The Charged Higgs Boson in the MSSM: Experimental Reach and Theoretical Accuracy

Sven Heinemeyer, IFCA (CSIC, Santander)

Seoul, 06/2008

1. Motivation

2. Experimental reach for the charged MSSM Higgs at the LHC

3. Theoretical Accuracy for $M_{H^\pm}$: improved prediction

4. Conclusions

1. 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:

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

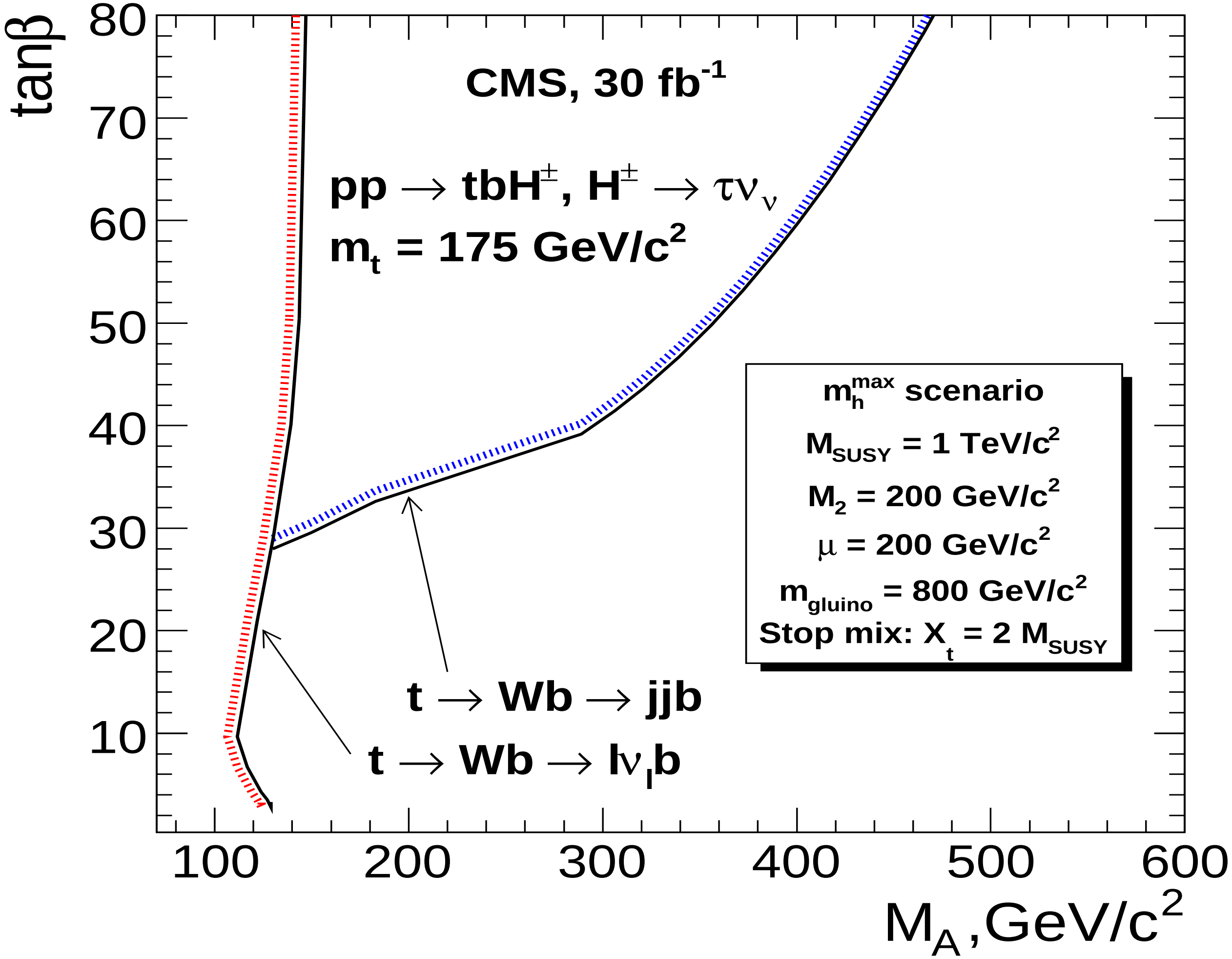
– measure its mass at the LHC or at the ILC

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

2. Experimental reach for the charged MSSM Higgs at the LHC

[M. Hashemi, S.H., R. Kinnunen, A. Nikitenko, G. Weiglein '08]

MSSM Higgs discovery contours in M_A–$\tan\beta$ plane
($m_h^{\rm max}$ benchmark scenario): *[CMS PTDR '06]*



light charged Higgs:

$$M_{H^\pm} < m_t$$

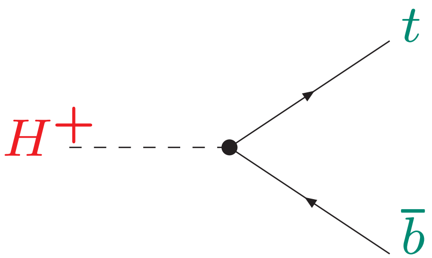
heavy charged Higgs:

$$M_{H^\pm} > m_t$$

Most powerful search modes for heavy MSSM Higgs bosons:

$$gb \to tH^\pm + X, \;\; H^\pm \to \tau\nu_\tau \text{ (low mass)}$$
$$pp \to t\bar{t} \to H^\pm + X, \;\; H^\pm \to \tau\nu_\tau \text{ (high mass)}$$

Enhancement factors compared to the SM case:



$$\sim y_b \, \frac{\tan\beta}{1+\Delta_b} \quad \Rightarrow \quad \frac{\tan^2\beta}{(1+\Delta_b)^2} \times \text{BR}(H^\pm \to \tau\nu_\tau)$$

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

$\Rightarrow$ strong μ dependence

$\Rightarrow$ Δ_b effects so far neglected by ATLAS/CMS

also relevant for $\text{BR}(H^\pm \to \tau\nu_\tau)$

also relevant: correct evaluation of $\Gamma(H^\pm \to \text{SUSY})$

$\Rightarrow$ additional effects on $\text{BR}(H^\pm \to \tau\nu_\tau)$

The light charged Higgs boson:

$$M_{H^\pm} < m_t$$

Main production channel:

$$pp \longrightarrow t\bar{t} \longrightarrow H^- \bar{b}\, t \quad \text{or} \quad t\, H^+ b$$

Close to threshold also contribution from:

$$gb \longrightarrow H^- t \quad \text{or} \quad g\bar{b} \longrightarrow H^+ \bar{t}$$

Relevant decay channel:

$$H^\pm \longrightarrow \tau\nu_\tau$$

Experimental analysis for CMS PTDR:

full simulation, 30 fb^{-1}

[*M. Baarmand, M. Hashemi and A. Nikitenko, CMS Note 2006/056*]

$\to$ no details here

Number of signal-like events:

channel	exp. efficiency
$pp \to t\bar{t} \to H^+ b\,\bar{t} \to (\tau^+ \bar{\nu}_\tau)\,(W^+ b);\quad \tau \to$ hadrons, $W \to l\nu_l$	0.0052
$pp \to t\bar{t} \to W^+\,W^- \to (\tau\nu_\tau)\,(l\nu_l);\quad \tau \to$ hadrons	0.00217
$pp \to t\bar{t} \to W^+\,W^- \to (l\nu_l)\,(l\nu_l)$	0.000859
$pp \to t\bar{t} \to W^+\,W^- \to$ (jet jet) $(l\nu_l)$	0.000134
$g\bar{b} \to H^+\bar{t} \to (\tau\nu_\tau)\,(Wb);\quad \tau \to$ hadrons, $W \to l\nu_l$	0.0052

$5\,\sigma$ discovery with 30 fb^{-1} $\Leftrightarrow$ $N_{\rm ev} > 5260$

Theory evaluation:

$\sigma(pp \to t\bar{t}) = 840\,\text{pb}$

$\sigma(gb \to H^{\pm}t)$: state-of-the-art

[*T. Plehn '02*] [*E. Berger, T. Han, J. Jiang and T. Plehn '03*]

$+\ \Delta_b$ corrections

BR($t \to H^{\pm}b$): Δ_b corrections included

BR($H^{\pm} \to \tau\nu_\tau, tb, W^{\pm(*)}h, \ldots$: Δ_b corrections included

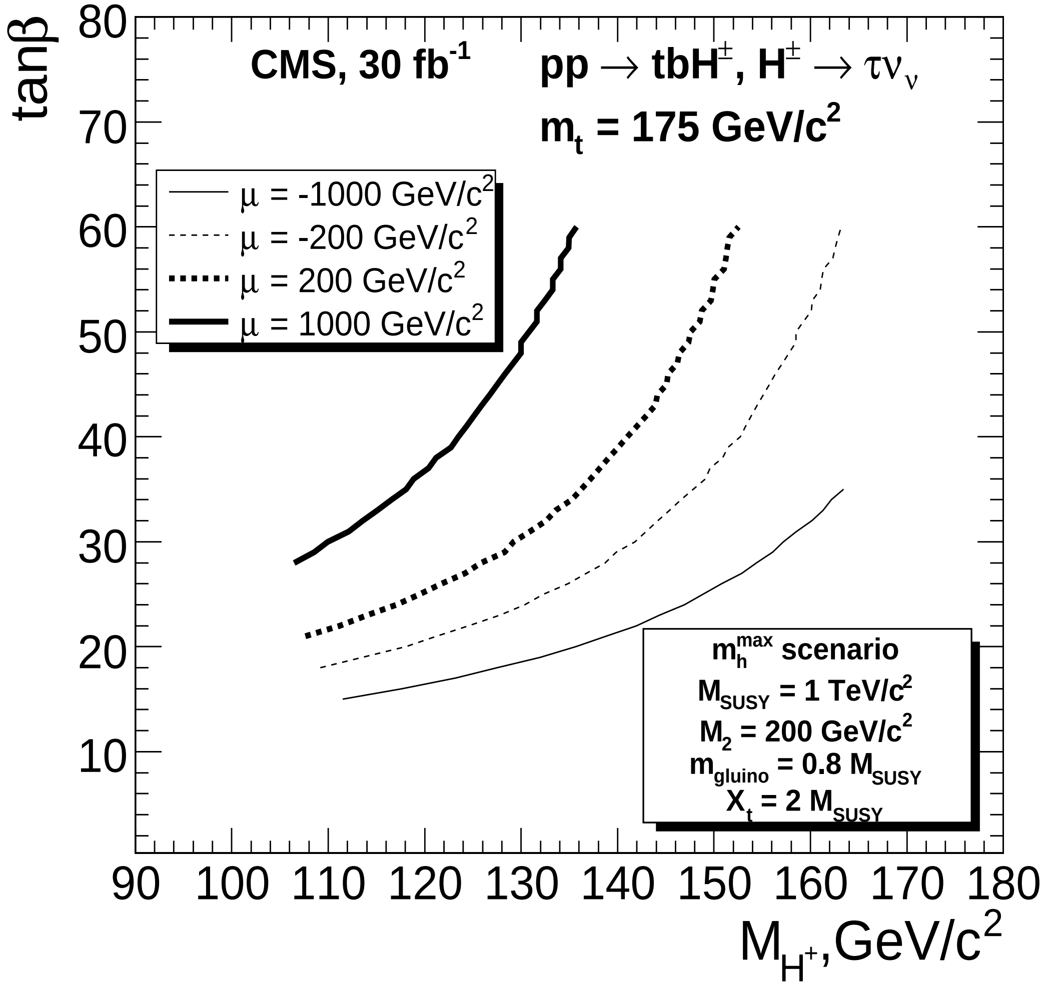
Fixed values for all other BRs

Everything evaluated with

`FeynHiggs (www.feynhiggs.de)`

Results for the m_h^{max} scenario:

[*M. Hashemi, S.H., R. Kinnunen, A. Nikitenko, G. Weiglein '08*]



$\Rightarrow$ strong variation with μ

$\Delta \tan\beta \gtrsim 15$

best coverage for $\mu = -1000$ GeV

worst coverage for $+1000$ GeV

$\Rightarrow$ corresponds to XS evaluation

The heavy charged Higgs boson:

$$M_{H^\pm} > m_t$$

Main production channel:

$$gb \longrightarrow H^- t \quad \text{or} \quad g\bar{b} \longrightarrow H^+ \bar{t}$$

Close to threshold also contribution from:

$$pp \longrightarrow t\bar{t} \longrightarrow H^- \bar{b}\, t \quad \text{or} \quad t\, H^+ b$$

Relevant decay channel:

$$H^\pm \longrightarrow \tau\nu_\tau$$

Experimental analysis for CMS PTDR:

full simulation, 30 fb^{-1}

[R. Kinnunen, CMS Note 2006/100]

$\to$ no details here

Number of signal events:

$$N_{\rm ev} = \mathcal{L} \times \sigma(pp \to H^\pm + X) \times \text{BR}(H^\pm \to \tau\nu_\tau) \times \text{BR}(\tau \to \text{hadrons}) \times \text{exp. eff.}$$

Experimental efficiencies:

$M_{H^\pm}$ [GeV]	171.6	180.4	201.0	300.9	400.7	600.8
exp. eff. [10^{-4}]	3.5	4.0	5.0	23	32	42

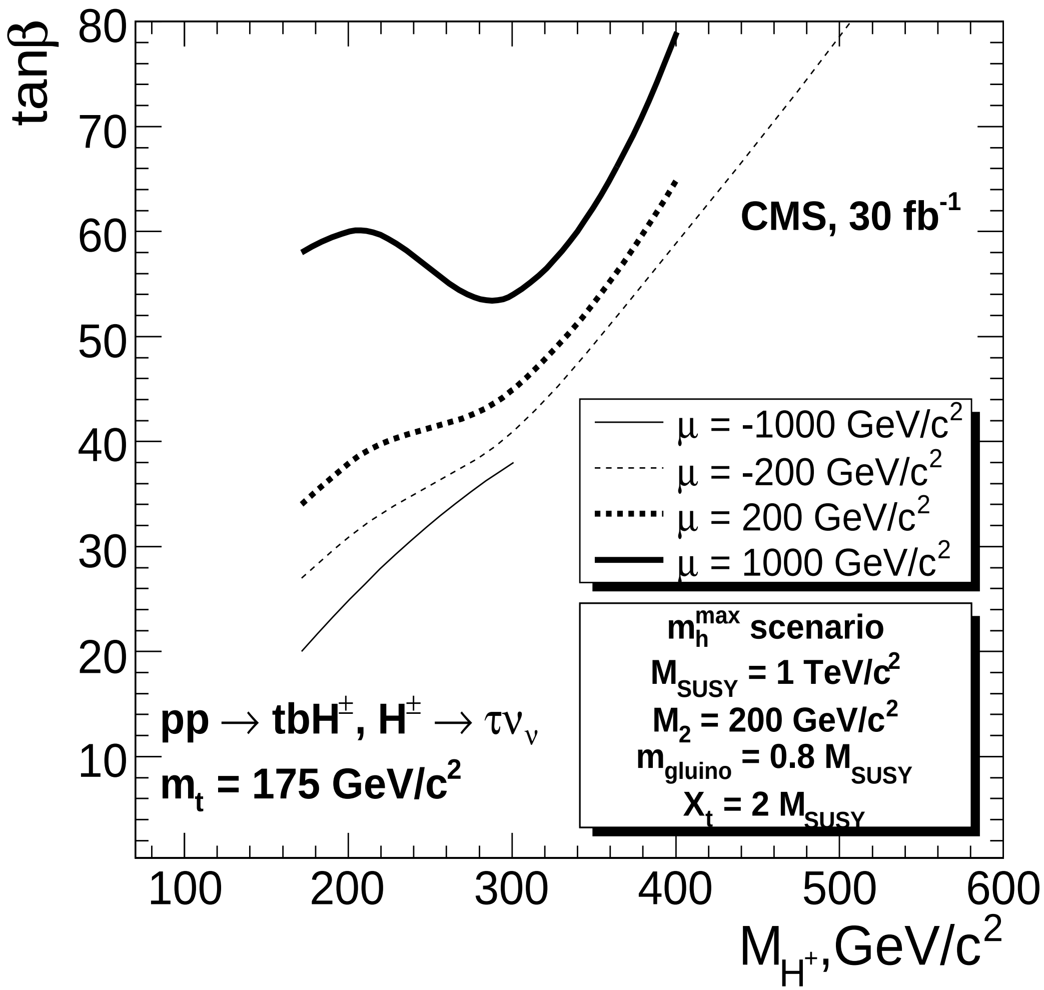
$5\,\sigma$ discovery with 30 fb^{-1} $\Leftrightarrow$ $N_{\rm ev} > 14.1$

Everything evaluated with

`FeynHiggs (www.feynhiggs.de)`

Results for the $m_h^{\rm max}$ scenario:

[*M. Hashemi, S.H., R. Kinnunen, A. Nikitenko, G. Weiglein '08*]



$\Rightarrow$ strong variation with μ

$\Delta \tan\beta$ up to ~ 40

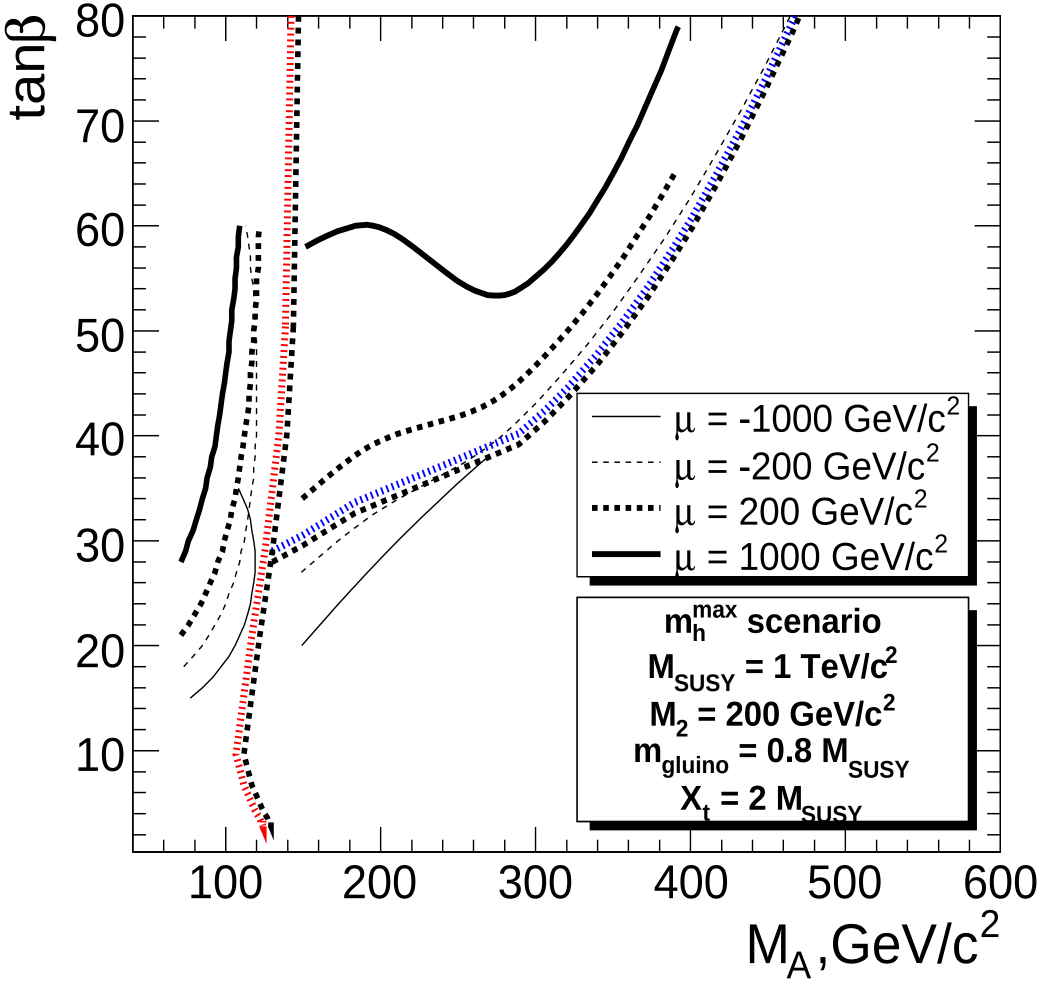
best coverage for $\mu = -1000$ GeV

worst coverage for $+1000$ GeV

$\Rightarrow$ corresponds to XS evaluation

Comparison with CMS PTDR (m_h^{max} scenario):

[*M. Hashemi, S.H., R. Kinnunen, A. Nikitenko, G. Weiglein '08*]



→ note: M_A–$\tan\beta$ plane

light charged Higgs:

always worse than PTDR

better $M_{H^\pm}$ calculation!

inclusion of Δ_b effects

heavy charged Higgs:

PTDR in "the middle"

new results partially

substantially worse

3. Theoretical accuracy for $M_{H^\pm}$: improved prediction

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

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

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

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:

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

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

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

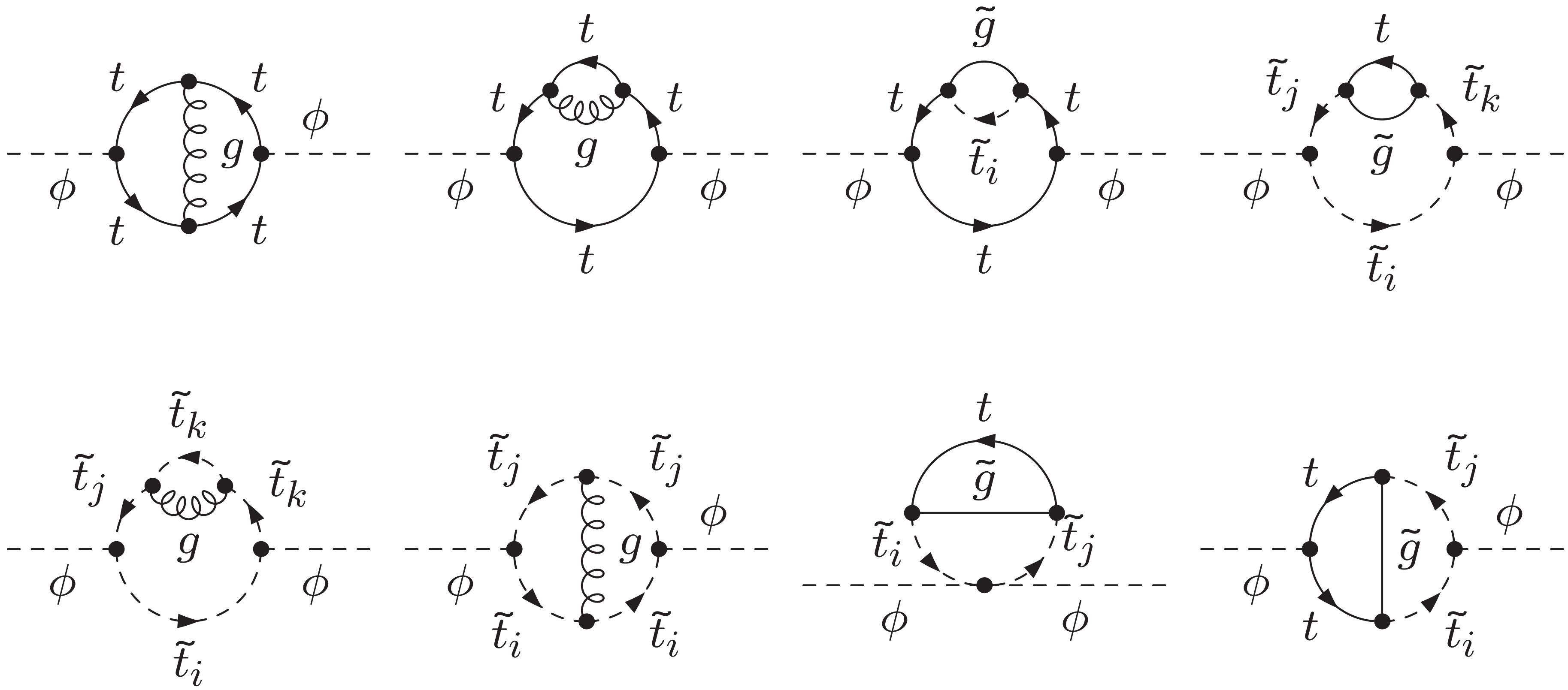
$$\delta Z^{(2)}_{H^+H^-} = 0$$

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

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

Contributions to the 2-loop self-energy:

2-loop self-energy diagrams:



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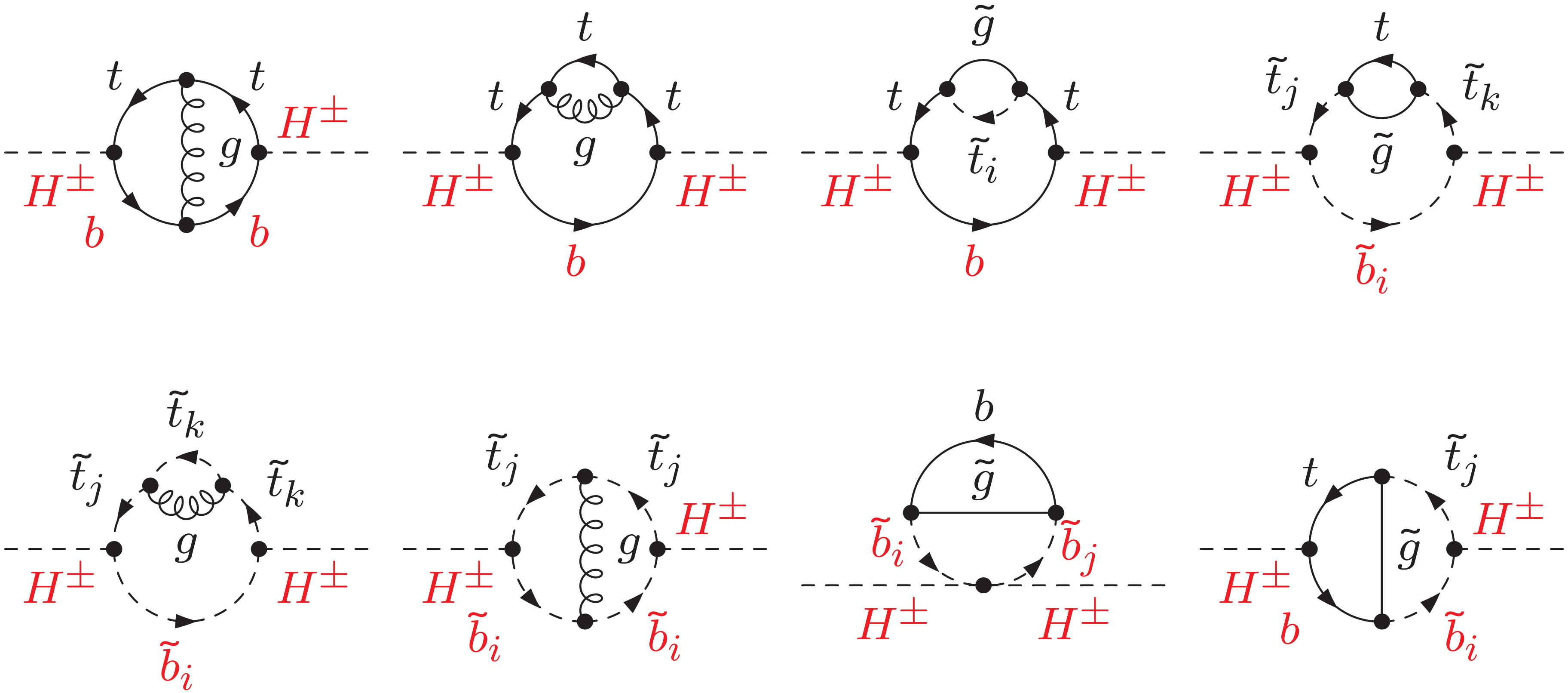


new: $H^{\pm}$ as external Higgs

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

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

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

– only y_t^2 contributions

– $g, g' \rightarrow 0$

– external momentum $\rightarrow 0$

$\Rightarrow$ 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

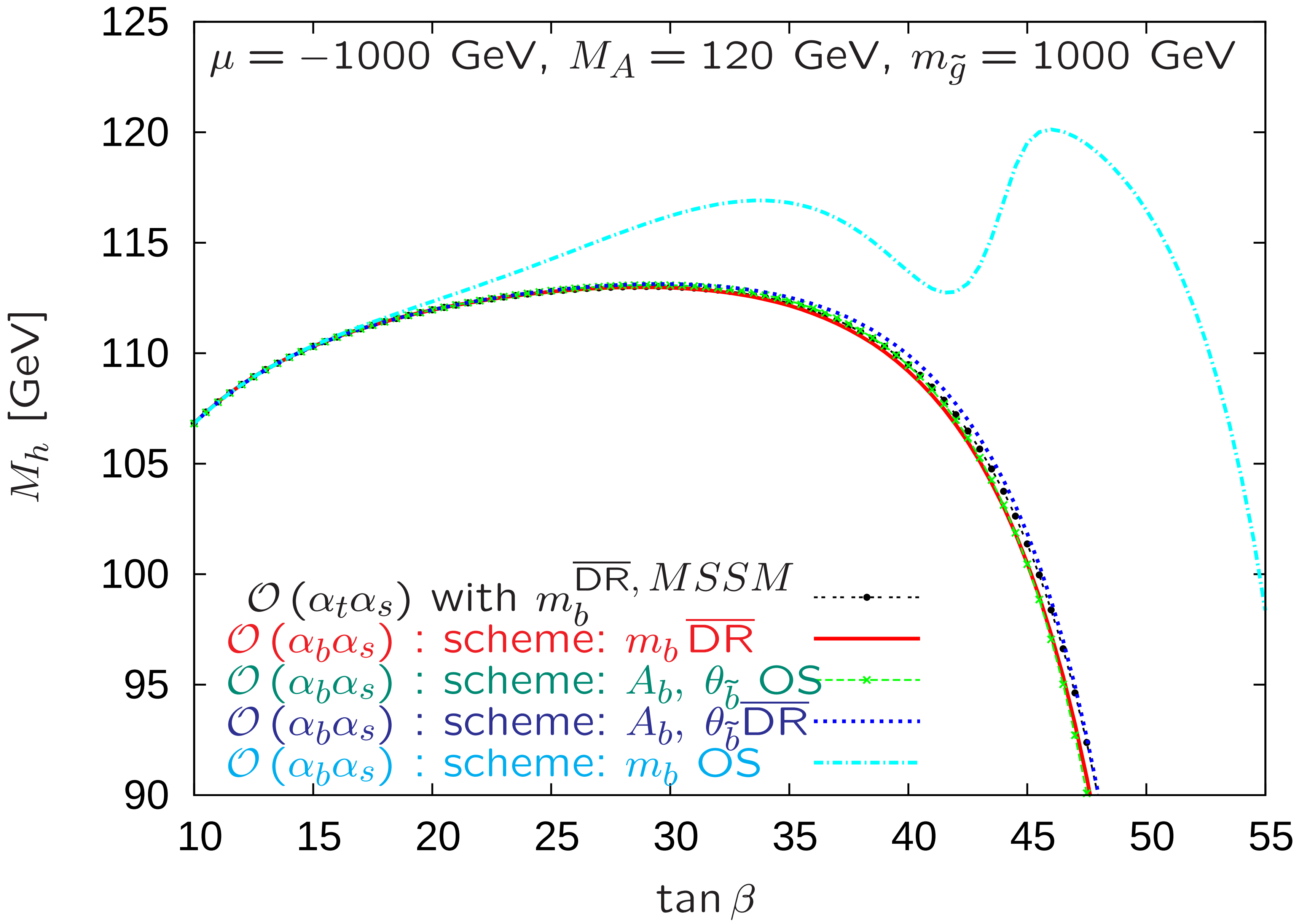
but not as many parameters ($SU(2)$)

$\Rightarrow$ 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 $\Leftarrow$ focus here

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

Experimental resolution:

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

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

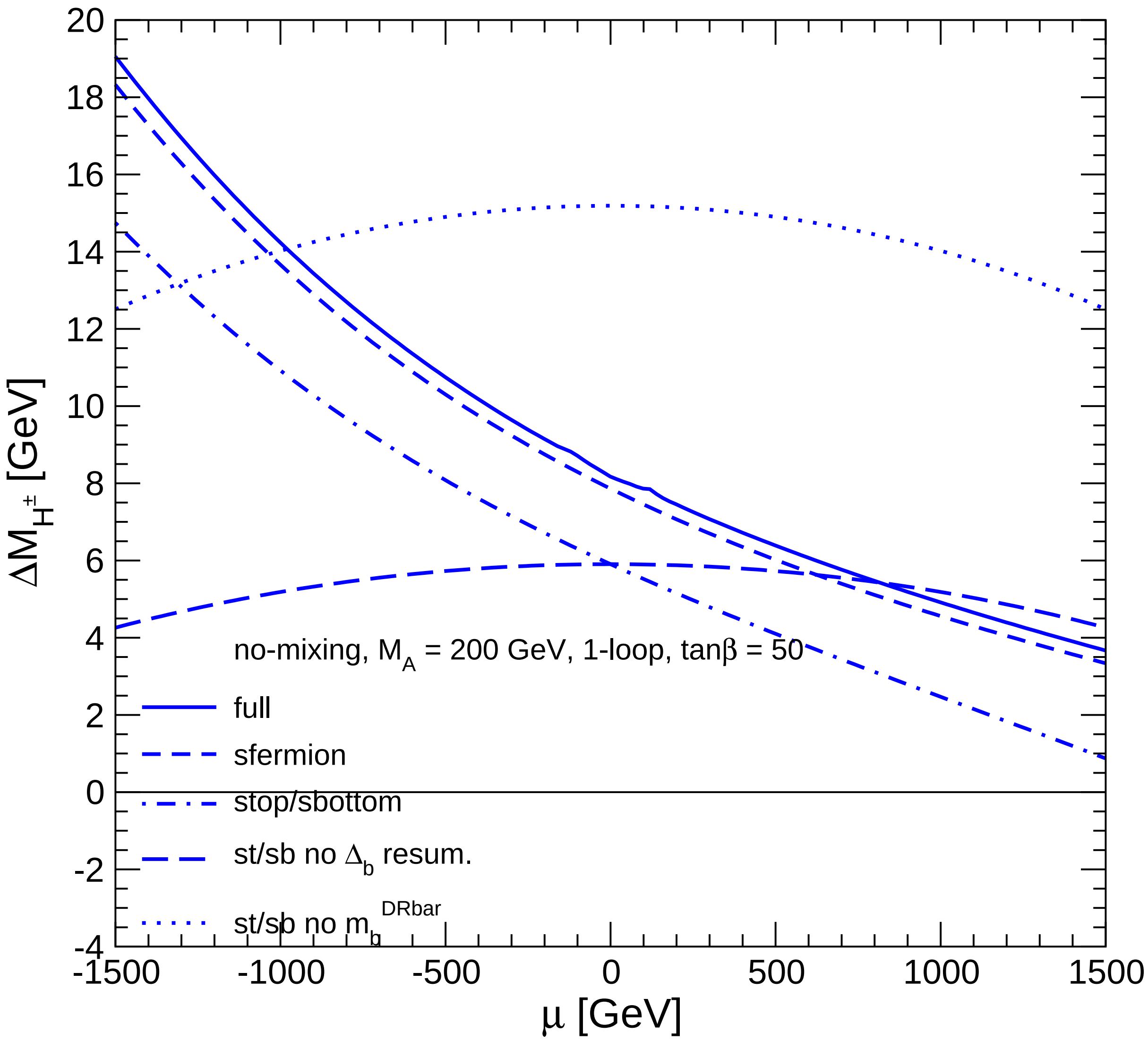
$$\text{ILC}: \Rightarrow \delta M_{H^\pm} \approx 0.5 \text{ GeV}$$

Higher masses:

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

1-loop, μ varied:

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



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

$\overline{m}_b$ important

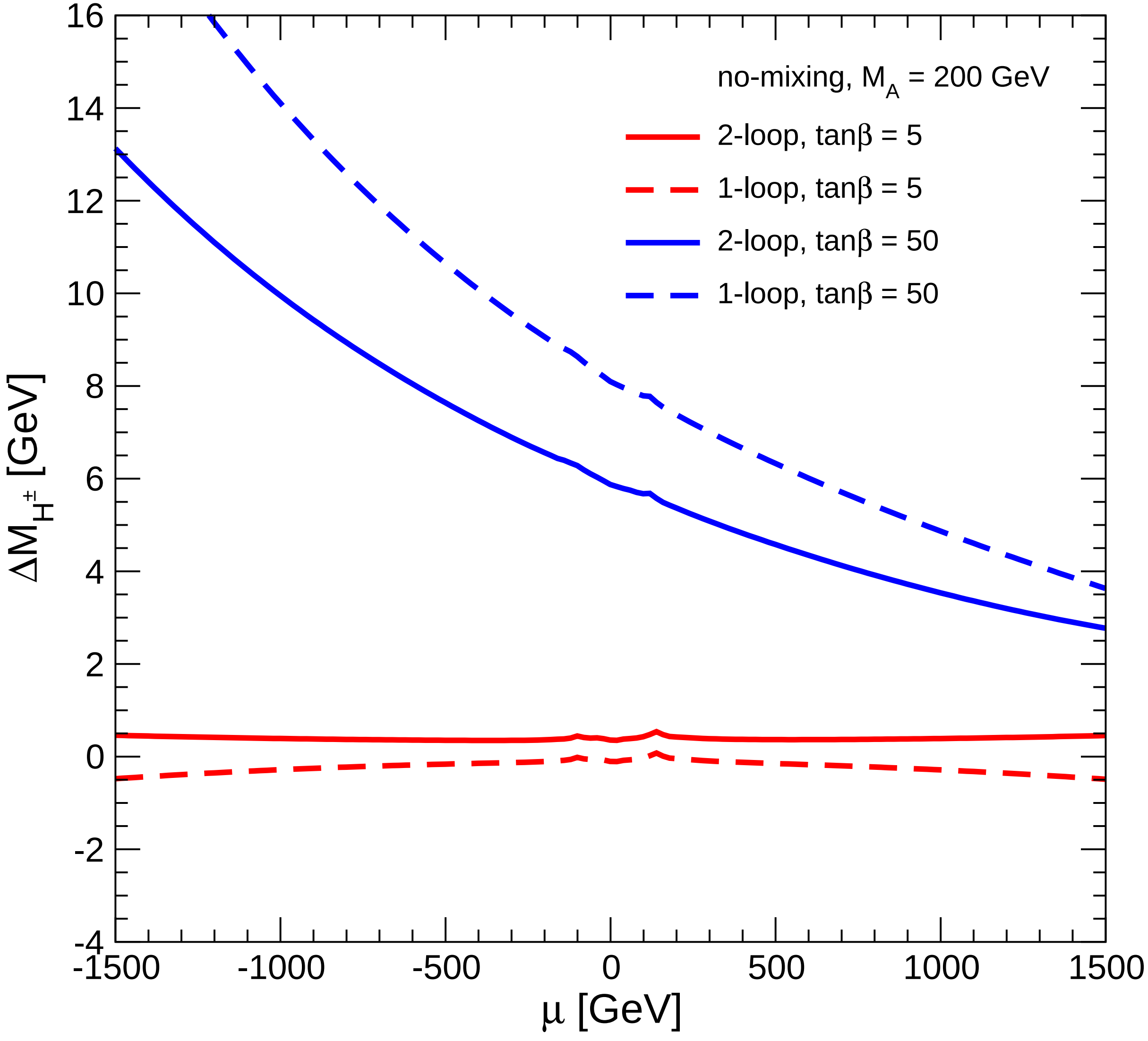
Δ_b important

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

non-sfermion
corrections small

2-loop, μ varied:

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



negative μ:

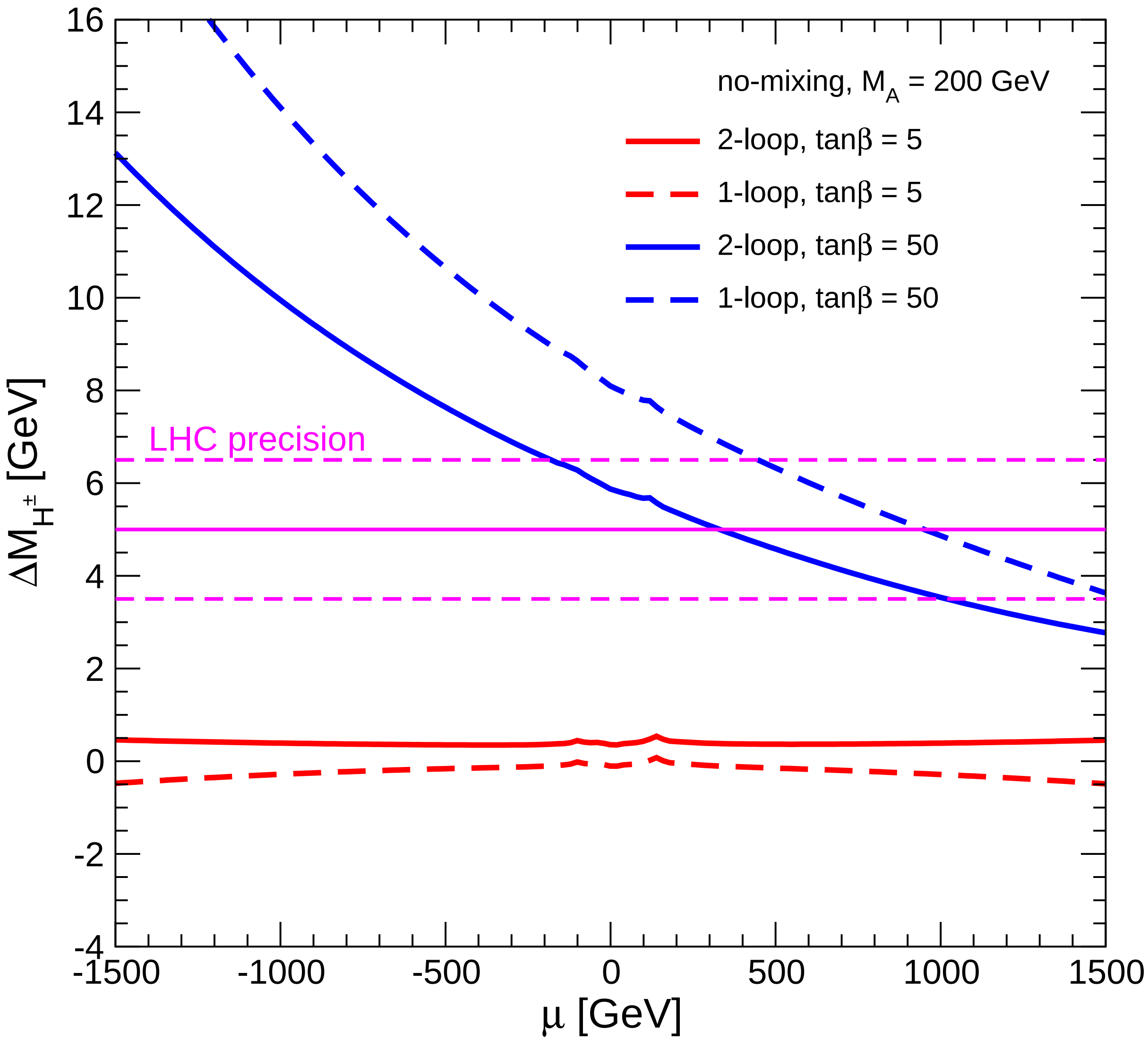
$\Delta M_{H^\pm} = 2 - 5$ GeV

positive μ:

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

2-loop, μ varied:

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



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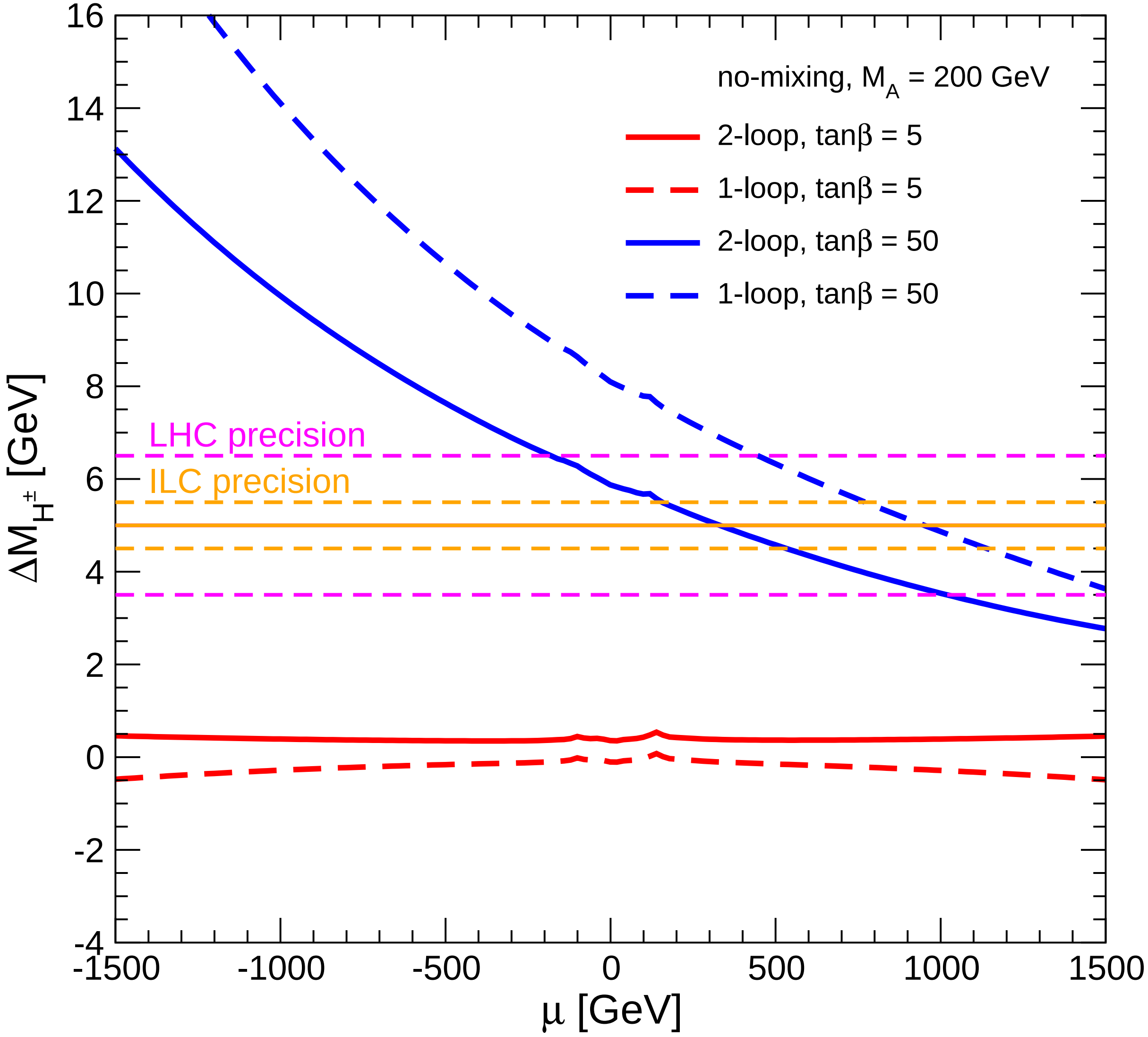

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How can **YOU** obtain the precision predictions?

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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 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
- $\text{BR}(H^+ \to \tilde{\chi}_i^0 \tilde{\chi}_j^+)$: decay to charginos and neutralinos
- H^+ production cross sections at LHC
- $\text{BR}(t \to H^+ \bar{b})$ for $M_{H^\pm} \le m_t$ ($H^\pm$ production at Tevatron/LHC)

4. Conclusinos

- Charged MSSM Higgs boson:

  mass and couplings predicted in terms of other model parameters
  $\Rightarrow$ test of the model, parameter determination

- Charged Higgs search at LHC:

  $\rightarrow$ used results from CMS based on 30 fb^{-1} (low and high $M_{H^\pm}$)
  – strong dependence on μ via Δ_b
  – strong impact on discovery contours
  – results somewhat worse than for CMS PTDR

- Theory prediction of $M_{H^\pm}$:

  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

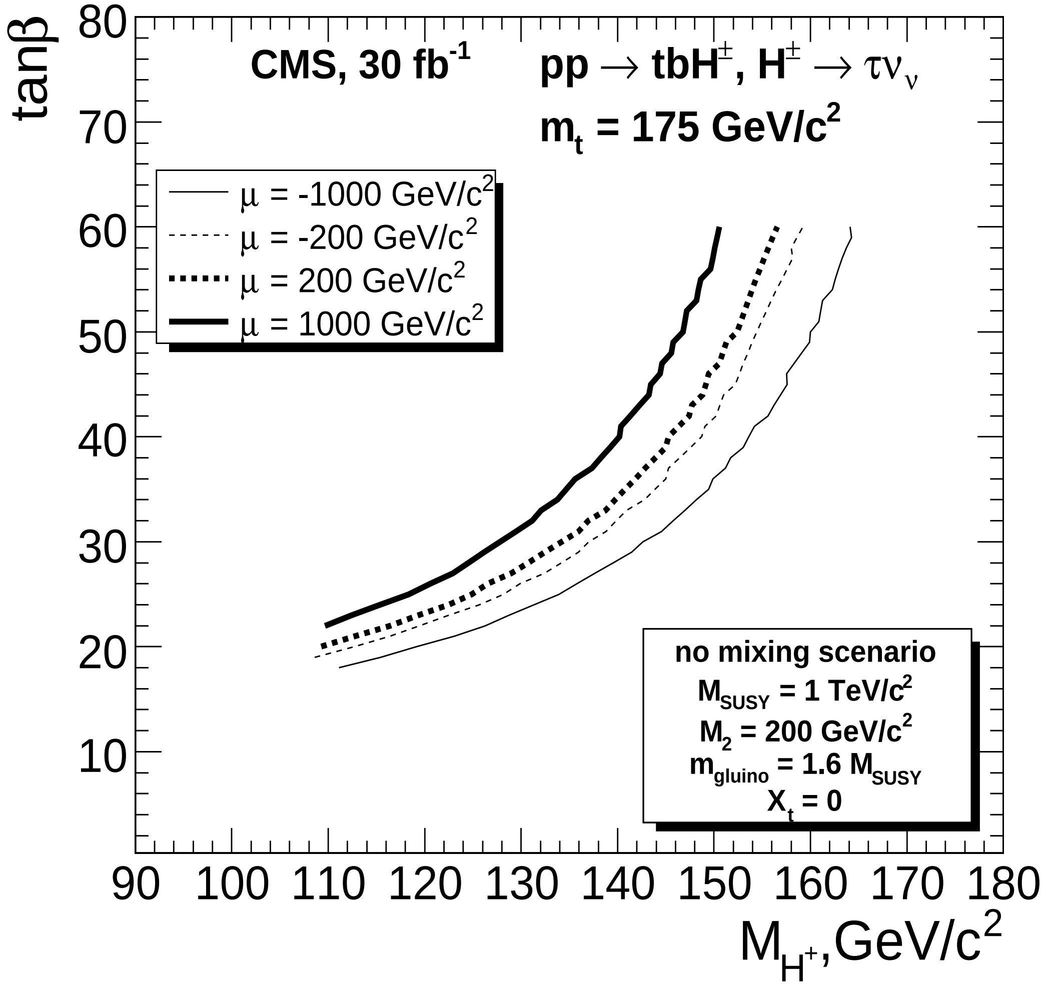
  two-loop: up to ~ 5 GeV
  $\Rightarrow$ relevant to match LHC/ILC precision

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

Back-up

Light charged Higgs: results for the no-mixing scenario:

[*M. Hashemi, S.H., R. Kinnunen, A. Nikitenko, G. Weiglein '08*]



$\Rightarrow$ smaller variation with μ

$\Delta \tan\beta \gtrsim 5$

best coverage for $\mu = -1000$ GeV
worst coverage for $+1000$ GeV
$\Rightarrow$ corresponds to XS evaluation

smaller variation $\Leftrightarrow$ smaller Δ_b

Heavy charged Higgs: results for the no-mixing scenario:

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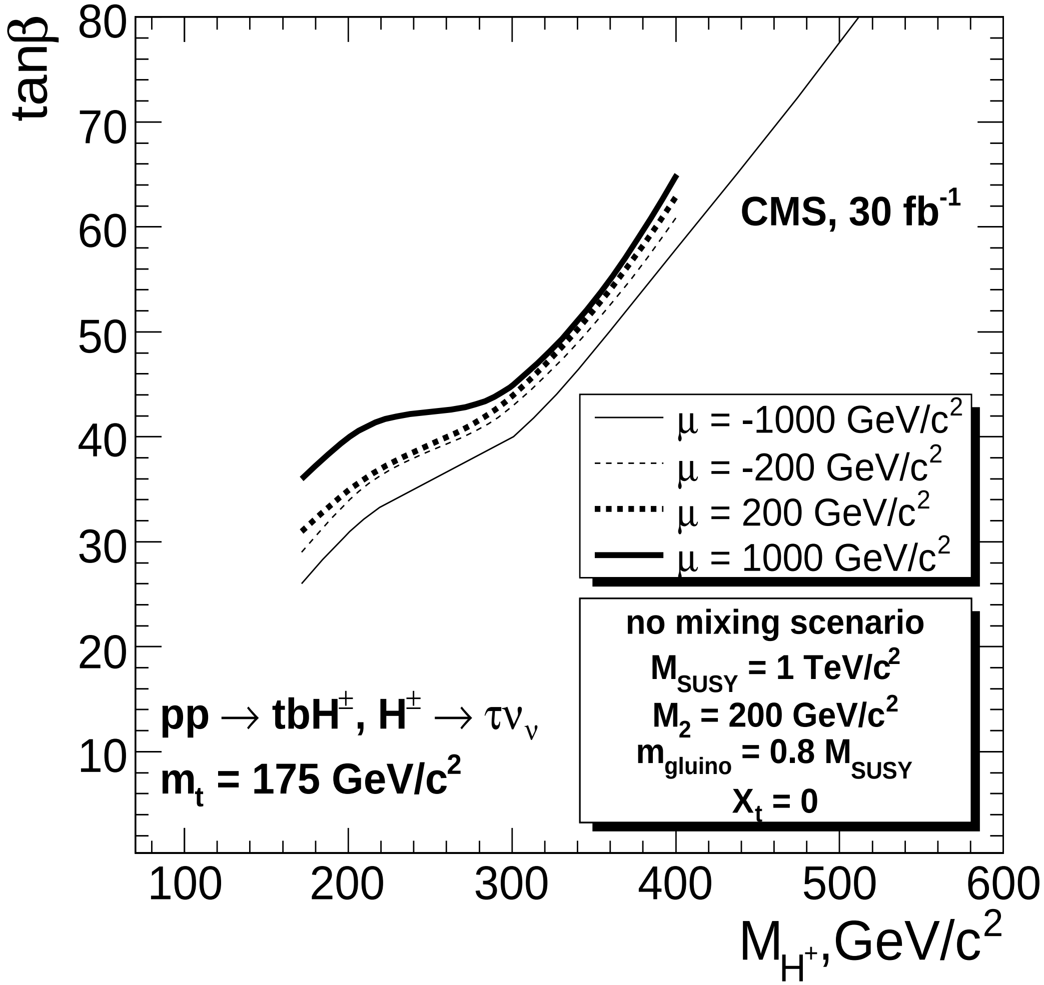


$\Rightarrow$ smaller variation with μ

$\Delta \tan\beta$ up to ~ 10

best coverage for $\mu = -1000$ GeV

worst coverage for $+1000$ GeV

$\Rightarrow$ corresponds to XS evaluation

smaller variation $\Leftrightarrow$ smaller Δ_b

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

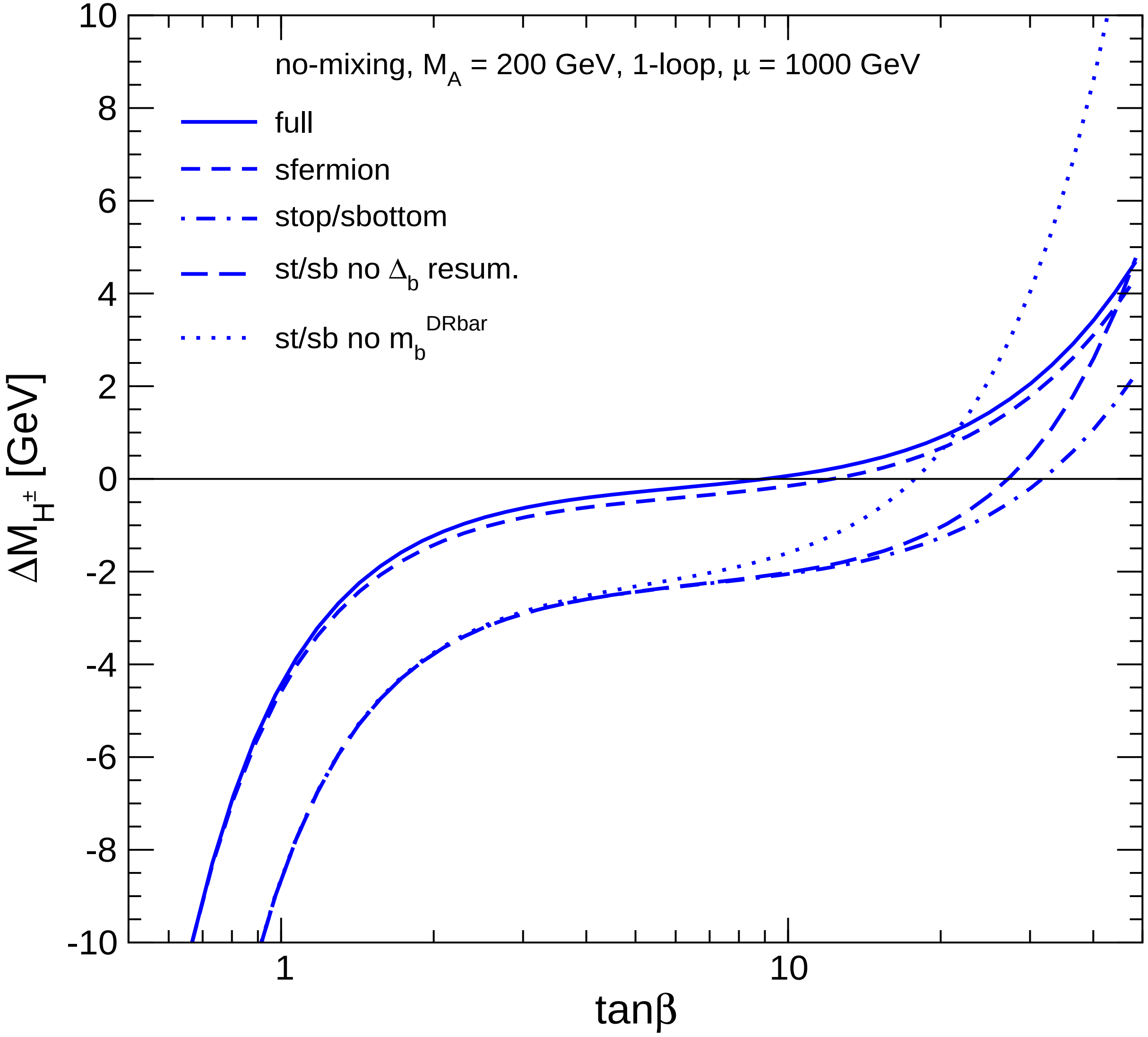
$\Rightarrow$ Studies needed(?) for

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

for all mass ranges!?

1-loop, tan β varied:

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



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2-loop, tan β varied:

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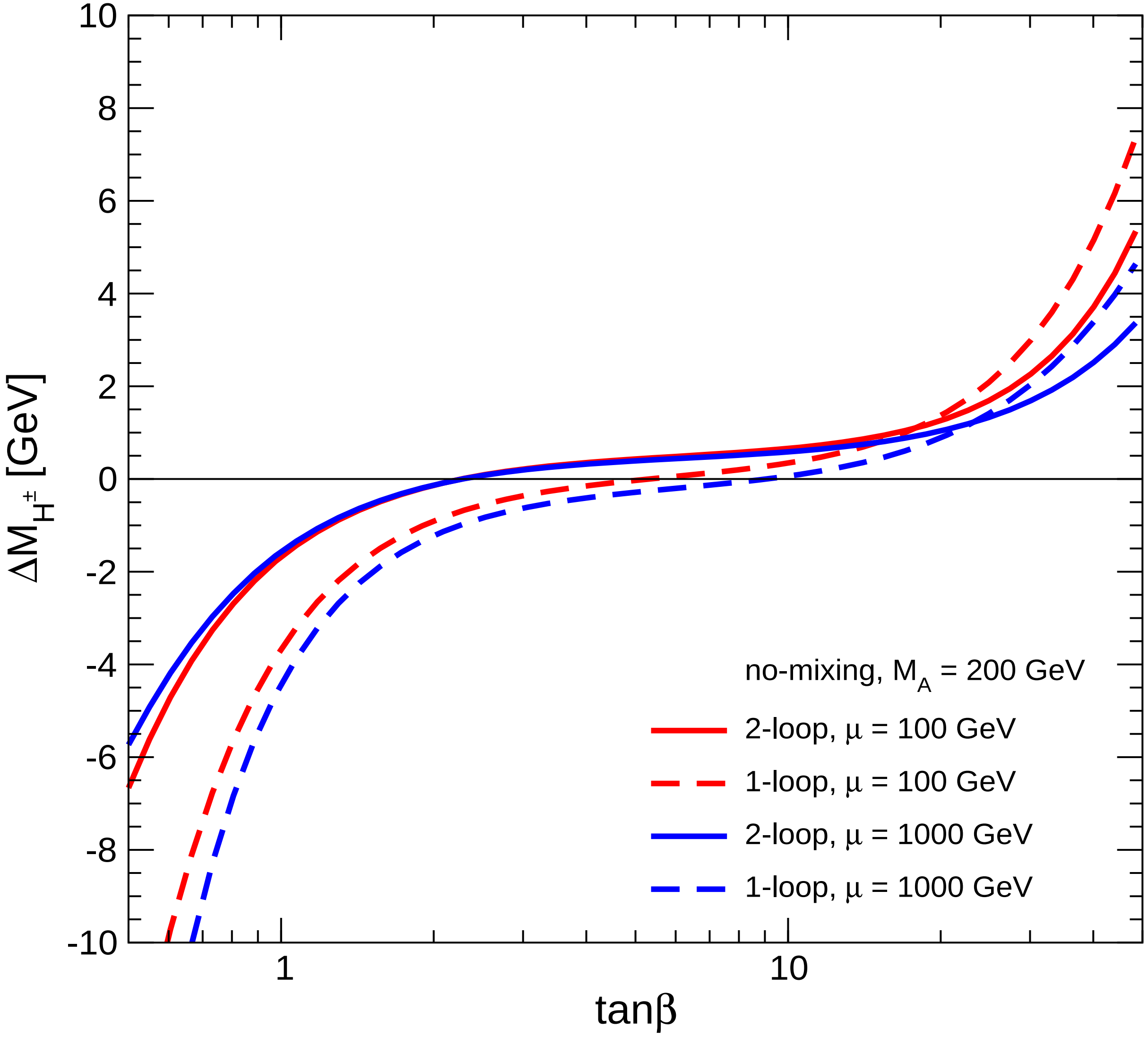

small tan β:
$\Delta M_{H^\pm} \gtrsim 4$ GeV

large tan β:
$\Delta M_{H^\pm} \sim 2$ GeV

2-loop, tan β varied:

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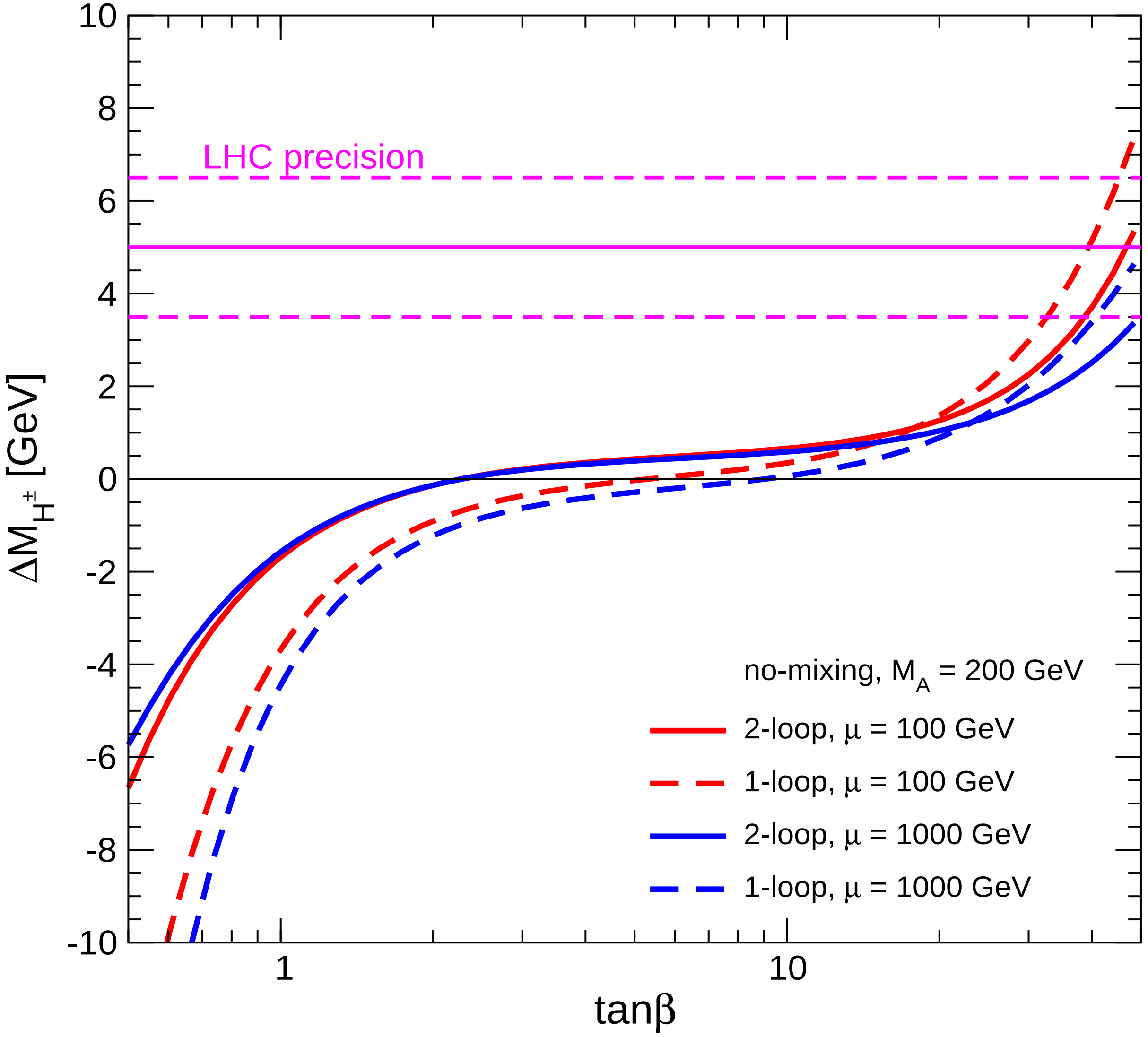

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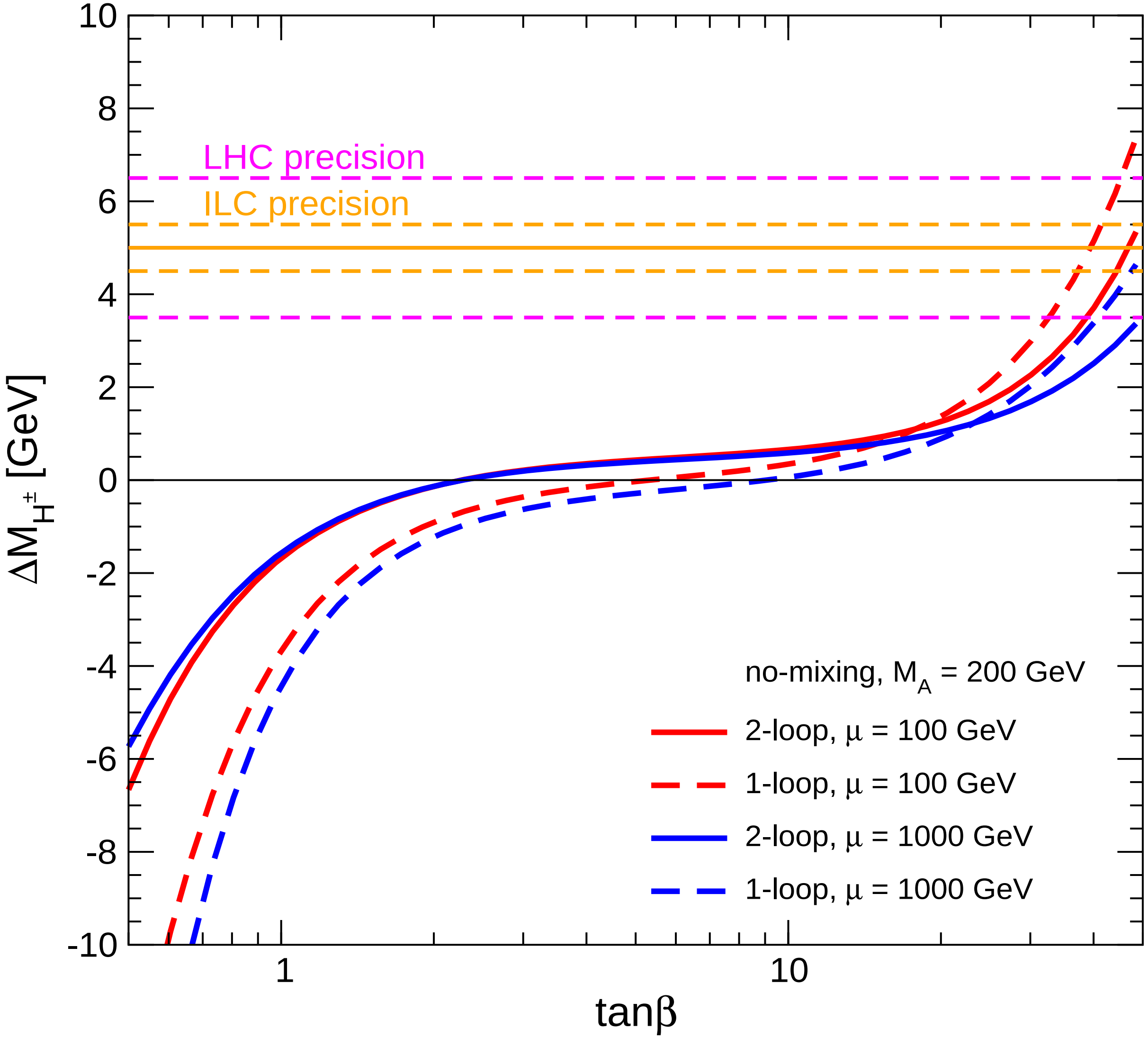

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