Mono-top Signature from Supersymmetric $t\bar{t}H$ Channel

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ABSTRACT: We point out that a distinctive mono-top signature is present in Natural SUSY scenarios when a scalar top-quark and higgsinos are almost mass degenerate. This signature originates from a supersymmetric counterpart of the $t\bar{t}H$ process, i.e. $pp \rightarrow \widetilde{t}\widetilde{t}\widetilde{h}$. Unlike mono-jet signatures exploiting initial state radiation, this channel can be regarded as a smoking gun signature of a light stop and higgsinos, allowing a direct probe of the stop and neutralino sectors. The production rate of this channel largely depends on the up-type higgsino components in the neutralinos while the stop sector is sensitive to angular distributions of top-quark’s decay products. We develop an optimal search strategy to capture the supersymmetric $t\bar{t}H$ process and find that a high luminosity LHC can probe the stop and higgsino sectors with $m_{\tilde{t}_1} \lesssim 380$ GeV and $m_{\tilde{t}_1} - m_{\tilde{\chi}^0_1} \lesssim m_W$. Additionally, we propose a kinematic variable with which one can measure the stop mixing in this channel.

KEYWORDS: Natural SUSY, Light Stops, Compressed Spectra
1 Introduction

After the long shut down CERN’s Large Hadron Collider (LHC) has resumed colliding protons, almost doubling the collision energy to 13 TeV. With this highest-ever energy, the LHC Run-2 expects to observe the processes with multiple heavy particles such as $t\bar{t}H$ [1–10], $tqH$ [11–16] and possibly $HH$ [17–27]. Observing these processes is not only interesting by its own right but also crucial to directly measure the interaction of the Higgs boson with top-quarks and Higgs boson itself.

Another compelling physics target of Run-2 is searches for new physics beyond the Standard Model. The leading candidate of such models is Supersymmetry (SUSY), in which the gauge hierarchy problem is elegantly solved due to the underlying symmetry between bosons and fermions. In the Minimal SUSY Standard Model (MSSM) the bare Higgs mass-squared parameter and the radiative correction to it are given by the mass scales of higgsinos and scalar top-quarks (stops), respectively. Naturalness, therefore, requires higgsinos and stops not to be significantly heavier than the gauge boson mass scale, whilst it leaves the rest of the spectrum rather unconstrained.\(^1\) Indeed, naturalness remains almost intact even if all other SUSY particles are pushed up to a few TeV, significantly heavier than their exclusion limit obtained in the Run-1 and early 13 TeV data collected in 2015. Such a scenario, called Natural SUSY, has been extensively studied in the literature [28–57].

Reflecting its importance and non-triviality [58–71], numerous ATLAS and CMS analyses have been devoted to light stop searches. The exclusion limit on the mass of the lighter stop, $\tilde{t}_1$, largely depends on its decay modes. In Natural SUSY lighter neutralinos ($\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0$) and

\(^1\)Except for gluinos. The gluinos contribute to the radiative corrections to the Higgs mass-squared parameter through renormalisation group evolution of the stop mass. Since the sensitivity of the gluino mass to naturalness is higher order compared to that of stops and higgsinos, in this paper we focus only on light stops and higgsinos.
the lighter charginos ($\tilde{\chi}^\pm_1$) are higgsino-like and almost mass degenerate: $m_{\tilde{\chi}^0_1} \simeq m_{\tilde{\chi}^0_2} \simeq m_{\tilde{\chi}^+_1}$. If $\tilde{t}_1 \rightarrow t\tilde{\chi}^0_1$ is kinematically forbidden ($m_{\tilde{t}_1} < m_{\tilde{\chi}^0_1} + m_t$), the decay mode of $\tilde{t}_1$ is dominated by $\tilde{t}_1 \rightarrow b\tilde{\chi}^\pm_1$. (1.1)

Due to the mass degeneracy between $\tilde{\chi}^\pm_1$ and $\tilde{\chi}^0_1$, the subsequent decay $\tilde{\chi}^\pm_1 \rightarrow f\bar{f}\tilde{\chi}^0_1$ would not be observable. ATLAS and CMS have searched for this process in the di-b-jet channel [72–74]. Currently, the most stringent bound, $m_{\tilde{t}_1} \gtrsim 840$ GeV for $m_{\tilde{\chi}^0_1} \lesssim 200$ GeV, comes from the 13 TeV ATLAS analysis [74] with the integrated luminosity of $3.2 \text{ fb}^{-1}$. However, this limit diminishes if the mass difference $\Delta m_{\tilde{t}_1-\tilde{\chi}^0_1} \equiv m_{\tilde{t}_1} - m_{\tilde{\chi}^0_1}$ gets compressed, because the $b$-quarks from the stop decays become soft and undetectable. For instance, it becomes as weak as $m_{\tilde{t}_1} \gtrsim 300$ GeV if $\Delta m_{\tilde{t}_1-\tilde{\chi}^0_1} \lesssim 50$ GeV.

The compressed stop-higgsino region can be searched for by exploiting the stop pair production associated with hard QCD initial state radiation (ISR). In such events the system of two stops is boosted recoiling against the high $p_T$ ISR jets, leading to a mono-jet signature as shown in the left panel of Fig. 1. Although the mono-jet channel is useful for discovery, it has some disadvantages.

- Since it requires at least one high $p_T$ QCD jet, the cross section is suppressed by the QCD coupling, $\alpha_s(\mu)$, approximately at the scale of the $p_T$ cut, $\sim O(100)$ GeV.
- There is a large QCD dijet background where one of the jets is badly mismeasured. Because of this and the above reason, the limit obtained from the mono-jet channel is rather weak: $m_{\tilde{t}_1} \gtrsim 270$ GeV for $\Delta m_{\tilde{t}_1-\tilde{\chi}^0_1} \lesssim 15$ GeV [73, 75]. The limit deteriorates if the mass difference increases since the $b$-quark from the $\tilde{t}_1 \rightarrow b\tilde{\chi}^\pm_1$ decay starts to be visible. For example, the limit is weakened to $m_{\tilde{t}_1} \gtrsim 200$ GeV for $\Delta m_{\tilde{t}_1-\tilde{\chi}^0_1} \gtrsim 50$ GeV [73, 75].
- The signal is entirely controlled by QCD interactions, hence the available information is limited. For example, even in the presence of an excess, it would be very difficult to find
out what types of particles are produced and how they decay as we would only observe
the jets from QCD radiation.

In this paper we point out that a large collision energy of 13 TeV LHC opens up the
possibility of observing the stop-top-higgsino production process, \( pp \rightarrow \tilde{t}_1 \tilde{t}_1 \chi^{0}\), providing an
additional handle for the compressed stop-higgsino region in Natural SUSY. This process is
nothing but a supersymmetric counterpart of the \( t\bar{t}H \) process, and analogously to the \( t\bar{t}H \) it
is crucial to directly probe the interaction between stops and higgsinos. Because the stop is
essentially invisible as its decay products are too soft to be observed in the compressed region,
the process leads to a distinctive mono-top signature as depicted in the right panel of Fig. 1.
The mono-top signature has been actively studied mainly in the context of the flavour violating
models [76–83]. The process discussed in this paper, however, does not belong to this type since
the mono-top nature emerges due to the kinematics of the stop’s decay products. In contrast to
the mono-jet channel, this process has the following advantages.

- Despite a large mass of the system, the production rate is not too small because the
  stop-top-higgsino interaction is proportional to the top Yukawa coupling, \( Y_t \).
- The QCD multijet background can be controlled by requiring an isolated lepton from
top-quark decays.
- The process contains rich information on the stop and neutralino sectors. For example, as
  will be shown in the next section, the production cross section depends dominantly on the
  up-type higgsino components in the neutralinos.\(^3\) On the other hand, the structure of the
  stop mixing can be probed by looking at the kinematic distributions of the \( b \)-jet and the
  lepton from the top-quark decay as we will see in section 4.

The paper is organised as follows. In the next section, we study the production cross section
of the supersymmetric \( t\bar{t}H \) process and discuss how the cross section does and does not depend
on the neutralino and the stop sectors. In section 3, an optimal search strategy is proposed based
on various kinematic distributions of the signal and background. We derive the 2-\( \sigma \) sensitivity
assuming 13 TeV LHC with 3 ab\(^{-1} \) of the integrated luminosity. In section 4, we demonstrate
how the stop mixing parameter can be probed by looking at the kinematic distributions of the
top-quark decay products. We conclude this paper in section 5.

## 2 Cross Section of the Supersymmetric \( t\bar{t}H \) process

Fig. 2 shows some of the tree-level diagrams contributing to the supersymmetric \( t\bar{t}H \) process,
i.e. \( pp \rightarrow \tilde{t}_1 \tilde{t}_1 \chi^{0} \) (\( i \in \{1, 2\} \)). As mentioned in the previous section, in Natural SUSY scenarios
\( \chi^{0}_1 \) and \( \chi^{0}_2 \) are higgsino-like and almost mass degenerate. Therefore, both \( \tilde{t}_1 \tilde{t}_2 \chi^{0}_1 \) and \( \tilde{t}_1 \tilde{t}_2 \chi^{0}_2 \)
processes contribute to the signal. In this paper, we focus on the compressed stop-higgsino
region, in particular \( m_{\tilde{t}_1} < m_{\chi^{0}_1} + m_W \), since searches for light stops in this parameter regime are
experimentally challenging. It is worthwhile to note that if the mass difference is larger than
\( m_t \), the supersymmetric \( t\bar{t}H \) process cannot easily be distinguished from the \( \tilde{t}_1 \) pair production

\(^2\)We consider both \( \tilde{t}_1 \chi^{0}_1 \) and \( \tilde{t}_1 \chi^{0}_2 \) but simply write \( \tilde{t}_1 \chi^{0}_i \).

\(^3\)The details of the neutralino sector may also be probed via the \( pp \rightarrow \tilde{q} \tilde{\chi}^{0}_1 \) process if squarks are light and \( \chi^{0}_1 \)
is gaugino-like [84, 85].
Figure 2: Representative Feynman diagrams for the supersymmetric $t\bar{t}H$ process. The $q\bar{q}$ initial states are also possible for the latter two diagrams. The red dots denote the stop-top-higgsino interaction. The stop propagator in the second diagram has to be far off-shell in our parameter region $m_{\tilde{t}_1} - m_{\chi_1^0} < m_W$, hence it is clearly separated from the stop pair production.

where one of the stops decays into $t$ and $\tilde{\chi}_i^0$. The compressed stop-higgsino region studied in this paper does not have such a complication. As can be seen in Fig. 2, the amplitude is proportional to the stop-top-neutralino vertex depicted by the red dots, and one can probe the stop and neutralino sectors through this interaction.

Before going to the details, we define the stop mixing as

$$
\begin{pmatrix}
i_1 \\
i_2
\end{pmatrix} = \begin{pmatrix}
\cos \theta_{\tilde{t}} & \sin \theta_{\tilde{t}} \\
-\sin \theta_{\tilde{t}} & \cos \theta_{\tilde{t}}
\end{pmatrix}
\begin{pmatrix}
i_R \\
i_L
\end{pmatrix}
$$

(2.1)

with $m_{i_1} \leq m_{i_2}$. The neutralino mass matrix is given by

$$
M_\psi = \begin{pmatrix}
M_1 & 0 & -\cos \beta \sin \theta_W m_Z & \sin \beta \sin \theta_W m_Z \\
0 & M_2 & \cos \beta \cos \theta_W m_Z & -\sin \beta \cos \theta_W m_Z \\
-\cos \beta \sin \theta_W m_Z & \cos \beta \cos \theta_W m_Z & 0 & -\mu \\
\sin \beta \sin \theta_W m_Z & -\sin \beta \cos \theta_W m_Z & -\mu & 0
\end{pmatrix}
$$

(2.2)

in the basis of $\psi_a = (B, \tilde{W}^0, \tilde{h}_d^0, \tilde{h}_u^0)$, where $\tan \beta$ is the ratio of the vacuum expectation values of the up- and down-type Higgs fields and $\theta_W$ is the weak mixing angle. The mass matrix is diagonalised as $NM_\psi N^T = \text{diag}(m_{\chi_1^0}, m_{\chi_2^0}, m_{\chi_3^0}, m_{\chi_4^0})$ with $|m_{\chi_i^0}| \leq |m_{\chi_j^0}|$ for $i < j$, and $\tilde{\chi}_i^0 = N_{ia} \psi_a$. If the electroweak gauginos are decoupled, the lighter two neutralinos become purely higgsino-like (pure higgsino limit) and the relevant components of the mixing matrix can be written as

$$
\begin{pmatrix}
N_{i3} & N_{i4} \\
N_{23} & N_{24}
\end{pmatrix} = \begin{pmatrix}
\frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \\
\frac{i}{\sqrt{2}} & \frac{i}{\sqrt{2}}
\end{pmatrix}.
$$

(2.3)

The stop-top-neutralino interaction is given by

$$
\mathcal{L} \supset -\frac{g}{\sqrt{2}} i \tilde{t}_i \sum_i \tilde{\chi}_i^0 \left[ (D_h^* \sin \theta_i + D_B \cos \theta_i) P_R + (D_h \cos \theta_i + D_{WB}^* \sin \theta_i) P_L \right] t + \text{h.c.}
$$

(2.4)

with

$$
D_h = \frac{m_t}{m_W \sin \beta} N_{i4}, \quad D_B = -2Q_u \tan \theta_W N_{i1}, \quad D_{WB} = N_{i2} + (2Q_u - 1)N_{i1} \tan \theta_W.
$$

(2.5)
where \( P_{R(L)} = \frac{1 + \gamma}{2} \) is the chirality projection operator and \( Q_u = 2/3 \) is the electric charge of the top-quark.

In order to parametrise the deviation from the pure higgsino limit, we define the higgsino measure \( R \) as

\[
R \equiv \sigma / \sigma_h ,
\]

where \( \sigma \) is the total cross section of the \( \tilde{t}_1 \tilde{t}_\chi^0_1 \) and \( \tilde{t}_1 \tilde{t}_\chi^0_2 \) processes in the model and \( \sigma_h \) is that for the pure higgsino limit with \( \tilde{t}_1 = \tilde{t}_R \) and \( \tan \beta \simeq 1 \). In the regime where \( \chi^0_{1(2)} \) are higgsino-like (\(|N_{i4}| \gg |N_{i1}|, |N_{i2}| \) for \( i \in \{1, 2\} \)) we find approximately

\[
R \simeq \frac{|N_{14}|^2 + |N_{24}|^2}{\sin^2 \beta} .
\] (2.7)

Within this approximation the cross section is independent of the stop mixing (we will confirm this numerically in section 3.2) and depends dominantly on the up-type higgsino components in \( \tilde{\chi}^0_1 \) (\( N_{14} \)) and \( \tilde{\chi}^0_2 \) (\( N_{24} \)) up to the \( 1/\sin^2 \beta \) factor.\(^4\)

Eq. (2.7) has an important implication. In the compressed stop-higgsino region (\( m_{\tilde{t}_i} \sim m_{\chi_2} \simeq m_{\chi_1} \)) the mono-top signal rate is determined by \( m_{\tilde{t}_i} \) and \( R \), whilst the mono-jet signal rate is fixed only by \( m_{\tilde{t}_i} \). Hence, measuring both mono-jet and mono-top signal rates allows to determine \( R \), enabling us to directly probe the neutralino sector independently of the details of the stop sector.

The red curves in Fig. 3 show the Leading Order (LO) cross sections of the \( \tilde{t}_1 \tilde{t} \tilde{\chi}^0_1 \) production (\( i = 1 \) and \( 2 \) are combined) at the 8 (dashed), 13 (solid) and 14 TeV (dashed-dotted) LHC in the pure higgsino limit, i.e. \( R \simeq 1 \). We fix \( \Delta m_{\tilde{t}_i - \tilde{\chi}^0_i} = 10 \) GeV, \( m_{\tilde{\chi}^0_i} = m_{\tilde{\chi}^0_1} + 5 \) GeV, \( \cos \theta_1 = 1 \) and \( \tan \beta = 20 \) in the calculation. We use MadGraph 5 \([86]\) to compute the cross section. The 13 TeV cross section varies from 105 to 0.53 fb as \( m_{\tilde{t}_i} \) increases from 200 to 600 GeV. The ratio between the 13 and 8 TeV cross sections (\( \sigma_{13 \tev} / \sigma_{8 \tev} \)) is about 5 (10) for \( m_{\tilde{t}_i} = 200 \) (600) GeV. The 14 TeV cross section is not larger than 1.5 times the 13 TeV cross section in the range of the plot.

The LO cross section of the supersymmetric \( t\bar{t}H \) process is compared with the Next-to-Leading Order (NLO) cross sections of the \( \tilde{t}_1 \) pair production (blue solid) \([87–91]\) and the Standard Model \( t\bar{t}H \) production (black solid) \([92]\) at the 13 TeV LHC. The NLO cross section of the \( \tilde{t}_1 \) pair production is \( \sim 700 \) times larger than the LO cross section of the \( \tilde{t}_1 \tilde{t} \tilde{\chi}^0_1 \) production at \( m_{\tilde{t}_i} = 200 \) GeV. This ratio decreases for larger stop masses and becomes \( \sim 400 \) at \( m_{\tilde{t}_i} = 600 \) GeV. This is because for larger \( m_{\tilde{t}_i} \) (and \( m_{\tilde{\chi}^0_i} \)), the relative importance of the top-quark mass decreases and the price to produce an extra top-quark diminishes. The \( \tilde{t}_1 \tilde{t} \tilde{\chi}^0_1 \) production at lower stop masses has a comparable cross section with that of the Standard Model \( t\bar{t}H \) process. The former is 105 fb at \( m_{\tilde{t}_i} = 200 \) GeV at LO, whereas the latter 508 fb \([92]\) at NLO. This is not surprising because these processes share the same coupling due to Supersymmetry.

\(^4\)This factor is never significant unless \( \tan \beta \) is extremely small. For instance \( \sin^2 \beta = 0.9, 0.8 \) and 0.5 for \( \tan \beta = 3, 2 \) and 1, respectively. Moreover, small \( \tan \beta \) is not favoured in Natural SUSY scenarios since realising \( m_h \simeq 125 \) GeV becomes even more challenging with light stops.
Figure 3: LO cross section of the supersymmetric $t\bar{t}H$ process ($pp \rightarrow \tilde{t}_1 \tilde{t}_1$ and $\tilde{t}_1 \tilde{t}_2$ are combined) in the pure higgsino limit at the 8 (red dashed), 13 (red solid) and 14 TeV (red dashed-dotted) LHC. The parameters are fixed as $\Delta m_{\tilde{t}_1-\tilde{\chi}_1^0} = 10$ GeV, $m_{\tilde{\chi}_1^0} = m_{\tilde{\chi}_2^0} + 5$ GeV, $\cos \theta_t = 1$ and $\tan \beta = 20$. These LO cross sections are compared with the NLO cross sections of the $\tilde{t}_1$ pair production (blue solid) and the Standard Model $t\bar{t}H$ production (black solid) at the 13 TeV LHC.

3 The Mono-top Search

3.1 The Search Strategy

In this section we study various kinematic distributions in the mono-top channel and develop an optimal search strategy. We also derive the 2-$\sigma$ sensitivity in the $(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^0})$ plane assuming the high luminosity phase ($\int L dt = 3$ ab$^{-1}$) of the 13 TeV LHC.

We begin by looking at the decay products of $\tilde{t}_1$ in the compressed stop-higgsino region at parton-level. The left panel of Fig. 4 shows the normalised transverse momentum distribution for $b$-quarks $p_{Tb}$ from the $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm$ decay. We display three distributions with $\Delta m_{\tilde{t}_1-\tilde{\chi}_1^0} = 8, 15$ and 45 GeV fixing $m_{\tilde{t}_1} = 317$ GeV and $m_{\tilde{\chi}_1^0} = m_{\tilde{\chi}_2^0} + 3$ GeV. Notice that for a small mass gaps, $\Delta m_{\tilde{t}_1-\tilde{\chi}_1^0} = 8$ and 15 GeV, almost all $b$-quarks do not pass the $p_{Tb} > 30$ GeV cut, whereas for a larger mass difference, $\Delta m_{\tilde{t}_1-\tilde{\chi}_1^0} = 45$ GeV, a significant fraction of the $b$-quarks do pass this selection.

The right panel of Fig. 4 shows the $p_T$ distribution of a fermion (quark or lepton) from the $\tilde{\chi}_1^\pm \rightarrow f\bar{f}'\tilde{\chi}_1^0$ decay. Differently from the left panel, we now fix $\Delta m_{\tilde{t}_1-\tilde{\chi}_1^0} = 45$ GeV and vary the mass difference between $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0$ as $\Delta m_{\tilde{\chi}_1^\pm-\tilde{\chi}_1^0} = 3, 6$ and 9 GeV.\footnote{In Natural SUSY scenarios the mass difference between $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0$ is smaller than 10 GeV if the electroweak gauginos are heavier than 1 TeV [93–95].} We observe that $p_{Tf}$...
increases on average as $\Delta m_{\tilde{t}_1-\tilde{t}_1}$ increases. However, for $\Delta m_{\tilde{t}_1-\tilde{t}_1} \leq 9$ GeV the majority of the decay products are always very soft, $p_{T,j} < 10$ GeV. We have also checked that the $p_{T,j}$ distribution is almost independent of $\Delta m_{\tilde{t}_1-\tilde{t}_1}$.

These distributions suggest that stop’s decay products are soft in the compressed region and unlikely to pass the standard lepton and jet reconstruction criteria. In this case, all the visible objects in the final state arise from the top-quark decay (and QCD radiation) as illustrated in the right panel of Fig. 1. This mono-top feature can be used to efficiently discriminate the signal from backgrounds.

We consider the mono-top signature of the $\tilde{t}_1 \chi_1^0(2)$ process with a leptonically decay, by requiring exactly one isolated lepton ($\ell = e$ and $\mu$) with $p_T > 10$ GeV ($N_\ell(p_T > 10$ GeV) = 1) and exactly one $b$-tagged jet with $p_T > 30$ GeV ($N_b(p_T > 30$ GeV) = 1). To reduce the $t\bar{t}$ background, we also demand the number of jets with $p_T > 30$ GeV must be less than or equal to three.\footnote{Vetoing jets with a $p_T$ much lower than the hard interaction scale may bring a large uncertainty proportional to a logarithm of the ratio of these two scales. For a study to understand and reduce this uncertainty, see \cite{96}.} Our baseline selection cut is thus summarised as

$$
N_\ell(p_T > 30$ GeV) $\leq 3, \quad N_b(p_T > 30$ GeV) = 1, \quad N_\ell(p_T > 10$ GeV) = 1.
$$

After these selections, the main backgrounds come from $t\bar{t}$ (831 pb \cite{97}), $tW$ (71 pb \cite{98}), $tZ$ (0.88 pb \cite{99}) and $W + b\bar{b}$ (2.55 pb), where the numbers in the brackets denote the production rate (before cuts) at NNLO+NNLL for $t\bar{t}$, at LO for $W + b\bar{b}$ and at NLO for all the other processes. The $t\bar{t}$ sample is generated with ALPGEN \cite{100} and Pythia6 \cite{101} and merged up to

![Figure 4](image-url)

**Figure 4:** Normalised transverse momentum distributions for the $b$-quark from the $\tilde{t}_1 \rightarrow b\tilde{t}_1^+$ decay (left panel) and the fermions from the subsequent $\tilde{t}_1^+ \rightarrow f f'\tilde{\chi}_1^0$ decay (right panel) at parton level. On the left panel we fix the chargino-neutralino mass difference to $\Delta m_{\tilde{t}_1-\tilde{t}_1} = 3$ GeV and vary the stop-neutralino mass difference as $\Delta m_{\tilde{t}_1-\tilde{t}_1} = 8, 15$ and 50 GeV, whereas on the right panel we fix $\Delta m_{\tilde{t}_1-\tilde{t}_1} = 45$ GeV and scan $\Delta m_{\tilde{t}_1-\tilde{t}_1} = 3, 6$ and 9 GeV. We assume $m_{\tilde{t}_1} = 317$ GeV for both panels.
Figure 5: Left: Normalised $m_{b\ell}$ distributions for the signal $\tilde{t}_1\tilde{\chi}_1^{0(2)}$ with $\Delta m_{\tilde{t}_1-\tilde{\chi}_1^0} = 8$ GeV (red solid) and 45 GeV (blue solid), $t\bar{t}$ (black solid), $tW$ (black dotted) and $W+b\bar{b}$ (blue dotted) samples after the baseline selection. Right: Transverse mass $m_T$ distributions after the baseline and $m_{b\ell} < 150$ GeV cuts expected at the 13 TeV LHC. The line types and colours are assigned in the same way as in the left panel apart from the $tW$, for which the black solid is used. In this plot the contributions of the $t\bar{t}$ and $tW$ where one or two $W$ (and $t$) decay(s) leptonically (including $\tau$) are also shown, which are $tt2l$ (black dashed), $t\bar{t}l$ (black dotted) and $tW2l$ (black dotted-dashed). For both plots the signal points have $m_{\tilde{t}_1} = 317$ GeV and $m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_2^0} = m_{\tilde{\chi}_1^0} + 3$ GeV.

one jet in MLM matching scheme. The signal and the other background samples are generated using MadGraph 5 [86] and showered and hadronized with Pythia 6.

The detector effects are included via the Delphes 3 package [102]. Jets are defined with the anti-$k_T$ algorithm in Fastjet [103, 104] with $R = 0.5$ and required $p_T > 20$ GeV and $|\eta| < 2.5$. We adopt the $b$-tagging efficiency of 70% with 15% mistag rate for $c$-quarks and 1% for light-quarks [105, 106]. The isolated leptons are defined only within the range of $p_T > 10$ GeV and $|\eta| < 2.4$.

Using the detector-level samples after applying the baseline selection Eq. (3.1), we now show the distributions of the invariant mass of the $b$ and $\ell$ ($\ell = e, \mu$) in the left panel of Fig. 5. As can be seen, the signal presents a Jacobian peak structure at $m_{b\ell} \sim 130$ GeV and most of the signal events fall below 150 GeV. This structure is expected if the $b$ and $\ell$ are originated from the same top-quark decay. Unlike the signal, the $m_{b\ell}$ distributions for $t\bar{t}$ and $W+b\bar{b}$ exhibit large tails exceeding 150 GeV. For $t\bar{t}$, this tail typically comes from the events where the $b$ and $\ell$ come from different top-quark decays. For $W+b\bar{b}$, the Jacobian peak structure is not expected at the first place, since there is no top-quark in the event. To exploit this feature we impose

$$m_{b\ell} < 150 \text{ GeV},$$

Another variable that is useful to control the background is the transverse mass of the
lepton and the missing energy vector: \( m_T = \sqrt{2p_T(1 - \cos \phi_{E_T})} \). If the lepton and the missing energy are originated from a single \( W \) boson, this variable is kinematically bounded from above by \( m_W \). This is the case for \( W + b\bar{b} \) and the fraction of the \( tt \) events where one of the tops decays hadronically and the other leptonically \( t\bar{t}l \) (including \( \tau \)). The right panel of Fig. 5 shows the \( m_T \) distribution for the 13 TeV LHC with 3 ab\(^{-1}\) of data. As expected, the \( m_T \) distributions in the \( W + b\bar{b} \) and \( t\bar{t}l \) samples sharply drop above \( m_T \sim m_W \). We require

\[
  m_T > 100 \text{ GeV} \quad (3.3)
\]
to further suppress these backgrounds. Above this threshold the dominant backgrounds become \( tt \) and \( tW \) where all \( W \)s and tops decay leptonically (including \( \tau \)), respectively denoted by \( tt2l \) and \( tW2l \).

In Fig. 6, we display the missing energy distribution for the signal and background samples after imposing the above selection cuts Eqs. (3.1), (3.2) and (3.3). The \( E_T^{\text{miss}} \) distribution falls faster for the total background than for the signal. We exploit this fact by defining three signal regions (SR1, SR2 and SR3) that correspond to different missing energy selections

\[
  E_T^{\text{miss}}/\text{GeV} > 450 \, (\text{SR1}), \ 500 \, (\text{SR2}), \ 550 \, (\text{SR3}). \quad (3.4)
\]

A detailed cut-flow table showing the number of signal and background events at a high luminosity LHC with \( \sqrt{s} = 13 \text{ TeV} \) and \( \int L\, dt = 3 \text{ ab}^{-1} \) is presented in Table 1. Three benchmark
Table 1: Number of signal and background events assuming a high luminosity LHC with √s = 13 TeV and ∫Ldt = 3 ab⁻¹. We present results for three signal benchmark points: (m_{t_1}, m_{\tilde{\chi}_1^0})/GeV = (317, 309), (317, 272) and (342, 334). The remaining parameters are fixed to m_{\tilde{\chi}_1^0} = m_{\tilde{\chi}_2^0} = m_{\tilde{\chi}_1^0} + 3 GeV, tan β = 20 and cos θ_L = 1. We assume that the higher order corrections to the signal tantamount to a factor K_{NLO} = 1.5.

| Process   | σ  | Baseline | m_{b\ell} < 150 | m_T > 100 | SR1    | SR2    | SR3    |
|-----------|----|----------|-----------------|------------|--------|--------|--------|
| t\bar{t} | 831 pb | 206 \cdot 10^6 | 165 \cdot 10^6 | 17.7 \cdot 10^6 | 463.3 | 142.6 | 55.2 |
| tW       | 71 pb  | 26.2 \cdot 10^6 | 20.7 \cdot 10^6 | 1.68 \cdot 10^6 | 308.5 | 130.9 | 55.5 |
| tZ       | 0.88 pb | 22.8 \cdot 10^3 | 21.6 \cdot 10^3 | 7.3 \cdot 10^3 | 26.1 | 15.1 | 8.0 |
| W + b\bar{b} | 2.55 pb | 1.82 \cdot 10^6 | 1.51 \cdot 10^6 | 42.3 \cdot 10^3 | 5.9 | 2.8 | 1.4 |
| BG total | 903 pb | 226 \cdot 10^4 | 41.1 \cdot 10^4 | 19.4 \cdot 10^6 | 803.8 | 291.4 | 120.1 |

| BP(317,309) | 23.7 fb | 5883 | 5491 | 3387 | 109 | (3.8,0.13) | (3.6,0.21) | (3.2,0.29) |
| BP(317,272) | 30.8 fb | 6522 | 5491 | 3123 | 60.2 | 34.9 | 19.1 |
| BP(342,334) | 16.7 fb | 4119 | 3834 | 2395 | 84.0 | 46.8 | 26.8 |

|         |         |         |         |         |         |         |         |
|         |         |         |         |         | (3.0,0.10) | (2.7,0.16) | (2.4,0.22) |

We now compare the signal and background in the signal region and derive the 2-σ sensitivity at a high luminosity LHC with √s = 13 TeV and ∫Ldt = 3 ab⁻¹. We present the sensitivity in a 2D parameter plane (m_{t_1}, m_{\tilde{\chi}_1^0}) assuming m_{\tilde{\chi}_1^0} = m_{\tilde{\chi}_2^0} = m_{\tilde{\chi}_1^0} + 3 GeV and do not consider the contribution from \tilde{t}_2. We also consider two extreme cases: \tilde{t}_1 = \tilde{t}_R and \tilde{t}_1 = \tilde{t}_L.

We first display the LO cross section of the signal in the (m_{t_1}, m_{\tilde{\chi}_1^0}) plane in Fig. 7 for the \tilde{t}_L (left panel) and \tilde{t}_R (right panel) cases. In the calculation we take the pure higgsino limit for the neutralino mixing and tan β = 20, i.e. \mathcal{R} \simeq 1. One can see that the cross section decreases as either m_{t_1} and m_{\tilde{\chi}_1^0} increases. This is contrasted with the \tilde{t}_1 pair production, where the cross section depends only on m_{t_1}. As suggested in Eq. (2.7), the cross section is almost unchanged between the \tilde{t}_L and \tilde{t}_R cases.

We now look how the signal efficiency changes across the (m_{t_1}, m_{\tilde{\chi}_1^0}) plane. As an example, we display the signal efficiency of SR2 in Fig. 8 for the \tilde{t}_L (left panel) and \tilde{t}_R (right panel) cases.

\footnote{We notice that the literature does not provide higher order corrections to the considered signal process. As we consider all the main backgrounds at least at NLO and given the similarities between the signal and stop pair production, we assume a similar NLO K-factor. We indicate however the importance of the precise NLO rate determination for future studies.}
Figure 7: The LO cross section in the \((m_{\tilde{t}_1}, m_{\tilde{\chi}_1^0})\) plane for the \(\tilde{t}_1 = \tilde{t}_L\) (left) and \(\tilde{t}_1 = \tilde{t}_R\) (right) cases.

Figure 8: The signal efficiency of SR2 in the \((m_{\tilde{t}_1}, m_{\tilde{\chi}_1^0})\) plane for the \(\tilde{t}_1 = \tilde{t}_L\) (left) and \(\tilde{t}_1 = \tilde{t}_R\) (right) cases.

As can be seen, the efficiency varies from 0.08% to \(\gtrsim 0.4\%\) in the region of the plots. The efficiency is smaller for larger mass difference, \(\Delta m_{\tilde{t}_1-\tilde{\chi}_1^0}\). For larger \(\Delta m_{\tilde{t}_1-\tilde{\chi}_1^0}\) the \(b\)-quark from the \(\tilde{t}_1\) decay becomes harder and more visible, with which the event more likely fails to pass the \(N_b = 1\) and \(N_j \leq 3\) cuts. We also observe that the efficiency increases for larger \(m_{\tilde{t}_1}\). Since the interaction scale is proportional to the mass of the system, the typical momentum scale of \(\tilde{t}_1\), \(t\) and \(\tilde{\chi}_1^0\) becomes larger as \(m_{\tilde{t}_1}\) increases. With those high \(p_T\) objects, events are more likely to pass the \(m_T\) and the missing energy cuts. The efficiencies are almost the same for the \(\tilde{t}_L\) and \(\tilde{t}_R\) cases. This suggests that our search strategy works independently of the details of the stop mixing.
We now show the 2-σ sensitivity expected at the 13 TeV LHC with $\int \mathcal{L} dt = 3 \text{ ab}^{-1}$ by the dark-, medium- and light-pink regions in Fig. 9, corresponding to $R = 0.5, 0.75$ and 1, respectively. The top and bottom panels are for the $\tilde{t}_L$ and $\tilde{t}_R$ cases. In deriving these sensitivities, only the signal regions with more than three expected signal events and $S/B > 0.1$ are used at each parameter point and $R$. We then select the signal region that has the largest $S/\sqrt{B}$. The most sensitive signal region for each parameter point and $R$ is given in Appendix A.

We also overlay the current 95% CL exclusion limit for the $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^0$ topology with $m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_0^\pm}$ by grey regions. The region surrounded by the blue curve is the 95% CL excluded region by the ATLAS di-$b$-jet search [74] using early 13 TeV data with 3.2 fb$^{-1}$. ATLAS interprets their analysis in the $\tilde{b}_1$ production with $\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$ and derived the excluded region in the $(m_{\tilde{b}_1}, m_{\tilde{\chi}_1^0})$ plane. Since the production cross section and the decay kinematics are the same between this $\tilde{b}_1$ model and the $\tilde{t}_1$ pair production with $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm$ at $m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_1^0}$ and $m_{\tilde{t}_1} = m_{\tilde{b}_1}$, we simply use the $\tilde{b}_1$ excluded region for $\tilde{t}_1$ by identifying $m_{\tilde{t}_1} = m_{\tilde{b}_1}$. In realistic models with higgsino-like $\tilde{\chi}_1^0$, $m_{\tilde{\chi}_1^\pm}$ is a few GeV larger than $m_{\tilde{\chi}_1^0}$. We therefore believe that the presented exclusion region in Fig. 9 is slightly aggressive in the compressed stop-higgsino region since the $b$-quark from $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm$ is softer compared to that from $\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$ at the same $m_{\tilde{\chi}_1^0}$ and $m_{\tilde{t}_1} = m_{\tilde{b}_1}$. The other two regions with dark and light green boundaries are the 95% CL excluded region by mono-jet searches by ATLAS [75] and CMS [73] based on Run-1 data.

One can see from Fig. 9 that the mono-top search is sensitive for smaller $\Delta m_{\tilde{t}_1-\tilde{\chi}_1^0}$. This is expected since the $b$-jet from $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm$ becomes visible for larger $\Delta m_{\tilde{t}_1-\tilde{\chi}_1^0}$, making the event difficult to pass the $N_b = 1$ and $N_j \leq 3$ cuts. The reach of the 2-σ sensitivity largely depends on the higgsino measure, $R$, to which the production cross section of the supersymmetric $t\bar{t}H$ process is proportional. Since the mono-jet search is only sensitive to the stop and neutralino masses, measuring both the mono-jet and mono-top signal rates enables us to directly probe the up-type higgsino components in the neutralinos through $R$. As can be seen, the sensitivity reaches up to $m_{\tilde{t}_1} \sim 375 \ (340) \ (285)$ GeV for $R = 1 \ (0.75) \ (0.5)$ at the most compressed region. We also observe that the 2-σ regions are almost identical between the $\tilde{t}_L$ and $\tilde{t}_R$ cases. This means the mono-top search presented in this section works regardless of the details of the stop sector.

We finally comment on possible contributions from the $\tilde{t}_1$ pair production, which is not included in our calculation. The final state of this process is two $b$-quarks from $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm$ and very soft fermions (possibly leptons) from $\tilde{\chi}_1^\pm \rightarrow f\tilde{\chi}_1^0$. As shown in Fig. 4, the hardness of the $b$-quarks varies depending on the mass gap between $\tilde{t}_1$ and $\tilde{\chi}_1^0$, whereas the leptons are always very soft as we fixed $\tilde{\chi}_1^\pm = \tilde{\chi}_1^0 + 3$ GeV. The missing energy is also tiny on average since the neutralinos are produced almost back-to-back in the transverse plane unless they are boosted recoiling against hard ISR jets. The efficiency of our event selection for the $\tilde{t}_1$ pair production is therefore extremely small. This very small efficiency can however be compensated to some extent by its considerably large production rate. We have checked numerically that the contribution from the $\tilde{t}_1$ pair production to our signal regions is about 30% of the $\tilde{t}_1 t\tilde{\chi}_1^0$ contribution in the most compressed region and rises to $\sim 70\%$ in moderately compressed region with $\Delta m_{\tilde{t}_1-\tilde{\chi}_1^0} \sim 50$ GeV. This suggests that the actual sensitivity of the mono-top search is slightly better than what is shown in Fig. 9, being our results conservative. We leave the detailed study including the $\tilde{t}_1$ pair production to future analyses.
Figure 9: The 2-σ sensitivities expected at the 13 TeV high luminosity LHC with $\int \mathcal{L} \, dt = 3 \text{ ab}^{-1}$ for $R = 0.5$ (dark-pink), 0.75 (medium-pink) and 1 (light-pink) for the $\tilde{t}_L$ (top) and $\tilde{t}_R$ (bottom) cases. In deriving these sensitivities, only the signal regions with more than three expected signal events and $S/B > 0.1$ are considered at each parameter point and $R$. The signal region with the largest $S/\sqrt{B}$ is then used to derive the sensitivity. The current 95% CL excluded region is filled by grey. The region surrounded by the blue curve is obtained from the 13 TeV ATLAS di-b-jet analysis with $\int \mathcal{L} \, dt = 3.2 \text{ fb}^{-1}$ [74]. The regions with dark and light green boundaries are excluded by the ATLAS [75] and CMS [73] mono-jet searches with Run-1 data corresponding to $\int \mathcal{L} \, dt \simeq 20 \text{ fb}^{-1}$. 
Figure 10: The distribution of the $p_T$ asymmetry, $A$, at $(m_{\tilde{t}_1}, m_{\chi^0_1}) = (317, 309)$ GeV. The blue and red histograms correspond to the $\tilde{t}_1 = \tilde{t}_L$ and $\tilde{t}_1 = \tilde{t}_R$, respectively. The events satisfy the selection cuts described in Eqs. (3.1), (3.2) and (3.3). The events in the left and right plots additionally satisfy $E_T^{\text{miss}}/\text{GeV} > 100$ and 400, respectively.

4 Probing the Stop Mixing

We have seen that the mono-top search presented in the previous section is insensitive to the stop mixing. The neutralino sector can be probed by measuring the signal rates of mono-jet and mono-top channels without assuming the details of the stop sector. In this section we demonstrate, however, that kinematic distributions of the top-quark decay products are sensitive to the stop sector and can be used to measure the stop mixing [107, 108].

At the vicinity of the pure higgsino limit, the dominant contribution to the stop-top-neutralino interaction comes from

$$-\mathcal{L} \supset Y_i \Phi_{t_R} \Phi_{H_u^0} \Phi_{H_d^0} |_{\theta^2} \supset Y_i \left( \bar{t}_R \tilde{t}_L \right) \bar{H}_u \supset Y_i \left( \cos \theta \bar{t}_L \bar{t}_1 + \sin \theta \bar{t}_R \bar{t}_1^* \right) N_{4\chi^0_i},$$

(4.1)

where $\Phi_i$ is the chiral superfield of $i$ and we have omitted the hermitian conjugate terms. As can be seen, if $\tilde{t}_1$ is mostly $\tilde{t}_R$ ($\cos \theta \sim 1$), the top-quark tends to be left-handed, and vice versa for $\tilde{t}_L$.

The chirality of the top-quark affects the kinematics of its decay products. For example, the angular distribution of the decay product $f (= b, \ell)$ is correlated with the top spin direction as [109–111]

$$\frac{1}{\Gamma_f} \frac{d\Gamma_f}{d \cos \theta_f} = \frac{1}{2} (1 + \omega_f P_t \cos \theta_f)$$

(4.2)

in the rest frame of the top-quark, where $\theta_f$ is the angle between the decay product $f$ and the top spin quantization axis, and $P_t$ is the degree of the top polarization

$$P_t \equiv \frac{N(\uparrow) - N(\downarrow)}{N(\uparrow) + N(\downarrow)}.$$ 

(4.3)
For the top-quark in the $pp \rightarrow \tilde{t}_1 \tilde{t}^0_{1(2)}$ process we obtain $P_t \simeq \cos 2\theta_{\tilde{t}}$ in the pure higgsino limit. The coefficient $\omega_f$ is given as $\omega_h = -0.41$ and $\omega_\ell = 1$ at tree level.

The fact that $\omega_h$ and $\omega_\ell$ have different signs means that in the rest frame of the top-quark their momentum vectors prefer to be in the opposite direction. If $\tilde{t}_1 = \tilde{t}_R (\cos \theta_{\tilde{t}} = 1), P_t = 1$ meaning that the boost of the top-quark is more likely to be in the direction of $\ell$ at the rest frame of the top. In this case, the lepton gets a positive boost on average, while the $b$-quark a negative. For $\tilde{t}_1 = \tilde{t}_L (\cos \theta_{\tilde{t}} = 0)$, the tendency is opposite. To capture this feature we define the $p_T$ asymmetry, $A$, as

$$A \equiv \frac{p_T(\ell) - p_T(b)}{p_T(\ell) + p_T(b)}.$$

We display the distribution of $A$ in Fig. 10 at $(m_{\tilde{t}_1}, m_{\tilde{\chi}^0_1}) = (317, 309)$ GeV for $\tilde{t}_1 = \tilde{t}_R$ (red) and $\tilde{t}_1 = \tilde{t}_L$ (blue). We only use the events that pass the selection cuts Eqs. (3.1), (3.2), (3.3) and $E_T^{\text{miss}}/\text{GeV} > 100$ (left panel) and 400 (right panel). As expected, the $p_T$ asymmetry is larger (meaning that the lepton is more energetic) for $\tilde{t}_L$ compared to $\tilde{t}_R$. The tendency is drastically enhanced if the $E_T^{\text{miss}}$ threshold is increased from 100 to 400 GeV, because the boost of the top-quark increases. This demonstrates that the $p_T$ asymmetry between the $\ell$ and $b$ is very useful variable to probe the stop mixing in the supersymmetric $t\bar{t}H$ process.

5 Conclusion

In this paper, we have studied the supersymmetric $t\bar{t}H$ process, i.e. $pp \rightarrow t\bar{t}h$. We showed that a distinctive mono-top signature arises from this channel for the Natural SUSY scenarios with small stop-higgsino mass differences. While the current searches explore this compressed stop-higgsino region with mono-jet channels exploiting the $\tilde{t}_1$ pair production associated with hard initial state radiation, our proposed channel serves complementary bounds granting a direct probe of the the stop and neutralino sectors.

We presented a detailed search strategy to capture the supersymmetric $t\bar{t}H$ process and found that a high luminosity LHC at 13 TeV can probe the stop and higgsino sectors if $m_{\tilde{t}_1} \lesssim 380$ GeV and $m_{\tilde{t}_1} - m_{\tilde{\chi}^0_1} \lesssim m_W$. We observe that this sensitivity enhances for smaller mass differences $\Delta m_{\tilde{t}_1} - m_{\tilde{\chi}^0_1}$ and that our mono-top search works regardless of the details of the stop sector.

Finally, we have demonstrated that the kinematic distributions of the top-quark decay products are sensitive to the stop sector and can be used to measure the stop mixing parameter. We proposed an asymmetry variable, $A$, to access this parameter. Fortunately for our purposes, the performance of this observable dovetails nicely with the large missing energy selections required to reduce the background.

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A The most sensitive signal region

Fig. 11 shows the most sensitive signal region (with the largest $S/\sqrt{B}$) for each parameter point and for $R = 0.5$ (left panel) 0.75 (centre panel) and 1 (right panel). The top and bottom
Figure 11: The most sensitive signal region (with the largest $S/\sqrt{B}$) for each parameter point and for $\mathcal{R} = 0.5$ (left panel) 0.75 (centre panel) and 1 (right panel). The top and bottom panels correspond to the $\tilde{t}_1 = \tilde{t}_L$ and $\tilde{t}_1 = \tilde{t}_R$ cases, respectively. The empty circles represent the parameter point where none of the signal regions satisfies the consistence criteria that the signal contribution must be greater than three and $S/B > 0.1$. 

panel correspond to the $\tilde{t}_1 = \tilde{t}_L$ and $\tilde{t}_1 = \tilde{t}_R$ cases, respectively. The empty circles represent the parameter points where non of the signal regions satisfies the sanity criteria that the signal contribution must be greater than three and $S/B > 0.1$. 


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