# Probing Natural SUSY from Stop Pair Production at the LHC postprint

**Authors:** Cao,J, Han,C, Wu,L, Yang,JM, Zhang,Y

**Date:** 2016-12-28T00:00:00+00:00

## Abstract

We consider the natural supersymmetry scenario in the framework of the R-parity conserving minimal supersymmetric standard model (called natural MSSM) and examine the observability of stop pair production at the LHC. We first scan the parameters of this s

## Full Text

## Preamble

Probing natural SUSY from stop pair production at the LHC

Junjie Cao[1],[2], Chengcheng Han[3], Lei Wu[3], Jin Min Yang[3], Yang Zhang[1],[3]

## Abstract

We consider the natural supersymmetry scenario in the framework of the R-parity conserving minimal supersymmetric standard model (called natural MSSM) and examine the observability of stop pair production at the LHC. We first scan the parameters of this scenario under various experimental constraints, including the SM-like Higgs boson mass, the indirect limits from precision electroweak data and B-decays. Then in the allowed parameter space we study the stop pair production at the LHC followed by the stop decay into a top quark plus a lightest neutralino or into a bottom quark plus a chargino. From detailed Monte Carlo simulations of the signals and backgrounds, we find the two decay modes are complementary to each other in probing the stop pair production, and the LHC with $\sqrt{s} = 14$ TeV and 100 fb $^{1}$ luminosity is capable of discovering the stop predicted in natural MSSM up to 450 GeV. If no excess events were observed at the LHC, the 95% C.L. exclusion limits of the stop masses can reach around 537 GeV.

PACS numbers: 14.80.Da, 14.80.Ly, 12.60.Jv

## Introduction

Although the standard model (SM) has been successful in describing the existing experimental data, it is suffering from the hierarchy problem and new physics based on certain symmetry is widely expected to appear at TeV scale to stabilize the electroweak hierarchy against radiative corrections. This belief was further strengthened by the recent discovery of the Higgs boson at the Large Hadron Collider (LHC) with its mass determined around 125 GeV [1]. This mass value agrees well with the prediction of low energy supersymmetry (SUSY), which is so far the most promising new physics candidate.

In SUSY, all known bosons and fermions have their supersymmetric partners, and the scalar top quarks (called stop ˜t  with i = 1, 2), as the top quark partners, can modify the property of the SM Higgs boson by exactly canceling out the dangerous quadratic divergence of the top quark loop. Obviously, the experimental determination of the stop properties is crucial to unravel the nature of supersymmetry in protecting the Higgs mass at the weak scale and thus solving the hierarchy problem. In fact, such activities have been carried out extensively at the hadronic colliders such as the LHC and the Tevatron [2-4], but in contrast with the strong mass bounds (about 1 TeV) on the gluino and the first generation squarks [5], a relatively light stop (say about 300 GeV) cannot be excluded. Nevertheless, it should be mentioned that the recently measured Higgs boson mass around 125 GeV may give some indications for the stop sector[6–8]. In the popular MSSM with moderate tan   and large m_A, the Higgs mass is given by [6]

$$m_h^2 \approx M_Z^2 \cos^2 2\beta + \frac{3m_t^4}{4\pi^2 v^2} \ln\left(\frac{M_S^2}{m_t^2}\right) + \frac{3m_t^4}{8\pi^2 v^2}\left(\frac{X_t^2}{M_S^2} - \frac{X_t^4}{12M_S^4}\right)$$

where v = 174 GeV, X_t   A_t -   cot   and M_S is the average stop mass scale defined by M_S² = m˜t m˜t . This expression indicates that, for the heavier stop ˜t  around 1 TeV as discussed above, the lighter stop ˜t  must be heavier than about 200 GeV and |X_t| must be larger than 1.5 TeV in order to push the Higgs mass up to 125 GeV [8]. About these constraints, one should keep in mind that they are independent of the decay modes of ˜t , but on the other hand, they may be greatly weakened if there exists additional contribution to the Higgs mass [8, 9].

On the theoretical side, there are good reasons to consider at least one stop significantly lighter than other squarks with a mass around several hundred GeV. Firstly, in some popular grand unification models, supersymmetry breaking is usually assumed to transmit to the visible sector at a certain high energy scale, and then Yukawa contributions to the renormalization group evolution tend to reduce stop masses more than other squark masses. Secondly, the chiral mixing for certain flavor squarks is proportional to the mass of the corresponding quark, and is therefore more sizable for stops. Such a mixing will further reduce the mass of the lighter stop. Thirdly, in the MSSM the minimization conditions of its Higgs potential imply [10]

$$\frac{M_Z^2}{2} = \frac{(m_{H_d}^2 + \Sigma_d) - (m_{H_u}^2 + \Sigma_u)\tan^2\beta}{\tan^2\beta - 1} - \mu^2,$$

and

$$m_{H_u}^2 = m_{H_u}^2(M_{GUT}) + \delta m_{H_u}^2$$

where m_{H_u}² represent the weak scale soft SUSY breaking masses of the Higgs fields, is the higgsino mass parameter, tan v_u/v_d. Σ_u and Σ_d arise from the radiative corrections to the Higgs potential and the dominant contribution to the Σ_u is given by

$$\delta m_{H_u}^2 \sim -\frac{3y_t^2}{8\pi^2} \times m_{\tilde{t}}^2 \ln\left(\frac{Q^2}{m_{\tilde{t}}^2}\right)$$

These two equations indicate that, if the individual terms on the right hand side of Eq. (2) are comparable in magnitude so that the observed value of M_Z is obtained without resorting to large cancelations, the natural values of and m˜t should be around 100 GeV and several hundred GeV respectively. Numerically, the requirement of Σ_u < M_Z²/2 (or Σ_u < v²) leads to m˜t , upper bounded by about 500 GeV (or 1.5 TeV) [11]. Moreover, we note that a light stop is also phenomenologically needed by electroweak baryogenesis [12] and may be welcomed by dark matter physics [13]. In the MSSM, although the gluino contributes at the one-loop level to m_{H_u}² and at two-loop level, the corrections are proportional to m˜g² and can be greatly enhanced by the large gluino mass[14]. In order to keep the naturalness, we expect m˜g to be lighter than about 3 TeV for m˜t < 1.5 TeV. However, since the current results of searching for supersymmetry indicate that a gluino with mass about 1 TeV can safely avoid the LHC constraints, we require 1 TeV < m˜g < 3 TeV in our calculation.

Motivated by the theoretical preference and the results of the LHC search for SUSY, the natural MSSM scenario has recently attracted broad attention [14-18], which focuses on the following parameter space of the MSSM [14, 17]:

- | | 100-200 GeV and m˜t , 1-1.5 TeV as preferred by Eq.(2) and Eq.(3);
- 1 TeV m˜g 3-4 TeV to escape the LHC constraint and at the same time to avoid spoiling color symmetry, while the electroweak-ino masses may still be at sub-TeV scale;
- m_A O(2)| | tan as suggested by the relation m_A² 2 ² + m_{H_u}² + m_{H_d}² + Σ_u + Σ_d and Eq.(2);

- m˜q , , m˜l , 10-50 TeV to provide a decoupling solution to the SUSY flavor and CP problems.

Since the stops are relatively light and sensitive for probing this scenario, there have recently been many theoretical studies on the collider signatures of the light directly produced stop in the R-parity conserving and violating MSSM[19]. For example, by using the top tagging technique, the sensitivity of stop searches was studied in the hadronic, semi-leptonic and di-leptonic channels[20–23]. In order to suppress the di-leptonic top backgrounds, the authors in Ref.[24] explored some new kinematic observables developed from M__T2 to improve the sensitivity of the stop searches. For the small mass splitting between stop and top, it is pointed out that the rapidity difference and spin correlation of the daughter products from stop decay can be helpful to discover the signal[25]. When the stop mass is close to the lightest supersymmetric particle mass, the monojet signature from ˜t ˜t * + j production is expected to be useful in detecting the stop[26]. If the stop mass is degenerate with the sum of the masses of its decay products, the searches based on missing transverse energy (E__T^miss or /E__T) have significant reach for stop masses above 175 GeV[27]. When R-parity is violated, the decay modes of the stop will be very different from the ones in R-parity conserving MSSM, such as stop decaying to dilepton and trilepton final states[28]. We also note that the constraints on the light stop in natural SUSY have been discussed by using the results from sparticle searches at the LHC, and indicated that they were mild and can be safely avoided currently[14, 17, 18, 29].

In this work, we investigate the potential of the LHC in probing the lighter stop ˜t predicted by the natural MSSM with R-parity, which is based on several considerations: (i) Most studies of stop searches have been carried out under some assumptions at the LHC in a model independent way or in simplified models. It will be meaningful to explore what might happen in a realistic model like MSSM under the currently available experimental constraints; (ii) Due to R-parity conservation, there will be sizeable missing energy appearing in sparticle productions and decays, which can be easily identified in the LHC data; (iii) One interesting phenomenological feature of the natural MSSM with R-parity is that both the lightest neutralino and the lighter chargino are Higgsino-like, and consequently ˜t always decays dominantly into t˜ and b˜ with ˜ → ˜ W*, which can greatly simplify the analysis of the ˜t detection at the LHC.

For this purpose, we first scan the parameter space of the natural MSSM by considering various constraints in Sec. II. Then in Sec. III we discuss the observability of ˜t through the direct stop pair production in the allowed parameter space by performing Monte Carlo simulations for the channel pp → ˜t ˜t * → t˜ ¯t˜ and the channel pp → ˜t ˜t * → b˜ → t˜ ¯b˜ . We will present their corresponding sensitivities for 8 TeV LHC and for 14 TeV LHC respectively. Finally in Sec. IV, we summarize the conclusions obtained in this work.

[Figure 1: see original paper]

## II. Scan Over The Parameter Space

Motivated by the natural MSSM, we scan the parameter space of the MSSM as follows:

- 1 tan 60,
- 100 GeV M 1 TeV,
- |A_t| 3 TeV,
- 100 GeV (M_˜Q , M_˜U ) 2 TeV,
- 90 GeV M_A 1 TeV.

For other unimportant parameters, we fix all the soft breaking parameters in the slepton sector and the first two generation sector at 10 TeV, and we assume A_t = A_b, M_˜U = M_˜D and M : M = 1 : 2 (inspired by the grand unification relation). In our scan, we consider the following constraints:

- We require the SM-like Higgs mass within the range 125 ± 2 GeV. We use the code FeynHiggs-2.8.6 [30] to calculate the mass and the code HiggsBounds-3.8.0 [31] to consider the experimental constraints on the Higgs sector of the natural MSSM.
- Since the natural MSSM has important implications in B-physics [32], we use the code SUSY_Flavor v2.0 [33] to consider the constraints from the processes B → X_s and B_s(d) → .
- We consider indirect constraints from the precision electroweak observables such as _l, sin² _l^eff, m_W and R_b. We use our own code for such calculation [34].
- We require the thermal relic density of the lightest neutralino (as the dark matter candidate) is below the WMAP value [35]. We use the code MicrOmega v2.4 [36] to calculate the density.

After analyzing the surviving samples, we find they have two main characteristics. One is that the Higgs mass of 125 ± 2 GeV requires m˜t 220 GeV and there is a rather strong correlation between m˜t and the ratio |A_t|/M_S, as shown in Fig.1. Here we further clarify that, if M_˜Q and M_˜U are at sub-TeV scale, the minimum of m˜t will be enhanced to about 300 GeV [8].

The other feature is that for most cases, the values of are significantly smaller than M so that the lightest neutralino is Higgsino-like. Fig.2 indicates that the surviving samples lie within two isolated regions. We checked that the lightest neutralino is bino-like in the left region and Higgsino-like in the right region. Here the bino(Higgsino)-like means it is still a mixed state but the dominant component is bino(Higgsino). For the light neutralino dark matter (bino-like), the main annihilation channel is through exchanging Z boson. The annihilation cross section is roughly proportional to 1/(4m_ ² - m_Z²)². When the neutralino mass is about 50 GeV-60 GeV, the annihilation cross section may be very large, so the relic density will be less than 0.1. When the neutralino becomes heavier (60 GeV-90 GeV, neutralino is still bino-like), the annihilation cross section will drop. The relic density becomes large and even exceeds the WMAP value, and these samples are excluded. This is the reason for the gap between 60 GeV-90 GeV. When the neutralino continues becoming heavy (>90 GeV), the dominant component of the neutralino will be Higgsino. The coupling between neutralino and Higgs gets important and annihilation rate goes up, then the relic density drops.

Regarding the natural MSSM, we have two comments. One is that in this scenario the di-photon signal of the SM-like Higgs boson can hardly be enhanced to satisfy the requirement of the LHC data. This is because in the framework of the MSSM, there are only two cases which can enhance the di-photon rate, i.e. the small  _eff scenario [37, 38] and the light ˜  scenario [6, 39], and in each case a large   is needed. In Ref.[40], the authors pointed out that the light stop with large couplings to Higgs boson in the SM+stop model can improve the SM fitting to the LHC and Tevatron data by enhancing Γ(h →   ) and suppressing Γ(h → gg). However, we should note that it does not mean that the di-photon production rate can reach the measurement of the LHC in a concrete MSSM model since the reduction of Γ(h → gg) is usually much stronger than the enhancement of Γ(h →   ) for large values of X_t (X_t = A_t -   tan  )[41]. The other is that recently the ATLAS collaboration searched for the gluino-mediated stop pair production followed by the decay ˜t  → b˜   → b  ˜   which set a lower bound m˜t   450 GeV [3]. This conclusion is not applicable to our calculations since we take the gluino mass to be larger than 1 TeV in the allowed parameter space of natural SUSY.

[Figure 2: see original paper]
[Figure 3: see original paper]

## III. Observability of Stop Pair Production at the LHC

In this section we discuss the LHC potential of discovering the stop through the direct stop pair production in the natural MSSM at √s = 8, 14 TeV. In Fig.3 we show the pp → ˜t ˜t * production rate at next-to-leading order for the surviving samples. In obtaining this figure we used the package Prospino2.1 [42] and the parton distribution function CTEQ6.6m [43] with the renormalization scale  _R and factorization scale  _F set to m˜t . This figure indicates that the maximal values of the cross section reach 5.5 pb and 25.7 pb for the LHC with √s = 8 TeV and √s = 14 TeV respectively, and with the increase of the stop mass, the production rates drop rapidly.

In Fig.4 we present various decay branching ratios of ˜t  which are obtained by using the package SDECAY [44]. This figure indicates that for m˜t   320 GeV where the decay channel ˜t  → t˜   does not open up, ˜t  decays into b˜   with a ratio of 100%, and as the stop becomes heavier, the branching ratios for ˜t  → b˜   may still be around 50%. In contrast, the branching ratios for ˜t  decays into t˜   , ,  and b˜   are usually less than 20%.

In the following we perform detailed Monte Carlo simulations to investigate the observability of the direct stop pair production at the LHC. We concentrate on the semi-leptonic analysis with the b-tagging efficiency 40%, where the signal consists of four jets (at least one b-jet), one lepton (e or  ), and missing transverse energy. We first consider the process

$$pp \to \tilde{t}_1\tilde{t}_1^* \to (t\tilde{\chi}_1^0)(\bar{t}\tilde{\chi}_1^0) \to (b\ell^+\nu\tilde{\chi}_1^0)(\bar{b}jj\tilde{\chi}_1^0) \text{ or } (bjj\tilde{\chi}_1^0)(\bar{b}\ell^-\bar{\nu}\tilde{\chi}_1^0)$$

From the ATLAS search for the signal t¯t + E_T^miss [2], we can see that the dominant SM background after the E_T^miss and M_T cuts is the t¯t di-leptonic channel with one lost lepton and two additional jets from initial state radiation to fake the hadronic W. Other backgrounds include t¯t semi-leptonic channel, t¯t di-leptonic channel with one   from top decay misidentified as a jet, W+jets and t¯tZ. Here we emphasize that the t¯tZ background becomes important for a heavy stop and should be considered in estimating the significance. In our calculation, we normalize the signal and the t¯t background to their NLO values [42, 45], and simulate the signal and backgrounds by MadGraph5 [46] interfaced with PYTHIA [47] and Delphes [48] to carry out the parton shower and fast detector simulation. We use the anti-k_t algorithm [49] with the distance parameter R = 0.4 to cluster jets and the MLM scheme [50] to match our matrix element with parton shower. We checked that the shapes of the matched W+1,2,3 partons are very similar, and for simplicity, we take W+2 jets samples in our calculations.

In our calculations, since we employ the variable M_W^T2 defined in Ref.[24], we checked our results with theirs for the same parameters at √s = 7 TeV and found they were consistent with each other.

In Fig.5, we show the distributions of /E_T, the transverse mass M_T defined in [2] and M_W^T2 for the backgrounds and our benchmark point m˜t  = 429 GeV and m˜    = 110 GeV (similar results are found for √s = 14 TeV). This figure indicates that most events of W+jj and semi-leptonic t¯t backgrounds are characterized by /E_T   100 GeV and M_T   100 GeV, and most events of the di-leptonic t¯t backgrounds are characterized by M_W^T2   170 GeV, while a significant fraction of the signal may have larger /E_T, M_T and M_W^T2. Fig.5 also indicates that the distributions of the t¯tZ background are quite similar to the signal and are difficult to suppress. Fortunately, the production rate of t¯tZ is much smaller than that of ˜t ˜t *.

In Table I, we present the significance S/√B of our benchmark point for 100 fb ¹ luminosity with √s = 8 TeV and 14 TeV respectively by sequentially imposing the cuts on /E_T, M_T and M_W^T2. It can be seen that, for the given reference point, the cut M_T > 150 GeV can greatly enhance the significance and M_W^T2 > 173 GeV further improves the significance by about 14% for √s = 8 TeV and 9% for √s = 14 TeV to reach 3.11 and 8.60 respectively.

[Figure 4: see original paper]
[Figure 5: see original paper]

**Table I**: The significance of stop pair production pp → ˜t ˜t * → t˜ ¯t˜ for 100 fb ¹ luminosity after imposing various cuts. Here we take m˜t = 429 GeV and m˜ = 110 GeV for illustration.

| /E_T-cut (GeV) | M_T-cut (GeV) | M_W^T2-cut (GeV) | S/√B (8TeV) | S/√B (14TeV) |
|---|---|---|---|---|
| 150 | 150 | 173 | 3.11 | 8.60 |

Therefore, for our simulations in the allowed parameter space, we take the following event selection criteria:

- One isolated electron or muon that passes the following requirements:
  - Electrons: E_T > 25 GeV and | | < 2.47 without 1.37 < | | < 1.52;
  - Muon: E_T > 20 GeV and | | < 2.5;
  - Events are rejected if they contain a second lepton candidate with P_T > 15 GeV;
- Four or more reconstructed jets with P_T > 25 GeV and | | < 2.5.
- /E_T > 150 GeV, M_T > 150 GeV, M_W^T2 > 173 GeV.

where the basic cuts about p_T and on leptons and jets are from the ATLAS report[2]. In order to improve the signal sensitivity, we increase the values of ATLAS cut /E_T from 100 GeV to 150 GeV to further suppress the semi-leptonic t¯t background and use the new cut M_W^T2 > 173 GeV to reduce the di-leptonic t¯t background in our calculations.

In Fig.6 we show the significance of the surviving samples with m˜t < 800 GeV. This figure indicates that the largest significance can be reached at m˜t 430 GeV where the significance is about 1.5 for √s = 8 TeV with 20 fb ¹ luminosity and 8.5 for √s = 14 TeV with 100 fb ¹ luminosity, and with the increase of the stop mass, the significance drops by one half for m˜t 500 GeV mainly due to the reduction of the production rate. Our results are not as optimistic as those in [20, 21, 24] because we have taken into account the branching ratio of ˜t → t˜ . Fig.6 also indicates that there are two branches for the significance in the mass region 320 GeV < m˜t < 600 GeV. We checked that the upper branch corresponds to high branching ratio of ˜t → t˜ , which varies from 42.1% to 57.7% and results in a large signal rate, while the lower branch corresponds to a small ratio due to the competition of the decay mode ˜t → t˜ .

The above analysis implies that, in order to fully explore the parameter space of the natural MSSM in stop detection, the decay mode ˜t → b˜ should also be considered. So we next consider the process

$$pp \to \tilde{t}_1\tilde{t}_1^* \to (b\tilde{\chi}_1^+)(\bar{b}\tilde{\chi}_1^-) \to (b\ell^+\nu\tilde{\chi}_1^0)(\bar{b}jj\tilde{\chi}_1^0) \text{ or } (bjj\tilde{\chi}_1^0)(\bar{b}\ell^-\bar{\nu}\tilde{\chi}_1^0)$$

Same as in Fig.5, we show the distributions of the three variables in Fig.7 for the benchmark point m˜t = 273.6 GeV, m˜ = 163.5 GeV and m˜ = 156.3

GeV. Compared with the distribution in Fig.5, one can see that more signal events have lower values of /E_T and lower M_T, due to the relatively light ˜t . Fig.7 also indicates the M_W^T2 variable is helpless in suppressing the di-leptonic t¯t events and any cut on M_W^T2 may hurt the signal greatly.

[Figure 6: see original paper]
[Figure 7: see original paper]

In Fig.8, we show the significance of the surviving samples for the process in Eq.(6). In order to keep more signal events, here we relax the cuts of /E_T and M_T used for the process in Eq.(5) as follows: /E_T > 100 GeV, M_T > 100 GeV. From this figure, one can learn that, due to the large stop pair production rate, the significance for m˜t = 250 GeV may reach 7 for √s = 8 TeV with 20 fb $^1$ luminosity and 64 for √s = 14 TeV with 100 fb $^1$ luminosity, but for m˜t = 400 GeV, the maximum value drops to 1.5 and 10 respectively.

[Figure 8: see original paper]

Finally, we summarize the significance of the direct stop pair production with the above two decay modes of ˜t for √s = 14 TeV and 100 fb $^1$ luminosity. The results are displayed in Fig.9 where only the maximal significance under each cut is shown. This figure indicates that, for m˜t < 400 GeV, detecting the stop pair production through the chargino decay is more effective, while for 400 GeV m˜t 450 GeV the neutralino decay is more effective. This figure also indicates that the LHC can discover ˜t predicted in natural MSSM up to 450 GeV. If no excess events were observed at the LHC, the 95% C.L. exclusion limits of the stop masses can go up to around 537 GeV no matter what decay modes of the stop in the natural MSSM.

[Figure 9: see original paper]

## IV. Conclusion

In this work we studied the direct stop pair production at the LHC in the natural MSSM. We scanned over the corresponding parameter space by considering various experimental constraints and then in the allowed parameter space we examined the observability of the direct stop pair production at the LHC through the semi-leptonic analysis. We focused on the following two channels:

$$pp \to \tilde{t}_1\tilde{t}_1^* \to (t\tilde{\chi}_1^0)(\bar{t}\tilde{\chi}_1^0) \to (b\ell^+\nu\tilde{\chi}_1^0)(\bar{b}jj\tilde{\chi}_1^0) \text{ or } (bjj\tilde{\chi}_1^0)(\bar{b}\ell^-\bar{\nu}\tilde{\chi}_1^0)$$

and

$$pp \to \tilde{t}_1\tilde{t}_1^* \to (b\tilde{\chi}_1^+)(\bar{b}\tilde{\chi}_1^-) \to (b\ell^+\nu\tilde{\chi}_1^0)(\bar{b}jj\tilde{\chi}_1^0) \text{ or } (bjj\tilde{\chi}_1^0)(\bar{b}\ell^-\bar{\nu}\tilde{\chi}_1^0)$$

and performed detailed Monte Carlo simulations about the signals and backgrounds. We found that for m˜t < 400 GeV the second channel is better while for 400 GeV   m˜t    450 GeV the first channel is better. We also found that the LHC with $\sqrt{s} = 14$ TeV and 100 fb $^{1}$ luminosity is capable of discovering ˜t predicted in natural MSSM up to 450 GeV. If no excess events were observed at the LHC, the 95% C.L. exclusion limits of the stop masses can reach around 537 GeV in the natural MSSM.

[Figure 10: see original paper]

## Note Added

Very recently, the ATLAS collaboration reported the result of the direct search for the stop pair production based on 4.7 fb $^{1}$ of data[51]. We validated our simulation by reproducing the ATLAS exclusion limit according to the assumptions and cuts in the report as follows:

- One isolated electron or muon passing ‘tight’ selection criteria;
  - Electrons: $E_T > 25$ GeV and $| | < 2.47$;
  - Muon: $E_T > 20$ GeV and $| | < 2.4$.
- Four or more jets with $| | < 2.5$ and $P_T > 80$, 60, 40 and 25 GeV, and at least one jet to be identified as a b-jet;
- $\Delta$ _min > 0.8, where $\Delta$ _min is the minimum azimuthal separation between the two highest $P_T$ jets and the missing transverse momentum direction;
- The jet-jet pair having invariant mass > 60 GeV and the smallest $\Delta R$ is selected to form the hadronically decaying W boson. The mass $m_{jjj}$ is reconstructed including a third jet closest in $\Delta R$ to the hadronic W boson momentum vector and 130 GeV $< m_{jjj} <$ 205 GeV is required;
- $E_T^{miss} > 150$ GeV, $E_T^{miss}/\sqrt{H_T} > 7$ GeV$^{1}/^{2}$ and $m_T > 120$ GeV;
- Events are rejected if they contain additional leptons passing looser selection criteria.

Here we treat the looser selection criteria as $P_T > 15$ GeV. The branching ratio of ˜t → t˜    is assumed to be 100%.

In Fig.10, we display the expected exclusion limit from our simulation. Considering the differences between the fast simulation and full detector simulation, we can see that our result is consistent with the ATLAS exclusion limit within the reasonable error range. We also expect our result can be improved by the simultaneous fits method used by ATLAS for five signal regions and three control regions, however, which is beyond the scope of our simulation.

It should be noted that the above stop mass limits can be avoided in our study, since the stop decays with a mixture of the branching ratios.

## Acknowledgement

Lei Wu thanks Xerxes Tata, Zijun Xu and Qiang Li for helpful discussion about the natural SUSY and MG/ME, and appreciates the organizers and lecturers at the KIAS school on MadGraph for LHC physics simulation (Oct. 24-29, 2011, KIAS, Seoul). This work was supported in part by the National Natural Science Foundation of China (NNSFC) under grant Nos. 10821504, 11135003, 10775039, 11075045, by Specialized Research Fund for the Doctoral Program of Higher Education with grant No. 20104104110001, and by the Project of Knowledge Innovation Program (PKIP) of Chinese Academy of Sciences under grant No. KJCX2.YW.W10.

## References

[1] ATLAS Collaboration, ATLAS-CONF-2012-093; CMS Collaboration, CMS-PAS-HIG-12-020; G. Aad et al. [ATLAS Collaboration], Phys. Lett. B 710, 49 (2012); S. Chatrchyan et al. [CMS Collaboration], Phys. Lett. B 710, 26 (2012).

[2] G. Aad et al. [ATLAS Collaboration], Phys. Rev. Lett. 108, 041805 (2012).

[3] G. Aad et al. [ATLAS Collaboration], Phys. Rev. D 85, 112006 (2012); Phys. Rev. Lett. 108, 241802 (2012); Phys. Rev. Lett. 108, 181802 (2012).

[4] V. M. Abazov et al. [D0 Collaboration], Phys. Lett. B 710, 578 (2012); Phys. Lett. B 696, 321 (2011); T. Aaltonen et al. [CDF Collaboration], Phys. Rev. Lett. 106, 191801 (2011); Phys. Rev. Lett. 107, 191803 (2011).

[5] S. Chatrchyan et al. [CMS collaboration], Phys. Rev. Lett. 107, 221804 (2011); G. Aad et al. [ATLAS collaboration], arXiv:1109.6572 [hep-exp].

[6] M. Carena, S. Gori, N. R. Shah and C. E. M. Wagner, JHEP 1203, 014 (2012).

[7] see, e.g., J. Cao et al. Phys. Lett. B 710, 665 (2012); H. Baer, V. Barger and A. Mustafayev, JHEP 1205, 091 (2012); L. Aparicio, D. G. Cerdeno and L. E. Ibanez, JHEP 1204, 126 (2012); J. Ellis, K. A. Olive and K. A. Olive, Eur. Phys. J. C 72, 2005 (2012); C. Balazs et al., arXiv:1205.1568. A. Fowlie et. al., arXiv:1206.0264;

[8] J. Cao, et al., JHEP 1203, 086 (2012).

[9] see, e.g., U. Ellwanger, JHEP 1203, 044 (2012); J. F. Gunion, Y. Jiang and S. Kraml, Phys. Lett. B 710, 454 (2012); U. Ellwanger and C. Hugonie, arXiv:1203.5048 [hep-ph]; D. A. Vasquez et. al., Phys. Rev. D 86, 035023 (2012).

[10] R. Arnowitt and P. Nath, Phys. Rev. D 46, 3981 (1992).

[11] S. F. King, M. Muhlleitner and R. Nevzorov, Nucl. Phys. B 860, 207 (2012).

[12] P. Huet and A. E. Nelson, Phys. Rev. D 53 (1996) 4578; M. Carena, G. Nardini, M. Quiros and C. E. M. Wagner, Nucl. Phys. B 812 (2009) 243; Y. Li, S. Profumo and M. Ramsey-Musolf, Phys. Lett. B 673 (2009) 95.

[13] K. Griest and D. Seckel, Phys. Rev. D 43 (1991) 3191; C. Boehm, A. Djouadi and M. Drees, Phys. Rev. D62 (2000) 035012.

[14] C. Brust, A. Katz, S. Lawrence and R. Sundrum, JHEP 1203, 103 (2012).

[15] D. Feldman, G. Kane, E. Kuflik and R. Lu, Phys. Lett. B 704, 56 (2011); H. Baer et al., JHEP 1010, 018 (2010); A. Cohen, D. B. Kaplan and A. Nelson, Phys. Lett. B 388, 588 (1996); M. Dine, A. Kagan and S. Samuel, Phys. Lett. B 243, 250 (1990).

[16] J. L. Feng and D. Sanford, arXiv:1205.2372 [hep-ph]; G. Bhattacharyya and T. S. Ray, JHEP 1205, 022 (2012); S. Krippendorf, H. P. Nilles, M. Ratz and M. W. Winkler, Phys. Lett. B 712, 87 (2012); B. C. Allanach and B. Gripaios, JHEP 1205, 062 (2012); S. Akula, M. Liu, P. Nath and G. Peim, Phys. Lett. B 709, 192 (2012); L. J. Hall, D. Pinner and J. T. Ruderman, JHEP 1204, 131 (2012); M. Asano, H. D. Kim, R. Kitano and Y. Shimizu, JHEP 1012, 019 (2010); R. Kitano and Y. Nomura, Phys. Rev. D 73, 095004 (2006); J. Hisano, K. Kurosawa and Y. Nomura, Nucl. Phys. B 584, 3 (2000); J. L. Feng, K. T. Matchev and T. Moroi, Phys. Rev. D 61, 075005 (2000); K. L. Chan, U. Chattopadhyay and P. Nath, Phys. Rev. D 58, 096004 (1998); G. W. Anderson, D. J. Castano and A. Riotto, Phys. Rev. D 55, 2950 (1997).

[17] H. Baer, V. Barger, P. Huang and X. Tata, JHEP 1205, 109 (2012).

[18] M. Papucci, J. T. Ruderman and A. Weiler, arXiv:1110.6926 [hep-ph];

[19] see, e.g., A. Choudhury and A. Datta, JHEP 1206, 006 (2012); K. Huitu, L. Leinonen and J. Laamanen, Phys. Rev. D 84, 075021 (2011); Y. Kats and D. Shih, JHEP 1108, 049 (2011); S. Bornhauser, M. Drees, S. Grab and J. S. Kim, Phys. Rev. D 83, 035008 (2011); N. Bhattacharyya, A. Choudhury and A. Datta, Phys. Rev. D 84, 095006 (2011); D. Casadei, R. Konoplich and R. Djilkibaev, Phys. Rev. D 82, 075011 (2010); K. Rolbiecki, J. Tattersall and G. Moortgat-Pick, Eur. Phys. J. C 71, 1517 (2011); M. Perelstein and A. Weiler, JHEP 0903, 141 (2009); T. Han, R. Mahbubani, D. G. E. Walker and L. -T. Wang, JHEP 0905, 117 (2009); M. Carena, A. Freitas and C. E. M. Wagner, JHEP 0810, 109 (2008); S. Kraml and A. R. Raklev, Phys. Rev. D 73, 075002 (2006); T. Han et al., Phys. Rev. D 70, 055001 (2004); A. Bartl et al., Phys. Lett. B 573, 153 (2003); J. Hisano, K. Kawagoe and M. M. Nojiri, Phys. Rev. D 68, 035007 (2003); J. Hisano, K. Kawagoe, R. Kitano and M. M. Nojiri, Phys. Rev. D 66, 115004 (2002); J. M. Yang and B. -L. Young, Phys. Rev. D 62, 115002 (2000);

[20] D. E. Kaplan, K. Rehermann and D. Stolarski, JHEP 1207, 119 (2012).

[21] T. Plehn, M. Spannowsky and M. Takeuchi, JHEP 1208, 091 (2012); Phys. Rev. D 85, 034029 (2012); JHEP 1105, 135 (2011); T. Plehn and M. Spannowsky,

arXiv:1112.4441; T. Plehn et al., JHEP 1010, 078 (2010); T. Plehn, G. P. Salam and M. Spannowsky, Phys. Rev. Lett. 104, 111801 (2010).

[22] J. Thaler and K. Van Tilburg, JHEP 1202, 093 (2012); J. Thaler and K. Van Tilburg, JHEP 1103, 015 (2011); J. Thaler and L. -T. Wang, JHEP 0807, 092 (2008).

[23] K. Rehermann and B. Tweedie, JHEP 1103, 059 (2011); M. Jankowiak and A. J. Larkoski, JHEP 1106, 057 (2011); L. G. Almeida et al., Phys. Rev. D 82, 054034 (2010); Phys. Rev. D 79, 074012 (2009); D. E. Kaplan et al., Phys. Rev. Lett. 101, 142001 (2008).

[24] Y. Bai, H. -C. Cheng, J. Gallicchio and J. Gu, arXiv:1203.4813 [hep-ph].

[25] Z. Han, A. Katz, D. Krohn and M. Reece, JHEP 1208, 083 (2012).

[26] M. Drees, M. Hanussek and J. S. Kim, arXiv:1201.5714 [hep-ph];

[27] D. S. M. Alves et al., arXiv:1205.5805 [hep-ph];

[28] C. Brust, A. Katz and R. Sundrum, JHEP 1208, 059 (2012); H. -T. Wei, et al., JHEP 1107, 003 (2011); N. Desai and B. Mukhopadhyaya, JHEP 1010, 060 (2010).

[29] X. -J. Bi, Q. -S. Yan and P. -F. Yin, Phys. Rev. D 85, 035005 (2012);

[30] M. Frank et al., JHEP 0702, 047 (2007); G. Degrassi et al., Eur. Phys. J. C 28, 133 (2003); S. Heinemeyer, W. Hollik and G. Weiglein, Comput. Phys. Commun. 124, 76 (2000); Eur. Phys. J. C 9, 343 (1999).

[31] P. Bechtle et al., Comput. Phys. Commun. 182, 2605 (2011); Comput. Phys. Commun. 181, 138 (2010).

[32] K. Ishiwata, N. Nagata and N. Yokozaki, Phys. Lett. B 710, 145 (2012).

[33] J. Rosiek et al., Comput. Phys. Commun. 181, 2180 (2010); A. Crivellin, L. Hofer and J. Rosiek, JHEP 1107, 017 (2011).

[34] J. Cao and J. M. Yang, JHEP 0812, 006 (2008).

[35] J. Dunkley et. al. [WMAP Collaboration], Astrophys. J. Suppl. 180, 306 (2009)

[36] G. Belanger et al., Comput. Phys. Commun. 182, 842 (2011).

[37] M. S. Carena et al., Eur. Phys. J. C 26, 601 (2003).

[38] J. Cao et al., Phys. Lett. B 703, 462 (2011);

[39] M. Carena et al., arXiv:1205.5842 [hep-ph].

[40] M. R. Buckley and D. Hooper, arXiv:1207.1445 [hep-ph].

[41] A. Djouadi, Phys. Lett. B 435, 101 (1998); [hep-ph/9901237].

[42] W. Beenakker et al., Nucl. Phys. B 515, 3 (1998);

[43] J. Pumplin et al., JHEP 0602, 032 (2006).

[44] M. Muhlleitner, A. Djouadi and Y. Mambrini, Comput. Phys. Commun. 168, 46 (2005).

[45] N. Kidonakis, Phys. Rev. D 82, 114030 (2010); V. Ahrens et al., Phys. Lett. B 703, 135 (2011); M. Cacciari et al., Phys. Lett. B 710, 612 (2012); S. Moch, P. Uwer and A. Vogt, arXiv:1203.6282.

[46] J. Alwall et al., JHEP 1106, 128 (2011).

[47] T. Sjostrand, S. Mrenna and P. Z. Skands, JHEP 0605, 026 (2006).

[48] S. Ovyn, X. Rouby and V. Lemaitre, arXiv:0903.2225 [hep-ph].

[49] M. Cacciari, G. P. Salam and G. Soyez, JHEP 0804, 063 (2008).

[50] F. Caravaglios, M. L. Mangano, M. Moretti and R. Pittau, Nucl. Phys. B 539, 215 (1999).

[51] G. Aad et al. [ATLAS Collaboration], arXiv:1208.2590 [hep-ex].

*Note: Figure translations are in progress. See original paper for figures.*

*Source: ChinaXiv —Machine translation. Verify with original.*