
We still believe in supersymmetry
You must be joking

Higgs and BSM Phenomenology

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

Cosener's house, 07/2019

1. Basics of the Higgs
2. BSM Higgs physics (theory)
3. Higgs boson(s) at the LHC
4. Further BSM phenomenology

Higgs and BSM Phenomenology

BSM Higgs physics (theory)

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

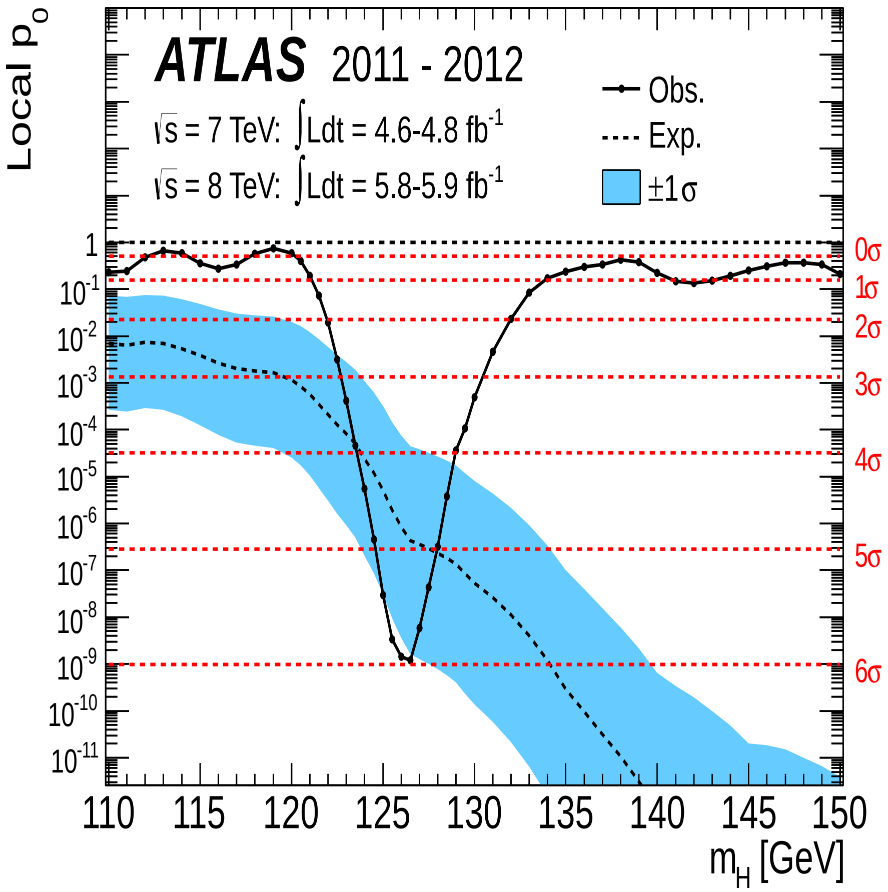
Cosener's house, 07/2019

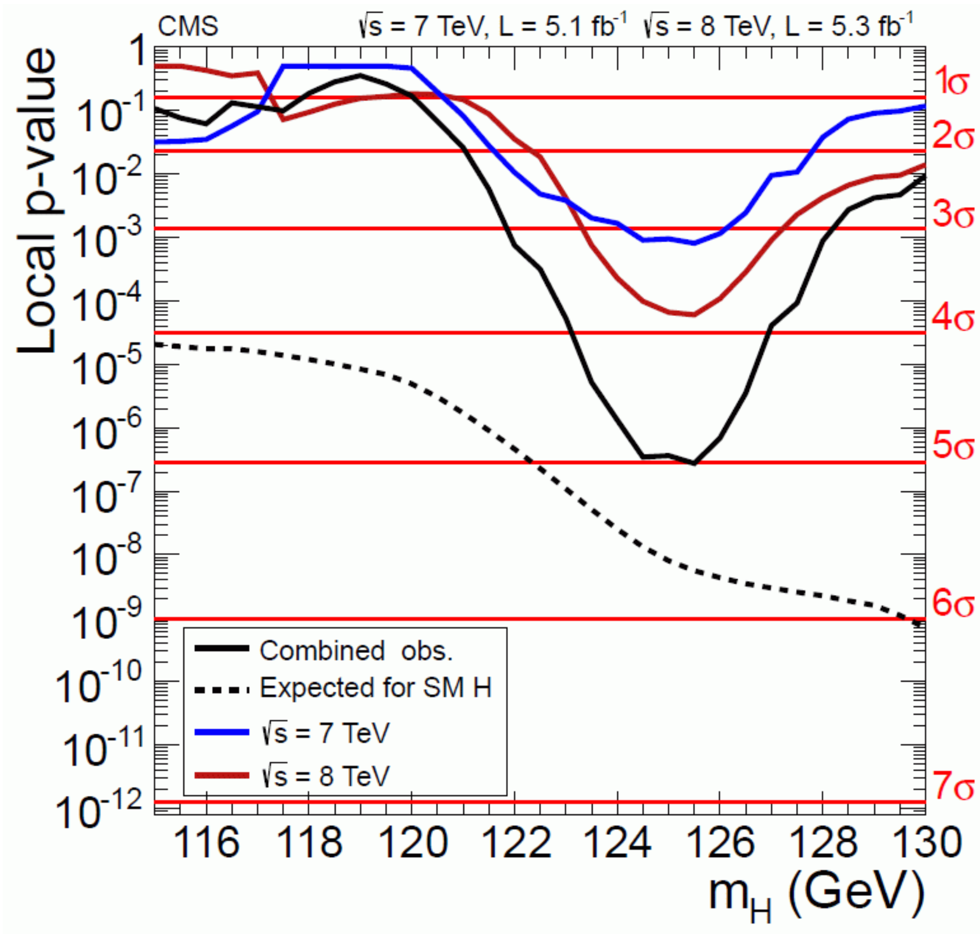
1. Why BSM Higgs Physics? Which BSM Higgs Physics?
2. MSSM Higgs Theory
3. NMSSM Higgs Theory
4. The lightest MSSM Higgs boson
5. The heavy MSSM Higgs bosons
6. The MSSM Higgs sector with $\mathcal{CP}$-violation
7. Little Higgs Models

1. Why BSM Higgs Physics? Which BSM Higgs Physics?

Fact I:

We have a discovery!

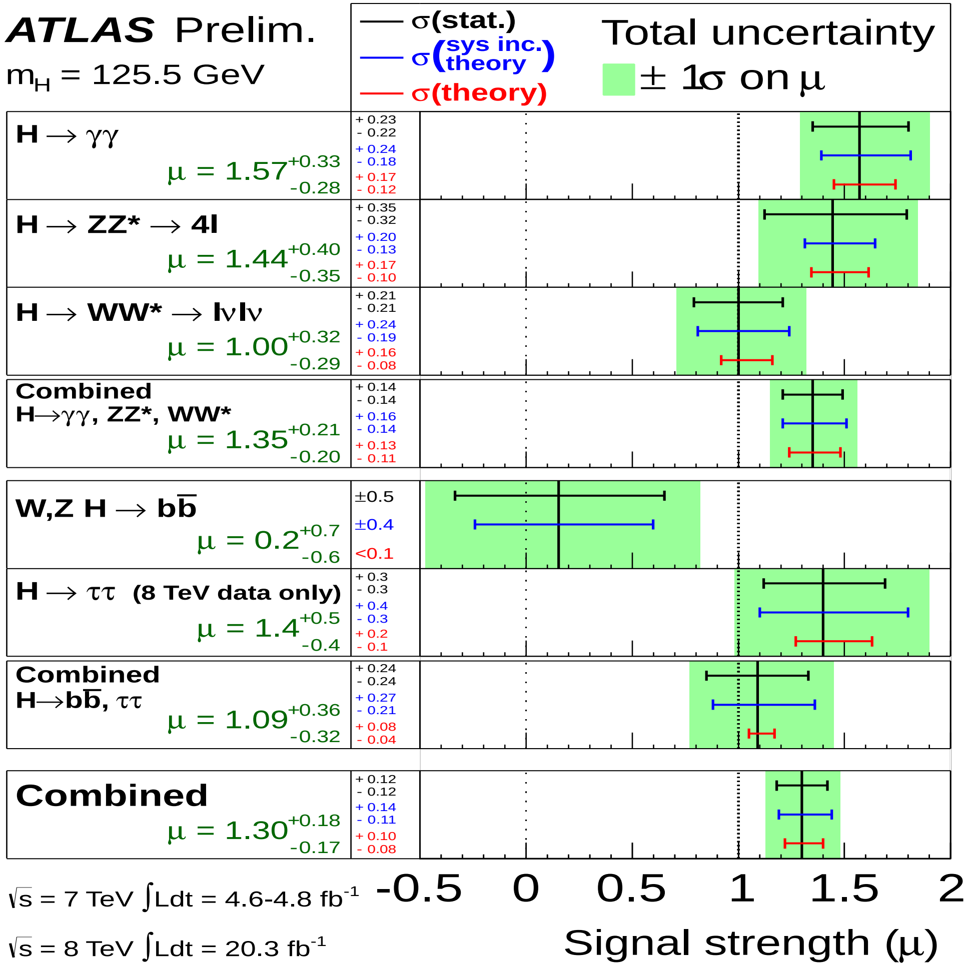


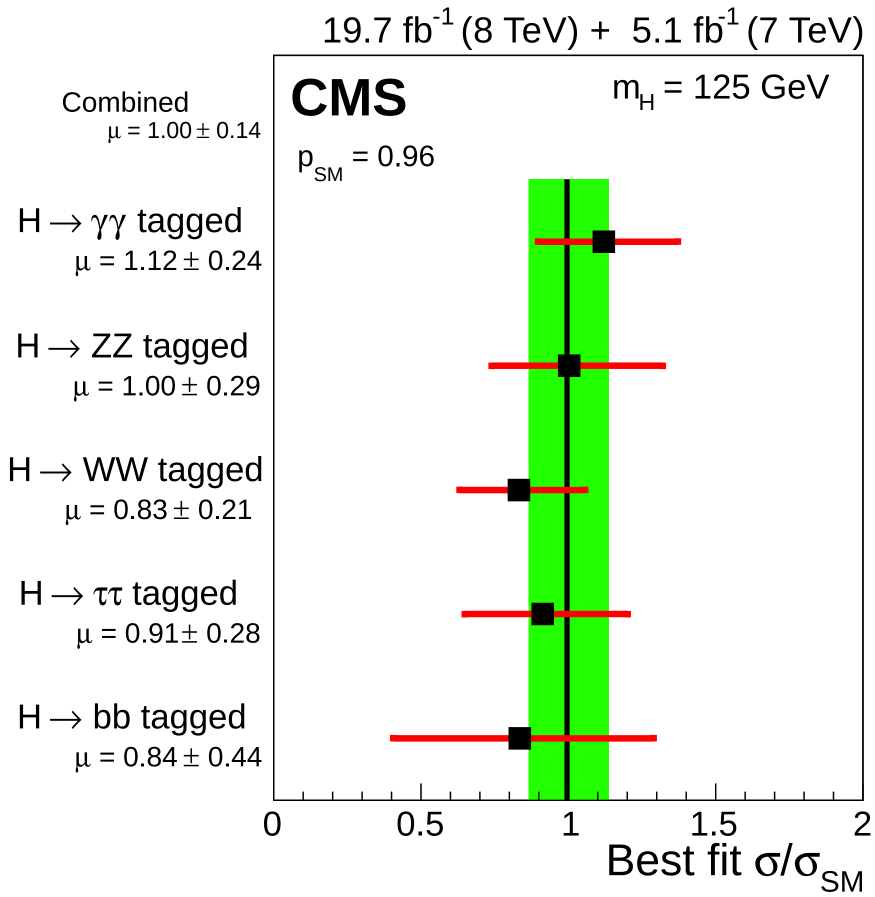


1. Motivation & Models

Fact I:

We have an SM-like discovery!





Fact II:

The SM cannot be the ultimate theory!

Some facts:

1. gravity is not included

2. the hierarchy problem

3. Dark Matter is not included

4. neutrino masses are not included

5. anomalous magnetic moment of the muon shows a $\sim 4\,\sigma$ discrepancy

Fact I & II:

We have a discovery!

The SM cannot be the ultimate theory!

Conclusion: It cannot be "the SM Higgs"!

Fact I & II:

We have a discovery!

The SM cannot be the ultimate theory!

Conclusion: It cannot be "the SM Higgs"!

Q: Does the BSM physics have any (relevant) impact on the Higgs?
Q': Which model?

Fact I & II:

We have a discovery!

The SM cannot be the ultimate theory!

Conclusion: It cannot be "the SM Higgs"!

Q: Does the BSM physics have any (relevant) impact on the Higgs?
Q': Which model?

A1: check changed properties

A2: check for additional Higgs bosons
A2': check for additional Higgs bosons above and below 125 GeV

The main questions:

- What are the couplings of this particle to other known elementary particles? Is its coupling to each particle proportional to that particles mass, as required by the BEH mechanism?
- What are the mass, total width, spin and $\mathcal{CP}$ properties of this particle? Are there additional sources of $\mathcal{CP}$ violation in the Higgs sector?
- What is the value of the particles self-coupling? Is this consistent with the expectation from the symmetry-breaking potential?
- Is this particle a single, fundamental scalar as in the SM, or is it part of a larger structure? Is it part of a model with additional scalar singlets/doublets/ldots?
  Or, could it be a composite state, bound by new interactions?
- Does this particle couple to new particles with no other couplings to the SM ("Higgs portal")? Is the particle mixed with new scalars of exotic origin, for example, the radion of extra-dimensional models?

Models with extended Higgs sectors:

Models with extended Higgs sectors:

Q: Can you tell me a few examples?

Models with extended Higgs sectors:

1. SM with addional Higgs singlet

2. Two Higgs Doublet Model (THDM): type I, II, III, IV

3. Minimal Supersymmetric Standard Model (MSSM)

4. MSSM with one extra singlet (NMSSM)

5. MSSM with more extra singlets

6. SM/MSSM with Higgs triplets

7. ...

⇒ BSM models without extended Higgs sectors still have changed Higgs properties (quantum corrections!)

⇒ SM + vector-like fermions, Higgs portal, Higgs-radion mixing, ...

Which model should we focus on?

Which model should we focus on? $\Rightarrow$ experimental data as guidance!

Which model should we focus on? $\Rightarrow$ experimental data as guidance!

Some “recent” measurements:

- top quark mass
- Higgs boson mass
- Higgs boson “couplings”
- Dark Matter (properties)

Which model should we focus on? ⇒ experimental data as guidance!

Some “recent” measurements:

- top quark mass
- Higgs boson mass
- Higgs boson “couplings”
- Dark Matter (properties)

Simple SUSY models predicted correctly:

- top quark mass
- Higgs boson mass
- Higgs boson “couplings”
- Dark Matter (properties)

Which model should we focus on? ⇒ experimental data as guidance!

Some "recent" measurements:

- top quark mass
- Higgs boson mass
- Higgs boson "couplings"
- Dark Matter (properties)

Simple SUSY models predicted correctly:

- top quark mass
- Higgs boson mass
- Higgs boson "couplings"
- Dark Matter (properties)

⇒ good motivation to look at SUSY! :-)

2. MSSM Higgs Theory

Comparison with SM case:

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

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

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

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

Q: How many (physical) Higgs bosons are there? And why?

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

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

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

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

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)

$$\tan\beta = \frac{v_2}{v_1}$$

Q: what are "normal" values of $\tan\beta$?

Rotation to physical basis:

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

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

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:

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

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

$$\Big\Downarrow \quad \leftarrow \ \text{Diagonalization}, \alpha$$

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

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

Tree-level result for m_h, m_H:

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

$\Rightarrow m_h \leq M_Z$ at tree level

Q: What does this imply?

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:

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

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

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

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

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

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

$\Rightarrow$ $g_{hVV} \le g_{HVV}^{\rm SM}$, 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

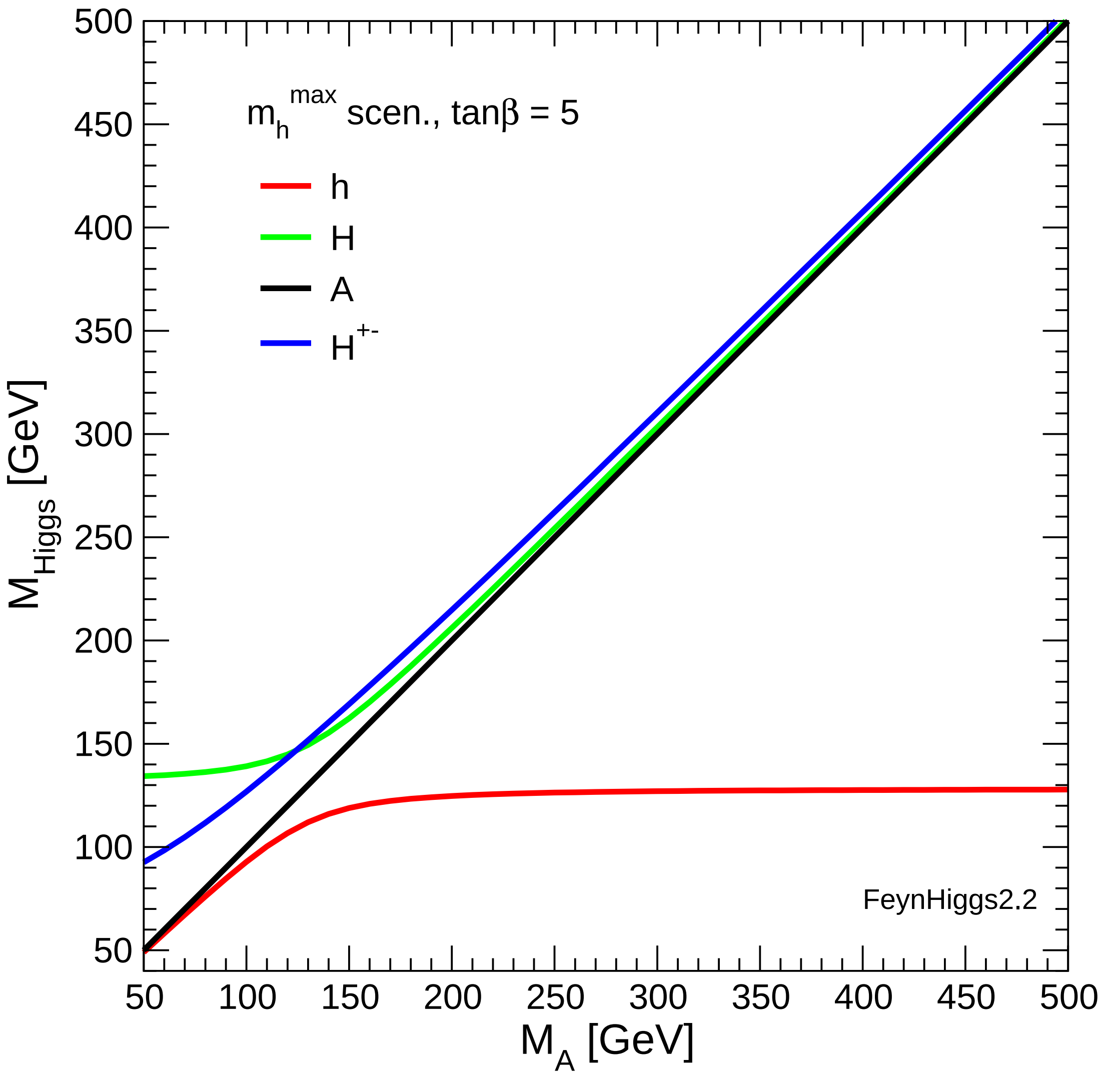
$\Rightarrow$ SM analysis applies!

The heavy MSSM Higgses:

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

$\rightarrow$ coupling to gauge bosons ~ 0

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



3. Some NMSSM Higgs theory (Z_3 invariant NMSSM)

MSSM Higgs sector: Two Higgs doublets

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

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

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

3. Some NMSSM Higgs theory (Z_3 invariant NMSSM)

NMSSM Higgs sector: Two Higgs doublets + one Higgs singlet

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

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

$$S = v_s + S_R + IS_I$$

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

Free parameters:

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

Higgs spectrum:

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

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:

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

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:

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

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:

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

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

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

4. 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:

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

$\Rightarrow$ 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)

Present status of M_h prediction in the MSSM:

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

The Higgs mass accuracy: experiment vs. theory:

Experiment:

ATLAS:	$M_h^{\text{exp}} = 125.36 \pm 0.37 \pm 0.18$ GeV
CMS:	$M_h^{\text{exp}} = 125.03 \pm 0.27 \pm 0.15$ GeV
combined:	$M_h^{\text{exp}} = 125.09 \pm 0.21 \pm 0.11$ GeV

The Higgs mass accuracy: experiment vs. theory:

Experiment:

ATLAS:	$M_h^{\text{exp}} = 125.36 \pm 0.37 \pm 0.18$ GeV
CMS:	$M_h^{\text{exp}} = 125.03 \pm 0.27 \pm 0.15$ GeV
combined:	$M_h^{\text{exp}} = 125.09 \pm 0.21 \pm 0.11$ GeV

MSSM theory:

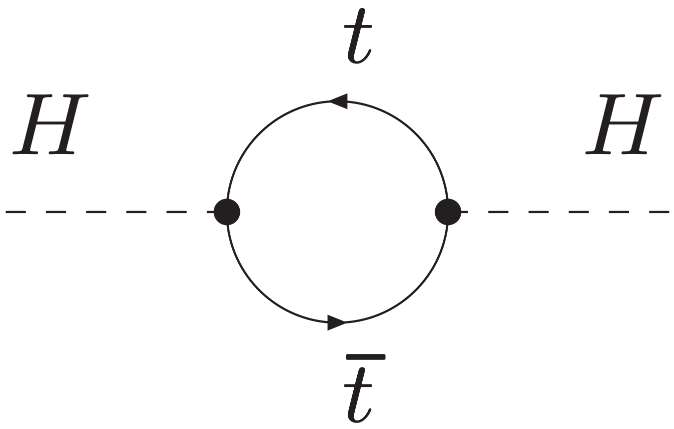
LHCHXSWG adopted FeynHiggs for the prediction of MSSM Higgs boson masses and mixings (considered to be the code containing the most complete implementation of higher-order corrections)

FeynHiggs: $\delta M_h^{\text{theo}} \sim 3$ GeV (now 2 GeV?)

$\rightarrow$ rough estimate, FeynHiggs contains algorithm to evaluate uncertainty, depending on parameter point

This is not a SUSY specific feature!

Nearly any model: large coupling of the Higgs to the top quark:



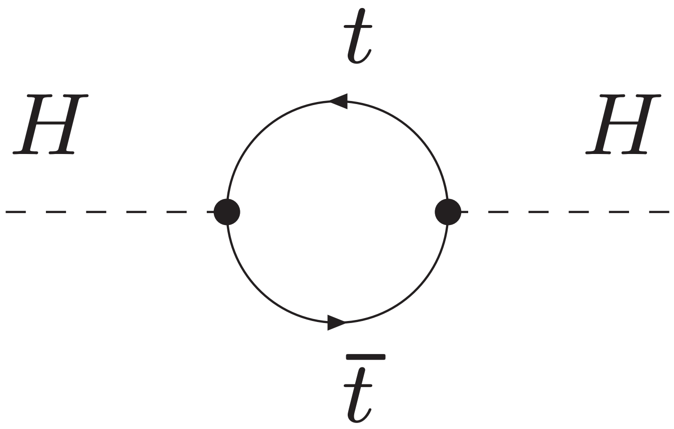
$\Rightarrow$ one-loop corrections $\Delta M_H^2 \sim G_\mu m_t^4$

$\Rightarrow$ M_H depends sensitively on m_t in all models where M_H can be predicted (SM: M_H is free parameter)

SUSY as an example: $\Delta m_t \approx \pm 1$ GeV $\Rightarrow$ $\Delta M_h \approx \pm 1$ GeV

This is not a SUSY specific feature!

Nearly any model: large coupling of the Higgs to the top quark:



$\Rightarrow$ one-loop corrections $\Delta M_H^2 \sim G_\mu m_t^4$

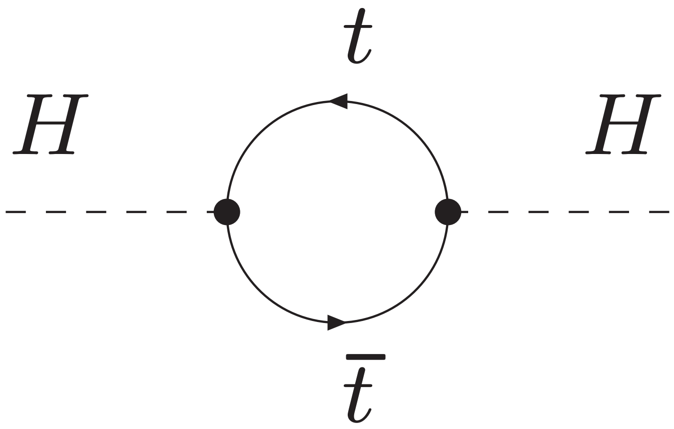
$\Rightarrow$ M_H depends sensitively on m_t in all models where M_H can be predicted (SM: M_H is free parameter)

SUSY as an example: $\Delta m_t \approx \pm 1$ GeV $\Rightarrow$ $\Delta M_h \approx \pm 1$ GeV

Q: Required precision for m_t?

This is not a SUSY specific feature!

Nearly any model: large coupling of the Higgs to the top quark:



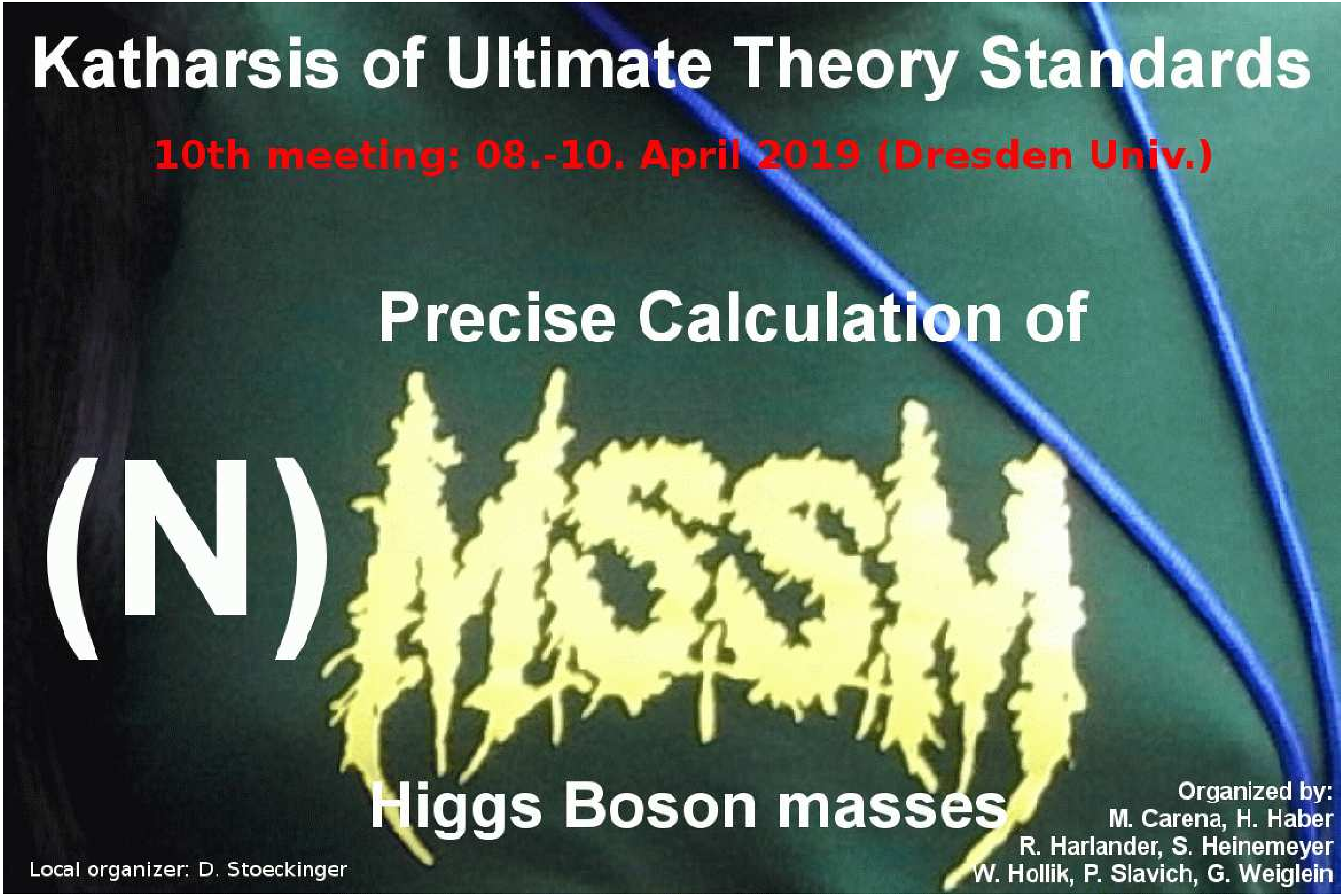
$\Rightarrow$ one-loop corrections $\Delta M_H^2 \sim G_\mu m_t^4$

$\Rightarrow$ M_H depends sensitively on m_t in all models where M_H can be predicted (SM: M_H is free parameter)

SUSY as an example: $\Delta m_t \approx \pm 1$ GeV $\Rightarrow$ $\Delta M_h \approx \pm 1$ GeV

$\Rightarrow$ Precision Higgs physics needs e^+e^- precision of $\mathcal{O}(50$ MeV$)$ in m_t!

Working group on M_h predictions: sites.google.com/site/kutsmh



$\Rightarrow$ next meeting: 11/2019 at MPI Munich

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 – '19*]

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

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

$$\boxed{M_h \lesssim 135 \text{ GeV}} \qquad \text{Note : } 125 < 135!$$

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

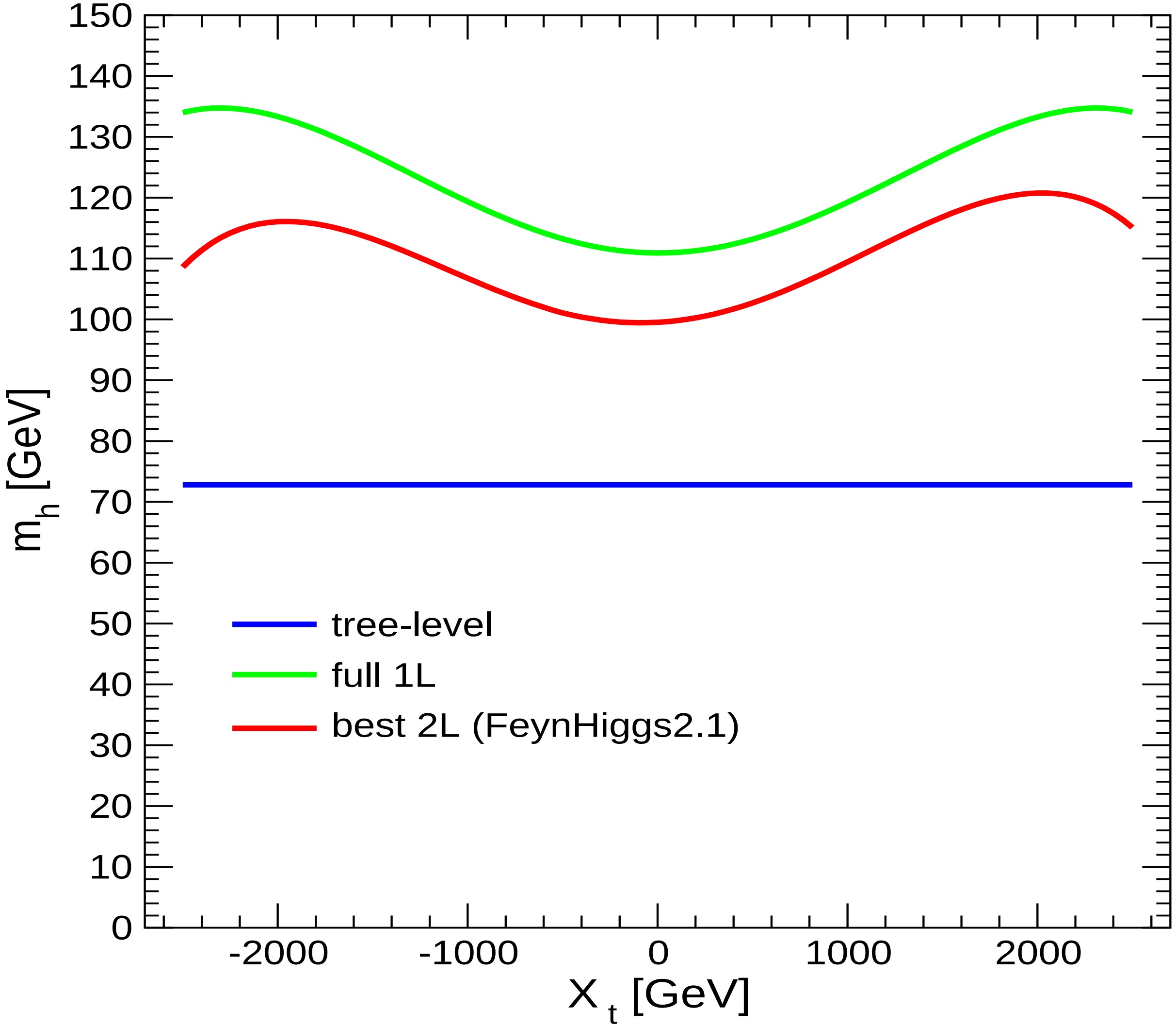
`www.feynhiggs.de`

[*H. Bahl, T. Hahn, S.H., W. Hollik, S. Passehr, H. Rzehak, G. Weiglein '98 – '19*]

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

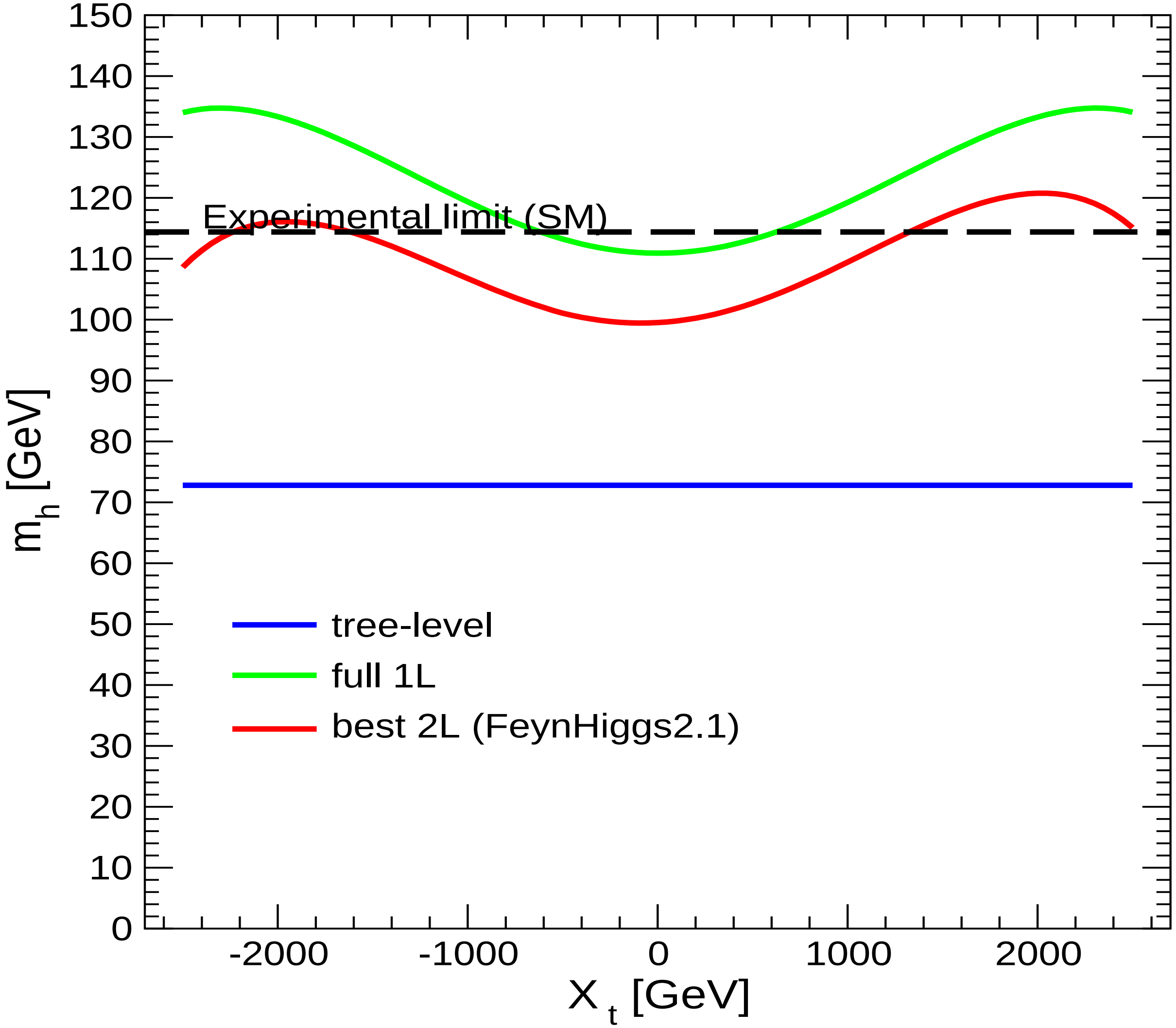
Effects of the two-loop corrections to the lightest Higgs mass:

Example for one set of MSSM parameters



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

Example for one set of MSSM parameters



Comparison with experimental limits

⇒ strong impact on bound on SUSY parameters

A simple exercise on stop masses:

⇒ 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)

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)

$\Rightarrow$ only certain combinations of stop parameters are compatible with the Higgs discovery.

Q: clear prediction for the LHC?

A simple exercise on stop masses:

⇒ 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)

⇒ only certain combinations of stop parameters are compatible with the Higgs discovery.

Q: clear prediction for the LHC?

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

A simple exercise on stop masses:

⇒ 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)

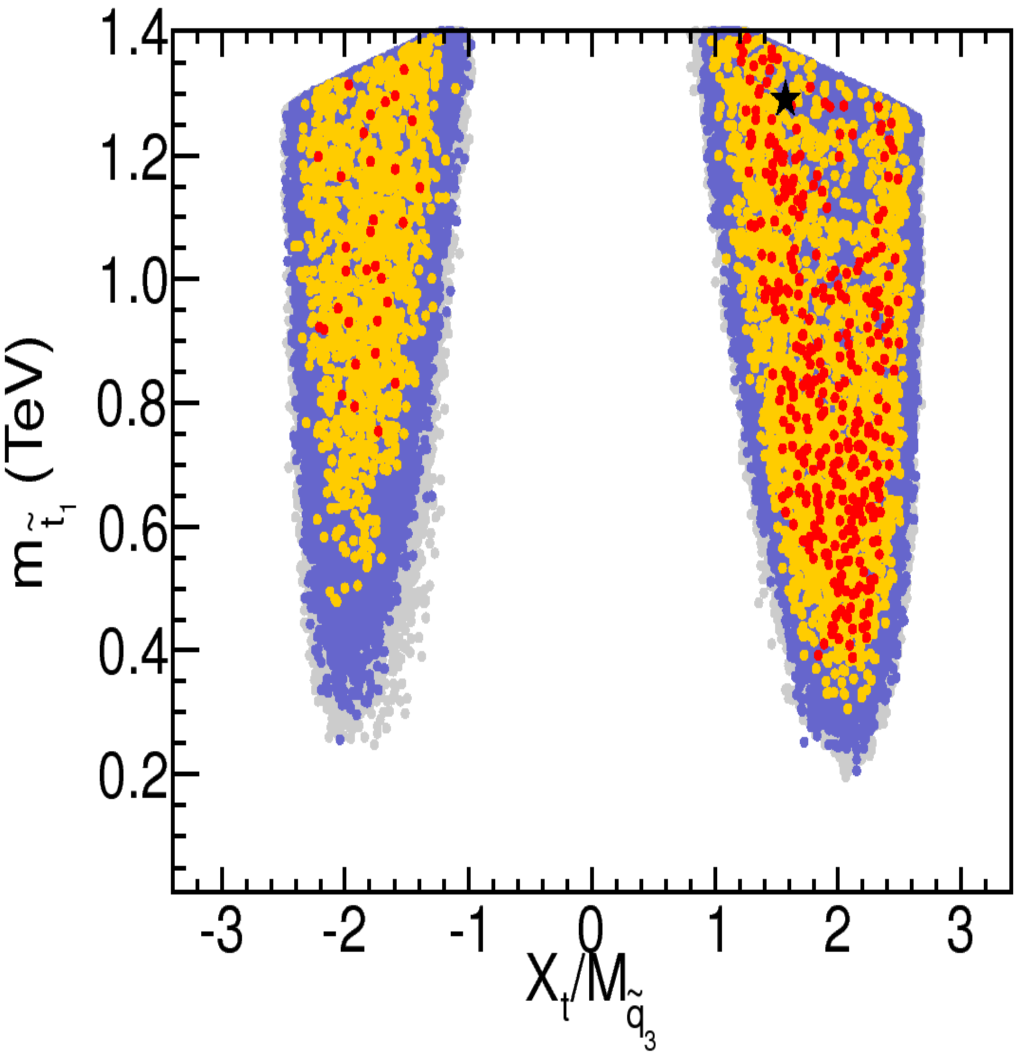
⇒ only certain combinations of stop parameters are compatible with the Higgs discovery.

Q: clear prediction for the LHC?

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

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: $\Delta\chi^2 < 5.99$

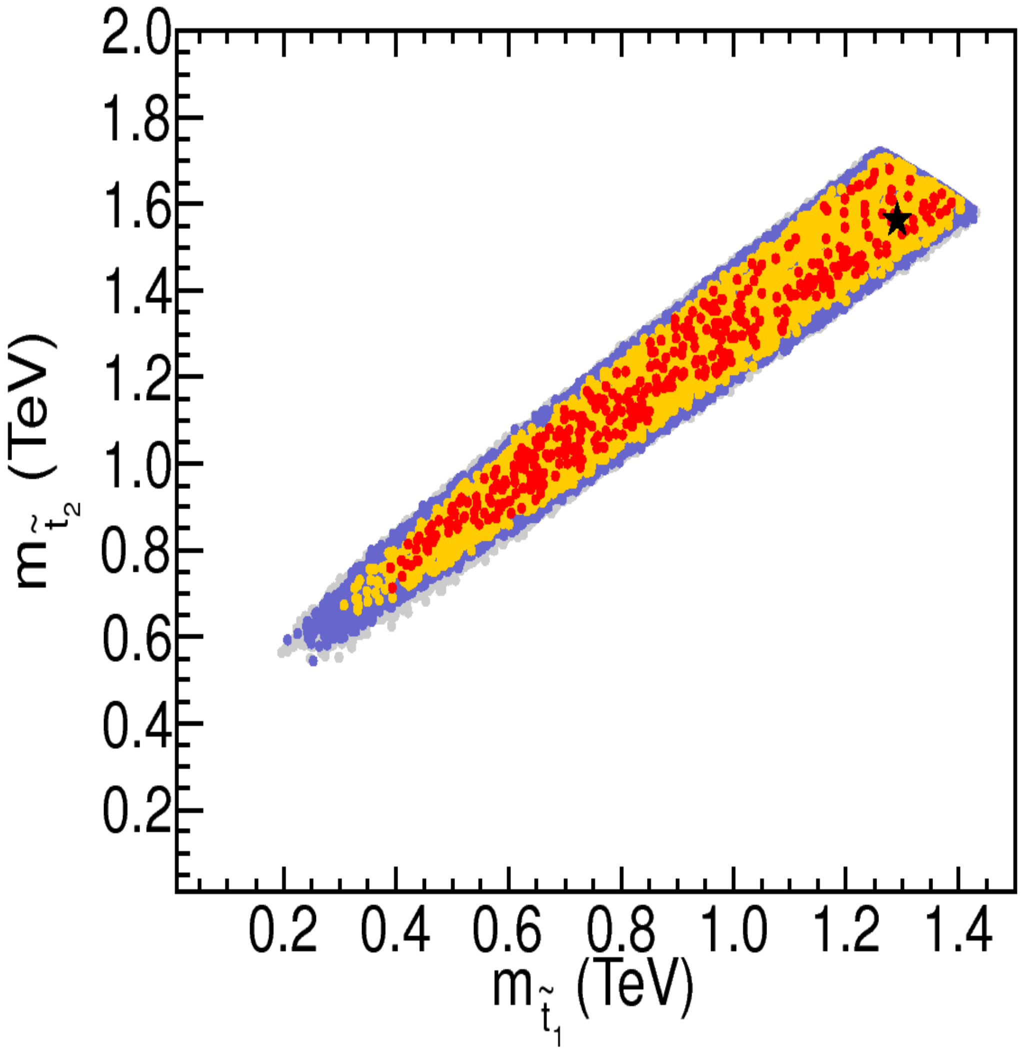
blue: all points HiggsBounds allowed

gray: all scan points

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

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: $\Delta\chi^2 < 5.99$

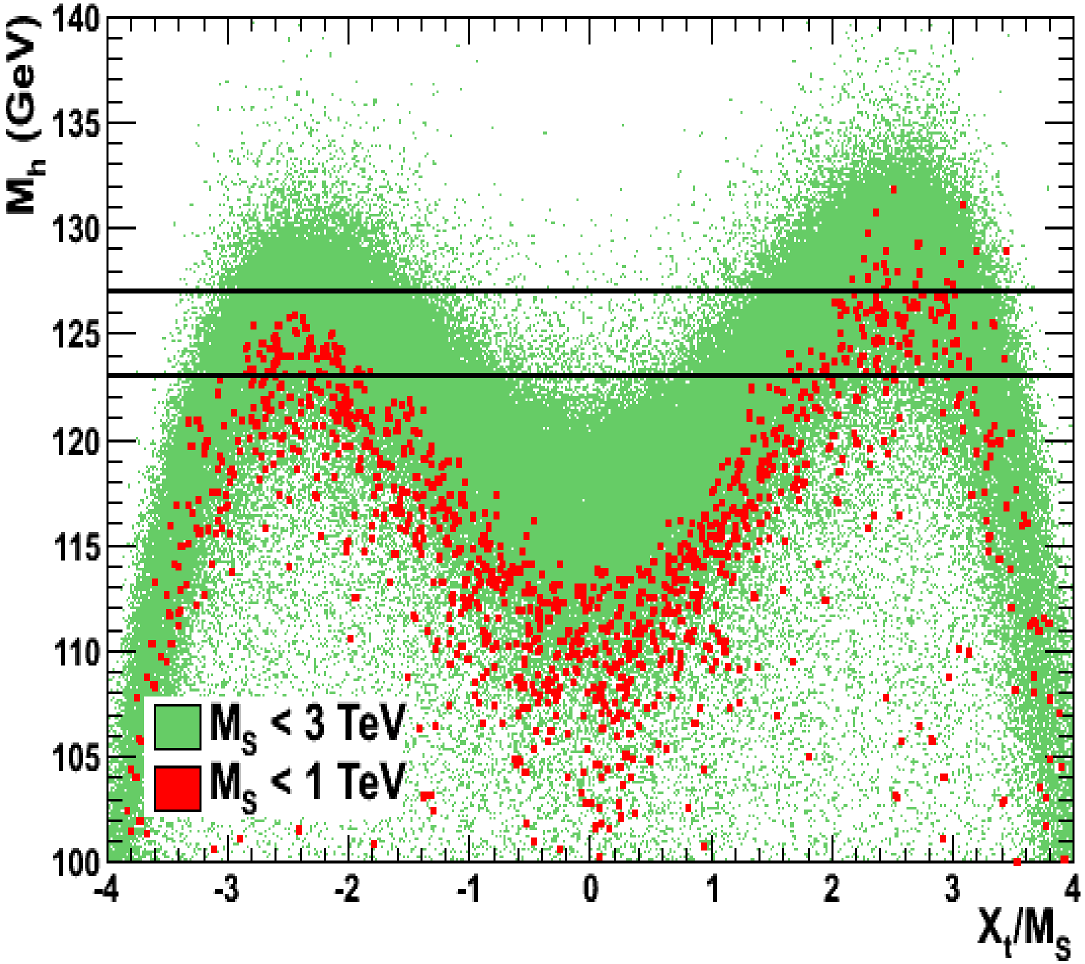
blue: all points HiggsBounds allowed

gray: all scan points

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

Stop masses for $M_h = 125$ GeV

[A. Arbey et al., '11]



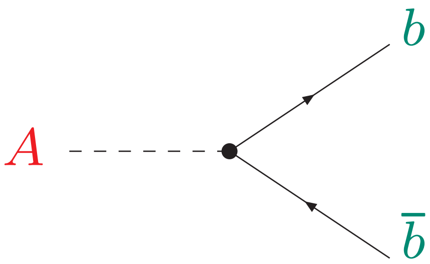
⇒ $M_h \sim 125$ GeV requires large X_t and/or large M_{SUSY}

⇒ no clear prediction for the LHC!

5. The heavy MSSM Higgs bosons

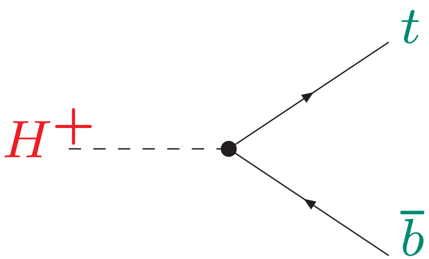
Differences compared to the SM Higgs:

Additional enhancement factors compared to the SM case:



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

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

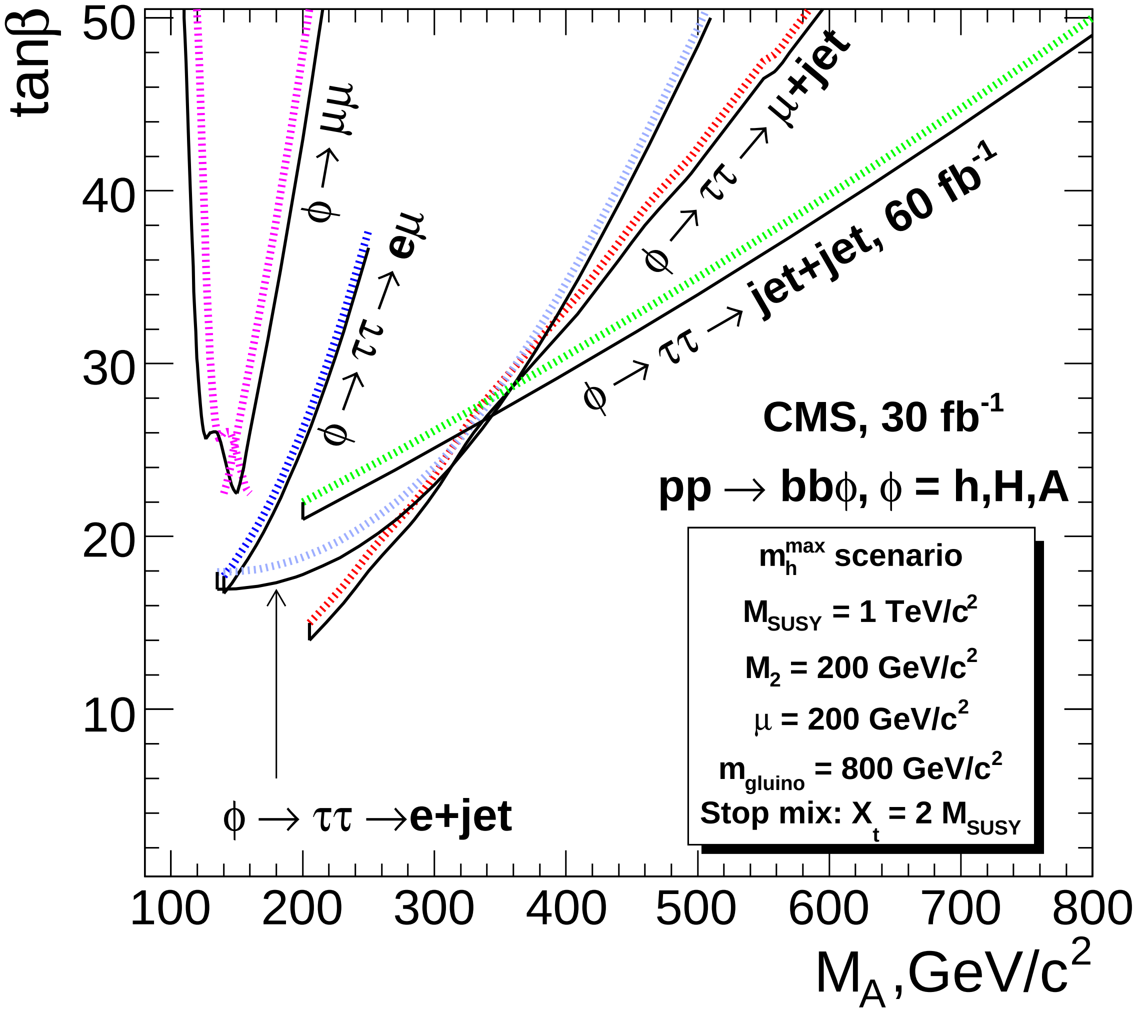
also relevant for $\mathrm{BR}(H/A \to \tau^+\tau^-)$, $\mathrm{BR}(H^\pm \to \tau\nu_\tau)$

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

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

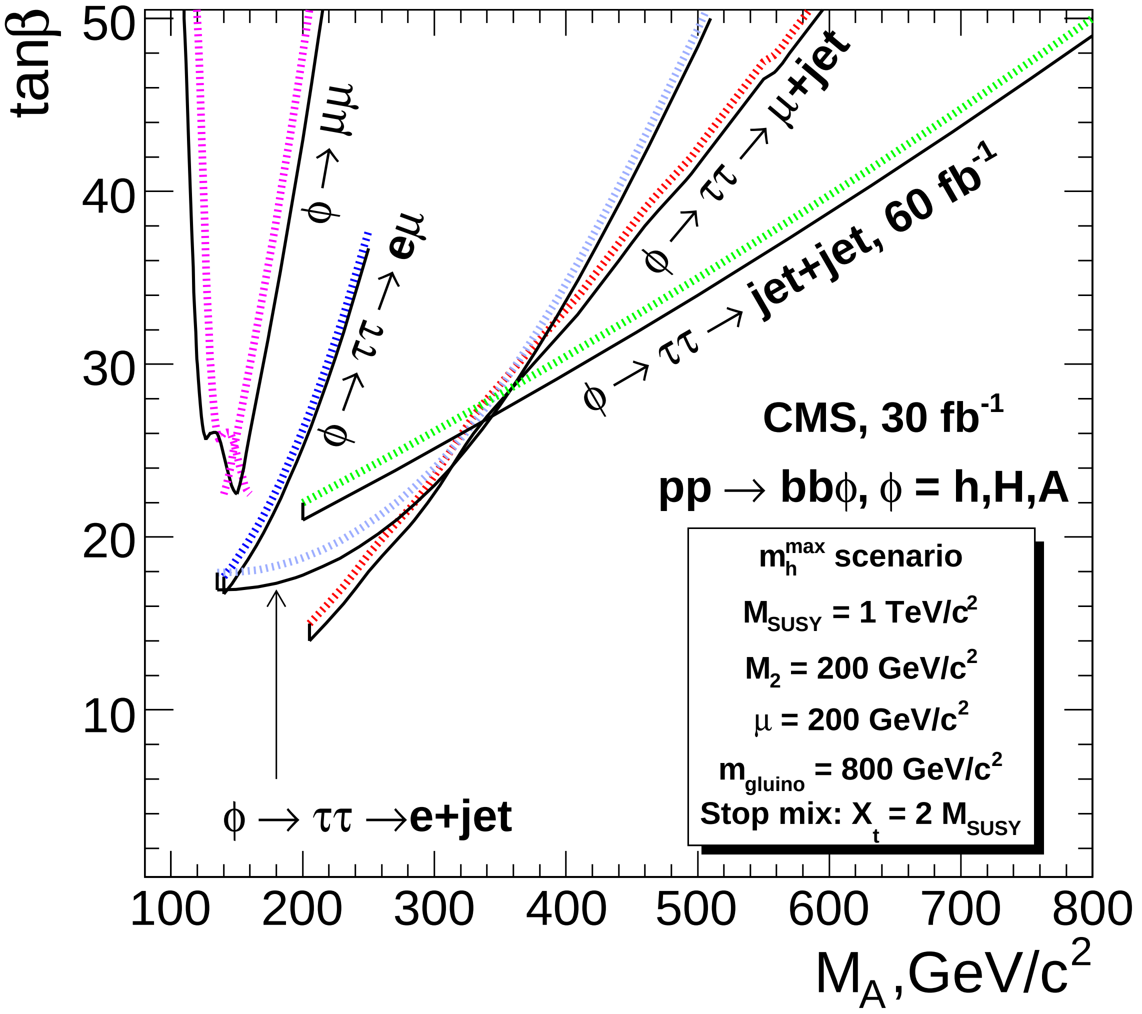
Pre-LHC results for neutral heavy Higgs bosons searches:

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



Pre-LHC results for neutral heavy Higgs bosons searches:

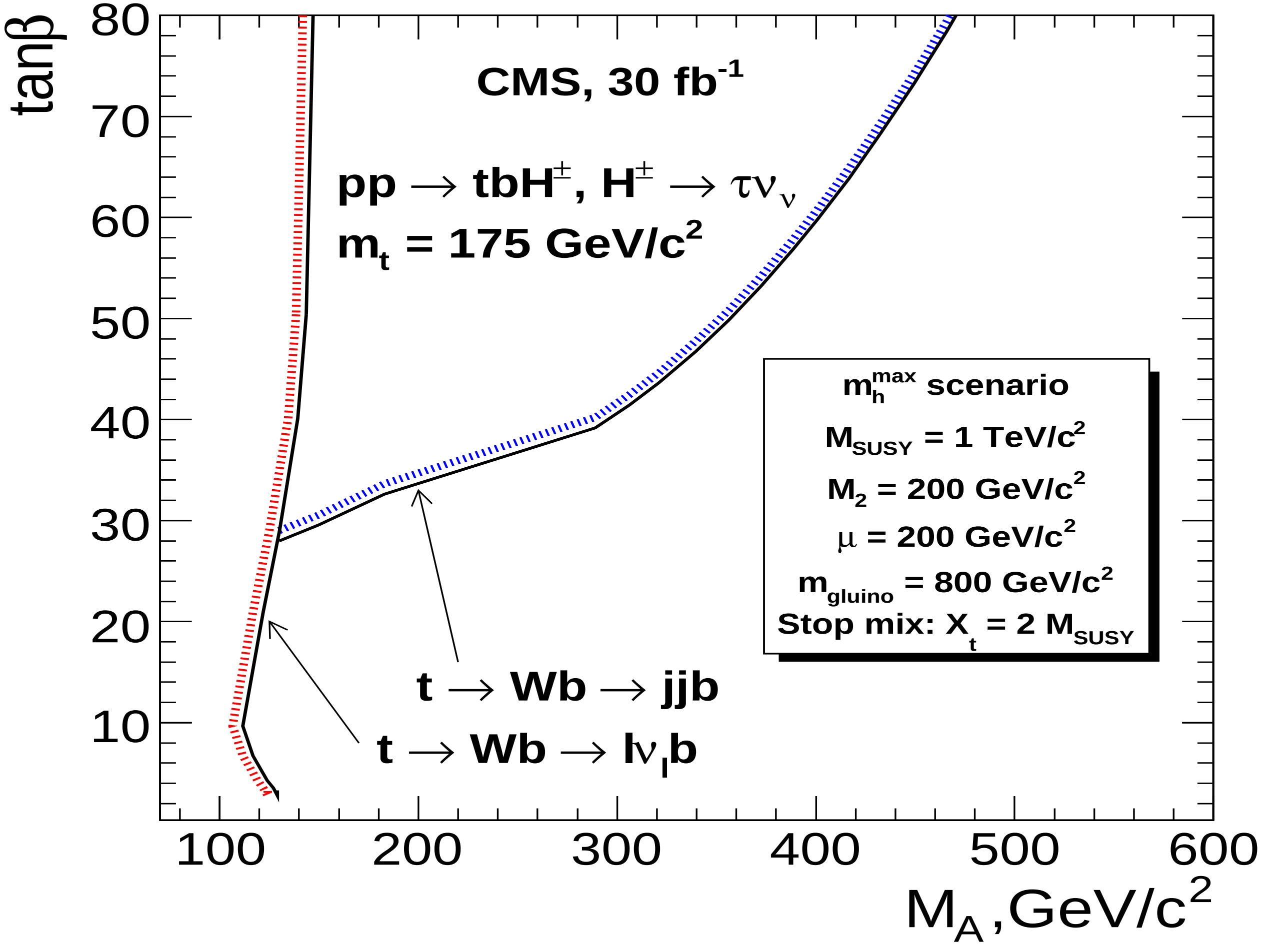
MSSM Higgs discovery contours in M_A–$\tan\beta$ plane $(\Phi = H, A)$
($m_h^{\rm max}$ benchmark scenario): [*CMS PTDR '06*]



Q: Why M_A small and $\tan\beta$ large?

Pre-LHC results for Charged Higgs boson searches:

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



light charged Higgs:

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

heavy charged Higgs:

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


Further Questions?

MSSM Higgs mass calculations: Method I

Higher-order corrections in the Feynman diagrammatic method:

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

Structure of higher-order corrections:

One-loop:

$$\Delta M_h^2 \sim m_t^2 \alpha_t \left[L + L^0\right] \ , \qquad L := \log\left(\frac{m_{\tilde{t}}}{m_t}\right)$$

Two-loop:

$$\Delta M_h^2 \sim m_t^2 \left\{\alpha_t\alpha_s \left[L^2 + L + L^0\right] + \alpha_t^2 \left[L^2 + L + L^0\right]\right\}$$

Three-loop:

$$\Delta M_h^2 \sim m_t^2 \Big\{ \quad \alpha_t\alpha_s^2 \left[L^3 + L^2 + L + L^0\right] \\ + \alpha_t^2\alpha_s \left[L^3 + L^2 + L + L^0\right] \\ + \alpha_t^3 \left[L^3 + L^2 + L + L^0\right] \Big\}$$

Partial results: *[S. Martin '07]* *[R. Harlander, P. Kant, L. Mihaila, M. Steinhauser '08]* *[R. Harlander, J. Klappert, A. Ochoa, A. Voigt '18]* $\Rightarrow$ *H3m/Himalaya*

H3m adds $\mathcal{O}\left(\alpha_t\alpha_s^2\right)$ corrections to *FeynHiggs*
Himalaya can be linked to other codes

Large $m_{\tilde{t}}$ $\Rightarrow$ large L $\Rightarrow$ resummation of logs necessary $\Rightarrow$ Method II

Advantages of Feynman-diagrammatic method:

– all contributions at fixed order are captured

– trivial to include many SUSY scales

– full control over Higgs boson self-energies
$\to$ needed for other quantities (production and decay)

Problems of Feynman-diagrammatic method:

– always only fixed order

– large logs not captured beyond the calculated order

Method II: EFT approach: Log resummation via RGE's:

Excellent overview paper: [P. Draper, G. Lee, C. Wagner, arXiv:1312.5743]

Simple example for log resummation:

SUSY mass scale: $M_{\rm SUSY} = M_{\rm S} \sim m_{\tilde{t}}$

Above $M_{\rm SUSY}$: MSSM
Below $M_{\rm SUSY}$: SM

Relevant SM parameters:
- quartic coupling λ
- top Yukawa coupling h_t ($\alpha_t = h_t^2/(4\,\pi)$)
- strong coupling constant g_s ($\alpha_s = g_s^2/(4\,\pi)$)

1. Take: $h_t(m_t), g_s(m_t)$

   SM RGEs for h_t, g_s: $h_t, g_s(m_t) \to h_t, g_s(M_{\rm S})$

2. Take $\lambda(M_{\rm S}), h_t(M_{\rm S}), g_s(M_{\rm S})$

   SM RGEs for λ, h_t, g_s: $\lambda, h_t, g_s(M_{\rm S}) \to \lambda, h_t, g_s(m_t)$

3. Evaluate M_h^2

$$M_h^2 \sim 2\lambda(m_t)v^2$$

Advantages of RGE log resummation:

– large logs taken into account to all orders

– calculation can easily be extended to very large scales

Problems of RGE log resummation:

– not all contributions at fixed order are captured

$\to$ sub-leading logs more difficult

$\to$ momentum dependence

– difficult (impossible?): include many different SUSY scales

– difficult (impossible?): control over Higgs boson self-energies

$\to$ needed for other quantities (production and decay)

The best of both worlds:

to get the most precise prediction of M_h:

Combination of FD and RGE result!

$$\Delta M_h^2 = (\Delta M_h^2)^{\mathrm{RGE}}(X_t^{\overline{\mathrm{MS}}}, M_S^{\overline{\mathrm{MS}}}, \overline{m}_t) - (\Delta M_h^2)^{\mathrm{FD,log}}(X_t, M_S, \overline{m}_t)$$

$$M_h^2 = (M_h^2)^{\mathrm{FD}} + \Delta M_h^2$$

⇒ many^2 technical aspects and complications . . .

⇒ combination of best FD result with
resummed LL, NLL corrections for large $m_{\tilde{t}}$

⇒ most precise M_h prediction for large $m_{\tilde{t}}$

⇒ first "hybrid code": FeynHiggs 2.10.0

[*T. Hahn, S.H., W. Hollik, H. Rzehak, G. Weiglein '13*]

Codes on the market:

1.) Fixed order codes: good for all scales low

- SuSpect
- SPheno/SARAH
- SoftSUSY/FlexibleSUSY
- H3m

2.) EFT codes: good for all scales high

- SusyHD
- MhEFT
- HSSUSY

3.) Hybrid codes: good always?!

- FeynHiggs
- FlexibleEFTHiggs

Obviously: quality depends on the details implemented

Possible & necessary refinements of the EFT calculation:

- Inclusion of EWino mass scale in RGE's
- Inclusion of gluino mass scale in RGE's
- Inclusion of EW effects in RGE's
- Inclusion of 3-loop RGEs plus 2-loop thresholds etc.
- "Two Higgs Doublet Model" below M_S
- Splitting in the scalar top sector
- ...

Possible & necessary refinements of the EFT calculation:

- Inclusion of EWino mass scale in RGE's
  $\Rightarrow$ included into FeynHiggs

- Inclusion of gluino mass scale in RGE's
  $\Rightarrow$ included into FeynHiggs

- Inclusion of EW effects in RGE's
  $\Rightarrow$ included into FeynHiggs

- Inclusion of 3-loop RGEs plus 2-loop thresholds etc.
  $\Rightarrow$ included into FeynHiggs

- "Two Higgs Doublet Model" below M_S
  $\Rightarrow$ private version of FeynHiggs exists, other code: MhEFT

- Splitting in the scalar top sector
  $\Rightarrow$ future work

- ...

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

6. The MSSM Higgs sector with $\mathcal{CP}$ violation

$$
\begin{aligned}
H_1 &= \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix} \\
H_2 &= \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix} e^{i\xi}
\end{aligned}
$$

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

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 $\phi_{\rm PQ}$

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

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

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

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

⇒ neutralinos: mass eigenstates

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

⇒ M_1, M_2, μ can be complex

⇒ only one new parameter

⇒ 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
(→ 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

⇒ 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 $\mathcal{CP}$ 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):

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

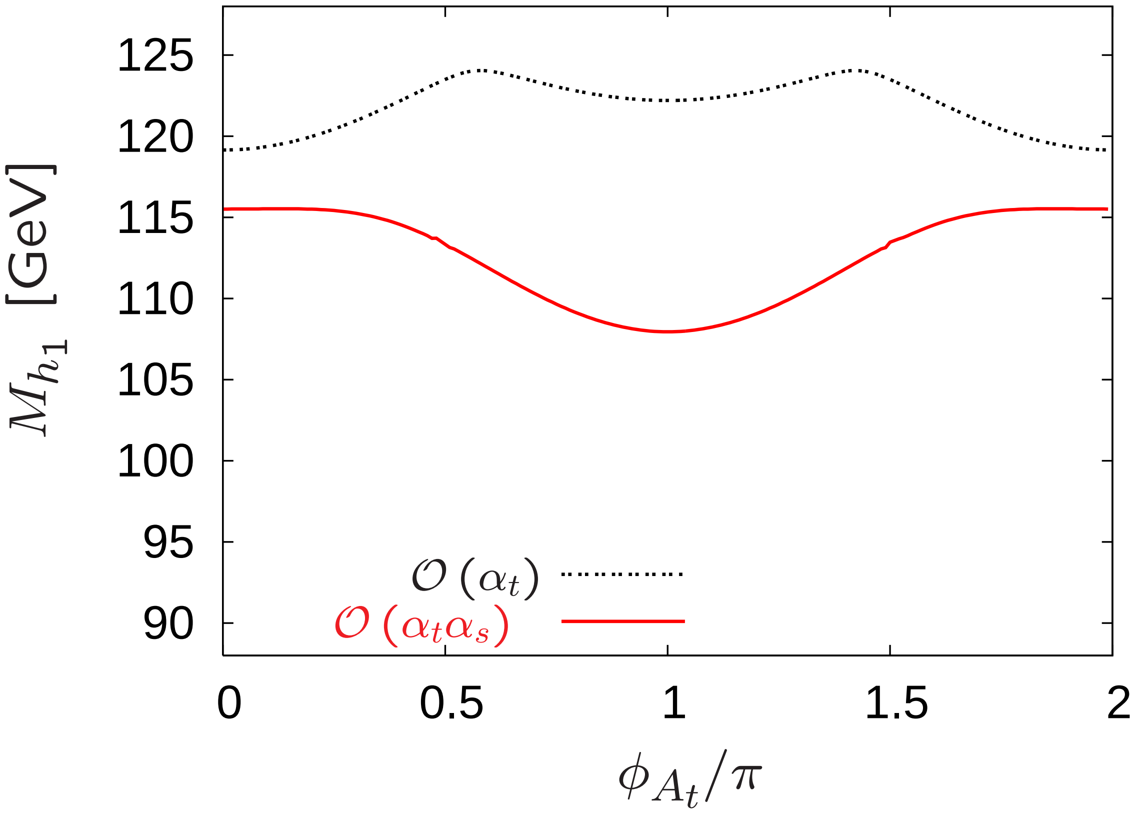
$\hat{\Sigma}_{ij}(q^2)$ $(i,j = h,H,A)$: renormalized Higgs self-energies

$\hat{\Sigma}_{Ah}, \hat{\Sigma}_{AH} \neq 0$ $\Rightarrow$ $\mathcal{CP}$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]



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

$|A_t| = 2000$ GeV

$\tan\beta = 10$

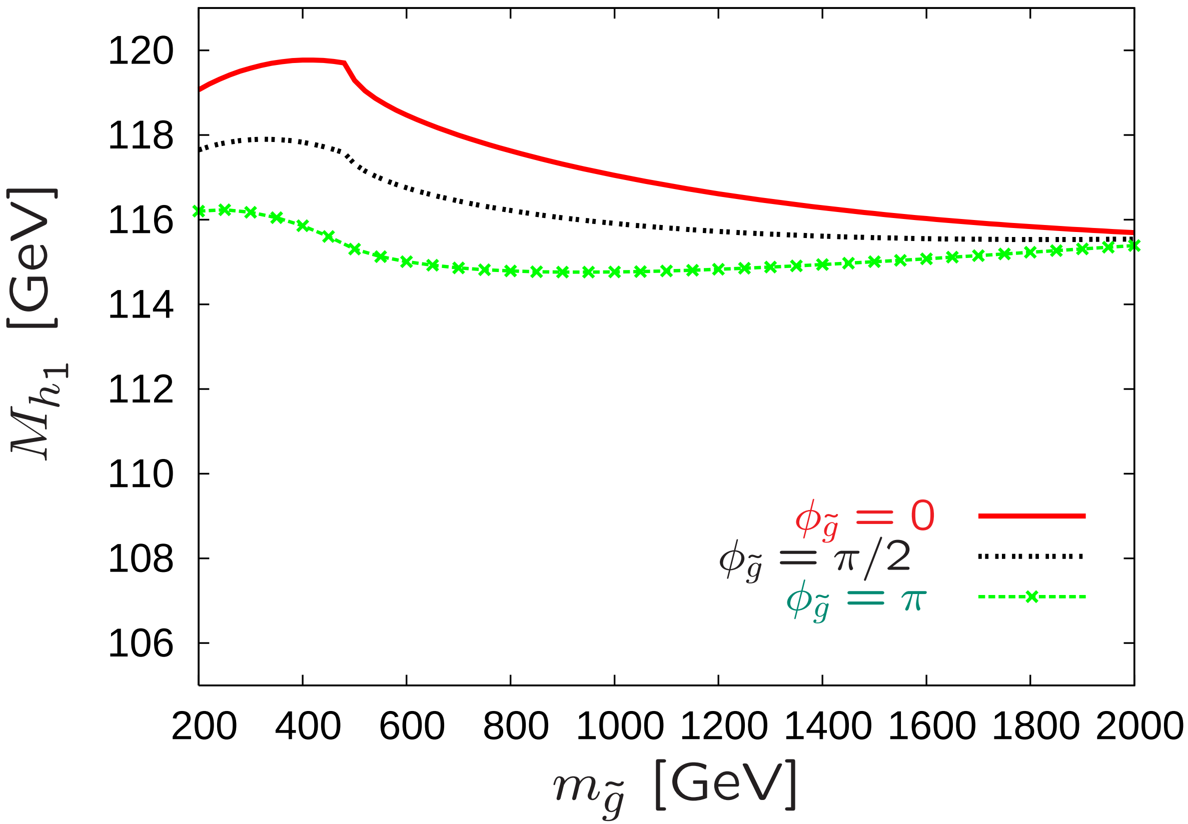
$M_{H^\pm} = 150$ GeV

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

7. Little Higgs models

Main idea of Little Higgs (LH):
light Higgs boson as a Nambu-Goldstone boson
of an approximate symmetry

Breaking of a gauge group:

$$G \to H \quad \text{at the scale } f$$

(with H being e.g. the SM gauge group)

Problem:
this set-up induces via gauge boson loops (quadratic divergences)

$$v \approx f$$

EWPO: $f = \mathcal{O}(1 \text{ TeV})$

$+$ quadratic divergences from top loops

$\Rightarrow$ simple idea does not work

Solution in LH models: "collective symmetry breaking"

consider a gauge group G such that

$$G \supset G_1 \times G_2$$

and each G_i contains the SM gauge group

Now after

$$G \to H \quad \text{at the scale } f$$

the gauge bosons of the extended gauge group (with $M \approx g\, f$) cancel the quadratic divergences and

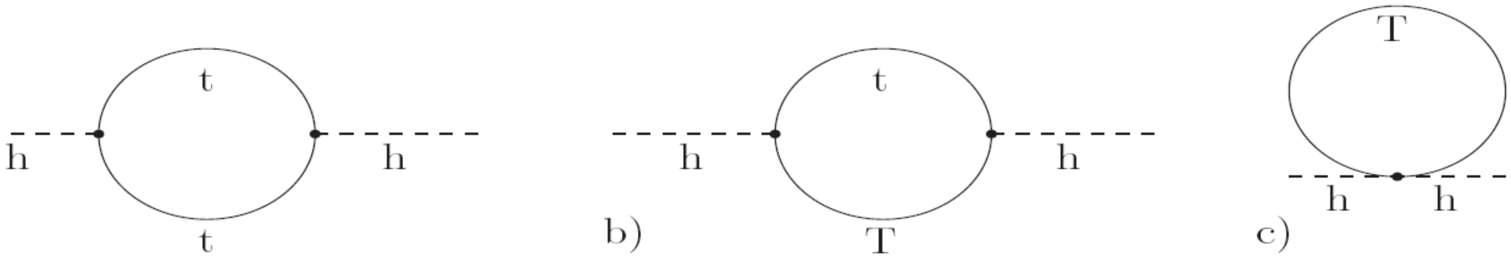
$$v \ll f$$

is possible

Still a problem: quadratic divergences from top loops

Still a problem: quadratic divergences from top loops

⇒ introduction of vectorial top-partner T fermions



Quadratic divergences:

– removed at one-loop
– not removed at two-loop
– log-divergences already at one-loop

⇒ theory valid up to $\Lambda = 4\pi f$

Little Higgs models:

Model depends on the gauge group G:

$$[SU(3)_L \times SU(3)_R]^4 : \text{ minimal moose model}$$

$$SU(5), SO(5) : \text{ littlest Higgs}$$

$$[SU(3) \times U(1)]^2 : \text{ simplest LH}$$

Common features:

– new gauge bosons
– new top partners (and possibly other partners)
– often additional scalar states . . .

General problem of LH models: EWPO!

New gauge bosons mix with SM gauge bosons
$\Rightarrow$ large tree-level contributions to EWPO

Solution 1:
$\Rightarrow$ make f large, $f =$ several TeV
($\rightarrow$ little hierarchy problem)

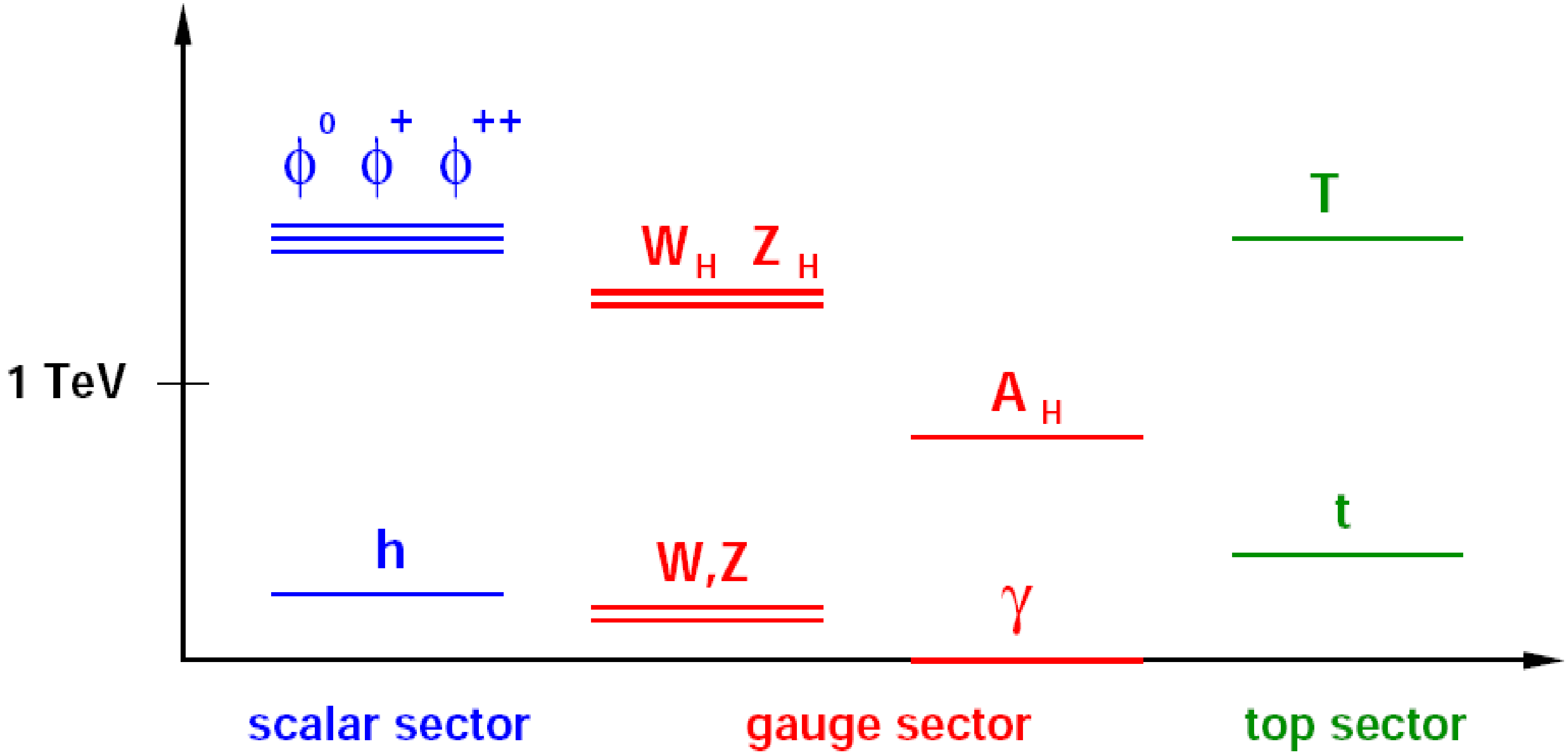
Solution 2:
new discrete symmetry: T parity (Z_2 symmetry)

SM: $T = +1$
LH: $T = -1$ $\Rightarrow$ no mixing between SM and new gauge bosons

additional heavy top states: allow for "heavy" Higgs boson

LTP is stable $\Rightarrow$ B_H is DM candidate

Generic Little Higgs particle spectrum:



LHC phenomenology of LH models:

very different for LH with or without T parity

LH with T parity:

QCD pair production: $pp \to TT$

with (cascade) decays of T: $T \to tB_H$
$\Rightarrow$ signal: missing energy

LH without T parity:

single production of T, B_H, Z_H, W_H, ...
with subsequent decay to SM particles
$\Rightarrow$ no missing energy

LHC phenomenology of LH models:

very different for LH with or without T parity

LH without T parity:

single production and decay of new LH particles possible