Exotic Stop Decay at the LHC

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Abstract

Current searches for the stop focus on the decay channels of $\tilde{t} \to t\chi_1^0$ or $\tilde{t} \to b\chi_1^\pm \to bW\chi_1^0$, leading to $tt/bbWW + E_T$ final states for stop pair production at the LHC. In supersymmetric scenarios with light gauginos other than the neutralino lightest supersymmetric particle (LSP), different decay modes of the stop could be dominant, which significantly weaken the current stop search limits at the LHC. Additionally, new decay modes offer alternative discovery channels for stop searches. In this paper, we study the stop decay in the Bino-like LSP case with light Wino or Higgsino next-to-LSPs (NLSPs), and identify cases in which additional decay modes become dominant. We also perform a detailed collider analysis for stop pair production with one stop decaying via $\tilde{t}_1 \to t\chi_2^0 \to th\chi_1^0$, and the other stop decaying via $\tilde{t}_1 \to b\chi_1^\pm \to bW\chi_1^0$, leading to the $bbbjj\ell + E_T$ collider signature. At the 14 TeV LHC with 300 fb$^{-1}$ integrated luminosity, the stop can be excluded up to about 1040 GeV at the 95% C.L., or be discovered up to 940 GeV at $5\sigma$ significance.

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I. INTRODUCTION

The discovery of a 125 GeV Higgs at the Large Hadron Collider (LHC) [1, 2] motivates the consideration of new physics beyond the Standard Model (SM). In the SM, the Higgs receives unstable quadratically divergent radiative corrections to its mass from the top quark loop. An unnatural cancellation is needed to recover the light physical Higgs mass, which is the so-called “naturalness problem” [3]. Supersymmetry (SUSY) provides a solution to the naturalness problem by introducing superpartners to the SM particles, with interactions following the SUSY relations. The quadratic divergence from the superpartners cancels that of the SM particles, with the remnant contributions being only logarithmically divergent. Given the large top Yukawa coupling, the top and stop sectors of the Minimal Supersymmetric Standard Model (MSSM) provide the largest radiative corrections to the Higgs mass. Stop masses cannot be too heavy in order to avoid excessive fine tuning of the Higgs mass. A TeV scale stop typically leads to fine tuning of about 1% [4]. Given the tight connection between the stop and Higgs sectors, it is important to fully explore the discovery potential of the stop at the LHC.

Most of the current searches for the light stop focus on the decay $\tilde{t} \to t\chi^0_1$ or $\tilde{t} \to b\chi^+_1 \to bW\chi^0_1$, leading to $tt + E_T$ or $bbWW + E_T$ final states for stop pair production at the LHC. However, due to the large SM background from $t\bar{t}$, searches for the stop can be very challenging. The current limits from ATLAS and CMS experiments exclude stops with masses up to about 645 GeV for a light neutralino LSP [5–15]. At energy of 14 TeV with 100 fb$^{-1}$ of integrated luminosity, the expected discovery sensitivity for stops at the LHC is about 1 TeV [16].

The current stop search limits, however, always assume the dominance of the stop decay channels mentioned above. The current limits could be significantly weakened when other stop decay modes open, which could occur in many regions of MSSM parameter space. On the other hand, the opening of new channels offers alternative discovery potential for stops at the LHC. Therefore, it is timely to study the non-minimal stop decay pattern as well as assess the stop discovery potential at the 14 TeV LHC.

Even under the usual assumption of a Bino-like LSP, the existence of other light neutralino states, for example, Wino-like or Higgsino-like next-to-LSPs (NLSPs) could lead to new decay channels for the stop. For instance, $\tilde{t}$ could decay to $t\chi^0_{2,3}$, with $\chi^0_{2,3}$ further
decaying to $Z\chi^0_1, h\chi^0_1$. Given the relatively large SU(2)$_L$ coupling and top Yukawa coupling, compared to the U(1)$_Y$ coupling relevant for the Bino-like LSP, decays to $t\chi^0_{2,3}$ could even be dominant despite the phase space suppression. In this paper, we study the stop decay branching fractions for the Wino- or Higgsino-like NLSP case, considering the minimal mixing and the maximal mixing scenarios in the stop sector, and outline the main search channels for the stops at the LHC.

Similarly, the current sbottom searches focus on $\tilde{b} \rightarrow b\chi^0_1$, with $bb + \not{E}_T$ being the dominant search channel. Given data collected at the LHC 7/8 TeV, sbottoms with masses up to 700 GeV are excluded [17]. Even in parameter space with highly degenerate sbottom and LSP masses, the sbottom is excluded with mass up to about 400 GeV [18]. The left-handed sbottom mass is related to the left-handed stop mass since they are controlled by the same soft SUSY breaking mass parameter. In this paper, we also study the left-handed sbottom decay pattern for various scenarios, as well as its collider signatures.

Given the discovery of the SM-like Higgs boson at the LHC, we can now use final states with a Higgs boson to search for new physics beyond the SM. To explore the 14 TeV LHC reach for the exotic stop decay channels, we performed a detailed collider analysis with a Higgs in the final state: $pp \rightarrow \tilde{t}_1\tilde{t}_1^* \rightarrow b\chi^0_1, t\chi^0_1 \rightarrow th\chi^0_1$, and other stop decaying via $\tilde{t}_1 \rightarrow b\chi^\pm_1 \rightarrow bW\chi^0_1$, leading to $bbbbjj\ell + \not{E}_T$ signature. By designing cuts to identify the signal while suppressing SM backgrounds, we obtained the 95% C.L. exclusion limit as well as the $5\sigma$ discovery reach at the 14 TeV LHC with 300 fb$^{-1}$ integrated luminosity. Final states with $\chi^0_2 \rightarrow Z\chi^0_1$ are left for future studies.

The rest of the paper is organized as the following. In Sec. II we present the third generation squark sector in the MSSM and discuss its connection to the Higgs sector. In Sec. III we discuss the stop and sbottom decays for various scenarios, as well as the collider signatures for stop/sbottom pair production. In Sec. IV we summarize the current LHC stop and sbottom search results from both ATLAS and CMS. In Sec. V we investigate the 14 TeV reach of the stop via final states with a Higgs. In Sec. VI we conclude.

II. MSSM STOP SECTOR

In this study, we work in the MSSM and focus primarily on the third generation squark sector. We decouple other SUSY particles: the gluino, sleptons, and the first and second
generation squarks. We also decouple the non-SM Higgs particles by setting $M_A$ large. The remaining SUSY particles in the model are the third generation squarks, the neutralinos and charginos.

The gauge eigenstates for the superpartners of the top and bottom quarks are $(\tilde{t}_L, \tilde{b}_L), \tilde{t}_R$ and $\tilde{b}_R$, with the left-handed states grouped as an SU(2)$_L$ doublet and the right-handed states as singlets. The mass matrix for the stop sector is

$$m_{\tilde{t}}^2 = \begin{pmatrix} M_{3SQ}^2 + m_{\tilde{t}}^2 + \Delta_{\tilde{t}L} & m_{\tilde{t}} \tilde{A}_t \\ m_{\tilde{t}} \tilde{A}_t & M_{3SU}^2 + m_{\tilde{t}}^2 + \Delta_{\tilde{t}R} \end{pmatrix},$$

with $M_{3SQ}$ and $M_{3SU}$ representing the soft SUSY breaking masses for $\tilde{t}_L$ and $\tilde{t}_R$, $m_{\tilde{t}}^2$ term coming from the F-term contribution in the SUSY Lagrangian and the $\Delta$ terms coming from the D-term contribution. The off-diagonal term $\tilde{A}_t$ is given by:

$$\tilde{A}_t = A_t - \mu \cot \beta,$$

for $A_t$ representing the trilinear coupling and $\mu$ representing the supersymmetric bilinear mass term in the Higgs sector.

The stop mass matrix can be diagonalized with a stop mixing angle $\theta_t$:

$$\begin{pmatrix} \tilde{t}_1 \\ \tilde{t}_2 \end{pmatrix} = \begin{pmatrix} \cos \theta_t & -\sin \theta_t \\ \sin \theta_t & \cos \theta_t \end{pmatrix} \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix},$$

with mass eigenstates $\tilde{t}_1, \tilde{t}_2$: $m_{\tilde{t}_1} < m_{\tilde{t}_2}$. For $M_{3SQ} < (>) M_{3SU}$, $\tilde{t}_1$ is mostly left-handed (right-handed), while for $M_{3SQ}^2 \sim M_{3SU}^2$, $\tilde{t}_{1,2}$ could be a mixture of the left- and right-handed states.

Given the large top Yukawa coupling, the stop sector provides the dominant contribution to the radiative corrections of the SM-like Higgs mass in the MSSM. For $M_{3SQ} = M_{3SU} = M_{SUSY}$, the correction to the SM-like Higgs mass squared is [19]:

$$\delta m_h^2 = \frac{3}{4\pi^2} y_t^2 m_{\tilde{t}}^2 \sin^2 \beta \left( \log \frac{M_{SUSY}^2}{m_{\tilde{t}}^2} + \frac{\tilde{A}_t^2}{M_{SUSY}^2} \left( 1 - \frac{\tilde{A}_t^2}{12M_{SUSY}^2} \right) \right).$$

(4)

In the minimal mixing case with $\tilde{A}_t = 0$, a large $M_{SUSY}$ is needed to provide a SM-like Higgs mass of 125 GeV. In the maximal mixing case with $\tilde{A}_t = \sqrt{6} M_{SUSY}$, a relatively small $M_{SUSY}$ can be accommodated given the additional contribution from the $\tilde{A}_t$ term. In the general MSSM when $M_{3SQ}^2 \neq M_{3SU}^2$, to provide a SM-like Higgs mass of 125 GeV,
the light stop $\tilde{t}_1$ can still be as light as 200 GeV. A large mass splitting between the stop mass eigenstates (and a large $\tilde{A}_t$ term), however, is typically needed, resulting in $m_{\tilde{t}_2} \gtrsim 500$ GeV in general \cite{20,21}.

Similarly, the mass matrix for the sbottom is given as:

$$m^2_{\tilde{b}} = \begin{pmatrix} M^2_{3SQ} + m^2_b + \Delta^d_{\tilde{b}L} & m_b \tilde{A}_b \\ m_b \tilde{A}_b & M^2_{3SD} + m^2_b + \Delta^d_{\tilde{b}R} \end{pmatrix},$$

(5)

with

$$\tilde{A}_b = A_b - \mu \tan \beta.$$  

(6)

Given the suppression of the off-diagonal terms by the small bottom mass, large mixing among the sbottom mass eigenstates is less common.

Since the stop sector provides the dominant contribution to the Higgs mass corrections, we decouple the right-handed sbottom in our analysis. The left-handed sbottom mass, however, is determined by $M_{3SQ}$ and could be relatively light. Given $m_b \tilde{A}_b, M^2_{3SQ} < M^2_{3SD}$, the light sbottom mass eigenstate is mostly left-handed: $\tilde{b}_1 \sim \tilde{b}_L$. Although the sbottom corrections to the Higgs mass are small compared to the stop corrections, there can be significant modifications to the Higgs couplings, especially the bottom Yukawa coupling \cite{22}.

III. STOP DECAY

We consider the neutralino/chargino spectrum with a Bino-like LSP. For simplicity, we consider three representative scenarios:

- Case I, Bino-like LSP with decoupled Winos and Higgsinos: $M_1 < m_{\tilde{t}_1 \tilde{b}_1} \ll |\mu|, M_2$.
- Case IA, Bino-like LSP with Wino-like NLSPs: $M_1 < M_2 < m_{\tilde{t}_1 \tilde{b}_1} \ll |\mu|$.
- Case IB, Bino-like LSP with Higgsino-like NLSPs: $M_1 < |\mu| < m_{\tilde{t}_1 \tilde{b}_1} \ll M_2$.

The decays of the light stop or sbottom highly depend on the low-lying neutralino/chargino spectrum, as well as the composition of the light stop and sbottom.

In each scenario, we consider two limiting cases with different stop left-right mixing. In the minimal mixing case, $\tilde{A}_t = A_t - \mu \cot \beta = 0$, the lightest stop mass eigenstate $\tilde{t}_1$ is either
purely $\tilde{t}_L$ ($M_{3SQ} < M_{3SU}$) or purely $\tilde{t}_R$ ($M_{3SQ} > M_{3SU}$). We decouple $\tilde{t}_2$ for simplicity.

In the maximal mixing case with $M_{3SQ} = M_{3SU} = M_{SUSY}$ and $|\tilde{A}_t| = \sqrt{6} M_{SUSY}$, both $\tilde{t}_{1,2}$ are a mixture of $\tilde{t}_L$ and $\tilde{t}_R$, with mass squared splitting $\Delta m^2_{\tilde{t}} \approx 2\sqrt{6} m_t M_{SUSY}$. In our analysis below, we use $\tilde{A}_t > 0$. Negative values of $\tilde{A}_t$ introduce little changes to the numerical results. Since $M_{3SQ}$ also controls the mass for $\tilde{b}_L$, there is a light $\tilde{b}_1 \sim \tilde{b}_L$ for the light $M_{3SQ}$ case, assuming small sbottom left-right mixing and a decoupled $\tilde{b}_R$.

The mass spectra for stops and sbottom are shown in Fig. 1. In the minimal mixing case (left panel), $m_{\tilde{t}_L} (m_{\tilde{t}_R})$, $m_{\tilde{b}_1} \sim M_{3SQ} (M_{3SU})$, especially for large $M_{3SQ}$ ($M_{3SU}$). In the maximal mixing case (right panel), the mass difference between $\tilde{b}_1$ and $\tilde{t}_1$ is typically about 250 GeV while the mass difference between $\tilde{t}_2$ and $\tilde{t}_1$ is about 350 GeV or larger.

We used SUSY-HIT [23] to calculate the supersymmetric particle spectrum and decay branching fractions. In this section, unless otherwise specified, we have set the Bino-like LSP mass parameter $M_1 = 100$ GeV, the intermediate gaugino mass parameters $M_2, \mu = 300$ GeV in Cases IA and IB, respectively, and $\tan \beta = 10$. 

FIG. 1: The mass spectra for stops and sbottom for the minimal mixing case (left panel) and the maximal mixing case with $M_{3SQ} = M_{3SU} = M_{SUSY}$ (right panel).
A. Case I: Bino-like LSP with decoupled Wino and Higgsino

The simplest case has a mass spectrum with stop(s), left-handed sbottom, and only the low-lying neutralino being the Bino-like LSP.

In the minimal mixing case with the light stop $\tilde{t}_1$ as a pure left- or right-handed state, $\tilde{t}_1$ either directly decays to $t\chi^0_1$ when it is kinematically accessible or through $bW^{(*)}\chi^0_1$ with 100% branching fraction. Similarly, in the case of small $M_{3SQ}$, $\tilde{b}_1$ decays directly through $b\chi^0_1$ with 100% branching fraction.

In the maximal mixing case, $\tilde{t}_1$, $\tilde{t}_2$, and $\tilde{b}_1$ appear in the spectrum, with a typical mass order $m_{\tilde{t}_1} < m_{\tilde{b}_1} < m_{\tilde{t}_2}$ with relatively large mass splittings of 150 GeV or larger. While the decay of $\tilde{t}_1$ is straightforward (100% into $bW^{(*)}\chi^0_1$), the decays of $\tilde{b}_1$ and $\tilde{t}_2$ could have multiple competing channels, as shown in Fig. 2. For $\tilde{b}_1$, it dominantly decays into $W\tilde{t}_1$ while the branching fraction of the conventional channel of $\tilde{b}_1 \rightarrow b\chi^0_1$ is only about a few percent or less. For $\tilde{t}_2$, it dominantly decays into a light stop/sbottom with a gauge boson: $Z\tilde{t}_1$ about 75% and $W\tilde{b}_1$ about 20%. The direct decay down to $t\chi^0_1$ is less than 10%.

The pair production of stops and sbottoms at the LHC, and their subsequent decays result in the appearance of various final states. In the left panel of Fig. 3 we show the $\sigma \times \text{BR}$ of final states $tt/bbWW + \not{E}_T$ for $\tilde{t}_1$ in the minimal and maximal mixing scenarios, as well as $bb + \not{E}_T$ for $\tilde{b}_1$ in the minimal mixing scenario at the 14 TeV LHC. These are the
Maximal Mixing Case I

FIG. 3: Case I: left panel shows $\sigma \times \text{BR}$ of final states for $\tilde{t}_1$ pair production in both the minimal and maximal mixing scenarios, as well as $\tilde{b}_1$ pair production in the minimal mixing scenario. The middle and right panel show $\sigma \times \text{BR}$ for various final states of $\tilde{b}_1$ and $\tilde{t}_2$ pair production, respectively, in the maximal mixing scenario. All channels include $E_T$ in the final states.

conventional channels where $\tilde{t} \rightarrow t/bW\chi_1^0$ and $\tilde{b} \rightarrow b\chi_1^0$ dominate. $\sigma \times \text{BR}$ is the same as the production cross sections for the stop pair and sbottom pair. The middle panel of Fig. 3 shows the $\sigma \times \text{BR}$ for $\tilde{b}_1\tilde{b}_1$ pair production in the maximal mixing scenario. The conventional channel $bb+E_T$ is highly suppressed, while $bbWWWW+E_T$ becomes dominant. The right panel of Fig. 3 shows the $\sigma \times \text{BR}$ for $\tilde{t}_2\tilde{t}_2$ pair production in the maximal mixing scenario. The current experimentally searched channel $ttZ+E_T$ is subdominant, only 10% of the dominant channel of $ttZZ+E_T$. $ttWWZ$ is the second dominant channel. The cross section, however, is relatively small, less than about 10 fb for $m_{\tilde{t}_2} \gtrsim 750$ GeV, given the heaviness of the second stop. Note that the range of the stop and sbottom masses are controlled by the choice of parameter $M_{3SQ}=M_{3SU}=M_{SUSY}=600\ldots 1500$ GeV in the maximal mixing case (see Fig. 1). Also note that all the cross sections shown in the plots are leading order only. The next leading order $K$-factor for stop and sbottom pair production process is about 1.33 at the 14 TeV LHC [24, 25], which has been taken into account in our collider analysis below in Sec. V.
B. Case IA: Bino LSP with Wino NLSP

The low lying neutralino/chargino spectrum in Case IA comprises of a Bino-like LSP, as well as a pair of Wino-like states: $\chi_2^0$ and $\chi^\pm_1$ with nearly degenerate masses. In the minimal mixing scenario, the decay branching fractions are shown in Fig. 4 for left-handed $\tilde{t}_1$ (left), $\tilde{b}_1$ (middle), and right-handed $\tilde{t}_1$ (right). For the left-handed $\tilde{t}_1$, decays to $b\chi^\pm_1$ ($\sim 70\%$ for large $m_{\tilde{t}_1}$) and $t\chi^0_2$ ($\sim 30\%$ for large $m_{\tilde{t}_1}$) dominate over $t\chi^0_1$ once kinematically accessible, due to the stronger SU(2)$_L$ coupling compared to the relatively weaker U(1)$_Y$ coupling. Similarly, $\tilde{b}_1 \rightarrow t\chi^\pm_1$ ($\sim 65\%$) and $\tilde{b}_1 \rightarrow b\chi^0_2$ ($\sim 30\%$) dominate over the conventional channel of $b\chi^0_1$ for sbottom. Given the dominant decay channels of the Wino-like neutralino/chargino\(^1\): $\chi^\pm_1 \rightarrow W\chi^0_1$, $\chi^0_2 \rightarrow Z/h\chi^0_1$, the dominant decay modes for $\tilde{t}_1$ and $\tilde{b}_1$ are: $\tilde{t}_1 \rightarrow bW\chi^0_1$, $tZ/h\chi^0_1$, $\tilde{b}_1 \rightarrow tW\chi^0_1$, $bZ/h\chi^0_1$. When $\tilde{t}_1$ is mostly right-handed, it decays to $t\chi^0_1$ almost 100\%, since its couplings to the Wino-like neutralino/charginos are highly suppressed.

The left, middle and right panels of Fig. 4 show the $\sigma \times$BR for pure left-handed $\tilde{t}_1\tilde{t}_1$, $\tilde{b}_1\tilde{b}_1$ and pure right-handed $\tilde{t}_1\tilde{t}_1$ pair production, respectively, in the minimal mixing scenario

\(^1\) For $\chi^0_1$, whether it decays preferably to $Z\chi^0_1$ or $h\chi^0_1$ depends on the sign of $\mu$, as explained in detail in Ref. 26.
of Case IA. For pure left-handed $\tilde{t}_1$, $bbWWZ/h + E_T$ is as important as the conventional channel $bbWW + E_T$, which could be an important new search channel for the stop. For pure left-handed $\tilde{b}_1$, the conventional channel of $bb + E_T$ is highly suppressed. New final states of $bbWWZ/h$ and $bbWWWW$ are dominant and comparable in size, with $bbZ/hZ/h$ being subdominant, opening up new channels for sbottom searches. The final state for the pure right-handed $\tilde{t}_1$ is still the conventional channel of $bbWW + E_T$, despite the existence of light Wino NLSPs in the spectrum.

For the maximally mixed scenario, the decay of $\tilde{t}_1$, $\tilde{b}_1$ and $\tilde{t}_2$ are shown in the left, middle and right panels of Fig. 6, respectively. For $\tilde{t}_1$ with large mass, the decay to $b\chi_{1}^{\pm}, t\chi_{2}^{0}$ still dominates over $t\chi_{1}^{0}$, but the corresponding branching fractions are smaller compared to the pure left-handed case (Fig. 4) due to the decrease of the coupling to the Wino-like state caused by the right-handed stop component. For $\tilde{b}_1$, while $t\chi_{1}^{\pm}$ and $b\chi_{2}^{0}$ modes still dominate over $b\chi_{1}^{0}$ mode, the new decay channel of $W\tilde{t}_1$ opens up and even dominates over most of the mass range. Its branching fraction varies between 100% to about 40% for $m_{\tilde{b}_1}$ between 400 GeV to 1800 GeV. For $\tilde{t}_2$, in addition to $b\chi_{1}^{\pm}$ and $t\chi_{1,2}^{0}$ (about a few percent to 20%), decays to a light stop/sbottom plus a gauge boson become comparable or even dominant: about 50% – 70% for $Z\tilde{t}_1$ and about 20% – 15% for $W\tilde{b}_1$.

The left, middle and right panels of Fig. 7 show the $\sigma \times$ BR for $\tilde{t}_1 \tilde{t}_1$, $\tilde{b}_1 \tilde{b}_1$, and $\tilde{t}_2 \tilde{t}_2$.
FIG. 6: Case IA: Branching fractions for $\tilde{t}_1$ (left), $\tilde{b}_1$ (middle) and $\tilde{t}_2$ (right) in the maximal mixing scenario.

FIG. 7: Case IA: $\sigma \times \text{BR}$ of various final states for pair production of $\tilde{t}_1$ (left), $\tilde{b}_1$ (middle), and $\tilde{t}_1$ (right) in the maximal mixing scenario.

respectively for the maximal mixing scenario of Case IA at the 14 TeV LHC. For the light stop, while the dominant channel is the conventional $bbWW + \not{E}_T$, the subdominant channel $bbWWZ/h + \not{E}_T$ could still have a sizable cross section. For the light sbottom, $bbWWWW + \not{E}_T$ becomes dominant. For the heavy stop, multiple channels open, with $bbWWZ/hZ/h + \not{E}_T$ being dominant, followed by $bbWWZ/h + \not{E}_T$, $bbWWWWZ/h + \not{E}_T$, and $bbWWZ/hZ/h + \not{E}_T$. 
FIG. 8: Case IB: branching fractions for left-handed \( \tilde{t}_1 \) (left), \( \tilde{b}_1 \) (middle), right-handed \( \tilde{t}_1 \) (right) in the minimal mixing scenario.

C. Case IB: Bino-LSP with Higgsino-NLSP

The low lying neutralino/chargino spectrum in Case IB comprises of a Bino-like LSP, as well a pair of Higgsino-like neutralino states \( \chi_{2,3}^0 \) and chargino states \( \chi_1^\pm \) with nearly degenerate masses. Fig. 8 shows the branching fractions of left-handed \( \tilde{t}_1 \) and \( \tilde{b}_1 \) and right-handed \( \tilde{t}_1 \) in the left, middle and right panels for the minimal mixing scenario. For \( \tilde{t}_1 \), decays to \( t\chi_{2,3}^0 \) dominate over \( b\chi_1^\pm \) and \( t\chi_1^0 \) since the former ones are controlled by the large top Yukawa coupling, compared to the small bottom Yukawa coupling and \( U(1)_Y \) couplings for the latter two. However, for \( \tilde{b}_1 \), the decay of \( t\chi_1^\pm \) becomes dominant since the \( \tilde{b}_L t_R H_u^+ \) coupling is proportional to the top Yukawa while its couplings to \( \chi_{2,3}^0 \) and \( \chi_1^0 \) are suppressed by the bottom Yukawa coupling and \( U(1)_Y \) couplings. For the right-handed \( \tilde{t}_1 \) case, it dominantly decays to \( b\chi_1^\pm \), reaching almost 50%, while decays to \( t\chi_2^0 + t\chi_3^0 \) are about 20%. All channels are controlled by the top Yukawa coupling while the latter ones have extra phase space suppression. Given the near degeneracy of the two Higgsino states \( \chi_{2,3}^0 \), contributions from final states involving \( \chi_{2,3}^0 \) are usually summed over in collider analyses.

Given the further decays of \( \chi_1^\pm \to W\chi_1^0, \chi_{2,3}^0 \to Z\chi_1^0/h\chi_1^0 \) as discussed in detail in [26], the pair production of stops and sbottoms lead to complicated final states at the collider. The left, middle and right panels of Fig. 9 show the \( \sigma \times \text{BR} \) for pure left-handed \( \tilde{t}_1 \tilde{t}_1 \), \( \tilde{b}_1 \tilde{b}_1 \) and pure right-handed \( \tilde{t}_1 \tilde{t}_1 \) pair production in the minimal mixing scenarios of Case IB. For pure left-handed \( \tilde{t}_1 \), \( bbWWZ/hZ/h + E_T \) is the dominant final state with the
FIG. 9: Case IB: $\sigma \times \text{BR}$ of various final states for pair production of left-handed $\tilde{t}_1$ (left), $\tilde{b}_1$ (middle), and right-handed $\tilde{t}_1$ (right) in the minimal mixing scenario.

For the maximal mixing scenario, the decay branching fractions for $\tilde{t}_1$, $\tilde{b}_1$, and $\tilde{t}_2$ are shown in the left, middle and right panels of Fig. 10 respectively. Since $\tilde{t}_1$ is an equal mixture of left- and right-handed components, the decays to $t\chi^0_{1,2,3}$ (dominant for $\tilde{t}_L$) and $t\chi^\pm_{1,2}$ are suppressed.
\[ \sigma \times BR \] (dominant for \( \tilde{t}_R \)) (see the left and right panel of Fig. 8) have roughly the same decay branching fraction, around 30% each. Decay to the conventional state of \( t\chi_1^0 \) is typically a few percent, unless other decay modes are kinematically unaccessible at small \( m_{\tilde{t}_1} \).

For \( \tilde{b}_1 \), the relative strength of \( t\chi_1^\pm \) and \( b\chi_{2,3}^0 \) is similar to that of the \( \tilde{b}_1 \) in the minimal mixing scenario, but the opening of the \( W\tilde{t}_1 \) mode dominates the decay for most of the mass range, leading to the suppression of the \( t\chi_1^\pm \) and \( b\chi_{2,3}^0 \) modes. With increasing \( m_{\tilde{b}_1} \), \( t\chi_1^\pm \) becomes more and more important, which dominates over \( W\tilde{t}_1 \) when \( m_{\tilde{b}_1} \gtrsim 1300 \text{ GeV} \).

For \( \tilde{t}_2 \), decay to \( Z\tilde{t}_1 \) is dominant, about 60% – 30% for \( m_{\tilde{t}_2} \) in the range of 700 – 1700 GeV. Decays to \( b\chi_1^\pm \), \( t\chi_{2,3}^0 \) are sub-dominant, around 10% – 20% for each channel. \( \tilde{t}_2 \rightarrow W\tilde{b}_1 \) is typically around 10% to about a few percent, while \( \tilde{t}_2 \rightarrow t\chi_1^0 \) is only at a few percent level.

The left, middle and right panel of Fig. 11 show the \( \sigma \times BR \) for \( \tilde{t}_1 \tilde{t}_1 \), \( \tilde{b}_1 \tilde{b}_1 \), and \( \tilde{t}_2 \tilde{t}_2 \) for the maximal mixing scenario of Case IB at the 14 TeV LHC. For the light stop, the dominant channel is \( bbWWZ/h + E_T \), followed by \( bbWWZ/hZ/h + E_T \). The conventional channel \( bbWW + E_T \) is suppressed by about a factor of 5. For the light sbottom, \( bbWWWW + E_T \) and \( bbWWWWZ/h + E_T \) are dominant. For the heavy stop, multiple channels open, with \( bbWWZ/hZ/h + E_T \) being dominant, followed by \( bbWWZ/hZ/hZ/h + E_T \) and \( bbWWZ/h + E_T \).

FIG. 11: Case IB: \( \sigma \times BR \) of various final states for pair production of \( \tilde{t}_1 \) (left), \( \tilde{b}_1 \) (middle), and \( \tilde{t}_2 \) (right) in the maximal mixing scenario.
Searches for direct stop pair production have been performed at both ATLAS and CMS, with about 20 fb\(^{-1}\) data at \(\sqrt{s} = 8\) TeV, and about 5 fb\(^{-1}\) data at \(\sqrt{s} = 7\) TeV \([5–15]\). The current searches mainly focus on two decay channels: \(\tilde{t}_1 \to t\chi_1^0\) and \(\tilde{t}_1 \to b\chi_1^\pm \to bW^{(*)}\chi_1^0\) \([5–7, 9–11]\). For small mass splitting \(m_{\tilde{t}} - m_{\chi_1^0}\), channels of \(\tilde{t} \to c\chi_1^0\), \(b f f'\chi_1^0\) have also been studied \([12]\). ATLAS results on fully hadronic final states exclude stops in the regions of \(270 < m_{\tilde{t}_1} < 645\) GeV for \(m_{\chi_1^0} < 30\) GeV, assuming both top squarks decay 100\% via \(\tilde{t}_1 \to t\chi_1^0\) \([5]\). Regions of \(245 < m_{\tilde{t}_1} < 400\) GeV for \(m_{\chi_1^0} < 60\) GeV, \(m_{\chi_1^\pm} = 2m_{\chi_1^0}\) are excluded for the scenario where the top squark is assumed to decay 100\% via \(\tilde{t}_1 \to bW\chi_1^0\). For semileptonic channels, stop masses between 210 GeV and 640 GeV are excluded at 95\% C.L. for a massless LSP \([6]\) assuming \(\text{BR}(\tilde{t}_1 \to t\chi_1^0) = 100\%\). Stop masses up to 500 GeV are excluded when \(\tilde{t}_1 \to b\chi_1^\pm\) dominates. Limits from the pure leptonic channels are much weaker \([7]\). Limits from CMS are similar \([9–11]\). Note that limits on the stop exclusion depend on the branching fractions of \(\tilde{t}_1 \to t\chi_1^0\) and \(\tilde{t}_1 \to b\chi_1^\pm\). For \(\tilde{t}_1 \to b\chi_1^\pm\), the limits also depend on the mass of the intermediate chargino.

Searches for the second stop utilize the decay of \(\tilde{t}_2 \to \tilde{t}_1 Z/h\), looking for signals including \(b\)-jets and large \(E_T\) with either same flavor leptons reconstruction of the Z boson \([8]\) and/or high \(p_T\) jet and \(b\)-jet multiplicities with additional leptons \([13, 14]\). The second stop mass is excluded up to about 600 GeV. Stop searches in scenarios with a Gravitino LSP are explored in Refs. \([8, 15]\). Stop searches in the R-parity violating MSSM can be found in Ref. \([27]\).

There are other theoretical studies in the literature on the stop searches at the LHC, mostly focusing on the stop decaying to light generation quarks \([28, 29]\) or a light stop with little missing energy, which mimics the WW signal at the LHC \([30–34]\).

V. COLLIDER ANALYSIS

In this section, we study the detectability of the light stop in Case IA with a mass hierarchy of \(M_1 < M_2 < M_{3SQ} \ll |\mu|, M_{3SU}\), resulting in a mass spectrum including a mostly left-handed stop and mostly left-handed sbottom, Wino-like NLSPs, and a Bino-like LSP. We choose a benchmark point with the specific set of parameters and the corresponding
mass spectrum shown in Table I. The value of $\tilde{A}_t$ is chosen such that the SM-like Higgs mass is around 125 GeV. Note that even though $\tilde{A}_t$ is set to a large value, the large mass splitting between $M_{3SQ}$ and $M_{3SU}$ results in a mostly left-handed $\tilde{t}_1$ and mostly right-handed $\tilde{t}_2$. Therefore, the decay patterns of $\tilde{t}_1$ and $\tilde{b}_1$ follow those of the Case IA: purely left-handed stop/sbottom in the minimal mixing scenario.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|c|c|c|c|}
\hline
$M_1$ & $M_2$ & $\mu$ & $\tilde{A}_t$ & $M_{3SQ}$ & $M_{3SU}$ & $\chi_1^0$ & $\chi_2^0$ & $\chi_1^+$ & $\tilde{t}_1$ & $h$ & $\tilde{b}_1$ \\
\hline
150 & 300 & 2000 & 2750 & 550 & 2000 & 151 & 319 & 319 & 538 & 125 & 526 \\
\hline
\end{tabular}
\caption{Mass parameters and mass spectrum of SUSY particles for the benchmark point. All masses are in units of GeV.}
\end{table}

The decay channels for the light stop of the benchmark point are shown in Table II. While the dominant decay channel is $\tilde{t}_1 \to b\chi_1^+$ with 78% branching fraction, the subdominant channel $\tilde{t}_1 \to t\chi_2^0$ is about 20%, providing an interesting signal where $\chi_2^0$ can either decay to a Higgs or a $Z$ boson. For our choice of parameters with $\mu > 0$, $\chi_2^0$ dominantly decays to $h\chi_1^0$, as shown in Table II. Flipping the sign of $\mu$ could lead to another interesting channel of $\chi_2^0 \to Z\chi_1^0$, which is left for future study.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|}
\hline
Decay & Branching Fraction \\
\hline
$\tilde{t}_1 \to t\chi_2^0$ & 20% \\
$\tilde{t}_1 \to b\chi_1^+$ & 78% \\
\hline
$\chi_2^0 \to Z\chi_1^0$ & 3% \\
\hline
$\chi_2^0 \to h\chi_1^0$ & 97% \\
$\chi_1^+ \to W^+\chi_1^0$ & 100% \\
\hline
\end{tabular}
\caption{Decay branching fractions of $\tilde{t}_1$, $\chi_2^0$ and $\chi_1^+$ for the benchmark point.}
\end{table}

For our benchmark point with the reduced branching fraction of $\text{BR}(\tilde{t}_1 \to b\chi_1^+) = 78\%$, the current collider search limits on the stop are much more relaxed: less than about 400 – 500 GeV for $m_{\tilde{t}_1}$. However, new search channels open up, which play a complementary role for stop searches at the LHC.

In our analysis, we study the stop pair production with one stop decaying via $\tilde{t}_1 \to t\chi_2^0 \to bW^+h\chi_1^0$ and the other stop decaying via $\tilde{t}_1 \to b\chi_1^+ \to bW^+\chi_1^0$. We consider semileptonic decays of the two $W$s and the Higgs decay to two $b$-quarks. The signal contains four $b$-jets, two jets, one isolated lepton and large missing energy. The presence of a single lepton helps to reduce QCD backgrounds without significant branching fraction suppression.
The dominant SM backgrounds are $t\bar{t}$ and $tt\bar{b}b$. While $t\bar{tt}h$ is an irreducible background, the production cross section is typically small. Other backgrounds consist of $ttW$, $ttZ$ and $b\bar{b}WW$.

Event samples are generated using Madgraph MG5\texttt{-aMC} V2.2.1 [35], processed through Pythia 6.420 [36] for fragmentation and hadronization and then through Delphes-3.1.2 [37] with the Snowmass combined LHC detector card [38] for detector simulation. Both the SM backgrounds and the stop pair production signal are normalized to theoretical cross sections, calculated including higher-order QCD corrections [24, 25, 39–43]. For the signal process, we scan the parameter range of $M_{3SQ} = 400 \ldots 1100$ GeV with step size of 25 GeV, and $M_1 = 3 \ldots 750$ GeV with step size of 25 GeV. We fix $M_2$ to be $M_2 = M_1 + 150$ GeV.

We apply the following event selection cuts:

- Events are required to have at least four isolated jets with
  \[ p_T^{j1,j2,j3} > 40 \text{ GeV}, \quad p_T^{j4} > 25 \text{ GeV}, \quad |\eta^j| < 2.5. \]  \( (7) \)

- Among the jets, at least two are $b$-tagged jets.

- One isolated lepton ($e$ or $\mu$) is required to have
  \[ p_T^\ell > 20 \text{ GeV with } |\eta^\ell| < 2.5. \]  \( (8) \)

Additional optimization cuts are applied to further enhance the signal and suppress the SM backgrounds:

- $E_T$, defined as the magnitude of the missing transpose momentum, $p_T^{\text{miss}}$, ranging from 100 to 200 GeV, in increments of 20 GeV.

- $H_T$, defined as the scalar sum of the $p_T$ of all surviving jets: $H_T = \sum p_T^{\text{jet}}$, ranging from 400 to 600 GeV, in increments of 50 GeV.

- Transverse mass $m_T$, defined as the invariant mass of the lepton and the missing transpose momentum:
  \[ m_T = \sqrt{2p_T^\ell E_T (1 - \cos \phi(p_T^\ell, p_T^{\text{miss}}))}, \]  \( (9) \)

ranging from 100 to 200 GeV, in increments of 20 GeV.
FIG. 12: The distribution of $\not{E}_T$ (left) and $m_T$ (right) for the signal at the benchmark point and the SM backgrounds.

- $N_j$, the number of all surviving jets satisfying $p_T^j > 25$ GeV and $|\eta^j| < 2.5$, to be at least 4, 5, or 6.

- $N_{bj}$, the number of all tagged $b$-jets, to be at least 2, 3, or 4.

The distributions of $\not{E}_T$ and $m_T$ for both the signal and the SM backgrounds are shown in Fig. 12. In the $\not{E}_T$ distribution, the $\not{E}_T$ for all the SM backgrounds comes only from the neutrino, which is typically smaller than that of the signal with additional $\not{E}_T$ contribution from the LSP. The transverse mass for the signal process extends beyond the SM threshold of the $W$ boson mass. The $H_T$ distribution of the signal is maximum at a higher value compared to the SM backgrounds.

In Table III, we present the cumulative cut efficiencies for the signal and dominant SM backgrounds with optimized cuts. By utilizing strong $\not{E}_T$, $H_T$ and $m_T$ cuts, we significantly reduce the SM backgrounds. The stop signal process typically generates multiple hard jets in our specified decay. The $N_{bj}$ cut further plays an important role in cutting $t\bar{t}$, $t\bar{t}W$, $t\bar{t}Z$ and $b\bar{b}WW$ backgrounds. $t\bar{t}$ is the dominant background given its large cross section. $t\bar{t}b\bar{b}$ is the second dominant background given its relatively large cross section and similar final states to the signal process. $t\bar{t}h$, $t\bar{t}Z$, $t\bar{t}W$ and $b\bar{b}WW$ can be sufficiently suppressed due to low cross sections. We optimize the significance $S/\sqrt{B}$ for all the combinations of the advanced cuts. We impose a constraint on the number of signal events, $N_s \geq 3$ for 300 fb$^{-1}$ in order to obtain sufficient statistics.
| Description   | $\tilde{t}_1 \tilde{t}_1$ | $\tilde{t}$ | $\tilde{t} \bar{b} \bar{b}$ | $\tilde{t} h$ | $\tilde{t} Z$ | $\tilde{t} W$ |
|--------------|----------------|-----------|----------------|---------|---------|---------|
| CS (fb)      | 23             | 261230    | 2346           | 108     | 221     | 218     |
| Basic cuts   | 38%            | 14%       | 24%            | 31%     | 30%     | 25%     |
| $E_T > 200$ GeV | 12%          | 0.23%     | 0.58%          | 1.2%    | 1.2%    | 1.2%    |
| $H_T > 500$ GeV | 7.6%        | 7.4 x 10^{-4} | 0.29%       | 0.78%   | 0.77%   | 0.69%   |
| $m_T > 160$ GeV | 2.4%         | 1.8 x 10^{-6} | 3.6 x 10^{-5} | 6.6 x 10^{-5} | 7.0 x 10^{-5} | 6.0 x 10^{-5} |
| $N_j \geq 5$ | 2.0%          | 8.5 x 10^{-7} | 2.1 x 10^{-5} | 3.7 x 10^{-5} | 3.8 x 10^{-5} | 2.6 x 10^{-5} |
| $N_{bj} \geq 2$ | 1.2%          | 2.9 x 10^{-7} | 1.1 x 10^{-5} | 2.2 x 10^{-5} | 1.1 x 10^{-5} | 7.6 x 10^{-6} |
| CS (fb) after cuts | 0.28          | 0.075     | 0.026          | 0.0023  | 0.0025  | 0.0017  |

TABLE III: The cumulative cut efficiencies for the signal at the benchmark point and all SM backgrounds. The cross sections shown in the second row are for the semileptonic final states.

FIG. 13: The plot shows the $5\sigma$ discovery reach (red) and 95% exclusion limits (black) of the stop in the $m_{\tilde{t}_1} - m_{\chi^0_1}$ plane for 14 TeV LHC with 300 fb$^{-1}$ of integrated luminosity. $M_2$ is fixed to be $M_1 + 150$ GeV and 10% systematic error is included.

In Fig. 13 we show the 95% C.L. exclusion limit and $5\sigma$ reach in the parameter space of $m_{\tilde{t}_1}$ versus $m_{\chi^0_1}$ for the 14 TeV LHC with 300 fb$^{-1}$ luminosity. For the $5\sigma$ reach, stop masses up to 740 GeV can be reached for a massless LSP and about 940 GeV with $m_{\chi^0_1} = 250$ GeV. The 95% C.L. exclusion limits are about 840 GeV for stops with a light $\chi^0_1$, while the reach is 1040 GeV for $m_{\chi^0_1} = 250$ GeV.
VI. SUMMARY AND CONCLUSION

Most of the current stop and sbottom searches at the LHC have been performed considering the channels of $tt + \slashed{E}_T$, $bbWW + \slashed{E}_T$ for stop and $bb + \slashed{E}_T$ for sbottom, assuming the stop and sbottom decay 100% into these channels. However, in many regions of MSSM parameter space, these decay channels are subdominant, resulting in relaxed bounds from current LHC searches. In this work, we studied decays of the stop and sbottom in the cases of a Bino-like LSP with either Wino-like or Higgsino-like NLSPs in the low energy spectrum, for the left- and right-handed stops and left-handed sbottom in the minimal mixing scenario, and $\tilde{t}_{1,2}$, $\tilde{b}_1$ in the maximal mixing scenario. We found that new decay channels of $\tilde{t}_1 \rightarrow t\chi^0_{2,3}$, $\tilde{b}_1 \rightarrow b\chi^0_{2,3}$, $t\chi^\pm_1$, $W\tilde{t}_1$ open up, which could even dominate over conventional channels. For the heavier stop state, $\tilde{t}_2$, a new channel of $\tilde{t}_2 \rightarrow W\tilde{b}_1$ appears in addition to $\tilde{t}_2 \rightarrow Z\tilde{t}_1$ in the maximal mixing scenario. Given the further decays of $\chi^0_{2,3}$ and $\chi^\pm_1$, pair production of stops and sbottoms at the LHC typically leads to $bb$ plus multiple gauge bosons plus $\slashed{E}_T$ final states. Conventional search channels of $bbWW + \slashed{E}_T$ and $bb + \slashed{E}_T$ could be highly suppressed.

We performed a detailed collider analysis for the reach of the stop at the 14 TeV LHC with 300 fb$^{-1}$ integrated luminosity for one particularly interesting channel in the Bino-like LSP with Wino-like NLSP case. We considered left-handed stop pair production with one stop decaying via $\tilde{t}_1 \rightarrow t\chi^0_2 \rightarrow bW\chi^0_1$ and the other stop decaying via $\tilde{t}_1 \rightarrow b\chi^\pm_1 \rightarrow bW\chi^0_1$, leading to $bbbjj\ell + \slashed{E}_T$ final states. Our results show that for a LSP mass of 250 GeV, the 95% C.L. exclusion reach is about 1040 GeV for the stop and the 5$\sigma$ reach is about 940 GeV. The reach decreases with smaller LSP mass.

Considering different low-lying neutralino/chargino spectra provides several promising channels for the stop and sbottom study. In this paper we focused on final states with a Higgs boson. Decays of $\chi^0_2$ to $Z\chi^0_1$ could be dominant with a different choice of sign($\mu$). Furthermore, a different mass spectrum of neutralino/chargino with LSP being either Wino-like or Higgsino-like might give rise to more interesting final states. It is important to identify the leading decay channels in various regions of parameter space to fully explore the reach of the LHC for the third generation squarks, which has important implications for the stabilization of the electroweak scale in supersymmetric models. The strategy developed in our analysis can be applied to the study of top partners in other new physics
scenarios as well.

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