The Charged Higgs Boson Mass in the MSSM: Meeting the ILC Precision

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1. Introduction/Motivation

2. Higher-order corrections to the charged Higgs boson mass

3. Numerical results

4. Conclusions

1. Introduction/Motivation

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)

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

In lowest order:

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

In lowest order:

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

$\Rightarrow$ higher-order corrections have to be taken into account!

ILC precision: $\Rightarrow$ situation not completely clear (to me)

1) *[Snowmass '05 Higgs report]*

$M_{H^\pm} \leq 300$ GeV ($\sqrt{s} = 800$ GeV)

$$e^+e^- \to H^+H^- \to (t\bar{b})(\bar{t}b)$$

$\Rightarrow \delta M_{H^\pm} \approx 4.5$ GeV

2) *[A. Ferrari, talk given at "$CH^\pm$arged 2006", Uppsala, Sweden]*

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

$$e^+e^- \to H^+H^- \to (\tau^+\bar{\nu}_\tau)(\tau^-\nu_\tau)$$

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

$\Rightarrow$ Studies needed(?) for

$$e^+e^- \to H^+H^- \to (\tau^+\bar{\nu}_\tau)(\tau^-\nu_\tau)$$

for all mass ranges!?

2. Higher-order corrections to the charged Higgs boson mass

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

output: neutral and charged Higgs masses, . . .

Tree-level:

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

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

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

with

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

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

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

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

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

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

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

Furthermore:

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

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

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

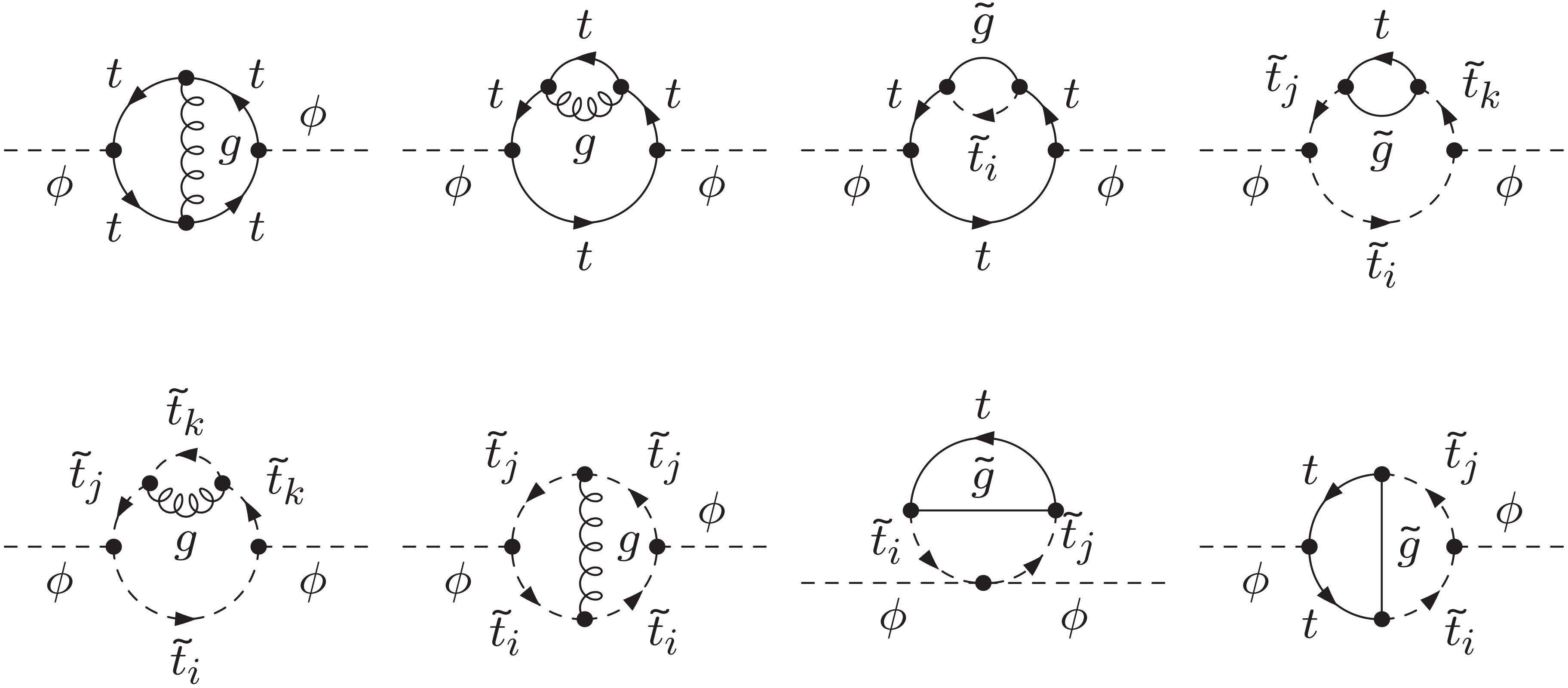
$$\delta Z^{(2)}_{H^+H^-} = 0$$

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

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

Contributions to the 2-loop self-energy:

2-loop self-energy diagrams:



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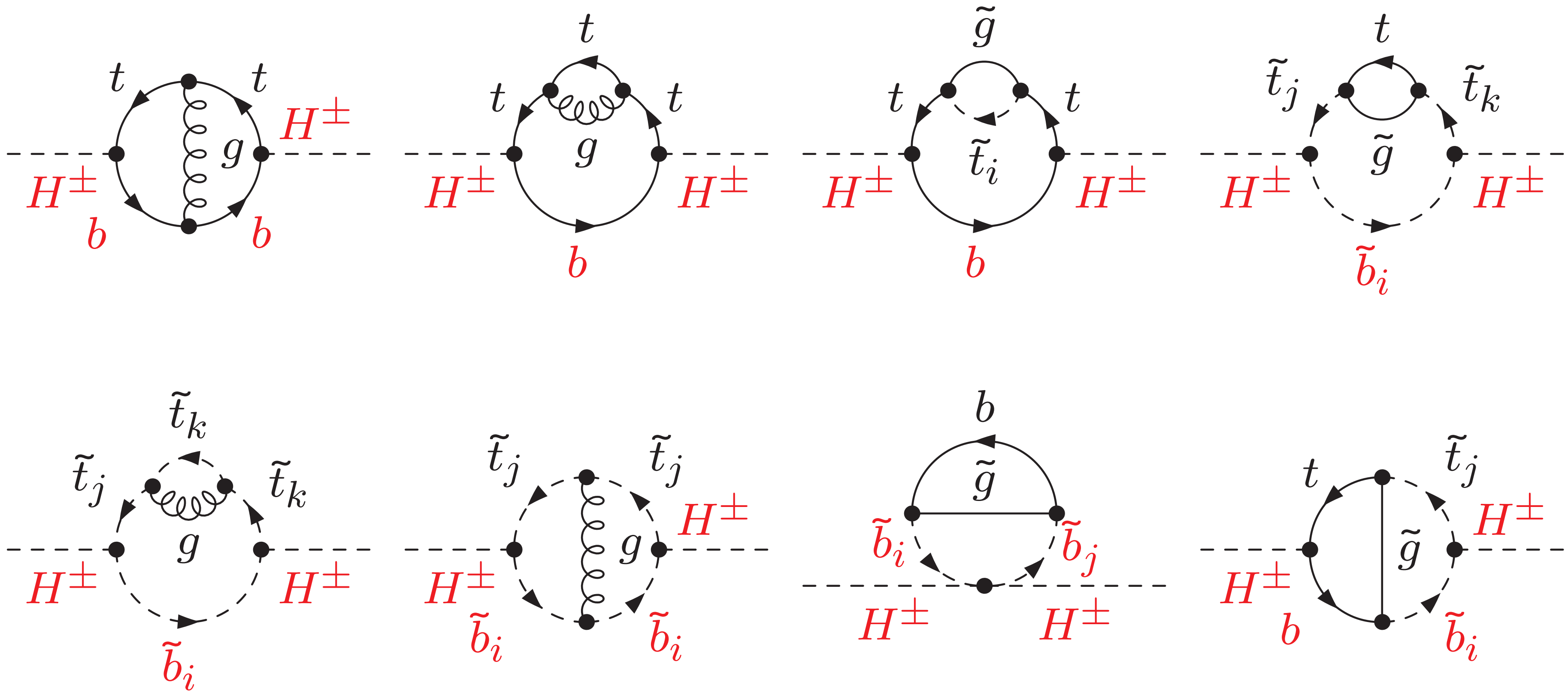
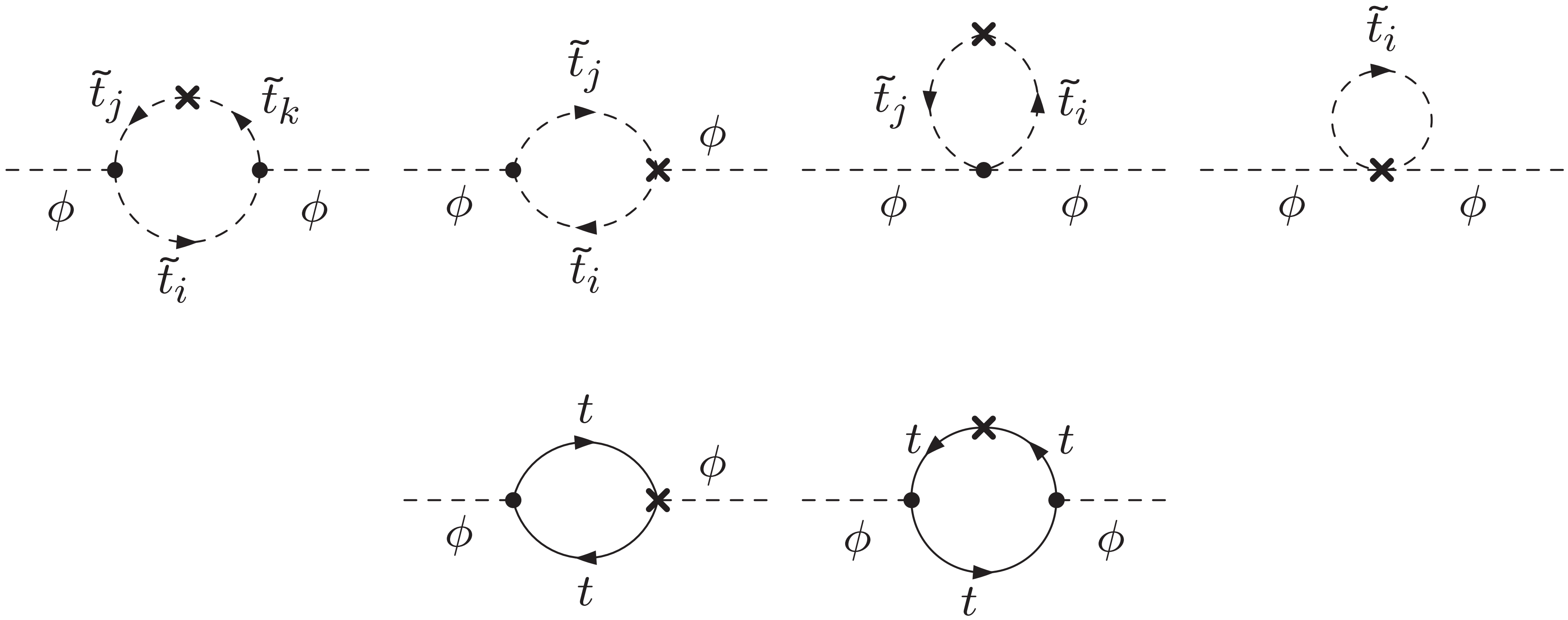


new: $H^{\pm}$ as external Higgs

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

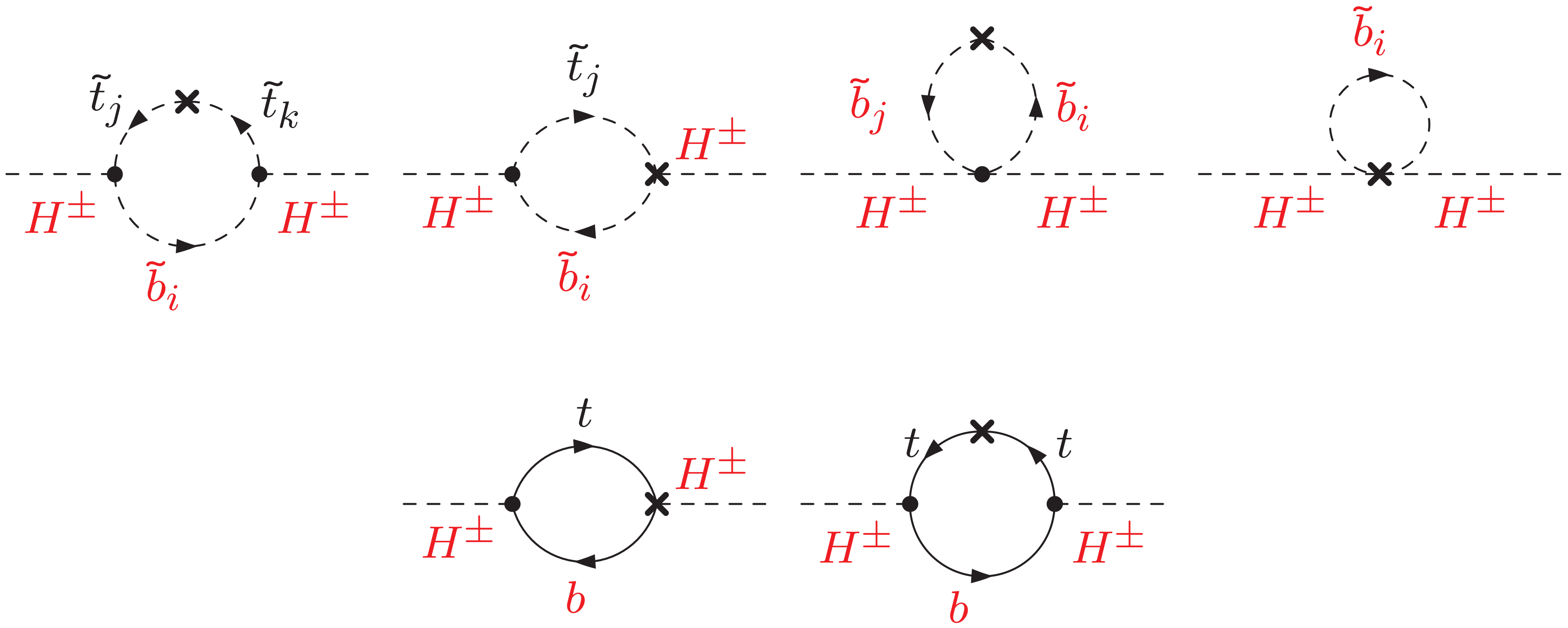
diagrams with counter term insertion:



$\phi = h, H, A$

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

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– $g, g' \to 0$

– 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

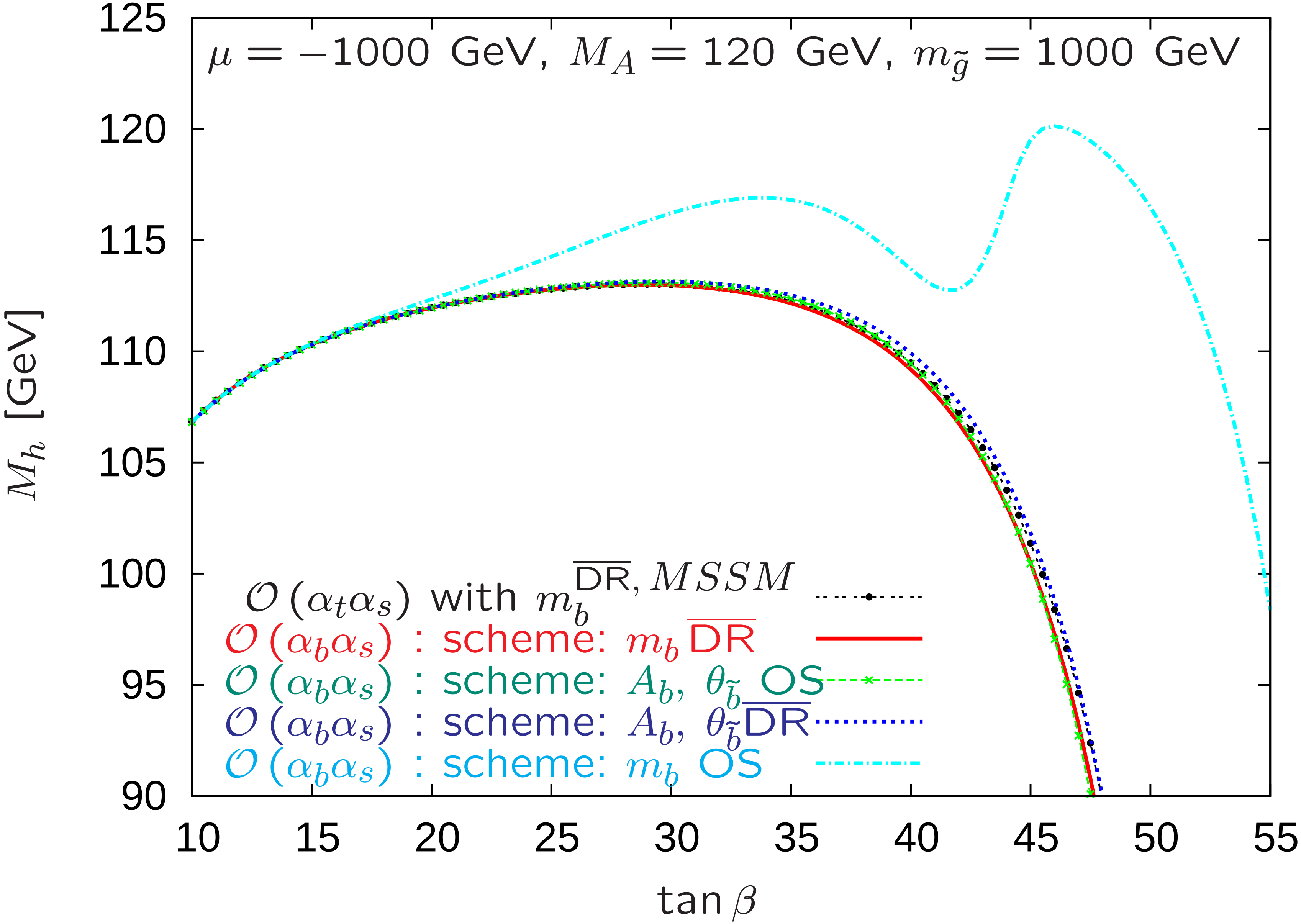
but not as many parameters ($SU(2)$)

$\Rightarrow$ 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]



3. Numerical results:

$\longrightarrow$ 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:

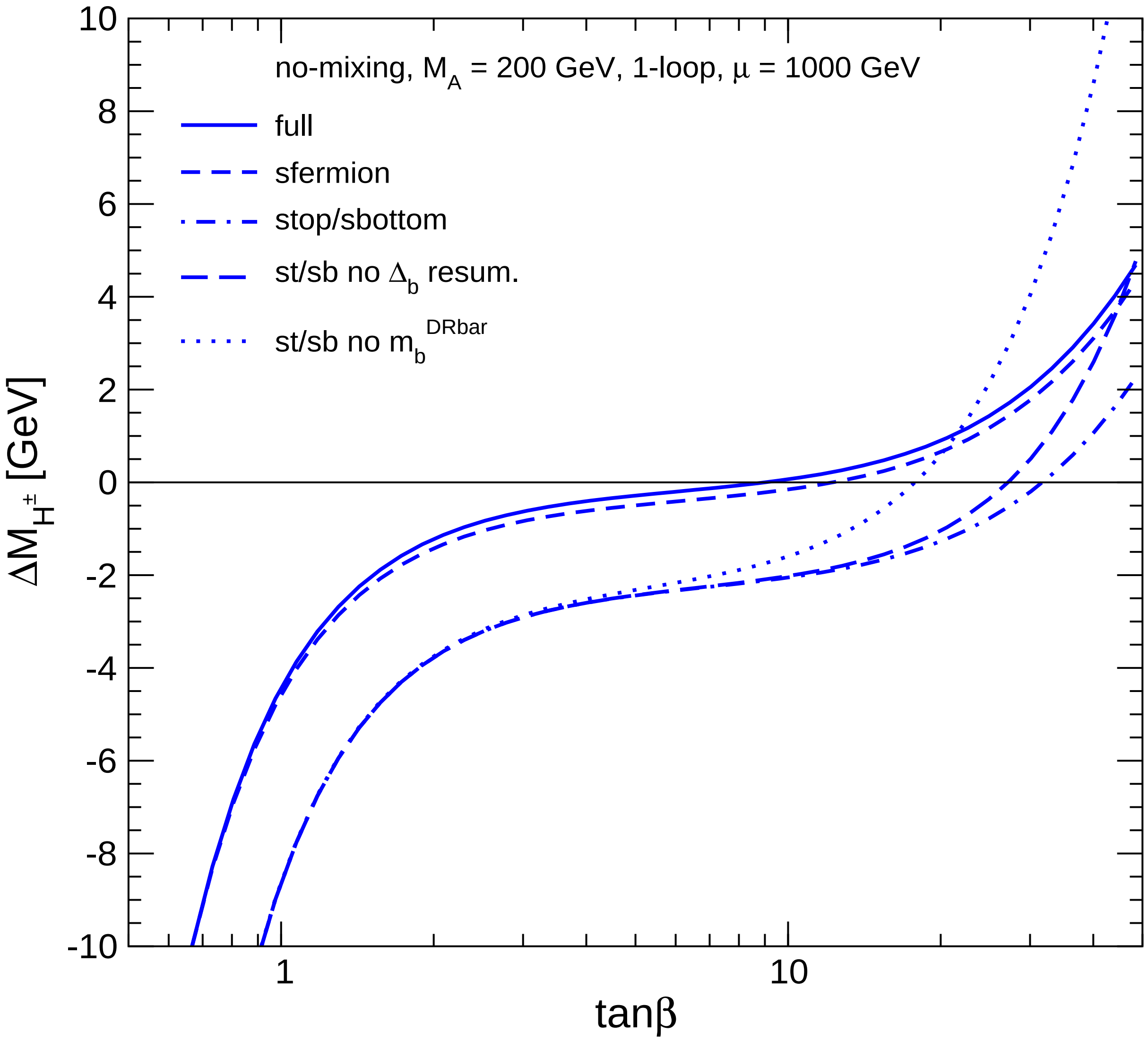
$$\text{LHC} : \Rightarrow \delta M_{H^\pm} \approx 1.5 \text{ GeV}$$

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

Higher masses:

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

1-loop, tan β varied:



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

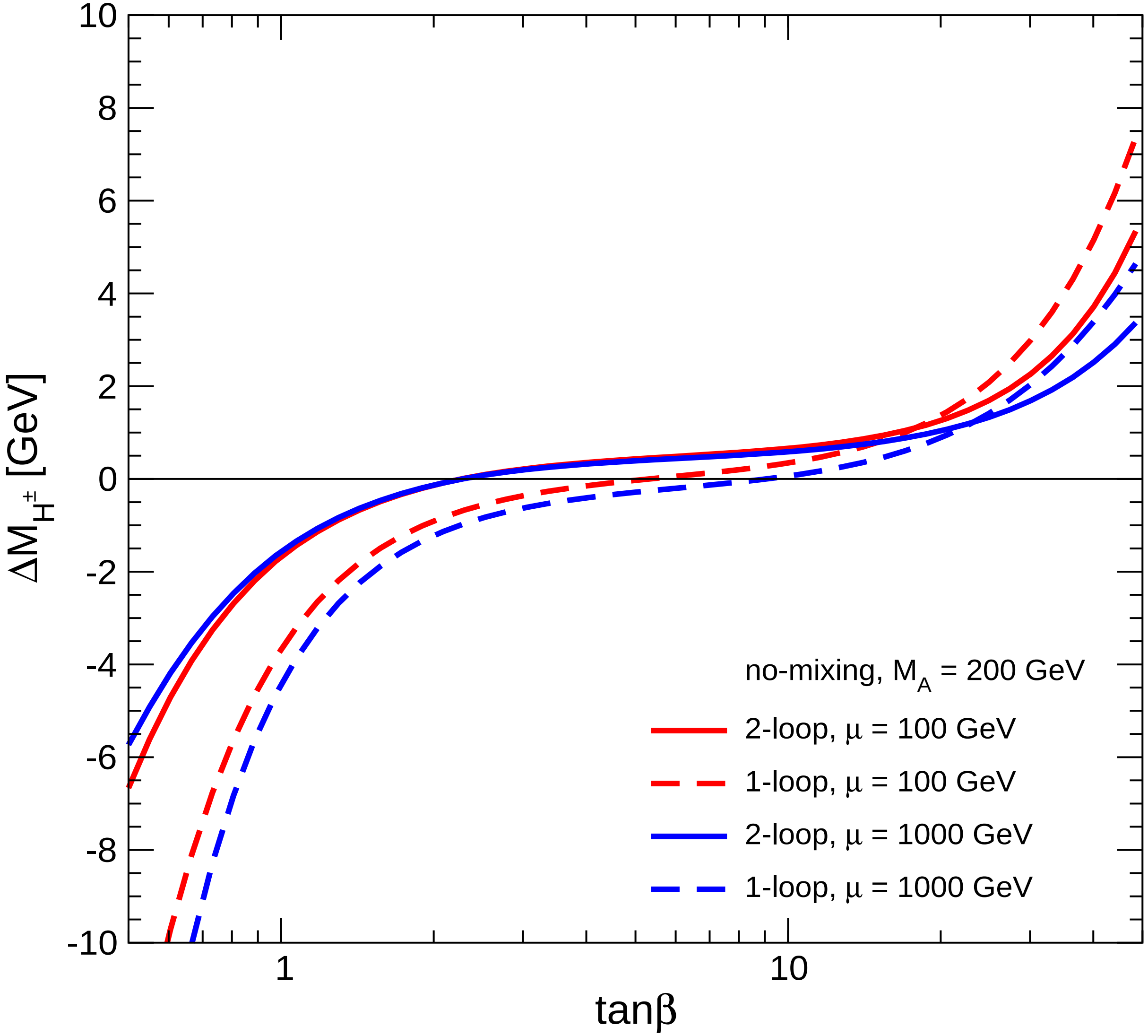
$\overline{m}_b$ important

Δ_b important

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

non-sfermion
corrections small

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



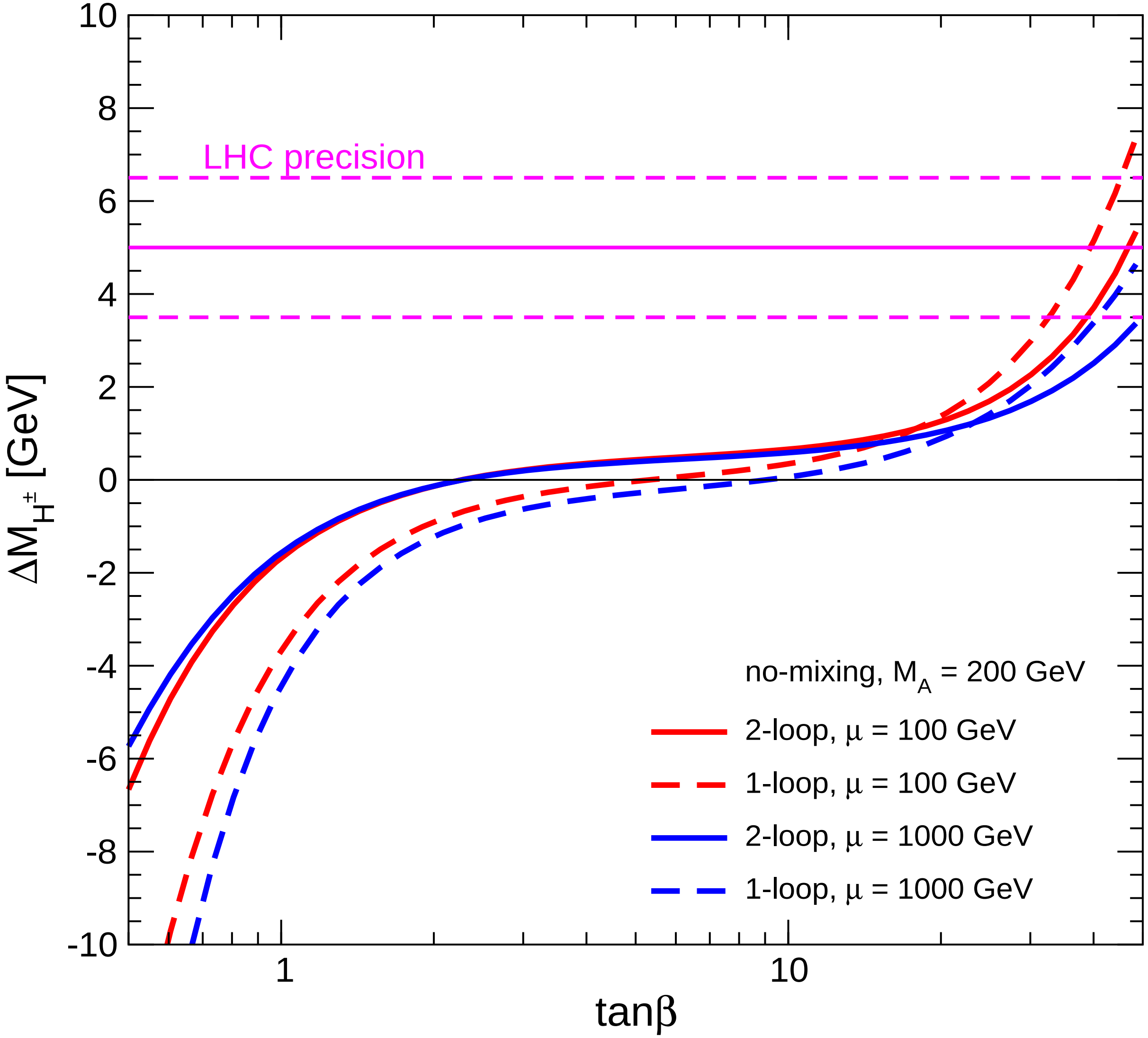
small $\tan\beta$:

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

large $\tan\beta$:

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

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



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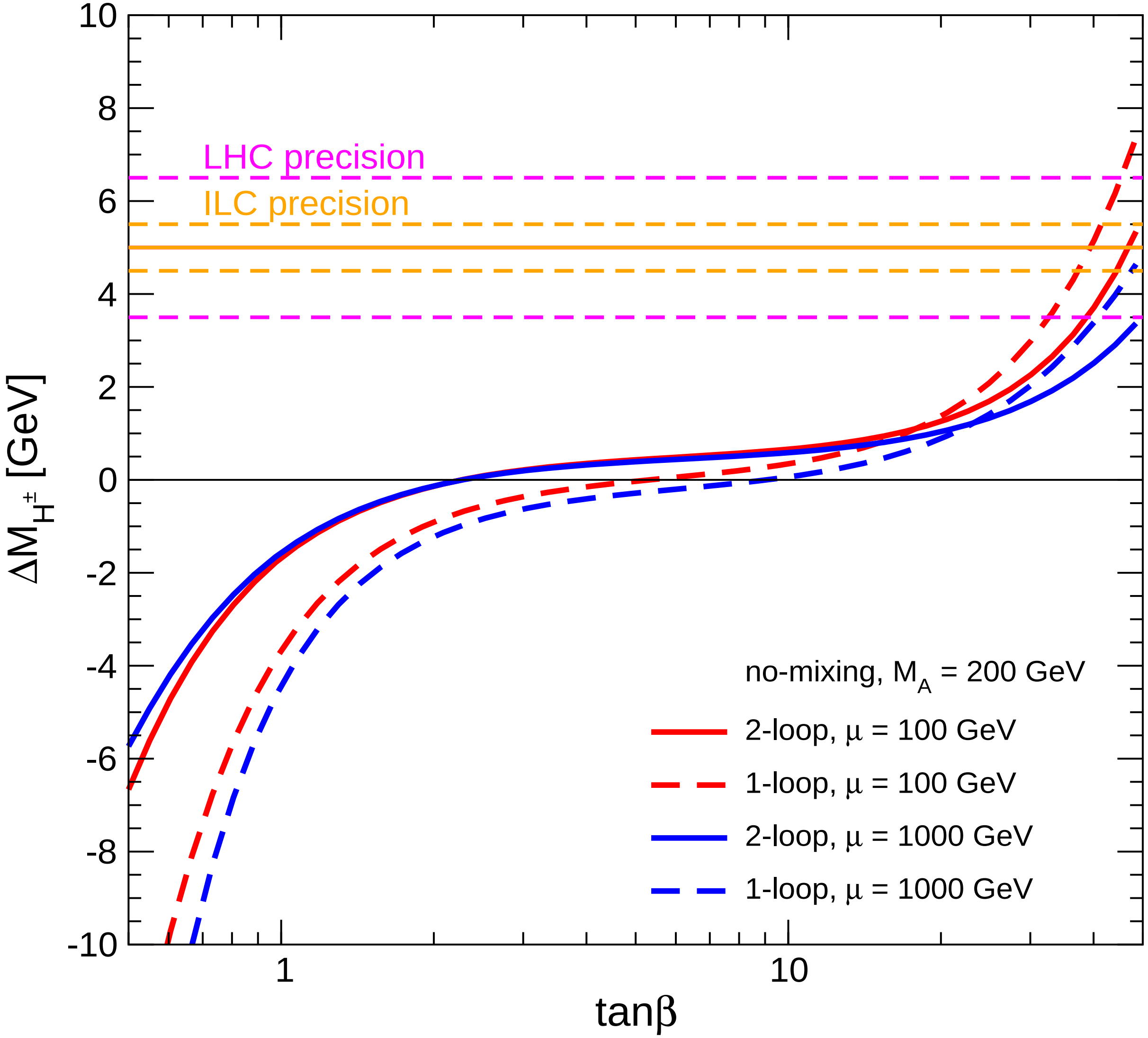


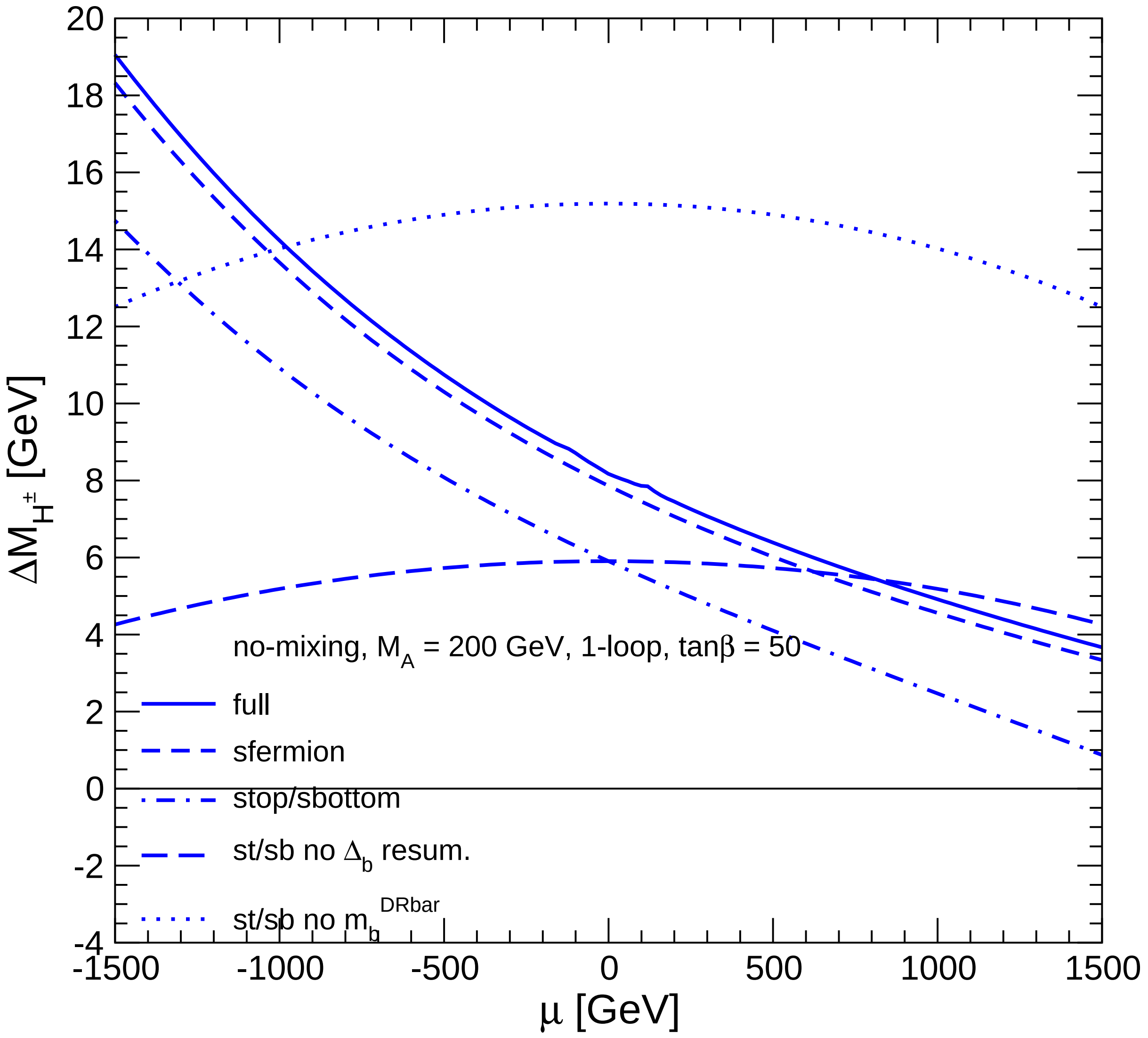
small tan β:

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

large tan β:

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

1-loop, μ varied:



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

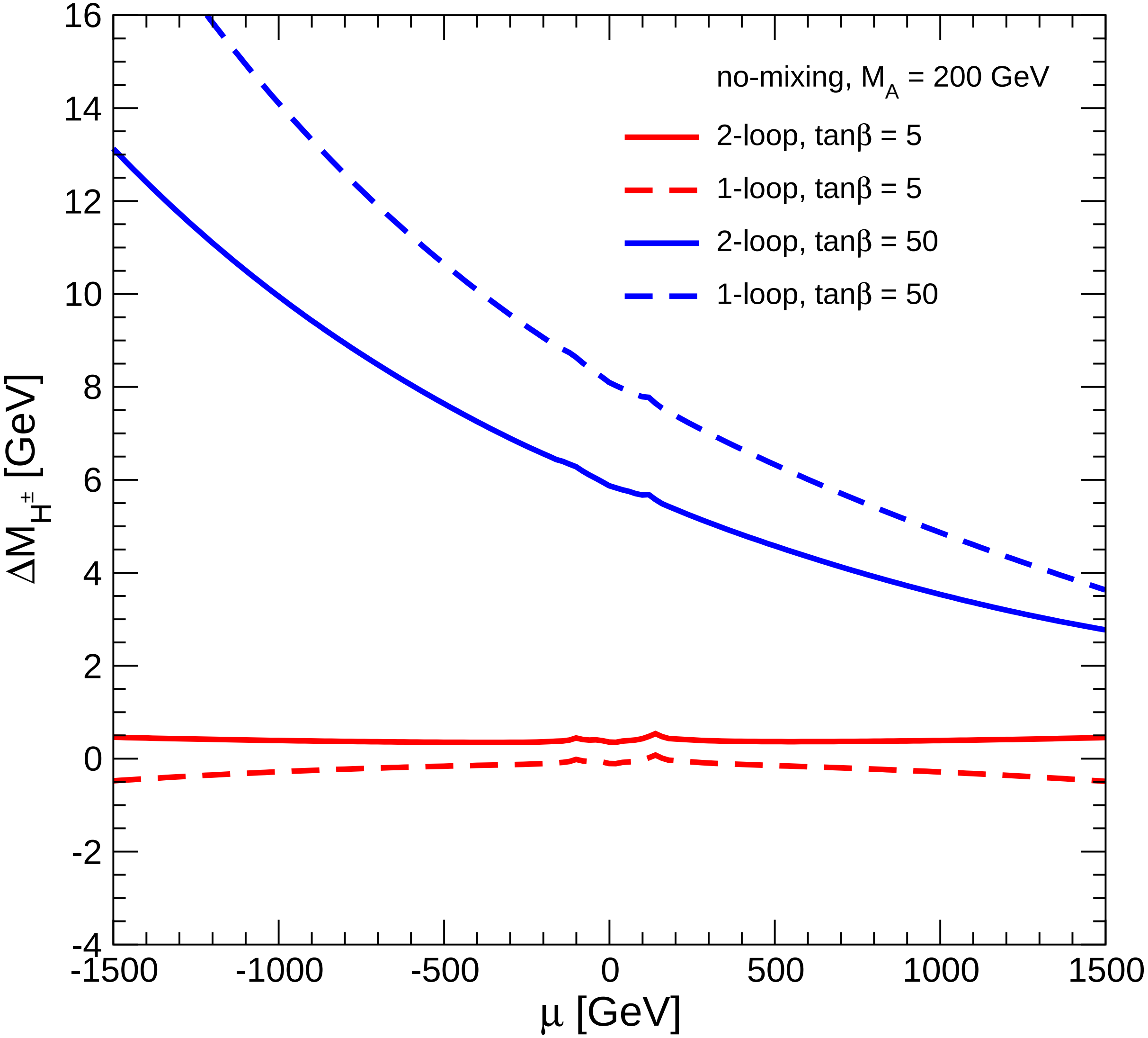
$\overline{m}_b$ important

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:



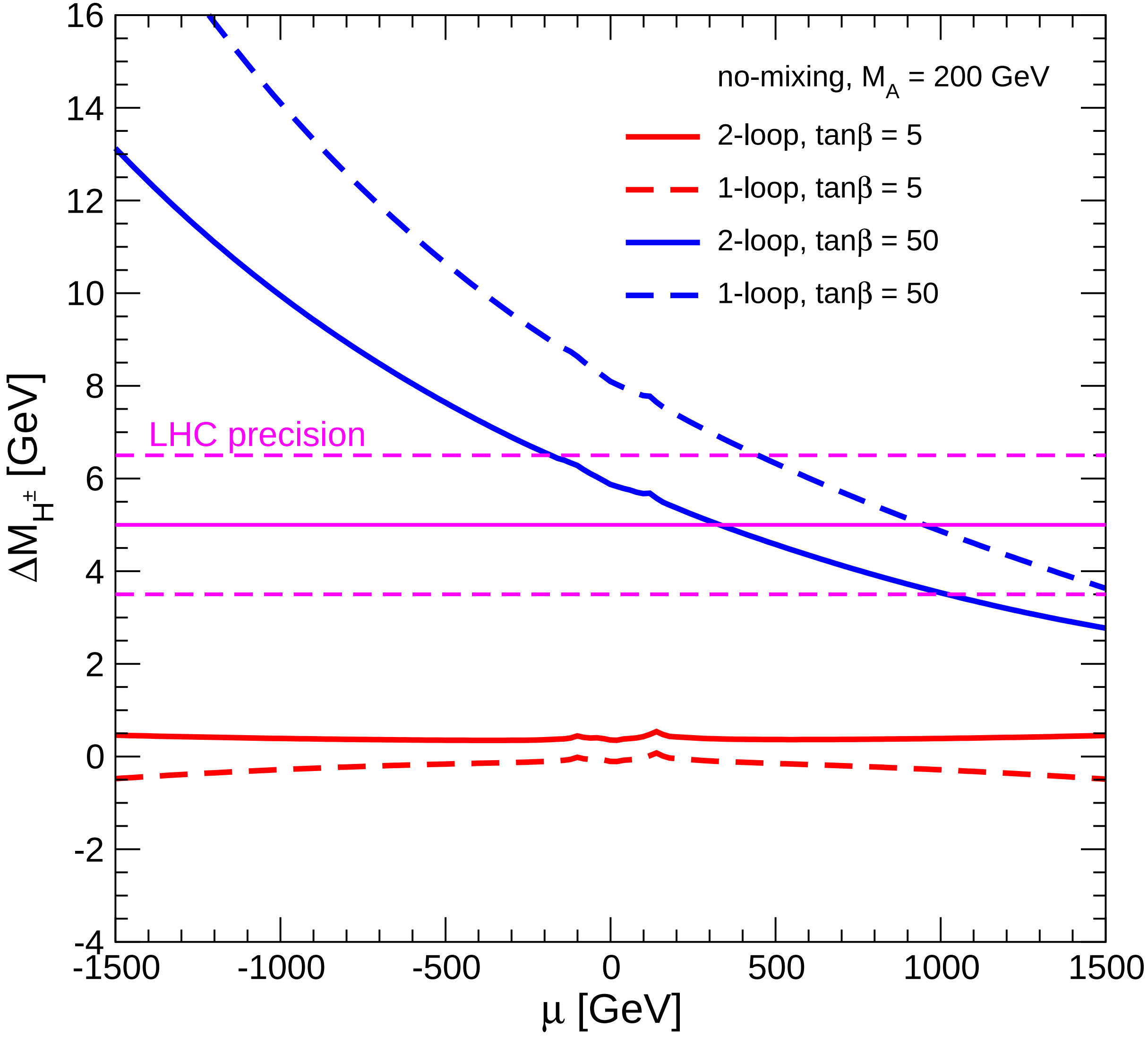
negative μ:

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

positive μ:

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

2-loop, μ varied:



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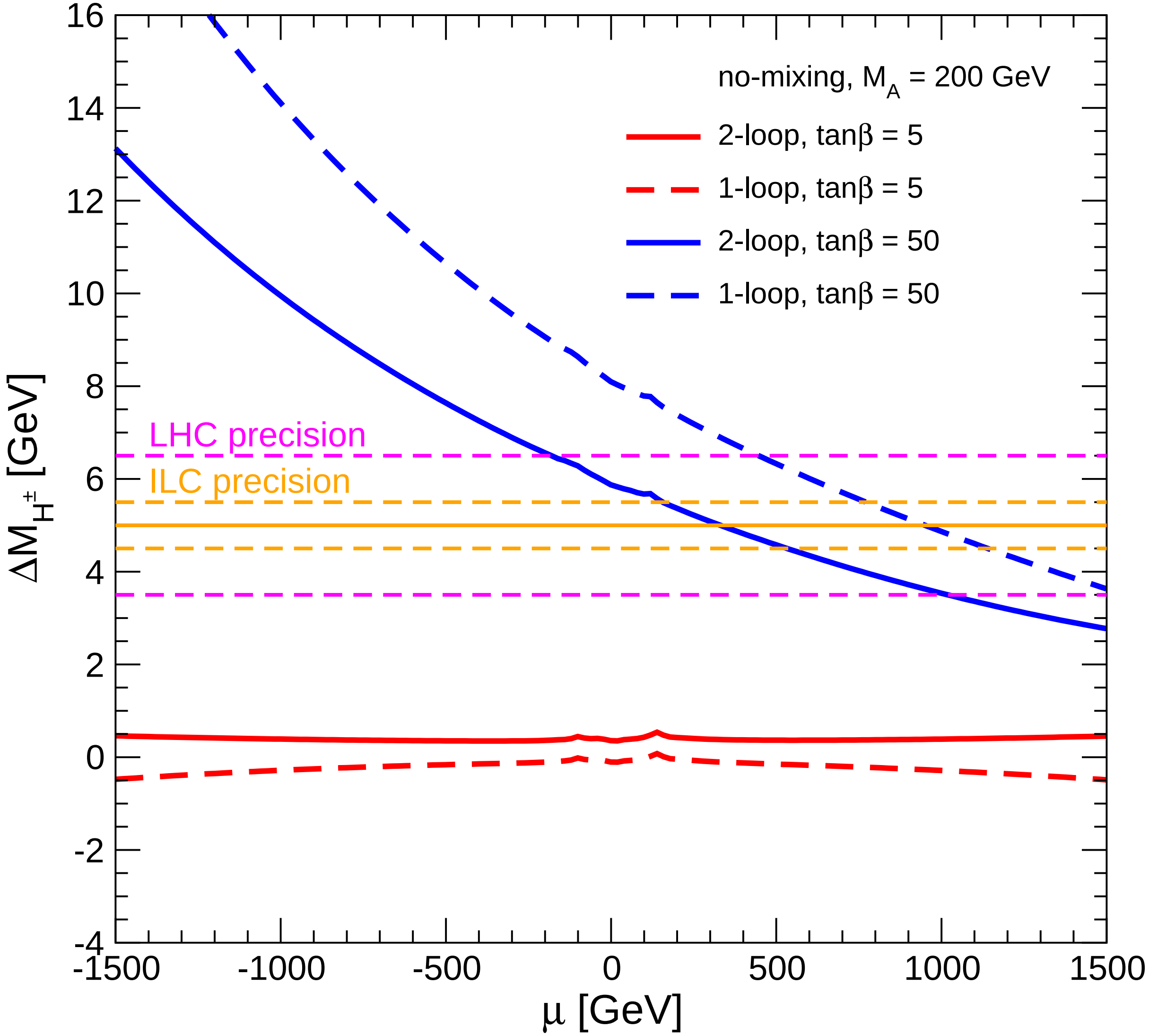

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How can **YOU** obtain the precision predictions?

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The evaluations are available in

FeynHiggs (www.feynhiggs.de)

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Included in FeynHiggs 2.6:

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

4. Conclusinos

- Charged MSSM Higgs boson mass:

  can be predicted in terms of other model parameters

- Included in our prediction:

  full one-loop + leading $\mathcal{O}(\alpha_t \alpha_s)$ two-loop
  major complication: renormalization

- one-loop: $10 - 20$ GeV
  $t/\tilde{t}/b/\tilde{b}$ 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

  two-loop: up to ~ 5 GeV

  $\Rightarrow$ relevant for ILC precision

- Everything is availble in FeynHiggs (www.feynhiggs.de)