

**Current experimental bounds on stop mass in natural SUSY (postprint) Zhang Wei<sup>1,2</sup>, Li Si<sup>3</sup>, Wang Wu<sup>1</sup>** <sup>1</sup>Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China <sup>2</sup>University of Chinese Academy of Sciences, Beijing 100049, China <sup>3</sup>Department of...

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### Abstract

Motivated by the recent progress of direct search for the productions of stop pair and sbottom pair at the LHC, we examine the constraints of the search results on the stop ( $t$ ) mass in natural SUSY. We first scan the parameter space of natural SUSY in the framework of MSSM, considering the constraints from the Higgs mass, B-physics and electroweak precision measurements. Then in the allowed parameter space we perform a Monte Carlo simulation for stop pair production followed by  $t \rightarrow t^0$  or  $t \rightarrow b^+$  and sbottom pair production followed by  $\tilde{b} \rightarrow b^0$  or  $\tilde{b} \rightarrow t^-$ . Using the combined results of ATLAS with 20.1 fb<sup>-1</sup> from the search of  $l + \text{jets} + E_{\text{T}}$ , hadronic  $t\bar{t} + E_{\text{T}}$  and  $2b + E_{\text{T}}$ , we find that a stop lighter than 600 GeV can be excluded at 95% CL in this scenario.

### Full Text

## Current Experimental Bounds on Stop Mass in Natural SUSY

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### Abstract

Motivated by recent progress in direct searches for stop pair and sbottom pair production at the LHC, we examine the constraints of these search results on the stop ( $\tilde{t}_1$ ) mass in natural SUSY. We first scan the parameter space of natural SUSY in the framework of MSSM, considering constraints from the Higgs mass, B-physics, and electroweak precision measurements. Then, in the allowed parameter space, we perform Monte Carlo simulations for stop pair production followed by  $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$  and sbottom pair production followed by  $\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$ ,  $\tilde{b}_1 \rightarrow t\tilde{\chi}_1^-$ , or  $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^+$ . Using the combined ATLAS results with  $20.1 \text{ fb}^{-1}$  from searches for  $\ell + \text{jets} + \cancel{E}_T$ , hadronic  $t\bar{t} + \cancel{E}_T$ , and  $2b + \cancel{E}_T$ , we find that a stop lighter than 600 GeV can be excluded at 95% CL in this scenario.

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### I. INTRODUCTION

The observation of a SM-like Higgs boson around 125 GeV by the ATLAS and CMS Collaborations [?] has had a great impact on the minimal supersymmetric standard model (MSSM), in which the naturalness problem is a key issue [?]. For electroweak naturalness, the stops play an important role by canceling the top quark loop, and thus LHC searches for stop pair production will shed light on this question in the MSSM. The ATLAS and CMS collaborations have also performed searches for supersymmetric particles with about  $20 \text{ fb}^{-1}$  of data [?]. The negative results of sparticle searches may indicate the natural SUSY scenario [?], in which the first two generations of squarks are heavy while the third generation of squarks are light.

In the framework of MSSM, the fine-tuning can be estimated by the Barbieri-Giudice measure [?]

$$\Delta = \max\{\Delta_{p_i}\}, \quad \Delta_{p_i} = \left| \frac{\partial \log M_Z^2}{\partial \log p_i^2} \right|$$

where  $p_i$  denotes the soft SUSY-breaking terms that enter the minimization conditions of the Higgs potential [?]

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

with  $\tan \beta \equiv v_u/v_d$ ,  $m_{H_u}^2$  representing the weak-scale soft SUSY breaking masses of the Higgs fields,  $\mu$  being the higgsino mass parameter, and  $\Sigma_u$  and  $\Sigma_d$  being the radiative corrections to the tree-level Higgs potential. In order to maintain naturalness, the parameters  $\mu$ ,  $m_{H_u}$ , and  $\Sigma_u$  are expected to be at the weak scale, which imposes constraints on the spectrum of MSSM [?]

$$\mu \lesssim 200 \text{ GeV} \left( \frac{m_h}{125 \text{ GeV}} \right)$$

$$M_3 \lesssim 900 \text{ GeV} \left( \frac{m_h}{125 \text{ GeV}} \right)$$

$$L^2 \lesssim 600 \text{ GeV} \left( \frac{m_h}{125 \text{ GeV}} \right)$$

with  $L_\Lambda = \sqrt{3}/\log(\Lambda/\text{TeV})$  coming from the leading-log approximation of the RGE [?]. Of course, in a given model like the MSSM, CMSSM, or natural SUSY, the fine-tuning extent depends on the parameters appearing on the left sides of Eqs. (3-5), which can be checked by examining the parameter space allowed by current experiments [?].

In this work we focus on natural SUSY and examine the constraints from LHC search results for stops and sbottoms [?, ?]. Note that some studies in this aspect have been performed in the literature [?, ?]. However, the study in [?] assumed a special scenario with  $A_t = 0$  and  $\tan\beta = 10$  and, as a result, the stop decay was much simplified, while the analysis in [?] did not consider the ATLAS sbottom search results. In our study we consider a more general natural SUSY with more experimental constraints. We first scan the parameter space of natural SUSY in the framework of MSSM, considering constraints from the LHC Higgs mass, B-physics, and electroweak precision measurements, and then in the allowed parameter space we perform a detailed Monte Carlo simulation for stop pair production with  $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$  and sbottom pair production with  $\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$ ,  $\tilde{b}_1 \rightarrow t\tilde{\chi}_1^-$ , or  $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^+$  at the LHC, applying the same cuts as in the ATLAS searches. Finally, using the combined ATLAS results with  $20.1 \text{ fb}^{-1}$  from searches for  $\ell + \text{jets} + \cancel{E}_T$ , hadronic  $t\bar{t} + \cancel{E}_T$ , and  $2b + \cancel{E}_T$ , we determine the allowed range for the stop in natural SUSY.

We organize the paper as follows. In Sec. II, we scan the parameter space and present the spectrum of natural SUSY allowed by the Higgs mass, B-physics, and electroweak precision measurements. In Sec. III we simulate direct stop/sbottom pair production and examine their constraints on the parameter space of natural SUSY. Finally, we draw our conclusions in Sec. IV.

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## ### II. A SCAN OF THE PARAMETER SPACE

In accordance with the definition of natural SUSY,  $\mu$  should have a value at the weak scale and the third generation of squarks should not be too far above the TeV scale. We therefore scan these parameters in the following ranges:  $100 \text{ GeV} \leq \mu \leq 200 \text{ GeV}$  and  $100 \text{ GeV} \leq (m_{\tilde{t}_L} = m_{\tilde{b}_L}, m_{\tilde{t}_R}) \leq 2 \text{ TeV}$ . In natural SUSY the gluino mass is supposed to be below several TeV. Since we focus on stop/sbottom direct searches, the gluino mass is not a sensitive parameter, which we fix at 2 TeV in our scan. The sleptons and first two generations of squarks in natural SUSY are supposed to be heavy, which we fix at 5 TeV. For the electroweak gaugino masses, we use the grand unification relation  $M_1 : M_2 = 1 : 2$  and take  $M_1 = 1 \text{ TeV}$  (in natural SUSY  $M_1$  is usually supposed to be larger than  $\mu$  and the lightest neutralino is higgsino-like). Further, we assume  $A_t = A_b$  and  $m_{\tilde{b}_R} = m_{\tilde{t}_R}$ , which in our scan vary in the ranges  $|A_t| \leq 3 \text{ TeV}$ ,

$1 \leq \tan \beta \leq 60$ , and  $90 \text{ GeV} \leq M_A \leq 1 \text{ TeV}$ , where the lower bound of  $M_A$  is indicated by LEP and B-decay constraints. Since the composition of the stop ( $\tilde{t}_1$ ) affects its decay modes, we scan the parameter space in two scenarios: (I)  $m_{\tilde{t}_R}$  is lighter than  $m_{\tilde{t}_L}$ ; (II)  $m_{\tilde{t}_L}$  is lighter than  $m_{\tilde{t}_R}$ .

In our scan we consider the following constraints: (1) We require the SM-like Higgs mass in the range of 123-127 GeV. We calculate the Higgs mass with FeynHiggs 2.8.9 [?] and impose experimental constraints from LEP, Tevatron, and LHC with HiggsBounds-3.8.0 [?]. (2) We require natural SUSY to satisfy various B-physics bounds at the  $2\sigma$  level. We use the package SuperIso v3.3 [?] to implement the constraints, including  $B \rightarrow X_s \gamma$  and the latest measurements of  $B_s \rightarrow \mu^+ \mu^-$ ,  $B_d \rightarrow X_s \mu^+ \mu^-$ , and  $B^+ \rightarrow \tau^+ \nu$ . (3) We require the SUSY prediction of precision electroweak observables such as  $\rho_l$ ,  $\sin^2 \theta_l^{\text{eff}}$ ,  $m_W$ , and  $R_b$  [?] to be within the  $2\sigma$  ranges of the experimental values. (4) We require the thermal relic density of the lightest neutralino (as the dark matter candidate) to be below the  $2\sigma$  upper limit of the Planck value [?]. We use the code MicrOmega v2.4 [?] to calculate the relic density.

In Fig. 1 [Figure 1: see original paper] we show the sparticle spectrum in the parameter space allowed by constraints (1-4) in natural SUSY. From the figure we can identify the following features and implications.

Firstly, for both  $m_{\tilde{t}_L} < m_{\tilde{t}_R}$  and  $m_{\tilde{t}_L} > m_{\tilde{t}_R}$ , the stop ( $\tilde{t}_1$ ) mass is heavier than about 200 GeV. The lower limit of the stop in the case of  $m_{\tilde{t}_L} > m_{\tilde{t}_R}$  is larger than in the case of  $m_{\tilde{t}_L} < m_{\tilde{t}_R}$ . The reason is that for  $m_{\tilde{t}_L} > m_{\tilde{t}_R}$  the Higgs mass receives a negative correction proportional to  $\cos 2\beta \log(m_{\tilde{t}_L}/m_{\tilde{t}_R})$  [?], and in order to enhance the Higgs mass to 125 GeV, the splitting between  $m_{\tilde{t}_L}$  and  $m_{\tilde{t}_R}$  is preferred to be small and a heavier stop mass is favored to balance the negative correction. Secondly, the masses of  $\tilde{\chi}_1^+$  and  $\tilde{\chi}_1^0$  are below 200 GeV and are nearly degenerate, which, due to the soft decay products, will weaken the constraints from direct electroweak gaugino searches at the LHC. However, this spectrum may strengthen some limits from direct stop/sbottom searches at the LHC since the final states  $b\tilde{\chi}_1^+$  ( $t\tilde{\chi}_1^-$ ) have the same signatures as  $b\tilde{\chi}_{1,2}^0$  ( $t\tilde{\chi}_{1,2}^0$ ).

### ### III. CONSTRAINTS FROM THE LHC SEARCH OF STOP/SBOTTOM

Since the decay modes of stop and sbottom affect the implications of direct searches, we first discuss their decay branching ratios. The relevant interactions between stop and neutralinos or charginos are given by [?]

$$\mathcal{L}_{\tilde{t}\tilde{\chi}^0} = \tilde{t}_1 \bar{\tilde{t}} (f_L^N P_L + f_R^N P_R) \tilde{\chi}_i^0 + \text{h.c.},$$

$$\mathcal{L}_{\tilde{b}\tilde{\chi}^\pm} = \tilde{t}_1 \bar{\tilde{b}} (f_L^C P_L + f_R^C P_R) \tilde{\chi}_i^\pm + \text{h.c.},$$

where  $P_{L/R} = (1 \mp \gamma_5)/2$  and

$$f_L^N = -\frac{1}{\sqrt{2}} g_2 [N_{\chi^0}]_{i\tilde{W}} + \frac{1}{3} g_1 [N_{\chi^0}]_{i\tilde{B}} \cos \theta_i - y_t [N_{\chi^0}]_{i\tilde{H}2} \sin \theta_i,$$

$$\begin{aligned}
 f_R^N &= \frac{4}{3}g_1[N_{\chi^0}]_{i\tilde{B}} \sin \theta_{\tilde{t}} - y_t[N_{\chi^0}]_{i\tilde{H}2} \cos \theta_{\tilde{t}}, \\
 f_L^C &= y_b[U_{\chi^+}]_{i\tilde{H}^-}^* \cos \theta_{\tilde{t}} - y_t[V_{\chi^+}]_{i\tilde{H}^-}^* \sin \theta_{\tilde{t}}, \\
 f_R^C &= -g_2[V_{\chi^+}]_{i\tilde{W}^-} \cos \theta_{\tilde{t}} + y_t[V_{\chi^+}]_{i\tilde{H}^-} \sin \theta_{\tilde{t}}.
 \end{aligned}$$

with  $y_t = 2m_t/(v \sin \beta)$  and  $y_b = 2m_b/(v \cos \beta)$  being the Yukawa couplings of top and bottom quarks, and  $\theta_{\tilde{t}}$  being the mixing angle between left- and right-handed stops ( $-\pi/2 \leq \theta_{\tilde{t}} \leq \pi/2$ ). The neutralino and chargino mixing matrices  $N_{ij}$ ,  $U_{ij}$ , and  $V_{ij}$  are defined in [?]. The interactions of the sbottom with neutralino or chargino can be obtained from the above expressions by replacing  $\theta_{\tilde{t}}$  with  $\theta_{\tilde{b}}$  and interchanging  $y_t$  and  $y_b$ .

In Fig. 2 [Figure 2: see original paper] we display the numerical results for the decay branching ratios of stop and sbottom. From the upper panel we can see that a light stop ( $\tilde{t}_1 < 370$  GeV) will be dominated by decays to  $b\tilde{\chi}_1^+$ . When the stop becomes heavier, the  $\tilde{t}_1 \rightarrow t\tilde{\chi}_{1,2}^0$  channels open and the decay  $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^+$  is suppressed. For  $m_{\tilde{t}_L} < m_{\tilde{t}_R}$ ,  $\text{Br}(\tilde{t}_1 \rightarrow b\tilde{\chi}_1^+)$  is around 50% and  $\text{Br}(\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0)$  and  $\text{Br}(\tilde{t}_1 \rightarrow t\tilde{\chi}_2^0)$  are approximately equal, varying between 25% and 50%. While for  $m_{\tilde{t}_L} > m_{\tilde{t}_R}$ ,  $\text{Br}(\tilde{t}_1 \rightarrow b\tilde{\chi}_1^+)$  is less than 25% and  $\text{Br}(\tilde{t}_1 \rightarrow t\tilde{\chi}_{1,2}^0)$  can only reach 25%. These features can be understood from Eqs. (10-13) in the chiral limit. From those expressions we can see that  $\tilde{t}_1$  becomes purely left-handed for  $\theta_{\tilde{t}} = 0$  and right-handed for  $\theta_{\tilde{t}} = \pm\pi/2$ . Since  $\tilde{\chi}_{1,2}^0$  are higgsino-like, the couplings  $C_{\tilde{t}\tilde{t}_1\tilde{\chi}^0}$  are proportional to  $y_t$  and nearly equal for both  $m_{\tilde{t}_L} < m_{\tilde{t}_R}$  and  $m_{\tilde{t}_L} > m_{\tilde{t}_R}$ . However, the coupling  $C_{b\tilde{t}_1\chi^+}$  is determined by the bottom Yukawa coupling  $y_b$  for  $m_{\tilde{t}_L} < m_{\tilde{t}_R}$  and by the top Yukawa coupling  $y_t$  for  $m_{\tilde{t}_L} > m_{\tilde{t}_R}$ . So we can infer that when  $\tilde{t}_1 \rightarrow t\tilde{\chi}_{1,2}^0$  is kinematically allowed,  $\text{Br}(\tilde{t}_1 \rightarrow b\tilde{\chi}_1^+)$  for  $m_{\tilde{t}_L} < m_{\tilde{t}_R}$  will be generally below  $\text{Br}(\tilde{t}_1 \rightarrow t\tilde{\chi}_{1,2}^0)$  and twice as large as  $\text{Br}(\tilde{t}_1 \rightarrow t\tilde{\chi}_{1,2}^0)$  for  $m_{\tilde{t}_L} > m_{\tilde{t}_R}$ . The sbottom decays shown in the lower panel can be understood by similar analysis.

In the following, we use the ATLAS direct stop/sbottom search data [?, ?] to constrain the parameter space of natural SUSY. The signals of the direct searches and the source of each signal in natural SUSY are shown in Table I [TABLE:I]. In our calculation we simulate the signals by MadGraph5 [?] and carry out the parton shower and fast detector simulation with PYTHIA [?] and Delphes [?]. We use the anti- $k_t$  algorithm [?] to cluster jets and the MLM scheme [?] to match our matrix element with parton shower. For the cross section of  $\tilde{t}\tilde{t}^*/\tilde{b}\tilde{b}^*$  we use the NLO results calculated by the package Prospino2.1 [?]. Before presenting the exclusion limits, in Appendix A we validate our simulations by adopting the same cut flow as ATLAS and comparing our results to the ATLAS results. We find that our results are consistent with ATLAS within reasonable error ranges. Then, we perform the simulation for each surviving sample in Fig. 2 and use the CLs method to obtain the 95% exclusion limit.

For each channel  $i$  after cut flow, we can define

$$\text{CL}_i = \frac{\text{Pois}(n_i|b_i + s_i)}{\text{Pois}(n_i|b_i)}$$

where  $s_i$  is the number of signal events from our Monte Carlo simulation, and  $n_i$  and  $b_i$  are respectively the number of observed and expected SM background events, which can be taken from the experimental papers. To account for systematic uncertainties, we allow the number of background events in each channel to fluctuate:  $b_i \rightarrow b_i(1 + \delta b_i)$ . Following the analysis in [?], we convolve the Poisson distribution with a Gaussian weighting factor and then integrate over  $b_i$ :

$$\text{Pois}(n_i|b_i + s_i) \rightarrow \int d(\delta b_i) \text{Gaus}(\delta b_i, f_{b_i}) \text{Pois}(n_i|b_i(1 + \delta b_i) + s_i)$$

where  $f_{b_i}$  is the width of the Gaussian distribution and is treated as the relative systematic uncertainty. Besides, we truncate the Gaussian integration in the case of negative background event numbers.

In Fig. 3 [Figure 3: see original paper] we show the constraints of the ATLAS stop/sbottom search data on the parameter space of natural SUSY. Generally, we can see that the stop mass can be more stringently constrained in the case of  $m_{\tilde{t}_L} < m_{\tilde{t}_R}$  than in the case of  $m_{\tilde{t}_L} > m_{\tilde{t}_R}$ , which can be understood from Fig. 2 and Table I.

In the former case, since  $\tilde{t} \rightarrow t\tilde{\chi}_{1,2}^0$  and  $\tilde{b} \rightarrow t\tilde{\chi}_1^-$  are the dominant decay modes for moderate stop/sbottom mass ( $m_{\tilde{t}_1} > 350$  GeV), by using the ATLAS data for hadronic  $t\bar{t} + \cancel{E}_T$  and  $\ell + \text{jets} + \cancel{E}_T$ , we can almost exclude  $350 < m_{\tilde{t}_1} < 590$  GeV and  $350 < m_{\tilde{t}_1} < 605$  GeV, respectively. We should mention that since  $\tilde{t} \rightarrow t\tilde{\chi}_{1,2}^0$  and  $\tilde{b} \rightarrow t\tilde{\chi}_1^-$  have the same signal, some samples with heavier stops can also be excluded by these two channels. But in the latter case, the stop mass is hardly bounded by stop searches due to the suppression of  $\tilde{t} \rightarrow t\tilde{\chi}_{1,2}^0$ . Besides, we note that the sbottom search data for  $2b + \cancel{E}_T$  can give a complementary constraint on the stop mass, which excludes a light stop between 235-350 GeV in the former case, and the exclusion limit can reach up to 545 GeV in the latter case.

In Fig. 4 [Figure 4: see original paper] we combine the above exclusion limits from the three channels using the CLs method. It can be seen that the data can exclude at 95% CL a stop between 200-670 GeV for  $m_{\tilde{t}_L} < m_{\tilde{t}_R}$  and 250-600 GeV for  $m_{\tilde{t}_L} > m_{\tilde{t}_R}$ . These combined limits are much stronger than the limits from any single channel.

Note that since our analysis aims at natural SUSY where the value of  $\mu$  is preferred to be small (usually below 200 GeV), our results are relevant for low  $\mu$ . If  $\mu$  becomes large (the lightest neutralino becomes heavy) but the stop mass is fixed, the small mass difference between them will make the visible

decay products (jets or leptons) from the stop soft. Thus the signal detection efficiency becomes lower and our direct search limits become weaker. We checked and found that when  $m_{\tilde{t}_1} = 500$  GeV,  $\mu > 300$  GeV can escape the constraints considered in this work. Besides, we note that if  $\mu$  gets heavier, the stop should also become heavy to keep the neutralino as the LSP, which will suppress the production rate of stop pairs and evade our constraints.

The effects of  $\tan\beta$  on our results are shown in Fig. 5 [Figure 5: see original paper] for the case of  $m_{\tilde{t}_L} < m_{\tilde{t}_R}$ . From this figure we see that the limits become weaker for large  $\tan\beta$ . The reason is that in the case of  $m_{\tilde{t}_L} < m_{\tilde{t}_R}$  the decay width of  $\tilde{t}_1 \rightarrow \tilde{\chi}_1^+ b$  is determined by  $y_b \sim 1/\cos\beta$ , while the decay width of  $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$  is determined by  $y_t \sim 1/\sin\beta$ , and thus when  $\tan\beta$  becomes large, the branching ratio of  $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$  will be suppressed. Then the limits on the stop mass, which dominantly come from the decay  $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$ , will become weak.

In the case of  $m_{\tilde{t}_L} > m_{\tilde{t}_R}$ , our results are not sensitive to the value of  $\tan\beta$  because in this case the decay widths of  $\tilde{t}_1 \rightarrow \tilde{\chi}_1^+ b$  and  $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$  are both determined by  $y_t$  and their branching ratios are not sensitive to  $\tan\beta$ .

In Fig. 6 [Figure 6: see original paper] we display the impact of direct stop/sbottom searches on the stop sector. From the left panel we see that two regions can be excluded by direct searches at 95% CL. The right panel shows that the range of  $2 < X_t/M_S < 3$  can be excluded for  $m_{\tilde{t}_1} < 600$  GeV at 95% CL.

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### ### IV. CONCLUSION

We studied the constraints of LHC search results on the stop mass in natural SUSY. Considering constraints from the Higgs mass, B-physics, and electroweak precision measurements, we scanned the parameter space of natural SUSY in the framework of MSSM, and then in the allowed parameter space we performed Monte Carlo simulations for stop pair production followed by  $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$  and sbottom pair production followed by  $\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$ ,  $\tilde{b}_1 \rightarrow t\tilde{\chi}_1^-$ , or  $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^+$ . Using the combined ATLAS results with  $20.1 \text{ fb}^{-1}$  from searches for  $\ell + \text{jets} + \cancel{E}_T$ , hadronic  $t\bar{t} + \cancel{E}_T$ , and  $2b + \cancel{E}_T$ , we found that a stop lighter than 600 GeV can be excluded at 95% CL.

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### ### APPENDIX A: COMPARISON OF OUR SIMULATION WITH THE ATLAS RESULTS

In the following we present the comparison of our simulation with the ATLAS results. In Tables II, III, and IV we present the results for  $2b + \cancel{E}_T$ ,  $\ell + \text{jets} + \cancel{E}_T$ , and hadronic  $t\bar{t} + \cancel{E}_T$ , respectively.

**TABLE II: Comparison of ATLAS and our simulation for  $2b + \cancel{E}_T$  when  $(\tilde{b}_1, \tilde{\chi}_1^0) = (600, 1)$  GeV**

| Cut   | ATLAS | Our simulation |
|---|-------|----------------|
| $\cancel{E}_T > 150$ GeV                          |       |                |
| $p_T(j_1), p_T(j_2), j_3$ (veto)                  |       |                |
| $\Delta\phi_{\min}(3 \text{ jets}, \cancel{E}_T)$ |       |                |
| $m_{\text{eff}}(j_1, j_2, j_3)$ and $b$ -tag      |       |                |
| $m_{CT} > 100$ GeV                                |       |                |

**TABLE III: Comparison of ATLAS and our simulation for  $\ell + \text{jets} + \cancel{E}_T$  when  $(\tilde{t}_1, \tilde{\chi}_1^0) = (650, 1)$  GeV**

| Cut  | ATLAS | Our simulation |
|--|-------|----------------|
| No selection                                 |       |                |
| 1 $\mu$ and 4 jets (80, 60, 40, 25)          |       |                |
| $\geq 1$ $b$ -tag in 4 leading jets          |       |                |
| $\cancel{E}_T > 100$ GeV                     |       |                |
| $\cancel{E}_T/H_T > 5$                       |       |                |
| $\Delta\phi(\text{jet}, \cancel{E}_T) > 0.8$ |       |                |
| $\cancel{E}_T > 200$ GeV                     |       |                |
| $\cancel{E}_T/H_T > 13$                      |       |                |
| $m_T > 140$ GeV                              |       |                |

**TABLE IV: Comparison of ATLAS and our simulation for hadronic  $t\bar{t} + \cancel{E}_T$  when  $(\tilde{t}_1, \tilde{\chi}_1^0) = (600, 0)$  GeV**

| Cut   | ATLAS | Our simulation |
|---|-------|----------------|
| No selection  |       |                |
| $e/\mu$ veto  |       |                |
| $\cancel{E}_T > 130$ GeV  |       |                |
| Jet multiplicity and $p_T > 30$ GeV                             |       |                |
| $\cancel{E}_T^{\text{track}}$                                   |       |                |
| $\Delta\phi(\text{jet}, \cancel{E}_T) > \pi/5$                  |       |                |
| $\Delta\phi(\cancel{E}_T, \cancel{E}_T^{\text{track}}) < \pi/3$ |       |                |
| $\tau$ veto and $b$ -tag  |       |                |
| $m_T(b\text{-jet}, \cancel{E}_T) > 175$ GeV                     |       |                |
| $80$ GeV $< m_{0,1}^{jj} < 270$ GeV                             |       |                |
| $\cancel{E}_T > 150$ GeV  |       |                |

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