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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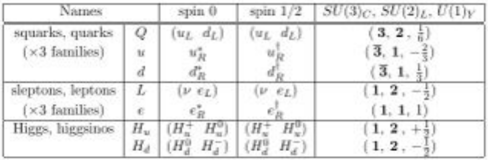
Introduction

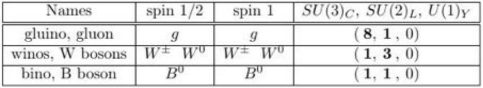
- Higgs Boson, discovered at LHC
- BSM physics ⟶ hierarchy problem, dark matter etc
- SM : low energy approx of SUSY
- MSSM - SM fermions and bosons are supplemented by bosonic and fermionic partners transforming under the same SM gauge group $\mathrm{SU(3)_C \times SU(2)_L \times U(1)_Y}$.

Particle content of MSSM



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

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	$(\,\mathbf{8},\,\mathbf{1}\,,\,0)$
winos, W bosons	$W^\pm \;\; W^0$	$W^\pm \;\; W^0$	$(\,\mathbf{1},\,\mathbf{3}\,,\,0)$
bino, B boson	B^0	B^0	$(\,\mathbf{1},\,\mathbf{1}\,,\,0)$

Table 0.2: Gauge supermultiplets in the Minimal Supersymmetric Standard Model.

- Higgs@125 GeV $\longrightarrow$ radiative corrections to Higgs mass important
- In SUSY models, this demands exessively heavy scalar sparticles(in CMSSM), stops(in MSSM)
- Stop loop is most important,
- In large μ 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 $A_t \longrightarrow$ larger m_h
- Increasing $\mu \longrightarrow$ -ve contribution from sbottom and stau loops $\longrightarrow$ proper m_h.
- Large A_t, $\mu \longrightarrow$ charge color breaking(CCB) global minima of MSSM scalar potential
- Revisit the CCB constraints numerically for a wider range of A_t and μ in search for stable and long-lived vacuum.
- B-Physics and Dark matter experimental results-constraints.

- MSSM - scalars like squarks and sleptons charged under $SU(3)_{color}$ or $U(1)_{EM}$.
- Non vanishing *vevs* $\longrightarrow$ CCB minima
- Non-observation of CCB processes $\longrightarrow$ 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 $\longrightarrow$ long-lived state
- Long-lived states $\longrightarrow$ 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,

$$\begin{aligned} V = &\left(m^2_{H_u} + \mu^2\right)|H_u|^2 + \left(m^2_{H_d} + \mu^2\right)|H_d|^2 + m^2_{\tilde{t}_L}|\tilde{t}_L|^2 + m^2_{\tilde{t}_R}|\tilde{t}_R|^2 - \\ &B_\mu\left(H_u H_d + \text{c.c.}\right) + \left(y_t A_t H_u \tilde{t}_L \tilde{t}_R + \text{c.c.}\right) - \left(y_t \mu \tilde{t}_L \tilde{t}_R H_d^* + \text{c.c.}\right) + \\ &y_t^2\left(|\tilde{t}_L \tilde{t}_R|^2 + |H_u \tilde{t}_L|^2 + |H_u \tilde{t}_R|^2\right) + \frac{g_2^2}{8}\left(|H_u|^2 - |H_d|^2 - |\tilde{t}_L|^2\right)^2 + \\ &\frac{g_1^2}{8}\left(|H_u|^2 - |H_d|^2 + \frac{1}{3}|\tilde{t}_L|^2 - \frac{4}{3}|\tilde{t}_R|^2\right)^2 + \frac{g_3^2}{6}\left(|\tilde{t}_L|^2 - |\tilde{t}_R|^2\right)^2 . \quad (1) \end{aligned}$$

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]

$$\Gamma/V = A\mathrm{e}^{-S[\bar{\phi}]/\hbar}. \tag{2}$$

Here, $\bar{\phi}$ is a particular configuration of the field ϕ for which δS$=$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

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

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

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

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

where $X_b = A_b - \mu \tan\beta$

m_h can increased by the interplay between A_t and μ. Thus for large values of these parameters one can generate suitable m_h keeping stop masses lighter. A_t, μ sensitive to CCB.

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

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

$$A_u^2 \leqslant 3[m_{H_u}^2 + \mu^2 + m_{Q_u}^2 + m_u^2]. \tag{6}$$

Considering the existence of long-lived states the above constraints modified to [Kusenko *et. al.*(1994), Cohen *et. al.*(2000)]

$$A_u^2 + 3\mu^2 \leqslant 7.5[m_{Q_u}^2 + m_u^2] \tag{7}$$

$$A_u^2 \leqslant \ 3[m_{H_u}^2 + \mu^2] + 7.5[m_{Q_u}^2 + m_u^2]. \tag{8}$$

- 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 μ significant contribution to m_h from the sbottom loop.
- Violation of CCB constraints for large A_t and μ
- non-zero *vevs* for stops and sbottom fields and scan over A_t and A_b and μ, while investigating the large μ 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 vacuua associated with a point in the multi-dimensional parameter space as "*long-lived" or "short-lived"*

Results

- Vacuum stability for low values of μ.
- Wide range of values of μ and A_t for a moderate and a large value of $\tan\beta$ considering non-zero *vevs* for stop and sbottom.
- $\mathrm{Br}(B_s \to \mu^+\mu^-)$, $\mathrm{Br}(B_s \to \mu^+\mu^-)$, 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 μ upto a TeV.
- Only stop fields ($\tilde{t}_L$ and $\tilde{t}_R$) non-zero *vevs*.

Our choice of parameters are as follows.

$$\begin{aligned} 500\ \mathrm{GeV} &\leqslant m_{\tilde{Q}_3} \leqslant 1500\ \mathrm{GeV}, \\ 500\ \mathrm{GeV} &\leqslant m_{\tilde{U}_3} \leqslant 1500\ \mathrm{GeV}, \\ 5 &\leqslant \tan\beta \leqslant 60, \\ 100\ \mathrm{GeV} &\leqslant \mu \leqslant 1000\ \mathrm{GeV}, \\ -3\ m_{\tilde{Q}_3} &\leqslant A_t \leqslant 3\ m_{\tilde{Q}_3}. \end{aligned} \tag{9}$$

All other sfermion masses to be at 1 TeV, $\mathrm{M_A}$= 1 TeV.
$\mathrm{M_1} = 100$ GeV, $\mathrm{M_2} = 300$ GeV and $\mathrm{M_3} = 1000$ 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

$$122 \leqslant m_h \leqslant 128 \text{ GeV}. \tag{10}$$

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

$$2.77 \times 10^{-4} \leqslant \mathrm{Br}(B \to X_s\gamma) \leqslant 4.09 \times 10^{-4}. \tag{11}$$

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

$$0.8 \times 10^{-9} \leqslant \mathrm{Br}(B_s \to \mu^+\mu^-) \leqslant 5 \times 10^{-9}. \tag{12}$$

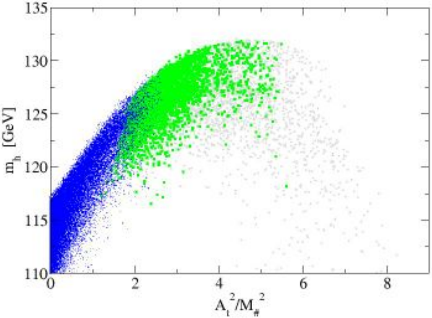


Figure: *The variation of m_h against $A_t^2/M_\#^2$, where $M_\#^2 = m_{H_2}^2 + \mu^2 + m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2$. Blue, green, grey dots correspond to stable, long-lived and short-lived vacua respectively. The first two type will comprise "safe" vacuum.*

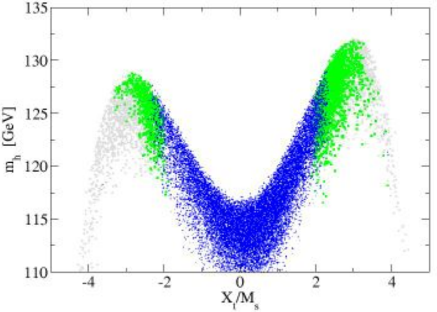


Figure: *The variation of m_h vs X_t/M_S, where $M_S = \sqrt{m_{\tilde{t}_L} m_{\tilde{t}_R}}$ Blue, green and grey dots corresponds to stable, long-lived and short-lived vacua respectively. Same color code followed in the other plots.*

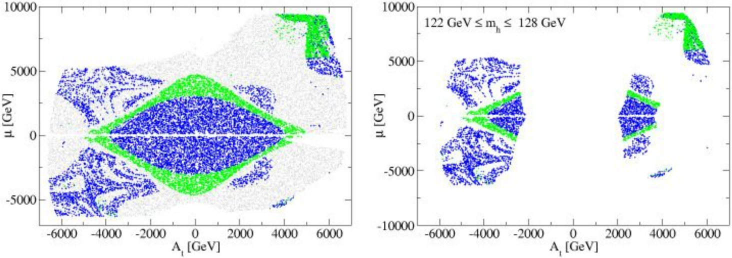
Scan over wide range of μ and A_t for $\tan\beta = 20$

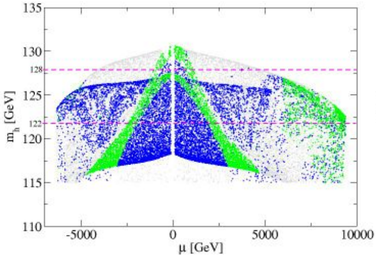
$m_{\tilde{Q}_3}, m_{\tilde{U}_3}, m_{\tilde{D}_3}$ at 2 TeV.
All other sfermion masses fixed at 1 TeV , $M_A = 1$ TeV. Allowed non-zero *vevs* for $\tilde{t}_L$,$\tilde{t}_R$,$\tilde{b}_L$ and $\tilde{b}_R$

$$\begin{aligned} -10\ \mathrm{TeV} &\leqslant \mathrm{A_t} \leqslant 10\ \mathrm{TeV}, \\ -11\ \mathrm{TeV} &\leqslant \mu \leqslant 11\ \mathrm{TeV}\ . \end{aligned} \tag{13}$$

Importance of non-vanishing A_b in context of vacuum stability in CCB scenario, for large μ 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,

$$\mathrm{M_1} = 500\ \mathrm{GeV},\ \mathrm{M_2} = 525\ \mathrm{GeV},\ \mathrm{M_3} = 1400\ \mathrm{GeV}\ . \tag{14}$$

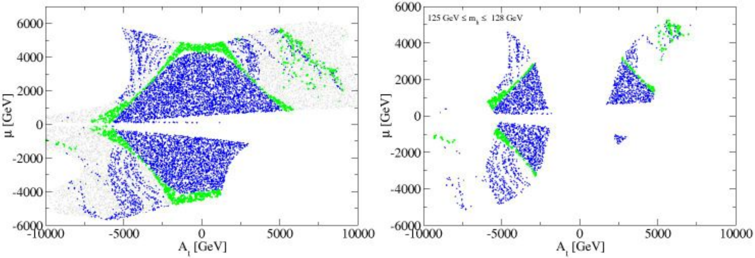

10000
5000
0
-5000
μ [GeV]
-6000
-4000
-2000
0
2000
4000
6000
A_t [GeV]
122 GeV ≤ m_h ≤ 128 GeV
10000
5000
0
-5000
-10000
μ [GeV]
-6000
-4000
-2000
0
2000
4000
6000
A_t [GeV]

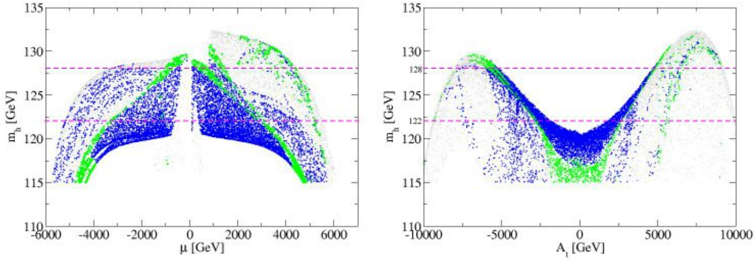

135
130
128
125
122
120
115
110
m_h [GeV]
-5000
0
5000
10000
μ [GeV]
135
130
128
125
122
120
115
110
m_h [GeV]
-6000
-4000
-2000
0
2000
4000
6000
A_t [GeV]

Scan over wide range of μ 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 μ, A_t and A_b.

$$\begin{aligned} -10\ \mathrm{TeV} \leqslant\ & \mathrm{A_t} \leqslant 10\ \mathrm{TeV}, \\ -6\ \mathrm{TeV} \leqslant\ & \mathrm{A_b} \leqslant 6\ \mathrm{TeV}, \\ -7\ \mathrm{TeV} \leqslant\ & \mu \leqslant 7\ \mathrm{TeV}\ . \end{aligned} \tag{15}$$


6000
4000
2000
0
-2000
-4000
-6000
μ [GeV]
-10000
-5000
0
5000
10000
A_t [GeV]
125 GeV ≤ m_h ≤ 128 GeV


135
130
125
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-6000
-4000
-2000
0
2000
4000
6000
m_h [GeV]
μ [GeV]
135
130
128
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122
120
115
110
-10000
-5000
0
5000
10000
m_h [GeV]
A_t [GeV]

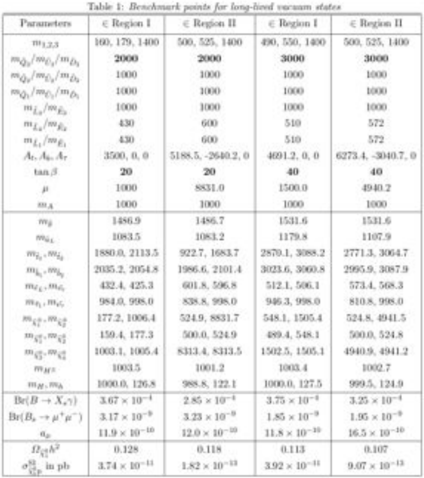

Table 1: *Benchmark points for long-lived vacuum states*

Parameters	$\in$ Region I	$\in$ Region II	$\in$ Region I	$\in$ Region II
$m_{1,2,3}$	160, 179, 1400	500, 525, 1400	490, 550, 1400	500, 525, 1400
$m_{\tilde{Q}_3}/m_{\tilde{U}_3}/m_{\tilde{D}_3}$	**2000**	**2000**	**3000**	**3000**
$m_{\tilde{Q}_2}/m_{\tilde{U}_2}/m_{\tilde{D}_2}$	1000	1000	1000	1000
$m_{\tilde{Q}_1}/m_{\tilde{U}_1}/m_{\tilde{D}_1}$	1000	1000	1000	1000
$m_{\tilde{L}_3}/m_{\tilde{E}_3}$	1000	1000	1000	1000
$m_{\tilde{L}_2}/m_{\tilde{E}_2}$	430	600	510	572
$m_{\tilde{L}_1}/m_{\tilde{E}_1}$	430	600	510	572
A_t, A_b, A_τ	3500, 0, 0	5188.5, -2640.2, 0	4691.2, 0, 0	6273.4, -3040.7, 0
$\tan\beta$	**20**	**20**	**40**	**40**
μ	1000	8831.0	1500.0	4940.2
m_A	1000	1000	1000	1000
$m_{\tilde{g}}$	1486.9	1486.7	1531.6	1531.6
$m_{\tilde{u}_L}$	1083.5	1083.2	1179.8	1107.9
$m_{\tilde{t}_1}, m_{\tilde{t}_2}$	1880.0, 2113.5	922.7, 1683.7	2870.1, 3088.2	2771.3, 3064.7
$m_{\tilde{b}_1}, m_{\tilde{b}_2}$	2035.2, 2054.8	1986.6, 2101.4	3023.6, 3060.8	2995.9, 3087.9
$m_{\tilde{e}_L}, m_{\tilde{e}_R}$	432.4, 425.3	601.8, 596.8	512.1, 506.1	573.4, 568.3
$m_{\tilde{\tau}_1}, m_{\tilde{\nu}_\tau}$	984.0, 998.0	838.8, 998.0	946.3, 998.0	810.8, 998.0
$m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_2^\pm}$	177.2, 1006.4	524.9, 8831.7	548.1, 1505.4	524.8, 4941.5
$m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_2^0}$	159.4, 177.3	500.0, 524.9	489.4, 548.1	500.0, 524.8
$m_{\tilde{\chi}_3^0}, m_{\tilde{\chi}_4^0}$	1003.1, 1005.4	8313.4, 8313.5	1502.5, 1505.1	4940.9, 4941.2
$m_{H^\pm}$	1003.5	1001.2	1003.4	1002.7
m_H, m_h	1000.0, 126.8	988.8, 122.1	1000.0, 127.5	999.5, 124.9
$\mathrm{Br}(B \to X_s\gamma)$	3.67×10^{-4}	2.85×10^{-4}	3.75×10^{-4}	3.25×10^{-4}
$\mathrm{Br}(B_s \to \mu^+\mu^-)$	3.17×10^{-9}	3.23×10^{-9}	1.85×10^{-9}	1.95×10^{-9}
a_μ	11.9×10^{-10}	12.0×10^{-10}	11.8×10^{-10}	16.5×10^{-10}
$\Omega_{\tilde{\chi}_1^0} h^2$	0.128	0.118	0.113	0.107
$\sigma^{SI}_{\tilde{\chi}_1^0 p}$ in pb	3.74×10^{-11}	1.82×10^{-13}	3.92×10^{-11}	9.07×10^{-13}

Conclusion

- 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 $\longrightarrow m_h$, with relatively light stop.
- Large value of trilinear coupling $|A_t|$ necessary $\longrightarrow$ CCB minima may appear.

- Very large $A_t \longrightarrow$ lighter stop but heavier Higgs for low μ.
- Large $\mu \longrightarrow$ negative contribution to m_h for sbottom and stau loops, for large $\tan\beta$
- Large μ, sensitive to CCB minima
- For large μ 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.