# FlexibleSUSY: an attempt towards automated BSM physics studies

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Beyond the BSM
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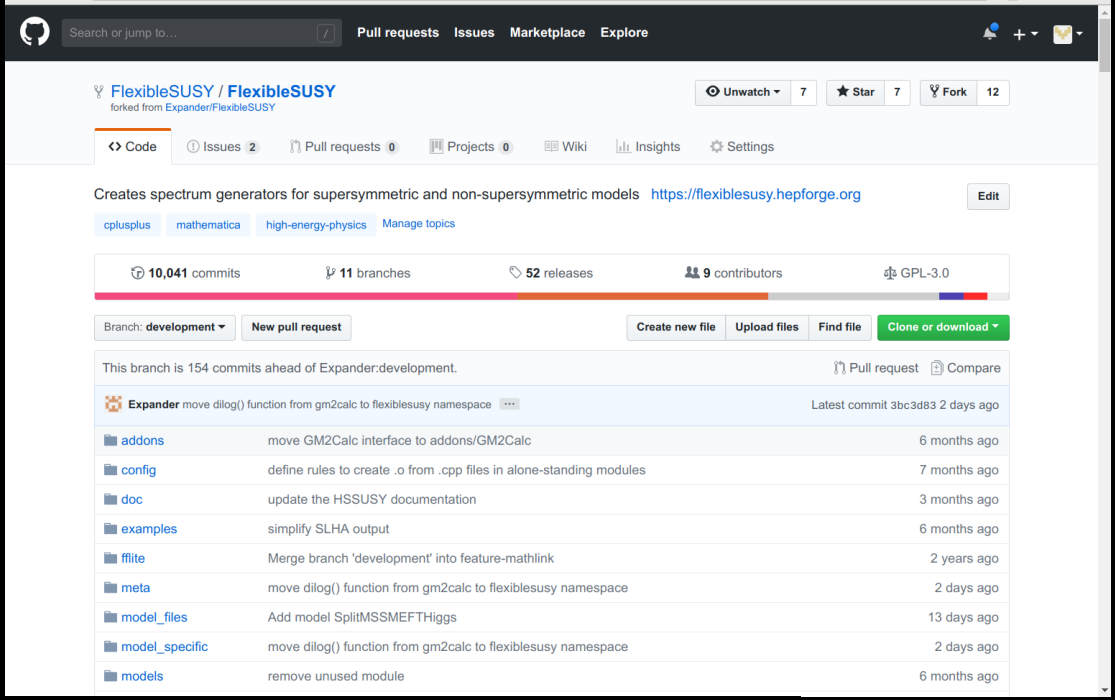
HOTEL 天坊 伊香保町, 02.10.2018

Refs.

- Athron, JhP, Stöckinger, Voigt, CPC190(2015)139
- Athron, JhP, Stöckinger, Voigt, NPPP273(2016)2424
- A,P,S,V, Steudtner, JHEP01(2017)079
- A,P,S,V, Bach, Harries, Kwasnitza, Ziebell, CPC230(2018)145
- JhP, 1809.07774


Secure https://github.com/FlexibleSUSY/FlexibleSUSY
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Creates spectrum generators for supersymmetric and non-supersymmetric models https://flexiblesusy.hepforge.org
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10,041 commits 11 branches 52 releases 9 contributors GPL-3.0
Branch: development New pull request
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This branch is 154 commits ahead of Expander:development.
Pull request Compare
Expander move dilog() function from gm2calc to flexiblesusy namespace
Latest commit 3bc3d83 2 days ago
addons move GM2Calc interface to addons/GM2Calc 6 months ago
config define rules to create .o from .cpp files in alone-standing modules 7 months ago
doc update the HSSUSY documentation 3 months ago
examples simplify SLHA output 6 months ago
fflite Merge branch 'development' into feature-mathlink 2 years ago
meta move dilog() function from gm2calc to flexiblesusy namespace 2 days ago
model_files Add model SplitMSSMEFTHiggs 13 days ago
model_specific move dilog() function from gm2calc to flexiblesusy namespace 2 days ago
models remove unused module 6 months ago

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# FlexibleSUSY online

Here the mass spectrum can be calculated online with FlexibleSUSY for the following models:

- CMSSM
- CMSSMNoFV
- CNMSSM
- CE6SSM
- E6SSM
- E6SSMEFTHiggs
- HGTHDMIIMSSMBC
- HSSUSY
- HTHDMIIMSSMBC
- lowMSSM
- lowNMSSM
- lowNMSSMTanBetaAtMZ
- MRSSM
- MRSSMEFTHiggs
- MSSM
- MSSMatMGUT
- MSSMEFTHiggs
- MSSMNoFV
- MSSMNoFVHimalaya
- MSSMNoFVatMGUT
- MSSMNoFVatMGUTHimalaya
- MSSMRHN

```
   13    1                    # Top pole mass QCD corrections (0 = 1L, 1 = 2L, 2 = 3L)
   14    1.000000000e-11      # beta-function zero threshold
   15    0                    # calculate observables (a_muon, ...)
   16    0                    # force positive majorana masses
   17    0                    # pole mass renormalization scale (0 = SUSY scale)
   18    0                    # pole mass renormalization scale in the EFT (0 = min(SUSY scale,
Mt))
   19    0                    # EFT matching scale (0 = SUSY scale)
   20    2                    # EFT loop order for upwards matching
   21    1                    # EFT loop order for downwards matching
   22    0                    # EFT index of SM-like Higgs in the BSM model
   23    1                    # calculate BSM pole masses
   24    123111321            # individual threshold correction loop orders
   25    0                    # ren. scheme for Higgs 3L corrections (0 = DR, 1 = MDR)
   26    1                    # Higgs 3-loop corrections O(alpha_t alpha_s^2)
   27    1                    # Higgs 3-loop corrections O(alpha_b alpha_s^2)
   28    1                    # Higgs 3-loop corrections O(alpha_t^2 alpha_s)
   29    1                    # Higgs 3-loop corrections O(alpha_t^3)
Block FlexibleSUSYInput
    0    0.00729735           # alpha_em(0)
    1    125.09               # Mh pole
Block SMINPUTS                # Standard Model inputs
    1    1.279340000e+02      # alpha^(-1) SM MSbar(MZ)
    2    1.166378700e-05      # G_Fermi
    3    1.176000000e-01      # alpha_s(MZ) SM MSbar
    4    9.118760000e+01      # MZ(pole)
    5    4.200000000e+00      # mb(mb) SM MSbar
    6    1.733000000e+02      # mtop(pole)
    7    1.777000000e+00      # mtau(pole)
    8    0.000000000e+00      # mnu3(pole)
    9    80.404               # MW pole
   11    5.109989020e-04      # melectron(pole)
   12    0.000000000e+00      # mnu1(pole)
   13    1.056583570e-01      # mmuon(pole)
   14    0.000000000e+00      # mnu2(pole)
   21    4.750000000e-03      # md(2 GeV) MS-bar
   22    2.400000000e-03      # mu(2 GeV) MS-bar
   23    1.040000000e-01      # ms(2 GeV) MS-bar
   24    1.270000000e+00      # mc(mc) MS-bar
Block MINPAR                  # Input parameters
    1    4000                 # m0
    2    4000                 # m12
    3    10                   # TanBeta
    4    1                    # SignMu
    5    0                    # Azero
```

calculate spectrum

```
Block MASS
   1000021     8.09090940E+03   # Glu
        24     8.04549182E+01   # VWm
   1000024     3.32399486E+03   # Cha(1)
   1000037     3.74482027E+03   # Cha(2)
        25     1.25302918E+02   # hh(1)
        35     5.98124238E+03   # hh(2)
        37     5.98193084E+03   # Hpm(2)
        36     5.98118887E+03   # Ah(2)
   1000012     4.72428794E+03   # Sv(1)
   1000014     4.74128382E+03   # Sv(2)
   1000016     4.74134405E+03   # Sv(3)
   1000022     1.81425594E+03   # Chi(1)
   1000023     3.32383603E+03   # Chi(2)
   1000025    -3.73587595E+03   # Chi(3)
   1000035     3.74475658E+03   # Chi(4)
   1000001     7.29014542E+03   # Sd(1)
   1000003     7.69476082E+03   # Sd(2)
   1000005     7.73454565E+03   # Sd(3)
   2000001     7.73456797E+03   # Sd(4)
   2000003     8.06968069E+03   # Sd(5)
   2000005     8.06970332E+03   # Sd(6)
   1000011     4.22026790E+03   # Se(1)
   1000013     4.25833274E+03   # Se(2)
   1000015     4.25846731E+03   # Se(3)
   2000011     4.72538073E+03   # Se(4)
   2000013     4.74226551E+03   # Se(5)
   2000015     4.74232533E+03   # Se(6)
   1000002     6.08894065E+03   # Su(1)
   1000004     7.29480367E+03   # Su(2)
   1000006     7.77140099E+03   # Su(3)
   2000002     7.77142652E+03   # Su(4)
   2000004     8.06942624E+03   # Su(5)
   2000006     8.06944866E+03   # Su(6)
Block UMIX
  1  1     9.88847933E-01   # Re(UM(1,1))
  1  2    -1.48928724E-01   # Re(UM(1,2))
  2  1     1.48928724E-01   # Re(UM(2,1))
  2  2     9.88847933E-01   # Re(UM(2,2))
Block VMIX
  1  1     9.90810719E-01   # Re(UP(1,1))
  1  2    -1.35255757E-01   # Re(UP(1,2))
  2  1     1.35255757E-01   # Re(UP(2,1))
  2  2     9.90810719E-01   # Re(UP(2,2))
Block PSEUDOSCALARMIX
  1  1    -1.01381606E-01   # ZA(1,1)
  1  2     9.94847611E-01   # ZA(1,2)
  2  1     9.94847611E-01   # ZA(2,1)
```

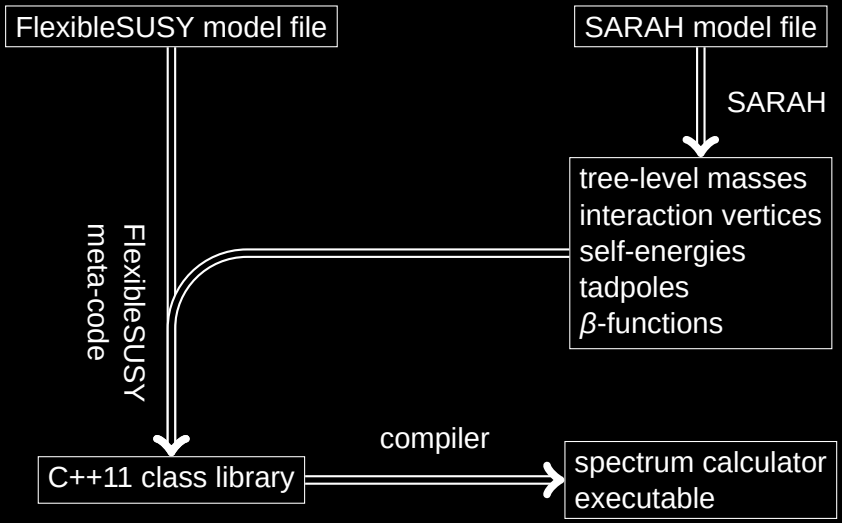
# Public spectrum calculators

| 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 $\beta$-functions etc. | done | invokes SARAH |

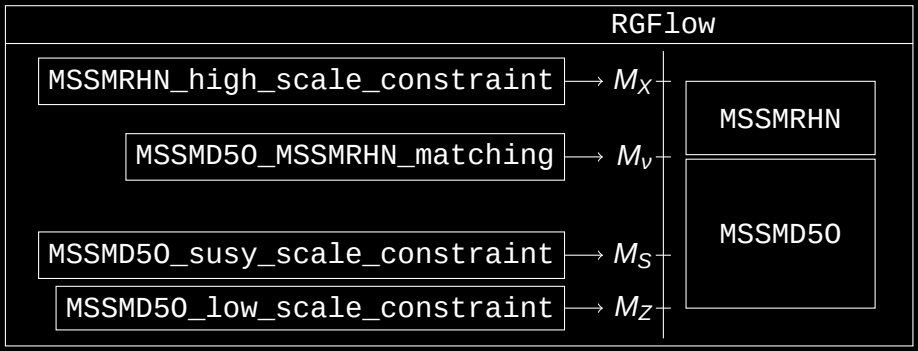
# FlexibleSUSY: a spectrum generator generator

# How FlexibleSUSY works



# Tower of effective field theories

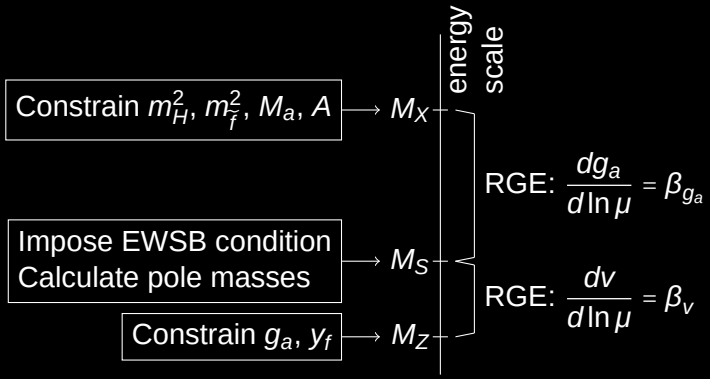
- Typical example: LFV from SUSY see-saw




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

# Boundary value problem

## MSSM example



# Boundary conditions at $M_X$

- CMSSM

$$(m_f^2)_{ij}(M_X) = m_0^2 \delta_{ij}$$
$$A_{ij}^f(M_X) = A_0$$
$$M_i(M_X) = M_{1/2}$$

- NUHMSSM

  Same as above except

  Higgs soft masses $\neq m_0$

- something else

# Pole mass spectrum

- Find $p$ such that

$$0 = \det\left[p^2 1 - m_{\text{tree}} - \Sigma(p^2)\right]$$

- By default, self energy $\Sigma$ is calculated to 1-loop
- In (N)MSSM, FlexibleSUSY calls external FORTRAN routines to evaluate 2-loop Higgs mass corrections

Slavich

# Higgs mass in MSSM

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

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

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

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

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

# Automated Higgs mass calculation

- 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 a variant of 2 implemented in FlexibleSUSY

  Athron, JhP, Stöckinger, Voigt, Steudtner

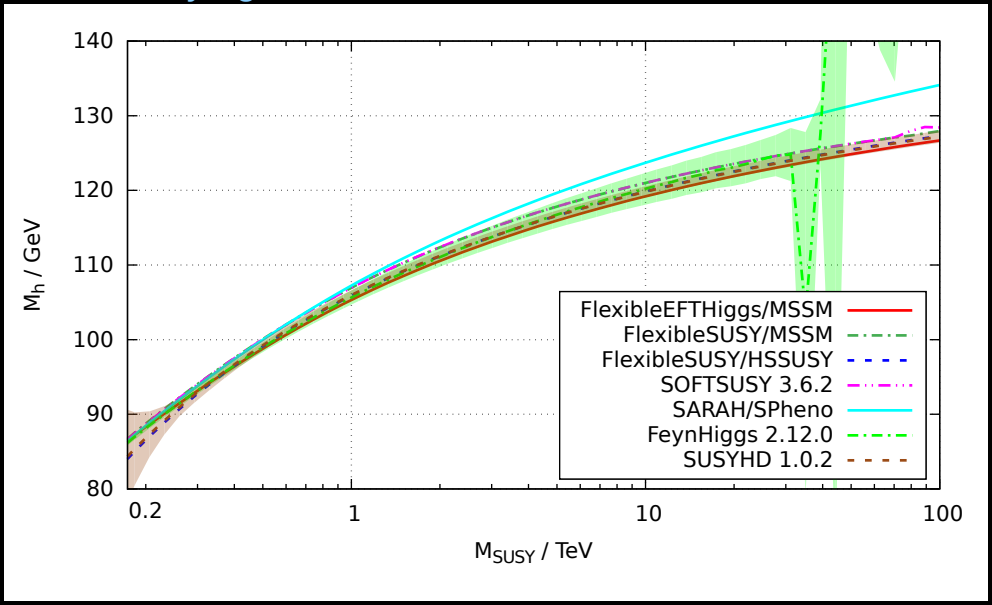
# FlexibleEFTHiggs

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

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

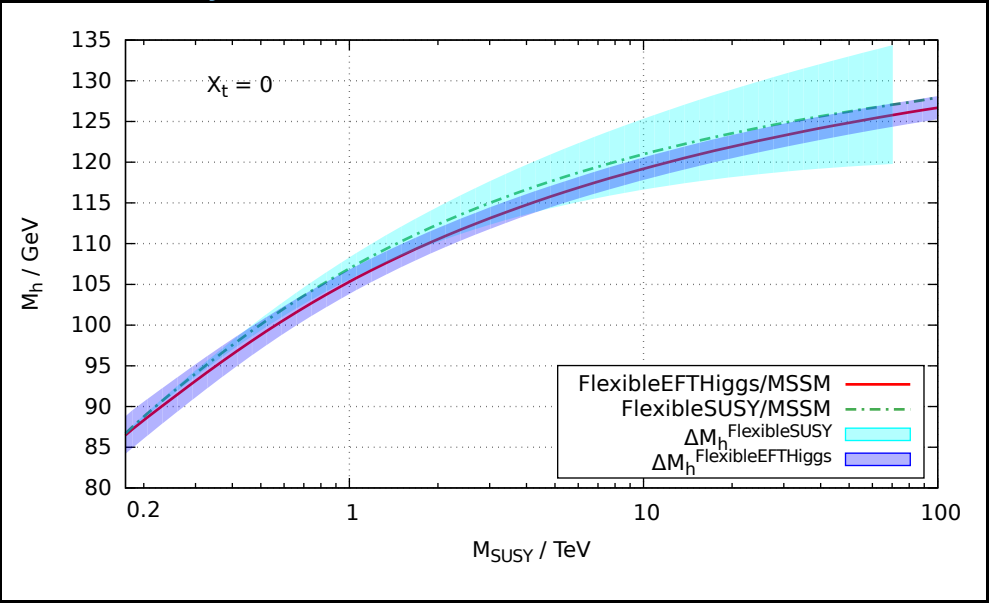
- Automatizable using only pole masses (available from SARAH)
- Not a full SMEFT, works only for $m_h$ calculation
- Current accuracy: 1-loop matching + 3-loop running
- Work on 2-loop matching is underway

# MSSM, varying $M_{SUSY}$



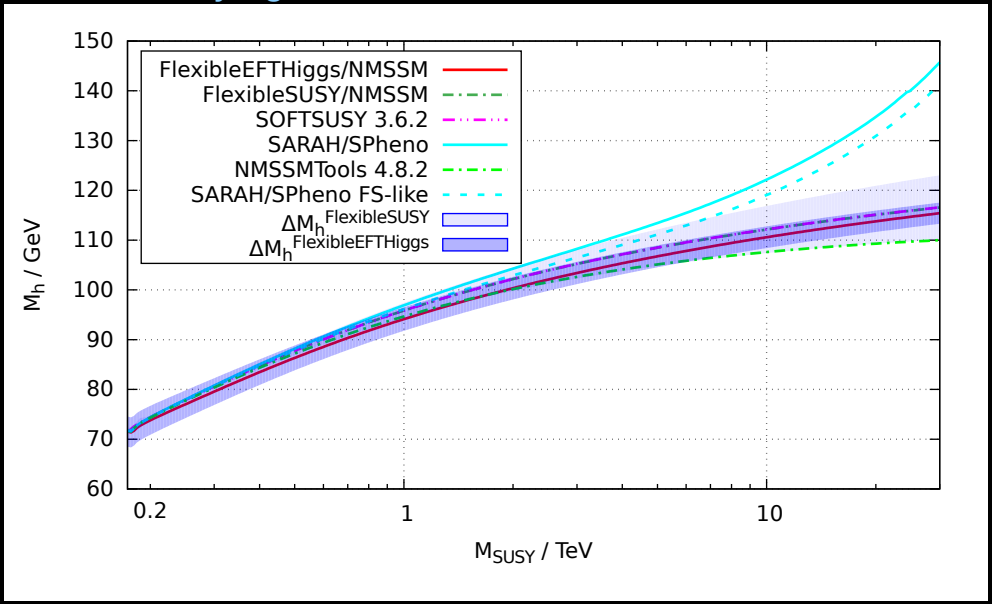

$\tan\beta = 5, \quad X_t = 0$

# MSSM theory uncertainties, $X_t = 0$



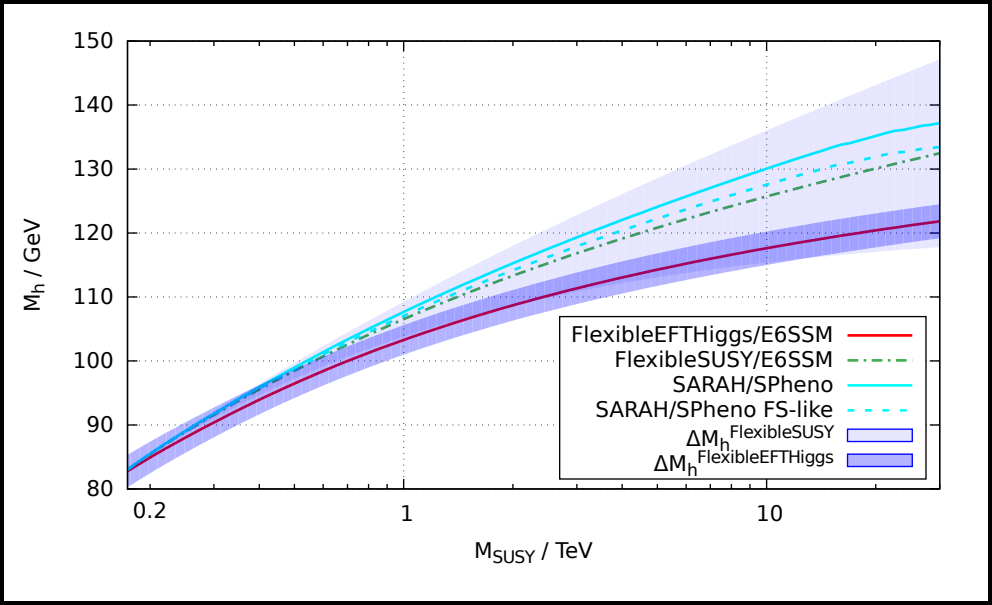

$\tan\beta = 5$

# NMSSM, varying $M_{SUSY}$



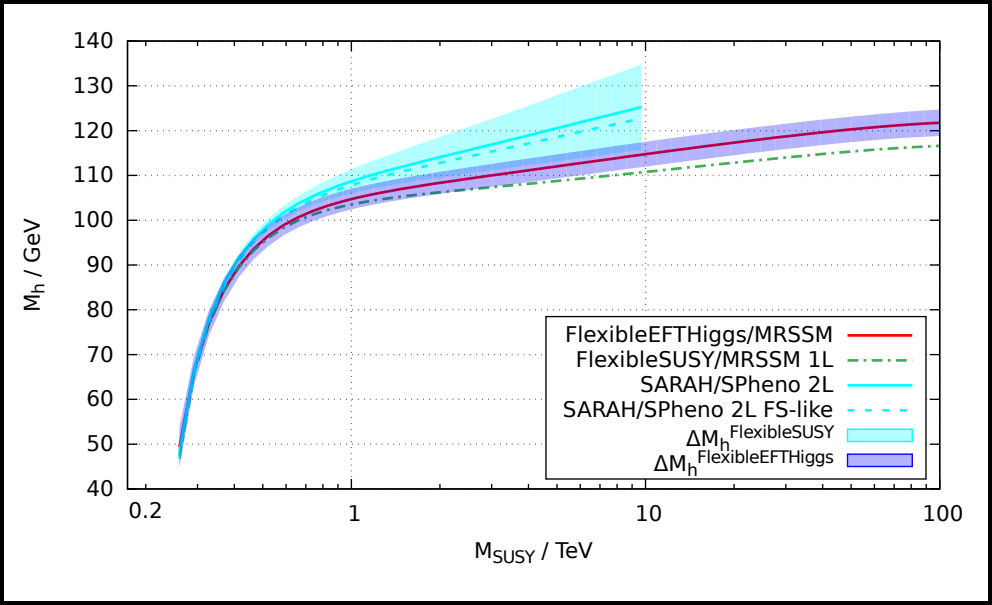

$\tan\beta = 5, \quad X_t = 0, \quad \lambda = \kappa = 0.4$

# $E_6$SSM



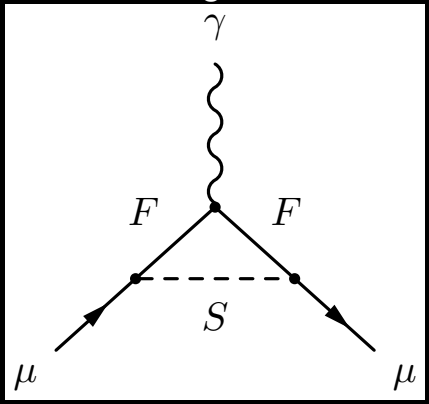

$\tan\beta = 5, \quad X_t = 0, \quad \lambda = 0.1$

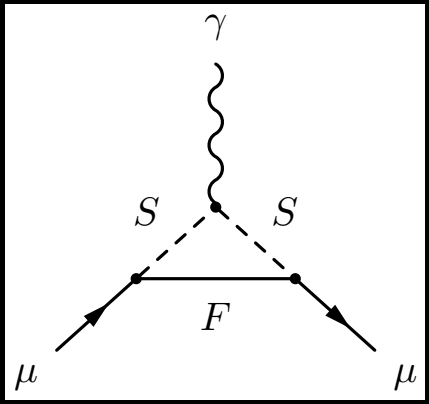
# MRSSM


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
$\Delta M_h^{FlexibleSUSY}$
$\Delta M_h^{FlexibleEFTHiggs}$

## FlexibleAMU for $a_\mu \equiv (g_\mu - 2)/2$

- Calculates $a_\mu^{\text{BSM}}$ at 1-loop level
- Generic diagrams

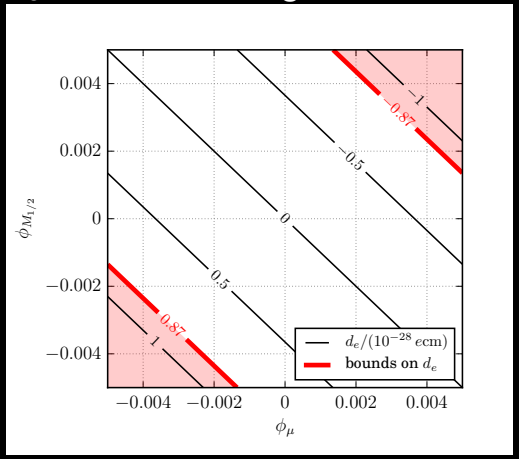


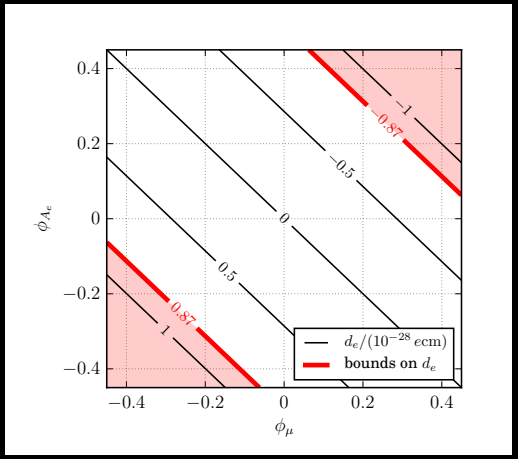

- All possible BSM diagrams are auto-generated
- Renormalization scale is set to running mass of lightest charged BSM particle in loop

# FlexibleCPV

- Allows for complex-valued parameters
- Calculates lepton EDMs at 1-loop level
- $d_e$ in *CP*-violating MSSM



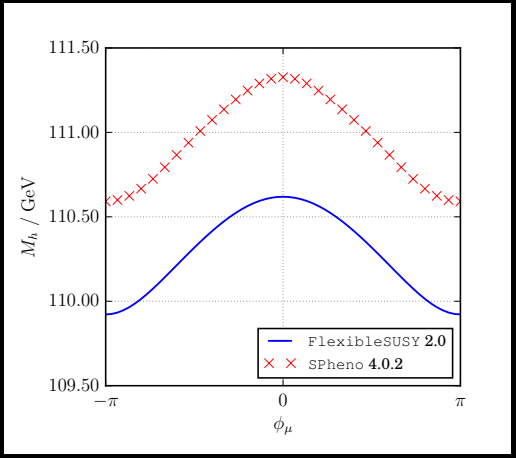

$\mu A_e > 0$

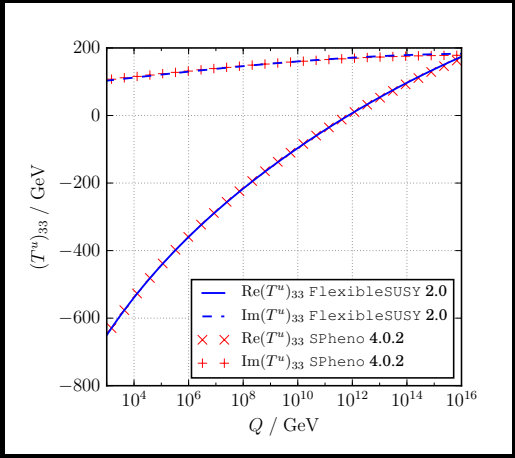



$\mu M_{1/2} > 0$

# FlexibleCPV

- *CP*-violating CMSSM



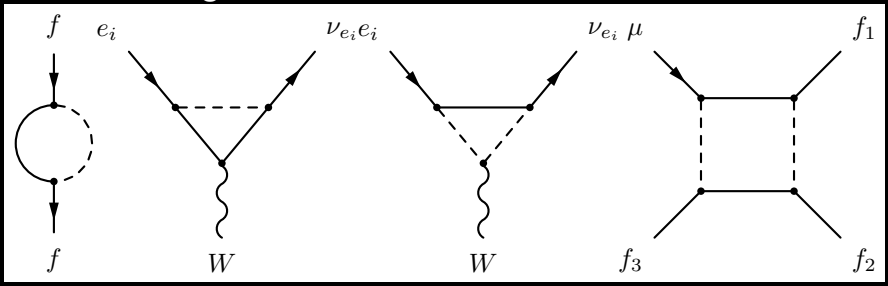




1-loop lightest Higgs pole mass

2-loop RG running of stop trilinear coupling

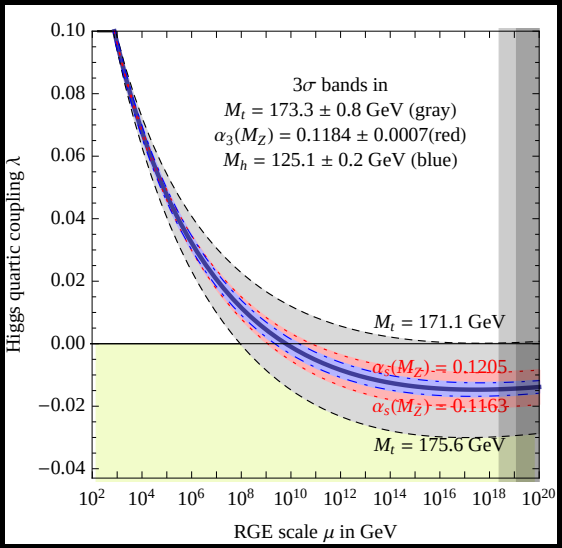
# FlexibleMW

- Calculates muon decay constant $G_F$ at 1-loop level
- Can determine $g_1$ and $g_2$ from $G_F$ and $M_Z$
- Generic diagrams




- All possible BSM diagrams are auto-generated

# EFT picture of bounds on $M_{\text{SUSY}}$




Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia (2013)

Matching condition of $\lambda$ at $M_{\text{SUSY}}$

$$\lambda = \frac{1}{4}\left(g_2^2 + g_Y^2\right)\cos^2 2\beta + \text{threshold corrections}$$

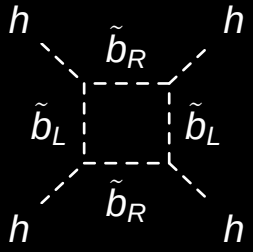
# Trilinears for fitting Higgs mass

- Supersymmetric trilinear $\Delta\mathcal{L}_{\text{SUSY}} = y_b \mu H_u^* \widetilde{Q} \tilde{b}^c$
  Soft SUSY breaking trilinears

$$\Delta\mathcal{L}_{\text{soft}} = T_t H_u \widetilde{Q} \tilde{t}^c - T_b H_d \widetilde{Q} \tilde{b}^c$$

enhance e.g. $h$-$\tilde{b}_L$-$\tilde{b}_R$ vertices in

$(T_t \equiv y_t A_t,\ T_b \equiv y_b A_b)$




- Use FlexibleSUSY-2.2.0 to calculate Higgs mass in high-scale (split) MSSM in EFT approach

# Vacuum metastability constraint

- Require $(\Gamma/V)T^4 < 1$ where $T$ is age of Universe and

$$\Gamma/V = A \exp\left(-S\left[\overline{\phi}\right]\right)$$

  with "bounce" $\overline{\phi}$
- Bounce of $\phi = \{h, H, \tilde{b}_L, \tilde{b}_R, \tilde{t}_L, \tilde{t}_R\}$ within tree-level scalar potential is numerically obtained using CosmoTransitions

Wainwright (2012)

- Estimate $A \approx M_{\text{SUSY}}^4$
  - $\rightsquigarrow$ $S \gtrsim 400$ is safe if $M_{\text{SUSY}} \approx 100$ GeV

Claudson, Hall, Hinchliffe (1983)

  - $\rightsquigarrow$ $S \gtrsim 560$ if $M_{\text{SUSY}} = M_{\text{Planck}}$

For 1-loop calculation of $A$, see Endo, Moroi, Nojiri, Shoji

# Metastability constraint does not decouple

- Consider action

$$S = \int dx^4 \left[ \frac{1}{2} (\partial\phi)^2 + \frac{1}{2} m^2 \phi^2 + A\phi^3 \right]$$

  whose bounce is $\overline{\phi}(x)$

- $\overline{\phi'}(x) \equiv a\overline{\phi}(ax)$ is then a bounce of

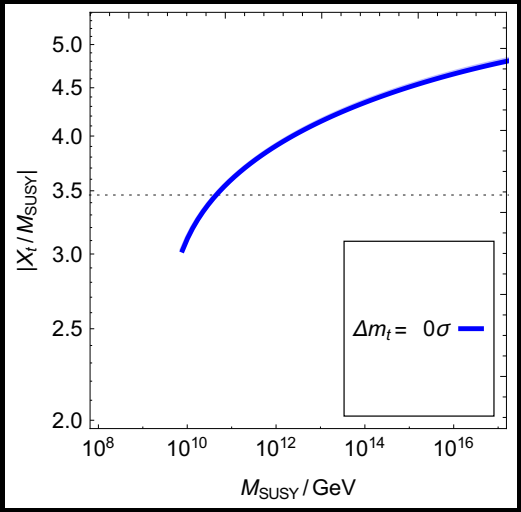
$$S' = \int dx^4 \left[ \frac{1}{2} (\partial\phi)^2 + \frac{1}{2} (am)^2 \phi^2 + (aA)\phi^3 \right]$$

  with

$$S\left[\overline{\phi}\right] = S'\left[\overline{\phi'}\right] = S(A/m)$$

  modulo scale anomaly

# $X_t$ reproducing correct $m_h$

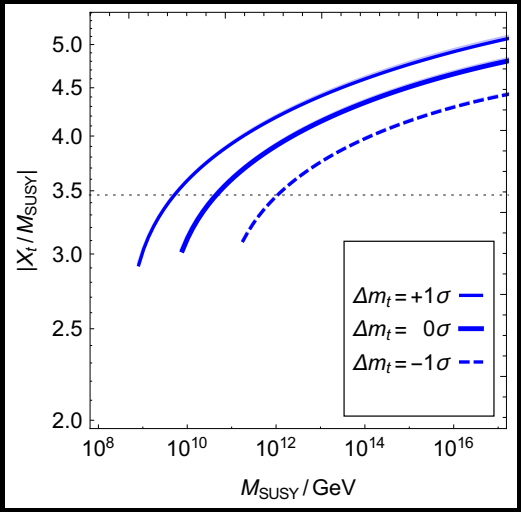



High-scale SUSY

$\mu > 0,\ T_t < 0$

$\tan\beta = 1,\ X_b = X_\tau = 0$

# $X_t$ reproducing correct $m_h$

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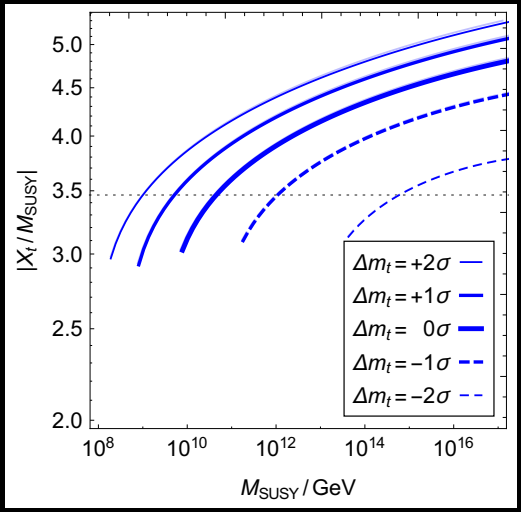


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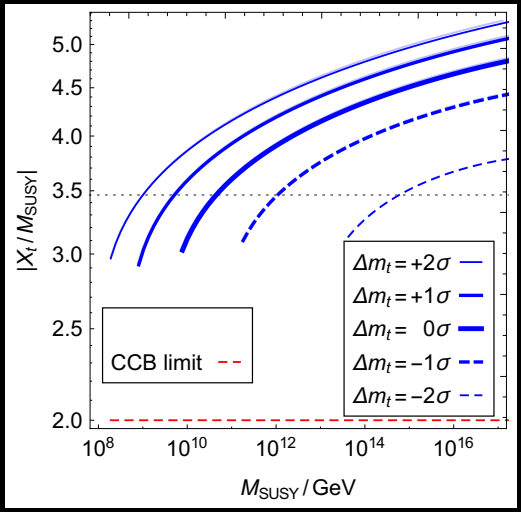


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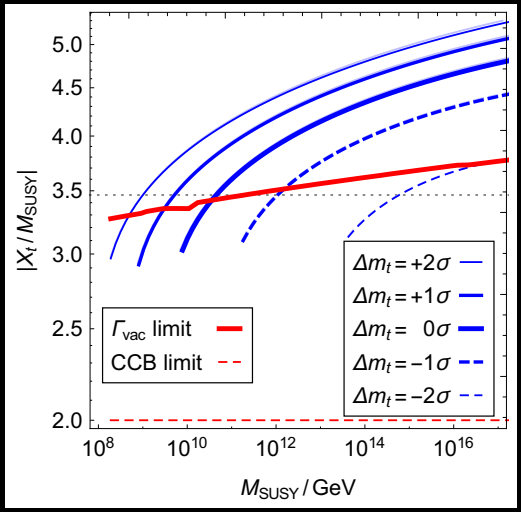
$\tan\beta = 1,\ X_b = X_\tau = 0$

# $X_t$ reproducing correct $m_h$

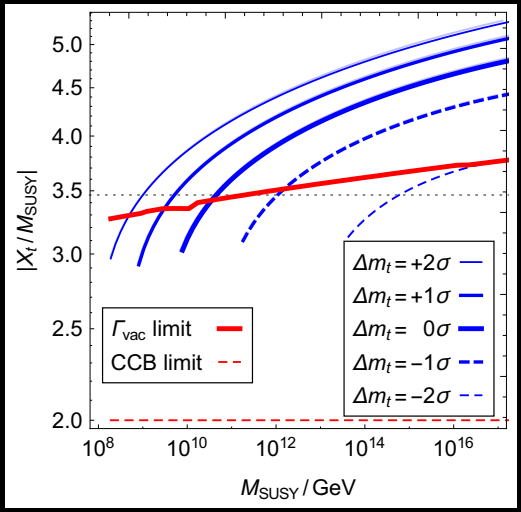



High-scale SUSY

$\mu > 0,\ T_t < 0$

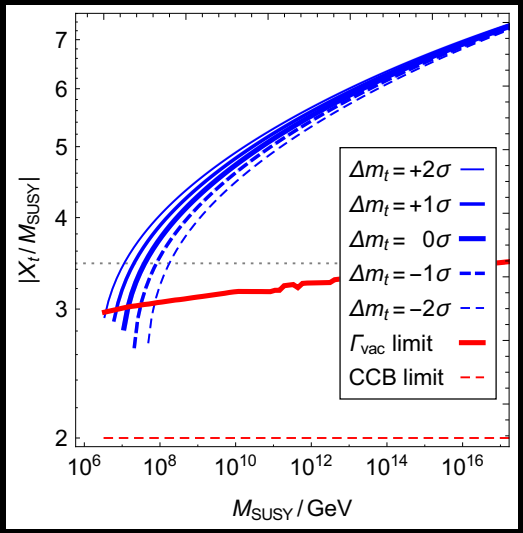
$\tan\beta = 1,\ X_b = X_\tau = 0$

# $X_t$ reproducing correct $m_h$




High-scale SUSY

$\mu > 0,\ T_t < 0$

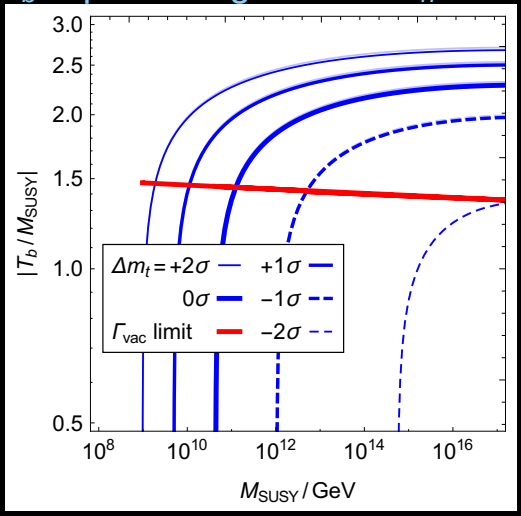



Split SUSY

$m_{1/2} = \mu = 1$ TeV

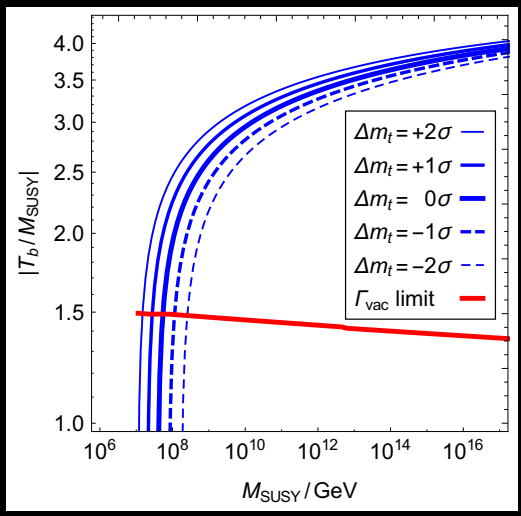
$\tan\beta = 1,\ X_b = X_\tau = 0$

# $T_b$ reproducing correct $m_h$




High-scale SUSY

$\mu > 0,\ T_b < 0$



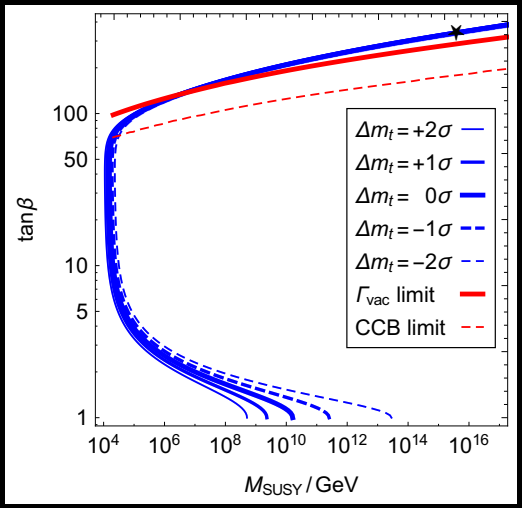

Split SUSY

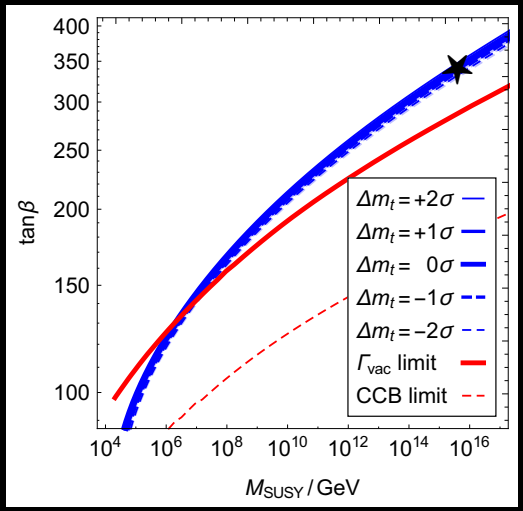
$m_{1/2} = \mu = 1$ TeV

$\tan\beta = 1,\ X_t = X_\tau = 0$

# Very high tan$\beta$ reproducing correct $m_h$

Pardo Vega, Villadoro (2015)




High-scale SUSY

$\mu < 0,\ T_b = 0,\ X_t = X_\tau = 0$

# Summary

- FlexibleSUSY auto-generates high-quality spectrum calculator codes for user-defined (**non-**)supersymmetric models
- New features of FlexibleSUSY 2 include:
  - `FlexibleEFTHiggs` for resummed $m_h$ calculation at NLO + NLL
  - `FlexibleAMU` for $(g_\mu - 2)$
  - `FlexibleCPV` for complex parameters and lepton EDMs
  - `FlexibleMW` for $\theta_W$ from $G_F$
- Developments underway: decays, LFV, QFV, 2-loop matching onto SM, 1-loop matching onto 2HDMs
- Metastability makes it difficult to reconcile arbitrarily high $M_{\text{SUSY}}$ with $m_h$ using trilinear couplings unless $m_t$ is lowered by $2\sigma$