Precise Higgs mass calculations in (non-)minimal supersymmetry at both high and low scales

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Refs.

- Athron, JhP, Stöckinger, Voigt, CPC190(2015)139
- Athron, JhP, Stöckinger, Voigt, NPPP273(2016)2424
- Athron, JhP, Stöckinger, Voigt, Steudtner, 1609.00371

Supersymmetry

- Symmetry interchanging a fermion and a boson
- Non-trivial extension of Poincaré group
- Phenomenological uses:
  - Alleviation of fine-tuning in Higgs mass
  - Lightest Higgs mass restricted to a limited range
  - Gauge coupling unification
  - Dark matter
- Potential dangers:
  - Proton decay
  - FCNC, CP-violation
  - Damage to BBN

Higgs mass in MSSM

Okada, Yamaguchi, Yanagida; Ellis, Ridolfi, Zwirner; Haber, Hempfling

$$\left(m_h^2\right)_0 = m_Z^2 \cos^2 2\beta$$

$$\left(\Delta m_h^2\right)_{1,\log} \simeq \frac{3g_2^2}{8\pi^2 m_W^2} m_t^4 \ln\left(\frac{M_{\rm SUSY}^2}{m_t^2}\right)$$

$$\left(\Delta m_h^2\right)_{1,\rm mix} \simeq \frac{g_2^2 N_c}{16\pi^2 m_W^2 M_{\rm SUSY}^2}\left[2m_t^4 X_t^2\left(1-\frac{X_t^2}{12M_{\rm SUSY}^2}\right) + 2m_b^4 X_b^2\left(1-\frac{X_b^2}{12M_{\rm SUSY}^2}\right)\right]$$

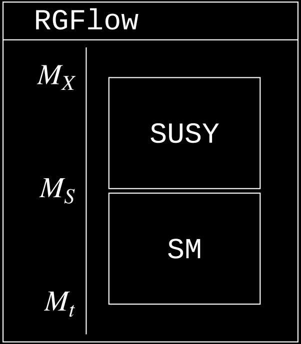
$$X_t \equiv A_t - \mu\cot\beta, \qquad X_b \equiv A_b - \mu\tan\beta$$

Can fit $m_h = 125\ \mathrm{GeV}$ for $M_{\rm SUSY} \lesssim 30\ \mathrm{TeV}$

Higgs mass in high-scale supersymmetry

Barbieri, Frigeni, Caravaglios, Okada, Yamaguchi, Yanagida, Haber, Hempfling, Casas, Espinosa, Quirós, Riotto, Carena, Wagner, Lee

- Large scale difference between m_t and M_{SUSY} requires resummation of large logs
- Take “tower-of-EFTs” approach
- Match quartic SM Higgs coupling λ against 4-point function of lightest full-theory Higgs at M_{SUSY}
- Let λ run from M_{SUSY} to m_t
- Calculate m_h from $\lambda(m_t)$



Resummation of large logs

- Renormalization group equation

$$\mu \frac{\partial \lambda}{\partial \mu} = \frac{\partial \lambda}{\partial \ln \mu} = \beta(\lambda)$$

- 1-loop β-function

$$\beta(\lambda) = \frac{b}{(4\pi)^2} \lambda^2$$

- Solution of RGE

$$\begin{aligned} \overline{\lambda}(p) &= \frac{\lambda}{1 - b\lambda/(4\pi)^2 \ln(p/\mu)} \\ &= \lambda + b\frac{\lambda^2}{(4\pi)^2} \ln\frac{p}{\mu} + b^2 \frac{\lambda^3}{(4\pi)^4} \ln^2\frac{p}{\mu} + \cdots \end{aligned}$$

Public spectrum calculators

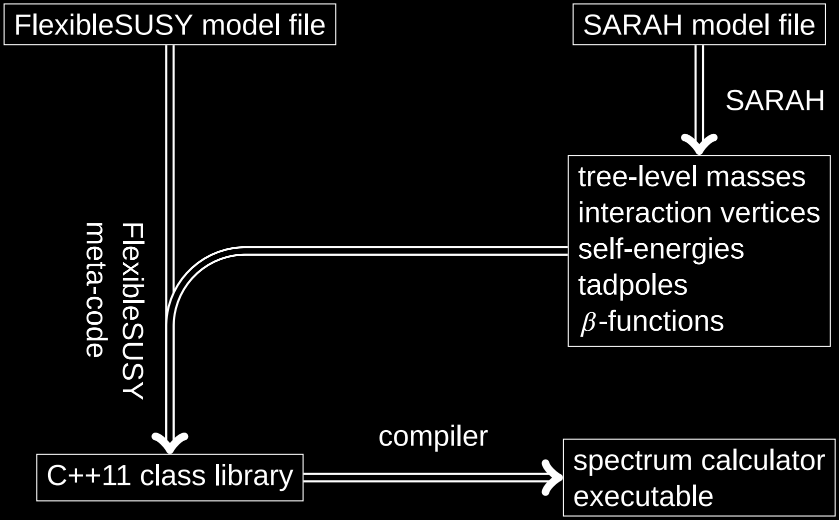
Model	Spectrum calculators
MSSM	ISASUSY, Softsusy, SPheno, SuSeFlav, SuSpect
NMSSM	NMSPEC, Softsusy
User-defined	SARAH Staub , **FlexibleSUSY**

	SARAH	FlexibleSUSY
generates code in	FORTRAN	C++11
reuses code from	SPheno	Softsusy
symbolic calculation of β-functions etc.	done	invokes SARAH

FlexibleSUSY: a modern technology

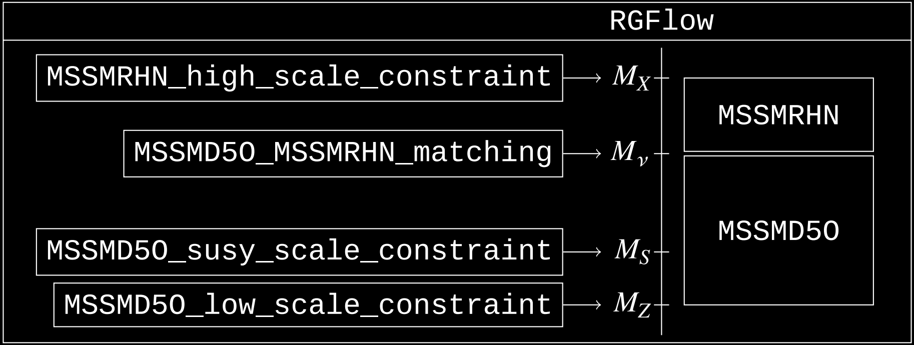
flexiblesusy.hepforge.org

How FlexibleSUSY works



Tower of effective field theories

- Typical example: LFV from SUSY see-saw



- Other configurations of interest:
  - GUT [$SU(5)$, $SO(10)$, E_6] $\rightarrow$ MSSM
  - Split-SUSY, high-scale SUSY

Specimen SARAH model file for MSSM

```
(* Vector superfields *)
Gauge[[1]]={B,   U[1], hypercharge, g1, False, RpM};
Gauge[[2]]={WB, SU[2], left,        g2, True,  RpM};
Gauge[[3]]={G,  SU[3], color,       g3, False, RpM};

(* Chiral superfields *)
SuperFields[[1]]={q,  3, {uL,  dL},   1/6, 2, 3, RpM};
SuperFields[[2]]={l,  3, {vL,  eL},  -1/2, 2, 1, RpM};
SuperFields[[3]]={Hd, 1, {Hd0, Hdm}, -1/2, 2, 1, RpP};
SuperFields[[4]]={Hu, 1, {Hup, Hu0},  1/2, 2, 1, RpP};
SuperFields[[5]]={d, 3, conj[dR],    1/3, 1, -3, RpM};
SuperFields[[6]]={u, 3, conj[uR],   -2/3, 1, -3, RpM};
SuperFields[[7]]={e, 3, conj[eR],      1, 1,  1, RpM};

(* Superpotential *)
SuperPotential = Yu u.q.Hu - Yd d.q.Hd - Ye e.l.Hd
               + \[Mu] Hu.Hd;
```

Specimen FlexibleSUSY model file for MSSM

```
FSDefaultSARAHModel = MSSM;
OnlyLowEnergyFlexibleSUSY = True;
FlexibleEFTHiggs = True;

SUSYScaleInput = {
   {vu, Sqrt[vu^2 + vd^2] Sin[ArcTan[TanBeta]]},
   {vd, Sqrt[vu^2 + vd^2] Cos[ArcTan[TanBeta]]},
   {MassB , M1Input},
   {MassWB, M2Input},
   {MassG , M3Input},
   {mq2, mq2Input}, {mu2, mu2Input}, {md2, md2Input},
   {ml2, ml2Input}, {me2, me2Input},
   {\[Mu], MuInput},
   {B[\[Mu]], mAInput^2/(TanBeta + 1/TanBeta)},
   {T[Yu], AuInput Yu},
   {T[Yd], AdInput Yd},
   {T[Ye], AeInput Ye}};
```

Automated Higgs mass calculation to 2-loops

- Categories of multi-loop Higgs mass calculation:
  1. Fixed-order:
     1. Diagrammatic approach

        Hempfling, Hoang, Heinemeyer, Hollik, Weiglein
     2. Effective potential

        Brignole, Dedes, Degrassi, Slavich, Zwirner, Martin
  2. Resummation via EFT

     Casas, Espinosa, Quirós, Riotto, Carena, Wagner
- SARAH performs 1 2 for user-defined models

  Goodsell, Nickel, Staub
- FlexibleEFTHiggs is an implementation of 2 in FlexibleSUSY

  Athron, JhP, Stöckinger, Voigt, Steudtner

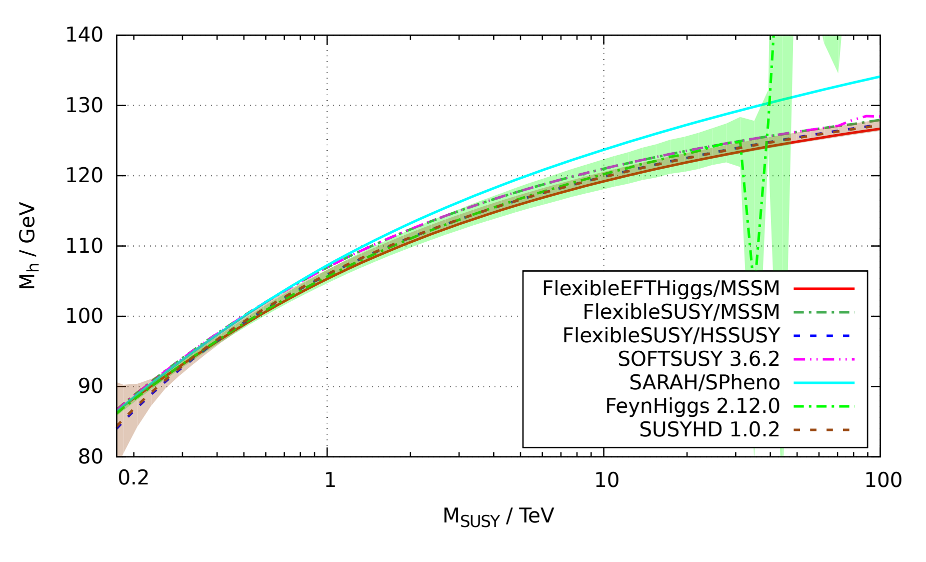
FlexibleEFTHiggs

- A variant of EFT approach
- Assume SM as EFT
- High-scale matching condition:

$$(M_h^{\text{SM}})^2 = (M_h^{\text{SUSY}})^2 \quad \text{instead of } \lambda\text{-matching}$$

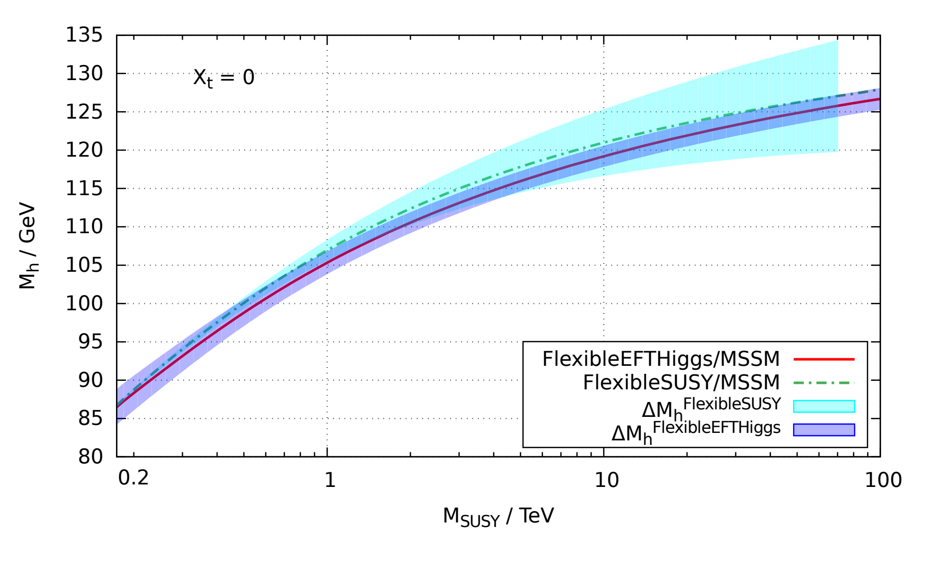
- Automatizable using only pole masses (available from SARAH)
- Not a full SMEFT, works only for m_h calculation
- Current accuracy: 1-loop matching + 3-loop running
- Work on 2-loop matching is underway

MSSM, varying M_{SUSY}



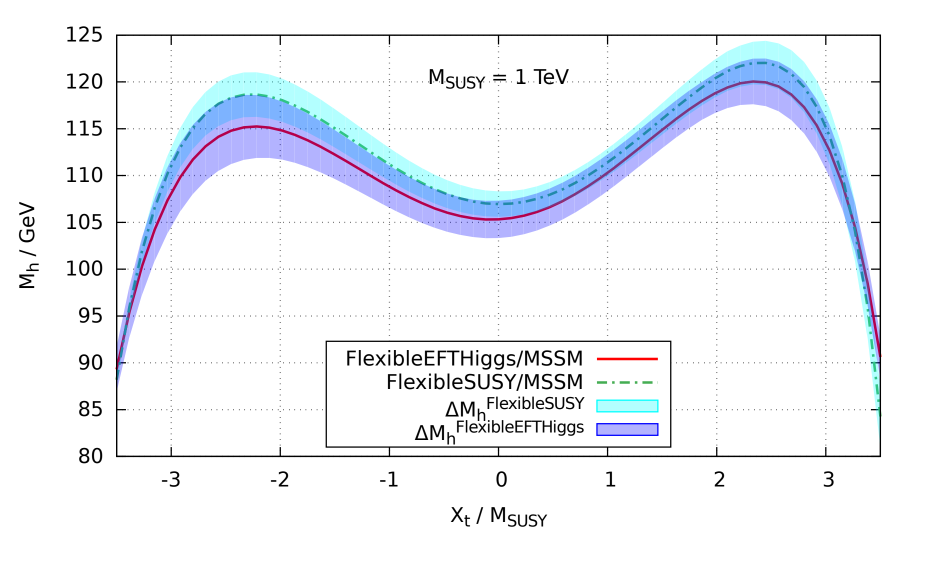
$$\tan\beta = 5, \quad X_t = 0$$

MSSM theory uncertainties, $X_t = 0$



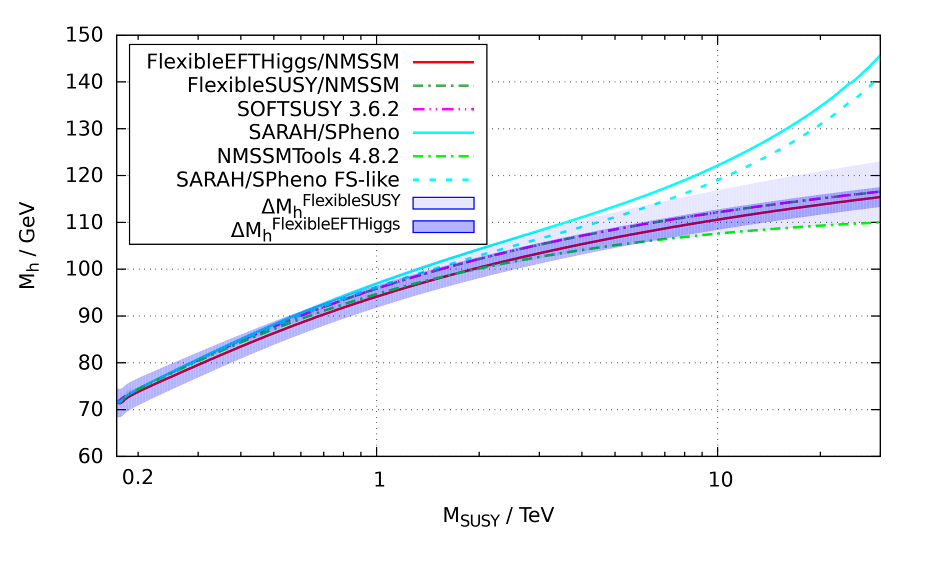
$\tan\beta = 5$

MSSM theory uncertainties, $X_t \neq 0$



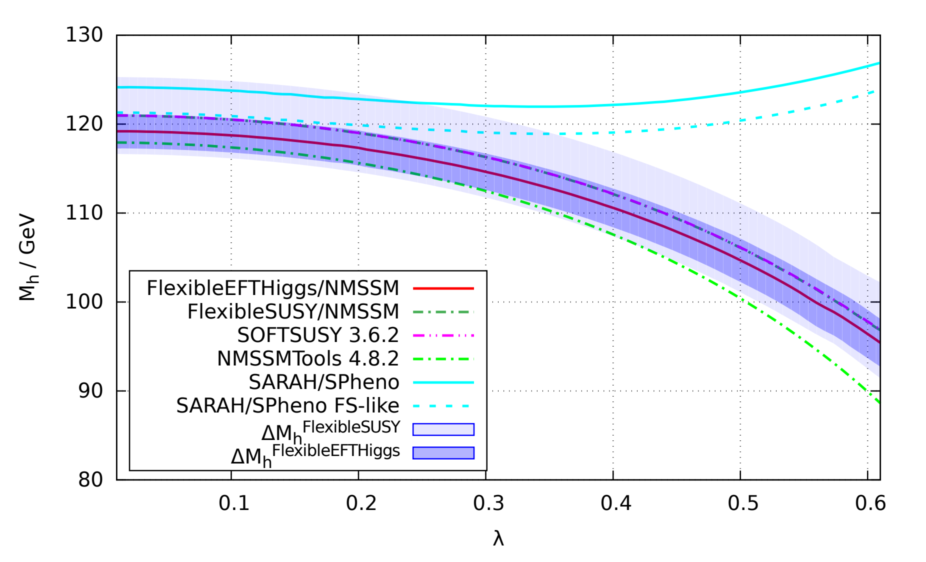
$\tan\beta = 5$

NMSSM, varying M_{SUSY}



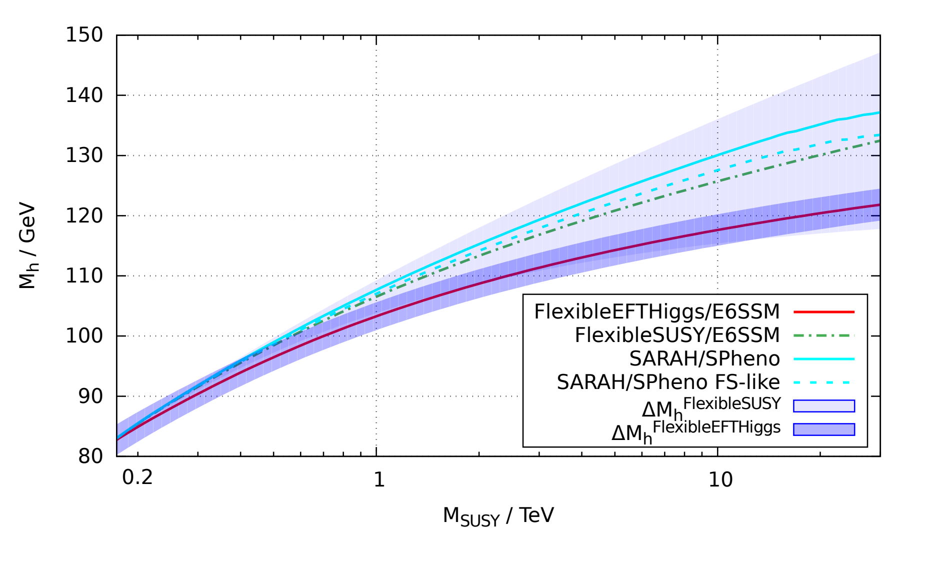
$$\tan\beta = 5, \quad X_t = 0, \quad \lambda = \kappa = 0.4$$

NMSSM, varying $\kappa = \lambda$



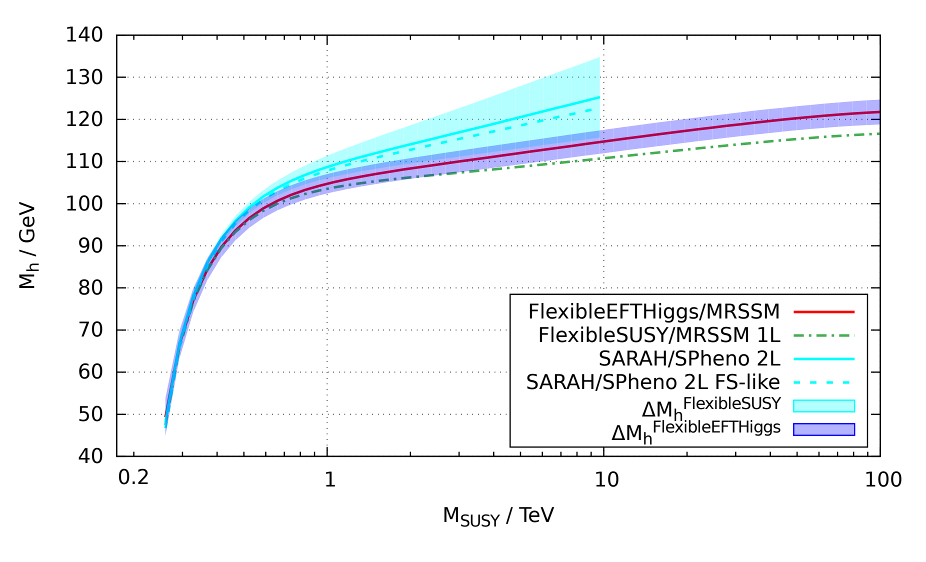
$$\tan\beta = 5, \quad X_t = 0, \quad M_{\text{SUSY}} = 10\ \text{TeV}$$

E_6SSM



$$\tan\beta = 5, \quad X_t = 0, \quad \lambda = 0.1$$

MRSSM



140
130
120
110
100
90
80
70
60
50
40
M_h / GeV
0.2
1
10
100
M_{SUSY} / TeV
FlexibleEFTHiggs/MRSSM
FlexibleSUSY/MRSSM 1L
SARAH/SPheno 2L
SARAH/SPheno 2L FS-like
$\Delta M_h^{\text{FlexibleSUSY}}$
$\Delta M_h^{\text{FlexibleEFTHiggs}}$

Summary

- High new physics scale calls for resummation in m_h calculation
- FlexibleEFTHiggs is a new FlexibleSUSY feature performing resummed m_h calculation in user-defined supersymmetric models
- FlexibleEFTHiggs agrees with SUSYHD in MSSM
- Also studied instances are NMSSM, E_6SSM, MRSSM
- FlexibleEFTHiggs' theory uncertainty is bounded at all scales in contrast to fixed-order calculations