Probing single stop production at future 100 TeV hadron collider

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Abstract

Top squark (stop) is a crucial part of supersymmetric models (SUSY) to understand the naturalness problem. Other than the traditional stop pair production, the single production via electroweak interaction provides signals with distinctive features which could help confirm the existence of the top squark. In this paper, we investigate the observability of stop through the mono-top and mono-bottom channel of the single stop production at the 100 TeV hadron collider, such as the SPPC, in a simplified Minimal Supersymmetric Standard Model (MSSM). With the integrated luminosity of 3000 fb⁻¹, we can probe the stop with mass up to 3.2 TeV (1.8 TeV) by the mono-top channel (mono-bottom channel) at 5σ level. Exclusion limits on stop mass and higgsino mass parameter μ are also presented for both channels.

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I. INTRODUCTION

The search for new physics beyond the Standard Model (BSM) is a primary goal for current and future colliders, though the Standard Model (SM) has been a huge success. One of the main motivations for BSM is the hierarchy problem caused by the Higgs mass quadratic divergence. Especially after the SM-like Higgs boson was discovered by the ATLAS [1] and CMS [2] collaborations in 2012, new physics based on certain symmetries is expected to appear at the TeV scale to stabilize the Higgs mass without fine-tuning. The low energy supersymmetry (SUSY) is one of the most appealing and natural BSM models that can solve the hierarchy problem, by introducing superpartners of SM particles and imposing supersymmetry between fermions and bosons.

Among the supersymmetric particles predicted by SUSY, the scalar top quark (stop), which is the SM top quark’s superpartner, can protect the Higgs mass by canceling the quadratic divergence of the top quark loop, and thus, serve as an elegant solution to the hierarchy problem. Therefore, searching for the stop has always been crucial to test SUSY naturalness [3–23]. During the LHC Run-1 and Run-2, searching for the stop, including the gluino-mediated stop production and the stop pair production, has been performed by the ATLAS and CMS collaborations. The search strategies depend on a variety of kinematically allowed phase spaces of the stop decay, which can be defined by the mass-splitting $\Delta m = m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0}$. When $\Delta m$ is much larger than the top quark mass, the top quark from stop decay is energetic. By using endpoint observables [24–26] and boosted technique [27–29], the stop signal can be well separated from the SM $t\bar{t}$ background. But when $\Delta m$ approximates zero, the decay products of stop are too soft to be observed, and thus the initial- or final-state radiation jet can be used to trigger the signal events selection [30–32].

The stop pair production has long been considered as the best discovery channel, but the significance of the single stop production, via the electroweak interaction, should not be underestimated. Studying the single stop production leads to two implications. On the one hand, the single stop production reveals the electroweak properties of the interaction between stop and neutralinos, which could serve as a complementary channel to its pair production through strong interaction and thus will be an essential task for future colliders. On the other hand, the collider signatures of the stop pair production, like $t\bar{t}$ plus missing
transverse energy, can also be present in the signals of other non-supersymmetric models, such as the littlest Higgs Model with T-parity. Whereas the unique signatures of the single stop production, such as mono-b signature, can exclusively confirm the existence of the stop and the SUSY models.

Given that the project of hadron-hadron collider at a centre-of-mass energy of 100 TeV has long been under consideration and extensively studied, such as the Super Proton-Proton Collider (SPPC) which is the second-phase project of the Circular Electron Positron Collider (CEPC), the discovery potential for new physics beyond the SM would be increased largely with its high collision energy. In this work, we study the single stop production process in the scenario of natural SUSY at the hadron collider of 100 TeV. This process includes the following two decay channels:

\[ pp \rightarrow \tilde{t}_1 \tilde{\chi}_1^- \rightarrow t_{X_{1,2}} \tilde{\chi}_1^0, \]
\[ pp \rightarrow \tilde{t}_1 \tilde{\chi}_1^- \rightarrow b_{X_{1,2}} \tilde{\chi}_1^-, \]

which are called mono-top and mono-bottom channels, respectively. The top from mono-top channel \( \tilde{t}_1 \rightarrow t_{X_{1,2}} \) can further decay to leptonic or full-hadronic final states. In consideration of the large QCD pollution on a hadron collider, we focus on the observability of the mono-bottom and the leptonic mono-top channels. This paper is organized as follows. Sec. II is the theoretical background of the single stop electroweak production process \( pp \rightarrow \tilde{t}_1 \tilde{\chi}_1^- \). Then in Sec. III, we study the observability of single stop production by performing Monte Carlo simulation of the mono-bottom and leptonic mono-top channels at the 100 TeV hadron collider. Finally we draw our conclusions in Sec. IV.

II. SINGLE PRODUCTION OF STOP IN A SIMPLIFIED MSSM

In the minimal supersymmetric standard model (MSSM), the kinetic terms of top-squark are given by

\[
\mathcal{L} = (D_\mu \tilde{t}_L^* D_\mu \tilde{t}_R^*) \left( \begin{array}{c} \tilde{t}_L^+ \tilde{t}_L^* \\ \tilde{t}_R^+ \tilde{t}_R^* \end{array} \right) - \left( \tilde{t}_L^0 \tilde{t}_R^0 \right) M_{\tilde{t}} \left( \begin{array}{c} \tilde{t}_L^+ \\ \tilde{t}_R^+ \end{array} \right),
\]

with the stop mass-squared matrix

\[
M_{\tilde{t}}^2 = \begin{pmatrix} m_{\tilde{t}L}^2 & m_t X_t^+ \\ m_t X_t & m_{\tilde{t}R}^2 \end{pmatrix},
\]
where

\[ m_{t_L}^2 = m_{\tilde{q}_3L}^2 + m_t^2 + m_Z^2 \left( \frac{1}{2} - \frac{2}{3} \sin^2 \theta_W \right) \cos 2\beta, \]
\[ m_{t_R}^2 = m_{\tilde{q}_3R}^2 + m_t^2 + \frac{2}{3} m_Z^2 \sin^2 \theta_W \cos 2\beta, \]
\[ X_t = A_t - \mu \cot \beta. \] (7)

In the above equations, \( A_t \) and \( \mu \) are stop trilinear parameter and the higgsino mass parameter, respectively. The mass eigenstates \( \tilde{t}_1 \) and \( \tilde{t}_2 \) can be obtained from

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

where \( \theta_t \) is the mixing angle between left-handed and right-handed stop.

The electroweakino sector of the MSSM is composed of bino \( (\tilde{B}) \), winos \( (\tilde{W}^0, \tilde{W}^+, \tilde{W}^-) \) and higgsinos \( (\tilde{H}^0_u, \tilde{H}^+_u, \tilde{H}^-_d, \tilde{H}^0_d) \). The four neutralinos \( \tilde{\chi}^0_{1,2,3,4} \) are mass eigenstates of bino, wino and neutral higgsinos \( (\tilde{B}, \tilde{W}, \tilde{H}^0_d, \tilde{H}^0_u) \), whose mass matrix is given by

\[
M_{\tilde{\chi}^0} =
\begin{pmatrix}
M_1 & 0 & -c_{\beta s_W} m_Z & s_{\beta s_W} m_Z \\
0 & M_2 & c_{\beta c_W} m_Z & -s_{\beta c_W} m_Z \\
-c_{\beta s_W} m_Z & c_{\beta c_W} m_Z & 0 & -\mu \\
s_{\beta s_W} m_Z & -s_{\beta c_W} m_Z & -\mu & 0
\end{pmatrix}.
\] (9)

If \( m_Z \) can be neglected, the neutralinos are almost bino-like, wino-like and higgsino-like with masses \( M_1, M_2, \mu \). While the two charginos \( \tilde{\chi}^{\pm}_{1,2} \) are mass eigenstates of charged wino and charged higgsinos \( (\tilde{W}^+, \tilde{H}^+_u, \tilde{W}^-, \tilde{H}^-_d) \). Similarly, the chargino mass matrix can be written as

\[
M_{\tilde{\chi}^{\pm}} =
\begin{pmatrix}
0 & X^T \\
X & 0
\end{pmatrix},
\]

where

\[
X =
\begin{pmatrix}
M_2 & \sqrt{2} s_{\beta W} \mu \\
\sqrt{2} c_{\beta W} \mu & \mu
\end{pmatrix}.
\] (11)

If \( m_W \) can be neglected, the charginos are almost wino-like and higgsino-like with masses \( M_2 \) and \( \mu \). Therefore, describing the electroweakinos can use just only four electroweakino parameters \( M_1, M_2, \mu \) and \( \tan \beta \).
FIG. 1. Feynman diagrams of the single stop production process $pp \rightarrow \tilde{t}_1 \tilde{\chi}_1^-$ at the partonic level.

The relevant couplings between stop and electroweakinos in the mass eigenstates are given by,

$$\mathcal{L}_{\tilde{t}_1\tilde{\chi}_0^i} = \bar{\tilde{t}}_1 \left( f^\nu_L P_L + f^\nu_R P_R \right) \tilde{\chi}_0^i + \text{h.c.},$$

(12)

$$\mathcal{L}_{\tilde{t}_1\tilde{\chi}_m^\pm} = \bar{\tilde{b}} \left( f^{\nu}_L P_L + f^{\nu}_R P_R \right) \tilde{\chi}_m^\pm \tilde{t}_1 + \text{h.c.},$$

(13)

with $P_L,R = (1 \mp \gamma^5)/2$, and the coefficients are

$$f^\nu_L = -\left[ \frac{g^2_2}{\sqrt{2}} N_{i2} + \frac{g_1}{3\sqrt{2}} N_{i1} \right] \cos \theta_i - y_t N_{i4} \sin \theta_i,$$

$$f^\nu_R = \frac{2\sqrt{2}}{3} g_1 N_{i1}^* \sin \theta_i - y_t N_{i4}^* \cos \theta_i,$$

$$f^{\nu}_L = y_b U_{m2}^* \cos \theta_i,$$

$$f^{\nu}_R = -g_2 V_{m1} \cos \theta_i + y_t V_{m2} \sin \theta_i.$$  (14)

Here $y_t = \sqrt{2} m_t/(v \sin \beta)$ is the top quark Yukawa coupling and $y_b = \sqrt{2} m_b/(v \cos \beta)$ is the bottom quark Yukawa coupling.

For the Eq. 9 and Eq. 11 the mass matrices can be diagonalized by a unitary matrix $N$ and two unitary matrices $U$ and $V$, respectively [31]. For $M_2 \ll \mu, M_1, V_{11}, U_{11} \sim 1, V_{12}, U_{12} \sim 0, N_{11,13,14}, N_{22,23,24} \sim 0$, and $N_{12,21} \sim 1$, the neutralino $\tilde{\chi}_1^0$ and the chargino $\tilde{\chi}_1^\pm$ are nearly degenerate winos ($\tilde{W}^\pm$). But for $\mu \ll M_{1,2}, V_{11}, U_{11}, N_{11,12,21,22} \sim 0, V_{12} \sim \text{sgn}(\mu), U_{12} \sim 1$ and $N_{13,14,23} = -N_{24} \sim 1/\sqrt{2}$, the lightest SUSY particles (LSP) are nearly degenerate higgsinos ($\tilde{H}^\pm$). Both the wino-like and the higgsino-like LSP scenarios can be probed at the LHC [35-42].

The partonic process of the single stop production is $g(p_a) b(p_b) \rightarrow \tilde{t}_1(p_1) \tilde{\chi}_1^-(p_2)$, the Feynman diagram of which is shown in FIG. 1. We present the cross sections of single stop production for left- and right-handed stop under Wino-like and Higgsino-like benchmarks with $\tan \beta = 10, 50$ at 100 TeV hadron collider in FIG. 2. In the Wino-like benchmark point, we set $M_2 = 300$ GeV and $\mu, M_1 = 2.5$ TeV, while in the Higgsino-like benchmark
point $\mu = 300$ GeV and $M_{1,2} = 2.5$ TeV. In our simulation, the mass spectrum of sparticles is evaluated by the package SUSYHIT [43]. Then, we use MadGraph5_aMC@NLO [44] to calculate the leading order cross sections of the stop single production process $pp \rightarrow \tilde{t}_1\tilde{\chi}^+_1$. The QCD corrections at next-to-leading order are included by applying a K-factor of 1.4 [45–47]. From FIG. 2, we can learn that for wino-like $\tilde{\chi}^+_1$, because of the gauge interactions, the cross section of the left-handed stop $\tilde{t}_L\tilde{W}^-$ production is larger than the right-handed stop $\tilde{t}_R$. However, for higgsino-like $\tilde{\chi}^+_1$, the cross section of the right-handed stop $\tilde{t}_R$ single production is much larger. In addition, the cross section of $\tilde{t}_R\tilde{H}^-$ is independent of $\tan \beta$, but $\tilde{t}_L\tilde{H}^-$ is not. This is because the coupling of $\tilde{t}_L$ with $\tilde{\chi}^+_1$ is dominated by the bottom Yukawa coupling and can be enhanced as the value of $\tan \beta$ increases.

![Figure 2](image-url)  
**FIG. 2.** The hadronic cross sections of the single stop production process $pp \rightarrow \tilde{t}_1\tilde{\chi}^-_1$ for left- and right-handed stop with $\tan \beta = 10, 50$ at 100 TeV hadron collider. And the charginos $\tilde{\chi}^{\pm}_1$ are wino-like and higgsino-like, respectively. The contribution of the charge-conjugate process of the single stop production $pp \rightarrow \tilde{t}^*_1\tilde{\chi}^+_1$ is included.
III. OBSERVABILITY OF MONO-TOP AND MONO-BOTTOM SIGNATURE AT THE 100 TEV HADRON COLLIDER

We use $\tilde{t}_R\tilde{H}^-$ production to study the observability of the mono-bottom and the leptonic mono-top signature for the single stop production at the 100 TeV hadron collider. In our Monte Carlo simulations, we set $\mu \ll M_{1,2}, m_{\tilde{e}_{3R}} \ll m_{\tilde{Q}_{3L}}$ and $\tan \beta = 50$, thus the electroweakinos are higgsino-like and the stop is right-handed. It should be noted that the branching ratios of $\tilde{t}_R \rightarrow t\tilde{\chi}_0^{0,1,2}$ and $\tilde{t}_R \rightarrow b\tilde{\chi}_1^\pm$ are both about 50% [48]. In the following study, we focus on a simplified MSSM framework where the higgsinos and right-handed stop are the only sparticles. We generate the parton-level signal and background events with MadGraph5_aMC@NLO. Then within the framework of CheckMATE2 [49], we use Pythia-8.2 [50] and Delphes [51] to implement the parton shower and the detector simulations, respectively. Given that the mass splitting between the higgsino-like LSP is small, thus the chargino $\tilde{\chi}_1^\pm$ and the neutralino $\tilde{\chi}_0^{0,1,2}$ are treated as missing transverse energy $E_T$ in our simulation. We adopt the b-jet tagging efficiency as 80% [52] and cluster the jets by the anti-$k_t$ algorithm with the cone radius $\Delta R = 0.4$ [53].

A. The mono-top channel

For the leptonic mono-top channel decay $\tilde{t}_1 \rightarrow t\tilde{\chi}_{1,2}^0 \rightarrow (b\ell^+\nu)\tilde{\chi}_1^{0,1,2}$, the largest SM background comes from the $pp \rightarrow t\bar{t}$ production followed by semi- and di-leptonic decay, because of the undetected lepton and the limited jet energy resolution that lead to large $E_T$. The single top production including $pp \rightarrow tj, tb$ and $tW$ can also fake the signal due to the missing leptons. As for the backgrounds from diboson production, such as $WW, WZ$ and $ZZ$, they will not be considered in this case owing to their relatively small cross sections and small missing energy in the final states. In order to enhance the signal, some kinematic cuts should be applied to suppress the background. The transverse mass of the lepton plus missing energy $M_T^{L}$ is needed because the lepton and missing energy of the backgrounds come from a $W$ boson’s decay, which can give an end-point to separate from the signal events [54]. The signal has one hard b-jet in the final state, thus the transverse momentum of the leading b-jet $p_T(b_1)$ can be used to suppress the background. Since the signal has fewer hard jets in the final state, $H_{T3}$, the scalar sum of the transverse momentum of jets
excluding the leading and subleading, can help reduce the $t\bar{t}$ background effectively [55].

In FIG. 3, we present the normalized distributions of $M_T$, $p_T(b_1)$, $H_{T3}$ and $N_l$ in the signal and backgrounds for a benchmark point at the 100 TeV hadron collider. From the curves of $M_T$ and $p_T(b_1)$ in FIG. 3(a) and FIG. 3(b), we can find that the ones for signal events tend to be more flat and smooth, while the ones for the SM background tend to distribute around the small $M_T$ and $p_T(b_1)$ which are well separated from the signal. In FIG. 3(c) one
| Cut                          | Signal | Background |
|-----------------------------|--------|------------|
| $m(\bar{t}_1, \mu)$ [GeV]  | (1000, 200) | $t\bar{t}$ single top |
| $N_l \geq 1$                | 442.14 | 1.44 · 10^7 | 2.94 · 10^6 |
| $N_b \geq 1$                | 406.62 | 1.34 · 10^7 | 2.61 · 10^6 |
| $p_T(b_1) > 250$ GeV        | 216.08 | 5.66 · 10^5 | 1.07 · 10^5 |
| $E_T > 800$ GeV             | 37.91  | 1.20 · 10^3 | 1.39 · 10^3 |
| $M_T > 850$ GeV             | 32.29  | 7.60 · 10^2 | 1.10 · 10^3 |
| $H_{T3} < 300$ GeV          | 4.46   | 20         | 22.9        |
| $\Delta \phi(j, E_T) > 0.6$| 2.38   | 4          | 8.25        |

TABLE I. A cut flow analysis of the cross sections for the mono-top signal and backgrounds at the 100 TeV hadron collider. The cross sections are shown in unit of fb.

can see that the variable $H_{T3}$ of signal events tends to be smaller than that of background events, as we infer in the above analysis. We also show the distribution of $N_l$ in FIG. 3(d), which is the number of final leptons, for signal and background, from which one can find that less leptons tend to be found in the signal events.

According to above distributions and analysis, the following cuts are applied:

- At least one lepton is required.
- At least one b-jet with $p_T(b_1) > 250$ GeV is required.
- We define five signal regions according to ($E_T$, $M_T$) cuts: (750, 800), (800, 850), (850, 900), (900,950), (950, 1000). They can well separate the backgrounds and signal.
- We require $H_{T3} < 300$ GeV to further suppress the top pair background events.
- A minimum azimuthal angle between $E_T$ and each of the jets $\Delta \phi(j, E_T) > 0.6$ is required to reduce the multi-jet background.

The cutflow of signal and background at every step of the above cuts is shown in TABLE II from which we can see that after these cuts, the background can be suppressed significantly with a relatively large amount of signal events surviving. In FIG. 5(a), we display the contour with respect to the higgsino mass parameter $\mu$ and stop mass $m_{\tilde{t}_1}$, for the statistical significance of 2$\sigma$ and 5$\sigma$ at the center-of-mass energy of 100 TeV and integrated luminosity
of 3000 fb$^{-1}$, from which we find that top squark with mass up to 3.2 TeV can be probed at 5σ level through the single stop production followed by a mono-top decay channel. The exclusion limits for stop mass and higgsino mass parameter can be reached at about 3.85 TeV and 1 TeV, respectively. It should be mentioned that the statistical significance would get worse when considering systematic uncertainties, the determination of which due to high pile-up in the future must be revisited with the real performance of upgraded detectors. In addition, our results may be improved by using some advanced analysis approaches, such as the recently proposed machine-learning methods for sensitivity enhancement in searching for sparticles at the LHC [56–59].

B. The mono-bottom channel

For the mono-bottom channel decay $\tilde{t}_1 \to b\tilde{\chi}_1^+ \to b(\ell^+\nu\tilde{\chi}_0^0)$, the SM background to the signal is dominated by the process $Z + jets$, since the light-flavor jets can be misidentified as b-jets and hence contaminate our signal. Besides, the SM top pair production should also be taken into account as background, due to the large missing energy in the final states as the one present in the signal process. The final states of signal process consist of one lepton and one b-jet, plus missing energy which are neutrino from W decay and neutralino from stop decay. As for the backgrounds, the $t\bar{t}$ production can undergo a semi- or di-leptonic decay that leads to two b-jets and one or two leptons. The $Z$ boson in $Z + jets$ process can decay into two charged leptons or two neutrinos that will be taken as missing energy. Thus the requirement of exact one lepton and one b-jet can suppress the background by a large amount. The mono-bottom from stop decay is more boosted than the one from top decay, leading to a relatively larger $p_T$. Besides, in the signal process, the final neutrino and neutralino both contribute to the missing energy, which will be larger than that in background events.

Based on the above analysis, we propose several cuts to be applied in order to improve the significance. We first show in FIG. 4 the distributions of four relevant variables, that are $p_T(b_1)$ the transverse momentum of the leading b-jet, $E_T$, $N_b$ the number of b-jets and $\Delta\phi(j, E_T)$ the minimum angular separation between the jets and $E_T$. From the curves in FIG. 4(a) and (b), one can see that the distributions of $p_T(b_1)$ and $E_T$ for signal are more flat and smooth compared with the background. The number of b-jets for signal is centered
FIG. 4. The normalized distributions of $p_T(b_1)$, $E_T$, $N_b$ and $\Delta \phi(j, E_T)$ for the mono-bottom signal and background events at the 100 TeV hadron collider. The benchmark point is $m_{\tilde{t}_1} = 1000$ GeV and $\mu = 200$ GeV.

around 1 while the backgrounds $t\bar{t}$ and $Z + jets$ tend to be distributed around 2 and 0, respectively. The distribution of $\Delta \phi(j, E_T)$ for signal tends to be more polarized at two ends of the range ($-\pi, \pi$) than that of backgrounds. We then summarize our cuts as follows:

- We reject events with leptons.
- We require at least one b-jet and $p_T(b_1) > 600$ GeV for the leading one.
Table II. A cut flow analysis of the cross sections for the mono-bottom signal and backgrounds at the 100 TeV hadron collider. The cross sections are shown in unit of fb.

- We define six signal regions according to $\vec{E}_T$ cuts: 700, 800, 900, 1000, 1100 and 1200.
- $\Delta \phi(j, \vec{E}_T) > 0.6$ is required to reduce the multi-jet background.

In Table II we present the cutflow under the above cuts, from which one can find that most of the background can be rejected while a relatively large amount of signal events survive.

With these cuts applied, a contour of stop mass versus the higgsino mass parameter is shown in Fig. 5(b). Through the mono-bottom decay channel from single stop production, we can probe the stop with mass up to around 1.8 TeV at 5σ statistical significance at a center-of-mass of 100 TeV with integrated luminosity of 3000 fb$^{-1}$. With no significant excess in the mono-bottom channel, the stop mass can be excluded up to about 2.55 TeV and the higgsino mass parameter $\mu$ up to about 1 TeV. We find that the mono-bottom is less sensitive than the mono-top due to the $Z + jets$ background, which is hard to be suppressed. Note that the mono-b channel has the value of S/B around percent level. The systematic uncertainty of background will become important in our analysis and the obtained sensitivity of mono-b channel should be interpreted under the extremely well control of system uncertainty. Please refer to the discussion about this at the end of Sec.III-A.

It should be noted that the best discovery channel for stop may still be the pair production. The single production, however, provides an instructive way to learn more about the SUSY particles and to explore more specific models. As we concluded in the Sec. II, for higgsino-like $\tilde{\chi}_1^\pm$, the single production cross section of the right-handed stop is much larger than that of the left-handed stop and independent of $\tan \beta$. In addition, the Focus Point SUSY model usually has the LSP chargino as higgsino-like, while the AMSB SUSY

| Cut                  | Signal   | Background |
|----------------------|----------|------------|
| $m(\tilde{t}_1, \mu)$ [GeV] | (1000, 200) | $Z + jets$  |
| Lepton veto          | 302.84   | 2.28 $\cdot$ 10$^7$  |
|                      |          | 9.62 $\cdot$ 10$^6$  |
| $N_b \geq 1$         | 270.89   | 1.14 $\cdot$ 10$^7$  |
|                      |          | 8.25 $\cdot$ 10$^6$  |
| $p_T(b_1) > 600$ GeV | 47.74    | 6.07 $\cdot$ 10$^4$  |
|                      |          | 4.67 $\cdot$ 10$^4$  |
| $\vec{E}_T > 700$ GeV| 23.92    | 2432        |
|                      |          | 648         |
| $\Delta \phi(j, \vec{E}_T) > 0.6$ | 12.22   | 1322        |
|                      |          | 376         |
model prefers a wino-like one. The single production has a larger cross section in the former case than in the latter one with the same stop and chargino masses \([48, 60]\). It should be emphasized again that the study of electroweak production of the stop is meaningful with the stop either discovered or even not observed. Furthermore, future precision measurement on the cross section of stop single production can be used to investigate the nature of stop and electroweakinos, which is also helpful in identifying different SUSY models.

![Graph](image)

**FIG. 5.** The statistical significance \(S/\sqrt{B}\) of the mono-top and the mono-bottom on the plane of stop mass \(m_{\tilde{t}_1}\) versus the higgsino mass parameter \(\mu\) at the 100 TeV hadron collider.

### IV. CONCLUSION

In this work, we studied the mono-top and mono-bottom decay channel of single stop production in a simplified MSSM framework where the higgsinos and stops are the only sparticles at the 100 TeV hadron collider. The single stop production leads to different signals from traditional stop pair production, which ends up with final states of top and anti-top quarks plus missing energy. We performed Monte Carlo simulation to study the observability of the mono-top and mono-bottom channel and found that through single stop production followed by the leptonic mono-top channel, we can probe the stop mass up to 3.2 TeV at 5\(\sigma\) statistical significance at the 100 TeV hadron collider with integrated
luminosity of $3000 \text{fb}^{-1}$, while the exclusion limits for stop mass and higgsino mass parameter $\mu$ are 3.85 TeV and 1 TeV, respectively. And by the mono-bottom channel, the stop mass can be probed up to 1.8 TeV at 5$\sigma$ statistical significance and excluded to about 2.55 TeV if no significant excess appears, while the higgsino mass parameter $\mu$ can be excluded to about 1 TeV. So the leptonic mono-top channel has a better sensitivity than the mono-bottom channel.

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[1] G. Aad *et al.* (ATLAS Collaboration), Phys. Lett. B 710, 49 (2012).
[2] S. Chatrchyan *et al.* (CMS Collaboration), Phys. Lett. B 710, 26 (2012).
[3] L. J. Hall, D. Pinner and J. T. Ruderman, JHEP 1204, 131 (2012).
[4] M. Papucci, J. T. Ruderman and A. Weiler, JHEP 1209, 035 (2012).
[5] C. Brust, A. Katz, S. Lawrence and R. Sundrum, JHEP 1203, 103 (2012).
[6] J. Cao, C. Han, L. Wu, J. M. Yang and Y. Zhang, JHEP 1211, 039 (2012).
[7] G. Belanger, D. Ghosh, R. Godbole and S. Kulkarni, JHEP 1509, 214 (2015);
[8] C. Han, K. Hikasa, L. Wu, J. M. Yang and Y. Zhang, JHEP 1310, 216 (2013).
[9] M. Backovic, A. Mariotti and M. Spannowsky, JHEP 1506, 122 (2015)
[10] A. Kobakhidze, N. Liu, L. Wu and J. M. Yang, Phys. Rev. D 92, 075008 (2015)
[11] B. Dutta *et al.*, Phys. Rev. D 90, 095022 (2014).
[12] J. Fan, R. Krall, D. Pinner, M. Reece and J. T. Ruderman, JHEP 1607, 016 (2016)
[13] M. Schlaffer, M. Spannowsky and A. Weiler, Eur. Phys. J. C 76, 457 (2016)
[14] D. Goncalves, K. Sakurai and M. Takeuchi, Phys. Rev. D 94, 075009 (2016)
[15] D. Goncalves, K. Sakurai and M. Takeuchi, Phys. Rev. D 95, no. 1, 015030 (2017)
[16] L. Wu and H. Zhou, Phys. Lett. B 794, 96 (2019)
[17] M. Abdughani, J. Ren, L. Wu and J. M. Yang, JHEP 1908, 055 (2019)
[18] G. H. Duan, L. Wu and R. Zheng, JHEP 1709, 037 (2017)
[19] C. Han, J. Ren, L. Wu, J. M. Yang and M. Zhang, Eur. Phys. J. C 77, no. 2, 93 (2017)
[20] N. Arkani-Hamed, T. Han, M. Mangano and L. T. Wang, Phys. Rept. 652 (2016) 1
[21] T. P. Tang, L. Wu and H. Zhou, arXiv:1909.02325 [hep-ph].
[22] G. H. Duan, X. Fan, K. i. Hikasa, B. Peng and J. M. Yang, arXiv:1912.01970 [hep-ph].
[23] H. Zhou and N. Liu, Phys. Lett. B 791, 1 (2019)
[24] C. G. Lester and D. J. Summers, Phys. Lett. B 463, 99 (1999)
[25] Y. Bai, H. C. Cheng, J. Gallicchio and J. Gu, JHEP 1207, 110 (2012)
[26] J. Cao, C. Han, L. Wu, J. M. Yang and Y. Zhang, JHEP 1211, 039 (2012)
[27] T. Plehn, M. Spannowsky and M. Takeuchi, JHEP 1208, 091 (2012)
[28] T. Plehn, M. Spannowsky and M. Takeuchi, JHEP 1105, 135 (2011)
[29] T. Plehn, M. Spannowsky, M. Takeuchi and D. Zerwas, JHEP 1010, 078 (2010)
[30] K. Hagiwara and T. Yamada, Phys. Rev. D 91, no. 9, 094007 (2015)
[31] D. Goncalves, D. Lopez-Val, K. Mawatari and T. Plehn, Phys. Rev. D 90, no. 7, 075007 (2014)
[32] G. Cacciapaglia, E. Conte, A. Deandrea, B. Fuks and H. S. Shao, Eur. Phys. J. C 79, no. 2, 174 (2019)
[33] H. Baer and X. Tata, Weak scale supersymmetry: From superfields to scattering events (Cambridge University Press, 2006).
[34] J. F. Gunion and H. E. Haber, Nucl. Phys. B 272, 1 (1986).
[35] G. F. Giudice and A. Pomarol, Phys. Lett. B 372, 253 (1996).
[36] C. Han, A. Kobakhidze, N. Liu, A. Saavedra, L. Wu and J. M. Yang, JHEP 1402, 049 (2014).
[37] Z. Han, G. D. Kribs, A. Martin and A. Menon, Phys. Rev. D 89, 075007 (2014);
[38] C. Han, D. Kim, S. Munir and M. Park, JHEP 1504, 132 (2015);
[39] D. Barducci, A. Belyaev, A. K. M. Bharucha, W. Porod and V. Sanz, JHEP 1507, 066 (2015)
[40] J. Bramante, A. Delgado, F. Elahi, A. Martin and B. Ostdiek, Phys. Rev. D 90, 095008 (2014);
[41] C. Han, L. Wu, J. M. Yang, M. Zhang and Y. Zhang, Phys. Rev. D 91, 055030 (2015)
[42] A. Ismail, E. Izaguirre and B. Shuve, Phys. Rev. D 94, 015001 (2016)
[43] A. Djouadi, M. M. Muhlleitner and M. Spira, Acta Phys. Polon. B 38, 635 (2007)
[44] J. Alwall et al., JHEP 1407, 079 (2014).
[45] L. G. Jin, C. S. Li and J. J. Liu, Phys. Lett. B 561, 135 (2003)
[46] L. G. Jin, C. S. Li and J. J. Liu, Eur. Phys. J. C 30, 77 (2003)
[47] D. Goncalves, D. Lopez-Val, K. Mawatari and T. Plehn, Phys. Rev. D 90, no. 7, 075007 (2014)
[48] G. H. Duan, K. i. Hikasa, L. Wu, J. M. Yang and M. Zhang, JHEP 1703, 091 (2017)
[49] D. Dercks, N. Desai, J. S. Kim, K. Rolbiecki, J. Tattersall and T. Weber, Comput. Phys. Commun. 221 (2017) 383
[50] T. Sjostrand, S. Mrenna and P. Z. Skands, JHEP 0605, 026 (2006).
[51] J. de Favereau et al. (DELPHES 3 Collaboration), JHEP 1402, 057 (2014).
[52] CMS Collaboration, b-Jet Identification in the CMS Experiment, CMS-PAS-BTV-11-004.
[53] M. Cacciari, G. P. Salam and G. Soyez, JHEP 0804, 063 (2008).
[54] C. Patrignani et al. (Particle Data Group), Chin. Phys. C 40, 100001 (2016).
[55] M. Aaboud et al. [ATLAS Collaboration], JHEP 1711 (2017) 195
[56] K. Albertsson et al., J. Phys. Conf. Ser. 1085, no. 2, 022008 (2018)
[57] M. Abdughani, J. Ren, L. Wu, J. M. Yang and J. Zhao, Commun. Theor. Phys. 71, no. 8, 955 (2019)
[58] J. Ren, L. Wu, J. M. Yang and J. Zhao, Nucl. Phys. B 943, 114613 (2019)
[59] S. Caron, J. S. Kim, K. Rolbiecki, R. Ruiz de Austri and B. Stienen, Eur. Phys. J. C 77, no. 4, 257 (2017)
[60] K. Hikasa, J. Li, L. Wu and J. M. Yang, Phys. Rev. D 93, 035003 (2016).