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Abstract

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Full Text

Preamble

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Top-squark in natural SUSY under current LHC run-2 data

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Abstract

We utilize recent LHC-13 TeV data to study the lower mass bound on the top-squark (stop) in natural supersymmetry. We recast the LHC sparticle inclusive search for ($\geq$ 1) jets + $\not{E}_T$ with the α_T variable, the direct stop pair searches (1-lepton channel and all-hadronic channel), and the monojet analyses. We find that these searches are complementary depending on stop and higgsino masses: for a heavy stop the all-hadronic stop pair search provides the strongest bound; for an intermediate stop the inclusive SUSY analysis with the α_T variable is most efficient; while for a compressed stop-higgsino scenario the monojet search plays the key role. Finally, the lower mass bound on a stop is: (i) 320 GeV for a compressed stop-higgsino scenario (mass splitting less than 20 GeV); (ii) 765 (860) GeV for higgsinos lighter than 300 (100) GeV.

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Introduction

The discovery of the Higgs boson is a great triumph for the Standard Model (SM). However, the SM Higgs mass is quadratically sensitive to the cutoff scale Λ (usually taken as GUT or Planck scale) via radiative corrections because of the lack of symmetry protection. This renders the SM with $m_h \sim 125$ GeV $\ll \Lambda$ rather unnatural. A well-known theory for solving this naturalness problem is supersymmetry.

Among various supersymmetric models, natural supersymmetry (NSUSY) is a well-motivated framework [**?**], which consists of a small set of sparticles closely related to naturalness, such as higgsinos, stops, and gluinos. This can be understood from the minimization of the Higgs potential [**?**]:

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

where μ is the higgsino mass parameter in the superpotential and contributes to M_Z at tree level, $\tan\beta \equiv v_u/v_d \gg 1$ is assumed in the last approximate equality, $m_{H_u}^2$ and $m_{H_d}^2$ denote the soft SUSY-breaking masses of the Higgs fields at the weak scale, and Σ_u and Σ_d arise from radiative corrections to the Higgs potential. Due to the large top Yukawa coupling, Σ_u is dominated by the stop at 1-loop level, while the gluino contributes to Σ_u via corrections to the stop mass. Other contributions from the first two generations of squarks and sleptons to M_Z are negligibly small. Therefore, the requirement of obtaining the correct value of M_Z without fine-tuning imposes upper bounds on the masses of higgsinos, stops, and gluinos [**?**, **?**].

With the recent ~ 15 fb^{-1} dataset at LHC run-2, stop and gluino masses have been excluded up to $\sim$ 1 TeV [**?**] and 1.8 TeV [**?**], respectively, while electroweakinos below $0.4 - 1$ TeV can also be covered for different decay channels [**?**]. However, these limits are obtained in simplified models and depend sensitively on assumptions about the nature of the lightest supersymmetric partner (LSP), the branching ratios of heavier sparticles, and the mass splitting between heavier sparticles and the LSP. Therefore, it is necessary to examine the current LHC run-2 coverage of NSUSY and assess the extent of fine-tuning. In this work, we utilize recent results from LHC run-2 inclusive sparticle searches and direct stop pair searches to constrain the stop mass in NSUSY. We compare their sensitivities and find that they are complementary in probing NSUSY. We also evaluate the electroweak fine-tuning measure in the allowed parameter space of NSUSY and comment on the prospects for covering the low fine-tuning parameter space of NSUSY at HL-LHC.

II. Constraints on Stop in NSUSY

In the MSSM, the stop mass matrix in the weak basis $(\tilde{t}_L, \tilde{t}_R)$ is given by:

$$\begin{pmatrix} m_Q^2 + m_t^2 + \cdots \& m_t X_t^\dagger \\ m_t X_t \& m_U^2 + m_t^2 + \cdots \end{pmatrix}$$

where $X_t = A_t - \mu \cot\beta$. The weak eigenstates $\tilde{t}_{L,R}$ can be rotated to the mass eigenstates $\tilde{t}_{1,2}$ by a unitary transformation:

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

After diagonalizing the mass matrix, we obtain the stop masses $m_{\tilde{t}_{1,2}}$ and the mixing angle $\theta_{\tilde{t}}$ $(-\pi/2 \leq \theta_{\tilde{t}} \leq \pi/2)$:

$$m_{\tilde{t}_{1,2}}^2 = \frac{1}{2}\left[(m_Q^2 + m_U^2) + 2m_t^2 \pm \sqrt{(m_Q^2 - m_U^2)^2 + 4m_t^2 X_t^2}\right],$$

$$\tan 2\theta_{\tilde{t}} = \frac{2m_t X_t}{m_Q^2 - m_U^2}.$$

The decays of the stop are determined by its interactions with neutralinos/charginos, given by:

$$\mathcal{L}_{\tilde{t}1\bar{b}\tilde{\chi}^+} = \tilde{t}_1 \bar{b}(f_L^C P_L + f_R^C P_R)\tilde{\chi}_i^+ + \text{h.c.},$$

$$\mathcal{L}_{\tilde{t}1\bar{t}\tilde{\chi}^0} = \tilde{t}_1 \bar{t}(f_L^N P_L + f_R^N P_R)\tilde{\chi}_i^0 + \text{h.c.},$$

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

$$f_L^N = -\frac{g_1 N_{i1}^*}{3\sqrt{2}} + g_2 N_{i2}^* \cos\theta_{\tilde{t}} - y_t N_{i4}^* \sin\theta_{\tilde{t}},$$

$$f_R^N = \frac{2\sqrt{2} g_1 N_{i1}^*}{3} \sin\theta_{\tilde{t}} - y_t N_{i4}^* \cos\theta_{\tilde{t}},$$

$$f_L^C = -g_2 V_{i1} \cos\theta_{\tilde{t}} + y_t V_{i2} \sin\theta_{\tilde{t}},$$

$$f_R^C = -y_b U_{i2}^* \cos\theta_{\tilde{t}},$$

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. The mixing matrices of neutralinos N_{ij} and charginos U_{ij}, V_{ij} are defined accordingly.

In NSUSY, $M_{1,2} \gg \mu$, so one has $V_{11}, U_{11}, N_{11,12,21,22} \sim 0$, $V_{12} \sim \mathrm{sgn}(\mu)$, $U_{12} \sim 1$ and $N_{13,14,23} = -N_{24} \sim 1/\sqrt{2}$. Thus $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_{1,2}^0$ are higgsino-like and nearly degenerate. The left-handed stop will mainly decay to $t\tilde{\chi}_1^0$ when phase space is accessible and $\tan\beta$ is small. While the couplings of the right-handed stop with $\tilde{\chi}_{1,2}^0$ are proportional to y_t, the branching ratios of $\tilde{t}_1 \to t\tilde{\chi}_{1,2}^0$ and $\tilde{t}_1 \to b\tilde{\chi}_{1,2}^+$ are about 25% and 50%, respectively [**?**].

To address the lower mass limit of the stop in NSUSY, we can focus on a right-handed stop. This is because the left-handed stop is linked with the left-handed sbottom by $SU(2)$ symmetry. Then, the left-handed sbottom decay channel $\tilde{b}_1 \to t\tilde{\chi}_1^-$ mimics the left-handed stop signals $\tilde{t}_1 \to t\tilde{\chi}_1^0$ since $\tilde{\chi}_{1,2}^0$ and $\tilde{\chi}_1^\pm$ are higgsino-like and degenerate in NSUSY. This enhances the LHC limit on a left-handed stop, which is stronger than the limit on a right-handed stop [**?**, **?**].

Now we examine the constraints on the NSUSY scenario that consists of a right-handed stop and higgsinos. We scan the parameter space in the ranges:

$$100 \text{ GeV} \leq m_{\tilde{Q}3}, m_{\tilde{U}3} \leq 2.5 \text{ TeV},$$

$$1 \text{ TeV} \leq A_t \leq 3 \text{ TeV},$$

$$5 \leq \tan\beta \leq 50.$$

The lower limit on the higgsino mass is motivated by LEP searches for electroweakinos. We require the stop mixing angle $|\sin\theta_{\tilde{t}}|^2 > 0.5$ to obtain a right-handed stop $\tilde{t}_1$. Since the gluino contributes to the naturalness measure at 2-loop level, low fine-tuning allows the gluino to have a mass up to several TeV, which may be beyond LHC reach. Therefore, we assume the gluino mass parameter $M_3 = 2$ TeV in our scan. Since electroweak gauginos, heavy Higgs bosons, sleptons, the first two generations of squarks, and the right-handed sbottom are not strongly related to naturalness, we decouple their contributions by fixing $M_1 = M_2 = m_A = m_{\tilde{\ell}} = m_{\tilde{q}_{1,2}} = m_{\tilde{d}R} = 2$ TeV at the weak scale.

In our scan, we impose the following indirect constraints:

- **Higgs mass**: We require that the lighter CP-even Higgs boson be the SM-like Higgs boson with a mass in the range 125 ± 2 GeV, calculated using FeynHiggs-2.11.2 [?]. The prediction of the SM-like Higgs mass depends on the spectrum generator. Differences arise from the choice of renormalization scheme and higher-order correction calculations. These effects often lead to a few GeV uncertainty for the SM-like Higgs mass in the MSSM [?].
- **Vacuum stability**: We impose the constraint of metastability of the vacuum state by requiring $|A_t| \lesssim 2.67\sqrt{m_Q^2 + m_U^2 + M_3^2}\cos^2\beta$ [?], because large trilinear parameter A_t can potentially lead to a global vacuum where charge and color are broken [?, ?].
- **Low-energy observables**: We require our samples to satisfy the bound from $B \to X_s\gamma$ at the 2σ level, implemented using SuperIso v3.3 [?].
- **Dark matter detection**: We require the thermal relic density of neutralino dark matter Ωh^2 to be below the 2σ upper limit from the 2015 Planck value [?] and the LUX WS2014-16 [?] results for the spin-independent neutralino-proton scattering cross section $\sigma_{\rm SI}$. We use MicrOmega v2.4 [?] to calculate Ωh^2 and $\sigma_{\rm SI}$, with $\sigma_{\rm SI}$ rescaled by a factor of $\Omega h^2/\Omega_{\rm PL}h^2$. The thermal relic density of light higgsino-like neutralino dark matter is typically low due to large annihilation rates in the early universe. One possible way to produce the correct relic density is introducing mixed axion-higgsino dark matter [?]. However, if the naturalness requirement is relaxed, heavy higgsino-like neutralino with mass $\sim 1-2$ TeV can solely produce the correct relic density in the MSSM [?].

The LHC run-2 experiments have covered a wide parameter space of the MSSM. We list the relevant LHC experimental analyses for our scenario:

- **From ATLAS**:
  - Stop, 0 lepton + (b)jets + $\not{E}_T$, 13.3 fb^{-1} [?]
  - Stop, 1 lepton + (b)jets + $\not{E}_T$, 13.3 fb^{-1} [?]
  - Stop, 2 leptons + (b)jets + $\not{E}_T$, 13.3 fb^{-1} [?]
  - Sbottom, 2 b-tagged jets + $\not{E}_T$, 3.2 fb^{-1} [?]
  - Compressed Spectrum, 1 jet + $\not{E}_T$, 3.2 fb^{-1} [?]
- **From CMS**:
  - Inclusive, 0 lepton + ≥ 1 jets + $\not{E}_T$ + α_T, 12.9 fb^{-1} [?]
  - Inclusive, 0 lepton + ≥ 1 jets + $\not{E}_T$ + M_{T2}, 12.9 fb^{-1} [?]
  - Inclusive, 0 lepton + ≥ 1 jets + $\not{E}_T$ + $H_{\rm miss}$, 12.9 fb^{-1} [?]
  - Stop, 0 lepton + (b)jets + $\not{E}_T$, 12.9 fb^{-1} [?]
  - Stop, 1 lepton + (b)jets + $\not{E}_T$, 12.9 fb^{-1} [?]

- Compressed Spectrum, 1 jet + soft lepton pair + $\not{E}_T$, 12.9 fb^{-1} [?]

It should be mentioned that the higgsinos $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_{1,2}^0$ have small mass differences in NSUSY. Then the decay products of $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$ are too soft to be tagged at the LHC. So the stop decays can be categorized into two topologies: $2b + \not{E}_T$ and $t\bar{t} + \not{E}_T$.

Among the current ATLAS searches for the stop, the all-hadronic final state channel has better sensitivity than those with leptons in the high stop mass region ($m_{\tilde{t}1} > 800$ GeV) because of the application of boosted top techniques. Similar results are obtained by the CMS collaboration. With decreasing mass splitting $\Delta m_{\tilde{t}1-\tilde{\chi}_1^0}$, conventional stop searches for energetic top quarks in the final states become less effective. In particular, if $\Delta m_{\tilde{t}1-\tilde{\chi}_1^0} \lesssim m_t$, the stop decay will be dominated by the four-body channel $\tilde{t}_1 \to bf\bar{f}'\tilde{\chi}_1^0$ [?] or the two-body loop channel $\tilde{t}_1 \to c\tilde{\chi}_1^0$ [?]. Then the decay products of the stop are usually very soft, so a high p_T hard jet from ISR/FSR is needed to tag these compressed stop events, such as in the ATLAS monojet analysis listed above. Note that the very recent CMS monojet with soft lepton pair analysis of compressed electroweakinos can exclude wino-like chargino mass $m_{\tilde{\chi}_1^{\pm}}$ up to 175 GeV for a mass difference of 7.5 GeV with respect to the LSP. However, this limit is not applicable to our scenario because the cross section of higgsino pair production is 1/4 of the wino pair.

On the other hand, both ATLAS and CMS experiments have performed inclusive SUSY searches for final states with (generally untagged) jets and large $\not{E}_T$, which can also be used to derive limits on parameter spaces in various simplified models. In our study, we reinterpret the recent CMS analysis of 0-lepton + (≥ 1) jets + $\not{E}_T$. This strategy is built around the kinematic variable α_T, constructed from jet-based quantities to provide strong discriminating power between genuine and misreconstructed $\vec{p}_{\text{miss}}$. Such a variable can highly suppress multijet backgrounds and is suitable for early searches at 13 TeV LHC. Based on these considerations, we use four LHC experimental analyses to constrain the NSUSY parameter space, listed in Table I.

In our Monte Carlo simulations, we use MadGraph5_{aMC}@NLO [?] to generate parton-level signal events, which are showered and hadronized by PYTHIA [?]. Detector simulation effects are implemented with Delphes [?]. Jets are clustered with the anti-k_T algorithm [?] using FastJet [?]. The stop pair production cross section at 13 TeV LHC is calculated by NLL-fast [?] with CTEQ6.6M PDFs [?]. We impose the ATLAS monojet constraint with MadAnalysis 5-1.1.12 [?]. The ATLAS 1-lepton stop and CMS 0-lepton stop analyses are implemented within the CheckMATE framework [?]. As mentioned above, we focus on the heavy stop mass range ($m_{\tilde{t}1} > 500$ GeV) for the CMS 0-lepton analyses because of improved sensitivity from top tagging techniques. Since the higgsinos $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_{1,2}^0$ are nearly degenerate in NSUSY, the stop decay $\tilde{t} \to b\tilde{\chi}^+$ gives the same topology as the sbottom decay $\tilde{b} \to b\tilde{\chi}^0$. Therefore, we can determine the exclusion limit on the stop using the cross section upper limit from CMS sbottom pair production.

In Fig. 1 [Figure 1: see original paper], we project samples allowed by Higgs mass, vacuum stability, $B \to X_s\gamma$, and dark matter constraints onto the $m_{\tilde{t}1}$ versus $m_{\tilde{\chi}_1^0}$ plane. To quantitatively evaluate naturalness, we use the electroweak fine-tuning measure Δ_{EW} [?]:

$$\Delta_{\mathrm{EW}} \equiv \max_i |C_i|/(M_Z^2/2),$$

where $C_\mu = -\mu^2$, $C_{H_u} = -m_{H_u}^2 \tan^2\beta/(\tan^2\beta - 1)$, $C_{H_d} = m_{H_d}^2/(\tan^2\beta - 1)$, $C_{\Sigma_u(i)} = -\Sigma_u(i)\tan^2\beta/(\tan^2\beta - 1)$, and $C_{\Sigma_d(i)} = \Sigma_d(i)/(\tan^2\beta - 1)$, with i labeling various loop contributions to Σ_u and Σ_d. The one-loop stop contributions $\Sigma_u(\tilde{t}_{1,2})$ are given by [?]:

$$\Sigma_u(\tilde{t}_{1,2}) = \frac{3y_t^2}{16\pi^2} F(m_{\tilde{t}_{1,2}}^2) \left[1 - \frac{g^2}{3y_t^2} - \frac{8g_2^2}{9y_t^2} - \frac{2\Delta_t}{3x_W}\right],$$

where the form factor $F(m^2) = m^2\left(\log\frac{m^2}{Q^2} - 1\right)$ with optimized scale $Q^2 = m_{\tilde{t}1}m_{\tilde{t}2}$, y_t is the top quark Yukawa coupling, and $\Delta_t = (m_{\tilde{t}1}^2 - m_{\tilde{t}2}^2)\cos 2\beta\left(\frac{1}{2} + M_Z^2\cos^2\theta_W\right)/4 - 2m_t^2 x_W$, with $x_W \equiv \sin^2\theta_W$.

In Fig. 1, triangles (grey), squares (cyan), and bullets (red) represent samples with electroweak fine-tuning $\Delta_{\mathrm{EW}} < 10$, $10 < \Delta_{\mathrm{EW}} < 30$, and $30 < \Delta_{\mathrm{EW}} < 300$, respectively. In our parameter space, low fine-tuning $4 < \Delta_{\mathrm{EW}} < 10$ requires higgsino mass $\mu \lesssim 200$ GeV and stop mass 0.4 TeV $\lesssim m_{\tilde{t}1} \lesssim$ 1.3 TeV. It can be seen that 70% of such parameter space can be covered by current LHC run-2 SUSY searches. A lighter stop mass ($m_{\tilde{t}1} \lesssim 0.4$ TeV) requires a large trilinear parameter A_t to satisfy the Higgs mass constraint, which leads to large Δ_{EW}.

From Fig. 1 it can be seen that the ATLAS monojet search produces a strong exclusion limit in the low stop mass region, excluding stop masses up to 320 GeV for $m_{\tilde{\chi}_1^0} = 300$ GeV. This is because when the stop mass is close to the LSP mass, the b-jets from stop decay $\tilde{t}_1 \to b\tilde{\chi}_1^+/bf\bar{f}'\tilde{\chi}_{1,2}^0$ or c-jets from $\tilde{t}_1 \to c\tilde{\chi}_{1,2}^0$ are too soft to be identified. Thus the monojet search is very sensitive in the low stop region.

In the moderate or heavy stop region, the stop dominantly decays to $b\tilde{\chi}_{1,2}^+$ and $t\tilde{\chi}_{1,2}^0$, producing $2b + E_{\mathrm{miss}}$ and $t\bar{t} + E_{\mathrm{miss}}$ signatures, respectively. The CMS inclusive search with α_T shows better sensitivity than the 0/1-lepton stop searches in most of the parameter space. However, we note that the exclusion limit from the CMS 0-lepton stop search is slightly stronger than the CMS inclusive search because of the application of top tagging techniques in the ATLAS analysis. Finally, we conclude that stop masses can be excluded up to 765 (850) GeV for $m_{\tilde{\chi}_1^0} < 300$ GeV ($m_{\tilde{\chi}_1^0} = 100$ GeV) by current LHC run-2 experiments. These limits are much stronger than LHC run-1 limits on NSUSY, which excluded stops below 600 GeV [?, ?, ?].

The future high-luminosity LHC is expected to cover stop and higgsino masses up to 1.5 TeV and 0.6 TeV, respectively [?]. At that time, most of the NSUSY parameter space with $\Delta_{\mathrm{EW}} < 30$ can be covered [?, ?]. In the framework of the MSSM, heavy stops or large A_t are needed to raise the Higgs mass to 125 GeV, which causes a little fine-tuning problem. In some extensions like the NMSSM [?], the Higgs mass receives an additional tree-level term and can possibly avoid such a little fine-tuning problem.

III. Conclusions

In this paper, we examined the lower mass limit of the stop in natural supersymmetry (NSUSY) using recent LHC-13 TeV data. We recast the LHC SUSY inclusive search for (≥ 1) jets + $\not{E}_T$ events with the α_T variable, direct stop pair searches (1-lepton channel and all-hadronic channel), and monojet analyses. We found that the inclusive SUSY analysis with α_T is complementary to direct stop pair analyses in probing NSUSY. Current LHC data can exclude stops up to 765 (860) GeV for $m_{\tilde{\chi}_1^0} < 300$ GeV ($m_{\tilde{\chi}_1^0} = 100$ GeV). While in the compressed region ($\Delta m_{\tilde{t}1-\tilde{\chi}_1^0} \lesssim 20$ GeV), the stop mass can still be as light as 320 GeV. About 70% of the NSUSY parameter space with $\Delta_{\mathrm{EW}} < 10$ can be covered by current LHC run-2 data. The future HL-LHC is expected to push the lower mass limits of the stop and higgsino up to 1.5 TeV and 0.6 TeV, respectively, and cover most NSUSY parameter space with $\Delta_{\mathrm{EW}} < 30$.

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