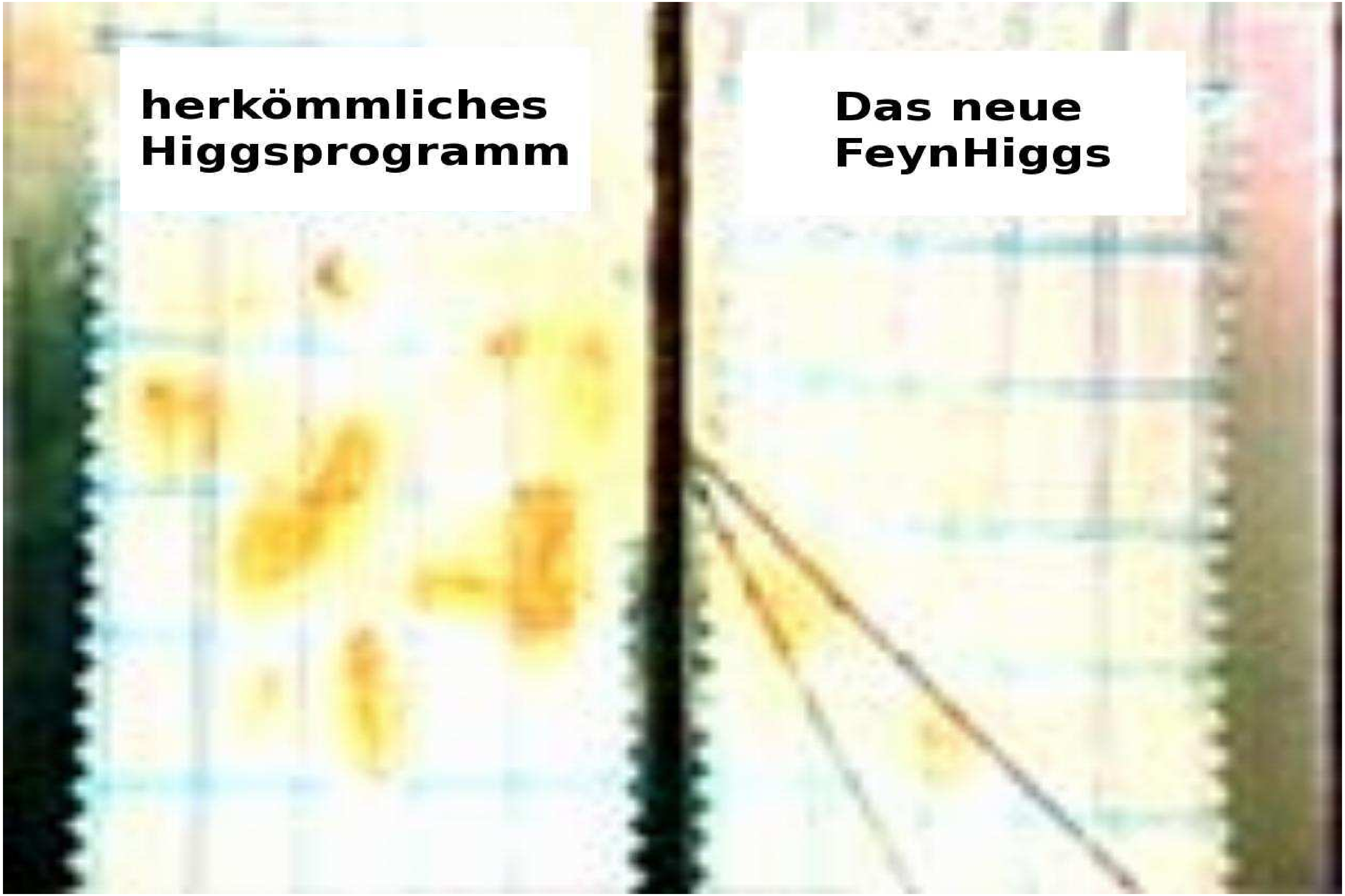

herkömmliches Higgsprogramm
Das neue FeynHiggs

FeynHiggs: New and Improved Predictions in the (N)MSSM

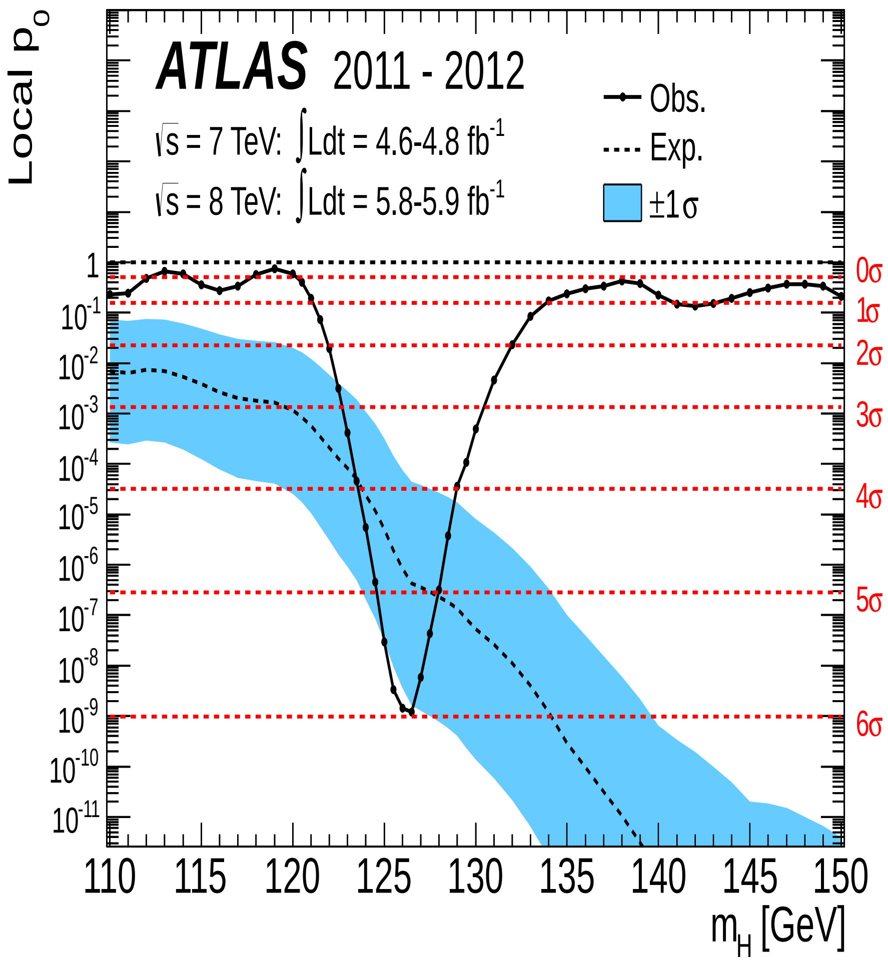
Sven Heinemeyer, IFT/IFCA (CSIC, Madrid/Santander)

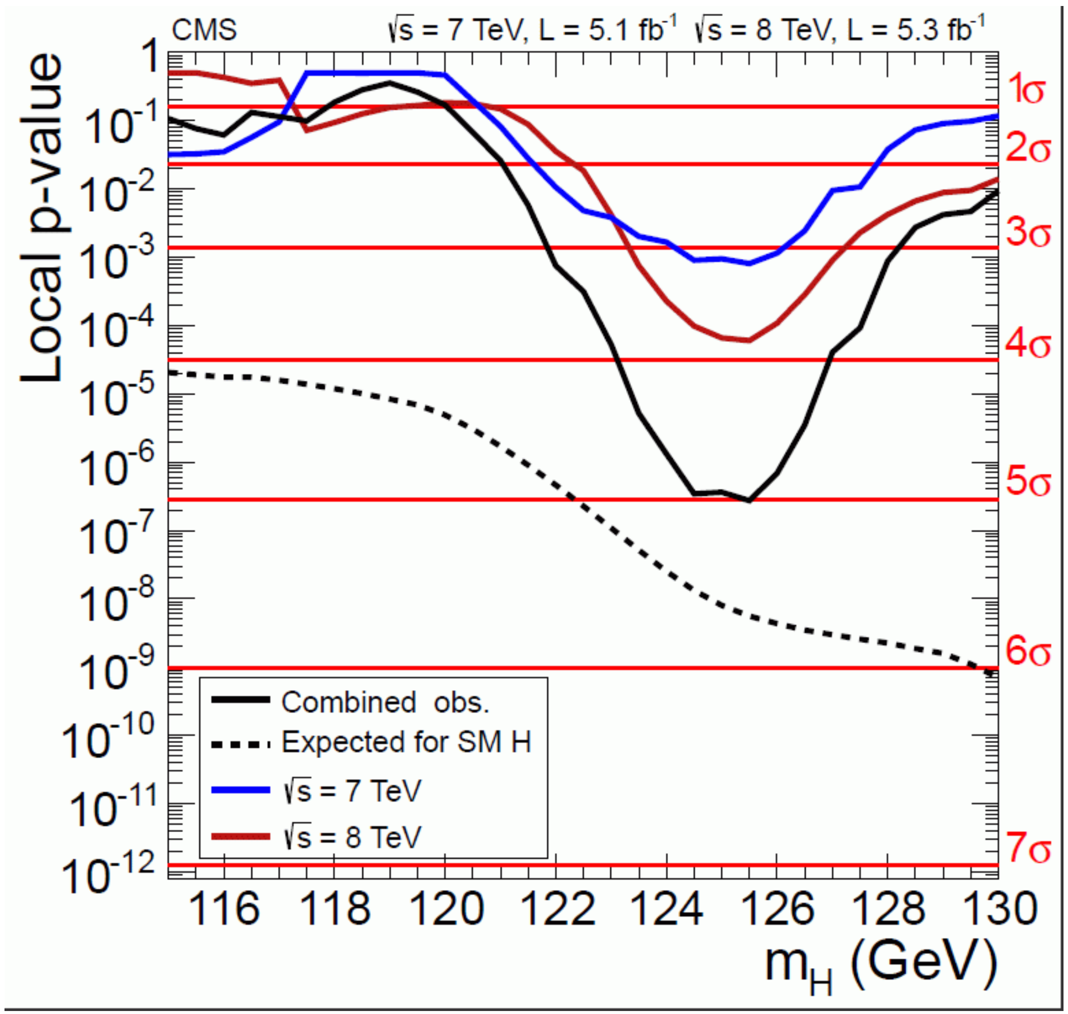
Melbourne, 07/2016

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

- Why FeynHiggs?
- Latest addition:
  Improved EFT contributions
- FeynHiggs and the NMSSM
- Conclusions

1. Why FeynHiggs



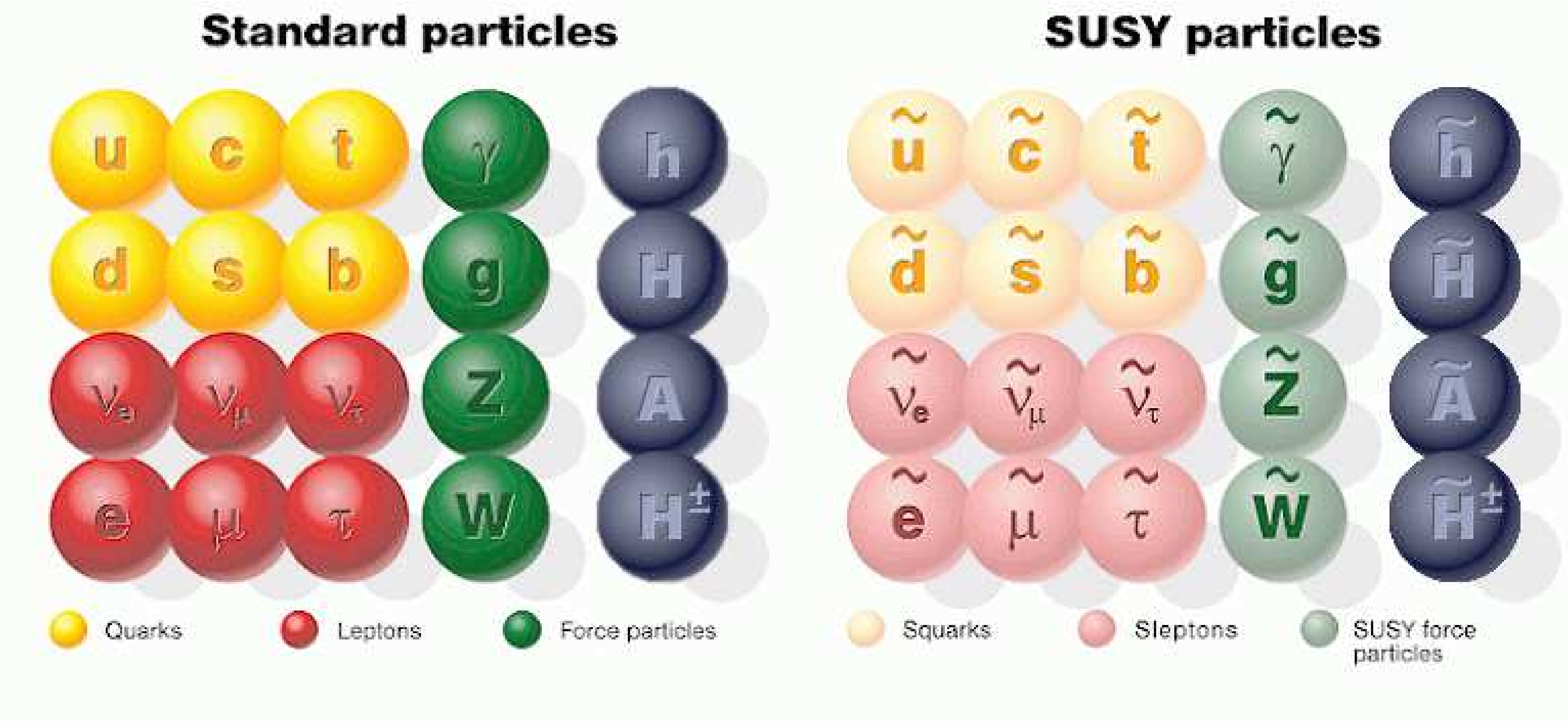


⇒ clear discovery at ∼ 125 GeV!

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

The MSSM:

⇒ Superpartners for Standard Model particles



Enlarged Higgs sector: Two Higgs doublets

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

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

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

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

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 with $\mathcal{CP}$ violation

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

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

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

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

gauge couplings, in contrast to SM

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

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

Input parameters: (to be determined experimentally)

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

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

FeynHiggs status

Latest version: FeynHiggs 2.12.0 (07/16) (3 days ago :-)
version FeynHiggs 2.12.1 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 LHCHXSWG

The (original) 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

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

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

Corrections included in FeynHiggs 2.10

$$\begin{pmatrix} k^2 - M_h^2 + \hat{\Sigma}_{hh}^{\bullet\bullet\bullet\bullet} & \hat{\Sigma}_{hH}^{\bullet\bullet\bullet\bullet} & \hat{\Sigma}_{hA}^{\bullet\bullet} \\ \hat{\Sigma}_{Hh}^{\bullet\bullet\bullet\bullet} & k^2 - M_H^2 + \hat{\Sigma}_{HH}^{\bullet\bullet\bullet\bullet} & \hat{\Sigma}_{HA}^{\bullet\bullet} \\ \hat{\Sigma}_{Ah}^{\bullet\bullet} & \hat{\Sigma}_{AH}^{\bullet\bullet} & k^2 - M_A^2 + \hat{\Sigma}_{AA}^{\bullet\bullet} \end{pmatrix}, \quad \hat{\Sigma}_{H^+H^-}^{\bullet\bullet}$$

- **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

$$\begin{pmatrix} k^2 - M_h^2 + \hat{\Sigma}_{hh}^{\bullet\bullet\bullet\bullet} & \hat{\Sigma}_{hH}^{\bullet\bullet\bullet\bullet} & \hat{\Sigma}_{hA}^{\bullet\bullet} \\ \hat{\Sigma}_{Hh}^{\bullet\bullet\bullet\bullet} & k^2 - M_H^2 + \hat{\Sigma}_{HH}^{\bullet\bullet\bullet\bullet} & \hat{\Sigma}_{HA}^{\bullet\bullet} \\ \hat{\Sigma}_{Ah}^{\bullet\bullet} & \hat{\Sigma}_{AH}^{\bullet\bullet} & k^2 - M_A^2 + \hat{\Sigma}_{AA}^{\bullet\bullet} \end{pmatrix}, \quad \hat{\Sigma}_{H^+H^-}^{\bullet\bullet}$$

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

before FeynHiggs 2.10.1:

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

FeynHiggs Update – p.11

2. Latest addition: Improved EFT contributions

[*H. Bahl et al. '16*]

$\Rightarrow$ Resummation of large logs via RGE's

Simple example for log resummation in $t/\tilde{t}$ sector:

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

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: $h_t, g_s(m_t) \to h_t, g_s(M_{\text{S}})$

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

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

3. Evaluate M_h^2

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

Combination of FD and RGE result:

$\Rightarrow$ 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 $X_t^{\overline{\text{MS}}}, M_S^{\overline{\text{MS}}}, \overline{m}_t$

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

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

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

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:

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

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

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

⇒ most precise M_h prediction for large $m_{\tilde{t}}$ ⇒ FeynHiggs 2.10.0

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

⇒ more in Georg's plenary talk tomorrow

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

New options in FeynHiggs:

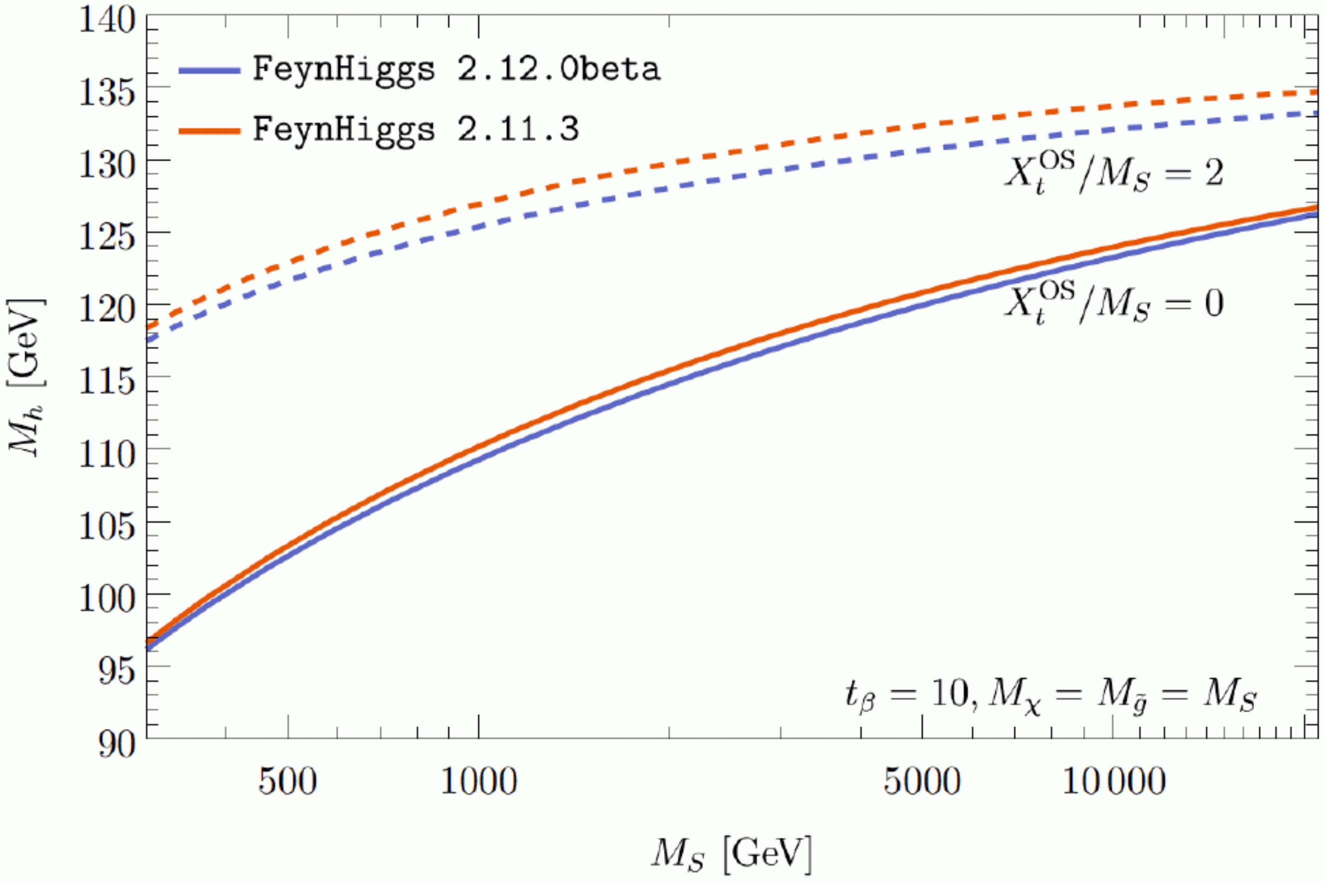
New resummation options controlled by new flag (not by `looplevel` anymore)

- `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:

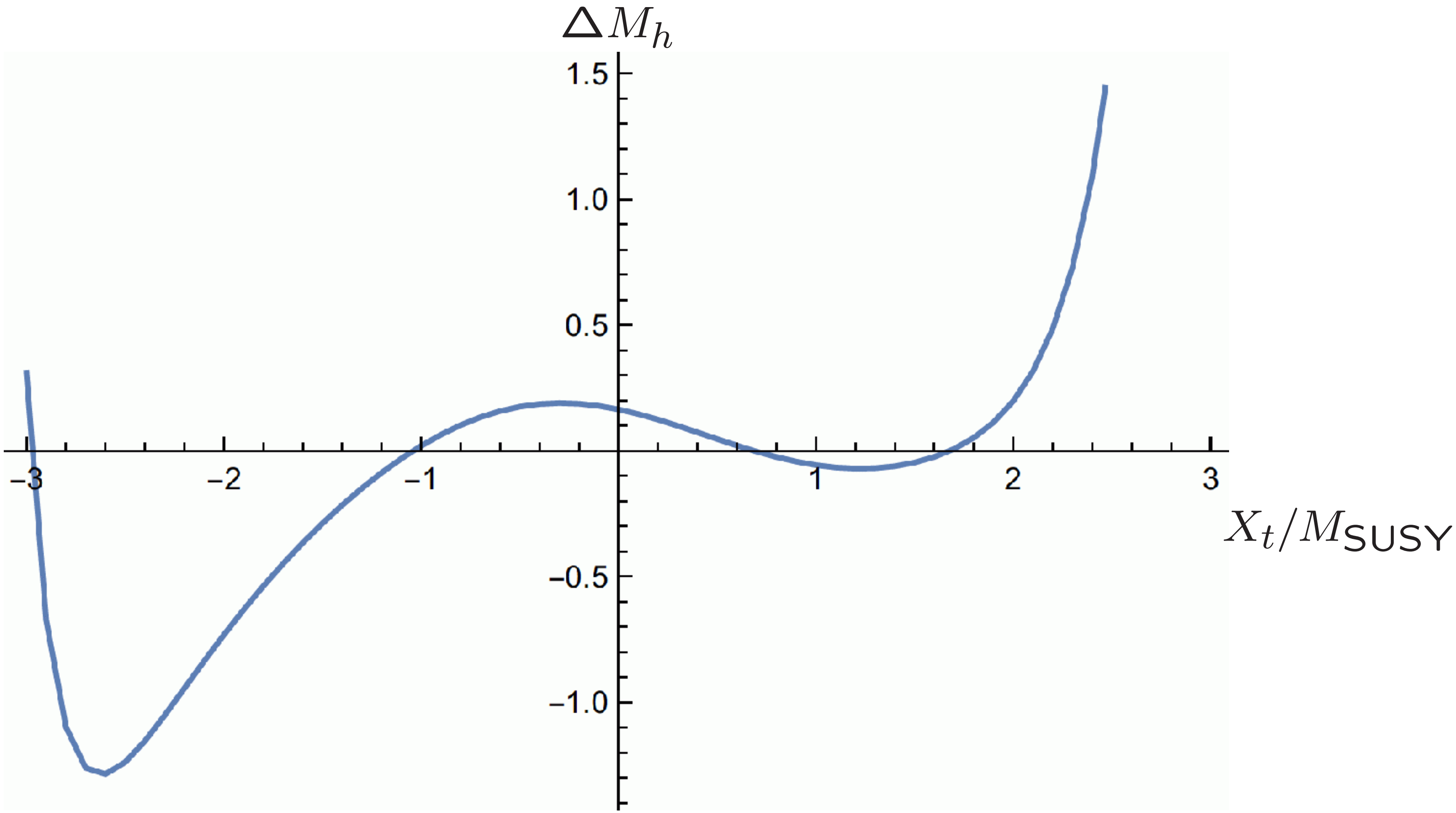


Main contribution → electroweak contributions to $\overline{\rm MS}$ top mass

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

Going from 2L RGE's to 3L RGE's (loglevel = 2 $\to$ 3):

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



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

$\Rightarrow$ non-negligible effects in both directions

3. FeynHiggs and the NMSSM

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

General idea:

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

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

- 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! :-) ⇒ see Sebastian's parallel talk tomorrow!

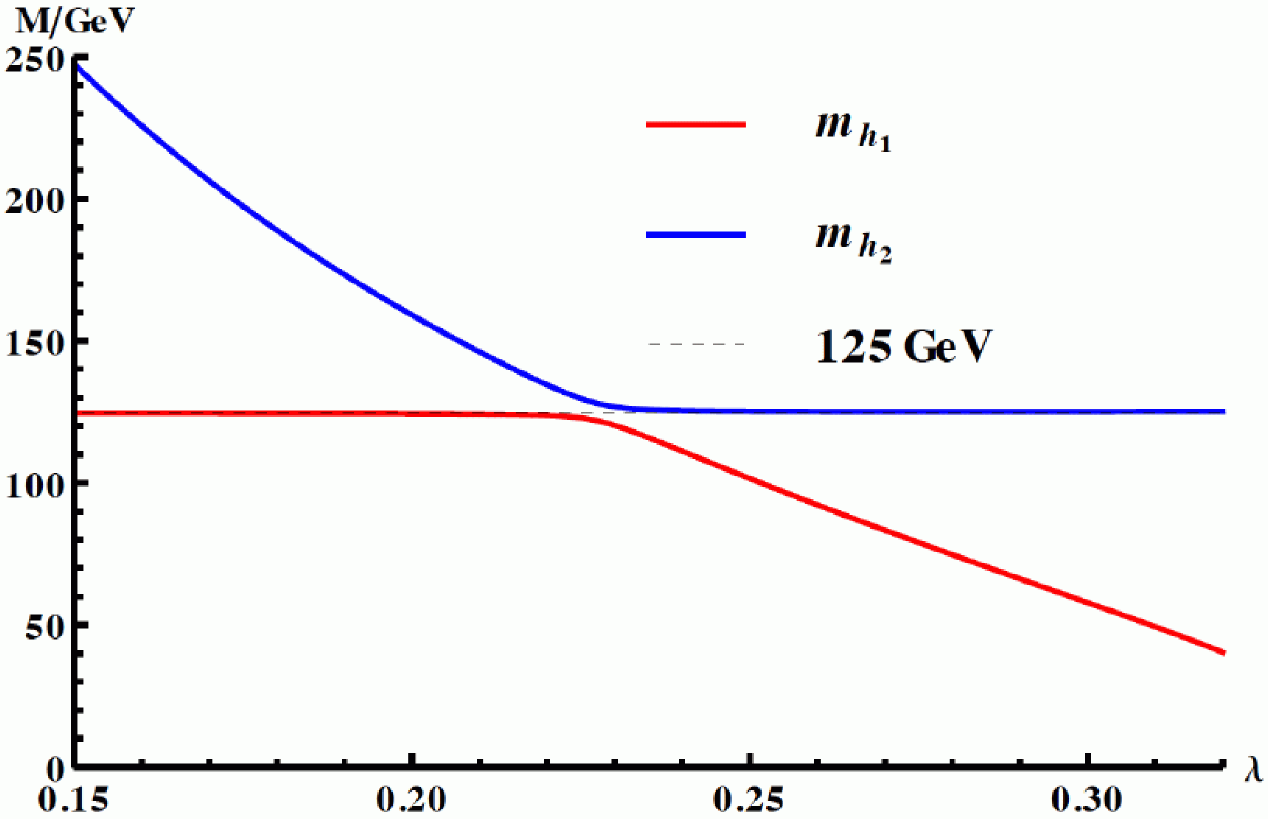
Sample Scenario

- 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

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

$$m_{\tilde{t}_1} \approx 1400\ \mathrm{GeV},\ m_{\tilde{t}_2} \approx 1600\ \mathrm{GeV}$$
$$m_{\tilde{b}_i} \approx 1500\ \mathrm{GeV},\ m_{\tilde{g}} \approx 1500\ \mathrm{GeV}$$

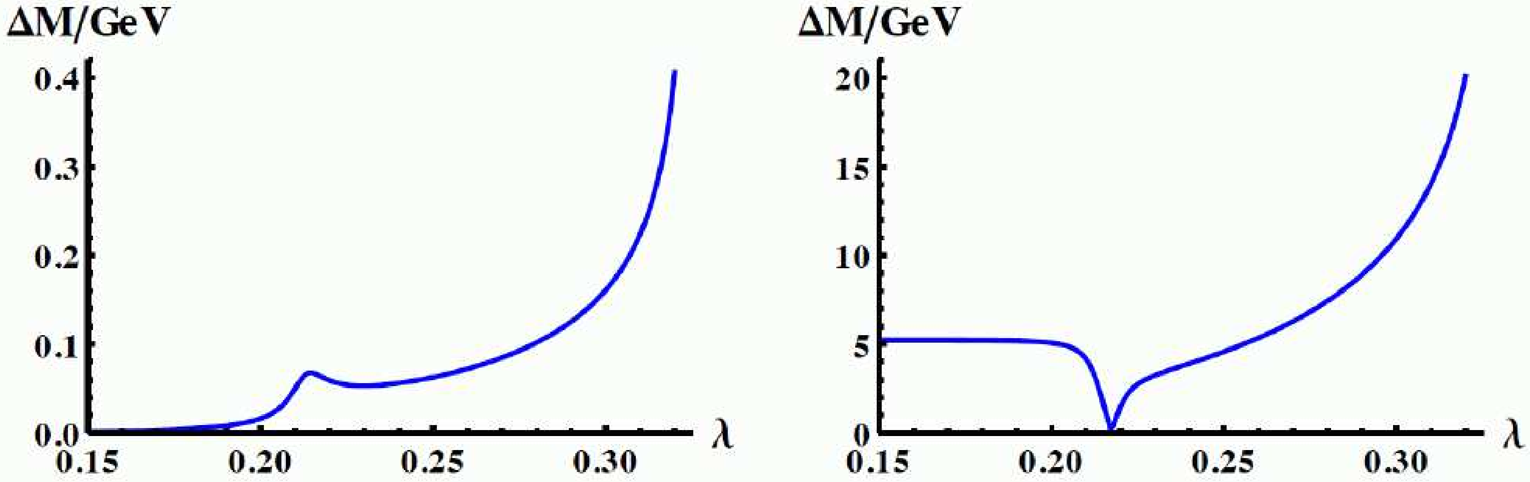
Lighter Masses @ 2-Loop Order: Sample Scenario



- mass decreasing with increasing λ belongs to singlet-like, constant mass to doublet-like state

Lightest Mass @ 1-Loop Order: Sample Scenario

Absolute difference between different mass predictions

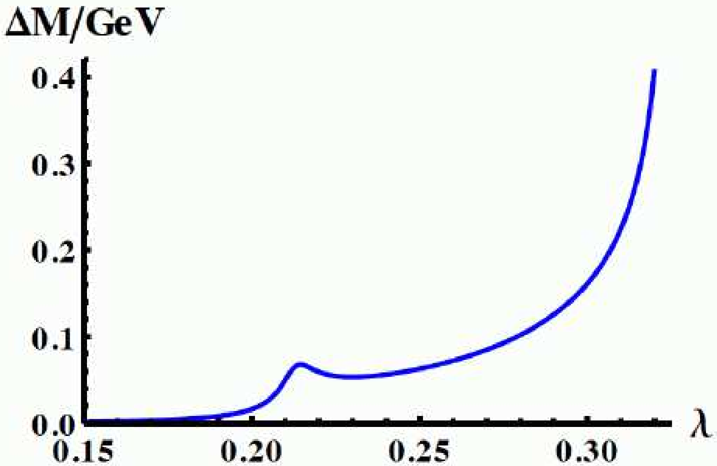


$$\Delta M = \left| m_{h_1}^{(Y_t)} - m_{h_1}^{(Y_t,\lambda)} \right| \qquad \Delta M = \left| m_{h_1}^{(Y_t,\lambda)} - m_{h_1}^{(1L)} \right|$$

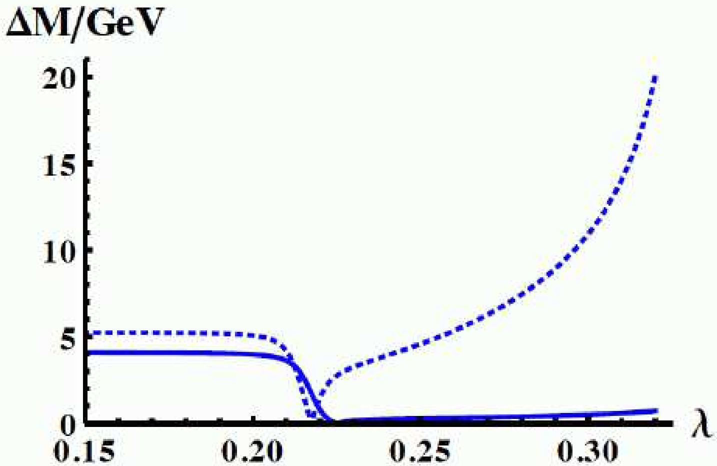
$\Longrightarrow$ influence of corrections beyond top/scalar top-sector is by far larger than those of the order $\mathcal{O}(Y_t\lambda, \lambda^2)$

Lightest Mass @ 1-Loop Order: Sample Scenario

Absolute difference between different mass predictions



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



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

include Higgs- & gauge-sector

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

Benchmark Point P1

- scenario that can explain the 750 GeV diphoton excess for $\lambda = 0.1$, benchmark point P1 from hep-ph/1602.07691

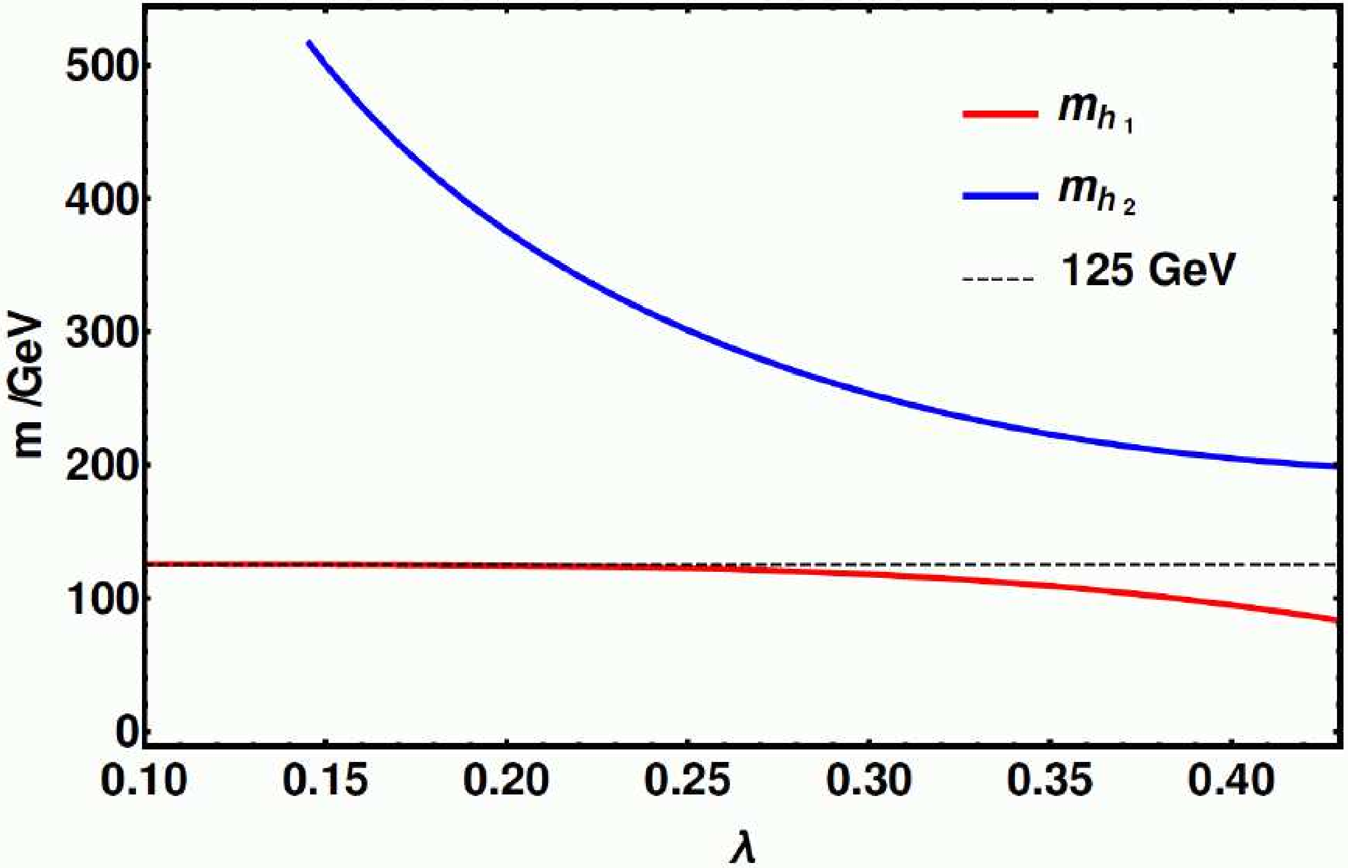
$$M_A = 760 \text{ GeV}, \ \mu_{\text{eff}} = 150 \text{ GeV}, \ \tan\beta = 10,$$
$$A_\kappa \approx 3 \cdot 10^{-3} \text{ GeV}, \ \kappa = 0.25,$$
$$m_{\tilde{Q}} = 1750 \text{ GeV}, \ A_t = -4000 \text{ GeV}, \ m_{\tilde{g}} \approx 3000 \text{ GeV}$$

where $M_A = M_{H^\pm} - M_W^2 + \lambda^2 v^2$

⇒ scenario to explain the di-photon excess

[F. Domingo, S.H., J. Kim, K. Rolbiecki '16]⇒ see Jong Soo's parallel talk tomorrow!

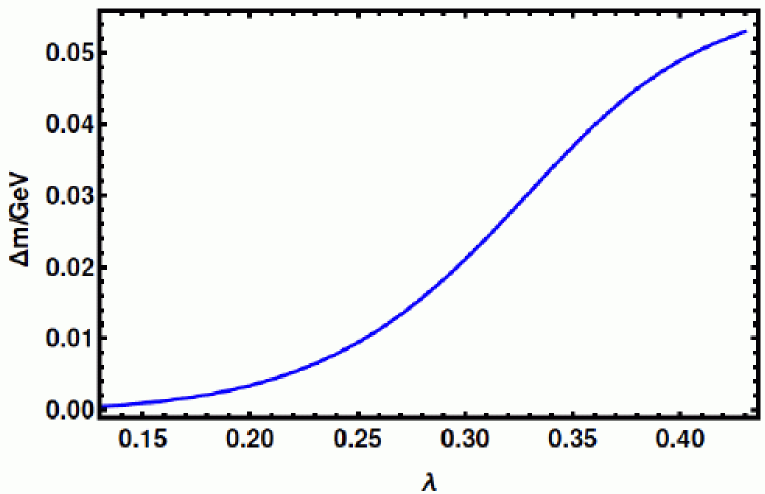
Lighter Masses @ 2-Loop Order: P1



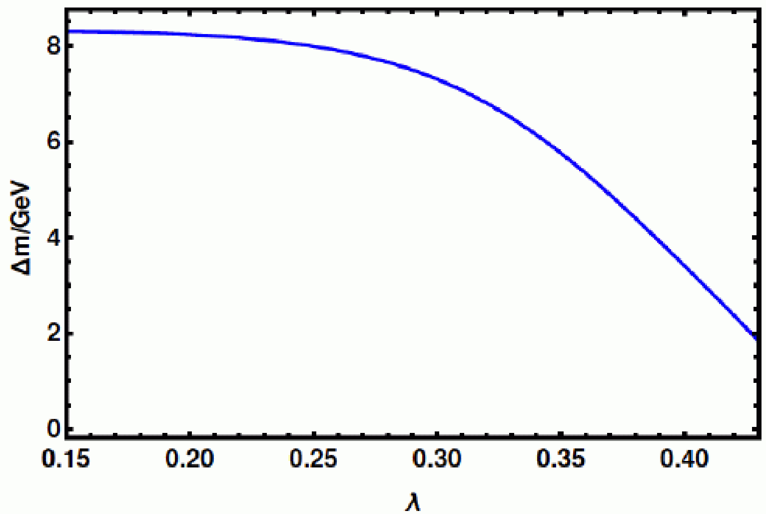
- mass decreasing with increasing λ belongs to singlet-like, constant mass to doublet-like state

Lightest Mass @ 1-Loop Order: P1

Absolute difference between different mass predictions



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



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

$\Longrightarrow$ results mirror sample scenario for small values of λ

4. Conclusinos

- High precision predictions in BSM models for Higgs physics are needed!
  $\rightarrow$ to match experimental accuracy at the LHC and ILC

- **FeynHiggs** provides these predictions for the (N)MSSM

- MSSM:
  – highest precision for masses, couplings, BRs, . . .
  – for low and high SUSY mass scales
  – only code that provides a combination of Feynman diagrammatic and EFT results
  – NEW: additional intermediate thresholds from gluino, charginos, neutranlinos; EW contributions
  – NEW: 3L RGE running

- NMSSM: (“internal version” exists):
  – combine genuine NMSSM contributions with known MSSM parts
  – $\Rightarrow$ very good approximation
  – $\Rightarrow$ highest possible precision in the NMSSM
  – public verion very soon . . .


Higgs Days at Santander 2016
Theory meets Experiment
19.-23. September
iFCA
Instituto de Física de Cantabria
CSIC
UC
UNIVERSIDAD DE CANTABRIA
contact: Sven.Heinemeyer@cern.ch
http://hdays.csic.es
local: Gervasio.Gomez@cern.ch


Further Questions?

Included in FeynHiggs 2.12.0 (I):

Evaluation of all Higgs boson masses and mixing angles

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

Evaluation of all neutral Higgs boson decay channels

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

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

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

Included in FeynHiggs 2.12.0 (II):

Evaluation of all neutral Higgs boson production cross sections at LHC

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

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

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

- all SM channels as above

Included in FeynHiggs 2.12.0 (III):

Evaluations for the charged Higgs boson (rMSSM/cMSSM)

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

Evaluation of additional couplings:

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

Included in FeynHiggs 2.12.0 (IV):

Evaluation of theory error on masses and mixing

$\to$ 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

$\Rightarrow$ Connection to Flavor physics

Evaluation of additional constraints (rMSSM/cMSSM)

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

Applicability and uncertainties

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:

Applicability and uncertainties

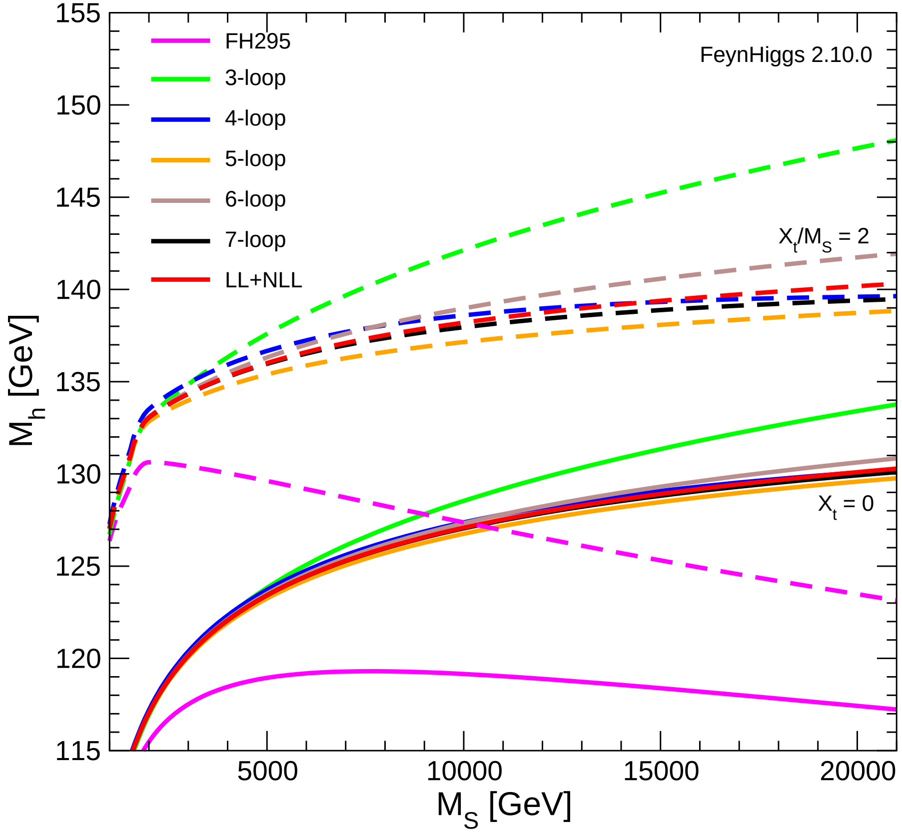
1.) SUSY mass scales below ~ 1 TeV require full calculation

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!

Applicability and uncertainties

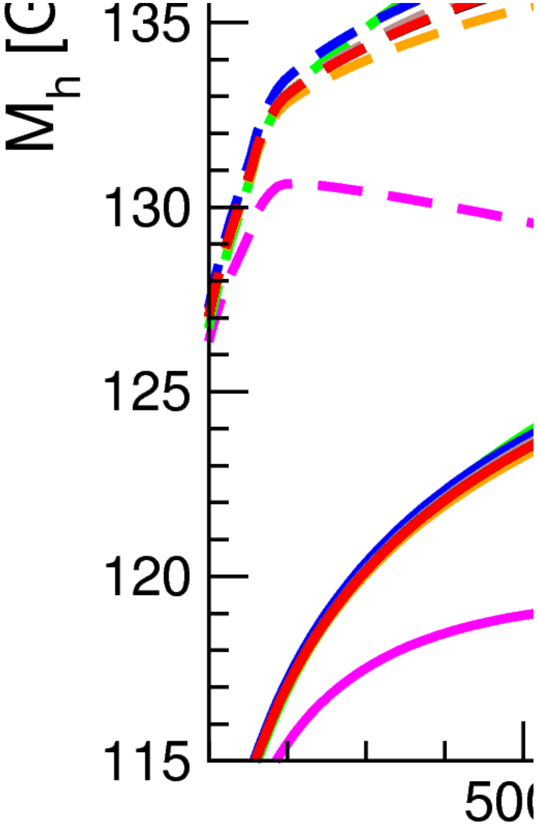
1.) SUSY mass scales below ~ 1 TeV require full calculation

2.) Log resum. for $t/\tilde{t}$ (beyond 2L) at M_S for $\Delta M_h^\text{diagrammatic} \sim 40$ GeV

– effects at $M_\text{S} = 1$ TeV: tiny

– at $M_\text{S} = 2$ TeV: $\Delta M_h^\text{log-resum} \sim 2$ GeV

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



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⇒ 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

arXiv.org > hep-ph > arXiv:1504.05200

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High Energy Physics - Phenomenology

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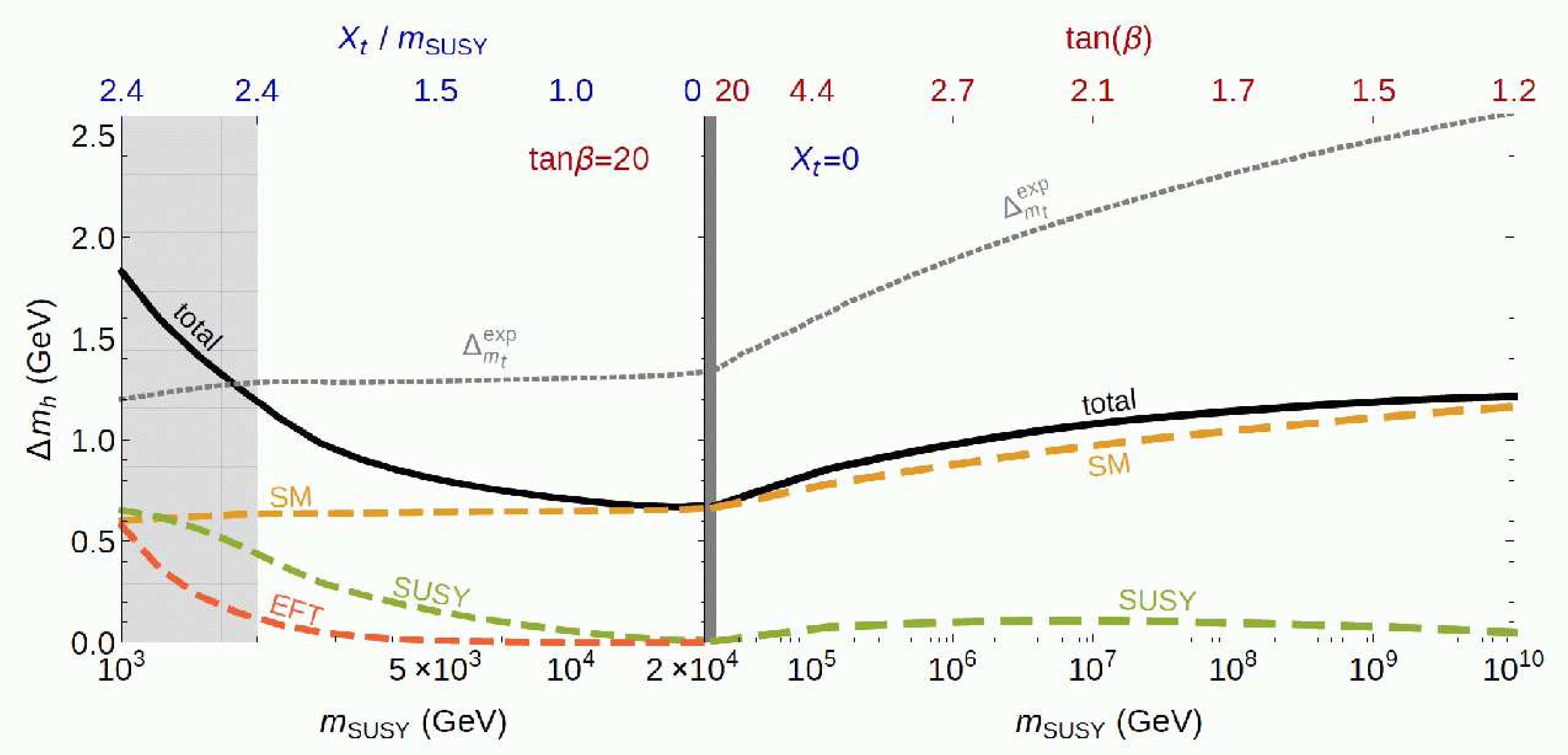
Does this mean that now there exists a better prediction for M_h in the MSSM with substantially smaller theory uncertainty?

Claim by SusyHD authors:

[*J. Pardo Vega, G. Villadoro '15*]

$\Rightarrow$ Predictions of high-scale SUSY model valid down to ~ 1 TeV, theoretical uncertainty in prediction of SM-like Higgs: ~ 1 GeV
("the theoretical uncertainty is within 1 GeV in most of the relevant parameter space")



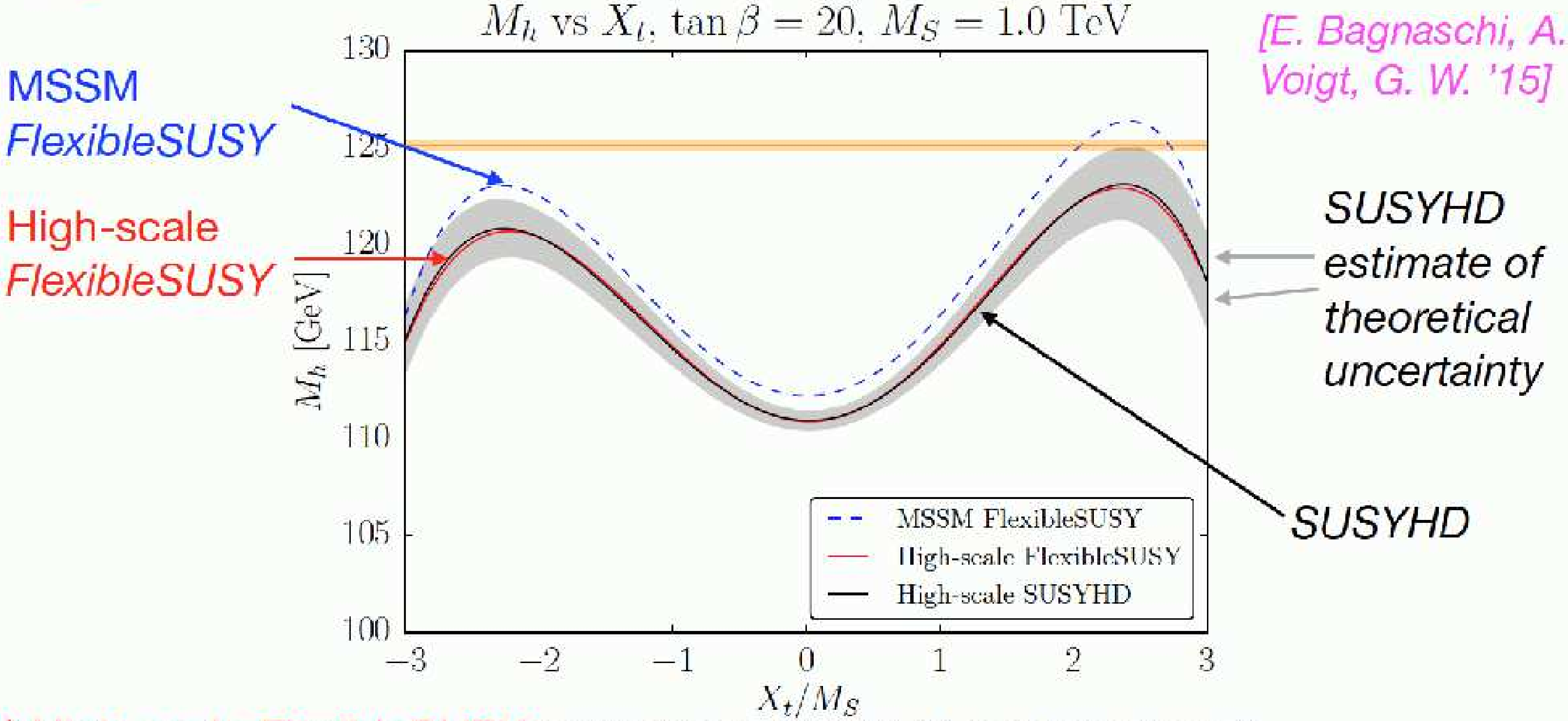
Uncertainty analysis (I)

[*G. Weiglein, HDays15*]

Comparison of full model and EFT result produced with the same code

MSSM *FlexibleSUSY*: full model calculation based on Pietro's 2-loop corrections in the DRbar scheme

High-scale *FlexibleSUSY*: EFT approach (work in progress)



⇒ High-scale *FlexibleSUSY* reproduces *SUSYHD* result very well

Sizable difference to full-model result (MSSM *FlexibleSUSY*), outside of estimate of theoretical uncertainty from *SUSYHD*

Off-shell effects, interference effects, 2HDM, MSSM and EFT, Georg Weiglein, Higgs Days at Santander 2015, Santander, 09 / 2015

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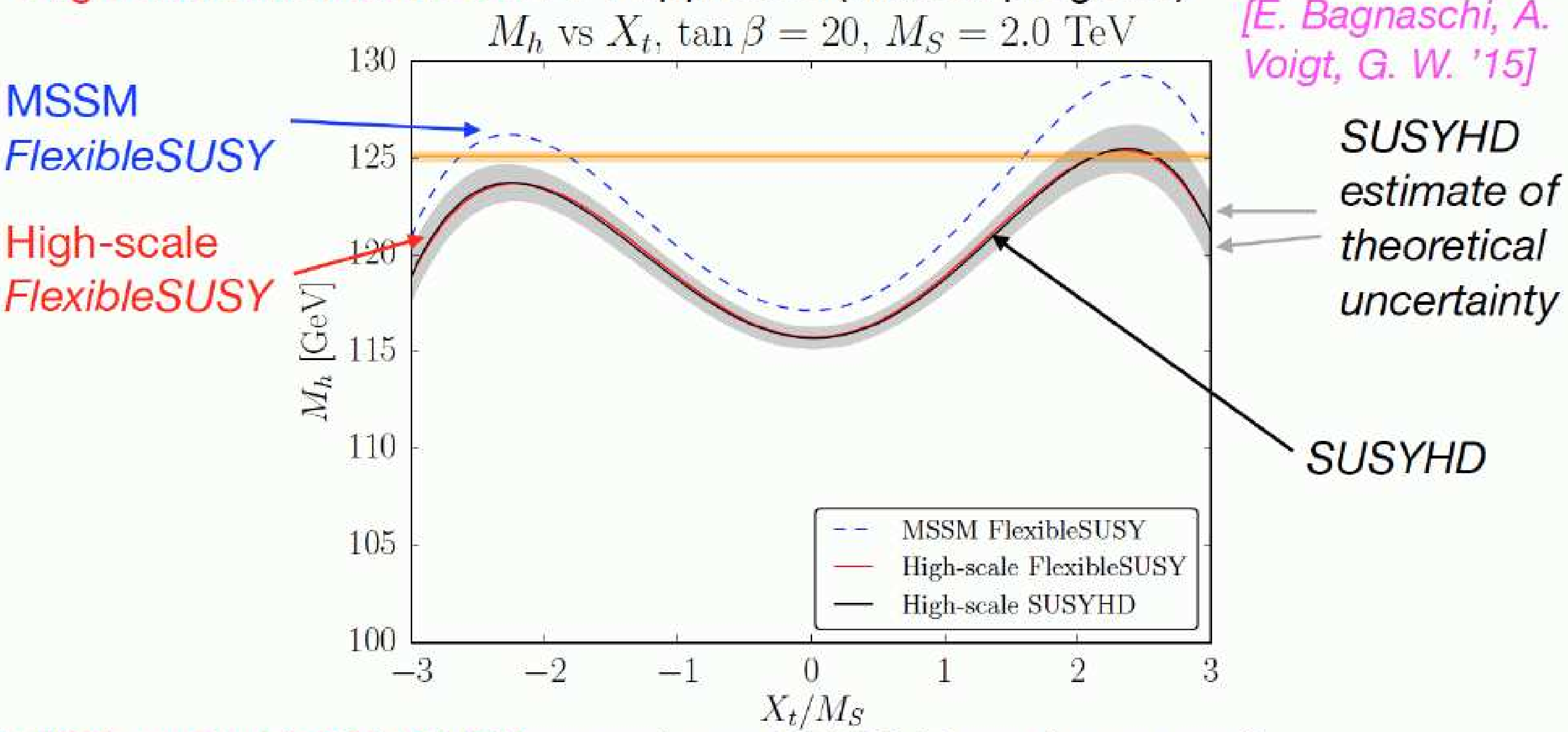
[E. Bagnaschi, A. Voigt, G. W. '15]



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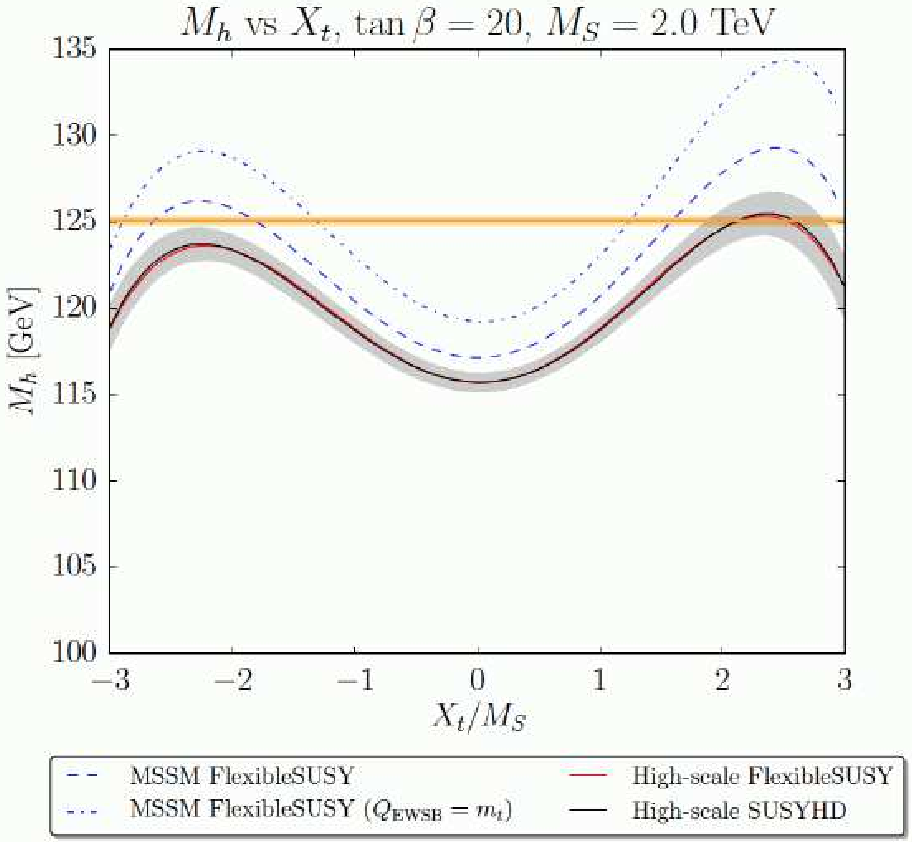
Off-shell effects, interference effects, 2HDM, MSSM and EFT, Georg Weiglein, Higgs Days at Santander 2015, Santander, 09 / 2015

Different options for doing the full model calculation in the DRbar scheme

Option 1: Higgs mass computation at scale $Q = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$
Option 2: First run parameters down to scale Q = m_t, compute Higgs mass there



FlexibleSUSY

[E. Bagnaschi, A. Voigt, G. W. '15]

⇒ Differences are of higher order, much larger than uncertainty estimated in *SUSYHD*

Off-shell effects, interference effects, 2HDM, MSSM and EFT, Georg Weiglein, Higgs Days at Santander 2015, Santander, 09 / 2015 25

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 renormalizaion 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: $\mathcal{O}\left(v^2/M_S^2\right)$ (prefactor 1)

⇒ uncertainty estimate of ~ 1 GeV
⇒ estimate for the multi-TeV range (no large scale diff.?!)
⇒ unclear to which low scales it can be extrapolated

Intermediate region:
⇒ both types of calculations can be used for uncertainty estimate

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

Screen Output

Input File

```
MT          172.7
MB          4.7
MW          80.4
MZ          91.1
MSusy       975
MA0         200
Abs(M_2)    332
Abs(MUE)    980
TB          50
Abs(At)     -300
Abs(Ab)     1500
Abs(M_3)    975
```

Command

FeynHiggs *file* [*flags*] →

```
-------------------- HIGGS MASSES --------------------
| Mh0     =   116.022817
| MHH     =   199.943497
| MA0     =   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
| DeltaMA0  =  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
MA0         200
Abs(M_2)    332
Abs(MUE)    980
TB          50
Abs(At)     -300
Abs(Ab)     1500
Abs(M_3)    975
```

Input File ("new")

```
MA0         227
TB          23
table ehoww.A2.dat MA0 TB
```

- Loops over parameter values possible (parameter scans).

  ```
  MA0         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 ⇒ link `libFH.a`

`call FHSetFlags(...)` :
→ specification of accuracy etc.

`call FHSetPara(...)` :
→ specify input parameters

`call FHGetPara(...)` :
→ obtain derived parameters

`call FHHiggsCorr(...)` :
→ obtain Higgs boson masses and mixings

`call FHUncertainties(...)` :
→ obtain theory error on Higgs boson masses and mixings from unknown higher-order corrections

`call FHCouplings(...), FHHiggsProds(...), ...` :
→ obtain decay widths, BRs, XSs, etc.

C) Called within Mathematica

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

  `Install[''MFeynHiggs'']`

- `FHSetFlags[...]` :
  $\rightarrow$ specification of accuracy etc.

  `FHSetPara[...]` :
  $\rightarrow$ specify input parameters

  `FHGetPara[]` :
  $\rightarrow$ obtain derived parameters

  `FHHiggsCorr[]` :
  $\rightarrow$ obtain Higgs boson masses and mixings

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

  `FHCouplings[], FHHiggsProds[], ...` :
  $\rightarrow$ 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

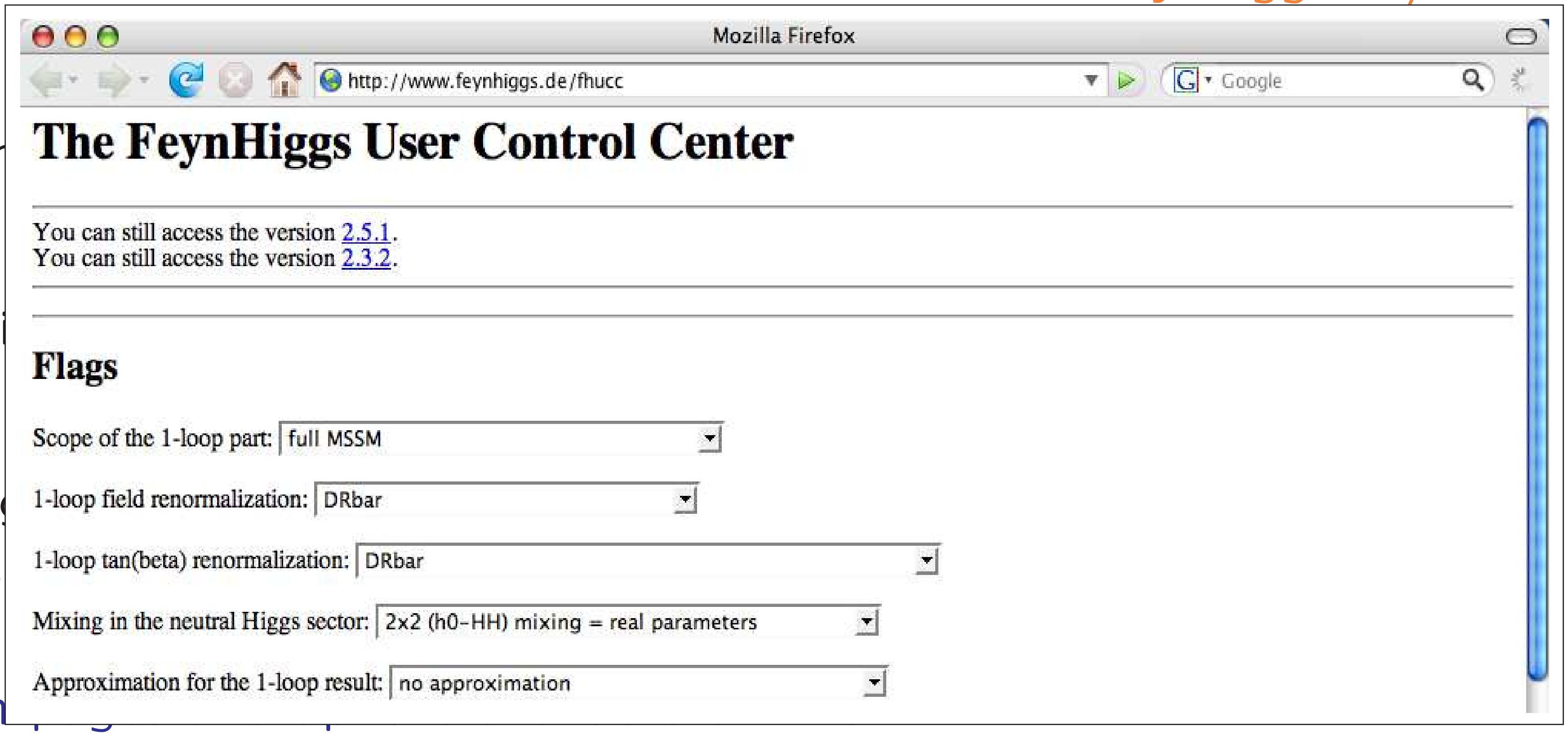
3. Obtain your results with a mouse click

$\Rightarrow$ for single points and checks of your downloaded version of FeynHiggs
$\Rightarrow$ 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. Obtai

⇒ for sin

⇒ always

Also man