
We still believe in supersymmetry
You must be joking

Higgs Physics

Sven Heinemeyer, IFT/IFCA (CSIC, Madrid/Santander)

Dubna, 07/2018

1. Before the Higgs discovery

2. The Higgs sector of the SM

3. The Higgs sector of the (N)MSSM

4. Higgs boson(s) at the LHC

Higgs Physics

The Higgs Sector of the (N)MSSM

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Madrid, 04/2018

1. MSSM Higgs Theory
2. NMSSM Higgs Theory
3. The lightest MSSM Higgs boson mass
4. The heavy MSSM Higgs bosons
5. The MSSM Higgs sector with $\mathcal{CP}$-violation

1. MSSM Higgs Theory

Comparison with SM case:

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

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

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

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

No soft SUSY-breaking terms allowed for chiral fermions

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

Furthermore: two doublets also needed for cancellation of anomalies, quadratic divergences

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)

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

Rotation to physical basis:

$$\begin{pmatrix} H^0 \\ h^0 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \phi_1^0 \\ \phi_2^0 \end{pmatrix} \qquad \tan(2\alpha) = \tan(2\beta)\frac{M_A^2 + M_Z^2}{M_A^2 - M_Z^2}$$

$$\begin{pmatrix} G^0 \\ A^0 \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \chi_1^0 \\ \chi_2^0 \end{pmatrix}, \quad \begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \phi_1^\pm \\ \phi_2^\pm \end{pmatrix}$$

Three Goldstone bosons (as in SM): G^0, $G^\pm$

$\longrightarrow$ longitudinal components of $W^\pm$, Z

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

h, H: neutral, $\mathcal{CP}$-even, A^0: neutral, $\mathcal{CP}$-odd, $H^\pm$: charged

Gauge-boson masses:

$$M_W^2 = \frac{1}{2}g'^2(v_1^2 + v_2^2), \quad M_Z^2 = \frac{1}{2}(g^2 + g'^2)(v_1^2 + v_2^2), \quad M_\gamma = 0$$

Parameters in MSSM Higgs potential V (besides g, g'):

$$v_1,\ v_2,\ m_1,\ m_2,\ m_{12}$$

relation for M_W^2, M_Z^2 $\Rightarrow$ 1 condition

minimization of V w.r.t. neutral Higgs fields H_1^1, H_2^2 $\Rightarrow$ 2 conditions

$\Rightarrow$ only two free parameters remain in V, conventionally chosen as

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

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

In lowest order:

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

Predictions for m_h, m_H from diagonalization of tree-level mass matrix:

$\phi_1 - \phi_2$ basis:

$$M^{2,\text{tree}}_{\text{Higgs}} = \begin{pmatrix} m^2_{\phi_1} & m^2_{\phi_1\phi_2} \\ m^2_{\phi_1\phi_2} & m^2_{\phi_2} \end{pmatrix} =$$

$$\begin{pmatrix} M_A^2 \sin^2\beta + M_Z^2 \cos^2\beta & -(M_A^2 + M_Z^2) \sin\beta \cos\beta \\ -(M_A^2 + M_Z^2) \sin\beta \cos\beta & M_A^2 \cos^2\beta + M_Z^2 \sin^2\beta \end{pmatrix}$$

$$\Bigg\Downarrow \leftarrow \text{Diagonalization}, \alpha$$

$$\begin{pmatrix} m_H^{2,\text{tree}} & 0 \\ 0 & m_h^{2,\text{tree}} \end{pmatrix}$$

Tree-level result for m_h, m_H:

$$m_{H,h}^2 = \frac{1}{2}\left[M_A^2 + M_Z^2 \pm \sqrt{(M_A^2 + M_Z^2)^2 - 4M_Z^2 M_A^2 \cos^2 2\beta}\right]$$

$\Rightarrow$ $m_h \leq M_Z$ at tree level

$\Rightarrow$ Light Higgs boson h required in SUSY

Measurement of m_h, Higgs couplings

$\Rightarrow$ test of the theory (more directly than in SM)

Higgs couplings, tree level:

$$g_{hVV} = \sin(\beta - \alpha)\, g_{HVV}^{\text{SM}}, \quad V = W^{\pm}, Z$$

$$g_{HVV} = \cos(\beta - \alpha)\, g_{HVV}^{\text{SM}}$$

$$g_{hAZ} = \cos(\beta - \alpha)\, \frac{g'}{2\cos\theta_W}$$

$$g_{hb\bar{b}}, g_{h\tau^+\tau^-} = -\frac{\sin\alpha}{\cos\beta}\, g_{Hb\bar{b},H\tau^+\tau^-}^{\text{SM}}$$

$$g_{ht\bar{t}} = \frac{\cos\alpha}{\sin\beta}\, g_{Ht\bar{t}}^{\text{SM}}$$

$$g_{Ab\bar{b}}, g_{A\tau^+\tau^-} = \gamma_5 \tan\beta\, g_{Hb\bar{b}}^{\text{SM}}$$

⇒ $g_{hVV} \leq g_{HVV}^{\text{SM}}$, g_{hVV}, g_{HVV}, g_{hAZ} cannot all be small

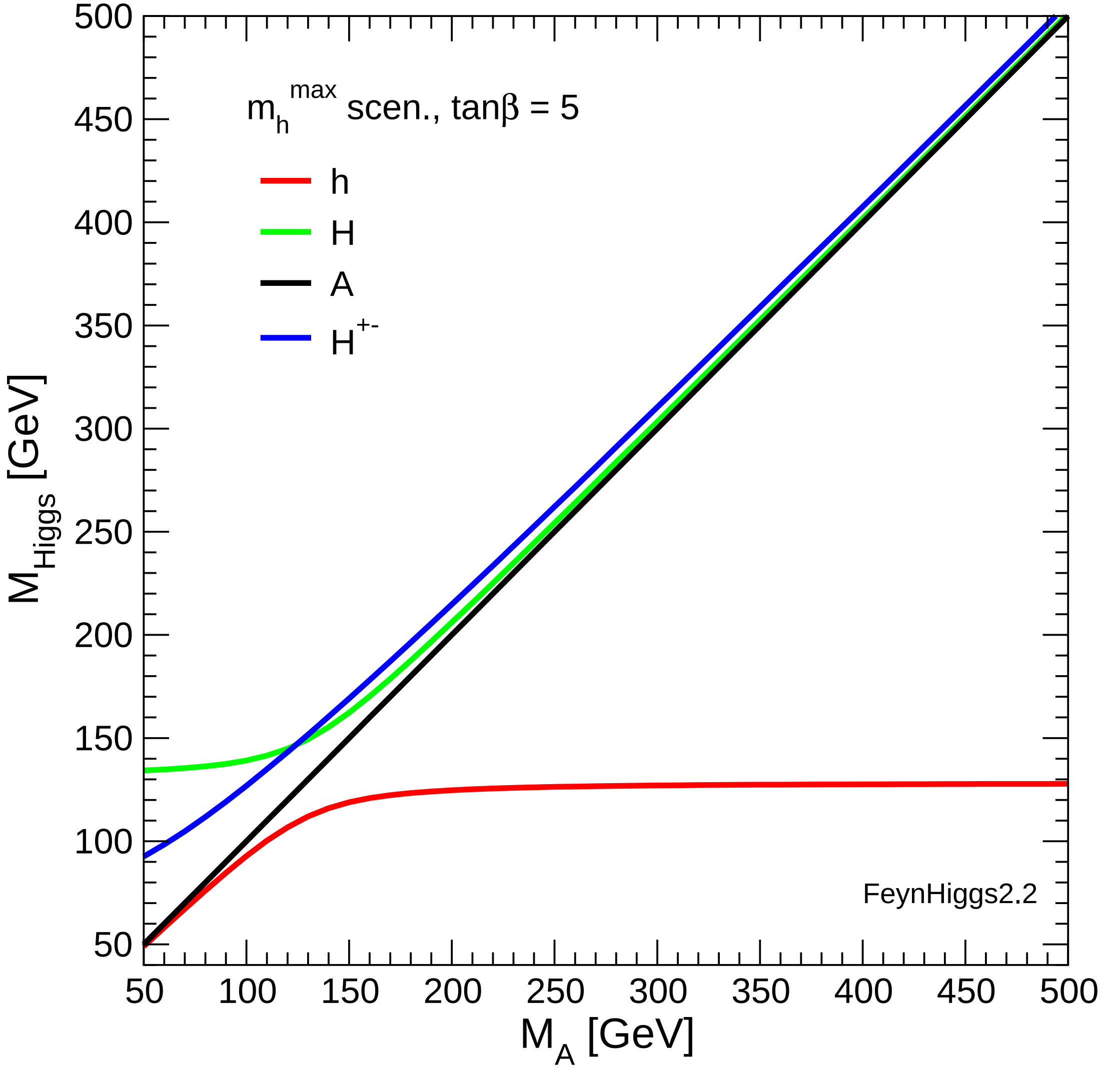
$g_{hb\bar{b}}, g_{h\tau^+\tau^-}$: significant suppression or enhancement w.r.t. SM coupling possible

The decoupling limit:

For $M_A \gtrsim 200$ GeV:

The lightest MSSM Higgs
is SM-like

$\Rightarrow$ SM analysis applies!



The heavy MSSM Higgses:

$M_A \approx M_H \approx M_{H^\pm}$

$\rightarrow$ coupling to gauge bosons ~ 0

$\Rightarrow$ no decay $H \rightarrow WW^{(*)}, \ldots$

2. Some NMSSM Higgs theory (Z_3 invariant NMSSM)

MSSM Higgs sector: Two Higgs doublets

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

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

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

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

2. Some NMSSM Higgs theory (Z_3 invariant NMSSM)

NMSSM Higgs sector: Two Higgs doublets + one Higgs singlet

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

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

$$S = v_s + S_R + IS_I$$

$$\begin{aligned} V = & (\tilde{m}_1^2 + |\not{\mu}\lambda S|^2)H_1\bar{H}_1 + (\tilde{m}_2^2 + |\not{\mu}\lambda S|^2)H_2\bar{H}_2 - m_{12}^2(\epsilon_{ab}H_1^aH_2^b + \text{h.c.}) \\ & + \frac{g'^2 + g^2}{8}(H_1\bar{H}_1 - H_2\bar{H}_2)^2 + \frac{g^2}{2}|H_1\bar{H}_2|^2 \\ & + |\lambda(\epsilon_{ab}H_1^aH_2^b) + \kappa S^2|^2 + m_S^2|S|^2 + (\lambda A_\lambda(\epsilon_{ab}H_1^aH_2^b)S + \frac{\kappa}{3}A_\kappa S^3 + \text{h.c.}) \end{aligned}$$

Free parameters:

$$\lambda,\ \kappa,\ A_\kappa,\ M_{H^\pm},\ \tan\beta,\ \mu_{\text{eff}} = \lambda v_s$$

Higgs spectrum:

$$\mathcal{CP}\text{−even} : h_1, h_2, h_3$$
$$\mathcal{CP}\text{−odd} : a_1, a_2$$
$$\text{charged} : H^+, H^-$$
$$\text{Goldstones} : G^0, G^+, G^-$$

Neutralinos:

$$\mu \to \mu_{\text{eff}}$$

compared to the MSSM: one singlino more

$$\to \tilde{\chi}^0_1, \tilde{\chi}^0_2, \tilde{\chi}^0_3, \tilde{\chi}^0_4, \tilde{\chi}^0_5$$

Mass of the lightest $\mathcal{CP}$-even Higgs:

$$m^2_{h,\text{tree},\text{NMSSM}} = m^2_{h,\text{tree},\text{MSSM}} + M_Z^2 \frac{\lambda^2}{g^2} \sin^2 2\beta$$

Mass of the $\mathcal{CP}$-odd Higgs:

$$\text{MSSM}: M_A^2 = -m_{12}^2(\tan\beta + \cot\beta) = \mu B(\tan\beta + \cot\beta)$$

$$\text{NMSSM}: \text{"}M_A^2\text{"} = \mu_{\text{eff}} B_{\text{eff}} (\tan\beta + \cot\beta)$$

with $B_{\text{eff}} = A_\lambda + \kappa\, s, \ \mu_{\text{eff}} = \lambda\, s$ $\Rightarrow$ one very light a_1

Mass of the charged Higgs:

$$\text{MSSM}: M_{H^\pm}^2 = M_A^2 + M_W^2 = M_A^2 + \frac{1}{2} v^2 g^2$$

$$\text{NMSSM}: M_{H^\pm}^2 = M_A^2 + v^2 \left(\frac{g^2}{2} - \lambda^2\right)$$

Mass of the lightest $\mathcal{CP}$-even Higgs:

$$m^2_{h,\text{tree,NMSSM}} = m^2_{h,\text{tree,MSSM}} + M_Z^2 \frac{\lambda^2}{g^2} \sin^2 2\beta$$

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Mass of the charged Higgs:

$$\text{MSSM} : M^2_{H^\pm} = M_A^2 + M_W^2 = M_A^2 + \frac{1}{2} v^2 g^2$$

$$\text{NMSSM} : M^2_{H^\pm} = M_A^2 + v^2 \left(\frac{g^2}{2} - \lambda^2 \right)$$

$\Rightarrow M_{h_1}^{\text{MSSM,tree}} \le M_{h_1}^{\text{NMSSM,tree}}$, one light a_1, $M_{H^\pm}^{\text{MSSM,tree}} \ge M_{H^\pm}^{\text{NMSSM,tree}}$

3. The lightest MSSM Higgs boson

MSSM predicts upper bound on M_h:

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

Large radiative corrections: → excursion

Yukawa couplings: $\frac{e\, m_t}{2 M_W s_W}$, $\frac{e\, m_t^2}{M_W s_W}$, ...

⇒ Dominant one-loop corrections: $\Delta M_h^2 \sim G_\mu m_t^4 \log\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right)$

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

Present status of M_h prediction in the MSSM:

Complete 1L, 'almost complete' 2L available, LL + NLL resummation ...

What is a mass

Definition: The mass of a particle is the pole of the propagator

Example: scalar particle

Propagator:

$$\frac{i}{q^2 - m^2}$$

q^2 : four-momentum squared
m^2: constant in the Lagrangian

If one chooses $q^2 = m^2$ then the propagator has a pole.
This q^2 is then the mass of the particle.

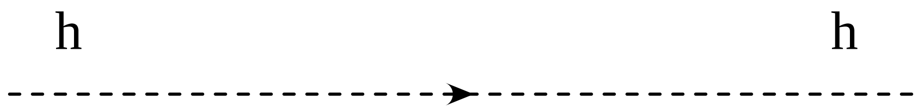
$\Rightarrow$ Pole of the propagator corresponds to zeroth of the inverse propagator.

Inverse propagator:

$$-i(q^2 - m^2)$$

Problem: quantum corrections

Higgs propagator:



$\Downarrow$ quantum corrections

Inverse propagator:

$$-i(q^2 - m^2) \quad \longrightarrow \quad -\,i\left(q^2 - m^2 + \hat{\Sigma}_h(q^2)\right)$$

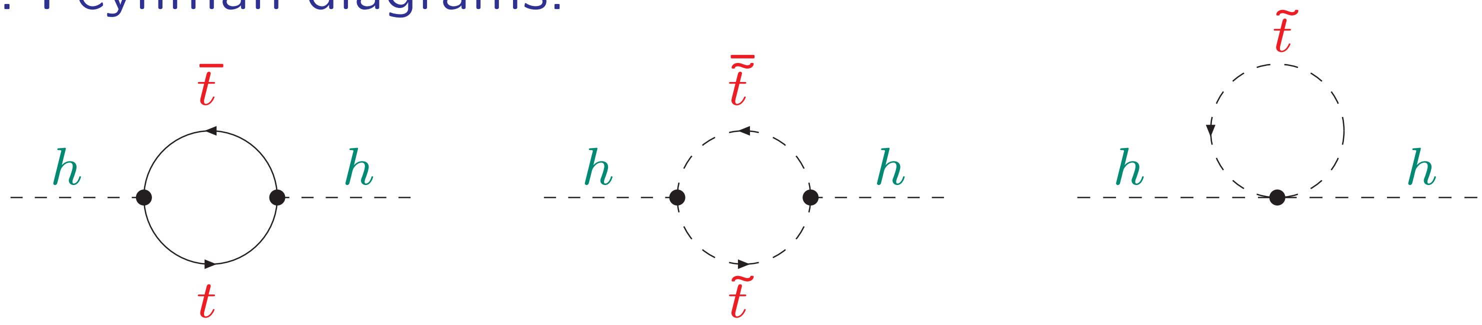
$\hat{\Sigma}_h(q^2)$: renormalized Higgs self-energy

Calculation of the blob:

$$= \hat{\Sigma}(q^2) = \hat{\Sigma}^{(1)}(q^2) + \hat{\Sigma}^{(2)}(q^2) + \ldots$$

: all MSSM particles contribute
main contribution: $t/\tilde{t}$ sector ($\tilde{t}$: scalar top, SUSY partner of the t)

1-Loop: Feynman diagrams:



Dominant 1-loop corrections: $\Delta m_h^2 \sim G_\mu m_t^4 \log\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right)$

size of the corrections: $\mathcal{O}$(50 GeV)

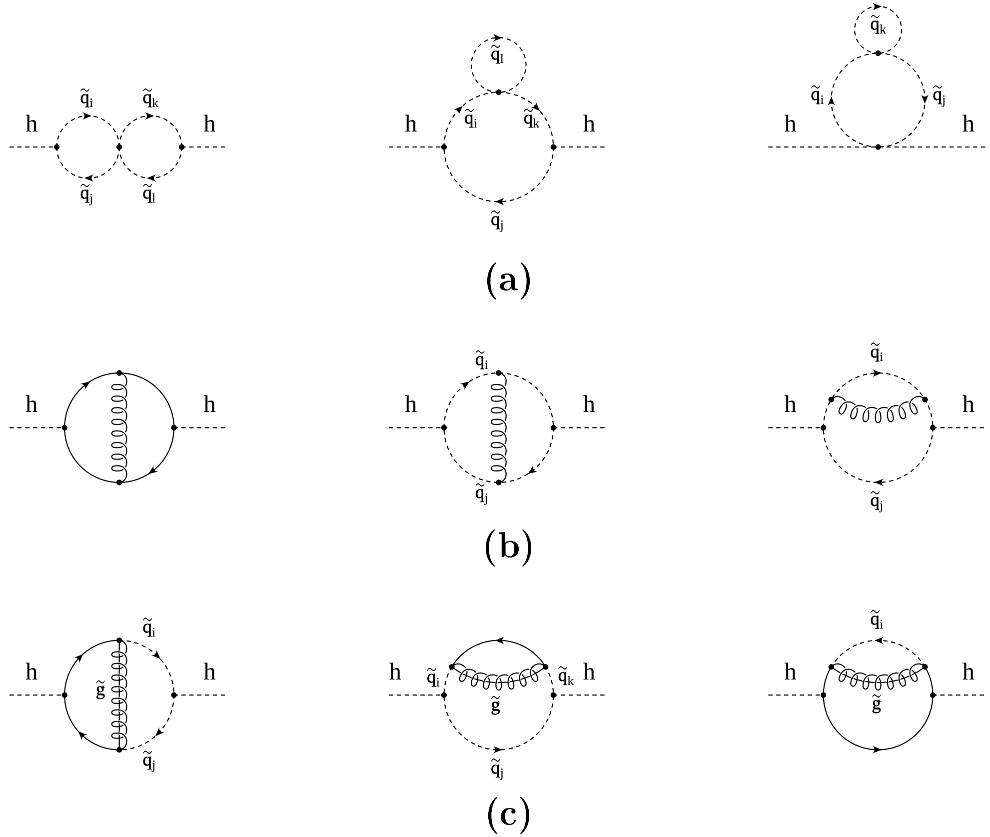
$\Rightarrow$ 2-Loop calculation necessary!

2-loop: $\hat{\Sigma}^{(2)}(0)$

[*S. H., W. Hollik, G. Weiglein '98*]

dominant contributions of $\mathcal{O}(\alpha_t \alpha_s)$:

(a) pure scalar diagrams
(b) diagrams with gluonexchange
(c) diagrams with gluinoexchange



Quite complicated calculation . . .
⇒ Need for computer algebra programms

[*'98 - '13:*] ⇒ many more corrections calculated!

End of excursion: Higgs mass calculations

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Mixing of the $\mathcal{CP}$-even Higgs bosons:

Propagator/Mass matrix at tree-level:

$$\begin{pmatrix} q^2 - m_H^2 & 0 \\ 0 & q^2 - m_h^2 \end{pmatrix}$$

Propagator / mass matrix with higher-order corrections
($\to$ Feynman-diagrammatic approach):

$$M_{hH}^2(q^2) = \begin{pmatrix} q^2 - m_H^2 + \hat{\Sigma}_{HH}(q^2) & \hat{\Sigma}_{Hh}(q^2) \\ \hat{\Sigma}_{hH}(q^2) & q^2 - m_h^2 + \hat{\Sigma}_{hh}(q^2) \end{pmatrix}$$

$\hat{\Sigma}_{ij}(q^2)$ $(i, j = h, H)$: renormalized Higgs self-energies

$\mathcal{CP}$-even fields can mix

$\Rightarrow$ complex roots of $\det(M_{hH}^2(q^2))$: $\mathcal{M}_{h_i}^2$ $(i = 1, 2)$: $\mathcal{M}^2 = M^2 - iM\Gamma$

Upper bound on M_h in the MSSM:

"Unconstrained MSSM":

M_A, $\tan\beta$, 5 parameters in $\tilde{t}$–$\tilde{b}$ sector, μ, $m_{\tilde{g}}$, M_2

$$M_h \lesssim 135\text{ GeV}$$

for $m_t = 173.2 \pm 0.9\,\text{GeV}$ and $m_{\tilde{t}} \lesssim 2$ TeV

(including theoretical uncertainties from unknown higher orders)

$\Rightarrow$ observable at the LHC

Obtained with:

FeynHiggs

`www.feynhiggs.de`

[*H. Bahl, T. Hahn, S.H., W. Hollik, S. Passehr, H. Rzehak, G. Weiglein '98 – '18*]

$\to$ all Higgs masses, couplings, BRs, XSs (easy to link, easy to use :-)

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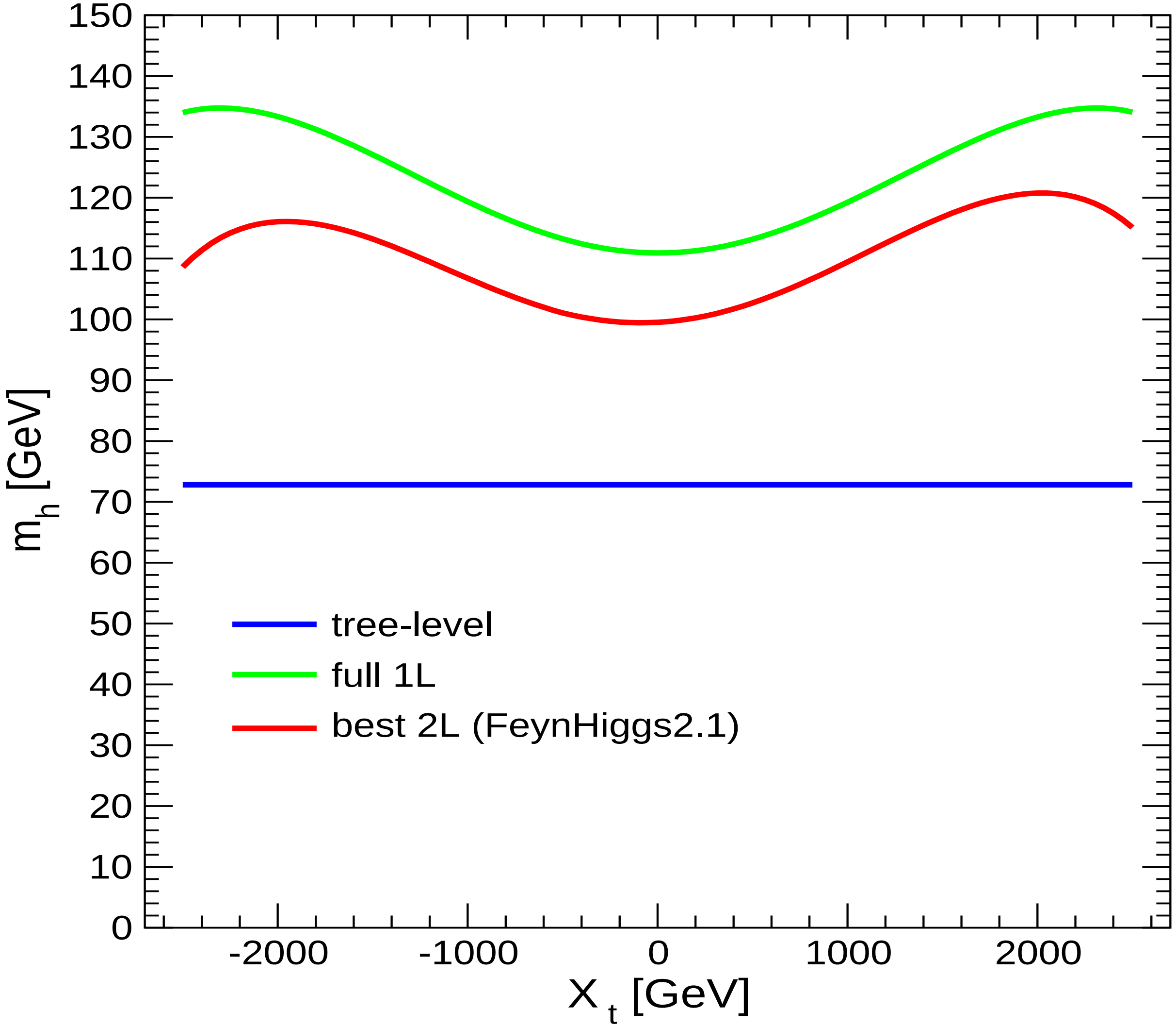
Effects of the two-loop corrections to the lightest Higgs mass:

Example for one set of MSSM parameters



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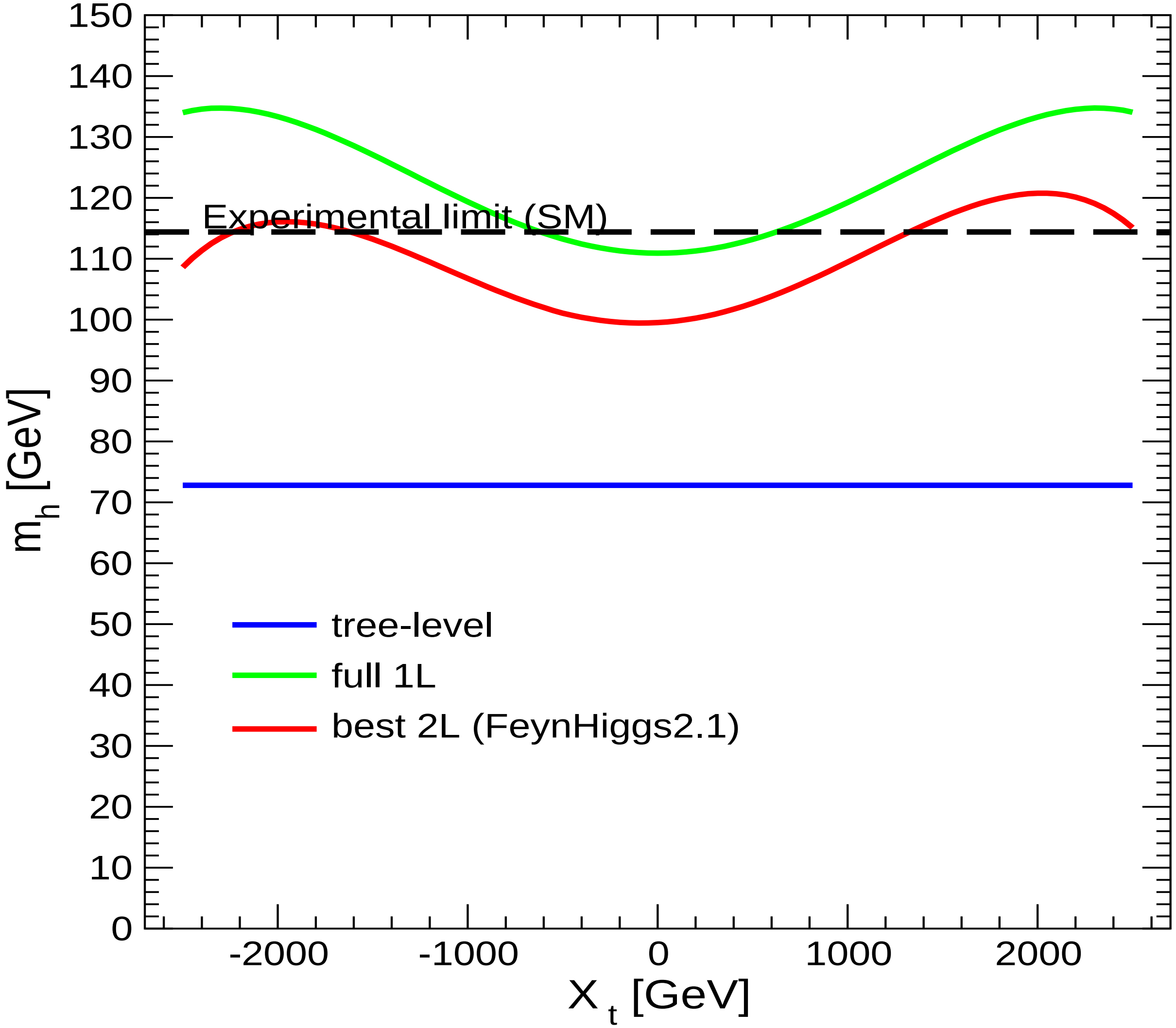

Comparison with experimental limits

⇒ strong impact on bound on SUSY parameters

A simple exercise on stop masses:

$\Rightarrow$ Dominant one-loop corrections: $\Delta M_h^2 \sim G_\mu m_t^4 \log\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right)$

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

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⇒ clear prediction for the LHC?

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For this exercise make sure:
⇒ use the best available Higgs mass calculation!

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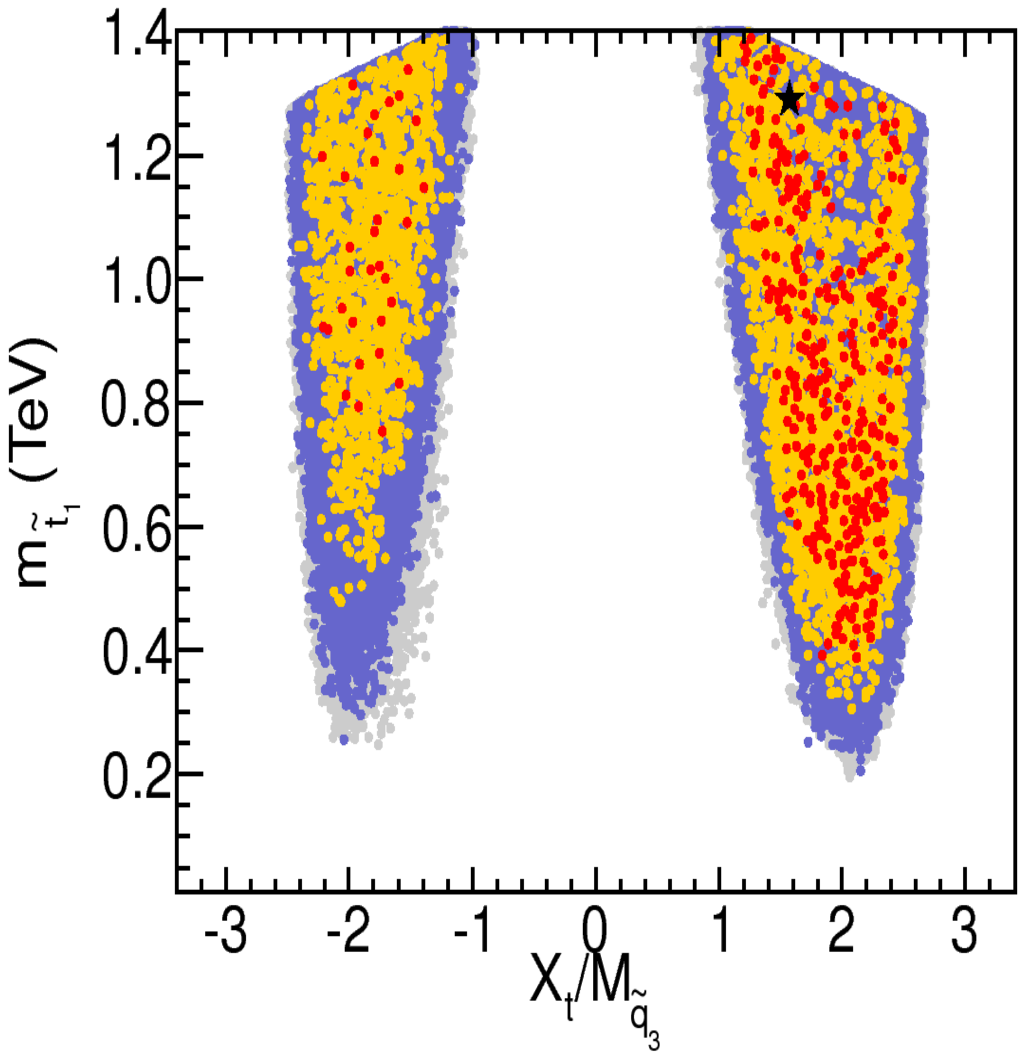
Stop masses:

[P. Bechtle, S.H., O. Stål, T. Stefaniak, G. Weiglein, L. Zeune '16]



$M_h = 125 \pm 3$ GeV

$\star$: best-fit point

red: $\Delta\chi^2 < 2.3$

orange: $\Delta\chi^2 < 5.99$

blue: all points HiggsBounds allowed

gray: all scan points

$\Rightarrow M_h \sim 125$ GeV requires large X_t and/or large M_{SUSY}

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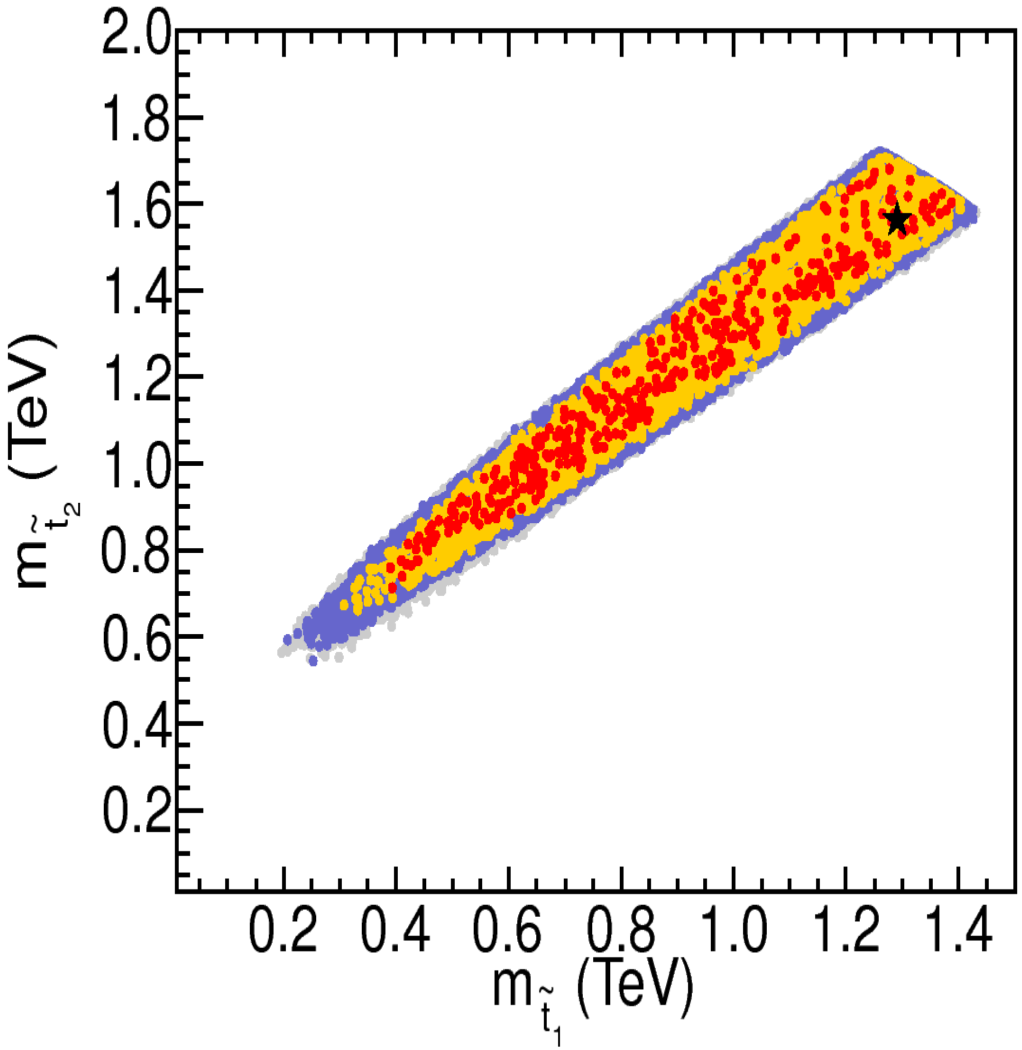

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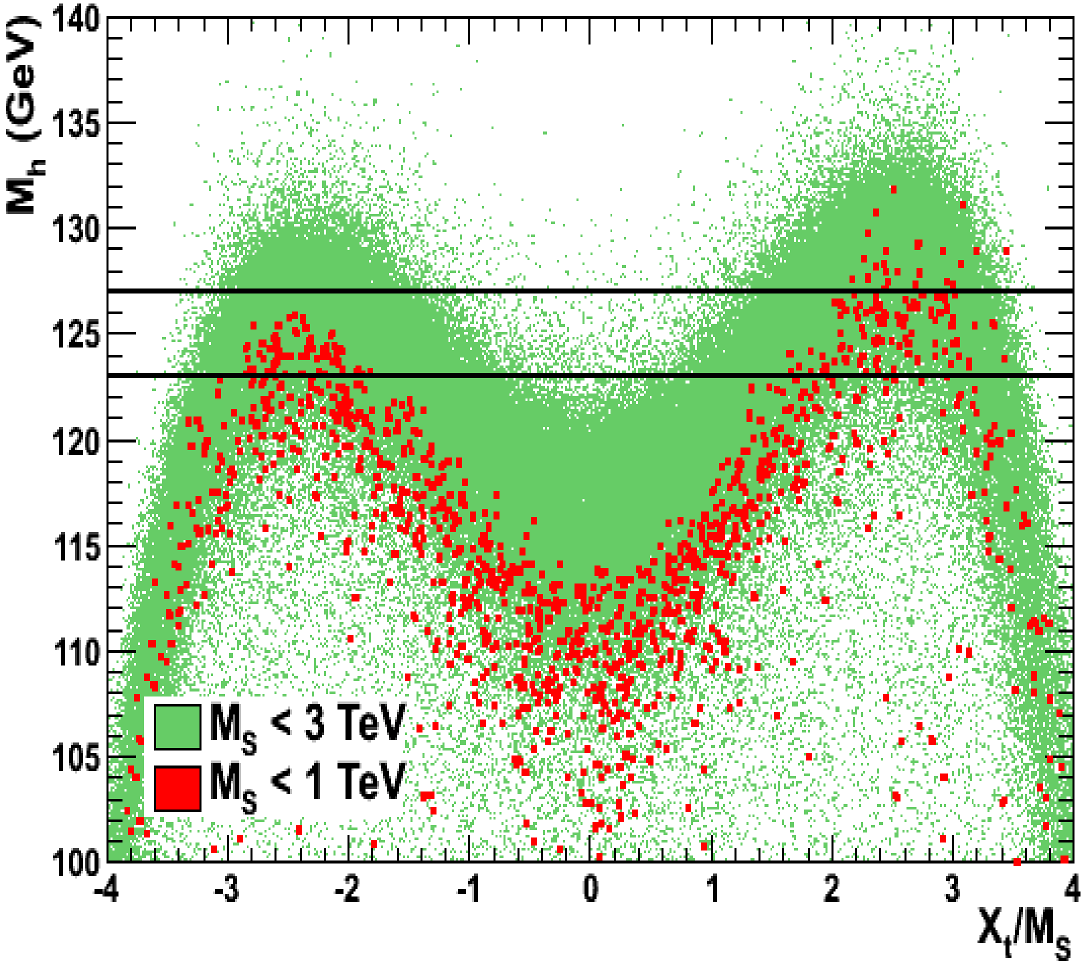
$\Rightarrow$ light and heavy stops compatible with $M_h \simeq 125$ GeV

Stop masses for $M_h = 125$ GeV

[*A. Arbey et al., '11*]



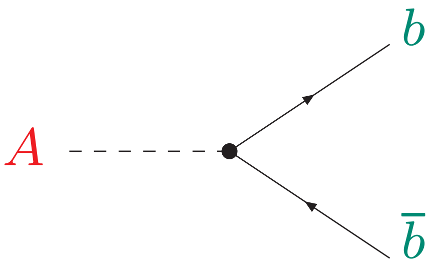
$\Rightarrow M_h \sim 125$ GeV requires large X_t and/or large M_{SUSY}

$\Rightarrow$ no clear prediction for the LHC!

4. The heavy MSSM Higgs bosons

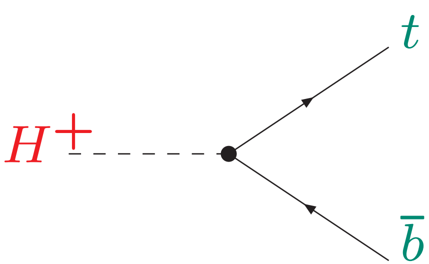
Differences compared to the SM Higgs:

Additional enhancement factors compared to the SM case:



$$y_b \quad \rightarrow \quad y_b \frac{\tan\beta}{1+\Delta_b}$$

At large $\tan\beta$: either $H \approx A$ or $h \approx A$



$$y_b \frac{\tan\beta}{1+\Delta_b}$$

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

$\Rightarrow$ other parameters enter $\Rightarrow$ strong μ dependence

Most powerful LHC search modes for heavy MSSM Higgs bosons:

$$b\bar{b} \to H/A \to \tau^+\tau^- + X$$
$$gb \to tH^\pm + X, \;\; H^\pm \to \tau\nu_\tau$$
$$pp \to t\bar{t} \to H^\pm + X, \;\; H^\pm \to \tau\nu_\tau$$

Enhancement factors compared to the SM case:

$$H/A \; : \; \frac{\tan^2\beta}{(1+\Delta_b)^2} \times \frac{\mathrm{BR}(H \to \tau^+\tau^-) + \mathrm{BR}(A \to \tau^+\tau^-)}{\mathrm{BR}(H \to \tau^+\tau^-)_{\mathrm{SM}}}$$

$$H^\pm \; : \; \frac{\tan^2\beta}{(1+\Delta_b)^2} \times \mathrm{BR}(H^\pm \to \tau\nu_\tau)$$

$\Rightarrow$ Δ_b effects

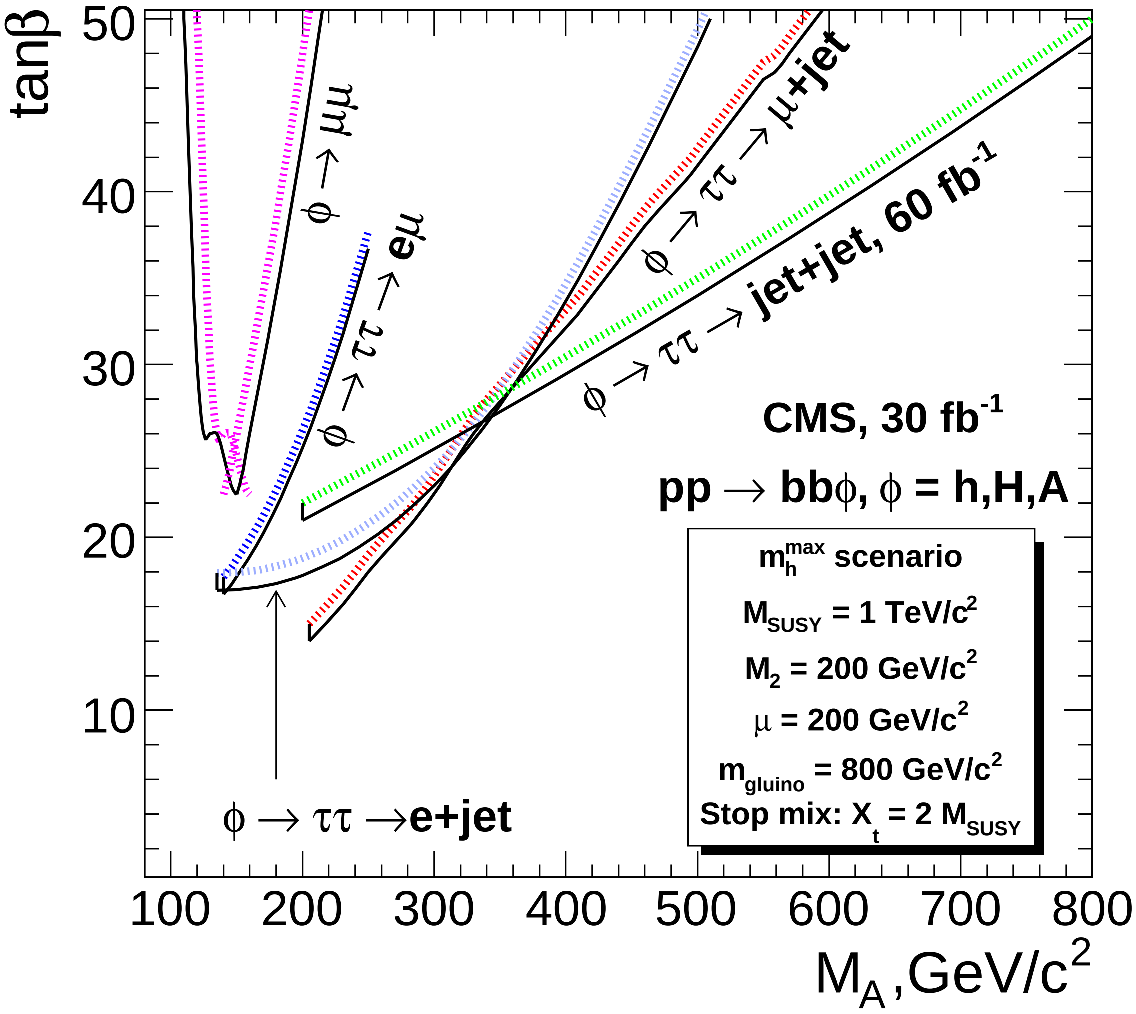
also relevant for $\mathrm{BR}(H/A \to \tau^+\tau^-)$, $\mathrm{BR}(H^\pm \to \tau\nu_\tau)$

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

$\Rightarrow$ additional effects on $\mathrm{BR}(H/A \to \tau^+\tau^-)$, $\mathrm{BR}(H^\pm \to \tau\nu_\tau)$

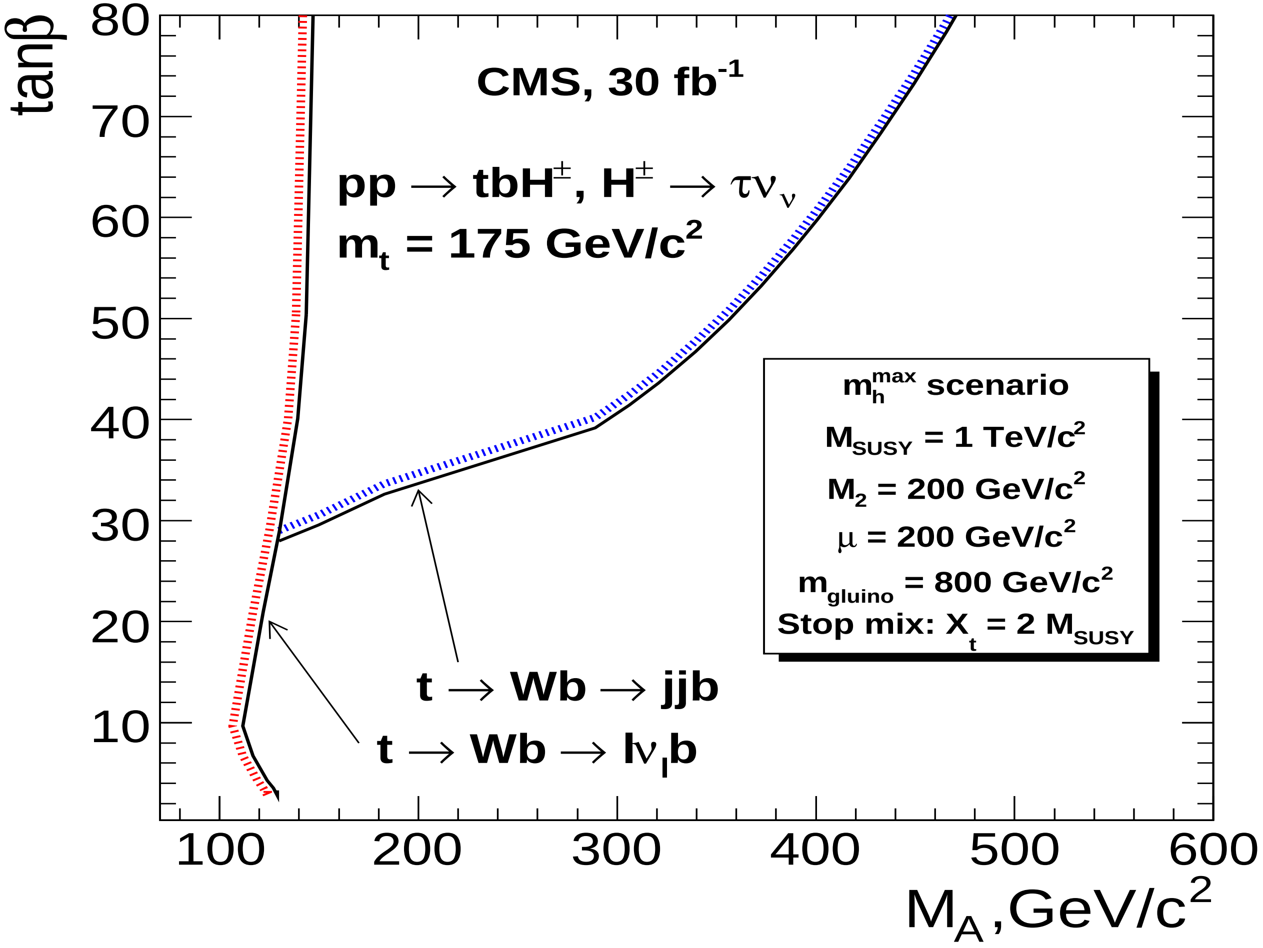
Pre-LHC results for neutral heavy Higgs bosons searches:

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



Pre-LHC results for Charged Higgs boson searches:

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:

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

5. The MSSM Higgs sector 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)

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

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 ϕ_{PQ}

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

  $\Rightarrow$ 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: $T_A^{\text{tree}} \propto \sin\xi \, m_{12}^2 \overset{!}{=} 0$
  $\Rightarrow \xi = 0 \Rightarrow$ 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:

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

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

More on complex phases: Neutralinos and charginos:

Higgsinos and electroweak gauginos mix

charged:

$$\tilde{W}^+, \tilde{h}_u^+ \to \tilde{\chi}_1^+, \tilde{\chi}_2^+, \qquad \tilde{W}^-, \tilde{h}_d^- \to \tilde{\chi}_1^-, \tilde{\chi}_2^-$$

Diagonalization of the mass matrix:

$$\mathbf{X} = \begin{pmatrix} M_2 & \sqrt{2}\sin\beta\, M_W \\ \sqrt{2}\cos\beta\, M_W & \mu \end{pmatrix},$$

$$\mathbf{M}_{\tilde{\chi}^-} = \mathbf{V}^* \mathbf{X}^\top \mathbf{U}^\dagger = \begin{pmatrix} m_{\tilde{\chi}_1^\pm} & 0 \\ 0 & m_{\tilde{\chi}_2^\pm} \end{pmatrix}$$

$\Rightarrow$ charginos: mass eigenstates

mass matrix given in terms of M_2, μ, $\tan\beta$ $\Rightarrow$ M_2, μ can be complex neutral:

$$\underbrace{\tilde{\gamma}, \tilde{Z}}_{\tilde{W}^0, \tilde{B}^0}, \tilde{h}_u^0, \tilde{h}_d^0 \to \tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$$

Diagonalization of mass matrix:

$$\mathbf{Y} = \begin{pmatrix} M_1 & 0 & -M_Z\, s_W \cos\beta & M_Z\, s_W \sin\beta \\ 0 & M_2 & M_Z\, c_W \cos\beta & -M_Z\, c_W \sin\beta \\ -M_Z\, s_W \cos\beta & M_Z\, c_W \cos\beta & 0 & -\mu \\ M_Z\, s_W \sin\beta & -M_Z\, c_W \sin\beta & -\mu & 0 \end{pmatrix},$$

$$\mathbf{M}_{\tilde{\chi}^0} = \mathbf{N}^* \, \mathbf{Y} \, \mathbf{N}^\dagger = \mathbf{diag}(m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_2^0}, m_{\tilde{\chi}_3^0}, m_{\tilde{\chi}_4^0})$$

$\Rightarrow$ neutralinos: mass eigenstates

mass matrix given in terms of M_1, M_2, μ, $\tan\beta$

$\Rightarrow$ M_1, M_2, μ can be complex

$\Rightarrow$ only one new parameter

$\Rightarrow$ MSSM predicts mass relations between neutralinos and charginos

Propagator/Mass matrix at tree-level: no $\mathcal{CP}$ violation:

$$\begin{pmatrix} q^2 - m_H^2 & 0 \\ 0 & q^2 - m_h^2 \end{pmatrix}$$

Propagator / mass matrix with higher-order corrections
($\to$ Feynman-diagrammatic approach):

$$M_{hH}^2(q^2) = \begin{pmatrix} q^2 - m_H^2 + \hat{\Sigma}_{HH}(q^2) & \hat{\Sigma}_{Hh}(q^2) \\ \hat{\Sigma}_{hH}(q^2) & q^2 - m_h^2 + \hat{\Sigma}_{hh}(q^2) \end{pmatrix}$$

$\hat{\Sigma}_{ij}(q^2)$ $(i, j = h, H)$: renormalized Higgs self-energies

$\mathcal{CP}$-even fields can mix

$\Rightarrow$ complex roots of det($M_{hH}^2(q^2)$): $\mathcal{M}_{h_i}^2 (i = 1, 2)$: $\mathcal{M}^2 = M^2 - iM\Gamma$

Propagator/Mass matrix at tree-level with $\not{CP}$ violation:

$$\begin{pmatrix} q^2 - m_A^2 & 0 & 0 \\ 0 & q^2 - m_H^2 & 0 \\ 0 & 0 & q^2 - m_h^2 \end{pmatrix}$$

Propagator / mass matrix with higher-order corrections
($\to$ Feynman-diagrammatic approach):

$$M_{hHA}^2(q^2) = \begin{pmatrix} q^2 - m_A^2 + \hat{\Sigma}_{AA}(q^2) & \hat{\Sigma}_{AH}(q^2) & \hat{\Sigma}_{Ah}(q^2) \\ \hat{\Sigma}_{HA}(q^2) & q^2 - m_H^2 + \hat{\Sigma}_{HH}(q^2) & \hat{\Sigma}_{Hh}(q^2) \\ \hat{\Sigma}_{hA}(q^2) & \hat{\Sigma}_{hH}(q^2) & q^2 - m_h^2 + \hat{\Sigma}_{hh}(q^2) \end{pmatrix}$$

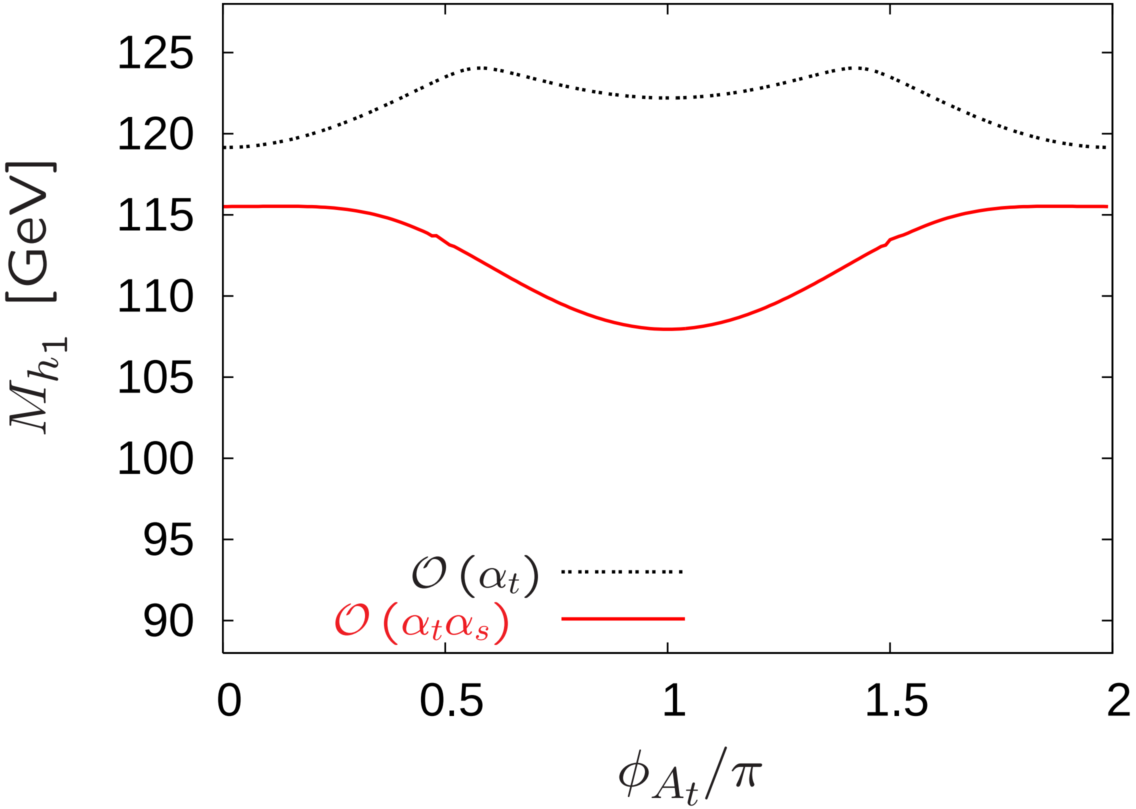
$\hat{\Sigma}_{ij}(q^2)$ $(i, j = h, H, A)$: renormalized Higgs self-energies

$\hat{\Sigma}_{Ah}, \hat{\Sigma}_{AH} \neq 0$ $\Rightarrow$ $\not{CP}$V, $\mathcal{CP}$-even and $\mathcal{CP}$-odd fields can mix

$\Rightarrow$ complex roots of det$(M_{hHA}^2(q^2))$: $\mathcal{M}_{h_i}^2 (i = 1, 2, 3)$: $\mathcal{M}^2 = M^2 - iM\Gamma$

M_{h_1} as a function of ϕ_{A_t}:

[S.H., W. Hollik, H. Rzehak, G. Weiglein '07]



$M_{\text{SUSY}} = 1000$ GeV

$|A_t| = 2000$ GeV

$\tan\beta = 10$

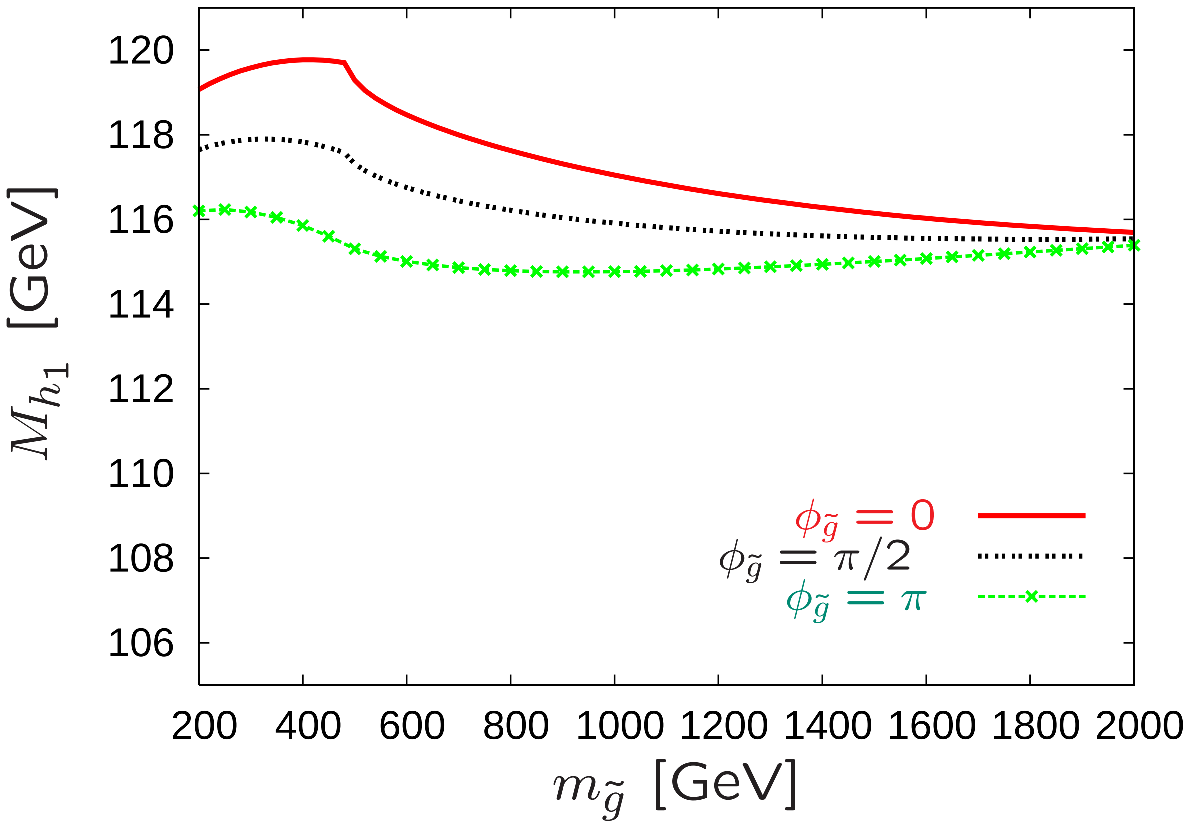
$M_{H^\pm} = 150$ GeV

OS renormalization

$\Rightarrow$ modified dependence on ϕ_{A_t} at the 2-loop level

M_{h_1} as a function of $\phi_{\tilde{g}}$:

[S.H., W. Hollik, H. Rzehak, G. Weiglein '07]



$M_{\text{SUSY}} = 500$ GeV
$A_t = 1000$ GeV
$\tan\beta = 10$
$M_{H^\pm} = 500$ GeV

OS renormalization

$\Rightarrow$ threshold at $m_{\tilde{g}} = m_{\tilde{t}} + m_t$

$\Rightarrow$ large effects around threshold

$\Rightarrow$ phase dependence has to be taken into account