Dynamical μ Term in Gauge Mediation

Antonio Delgado

University of Notre Dame

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Based on: *A. D., G.F. Giudice and P.Slavich, Phys. Lett. B **653** (2007) 424*

Outline of the talk

1) The μ and B_μ problems in SUSY theories with gauge mediation

2) Attempts to solve the problems within the NMSSM

3) The N-GMSB: NMSSM+GMSB with singlet-messenger interactions

4) Phenomenology of the N-GMSB

The μ problem in SUSY theories

In SUSY extensions of the SM we must introduce two Higgs doublets with opposite hypercharge:

- To give mass to both up- and down-type quarks
- To allow for a higgsino mass term
- To cancel anomalies

Higgs/higgsino mass term in the superpotential

$$\mathcal{L} \supset \mu \int d^2\theta \; H_d \, H_u$$

There are also soft SUSY-breaking mass terms for the Higgses in the scalar potential

$$V_{\rm soft} \supset m^2_{H_d} \, |H_d|^2 + m^2_{H_u} \, |H_u|^2 - B_\mu \, (H_d \, H_u + {\rm h.c.})$$

In the MSSM, μ is the only superpotential term with the dimension of a mass

The μ problem: if μ is allowed in the SUSY limit, why is it not of $\mathcal{O}(M_P)$?

The *Giudice-Masiero* mechanism: (1988)

μ *is forbidden in the SUSY limit, and is generated in the low-energy theory by SUSY-breaking effects*

Parametrize the SUSY-breaking sector with a chiral superfield X that acquires a vev

$$\langle X \rangle = M + \theta^2 F$$

The SUSY-breaking spurion couples to the Higgses in a non-minimal Kahler potential

$$\mathcal{L} \supset \int d^4\theta \, H_d \, H_u \left(\frac{X^\dagger}{M} + \frac{X^\dagger X}{M^2} + \ \ldots \right)$$

$$\sim \frac{F}{M} \int d^2\theta \, H_d \, H_u + \left(\frac{F}{M} \right)^2 (H_d \, H_u + \text{h.c.}) + \ \ldots$$

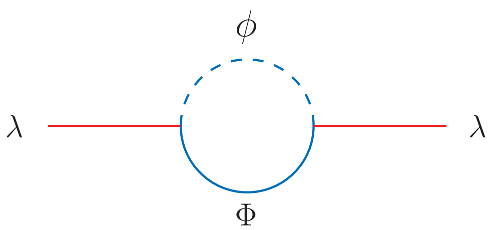
Therefore, $\mu \sim \frac{F}{M}$, $B_\mu \sim \left(\frac{F}{M} \right)^2 \longrightarrow \frac{B_\mu}{\mu} \sim \frac{F}{M}$

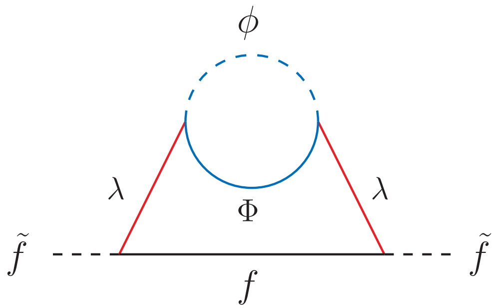
In gravity-mediated SUSY-breaking $\tilde{m} \sim \frac{F}{M_P} \sim \text{TeV}$ is the typical soft mass

In gauge mediation the SUSY-breaking sector couples only to heavy messenger fields

$$\mathcal{L} \supset \kappa \int d^2\theta \; X \, \Phi \, \bar{\Phi} \; , \qquad m_\Phi^2 = |\kappa \, M|^2 \; , \qquad m_\phi^2 = |\kappa \, M|^2 \pm |\kappa \, F|$$

The soft masses for the MSSM fields are generated at loop level by the gauge interactions





$$M_\lambda \sim m_{\tilde{f}} \sim \frac{\alpha}{4\pi} \frac{F}{M}$$

$$A_{\tilde{f}} \sim \mathcal{O}(\alpha^2)$$

Models with calculable soft terms (GMSB, AMSB, ...) suffer from a more severe μ problem:

In the Giudice-Masiero mechanism μ and B_μ are generated at the same loop level

$$\mathcal{L} \supset \frac{\alpha}{4\pi} \int d^4\theta \; H_d \, H_u \, f\left(X, X^\dagger\right) \longrightarrow \mu \sim \frac{\alpha}{4\pi} \frac{F}{M}$$

Since $\dfrac{B_\mu}{\mu} \sim \dfrac{F}{M}$, $\quad \mu \sim \tilde{m} \sim \mathrm{TeV} \longrightarrow B_\mu \sim (10 - 100 \; \mathrm{TeV})^2$!!!

Such a huge B_μ would require an unacceptable fine tuning in the Higgs sector

Models have been proposed in which B_μ is generated at higher order than μ , e.g.:

$$\mathcal{L} \supset \frac{\alpha}{4\pi} \int d^4\theta \; H_d \, H_u \, D^2 \, f\left(X, X^\dagger\right)$$

(*Dvali, Giudice, Pomarol 1996*)

NMSSM alternative: *generate μ and B_μ at the weak scale through the vev of a light singlet*

$$\mathcal{L} \supset \lambda \int d^2\theta \; N \, H_d \, H_u \quad \longrightarrow \quad \mu = \lambda \, \langle N \rangle \; , \qquad B_\mu = \lambda \, \langle F_N \rangle$$

Is it worth the pain? a light singlet requires the introduction of several new soft terms, and it can even pick up a tadpole from the SUSY-breaking sector, destabilizing the hierarchy

- Neither of these issues is too problematic in gauge mediation, where the soft terms are calculable and the SUSY-breaking scale is relatively low
- Also, the singlet-doublet interaction can give a positive contribution to the lightest Higgs boson mass and help lifting it above the LEP bound

Do we get an acceptable EWSB? We must generate a substantial vev $\langle N \rangle \gtrsim \mathcal{O}(v)$, but the soft SUSY-breaking parameters for the singlet are zero at the messenger scale

The Higgs sector of the NMSSM

Superpotential and soft SUSY-breaking interactions for the Higgses and the singlet

$$W \;\supset\; \lambda\, N\, H_d\, H_u - \frac{k}{3}\, N^3$$

$$V_{\rm soft} \;\supset\; \tilde m^2_{H_u}|H_u|^2 + \tilde m^2_{H_d}|H_d|^2 + \tilde m^2_N|N|^2 + \left(\lambda A_\lambda N H_d H_u - \frac{k}{3} A_k N^3 + {\rm h.c.}\right)$$

Tree-level potential for the neutral scalars

$$\begin{aligned} V_0 \;&=\; \frac{g^2+g'^2}{8}\left(|H_d|^2-|H_u|^2\right)^2 + \lambda^2\,|N|^2\left(|H_d|^2+|H_u|^2\right) + \left|\lambda H_d H_u - k N^2\right|^2 \\ &+\; \tilde m^2_{H_u}|H_u|^2 + \tilde m^2_{H_d}|H_d|^2 + \tilde m^2_N|N|^2 + \left(\lambda A_\lambda N H_d H_u - \frac{k}{3} A_k N^3 + {\rm h.c.}\right) \end{aligned}$$

Define MSSM-like parameters: $v^2 \;\equiv\; \langle H_d\rangle^2 + \langle H_u\rangle^2\,, \quad \tan\beta \;\equiv\; \dfrac{\langle H_u\rangle}{\langle H_d\rangle}\,,$

$$\mu \;\equiv\; \lambda\,\langle N\rangle\,, \quad B_\mu \;\equiv\; \lambda\, k\,\langle N\rangle^2 - \frac{\lambda^2\, v^2}{2}\,\sin 2\beta - \lambda\, A_\lambda\,\langle N\rangle$$

Two of the minimization conditions for the scalar potential are just as in the MSSM

$$\mu^2 = \frac{\tilde{m}^2_{H_d} - \tilde{m}^2_{H_u}\tan^2\beta}{\tan^2\beta - 1} - \frac{g^2 + g'^2}{4} v^2 ,$$

$$\sin 2\beta = \frac{2\,B_\mu}{\tilde{m}^2_{H_d} + \tilde{m}^2_{H_u} + 2\mu^2},$$

And the third is:

$$2\,k^2\,\langle N\rangle^2 - k\,A_k\,\langle N\rangle + \tilde{m}^2_N = \lambda^2 v^2 \left[-1 + \frac{k}{\lambda}\sin 2\beta - \frac{A_\lambda}{\langle N\rangle}\frac{\sin 2\beta}{2\lambda}\right]$$

In gauge mediation we have $|\tilde{m}_N|,\ A_\lambda,\ A_k \ll v$. Can we get $\langle N\rangle \gtrsim \mathcal{O}(v)$?

NO: $$\langle N\rangle \approx \frac{v}{\sqrt{2}}\,\frac{\lambda}{k}\sqrt{-1 + \frac{k}{\lambda}\sin 2\beta} < v$$

This also results in a very light scalar+pseudoscalar pair (ruled out by searches at LEP).

We need some mechanism to generate sizeable soft SUSY-breaking terms for the singlet

$$|\tilde{m}_N|,\ A_\lambda,\ A_k \sim \mathcal{O}(\tilde{m}) \longrightarrow \langle N\rangle \gg v$$

In the limit $\langle N \rangle \gg v$ the minimization condition for the singlet is approximated by

$$2\,k^2\,\langle N\rangle^2 - k\,A_k\,\langle N\rangle + \tilde{m}_N^2 \;\approx 0 \quad \longrightarrow \quad \langle N\rangle \;\approx\; \frac{A_k}{4\,k}\left(1+\sqrt{1-8\,\frac{\tilde{m}_N^2}{A_k^2}}\;\right)$$

For this to be deeper than the origin we need $w \;\equiv\; \left(1+\sqrt{1-8\,\frac{\tilde{m}_N^2}{A_k^2}}\;\right) \;>\; \frac{1}{3}$

The tree-level masses for the *two* CP-odd (a_i) and *three* CP-even (h_i) neutral scalars are

$$m_{a_1}^2 \;=\; \frac{2\,B_\mu}{\sin 2\beta} \;+\; \mathcal{O}(v^2)\;, \qquad\qquad m_{a_2}^2 \;=\; \frac{3\,k^2}{w}\,\langle N\rangle^2 \;+\; \mathcal{O}(v^2)\;,$$

$$m_{h_1}^2 \;=\; M_Z^2\,\cos^2 2\beta + \lambda^2\,v^2\left\{\sin^2 2\beta - \frac{\left[\frac{\lambda}{k} + \left(\frac{A_\lambda}{2w\,A_k} - 1\right)\,\sin 2\beta\right]^2}{1-\frac{1}{4w}}\right\} \;+\; \mathcal{O}(v^4)\;,$$

$$m_{h_2}^2 \;=\; m_{a_1}^2 \;+\; \mathcal{O}(v^2)\;, \qquad\qquad m_{h_3}^2 \;=\; \frac{4w-1}{3}\,m_{a_2}^2 \;+\; \mathcal{O}(v^2)$$

We must include radiative corrections. Defining the effective potential $V_{\rm eff} = V_0 + \Delta V$ the mass matrices for CP-even and CP-odd parts of $\phi_i = (H_d,\, H_u,\, N)$ become

$$(\mathcal{M}^2_{S,P})^{\rm eff} = \sqrt{Z}\,\left[\,(\mathcal{M}^2_{S,P})^0 + \Delta\mathcal{M}^2_{S,P}\right]\sqrt{Z}$$

$$\left(\Delta\mathcal{M}^2_S\right)_{ij} = \frac{1}{2}\,\frac{\partial^2\,\Delta V}{\partial\,{\rm Re}\,\phi_i\,\partial\,{\rm Re}\,\phi_j}\Bigg|_{\rm min}\,, \qquad \left(\Delta\mathcal{M}^2_P\right)_{ij} = \frac{1}{2}\,\frac{\partial^2\,\Delta V}{\partial\,{\rm Im}\,\phi_i\,\partial\,{\rm Im}\,\phi_j}\Bigg|_{\rm min}$$

We keep the $\mathcal{O}(h_t^4)$ terms in $\Delta\mathcal{M}^2_{S,P}$ and the $\mathcal{O}(h_t^2)$ terms in Z . We also include some leading-logarithmic two-loop corrections controlled by the top Yukawa and strong couplings. For m_{h_1} we agree with the code NMHDECAY (*Ellwanger, Hugonie & Gunion*) within 5 GeV

In the limit of heavy singlet the dominant $\mathcal{O}(h_t^4)$ corrections to m_{h_1} are just as in the MSSM:

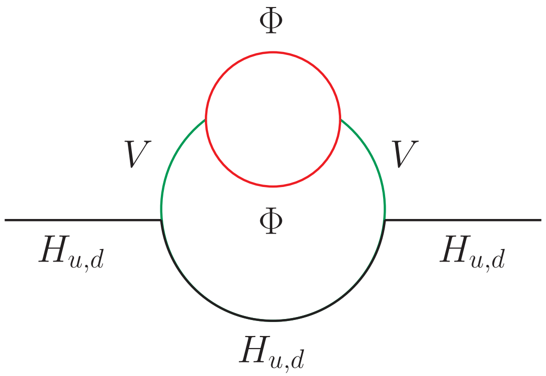
$$(\Delta m^2_{h_1})^{1-{\rm loop}} \simeq \frac{3\,m_t^4}{4\,\pi^2\,v^2}\left(\ln\frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_S^2} - \frac{X_t^4}{12\,M_S^4}\right)\,, \qquad \Big(X_t = A_t + \lambda\,\langle N\rangle\,\cot\beta\Big)$$

In GMSB $A_t(M) \simeq 0$, and only a moderate weak-scale value is generated by RG evolution

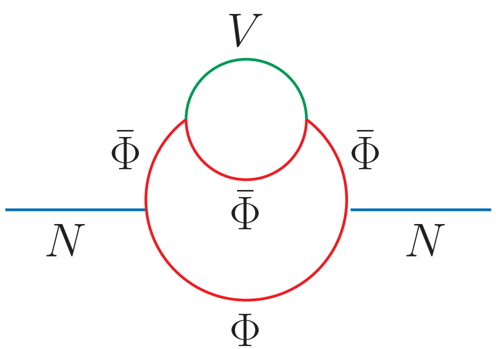
→ We will need a largish M_S (~ TeV) to evade the LEP bounds on the Higgs mass

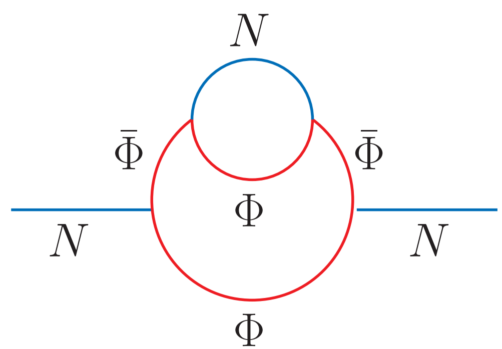
NMSSM+GMSB with singlet-messenger interactions: *N-GMSB*

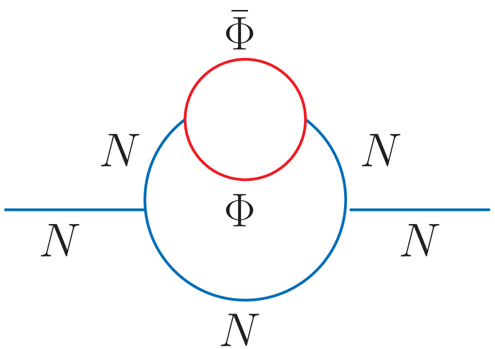
The soft masses for the Higgs doublets are mediated by the gauge interactions:



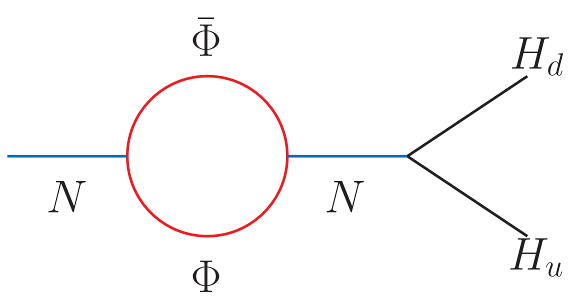
To generate a mass for the singlet we can couple it directly to the messengers

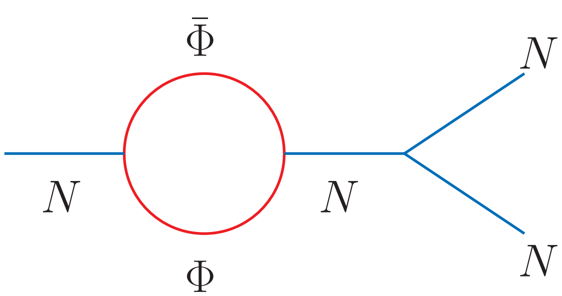






This will also generate trilinear interactions (but no mass term) at one loop





We must introduce two pairs of messenger fields in the **5** and $\bar{\mathbf{5}}$ representations of SU(5)

$$W \supset X \left(\bar{\Phi}_1\, \Phi_1 + \bar{\Phi}_2\, \Phi_2\right) + \xi\, N\, \bar{\Phi}_1\, \Phi_2 + \lambda\, N\, H_d\, H_u - \frac{k}{3}\, N^3$$

($X = M + \theta^2 F$ parametrizes the SUSY-breaking sector)

A single messenger pair $(\Phi, \bar{\Phi})$ coupling to both X and N would destabilize the weak scale

$$W \;\supset\; X\,\bar{\Phi}\,\Phi \;+\; \xi\, N\,\bar{\Phi}\,\Phi \quad \longrightarrow \quad V_{\rm eff} = \frac{\xi\, d_\Phi}{16\pi^2}\, N\, \frac{F^2}{M}$$

We must also distinguish between the doublet and triplet components of the messengers

This model was first proposed (without a detailed study) by Giudice & Rattazzi in 1997

We must introduce two pairs of messenger fields in the **5** and **$\bar{5}$** representations of SU(5)

$$W \supset X \sum_{i=1}^{2} \left(\kappa_i^D \bar{\Phi}_i^D \Phi_i^D + \kappa_i^T \bar{\Phi}_i^T \Phi_i^T\right) + N \left(\xi_D \bar{\Phi}_1^D \Phi_2^D + \xi_T \bar{\Phi}_1^T \Phi_2^T\right) + \lambda N H_d H_u - \frac{k}{3} N^3$$

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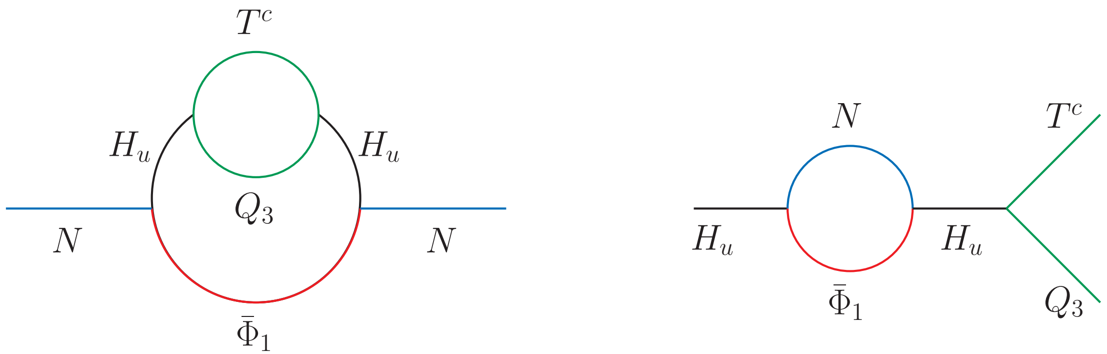
Variations & Alternatives

- *"Yukawa Deflected Gauge Mediation" (Chacko, Katz, Perazzi & Ponton 2002)*

$$W \supset \lambda N H_d H_u - \frac{k}{3} N^3 + \xi N \bar{\Phi}_1^D H_u + h_t H_u Q_3 T^c$$

Additional messenger-Yukawa contributions to the soft mass parameters:



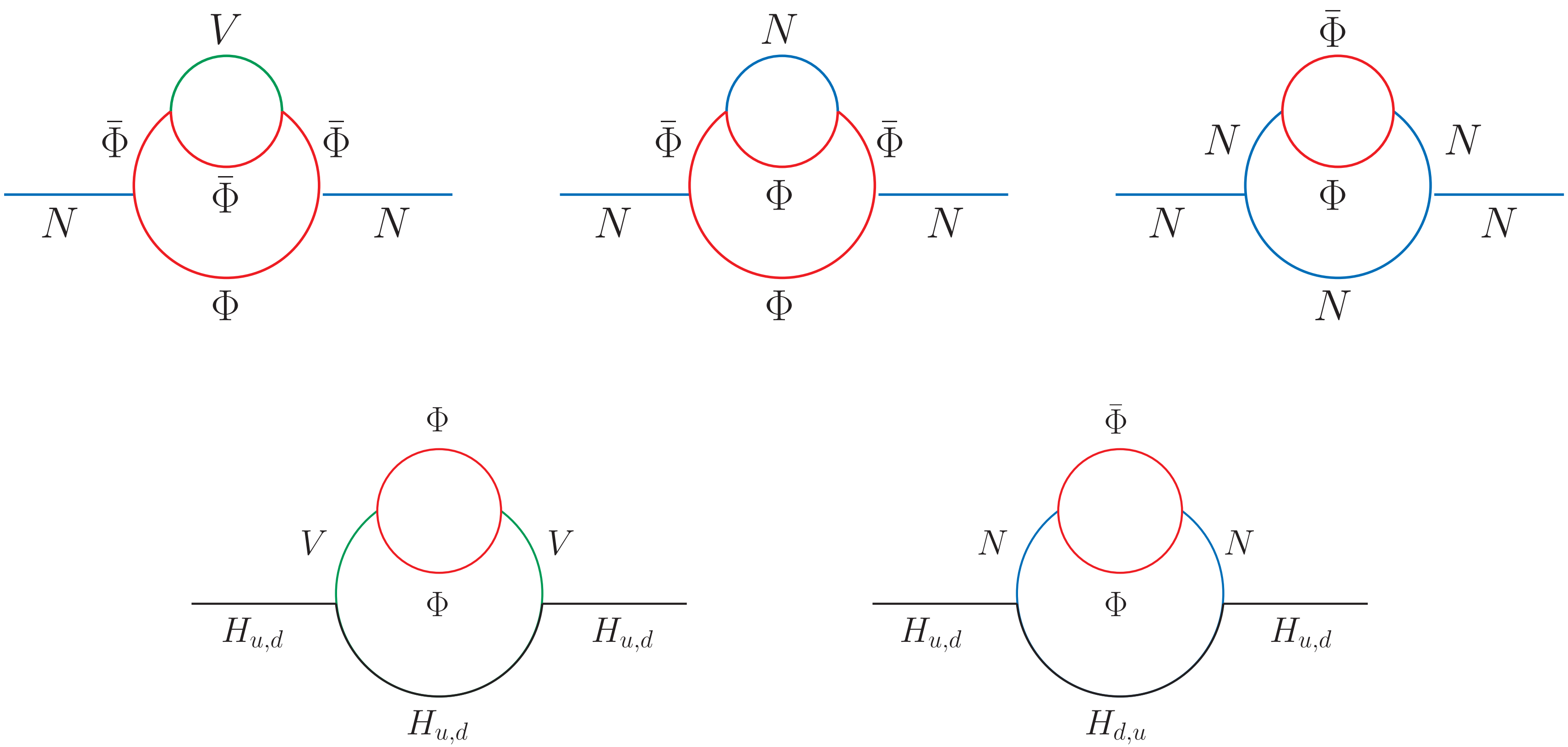
- *Add extra vector-like quarks (Dine & Nelson 1993, Agashe & Graesser 1997, de Gouvea, Friedland & Murayama 1997)*

$$W \supset \lambda N H_d H_u - \frac{k}{3} N^3 + \xi N Q \bar{Q}$$

The soft squark masses give a large and negative contribution to the running of $\tilde{m}_N^2$

New matter (squarks & quarks) at the TeV scale. Watch out for contributions to electroweak precision observables and FCNCs

Now we need to compute the new contributions to the soft SUSY-breaking masses



A lot of 2-loop diagrams!!!

Interlude: *a smart way to extract the soft terms at the messenger scale from the wave function renormalization of the observable fields* (*Giudice & Rattazzi 1997*)

$$\mathcal{L} \supset \int d^4\theta\, Z_Q(X, X^\dagger)\, Q^\dagger Q \;+\; \left(\int d^2\theta\, W(Q) \;+\; \text{h.c} \right)$$

Expand the w.f.r. of the matter superfields around the origin in superspace

$$\mathcal{L} \supset \int d^4\theta \left(Z_Q + \frac{\partial Z_Q}{\partial X} F\,\theta^2 + \frac{\partial Z_Q}{\partial X^\dagger} F^\dagger\,\bar\theta^2 + \frac{\partial^2 Z_Q}{\partial X \partial X^\dagger} F F^\dagger\,\theta^2 \bar\theta^2 \right)\Bigg|_{X=M} Q^\dagger Q$$

Redefine the superfields so that they are canonically normalized:

$$Q' \equiv Z_Q^{\frac{1}{2}} \left(1 + \frac{\partial \ln Z_Q}{\partial X} F\,\theta^2 \right)\Bigg|_{X=M} Q$$

This kills the terms linear in F and leaves a soft (mass)² for the scalar component:

$$\tilde m_Q^2 \;=\; -\, \frac{\partial^2 \ln Z_Q}{\partial \ln X\, \partial \ln X^\dagger}\Bigg|_{X=M} \frac{F F^\dagger}{M M^\dagger}$$

The redefinition of the superfields in W also induces A-terms in the scalar potential

$$V \;=\; \sum_i A_i\, Q_i \frac{\partial W}{\partial Q_i} \;+\; \text{h.c.}\,, \qquad\qquad A_i \;=\; \frac{\partial \ln Z_{Q_i}}{\partial \ln X}\Bigg|_{X=M} \frac{F}{M}$$

The question is: how does the w.f.r. $Z_Q(X, X^\dagger)$ *depend on* X *and* $X^\dagger$*???*

The Lagrangian is invariant under the symmetry $X \to e^{i\varphi}\, X\,, \quad \bar{\Phi}\Phi \to e^{-i\varphi}\,\bar{\Phi}\Phi$

→ Z_Q can only depend on the combination $X^\dagger X$

Analytical continuation in superspace: determine how Z_Q depends on the messenger mass M, then replace $M \to \sqrt{X^\dagger X}$

$$\frac{\partial \ln Z_Q(X, X^\dagger)}{\partial \ln X}\bigg|_{X=M} = \frac{\partial \ln Z_Q(M)}{2\,\partial \ln M}\,, \qquad \frac{\partial^2 \ln Z_Q(X, X^\dagger)}{\partial \ln X \partial \ln X^\dagger}\bigg|_{X=M} = \frac{\partial^2 \ln Z_Q(M)}{4\,\partial(\ln M)^2}$$

M enters Z_Q as the scale at which the messengers are integrated out of the theory, inducing discontinuities in the anomalous dimensions of the matter superfields

$$\ln \frac{Z_Q(\mu)}{Z_Q(\Lambda)} = \int_{\ln \Lambda}^{\ln M} dt\, \gamma_Q^{(+)} + \int_{\ln M}^{\ln \mu} dt\, \gamma_Q^{(-)}\,, \qquad \gamma_Q^{(\pm)} \equiv \frac{d \ln Z_Q}{d \ln \mu}\bigg|_{\substack{\mu > M \\ \mu < M}}$$

$$\ln Z_Q(\mu) \approx \text{const.} + \Delta\gamma_Q \ln M + \mathcal{O}(>1\,\text{loop})\,, \qquad \Delta\gamma_Q = \gamma_Q^{(+)} - \gamma_Q^{(-)}$$

A-terms generated at 1-loop: $$A_i(M) = \frac{\Delta\gamma_{Q_i}}{2}\,\frac{F}{M}$$

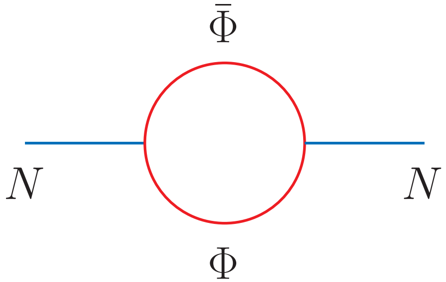
(mass)^2 terms generated at 2-loop:

$$\tilde{m}_Q^2(M) = -\frac{1}{4}\sum_i \left[\beta^{(+)}_{\lambda_i}\frac{\partial\left(\Delta\gamma_Q\right)}{\partial\lambda_i^2} - \Delta\beta_{\lambda_i}\frac{\partial\gamma_Q^{(-)}}{\partial\lambda_i^2}\right]_{\mu=M}\frac{F^2}{M^2}$$

Two-loop results just out of the one-loop RGE. No need to compute Feynman diagrams!!

One-loop contributions to (mass)^2 terms can be generated at higher orders in F/M^2

e.g.



$$\approx\ -\frac{\xi^2}{16\pi^2}\,\frac{F^4}{M^6}$$

For $\xi = \mathcal{O}(1)$ these contributions are negligible as long as $M > 4\pi\, F/M \quad (\simeq 10^6\,\mathrm{GeV})$

$$\beta^{(\pm)}_{\lambda_i} \equiv \left. \frac{d\lambda_i^2}{d\ln\mu} \right|_{\substack{\mu>M \\ \mu<M}} , \qquad \Delta\beta_{\lambda_i} = \beta^{(+)}_{\lambda_i} - \beta^{(-)}_{\lambda_i}$$

(mass)² terms generated at 2-loop:

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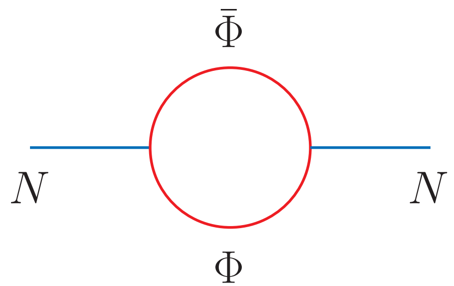

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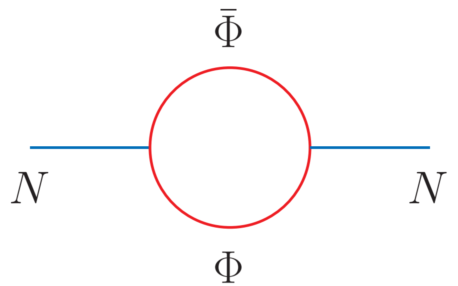

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For $\xi = \mathcal{O}(1)$ these contributions are negligible as long as $M > 4\pi\, F/M$ $(\simeq 10^6\,\mathrm{GeV})$

Soft SUSY-breaking masses for the N-GMSB

At the messenger scale the gaugino and sfermion soft masses are as in the usual GMSB

$$M_i = n\, c_i \,\frac{\alpha_i}{4\,\pi}\,\frac{F}{M}\,, \qquad m^2_{\tilde f} = 2\,n\,\sum_i c_i\, C_i^{\tilde f}\,\frac{\alpha_i^2}{(4\,\pi)^2}\,\frac{F^2}{M^2}\,, \qquad (n=2)$$

The singlet-messenger interactions generate A-terms at 1-loop and scalar masses at 2-loop

$$A_\lambda \;=\; \frac{A_k}{3} \;=\; -\,\frac{1}{16\pi^2}\,\left(2\,\xi_D^2 + 3\,\xi_T^2\right)\frac{F}{M}\,,$$

$$\begin{aligned}\tilde m_N^2 \;&=\; \frac{1}{(16\pi^2)^2}\left[8\xi_D^4 + 15\xi_T^4 + 12\xi_D^2\xi_T^2 - 16 g_s^2\xi_T^2 - 6g^2\xi_D^2 - 2g'^2\left(\xi_D^2 + \frac{2}{3}\xi_T^2\right)\right.\\ &\qquad \left. -\,4k^2\left(2\xi_D^2 + 3\xi_T^2\right)\right]\frac{F^2}{M^2}\end{aligned}$$

$$\tilde m^2_{H_u} = \tilde m^2_{H_d} = \frac{1}{(16\pi^2)^2}\left[n\left(\frac{3\,g^4}{2} + \frac{5\,g'^4}{6}\right) - \lambda^2\left(2\,\xi_D^2 + 3\,\xi_T^2\right)\right]\frac{F^2}{M^2}$$

All these parameters are then evolved down to the weak scale with the RGE of the NMSSM

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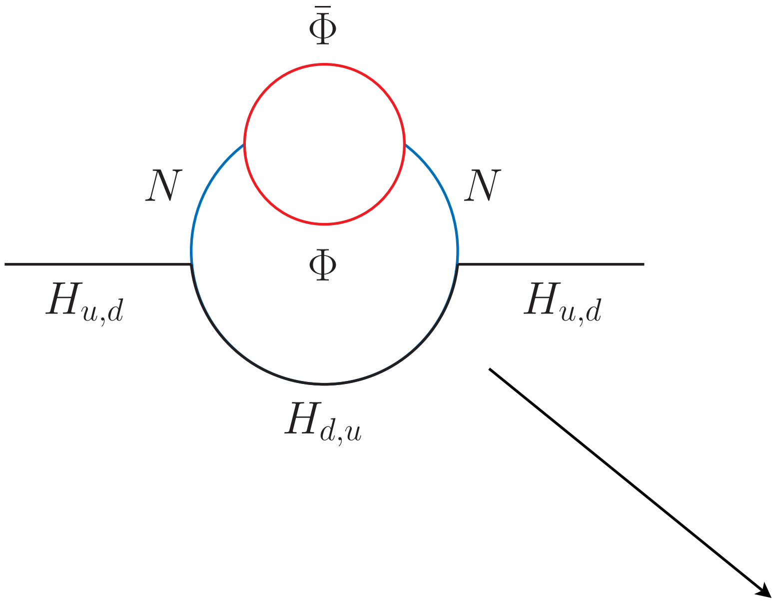


$$\tilde m^2_{H_u} = \tilde m^2_{H_d} = \frac{1}{(16\pi^2)^2}\left[n \left(\frac{3\, g^4}{2} + \frac{5\, g'^4}{6} \right) - \lambda^2 \left(2\, \xi_D^2 + 3\, \xi_T^2 \right) \right] \frac{F^2}{M^2}$$

All these parameters are then evolved down to the weak scale with the RGE of the NMSSM

Soft SUSY-breaking masses for the N-GMSB

At the messenger scale the gaugino and sfermion soft masses are as in the usual GMSB

$$M_i = n\, c_i \,\frac{\alpha_i}{4\,\pi}\,\frac{F}{M}\,, \qquad m^2_{\tilde f} = 2\,n \sum_i c_i\, C_i^{\tilde f}\,\frac{\alpha_i^2}{(4\,\pi)^2}\,\frac{F^2}{M^2}\,, \qquad (n=2)$$

The singlet-messenger interactions generate A-terms at 1-loop and scalar masses at 2-loop

$$A_\lambda \;=\; \frac{A_k}{3} \;=\; -\,\frac{1}{16\pi^2}\,\left(2\,\xi_D^2 + 3\,\xi_T^2\right)\frac{F}{M}\,,$$

$$\tilde m_N^2 \;=\; \frac{1}{(16\pi^2)^2}\left[8\xi_D^4 + 15\xi_T^4 + 12\xi_D^2\xi_T^2 - 16 g_s^2 \xi_T^2 - 6 g^2 \xi_D^2 - 2 g'^2\left(\xi_D^2 + \frac{2}{3}\xi_T^2\right)\right.$$
$$\left. -\,4k^2\left(2\xi_D^2 + 3\xi_T^2\right)\right]\frac{F^2}{M^2}$$

$$\tilde m^2_{H_u} = \tilde m^2_{H_d} = \frac{1}{(16\pi^2)^2}\left[n\left(\frac{3\,g^4}{2} + \frac{5\,g'^4}{6}\right) - \lambda^2\left(2\,\xi_D^2 + 3\,\xi_T^2\right)\right]\frac{F^2}{M^2}$$

All these parameters are then evolved down to the weak scale with the RGE of the NMSSM

Phenomenology of the N-GMSB

Three new parameters w.r.t. the usual GMSB: $\xi_U \equiv \xi_{D,T}(M_{\rm GUT})\,,\ \lambda\,,\ k$ (but no μ)

The size of the soft SUSY-breaking parameters is determined by M and F. We choose them such as to maximize the radiative correction to the light Higgs mass

- Large F/M generates a sizeable stop mass scale $M_S \equiv \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$
- Large M generates a sizeable $A_t(M_S)$ through RG evolution

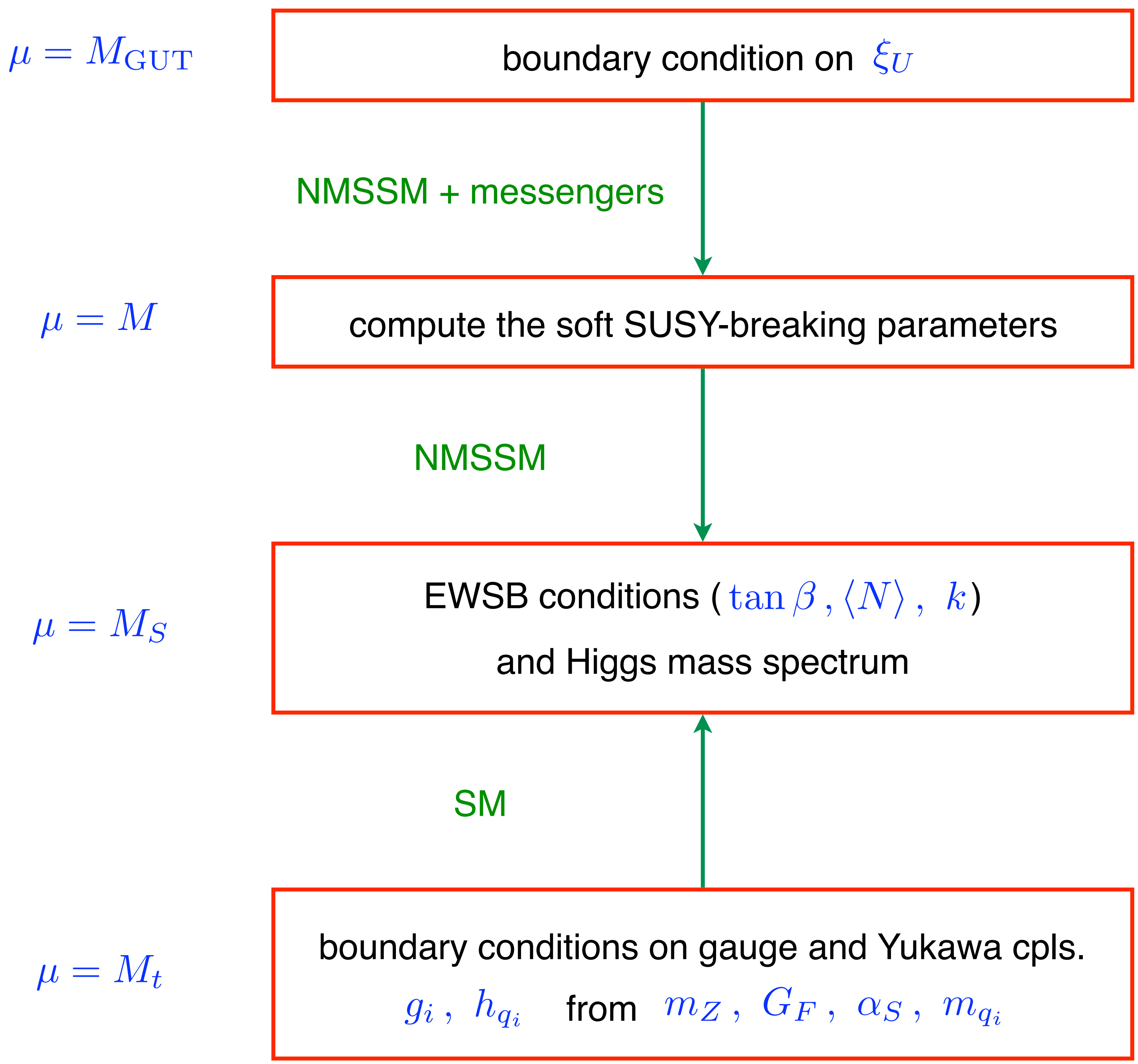
Take $M = 10^{13}$ GeV and $F/M = 1.72 \times 10^5$ GeV (such that $M_S \approx 2$ TeV, $A_t \approx -1.4$ TeV)

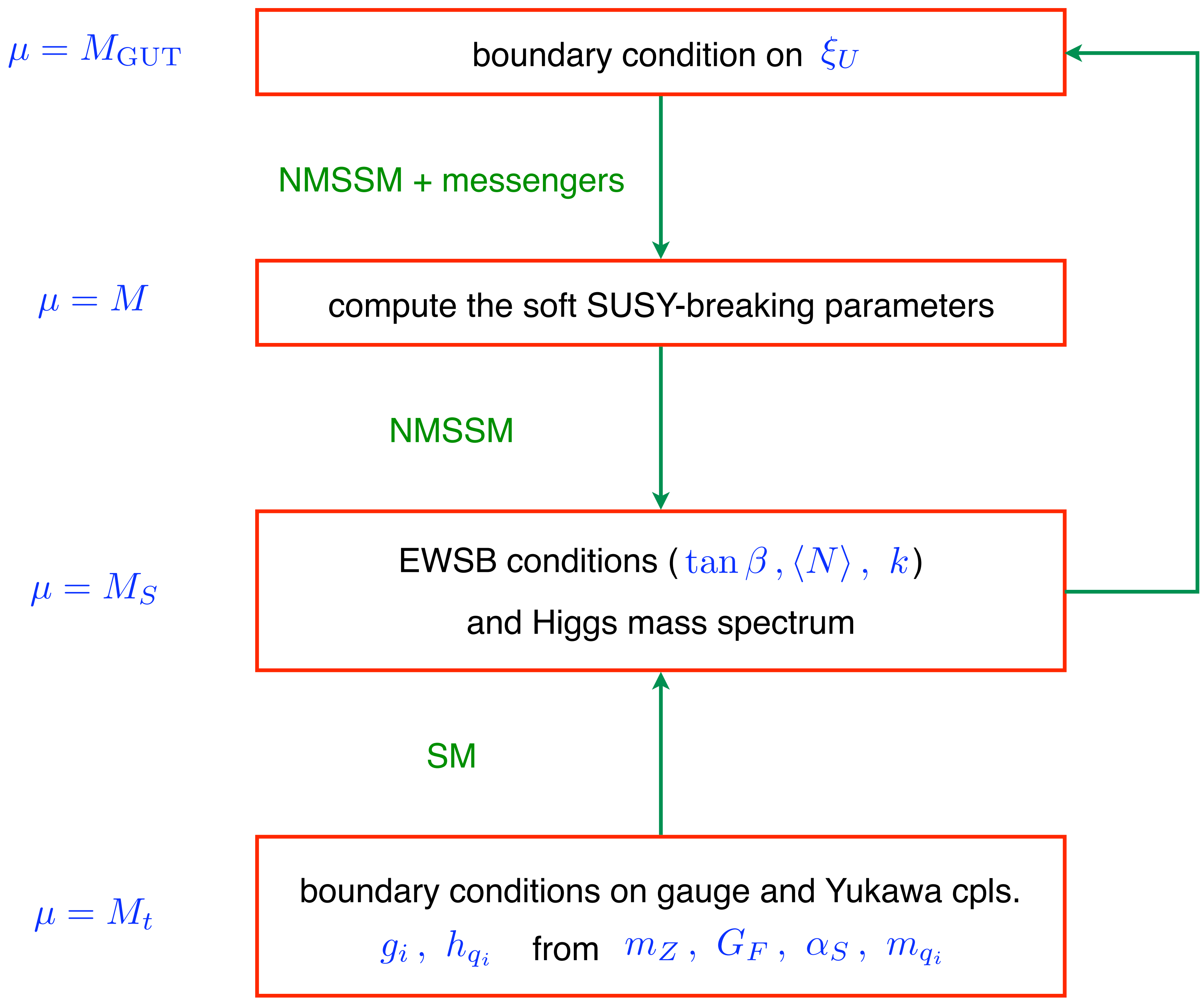
The EWSB conditions imposed at the scale M_S determine $\langle H_d\rangle\,,\ \langle H_u\rangle$ and $\langle N\rangle$.
Fixing $v^2 = \langle H_d\rangle^2 + \langle H_u\rangle^2$ as input, we can use them to determine $\tan\beta\,,\ \langle N\rangle$ and k

→ Two free parameters to play with: ξ_U and $\lambda(M_S)$

Conditions on the parameters are imposed at different scales ($M_t\,,\ M_S\,,\ M\,,\ M_{\rm GUT}$)

→ We need to solve the RGE of a tower of effective theories


$\mu = M_{\rm GUT}$
boundary condition on ξ_U
NMSSM + messengers
$\mu = M$
compute the soft SUSY-breaking parameters
NMSSM
$\mu = M_S$
EWSB conditions ($\tan\beta$, $\langle N \rangle$, k)
and Higgs mass spectrum
SM
$\mu = M_t$
boundary conditions on gauge and Yukawa cpls.
g_i , h_{q_i} from m_Z , G_F , α_S , m_{q_i}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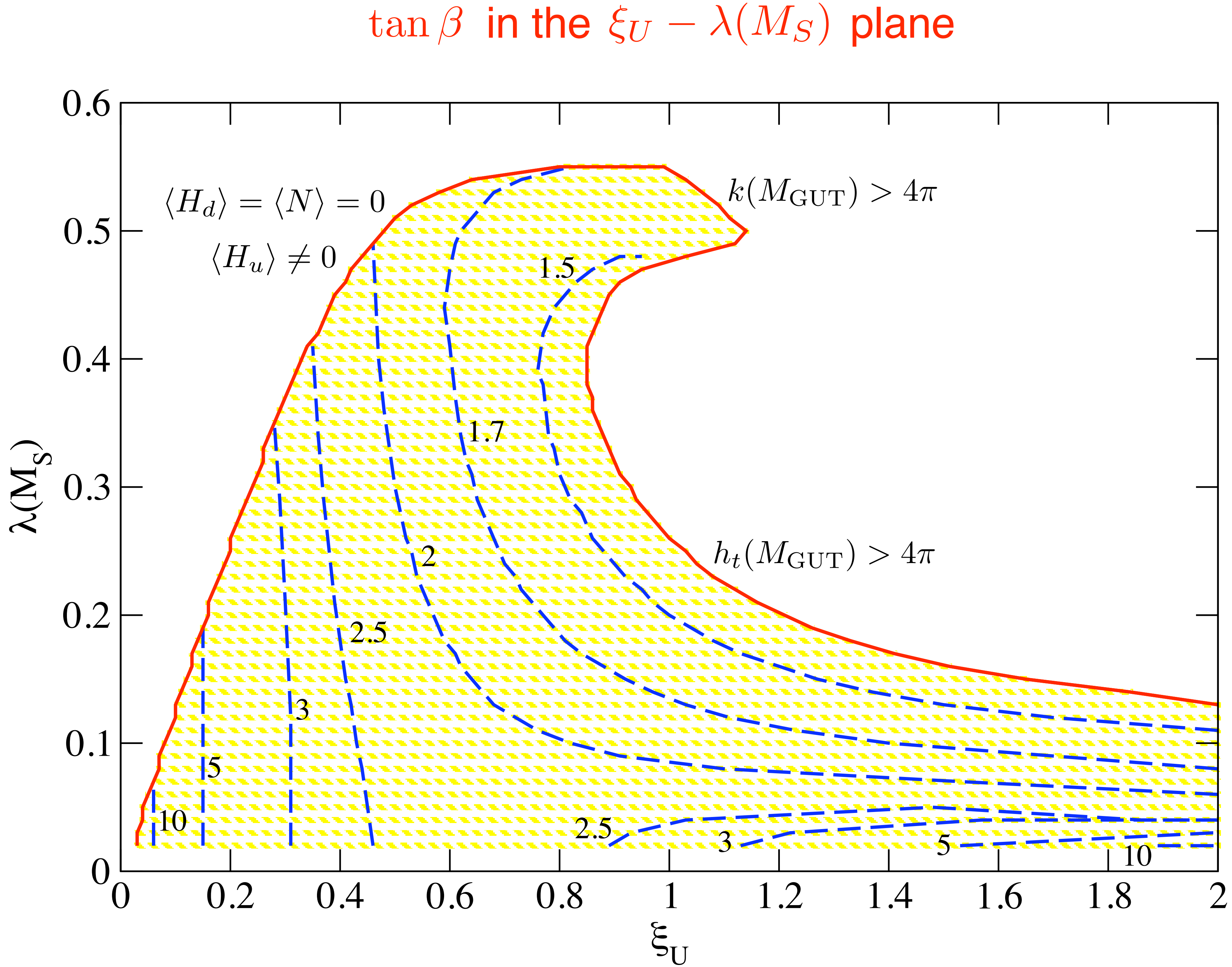
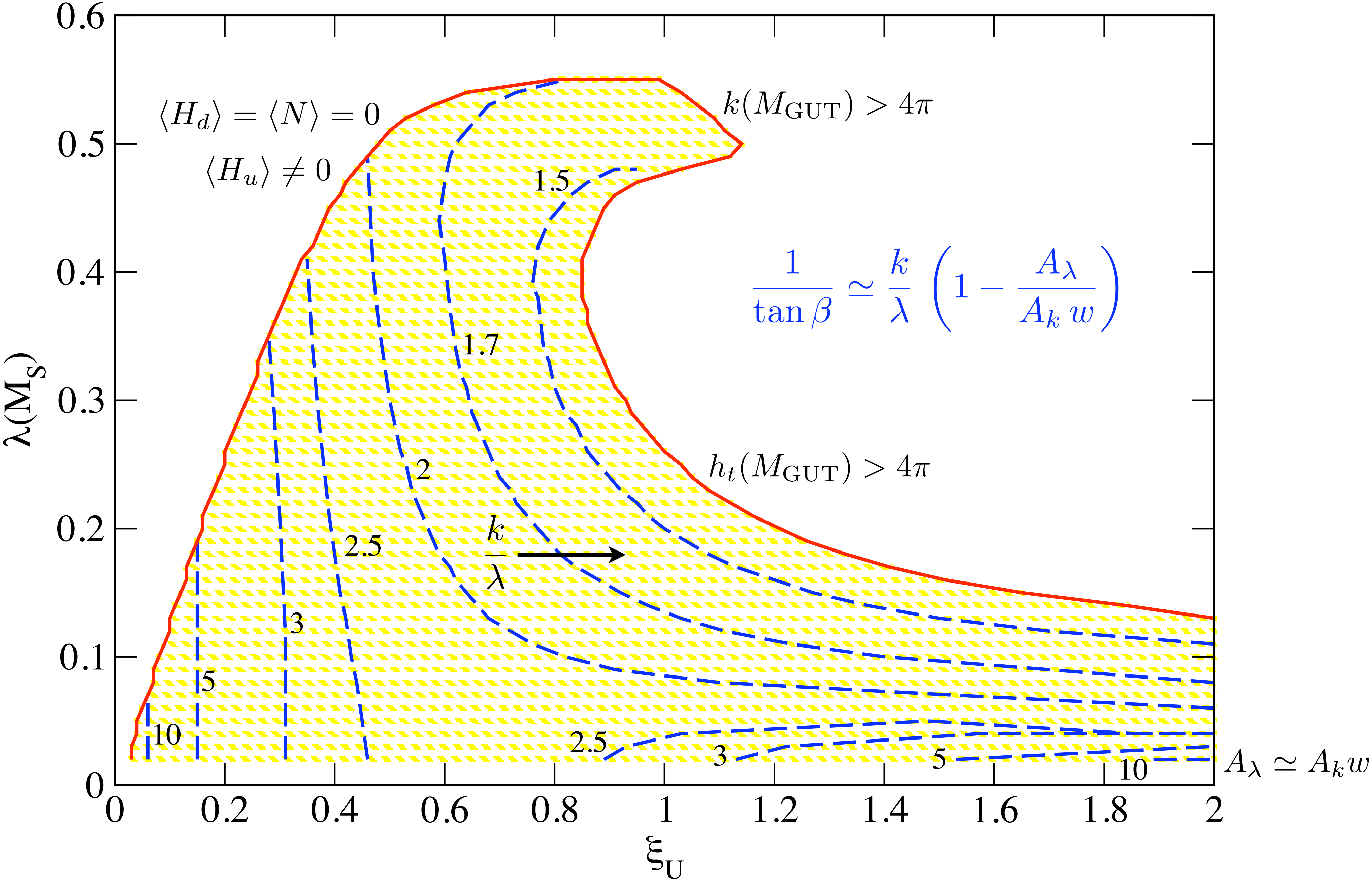
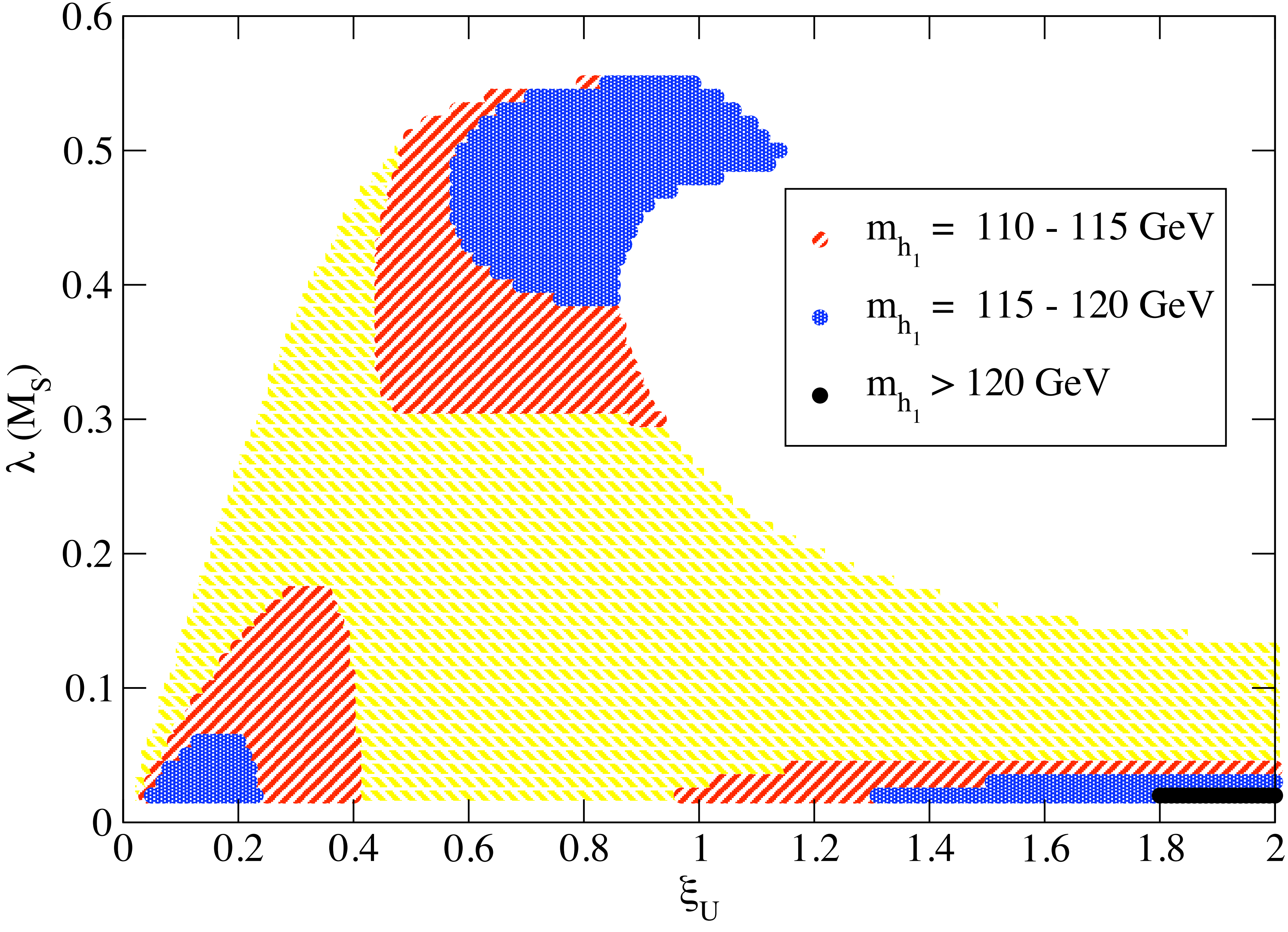


$\tan\beta$ in the $\xi_U - \lambda(M_S)$ plane
$\langle H_d \rangle = \langle N \rangle = 0$
$\langle H_u \rangle \neq 0$
$k(M_{\rm GUT}) > 4\pi$
$h_t(M_{\rm GUT}) > 4\pi$
1.5
1.7
2
2.5
3
5
10
2.5
3
5
10
$\lambda(M_S)$
ξ_U
0
0.1
0.2
0.3
0.4
0.5
0.6
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

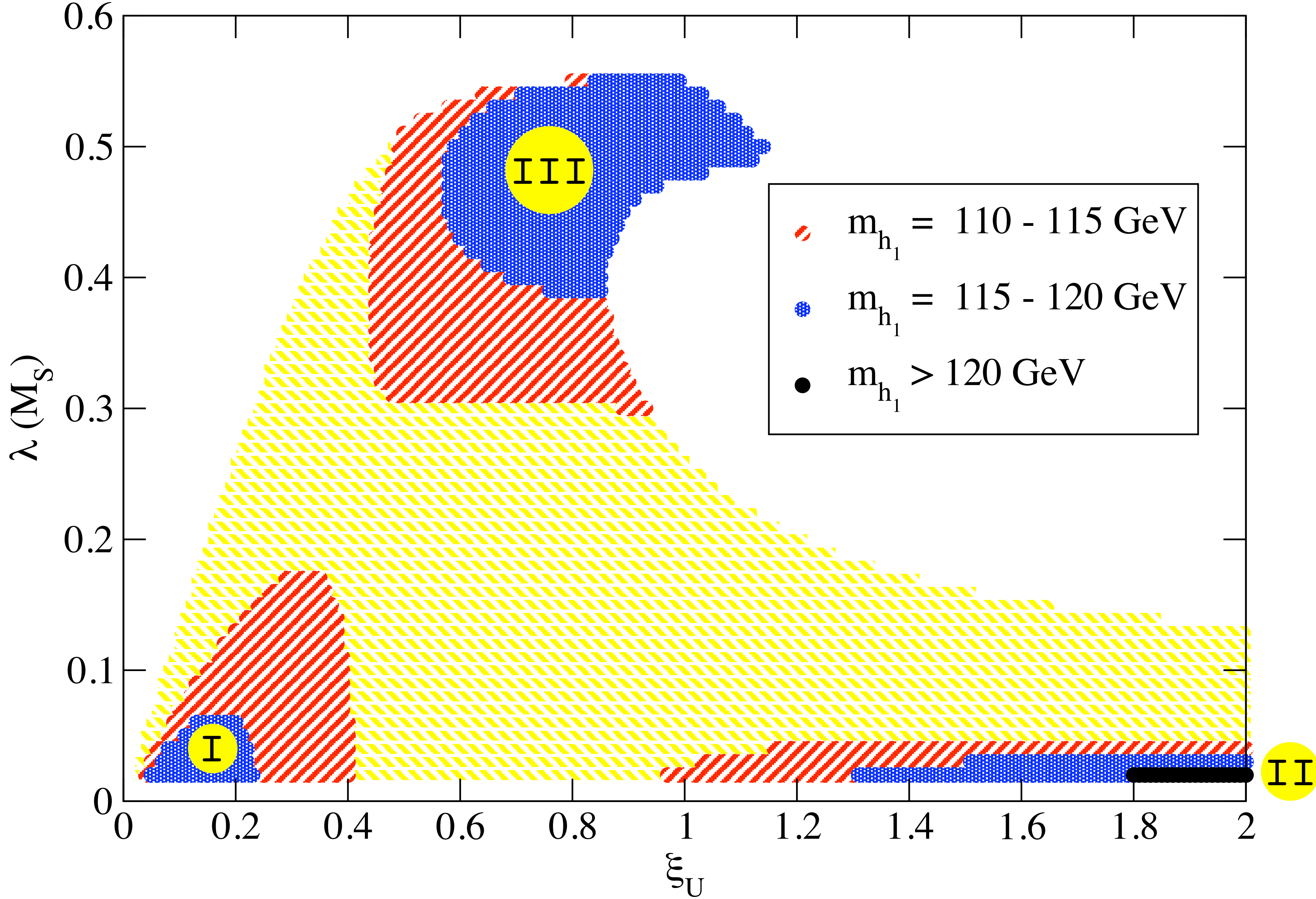
$\tan\beta$ in the $\xi_U - \lambda(M_S)$ plane



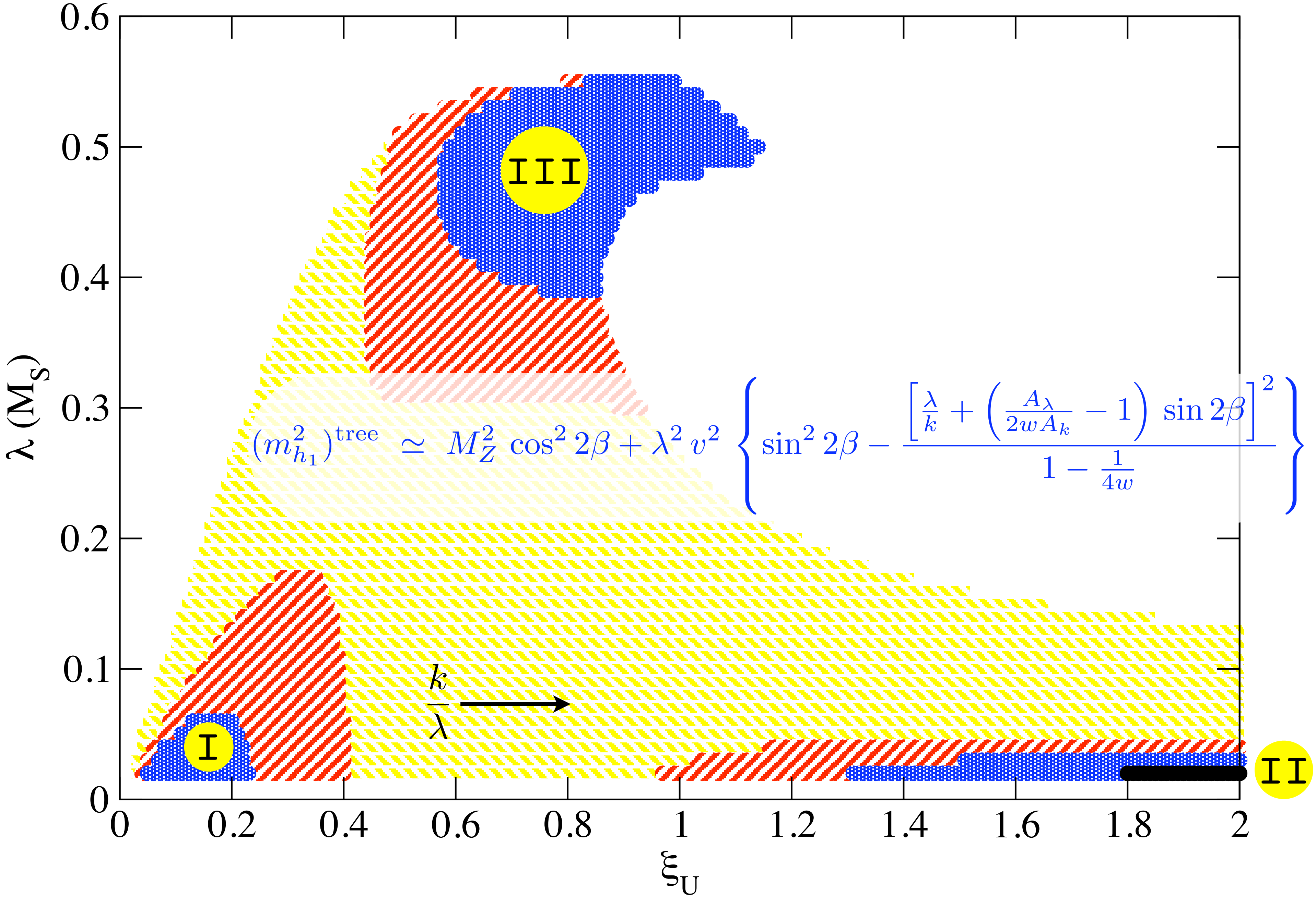
m_{h_1} in the $\xi_U - \lambda(M_S)$ plane



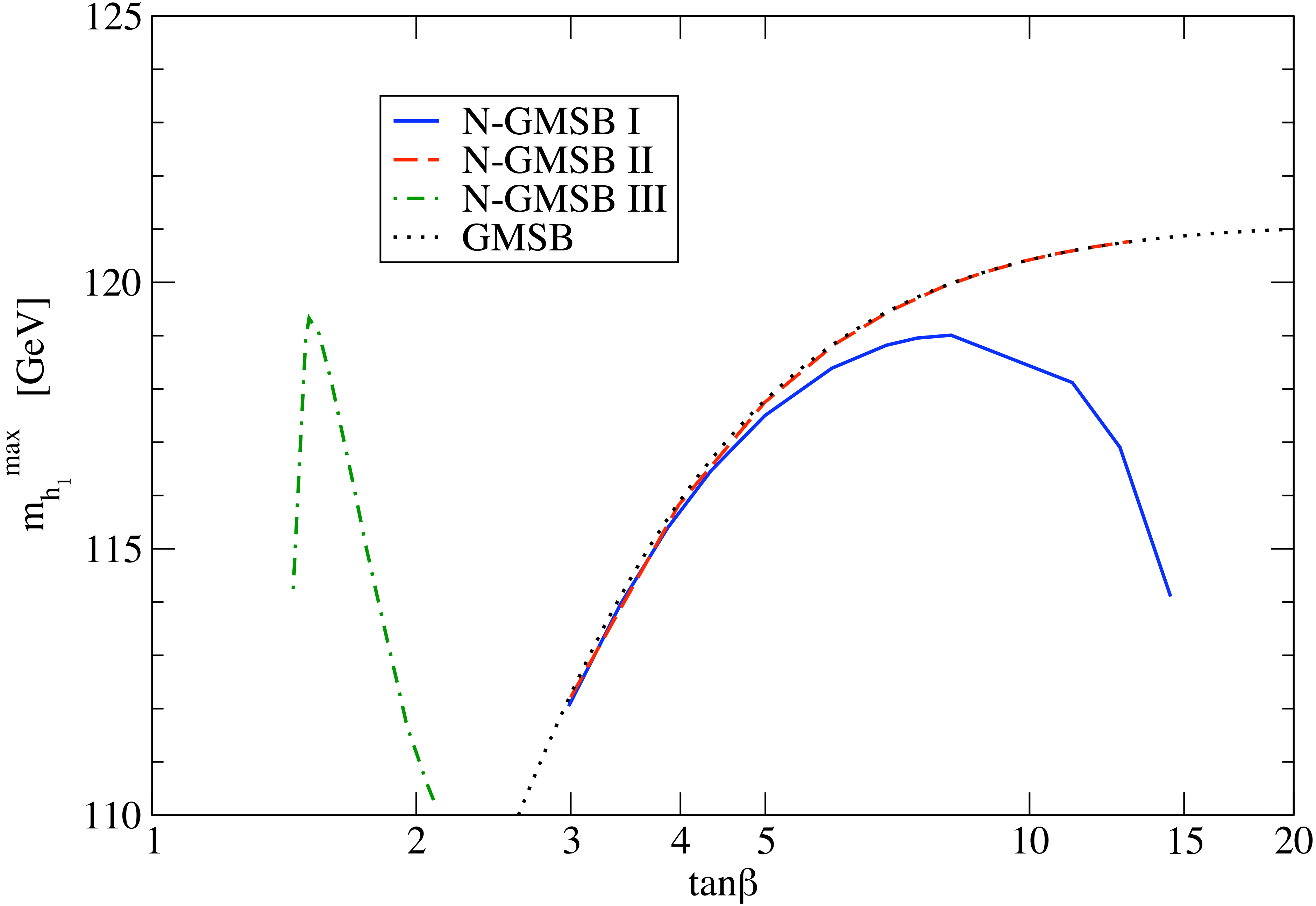
m_{h_1} in the $\xi_U - \lambda(M_S)$ plane



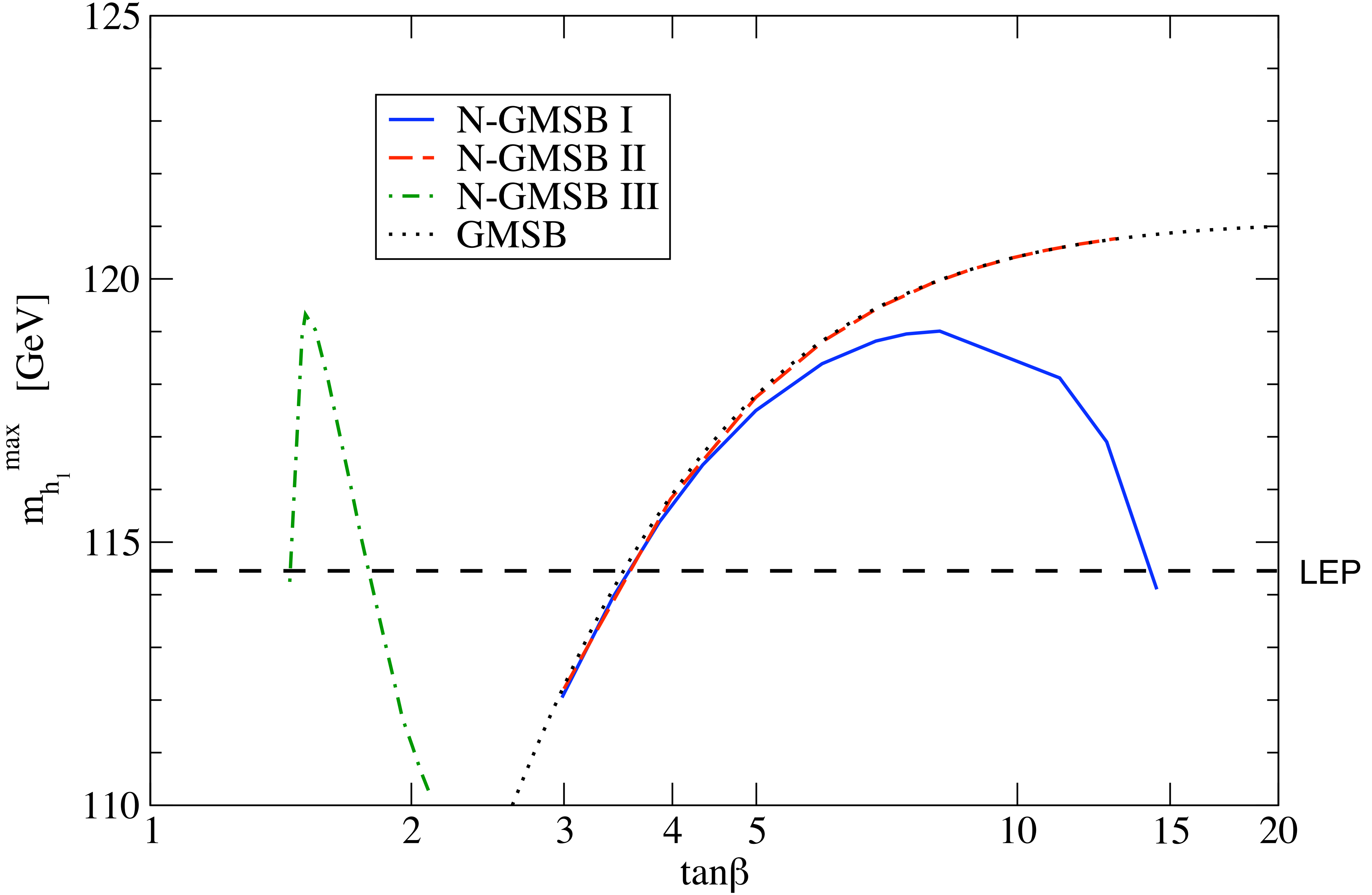
m_{h_1} in the $\xi_U - \lambda(M_S)$ plane



$(m_{h_1})^{\max}$ vs $\tan\beta$ in the three regions



$(m_{h_1})^{\max}$ vs $\tan\beta$ in the three regions



The other NMSSM particle masses:

$$m_{a_1}\,,\; m_{h_2} \;\sim\; \mu\,, \qquad m_{a_2}\,,\; m_{h_3}\,,\; M_{\tilde{N}} \;\sim\; \frac{k}{\lambda}\,\mu$$

- **Region I** $\quad \mu \lesssim M_S\,, \quad \lambda \ll 1\,, \quad \dfrac{k}{\lambda} \ll 1$

  - The singlet-like scalars and the singlino are much lighter than the MSSM-like particles
  - The singlino can be the NLSP. Peculiar decay chain $\tilde{B} \longrightarrow \tilde{N}\, h_1 \longrightarrow \tilde{G}\, a_2\, h_1$

- **Region II** $\quad \mu \lesssim M_S\,, \quad \lambda \ll 1\,, \quad \dfrac{k}{\lambda} \gg 1$

  - The singlet-like scalars and the singlino are much heavier and essentially decoupled
  - This region corresponds to the *MSSM limit* of the NMSSM

- **Region III** $\quad \mu \gtrsim M_S\,, \quad \lambda \sim 0.5\,, \quad \dfrac{k}{\lambda} \sim 1$

  - All the scalars except h_1 , as well as the singlino, are quite heavy
  - m_{h_1} can be pushed to ~160 GeV if we give up perturbativity up to the GUT scale

Representative mass spectra

- **Region I** $\xi_U = 0.06\,,\quad \lambda(M_S) = 0.02$

$$M_S \approx 2\,\mathrm{TeV}\,,\quad \mu \approx -1.4\,\mathrm{TeV}\,,\quad A_t \approx -1.5\,\mathrm{TeV}\,,\quad \frac{k}{\lambda} \approx \frac{1}{7}\,,\quad \tan\beta \approx 11$$
$$M_1 \approx 480\,\mathrm{GeV}\,,\quad M_2 \approx 880\,\mathrm{GeV}\,,\quad M_3 \approx 2.3\,\mathrm{TeV}\,,\quad M_{\tilde{N}} \approx 400\,\mathrm{GeV}\,,$$
$$m_{h_1} = 118\,\mathrm{GeV}\,,\quad m_{h_2} \approx m_{a_1} \approx 1.8\,\mathrm{TeV}\,,\quad m_{h_3} \approx 380\,\mathrm{GeV}\,,\quad m_{a_2} \approx 210\,\mathrm{GeV}$$

- **Region II** $\xi_U = 2\,,\quad \lambda(M_S) = 0.02$

$$M_S \approx 2\,\mathrm{TeV}\,,\quad \mu \approx -1.4\,\mathrm{TeV}\,,\quad A_t \approx -1.5\,\mathrm{TeV}\,,\quad \frac{k}{\lambda} \approx 5\,,\quad \tan\beta \approx 13$$
$$M_1 \approx 480\,\mathrm{GeV}\,,\quad M_2 \approx 880\,\mathrm{GeV}\,,\quad M_3 \approx 2.3\,\mathrm{TeV}\,,\quad M_{\tilde{N}} \approx 14\,\mathrm{TeV}\,,$$
$$m_{h_1} = 121\,\mathrm{GeV}\,,\quad m_{h_2} \approx m_{a_1} \approx 1.7\,\mathrm{TeV}\,,\quad m_{h_3} \approx 7\,\mathrm{TeV}\,,\quad m_{a_2} \approx 21\,\mathrm{TeV}$$

- **Region III** $\xi_U = 1\,,\quad \lambda(M_S) = 0.5$

$$M_S \approx 2\,\mathrm{TeV}\,,\quad \mu \approx -2.6\,\mathrm{TeV}\,,\quad A_t \approx -1.2\,\mathrm{TeV}\,,\quad \frac{k}{\lambda} \approx 0.8\,,\quad \tan\beta \approx 1.5$$
$$M_1 \approx 480\,\mathrm{GeV}\,,\quad M_2 \approx 880\,\mathrm{GeV}\,,\quad M_3 \approx 2.3\,\mathrm{TeV}\,,\quad M_{\tilde{N}} \approx 4.3\,\mathrm{TeV}\,,$$
$$m_{h_1} = 119\,\mathrm{GeV}\,,\quad m_{h_2} \approx m_{a_1} \approx 3\,\mathrm{TeV}\,,\quad m_{h_3} \approx 3.6\,\mathrm{TeV}\,,\quad m_{a_2} \approx 4\,\mathrm{TeV}$$

Summary

- The B_μ problem of gauge mediation can be solved by adding a new singlet
- For an acceptable EWSB we must introduce singlet-messenger interactions that generate sizeable soft SUSY-breaking terms for the singlet
- As usual in GMSB, satisfying the LEP bound on the Higgs mass requires large values of the stop masses, and the model is somewhat fine-tuned
- Still, there are three distinct regions of the parameter space with acceptable Higgs mass spectrum and potentially interesting collider signatures