$SU(5)$ With Mirage Mediation: Dark Matter and LHC Implications

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Outline

The Standard Model

- The SM is a gauge theory of fields of spin 0, $1/2$ and 1 based on $SU(3)_c \times SU(2)_L \times U(1)_Y$

  $SU(3)_c \rightarrow$ QCD, confinement

  $SU(2)_L \times U(1)_Y \rightarrow$ electroweak interactions, chiral, spontaneous symmetry breaking

$$SU(2)_L \times U(1)_Y \rightarrow U(1)_{\mathrm{em}}$$

- The SM is one of the most successful theories in physics. It has been tested rigorously.

  $W^{\pm}, Z$ bosons

  Rare B-meson decays: $B_s \rightarrow \mu^+\mu^-$, $b \rightarrow s\gamma$

  The Higgs Boson

Standard Model

SM is not a fundamental theory!

- Gauge Hierarchy problem: $\delta m_h^2 \propto \Lambda^2$
- The gauge symmetry
- The Higgs vacuum stability: $\lambda < 0$ for $\Lambda \gtrsim 10^{10}$ GeV

  Stability Condition[1]: $m_h > (129.6 \pm 1.5)$ GeV
- Neutrino masses and mixings
- Dark matter

SUSY is a symmetry that relates fermions and bosons

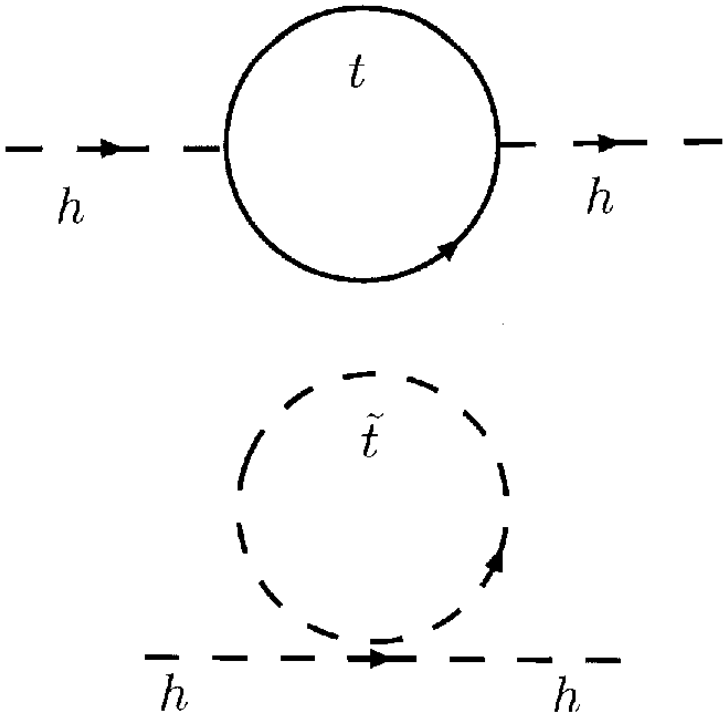
$$Q\,|fermion\rangle = |boson\rangle\,, \quad Q\,|boson\rangle = |fermion\rangle$$

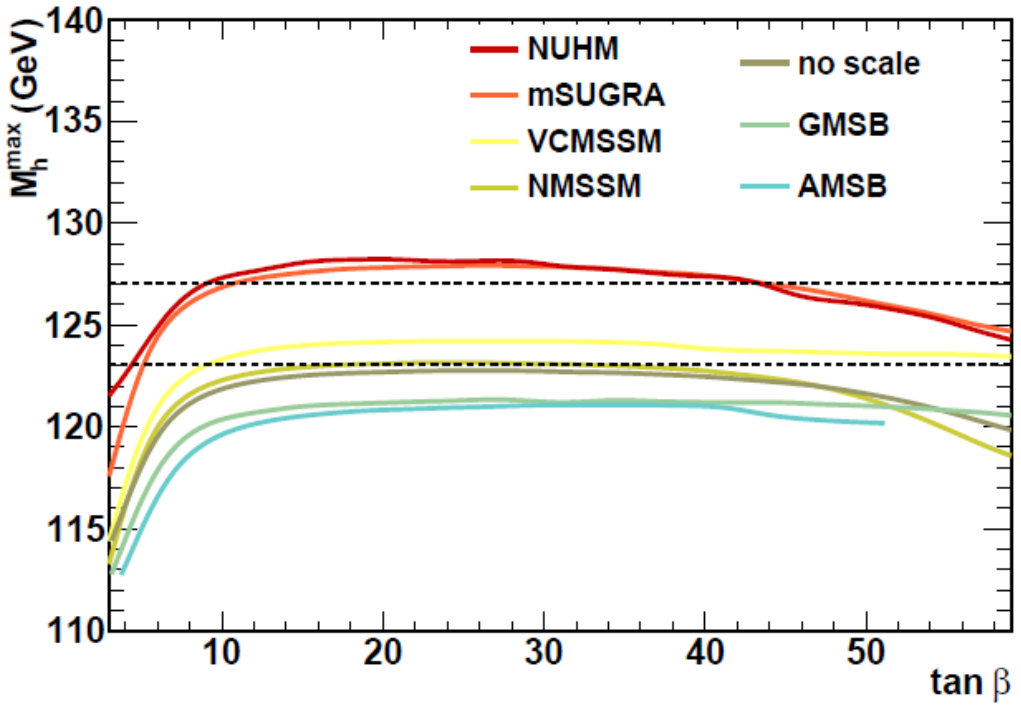
Holomorphy Condition

Two Higgs doublets $H_u, H_d \Rightarrow h, H, A, H^{\pm}$

$h \sim H_{\mathrm{SM}}$ when $m_h \ll m_H \sim m_A$ (Decoupling Limit)

Resolution to the gauge hierarchy problem.





$$m_h \lesssim 130 \text{ GeV}$$

- R-Parity: $R = (-1)^{3B+L+2S} \Rightarrow$ Stable LSP

  sneutrino, gravitino, neutralino

- Radiative Electroweak Symmetry Breaking

$$V_H = (|\mu|^2 + m_{H_u}^2)|H_u^0|^2 + (|\mu|^2 + m_{H_d}^2)|H_u^d|^2 - (bH_u^0 H_d^0 + \text{c.c.})$$

$$+\frac{1}{8}(g + g')(|H_u^0|^2 - |H_d^2|)^2$$

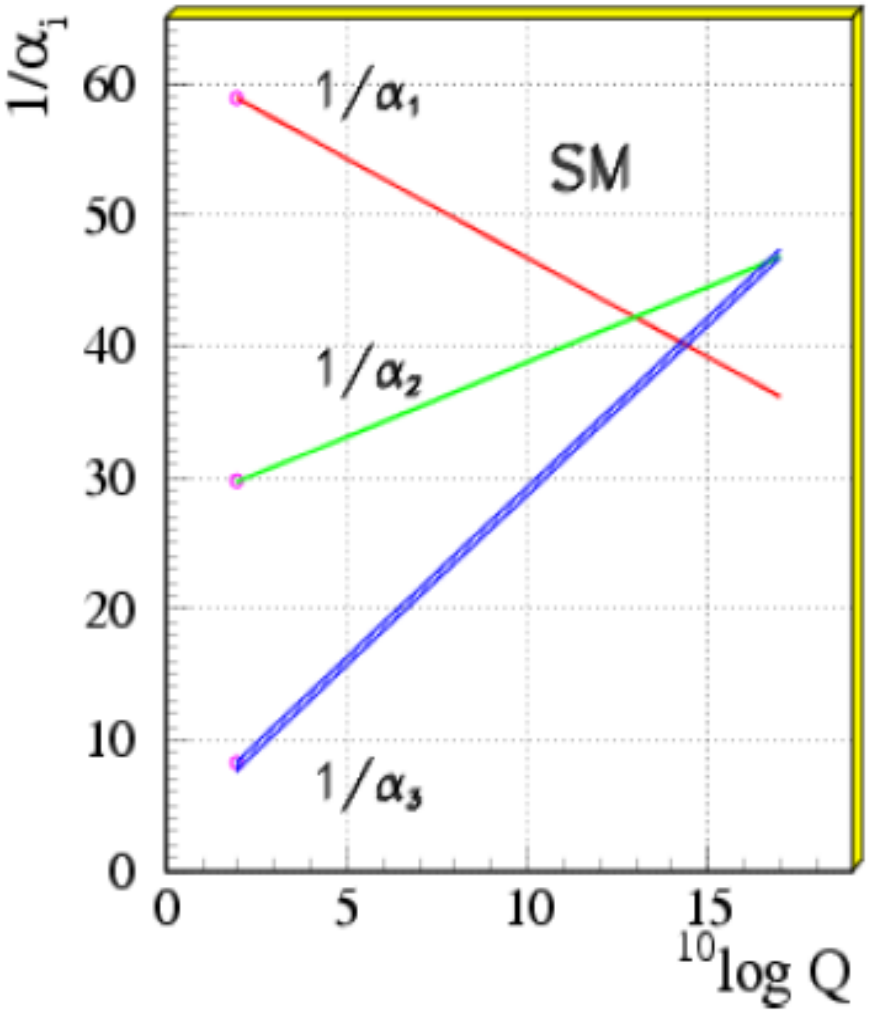
$$2b < (|\mu|^2 + m_{H_u}^2) + (|\mu|^2 + m_{H_d}^2)$$

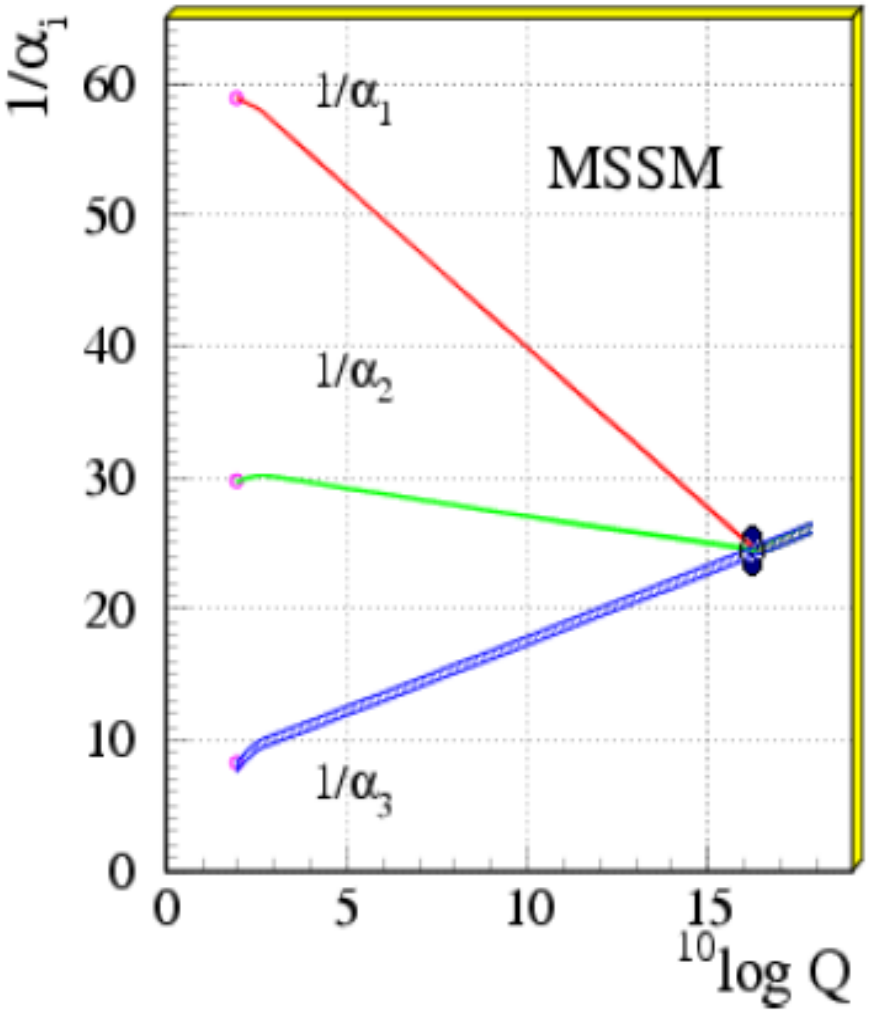
$$b^2 > (|\mu|^2 + m_{H_u}^2)(|\mu|^2 + m_{H_d}^2)$$

$$m_{H_u} \neq m_{H_d}$$

$$m_{H_u} < 0,\ m_{H_u} \ll m_{H_d}$$

Unification of gauge couplings





SUSY GUT - $SU(5)$

$$\bar{5} = \begin{pmatrix} d_1^c \\ d_2^c \\ d_3^c \\ e \\ -\nu \end{pmatrix}, \quad 10 = \begin{pmatrix} 0 & u_3^c & -u_2^c & u_1 & d_1 \\ -u_3^c & 0 & u_1^c & u_2 & d_2 \\ u_2^c & -u_1^c & 0 & u_3 & d_3 \\ -u_1 & -u_2 & -u_3 & 0 & e^c \\ -d_1 & -d_2 & -d_3 & -e_c & 0 \end{pmatrix}$$

MSSM Higgs doublets: $H_u, H_d \in 5_H, \bar{5}_H \Rightarrow y_b = y_\tau$

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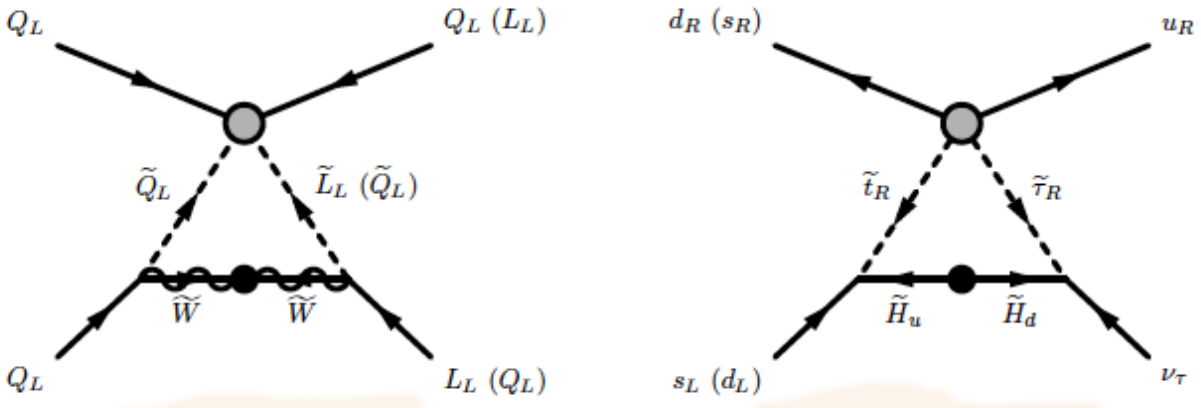

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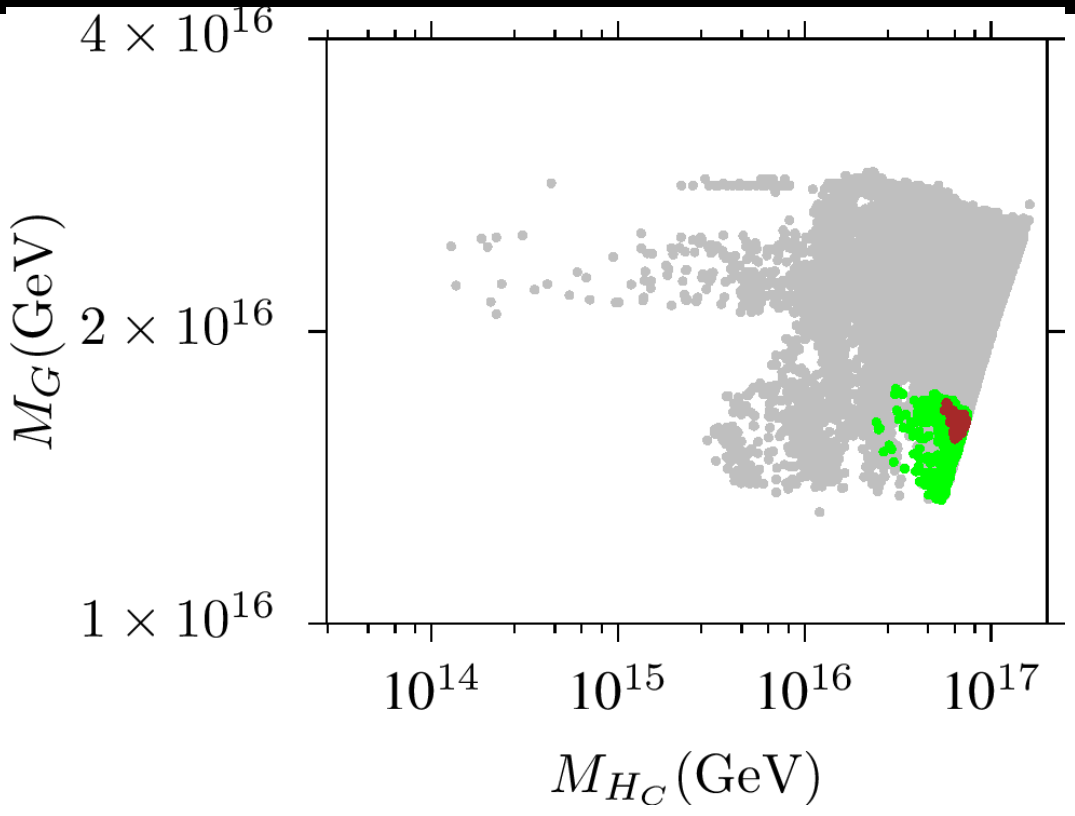


Green points are allowed by the mass bounds and rare decays of $B-$meson. Brown points are also compatible with the Planck bound on the relic abundance of neutralino LSP within 5σ.

Perturbativity + Gravitational Smearing[a] + $\Sigma^4 \longrightarrow M_{H_C} \simeq 7 \times 10^{16}$ GeV[b].

[a] T. Dasgupta, P. Mamales, P. Nath; Phys. Rev. D52 (1995), 5366.

[b] K.S. Babu, Ilia Gogoladze, Cem Salih Un, "Proton Decay in sMSSM Framework", in preparation.

SUSY $SU(5)$ with Mirage Mediation[1]

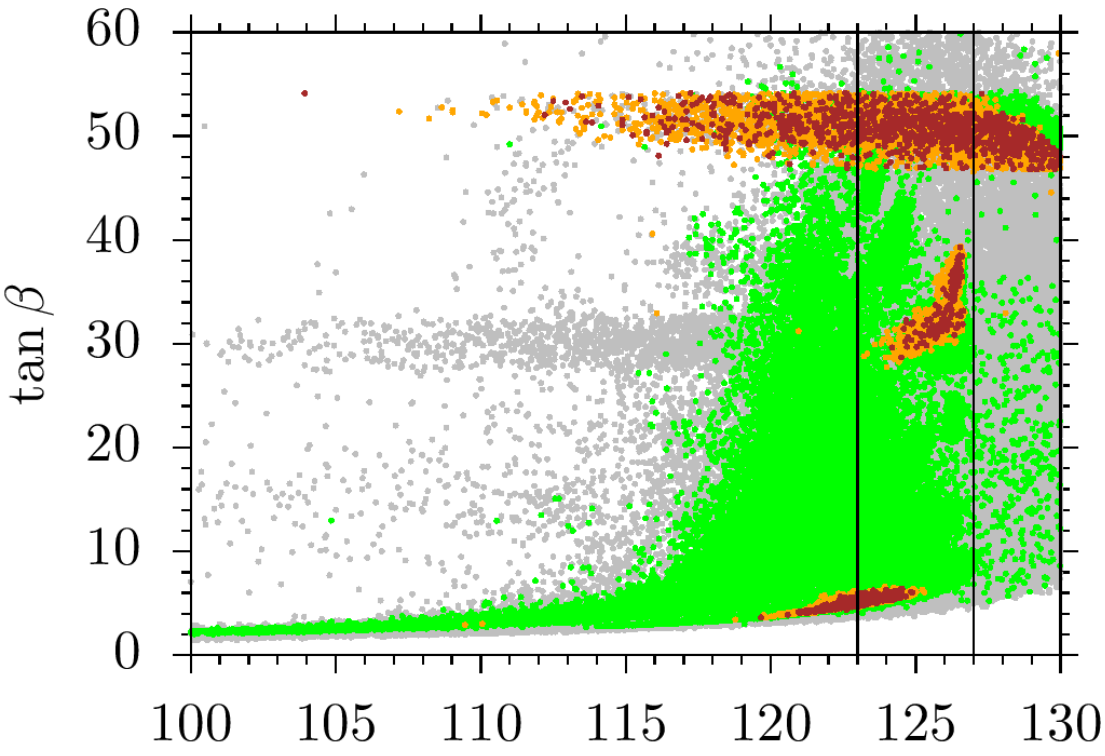
- Mirage Mediated SUSY Breaking = Gravity Mediation + Anomaly Mediation
- $M_i = \left(1 + \frac{g_5^2 b_i \alpha}{16\pi^2} \log\left(\frac{M_{Pl}}{m_{3/2}}\right)\right) M_{1/2}$
- $b_1 = 33/5,\ b_2 = 1,\ b_3 = -1$
- $m_{10}, m_5, m_{H_d}, m_{H_u}, A_t, A_b = A_\tau, \tan\beta, m_{3/2}, \alpha$

SUSY $SU(5)$ with Mirage Mediation

$$
\begin{aligned}
m_h &= 123 - 127\ \mathrm{GeV} \\
m_{\tilde{g}} &\geq 2.1\ \mathrm{TeV} (800\ \mathrm{GeV}\ \text{if}\ m_{\tilde{g}} \lesssim 1.1 m_{\tilde{\chi}_1^0}) \\
0.8 \times 10^{-9} \leq \mathrm{BR}(B_s \to \mu^+ \mu^-) &\leq 6.2 \times 10^{-9}\ (2\sigma) \\
2.99 \times 10^{-4} \leq \mathrm{BR}(b \to s\gamma) &\leq 3.87 \times 10^{-4}\ (2\sigma) \\
0.15 \leq \frac{\mathrm{BR}(B_u \to \tau\nu_\tau)_{\mathrm{MSSM}}}{\mathrm{BR}(B_u \to \tau\nu_\tau)_{\mathrm{SM}}} &\leq 2.41\ (3\sigma) \\
0.0913 \leq \Omega_{\mathrm{CDM}} h^2 (\mathrm{WMAP9}) &\leq 0.1363\ (5\sigma) \qquad .
\end{aligned}
$$

$$
R_{b\tau} \equiv \frac{\mathrm{Max}(y_b, y_\tau)}{\mathrm{Min}(y_b, y_\tau)},
$$

Higgs boson mass excluded the region with $\tan\beta < 20$, when the gaugino masses are universal[1].

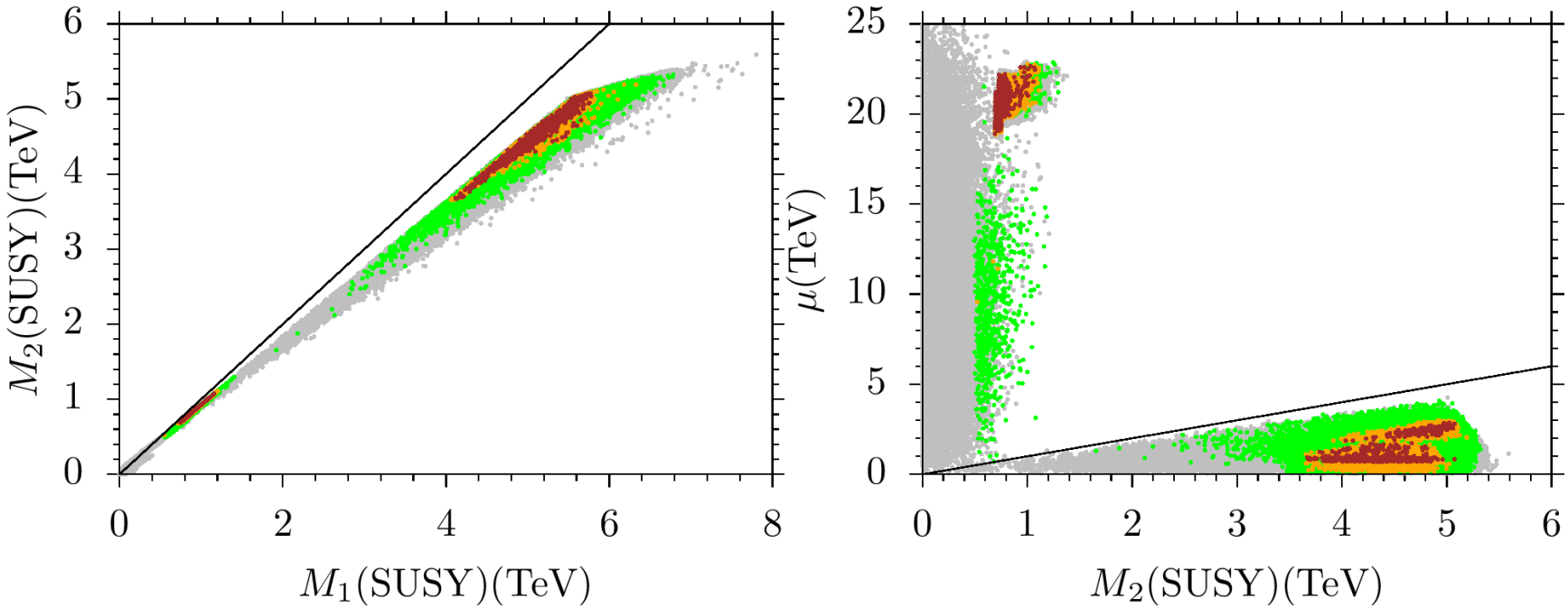


All points are compatible with REWSB and LSP neutralino. Green points satisfy the mass bounds and constraints from rare decays of $B-$meson. Orange points are a subset of green and compatible with $b-\tau$ YU. Brown points form a subset of orange, and they are allowed by the WMAP bound on relic abundance of LSP neutralino within 5σ.

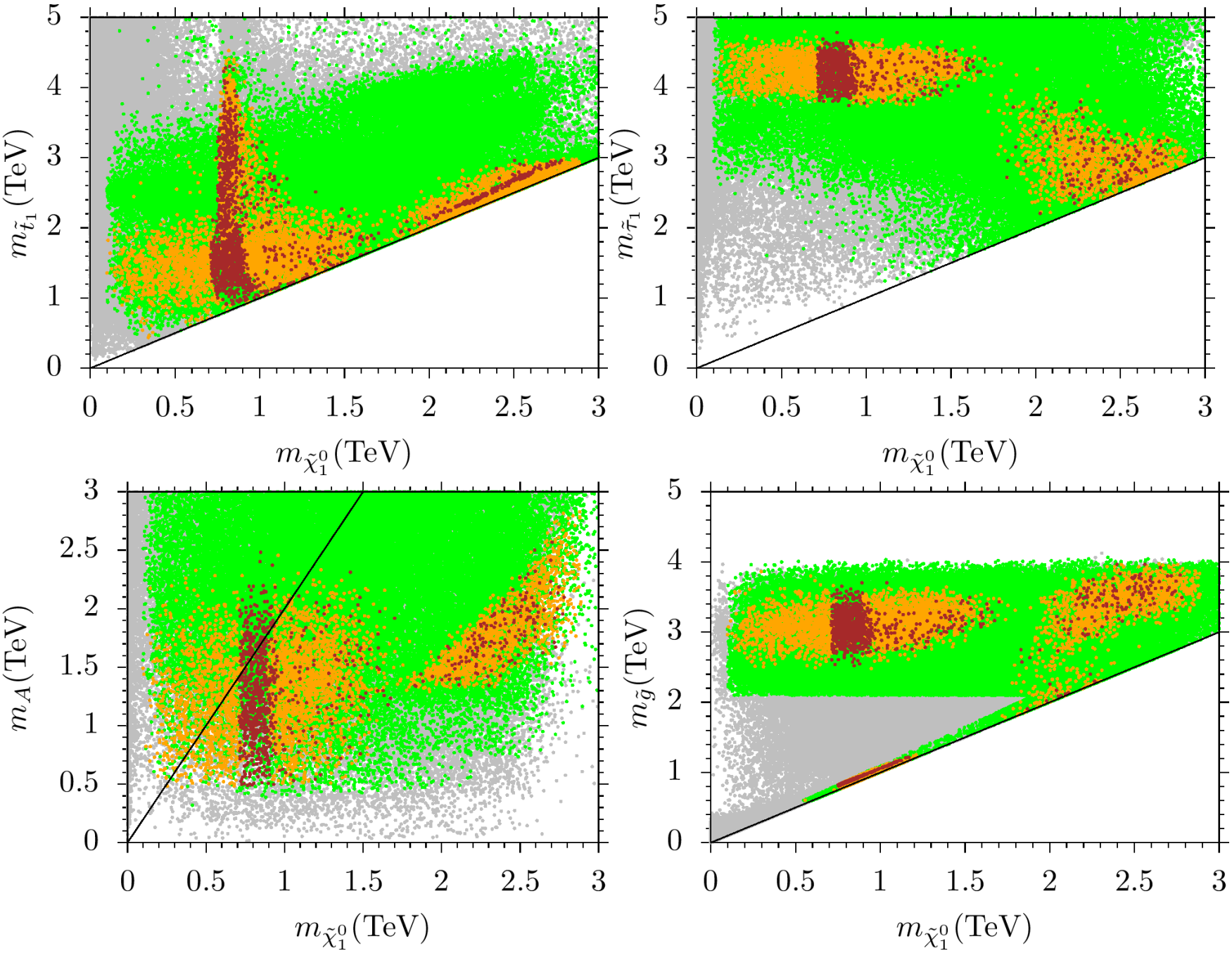
$$\Delta m_h^2 \simeq \frac{m_t^4}{16\pi^2 v^2 \sin^2\beta}\frac{\mu A_t}{M_{\rm SUSY}^2}\left[\frac{A_t^2}{M_{\rm SUSY}^2}-6\right]+$$
$$\frac{y_b^4 v^2}{16\pi^2}\sin^2\beta\frac{\mu^3 A_b}{M_{\rm SUSY}^4}+\frac{y_\tau^4 v^2}{48\pi^2}\sin^2\beta\frac{\mu^3 A_\tau}{m_{\tilde\tau}^4}\quad .$$

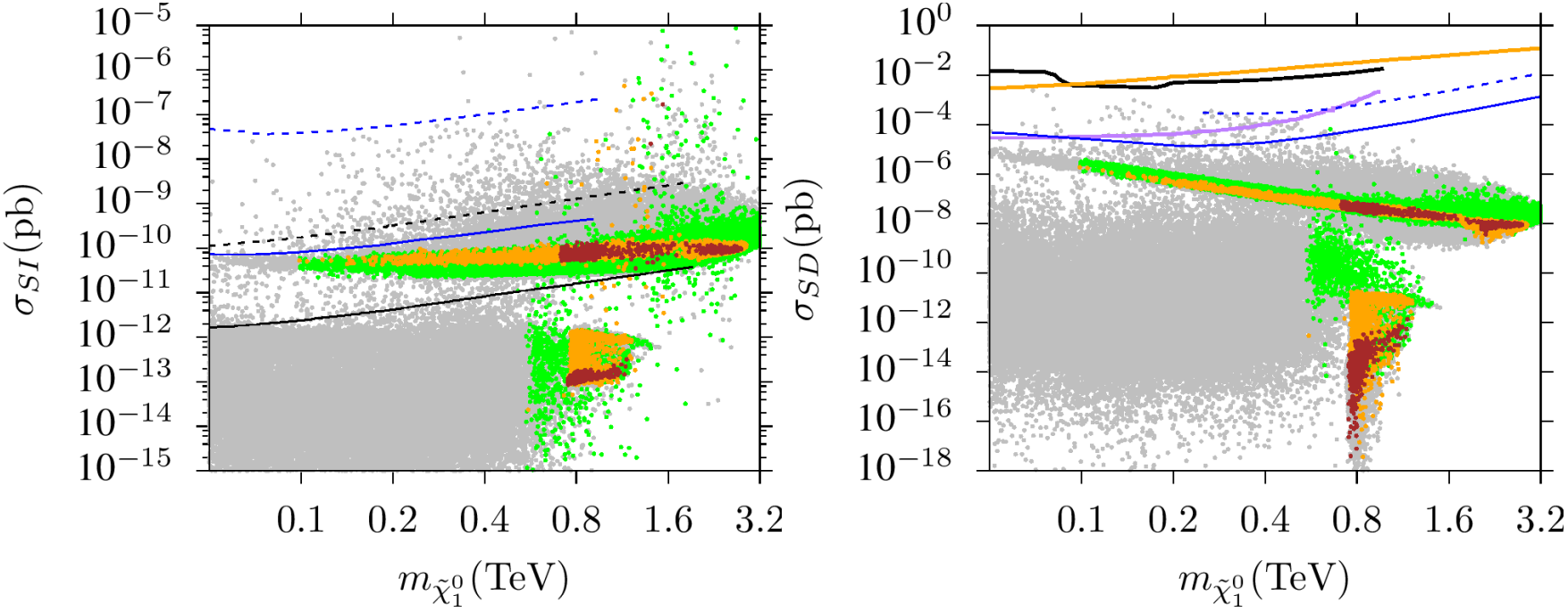
[1] H. Baer, I. Gogoladze, A. Mustafayev, S. Raza, Q. Shafi; JHEP 1203 (2012), 047.

Dark Matter Implications



Masses of neutralinos. The color coding is the same as those used in the previous plot.


$m_{\tilde{t}_1}$ (TeV)
$m_{\tilde{\chi}_1^0}$ (TeV)
$m_{\tilde{\tau}_1}$ (TeV)
$m_{\tilde{\chi}_1^0}$ (TeV)
m_A (TeV)
$m_{\tilde{\chi}_1^0}$ (TeV)
$m_{\tilde{g}}$ (TeV)
$m_{\tilde{\chi}_1^0}$ (TeV)

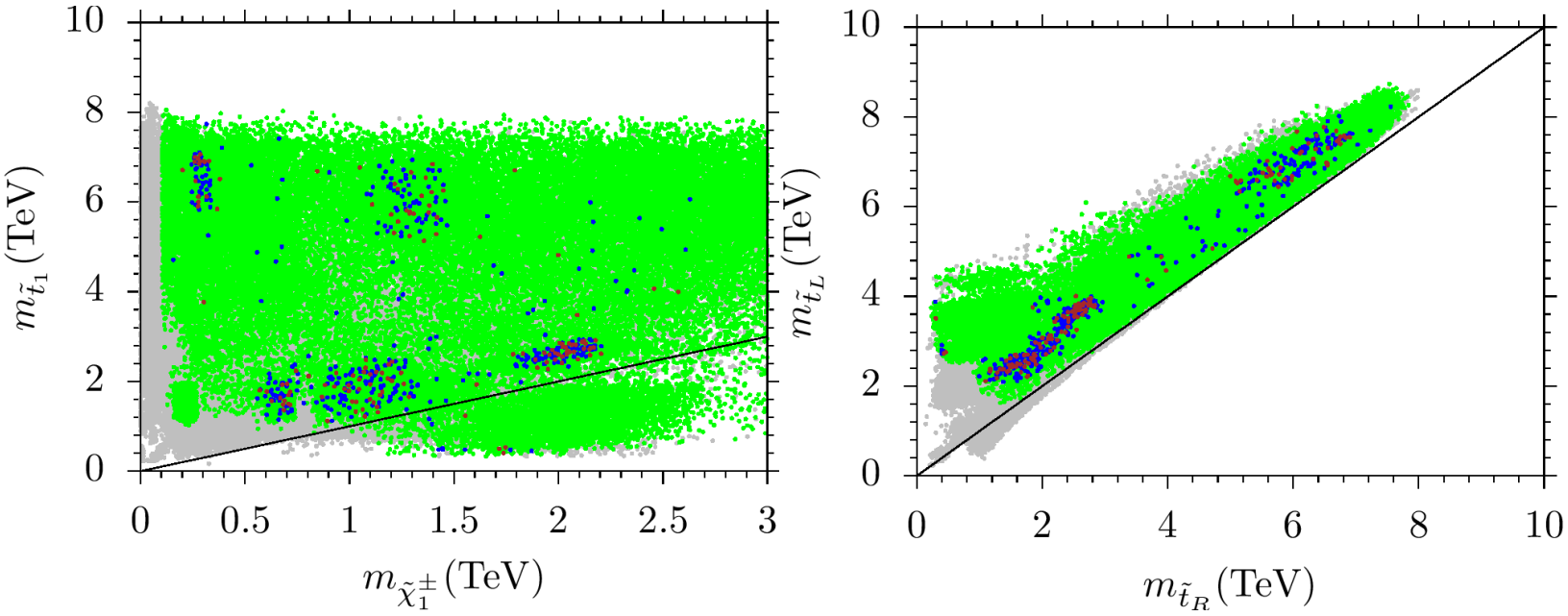


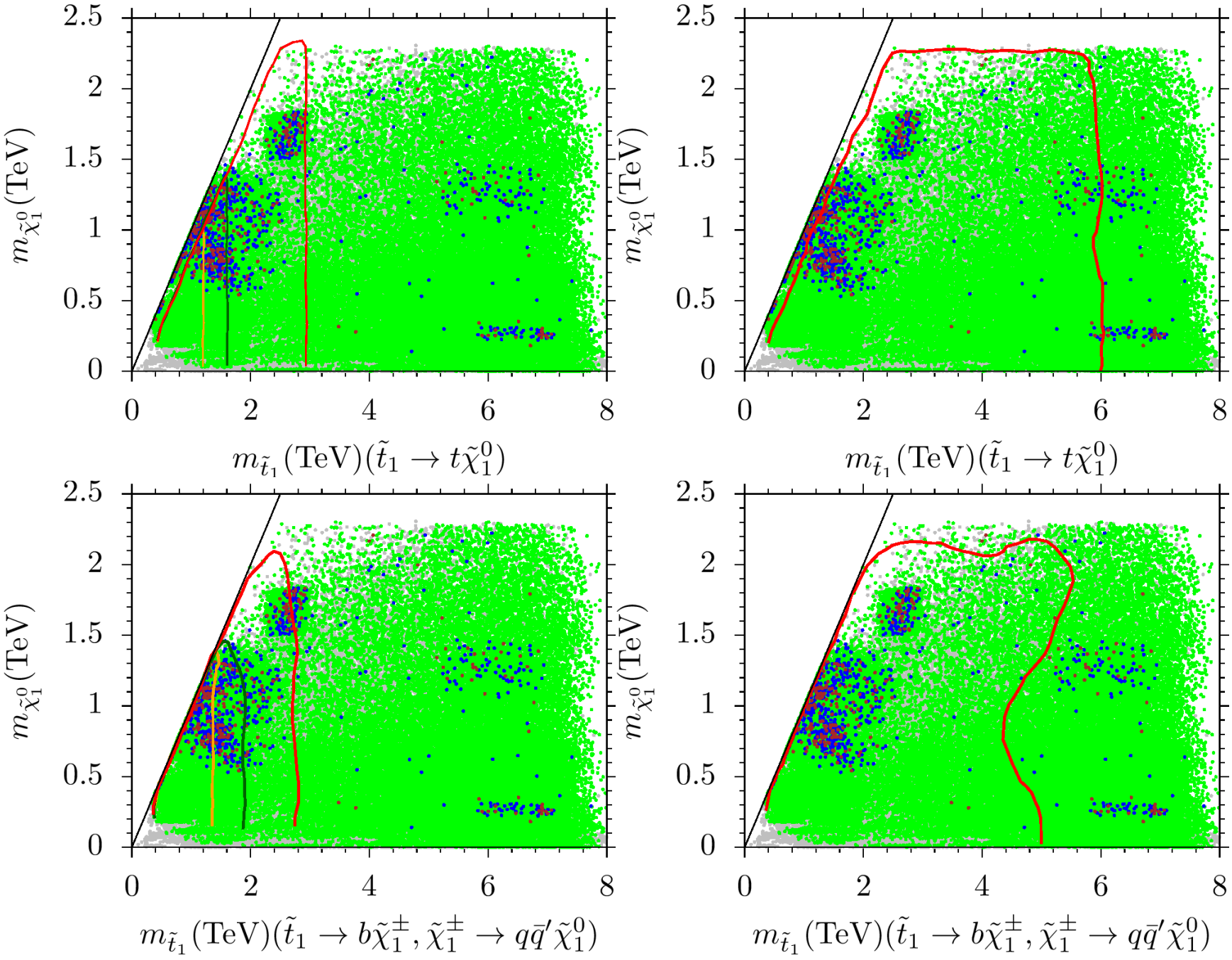
Spin-independent (left) and spin-dependent (right) scattering cross-sections versus the LSP neutralino mass. In the $\sigma_{SI} - m_{\tilde{\chi}_1^0}$ plane, the dashed (solid) blue line represents the current (future) results from the SuperCDMS experiment. The dashed (solid) line indicates the current (future) results from the LUX-Zeplin experiment. In the $\sigma_{SD} - m_{\tilde{\chi}_1^0}$ plane, the solid black line represents the currrent bound from Super-K , while the orange solid line is set by the LUX results. The purple line is obtained from the collider analyses . The dashed (solid) blue line shows the current (future) results from IceCube DeepCore.

Signal 1 : $pp \to \tilde{t}_1 \tilde{t}_1 \xrightarrow{\tilde{t}_1 \to t\tilde{\chi}_1^0} t\bar{t}\tilde{\chi}_1^0\tilde{\chi}_1^0$

Signal 2 : $pp \to \tilde{t}_1 \tilde{t}_1 \xrightarrow{\tilde{t}_1 \to b\tilde{\chi}_1^\pm} b\bar{b}\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp \xrightarrow{\tilde{\chi}_1^\pm \to W^\pm\tilde{\chi}_1^0} \to b\bar{b}W^\pm W^\mp\tilde{\chi}_1^0\tilde{\chi}_1^0$

Signal 3 : $pp \to \tilde{t}_1 \tilde{t}_1 \xrightarrow{\tilde{t}_1 \to b\tilde{\chi}_1^\pm} b\bar{b}\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp \xrightarrow{\tilde{\chi}_1^\pm \to q\bar{q}'\tilde{\chi}_1^0} \to b\bar{b}(q\bar{q}')(q\bar{q}')\tilde{\chi}_1^0$




$m_{\tilde{\chi}_1^0}$(TeV)
$m_{\tilde{t}_1}$(TeV)$(\tilde{t}_1 \to t\tilde{\chi}_1^0)$
$m_{\tilde{t}_1}$(TeV)$(\tilde{t}_1 \to b\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \to q\bar{q}'\tilde{\chi}_1^0)$
0
0.5
1
1.5
2
2.5
2
4
6
8

Conclusion

- SUSY $SU(5)$ still survive under the proton decay: heavy squarks
- Consistent with the Higgs boson mass constraint for $\tan\beta < 20$,
- Favors Stop, stau, gluino coannihilation scenarios as well as $A-$resonance solutions,
- Higgsino DM, Wino DM or bino-wino mixture
- Stop signal through decay mode involving chargino is not available at the current experiments,
- Stop can be probed up to about 5-6 TeV in future collider experiments.