Opening Up the Compressed Region of Top Squark Searches at 13 TeV LHC

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Light top superpartners play a key role in stabilizing the electroweak scale in supersymmetric theories. For $R$-parity conserved supersymmetric models, traditional searches are not sensitive to the compressed regions. In this Letter, we propose a new method targeting this region, with top squark and neutralino mass splitting ranging from $m_t - m_{\chi} \gtrsim m_t$ to about 20 GeV. In particular, we focus on the signal process in which a pair of top squarks are produced in association with a hard jet, and we define a new observable $R_M$ whose distribution has a peak in this compressed region. The position of the peak is closely correlated with $m_t$. We show that for the 13 TeV LHC with a luminosity of 3000 fb$^{-1}$, this analysis can extend the reach of the top squark in the compressed region to $m_t$ around 800 GeV.

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Introduction.—With the discovery of the Higgs boson [1,2], particle physics reached an important milestone. However, the mechanism of stabilizing the electroweak scale from large quantum corrections is one of the outstanding mysteries. In most of the models addressing this problem, a key ingredient is a light top partner. As the most prominent example, in supersymmetry, the top squark $\tilde{t}$ should be less than about a TeV to be an effective solution to the fine-tuning problem [3]. Traditional searches for top squarks focus on pair production of top squarks where each of them decays into $t$ and the lightest supersymmetric particle (LSP), $\chi$. If $m_\tilde{t} \gg m_\chi + m_t$, the top quark can be quite energetic. In the top pair production, a main background of this search, most of the top quarks are produced near the threshold. Based on this observation, various kinematical variables (e.g., $m_{T2}$ [4–8], $H_T$ [9], the razor variables [10–12], and the variables invented in Ref. [13]) have been defined to distinguish top squark pair production from top pair production. For recent global studies of the minimal version of the supersymmetric standard model, see Ref. [14] and the references therein. However, in the compressed region where $m_\tilde{t} \approx m_t + m_\chi$, the kinematics of the top quarks from top squark decay are similar to those in the top pair production, and such observables are less sensitive. In the region that $m_\chi \ll m_\tilde{t} \approx m_t$, spin correlations of the top quarks can help to distinguish the signal from the background [15–17]. Such analysis has been done by the CDF, D0, ATLAS, and CMS collaborations [18–25]. However, with larger $m_\tilde{t}$ this method does not work well due to a smaller production rate. In other extreme regions of the parameter space $m_\tilde{t} \approx m_\chi$, $\tilde{t}$ decays into four-body final states or a light quark plus the LSP through flavor-changing processes. In cases where the flavor-changing processes are important, charm tagging can be useful [26–28]. However, the jets from the decay are usually soft and cannot be identified. The leading search channel is monojet + missing transverse energy (MET) [29–40]. Light top squarks can also be probed directly by comparing the observed $tt$ or $W^+W^−$ pair production rate with theoretical calculations [41–43]. However, it will be difficult for this method to benefit from larger luminosity and higher energies in future runs of the LHC since its sensitivity is mainly limited by systematic errors. Vector boson fusion tagging has also been proposed to search for a top squark in the compressed region, and it has been shown that it still cannot fully close the gap in the compressed region [44]. If the lifetime of the top squark is long enough, a pair of top squarks can form a bound state, the top squarkonium. In this case, searches of the top squarkonium can be sensitive to these compressed regions [45–47]. For recent detailed studies of LHC sensitivities, see Ref. [48] and the references therein. In this region, the top squarks can also hadronize first and then decay with displaced vertices [49]. If the heavier top squark is reachable, one can also study the decay of the heavier top squark to the Higgs boson or $Z_0$ together with the lighter top squark [50–53]. If the sleptons or charginos are lighter than the compressed top squark, the decay pattern of the top squark can be changed dramatically. See Ref. [54] for a recent study of these scenarios. Constraints on masses of the two top squarks can also be inferred from the measurement of the Higgs mass and production rate [55,56]. Light top squarks also get constraints from low energy precision experiments such as the $b \rightarrow s\gamma$ experiment [57–59].

However, it is still difficult for current searches to cover the compressed region with mass splitting ranging from $m_\tilde{t} - m_\chi \gtrsim m_t$ to much smaller values of about 20 GeV. In this Letter, we introduce a new kinematical observable which targets the kinematics of this compressed region, and we demonstrate its effectiveness. We note that there are
other studies focusing on a similar parameter region [35,60,61]. In particular, the strategy adopted in Ref. [35] can cover parameter space around $m_t \approx m_W + m_b + m_\chi$, although it is less effective for $m_t \approx m_t + m_\chi$.

Kinematics around the compressed region.—In the compressed region $m_t \gtrsim m_t + m_\chi$, the $\tilde{t}$ first decays into a pair consisting of $t$ and $\chi$. Because of the compressed nature of the rest frame of $\tilde{t}$, $\chi$ and $t$ are almost at rest. Therefore, in the lab frame, the transverse momenta of $\tilde{t}$ and $\chi$ have a simple relation such that $\vec{p}_T(\chi) = (m_\chi/m_t)\vec{p}_T(\tilde{t})$. Therefore, in the process of $\tilde{t}$ pair production, the contributions to MET from the two $\chi$’s approximately cancel each other, and as a result the kinematics of the top quarks from $\tilde{t}$ pair production is very similar to that of top pair production, making the search very difficult. We propose focusing on events with an additional hard jet from initial state radiation (ISR). In this case, we have $\vec{p}_T(j_{\text{ISR}}) = -[\vec{p}_T(\tilde{t}_1) + \vec{p}_T(\tilde{t}_2)]$, where $\tilde{t}_1$ and $\tilde{t}_2$ are the two top squarks produced in this process. Therefore, the ratio between MET and the $p_T(j_{\text{ISR}})$

$$R_M = \frac{\vec{p}_T}{\vec{p}_T(j_{\text{ISR}})} \approx m_\chi/m_t,$$  

(1)

where $p_T$ is the total MET in this process. Hence, we expect a peaklike feature in the $R_M$ distribution. Reference [60] also noted a similar kinematical feature. The spread of this peak can come from several sources. In the rest frame of $\tilde{t}$, the momentum acquired by $\chi$ can be written as

$$\Delta p_\chi = \frac{[m_\chi^2 - (m_t + m_\chi)^2][m_\chi^2 - (m_t - m_\chi)^2]}{2m_t}.$$  

(2)

Therefore, in the compressed region,

$$\Delta p_\chi \approx \left(\frac{2m_t m_\chi \Delta m}{m_t}\right)^{1/2} \lesssim (2m_t \Delta m)^{1/2},$$  

(3)

where $\Delta m \equiv m_t - m_\chi - m_t$. In most of the parameter space we are interested in this study, the boosts of the $\tilde{t}$’s are small. Therefore,

$$\Delta R_{\text{parton}} = \Delta p_\chi/\vec{p}_T(j_{\text{ISR}})$$  

(4)

can serve as a good estimate of the width of the peak in the $R_M$ distribution at parton level. In practice, additional soft radiation and detector effects will also smear the distribution of $R_M$. Nevertheless, as we will demonstrate, there is still a peak in the $R_M$ distribution around $m_\chi/m_t$ in the compressed region.

In the compressed region where $m_t \gtrsim m_t + m_\chi$, the $\tilde{t}$ decays into $\chi$ and $b$ and $W$ through a virtual $t$. Neglecting the spin correlation between the initial and final states, the differential decay width of $\tilde{t}$ with respect to the invariant mass of the virtual $t$ can be written as

$$\frac{d\Gamma_{\tilde{t}}}{dq_t} \approx \frac{\Gamma_{\tilde{t}}(q_t)}{\pi} \frac{q_t^2 \Gamma_{\chi}(q_t)}{(q_t^2 - m_t^2)^2},$$  

(5)

where $q_t$ is the virtual mass of the top quark. $\Gamma_{\tilde{t}}(q_t)$ is the two-body decay width of $\tilde{t}$ with replacement $m_t \to q_t$, and $\Gamma_{\chi}(q_t)$ is the decay width of $t$, replacing $m_t \to q_t$. Equation (5) implies that $q_t$ prefers to be as close to $m_t$ as possible, with maximal value $q_{t\text{max}} = m_t - m_\chi$. Hence, even when the top quarks are virtual, the $\chi$ decayed from each $\tilde{t}$ still prefers to be at rest in the rest frame of $\tilde{t}$. Therefore, the relation shown in Eq. (1) still holds approximately. Since we are not far away from the region where the top is on shell, we expect the spread of the peak at parton level to still be around the value given by Eq. (3), with the replacement $\Delta m \to |\Delta m|$.

Similarly, we also expect to see a sharp peak in the $R_M$ distribution at the compressed region $m_t \approx m_W + m_b + m_\chi$, where the $W$ boson and the LSP is approximately stationary in the top squark rest frame. The width of the peak in the $R_M$ distribution at parton level can be estimated using Eq. (4), with $m_t$ in Eq. (3) replaced by $m_W$.

Standard model (SM) background and basic cuts.—For this analysis, it is crucial to identify which jet is from ISR. $\tilde{t}$’s with a mass of several hundred GeV are not usually highly boosted. Therefore, in the compressed region, the $\tilde{t}$’s from the $\tilde{t}$ decay are also not highly boosted. Thus, the $p_T$ of the hardest jet in the decay chain of the $\tilde{t}$ is around $m_t$. As a consequence, if we require $p_T(j_0) \gg m_t$, where $j_0$ is the hardest jet, we find that it is very probable that $j_0$ is $j_{\text{ISR}}$. Hence, we will use the ratio $p_T/j_0$ as an approximation for $R_M$. The requirement of a large $p_T(j_0)$ also helps reduce the QCD background and sharpen the peak of the $R_M$ distribution, as shown in Eq. (4). In practice, we require $p_T(j_0) > 700$ GeV.

The leptonic decay of $t$ is always accompanied by neutrinos, which smears the peak structure in the $R_M$ distribution. In this analysis, we focus on the hadronic decays and veto events with charged leptons. At parton level, six soft jets from top decay appears. In practice, some of these soft jets may merge into a harder one. Therefore, we require at least three subleading jets with $p_T > 60$ GeV.

An important kinematical feature of the signal is that, in the compressed region, the $p_T(j_{\text{ISR}})$ is approximately in the opposite direction as the $p_T$. Therefore, we require $|\phi(j_0) - \phi_{\text{MET}} - \pi| < 0.15$. At the same time, we expect a significant QCD background from the mismeasurement of jet energy. To reduce the background due to the mismeasurement of the subleading jets, we require $|\phi_{\text{MET}} - \phi_j| > 0.2$ for all of the jets with $p_T > 60$ GeV. Requiring $p_T > 60$ GeV also helps to reduce pileup effects, which are significant during the high luminosity runs of the LHC.

To further reduce the QCD background, we require at least one $b$ jet to appear in the final state. The $b$-tagging efficiency we use is the exact $b$ tagging in the PGS detector simulator [62], in which the $b$-tagging efficiency is about 40% for $p_T(b) > 100$ GeV and within $|\eta| < 1.2$. For such a tagging efficiency, the mistag rate of light partons for
the CMS detector can be as small as 0.1% [63]. Detailed simulation shows that the main QCD background is from the processes with $b$ and $c$ quarks in the final states. Since it is very unlikely for a $b$ jet to be the leading ISR jet in the signal, we veto events where the leading jet has passed the loose $b$ tagging in the PGS detector simulation [62], which is around 45% for a jet with $p_T > 700$ GeV. This is smaller than the current benchmark $b$-tagging efficiency of the CMS and ATLAS detectors; therefore, our result is conservative.

**Numerical results.**—For both the background and the signal, the parton level simulations are done using MadGraph5/MadEvent [64] followed by a parton shower with PYTHIA6.4 [65]. The detector simulation is done using PGS4 [62] with an anti-$k_T$ jet algorithm with a distance parameter of 0.5 [66]. For the background, the MLM [67] matching scheme is also used to avoid double counting. For a signal, we checked the results from simulations with and without matching to ensure that the difference was within 20%. With all of the basic cuts discussed above, the $R_M$ distribution from SM processes with the cuts previously described is shown in Fig. 1. The dominant contribution to the background is from $t\bar{t}$ pair production with a hard ISR jet. In our signal region with a large $R_M$, a significant amount of MET is required. Since we veto events with charged leptons in the final state, the dominant contribution to the background is from leptonic decays of a top with $e/\mu$s. The second leading background comes from QCD multijet production with at least one of the jets containing a bottom or charm quark. The background from electroweak processes is not important due to their smaller rates.

From Fig. 1 one can see that both the $t\bar{t} + j_{\text{ISR}}$ background and the QCD background exponentially decrease with $R_M$ due to the lack of the source of MET. The background from electroweak processes is relatively flat but with a suppressed rate, as shown in Fig. 1. The total background is well fitted by a function

$$\frac{d\sigma}{dR_M} = A \exp(-BR_M),$$

where $A$ and $B$ depend on the details of the cuts, and in the current choice $A = 47$ fb and $B = 5.6$.

For the signal, the $R_M$ distribution for $m_t = 350$ GeV and several different $m_\chi$’s are shown in Fig. 2. To make the feature easier to visualize, we choose points very close to the mass thresholds with $\Delta m \approx 2$ GeV. One can see that in all cases the $R_M$ distribution is peaked at around $m_\chi/m_t$, with widths around 0.2. From Eq. (5), the width generated by the phase space of the decay of $\tilde{t}$ is about 0.05. Therefore, the typical width of the peak of the $R_M$ distribution induced by the parton shower and detector effect is about 0.2.

In order to take advantage of the peak in the $R_M$ distribution and the fact that the background decays exponentially with $R_M$, we add another cut that, for $m_\chi < m_t + m_\chi$,

$$\left(\frac{m_\chi}{m_t}\right) - 0.05 < \frac{p_T}{p_T(j_0)} < \left(\frac{m_\chi}{m_t}\right) + 0.15.$$

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**FIG. 1** (color online). Contributions to the background from various processes, after the basic cuts described in the text.

**FIG. 2** (color online). $R_M$ distributions for $m_t = 350$ GeV on both sides of the $m_t = m_\chi + m_\tau$ (top) and $m_t = m_\chi + m_W + m_b$ (bottom).
and for \( m_t > m_t + m_x \),

\[
\left( \frac{m_t - m_t}{m_t} \right) - 0.05 < \frac{p_T}{p_T(j_0)} < \left( \frac{m_t - m_t}{m_t} \right) + 0.15. \tag{8}
\]

As \( m_x \to 0 \), the background in the cut window defined in Eq. (7) grows exponentially. Therefore, for the region \( m_t > m_t + m_x \), we choose a different window [as shown in Eq. (8)] which is independent of \( m_x \), so that more parameter space in the bulk region can be covered effectively. We define the \( 5\sigma \) and \( 2\sigma \) expected limit by \( S/\sqrt{B} = 5 \) and \( S/\sqrt{B} + S = 2 \), where \( S \) and \( B \) are the signal and the background after all of the cuts. The \( 5\sigma \) reach at CMS with the center-of-mass energy of 13 TeV and luminosities of 300 and 3000 fb\(^{-1}\) are shown in the left panel of Fig. 3 together with the expected \( 5\sigma \) sensitivity of the direct top squark pair production at the 14 TeV LHC with the CMS detector \([68]\). The right panel shows the \( 2\sigma \) expected 95% C.L. exclusion limit together with the current combined limit from direct top squark pair production \([39,69,70]\). The current limits and the prospective reach of ATLAS are similar to CMS \([28,71–74]\), which are not shown here. One can see that \( \tilde{t} \) in the compressed region with a mass of around 600 GeV can be discovered in the LHC with 3000 fb\(^{-1}\). It can also exclude a top squark with a mass of up to about 800 GeV. Notice that there are “spikelike” features around the thresholds, \( m_t - m_x \approx m_t \) and \( m_t - m_x \approx m_W + m_b \), due to the fact that the peak in \( R_M \) is sharper around these thresholds.

**Conclusion and discussion.**—We point out a useful kinematical feature in the production of a top squark associated with an ISR jet, which can enhance the sensitivity in the compressed regions, with mass splitting ranging from \( m_t - m_t \approx m_t \) to about 20 GeV. We show that, in this region, the observable \( R_M \) defined in Eq. (1) has a peak around \( m_x/m_t \). Using this kinematical feature, we estimate that this gap can be covered up to around 800 GeV with the 13 TeV LHC at a luminosity of 3000 fb\(^{-1}\).

Although we have focused on the top squark searches, the same technique is obviously applicable to the search of other top partner signals with similar final states.

In the discussion, we neglect the flavor-changing decay mode \( \tilde{t} \to \chi c \) since it is model dependent and strongly constrained by flavor physics. It has been shown that, in the minimal flavor violation scenario, the branching ratio of this process is often subdominant to the four-body decay of the top squark in the region where \( m_t < m_x + m_W + m_b \) \([34]\). For detailed next-to-leading-order studies of the top squark decay pattern in this region, see Refs. \([49,75,76]\). This method is also applicable to other decay chains of the top squark in the compressed region \([77]\).

The main background of this analysis is from top pair production associated with ISR jets, with at least one element of the top pair decaying leptonically, and the charged lepton fails the lepton veto. A majority of these events have the charged lepton close to hadronic activities. One may be able to distinguish these events further with alternative lepton isolation criteria. The top quarks generated from the top squark decay in the signal display, in general, a smaller boost than the top quarks from the background since \( m_t > m_x \), which is assumed in this analysis. We may be able to use this property to further distinguish the top quarks from the signal and from the background. We leave this analysis to future work.
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