Surviving scenario of stop decays for ATLAS $\ell + jets + E_T^{\text{miss}}$ search

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Recently ATLAS reported a 3.3$\sigma$ excess in the stop search with $\ell + jets + E_T^{\text{miss}}$ channel. We try to interpret the signal by a light stop pair production in the MSSM. We find: (1) simple models where stop decays into a higgsino or a bino are not favored. (2) an extension of them can explain the data at 2$\sigma$ level without conflicting with the other search channels. A surviving possibility includes a light stop and a light higgsino, which is expected in a natural SUSY scenario.

I. INTRODUCTION.

Supersymmetry (SUSY) is one of the most fascinating models beyond the Standard Model (SM), which can simultaneously solve the naturalness problem, explain the cosmic dark matter and achieve the gauge coupling unification. Searching for the SUSY particles is an important task for LHC especially after the discovery of Higgs. With the recent 13 fb$^{-1}$ dataset of LHC, a gluino and a stop lighter than 1.8 TeV and 900 GeV have been excluded out respectively if the mass splitting between the stop and the LSP is large enough, and the mass of an electroweakino has been excluded to 0.4-1 TeV depending on the decay mode. All the results push SUSY scale much higher than before, which further challenges our understanding on the naturalness problem.

Among those tens of super-particles, the top partner-stop, plays the most important role to understand the naturalness in SUSY models. In the framework of natural supersymmetry, a light stop and higgsino are usually predicted [1]. Lots of works have been done on searching for such light stops and higgsinos [2]. Recently ATLAS reported some excesses in the stop search with $\ell + jets + E_T^{\text{miss}}$ channel [3]. Seven signal regions are defined and three of them observed more than 2$\sigma$ excesses, among which the most significant one could reach 3.3$\sigma$. Although no significant excess is reported by CMS in the same channel [4], they observe mild excesses in several signal regions. Even in the 0 lepton channel searches [5–7], ATLAS and CMS both show small excesses with a lower significance. If they are true signals it is likely due to new particles.

In this paper, we study the interpretation of the excesses as light stop pair production in the minimal supersymmetric standard model (MSSM). Although ATLAS and CMS have done the similar analyses based on the simplified models, the results might be changed in a concrete model of MSSM. We show that the simplified models where stop decays into a higgsino or a bino are not favored by other stop searches while extended models could provide a better fit to the excess.

This paper is organized as follows. We first briefly overview the ATLAS $\ell + jets + E_T^{\text{miss}}$ search and the other constraints at the LHC in Section II. In Section III we interpret the excess by a light stop pair production in the MSSM. In Section IV, we discuss the dark matter constraints, such as the relic abundance and the direct detection constraints. We draw our conclusions in Section V.

II. STOP SEARCHES

A. ATLAS $\ell + jets + E_T^{\text{miss}}$ search

The ATLAS $\ell + jets + E_T^{\text{miss}}$ search mainly aims at stop pair production followed by stop decay into top and neutralino, where one of the resulting top decay leptonically. Although more details are found in [3] we summarize some of the selection cuts and the results in Table I. Seven signal regions are defined for the searches. Among them, the signal regions of DM$_{\text{low}}$, bC2x$_{\text{diag}}$ and SR1 observe 3.3$\sigma$, 2.6$\sigma$, 2.2$\sigma$ excesses, respectively. Interestingly, the SR1 signal region was already defined before and an excess around 2.3$\sigma$ had been reported even with the 3.2 fb$^{-1}$ data [8].

We provide brief comments on the search results.

(1) These seven signal regions are not exclusive. SR1, bC2x$_{\text{diag}}$ and DM$_{\text{low}}$, where the excesses are observed, could share the same signal events.

(2) The DM$_{\text{low}}$ and DM$_{\text{high}}$ shows similar excesses cut a lower $m_T$ cut and a tighter $m_T$ cut in DM$_{\text{low}}$. Since no excess is observed in the DM$_{\text{high}}$, hard $m_T$ events are not preferred.

(3) The bC2x$_{\text{med}}$ requires very high $p_T$ bottoms compared with the bC2x$_{\text{diag}}$. Since no excess is observed in the bC2x$_{\text{med}}$, presence of hard bottoms is not preferred.

In the following we focus on the excess in the signal region DM$_{\text{low}}$. The estimated event number of background

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Table I: Summary of some of the selection cuts and the results of the seven signal regions defined in ATLAS stop search in $\ell + jets + E_T^{miss}$ channel.

| Signal region | SR1 | tN_high | bC2x_diag | bC2x_med | bCbv | DM_low | DM_high |
|---------------|-----|---------|-----------|----------|------|--------|--------|
| $(n_j, n_b)$  | $(\geq 4, \geq 1)$ | $(\geq 4, \geq 1)$ | $(\geq 4, \geq 2)$ | $(\geq 4, \geq 2)$ | $(\geq 2, = 0)$ | $(\geq 4, \geq 1)$ | $(\geq 4, \geq 1)$ |
| $E_T$ [GeV]   | 260 | 450 | 230 | 210 | 360 | 300 | 330 |
| $m_T$ [GeV]   | 170 | 210 | 170 | 140 | 200 | 120 | 220 |
| $a_{m_T}$ [GeV] | 175 | 175 | 170 | 210 | - | 140 | 170 |
| Total background | 24 ± 3 | 3.8 ± 0.8 | 22 ± 3 | 13 ± 2 | 7.8 ± 1.8 | 17 ± 2 | 15 ± 2 |
| Observed      | 37  | 5    | 37  | 14  | 7   | 35   | 21   |
| $p_0(\sigma)$ | 0.012(2.2) | 0.26(0.6) | 0.004(2.6) | 0.40(0.3) | 0.50(0) | 0.004(3.3) | 0.09(1.3) |
| $N_{0_{obs}}^{\text{limit}}(95\% \text{ CL})$ | 26.0 | 7.2 | 27.5 | 9.9 | 7.2 | 28.3 | 15.6 |

TABLE I: Summary of some of the selection cuts and the results of the seven signal regions defined in ATLAS stop search in $\ell + jets + E_T^{miss}$ channel.

is $17 \pm 2$ while the observed number of events is 35 in DM\text{low}. From the background+signal hypothesis, estimated $2\sigma$-confidence interval for the number of signal is [7.4, 32.6] and the central value is 18.0. We summarize the confidence intervals used in our analysis in Table II. All the other signal regions listed in the Table I are considered for setting 95\% C.L. exclusion contours. Note that we don’t combine the results from different signal regions as they are not statistically independent. Instead, we overlay the preferred signal regions and the exclusion contours in the following analysis.

Table II: Confidence-intervals of the number of signal in DM\text{low} used in our analysis.

| Signal region | $2\sigma$ upper | $1\sigma$ upper | central | $1\sigma$ lower | $2\sigma$ lower |
|---------------|-----------------|-----------------|---------|-----------------|-----------------|
| DM\text{low}  | 32.6            | 24.7            | 18.0    | 12.2            | 7.4             |

TABLE II: Confidence-intervals of the number of signal in DM\text{low} used in our analysis.

B. Other stop search constraints

There are other stop searches based on 0 lepton, 1 lepton, and 2 leptons both from ATLAS and CMS, which constrain the stop parameter space. We have found the 1 lepton search constraints from CMS [4] gives more or less similar to that of the ATLAS, therefore, considering the signal regions with no excess in ATLAS 1 lepton search is enough. The two lepton search channels do not set strong constraints [9], and we did not consider them in this paper. The CMS 0 lepton search channels set slightly stronger bound than those of ATLAS, therefore, we consider the following two hadronic stop search channels at CMS to set the 95\% CL exclusion. The CMS boosted top search requires top tagging and is especially sensitive to the stop with a large mass splitting with LSP, where boosted tops are expected in the final state. The CMS hadronic stop search aims at more conventional topologies from stop decay. In the following, the ATLAS 1 lepton search is denoted as ATLAS\_1L, the CMS hadronic stop search [5] is denoted as CMS\text{hadronic} and CMS boosted top search [6] is denoted as CMS\text{boosted}.

III. SIMPLIFIED MODELS

In this paper we interpret the excess from a light stop pair production and their decays. We assume the lightest stop dominantly consists of the right handed stop ($\tilde{t}_R$). The $\tilde{t}_L$ usually is accompanied by $\tilde{b}_L$ which is close in mass, and it is constrained strongly with a bound up to about 1 TeV [10]. We first consider a simple 1-step decay from the right-handed stops. Depending on the dominant component of the LSP, the constraints are modified as the decay modes change. We scan the parameter space to figure out the corresponding $2\sigma$ favored region in DM\text{low}.

Our simulation for ATLAS\_1L and CMS\text{hadronic} searches are based on MadGraph + Pythia [11, 12], and the generated signal events are passed to Delphes3 [13] for a detector simulation. For recasting CMS\text{boosted} search we simply compare the cross sections rescaled with $BR(\tilde{t} \rightarrow t\tilde{\chi})^2$ with the upper bound of the cross section given in the CMS paper assuming the best sensitivity is from two boosted top tagged events.

FIG. 1: Stop decay in the simplified model.
A. Bino LSP

We first consider the simplest model: the lightest supersymmetric particle (LSP) is bino and the next-lightest supersymmetric particle (NLSP) is $t_R$. As shown in Fig 1, the only decay channel is $t \rightarrow \chi_1^0 + t$ in this model, which is frequently assumed for many analyses in ATLAS and CMS. In Fig 2 we show the $2\sigma$ favored region by the excess in $\text{DM}_{\text{low}}$ and the 95% C.L. exclusion contours on the $(m_t, m_{\chi_1^0})$ plane from ATLAS_1L, CMS_hadronic, and CMS_boosted searches. The strongest limit is from CMS_boosted search because the tops in the final state tend to be boosted. We find all the 1$\sigma$ region are excluded out by CMS_boosted and almost all the 2$\sigma$-region is excluded.

B. Higgsino LSP

To ease the tension from CMS_boosted stop search, we may consider a model where the stop has other decay channels than the direct decay into top and LSP. As an example, we consider another simplified model where LSP is higgsino. For the higgsino LSP case, the higgsinos ($\chi_{1,2}^0$) and charged higgsino ($\chi_1^\pm$) is naturally degenerate. As the typical mass difference is $\sim$ GeV, we cannot observe the decay products from those particles essentially and all particles behaves like LSP in terms of the collider signature at the LHC. The branching ratios are $BR(t_R \rightarrow t\chi_{1,2}^0) \sim BR(t_R \rightarrow b\chi_1^\pm)$ $\sim 50\%$ when the phase space suppression due to the top mass is negligible. Thus, the contribution of the two boosted tops is reduced by a factor $1/4$. Since CMS_boosted stop search relays on two boosted tops in the final states, the constraint becomes much weaker. On the other hand, the $1\ell$ signal can originate from events with one stop decay into a top and the other into a bottom, thus, there are no strong reduction factor. In Fig 3 we show the signal preferred region and several exclusion contours. In the plot we fixed $\tan \beta = 10$. Note the branching ratios of stop decay do not change a lot when we vary the $\tan \beta$ because higgsino-stop coupling only comes from the yukawa. The gray region is limited by direct chargino search from LEP[14]. The CMS_boosted stop search becomes significantly weaker, and there appears a large region not excluded by either ATLAS_1L and CMS_boosted but in the 2$\sigma$ favored region. However, the CMS_hadronic constraints are still strong enough to exclude the whole 2$\sigma$ signal favored region. It is because reducing $BR(t_R \rightarrow t\chi_{1,2}^0)$ also reduce the number of 1 lepton signals, while the conventional 0 lepton signals are not reduced and it results in a similar sensitivity to the Bino LSP case.

C. Higgsino + Bino LSP

Although by reducing $BR(t_R \rightarrow t\chi_1^0)$ the tension between CMS_boosted and ATLAS_1L searches could be eased, it also reduces the signal events and makes the conventional hadronic stop search relatively more effective. To avoid this situation, keeping more signal events while reducing top branching ratio is necessary, therefore, it is preferable to find a way to make the $BR(t_R \rightarrow b\chi_1^\pm)$ also contribute to enhance the lepton signals. We consider here a model where NLSP is higgsino and LSP is bino. Since the chargino will decay into $W^\pm$ plus neutralino, one lepton could come from the $W$ decay through a two step decay. We set the mass difference between stop and higgsino 150 GeV to forbid $t \rightarrow H_1^0 + t$ decay and make the discussion simpler. We have checked that opening $t \rightarrow H_1^0 + t$ mode also gives similar final results.

In Fig 5, we show our simulation results recasting the
FIG. 4: Stop decay in the Higgsino + Bino LSP model.

**ATLAS**\_1L, **CMS**\_hadronic, and **CMS**\_boosted searches on the \((m_\tilde{t}, m_{\chi^0})\) plane assuming \(m_{\tilde{\chi}^\pm} = m_\tilde{t} - 150\) GeV. Large parameter region in the Higgsino + Bino LSP model satisfying \(m_\tilde{t} \sim 800\) GeV with \(m_{\tilde{\chi}^\pm} \lesssim 350\) GeV or \(650\) GeV \(\lesssim m_\tilde{t} \lesssim 800\) GeV with \(m_{\chi^0} \sim 350\) GeV is found consistent within 2\(\sigma\) to all constraints although 1\(\sigma\) favored region is still excluded by both **ATLAS**\_1L and **CMS**\_hadronic.

**ATLAS**\_1L also provides the \(E_T\)\_miss and \(m_T\) distributions in **DM**\_1Low. We have selected three benchmark points, which are indicated with crosses in Fig 5, and show the expected distributions. The background distributions we just take from the **ATLAS** plots. The benchmark points with stop-bino mass 650–350 GeV, 750–300 GeV, 800–200 GeV predict the signal events in **DM**\_1Low to be 9.4 (1.6\(\sigma\)), 9.8 (1.5\(\sigma\)) and 8.3 (1.8\(\sigma\)), respectively. The numbers in the parentheses indicate the statistical deviations assuming the corresponding signal injection, to be compared with 3.3 \(\sigma\) of no signal assumption. Although all the benchmark points are consistent within 2\(\sigma\) based on the total number of events in **DM**\_1Low the predicted distributions are different. We find compressed spectrum is slightly preferred as the overflow bin doesn’t contain much events. In the future these distributions would be important to distinguish between models.

Although we only consider the Higgsino-Bino case (we denote the case with Higgsino NLSP and Bino LSP as Higgsino-Bino, etc. in the following), we would like give some comments on other possibilities. Since the coupling between stop (\(t_R\)) and Wino is suppressed by the neutralino mixing, the Wino-Bino (Wino-Higgsino) cases are essentially reduced to the Bino (Higgsino) LSP case. With the large L-R mixing in stop sector we can tune the relative branching ratios by the stop mixing angle and the collider signature of the Wino-Bino case could be similar to the Higgsino-Bino model. Three remaining possibilities are Bino-Higgsino, Bino-Wino, and Higgsino-Wino cases. For the Bino-Higgsino case, the stop dominantly decays into a higgsino, as stop couples higgsinos through the top yukawa coupling, which is much stronger than bino through the gauge coupling, and due to the phase space suppression, therefore, it is again reduced to the Higgsino LSP case. The Higgsino-Wino case is similar to the Higgsino-Bino case but the higgsino decay pattern is more complex, and branching ratio into \(W\) would be suppressed. The Bino-Wino case might be
an interesting possibility but constrained by the multi-lepton searches. On the other hand, direct detection con-straint must be significantly weak for this case whereas indirect searches might be dangerous. Also notice that the long lived charged particle searches at 8 TeV LHC already set the lower bound of the wino mass around 270 GeV [15], and the allowed parameter space would be highly constrained.

IV. DARK MATTER

In the previous section, we study the case where bino is the LSP. It might overclose the universe because the pair annihilation cross section of bino like dark matter is rather small. An interesting possibility is to resort to the slepton co-annihilation. If a slepton is nearly degenerate with the bino LSP $\sim 5$ GeV [16] it would help to reduce the relic abundance to the observed one. One may wonder inserting slepton in the spectrum will affect the decay mode of the chargino. As the coupling between slepton and higgsino is proportional to the corresponding lepton yukawa coupling only a light stau with a large $\tan \beta$ could affect the branching ratios. Note that the chargino decaying into neutralino plus $W$ is dominated by the longitudinal mode of $W$ (from $H-H-B$ interaction), and not suppressed by the Higgsino-bino mixing. The stau decaying channel only becomes sizable when the $\gamma_t$ is enhanced by very large $\tan \beta$. Taking $\tan \beta = 10$ as an example, we find in our $2\sigma$ favored region, the stau decay mode at most has a branching ratio of $\sim 12\%$. If we reduce the $\tan \beta = 5$, this decay branching ratio only takes $3\%$, so our Fig 5 is essentially unchanged. Moreover, the $\tau$ emitted from the $\tilde{\tau}$ decay is not detectable at the collider due to the small mass difference.

The dark matter direct search also constrains the Higgsino-Bino model due to the mixing between higgsino and bino. In Fig 5 we draw the sensitivity of the latest LUX results [17] the parameter space on the left side of the line has been excluded. In the plot we fix $m_{\chi} - m_{\chi^0} = 150$ GeV and $\tan \beta = 10$, and the Higgs mass is also tuned to be 125 GeV. We find one of our benchmark points has been excluded out and one just lives the boundary of exclusion line. Therefore the future dark matter direct search will be important to test this scenario if the signal is confirmed at the LHC. Note that in the case of $\text{sign}(M_1/\mu) = -1$, there exists a blind spot region for dark matter direct search when $M_1 + \mu \sin 2\beta = 0$ is satisfied[18, 19].

We may also assume R-parity is violated and bino could decay into SM particles with the life time long enough in a collider time scale. In such a case, the constraints discussed in this section are not applicable.

V. CONCLUSION

In this paper, we try to interpret the $3.3\sigma$ excess reported in ATLAS $\ell + \text{jets} + \slashed{E}_T$ channel by a light stop pair production in the MSSM. After considering the consistency with other stop searches, we find: (1) simple models where stop decays into a higgsino or a bino are not favored by the other search channels (2) an extension of them, Higgsino-Bino LSP, can explain the data at $2\sigma$ level without conflicting with the other search channels. It is remarkable that the SUSY spectrum in the surviving stop decay scenario for the possible excess, that is a light stop and a light Higgsino, is nothing but what we expect in a natural SUSY.

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