Probing stops in the coannihilation region at the HL-LHC:  
a comparative study of different processes

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Abstract

In the minimal supersymmetric model, the coannihilation of the lighter stop $\tilde{t}_1$ and bino-like dark matter $\chi$ provides a feasible way to accommodate the correct dark matter relic abundance. In this scenario, due to the compressed masses, $\tilde{t}_1$ merely appears as missing energy at the LHC and thus the pair production of $\tilde{t}_1$ can only be probed by requiring an associated energetic jet. Meanwhile, since $\tilde{t}_2$ and $\tilde{b}_1$ are correlated in mass and mixing with $\tilde{t}_1$, the production of $\tilde{t}_2\tilde{t}_2^*$ or $\tilde{b}_1\tilde{b}_1^*$, each of which dominantly decays into $\tilde{t}_1$ plus $Z$, $h$ or $W$ boson, may serve as a complementary probe. We examine all these processes at the HL-LHC and find that the $2\sigma$ sensitivity to $\chi$ mass can be as large as about 570 GeV, 600 GeV and 1.1 TeV from the production process of $\tilde{t}_1\tilde{t}_1^* + \text{jet}$, $\tilde{t}_2\tilde{t}_2^*$ and $\tilde{b}_1\tilde{b}_1^*$, respectively.
I. INTRODUCTION

The nature of dark matter (DM) remains a mystery in particle physics. In minimal supersymmetric standard model (MSSM) with conserved $R$–parity, the lightest neutralino $\chi$ can serve as a DM candidate. However, the null results of DM direct detections [1–3] give significant constraints on the neutralino sector in the MSSM. It is notable that the stop-bino coannihilation, in which DM is the bino-like lightest supersymmetric particle (bino-LSP) and the stop ($\tilde{t}_1$) is the next-to-lightest supersymmetric particle (NLSP) and nearly degenerate with the bino-LSP, provides a feasible mechanism to accommodate the DM relic abundance. Because of the extremely weak interaction between the bino-LSP and nucleons, this scenario can easily evade the DM direct detection constraints [4]. However, the search of stops at the LHC in this scenario is rather challenging\(^1\). The reason is that due to the compressed masses, $\tilde{t}_1$ is merely appearing as missing energy and the pair production of $\tilde{t}_1$ can only be probed by requiring an associated energetic jet.

On the other hand, we should note that $\tilde{t}_2$ and $\tilde{b}_1$ are correlated with $\tilde{t}_1$ since $\tilde{t}_{L,R}$ mix into mass eigenstates $\tilde{t}_{1,2}$ (see the following section) while $\tilde{b}_L$ ($\tilde{b}_1 = \tilde{b}_L$, neglecting the sbottom mixing) has the same soft mass as $\tilde{t}_L$. Furthermore, to avoid fine-tuning, these particles should not be too heavy\(^2\) because at one-loop level we approximately have [13, 14]

$$\Delta \equiv \frac{\delta m^2_h}{m^2_h} = \frac{3y_t^2}{4\pi^2 m^2_h} (m^2_{Q_3} + m^2_{U_3} + A^2_t) \log \frac{\Lambda}{m_{\text{SUSY}}} \quad \text{(1)}$$

where $m_{\text{SUSY}} = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$, $\Lambda$ is the cut-off scale, $Q_3 = (\tilde{t}_L, \tilde{b}_L)$ and $U_3 = \tilde{t}_R$. Therefore, the production of $\tilde{t}_2 \tilde{t}_2$ or $\tilde{b}_1 \tilde{b}_1$, followed by the dominant decays into $\tilde{t}_1$ plus $Z$, $h$ or $W$ boson, may serve as a complementary probe of stops in such a stop-bino coannihilation scenario.

In this work we perform a comprehensive study for all these correlated processes at the HL-LHC (14 TeV, 3000 fb\(^{-1}\)). We will first perform a scan to figure out the stop-bino coannihilation parameter space. Then we display the properties of $\tilde{t}_{1,2}$ and $\tilde{b}_1$ in this stop-bino coannihilation parameter space. For the $\tilde{t}_1 \tilde{t}_1^* + \text{jet}$ production which has been searched at the LHC, we will show its current sensitivity and then extend the coverage to the HL-

\(^1\) The search of stops at the LHC has been a hot topic and numerous studies have been performed in various cases, e.g., the large or small stop-top or stop-LSP mass splitting [5, 7], the single stop production [8], the stop in natural SUSY [9], machine learning in stop production [10] and other miscellaneous cases [11].

\(^2\) Note that the stops cannot be too light in order to give the 125 GeV Higgs mass except a singlet is introduced [12].
LHC. For the productions $\tilde{t}_2\tilde{t}_2^*$ and $\tilde{b}_1\tilde{b}_1^*$, followed the dominant decays $\tilde{t}_2 \rightarrow \tilde{t}_1 + Z/h$ and $\tilde{b}_1 \rightarrow \tilde{t}_1 + W$, we will examine the HL-LHC sensitivities through Monte Carlo simulations of the signals and backgrounds.

The structure of this paper is organized as follows. In Sec. II, we briefly review stop-bino coannihilation scenario and discuss the details of our scan. In Sec. III, we perform detailed Monte Carlo simulations for the productions of $\tilde{t}_1\tilde{t}_1^*$ + jet, $\tilde{t}_2\tilde{t}_2^*$ and $\tilde{b}_1\tilde{b}_1^*$ at the HL-LHC. Finally, we give our conclusions in Sec. IV.

II. STOP-BINO COANNIHILATION

In the MSSM, the mass matrix of stop sector in gauge-eigenstate basis ($\tilde{t}_L, \tilde{t}_R$) is given by

$$ M_t^2 = \begin{pmatrix} m_{\tilde{t}_L}^2 & m_{\tilde{t}_R}^2 \\ m_{\tilde{t}_L} X_t & m_{\tilde{t}_R}^2 \end{pmatrix} $$

(2)

where

$$ m_{\tilde{t}_L}^2 = m_{\tilde{Q}_3}^2 + m_{\tilde{t}}^2 + m_Z^2 \left( \frac{1}{2} - \frac{2}{3} \sin^2 \theta_W \right) \cos 2\beta, $$

(3)

$$ m_{\tilde{t}_R}^2 = m_{\tilde{U}_{3R}}^2 + m_{\tilde{t}}^2 + \frac{2}{3} m_Z^2 \sin^2 \theta_W \cos 2\beta, $$

(4)

$$ X_t = A_t - \mu \cot \beta. $$

(5)

The mixing between $\tilde{t}_L$ and $\tilde{t}_R$ is induced by $X_t = A_t - \mu \cot \beta$, where $A_t$ is the stop soft-breaking trilinear coupling. One can diagonalize the mass matrix through a rotation

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

(6)

where $\tilde{t}_1$ and $\tilde{t}_2$ are the mass eigenstates of lighter and heavier stops, respectively. The mixing angle $\theta_t$ between $\tilde{t}_L$ and $\tilde{t}_R$ is determined by

$$ \tan 2\theta_t = \frac{2m_t X_t}{m_{\tilde{t}_L}^2 - m_{\tilde{t}_R}^2}. $$

(7)

In the early universe, the freeze-out number density for the bino-LSP DM will be over-abundant because the annihilation cross section $\sigma$ in the Boltzmann equation is too small to keep DM thermal equilibrium with SM particles for sufficient time\(^3\). When the stop ($\tilde{t}_1$)

\(^3\) The $Z/h$ funnel as another exception is that the annihilation cross section could be enhanced when bino-LSP mass becomes half of $m_{Z/h}$. 

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mass is close to bino-LSP mass, the annihilation cross section $\sigma$ is replaced by the effective cross section \[15\]

$$\sigma_{\text{eff}} = \sum_{ij} \sigma_{ij} r_i r_j \tag{8}$$

with

$$r_i = \frac{g_i (1 + \Delta_i)^{3/2} e^{-\Delta_i/T}}{\sum_k g_k (1 + \Delta_k)^{3/2} e^{-\Delta_k/T}} \tag{9}$$

where $\Delta_i = (m_i - m_\chi)/T$, $m_i$ and $g_i$ are the mass and degrees of freedom of the particle $i = \{\chi, \tilde{t}_1\}$, and $\sigma_{ij}$ denotes the cross section of particle $i$ annihilating with particle $j$. The annihilation modes of $\tilde{t}_1$ with $\chi$ or itself can enhance $\sigma_{\text{eff}}$ if $\tilde{t}_1$ is nearly degenerate with the bino-LSP. We can also see that $\sigma_{\tilde{t}_1\tilde{t}_1}$ is suppressed by double exponents compared to $\sigma_{\chi\chi}$, while $\sigma_{\tilde{t}_1\chi}$ is suppressed by single exponent. Therefore, when the mass splitting $\Delta_{\tilde{t}_1}$ is small, the contribution to relic abundance from the $\tilde{t}_1\chi$ annihilation tends to be more important than that from the $\tilde{t}_1\tilde{t}_1$ annihilation, although this also depends on their respective cross section.

In order to obtain the stop-bino coannihilation parameter space, we use SuSpect 2.41 \[16\] to calculate the mass spectrum and SDECAY 1.5 \[17\] to evaluate sparticle decay width and branching ratio. We regard the lighter stop as right-handed dominated. The reason for such assumption is that if $m_{\tilde{t}_R} = m_{\tilde{t}_L}$ at some high energy scale, $m_{\tilde{t}_R}$ tends to be smaller than $m_{\tilde{t}_L}$ at the electroweak scale from the renormalization group equations (RGE) evolution \[18\]. The stop mixing angle $\cos^2 \theta_{\tilde{t}} \lesssim 0.5$ is required so that the lighter stop $\tilde{t}_1$ is right-handed dominant. Except for $\{M_1, m_{Q_3}, m_{U_3}, A_t\}$, other soft-breaking masses (including the CP-odd Higgs mass $M_A$) and trilinear couplings are set to 5 TeV and zero, respectively. The higgsino mass parameter $\mu$ and $\tan \beta$ are chosen as 3 TeV and 20. The micrOMEGAs 4.3.5 \[19\] is used to compute the DM relic abundance $\Omega_\chi h^2$.

In our scan we impose the following constraints\(^4\):

(i) The lighter CP-even Higgs mass is required to be in the range of $125 \pm 3$ GeV \[20, 22\].

(ii) The DM relic abundance satisfies the observed value $\Omega_\chi h^2 = 0.1186 \pm 0.0020$ within $2\sigma$ range \[23\].

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\(^4\) Here we do not require SUSY to explain the muon g-2 anomaly, which requires light sleptons \[21\]
(iii) To avoid the existence of a color or charge breaking vacuum deeper than the electroweak vacuum in the scalar potential, the trilinear coupling $A_t$ should not exceed the upper bound $A_t^2 \lesssim 2.67(m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2 + \mu^2 + m_{H_u}^2)$ \cite{21}.

In the left panel of Fig. 1 we display the stop-bino coannihilation parameter space that satisfies the constraints (i)–(iii), where the $B$ physics constraints are ignored because of the decoupled higgsino mass parameter, and the contribution of the stops to $h \rightarrow \gamma\gamma$ (and $gg$) \cite{18} is also negligibly small. We can see that the mass splitting $\Delta m(\tilde{t}_1, \chi)$ increases with $|\cos\theta_{\tilde{t}}|$ because the component of left-handed stop annihilates with itself more efficiently due to the SU(2)$_L$ interaction. Besides, it can be seen that the maximal value of $m_\chi$ is about 1.8 TeV, where $\tilde{t}_1\tilde{t}_1^* \rightarrow gg$ is the dominant annihilation mode because of the QCD interaction and small mass splitting $\Delta m(\tilde{t}_1, \chi)$ or small $\Delta_{\tilde{t}_1}$.

**FIG. 1:** Scatter plots of the stop-bino coannihilation parameter space satisfying the constraints (i)–(iii). The left panel shows the DM mass $m_\chi$ versus mass splitting $\Delta m(\tilde{t}_1, \chi)$ with the colormap denoting the size of $|\cos\theta_{\tilde{t}}|$. The dashed magenta curve and the solid black curve are the 2$\sigma$ sensitivities of the $\tilde{t}_1\tilde{t}_1^* +$ jet production from the current ATLAS search \cite{25} and our simulations for the HL-LHC, respectively. The right panel shows the stop $\tilde{t}_1$ decay width of the four-body channel $\tilde{t}_1 \rightarrow bff'\chi$ and the FCNC two-body channel $\tilde{t}_1 \rightarrow c\chi$. 
III. PROBING STOPS IN THE COANNIHILATION REGION AT THE HL-LHC

A. The $\tilde{t}_1\tilde{t}_1^* + \text{jet}$ production

Since the lighter stop is nearly degenerate with the bino-LSP, the two-body decay channel $\tilde{t}_1 \to t\chi$ and three-body decay channel $\tilde{t}_1 \to bW\chi$ are kinematically forbidden. The lighter stop will dominantly decay via the four-body channel $\tilde{t}_1 \to bf\bar{f}'\chi$ and loop induced flavor-changing neutral current (FCNC) two-body channel $\tilde{t}_1 \to c\chi$. The contribution to $\tilde{t}_1 \to bf\bar{f}'\chi$ comes from the top quark exchange diagram and the interference between top quark and sfermions exchange diagrams because sparticles, except for $\tilde{t}_1, \tilde{b}_1$ and $\chi$, are decoupled in our scenario. The flavor mixing of the lighter stop with charm-squark which can emerge from radiative corrections induces the lighter stop FCNC decay $\tilde{t}_1 \to c\chi$. Their decay widths are given by [26–29]

$$
\Gamma(\tilde{t}_1 \to c\chi) = \frac{8}{9} \alpha|\epsilon|^2 \frac{\Delta m(\tilde{t}_1, \chi)^2}{m_{\tilde{t}_1}}, \tag{10}
$$

$$
\Gamma_{4\text{-body}} \equiv \Gamma(\tilde{t}_1 \to bf\bar{f}'\chi) = O(10^{-5}) \alpha^3 \cos^2 \theta_{\tilde{t}_1} \frac{\Delta m(\tilde{t}_1, \chi)^8}{m_t^2 m_W^4 m_{\tilde{t}_1}^4}, \tag{11}
$$

where $\epsilon$ is $O(10^{-4})$ if all soft-breaking parameters have the same order of magnitude. It is clear that the four-body decay width increases more sharply with $\Delta m(\tilde{t}_1, \chi)$ than the FCNC two-body decay width, as shown in the right panel of Fig. [1]. However, due to the ratio of $\Gamma_{4\text{-body}} / \Gamma(\tilde{t}_1 \to c\chi)$ is suppressed by $\Delta m(\tilde{t}_1, \chi)^6 / m_t^2 m_W^4$ and the small coefficient, the four-body decay is not competitive with the $\tilde{t}_1 \to c\chi$ decay.

Because the soft $c$-jet from the $\tilde{t}_1 \to c\chi$ decay is hard to detect, the search strategy for this coannihilation scenario is usually to exploit the $\tilde{t}_1\tilde{t}_1^*$ production in association with an energetic jet from the initial state radiation (ISR) which boosts $\tilde{t}_1\tilde{t}_1^*$ system and produces large missing energy at the LHC. The parton level events of the signal and backgrounds are generated with MadGraph5_aMC@NLO [30]. Then, the event parton showering and hadronization are performed by Pythia [31]. We use Delphes [32] to implement detector simulations where the anti-$k_t$ jet algorithm and $\Delta R = 0.4$ [33] are set for the jet clustering.

To discriminate the signal and backgrounds, we require a leading jet with $p_T(j_1) > 300$ GeV, $|\eta| < 2.4$ and azimuthal angle $\Delta\phi(j_1, \slashed{E}_T) > 0.4$. We veto events with electrons with $p_T > 20$ GeV, $|\eta| < 2.47$ or muons with $p_T > 10$ GeV, $|\eta| < 2.5$ to reduce the $W(\to \ell\nu\ell)j$ and $t\bar{t}$ backgrounds. Events having more than four jets with $p_T > 30$ and $|\eta| < 2.8$ are
vetoed. The signal regions are defined with $E_T^{\text{miss}}$ cuts: 300 GeV, 500 GeV, 700 GeV and 900 GeV. The signal significance is calculated as $S/\sqrt{B}$ in which the total background $B = \sum_i [B_i + (0.01B_i)^2]$ ($i = Z(\rightarrow \nu\bar{\nu})j, W(\rightarrow \ell\nu\bar{\nu})j, W(\rightarrow \tau\nu_{\tau})j$), where the systematic error on the backgrounds is set to 1%.

In the left panel of Fig. 1, we display the 2σ exclusion limits at the 13 TeV LHC with $\mathcal{L} = 36.1$ fb$^{-1}$ (the region on the left side of the curve is excluded) and the sensitivity at the 14 TeV LHC with $\mathcal{L} = 3000$ fb$^{-1}$. We can see that the current monojet search gives a loose limit on the bino-LSP DM mass $m_\chi \gsim 260$ GeV and this limit can be raised to 570 GeV at the 14 TeV LHC with $\mathcal{L} = 3000$ fb$^{-1}$.

B. The $\tilde{t}_2\tilde{t}_2^*$ production

From the naturalness argument in Sec. 1, $\tilde{t}_2$ can not be too heavy and the $\tilde{t}_2\tilde{t}_2^*$ production can be sizable at the LHC. Since the LSP is bino-like in our scenario, the $\tilde{t}_2$ decay modes are mainly $\tilde{t}_2 \rightarrow \tilde{t}_1 Z$ and $\tilde{t}_2 \rightarrow \tilde{t}_1 h$. The corresponding decay widths are given by [34]

\begin{align}
\Gamma(\tilde{t}_2 \rightarrow \tilde{t}_1 Z) & \approx \frac{g_2^2 \sin^2 2\theta_i m_{t_2}^3}{256 \pi m_W^2} \lambda^{3/2}(m_{t_2}^2, m_{\tilde{t}_1}^2, m_Z^2), \\
\Gamma(\tilde{t}_2 \rightarrow \tilde{t}_1 h) & \approx \frac{g_2^2 \cos^2 2\theta_i m_{t_2}^2 X_t^2}{64 \pi m_W^2 m_{t_2}^2} \lambda^{1/2}(m_{t_2}^2, m_{\tilde{t}_1}^2, m_h^2),
\end{align}

where $\lambda(a, b, c) = [1 - (b + c)/a]^2 - 4bc/a^2$ is the kinematic factor. In the limits $m_{t_2}^2, m_{\tilde{t}_1}^2 \gg m_{Z,h}^2$, the factor $\lambda(m_{t_2}^2, m_{\tilde{t}_1}^2, m_{Z,h}^2)$ approximately equals to $(1 - m_{\tilde{t}_1}^2/m_{t_2}^2)^2$ and then

\begin{equation}
\frac{\Gamma(\tilde{t}_2 \rightarrow \tilde{t}_1 h)}{\Gamma(\tilde{t}_2 \rightarrow \tilde{t}_1 Z)} \approx \cos^2 2\theta_i = 1 - \frac{4m_{t_2}^2 X_t^2}{(m_{t_2}^2 - m_{\tilde{t}_1}^2)^2}.
\end{equation}

It should be noted that the decay width $\Gamma(\tilde{t}_2 \rightarrow \tilde{t}_1 Z)$ is always larger than $\Gamma(\tilde{t}_2 \rightarrow \tilde{t}_1 h)$ even though the small loop corrections are taken into account [35, 36]. In Fig. 2, we plot the branching ratio of $\tilde{t}_2 \rightarrow \tilde{t}_1 Z$ and $\tilde{t}_2 \rightarrow \tilde{t}_1 h$. It is clear that $\text{Br}(\tilde{t}_2 \rightarrow \tilde{t}_1 h)$ is lower than $\text{Br}(\tilde{t}_2 \rightarrow \tilde{t}_1 Z)$ and their difference decreases with the mass splitting $\Delta m(\tilde{t}_2, \tilde{t}_1)$ between heavier and lighter stops. Since the masses of $\tilde{t}_1$ and the bino-LSP are nearly degenerate, the $\tilde{t}_1$ will appear as missing energy and the signal of $\tilde{t}_2\tilde{t}_2^*$ production at the LHC is

\begin{equation}
pp \rightarrow \tilde{t}_2\tilde{t}_2^* \rightarrow ZZ + E_T^{\text{miss}} \quad \text{or} \quad Z h + E_T^{\text{miss}} \tag{15}
\end{equation}

where we neglect the $hh + E_T^{\text{miss}}$ channel because its production rate is smaller than the above channels. Here we investigate the $2\ell 2b$ final states, in which leptons come from $Z$ decay and
bottom quarks are from $Z/h$ decay, along with large missing energy. The requirement of two leptons can efficiently reduce the QCD multi-jets backgrounds$^5$.

The main SM backgrounds are $t\bar{t} +$ jets, $tWj$, $ZZjj$ and $WWjj$. To discriminate the signal and backgrounds, the following cuts are imposed:

(i) The event is required to have exact two leptons which form the opposite sign and same flavor dilepton with $p_T(\ell) > 30$ GeV and $|\eta_\ell| < 2.5$, where $\ell = e, \mu$. According to the left panel of Fig. 3, the invariant masses of dilepton should be required in range of 80 GeV $< m_{\ell\ell} < 100$ GeV to reconstruct $Z$ bosons.

(ii) Jets must have $p_T(j) > 30$ GeV and $|\eta_j| < 2.5$. We require two $b$-jets and the $b$-jet tagging efficiency is set to be 80%.

(iii) From the right panel of Fig. 3, the signal regions are designed according to $E_T^{miss}$ cuts: 300 GeV, 350 GeV, 400 GeV, 450 GeV and 500 GeV.

$^5$ Tagging a soft $c$-jet from $\tilde{t}_1$ or boosted bosons $Z/h$ may help to suppress the backgrounds.
FIG. 3: The distributions of $m_{\ell\ell}$ and $E_T^{\text{miss}}$ for backgrounds and signal at the 14 TeV LHC after requiring exactly 2 leptons and 2 $b$-jets. The signal benchmark point is chosen as $(m_{\tilde{t}_2}, m_{\tilde{t}_1}, m_\chi) = (962, 468, 424)$ GeV.

TABLE I: The cut flow of events number for backgrounds and the signal at the HL-LHC. The signal benchmark point is $(m_{\tilde{t}_2}, m_{\tilde{t}_1}, m_\chi) = (962, 468, 424)$ GeV.

| cut  | 2 leptons $p_T^{\ell} > 30$ GeV, $|\eta^{\ell}| < 2.5$ | 2 $b$-jets $p_T^{b} > 30$ GeV, $|\eta^{b}| < 2.5$ | $|m_{\ell\ell}-m_Z| < 10$ GeV | $E_T > 450$ GeV |
|------|-------------------------------------------------|-------------------------------------------------|----------------------------|------------------|
| $t\bar{t}j$ | 1.24E+8 | 4.105E+7 | 5.849E+6 | 653 |
| $tWj$ | 7.393E+6 | 1.349E+6 | 1.769E+5 | 30 |
| $ZZjj$ | 7.212E+5 | 5.159E+4 | 4.531E+4 | 62 |
| $WWjj$ | 2.603E+6 | 8.913E+4 | 1.506E+4 | 38 |
| signal | 3247 | 581 | 379 | 149 |

In Table I a detailed cut flow of events number for backgrounds and the signal is displayed. We can see that the $t\bar{t}j$ production is the largest SM background and the sum of other backgrounds is also non-negligible. The requirement of the two-lepton invariant mass within the range of 80–100 GeV can reduce the backgrounds by around 85%. It is clear that the cut of $E_T > 450$ GeV can remove backgrounds by near four orders of magnitude and this is consistent with the distributions of the missing energy for backgrounds and the signal.
FIG. 4: Same as Fig. 1, but showing the observability of the $\tilde{t}_2\tilde{t}_2^*$ production on the $(m_{\tilde{t}_2}, m_\chi)$ plane. The colormap represents the lighter sbottom mass $m_{\tilde{b}_1}$. The blue curve is the $2\sigma$ significance and the left region has a sensitivity above $2\sigma$ level.

shown in Fig. 3. After imposing all these cuts, the significance $S/\sqrt{B}$ for the benchmark point is about 5.32$\sigma$.

In Fig. 4 we present the observability for the $\tilde{t}_2\tilde{t}_2^*$ production. The points to the left of the blue curve have a sensitivity above $2\sigma$ level and the colormap shows the change in $m_{\tilde{b}_1}$. We can see that this stop pair production can cover $m_\chi \lesssim 600$ GeV for $m_{\tilde{t}_2} \lesssim 1100$ GeV at $2\sigma$ level. This result is not sensitive to the mass splitting $\Delta m(\tilde{t}_1, \chi)$.

C. The $\tilde{b}_1\tilde{b}_1^*$ production

The sbottom $\tilde{b}_1$ is lighter than the stop $\tilde{t}_2$ because of the mixing between left and right handed stops. Since $\tilde{b}_1$ is left-handed in our scenario, it could decay to the longitudinal component of $W$ boson in association with $\tilde{t}_1$. The branching ratio of $\tilde{b}_1 \to \tilde{t}_1 W$ is depicted in Fig. 2. As we see, $\tilde{b}_1$ dominantly decays to $W$ boson plus $\tilde{t}_1$. Then, the signal of $\tilde{b}_1\tilde{b}_1^*$
production at the LHC is

\[ pp \rightarrow \tilde{b}_1 \tilde{b}_1^* \rightarrow W^+ W^- + E_T^{\text{miss}}. \]  

(16)

FIG. 5: The distributions of \( E_T^{\text{miss}} \) and \( m_{T2} \) for backgrounds and the signal at the 14 TeV LHC. The signal benchmark point is chosen as \((m_{\tilde{b}_1}, m_{\tilde{t}_1}, m_\chi) = (1200, 910, 870) \) GeV.

TABLE II: The cut flow analysis of events number for backgrounds and the signal at the HL-LHC. The signal benchmark point is \((m_{\tilde{b}_1}, m_{\tilde{t}_1}, m_\chi) = (1200, 910, 870) \) GeV.

| cut | \( \tilde{t}\tilde{t} \) | \( tW \) | \( WW \) | \( \tilde{t}\tilde{t}Z \) | signal |
|-----|-----------|-------|-------|-------------|--------|
| \( \sum p_T^\ell > 200 \) GeV | 251 | 82 | 234 | 2312 | 169 |
| \( p_T^{\tilde{b}} > 50 \) GeV veto | 119 | 54 | 226 | 810 | 142 |
| \( E_T^{\text{miss}} > 200 \) GeV | 112 | 52 | 221 | 179 | 103 |

Similar to the search in case of \( \text{Br}(\tilde{b}_1 \to \tilde{t}_1 W) = 1 \) [39], we investigate \( 2\ell E_T^{\text{miss}} \) final state to probe this sbottom pair production. We require exactly two opposite-sign leptons with \( p_T^\ell > 25 \) GeV and \( |\eta_\ell| < 2.4 \) to suppress the QCD multi-jet backgrounds. The invariant mass of dilepton is required out of the range \(|m_\ell - m_Z| < 30 \) GeV to remove \( WZ, ZZ \) and \( Z+\)jets backgrounds. Since the stop \( \tilde{t}_1 \) boosts the \( W \) boson, the sum of the two leptons’ transverse momentum \( \sum p_T^\ell > 200 \) GeV can be used for further separating the
FIG. 6: Same as Fig. 1, but showing the observability of the $\tilde{b}_1 \tilde{b}_1^*$ production on the $(m_{\tilde{b}_1}, m_{\chi})$ plane. The colormap represents the change in $m_{\tilde{t}_2}$. The blue curve is the $2\sigma$ significance and the left region has a sensitivity above $2\sigma$ level.

signal from backgrounds. Any $b$-jet with $p_T^b > 50$ GeV is vetoed for suppressing $t\bar{t}$, $tW$ and $t\bar{t}Z$ backgrounds. A detailed cut flow of events number for backgrounds and the signal is displayed in Table II. After the $\sum p_T^\ell > 200$ GeV requirement, we present the distributions of $E_T^{\text{miss}}$ and $m_{T2}$ of the two-lepton system in Fig. 5. It is clear that $E_T^{\text{miss}} > 200$ GeV can reduce the $t\bar{t}Z$ background efficiently. The variable $m_{T2}$ of the backgrounds has an endpoint around $M_W$. For a larger $m_{T2}$, the $t\bar{t}Z$ becomes the dominant background. We separate the signal regions according to $m_{T2}$ cuts: 100 GeV, 150 GeV and 175 GeV.

We display the observability of the $\tilde{b}_1 \tilde{b}_1^*$ production in Fig. 6. It can be seen that such sbottom pair production can cover $m_\chi \lesssim 1.1$ TeV for $m_{\tilde{b}_1} \lesssim 1375$ GeV at $2\sigma$ level. Correspondingly, the lower bound of $m_{\tilde{t}_2}$ can be pushed up to around 1.4 TeV. Therefore, this result is obviously better than the $\tilde{t}_2 \tilde{t}_2^*$ production. This is mainly because this sbottom pair production has a cleaner signal.
IV. CONCLUSIONS

We have studied the stop-bino coannihilation region, in which the observed dark matter relic abundance can be reproduced. To test the scenario, we have examined three correlated production processes $\tilde{t}_1\tilde{t}_1^* + \text{jet}$ (the $\tilde{t}_1$'s being invisible), $\tilde{t}_2\tilde{t}_2^*$ and $\tilde{b}_1\tilde{b}_1^*$, followed by the decays $\tilde{t}_2 \to \tilde{t}_1 + Z/h$ and $\tilde{b}_1 \to \tilde{t}_1 + W$, at the HL-LHC. Through Monte Carlo simulations for the signals and backgrounds, we found that the $2\sigma$ sensitivity to the bino-like LSP can reach about 570 GeV, 600 GeV and 1.1 TeV from the production process of $\tilde{t}_1\tilde{t}_1^* + \text{jet}$, $\tilde{t}_2\tilde{t}_2^*$ and $\tilde{b}_1\tilde{b}_1^*$, respectively. These three channels should be jointly considered at the future HL-LHC experiment.

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