Higgs mass and vacuum stability with high-scale supersymmetry

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Ref.

- JhP, 1809.07774

Supersymmetry

- Symmetry interchanging a fermion and a boson
- Non-trivial extension of Poincaré group
- Elegant QFT framework
- Implied by superstring theory

(Not too) high-scale supersymmetry

- Escapes LHC searches for superpartners
- Reproduces correct Higgs mass and decays
- For EeV-scale gravitino dark matter

Benakli, Chen, Dudas, Mambrini, Olive

- For *D*-term hybrid inflation

Domcke, Schmitz

- For fermion flavour structure

Liu, Zhao

- As a selection out of string landscape

Fox, Kaplan, Katz, Poppitz, Sanz, Schmaltz, Schwartz, Weiner;

Hall, Nomura

Higgs mass in MSSM

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

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

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

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

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

Can fit $m_h = 125$ GeV

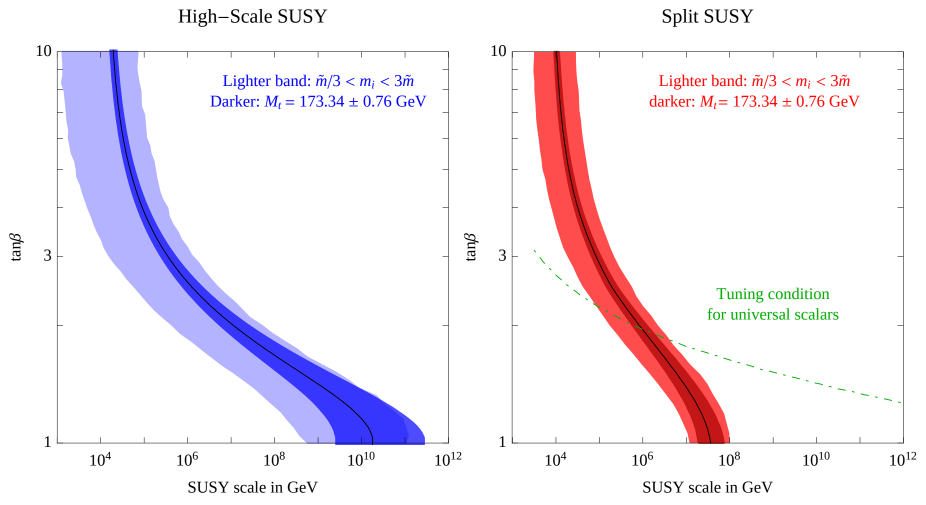
Higgs mass in high-scale MSSM

Casas, Espinosa, Quirós, Riotto, Carena, Wagner

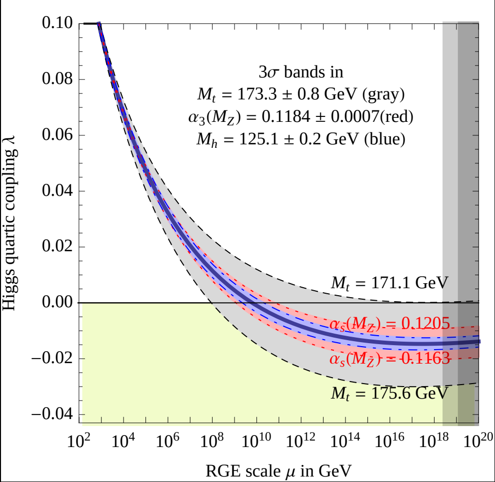
- Large scale difference between m_t and M_{SUSY} requires resummation of large logs
- Take EFT approach with SM as an EFT of MSSM
- Match quartic SM Higgs coupling λ to 4-point function of lightest MSSM Higgs at M_{SUSY}
- Let λ run from M_{SUSY} to m_t
- Calculate m_h from $\lambda(m_t)$

Upper bounds on M_{SUSY} from Higgs mass

Bagnaschi, Giudice, Slavich, Strumia (2014)



EFT picture of bounds on M_{SUSY}



Matching condition of λ at M_{SUSY}

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

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

Very high-scale supersymmetry

- Introduce extra fields to deflect λ running
  - 2HDM as EFT

    Bagnaschi, Brümmer, Buchmüller, Voigt, Weiglein (2016)
  - FSSM

    Benakli, Darmé, Goodsell, Slavich (2014)
  - Additional complex scalar of $(\mathbf{1}, \mathbf{3}, 0)$ rep.

    S. Ellis, Gherghetta, Kaneta, Olive (2018)
- Invoke large negative threshold corrections to λ
  - from large sbottom trilinear coupling

$$\left(\Delta\lambda_{\tilde{b}}\right)_{1,\text{mix}} \simeq -\frac{(y_b\mu)^4}{32\pi^2 m_{\tilde{b}}^4}$$

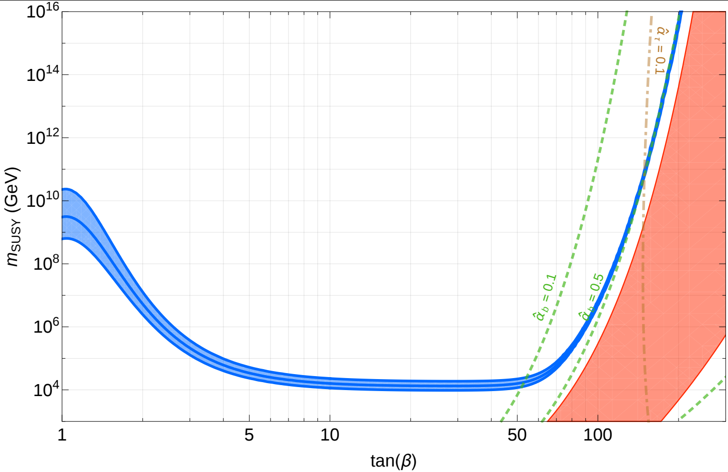
    Pardo Vega, Villadoro (2015)
  - from highly non-degenerate sparticle masses

    S. Ellis, Wells (2017)

$$\mu/m_{1/2} \sim 10^{-4} \quad \rightsquigarrow \quad |\mu| \lesssim 10^{14}\ \text{GeV}$$

Sbottom/stau threshold corrections to λ

Pardo Vega, Villadoro (2015)



Loop-induced "wrong" Higgs coupling allows for tan$\beta \in (50, \infty)$

Dobrescu, Fox; Altmannshofer, Straub; Bach, JhP, Stöckinger, Stöckinger-Kim

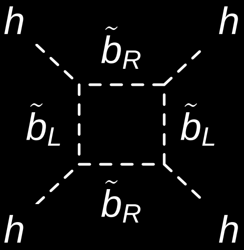
Trilinears for fitting Higgs mass

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

  Soft SUSY breaking trilinears

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

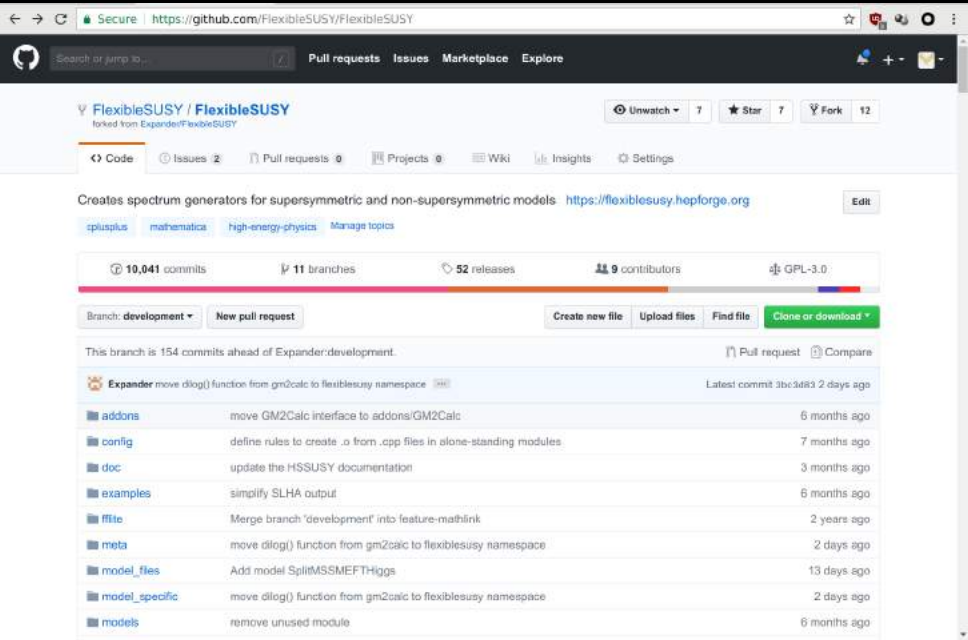
  enhance e.g. h-$\tilde{b}_L$-$\tilde{b}_R$ vertices in



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

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

Athron, Bach, Harries, Kwasnitza, JhP, Stöckinger, Voigt, Ziebell (2018)


Secure | https://github.com/FlexibleSUSY/FlexibleSUSY
Pull requests Issues Marketplace Explore
FlexibleSUSY / FlexibleSUSY
forked from Expander/FlexibleSUSY
Unwatch 7 Star 7 Fork 12
Code Issues 2 Pull requests 0 Projects 0 Wiki Insights Settings
Creates spectrum generators for supersymmetric and non-supersymmetric models https://flexiblesusy.hepforge.org
Edit
cplusplus mathematica high-energy-physics Manage topics
10,041 commits
11 branches
52 releases
9 contributors
GPL-3.0
Branch: development
New pull request
Create new file Upload files Find file Clone or download
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

Secure | https://flexiblesusy.hepforge.org

Authors

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- Markus Bach
- Dylan Harries
- Thomas Kwasnitza
- Jae-hyeon Park
- Dominik Stöckinger
- Alexander Voigt
- Jobst Ziebell

The following people have made major contributions to FlexibleSUSY:

- Tom Steudtner (FlexibleEFTHiggs)

References

If you use **FlexibleSUSY** in your work, please cite the FlexibleSUSY manuals:

- FlexibleSUSY — A spectrum generator generator for supersymmetric models
  [CPC 190 (2015) 139-172]
- FlexibleSUSY 2.0: Extensions to investigate the phenomenology of SUSY and non-SUSY models
  [arxiv:1710.03760]

If you use **FlexibleEFTHiggs** in your work, please cite the FlexibleEFTHiggs paper:

- Precise Higgs mass calculations in (non-)minimal supersymmetry at both high and low scales
  [JHEP 1701 (2017) 079]

If you use **FlexibleSUSY+Himalaya** or **Himalaya** in your work, please cite the FlexibleSUSY+Himalaya paper and the paper where the 3-loop expressions have been presented:

Vacuum (meta)stability

- A large trilinear can cause a CCB minimum
- Estimate decay rate of our vacuum

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

where "bounce" $\bar{\phi}$ is a solution to $\delta S\left[\bar{\phi}\right] = 0$

$$S[\phi(\rho)] = 2\pi^2 \int_0^\infty d\rho\,\rho^3 \left[\frac{1}{2}\left(\frac{d\phi}{d\rho}\right)^2 + V(\phi)\right]$$

$$\bar{\phi}(\rho = \infty) = \phi^f, \quad \frac{d\bar{\phi}}{d\rho}(\rho = 0) = 0$$

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

How to impose metastability constraint

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

- Bounce of $\{h, H, \tilde{b}_L, \tilde{b}_R, \tilde{t}_L, \tilde{t}_R\}$ 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 $\bar{\phi}(x)$

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

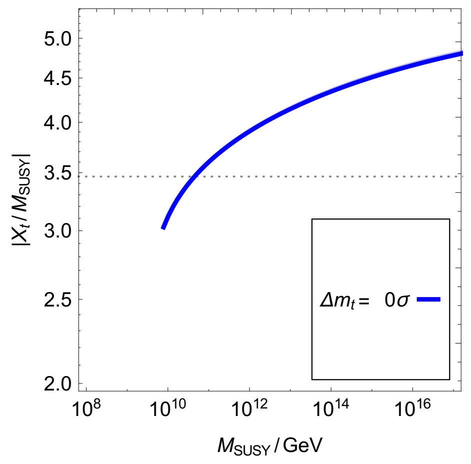
$$S' = \int dx^4 \left[\frac{1}{2} (\partial\phi)^2 + \frac{1}{2} (am)^2 \phi^2 + (aA)\phi^3 \right]$$

with

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

modulo scale anomaly

X_t reproducing correct m_h



$$m_t = (173.34 \pm 0.76)\ \text{GeV}$$

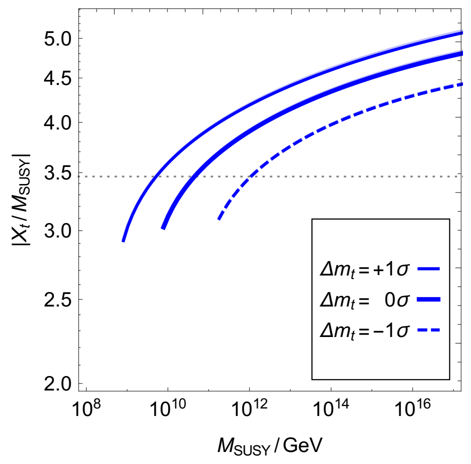
ATLAS, CDF, CMS, DØ (2014)

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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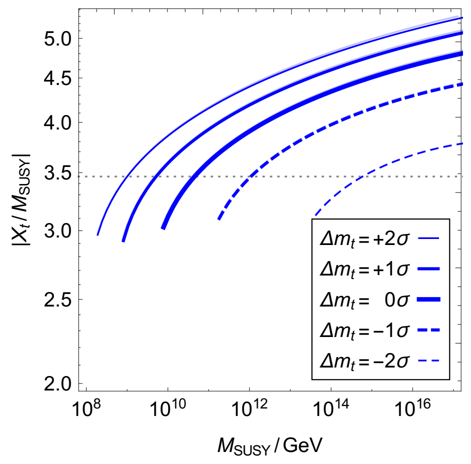

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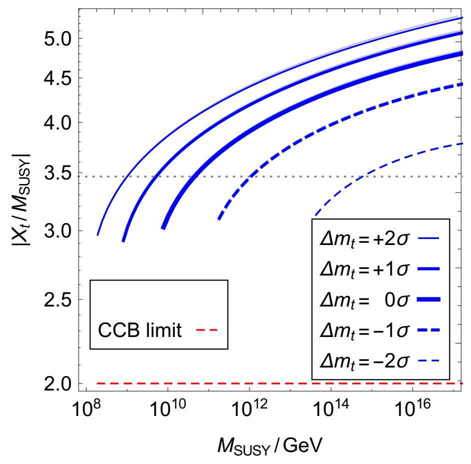

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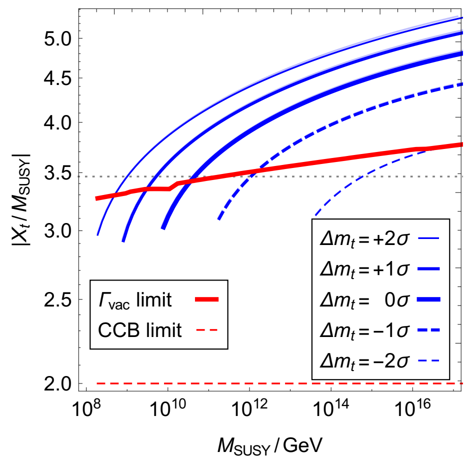

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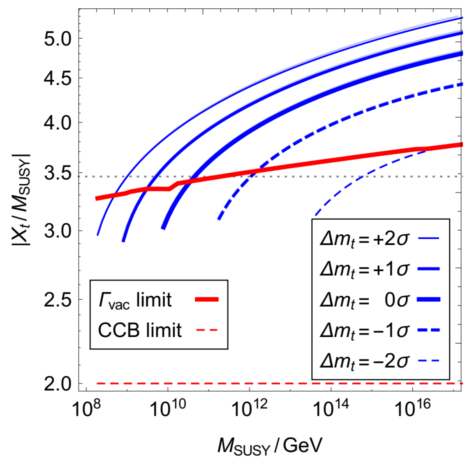
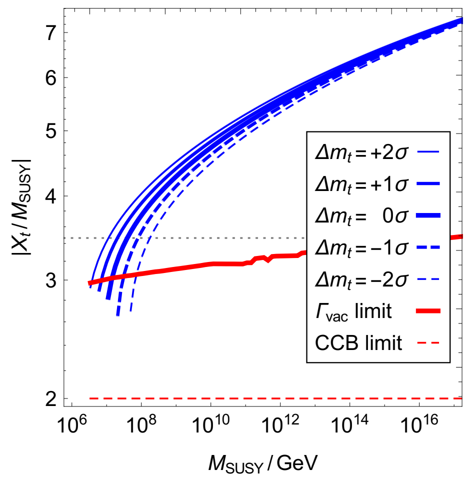




High-scale SUSY

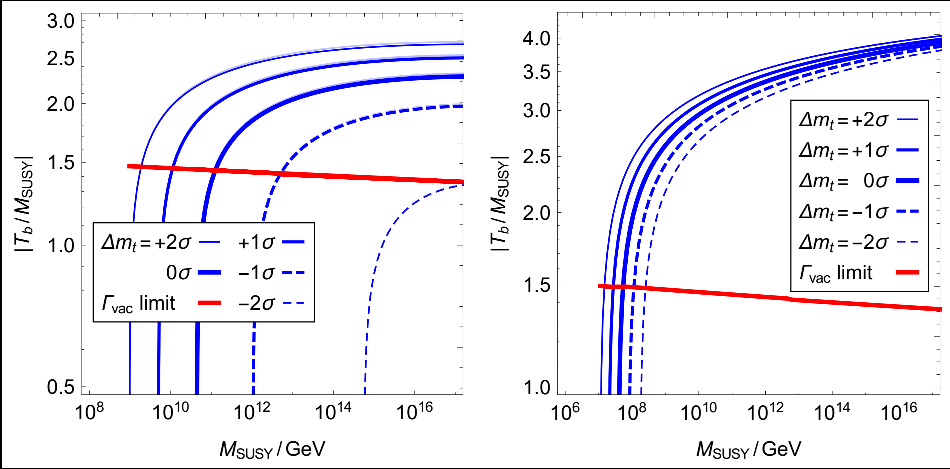
$\mu > 0, \; T_t < 0$

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

$\mu > 0, \; T_b < 0$

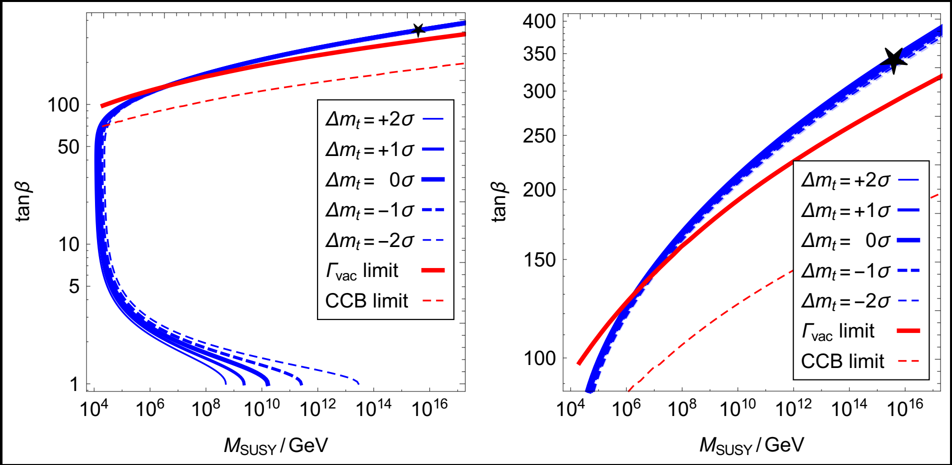
Split SUSY

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

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

Very high $\tan\beta$ reproducing correct m_h

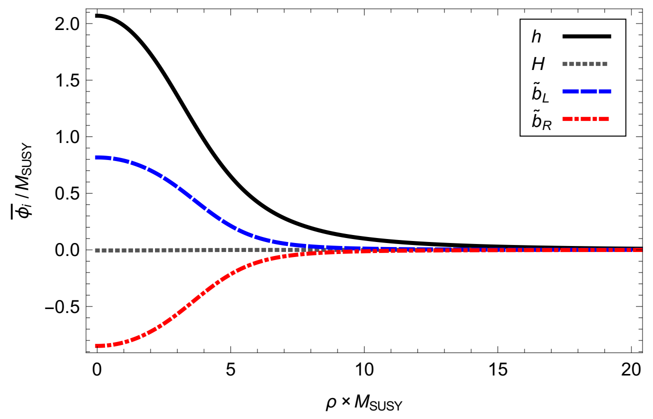
Pardo Vega, Villadoro (2015)



High-scale SUSY

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

Specimen bounce profile



High-scale SUSY

$-\mu = M_{\rm SUSY} = 3.88 \times 10^{15}$ GeV, $T_b = 0$, $\tan\beta = 340$

$\rightsquigarrow$ $S = 275$

Summary

- Easy to find (large) trilinear couplings yielding negative threshold corrections to quartic Higgs coupling that fit correct m_h for all M_{SUSY} up to M_{Planck}
- With metastability imposed on high-scale MSSM
  - $m_t = m_{t,\text{cent}}$
    $\rightsquigarrow X_{b,t}$ can make little difference
  - $m_t = m_{t,\text{cent}} - 2\sigma$
    $\rightsquigarrow X_{b,t}$ can push M_{SUSY} up to $\sim 10^{17}$ GeV
- Very high $\tan\beta$ cannot fit m_h for $M_{\text{SUSY}} \gtrsim 10^8$ GeV due to vacuum decay
- In split MSSM, $X_{b,t}$ can make little difference