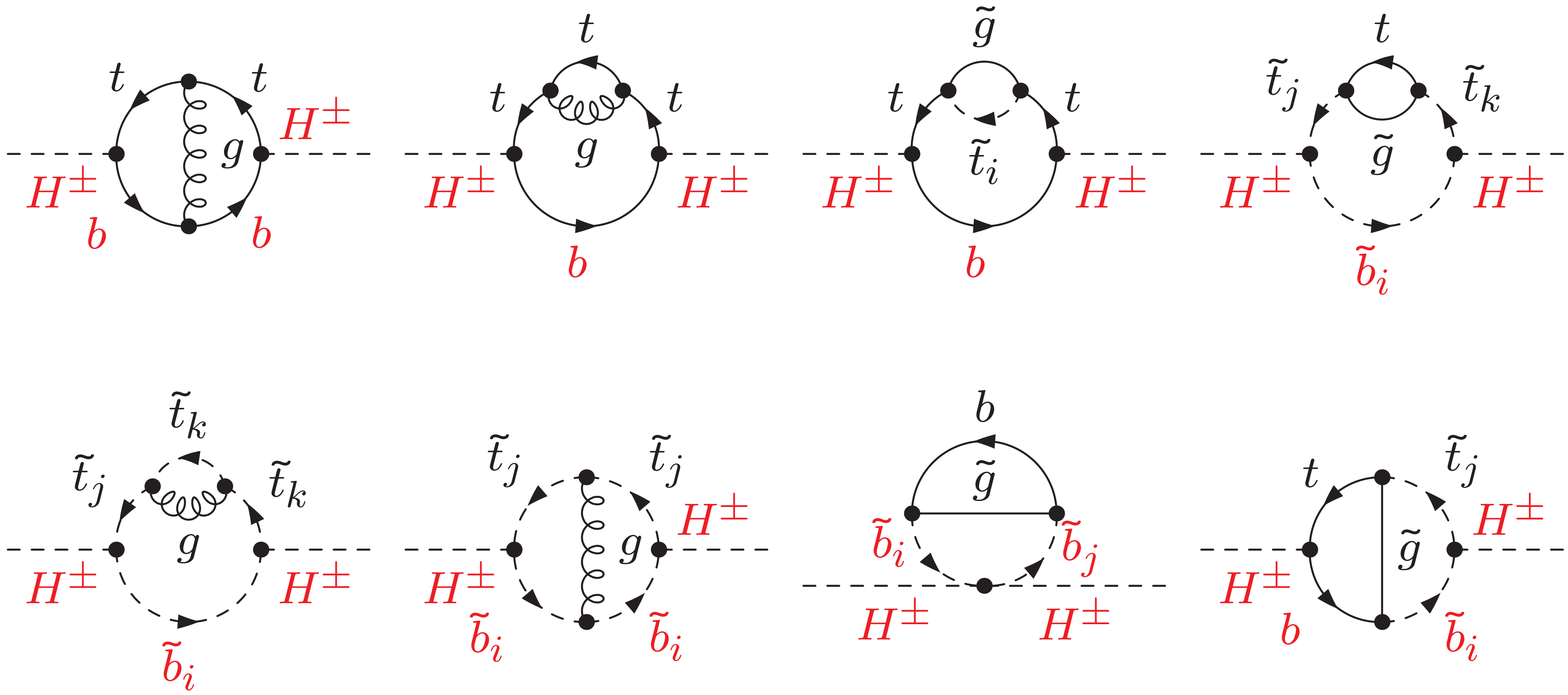
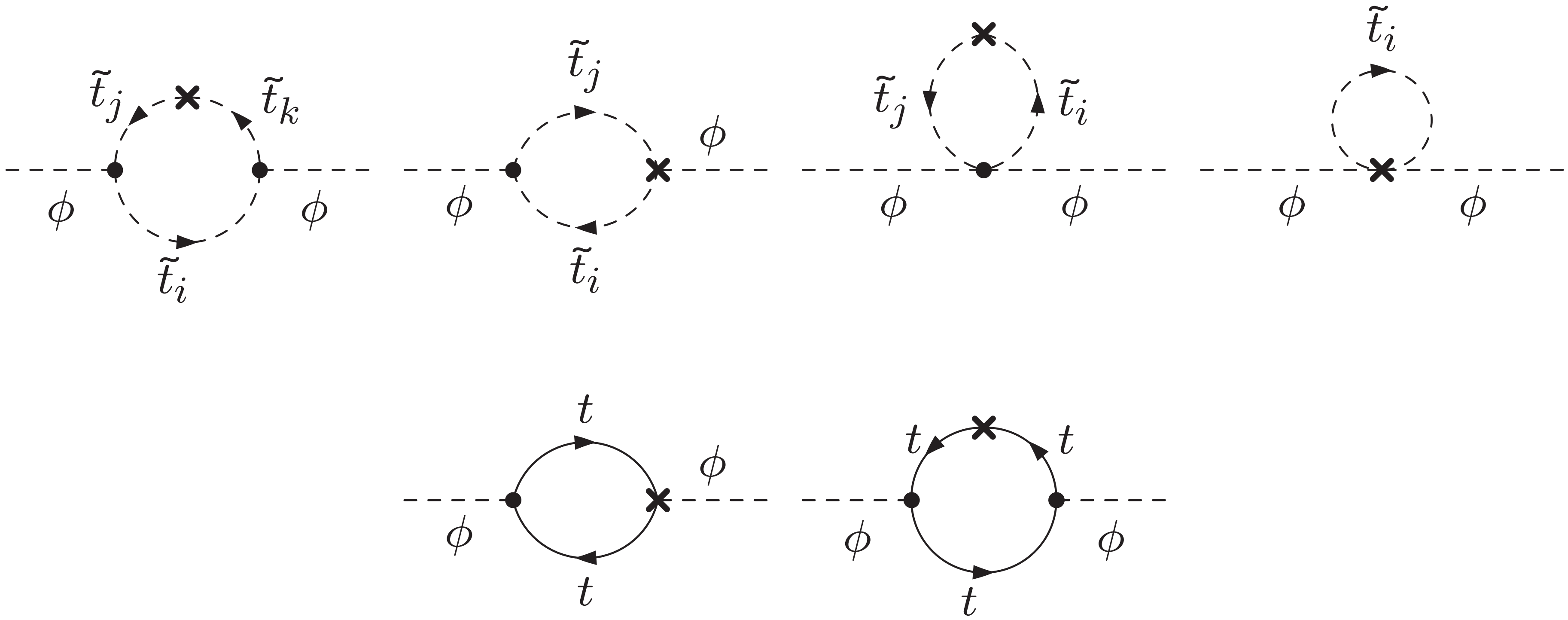


new: $H^\pm$ as external Higgs

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

Contributions to the 2-loop self-energy:

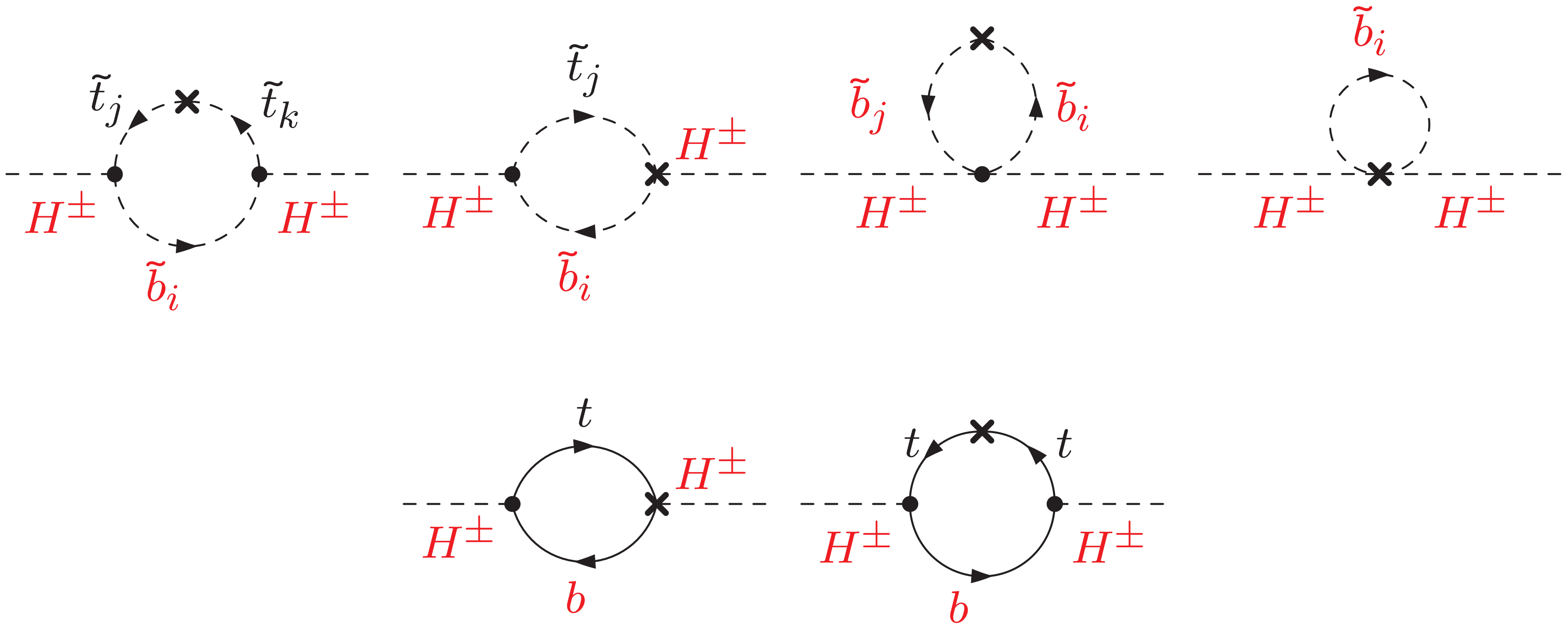
diagrams with counter term insertion:



$\phi = h, H, A$

Contributions to the 2-loop self-energy:

diagrams with counter term insertion:



new: $H^\pm$ as external Higgs

$\Rightarrow$ $b/\tilde{b}$ enter (even diagrams without $t/\tilde{t}$)

$\Rightarrow$ renormalization of the $\tilde{b}$ sector

$\mathcal{O}(\alpha_t \alpha_s)$ 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
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– only y_t^2 contributions

– $g, g' \to 0$

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$\Rightarrow$ 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

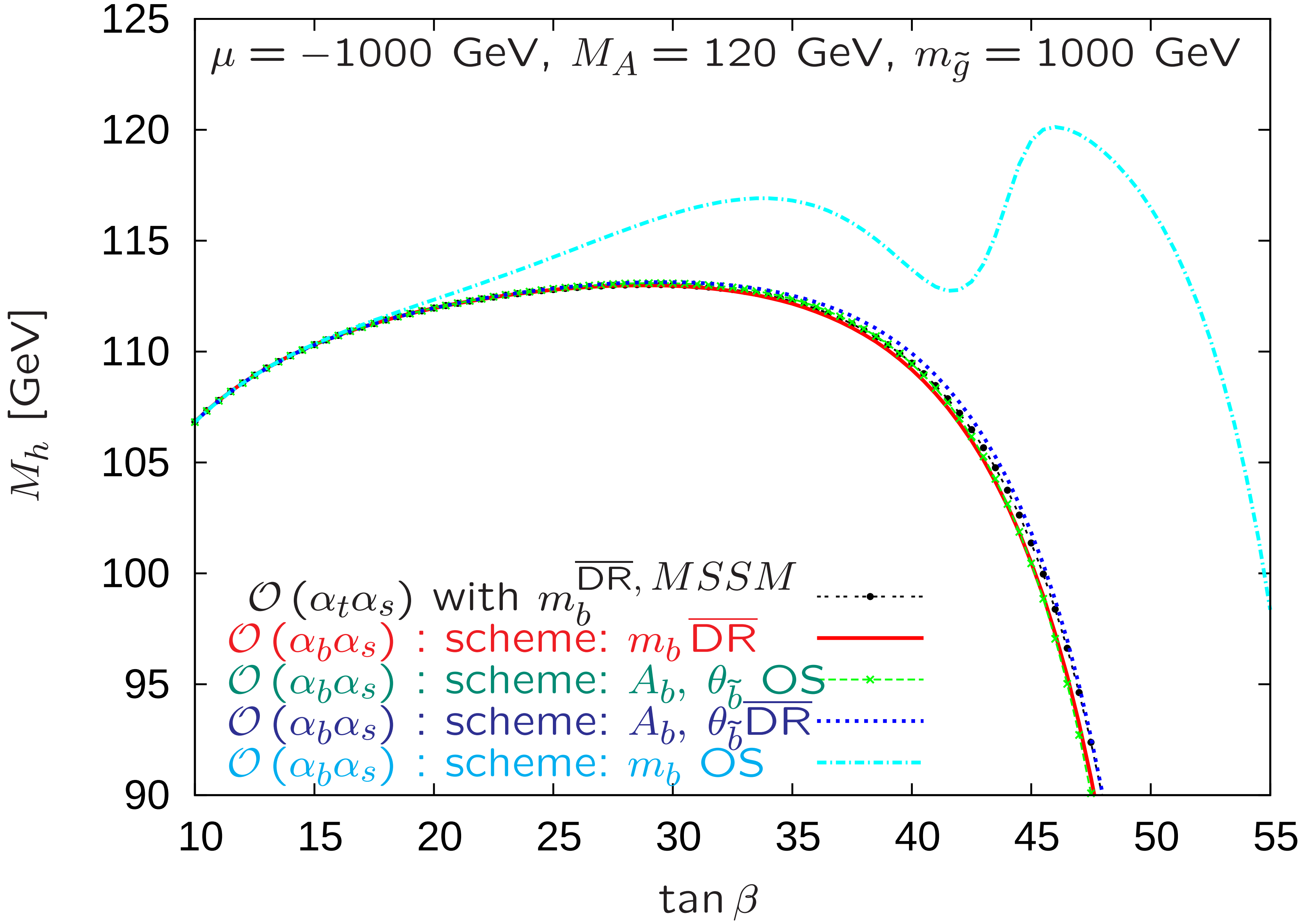
but not as many parameters ($SU(2)$)

$\Rightarrow$ 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^{max} scenario similar, slightly smaller corrections)

Experimental resolution:

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

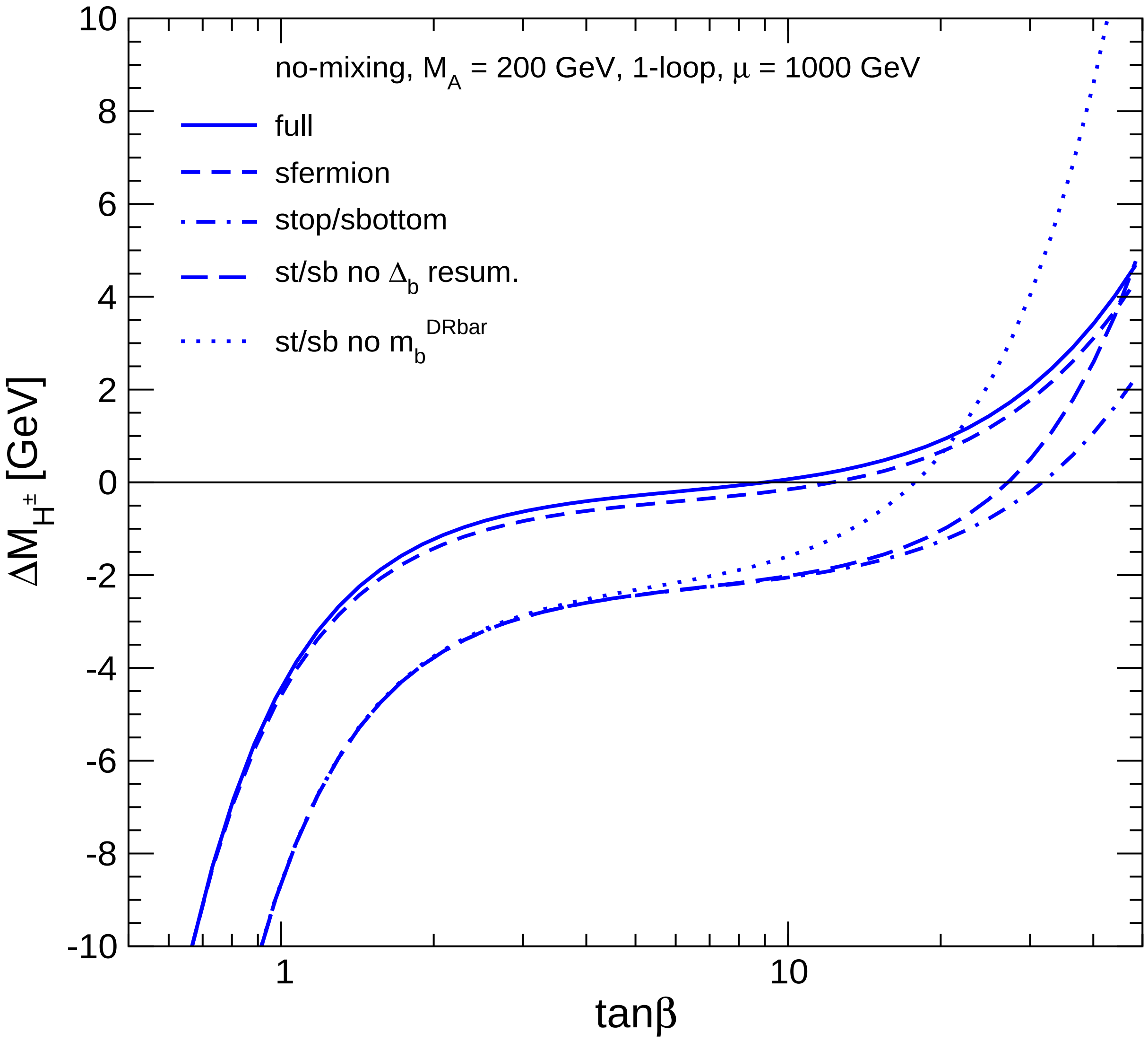
$$\text{LHC} : \Rightarrow \delta M_{H^\pm} \approx 1.5 \text{ GeV}$$

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

Higher masses:

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

1-loop, tan β varied:



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

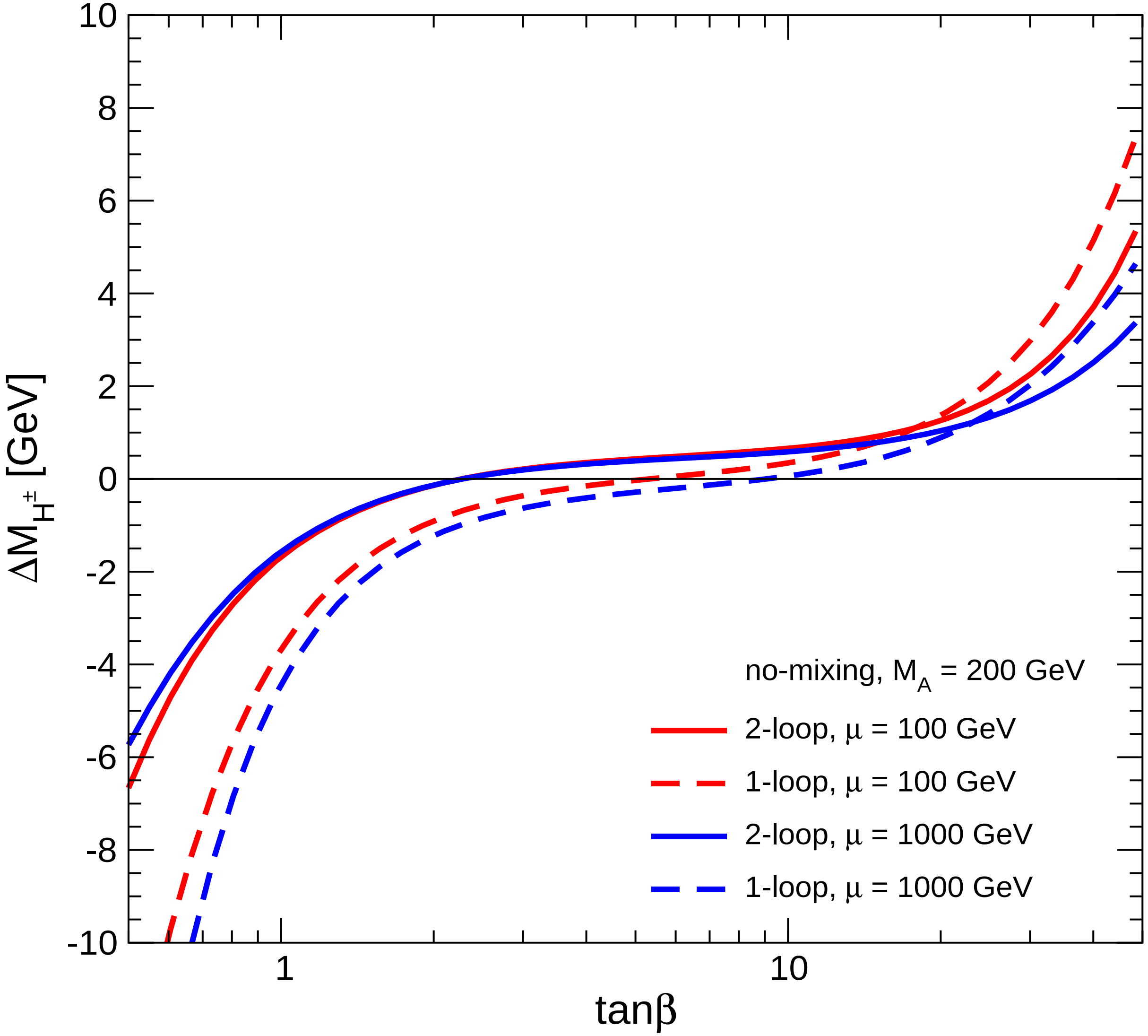
$\overline{m}_b$ important

Δ_b important

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

non-sfermion
corrections small

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



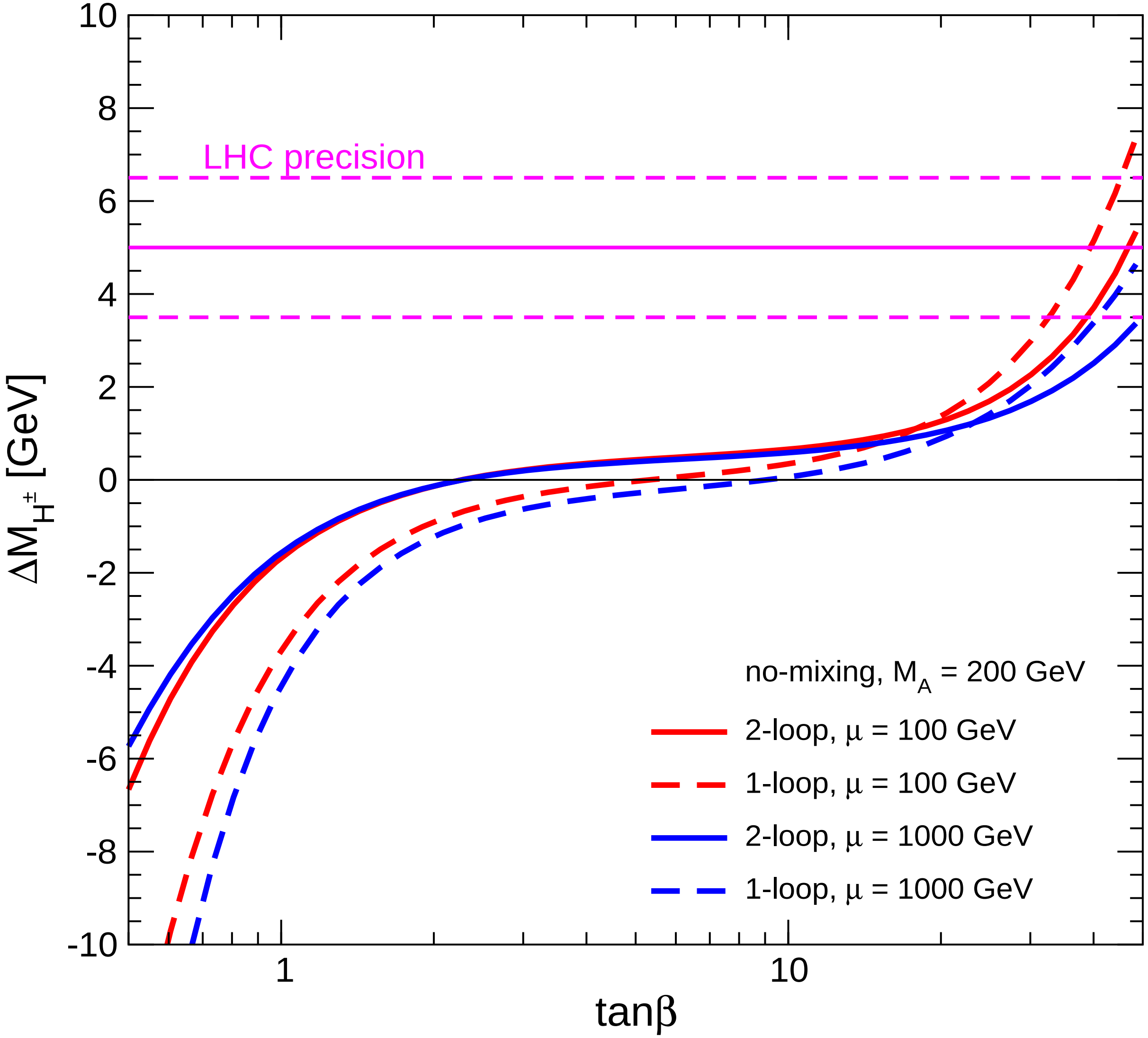
small $\tan\beta$:

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

large $\tan\beta$:

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

2-loop, tan β varied:



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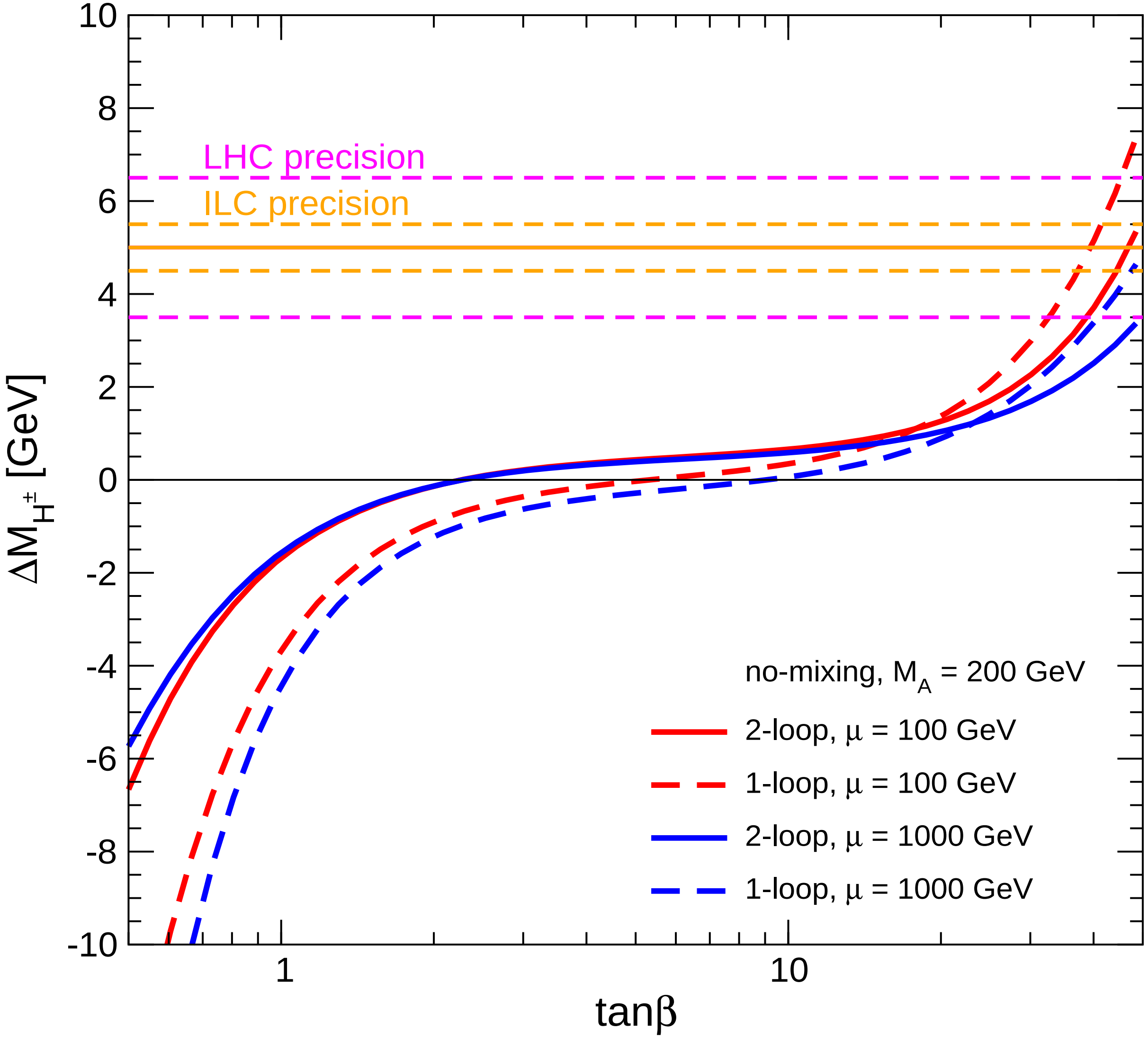

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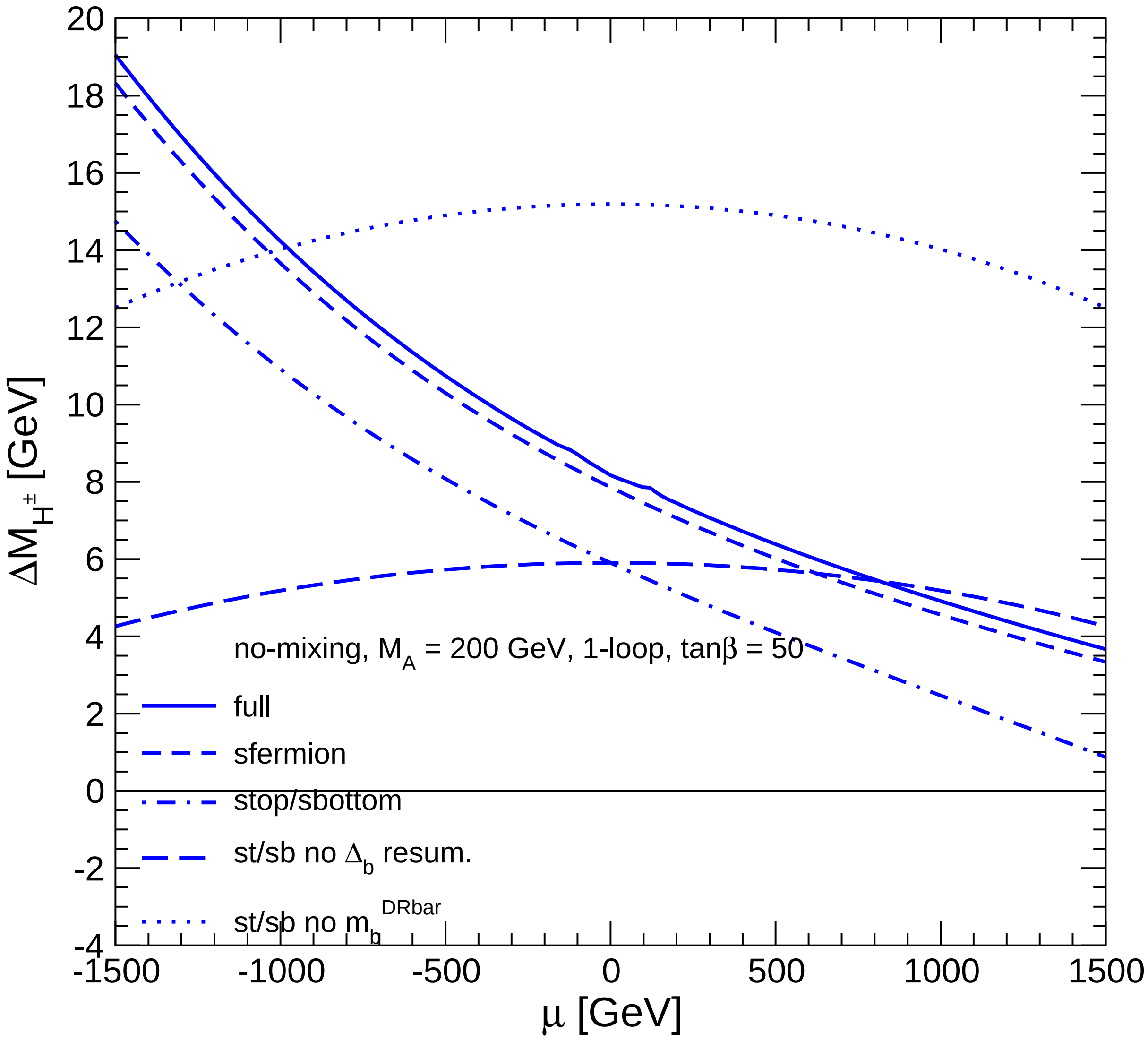
1-loop, μ varied:



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

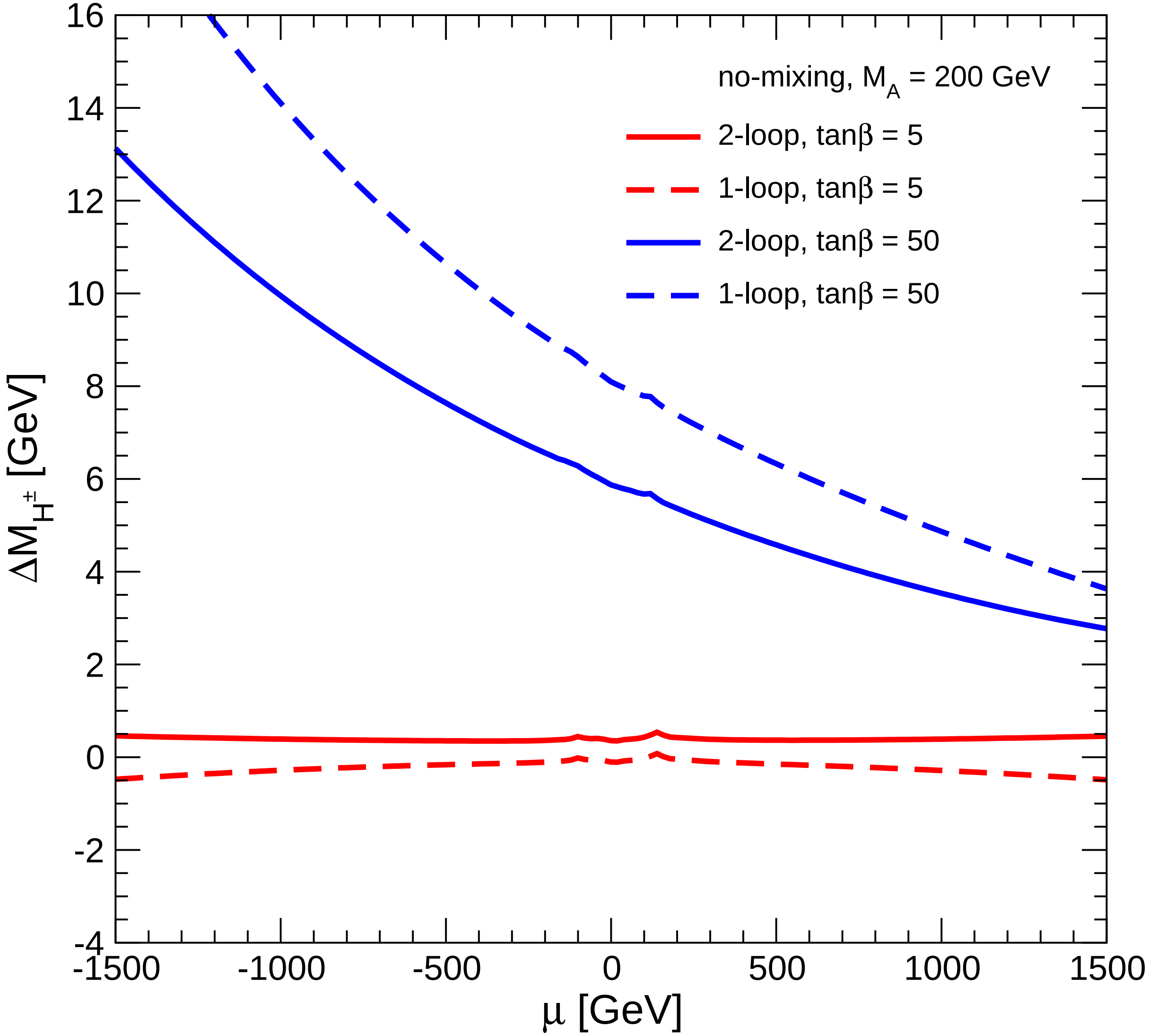
$\overline{m}_b$ important

Δ_b important

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

non-sfermion
corrections small

2-loop, μ varied:



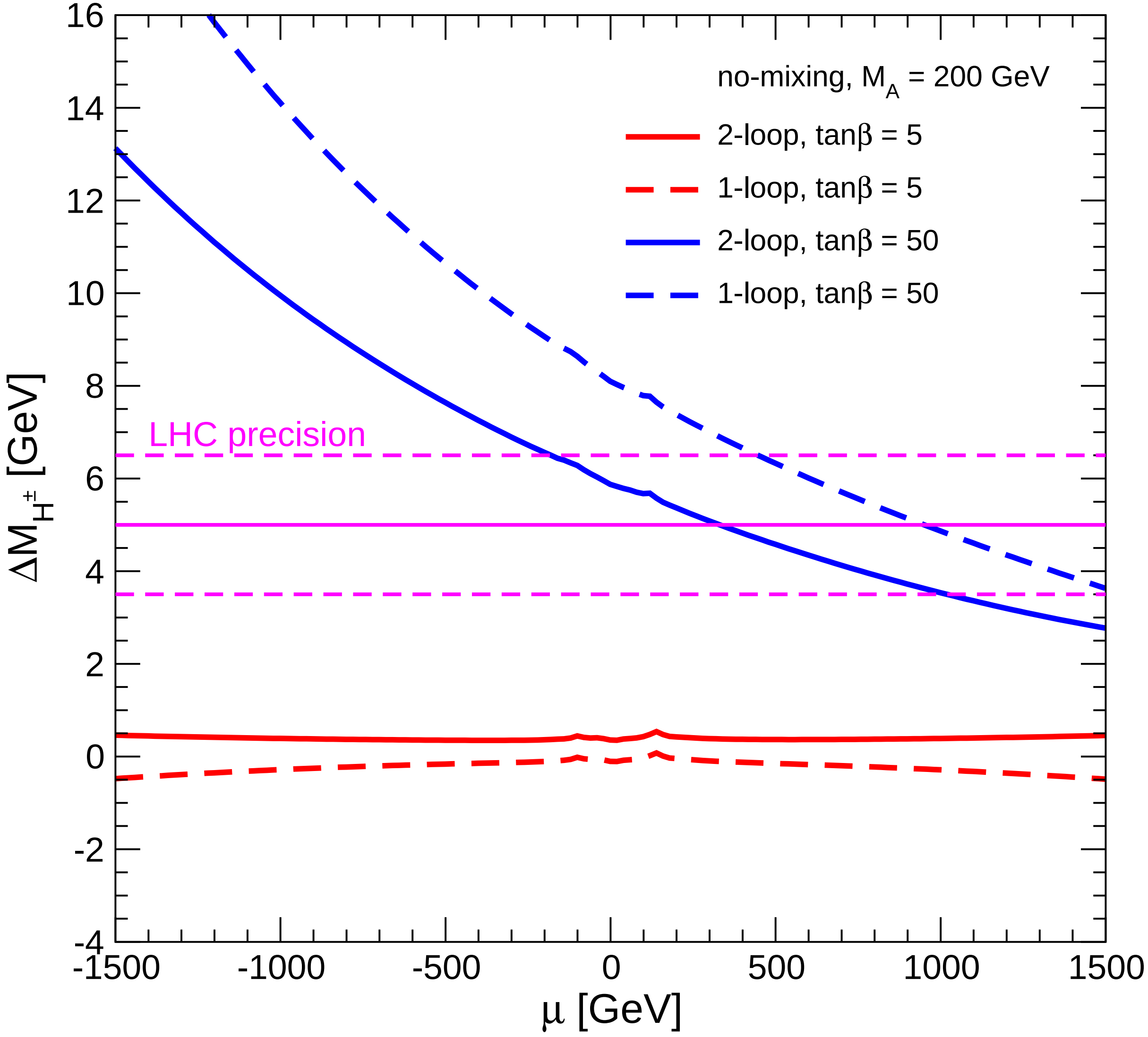
negative μ:

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

positive μ:

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

2-loop, μ varied:



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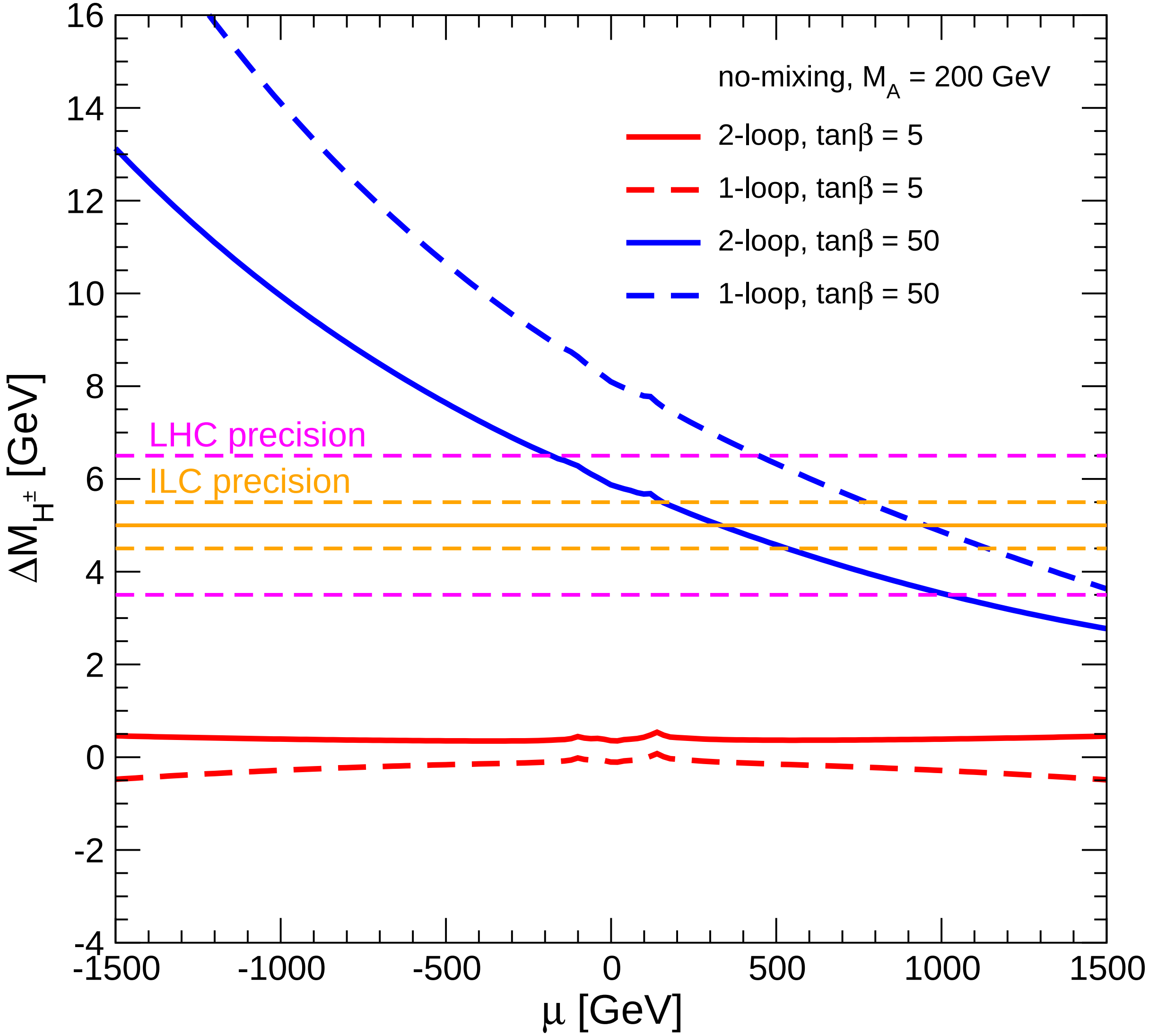

negative μ:

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

3. Decay into cMSSM Higgs bosons

[*S.H., H. Rzehak, C. Schappacher, G. Weiglein '08*]

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, $\arg(m_{12})$

The Higgs sector of the cMSSM at tree-level:

- phase of m_{12} :

  $m_{12} = 0$ and $\mu = 0 \Rightarrow$ additional $U(1)$ (PQ) symmetry

  reality: $m_{12} \neq 0$, $\mu \neq 0$

  $\Rightarrow$ perform PQ transformation with $\phi_{\rm PQ}$

$$\begin{aligned} m_{12}^{2\prime} &= |m_{12}^2| e^{i(\phi_{m_{12}} - \phi_{\rm PQ})} \\ \mu' &= |\mu| e^{i(\phi_\mu - \phi_{\rm PQ})} \end{aligned}$$

  $\Rightarrow$ m_{12} can always be chosen real

- phase of H_2: ξ :

  mixing between $\mathcal{CP}$-even and $\mathcal{CP}$-odd states:

$$\mathcal{M}_{\mathcal{CP}-\text{even},\mathcal{CP}-\text{odd}} = \begin{pmatrix} 0 & m_{12}^2 \sin\xi \\ -m_{12}^2 \sin\xi & 0 \end{pmatrix}$$

  Tadpoles have to vanish: $T_A^{\rm tree} \propto \sin\xi \, m_{12}^2 \stackrel{!}{=} 0$
  $\Rightarrow \xi = 0 \Rightarrow$ no $\mathcal{CP}$V at tree-level

The Higgs sector of the cMSSM at the loop-level:

Complex parameters enter via loop corrections:

- μ : Higgsino mass parameter
- $A_{t,b,\tau}$: trilinear couplings $\Rightarrow X_{t,b,\tau} = A_{t,b,\tau} - \mu^*\{\cot\beta, \tan\beta\}$ complex
- $M_{1,2}$: gaugino mass parameter (one phase can be eliminated)
- M_3 : gluino mass parameter

$\Rightarrow$ can induce $\mathcal{CP}$-violating effects

Result:

$$(A, H, h) \rightarrow (h_3, h_2, h_1)$$

with

$$m_{h_3} > m_{h_2} > m_{h_1}$$

$\Rightarrow$ strong changes in Higgs couplings to SM gauge bosons and fermions

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

$$m^2_{\tilde{t}_{1,2}} = m_t^2 + \frac{1}{2}\left(M^2_{\tilde{t}_L} + M^2_{\tilde{t}_R} \mp \sqrt{(M^2_{\tilde{t}_L} - M^2_{\tilde{t}_R})^2 + 4m_t^2|X_t|^2}\right)$$

$\Rightarrow$ independent of ϕ_{X_t}

but $\theta_{\tilde{t}}$ is now complex

$SU(2)$ relation $\Rightarrow M_{\tilde{t}_L} = M_{\tilde{b}_L}$ $\Rightarrow$ relation between $m_{\tilde{t}_1}, m_{\tilde{t}_2}, \theta_{\tilde{t}}, m_{\tilde{b}_1}, m_{\tilde{b}_2}, \theta_{\tilde{b}}$

The phases also enter in the tree-level couplings:

$$\tilde{t}_i - \tilde{t}_j - \phi \;:\; \text{complex } A_t, \mu$$
$$\tilde{b}_i - \tilde{b}_j - \phi \;:\; \text{complex } A_b, \mu$$
$$\tilde{\tau}_i - \tilde{\tau}_j - \phi \;:\; \text{complex } A_\tau, \mu$$
$$\tilde{t}_i - \tilde{b}_j - H^\pm \;:\; \text{complex } A_t, A_b, \mu$$

$\Rightarrow$ good channels to learn about complex phases

Existing analyses have been restricted to tree-level so far

[*A. Bartl et al. '03 - '06*]

$\Rightarrow$ full one-loop analysis needed

⇒ full one-loop analysis needed

⇒ full one-loop calculation including

– complex phases

– hard QED and QCD radiation

Reliable prediction for BR($\tilde{t}_2 \to \tilde{t}_1 \phi$), $\phi = h, H, A$, requires:

one-loop calculation of:

$\Gamma(\tilde{t}_2 \to \tilde{t}_1\, \phi)$

$\Gamma(\tilde{t}_2 \to \tilde{t}_1\, Z)$

$\Gamma(\tilde{t}_2 \to t\, \tilde{g}/\tilde{\chi}^0)$ ⇒ complex gluino/neutralino sector enters

$\Gamma(\tilde{t}_2 \to \tilde{b}_i\, H^\pm/W^\pm)$ ⇒ complex sbottom sector enters

$\Gamma(\tilde{t}_2 \to b\tilde{\chi}^\pm)$ ⇒ complex chargino sector enters

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$\Gamma(\tilde{t}_2 \to \tilde{b}_i\, H^\pm/W^\pm)$ ⇒ complex sbottom sector enters

$\Gamma(\tilde{t}_2 \to b\tilde{\chi}^\pm)$ ⇒ complex chargino sector enters

⇒ All sectors of the complex MSSM enter

⇒ combination of various tools and analyses:

– FeynArts/FormCalc for one-loop diagrams *[T. Hahn et al.]*

– MSSM counter term model file *[T. Fritzsche et al. '07]*

– LoopTools for numerical evaluation *[T. Hahn]*

– Renormalization: as usual the biggest issue

  * complex Higgs sector *[M. Frank et al. '06]*
  * complex stop/sbottom sector *[H. Rzehak et al. '04, '07]*
  * complex chargino/neutralino sector
  * complex gluino sector

People used to choose the most convenient renormalization for their problem/sector
⇒ no longer possible

Complex renormalization:

- 1) A_t complex

  $\Rightarrow$ renormalization of $|A_t|$ and ϕ_{A_t}: $\delta A_t = e^{i\,\phi_{A_t}} \delta|A_t| \; + \; i\, A_t\, \delta\phi_{A_t}$

  $\Rightarrow$ $\overline{\text{DR}}$ renormalization

- 2) alternatively $\theta_{\tilde{t}}$ complex

  $\Rightarrow$ renormalization of $|\theta_{\tilde{t}}|$ and $\phi_{\tilde{t}}$:

  $\Rightarrow$ On-shell renormalization via

$$\widetilde{\text{Re}}\hat{\Sigma}_{\tilde{t}_{12}}(m^2_{\tilde{t}_1}) + \widetilde{\text{Re}}\hat{\Sigma}_{\tilde{t}_{12}}(m^2_{\tilde{t}_2}) \stackrel{!}{=} 0$$

$$\Rightarrow \widetilde{\text{Re}}\Sigma_{\tilde{t}_{12}}(m^2_{\tilde{t}_1}) + \widetilde{\text{Re}}\Sigma_{\tilde{t}_{12}}(m^2_{\tilde{t}_2}) = e^{i\phi_{\tilde{t}}}(m^2_{\tilde{t}_1} - m^2_{\tilde{t}_2}) \times (\delta\theta_{\tilde{t}} + i\, s_{\tilde{t}}\, c_{\tilde{t}}\, \delta\phi_{\tilde{t}})$$

  $\Rightarrow$ evaluate $\delta|A_t|$ and $\delta\phi_{A_t}$ as dependent parameters

- 3) A_b, $\theta_{\tilde{b}}$ complex

  $\rightarrow$ like for A_t, $\theta_{\tilde{t}}$

  Note: $\delta m^2_{\tilde{b}_1}$ cannot be fixed via on-shell condition anymore

  $\Rightarrow$ dependent parameter, enters δA_b, $\delta\phi_{A_b}$

- 4) M_1, M_2, μ complex

  $\Rightarrow$ On-shell conditions for $m_{\tilde{\chi}^\pm_1}$, $m_{\tilde{\chi}^\pm_2}$, $m_{\tilde{\chi}^0_1}$

Results:

Finite results for:

$$\Gamma(\tilde{t}_2 \to \tilde{t}_1\, \phi)$$
$$\Gamma(\tilde{t}_2 \to \tilde{t}_1\, Z)$$
$$\Gamma(\tilde{t}_2 \to t\, \tilde{g}/\tilde{\chi}^0)$$
$$\Gamma(\tilde{t}_2 \to \tilde{b}_i\, H^\pm/W^\pm)$$
$$\Gamma(\tilde{t}_2 \to b\, \tilde{\chi}^\pm)$$

$$\Gamma(\tilde{b}_2 \to \tilde{b}_1\, \phi)$$
$$\Gamma(\tilde{b}_2 \to \tilde{b}_1\, Z)$$
$$\Gamma(\phi_i \to \phi_j\, \phi_k)$$
$$\Gamma(\phi \to f\, \bar{f})$$
$$\Gamma(\phi \to \tilde{t}_i\, \tilde{t}_j)$$
$$\Gamma(\tilde{\chi}^0_i \to \tilde{\chi}^0_j\, \tilde{f}/\phi)$$

Still working on the fine-tuning of renormalization

$\Rightarrow$ no numerical results yet :-(

4. Conclusinos

- Main goal: measure the SUSY Lagrangian

  ⇒ measure as many observables as possible

  ⇒ calculate these observables at one-, two-, . . . loops

- Charged MSSM Higgs boson mass:

  full one-loop + leading $\mathcal{O}(\alpha_t\alpha_s)$ two-loop
  major complication: renormalization
  one-loop: 10 – 20 GeV
  two-loop: up to ∼ 5 GeV ⇒ relevant for LHC/ILC

- Decays to Higgs bosons

  full one-loop in the complex MSSM
  major complications: all sectors of the cMSSM enter
  renormalization of all the sectors
  → finite result for all relevant processes

- Everything will be implemented into FeynHiggs (www.feynhiggs.de)