

**herkömmliches
Higgsprogramm**

**Das neue
FeynHiggs**

FeynHiggs: Status and Prospects

Sven Heinemeyer, IFCA (CSIC, Santander)

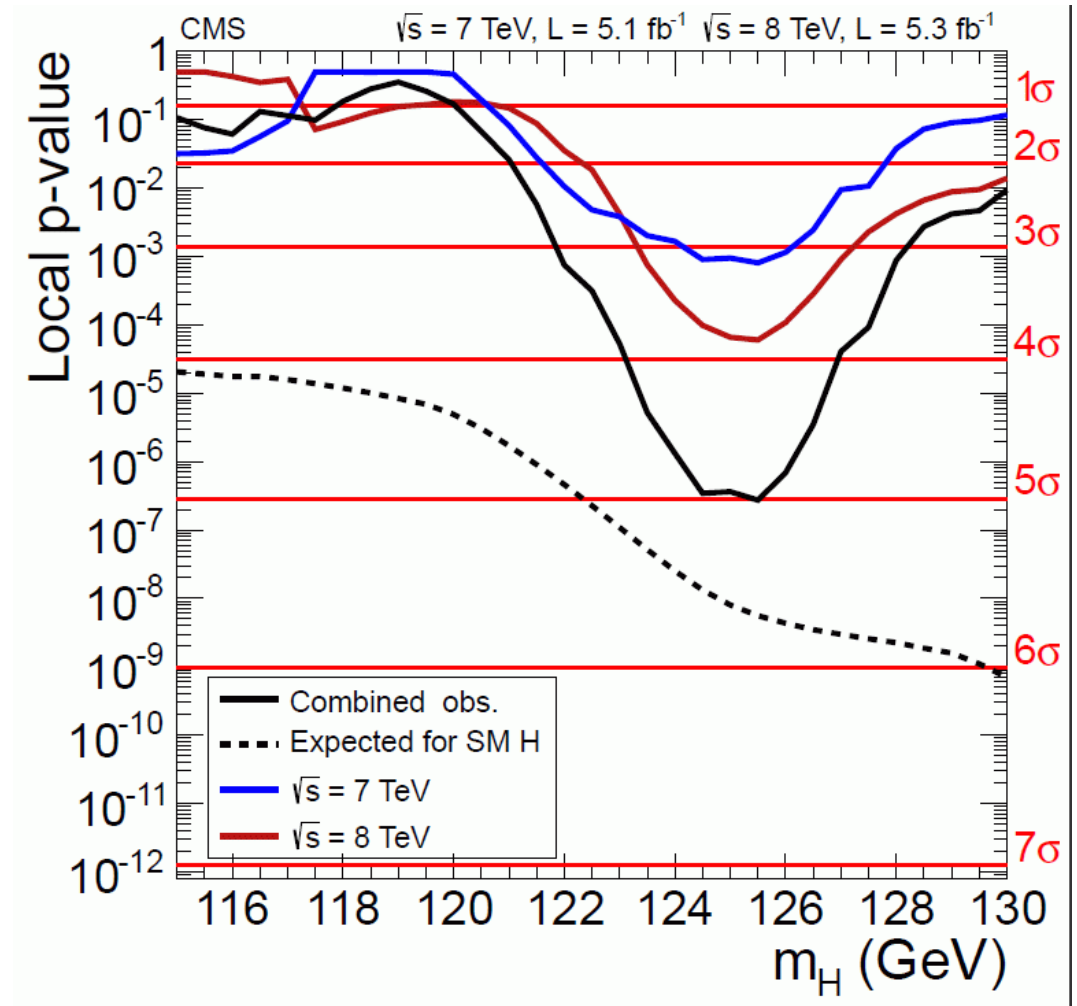
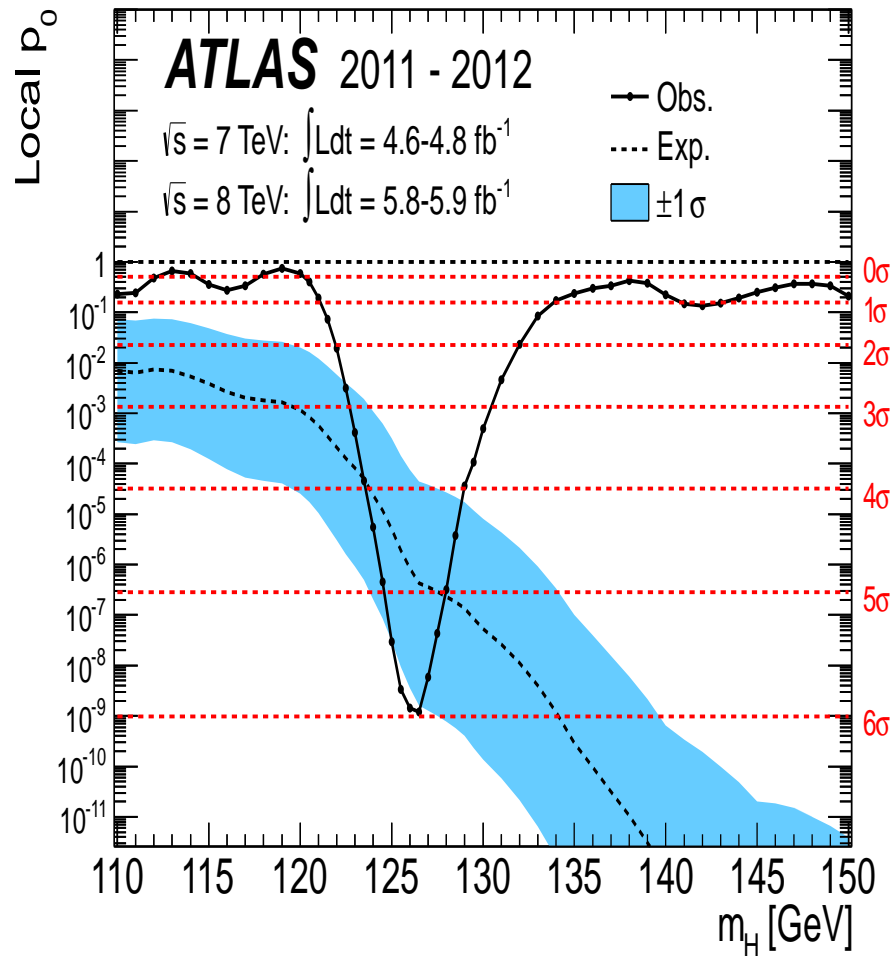
Lake Tahoe, 08/2015

with *T. Hahn, W. Hollik, H. Rzehak and G. Weiglein*

- FeynHiggs status
- Latest additions
- FeynHiggs vs. EFT approach
- FeynHiggs: prospects



1. Motivation

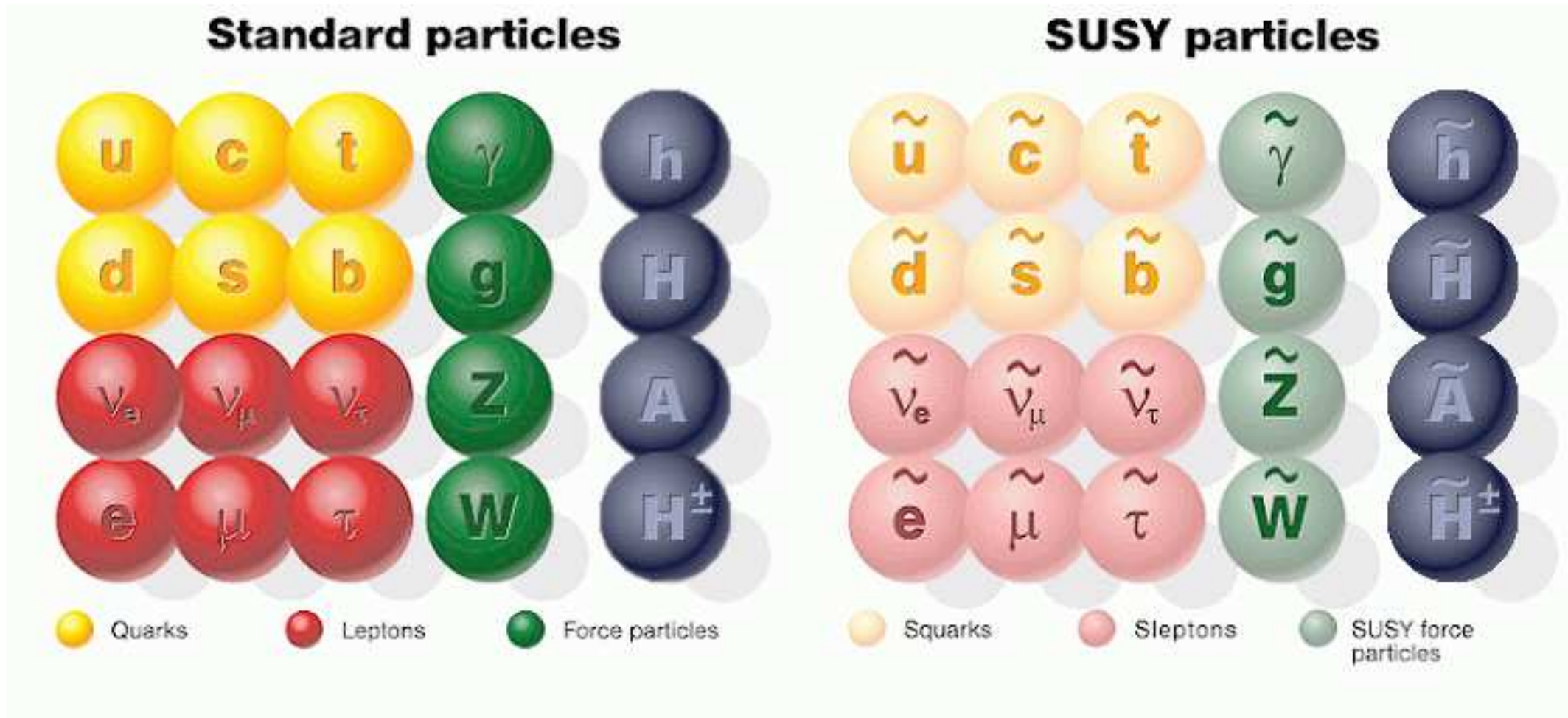


\Rightarrow clear discovery at $\sim 125 \text{ GeV}$!

\Rightarrow can be interpreted as the light(/heavy) CP -even MSSM Higgs

The MSSM:

⇒ Superpartners for Standard Model particles



Enlarged Higgs sector: Two Higgs doublets

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

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

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)

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

Needed for LHC/ILC/. . . physics:

Precise and consistent prediction of

- Higgs boson masses
- Higgs boson mixings
- Higgs boson couplings
- Higgs boson production cross sections
- Higgs boson decay widths/branching ratios
- . . .

⇒ (partially) provided by FeynHiggs

2. FeynHiggs status

Latest version: FeynHiggs 2.11.2 (07/15)

version FeynHiggs 2.11.3 nearly ready . . . :-)

FeynHiggs compiles on all modern platforms

FeynHiggs provides:

- Higgs boson masses
- Higgs boson couplings
- Higgs boson decay widths
- Higgs boson production cross sections (4π , good approx.)
- evaluation of other observables to test the validity of parameters
- all this for the neutral and charged Higgs bosons
- all this in the MSSM with real or complex parameters

⇒ the Standard Code for masses couplings, some decays in the LHCHSWG

The core: MSSM Higgs mass calculation

Propagator/Mass matrix at tree-level:

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

Propagator / mass matrix with higher-order corrections (FD 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

$\hat{\Sigma}_{Ah}, \hat{\Sigma}_{AH} \neq 0 \Rightarrow \mathcal{CPV}$, \mathcal{CP} -even and \mathcal{CP} -odd fields can mix

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

Corrections included in FeynHiggs 2.10

$$\left(\begin{array}{ccc} k^2 - M_h^2 + \hat{\Sigma}_{hh} & \hat{\Sigma}_{hH} & \hat{\Sigma}_{hA} \\ \hat{\Sigma}_{Hh} & k^2 - M_H^2 + \hat{\Sigma}_{HH} & \hat{\Sigma}_{HA} \\ \hat{\Sigma}_{Ah} & \hat{\Sigma}_{AH} & k^2 - M_A^2 + \hat{\Sigma}_{AA} \end{array} \right), \hat{\Sigma}_{H^+H^-}$$

- **Full one-loop evaluation (all phases, k^2 dependence).**

Frank, Heinemeyer, Hollik, Weiglein 2002

- **Leading $\mathcal{O}(\alpha_s \alpha_t)$ two-loop corrections in the cMSSM.**

Heinemeyer, Hollik, Rzehak, Weiglein 2007

- **Leading $\mathcal{O}(\alpha_t^2)$ + subleading $\mathcal{O}(\alpha_s \alpha_b, \alpha_t \alpha_b, \alpha_b^2)$ two-loop corrections in the rMSSM (phases only partially included).**

Degrassi, Slavich, Zwirner 2001 – Brignole, Degrassi, Slavich, Zwirner 2001, 02

Dedes, Degrassi, Slavich 2003

- **RGE-resummed leading logs**

Hahn, Heinemeyer, Hollik, Rzehak, Weiglein 2013



FeynHiggs Update – p.10

New: k^2 Dependence @ 2L

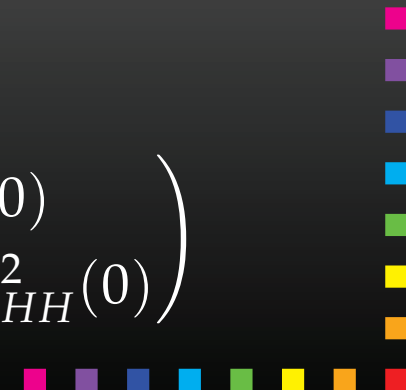
$$\left(\begin{array}{cc} k^2 - M_h^2 + \hat{\Sigma}_{hh} & \hat{\Sigma}_{hH} \\ \hat{\Sigma}_{Hh} & k^2 - M_H^2 + \hat{\Sigma}_{HH} \end{array} \right), \hat{\Sigma}_{H^+H^-}$$

$$\left(\begin{array}{cc} \hat{\Sigma}_{Ah} & \hat{\Sigma}_{AH} \\ \hat{\Sigma}_{hA} & \hat{\Sigma}_{HA} \\ k^2 - M_A^2 + \hat{\Sigma}_{AA} & \end{array} \right)$$

$$\left(\begin{array}{cc} k^2 - M_h^2 + \hat{\Sigma}_{hh}^{(1)}(k^2) + \hat{\Sigma}_{hh}^{(2)}(k^2) & \hat{\Sigma}_{hH}^{(1)}(k^2) + \hat{\Sigma}_{hH}^{(2)}(k^2) \\ \hat{\Sigma}_{Hh}^{(1)}(k^2) + \hat{\Sigma}_{Hh}^{(2)}(k^2) & k^2 - M_H^2 + \hat{\Sigma}_{HH}^{(1)}(k^2) + \hat{\Sigma}_{HH}^{(2)}(k^2) \end{array} \right)$$

before FeynHiggs 2.10.1:

$$\left(\begin{array}{cc} k^2 - M_h^2 + \hat{\Sigma}_{hh}^{(1)}(k^2) + \hat{\Sigma}_{hh}^{(2)}(0) & \hat{\Sigma}_{hH}^{(1)}(k^2) + \hat{\Sigma}_{hH}^{(2)}(0) \\ \hat{\Sigma}_{Hh}^{(1)}(k^2) + \hat{\Sigma}_{Hh}^{(2)}(0) & k^2 - M_H^2 + \hat{\Sigma}_{HH}^{(1)}(k^2) + \hat{\Sigma}_{HH}^{(2)}(0) \end{array} \right)$$



Included in FeynHiggs 2.11.2 (I):

Evaluation of all Higgs boson masses and mixing angles

- $M_{h_1}, M_{h_2}, M_{h_3}, M_{H^\pm}$, α_{eff} , \mathbf{Z}_{ij} , \mathbf{U}_{ij} , ...

Evaluation of all neutral Higgs boson decay channels

- total decay width Γ_{tot}
- $\text{BR}(h_i \rightarrow f\bar{f})$: decay to SM fermions
- $\text{BR}(h_i \rightarrow \gamma\gamma, Z^{(*)}Z^{(*)}, W^{(*)}W^{(*)}, gg)$: decay to SM gauge bosons
- $\text{BR}(h_i \rightarrow h_j Z^{(*)}, h_j h_k)$: decay to gauge and Higgs bosons
- $\text{BR}(h_i \rightarrow \tilde{f}_i \tilde{f}_j)$: decay to sfermions
- $\text{BR}(h_i \rightarrow \tilde{\chi}_i^\pm \tilde{\chi}_j^\mp, \tilde{\chi}_i^0 \tilde{\chi}_j^0)$: decay to charginos, neutralinos

Evaluation for the SM Higgs (same masses as the three MSSM Higgses)

- total decay width $\Gamma_{\text{tot}}^{\text{SM}}$
- $\text{BR}(h_i^{\text{SM}} \rightarrow f\bar{f})$: decay to SM fermions
- $\text{BR}(h_i^{\text{SM}} \rightarrow \gamma\gamma, ZZ^{(*)}, WW^{(*)}, gg)$: decay to SM gauge bosons

Included in FeynHiggs 2.11.2 (II):

Evaluation of all neutral Higgs boson production cross sections at LHC

SM: (more or less) up-to-date, MSSM: additional effective couplings

- $gg \rightarrow h_i$: gluon fusion
- $WW \rightarrow h_i, ZZ \rightarrow h_i$: gauge boson fusion
- $W \rightarrow Wh_i, Z \rightarrow Zh_i$: Higgs strahlung
- $b\bar{b} \rightarrow b\bar{b}h_i$: bottom Yukawa process
- $b\bar{b} \rightarrow b\bar{b}h_i, h_i \rightarrow b\bar{b}$, one b tagged
- $t\bar{t} \rightarrow t\bar{t}h_i$: top Yukawa process
- $\tilde{t}\tilde{t} \rightarrow \tilde{t}\tilde{t}h_i$: stop Yukawa process

Evaluation for the SM Higgs (same masses as the three MSSM Higgses)

- all SM channels as above

Included in FeynHiggs 2.11.2 (III):

Evaluations for the charged Higgs boson (rMSSM/cMSSM)

- total decay width Γ_{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)

Included in FeynHiggs 2.11.2 (IV):

Evaluation of theory error on masses and mixing

→ estimate of uncertainty in $M_{h_i}, \mathbf{U}_{ij}, \mathbf{Z}_{ij}$ from unknown higher-order corr.

Evaluation of masses, mixing and decay in the NMFV/LFV MSSM

NMFV: Non Minimal Flavor Violation LFV: Lepton Flavor Violation
⇒ Connection to Flavor physics

Evaluation of additional constraints (rMSSM/cMSSM)

- ρ -parameter: $\Delta\rho^{\text{SUSY}}$ at $\mathcal{O}(\alpha), \mathcal{O}(\alpha\alpha_s), \dots$, including **FV** effects
⇒ $M_W, \sin^2\theta_{\text{eff}}$ via SM formula + $\Delta\rho^{\text{SUSY}}$, including **FV** effects
- anomalous magnetic moment of the μ : $(g-2)_\mu$
- $\text{BR}(b \rightarrow s\gamma)$, including **NMFV** effects
- $\text{BR}(B_s \rightarrow \mu^+\mu^-)$, including **NMFV** effects
- EDMs of electron, neutron, Hg, ...

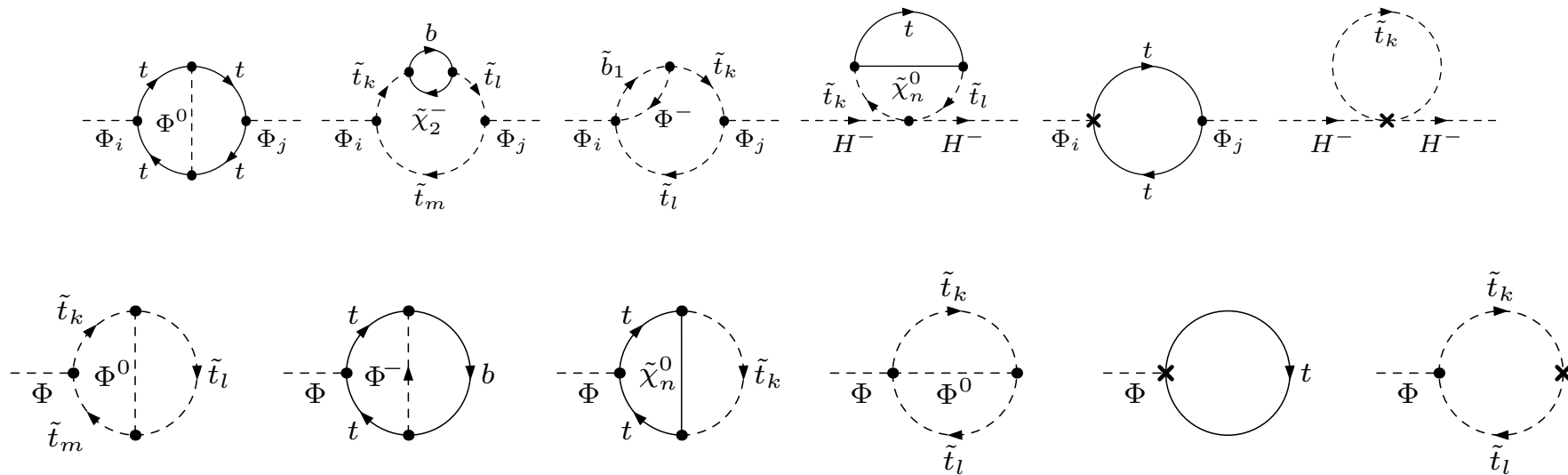
3. Latest additions

- $\mathcal{O}(\alpha_t^2)$ corrections in cMSSM
- $\mathcal{O}(p^2\alpha_t\alpha_s)$ corrections in rMSSM
 $\overline{\text{DR}}$ renormalization of m_t in two-loop corrections
- log-resummation in t/\tilde{t} sector
- . . .

3A) $\mathcal{O}(\alpha_t^2)$ corrections in the cMSSM

Two-loop top-Yukawa-coupling corrections to the Higgs boson masses in the complex MSSM

[W. Hollik, S. Passehr '14]

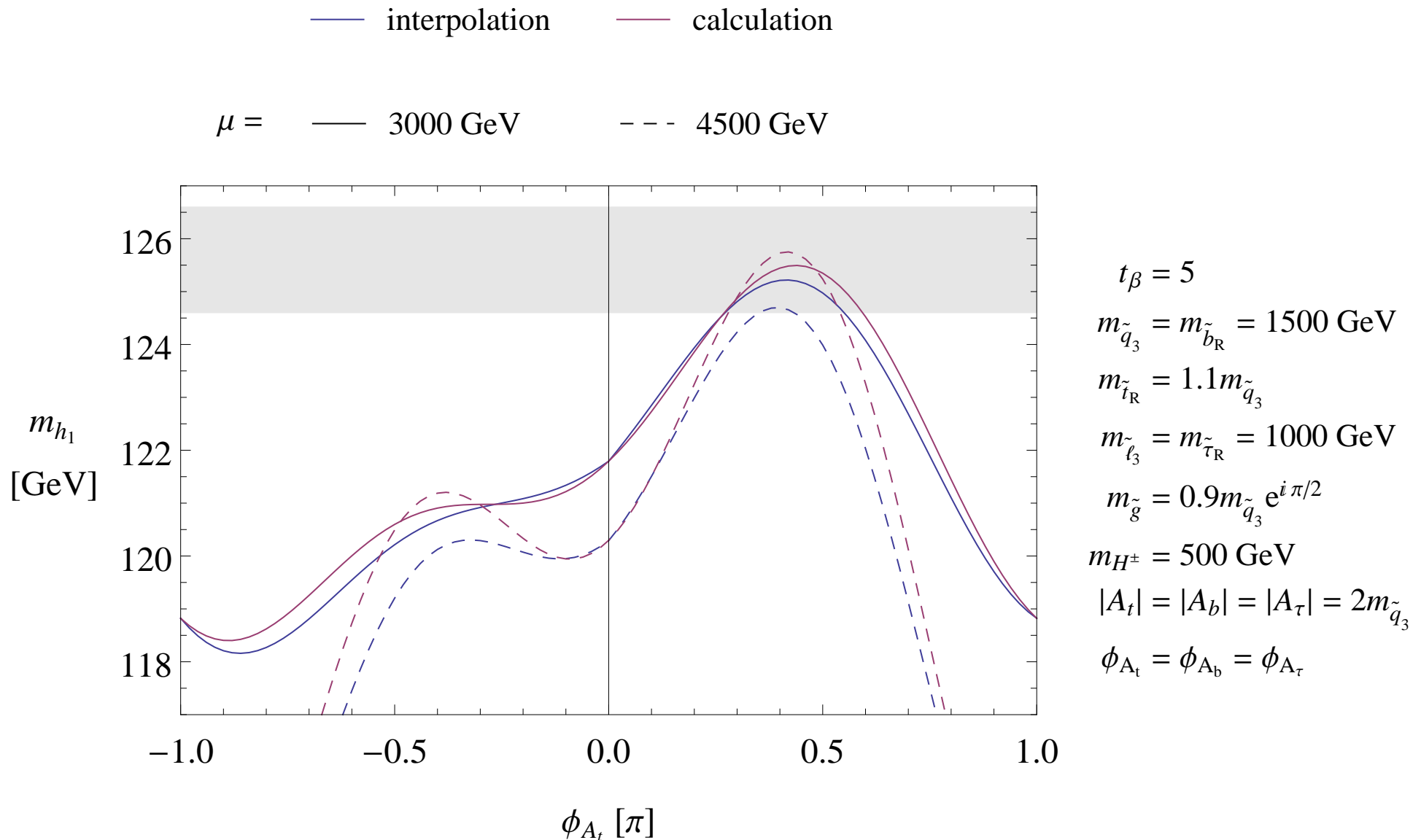


\Rightarrow effects in M_{h_1} of $\mathcal{O}(1 \text{ GeV})$

\Rightarrow equally $\mathcal{O}(\alpha_t^2)$ corrections to M_{H^\pm} in rMSSM

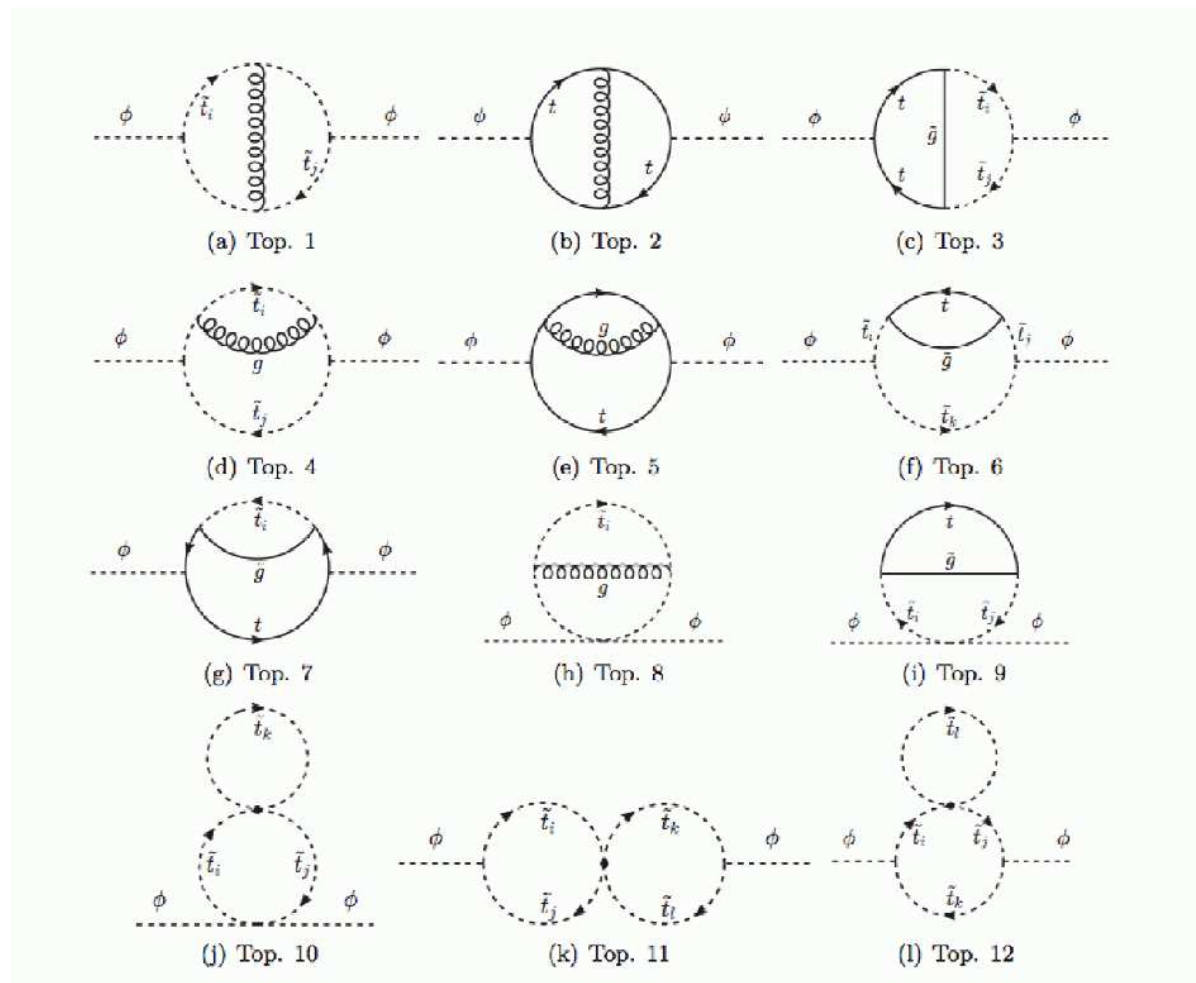
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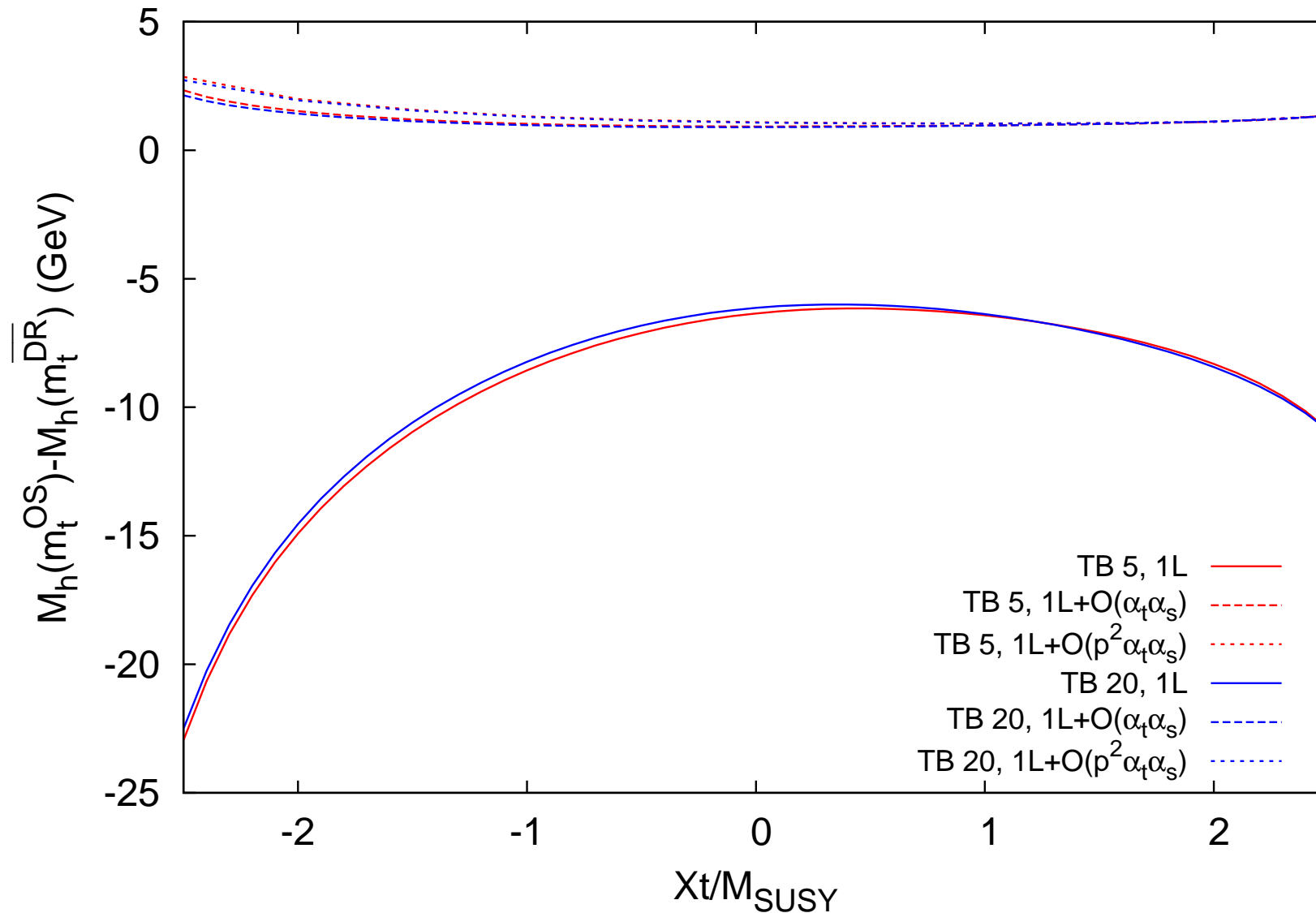
3B) $\mathcal{O}(p^2 \alpha_t \alpha_s)$ corrections in the rMSSM

[S. Borowka, T. Hahn, S.H., G. Heinrich, W. Hollik '14]



\Rightarrow also $\overline{\text{DR}}$ renormalization of m_t in two-loop corrections

X_t dependence in light-stop scenario:



⇒ strong reduction of RS dependence at the two-loop level

⇒ additional possibility of estimate of higher-order uncertainties

3C) Log-resummation in t/\tilde{t} sector via RGE's

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

⇒ see G. Lee's talk

Simple example for log resummation:

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

Above M_{SUSY} : MSSM

Below M_{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 ($\alpha_s = g_s^2/(4\pi)$)

Procedure (as in FeynHiggs):

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 λ, h_t, g_s : $\lambda, h_t, g_s(M_S) \rightarrow \lambda, h_t, g_s(m_t)$

3. Evaluate M_h^2

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

Combination of FD and RGE result:

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

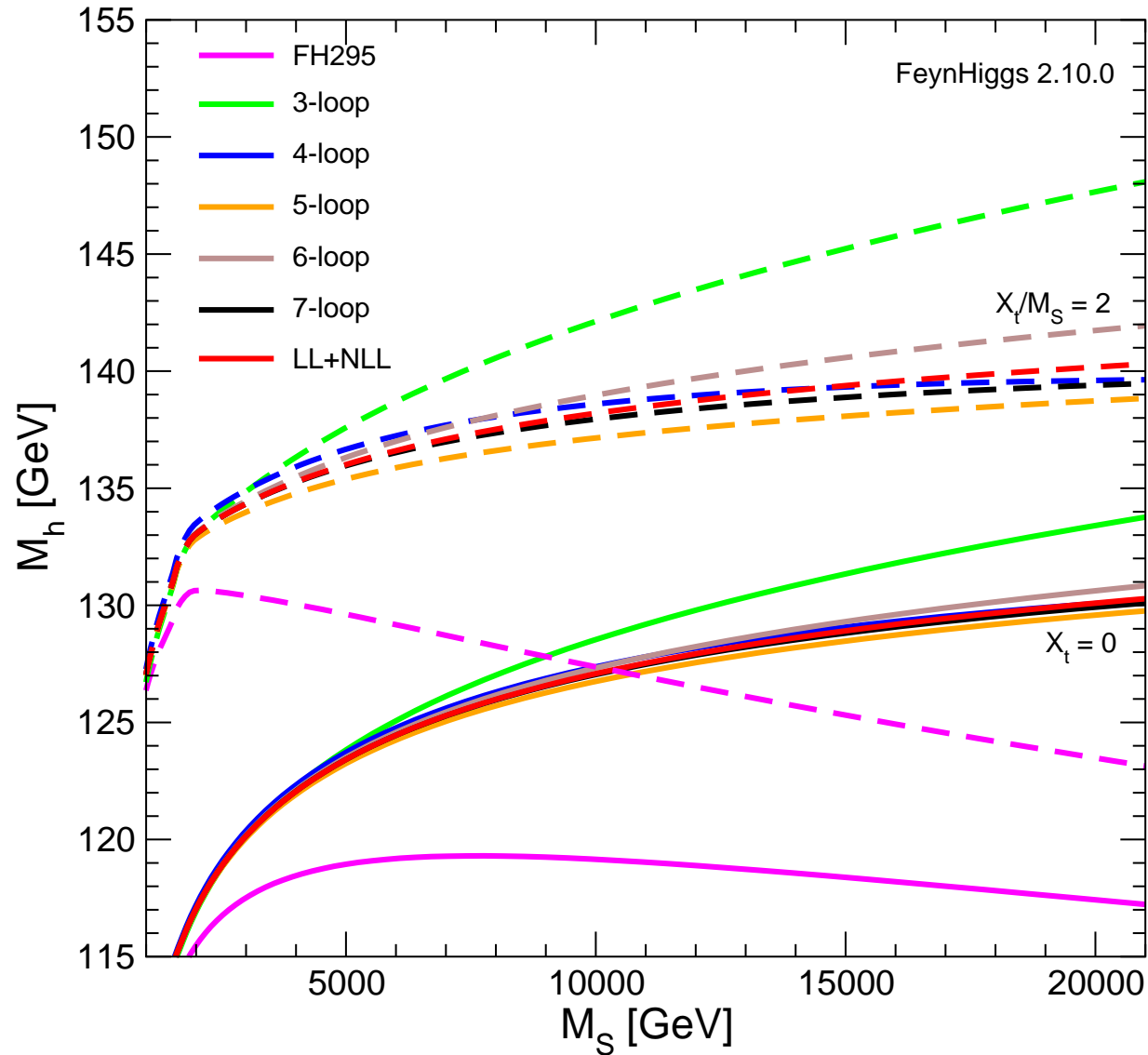
Problem:

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

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

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

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



⇒ 3-loop good for $M_S \lesssim 2$ TeV, 7-loop: $\Delta \sim 1$ GeV for $M_S = 20$ TeV

4. FeynHiggs vs. EFT approach

⇒ Importance of precise M_h^{MSSM} predictions

The Higgs mass accuracy: experiment vs. theory:

Experiment:

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

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

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

MSSM theory:

LHCHSWG 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)

$$\text{FeynHiggs:} \quad \delta M_h^{\text{theo}} \sim 3 \text{ GeV}$$

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

SusyHD: Higgs mass Determination in Supersymmetry

Javier Pardo Vega, Giovanni Villadoro

(Submitted on 20 Apr 2015)

We present the state-of-the-art of the effective field theory computation of the MSSM Higgs mass, improving the existing ones by including extra threshold corrections. We show that, with this approach, the theoretical uncertainty is within 1 GeV in most of the relevant parameter space. We confirm the smaller value of the Higgs mass found in the EFT computations, which implies a slightly heavier SUSY scale. We study the large $\tan(\beta)$ region, finding that sbottom thresholds might relax the upper bound on the scale of SUSY. We present SusyHD, a fast computer code that computes the Higgs mass and its uncertainty for any SUSY scale, from the TeV to the Planck scale, even in Split SUSY, both in the DRbar and in the on-shell schemes. Finally, we apply our results to derive bounds on some well motivated SUSY models, in particular we show how the value of the Higgs mass allows to determine the complete spectrum in minimal gauge mediation.

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Does this mean that now there exists a better prediction for M_h in the MSSM with substantially smaller theory uncertainty?

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Does this mean that now there exists a better prediction for M_h in the MSSM with substantially smaller theory uncertainty?

⇒ We will try to give some answers: full diagrammatic vs. EFT, uncertainty estimates, ...

FeynHiggs approach (simplified): “from below”

Propagator / mass matrix with higher-order corrections

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

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

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

\Rightarrow Feynman-diagrammatic approach

- diagrammatic calculation up to the **two-loop level**
- all MSSM particles contribute
 main contribution: t/\tilde{t} sector
- all (possibly different) mass scales taken into account explicitly
- self-energies as building blocks for further evaluations

\Rightarrow FeynHiggs provides consistent predictions for Higgs masses, Higgs couplings, Higgs BRs, . . .

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

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

To capture effects of large stop mass scales:

Resummation of leading and next-to-leading Logs from t/\tilde{t} sector:

$$L := \log\left(\frac{m_{\tilde{t}}}{m_t}\right) \quad \Rightarrow \text{at } n\text{-loop order} : \sim \sum_{k=1}^n \alpha_s^k \alpha_t^{n-k} \times L^n, L^{n-1}$$

Assumes that all SUSY mass scales are high at $m_{\tilde{t}}$

\Rightarrow added consistently to the diagrammatic result

EFT approach (simplified / SusyHD): “from above”

- Assume all SUSY mass scales at one high scale M_S
Below M_S : only SM (“heavy particles integrated out”)
⇒ mass gap between EW scale and SUSY scale required
- EW scale input: SM parameter: $h_t(m_t), g_s(m_t), \dots$ at the 2-loop level
- SUSY enters only via threshold corrections at M_S at the 2-loop level
- Between EW scale m_t and SUSY scale M_S :
SM RGEs at the 3-loop level

$$\lambda(m_t), h_t(m_t), g_s(m_t), \dots \leftrightarrow \lambda(M_S)h_t(M_S), g_s(M_S), \dots$$

⇒ captured: logs of type L^n, L^{n-1}, L^{n-2}

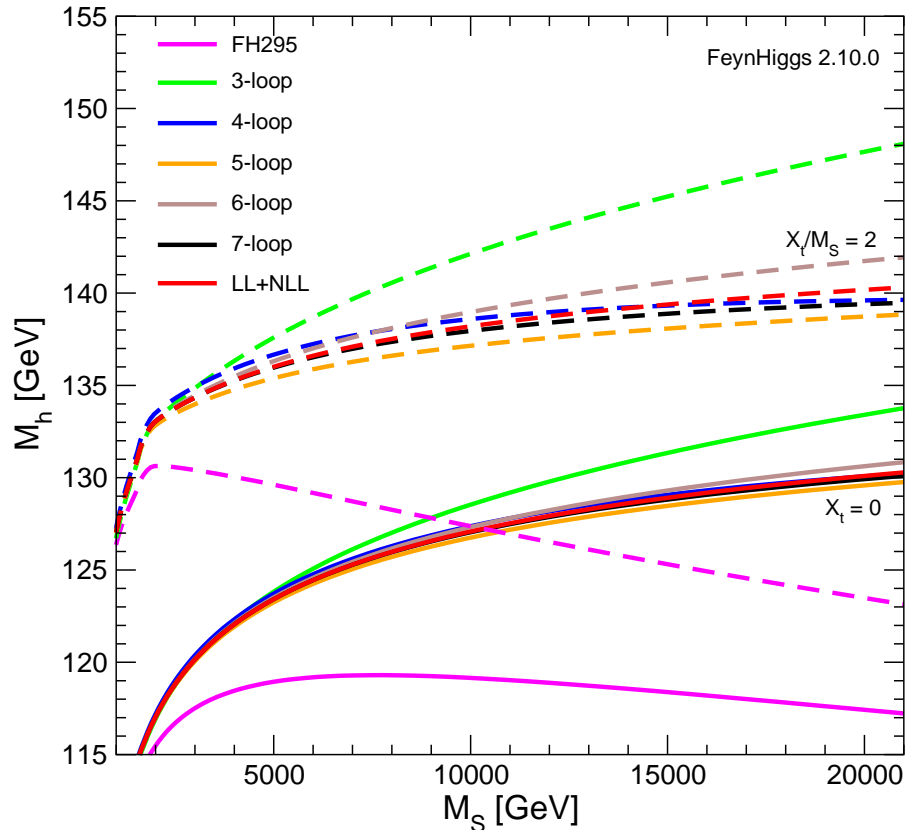
- Evaluate running mass: $M_h^2 \sim 2\lambda(m_t)v^2$ ⇒ conversion to pole mass
- Log resummation in t/\tilde{t} sector: SusyHD: 3-loop , FeynHiggs: 2-loop

Ranges of applicability:

- 1.) SUSY mass scales below ~ 1 TeV require full calculation
- 2.) Log resum. for t/\tilde{t} (beyond 2L) at M_S
 - effects at $M_S = 1$ TeV:
 - at $M_S = 2$ TeV:
 - at $M_S = 3$ TeV:

Ranges of applicability:

- 1.) SUSY mass scales below ~ 1 TeV require full calculation
- 2.) Log resum. for t/\tilde{t} (beyond 2L) at M_S for $\Delta M_h^{\text{diagrammatic}} \sim 40$ GeV
 - effects at $M_S = 1$ TeV: tiny
 - at $M_S = 2$ TeV: $\Delta M_h^{\text{log-resum}} \sim 2$ GeV
 - at $M_S = 3$ TeV: $\Delta M_h^{\text{log-resum}} \gtrsim 3$ GeV



$M_h(M_S)$ for various approximations:

[FeynHiggs 2.10.0]

magenta: no log-resum for t/\tilde{t}

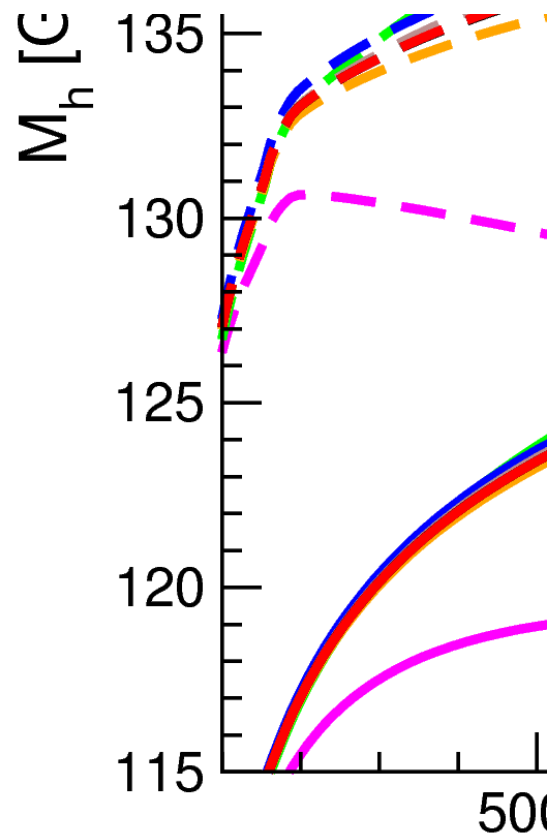
red: log-resum at 2-loop level

(\rightarrow included in FH)

All other logs less relevant!

Ranges of applicability:

- 1.) SUSY mass scales below ~ 1 TeV require full calculation
- 2.) Log resum. for t/\tilde{t} (beyond 2L) at M_S for $\Delta M_h^{\text{diagrammatic}} \sim 40$ GeV
 - effects at $M_S = 1$ TeV: tiny
 - at $M_S = 2$ TeV: $\Delta M_h^{\text{log-resum}} \sim 2$ GeV
 - at $M_S = 3$ TeV: $\Delta M_h^{\text{log-resum}} \gtrsim 3$ GeV



$M_h(M_S)$ for various approximations:
[FeynHiggs 2.10.0]

magenta: no log-resum for t/\tilde{t}

red: log-resum at 2-loop level

(\rightarrow included in FH)

All other logs less relevant!

Ranges of applicability:

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– at $M_S = 3$ TeV: $\Delta M_h^{\text{log-resum}} \gtrsim 3$ GeV

⇒ FeynHiggs gives most reliable predictions for SUSY mass scales below the level of 2 – 3 TeV, where log contributions are not too large i.e. at the scales relevant/interesting for LHC physics (e.g. with light EW SUSY particles in the spectrum)

⇒ uncertainty estimate based on diagrammatic calculation reliable

⇒ EFT gives most reliable predictions for all SUSY mass scales in the multi-TeV range

⇒ intermediate region:

both types of calculations can be used for uncertainty estimate

Uncertainty estimates:

FeynHiggs (diagrammatic + log-resum): linear sum of

- missing 3-loop corrections in t/\tilde{t} sector (change of m_t def.)
 - missing 2-loop corrections in b/\tilde{b} sector (Δ_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 ~ 1 GeV

⇒ estimate for the multi-TeV range

⇒ unclear to which low scales it can be extrapolated

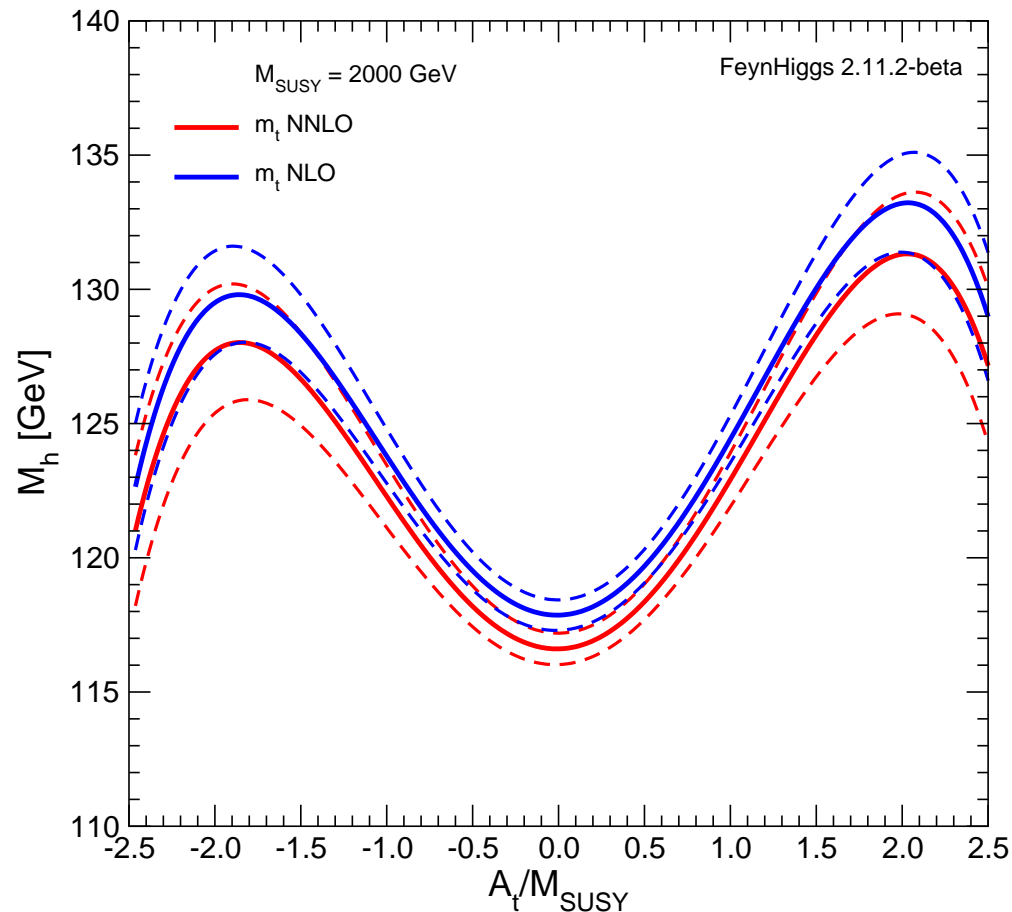
Uncertainty estimate in SusyHD:

- non-log terms via threshold corrections to $\lambda(M_S)$
 - neglects terms of $\mathcal{O}(m_t/M_{\text{SUSY}})$
 - non-log terms can be sizable, $\mathcal{O}(m_t/M_{\text{SUSY}})$ can easily be of $\mathcal{O}(\text{GeV})$
 - theoretical unc. in SusyHD for threshold terms via scale variation
 \Rightarrow does not capture non-log terms
- Effects of $m_t(m_t)^{\text{NLO}} \rightarrow m_t(m_t)^{\text{what ever exists}}$ in SusyHD: 4 GeV
Effects of $m_t(m_t)^{\text{NLO}} \rightarrow m_t(m_t)^{\text{NNLO}}$ in [Draper, Lee, Wagner '13]: $\lesssim 2 \text{ GeV}$
(consistent)
Difference should give indication of theory uncertainties $\gtrsim 2 \text{ GeV}$
- Effects of uncertainty of higher-dimensional operators $\mathcal{O}(v^2/M_S^2)$
(prefactor 1) \Rightarrow very optimistic
- Not clear where (e.g. at $M_S = 2 \text{ TeV}$) differences between SusyHD and FeynHiggs originate from

SusyHD claim: large effects from top Yukawa coupling $m_t(m_t)$:

SusyHD: 2-loop, FeynHiggs: 1-loop (consistent choice!) $\Rightarrow \Delta \lesssim 9$ GeV

Shift in $m_t(m_t)$ from NLO to NNLO: 1.8 GeV (for $A_t/M_{\text{SUSY}} \sim 2$)



\Rightarrow not the reason for discrepancy, effects captured by FH unc. estimate

\Rightarrow EFT: effect of missing non-log contributions?

Uncertainty estimate too small ... ?!

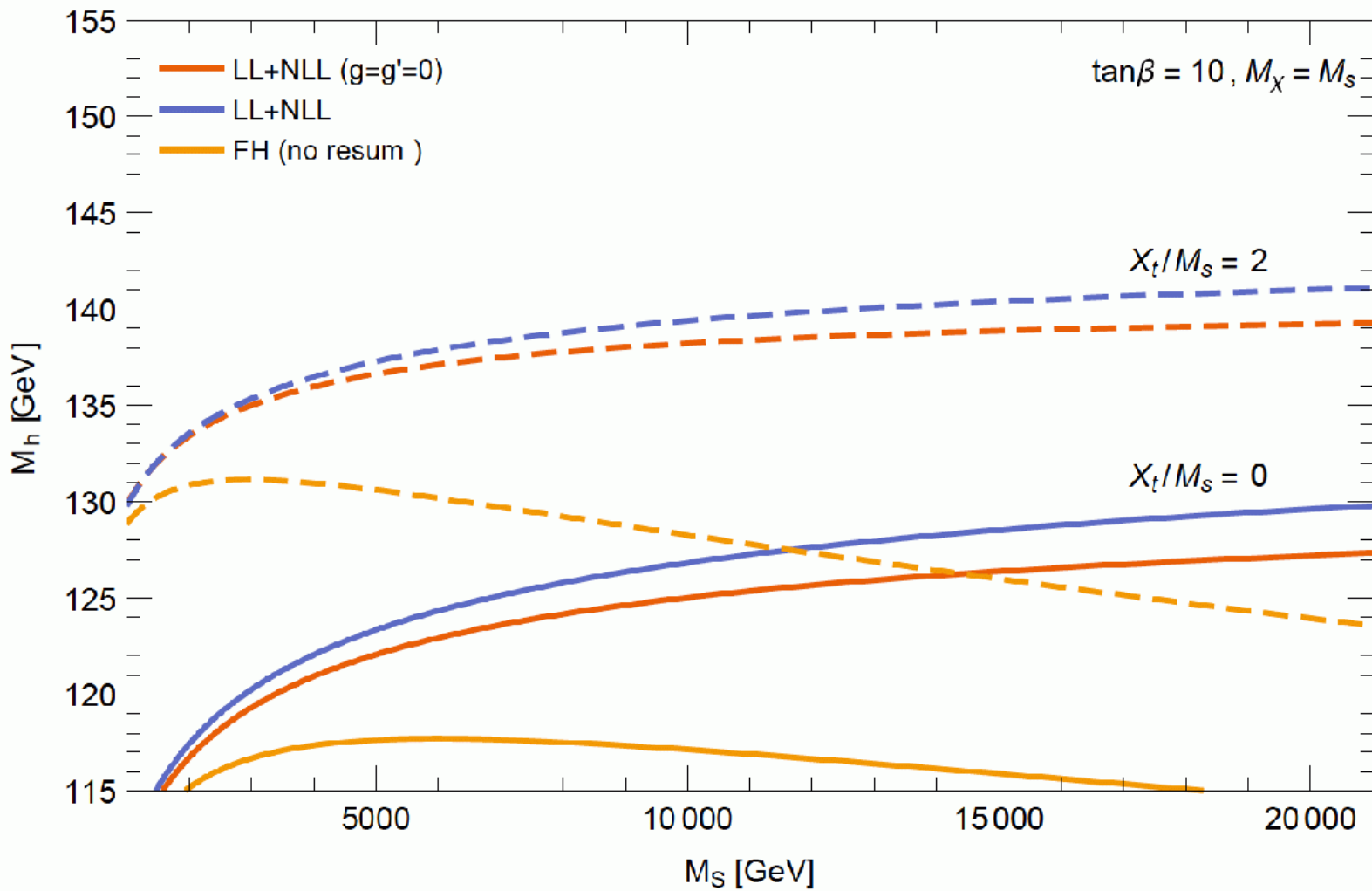
5. FeynHiggs prospects

- Inclusion of further diagrammatic corrections, e.g. $\mathcal{O}(\alpha\alpha_s)$, see [*Degrassi, Slavich, di Vita '14*]
- Inclusion of further log-resummed corrections
- Extension to the **NMSSM**
⇒ with all features as now in the MSSM
- . . .

Inclusion of further log-resummed results

[H. Bahl, W. Hollik '15 – PRELIMINARY]

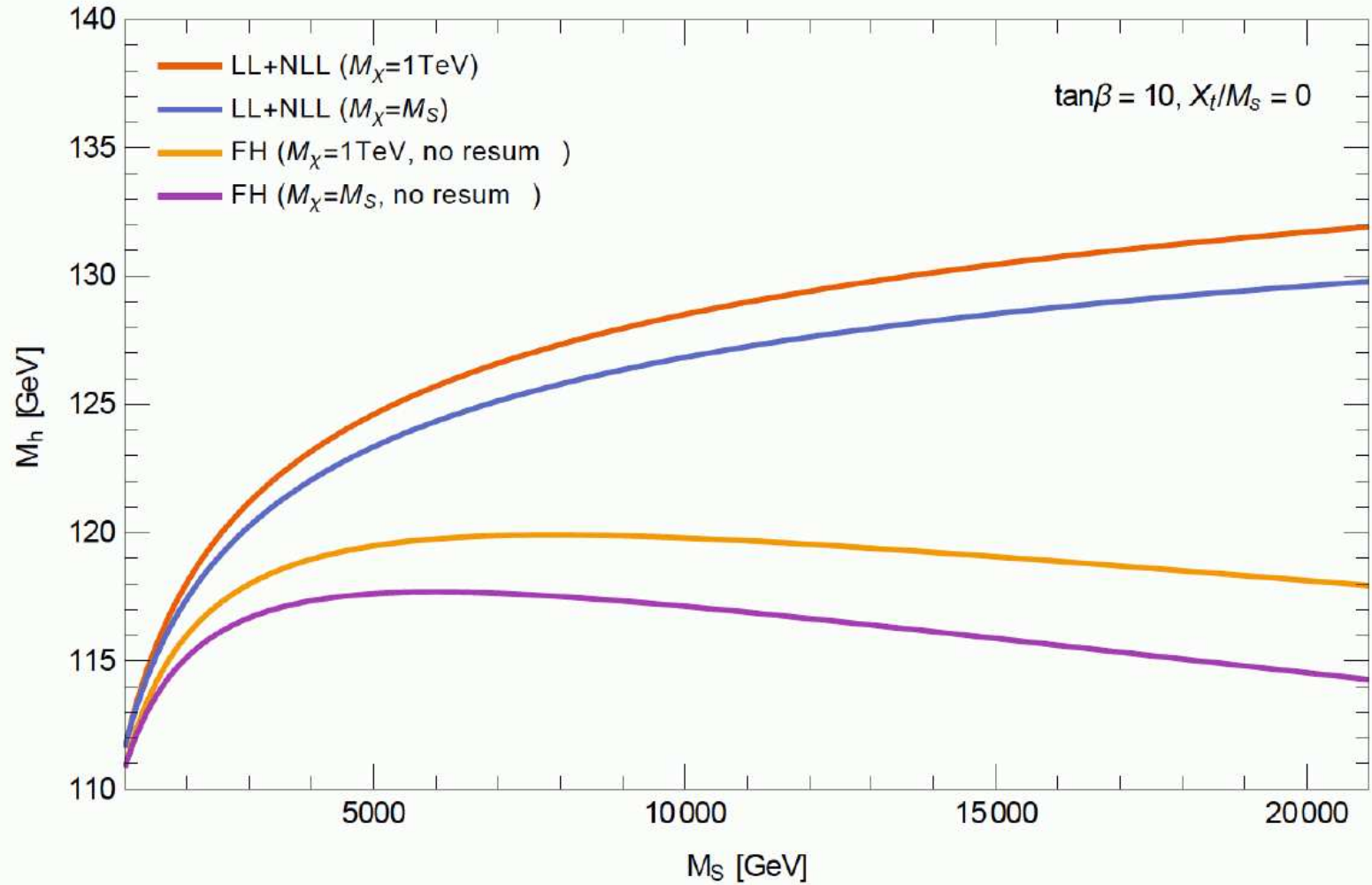
Inclusion of EW effects in RGE's:



Inclusion of further log-resummed results

[H. Bahl, W. Hollik '15 – PRELIMINARY]

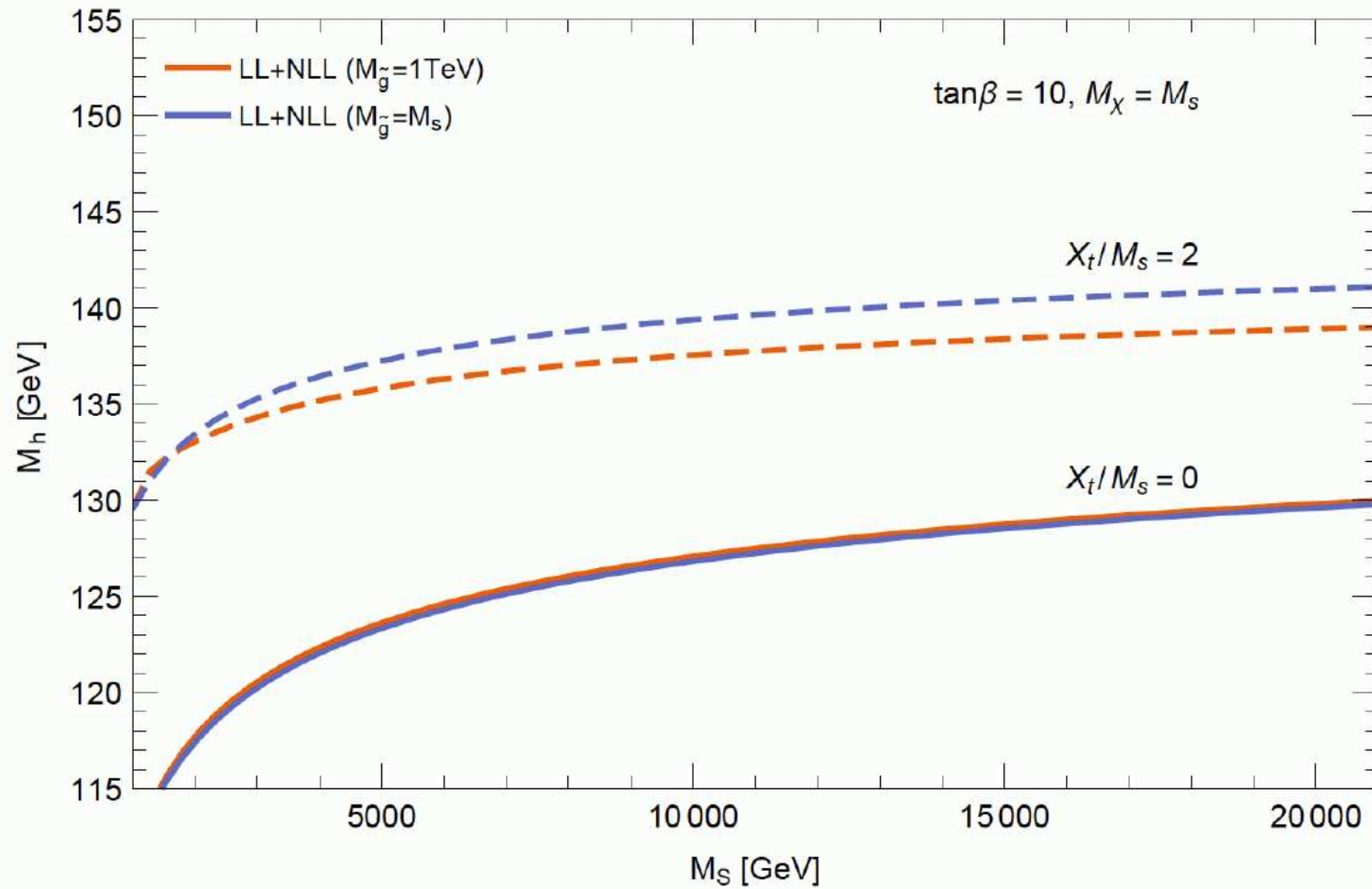
Inclusion of EWino mass scale in RGE's:



Inclusion of further log-resummed results

[H. Bahl, W. Hollik '15 – PRELIMINARY]

Inclusion of gluino mass scale in RGE's:



Extension to the NMSSM

(taken from talk by [\[P. Drechsel '15\]](#))

General idea (first step/version):

- ▶ 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

⇒ “internal” version exists! :-)

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

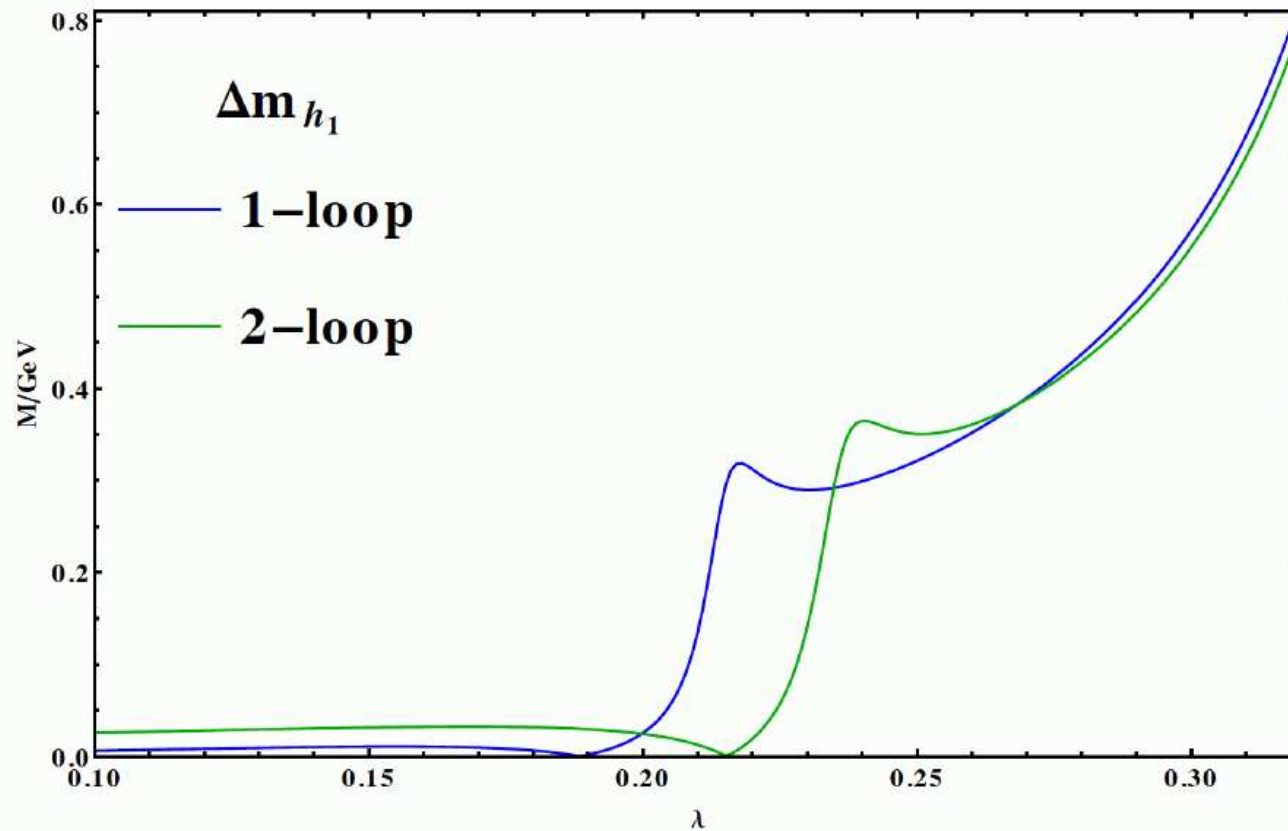
$$\begin{aligned}M_{H^\pm} &= 1000 \text{ GeV}, \mu_{\text{eff}} = 125 \text{ GeV}, \\A_\kappa &= -300 \text{ GeV}, A_t = -2000 \text{ GeV}, \\ \tan \beta &= 8, \kappa = 0.2\end{aligned}$$

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

(taken from talk by [P. Drechsel '15])

Backup: Comparison with NMSSMTOOLS I

- ▶ difference 1-loop: δZ_e , difference 2-loop: $\mathcal{O}(Y_t \lambda, \lambda^2)$
- ▶ $\Delta m_{h_1} = \left| m_{h_1}^{(\text{FH})} - m_{h_1}^{(\text{NC})} \right|$



Higgs Days at Santander 2015

Theory meets Experiment

14.-18. September

contact: Sven.Heinemeyer@cern.ch

<http://www.ifca.es/HDays15>



Back-up

How to run FeynHiggs

1. Go to www.feynhiggs.de
2. Download the latest version
3. type `./configure`, `make`, `make install`
⇒ library `libFH.a` is created
4. 4 possible ways to use *FeynHiggs*:
 - A) `Command-line mode` (allows also `running on the GRID`)
 - B) called from a Fortran/C++ code
 - C) called within `Mathematica`
 - D) `WWW mode`processing of `Les Houches Accord` data possible
5. Detailed `instructions` and `help` are provided in the `man pages`

A) Command-line mode

Input File

```
MT      172.7
MB       4.7
MW      80.4
MZ      91.1
MSusy   975
MAO     200
Abs(M_2) 332
Abs(MUE) 980
TB       50
Abs(At) -300
Abs(Ab) 1500
Abs(M_3) 975
```

Command

```
FeynHiggs file [flags]
```

Screen Output

```
----- HIGGS MASSES -----
| Mh0    = 116.022817
| MHH    = 199.943497
| MAO    = 200.000000
| MHp    = 216.973920
| SAeff  = -0.02685112
| UHiggs = 0.99999346 -0.00361740 0.00000000 \
|        0.00361740 0.99999346 0.00000000 \
|        0.00000000 0.00000000 1.00000000
----- ESTIMATED UNCERTAINTIES -----
| DeltaMh0 = 1.591957
| DeltaMHH = 0.004428
| DeltaMAO = 0.000000
| DeltaMHp = 0.152519
...

```

- Loops over parameter values possible (parameter scans).
- Mask off details with `FeynHiggs file [flags] | grep -v %`
- `table` utility converts to machine-readable format, e.g.
`FeynHiggs file [flags] | table TB Mh0 > outfile`

Example for new M_A - $\tan \beta$ planes:

Input File (“normal”)

```
MT      172.7
MB      4.7
MW      80.4
MZ      91.1
MSusy   975
MAO     200
Abs(M_2) 332
Abs(MUE) 980
TB      50
Abs(At) -300
Abs(Ab) 1500
Abs(M_3) 975
```

Input File (“new”)

```
MAO      227
TB       23
table ehoww.A2.dat MAO TB
```

- Loops over parameter values possible (parameter scans).

```
MAO      200 500 10
```

```
TB       5 50 *2
```

- Mask off details with `FeynHiggs file [flags] | grep -v %`

- `table` utility converts to machine-readable format, e.g.

```
FeynHiggs file [flags] | table TB Mh0 > outfile
```

SUSY Les Houches Accord(2) Format

Input File

```
BLOCK MODSEL
  1  1
BLOCK MINPAR
  1  0.10000E+03 # m0
  2  0.25000E+03 # m12
  3  0.10000E+02 # tanb
  4  0.10000E+01 # sgn mu
  5 -0.10000E+03 # A
BLOCK SMINPUTS
  4  0.91187E+02 # MZ
  5  0.42500E+01 # mb(mb)
  6  0.17500E+03 # t
...
```

Command
FeynHiggs file [flags]

file.fh

```
BLOCK MASS
  25  1.12697840E+02 # Mh0
  35  4.00145460E+02 # MHH
  36  3.99769788E+02 # MA0
  37  4.08050556E+02 # MHp
  ...
BLOCK ALPHA
      -1.10658125E-01 # Alpha
  ...
```

- { Uses / was developed into } the SLHA(2) I/O Library. [*T. Hahn '04, '06*]
- SLHA(2) can also be used in Library Mode with `FHSetSLHA`.
- *FeynHiggs* tries to read each file in SLHA(2) format first. If that fails, fallback to native format.

B) Called from a Fortran/C++ code

Link *FeynHiggs* as a subroutine \Rightarrow link `libFH.a`

`call FHSetFlags(...)` :

\rightarrow specification of accuracy etc.

`call FHSetPara(...)` :

\rightarrow specify input parameters

`call FHGetPara(...)` :

\rightarrow obtain derived parameters

`call FHHiggsCorr(...)` :

\rightarrow obtain Higgs boson masses and mixings

`call FHUncertainties(...)` :

\rightarrow obtain theory error on Higgs boson masses and mixings from unknown higher-order corrections

`call FHCouplings(...), FHHiggsProds(...), ...` :

\rightarrow obtain decay widths, BRs, XSs, etc.

C) Called within Mathematica

- install the `math link` to `MFeynHiggs` , e.g.:

```
Install[,'MFeynHiggs']
```

- `FHSetFlags[...]` :
→ specification of accuracy etc.

`FHSetPara[...]` :
→ specify input parameters

`FHGetPara[]` :
→ obtain derived parameters

`FHHiggsCorr[]` :
→ obtain Higgs boson masses and mixings

`FHUncertainties[]` :
→ obtain theory error on Higgs boson masses and mixings from
unknown higher-order corrections

`FHCouplings[]`, `FHHiggsProds[]`, ... :
→ obtain decay widths, BRs etc.

D) WWW mode

1. The FeynHiggs User Control Center is available at
www.feynhiggs.de/fhucc
2. Enter you parameters on-line in the web page
3. Obtain your results with a mouse click

⇒ for single points and checks of your downloaded version of FeynHiggs
⇒ always the latest version

Also man pages and api are available on-line

D) WWW mode

1. The FeynHiggs User Control Center is available at

www.feynhiggs.de/fhucc

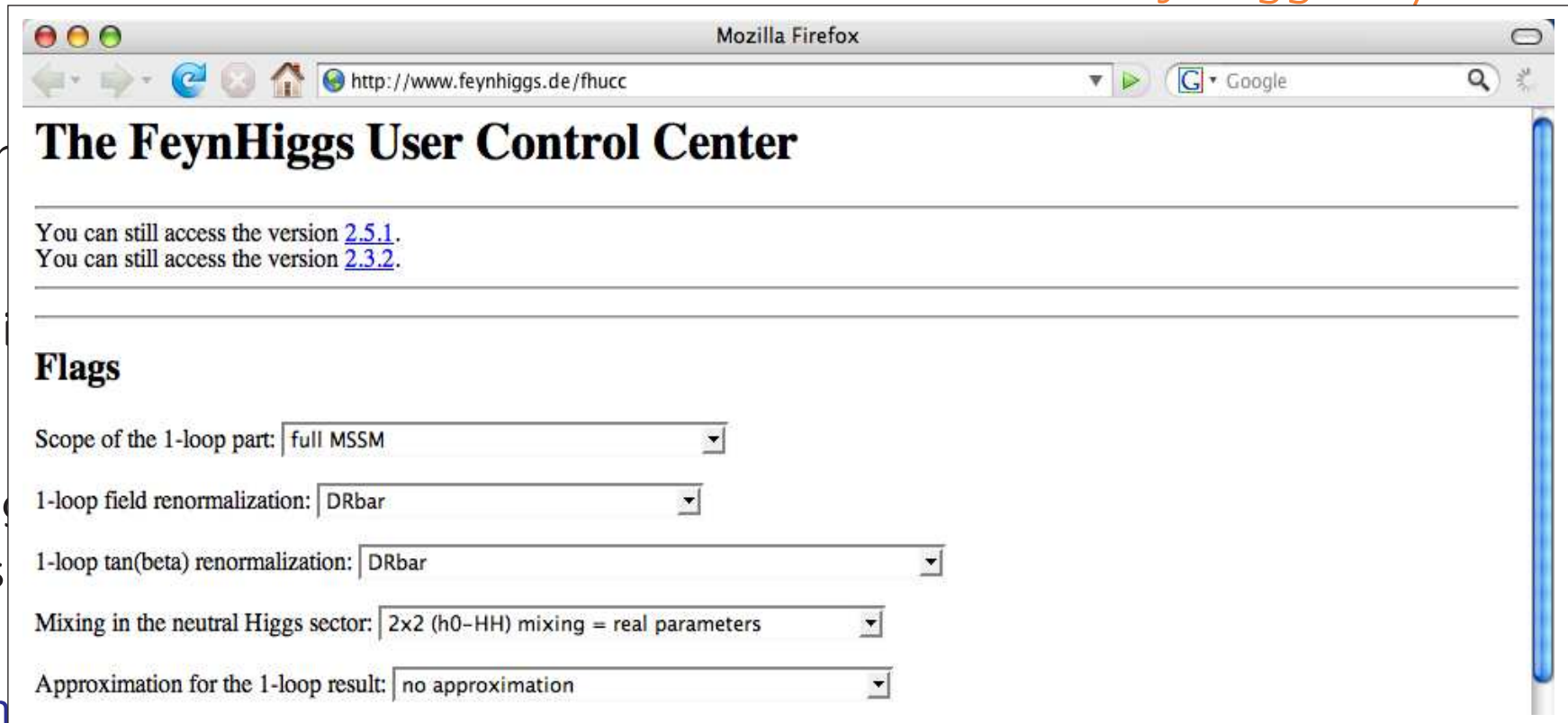
2. Enter

3. Obtain

⇒ for single

⇒ always

Also man



Resumming Stop-sector Contributions

M_S  we know: $\lambda(M_S)$

m_t we want: $M_h^2 = 2 \lambda(m_t) v^2$



Resumming Stop-sector Contributions

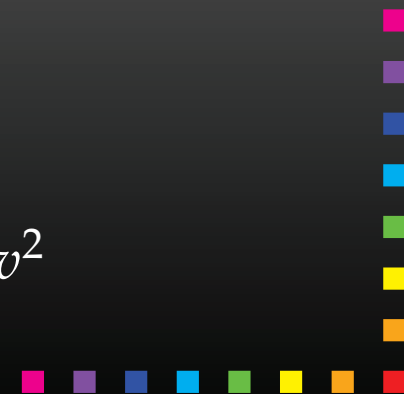
M_S ← we know: $\lambda(M_S)$

no SUSY particles

assumed here

SM running

m_t ← we want: $M_h^2 = 2 \lambda(m_t) v^2$



Standard Model RGEs

$$g_s^{2'} = \frac{1}{16\pi^2} g_s^4 (G_1 + \frac{1}{16\pi^2} G_2),$$

$$G_1 = \frac{2}{3} N_f - 11,$$

$$G_2 = (\frac{38}{3} N_f - 102) g_s^2 - 2h_t^2,$$

$$h_t^{2'} = \frac{1}{16\pi^2} h_t^2 (H_1 + \frac{1}{16\pi^2} H_2),$$

$$H_1 = \frac{9}{2} h_t^2 - 8g_s^2,$$

$$H_2 = 6h_t^2(6g_s^2 - 2h_t^2 - \lambda) + \frac{3}{2}\lambda^2 + (\frac{40}{9} N_f - \frac{404}{3}) g_s^4,$$

$$\lambda' = \frac{1}{16\pi^2} \frac{1}{2} (\Lambda_1 + \frac{1}{16\pi^2} \Lambda_2),$$

$$\Lambda_1 = 12(\lambda^2 - h_t^4 + \lambda h_t^2),$$

$$\Lambda_2 = h_t^2(3h_t^2(20h_t^2 - \lambda) + g_s^2(80\lambda - 64h_t^2) - 72\lambda^2) - 78\lambda^3.$$

Espinosa, Quiros 1991 – Arason et al. 1992



FeynHiggs Update – p.5

Integrating the RGEs

M_S

start from

g_s^2, h_t^2 from 1L RGE (analytic)

$$\lambda(M_S) = \frac{3}{8\pi^2} h_t^4 \left(\frac{X_t}{M_S}\right)^2 \left(1 - \frac{1}{12} \left(\frac{X_t}{M_S}\right)^2\right)$$

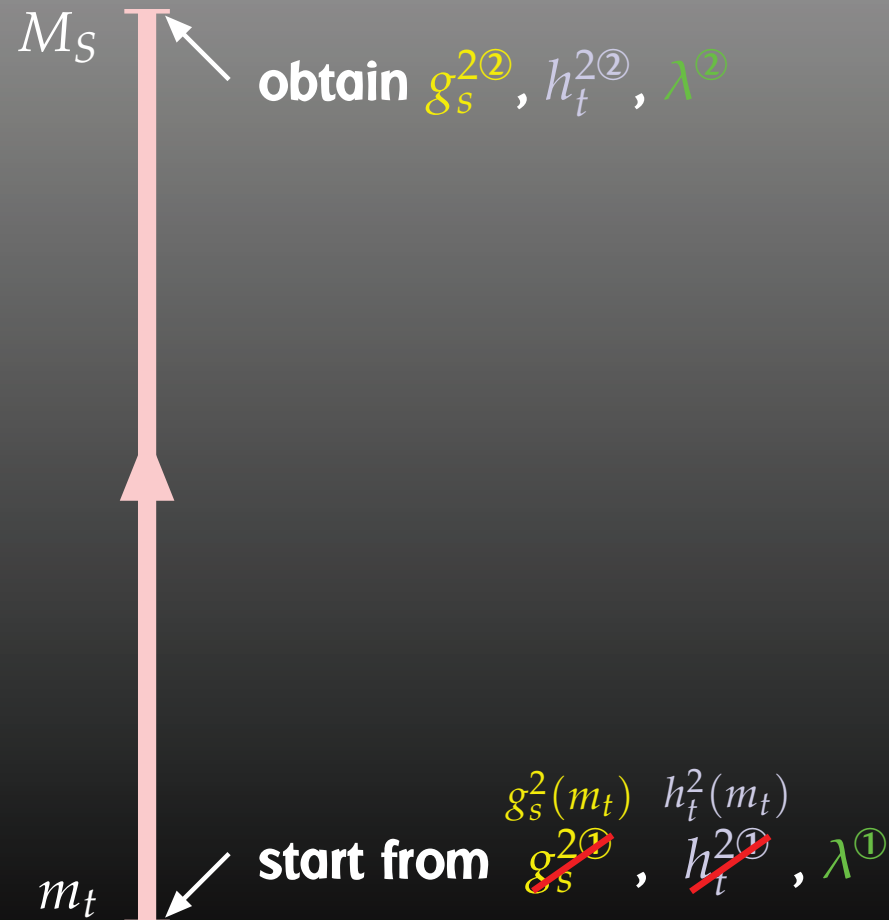
Carena et al. 2000

m_t

obtain $g_s^{2\textcircled{1}}, h_t^{2\textcircled{1}}, \lambda^{\textcircled{1}}$



Integrating the RGEs



Integrating the RGEs

M_S start with $g_s^{2②}$, $h_t^{2②}$, ~~$\lambda^{2②}$~~
 $\lambda(M_S)$

must subtract double counting!

m_t obtain $g_s^{2③}$, $h_t^{2③}$, $\lambda^{③} = \lambda(m_t)$

