Exploring Non-Holomorphic MSSM for constraints from Charge and Color Breaking vacuum in context of Higgs@125 GeV

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Outline

Based on : **JHEP 1710 (2017) 154, Jyotiranjan Beuria and AD**

Introduction

- Non-Holomorphic MSSM (NHSSM) is one of the simplest extension of MSSM with identical particle content.
- NH parameters in the model are trilinear soft parameters (A's) and bare Higgsino mass (μ').
- These NH parameters attribute to interesting phenomenological features of NHSSM.
- The NH trilinear parameters A'_t, A'_b, A'_τ modify the scalar potential.
- They are in general sensitive to CCB vacuum.
- Besides phenomenological constraints, the NH trilinear parameters should be constrained by desiring the EWSB vacuum to be safe.

NHSSM

The trilinear soft terms in MSSM and the NH soft-terms in NHSSM

$$-\mathcal{L}_{soft} \supset \tilde{Q} \cdot H_u y_t A_t \tilde{U} + \tilde{Q} \cdot H_d y_b A_b \tilde{D} + \tilde{L} \cdot H_d y_\tau A_\tau \tilde{E} + h.c. \quad (1)$$

$$-\mathcal{L}'_{soft} \supset \tilde{Q} \cdot H_d^c y_t A'_t \tilde{U} + \tilde{Q} \cdot H_u^c y_b A'_b \tilde{D} + \tilde{L} \cdot H_u^c y_\tau A'_\tau \tilde{E} + \mu' \tilde{H}_u \cdot \tilde{H}_d + h.c. \quad (2)$$

The scalar potential at tree-level considering only the Higgs and the stop fields :

$$\begin{aligned} \mathrm{V}|_{\mathrm{tree}} = \; & m_2^2 H_u^2 + m_1^2 H_d^2 + m_{\tilde{t}_L}^2 \tilde{t}_L^2 + m_{\tilde{t}_R}^2 \tilde{t}_R^2 - 2B_\mu H_d H_u + 2y_t A_t H_u \tilde{t}_R \tilde{t}_L \\ & -2y_t(\mu + A'_t)\tilde{t}_L \tilde{t}_R H_d + y_t^2 (H_u^2 \tilde{t}_L^2 + H_u^2 \tilde{t}_R^2 + \tilde{t}_R^2 \tilde{t}_L^2) + \\ & \frac{g_1^2}{8}(H_u^2 - H_d^2 + \frac{\tilde{t}_L^2}{3} - \frac{4\tilde{t}_R^2}{3})^2 + \frac{g_2^2}{8}(H_u^2 - H_d^2 - \tilde{t}_L^2)^2 + \\ & \frac{g_3^2}{6}(\tilde{t}_L^2 - \tilde{t}_R^2)^2 \end{aligned} \quad (3)$$

CCB in NHSSM

In the direction where $|H_d| = |H_u| = |\tilde{t}_R| = |\tilde{t}_L| = \zeta$, the potential reads as follows.

$$\mathbf{V}_{\text{tree}} = a\zeta^4 + b\zeta^3 + c\zeta^2. \tag{4}$$

where a, b, c are functions of soft masses and other parameters present in the potential. The CCB constraints in NHSSM for stop fields :

$$\left[|A_t| + |\mu| + |A_t'|\right]^2 < 3\left\{1 - \frac{g_1^2 + g_2^2}{24y_t^2}\right\}\left(m_1^2 + m_2^2 + m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2 - 2B_\mu\right). \tag{5}$$

Since $y_t > g_1, g_2$ the constraint may be approximated as:

$$\left[|A_t| + |\mu| + |A_t'|\right]^2 < 3\left(m_1^2 + m_2^2 + m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2 - 2B_\mu\right). \tag{6}$$

In the MSSM limit ($A'_t \longrightarrow 0$) for 3 *vev* scenario with $H_d = 0$ the above equation leads to

$$A_t^2 < 3(m_2^2 + m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2). \text{ Traditionally used in MSSM} \qquad (7)$$

Limitations of the analytic CCB constraint in NHSSM.

- Only direction of equal *Vevs* are considered. This is hardly a realistic scenario.
- The analytic constraint is derived only for tree-level scalar potential. Radiative corrections and thermal effects may significantly modify the vacuum structure.
- Only absolute stability is predicted, but a realistic scenario should accommodate cosmologically long-lived vacuum as well.
- Effects of other squarks need to be explored

CCB Minima and Higgs@125

- Higgs@125 GeV demands large radiative corrections.
- The radiation correction to m_{h_1} arising out of $\tilde{t}$ loops is affected by A'_t.
- Constraints for processes like $\mathrm{Br}(B \to X_s + \gamma)$ are easily satisfied for large $\tan\beta$ via inclusion of contributions arising out of μ' and A'_t.
- Hence, phenomenologically interesting region is explored for vacuum stability against CCB minima.

Location of CBB minima and effect of A'_t on V

- Demanding low EWFT, μ is fixed at $\mu = 200$ GeV.
- Choice of parameters:
  $m_{\tilde{t}_L} = m_{\tilde{t}_R} = m_{\tilde{b}_R} = 2$ TeV,
  $B_\mu = 2 \times 10^5$ GeV^2 &
  $y_t A_t = 2$ TeV.
- Large $|A'_t|$ thus essentially can lower the potential.
- Effect is enhanced for small $\tan\beta$.

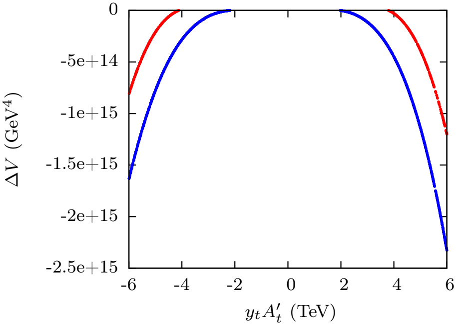
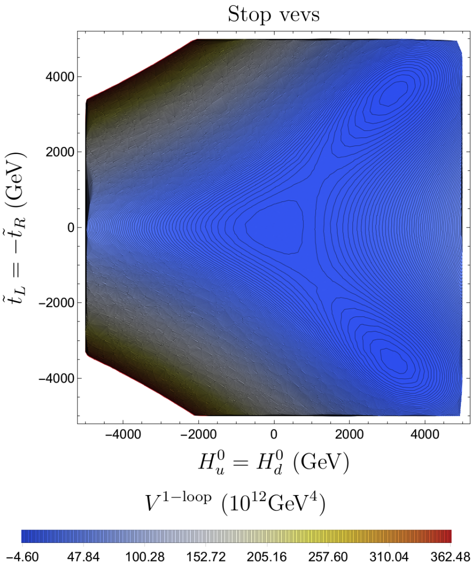


Figure: ΔV represents the depth of the potential at the deeper CCB vacuum with respect to the field origin.The red and blue points correspond to $\tan\beta = 50$ and $\tan\beta = 5$ respectively.

Schematic locations of minima

- Exploration of Variable *vevs*.
- Choice of parameters:
  $y_t A_t = 2\ \mathrm{TeV}, m_{\tilde{t}_L} = m_{\tilde{b}_R} = 1\ \mathrm{TeV}, m_{\tilde{t}_R} = 2\ \mathrm{TeV}\ \&\ y_t A_t' = -3600\ \mathrm{GeV}$
- The central contour encloses the DSB minima, while the other two contours that encircle regions with non-zero *vevs* for stops represent CCB minima.



Effect of A'_t on $m_{\tilde{t}_1}$ in context of safe vacuum

- A four *Vev* scenario with non-vanishing *Vevs* for Higgs and stops is explored.
- Define: $\mathcal{M}^2_{\tilde{t}} = \left[m_1^2 + m_2^2 + m^2_{\tilde{t}_L} + m^2_{\tilde{t}_R} - 2B_\mu\right]$ and $\widetilde{A_t}^2 = (|A_t| + |\mu| + |A'_t|)^2$
- The CCB constraint in NHSSM becomes $\frac{\widetilde{A_t}^2}{\mathcal{M}^2_{\tilde{t}}} < 3$ $\because y_t > g_1, g_2$ in general.
- Analysis: $y_t A_t = 2$ TeV and all scalar mass except $m_{\tilde{t}_L}$ fixed at 2 TeV.

$$\begin{aligned} -1\ \mathrm{TeV} &\leq \mu' \leq 1\ \mathrm{TeV} \\ -6\ \mathrm{TeV} &\leq y_t A'_t \leq 6\ \mathrm{TeV} \\ 500\ \mathrm{GeV} &\leq m_{\tilde{t}_L} \leq 2\ \mathrm{TeV}. \end{aligned} \tag{8}$$

vacuum stability profile in $y_t A'_t - m_{\tilde{t}_1}$ plane

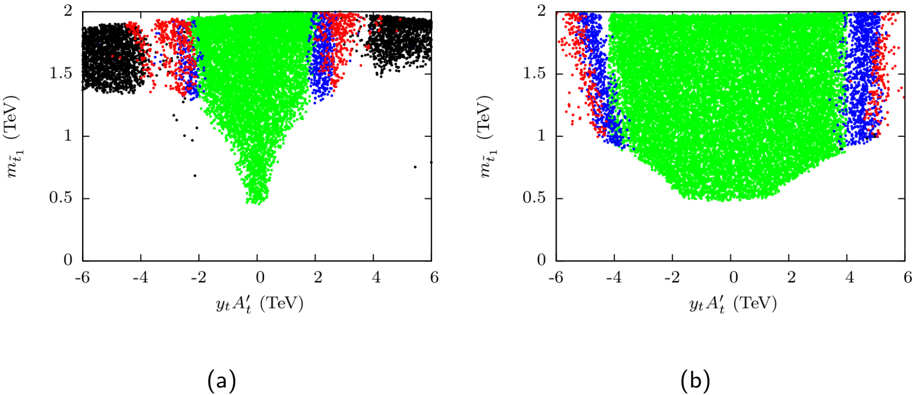


Figure: *The stability profile of the DSB minima in $y_t A'_t - m_{\tilde{t}_1}$ plane corresponding to the scan of Eq.8. Figs.3(a) and 3(b) corresponds to* $(5 < \tan\beta < 10)$ *and* $(40 < \tan\beta < 50)$ *respectively. The green and blue points corresponds to stable and long-lived states respectively (safe-vacuum). The black and red regions are excluded via quantum tunneling and thermal effects. (dangerous vacuum)*

- $m_{\tilde{t}_1}$ could be rather large in the region of metastability triggered by large $|y_t A'_t|$.
- We have kept $m_{\tilde{t}_R}$ fixed at 2 TeV. Hence large $m_{\tilde{t}_L}$ along with large $|y_t A'_t|$ facilitate the appearance of deeper CCB vacua by inducing large mixing between $\tilde{t}_L$ and $\tilde{t}_R$.
- Thus, $m_{\tilde{t}_1}$ becomes large for large $|y_t A'_t|$.
- We also notice that due to $\tan\beta$ suppression, the spread of green points in Fig.3(b) is more compared to Fig.3(a).
- Furthermore, the flat green edge ($m_{\tilde{t}_L} \approx m_{\tilde{t}_1} \approx 500$ GeV) is also broader compared to Fig.3(a) for the same reason.

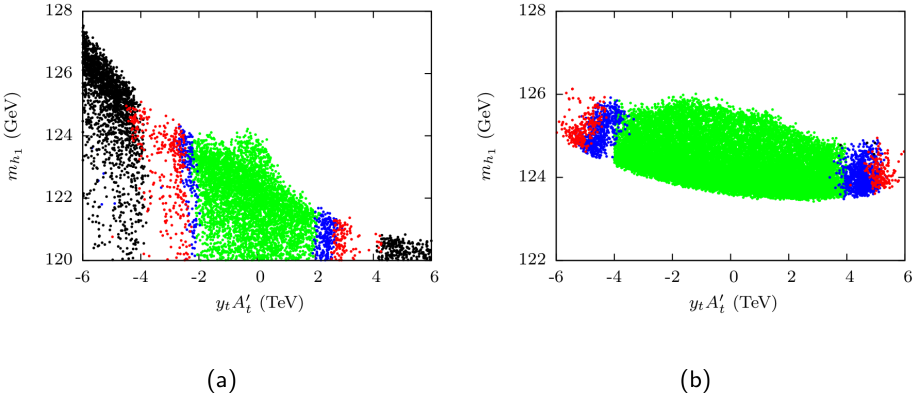
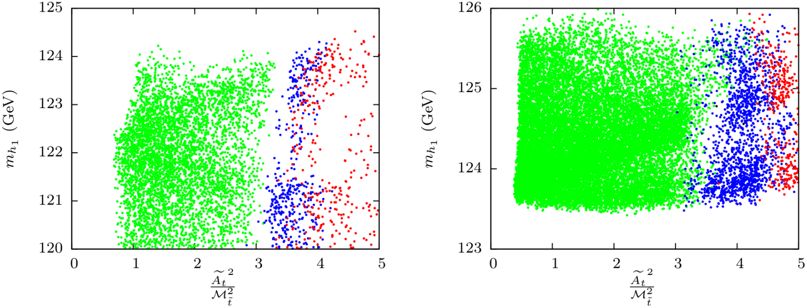


Figure: *The stability profile of DSB minima in* $y_t A'_t - m_{h_1}$ *plane corresponding to the scan of Eq.8. Figs.4(a) and 4(b) corresponds to* $(5 < \tan\beta < 10)$ *and* $(40 < \tan\beta < 50)$ *respectively. The color codes are same as that for Fig.3.*

- The effect of $y_t A_t'$ on m_{h_1} is more prominent in low $\tan\beta$ region.
- For low $\tan\beta$ and $|y_t A_t'| \gtrsim 3$ TeV the DSB minima becomes unsafe and they are excluded via quantum tunneling or thermal effects.
- For $40 \leq \tan\beta \leq 50$, comparatively large values of $|y_t A_t'|$ (< 4 TeV), is allowed in the region of parameter space associated with safe vacuum.

Finally the applicability of the derived CCB constraint is analyzed.
The stability profile of the DSB vacuum is explored in $\frac{\widetilde{A_t}^2}{\mathcal{M}_{\tilde{t}}^2} - m_{h_1}$ plane.

Applicability of CCB constraint in NHSSM



(a) (b)

Figure: *Fig.5(a) (5(b)) refers to* $5 \leq \tan\beta \leq 10$ *(*$40 \leq \tan\beta \leq 50$*).*

- The variable in the horizontal axis is predicted to be less than 3 for stable DSB minima according to Eq. 6.
- The constraint holds quite reliably for the chosen region of parameter space.
- However, since the analytic constraint of Eq. 6 was derived under the consideration of stable vacua only, the constraint may be relaxed in the present scenario where, we also include long-lived DSB minima as viable vacua of the theory.
- This is evident from the extent of the long-lived states in the region where $3 \lesssim \frac{\widetilde{A_t}^2}{\mathcal{M}_{\tilde{t}}^2} \lesssim 4$.
- We observe that the safe vacua spread over a wider range of $\frac{\widetilde{A_t}^2}{\mathcal{M}_{\tilde{t}}^2}$ for large $\tan\beta$.

Summary

- The NHSSM is constructed via inclusion of non-holomorphic (NH) SUSY breaking soft trilinear interactions with the coefficients A'_t, A'_b etc. along with a NH higgsino mass soft parameter (μ').
- Features of NHSSM
  - Easy accommodation of results from B-physics process.
  - Adequate value of m_{h_1} is obtained for comparatively lighter $\tilde{t}_1$ and smaller A_t.
  - Low EWFT for a Higgsino DM scenario consistent with PLANCK data.
- The scalar potential (that includes the squarks as well) is modified by the NH parameters (A'_t, A'_b etc).
- Large $|A'_t|$ effectively lowers the scalar potential that may lead to the appearance of global CCB minima.

- Analytic constraint that is derived assuring absolute stability of the vacuum is sufficient but not necessary once long-lived DSB minima is taken into account.
- Moreover in order to consider one loop corrected potential and thermal effects, numerical analysis using `Vevacious` is performed in order to constrain the NH parameters by demanding the DSB minima to be safe.
- We find that A_t' is more sensitive to CCB minima for lower regime of $\tan\beta$.
- Region of parameter space consistent with Higgs@125 GeV is associated with both safe and dangerous vacuum. Hence examination of vacuum stability is extremely important.

Outlook

- We discuss vacuum stability against CCB by taking into account the role of stop scalar fields.
- However in a more elaborate analysis role of sbottom fields needs to be explored.
- We principally focus on third generation of squarks, since the rate of tunneling to deeper CCB minima increases with increase in the yukawa couplings. $(\mathrm{Rate} \propto e^{-\frac{a}{y^2}})$.
- One may explore the of stau fields in context of exclusive charge breaking vacuum.

For Further Reading I

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Thank You for your attention