Higgs and Z Assisted Stop Searches at Hadron Colliders

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Abstract

Current searches for the light top squark (stop) mostly 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 \( t\bar{t}/bbWW + \not\!E_T \) final states for stop pair productions at the LHC. However, in supersymmetric scenarios with light neutralinos and charginos other than the neutralino lightest supersymmetric particle (LSP), more than one decay mode of the stop could be dominant. While those new decay modes could significantly weaken the current stop search limits at the LHC, they also offer alternative discovery channels for stop searches. In this paper, we studied the scenario with light Higgsino next-to-LSPs (NLSPs) and Bino LSP. The light stop decays primarily via \( \tilde{t}_1 \to t\chi_2^0/\chi_3^0 \), with the neutralinos subsequent decaying to a Z boson or a Higgs boson: \( \chi_2^0/\chi_3^0 \to \chi_1^0 h/Z \). Pair production of light stops at the LHC leads to final states of \( t\bar{t}h\not\!E_T, t\bar{t}hZ\not\!E_T \) or \( t\bar{t}ZZ\not\!E_T \). We consider three signal regions: one charged lepton (1\( \ell \)), two opposite sign charged leptons (2 OS \( \ell \)) and at least three charged leptons (\( \geq 3\ell \)). We found that the 1\( \ell \) signal region of channel \( t\bar{t}h\not\!E_T \) has the best reach sensitivity for light stop searches. For 14 TeV LHC with 300 fb\(^{-1}\) integrated luminosity, a stop mass up to 900 GeV can be discovered at 5\( \sigma \) significance, or up to 1050 GeV can be excluded at 95% C.L. Combining all three decay channels for 1\( \ell \) signal region extends the reach for about 100–150 GeV. We also studied the stop reach at the 100 TeV pp collider with 3 ab\(^{-1}\) luminosity, with discovery and exclusion reach being 6 TeV and 7 TeV, respectively.

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I. INTRODUCTION

The milestone discovery of a light Standard Model (SM)-like Higgs boson at the Large Hadron Collider (LHC) \cite{1, 2} calls for the new physics beyond the SM to solve the “Hierarchy problem” \cite{3}. Among various new physics beyond the Standard Model, Supersymmetry (SUSY) remains to be one of the most attractive candidates because of the elegant solution to the “Hierarchy problem” and the accommodation of the light SM-like Higgs. In the supersymmetric models, the third generation scalar tops (stop) might be the most relevant ones given the large top Yukawa coupling to the Higgs sector. Searching for the heavy top partners is one of the primary goals of the LHC to solve the puzzle of electroweak symmetry breaking and the stabilization of the weak scale. The masses for stops are constrained to be less than about a few TeV to avoid extra fine-tuning to the light Higgs mass. There are two scalar tops in the Minimal Supersymmetric Standard Model (MSSM): $\tilde{t}_L$ and $\tilde{t}_R$, which are the superpartners of the left- and right-handed top quarks, respectively. To provide large enough loop corrections to the tree-level Higgs mass ($m_{h,\text{tree}} \leq m_Z$), a large left-right mixing between $\tilde{t}_L$ and $\tilde{t}_R$ is typically needed, leading to two mass eigenstates, $\tilde{t}_1$ and $\tilde{t}_2$, with relatively large mass splittings. One of the stops can be as light as a few hundred GeV, leaving the LHC an ideal place to search for those relatively light stops.

There are many ongoing searches for the stops by the ATLAS and CMS groups \cite{4-19} and most of the searches focus on the following decay modes: $\tilde{t}_1 \to t\chi^0_1$ and $\tilde{t}_1 \to b\chi^\pm_1 \to bW\chi^0_1$, assuming a 100% decay branching fraction into those two channels. The current experimental search limits from those two channels exclude the stop mass up to 1120 GeV for a very light Lightest Supersymmetric Particle (LSP) $\chi^0_1$ \cite{4-13}. In cases where the mass splitting between the stops and the LSP is very small, the stop mass up to about 580 GeV is excluded \cite{4, 14-17} for decay channels of $\tilde{t}_1 \to c\chi^0_1$ and $\tilde{t}_1 \to bf\chi^0_1$. There are also direct searches for the heavier scalar top by the ATLAS and CMS groups using the decay channel of $\tilde{t}_2 \to \tilde{t}_1 h/Z$ \cite{19, 20}, with $\tilde{t}_1$ further decaying to a top quark and an LSP near the top quark threshold. The heavier stop mass is excluded up to about 800 GeV at 95% C.L. for final states with a $Z$ and/or $h$, assuming a 100% decay branching fraction.

The current light stop searches considered a 100% decay branching fraction of stops decaying into particular search channels for simplicity. However, in realistic MSSM, there are typically more than one decay modes open, depending on the mass spectrum of neu-
tralinos and charginos, which significantly weakens the current search limits \cite{21, 22}. The scenario we consider in this work is Higgsino-like Next-to-LSPs (NLSPs) and a Bino-like LSP with mass hierarchy $M_1 < \mu < M_{3\text{SQ}} \ll M_2$. The lighter stop dominantly decays via $\tilde{t}_1 \to t \chi^0_2/\chi^0_3$ given the large SU(2)$_L$ gauge coupling and large top Yukawa coupling of a mostly left-handed $\tilde{t}_1$, with neutralinos subsequent decaying to a gauge boson or a Higgs boson $\chi^0_2/\chi^0_3 \to \chi^0_i h/Z$, leading to $t\bar{t}hh E_T, t\bar{t}ZZ E_T$ or $t\bar{t}hZ E_T$ final states for the stop pair production at the LHC. Given the relatively clean final states containing at least one lepton at the LHC, our search regions are characterized by the charged leptons: 1 $\ell$ signal region with exact one lepton ($e$ or $\mu$), 2 OS $\ell$ signal region with exact two opposite-sign (OS) leptons, and $\geq 3\ell$ signal region with at least three leptons.

The rest of the paper is organized as follows. In Section II, we briefly review the stop sector in the MSSM, introduce the mass and mixing parameters, and explore the stop decay in different scenarios. In Section III, we summarize the current LHC search limits on stop search by both ATLAS and CMS collaborations, and validate our simulation with the CMS study of $\tilde{t}_2$ \cite{19}, which has the same final states as our process. We also recast the CMS results in $m_{\tilde{t}_1}$ vs. $m_{\chi^0_1}$ plane. In Section IV, we perform a detailed collider analysis of stop search sensitivity in the three signal regions at the $\sqrt{s} = 14$ TeV LHC. In Section V, we extend our analyses to the future $\sqrt{s} = 100$ TeV pp machine. In Section VI, we conclude.

II. MSSM STOP SECTOR

We work in the framework of the MSSM and focus primarily on the third generation squark sector, with relatively light Higgsino-like NLSPs (a small $|\mu|$) and a Bino-like LSP (a small $M_1$). Other SUSY particles including the Winos, gluinos, sleptons, and the first and second generation squarks are assumed to be heavy and decoupled to be 2 TeV. We also decouple the non-SM heavy Higgses by setting $m_A$ to be 2 TeV.

The gauge eigenstates of the third generation squarks are $(\tilde{t}_L, \tilde{b}_L), \tilde{t}_R$ and $\tilde{b}_R$, with $(\tilde{t}_L, \tilde{b}_L)$ forming a SU(2)$_L$ doublet with a soft SUSY breaking mass $M_{3\text{SQ}}, \tilde{t}_R$ and $\tilde{b}_R$ being SU(2)$_L$ singlets with soft breaking masses $M_{3\text{SU}},$ and $M_{3\text{SD}},$ respectively. The mass matrix of the stop sector is \cite{23, 24}

$$m^2_t = \begin{pmatrix} M^2_{3\text{SQ}} + m^2_t + \Delta_{\tilde{u}_L} & m_t \tilde{A}_t \\ m_t \tilde{A}_t & M^2_{3\text{SU}} + m^2_t + \Delta_{\tilde{u}_R} \end{pmatrix},$$ \hspace{2cm} (1)
where the $\Delta_{\tilde{u}_L}$ and $\Delta_{\tilde{u}_R}$ terms come from the D-term contribution in the MSSM, which are to the order of $m_Z^2$. The off-diagonal left-right mixing term $\tilde{A}_t$ is given by:

$$\tilde{A}_t = A_t - \mu / \tan \beta,$$  \hspace{1cm} (2)

with $A_t$ representing the trilinear coupling, $\tan \beta = \langle H_u^0 \rangle / \langle H_d^0 \rangle$ being the ratio of the vacuum expectation values of two Higgs fields $H_u^0$ and $H_d^0$ in the MSSM.

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

$$\begin{pmatrix}
\tilde{t}_1 \\
\tilde{t}_2
\end{pmatrix} = \begin{pmatrix}
\cos \theta_t & -\sin \theta_t \\
\sin \theta_t & \cos \theta_t
\end{pmatrix}
\begin{pmatrix}
\tilde{t}_L \\
\tilde{t}_R
\end{pmatrix},$$  \hspace{1cm} (3)

resulting in two mass eigenstates $\tilde{t}_1$ and $\tilde{t}_2$, with convention $m_{\tilde{t}_1} < m_{\tilde{t}_2}$. For $M_{3SQ} < (>) M_{3SU}$, $\tilde{t}_1$ is mostly left-handed (right-handed), while for $M_{3SQ} \sim M_{3SU}$, $\tilde{t}_{1,2}$ could be mixtures of $\tilde{t}_L$ and $\tilde{t}_R$.

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 \cite{25, 26}:

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

In the minimal mixing case with $\tilde{A}_t = 0$, a large $M_{SUSY}$ around 5~to 10 TeV is needed to guarantee a SM-like Higgs mass $\sim 125$ GeV. In the maximal mixing case with $\tilde{A}_t = \sqrt{6}M_{SUSY}$, a relatively small $M_{SUSY} \sim$ TeV can be accommodated given the additional contribution from the $\tilde{A}_t$ term. In the general MSSM where $M_{3SQ}^2 \neq M_{3SU}^2$, the light stop $\tilde{t}_1$ as light as 200 GeV is still consistent with a SM-like Higgs mass around 125 GeV. A large mass splitting between the stop mass eigenstates, however, is typically needed, resulting in $m_{\tilde{t}_2} \gtrsim 500$ GeV in general \cite{27, 28}.

In the scenario of Higgsino-like NLSPs and a Bino-like LSP, the two neutralinos $\chi^0_2$, $\chi^0_3$ and charginos $\chi^\pm_1$ are nearly degenerate, leading to almost undistinguishable collider signals. To illustrate the MSSM mass parameters and the corresponding mass spectrum, we showed one benchmark point in Table II which consists of a mostly left-handed stop, three almost degenerate Higgsino-like NLSPs ($\chi^0_2$, $\chi^0_3$ and $\chi^\pm_1$), and a Bino-like LSP ($\chi^0_1$). $\tilde{A}_t$ is chosen such that the SM-like Higgs mass is in the range of 125 ~ 126 GeV. Even though $\tilde{A}_t$ is large, the mixing between $\tilde{t}_L$ and $\tilde{t}_R$ is still small because of the large mass
difference between those two components. If there is a significant left-right mixing, then the \( \tilde{t}_1 \rightarrow t\chi^0_2 \) channel is highly suppressed, while the \( \tilde{t}_1 \rightarrow \chi^+_1 b \) channel will have a comparable branching fraction with \( \tilde{t}_1 \rightarrow t\chi^0_3 \).

| \( M_1 \) | \( \mu \) | \( M_2 \) | \( A_t \) | \( M_{3S}Q \) | \( M_{3SU} \) | \( \tan \beta \) | \( \chi^0_1 \) | \( \chi^0_2 \) | \( \chi^0_3 \) | \( \chi^\pm_1 \) | \( \tilde{t}_1 \) | \( h \) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 150 | 300 | 2000 | 2890 | 650 | 2000 | 10 | 145 | 308 | 311 | 305 | 620 | 125 |

TABLE I: Mass parameters and mass spectrum of SUSY particles for one benchmark point. All masses are in units of GeV.

| Decay channel | Branching fraction | Decay channel | Branching fraction |
|---|---|---|---|
| \( \tilde{t}_1 \rightarrow t\chi^0_1 \) | 3% | \( \chi^0_2 \rightarrow Z\chi^0_1 \) | 96% |
| \( \tilde{t}_1 \rightarrow t\chi^0_2 \) | 44% | \( \chi^0_2 \rightarrow h\chi^0_1 \) | 4% |
| \( \tilde{t}_1 \rightarrow t\chi^0_3 \) | 49% | \( \chi^0_3 \rightarrow Z\chi^0_1 \) | 16% |
| \( \tilde{t}_1 \rightarrow b\chi^+_1 \) | 4% | \( \chi^0_3 \rightarrow h\chi^0_1 \) | 84% |

TABLE II: The decay branching fractions of \( \tilde{t}_1 \), \( \chi^0_2 \) and \( \chi^0_3 \) for the benchmark point listed in Table I. \( \chi^0_1 \) 100% decays to \( W^\pm\chi^0_1 \).

For this benchmark point, the decay branching fractions are shown in Table II. \( \tilde{t}_1 \rightarrow t\chi^0_{2,3} \) are dominant, with branching fractions close to 50\% each, given the large SU(2)\(_L\) gauge coupling and large top Yukawa coupling of a mostly left-handed \( \tilde{t}_1 \). The decay channels of \( \tilde{t}_1 \rightarrow t\chi^0_1 \) and \( \tilde{t}_1 \rightarrow b\chi^+_1 \) are highly suppressed due to the relatively small U(1)\(_Y\) gauge coupling and bottom Yukawa coupling, with branching fractions of only 3 – 4\%, leading to large relaxation of the current search limits. Neutralinos \( \chi^0_2/\chi^0_3 \) subsequently decay to a Higgs boson or a Z boson. In the case of positive \( \mu \), the \( \chi^0_2 (\chi^0_3) \) dominantly decays to \( Z\chi^0_1 (h\chi^0_1) \), and reversed for negative \( \mu \) value [29]. Therefore, changing the sign of \( \mu \) has negligible impact on the collider analysis. Given the degeneracy of \( \chi^0_2 \) and \( \chi^0_3 \), the stop dominantly decays to \( th\chi^0_1 \) and \( tZ\chi^0_1 \), with branching fractions of about 45\%, respectively. The left-handed sbottom decay modes of \( \tilde{b}_1 \rightarrow b\chi^0_2/\chi^0_3 \) are highly suppressed due to the small bottom Yukawa coupling, while \( \tilde{b}_1 \rightarrow t\chi^+_1 \) becomes dominant with branching fraction as high as 98\%. Therefore the sbottom signal will not contaminate the stop signal.

At the LHC, the \( \tilde{t}_1\tilde{t}_1^* \) pair production leads to interesting final states of \( tt\ell hE_T, ttZ\ell E_T \) and \( t\ell ZZ\ell E_T \). The branching fractions are shown in Fig. I for three different \( M_1 \) values of
$\bar{t}_1$ \[\text{GeV}\]

$M_1 = 3$ GeV

$M_1 = 150$ GeV

$M_1 = 300$ GeV

FIG. 1: The branching fractions of three different channels $t\bar{t}hh\not{E_T}$, $t\bar{t}hZ\not{E_T}$ and $t\bar{t}ZZ\not{E_T}$ as a function of light stop mass for the mostly left-handed stop pair production. Three choices of $M_1 = 3, 150, 300$ GeV are presented, with $\mu$ fixed to be $M_1 + 150$ GeV and $\tan \beta = 10$.

3, 150 and 300 GeV, with $\mu = 150$ GeV + $M_1$. When $M_1$ is small, $\chi_{2,3}^0$ decay more to $Z\chi_1^0$, consequently leading to a suppressed channel $t\bar{t}hh\not{E_T}$, as shown in the left panel of Fig. 1. As $M_1$ increases, $BR(\chi_2^0/\chi_3^0 \rightarrow h\chi_1^0) \approx BR(\chi_2^0/\chi_3^0 \rightarrow Z\chi_1^0) \approx 50\%$. The branching fraction of $\bar{t}_1 \rightarrow t\chi_2^0/\chi_3^0 \rightarrow th\chi_1^0$ and $\tilde{t}_1 \rightarrow t\chi_2^0/\chi_3^0 \rightarrow tZ\chi_1^0$ are almost equal, about 45% each. The resulting branching fractions for $t\bar{t}hh\not{E_T}$ and $t\bar{t}ZZ\not{E_T}$ are about 20%, respectively, while $BR(t\bar{t}hZ\not{E_T})$ is about 45%.

III. CURRENT COLLIDER SEARCH LIMITS ON STOP AND RECASTING EXPERIMENTAL RESULTS

A. Current collider search limits on stop

Searches for direct stop pair production have been performed at both ATLAS and CMS, with the latest results using about 36 fb$^{-1}$ data at $\sqrt{s} = 13$ TeV [4–17]. We summarize the current search bounds in Table III.

The current searches for the stop mainly focus on the decay channel $\bar{t}_1 \rightarrow t\chi_1^0$ and $\tilde{t}_1 \rightarrow b\chi_1^\pm \rightarrow bW^(*)\chi_1^0$, assuming a 100% decay branching fraction into these two channels. Hadronic, semileptonic, and dileptonic channels have been analyzed, with the semileptonic
\[ \tilde{t}_1 \rightarrow t\chi_1^0, \tilde{t}_1 \rightarrow b\chi_1^\pm \rightarrow bW\chi_1^0 \]
\[ \tilde{t}_1 \rightarrow c\chi_1^0, \tilde{t}_1 \rightarrow bf'\chi_1^0 \]

| \( \ell \) | ATLAS | CMS |
|---|---|---|
| 0 | 1000 GeV | 1070 GeV |
| 1 | 940 GeV | 1120 GeV |
| 2 | 720 GeV | 800 GeV |

| \( \ell \) | | |
|---|---|---|
|  | 400 GeV | 580 GeV |

TABLE III: Current mass bounds on the stop (with a small \( m_{\chi_1^0} \)) from the direct searches at the 13 TeV LHC with 36 fb\(^{-1}\) integrated luminosity [4–17]. The 0\( \ell \), 1\( \ell \) and 2\( \ell \) mean the all-hadronic, semileptonic and dileptonic final states.

channel typically providing the best limit. The upper limits on the stop mass are about 1120 GeV, depending on the assumption of the decay branching fractions, and masses of the neutralinos and charginos.

In addition to the above two searching channels, the ATLAS and CMS groups also used two different analysis strategies to optimize the search sensitivity of direct stop searches for the decay channels of \( \tilde{t}_1 \rightarrow c\chi_1^0 \) and \( \tilde{t}_1 \rightarrow bf'\chi_1^0 \), in particular, for small mass splitting between stop and \( \chi_1^0 \). The upper limit on the stop mass is much weaker, about 580 GeV at 95% C.L. [4, 14–17].

B. Recasting CMS search results

Both ATLAS and CMS groups performed the search for the heavier stop (\( \tilde{t}_2 \)) [18, 19] with cascade decays of \( \tilde{t}_2 \rightarrow \tilde{t}_1 h \) and/or \( \tilde{t}_2 \rightarrow \tilde{t}_1 Z \) with \( \tilde{t}_1 \) further decaying via \( \tilde{t}_1 \rightarrow t\chi_1^0 \) assuming mass relation \( m_{\tilde{t}_1} - m_{\chi_1^0} = m_t \), leading to the finals states of \( t\bar{t}hE_T, t\bar{t}ZE_T \) and \( tZ ZZ E_T \) for the pair production of \( \tilde{t}_2 \) at the LHC. The analysis of the CMS group is based on the multiplicities of the leptons, jets, \( b \)-jets, missing energy \( E_T \), transverse mass \( m_T \) and \( H_T \), as demonstrated in Table I in Ref. [19]. The signal regions included in their analysis are: one charged lepton (1\( \ell \)), two opposite-sign charged leptons (2 OS \( \ell \)), two same-sign charged leptons (2 SS \( \ell \)) and at least three charged leptons (\( \geq 3\ell \)). The at least three leptons signal region is further split into two signal regions: on-\( Z \), when there is a pair of same flavor, opposite-sign charge leptons that has an invariant mass within 15 GeV of the nominal \( Z \) boson mass; and off-\( Z \), where no such lepton pair exists or the invariant mass lies outside the \( Z \) mass window. The background predictions and observed data yields for signal regions are listed in Table II, III, IV in Ref. [19].
We first reproduce the CMS exclusion limits for $\tilde{t}_2$ as a validation of our analyses. Event samples are generated using Madgraph 5 [30], processed through Pythia 6 [31] for the fragmentation and hadronization and then through Delphes 3 [32] for the detector simulation. The root package TLimit [33] is used to calculate the 95% confidence level upper limits. Fig. 2 shows the comparison of the 95% C.L. upper limits between CMS results ("+" symbol lines) [19] and our simulations (solid lines) in the plane of $m_{\tilde{t}_2}$ vs. $m_{\tilde{t}_1}$ for $\tilde{t}_2 \rightarrow \tilde{t}_1 h$ (left) and $\tilde{t}_2 \rightarrow \tilde{t}_1 Z$ (right) assuming a 100% branching fraction. Our simulations match the CMS results quite well except for the edge region. The discrepancy between the CMS results and our simulations are mostly due to the different detector simulations of the signal process and systematics estimation.

![Fig. 2: The comparison of 95% C.L. upper limits between CMS results ("+" symbol lines) and our simulations (solid lines) for the LHC $\tilde{t}_2$ pair production, with $\tilde{t}_2 \rightarrow \tilde{t}_1 h$ (left) and $\tilde{t}_2 \rightarrow \tilde{t}_1 Z$ (right) assuming a 100% branching fraction. Our simulations match the CMS results quite well except for the edge region. The discrepancy between the CMS results and our simulations are mostly due to the different detector simulations of the signal process and systematics estimation.](image)

Combining both $h$- and $Z$-channel, the 95% C.L. upper limits in the plane of $m_{\tilde{t}_2}$ vs $m_{\tilde{t}_1}$ for $BR(\tilde{t}_2 \rightarrow \tilde{t}_1 Z) = 100\%$ (purple), 50\% (black) and 0\% (red) are shown in the left panel of Fig. 3 for the comparison between the CMS results and our simulations. The decay channel of $\tilde{t}_2 \rightarrow \tilde{t}_1 h$ is only considered when the Higgs boson production is kinematically open.
FIG. 3: The comparison of 95% C.L. upper limits between CMS results (“+” symbol lines) and our simulations (solid lines) for the LHC $\tilde{t}_2$ pair production, with combined $\tilde{t}_2 \rightarrow \tilde{t}_1 h/Z$ and $\tilde{t}_1 \rightarrow t\chi^0_1$, assuming $BR(\tilde{t}_2 \rightarrow \tilde{t}_1 Z) + BR(\tilde{t}_2 \rightarrow \tilde{t}_1 h) = 100\%$. Results from the 8 TeV LHC with 19.5 $fb^{-1}$ are used here. Right panel shows the recast of the CMS $\tilde{t}_2$ limits to the plane of $m_{\tilde{t}_1}$ vs. $m_{\chi^0_1}$, considering $\tilde{t}_1\tilde{t}^*_1$ production with decays of $\tilde{t}_1 \rightarrow t\chi^0_2,3 \rightarrow th/Z\chi^0_1$.

Since the CMS $\tilde{t}_2$ search channel has the same final states as our $\tilde{t}_1$ study: $\tilde{t}_1\tilde{t}^*_1$ pair production with $\tilde{t}_1 \rightarrow t\chi^0_{2,3} \rightarrow th/Z\chi^0_1$, we recast the CMS $\tilde{t}_2$ search limits at 8 TeV LHC to that of the lighter stop in the scenario of Higgsino-NLSP and Bino-LSP. We use exactly the same event selections as the CMS $\tilde{t}_2$ search to obtain our simulated signal event yields after cuts and we use the backgrounds estimations and observed data yields in Ref. [19] to get the lighter stop search limits. The recasted results in the plane of $m_{\tilde{t}_1}$ vs. $m_{\chi^0_1}$ are shown in the right panel of Fig. 3 for $ttZZE_T$ (including 3$\ell$ “on-Z”) and $t\bar{t}hZE_T$ (including 1$\ell$, 2 OS $\ell$, 3$\ell$ “off-Z” and 3$\ell$ “on-Z”) channels. Because the reach of the 2 SS $\ell$ signal region is very low, it is not considered in this analysis. There is also no excluding reach for the channel of $t\bar{t}h\ell E_T$ due to its low branching fraction as shown in Fig. 3. The light stop mass up to 480 GeV is excluded at 95% C.L. for a small mass LSP $\sim 25$ GeV via the $t\bar{t}hZE_T$ channel. For the $ttZZE_T$ channel, the light stop mass up to 530 GeV is excluded at 95% C.L. for a massless LSP.
IV. COLLIDER ANALYSES AT $\sqrt{s} = 14$ TEV

In MSSM with more than one neutralino/chargino lighter than the stop, typically more than one decay mode for stop are present, some of which even dominate the most commonly studied channels of $\tilde{t}_1 \rightarrow t\chi_0^0/b\chi_1^+$. Those extra stop decay modes weaken the current search limits using $\tilde{t}_1 \rightarrow t\chi_0^0/b\chi_1^+$. Furthermore, the new decay channels offer alternative discovery potential for the stops. In our analyses, we work in the scenario of a Bino LSP with Higgsino NLSPs lighter than $\tilde{t}_1$, assuming the mass hierarchy of $M_1 < \mu < M_{3SQ} \ll M_2$.

The benchmark point shown in Table II is only for the illustration purpose. In the following analyses, we perform a broad scan over the mass parameter space:

- $M_{3SQ}$ from 400 to 1250 GeV with a step size of 25 GeV, corresponding to $m_{\tilde{t}_1}$ varying from 350 GeV to about 1260 GeV.
- $M_1$ is scanned from 3 GeV to 750 GeV, in the step size of 25 GeV.
- $\mu$ is fixed to be $\mu = M_1 + 150$ GeV.
- We further require $m_{\tilde{t}_1} > m_{\chi^0_2}/m_{\chi^0_3} + m_t$ such that $\tilde{t}_1 \rightarrow t\chi^0_2/\chi^0_3$ is kinematically open.

Event samples including signals and all the SM backgrounds are generated for 14 TeV LHC, using Madgraph 5 [30], processed through Pythia 6 [31] for the fragmentation and hadronization, and then through Delphes 3 [32] with the Snowmass combined LHC No-Pile-up detector card [34] for the detector simulation. Both the SM backgrounds and the stop pair production signal are normalized to the predicted cross sections, calculated including higher-order QCD corrections [35–42]. For the event generation, the top quark mass $m_t$ is set to be 175 GeV, and the Higgs mass $m_h$ is set to be 125 GeV.

A. Event Selection

For the stop pair production $\tilde{t}_1\tilde{t}_1^*$ at the LHC, both stops decay via $t\chi_0^0/\chi_3^0$ with neutralinos subsequent decaying to a $Z$ boson or a Higgs boson, leading to final states of $tthhE_T$, $t\bar{t}ZZE_T$ and $t\bar{t}hZE_T$. Similar to the CMS $\tilde{t}_2$ searches, we divide the signal regions into three primary categories: (1) one charged lepton (1$\ell$), (2) two opposite-sign charged leptons (2OS $\ell$), (3) at least three charged leptons ($\geq 3\ell$). “on-$Z$” region and “off-$Z$” region are further defined for the $\geq 3\ell$ case, with $m_{ell}$ window of $m_Z \pm 15$ GeV. The signal region of two same-sign leptons is not considered in this analysis because the cross section of this
signal region is quite small, which results in limited reach of this signal region.

The jets are reconstructed using \( \text{anti-}k_t \) algorithm with cone radius of 0.5. All jets are required to meet the basic selection cuts of \( p_T^j > 30 \text{ GeV} \) and \( \eta^j < 2.5 \). All leptons (\( e \) or \( \mu \)) are required to meet the basic selection cuts of \( \eta^\ell < 2.5 \) and \( p_T^\ell > 10 \text{ GeV} \). In addition to the selection cuts mentioned above, we also apply some advanced cuts which are defined below:

- \( \not{E}_T \), the magnitude of the missing transpose momentum \( p_T^{\text{miss}} \).
- \( H_T \), the scalar sum of the \( p_T \) of all the jets which meet the basic selection cuts:
  \[ H_T = \sum_{j} p_T^j. \]
- \( m_T \), the invariant mass of the lepton and the missing transpose momentum:
  \[ m_T = \sqrt{2p_T^\ell \not{E}_T(1 - \cos \phi(p_T^\ell, p_T^{\text{miss}}))}. \] (5)
- \( M_{T2} \) [43–45], the lower bound on the transverse mass resulting from two missing energies.
  \[ M_{T2}(p_T^{\ell_1}, p_T^{\ell_2}, p_T^{\text{miss}}) = \min_{p_T^{\text{miss}+p_T^{\text{miss}}=p_T^{\text{miss}}}} \{ \max\{m_T(p_T^{\ell_1}, p_T^{\text{miss}}), m_T(p_T^{\ell_2}, p_T^{\text{miss}})\} \}. \] (6)
- \( m_{\ell\ell} \), the invariant mass of two OS leptons which survive the basic selection cuts.
- \( N_j \), the number of all the jets which meet the basic selection cuts.
- \( N_b \), the number of all the \( b \) jets which meet the basic selection cuts.

We summarize the cuts we used in Table IV.

**B. Results of one lepton signal region**

In this section and the following sections, we focus on the discovery/exclusion reach of the light stop at the 14 TeV LHC with integrated luminosity of 300 \( \text{fb}^{-1} \). In the \( 1\ell \) signal region, the advanced selection cuts of \( \not{E}_T, H_T, m_T \), \( N_j \) and \( N_b \) are used to cut down the huge SM backgrounds. Table V shows the cumulative cut efficiencies after each level of advanced cuts and final cross sections for both signal as well as the SM backgrounds, for
## Basic Cuts

- Leading three jets \( p_T > 40 \)
  - \( N_j \geq 4, N_b \geq 2 \)
- Exact one lepton with \( p_T > 25 \)
  - \( \Delta R(j, l) > 0.4 \)
  - \( \Delta \Phi(j, p_T^{\text{miss}}) > 0.8 \)
- Exact two leptons with \( p_T > 25 \)
- \( \Delta R(j, l) > 0.4, \Delta R(l, l) > 0.4 \)
- \( \Delta \Phi(j, p_T^{\text{miss}}) > 0.8 \)
- \( \Delta \Phi(l, l) > 0.8 \)

## Advanced Cuts

| \( \ell \) |
|----------------|
| 1 \( \ell \) |
| 2OS \( \ell \) |
| \( \geq 3 \ell \) |

- \( \mathcal{E}_T > 100, 125, 150, 175, 200 \)
- \( H_T > 400, 450, 500, 550, 600 \)
- \( m_T > 100, 125, 150, 175, 200 \)
- \( |m_{hh} - m_Z| < 5, 10, 15 \)
- \( N_j \geq 4, 5, 6, 7 \)
- \( N_b \geq 2, 3, 4, 5 \)
- \( \mathcal{E}_T > 150, 175, 200, 225, 250 \)
- \( H_T > 400, 450, 500, 550, 600 \)
- \( M_{T2} > 60, 70, 80, 90 \)
- \( N_j \geq 4, 5, 6 \)
- \( N_b \geq 2, 3, 4 \)
- \( \mathcal{E}_T > 150, 175, 200, 225, 250 \)
- \( H_T > 400, 450, 500, 550, 600 \)
- \( |m_{hh} - m_Z| < 5, 10, 15 \)
- \( N_j \geq 2, 3, 4, 5 \)
- \( N_b \geq 1, 2, 3 \)

### Table IV: The basic cuts and the advanced cuts for the three primary signal regions of 1\( \ell \), 2OS \( \ell \), and \( \geq 3 \ell \). All mass units are in GeV.

As expected, the signal process has larger \( m_T \) and \( \mathcal{E}_T \) than the background processes due to the extra contributions from the LSP. \( t\bar{t}, t\bar{t}b\bar{b} \) and \( t\bar{t}Z \) are the dominant backgrounds after strong \( \mathcal{E}_T, H_T \) and \( m_T \) cuts. The irreducible SM backgrounds \( t\bar{t}h\bar{h}, t\bar{t}hZ \) and \( t\bar{t}ZZ \) are almost negligible because of the very low production cross sections.

In Fig. 4, the 95% C.L. upper limits (black curve) and 5\( \sigma \) discovery (red curve) reach are shown in the plane of MSSM parameter \( m_{\tilde{t}} \) vs \( m_{\chi_1^0} \) for the stop pair production \( pp \rightarrow \tilde{t}_1\tilde{t}_1^* \rightarrow \tilde{t}\chi_2^0/\chi_3^0 \rightarrow t\bar{t}hh\mathcal{E}_T \) (top left), \( t\bar{t}hZ\mathcal{E}_T \) (top right) and \( t\bar{t}ZZ\mathcal{E}_T \) (bottom left) at the 14 TeV LHC with 300 fb\(^{-1}\) integrated luminosity. \( \mu \) is fixed to be \( M_1 + 150 \) GeV and 10% systematic uncertainties are assumed. All combinations of the values of advanced cuts for \( \mathcal{E}_T, H_T, m_T, N_j \) and \( N_{bj} \), as given in Table. are examined. The optimized combination that gives the best significance is used for a particular mass point. The channel \( t\bar{t}h\bar{h}\mathcal{E}_T \) has no sensitivity in the low \( \chi_1^0 \) mass region because of the very low branching fraction of the \( t\bar{t}h\bar{h}\mathcal{E}_T \) channel. In contrary, the channel \( t\bar{t}ZZ\mathcal{E}_T \) has the largest reach in the low \( \chi_1^0 \) mass region due to its large branching fraction. The \( thhZ\mathcal{E}_T \) has the best reach in the whole mass parameter region because of its comparably large branching.
Process $\tilde{t}_1\tilde{t}_1 (t\bar{t}h)$  $\tilde{t}_1\tilde{t}_1 (t\bar{t}hZ)$  $\tilde{t}_1\tilde{t}_1 (t\bar{t}ZZ)$  $\tilde{t}^{\text{semi}}$  $t\bar{t}b\bar{b}$  $t\bar{t}Z$  $t\bar{t}W^{\pm}$  $t\bar{t}h$  $t\bar{t}hh$  $t\bar{t}hZ$  $t\bar{t}ZZ$

| $\sigma$ (fb) | Basic cuts | $E_T > 175$ GeV | $H_T > 500$ GeV | $m_T > 150$ GeV | $N_j \geq 7$ | $N_b \geq 2$ | $\sigma$ (fb) |
|---|---|---|---|---|---|---|---|
| 35 | 11.0% | 4.6% | 3.6% | 1.6% | 0.5% | 0.5% | 0.175 |
| 80 | 8.7% | 4.3% | 3.4% | 1.6% | 0.45% | 0.45% | 0.36 |
| 46 | 5.7% | 3.1% | 2.3% | 1.3% | 0.31% | 0.31% | 0.14 |
| 261230 | 1.9% | $5.2 \times 10^{-4}$ | $1.6 \times 10^{-4}$ | $8.4 \times 10^{-7}$ | $5 \times 10^{-8}$ | $5 \times 10^{-8}$ | 0.013 |
| 8305 | 3.2% | 0.17% | $9.3 \times 10^{-4}$ | $7.4 \times 10^{-5}$ | $6.6 \times 10^{-6}$ | $6.6 \times 10^{-6}$ | 0.055 |
| 1095 | 2.3% | 0.23% | 0.12% | $2.7 \times 10^{-4}$ | $2.2 \times 10^{-5}$ | $2.2 \times 10^{-5}$ | 0.024 |
| 747 | 1.8% | 0.18% | 0.11% | $9.7 \times 10^{-5}$ | $4.8 \times 10^{-6}$ | $4.8 \times 10^{-6}$ | 3.6 | $10^{-3}$ |
| 572 | 4.6% | 0.34% | 0.22% | $1.6 \times 10^{-4}$ | $1.4 \times 10^{-5}$ | $1.4 \times 10^{-5}$ | 8.1 | $10^{-3}$ |
| 0.83 | 10.8% | 1.1% | 0.87% | 0.012% | $1.7 \times 10^{-4}$ | $1.7 \times 10^{-4}$ | 1.5 | $10^{-4}$ |
| 1.41 | 7.4% | 1.2% | 0.85% | 0.022% | $3.3 \times 10^{-4}$ | $3.3 \times 10^{-4}$ | 4.6 | $10^{-4}$ |
| 1.73 | 4.1% | 0.74% | 0.51% | 0.016% | $2.0 \times 10^{-4}$ | $2.0 \times 10^{-4}$ | 3.5 | $10^{-4}$ |

TABLE V: cumulative cut efficiencies after each level of cuts and the final cross sections for the signal $\tilde{t}_1\tilde{t}_1 \rightarrow t\bar{t}hhE_T$, $t\bar{t}hZE_T$ and $t\bar{t}ZZE_T$, as well as SM backgrounds for $1\ell$ signal region for the benchmark point listed in Table. I. Note that the cross section for $t\bar{t}$ is shown for the semileptonic decay only, which is the dominant $t\bar{t}$ background.

fraction. For the channel $t\bar{t}hhE_T$, stop masses up to 750 GeV can be discovered at the $5\sigma$ significance level for $m_{\chi^0_1} = 220$ GeV, and the 95% C.L. exclusion limits are about 950 GeV for $m_{\chi^0_1} = 250$ GeV. The $5\sigma$ discovery reach can go up to 900 GeV (820 GeV), or the stop masses up to 1050 GeV (960 GeV) can be excluded at the 95% C.L. for the channel $t\bar{t}ZE_T$ ($t\bar{t}ZZE_T$). Limits with 20% systematic uncertainties are about 100 GeV worse.

The combination of all three channels gives better reach, which is shown in the bottom right panel of Fig. I. The specific set of advanced selection cuts used to do the signal combinations are: $E_T > 200$ GeV, $H_T > 550$ GeV, $m_T > 200$ GeV, $N_j \geq 7$ and $N_{bj} \geq 2$. The stop mass can be discovered at $5\sigma$ significance up to 1030 GeV, or excluded at 95% C.L. up to 1200 GeV for the $1\ell$ signal region.
FIG. 4: The 95% C.L. upper limits (black) and 5σ discovery reach (red) are shown in the plane of MSSM parameter space $m_{\tilde{t}_1}$ vs $m_{\chi_0^1}$ for the stop pair production $pp \to \tilde{t}_1 \tilde{t}_1 \to t\bar{t}h_h \chi_1^0 \chi_3^0 \to t\bar{t}hh\not{E_T}$ (top left), $t\bar{t}h Z \not{E_T}$ (top right), $t\bar{t}ZZ \not{E_T}$ (bottom left), combined channels (bottom right) for the $1\ell$ signal region at the 14 TeV LHC with 300 fb$^{-1}$ integrated luminosity. $\mu$ is fixed to be $M_1 + 150$ GeV. 10% systematic error has been included in the analyses. The color coding on the right indicates the signal significance to guide the eye.

C. Results of 2 OS $\ell$ signal region

In the 2 OS $\ell$ signal region, in addition to the advanced cuts of $H_T, \not{E_T}, M_{T2}, N_j$ and $N_{b\ell}$, $m_{\ell\ell}$ are also used for the $t\bar{t}h Z \not{E_T}$ and $t\bar{t}ZZ \not{E_T}$ channels. The normalized distributions of $M_{T2}$ and $m_{\ell\ell}$ for the signal processes and the SM backgrounds are shown in Fig. 5. The $M_{T2}$ distribution for the signal extends to larger value, while the $M_{T2}$ distributions for the SM backgrounds are cut off at $m_W$ given that the two leptons of the SM backgrounds
mostly come from leptonic $W$ Decay. The $m_{\ell\ell}$ distribution for the signals and SM $t\bar{t}Z$ has a sharp peak at the $Z$ boson mass, while the $m_{\ell\ell}$ distributions for the other SM backgrounds spread out because the two leptons are not from the $Z$ boson decay.

Table VI illustrates the cumulative cut efficiencies after each level of advanced cut and the final cross sections for the signals and SM backgrounds in the 2 OS $\ell$ signal region for the benchmark point. The dominant background in the 2 OS $\ell$ signal region is $t\bar{t}Z$, given its relatively large cross section and similar final states to the signal processes. $t\bar{t}$ is the second dominant background due to its large cross section. A significance of about $12\sigma$ ($7.7\sigma$) can be reached for signal channel $t\bar{t}hZ E_T$ ($t\bar{t}ZZ E_T$) for the Table. II benchmark point at the 14 TeV LHC with 300 fb$^{-1}$ integrated luminosity, including 10% systematic error.

For the 2 OS $\ell$ signal region, the $5\sigma$ discovery reach (red curve) and 95% C.L. exclusion limit (black curve) are shown in Fig. 6 for the 14 TeV LHC with 300 fb$^{-1}$ integrated luminosity, including 10% systematic uncertainties. The channel $t\bar{t}hh E_T$ has no reach because of its low branching fraction of the dilepton channel. A stop mass up to 800 GeV (920 GeV) can be discovered at $5\sigma$ significance, and excluded up to 900 GeV (980 GeV) at 95% C.L. for the channel $t\bar{t}hZ E_T$ ($t\bar{t}ZZ E_T$). Limits with 20% systematic uncertainties
are very similar to that of 10% case since the error is mostly statistically dominated.

The bottom panel of Fig. 6 shows the reach of 2 OS $\ell$ signal region combining both the $t\bar{t}hZ E_T$ and $t\bar{t}ZZ E_T$ channels. The stop mass up to 930 GeV can be discovered at 5$\sigma$ significance, or a stop mass less than about 1060 GeV is excluded at the 95% C.L. for the 2 OS $\ell$ signal region. The specific set of advanced selection cuts used to do the signal combinations are: $E_T > 150$ GeV, $H_T > 500$ GeV, $|m_{\ell\ell} - m_Z| < 5$ GeV, $M_{T2} > 80$ GeV, $N_j \geq 5$ and $N_{bj} \geq 2$.

D. Results of $\geq 3\ell$ signal region

For signal region with at least 3 leptons, it is further divided into “off-Z” and “on-Z” signal region. The “off-Z” signal region is applied to the $t\bar{t}hh E_T$ channel, while the “on-Z” signal region is applied to the $t\bar{t}hZ E_T$ and $t\bar{t}ZZ E_T$ channels. The cumulative cut efficiencies after each level of advanced cuts and cross sections for the “on-Z” signal region

| Process          | $\sigma$ (fb) | Basic cuts | $E_T >$ 100 GeV | $H_T >$ 400 GeV | $M_{T2} >$ 80 GeV | $|m_{\ell\ell} - m_Z| <$ 5 GeV | $N_j \geq$ 6 | $N_{bj} \geq$ 2 | $\sigma$ (fb) after cuts |
|------------------|--------------|------------|-----------------|-----------------|------------------|---------------------------|-------------|-------------|------------------|
| $\tilde{t}\bar{t}(\tilde{t}\bar{t}hZ)$ | 80           | 1.7%       | 1.3%            | 1.1%            | 0.34%            | 0.2%                      | 0.1%        | 0.1%        | 0.1%             |
| $\tilde{t}\bar{t}(\tilde{t}\bar{t}ZZ)$ | 46           | 1.6%       | 1.2%            | 1.1%            | 0.35%            | 0.24%                     | 0.11%       | 0.11%       | 0.08             |
| $\tilde{t}\tilde{t}_{di-lep}$         | 33330        | 0.4%       | 0.14            | $5 \times 10^{-4}$ | $2 \times 10^{-5}$ | $1 \times 10^{-6}$ | $9 \times 10^{-8}$ | $9 \times 10^{-8}$ | 0.003           |
| $\tilde{t}\bar{t}b\bar{b}$             | 8305         | 0.18%      | 6 $\times 10^{-4}$ | $3 \times 10^{-4}$ | $1 \times 10^{-5}$ | $4 \times 10^{-7}$ | $1.2 \times 10^{-7}$ | $1.2 \times 10^{-7}$ | 0.001           |
| $\tilde{t}\bar{t}Z$                    | 1095         | 0.4%       | 9 $\times 10^{-4}$ | $5.3 \times 10^{-4}$ | $5 \times 10^{-5}$ | $2.7 \times 10^{-5}$ | $5.4 \times 10^{-6}$ | $5.4 \times 10^{-6}$ | 0.006           |
| $\tilde{t}\bar{t}W^\pm$                | 747          | 0.2%       | 9.3 $\times 10^{-4}$ | $5.1 \times 10^{-4}$ | $1.1 \times 10^{-5}$ | $3.2 \times 10^{-7}$ | $1.2 \times 10^{-7}$ | $1.2 \times 10^{-7}$ | -               |
| $\tilde{t}\tilde{t}h$                   | 572          | 0.6%       | 0.2%            | 0.1%            | 2.9 $\times 10^{-5}$ | $1.2 \times 10^{-6}$ | $3.5 \times 10^{-7}$ | $3.5 \times 10^{-7}$ | -               |
| $\tilde{t}\tilde{t}hh$                  | 0.83         | 3.1%       | 1.2%            | 1.0%            | 3.5 $\times 10^{-4}$ | $1.9 \times 10^{-5}$ | $4.8 \times 10^{-6}$ | $2.5 \times 10^{-6}$ | -               |
| $\tilde{t}\tilde{t}hZ$                  | 1.41         | 2.2%       | 0.8%            | 0.7%            | $6 \times 10^{-4}$ | $2.4 \times 10^{-4}$ | $5.9 \times 10^{-5}$ | $5.9 \times 10^{-5}$ | -               |
| $\tilde{t}\tilde{t}ZZ$                  | 1.73         | 1.2%       | 0.4%            | 0.3%            | $6 \times 10^{-4}$ | $3 \times 10^{-4}$ | $9 \times 10^{-5}$ | $9 \times 10^{-5}$ | -               |

TABLE VI: Cumulative cut efficiencies after each level of advanced selection cuts and cross sections for the signal $\tilde{t}\tilde{t} \to t\bar{t}hZ E_T$ and $t\bar{t}ZZ E_T$ as well as SM backgrounds in the 2 OS $\ell$ signal region at the 14 TeV LHC. $t\bar{t}hh E_T$ is not listed here due to the small significance. Note that only dileptonic decay of $t\bar{t}$ is in used this analysis.
FIG. 6: The 95% C.L. upper limits (black) and 5σ discovery reach (red) are shown in the plane of MSSM parameter space $m_{\tilde{t}_1}$ vs $m_{\chi^0_1}$ for the stop pair production $pp \to \tilde{t}_1 \tilde{t}_1^* \to t\bar{t}h\chi_1^0/\chi_3^0 \to t\bar{t}hZ\not{E}_T$ (top left) and $t\bar{t}Z\not{E}_T$ (top right) and combined reach (bottom middle) in the 2 OS $\ell$ signal region at 14 TeV LHC with 300 fb$^{-1}$ integrated luminosity.

are shown in Table VII for the benchmark point. We do not list such table for the “off-Z” signal region because the reach is very small for all three channels. As can be seen from Table VII the $t\bar{t}Z$ is the dominant background, followed by the $t\bar{t}h$ process. The $t\bar{t}$ and $t\bar{b}b$ processes are highly suppressed.

The 95% C.L. upper limits (black curve) and 5σ discovery reach (red curve) for the “on-Z” signal region are shown in Fig. 6. 10% systematic uncertainties are assumed. $t\bar{t}hh\not{E}_T$ channel has almost no reach, therefore not shown in the plot. A stop mass up to 780 GeV (850 GeV) for the channel $t\bar{t}hZ\not{E}_T$ ($t\bar{t}ZZ\not{E}_T$) can be discovered at the 5σ significance, and up to about 860 GeV (960 GeV) for 95% C.L. exclusion. Limits with 20% systematic
on-Z

| Process          | $\sigma$ (fb) | Basic cuts | $E_T >$ 175 GeV | $H_T >$ 400 GeV | $|m_{\ell\ell} - m_Z| <$ 5 GeV | $N_j \geq$ 4 | $N_b \geq$ 1 | $\sigma$ (fb) after cuts |
|------------------|--------------|------------|-----------------|-----------------|-----------------------------|-------------|-------------|--------------------------|
| $\tilde{t}_1\tilde{t}_1(t\tilde{h}Z)$ | 80 | 1% | 0.4% | 0.3% | 0.27% | 0.23% | 0.23% | 0.19 |
| $\tilde{t}_1\tilde{t}_1(t\tilde{t}ZZ)$ | 46 | 1.5% | 0.7% | 0.5% | 0.46% | 0.35% | 0.35% | 0.16 |
| $t\tilde{t}$ | 1095 | 0.8% | 5 x 10^{-4} | 2 x 10^{-4} | 1.7 x 10^{-4} | 8.1 x 10^{-5} | 8.1 x 10^{-5} | 0.09 |
| $t\tilde{t}W^{\pm}$ | 747 | 7 x 10^{-4} | 6.6 x 10^{-5} | 1.8 x 10^{-5} | 6.4 x 10^{-6} | 2.4 x 10^{-6} | 2.4 x 10^{-6} | 0.002 |
| $t\tilde{t}h$ | 572 | 0.1% | 1.1 x 10^{-4} | 4.4 x 10^{-5} | 1.6 x 10^{-5} | 9.4 x 10^{-6} | 9.4 x 10^{-6} | 0.005 |
| $t\tilde{t}h\tilde{h}$ | 0.83 | 0.7% | 9 x 10^{-4} | 5 x 10^{-4} | 2 x 10^{-4} | 1.4 x 10^{-4} | 1.4 x 10^{-4} | - |
| $t\tilde{t}hZ$ | 1.41 | 1.8% | 0.21% | 0.1% | 9 x 10^{-4} | 5.7 x 10^{-4} | 5.7 x 10^{-4} | - |
| $t\tilde{t}ZZ$ | 1.73 | 2.2% | 0.32% | 0.17% | 0.14% | 8.3 x 10^{-4} | 8.3 x 10^{-4} | - |

TABLE VII: Cumulative cut efficiencies after each level of advanced selection cuts and cross sections for the signal $\tilde{t}_1\tilde{t}_1 \to t\tilde{h}Z E_T$ and $t\tilde{t}ZZ E_T$ as well as SM backgrounds in the $\geq 3\ell$ “on-Z” signal region at the 14 TeV LHC. The $t\tilde{t}h\tilde{h}$ has no reach sensitivity because of the extremely low branching fraction of three leptons channel. The $t\tilde{t}$ and $t\tilde{t}bb$ processes are also not listed since they are highly suppressed after all the cuts.

uncertainties are very similar to that of 10% case. The reach for the “off-Z” signal region is much smaller than that of “on-Z” signal region.

The combined reaches of $t\tilde{t}hZ E_T$ and $t\tilde{t}ZZ E_T$ channels for the $\geq 3\ell$ “on-Z” signal region are shown in the bottom panel of Fig. 7. The 5$\sigma$ reach of a stop mass is about 880 GeV, and the 95% C.L. exclusion limit can reach up to 1000 GeV. The specific set of advanced selection cuts used to do the signal combinations are: $E_T > 200$ GeV, $H_T > 500$ GeV, $|m_{\ell\ell} - m_Z| < 5$ GeV, $N_j \geq 7$ and $N_b \geq 1$.

### E. Results of combined channels

For each signal region, the combined reach of all three channels are shown in previous sections. Here we discuss the reach of each individual channel, combining all the signal regions. In Fig. 8 we show the 5$\sigma$ discovery reach (red curve) and 95% C.L. exclusion limit (black curve) for combination of three signal regions of $t\tilde{t}hh E_T$ (top left panel), $t\tilde{t}hZ E_T$
FIG. 7: The 95% CL upper limits (black curve) and 5σ discovery reach (red curve) are shown in the plane of MSSM parameter space $m_{\tilde{t}_1}$ vs $m_{\chi^0_1}$ for the stop pair production $pp \rightarrow \tilde{t}_1 \tilde{t}^*_1 \rightarrow t\bar{t}hZ\chi^0_1$ (top left) and $t\bar{t}ZZ\chi^0_1$ (top right) and combined reach (bottom middle) in the $\geq 3\ell$ “on-Z” signal region at the 14 TeV LHC with 300 fb$^{-1}$ integrated luminosity. $\mu$ is fixed to be $M_1 + 150$ GeV.

channel (top right panel) and $t\bar{t}ZZ\mathcal{E}_T$ channel (bottom middle panel). Since both the 2 OS $\ell$ and $\geq 3\ell$ have no reach for $t\bar{t}hh\mathcal{E}_T$ channel, the combined reach for $t\bar{t}hh\mathcal{E}_T$ is simply the 1 $\ell$ reach as in the top left panel of Fig. 4. For both $t\bar{t}hZ\mathcal{E}_T$ and $t\bar{t}ZZ\mathcal{E}_T$ channel, 1 $\ell$ signal region gives the best sensitivity. The 5σ reach can discover a stop with mass up to 950 GeV, and the 95% exclusion limits can reach up to 1100 GeV for the channel $t\bar{t}hZ\mathcal{E}_T$. The corresponding limit for the channel $t\bar{t}ZZ\mathcal{E}_T$ is a little weaker due to the smaller branching fraction. In dashed lines, we also show the reach of $t\bar{t}hh\mathcal{E}_T$ and $t\bar{t}ZZ\mathcal{E}_T$ channel assuming a 100% decay branching fraction.
V. COLLIDER ANALYSIS AT $\sqrt{s} = 100$ TEV

To explore the physics potential of the future 100 TeV $pp$ machine, it is critical to explore the complete parameter space of the MSSM. We scan the MSSM stop and neutralino/chargino mass parameter in the following region:

- $M_{3\text{SQ}}$ from 1000 to 8000 GeV in a step of 250 GeV, corresponding to $m_{\tilde{t}_1}$ from 1009 GeV to 8001 GeV.
- $M_1$ is scanned from 5 GeV to 5000 GeV, in the step of 250 GeV.
- $\mu$ is fixed to be $\mu = M_1 + 500$ GeV.
• We further require $m_{\tilde{t}_1} > m_{\chi_2^0}/m_{\chi_3^0} + m_t$ such that $\tilde{t}_1 \to t\chi_2^0/\chi_3^0$ is kinematically open.

At the 100 TeV future machine, the decay kinematics will be significantly different from that of the LHC. The decay products such as the top quark from heavy stop are highly boosted as discussed in Ref. [46], leading to highly collinear leptons with the high $p_T$ jets. So we do not require the separation $\Delta R(j, l)$ between jets and leptons to be larger than 0.5 at the Monte Carlo event generation stage. The Delphes 3 Snowmass combined LHC No-Pile-up detector card [34] is modified for the 100 TeV future collider for the detector simulation. We allow up to one additional parton in the final state, and adopt the MLM matching scheme [47] with $x_{qcut} = 80$ GeV for $t\bar{t}j$ background. Both the SM backgrounds and the stop pair production signal are normalized to theoretical cross sections, calculated including higher-order QCD corrections [37, 48]. At the event generation level, we apply the $S_T$ cut (the scalar sum of $p_T$ for all partons) as following: $S_T \geq 3$ TeV for the $t\bar{t}j$ background and $S_T \geq 1$ TeV for the $t\bar{t}B$ background, where $B$ stands for bosons including $W$, $Z$ and $h$.

We apply the following cuts for both the signal and the SM backgrounds:

• All jets reconstructed using anti-$k_t$ algorithm [49] with cone radius $R = 0.5$ are required to have $p_T > 50$ GeV and $|\eta| < 2.5$, including at least two jets with $p_T > 1000$ (500) GeV.

• All leptons ($e$ or $\mu$) are required to have $p_T > 30$ GeV and $|\eta| < 2.5$, including at least one lepton with $p_T > 100$ (200) GeV contained within a $\Delta R = 0.5$ cone centered around one of the two leading jets.

• The separation $\Delta \Phi(p_T^{miss}, j)$ between the missing transverse momentum and jets with $p_T > 100$ (200) GeV and $|\eta| < 2.5$ is required to be larger than 1.0.

• $m_T$ to be greater than 500, 750, 1000, 1250, 1500 GeV.

• $E_T$ to be greater than 1, 1.5, 2, 2.5, 3, 3.5, 4 TeV.

• $H_T$ to be greater than 2, 3, 4, 5, 6 TeV.

• $N_j$ to be at least 4, 5, 6, 7; $N_{bj}$ to be at least 2, 3, 4, 5.
FIG. 9: Normalized distributions of $E_T$ (left) and $m_T$ (right) for the signal channel $t\bar{t}hZE_T$ with $m_{\tilde{t}_1} = 4000$ GeV and $m_{\tilde{\chi}^0_1} = 1000$ GeV as well as SM backgrounds after the $N_j$, $N_\ell$ and $\Delta \Phi(p_T^{miss}, j)$ cuts.

The above selection cuts are efficient to suppress the SM backgrounds. For example, after imposing the collinear leptons to the two leading jets requirement on the SM backgrounds, the selected samples mainly contain the boosted heavy quarks. The neutrinos in the form of $E_T$ from their decay are highly aligned with the jet momenta. However, the signal $E_T$ has extra contribution from the LSP, which is usually not aligned with the jet momenta. Therefore it is useful to impose the angle separation $\Delta \Phi(p_T^{miss}, j)$ cut between $E_T$ and the jets with $p_T^j > 100$ (200) GeV and $|\eta|^j < 2.5$ to suppress the $t\bar{t}j$ and $t\bar{t}B$ backgrounds. The normalized distributions of $E_T$ and $m_T$ after the above cuts are displayed in Fig. 9. The $E_T$ and $m_T$ distributions of the signal are very broad because of the extra contribution from the LSP. Contrarily, the $E_T$ and $m_T$ distributions of the SM backgrounds are typically bounded around $m_W$. Those two selection cuts are highly efficient to suppress the SM backgrounds. Table VIII shows the cross sections, yields and cumulative cut efficiencies after each level of selection cut for the signals with $m_{\tilde{t}_1} = 4000$ GeV and $m_{\tilde{\chi}^0_1} = 1000$ GeV as well as the SM backgrounds. The $t\bar{t}B$ ($B = W, Z, h$) is the dominant background after all cuts. Other SM backgrounds are typically small after strong selection cuts, then they can be neglected. The discovery significance for the channel $t\bar{t}hZE_T$ can reach 7$\sigma$ for this benchmark point.
| Description | $\tilde{t}_1\tilde{t}_1 (t\bar{t}h)$ | $\tilde{t}_1\tilde{t}_1 (t\bar{t}hZ)$ | $\tilde{t}_1\tilde{t}_1 (t\bar{t}ZZ)$ | $t\bar{t}j$ | $t\bar{t}B$ |
|-------------|-------------------------------|--------------------------------|-------------------------------|---------------|-------------|
| CS (fb) before cuts | 0.66 | 1.32 | 0.67 | 2670 | 2003 |
| $N_j \geq 2$ | 94% | 93% | 92% | 93% | 40% |
| $N_\ell \geq 1$ | 37% | 37% | 35% | 40.6% | 8.6% |
| $\Delta \Phi(j, E_T)$ | 5.5% | 6.6% | 7.5% | 1.7% | 7.3 x 10^{-3} |
| $E_T > 1500$ GeV | 2.5% | 3.3% | 4.1% | 2.9 x 10^{-5} | 6.6 x 10^{-5} |
| $H_T > 4000$ GeV | 1.2% | 1.6% | 1.9% | 1.0 x 10^{-5} | 8.5 x 10^{-6} |
| $m_T > 1000$ GeV | 7.4 x 10^{-3} | 1.1% | 1.4% | 3.2 x 10^{-6} | 5.4 x 10^{-6} |
| $N_j \geq 5$ | 5.8 x 10^{-3} | 8.3 x 10^{-3} | 8.7 x 10^{-3} | 1.8 x 10^{-6} | 2.4 x 10^{-6} |
| $N_{bj} \geq 2$ | 4.9 x 10^{-3} | 6.0 x 10^{-3} | 5.5 x 10^{-3} | 3.1 x 10^{-7} | 1.3 x 10^{-6} |
| CS (fb) after cuts | 3.2 x 10^{-3} | 8.0 x 10^{-3} | 3.7 x 10^{-3} | 8.3 x 10^{-4} | 2.6 x 10^{-3} |
| Event Yields (3ab$^{-1}$) | 9.6 | 24 | 11.1 | 2.5 | 7.8 |

TABLE VIII: The cumulative cut efficiencies, cross sections and yields for the signal with $m_{\tilde{t}_1} = 4000$ GeV and $m_{\chi_1^0} = 1000$ GeV as well as SM backgrounds for 100 TeV $pp$ collider with 3 ab$^{-1}$ integrated luminosity. The $B$ stands for bosons including $W$, $Z$ and $h$.

In Fig. 10, the 95% C.L. upper limits (black curve) and $5\sigma$ discovery reach (red curve) based on $\geq 1\ell$ signal regions are shown in the plane of MSSM parameter space $m_{\tilde{t}_1}$ vs $m_{\chi_1^0}$ for the stop pair production $pp \rightarrow \tilde{t}_1\tilde{t}_1^* \rightarrow t\bar{t}\chi_2^0/\chi_3^0 \rightarrow t\bar{t}hhE_T$ (top left), $t\bar{t}hZ E_T$ (top right), $t\bar{t}ZZ E_T$ (bottom left) and all channels combined (bottom right) at 100 TeV LHC with 3 ab$^{-1}$ integrated luminosity. $\mu$ is fixed to be $M_1 + 500$ GeV and 10% systematic uncertainties are assumed. The channel $t\bar{t}hZ E_T$ has the best reach sensitivity due to its large branching fraction, with discovery reach about 5 TeV and exclusion reach about 6 TeV. Combining all three channels, the discovery (exclusion) reach could be pushed to about 6 (6.6) TeV. This will greatly improve our understanding of the TeV scale SUSY and the nature of electroweak breaking. For $t\bar{t}hhE_T$ and $t\bar{t}ZZ E_T$, we also show the reach assuming a 100% decay branching fraction in dashed lines.
FIG. 10: The 95% CL upper limits (black curve) and 5σ discovery reach (red curve) are shown in the plane of MSSM parameter space $m_{\tilde{t}_1}$ vs $m_{\chi_0}$ for the stop pair production $pp \rightarrow \tilde{t}_1 \tilde{t}_1^* \rightarrow t\bar{t}h h \chi_1^0$ (top left), $t\bar{t}h Z E_T$ (top right), $t\bar{t}Z Z E_T$ (bottom left) and combined channels (bottom right) at 100 TeV future pp collider with 3000 fb$^{-1}$ integrated luminosity for $\geq 1\ell$ signal region. $\mu$ is fixed to be $M_1 + 500$ GeV and 10% systematic uncertainties are assumed. Solid line stands for the realistic MSSM scenario and dotted line represents the simplified model assuming a 100% decay branching fraction. The color coding on the right indicates the signal significance to guide the eye.

VI. SUMMARY AND CONCLUSION

Most of the current stop searches at the LHC have been performed considering the channels of $t\bar{t} E_T$, $b\bar{b}W W E_T$ for the stop sector, assuming the stop 100% decaying to either $t\chi_1^0$ or $b\chi_1^\pm$. However, in MSSM parameter space with light neutralinos and charginos
other than the LSP, these decay channels become subdominant or even highly suppressed, resulting in much relaxed bounds from current LHC searches. In this work, we studied the stop decay behavior in the scenario of a Bino-like LSP ($M_1$) with Higgsino-like NLSPs ($\mu$). The new decay channels of $\tilde{t}_1 \rightarrow t\chi^0_2/\chi^0_3$ dominate because of the large SU(2)$_L$ coupling and top Yukawa coupling. Given the further decays of $\chi^0_2/\chi^0_3$ to a Higgs boson or $Z$ boson, the stop pair production at the LHC leads to $t\bar{t}h\ell E_T$, $t\bar{t}hZ\ell E_T$ and $t\bar{t}ZZ\ell E_T$ final states.

In this work, we focused on the stop search sensitivity at the 14 TeV LHC with 300 fb$^{-1}$ integrated luminosity, in three primary signal regions based on lepton multiplicities: 1 $\ell$, 2 OS $\ell$ and $\geq 3\ell$. We combined all the three production channels or three signal regions to obtain the best reach. We also explore the reach at the future 100 TeV $pp$ collider with 3000 fb$^{-1}$ integrated luminosity. The 95% C.L. exclusion and 5 $\sigma$ discovery reach are summarized in Fig. 11.

![Fig. 11](image_url)

**FIG. 11:** The 5 $\sigma$ discovery reach and 95% exclusion limit of light stop mass for three primary signal regions at the 14 TeV LHC with 300 fb$^{-1}$ integrated luminosity (left panel) and at least one lepton signal region at the future 100 TeV $pp$ collider with 3000 fb$^{-1}$ integrated luminosity (right panel).

Although we only consider one very interesting scenario of MSSM parameter space, 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 analyses can be applied to the study of top partners in other
new physics scenarios as well.

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