

Single top squark production as a probe of natural supersymmetry at the LHC (postprint)

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Abstract

Light top squarks (stops) and light higgsinos are the key features of natural supersymmetry (SUSY), where the higgsinos $\tilde{\chi}_{1\pm}^0$ and $\tilde{\chi}_{1,2}^0$ are nearly degenerate and act as the missing transverse energy (ET) at the LHC. Besides the pair strong

Full Text

Single Top Squark Production as a Probe of Natural Supersymmetry at the LHC

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Light top squarks (stops) and light higgsinos are the key features of natural SUSY, where the higgsinos $\tilde{\chi}_{1,2}^\pm$ and $\tilde{\chi}_{1,2}^0$ are nearly degenerate and act as the missing transverse energy (E_T^{miss}) at the LHC. Besides strong production, the stop can be produced via electroweak interactions. The determination of the electroweak properties of the stop is an essential task for the LHC and future colliders. In this paper, we investigate single stop (\tilde{t}_1) production $pp \rightarrow \tilde{t}_1 + E_T^{\text{miss}}$ in natural SUSY at the LHC, which yields the monotop signature $t + E_T^{\text{miss}}$ from $\tilde{t}_1 \rightarrow t\tilde{\chi}_{1,2}^0$ or the monobottom signature $b + E_T^{\text{miss}}$ from $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^+$. We perform Monte Carlo simulations for these signatures and obtain the following

results: (1) The signal $b + E_T^{\text{miss}}$ has better sensitivity than $t + E_T^{\text{miss}}$ for probing natural SUSY; (2) The parameter region with higgsino mass $100 \text{ GeV} \leq \mu \leq 225 \text{ GeV}$ and stop mass $m_{\tilde{t}_1} \leq 620 \text{ GeV}$ can be probed through single stop production with $S/\sqrt{B} > 3$ and $4\% \leq S/B \leq 19\%$ at the 14 TeV HL-LHC with an integrated luminosity of 3000 fb^{-1} .

Introduction

The search for supersymmetry (SUSY) is a long-standing important task in particle physics. One prime motivation for weak-scale SUSY is that it protects the Higgs vacuum expectation value without unnatural fine-tuning of the theory parameters. In the minimal supersymmetric standard model (MSSM), only a small subset of the supersymmetric partners strongly relates to the naturalness of the Higgs potential [?]. This can be seen from the minimization of the Higgs potential [?]:

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

where μ is the higgsino mass parameter, and $m_{H_u}^2$ denote the weak-scale soft SUSY breaking masses of the Higgs fields. A moderate or large $\tan \beta \equiv v_u/v_d$ is assumed in the last approximate equality. Σ_u and Σ_d arise from radiative corrections to the Higgs potential, and the one-loop dominant contribution to Σ_u is given by [?]:

$$\Sigma_u = \frac{3y_t^2}{16\pi^2} \times m_{\tilde{t}}^2 \ln \left(\frac{Q^2}{m_{\tilde{t}}^2} \right).$$

In order to obtain the observed value of M_Z without large cancellations in Eq. (1), each term on the right-hand side should be comparable in magnitude. Thus, the higgsino mass μ must be of order $\sim 100 - 200 \text{ GeV}$, and the requirement of $\Sigma_u \sim M_Z^2/2$ produces an upper bound on the stop mass of about 500 GeV [?, ?] (a 125 GeV Higgs mass can be achieved by a large stop trilinear coupling without very heavy stops in the MSSM or by extending the MSSM with additional D-terms or F-terms [?]). In addition, since the gluino contributes to m_{H_u} at two-loop level, it is also upper bounded by naturalness [?] (however, direct LHC searches have pushed the gluino up to the TeV scale [?, ?] while the recent ATLAS Z-peaked excess may indicate a gluino around 800 GeV [?]).

Therefore, to test SUSY naturalness, the crucial task is to search for light stops or higgsinos. The search strategy for pair production of these nearly degenerate higgsinos has been studied recently [?]. During LHC Run-1, the ATLAS and CMS collaborations performed extensive searches for stops through gluino-mediated stop production [?, ?] or direct stop pair production [?, ?]. Meanwhile, many theoretical studies aiming to improve LHC sensitivity to a light stop have

been proposed [?]. Current LHC constraints indicate a stop mass bound of hundreds of GeV [?]; however, those results are affected by the stop polarization states and branching ratios. The constraints on the right-handed stop from LHC Run-1 direct searches [?, ?] are usually weakened by branching ratio suppression, which can still be as light as 230 GeV in some compressed region [?]. If the stop mass is heavier than about 450 GeV, it is allowed in most parameter space. Therefore, in our work we require the stop mass to be heavier than 450 GeV [?].

Usually, stop pair production provides the most sensitive way to search for stops at the LHC. However, the stop can also participate in electroweak interaction processes. The determination of the electroweak properties of the stop is an essential task for the LHC and future colliders.

In this work, we study single stop production $pp \rightarrow \tilde{t}_1 + E_T^{\text{miss}}$ in natural SUSY at the LHC. The observation of single stop production will test the electroweak properties of the stop and the naturalness of supersymmetry. In the following, we perform Monte Carlo simulations for single stop production and examine its sensitivity at the LHC.

Since the cross section of single stop production is not sensitive to $\tan\beta$, we take $\tan\beta = 50$ for simplicity. We find that the single stop cross section can still reach about 200 fb when $m_{\tilde{t}_1} \approx 450$ GeV. The NLO K-factor of the process $pp \rightarrow \tilde{t}_1 \tilde{\chi}_1^-$ ranges from 1.25 to 1.33. When the stop becomes heavy, the single stop production cross section decreases, but slower than pair production, due to kinematics.

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

$$\begin{aligned} pp &\rightarrow \tilde{t}_1 \tilde{\chi}_1^- \rightarrow t \tilde{\chi}_{1,2}^0 \tilde{\chi}_1^- \rightarrow bj\bar{j} + E_T^{\text{miss}}, \\ pp &\rightarrow \tilde{t}_1 \tilde{\chi}_1^- \rightarrow b \tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow b + E_T^{\text{miss}}. \end{aligned}$$

[Figure 1: see original paper] The cross sections of $\tilde{t}_1 \tilde{t}_1^*$ and $\tilde{t}_1 \tilde{\chi}_1^-$ productions at the 14 TeV LHC for $\tan\beta = 50$ and degenerate higgsinos with mass $\mu = 100$ GeV. The contribution of the conjugate process $\tilde{t}_1^* \tilde{\chi}_1^+$ is included.

Calculations and Simulations

At the LHC, single stop production is induced by electroweak interactions and proceeds through the following process (see Fig. 1 for the corresponding Feynman diagrams):

$$pp \rightarrow \tilde{t}_1 \tilde{\chi}_1^-.$$

Since in natural SUSY the light higgsinos are nearly degenerate, the decay products of $\tilde{\chi}_1^-$ will carry small energies and hence are too soft to be observed

in the detector. Thus, the associated production of $\tilde{t}_1 \tilde{\chi}_1^-$ can be identified as $\tilde{t}_1 + E_T^{\text{miss}}$, which provides a distinctive signature at the LHC.

In Fig. 1, we show the next-to-leading order (NLO) cross sections of stop pair and single stop productions for $\mu = 100$ GeV at 14 TeV LHC using the packages Prospino2 [?] and MadGolem [?], respectively. The renormalization and factorization scales are taken as half the average of the final-state masses. In the calculations of $\tilde{t}_1 \tilde{\chi}_1^-$, we use the LO and NLO parton densities given by CTEQ6L1 and CTEQ6M with five active flavors [?]. The contribution of the conjugate process $\tilde{t}_1^* \tilde{\chi}_1^+$ is included. Except for the higgsino mass parameter μ and right-handed stop soft mass m_{U_3} , we assume other soft supersymmetric masses at 1 TeV, and use the packages SOFTSUSY-3.3.9 [?] and MSSMCalc [?] to calculate masses, couplings, and branching ratios of the sparticles.

For the decay $\tilde{t}_1 \rightarrow t \tilde{\chi}_{1,2}^0$, the SM backgrounds to the signal $bjj + E_T^{\text{miss}}$ arise from semi- and full-hadronic $t\bar{t}$ events [?], where the undetected lepton and limited jet energy resolution lead to relatively large missing transverse energy. The processes W +jets and Z +jets can fake the signal when one of the light-flavor jets is mis-tagged as a b-jet. Additionally, single top can mimic our signal when the lepton from the W boson decay is missed at the detector. The $t\bar{t} + V$ backgrounds are not considered in our simulations due to their small missing energy or cross sections compared to the above backgrounds.

[Figure 2: see original paper] The parton-level p_T distribution of the top quark in the channel $\tilde{t}_1 \rightarrow t \tilde{\chi}_{1,2}^0$ for $\mu = 100$ GeV at 14 TeV LHC.

In Fig. 2, we present the parton-level p_T distribution of the top quark in the channel $\tilde{t}_1 \rightarrow t \tilde{\chi}_{1,2}^0$ for $\mu = 100$ GeV at 14 TeV LHC. It can be seen that with increasing stop mass, the top quark produced from stop decay is boosted and has larger p_T . Therefore, in the analysis of the $\tilde{t}_1 \rightarrow t \tilde{\chi}_{1,2}^0$ channel, we respectively adopt HEPTopTagger [?] and normal hadronic top reconstruction methods for each sample to identify the top quark in the final states and present our results with the better performing method. The detailed analysis strategies are as follows:

- Events with any isolated leptons are rejected.
- **Method-1:** We use Cambridge-Aachen (CA) algorithms [?] in Fastjet [?] to cluster jets with $R = 1.5$ to obtain top-jet candidates. Each candidate must have the top quark substructure required by HEPTopTagger. B-tagging is also imposed in the top-jet reconstruction. Other energy deposits outside the top-jet are further reconstructed as normal jets using the anti- k_t algorithm with $R = 0.4$ [?]. The top mass window used in our analysis is $150 < m_t < 200$ GeV, while the W window is taken as the default value in HEPTopTagger.
- **Method-2:** In normal hadronic top quark reconstruction, a pair of jets is selected with 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 $\Delta\phi(E_T^{\text{miss}}, p_T(b_1)) > 1$

- are required. The anti- k_t algorithm is used for jet clustering with $R = 0.4$.
- We keep events with exactly one reconstructed top quark and require $150 \text{ GeV} < m_{\text{rec}} < 200 \text{ GeV}$.
 - The extra leading jet j_1 outside the reconstructed top quark object is vetoed if $p_T(j_1) > 30 \text{ GeV}$ and $|\eta(j_1)| < 2.5$.
 - We define signal regions with $(E_T^{\text{miss}}, p_T(j_{\text{top}}))$ cuts: (200, 100), (250, 150), (300, 200), (350, 250) for Method-1, and $(p_T(b), E_T^{\text{miss}})$ cuts: (200, 50), (250, 50), (300, 100), (350, 100) GeV for Method-2.

For the decay $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^+$, the SM backgrounds to the signal $b + E_T^{\text{miss}}$ are dominated by W +jets and Z +jets processes when light-flavor jets are mis-identified as b-jets [?]. The $t\bar{t}$ events become 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.
- We require exactly one hard b-jet in the final state, but allow an additional softer jet with $p_T(j_1) < 30 \text{ GeV}$ and $\Delta\phi(E_T^{\text{miss}}, p_T(j_1)) > 2$. Since the hardness of the b-jet from stop decay depends on the mass splitting between \tilde{t}_1 and $\tilde{\chi}_1^-$, we define three signal regions for each sample according to $(E_T^{\text{miss}}, p_T(b))$ cuts: (100, 70), (150, 100), and (250, 200) GeV.

Finally, we use the most sensitive signal region (with the highest S/B) for each decay mode and show our results in Fig. 3 [Figure 3: see original paper] and Fig. 4 [Figure 4: see original paper], respectively. In our study, we omit QCD multijet backgrounds, whose correct treatment requires experimental data-driven methods and hence depends on the realistic detector environments of the 14 TeV LHC. As discussed in [?, ?, ?], the requirements of high $p_T(b_1)$ and large E_T^{miss} with a separation $\Delta\phi(E_T^{\text{miss}}, p_T(j_1))$ can usually be expected to greatly reduce fake contamination from QCD backgrounds and allow for good signal selection efficiency.

The parton-level signal and background events are generated with MadGraph5 [?], where W/Z +jets is matched up to 3 jets using the MLM matching scheme [?] and setting $xq_{\text{cut}} = 30 \text{ GeV}$. For the value of q_{cut} in matching, we take it to $\max(xq_{\text{cut}} + 5, xq_{\text{cut}} \times 1.2)$ [?] in our simulation. We perform parton shower and fast detector simulations with PYTHIA [?] and Delphes [?]. We assume a b-jet tagging efficiency of 70% [?] and misidentification efficiencies of c-jets and light jets as 10% and 0.1%, respectively. The $t\bar{t}$ cross section is normalized to the approximately next-to-next-to-leading order value $\sigma_{t\bar{t}} = 920 \text{ pb}$ [?].

Results and Discussions

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

Process	Method-1	Method-2
$W+\text{jets}$	$< 10^{-2}$	2.20
$Z+\text{jets}$	0.80	0.13
$t\bar{t}$	4.0%	3.9
S/B	0.55	0.24
S/\sqrt{B}	0.044	3.2%
	2.1	

In Table I, we compare the results of $pp \rightarrow \tilde{t}_1(\rightarrow t\tilde{\chi}_{1,2}^0)\tilde{\chi}_1^-$ for a benchmark point $(m_{\tilde{t}_1}, \mu) = (611, 100)$ GeV in Method-1 and Method-2 at 14 TeV LHC. From this table we can see that the $Z+\text{jets}$ background in Method-1 is smaller than in Method-2, while the $t\bar{t}$ background in Method-1 is larger than in Method-2. However, more signal events can be retained in Method-1 than in Method-2. Therefore, the overall effects make Method-1 have better sensitivity for reconstructing the top quark in the region with large mass splitting between \tilde{t}_1 and $\tilde{\chi}_1^-$.

At 14 TeV LHC with $\mathcal{L} = 3000 \text{ fb}^{-1}$, the statistical significance S/\sqrt{B} for our benchmark point can reach 3.9σ (2.1σ) with $S/B = 4.0\%$ (3.2%) in Method-1 (Method-2).

Table II: The cross sections of $V+\text{jets}$, $t\bar{t}$, and $\tilde{t}_1(\rightarrow b\tilde{\chi}_1^+)\tilde{\chi}_1^-$ for a benchmark point $(m_{\tilde{t}_1}, \mu) = (496, 200)$ GeV and $\tan\beta = 10$ at 14 TeV LHC with $\mathcal{L} = 3000 \text{ fb}^{-1}$. The cross sections are in units of fb.

Process	Cross Section
$W+\text{jets}$	1.10
$Z+\text{jets}$	0.20
$t\bar{t}$	5.1%
S/B	5.5
S/\sqrt{B}	

In Table II, we show the cross sections of $V+\text{jets}$, $t\bar{t}$, and $\tilde{t}_1(\rightarrow b\tilde{\chi}_1^+)\tilde{\chi}_1^-$ for a benchmark point $(m_{\tilde{t}_1}, \mu) = (496, 200)$ GeV at 14 TeV LHC. Different from the $\tilde{t}_1 \rightarrow t\tilde{\chi}_{1,2}^0$ channel, the $Z+\text{jets}$ background is dominant over $t\bar{t}$ since only one hard b-jet is required in the final state. From Table II we can see that S/\sqrt{B} and S/B can reach 5.5 and 5.1% for $\mathcal{L} = 3000 \text{ fb}^{-1}$, respectively.

[Figure 3: see original paper] The dependence of the significance of the channel $\tilde{t}_1 \rightarrow t\tilde{\chi}_{1,2}^0$ on the higgsino mass μ and stop mass $m_{\tilde{t}_1}$ at 14 TeV LHC with $\mathcal{L} = 3000 \text{ fb}^{-1}$.

In Fig. 3, we display the dependence of statistical significance S/\sqrt{B} of the channel $\tilde{t}_1 \rightarrow t\tilde{\chi}_{1,2}^0$ on the higgsino mass μ and stop mass $m_{\tilde{t}_1}$ at 14 TeV LHC

with $\mathcal{L} = 3000 \text{ fb}^{-1}$. We can see that values of S/\sqrt{B} decrease with increasing μ because of cut efficiency reduction. When the stop becomes heavy, the cross section of $\tilde{t}_1 \tilde{\chi}_1^-$ is suppressed. However, as a result of applying the HEPTop-Tagger method, more signal events can be retained, particularly in the mass range $450 \text{ GeV} \leq m_{\tilde{t}_1} \leq 650 \text{ GeV}$. Therefore, when $\mu \leq 150 \text{ GeV}$, the stop mass $m_{\tilde{t}_1} \leq 610 \text{ GeV}$ can be probed at $\geq 3\sigma$ statistical significance with $S/B \leq 8\%$.

[Figure 4: see original paper] Same as Fig. 3, but for the decay channel $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^+$.

In Fig. 4, the statistical significance S/\sqrt{B} of the channel $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^+$ is presented on the plane of higgsino mass μ versus stop mass $m_{\tilde{t}_1}$ at 14 TeV LHC with $\mathcal{L} = 3000 \text{ fb}^{-1}$. It can be seen that the sensitive stop region lies in $450 \text{ GeV} \leq m_{\tilde{t}_1} \leq 620 \text{ GeV}$, where a hard b-jet ($p_T > 200 \text{ GeV}$) and sizable E_T^{miss} ($E_T^{\text{miss}} > 250 \text{ GeV}$) can be used to effectively suppress backgrounds. But when the stop mass increases, S/\sqrt{B} rapidly decreases. We see that the higgsino mass region $100 \text{ GeV} \leq \mu \leq 225 \text{ GeV}$ and stop mass $m_{\tilde{t}_1} \leq 620 \text{ GeV}$ can be covered at $\geq 3\sigma$ statistical significance with S/B varying from 4% to 19%.

Conclusions

Even though its exclusion limit for the stop may not be as good as pair production, the stop can participate not only in strong interaction processes but also in electroweak interaction processes. The determination of the electroweak properties of the stop is an essential task for the LHC and future colliders. In this work we propose to probe natural SUSY by using the electroweak single-stop production $pp \rightarrow \tilde{t}_1 + E_T^{\text{miss}}$ at the LHC (here the missing energy is from the nearly degenerate higgsinos).

By analyzing the decay channels of the stop $\tilde{t}_1 \rightarrow t\tilde{\chi}_{1,2}^0$ and $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^+$, we obtain the following observations: (1) The decay $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^+$ has better sensitivity than $\tilde{t}_1 \rightarrow t\tilde{\chi}_{1,2}^0$; (2) The parameter region with higgsino mass $100 \text{ GeV} \leq \mu \leq 225 \text{ GeV}$ and stop mass $m_{\tilde{t}_1} \leq 620 \text{ GeV}$ can be covered with $S/\sqrt{B} > 3$ and $4\% \leq S/B \leq 19\%$ at 14 TeV HL-LHC with an integrated luminosity of 3000 fb^{-1} . Thus, searches for single stop production will directly test the naturalness of supersymmetry and the electroweak properties of the stop.

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