Collider Phenomenology of Natural SUSY: Stop and Higgsinos

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Naturalness in the SM

When confronted with experiments, the Standard Model (SM) has proven to be very robust both in its general structure as well as in every detail tested so far, in particular the discovery of the Higgs boson.

$$m_h^{LHC} = 125.09 \pm 0.21(stat.) \pm 0.11(syst.)\ \mathrm{GeV}^1$$

However, a satisfactory understanding of the origin of electro-weak symmetry breaking has been an ever elusive problem. Many other possibilities have been proposed in the past decades. There is one guiding principle, known as the Naturalness Principle.

[1] The ATLAS and CMS Collaborations, arXiv:1503.07589

Naturalness in the SM

In the SM, the naturalness problem is usually stated as *quantum corrections to the Higgs mass are quadratically divergent*, or in equations,

$$\delta m_h^2 = \left[\frac{1}{4}(9g^2 + 2g^{'2} - 6y_t^2 + 6\lambda)\right]\frac{\Lambda^2}{32\pi^2}.$$

It is natural to assume the cut-off scale Λ at least the Planck scale ($\sim 10^{19}$ GeV), where the gravity becomes strong and quantum gravity effects are relevant. If there is nothing but the SM between the scale of EWSB and the Planck mass, the bare parameters of the Higgs potential have to be adjusted to cancel the quantum corrections to one part in $\sim 10^{15}$!

Naturalness in the SM

Naturalness stated without mention to cut-off or regularization dependence:

" The naturalness problem is that the mass of a fundamental scalar is quadratically sensitive to high energy thresholds "

This is a statement about renormalized quantities and has nothing to do with the regularization method used. We can see this from a toy model that is a Yukawa type theory with two scalars and a fermion. E.g.,

$$\begin{aligned}\mathcal{L} &= \frac{1}{2}(\partial_\mu\phi)^2 + \frac{1}{2}(\partial_\mu\Phi)^2 + \bar{\psi}i\partial\!\!\!/\psi - \frac{1}{2}m_\phi^2\phi^2 - \frac{1}{2}m_\Phi^2\Phi^2 \\ &\quad - m_\psi\bar{\psi}\psi - \frac{1}{4}\lambda\phi^2\Phi^2 - y_\phi\phi\bar{\psi}\psi - y_\Phi\Phi\bar{\psi}\psi.\end{aligned}$$

In principle we could have written more terms in the Lagrangian but we just show how a heavy threshold affects differently scalar and fermion masses.

Naturalness in the SM

Using dimensional regularization and the $\overline{MS}$ renormalization scheme, we obtain at one loop, for the scalar mass,

$$\delta m_\phi^2 = \frac{y_\phi^2}{4\pi^2} m_\psi^2 \left[1 - 2\ln\frac{m_\psi^2}{\mu^2} + \mathcal{O}(m_\phi^2/m_\psi^2)\right] - \frac{\lambda}{32\pi^2} m_\Phi^2 \left[1 - \ln\frac{m_\Phi^2}{\mu^2}\right];$$

for the fermion mass,

$$\delta m_\psi = m_\psi \left[\frac{5}{4} - \frac{3}{2}\ln\frac{m_\Phi^2}{\mu^2} + \mathcal{O}(m_\psi^2/m_\Phi^2)\right] + (\Phi \to \phi)\,.$$

We see that, if ψ or Φ are heavy,

- δm_ϕ is quadratically sensitive to these large scales (m_Φ and m_ψ), even if we set $m_\phi = 0$ at tree level;
- δm_ψ is only logarithmically sensitive to the heavy scale (m_Φ);
- δm_ψ is proportional to m_ψ itself and therefore if we start with a light fermion, it will remain light after radiative corrections have been taken into account.

Naturalness in the SM

Thus, scalar masses are unstable, quadratically sensitive to higher energy thresholds whereas fermion masses are stable against radiative corrections since they are protected by the symmetry. To see this, we consider

$$\mathcal{L} = \bar{\psi} i \partial\!\!\!/ \psi + m \bar{\psi}\psi = \bar{\psi}_L i \partial\!\!\!/ \psi_L + \bar{\psi}_R i \partial\!\!\!/ \psi_R + m(\bar{\psi}_L \psi_L + \bar{\psi}_R \psi_R).$$

This theory has a global $U(1)$ symmetry $\psi \to e^{i\alpha}\psi$. However, if we take the mass to zero, there is a larger, chiral symmetry $\psi \to e^{i\gamma_5 \alpha}\psi$.

't Hooft's Doctrine of Naturalness[2]:

At any energy scale μ, a set of parameters, $\alpha_i(\mu)$ describing a system can be small, if and only if, in the limit $\alpha_i(\mu) \to 0$ for each of these parameters, the system exhibits an enhanced symmetery.

[2] G.'t Hooft: in Recent Developments in Field Theories, ed. G.'t Hooft et al., Plenum Press, New York, 1980, page 135.

Let us see how supersymmetry solves the hierarchy problem.
We consider as an example the top mass contribution to the Higgs mass squared. Supersymmetry requires a superpartner for each SM particle.

$$q_L \leftrightarrow \tilde{q}_L \equiv (\tilde{t}_L, \tilde{b}_L), \quad t_R \leftrightarrow \tilde{t}_R$$

Let us consider the following interaction Lagrangian,

$$\mathcal{L}_{int} = -(\lambda_F \bar{t}_R \phi^\dagger q_L + h.c.) + \lambda_L |\phi^\dagger \tilde{q}_L|^2 + \lambda_R |\tilde{t}_R \phi|^2,$$

To this Lagrangian we could add other terms that are gauge invariant but supersymmetry breaking,

$$\mathcal{L}_{soft} = \lambda_{LR}(\tilde{t}_R \tilde{q}_L^i \epsilon^{ij} \phi^j + h.c.) + m_L^2 \tilde{q}_L^\dagger \tilde{q}_L + + m_L^2 \tilde{t}_R^\dagger \tilde{t}_R.$$

Naturalness and Supersymmetry

Let us assume for simplicity that $\lambda_{LR} = 0$. The one loop correction to the Higgs mass is given by

$$\begin{aligned} \delta m_h^2 &= -\frac{2N_c\lambda_F^2}{16\pi^2}[\Lambda^2 - 6m_F^2 \ln\frac{\Lambda}{m_F} + 2m_F^2] \\ & - \sum_{s=L,R}\left\{\frac{\lambda_s N_c}{16\pi^2}[-\Lambda^2 + 2m_s^{'2}\ln\frac{\Lambda}{m_s^{'}}] + \frac{(\lambda_s v)^2 N_c}{16\pi^2}[1 - 2\ln\frac{\Lambda}{m_s^{'}}]\right\}. \end{aligned}$$

where $m_F \equiv \lambda_F v/\sqrt{2}$. If we have $\lambda_L = \lambda_R = |\lambda_F|^2$, as required by SUSY, we get an exact cancellation of quadratic divergencies,

$$\begin{aligned} \delta m_h^2 &= \frac{2N_c\lambda_F^2}{16\pi^2}[(m_L^{'2} + m_R^{'2} - 2m_F^2)\ln\frac{\Lambda}{m_F} \\ & -6m_F^2\ln\frac{m_L^{'}}{m_R^{'}} + (m_R^{'2} + 2m_F^2)\ln\frac{m_L^{'}}{m_R^{'}}]. \end{aligned}$$

In fact, if SUSY was exactly unbroken ($\mathcal{L}_{soft} = 0$), then we have $m_L^{'} = m_R^{'} = m_F$ and the whole contribution cancels exactly,

$$\delta m_h^2 = 0 \quad \text{(unbroken SUSY)}.$$

However $m_L^{'} = m_R^{'} = m_F$ is not allowed phenomenologically but we have seen that we can add SUSY breaking terms that do not spoil the cancellation of quadratic divergencies (soft SUSY breaking terms). If $m_F \ll m_L \sim m_R$ and define $m_{\tilde{t}}^2 \equiv (m_L^2 + m_R^2)/2$, we get

$$\delta m_h^2 \approx -\frac{2N_c}{16\pi^2}|\lambda_t|^2 m_{\tilde{t}}^2 \ln\frac{\Lambda^2}{m_{\tilde{t}}^2}.$$

so that we see that physically, the quadratic divergence is cut-off by the stop mass.

One way to evaluate naturalness in SUSY models is to examine the minimization condition from the Higgs sector scalar potential, which determines the Z-boson mass. (Alternatively, one may examine the mass formula for m_h and arrive at similar conclusions.) In the MSSM there are two doublets of complex scalar fields of opposite hypercharges:

$$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}, \qquad H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}.$$

The scalar Higgs potential consists of the F-terms of the superpotential,

$$V_F = -\sum_i |W^i|^2 \quad \text{with} \quad W^i = \partial W / \partial S_i,$$
$$(W = \bar{u} y_u Q H_u - \bar{d} y_d Q H_d - \bar{e} y_e L H_u + \mu H_u H_d)$$

and the D-terms,

$$V_D = \frac{1}{2} \sum_{a=1}^{3} \left(\sum_i g_a S_i^* T^a S_i \right)^2,$$

as well as the soft SUSY-breaking mass terms,

$$\mathcal{L}_{soft} = -(m^2)^i_j S^{j*} S_i - (\frac{1}{2} B^{ij} \mu^{ij} S_i S_j + \frac{1}{6} A^{ijk} y^{ijk} S_i S_j S_k + c.c),$$

Implications of SUSY Naturalness for Collider Searches

The full tree-level Higgs potential is given by

$$V^{(0,MSSM)} = m_1^2|H_u|^2 + m_2^2|H_d|^2 - B\mu\epsilon_{\alpha\beta}(H_u^\alpha H_d^\beta + h.c.)$$

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

where $m_{1,2}^2 = m_{H_{u,d}}^2 + \mu^2$. The quartic Higgs couplings are fixed by D-terms in terms of the gauge couplings g and g' in the MSSM [3]. Including the one-loop radiative corrections (in the effective potential approximation and using the DR regularization scheme),

[3] see the recent study of the Higgs self-couplings in SUSY: L. Wu, J. M. Yang, C.-P. Yuan and M. Zhang, Phys. Lett. B 747 (2015) 378-389.

Implications of SUSY Naturalness for Collider Searches

$$\Delta V^{(1,MSSM)} = \sum_i \frac{(-1)^{2s_i}}{64\pi^2}(2s_i+1)c_i m_i^4 \left[\ln(\frac{m_i^2}{Q^2} - \frac{3}{2})\right].$$

where the sum over i runs over all fields that couple to Higgs fields, m_i^2 are the Higgs-field-dependent mass squared values, and $c_i = c_{col}c_{cha}$, with $c_{col} = 3(1)$ for colored (uncolored) particles and $c_{cha} = 2(1)$ for charged (neutral) particles, and s_i is their spin quantum number.

Minimization of the scalar potential $V = V^{(0)} + \Delta V^{(1)}$ allows one to compute the gauge boson masses in terms of the Higgs field vacuum expectation values v_u and v_d and leads to the conditions that

$$\begin{aligned} B\mu v_d &= (m_{H_u}^2 + \mu^2 - g_Z^2(v_d^2 - v_u^2))v_u + \Sigma_u \\ B\mu v_u &= (m_{H_d}^2 + \mu^2 + g_Z^2(v_d^2 - v_u^2))v_d + \Sigma_d \end{aligned}$$

Implications of SUSY Naturalness for Collider Searches

Here $\Sigma_{u,d} = \partial \Delta V / \partial H_{u,d}|_{min}$ and $g_Z^2 = (g^2 + g'^2)/8$. By $SU(2)$ invariance, the scalar potential V depends on the scalar fields as $V(H_u^\dagger H_u, H_d^\dagger H_d, H_u H_d + c.c.)$; then we have

$$\Sigma_u = \Sigma_u^u v_u + \Sigma_u^d v_d, \quad \Sigma_d = \Sigma_d^u v_u + \Sigma_d^d v_d, \quad \Sigma_d^u = \Sigma_u^d$$

$$\text{with} \quad \Sigma_u^u = \partial \Delta V / \partial |H_u|^2|_{min}, \quad \Sigma_d^u = \partial \Delta V / \partial |H_d|^2|_{min},$$
$$\Sigma_u^d = \partial \Delta V / \partial (H_u H_d + c.c.)|_{min}$$

In this case, the minimization conditions can be expressed as

$$\boxed{\frac{M_Z^2}{2} = \frac{(m_{H_d}^2 + \Sigma_d^d) - (m_{H_u}^2 + \Sigma_u^u) \tan^2\beta}{\tan^2\beta - 1} - \mu^2}$$

$$\boxed{B\mu = \frac{1}{2} \sin 2\beta((m_{H_u}^2 + \mu^2 + \Sigma_u^u) + (m_{H_d}^2 + \mu^2 + \Sigma_d^d)) + \Sigma_u^d.}$$

Implications of SUSY Naturalness for Collider Searches

$$\boxed{\frac{M_Z^2}{2} = \frac{(m_{H_d}^2 + \Sigma_d^d) - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{\tan^2\beta - 1} - \mu^2}$$

To obtain a natural value of M_Z on the left-hand side, one would like each term C_i (with $i = H_u, H_d, \mu, \Sigma_u^u(k), \Sigma_d^d(k)$) on the right-hand side to have an absolute value of order $M_Z^2/2$.

- μ contributes to Δ_{EW} at tree-level;
- Σ_u^u and Σ_d^d contribute to Δ_{EW} at 1-loop level but Σ_d^d is suppressed by large $\tan\beta$;
- Due to the extra color factor (compared with non-colored sparticles) and the large Yukawa coupling (compared with other squarks), the dominant contribution to 1-loop corrections Σ_u^u and Σ_d^d is from the stop sector.

Implications of SUSY Naturalness for Collider Searches

$$\begin{aligned}
\Sigma_u^u(\tilde{t}_{1,2}) &= \frac{3}{16\pi^2} F(\tilde{t}_{1,2}) \times \left[y_t^2 - g_Z^2 \mp \frac{y_t^2 A_t^2 - 8 g_Z^2 (\frac{1}{4} - \frac{2}{3} s_w^2) \Delta_t}{m_{\tilde{t}_2} - m_{\tilde{t}_1}} \right]. \\
\Sigma_d^d(\tilde{t}_{1,2}) &= \frac{3}{16\pi^2} F(\tilde{t}_{1,2}) \times \left[g_Z^2 \mp \frac{y_t^2 \mu^2 + 8 g_Z^2 (\frac{1}{4} - \frac{2}{3} s_w^2) \Delta_t}{m_{\tilde{t}_2} - m_{\tilde{t}_1}} \right]. \\
F(m^2) &= m^2 \left(\ln \frac{m^2}{Q^2} - 1 \right); \quad Q^2 = m_{\tilde{t}_1} m_{\tilde{t}_2}; \quad \Delta_t = (m_{\tilde{t}_L}^2 - m_{\tilde{t}_R}^2)/2
\end{aligned}$$

The electroweak fine-tuning measurement is defined to evaluate the naturalness [4]

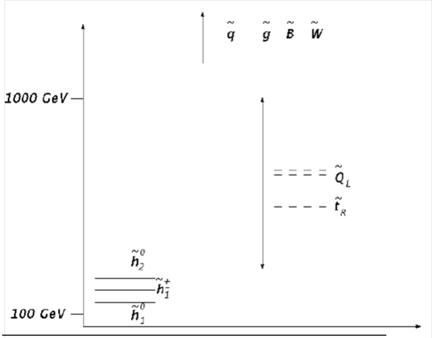
$$\Delta_{EW} \equiv max(C_i)/(M_Z^2/2).$$

Note that Δ_{EW} depends only on the weak scale parameters of the theory and hence is essentially fixed by the particle spectrum, independent of how superpartner masses arise[5].

[4] H. Baer, *et al.*, Phys. Rev. Lett. 109, 161802 (2012).
[5] H. Baer, *et al.*, Phys. Rev. D 88, 095013 (2013)

Implications of SUSY Naturalness for Collider Searches

So, in the MSSM, if requiring $\Delta_{EW} \lesssim 30$, we will have the following spectrum (Note: the gluino can contribute to Δ_{EW} at 2-loop level. The recent ATLAS 3σ Z-peak excess may support a gluino with mass less than 1 TeV [6]). A similar result can be obtain in the underlying theories from the cut-off argument [7].



- $|\mu| \lesssim 200$ GeV;
- $m_{\tilde{t}_1} \lesssim 600$ GeV;
- $m_{\tilde{g}} \lesssim 1.5 - 2$ TeV;
- other sparticles are decoupled to avoid the CP and flavor problems.

[6]See example, A. Kobakhidze, L. Wu, J. M. Yang, arXiv:1504.xxxxx

[7]See recent example, C. Brust, *et al*, J. High Energy Phys. 03 (2012) 103.

Implications of SUSY Naturalness for Collider Searches

Aiming for the above natural spectrum, we conclude that:

- The most robust test of naturalness is to search for the light Higgsinos! But they have small cross sections at the LHC. Besides, an effective handle is needed to tag pure Higgsinos production. It is feasible but challenging at the LHC.
- The stop and gluino have the larger cross sections but their contributions to naturalness are model dependent. In other words, even a heavy stop and gluino, can still produce an acceptable fine-tuning, due to the potential cancellations in the Δ_{EW} [8].

[8] S. Martin, Phys. Rev. D 89, 035011 (2014); I. Gogoladze, *et al*, Int. J. Mod. Phys. A 28 (2013) 1350046; H. Baer, *et al.*, Phys. Rev. Lett. 109, 161802 (2012); J. Feng *et al*, Phys. Rev. D 86, 055015 (2012).

Confronting Natural SUSY with the LHC

We propose two simplified (the irrelevant sparticles are decoupled.) natural SUSY scenarios for the LHC searches:

- Light Higgsinos with Stop;
- Higgsinos world.

In the MSSM, the neutralino mass matrix is given by,

$$\mathcal{M}_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -c_\beta s_W M_Z & s_\beta s_W M_Z \\ 0 & M_2 & c_\beta c_W M_Z & -s_\beta c_W M_Z \\ -c_\beta s_W M_Z & c_\beta c_W M_Z & 0 & -\mu \\ s_\beta s_W M_Z & -s_\beta c_W M_Z & -\mu & 0 \end{pmatrix},$$

and the chargino mass matrix is given by,

$$\mathcal{M}_{\tilde{\chi}^\pm} = \begin{pmatrix} M_2 & \sqrt{2} M_W s_W \\ \sqrt{2} M_W c_W & \mu \end{pmatrix}.$$

In either simplified case, requiring $\mu \ll M_1, M_2$, we can have (LO approximation):

$$
\begin{aligned}
m_{\tilde{\chi}_1^0} &\simeq \mu; \\
\Delta m_{\tilde{\chi}_1^\pm - \tilde{\chi}_1^0} &= \frac{M_W^2}{2M_2}\left(1 - \sin 2\beta - \frac{2\mu}{M_2}\right) + \frac{M_W^2}{2M_1}\tan^2\theta_W (1 + \sin 2\beta) \\
&\simeq 0; \\
\Delta m_{\tilde{\chi}_2^0 - \tilde{\chi}_1^0} &= \frac{M_W^2}{2M_2}\left(1 - \sin 2\beta + \frac{2\mu}{M_2}\right) + \frac{M_W^2}{2M_1}\tan^2\theta_W (1 - \sin 2\beta) \\
&\simeq 0.
\end{aligned}
$$

The nearly degenerate Higgsinos: $\tilde{\chi}_{1,2}^0$ and $\tilde{\chi}_1^\pm$ are the key feature of Natural SUSY and will lead to the distinctive collider signatures at the LHC.

Scenario-1: Light Higgsinos with Stop: Lower Limit

In this section, we focus on the natural SUSY with light Higgsinos and stop, and examine the lower limit of the stop mass under the current constraints [9].

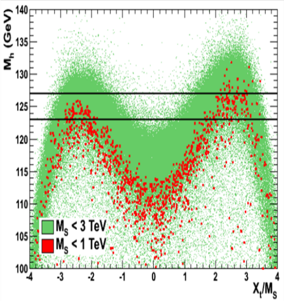
1. Indirect Constraints:

Higgs Mass:

$$M_h^2 \simeq |M_Z \cos 2\beta|^2 + \frac{3m_t^4}{2\pi^2 v^2 \sin^2\beta}\left[\ln\frac{M_S^2}{m_t^2} + \frac{X_t^2}{2M_S^2}\left(1 - \frac{X_t^2}{6M_S^2}\right)\right]$$

Comments:

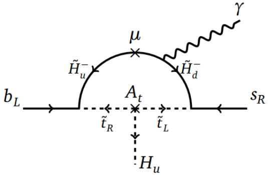
- $\tan\beta \gtrsim 10$ to maximize tree-level value;
- maximal mixing case: $X_t = \sqrt{6}M_S$;
- heavy stops case: large $M_S = \sqrt{m_{\tilde{t}_1\tilde{t}_2}}$.



[9] C. Han, K. Hikasa, L. Wu, J. M. Yang and Y. Zhang, JHEP 1310 (2013) 216.

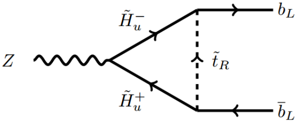
Scenario-1: Light Higgsinos with Stop: Lower Limit

B-Physics: $B \to X_s \gamma$



$$\mathcal{M}_{\tilde{t},\tilde{H}} \sim m_t^2 \frac{A_t \mu}{m_{\tilde{t}}^4} \tan\beta$$

R_b: $Z \to b\bar{b}$



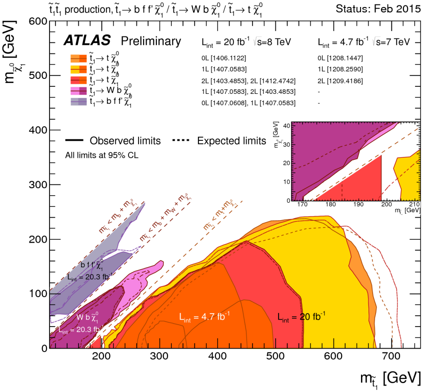
$$\Delta R_b^{SUSY} \sim \sin\theta_{\tilde{t}_1}^2 \frac{m_Z^2}{m_{\tilde{t}_1}^2} \ln \frac{\mu^2}{m_{\tilde{t}_1}^2}$$

Higgs data: $gg \to h$ and $h \to \gamma\gamma$

$$r_G^{\tilde{t}} \equiv \frac{c_{hgg}^{\tilde{t}}}{c_{hgg}^{SM}} \approx \frac{1}{4}\left(\frac{m_t^2}{m_{\tilde{t}_1}^2} + \frac{m_t^2}{m_{\tilde{t}_2}^2} - \frac{m_t^2 X_t^2}{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}\right); \qquad r_\gamma^{\tilde{t}} \equiv \frac{c_{h\gamma\gamma}^{\tilde{t}}}{c_{h\gamma\gamma}^{SM}} \approx -0.28 r^{\tilde{t}_G}$$

Scenario-1: Light Higgsinos with Stop: Lower Limit

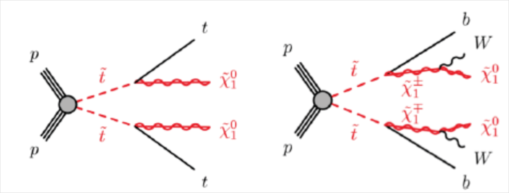
1. Direct Constraints:

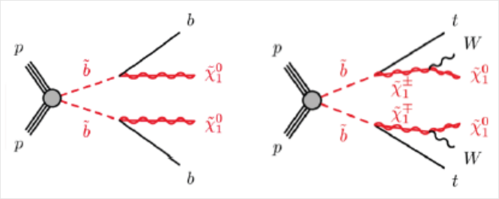


Although the current LHC constraints indicate a stop mass bound of hundreds of GeV, these results strongly rely on the assumptions of the branching ratios of the stop, the nature of neutralinos and the mass splitting between the sparticles.

Scenario-1: Light Higgsinos with Stop: Lower Limit

Note that: the stop and sbottom pair production will produce the same topologies due to the degenerate Higgsinos $\tilde{\chi}^0_{1,2}$ and $\tilde{\chi}^\pm_1$.





Scenario-1: Light Higgsinos with Stop: Lower Limit

Next, we scan the parameter space:

$$100\ \mathrm{GeV} \leq \mu \leq 200\ \mathrm{GeV}, \quad 100\ \mathrm{GeV} \leq (m_{\tilde{Q}_{3L}},\ m_{\tilde{t}_R} = m_{\tilde{b}_R}) \leq 2\ \mathrm{TeV}$$
$$-3\ \mathrm{TeV} \leq A_t = A_b \leq 3\ \mathrm{TeV}, \ \ 1 \leq \tan\beta \leq 60, \ \ 90\ \mathrm{GeV} \leq M_A \leq 1\ \mathrm{TeV}.$$

Gluino mass is fixed at 2 TeV, and the sleptons and first two generations of squarks masses are fixed at 5 TeV. We assume the grand unification relation $M_1 : M_2 = 1 : 2$ and take $M_1 = 1$ TeV. We consider the following constraints:

(1) the Higgs mass in the range of 123–127 GeV;

(2) $b \to s\gamma$ bounds at 2σ level;

(3) the EWPO and R_b in 2σ ranges of the experimental values;

(4) the thermal relic density of the LSP below the 2σ upper limit of the Planck value;

(5) direct stop/sbottom pair production: $\ell + jets + \not{E}_T$, $2b + \not{E}_T$ and $t\bar{t}$(hadronic)$+\not{E}_T$.

Scenario-1: Light Higgsinos with Stop: Lower Limit

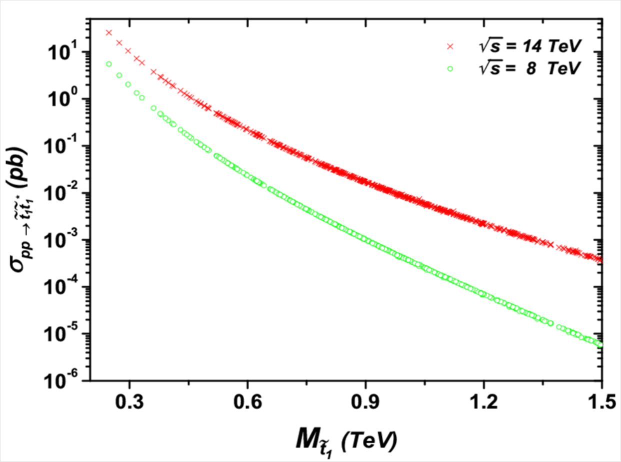
Table 1: Stop/sbottom pair searches and source in natural SUSY [10].

stop/sbottom pair searches	Source in natural SUSY
$\ell + jets + \not{E}_T$	$pp \to \tilde{t}_1\tilde{t}_1$ $(\tilde{t}_1 \to t\tilde{\chi}^0_{1,2})$ $pp \to \tilde{b}_1\tilde{b}_1$ $(\tilde{b}_1 \to t\tilde{\chi}^-_1)$
$t\bar{t}$(hadronic)$+\not{E}_T$	$pp \to \tilde{t}_1\tilde{t}_1$ $(\tilde{t}_1 \to t\tilde{\chi}^0_{1,2})$ $pp \to \tilde{b}_1\tilde{b}_1$ $(\tilde{b}_1 \to t\tilde{\chi}^-_1)$
$2b + \not{E}_T$	$pp \to \tilde{t}_1\tilde{t}_1$ $(\tilde{t}_1 \to b\tilde{\chi}^+_1)$ $pp \to \tilde{b}_1\tilde{b}_1$ $(\tilde{b}_1 \to b\tilde{\chi}^0_{1,2})$

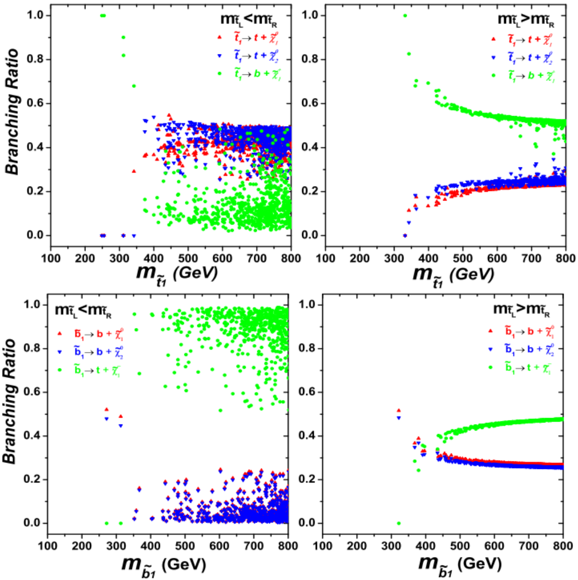
[10] ATLAS-CONF-2013-024;ATLAS-CONF-2013-037;ATLAS-CONF-2013-053

Scenario-1: Light Higgsinos with Stop: Lower Limit

Cross sections of stop pair at the LHC:



Branching ratios of stop and sbottom:



Scenario-1: Light Higgsinos with Stop: Lower Limit

The decay modes of the stop is affected by the handness of stop. We can understand this from the interactions between the stop and the neutralinos/charginos:

$$\begin{aligned}\mathcal{L}_{\tilde{t}_1\bar{b}\tilde{\chi}_i^+} &= \tilde{t}_1\bar{b}(f_L^C P_L + f_R^C P_R)\tilde{\chi}_i^+ + h.c.\ , \\ \mathcal{L}_{\tilde{t}_1\bar{t}\tilde{\chi}_i^0} &= \tilde{t}_1\bar{t}(f_L^N P_L + f_R^N P_R)\tilde{\chi}_i^0 + h.c.\ ,\end{aligned}$$

where $P_{L/R} = (1 \mp \gamma_5)/2$ and

$$\begin{aligned} f_L^N &= -\left[\frac{g_2}{\sqrt{2}}N_{i2} + \frac{g_1}{3\sqrt{2}}N_{i1}\right]\cos\theta_{\tilde{t}} - y_t N_{i4}\sin\theta_{\tilde{t}} \\ f_R^N &= \frac{2\sqrt{2}}{3}g_1 N_{i1}^*\sin\theta_{\tilde{t}} - y_t N_{i4}^*\cos\theta_{\tilde{t}}, \\ f_L^C &= y_b U_{i2}^*\cos\theta_{\tilde{t}}, \\ f_R^C &= -g_2 V_{i1}\cos\theta_{\tilde{t}} + y_t V_{i2}\sin\theta_{\tilde{t}}. \end{aligned}$$

with $y_t = \sqrt{2}m_t/(v\sin\beta)$ and $y_b = \sqrt{2}m_b/(v\cos\beta)$ being the Yukawa couplings of top and bottom quarks, and $\theta_{\tilde{t}}$ being the mixing angle between left- and right-handed stops $(-\pi/2 \le \theta_{\tilde{t}} \le \pi/2)$.

Scenario-1: Light Higgsinos with Stop: Lower Limit

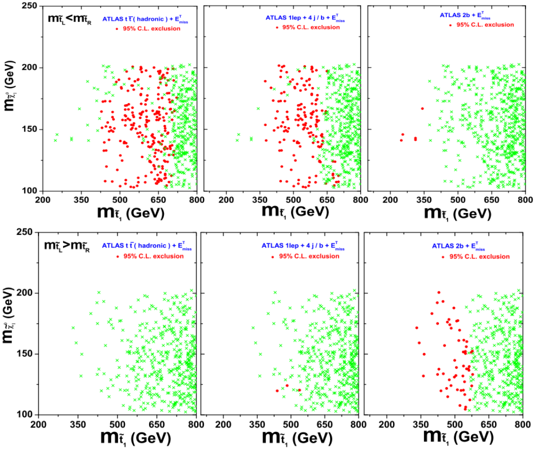
When $M_{1,2} \gg \mu$, one has $V_{11}, U_{11}, N_{11,12,21,22} \sim 0$, $V_{12} \sim \mathrm{sgn}(\mu)$, $U_{12} \sim 1$ and $N_{13,14,23} = -N_{24} \sim 1/\sqrt{2}$.

- if the stop is left-handed ($\theta_{\tilde{t}} = 0$), the couplings with $\tilde{\chi}^0_{1,2}$ are proportional to top Yukawa coupling y_t while the couplings with $\tilde{\chi}^\pm_1$ are dominated by the bottom Yukawa coupling y_b. Thus, the left-handed stop will mainly decay to $t\tilde{\chi}^0_{1,2}$ when the phase space is accessible.
- if the stop is a right-handed ($\theta_{\tilde{t}} = \pm\pi/2$), the couplings of the stop with $\tilde{\chi}^0_{1,2}$ and $\tilde{\chi}^\pm_1$ are proportional to y_t, and the branching ratios of $\tilde{t}_1 \to t\tilde{\chi}^0_{1,2}$ and $\tilde{t}_1 \to b\tilde{\chi}^+_1$ are about 25% and 50%, respectively.

The interactions of the sbottom with neutralino or chargino can be obtained from above expressions by replacing $\theta_{\tilde{t}}$ with $\theta_{\tilde{b}}$ and interchanging y_t and y_b.

Scenario-1: Light Higgsinos with Stop: Lower Limit

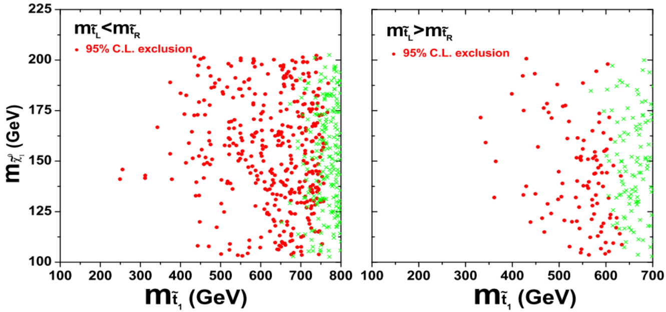
Results:



- For a left-handed (right-handed) stop, $t\bar{t} + \not{E}_T$ is more (less) sensitive than $2b + \not{E}_T$;

Scenario-1: Light Higgsinos with Stop: Lower Limit

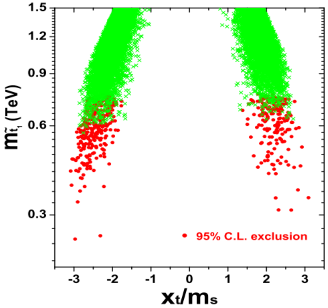
Results:



- A stop lighter than 600 GeV can be excluded at 95% C.L. in our scenario;
- Special phase spaces are NOT emphasized, which usually need more targeted analysis.

Scenario-1: Light Higgsinos with Stop: Lower Limit

Results:



- the range of $2 < X_t/M_s < 3$ can be excluded for $m_{\tilde{t}_1} < 600$ GeV at 95% C.L..

Scenario-1: Light Higgsinos with Stop: Mono-stop

In this section, we still focus on the natural SUSY with light Higgsinos and stop, and propose a novel stop signature at the LHC: *Mono-stop* [11].

Some comments on the direct stop searches at the LHC:

- Traditional searches focus on $\tilde{t}_1\tilde{t}_1^*$ production with $t\bar{t} + \not{E}_T$ in the final states.
- If $m_{\tilde{t}} \gg m_\chi + m_t$, the top quark can be quite energetic. But most of the top pair events in $t\bar{t}$ background are produced near the threshold. Several kinematical variables (e.g. m_{T2}, H_T etc) have been defined to distinguish stop pair production from top pair production [12].

[11] K. Hikasa, J. Li, L. Wu and J. M. Yang, arXiv:1505.06006.
[12] J. Cao, C. Han, L. Wu, J. M. Yang and Y. Zhang, JHEP 1211 (2012) 039

Scenario-1: Light Higgsinos with Stop: Mono-stop

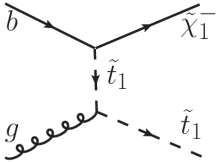
- If $m_{\tilde{t}} \approx m_t + m_\chi$, the kinematics of the top quarks from stop decay are similar to those in the top pair production, and the above observables are less sensitive. Light stops can be tested by comparing the observed $t\bar{t}$ production rate with theoretical calculations. However, it will be difficult for this method to be benefited from larger luminosity and higher energies in the future runs of LHC, since its sensitivity is mainly limited by systematic errors.
- If $m_\chi \ll m_{\tilde{t}} \approx m_t$, spin correlations of the top quarks can help to distinguish the signal from background. However, with larger $m_{\tilde{t}}$ this method does not work well due to smaller production rate.

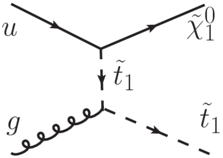
Scenario-1: Light Higgsinos with Stop: Mono-stop

- If $m_{\tilde{t}} \approx m_{\chi}$, stop decays into 4 body final states or a light quark plus the LSP. The jets from the decay are usually soft and cannot be identified. The leading search channel is mono-jet + MET. Vector boson fusion (VBF) tagging has also been proposed, and it has been shown that it is still cannot fully close the gap in the compressed region.
- If the life-time of the stop is long enough, a pair of stops can form a bound state, the stoponium. In this case, searches of the stoponium can be sensitive to these compressed regions

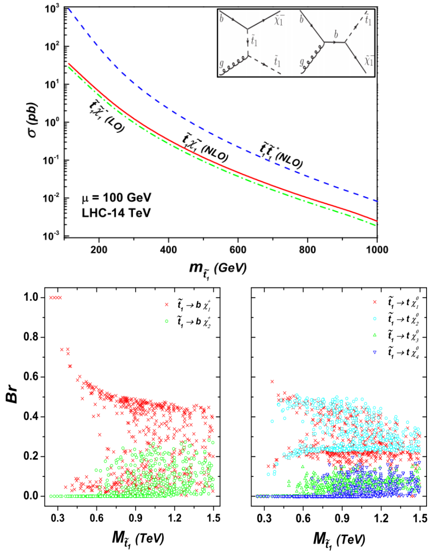
Scenario-1: Light Higgsinos with Stop: Mono-stop

- What's the mono-stop?
  It refers to the stop and invisible particles (at detector level) associated production.
- How can we have the mono-stop?
  It can be induced by the FCNC interactions or degenerate spectrum.





Scenario-1: Light Higgsinos with Stop: Mono-stop



- **Why is the mono-stop important?**

(1) The mono-stop cross section can reach tens of pb for $m_{\tilde{t}_1} \lesssim 340$ GeV;

(2) When the stop becomes heavy, the mono-stop production cross section will decrease, but slower than the pair production, due to the kinematics;

(3) If the stop has the democratic decay branching ratios, this channel also benefits the less branching ratio suppression as a comparison with stop pair production.

Scenario-1: Light Higgsinos with Stop: Mono-stop

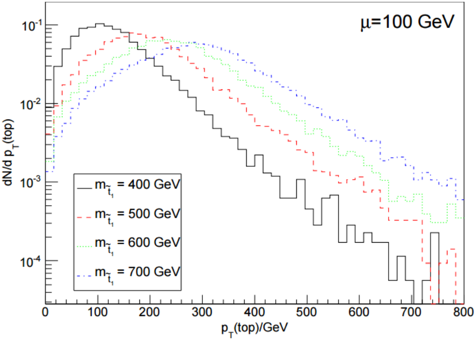
Next, we investigate the LHC observability of the mono-stop signatures with the sequent decays $\tilde{t}_1 \to t\tilde{\chi}^0_{1,2}$ and $\tilde{t}_1 \to b\tilde{\chi}^+_1$:

$$pp \to \tilde{t}_1\tilde{\chi}^-_1 \to t\tilde{\chi}^0_{1,2}\tilde{\chi}^-_1 \to bjj + \not{E}_T,$$
$$pp \to \tilde{t}_1\tilde{\chi}^-_1 \to b\tilde{\chi}^+_1\tilde{\chi}^-_1 \to b + \not{E}_T.$$

For the decay $\tilde{t}_1 \to t\tilde{\chi}^0_{1,2}$,

- The main background is the semi- and full-hadronic $t\bar{t}$ events, where the missed lepton and the limited jet energy resolution will lead to the relatively large missing transverse energy;
- The processes $W + \mathrm{jets}$ and $Z + \mathrm{jets}$ can also fake the signal when one of those light-flavor jets are mis-tagged as a b-jet;
- The single top and $t\bar{t} + V$ backgrounds are not considered in our simulations due to their small missing energy or cross sections compared to the above backgrounds.

Scenario-1: Light Higgsinos with Stop: Mono-stop



With the increase of stop mass, the top quark produced from stop decay is boosted and has larger p_T. So, in the analysis of $\tilde{t}_1 \to t\tilde{\chi}^0_{1,2}$ channel, we adopt HEPTopTagger and normal hadronic top reconstruction methods, respectively and present our results with the best one. We assume the b-jet tagging efficiency as 70% and a misidentification efficiency of c-jets and light jets as 10% and 0.1%, respectively.

Scenario-1: Light Higgsinos with Stop: Mono-stop

The detailed analysis strategies are the followings:

- Events with any isolated leptons are rejected;
- **Method-1**: We use C-A algorithms in the Fastjet to cluster the jets with $R = 1.5$ to obtain the top-jet candidates. Each candidate must have the top quark substructure required by the HEPTopTagger. The b-tagging is also imposed in the top-jet reconstruction. Other energy deposits outside the top-jet are further reconstructed as the normal jets by using anti-k_t algorithm with $R = 0.4$;
- **Method-2**: In normal hadronic top quark reconstruction, a pair of jets is selected with the invariant mass $m_{jj} > 60$ GeV and the smallest ΔR. A third jet closest to this di-jet system is used to constitute the top quark candidate. Among these three jets, at least one b-jet and $\Delta\phi(\not{E}_T, p_T(b_1)) > 1$ is required. The anti-k_t algorithm is used for jet clustering with $R = 0.4$;

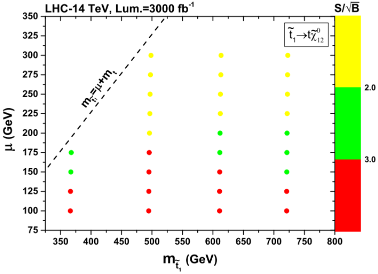
Scenario-1: Light Higgsinos with Stop: Mono-stop

- We keep the events with the exact one reconstructed top quark and require 150 GeV $< m_t^{\rm rec} <$ 200 GeV;
- The extra leading jet j_1 outside the reconstructed top quark object is vetoed if $p_T(j_1) > 30$ GeV and $|\eta(j_1)| < 2.5$;
- We define eight signal regions for each sample according to $(\not{E}_T, p_T(j_{\rm top}))$ cuts: (200, 100), (250, 150), (300, 200), (350, 250), and $(p_T(b), \not{E}_T)$ cuts: (200, 50), (250, 50), (300, 100), (350, 100) GeV.

Table 2: The cross sections of $V + {\rm jets}$, $t\bar{t}$ and $\tilde{t}_1(\to t\tilde{\chi}^0_{1,2})\tilde{\chi}^-_1$ for a benchmark point $(m_{\tilde{t}_1}, \mu) = (611, 100)$ GeV and $\tan\beta = 10$ in Method-1 and Method-2 at 14 TeV LHC with $\mathcal{L} = 3000$ fb^{-1}. The cross sections are in unit of fb.

cuts	$W + {\rm jets}$	$Z + {\rm jets}$	$t\bar{t}$	S	S/B	$S/\sqrt{B}$
Method-1	$< 10^{-2}$	0.29	1.90	0.13	6.0%	4.9
Method-2	$< 10^{-2}$	0.59	0.74	0.044	3.4%	2.1

Scenario-1: Light Higgsinos with Stop: Mono-stop



- $S/\sqrt{B}$ decrease with the increase of μ because of the cut efficiency reduction;
- When the stop becomes heavy, the cross section of $\tilde{t}_1\tilde{\chi}_1^-$ is suppressed;
- More signal events can be kept in the mass range 450 GeV $\lesssim m_{\tilde{t}_1} \lesssim$ 650 GeV due to top-tagger;
- when $\mu \lesssim 175$ GeV, the stop mass 360 GeV $\lesssim m_{\tilde{t}_1} \lesssim$ 725 GeV can be probed at $\gtrsim 3\sigma$ statistical significance with $S/B \lesssim 9\%$.

Scenario-1: Light Higgsinos with Stop: Mono-stop

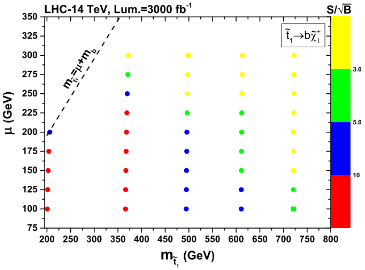
For the decay $\tilde{t}_1 \to b\tilde{\chi}_1^+$,

- The main background is the processes $W + \text{jets}$ and $Z + \text{jets}$ when the light-flavor jets are mis-identified as b-jets;
- The $t\bar{t}$ events become the sub-leading backgrounds due to their large multiplicity.

The signal events are selected to satisfy the following criteria:

- Events with any isolated leptons are rejected;
- Exact one hard b-jet in the final states, but allow an additional softer jet with $p_T(j_1) < 30$ GeV and $\Delta\phi(\not{E}_T, p_T(j_1)) > 2$.
- Since the hardness of b-jet from stop decay depends on the mass splitting between $\tilde{t}_1$ and $\tilde{\chi}_1^-$, we define four signal regions for each sample according to $(\not{E}_T, p_T(b))$ cuts: (30, 20), (70, 40), (150, 100) and (250, 200) GeV.

Scenario-1: Light Higgsinos with Stop: Mono-stop



- The most sensitive stop region lies in 350 GeV $\lesssim m_{\tilde{t}_1} \lesssim$ 450 GeV, where a hard b-jet ($p_T >$ 200 GeV) and the sizable $\not{E}_T$ ($\not{E}_T >$ 250 GeV) can be used to effectively suppress the backgrounds;
- When the stop mass increases, $S/\sqrt{B}$ will rapidly decrease;
- the higgsino mass 100 GeV$\lesssim \mu \lesssim$ 225 GeV and the stop mass 200 GeV $\lesssim m_{\tilde{t}_1} \lesssim$ 620 GeV can be covered at $\gtrsim 3\sigma$ statistical significance with S/B varying from 4% to 27%.

Scenario-2: Higgsinos World: Mono-jet

In this section, we move to the natural SUSY with only light Higgsinos, and propose to use the mono-jet events to probe this Higgsino world at the LHC [13].
Once more, M_Z,

$$\boxed{\frac{M_Z^2}{2} \simeq -(m_{H_u}^2 + \Sigma_u^u) - \mu^2}$$

- μ as an indicator of naturalness;
- hyperbolic branch/focus point region (HB/FP) in mSUGRA, however, only for small values of A_0/m_0.
- non-universal gaugino masses(large $SU(2)/SU(3)$ gaugino mass ratio at GUT scale);
- non-universal Higgs masses, usually for $A_0/m_0 \sim -(1-2)$.

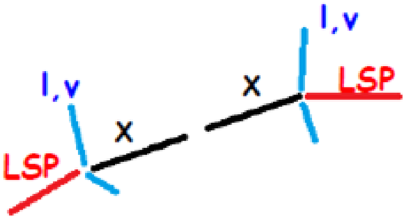
[13] C. Han, A. Kobakhidze, N. Liu, L. Wu and J. M. Yang, JHEP 1402 (2014) 049.

Scenario-2: Higgsinos World: Mono-jet

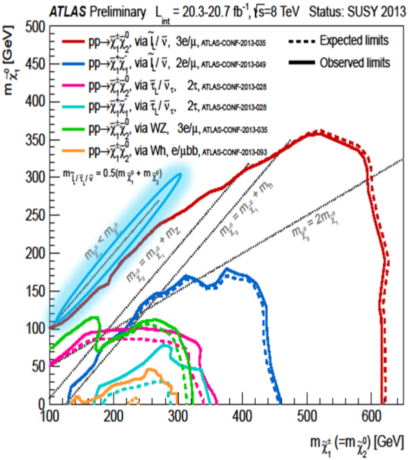
When $M_{1,2} \gg \mu$, $m_{\tilde{\chi}_2^0, \tilde{\chi}_1^\pm} \simeq m_{\tilde{\chi}_1^0}$ (but not enough to form long-lived particles). The small-splitting region is generally less sensitive because visible particles are soft and LSPs are back-to-back causing small MET. To see this, consider a simple two body decay involving one massless particle, in the rest frame of the decaying particle. The massless particles momentum is then given by:

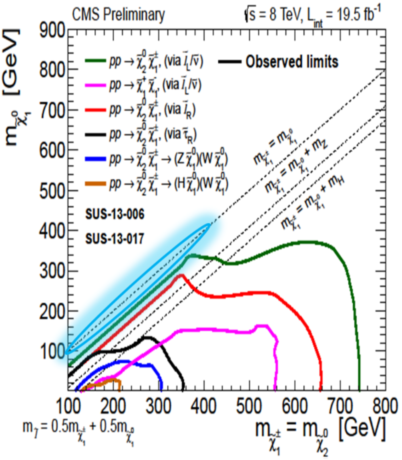
$$\boxed{p = \frac{m_2^2 - m_1^2}{2m_2} \approx \Delta m}$$

with $m_2 = m_1 + \Delta m$ and assuming $\Delta m \ll m_1$.

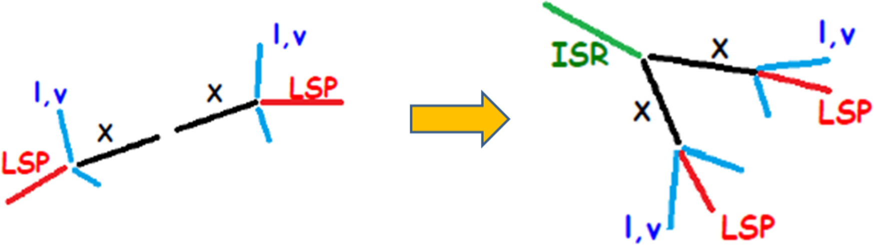


Scenario-2: Higgsinos World: Mono-jet



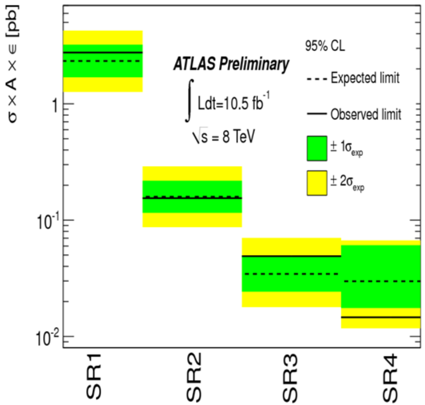


Scenario-2: Higgsinos World: Mono-jet



To improve the sensitivity in compressed region, ISR jets is very helpful. ISR jet boosts parent electrowinos, MET becomes larger as LSPs align.

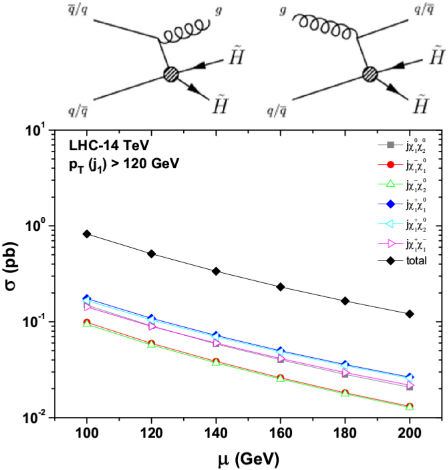
Scenario-2: Higgsinos World: Mono-jet



2.8 pb, 0.16 pb, 0.05 pb, and 0.02 pb

No limit can be obtained from current LHC searches, due to small cross section.

Scenario-2: Higgsinos World: Mono-jet



The largest contribution comes from $\tilde{\chi}_1^+\tilde{\chi}_1^0 j$ due to *ug* initial states. Signal is enhanced by the sum of all the higgsinos final states and can reach nearly pb-level.

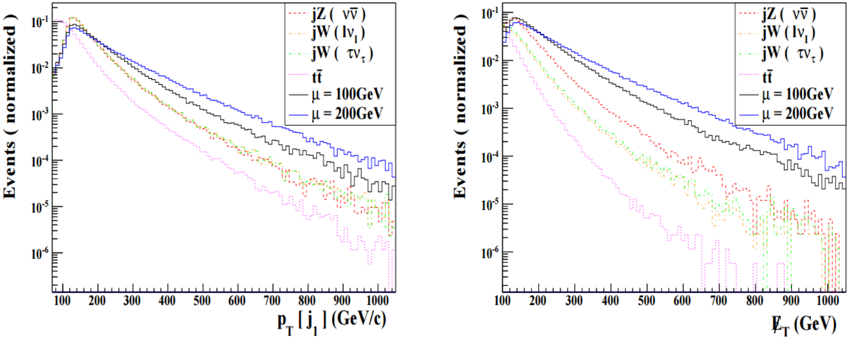
Scenario-2: Higgsinos World: Mono-jet

For the monojet signal,

- $pp \to Z(\to \nu\bar{\nu}) + j$, which is the main irreducible background with the same topology as our signals;
- $pp \to W(\to \ell\nu) + j$, this process fakes the signal only when the charged lepton is outside the acceptance of the detector or close to the jet;
- $pp \to W(\to \tau\nu) + j$, this process may fake the signal since a secondary jet from hadronic tau decays tend to localize on the side of $\not{E}_T$;
- $pp \to t\bar{t}$, this process may resemble the signal, but also contains extra jets and leptons. This allows to highly suppress $t\bar{t}$ background by applying a b-jet, lepton and light jet veto.

We use the b-jet tagging efficiency parametrisation given in and include a misidentification 10% and 1% for c-jets and light jets respectively. We also assume the τ tagging efficiency is 40% and include the mis-tags of QCD jets by using Delphes.

Scenario-2: Higgsinos World: Mono-jet



The signals have a harder p_T and $\not{E}_T$ than the backgrounds.

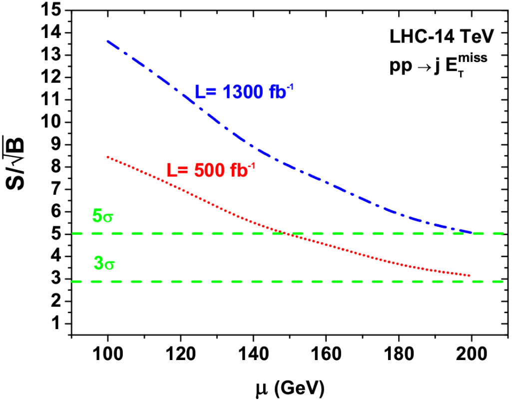
Scenario-2: Higgsinos World: Mono-jet

The signal events are selected to satisfy the following criteria:

- We require large missing transverse energy $\not{E}_T > 500$ GeV;
- The leading jet is required to have $p_T(j_1) > 500$ GeV and $|\eta_{j_1}| < 2$;
- events with more than two jets with p_T above 30 GeV in the region $|\eta| < 4.5$ are rejected;
- We veto the second leading jet with $p_T(j_2) > 100$ GeV and $|\eta_{j_2}| < 2$;
- A veto on events with an identified lepton $(\ell = e, \mu, \tau)$ or b-jet is imposed to reduce the background of $W + j$ and $t\bar{t}$.

cut	$Z(\nu\bar{\nu}) + j$	$W(\ell\nu_\ell) + j$	$W(\tau\nu_\tau) + j$	$t\bar{t}$	Signal ($\mu = 100$ GeV)	Signal ($\mu = 200$ GeV)
$p_T(j_1) > 500$GeV	69322	241740	119078	210943	1242	415
$\not{E}_T > 500$GeV	26304	28209	16513	2786	950	335
veto on $p_T(j_2) > 100$, $p_T(j_3) > 30$	16988	12194	7577	306	602	223
veto on e, μ, τ	16557	3963	3088	102	597	220
veto on $b-$jets	16303	3867	3046	56	576	214

Scenario-2: Higgsinos World: Mono-jet



The higgsino mass range μ in $100 - 200$ GeV can be probed at $S/\sqrt{B} = 5\sigma$ and $2\% \lesssim S/B \lesssim 5\%$ through the monojet search at 14 TeV HL-LHC with 1300 fb^{-1} luminosity.

Conclusions

- Natural SUSY provides a excellent framework of solving naturalness problem without conflicting with experiments. The nearly degenerate Higgsinos are the key feature of Natural SUSY;
- The direct and indirect constraints on the stop sector indicate a left-handed stop should be heavier than about 600 GeV in the Natural SUSY;
- The higgsino mass range in $100 - 200$ GeV can be covered at $S/\sqrt{B} = 5\sigma$ through the monojet search at the HL-LHC, if one can well understand the systematical error;
- The mono-stop search can play a complementary role in searching for the stop, especially when the stop becomes heavy and has democratic decay branching ratios. A stop mass 200 GeV $\lesssim m_{\tilde{t}_1} \lesssim$ 620 GeV, can be probed at $S/\sqrt{B} > 3$ at the HL-LHC.

LHC Run-2 and Natural SUSY

LHC Run-2 will be a machine of *Higgs Precision and Small Excess*.

- Probing natural susy usually requires more luminosity than LHC Run-2;
- The null results of the direct searches for sparticles and indirect constraints from Higgs data will further squeeze the parameter space of Natural SUSY;
- It will be interesting to attempt to explain various small excess in the Natural SUSY.

Backup for HEPTopTagger

Our starting point is the C/A jet algorithm with $R = 1.5$. For a top candidate, which typically has a jet mass above 200 GeV, we assume that there could be a complex hard substructure inside the fat jet. To reduce this fat jet to the relevant substructures we apply the following recursive procedure.

(1) The last clustering of the jet j is undone, giving two subjets j_1, j_2, ordered such that $m_{j_1} > m_{j_2}$;

(2) If $m_{j_1} > 0.8 m_j$ (i.e. j_2 comes from the underlying event or soft QCD emission) we discard j_2 and keep j_1, otherwise both j_1 and j_2 are kept;

(3) For each subjet j_i that is kept, we either add it to the list of relevant substructures (if $m_{j_i} < 30$ GeV) or further decompose it recursively;

(4) In the resulting set of relevant substructures, we examine all two-subjet configurations to see if they could correspond to a W boson: after filtering, $m_W^{rec} = 65 - 95$ GeV;

Backup for HEPTopTagger

Our starting point is the C/A jet algorithm with $R = 1.5$. For a top candidate, which typically has a jet mass above 200 GeV, we assume that there could be a complex hard substructure inside the fat jet. To reduce this fat jet to the relevant substructures we apply the following recursive procedure.

(5) To tag the top quark, we then add a third subjet and, again after filtering, requiring $m_t^{rec} = 150 - 200$ GeV;

(6) We additionally require that the W helicity angle θ with respect to the top candidate satisfies $\cos\theta < 0.7$;

(7) For more than one top tag in the event we choose the one with the smaller: $|m_t^{rec} - m_t^{ploe}| + |m_W^{rec} - m_W^{pole}|$.

The resulting top tagging efficiency in the signal, including underlying event, is 43%.