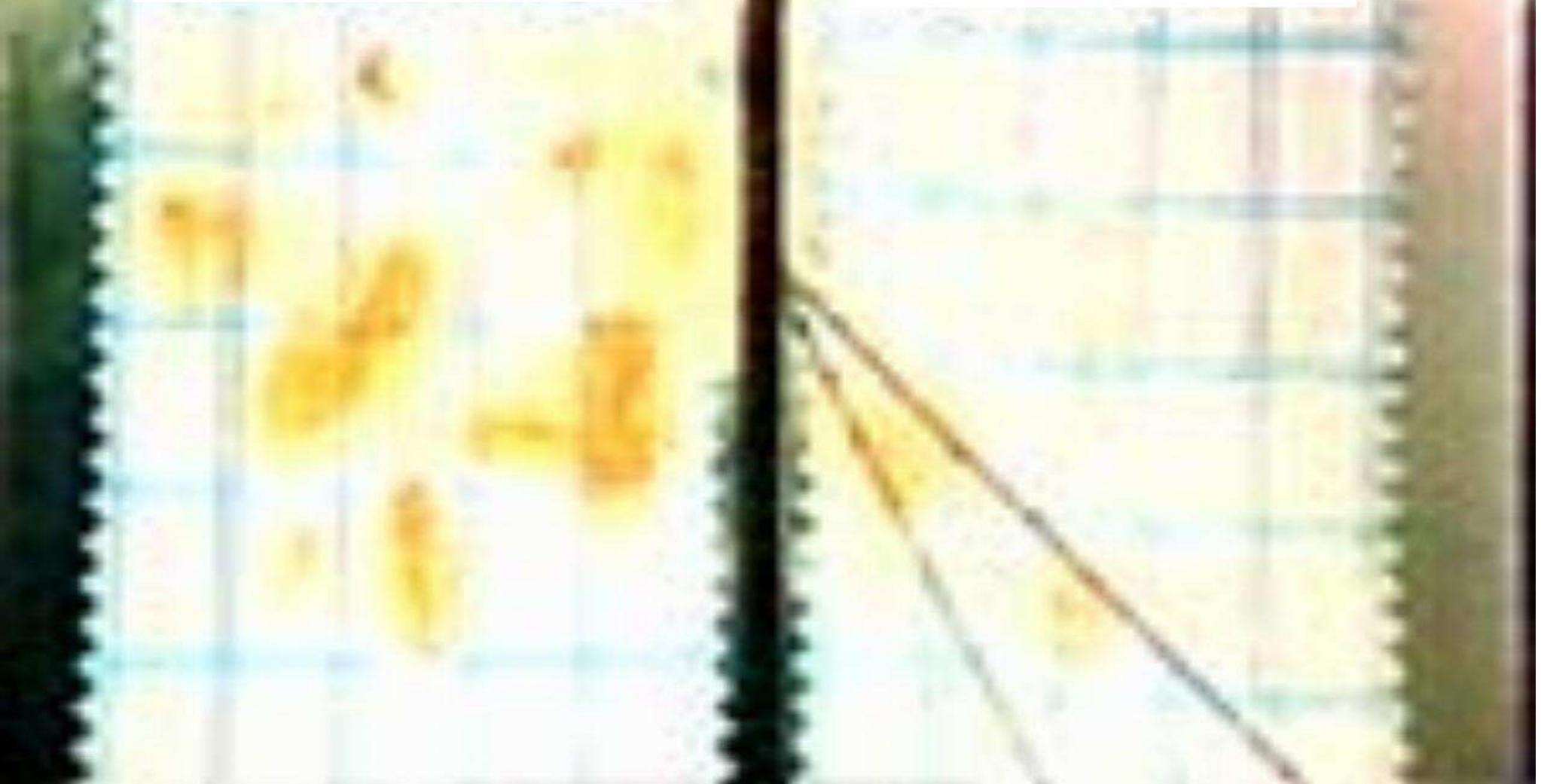


**herkömmliches  
Higgsprogramm**

**Das neue  
FeynHiggs**



# Higgs Predictions in the (N)MSSM: Towards the LC precision

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

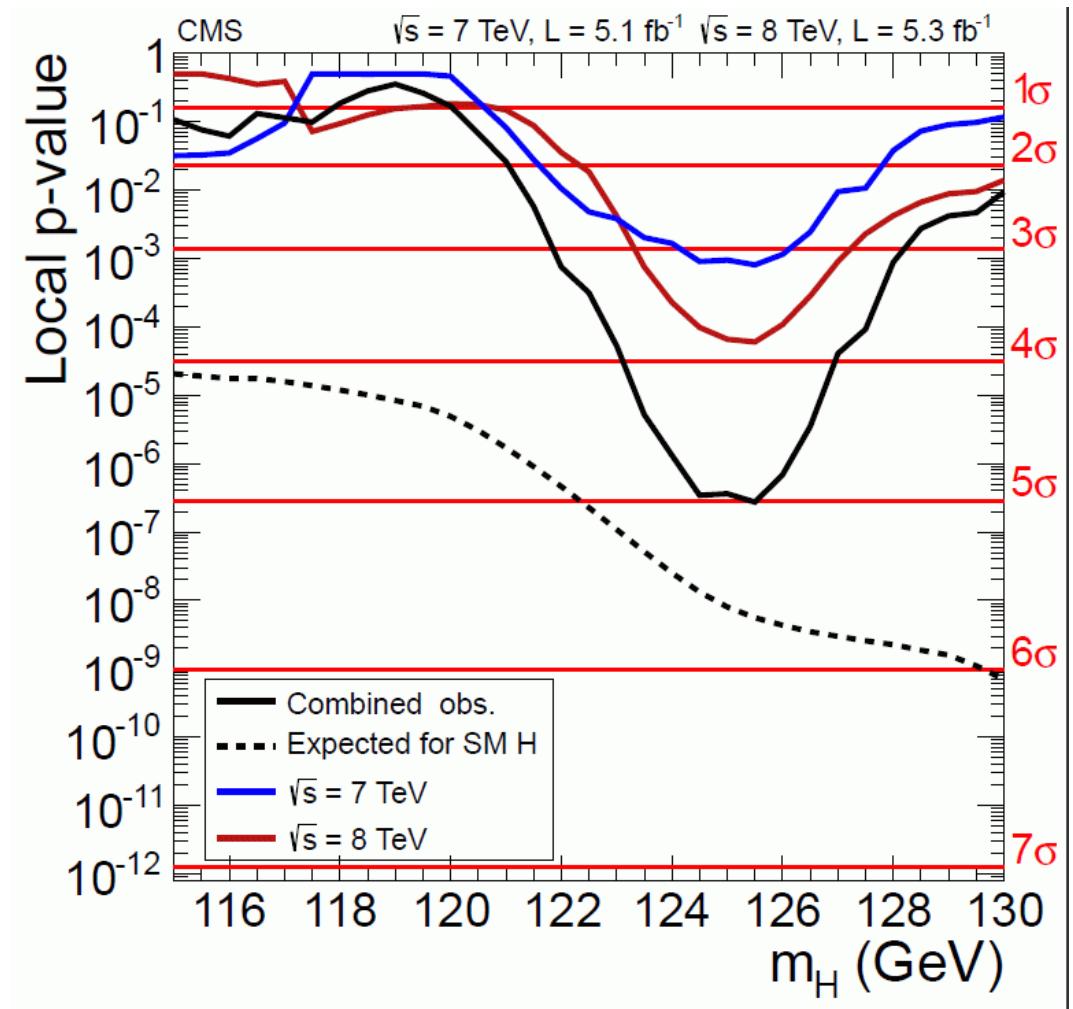
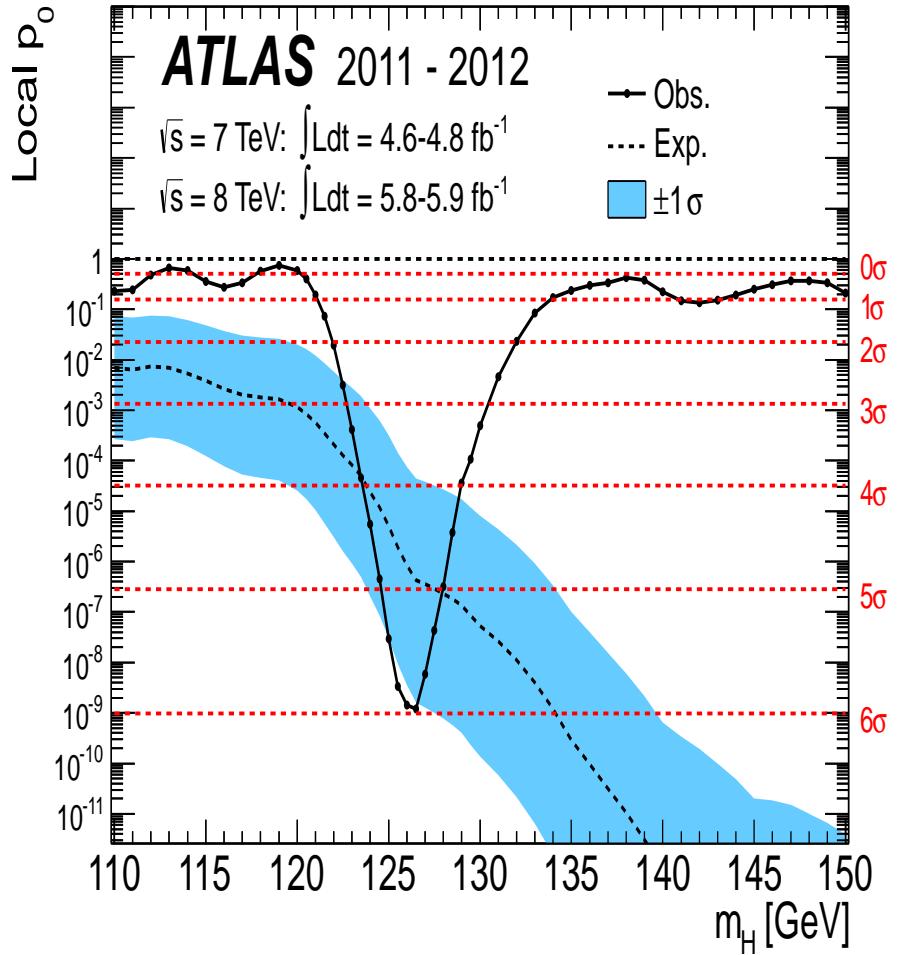
Fukuoka, 05/2018

FeynHiggs team: *H. Bahl, F. Domingo, T. Hahn, S.H., W. Hollik,  
S. Paßehr, H. Rzehak and G. Weiglein*

- The Quest for Precision
- MSSM Higgs mass calculations
- NMSSM Higgs mass calculations
- (N)MSSM Higgs decays
- Conclusions



# 1. The Quest for Precision



⇒ clear discovery at  $\sim 125$  GeV!

⇒ can be interpreted as the light(/heavy)  $\mathcal{CP}$ -even MSSM Higgs

## The Higgs mass accuracy: experiment vs. theory:

### Experiment:

ATLAS:  $M_h^{\text{exp}} = 125.36 \pm 0.37 \pm 0.18 \text{ GeV}$

CMS:  $M_h^{\text{exp}} = 125.03 \pm 0.27 \pm 0.15 \text{ GeV}$

combined:  $M_h^{\text{exp}} = 125.09 \pm 0.21 \pm 0.11 \text{ GeV}$

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combined:  $M_h^{\text{exp}} = 125.09 \pm 0.21 \pm 0.11 \text{ GeV}$

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

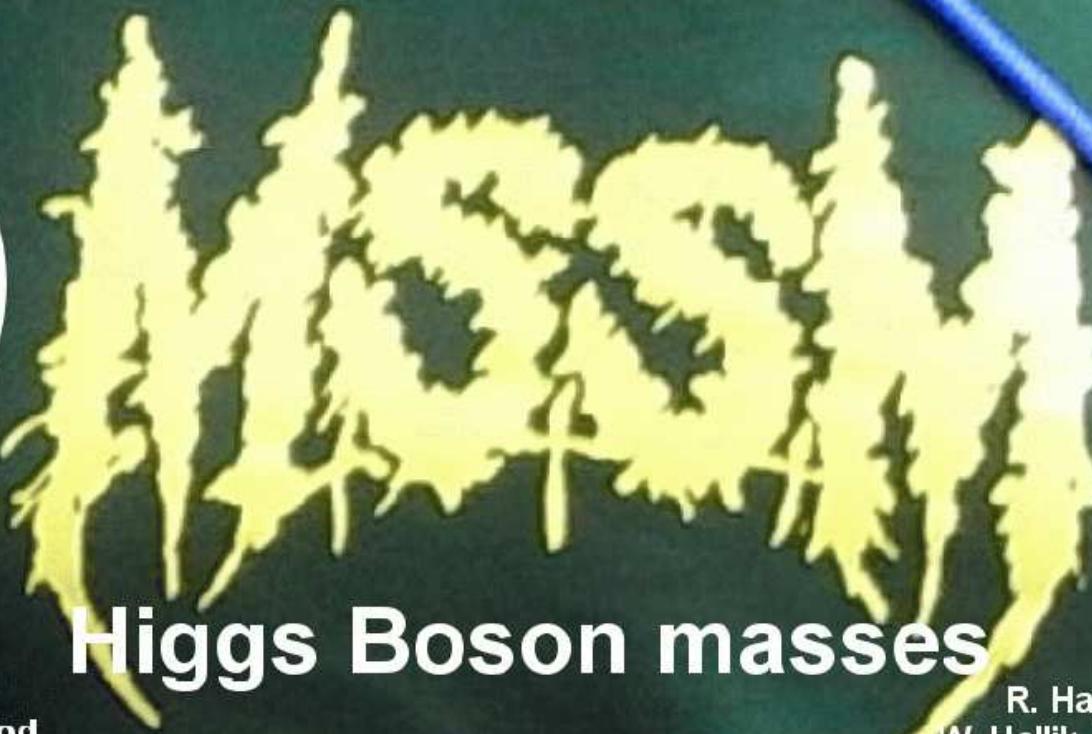
→ rough estimate, FeynHiggs contains algorithm to evaluate uncertainty, depending on parameter point

# Katharsis of Ultimate Theory Standards

**9th meeting: 16.-18. July 2018 (Würzburg Univ.)**

Precise Calculation of

(N)



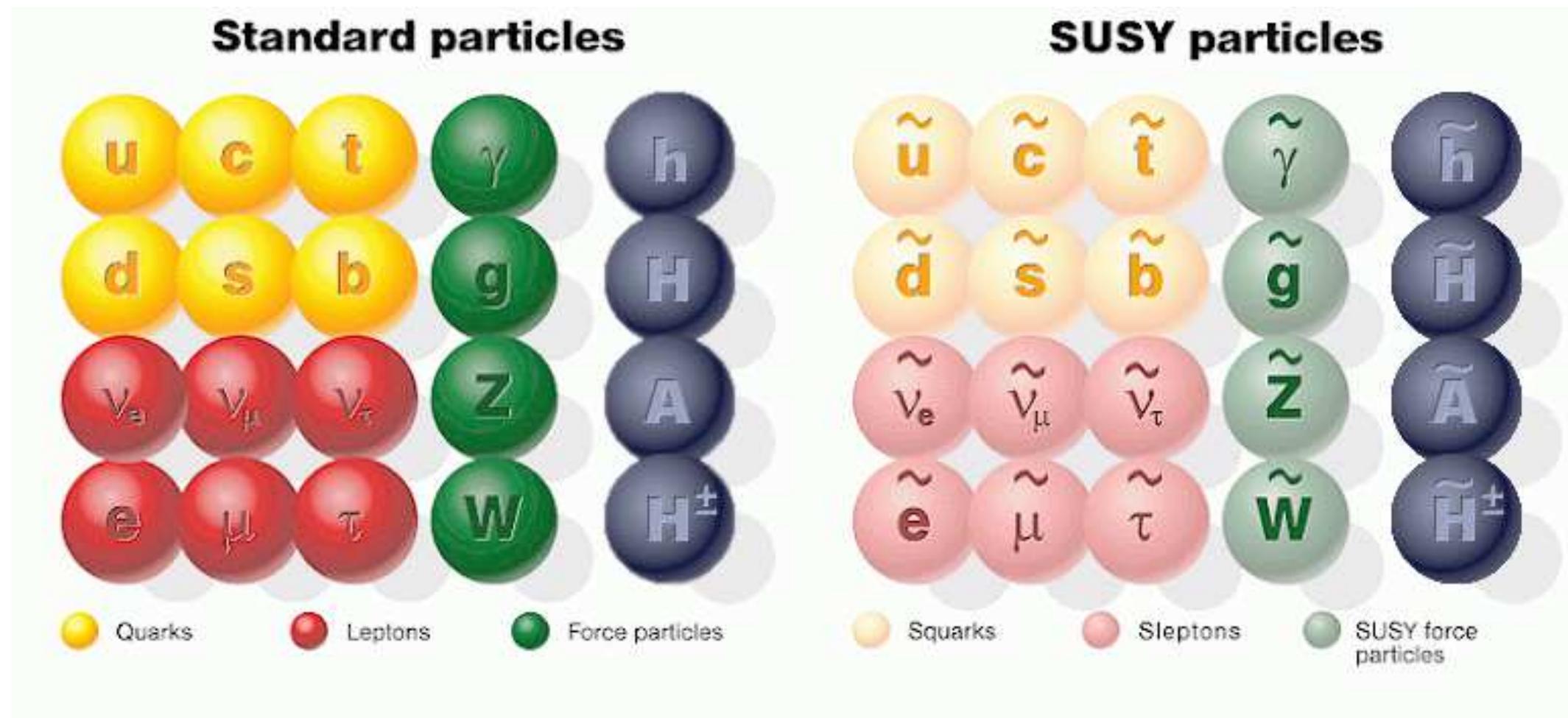
Higgs Boson masses

**Local organizer:** W. Porod

Organized by:  
M. Carena, H. Haber  
R. Harlander, S. Heinemeyer  
W. Hollik, P. Slavich, G. Weiglein

## The MSSM:

→ Superpartners for Standard Model particles



## Enlarged Higgs sector: Two Higgs doublets

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

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

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

$$+ \underbrace{\frac{g'^2 + g^2}{8}}_{\text{gauge couplings, in contrast to SM}} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}}_{\text{gauge couplings, in contrast to SM}} |H_1 \bar{H}_2|^2$$

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)

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

## Enlarged Higgs sector: Two Higgs doublets with $\mathcal{CP}$ violation

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

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

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

$$+ \underbrace{\frac{g'^2 + g^2}{8}}_{\text{gauge couplings, in contrast to SM}} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}}_{\text{gauge couplings, in contrast to SM}} |H_1 \bar{H}_2|^2$$

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

2  $\mathcal{CP}$ -violating phases:  $\xi, \arg(m_{12}) \Rightarrow$  can be set/rotated to zero

Input parameters: (to be determined experimentally)

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

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

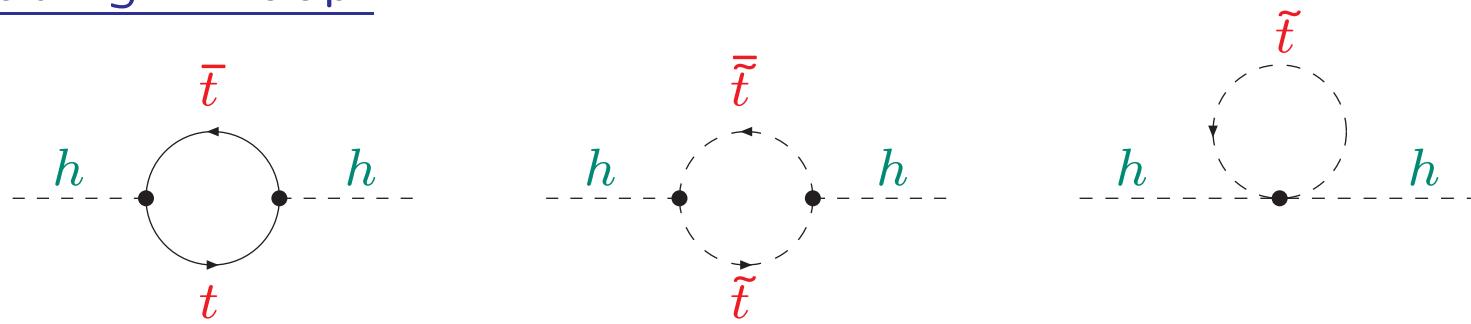
## Calculation of renormalized Higgs boson self-energies:

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

all MSSM particles contribute

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

### Very leading 1-Loop:



### 2-Loop:

To avoid large corrections:

On-shell renormalization of the scalar top sector  $\Rightarrow X_t^{\text{OS}}$

$$\sim m_t^4 \left[ \log^2 \left( \frac{m_{\tilde{t}}}{m_t} \right) + \log \left( \frac{m_{\tilde{t}}}{m_t} \right) \right]$$

## Structure of higher-order corrections:

One-loop:

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

Two-loop:  $\Delta M_h^2 \sim m_t^2 \{ \alpha_t \alpha_s [L^2 + L + L^0] + \alpha_t^2 [L^2 + L + L^0] \}$

Three-loop:

$$\begin{aligned} \Delta M_h^2 \sim m_t^2 \{ & \alpha_t \alpha_s^2 [L^3 + L^2 + L + L^0] \\ & + \alpha_t^2 \alpha_s [L^3 + L^2 + L + L^0] \\ & + \alpha_t^3 [L^3 + L^2 + L + L^0] \} \end{aligned}$$

Partial results: [S. Martin '07]

[R. Harlander, P. Kant, L. Mihaila, M. Steinhauser '08]  $\Rightarrow$  H3m

H3m adds  $\mathcal{O}(\alpha_t \alpha_s^2)$  corrections to FeynHiggs

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  
→ 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:  $M_{\text{SUSY}} = M_S \sim m_{\tilde{t}}$

Above  $M_{\text{SUSY}}$ : MSSM

Below  $M_{\text{SUSY}}$ : SM

Relevant SM parameters:

- quartic coupling  $\lambda$
- 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  $h_t, g_s$ :  $h_t, g_s(m_t) \rightarrow h_t, g_s(M_S)$

2. Take  $\lambda(M_S), h_t(M_S), g_s(M_S)$

SM RGEs for  $\lambda, h_t, g_s$ :  $\lambda, h_t, g_s(M_S) \rightarrow \lambda, h_t, g_s(m_t)$

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
  - sub-leading logs more difficult
  - momentum dependence
- difficult (impossible?): include many different SUSY scales
- difficult (impossible?): control over Higgs boson self-energies
  - 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!

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Combination of FD and RGE result!

⇒ example of first/original FeynHiggs implementation

Problem:

Some terms exist in both calculations!

One-loop:

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

Two-loop:

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

## Combination of FD and RGE result:

- ⇒ to avoid double counting:  
subtract leading and subleading logs at one- and two-loop

Problem:

- FD result with  $X_t^{\text{OS}}, M_S^{\text{OS}}, \overline{m}_t$
- RGE result with  $X_t^{\overline{\text{MS}}}, M_S^{\overline{\text{MS}}}, \overline{m}_t$

$$\overline{m}_t = \frac{m_t^{\text{pole}}}{1 + \frac{4}{3\pi}\alpha_s(m_t^{\text{pole}}) - \frac{1}{2\pi}\alpha_t(m_t^{\text{pole}})}$$

$$X_t^{\overline{\text{MS}}} = X_t^{\text{OS}} \left[ 1 + 2L \left( \frac{\alpha_s}{\pi} - \frac{3\alpha_t}{16\pi} \left( 1 - \frac{X_t^2}{M_S^2} \right) \right) \right]$$

$$M_S^{\overline{\text{MS}}} \sim M_S^{\text{OS}} : \text{no log differences!}$$

## Combination of FD and RGE result:

$$\Delta M_h^2 = (\Delta M_h^2)^{\text{RGE}}(X_t^{\overline{\text{MS}}}, M_S^{\overline{\text{MS}}}, \overline{m}_t) - (\Delta M_h^2)^{\text{FD,LL1,LL2}}(X_t^{\text{OS}}, M_S^{\text{OS}}, \overline{m}_t)$$

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

Technical aspect:

$$(\Delta M_h^2)^{\text{FD,LL1,LL2}}(X_t^{\text{OS}}, M_S^{\text{OS}}, \overline{m}_t) \\ := (\Delta M_h^2)^{\text{FD,LL1,LL2}}(X_t^{\overline{\text{MS}}}, M_S^{\overline{\text{MS}}}, \overline{m}_t) \Big|_{X_t^{\overline{\text{MS}}} \rightarrow X_t^{\text{OS}}, M_S^{\overline{\text{MS}}} = M_S^{\text{OS}}}$$

- ⇒ 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

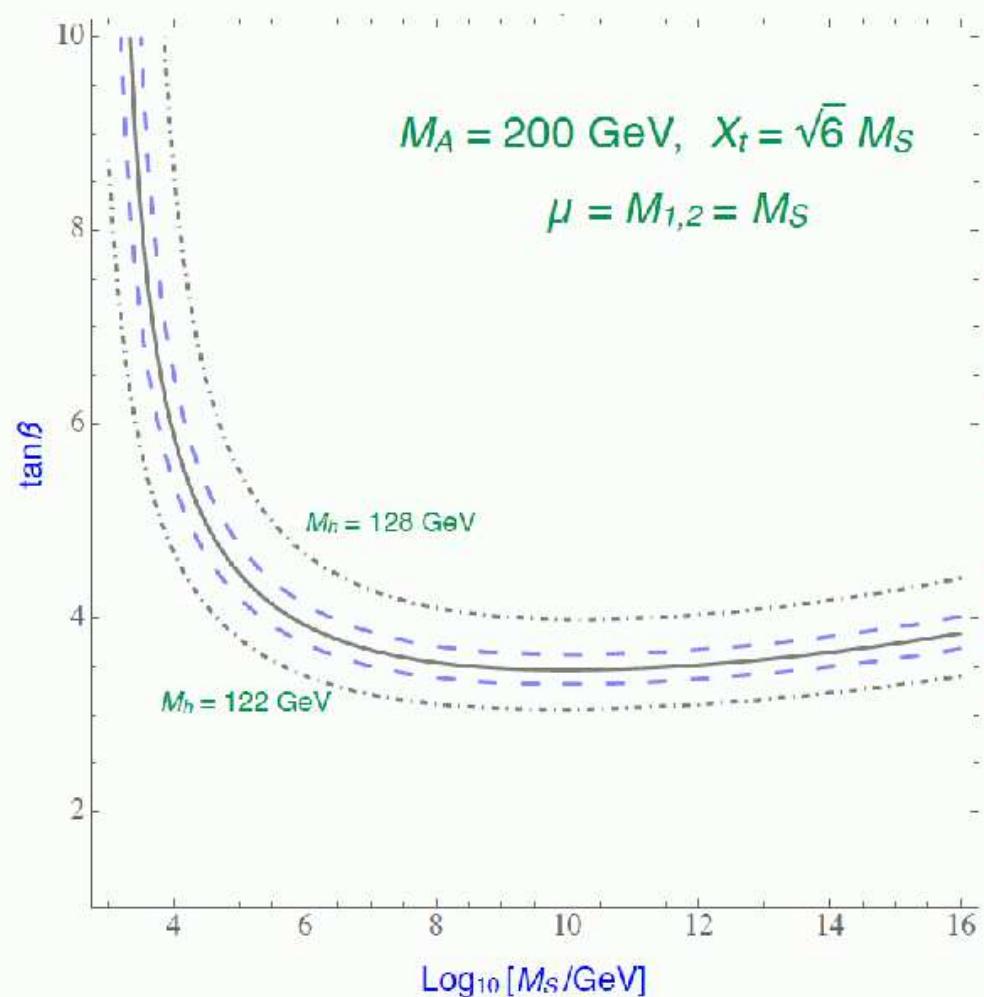
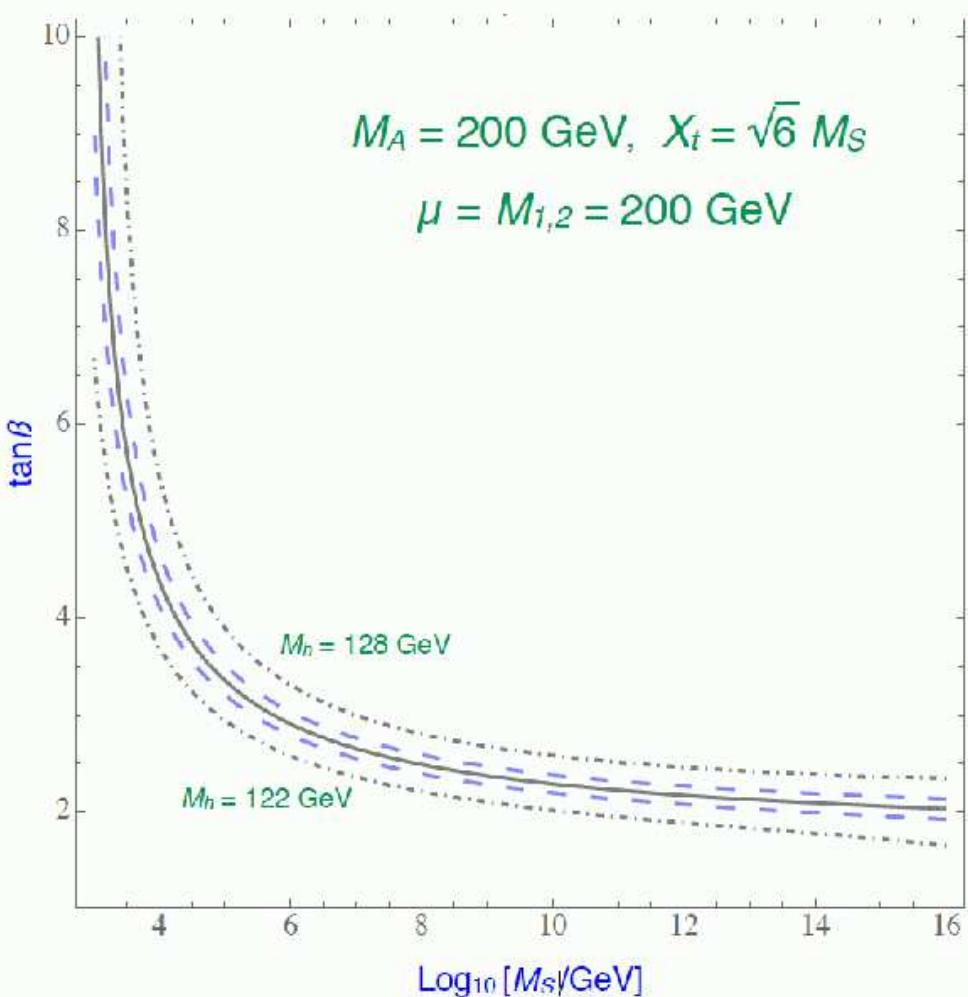
## Possible & necessary refinements of the EFT calculation:

- 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  
⇒ included into FeynHiggs
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- Inclusion of EW effects in RGE's  
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- Inclusion of 3-loop RGEs plus 2-loop thresholds etc.  
⇒ included into FeynHiggs
- “Two Higgs Doublet Model” below  $M_S$   
⇒ private version of FeynHiggs exists, other code: MhEFT
- Splitting in the scalar top sector  
⇒ future work
- ...

## 2HDM as low-energy theory: MhEFT



$\Rightarrow M_h = 125 \text{ GeV}$  and low  $M_A$ ,  $\tan\beta$  cannot “everywhere” be realized!

## Where are we with the uncertainties?

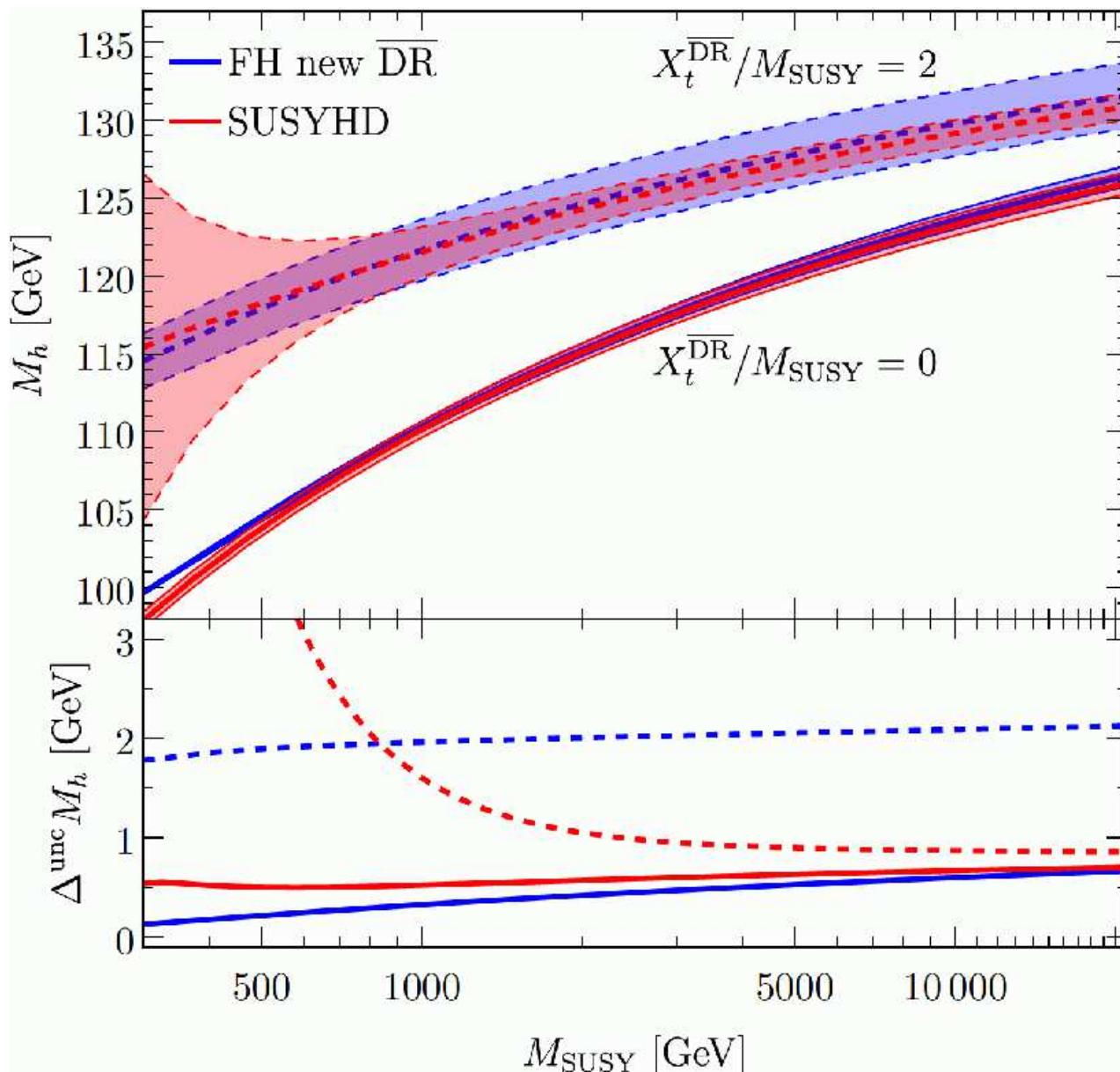
Can/Do we meet the LHC or even the LC precision?

FeynHiggs (hybrid): linear sum of

- missing 3-loop corrections in  $t/\tilde{t}$  sector (change of  $y_t$  def.)
- missing 2-loop corrections in  $b/\tilde{b}$  sector ( $\Delta_b$  resummation)
- missing 2-loop corrections in EW sector (change of renormalization scale)  
⇒ reliable estimate up to 2 – 3 TeV or higher

SusyHD (EFT): linear sum of

- SM unc.: missing corrections from matching at  $m_t$  and RGE evolution
- MSSM unc.: missing corrections from matching at  $M_S$
- EFT unc.: effects not captured by EFT:  $\mathcal{O}(v^2/M_S^2)$  (prefactor 1)  
⇒ uncertainty estimate of  $\sim 1$  GeV  
⇒ estimate for the multi-TeV range (non-log pieces???!)  
⇒ unclear to which low scales it can be extrapolated



FH 2.14.0 vs. SusyHD

- simple one-scale scenario
- SHD underestimates the non-log corrections
- SHD has large uncertainty for small  $M_{\text{SUSY}}$

Overall  $M_h$  uncertainty:  
 $\delta M_h^{\text{intrinsic}} \sim \pm 2 \text{ GeV}$

⇒ long<sup>2</sup> way to go for LC!

### 3. NMSSM Higgs mass calculations ( $Z_3$ invariant NMSSM)

MSSM Higgs sector: Two Higgs doublets

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

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

### 3. NMSSM Higgs mass calculations ( $Z_3$ invariant NMSSM)

NMSSM Higgs sector: Two Higgs doublets + one Higgs singlet

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

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

$$S = v_s + S_R + IS_I$$

$$V = (\tilde{m}_1^2 + |\mu\lambda S|^2)H_1\bar{H}_1 + (\tilde{m}_2^2 + |\mu\lambda S|^2)H_2\bar{H}_2 - m_{12}^2(\epsilon_{ab}H_1^aH_2^b + \text{h.c.})$$

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

$$+ |\lambda(\epsilon_{ab}H_1^aH_2^b) + \kappa S^2|^2 + m_S^2|S|^2 + (\lambda A_\lambda(\epsilon_{ab}H_1^aH_2^b)S + \frac{\kappa}{3}A_\kappa S^3 + \text{h.c.})$$

Free parameters:

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

## Higgs spectrum:

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

## Neutralinos:

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

compared to the MSSM: one singlino more

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

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

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

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

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

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

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

Mass of the charged Higgs:

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

**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:

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

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

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

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

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

Mass of the charged Higgs:

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

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

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

General idea: treat the MSSM part exactly as in the MSSM

- ▶ full inverse propagator in CP-even sector for mass determination

$$\Delta^{-1}(k^2) = i \left[ k^2 \mathbb{1} - \underbrace{\mathcal{M}_{\phi\phi} + \hat{\Sigma}_{\phi\phi}^{(1L)}(k^2)}_{\text{NMSSM}} + \underbrace{\hat{\Sigma}_{\phi\phi}^{(2L)}(k^2 = 0)}_{\text{MSSM/FEYNHIGGS}} \right]$$

- ▶ included corrections from FEYNHIGGS at 2-loop order:
  - ▶ orders  $\mathcal{O}(\alpha_s \alpha_t, \alpha_s \alpha_b, \alpha_t^2, \alpha_t \alpha_b)$
  - ▶ resummed large logarithms

⇒ any deviation from the MSSM can directly attributed to the extended model!

⇒ kind of obvious, but only FeynHiggs does it ...

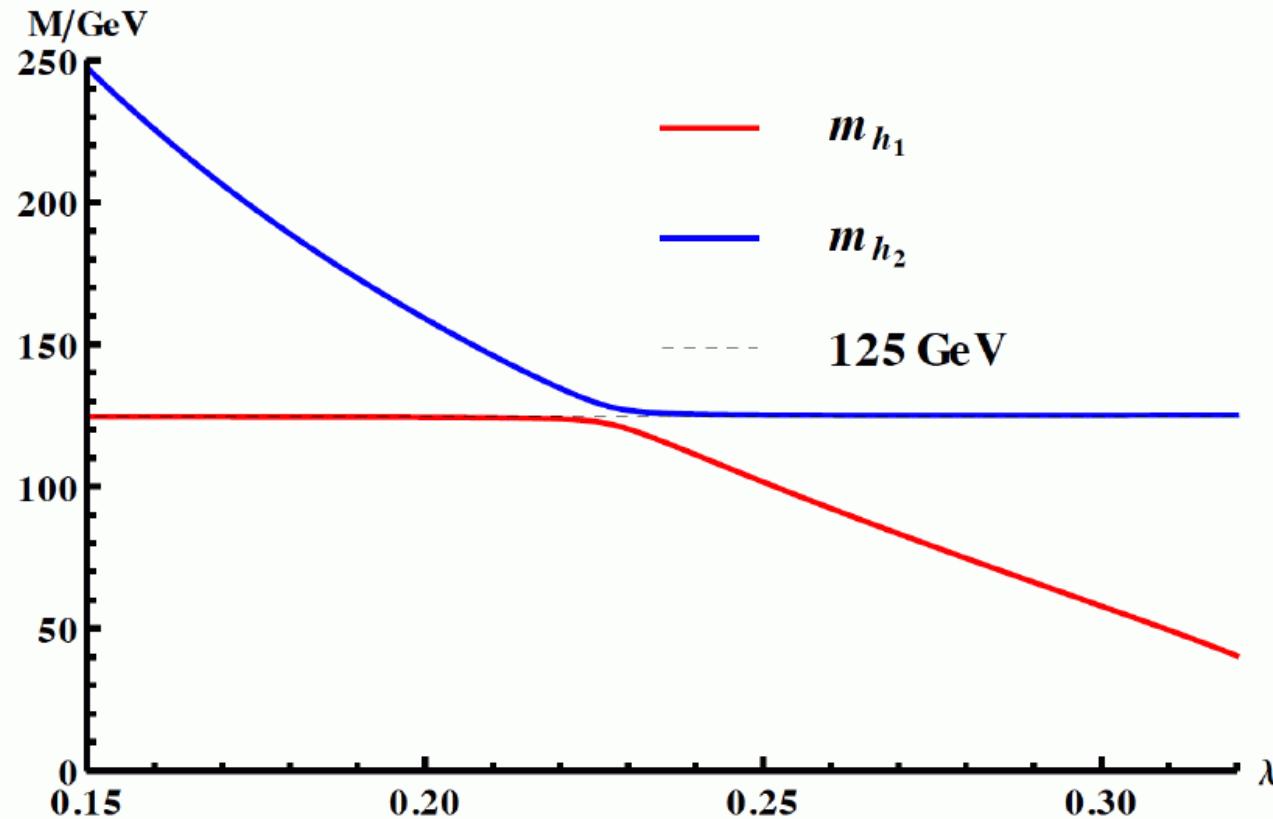
## Sample Scenario

- ▶ genuine NMSSM-scenario with a second lightest CP-even state can be interpreted as the Higgs-boson the signal at 125 GeV and a lighter singlet-like state

$$\begin{aligned} M_{H^\pm} &= 1000 \text{ GeV}, \mu_{\text{eff}} = 125 \text{ GeV}, \\ A_\kappa &= -300 \text{ GeV}, A_t = -2000 \text{ GeV}, \\ \tan \beta &= 8, \kappa = 0.2 \end{aligned}$$

$$\begin{aligned} m_{\tilde{t}_1} &\approx 1400 \text{ GeV}, m_{\tilde{t}_2} \approx 1600 \text{ GeV} \\ m_{\tilde{b}_i} &\approx 1500 \text{ GeV}, m_{\tilde{g}} \approx 1500 \text{ GeV} \end{aligned}$$

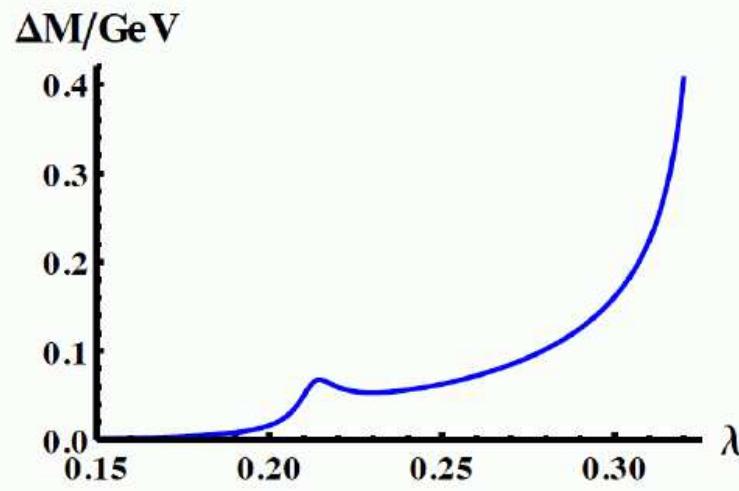
## Lighter Masses @ 2-Loop Order: Sample Scenario



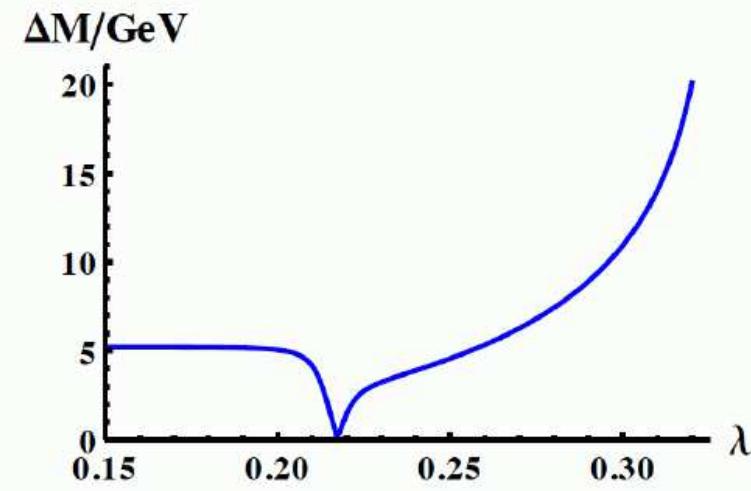
- ▶ mass decreasing with increasing  $\lambda$  belongs to singlet-like, constant mass to doublet-like state

## Lightest Mass @ 1-Loop Order: Sample Scenario

Absolute difference between different mass predictions



$$\Delta M = \left| m_{h_1}^{(Y_t)} - m_{h_1}^{(Y_t, \lambda)} \right|$$

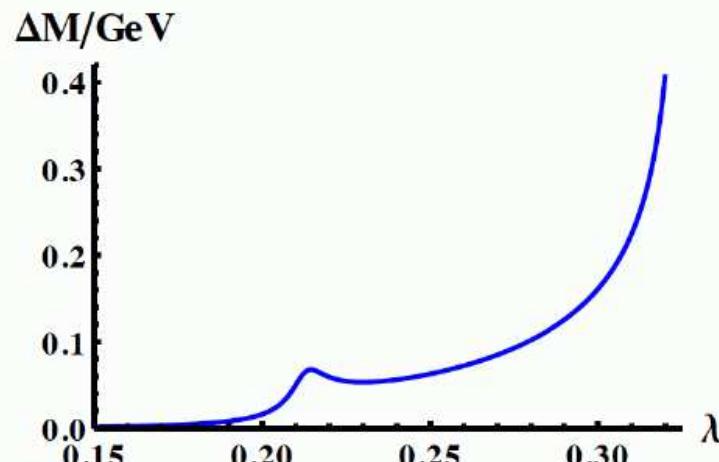


$$\Delta M = \left| m_{h_1}^{(Y_t, \lambda)} - m_{h_1}^{(1L)} \right|$$

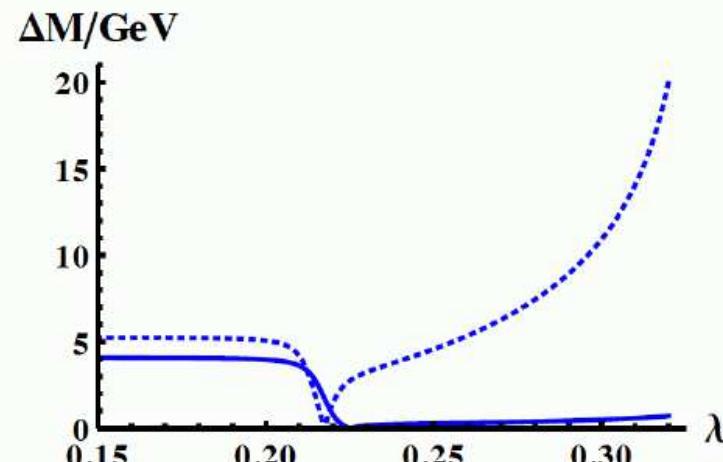
⇒ influence of corrections beyond top/scalar top-sector is by far larger than those of the order  $\mathcal{O}(Y_t \lambda, \lambda^2)$

## Lightest Mass @ 1-Loop Order: Sample Scenario

Absolute difference between different mass predictions



$$\Delta M = \left| m_{h_1}^{(Y_t)} - m_{h_1}^{(Y_t, \lambda)} \right|$$



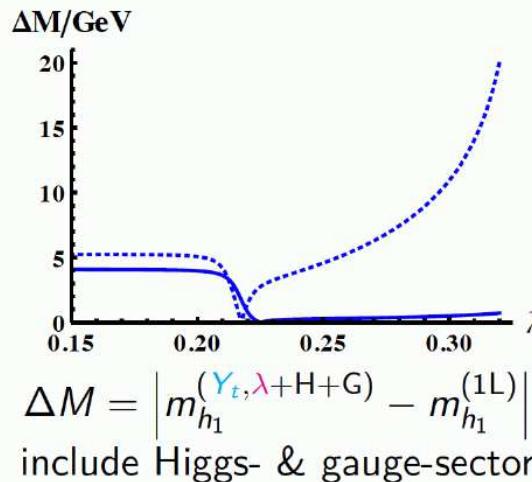
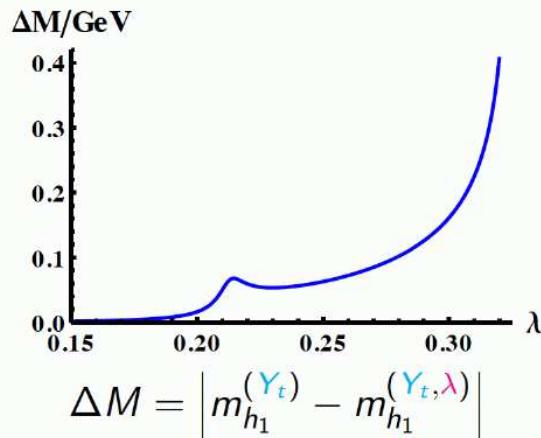
$$\Delta M = \left| m_{h_1}^{(Y_t, \lambda + H + G)} - m_{h_1}^{(1L)} \right|$$

include Higgs- & gauge-sector

⇒ influence of corrections beyond top/scalar top-sector is by far larger than those of the order  $\mathcal{O}(Y_t \lambda, \lambda^2)$

## Lightest Mass @ 1-Loop Order: Sample Scenario

Absolute difference between different mass predictions



⇒ influence of corrections beyond top/scalar top-sector is by far larger than those of the order  $\mathcal{O}(Y_t \lambda, \lambda^2)$

- ⇒ we need two-loop calculations rather from the Higgs/gauge sector than from the genuine NMSSM  $t/\tilde{t}$  sector!
- ⇒ those are not available and more complicated
- ⇒ NMSSM has intrinsically larger uncertainties than the MSSM

What has been done so far: thorough explanation of differences

- ▶ between public  $\overline{\text{DR}}$  codes [Staub et. al. '15]:  
SPheno, FlexibleSUSY, NMSSMTools, SoftSUSY, NMSSMCALC
- ▶ between hybrid on-shell/ $\overline{\text{DR}}$  codes [Drechsel, Gröber et. al. '16]:  
NMSSMCALC, NMSSM-FeynHiggs

What needs to be done:

- ▶ comparison of  $\overline{\text{DR}}$  and on-shell codes
- ▶ estimation theoretical uncertainty

⇒ here some examples of the OS/ $\overline{\text{DR}}$ comparison → back-up

⇒ based on [P. Drechsel, R. Gröber, S.H., M. Mühlleitner, G. Weiglein '16]

## Understanding the NMSSM $M_{h_1}$ calculations

- no dedicated uncertainty estimate yet
  - large differences between codes, largely understood
  - in comparison with the MSSM:
    - additional uncertainties due to genuine NMSSM effects
    - gauge/higgsino contributions can be more important than in the MSSM
- ⇒ at least 1 – 2 GeV more than in the MSSM ??!!
- ⇒ an even larger theory effort will be necessary to match the LC precision
- ⇒ dedicated session at the KUTS9 meeting in Würzburg

## 4. (N)MSSM Higgs decays (in FeynHiggs)

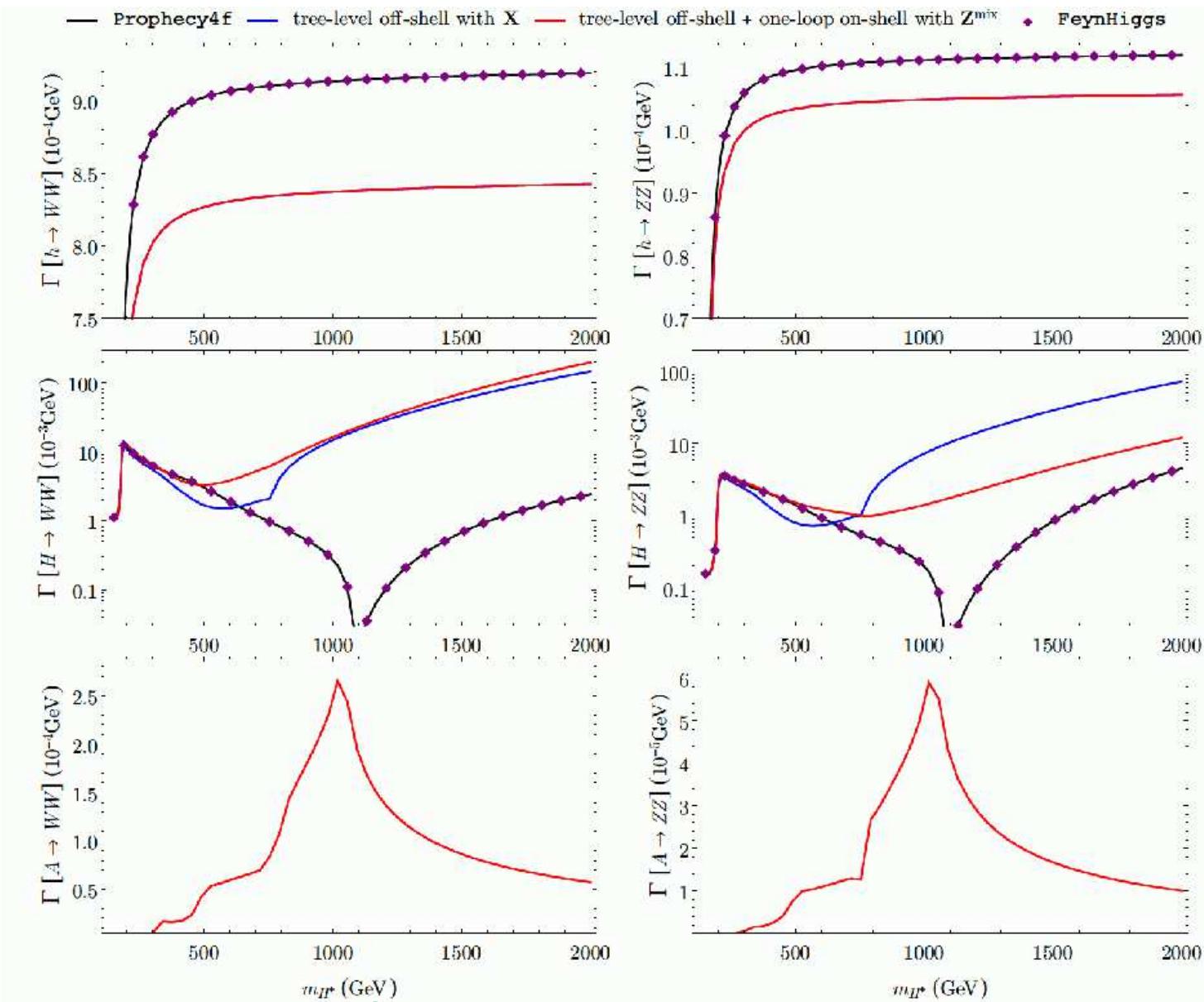
Evaluation of all MSSM Higgs boson masses and mixing angles

- $M_{h_1}, M_{h_2}, M_{h_3}, M_{H^\pm}, \alpha_{\text{eff}}, Z_{ij}, U_{ij}, \dots \Rightarrow$  precision discussed before

Evaluation of all neutral MSSM Higgs boson decay channels (so far)

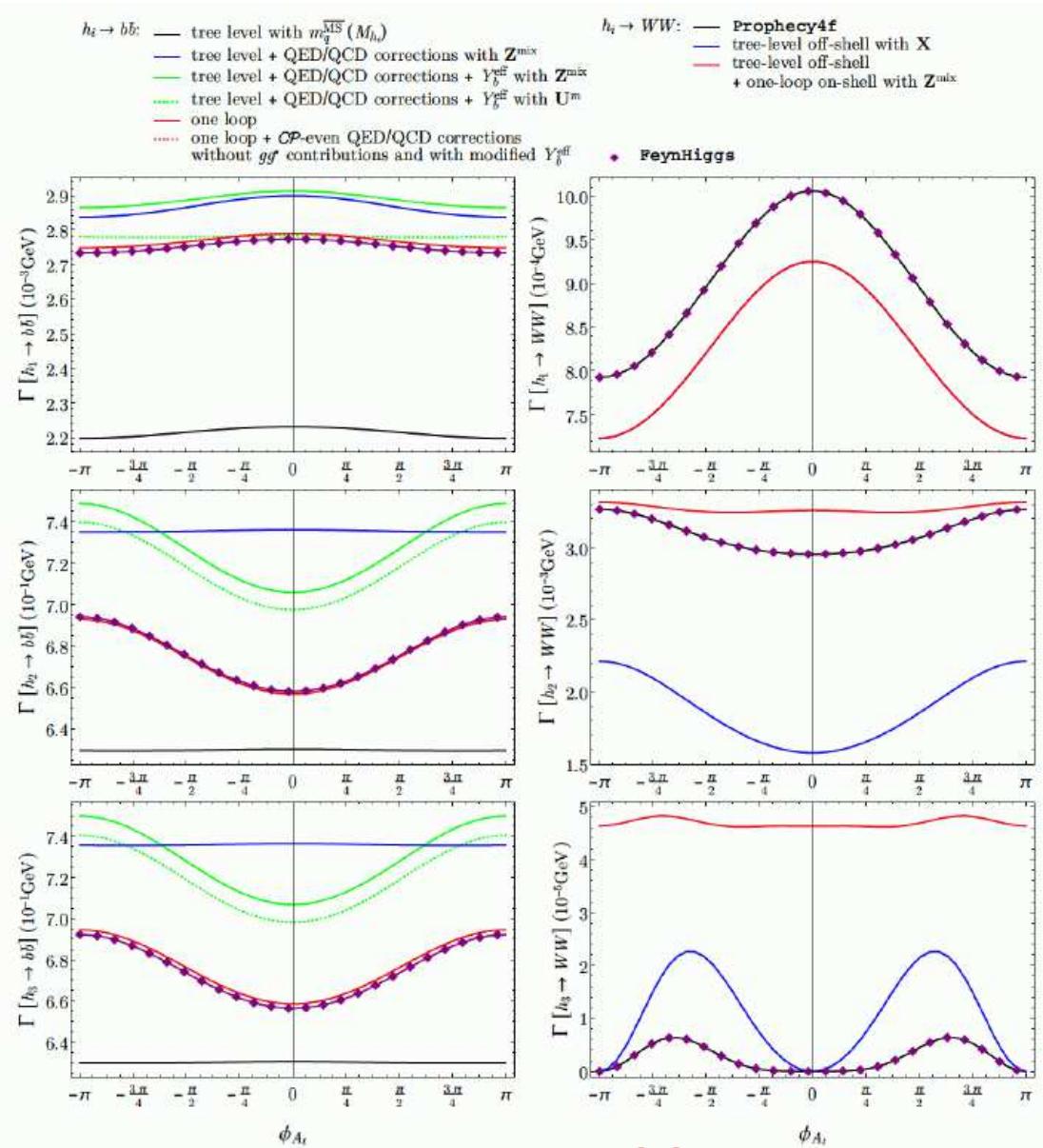
- total decay width  $\Gamma_{\text{tot}}$
- $\text{BR}(h_i \rightarrow f\bar{f})$ : decay to SM fermions: full 1L, running  $m_q$  at 3L,  $Z_{ij}$
- $\text{BR}(h_i \rightarrow Z^{(*)}Z^{(*)}, W^{(*)}W^{(*)})$ : decay to massive SM gauge bosons:  
Prophecy4f  $\oplus$  coupling factors,  $U_{ij}$
- $\text{BR}(h_i \rightarrow \gamma\gamma, gg)$ : decay to massless SM gauge bosons:  
NLO QCD,  $gg$ : NNLO, NNLL from SM,  $U_{ij}$
- $\text{BR}(h_i \rightarrow h_j Z^{(*)}, h_j h_k)$ : decay to gauge and Higgs bosons:  
 $h_j Z^{(*)}$ :  $U_{ij}$ ,  $h_j h_k$ : full 1L, log-resum,  $Z_{ij}$
- $\text{BR}(h_i \rightarrow \tilde{f}_i \tilde{f}_j)$ : decay to sfermions:  $U_{ij}$
- $\text{BR}(h_i \rightarrow \tilde{\chi}_i^\pm \tilde{\chi}_j^\mp, \tilde{\chi}_i^0 \tilde{\chi}_j^0)$ : decay to charginos, neutralinos:  $U_{ij}$

# Bringing the NMSSM to the same level [F. Domingo et al. '18 – PRELIMINARY]



⇒ relevant improvements for heavy Higgses ⇒ to be included into FH3.0

# Bringing the NMSSM to the same level [F. Domingo et al. '18 – PRELIMINARY]



⇒ relevant complex phase dep.

⇒ NMSSM to be included into FH3.0

## Overall (N)MSSM Higgs decay uncertainty estimates

[*F. Domingo et al. '18 – PRELIMINARY*]

- $h_i \rightarrow q\bar{q}$ : SM-like: SM NNLO QCD, EW NNLO, SUSY 2L:  $\sim 5\%$   
heavy: as SM-like, Sudakov logs:  $\sim 5 – 10\%$
- $h_i \rightarrow \ell\bar{\ell}$ : SM-like:  $\lesssim 1\%$   
heavy: Sudakov logs for very heavy Higgses  $\lesssim 10\%$
- $h_i \rightarrow WW^{(*)}, ZZ^{(*)}$ : SM-like:  $\lesssim 1\%$   
heavy: missing 2L (very small width):  $\lesssim 50\%$
- $h_i \rightarrow \gamma\gamma, gg, \gamma Z$ :  $\gamma\gamma$ : NNLO QCD, EW:  $\lesssim 4\%$   
 $gg$ : NNLO QCD, EW:  $\lesssim 4\%$   
 $\gamma Z$ : NLO:  $\sim 5\%$
- $h_i \rightarrow$  SUSY SUSY: [*S.H., C. Schappacher '14-'16*]  
1L effects  $10 – 20\%$ , 2L?
- all decays:  $U_{ij}, Z_{ij}$ : few %, effects close to threshold?  
⇒ approaching LC precision for SM-like Higgs (not for heavy Higgses yet)

## 5. Conclusions

- High precision predictions in BSM models for Higgs physics are needed!  
→ to match experimental accuracy at the LHC and ILC/CLIC
- **FeynHiggs** provides these predictions for the (N)MSSM  
(⇒ code adopted by the LHCHXSWG)  
⇒ first and most developed “hybrid code” – necessary for high precision
- MSSM:
  - uncertainties (partially) re-evaluated
  - simple one-scale scenario:  $\delta M_h \sim 2 \text{ GeV}$
- NMSSM: (“internal FH version” exists):
  - combine genuine NMSSM contributions with known MSSM parts
  - ⇒ very good approximation
  - ⇒ highest possible precision in the NMSSM
  - $\delta M_{h_1}^{\text{NMSSM genuine}} \gtrsim 1 - 2 \text{ GeV}$
- (N)MSSM Higgs decays:  
approaching LC precision for SM-like Higgs (not for heavy Higgses yet)

# Higgs Days at Santander 2018

Theory meets Experiment

10.-14. September



Contact: [Sven.Heinemeyer@cern.ch](mailto:Sven.Heinemeyer@cern.ch)  
Local: [Gervasio.Gomez@cern.ch](mailto:Gervasio.Gomez@cern.ch)  
<http://hdays.csic.es>



Further Questions?

## New in FH2.12.0: inclusion of further log-resummed results

New options in FeynHiggs:

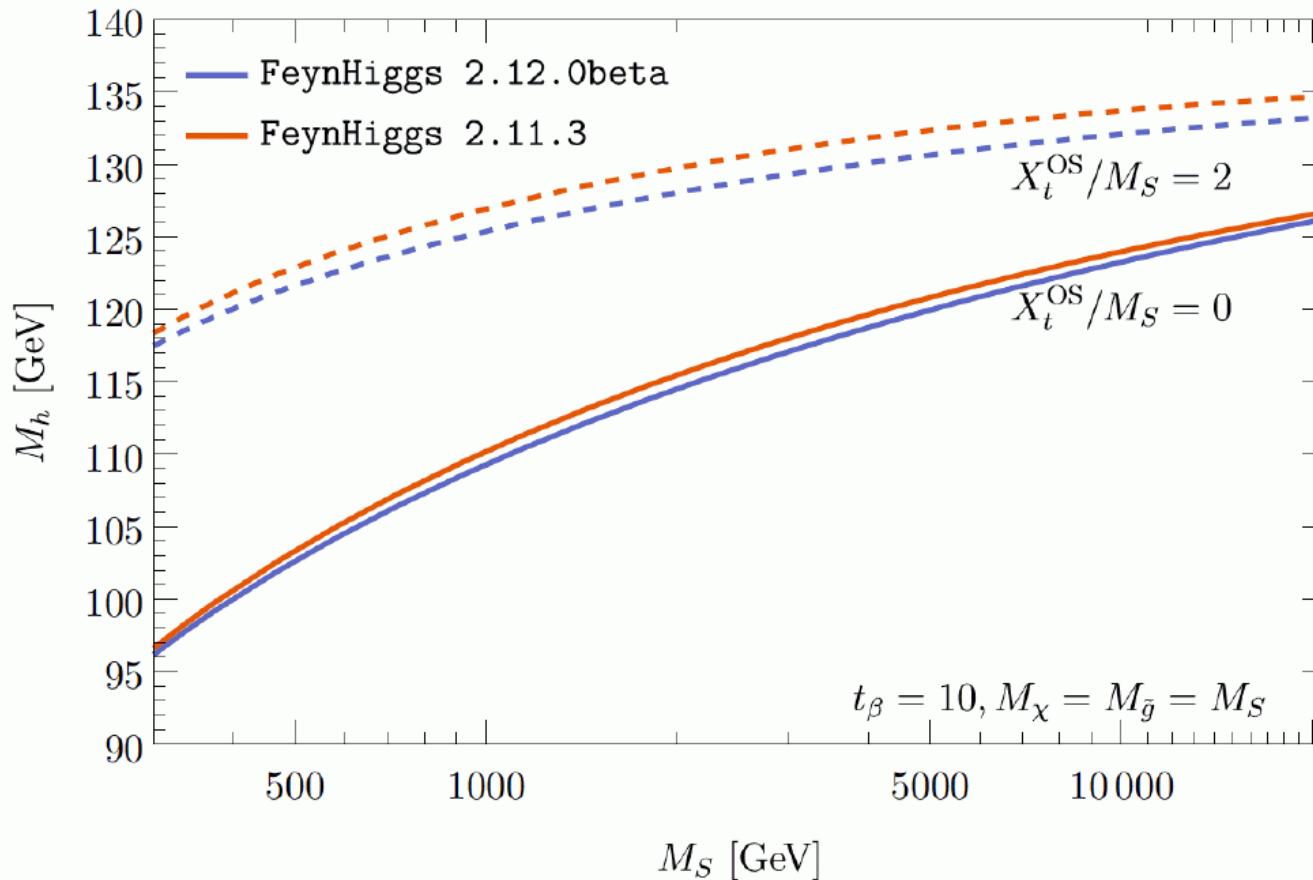
New resummation options controlled by new flag  
(not by `looplevel` anymore)

- ▶ `loglevel = 0`: no resummation
- ▶ `loglevel = 1`:  $\mathcal{O}(\alpha_s, \alpha_t)$  LL+NLL
- ▶ `loglevel = 2`: full LL+NLL
- ▶ `loglevel = 3`: full LL+NLL and  $\mathcal{O}(\alpha_s, \alpha_t)$  NNLL

$\overline{\text{MS}}$  top mass (Yukawa coupling) automatically chosen  
accordingly

## New in FH2.12.0: inclusion of further log-resummed results

Inclusion of EW effects in RGE's:

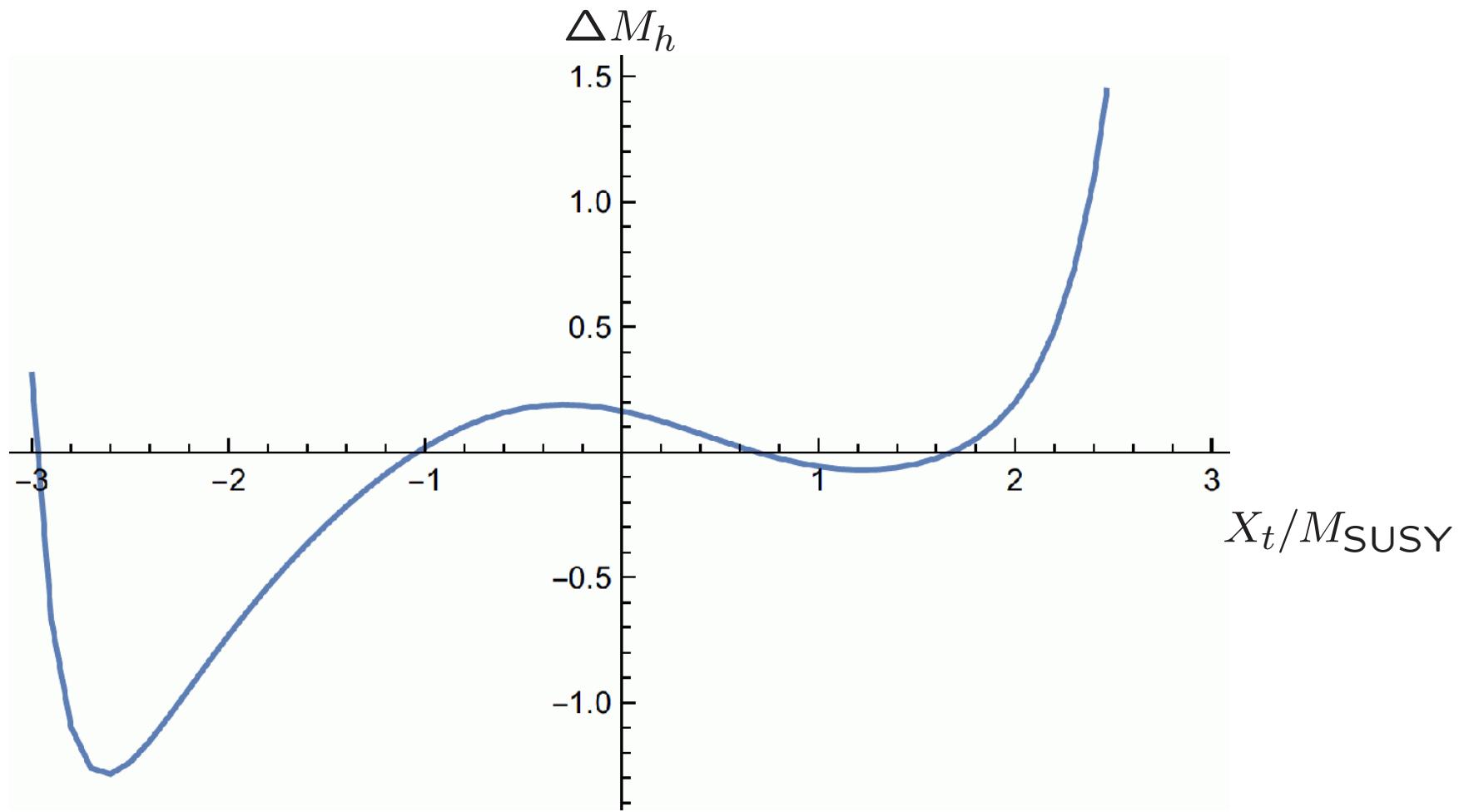


Main contribution → electroweak contributions to  $\overline{\text{MS}}$  top mass

## New in FH2.12.0: inclusion of further log-resummed results

Going from 2L RGE's to 3L RGE's (`loglevel = 2 → 3`):

$M_{\text{SUSY}} = 1 \text{ TeV}$ ,  $\tan \beta = 10$



Note:  $m_t^{\text{NNLO}}$  used for 2L and 3L RGEs

⇒ non-negligible effects in both directions

## Test Point (TP) Scenarios

Comparison takes place for several physical scenarios with different properties:

TP1 MSSM-like point

TP2 MSSM-like point with large stop splitting

TP3 Point with light singlet and  $\lambda$  close to the perturbativity limit

TP4 Point with heavy singlet and  $\lambda$  close to the perturbativity limit

TP5 Point with singlet slightly lighter than 125 GeV

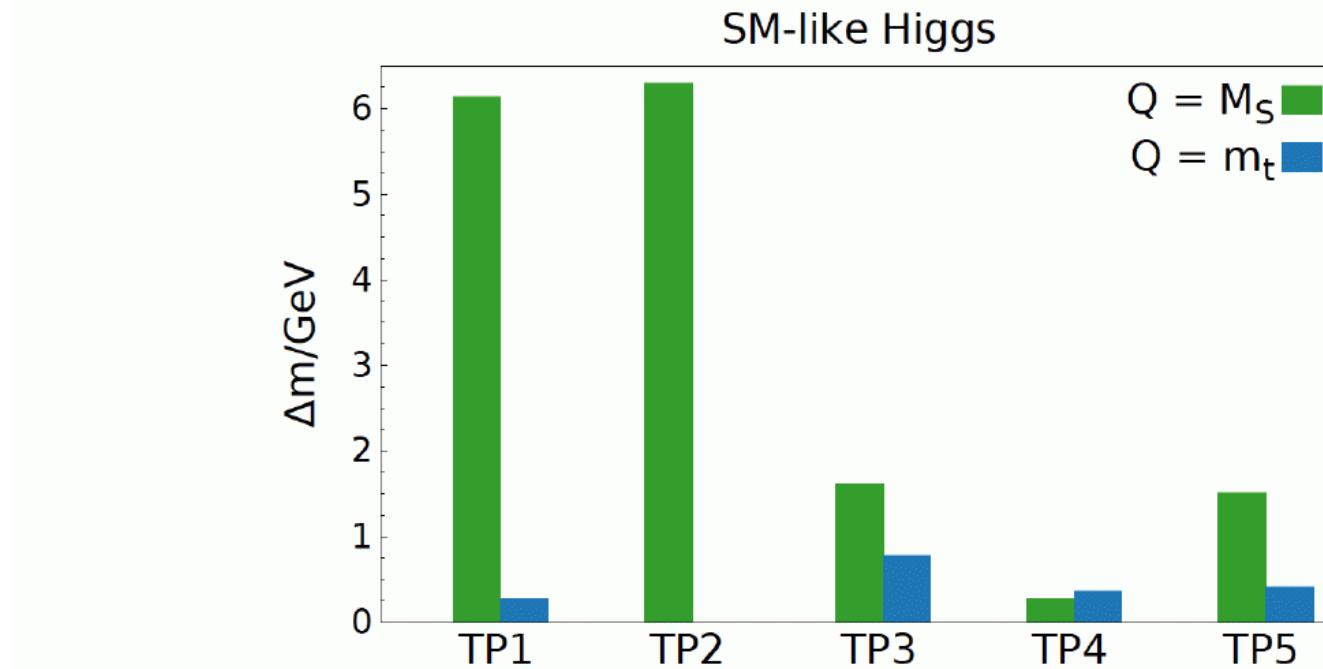
TP scenarios originally defined at scale

$$M_S = \frac{1}{2}(M_{\tilde{Q}_3} + M_{\tilde{t}_R}) \approx 750\text{--}1500 \text{ GeV}$$

⇒ evaluation at  $Q = m_t, M_S$

Comparison “out-of-the-box”:  $\Delta m = M_h^{\text{NC}} - M_h^{\text{N-FH}}$

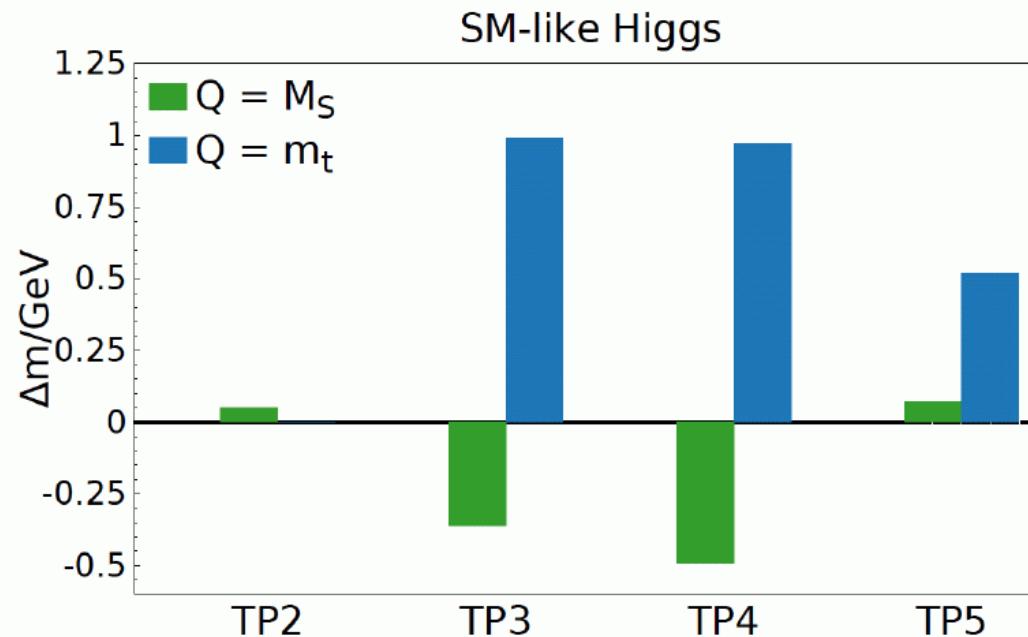
Q	TP1		TP2		TP3		TP4		TP5	
	$M_S$	$m_t$	$M_S$	$m_t$	$M_S$	$m_t$	$M_S$	$m_t$	$M_S$	$m_t$
$M_h^{\text{NC}}$	121.84	113.47	120.42	—	126.16	125.80	126.44	126.65	124.44	123.51
$M_h^{\text{N-FH}}$	115.70	113.20	114.12	—	124.55	125.02	126.17	126.29	122.93	123.10



⇒ large differences, largely understood – but surprizing?!

Comparison adapted:  $\Delta m = M_h^{\text{NC}} - M_h^{\text{N-FH}}$

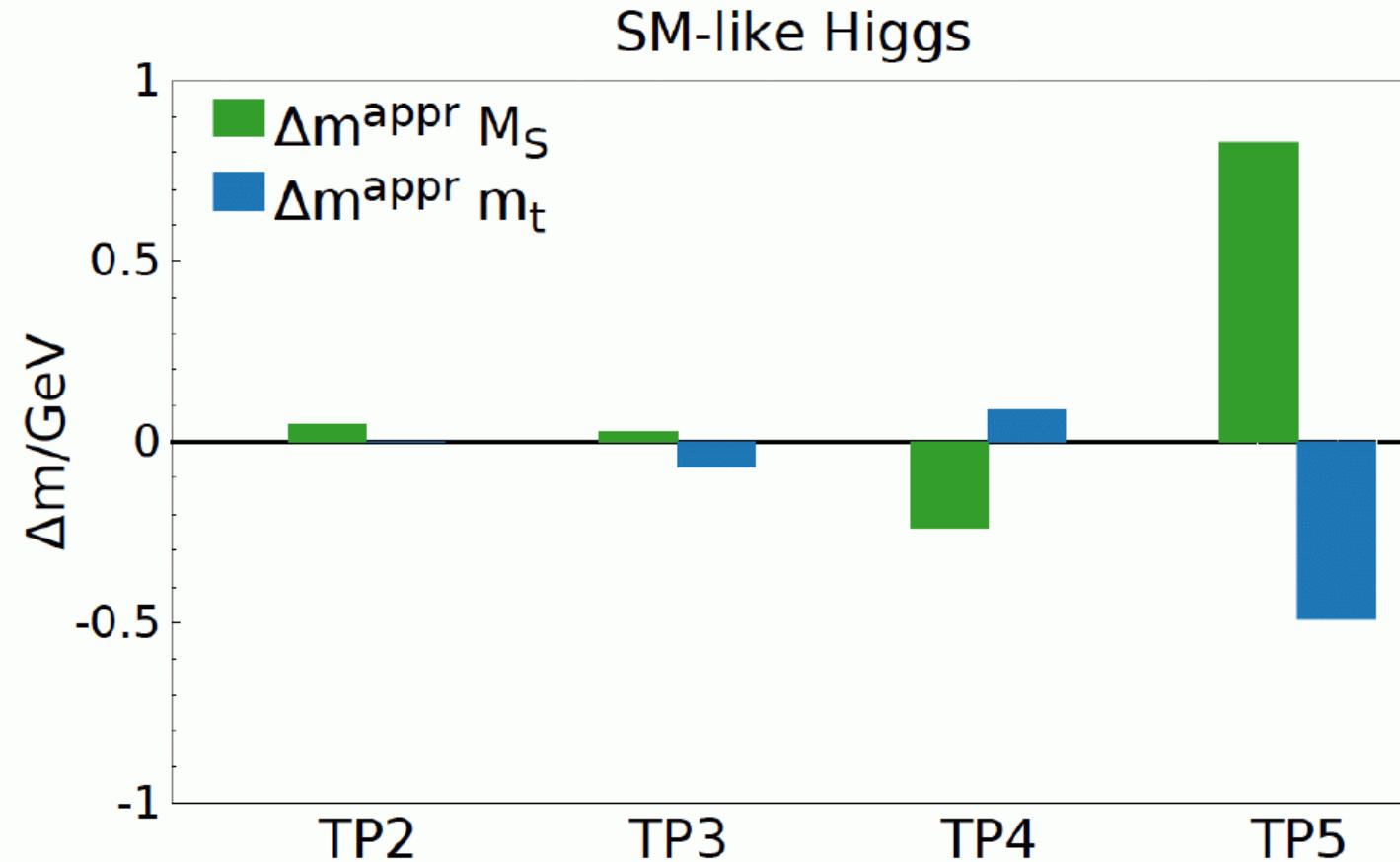
Q	TP2		TP3		TP4		TP5	
	$M_S$	$m_t$	$M_S$	$m_t$	$M_S$	$m_t$	$M_S$	$m_t$
$M_h^{\text{NC}}$	114.70	—	123.90	125.87	125.07	126.71	122.88	123.60
$M_h^{\text{N-FH}}$	114.65	—	124.26	124.88	125.56	125.74	122.81	123.08



⇒ Much better agreement due to adapted couplings  $\alpha_s$  and  $\alpha!$

⇒ indication of some missing higher-order corrections

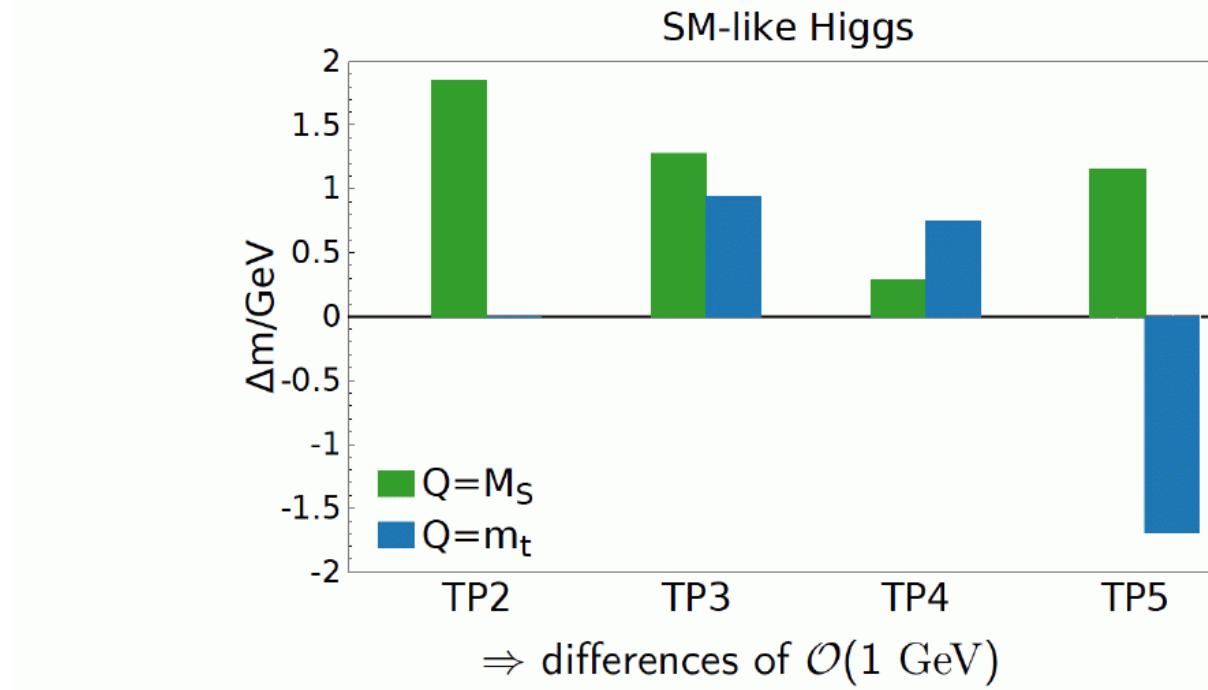
MSSM-approximation:  $\Delta m^{\text{appr}} = \Delta m^{2\text{L}} - \Delta m^{1\text{L}}$



⇒ MSSM-approximation overall very accurate for TP2-4

Comparison on-shell and  $\overline{\text{DR}}$ :  $\Delta m = M_h^{\text{OS}} - M_h^{\overline{\text{DR}}}$

$Q$	TP2		TP3		TP4		TP5	
	$M_S$	$m_t$	$M_S$	$m_t$	$M_S$	$m_t$	$M_S$	$m_t$
$M_h^{\text{OS}}$	120.42	—	126.16	125.80	126.44	126.65	124.44	123.51
$M_h^{\overline{\text{DR}}}$	118.57	—	124.88	124.86	126.15	125.90	123.28	125.20



⇒ indication of some missing corrections beyond 2L?!

## Evaluations for the charged Higgs boson (rMSSM/cMSSM)

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

## Evaluation of additional couplings:

- $g(V \rightarrow V h_i, h_i h_j)$ : coupling of gauge and Higgs bosons
- $g(h_i h_j h_k)$ : all Higgs self couplings (including charged Higgs)