Exploring MSSM for charge and color breaking and other constraints in the context of Higgs@125 GeV.

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Outline

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Introduction

- Higgs Boson, discovered at LHC
- BSM physics \(\rightarrow\) hierarchy problem, dark matter etc
- SM : low energy approx of SUSY
- MSSM - SM fermions and bosons are supplemented by bosonic and fermionic partners transforming under the same SM gauge group \(SU(3)_C \times SU(2)_L \times U(1)_Y\).
Particle content of MSSM

| Names                                      | spin 0     | spin 1/2                | $SU(3)_C$, $SU(2)_L$, $U(1)_Y$ |
|--------------------------------------------|------------|-------------------------|---------------------------------|
| squarks, quarks                           | $Q$        | $(u_L, d_L)$             | $(3, 2, \frac{1}{6})$          |
| (×3 families)                              | $u$        | $u_R^*$                  | $(\bar{3}, 1, -\frac{2}{3})$   |
|                                            | $d$        | $d_R^*$                  | $(\bar{3}, 1, \frac{1}{3})$    |
| sleptons, leptons                         | $L$        | $(\nu, e_L)$             | $(1, 2, -\frac{1}{2})$         |
| (×3 families)                              | $e$        | $e_R^*$                  | $(1, 1, 1)$                     |
| Higgs, higgsinos                           | $H_u$      | $(H_u^+, H_u^0)$          | $(1, 2, +\frac{1}{2})$         |
|                                            | $H_d$      | $(H_d^0, H_d^-)$          | $(1, 2, -\frac{1}{2})$         |

Table 0.1: Chiral supermultiplets in the Minimal Supersymmetric Standard Model. The spin-0 fields are complex scalars, and the spin-1/2 fields are left-handed two-component Weyl fermions.

| Names               | spin 1/2 | spin 1     | $SU(3)_C$, $SU(2)_L$, $U(1)_Y$ |
|---------------------|----------|------------|---------------------------------|
| gluino, gluon       | $g$      | $g$        | $(8, 1, 0)$                     |
| winos, W bosons     | $W^\pm$  | $W^0$      | $(1, 3, 0)$                     |
| bino, B boson       | $B^0$    | $B^0$      | $(1, 1, 0)$                     |

Table 0.2: Gauge supermultiplets in the Minimal Supersymmetric Standard Model.
Higgs@125 GeV → radiative corrections to Higgs mass important

In SUSY models, this demands excessively heavy scalar sparticles (in CMSSM), stops (in MSSM)

Stop loop is most important,

In large $\mu$ region, for large $\tan \beta$, sbottom and stau loop significant.

However large radiative correction possible for relatively lighter stops by enhancing contribution from mixing terms.
- Suitable enhancement of $A_t \rightarrow$ larger $m_h$
- Increasing $\mu \rightarrow$ -ve contribution from sbottom and stau loops $\rightarrow$ proper $m_h$.
- Large $A_t$, $\mu \rightarrow$ charge color breaking (CCB) global minima of MSSM scalar potential
- Revisit the CCB constraints numerically for a wider range of $A_t$ and $\mu$ in search for stable and long-lived vacuum.
- B-Physics and Dark matter experimental results-constraints.
MSSM - scalars like squarks and sleptons charged under $SU(3)_{\text{color}}$ or $U(1)_{\text{EM}}$. 

Non vanishing vevs $\rightarrow$ CCB minima 

Non-observation of CCB processes $\rightarrow$ the Universe rests at a SML charge color conserving minima with non zero vevs only for Higgs. 

Strong analytic constraints on pMSSM parameters 

Universe in a SM like false vacuum $\rightarrow$ long-lived state 

Long-lived states $\rightarrow$ expansion of the allowed pMSSM parameter space.
Aspects of CCB minima, Decay of False Vacuum and MSSM

Rate of tunneling from SM like false vacuum to global CCB minima $\sim e^{-a/y^2}$. [Langacker 1994]

Decay rate is significantly large only for sfermions of third generations (large Yukawa coupling).

The MSSM scalar potential for Higgs and stop sector,

$$V = (m_{H_u}^2 + \mu^2) |H_u|^2 + (m_{H_d}^2 + \mu^2) |H_d|^2 + m_{\tilde{t}_L}^2 |\tilde{t}_L|^2 + m_{\tilde{t}_R}^2 |\tilde{t}_R|^2 -$$

$$B_\mu (H_u H_d + \text{c.c.}) + (y_t A_t H_u \tilde{t}_L \tilde{t}_R + \text{c.c.}) - (y_t \mu \tilde{t}_L \tilde{t}_R H_d^* + \text{c.c.}) +$$

$$y_t^2 (|\tilde{t}_L \tilde{t}_R|^2 + |H_u \tilde{t}_L|^2 + |H_u \tilde{t}_R|^2) + \frac{g_2^2}{8} (|H_u|^2 - |H_d|^2 - |\tilde{t}_L|^2)^2 +$$

$$\frac{g_1^2}{8} \left( |H_u|^2 - |H_d|^2 + \frac{1}{3} |\tilde{t}_L|^2 - \frac{4}{3} |\tilde{t}_R|^2 \right)^2 + \frac{g_3^2}{6} (|\tilde{t}_L|^2 - |\tilde{t}_R|^2)^2 . \quad (1)$$
Global CCB minima for large $y_t A_t H_u \tilde{t}_R \tilde{t}_L$ and $y_t \mu \tilde{t}_L \tilde{t}_R H_d^*$

Calculation of False vacuum decay for a single scalar field is given by, [Coleman 1977]

$$\frac{\Gamma}{V} = Ae^{-S[\phi]/\hbar}.$$  \hspace{1cm} (2)

Here, $\bar{\phi}$ is a particular configuration of the field $\phi$ for which $\delta S=0$.

Analytical calculation for the simplest case of a single scalar field under certain approximations namely, *thin wall* and *thick wall* scenario.[Coleman (1977), Langacker(1994) et. al.]
Accurate analysis with many scalar fields → approximations may not be valid → numerical computation

Radiative corrections to $m_h$

$m_h > m_{h,\text{tree}}$ Radiative correction extremely important. For stop loop, the contribution is given by,

$$\Delta m_{h,\text{top}}^2 = \frac{3g_2^2 \tilde{m}_t^4}{8\pi^2 M_W^2} \left[ \ln \left( \frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{\tilde{m}_t^2} \right) + \frac{X_t^2}{m_{\tilde{t}_1} m_{\tilde{t}_2}} \left( 1 - \frac{X_t^2}{12m_{\tilde{t}_1} m_{\tilde{t}_2}} \right) \right], \quad (3)$$

where $X_t = A_t - \mu \cot \beta$, at $E = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$

For sbottom loop,

$$\Delta m_{h,\text{bottom}}^2 = \frac{3g_2^2 \tilde{m}_b^4}{8\pi^2 M_W^2} \left[ \ln \left( \frac{m_{\tilde{b}_1} m_{\tilde{b}_2}}{\tilde{m}_b^2} \right) + \frac{X_b^2}{m_{\tilde{b}_1} m_{\tilde{b}_2}} \left( 1 - \frac{X_b^2}{12m_{\tilde{b}_1} m_{\tilde{b}_2}} \right) \right], \quad (4)$$

where $X_b = A_b - \mu \tan \beta$
$m_h$ can increased by the interplay between $A_t$ and $\mu$. Thus for large values of these parameters one can generate suitable $m_h$ keeping stop masses lighter. $A_t$, $\mu$ sensitive to CCB.

**Analytic CCB constraints**

Obtained under different simplifying relations between the vevs of the concerned fields. [Casas et. al. 1996]

\[
A_u^2 + 3\mu^2 \leq 3[m_{Q_u}^2 + m_u^2]. \tag{5}
\]

\[
A_u^2 \leq 3[m_{H_u}^2 + \mu^2 + m_{Q_u}^2 + m_u^2]. \tag{6}
\]
Considering the existence of long-lived states, the above constraints are modified to [Kusenko et al. (1994), Cohen et al. (2000)]

\[ A_u^2 + 3\mu^2 \leq 7.5[m_{Qu}^2 + m_u^2] \] (7)

\[ A_u^2 \leq 3[m_{Hu}^2 + \mu^2] + 7.5[m_{Qu}^2 + m_u^2]. \] (8)
CCB constraints not unique and may be too stringent.

Relaxed constraints found to be neither necessary nor sufficient.

Numerical investigation of vacuum stability in CCB scenario using Vevacious.

Large $\mu$ significant contribution to $m_h$ from the sbottom loop.

Violation of CCB constraints for large $A_t$ and $\mu$

non-zero vevs for stops and sbottom fields and scan over $A_t$ and $A_b$ and $\mu$, while investigating the large $\mu$ regions.
Vevacious is a new publicly available code [Staub et. al.(2012)] that

- Takes a model file
- Takes an SLHA file
- Prepares and run the code HOM4PS2 to find all the tree level extrema.
- Prepares and run the code PyMinuit
- If the global minima is not an SM like vacuum, then calculates the tunneling time using (CosmoTransition) to identify the SM like vacuaua associated with a point in the multi-dimensional parameter space as "long-lived" or "short-lived"
Results

- Vacuum stability for low values of $\mu$.
- Wide range of values of $\mu$ and $A_t$ for a moderate and a large value of $\tan \beta$ considering non-zero vevs for stop and sbottom.
- $\text{Br}(B_s \rightarrow \mu^+\mu^-)$, $\text{Br}(B_s' \rightarrow \mu^+\mu^-)$, direct detection cross section and relic abundance for neutralino dark matter
Study of generic region of pMSSM parameter space for the stability of vacuum

- The parameter space spans a broad range of tan $\beta$
- Third generation of up-type squark masses varied
- $A_t$ and $\mu$ upto a TeV.
- Only stop fields ($\tilde{t}_L$ and $\tilde{t}_R$) non-zero vevs.
Our choice of parameters are as follows.

\[
\begin{align*}
500 \text{ GeV} & \leq m_{\tilde{Q}_3} \leq 1500 \text{ GeV}, \\
500 \text{ GeV} & \leq m_{\tilde{U}_3} \leq 1500 \text{ GeV}, \\
5 & \leq \tan \beta \leq 60, \\
100 \text{ GeV} & \leq \mu \leq 1000 \text{ GeV}, \\
-3 m_{\tilde{Q}_3} & \leq A_t \leq 3 m_{\tilde{Q}_3}.
\end{align*}
\]

(9)

All other sfermion masses to be at 1 TeV, $M_A = 1$ TeV, $M_1 = 100$ GeV, $M_2 = 300$ GeV and $M_3 = 1000$ GeV. All other trilinear couplings are set to zero.
Uncertainties in the computation of radiative corrections to Higgs mass
we assume a 3 GeV window in $m_h$

$$122 \leq m_h \leq 128 \text{ GeV.}$$  \hspace{1cm} (10)

The experimental limits on $\text{Br}(B \to X_s \gamma)$
$\text{Br}(B \to X_s \gamma) = [3.42 \pm 0.22] \times 10^{-4}$ which at 3$\sigma$ level results into

$$2.77 \times 10^{-4} \leq \text{Br}(B \to X_s \gamma) \leq 4.09 \times 10^{-4}.$$  \hspace{1cm} (11)

The recent constraints from $\text{Br}(B_s \to \mu^+\mu^-)$ as obtained from CMS and LHCb indicate $\text{Br}(B_s \to \mu^+\mu^-) = [2.9 \pm 0.7] \times 10^{-9}$, which at 3$\sigma$ level leads to

$$0.8 \times 10^{-9} \leq \text{Br}(B_s \to \mu^+\mu^-) \leq 5 \times 10^{-9}.$$  \hspace{1cm} (12)
Figure: The variation of $m_h$ against $A_t^2/M_{\#}^2$, where $M_{\#}^2 = m_{H_2}^2 + \mu^2 + m_{t_L}^2 + m_{t_R}^2$. Blue, green, grey dots correspond to stable, long-lived and short-lived vacua respectively. The first two type will comprise “safe” vacuum.
Study of generic region of pMSSM parameter space for the stability of the vacuum.

Scan over wide range of $\mu$ and $A_t$ for $\tan \beta = 20$
Scan over wide range of $\mu$ and $A_t$ for $\tan \beta = 40$

Figure: The variation of $m_h$ vs $X_t/M_S$, where $M_S = \sqrt{m_{\tilde{t}_L}m_{\tilde{t}_R}}$

Blue, green and grey dots correspond to stable, long-lived and short-lived vacua respectively. Same color code followed in the other plots.
Scan over wide range of $\mu$ and $A_t$ for $\tan \beta = 20$

$m_{\tilde{Q}_3}, m_{\tilde{U}_3}, m_{\tilde{D}_3}$ at 2 TeV.

All other sfermion masses fixed at 1 TeV, $M_A = 1$ TeV. Allowed non-zero vevs for $\tilde{t}_L, \tilde{t}_R, \tilde{b}_L$ and $\tilde{b}_R$

$$-10 \text{ TeV} \leq A_t \leq 10 \text{ TeV},$$
$$-11 \text{ TeV} \leq \mu \leq 11 \text{ TeV}.$$ (13)

Importance of non-vanishing $A_b$ in context of vacuum stability in CCB scenario, for large $\mu$ zones.

However, non-vanishing $A_b$ would hardly have an effect on $m_h$.

Hence we use the following range for $A_b$ namely, $-6$ TeV to 6 TeV

Gaugino mass parameters are fixed at,

$$M_1 = 500 \text{ GeV}, \quad M_2 = 525 \text{ GeV}, \quad M_3 = 1400 \text{ GeV}.$$ (14)
Study of generic region of pMSSM parameter space for the stability of vacuum

Scan over wide range of $\mu$ and $A_t$ for $\tan\beta = 20$

Scan over wide range of $\mu$ and $A_t$ for $\tan\beta = 40$
Study of generic region of pMSSM parameter space for the stability of vacuum.

Scan over wide range of $\mu$ and $A_t$ for $\tan \beta = 20$

Scan over wide range of $\mu$ and $A_t$ for $\tan \beta = 40$
A larger value (3 TeV) for the third generation of squark mass parameter.

The combined sbottom and stau loop contributions typically amounts to 10-15 percent within the range of Higgs boson mass.

We choose the following ranges for \( \mu, A_t \), and \( A_b \):

\[
- 10 \ \text{TeV} \leq A_t \leq 10 \ \text{TeV}, \\
- 6 \ \text{TeV} \leq A_b \leq 6 \ \text{TeV}, \\
- 7 \ \text{TeV} \leq \mu \leq 7 \ \text{TeV} .
\]  
(15)
Study of generic region of pMSSM parameter space for the stability of vacuum

Scan over wide range of $\mu$ and $A_t$ for $\tan \beta = 20$

Scan over wide range of $\mu$ and $A_t$ for $\tan \beta = 40$
Study of generic region of pMSSM parameter space for the stability of the vacuum
Scan over wide range of $\mu$ and $A_t$ for $\tan \beta = 20$
Scan over wide range of $\mu$ and $A_t$ for $\tan \beta = 40$
Study of generic region of pMSSM parameter space for the stability
of the vacuum

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|}
\hline
\textbf{Parameters} & \textbf{\varepsilon \text{ Region I}} & \textbf{\varepsilon \text{ Region II}} & \textbf{\varepsilon \text{ Region I}} & \textbf{\varepsilon \text{ Region II}} \\
\hline
\text{m}_{1,2,3} & 160, 179, 1400 & 500, 525, 1400 & 490, 550, 1400 & 500, 525, 1400 \\
\text{m}_{H_d}/m_{H_u}/m_{H_d} & 2000 & 2000 & 3000 & 3000 \\
\text{m}_{Q_2}/m_{Q_1}/m_{Q_2} & 1000 & 1000 & 1000 & 1000 \\
\text{m}_{U_2}/m_{U_1}/m_{U_2} & 1000 & 1000 & 1000 & 1000 \\
\text{m}_{L_2}/m_{L_1}/m_{E_2} & 430 & 600 & 510 & 572 \\
\text{m}_{L_1}/m_{E_1} & 430 & 600 & 510 & 572 \\
\text{A}_{t}, A_{h}, A_{t} & 3500, 0, 0 & 5188.5, -2640.2, 0 & 6291.2, 0, 0 & 6273.4, -3040.7, 0 \\
\text{tan}\beta & 20 & 20 & 40 & 40 \\
\mu & 1000 & 8831.0 & 1500.0 & 4940.2 \\
\mu & 1000 & 1000 & 1000 & 1000 \\
\hline
\text{m}_{b} & 1480.9 & 1486.7 & 1531.6 & 1531.6 \\
\text{m}_{t_h} & 1083.5 & 1083.2 & 1179.8 & 1107.9 \\
\text{m}_{t}, m_{\chi} & 1880.0, 2113.5 & 922.7, 1683.7 & 2870.1, 3088.2 & 2771.3, 3064.7 \\
\text{m}_{b}, m_{\chi} & 2055.2, 2054.8 & 1986.6, 2101.4 & 3023.6, 3008.8 & 2995.9, 3087.9 \\
\text{m}_{t}, m_{\chi} & 432.4, 425.3 & 601.8, 596.8 & 512.1, 566.1 & 573.4, 568.3 \\
\text{m}_{b}, m_{\chi} & 984.0, 998.0 & 838.8, 998.0 & 946.3, 998.0 & 810.8, 998.0 \\
\text{m}_{t}, m_{\chi} & 177.2, 1006.4 & 524.9, 883.17 & 548.1, 1505.4 & 524.8, 491.5 \\
\text{m}_{b}, m_{\chi} & 159.4, 177.3 & 500.0, 524.9 & 489.4, 548.1 & 500.0, 524.8 \\
\text{m}_{t}, m_{\chi} & 1003.1, 1005.4 & 8313.4, 8313.5 & 1502.5, 1505.4 & 4940.9, 4941.2 \\
\text{m}_{H_2} & 1003.5 & 1001.2 & 1003.4 & 1002.7 \\
\text{m}_{b}, m_{\chi} & 1000.0, 1268.8 & 988.8, 122.1 & 1000.0, 127.5 & 999.5, 124.9 \\
\text{B}_{k}(B\rightarrow X_s\gamma) & 3.67 \times 10^{-4} & 2.85 \times 10^{-4} & 3.75 \times 10^{-4} & 3.25 \times 10^{-4} \\
\text{B}_{k}(B_s\rightarrow \mu^+\mu^-) & 3.17 \times 10^{-9} & 3.23 \times 10^{-9} & 1.85 \times 10^{-9} & 1.95 \times 10^{-9} \\
\alpha_{\mu} & 11.9 \times 10^{-10} & 12.0 \times 10^{-10} & 11.8 \times 10^{-10} & 16.5 \times 10^{-10} \\
\text{BR(FG)}^2 & 0.128 & 0.118 & 0.113 & 0.107 \\
\text{BR(\phi)}^2 & 3.74 \times 10^{-11} & 1.82 \times 10^{-11} & 3.92 \times 10^{-11} & 9.07 \times 10^{-13} \\
\hline
\end{tabular}
\caption{Benchmark points for long-lived vacuum states}
\end{table}
The Higgs boson has been discovered at LHC with its mass around 125 GeV, relatively heavy, not friendly to Hierarchy problem.

Exploration of the MSSM parameter space that may still be associated with a relatively lighter SUSY spectra.

Large radiative corrections to the Higgs boson mass required.

Considering large mixing between the left and the right scalar components $m_h$, with relatively light stop.

Large value of trilinear coupling $|A_t|$ necessary $\rightarrow$ CCB minima may appear.
- Very large $A_t \rightarrow$ lighter stop but heavier Higgs for low $\mu$.
- Large $\mu \rightarrow$ negative contribution to $m_h$ for sbottom and stau loops, for large $\tan \beta$
- Large $\mu$, sensitive to CCB minima
- For large $\mu$ and large $A_t$, there exist region characterized by long-lived SM like vacuum, that are otherwise excluded by traditional CCB constraints.
- These region are characterized by lighter stops.
- The above region compatible with low energy constraints and dark matter direct detection results and give adequate relic abundance.