Reducing Top Quark Background to (“Non-Stealthy”) Stops

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Abstract: We present the current status for direct stop searches in the $R$-parity conserving case. We concentrate the parameter space with a large mass splitting between stop and neutralino (or chargino) masses. We discuss experimental search strategies and results with 0, 1, and 2 leptons. We also briefly comment on gluino mediated stop production.

Keywords: Top quark, Supersymmetry, MSSM, Hadronic Colliders, LHC
1 Introduction

Supersymmetry has long been considered a leading solution to the hierarchy problem \[1\]. As shown in other snowmass reports, vanilla SUSY scenarios with \(R\) parity conservation and, for example, approximate degeneracy between all the squarks, is now well constrained above the TeV scale. The squarks, however, need not all be degenerate for SUSY to solve the hierarchy problem \[2\], and recent LHC exclusions of vanilla scenarios has renewed focus on so-called natural SUSY \[3, 4\]. In this scenario, only the fields needed to solve the hierarchy problem are included in the low energy effective theory. These include the scalar top or stop \(\tilde{t}\), as well as the fermionic partner of the gluon, the gluino \(\tilde{g}\).

Motivated by dark matter and proton decay, we consider \(R\)-parity to be a good symmetry and imagine a neutral lightest supersymmetric particle (LSP) which all superpartners decay to and which escapes the detectors. We will denote the LSP by \(\chi^0\); it could be a neutralino or a more exotic gravitino or singlino. Here, we will consider direct production of stops with the decay of \(\tilde{t} \to t\chi^0\), and we will also consider decays to charginos \(\tilde{t} \to b\chi^+\) with the subsequent decay \(\chi^+ \to W^{(*)}\chi^0\) where the \(W\) may or may not be on shell. We also briefly consider gluino pair production with the decay \(\tilde{g} \to \tilde{t}\tilde{t}\).

A representative sample of searches from the ATLAS collaboration is given in Fig. 1. The bounds for the \(\tilde{t} \to t\chi^0\) scenario presented in the stop-LSP mass plane fully capture all the information, while for the \(\tilde{t} \to b\chi^+\) scenario, the parameter space is three dimensional.
2.1 Current Experimental Constraints

Figure 1. A combination of some of the latest bounds from the ATLAS collaboration for direct production of stops with in the stop-LSP mass plane [5]. The shaded regions are excluded with the regions on the right being for $\tilde{t} \rightarrow t \chi^0$ and the regions on the left being for $\tilde{t} \rightarrow b \chi^+ \chi^-$. The experiments present two dimensional slices of the bounds. A convenient parameter in this scenario is $x$ with $m_{\chi^0} = x \cdot m_t + (1 - x) \cdot m_{\chi^0}$.

This document is organized by search strategies with different numbers of leptons in the final state. We will give brief summaries of the experimental status, and then discuss potential improvements, most of which are given in the phenomenology literature.

2 Fully Hadronic Channel

The fully hadronic channel $t\bar{t}^* \rightarrow t\bar{t} + \chi^0\chi^0$ with a final state of $bjbjj\chi^0\chi^0$ has the largest branching fraction. Furthermore, there is no missing energy from neutrinos in the top decay, so the bulk of the real missing energy comes from the $\chi^0$. The dominant background is semileptonic top production, where the lepton is either lost, or a hadronic $\tau$.

2.1 Current Experimental Constraints

We have the following applicable experimental searches from CMS and ATLAS

- ATLAS with 4.7 fb$^{-1}$ at 7 TeV: for the $\tilde{t} \rightarrow t\chi^0$ scenario, $m_{\tilde{t}} < 330$ GeV or $m_{\tilde{t}} > 500$ GeV at 95% C.L. for a massless LSP and there is no bound for LSP masses above
90 GeV [6]. This search requires at least six jets, and forces the invariant mass of different triplets to be between 80 and 270 GeV.

- CMS with 4.98 fb$^{-1}$ at 7 TeV: for the $\tilde{t} \to t\chi^0$ scenario, $m_{\tilde{t}} < 300$ GeV or $m_{\tilde{t}} > 390$ GeV at 95% C.L. for a massless LSP, with no bound for an LSP mass above 70 GeV. They also place a bound on the $\tilde{t} \to b\chi^\pm$ scenario with the mixing parameter $x = 0.75$, $m_{\tilde{t}} < 270$ GeV or $m_{\tilde{t}} > 380$ GeV at 95% C.L. for neutralino masses less than approximately 60 GeV [7]. No requirement is made on jet invariant masses.

- CMS with 11.7 fb$^{-1}$ at 8 TeV: search for $b$-jets + missing energy using the $\alpha_T$ variable [8]. Places bound on direct $\tilde{b}$ production with $\tilde{b} \to b\chi^0$ of $m_{\tilde{b}} < 650$ GeV for LSP mass less than 200 GeV [9]. This constrains models where $\tilde{t} \to b\chi^+$ with $\chi^+$ nearly degenerate with $\chi^0$. There is a version of this analysis with 7 TeV data which interprets the limits in a $\tilde{t} \to t\chi^0$ scenario and sets the bound $m_{\tilde{t}} < 320$ GeV or $m_{\tilde{t}} > 500$ GeV for massless LSP [10].

- CMS with 4.7 fb$^{-1}$ at 7 TeV using razor variables [11]. Place bound on $\tilde{t} \to t\chi^0$ scenario $m_{\tilde{t}} < 320$ GeV or $m_{\tilde{t}} > 430$ GeV for massless LSP [12]. Also interpret limit in $\tilde{b} \to b\chi^0$ scenario.

### 2.2 New Variables to Improve the Current Searches

Phenomenological studies to improve this channel are based primarily on top-tagging [13–16]. The experimental searches referenced above do not fully utilize all the information that comes from the fact that there are on-shell tops in the final state. The ATLAS search [6] takes the three closest jets to one another in $\eta - \phi$ space and requires their invariant mass to be between 80 and 270 GeV, and it also requires three other jets to be in that window. Some of the CMS results [7, 9, 10] require $b$-tagged jets in the event. If there is large splitting between the mass of the stop and the LSP, the tops in the final state will be at least moderately boosted. This allows the use of jet substructure to reduce combinatoric background from jet pairing. With jet substructure techniques, experiments can not only use the fact that the top quark mass is known, but also the fact that the top decays to an on-shell $W$ whose mass is also known.

The phenomenological studies [13–15] use the HEP top tagger originally laid out in [13]. This involves first constructing fat jets, and then looking at the invariant masses of the three leading subjets in the fat jet to see if they look sufficiently top like. These analyses also incorporate standard cuts like missing energy, $b$-tagging, and $m_{T2}$. They make projections for reach at 14 TeV [13] as well as 7 [15] and 8 TeV [14, 15]. In [16], they take the invariant mass of the three highest $p_T$ jets which is similar in spirit to the ATLAS strategy in [6].

### 3 Single Leptonic Channel

The single-leptonic channel has been demonstrated to be the best channel to probe the parameter space of direct stop production with $\bar{t}t^* \to tt + \chi^0\chi^0$. The final state is $tt + E_T^{\text{miss}} \to$
\( b\bar{b}\ell\ell jj + E_T^{\text{miss}} \). The same final state can also be used to search for stop decaying into chargino via \( \tilde{t}\tilde{t}^* \to \bar{b}b + \chi^+\chi^- \to \bar{b}bW^+W^0\chi^0\chi^0 \). The main background is dileptonic \( t\bar{t} \) where one lepton is lost or a hadronic \( \tau \).

### 3.1 Current Experimental Constraints

We have the following results at ATLAS and CMS

- **ATLAS with 4.7 fb\(^{-1}\) at 7 TeV:** for the \( \tilde{t} \to t\chi^0 \) scenario, \( m_{\tilde{t}} < 230 \) GeV or \( m_{\tilde{t}} > 440 \) GeV at 95\% C.L. for a massless LSP and \( m_{\tilde{t}} > 400 \) GeV for the LSP masses up to 125 GeV [17]. The ATLAS search requires hadronic top mass reconstruction and has models assuming large right-handed polarization.

- **ATLAS with 13.0 fb\(^{-1}\) at 8 TeV:** for the \( \tilde{t} \to t\chi^0 \) scenario, \( m_{\tilde{t}} < 225 \) GeV or \( m_{\tilde{t}} > 560 \) GeV at 95\% C.L. for a massless LSP and \( m_{\tilde{t}} > 500 \) GeV for \( m_{\chi^0} \) up to 175 GeV [18]. Assuming \( \tilde{t} \to b\chi^\pm \), then \( m_{\tilde{t}} > 350 \) GeV for massless LSPs and a chargino mass of 150 GeV [18]. This search has used two asymmetric \( M_{T2} \) variables: \( aMT2 \) and \( m_{T2}^\tau \) to discriminate against dileptonic \( t\bar{t} \) background where one lepton is lost or decays into a hadronically decaying \( \tau \).

- **CMS with 9.7 fb\(^{-1}\) at 8 TeV:** for the \( \tilde{t} \to t\chi^0 \) scenario, \( m_{\tilde{t}} < 230 \) GeV or \( m_{\tilde{t}} > 430 \) GeV at 95\% C.L. for neutralino masses less than approximately 110 GeV. For the \( \tilde{t} \to b\chi^\pm \) scenario with the mixing parameter \( x = 0.75 \), \( m_{\tilde{t}} < 160 \) GeV or \( m_{\tilde{t}} > 420 \) GeV at 95\% C.L. for neutralino masses less than approximately 120 GeV. For \( x = 0.5 \), \( m_{\tilde{t}} < 260 \) GeV or \( m_{\tilde{t}} > 340 \) GeV at 95\% C.L. for neutralino masses less than approximately 80 GeV [19].

### 3.2 New Variables to Improve the Current Searches

The phenomenological papers studying the single-leptonic stop searches have mainly built on \( M_{T2} \) variables [14, 20–23] in the \( \tilde{t} \to t\chi^0 \) scenario and [24] in the \( \tilde{t} \to b\chi^\pm \) scenario. Given the current limits on the stop masses and the dominant \( t\bar{t} \) dileptonic background with a hadronic \( \tau \), the following lists could potentially further improve the sensitivity

- Reconstruct \( \tau \) object and reject events containing one or more \( \tau \)'s.

- The hadronic top in the signal could be boosted for a large hierarchy between the stop and neutralino mass. One can use the standard jet substructure technique to tag the boosted top. For the leptonic top, one can guess the neutrino momentum associated with the lepton and reconstruct the full momentum of the leptonic top quark [21]. Then, one can use the simplest \( M_{T2} \) to further cut the backgrounds.

### 4 Dileptonic Channel

For the di-leptonic channel, the final state is \( t\bar{t} + E_T^{\text{miss}} \to b\bar{b}\ell\ell v_{\ell}v_{\bar{\ell}} + E_T^{\text{miss}} \). The same final state can also be used to search for stop decaying into chargino via \( \tilde{t}\tilde{t}^* \to \bar{b}b + \chi^+\chi^- \to \bar{b}bW^+W^0\chi^0\chi^0 \).
4.1 Current Experimental Constraints

We have the following result at ATLAS

- ATLAS with 13.0 fb$^{-1}$ at 8 TeV: for the $\tilde{t} \to b\chi^+$ scenario, $m_{\tilde{t}} < 150$ GeV or $m_{\tilde{t}} > 450$ GeV at 95% C.L. for a chargino approximately degenerate in mass with the scalar top and a massless LSP [25]. This analysis has used the $M_{T2}$ variable constructed by the two opposite-sign leptons and missing transverse momentum.

4.2 New Variables to Improve the Search

The current search at ATLAS [25] has only used a $M_{T2}$ variable including the two leptons. Diboson production is the dominant background for $M_{T2} > 100$ GeV. The signal events have two $b$-jets, so one could require at least one $b$-jet in the final state to further cut the diboson background. Additional $M_{T2}$ variables constructed from two jets and missing transverse momentum could be also useful.

5 Gluino Mediated Stop Production

The gluino, $\tilde{g}$, the fermion partner of the gluon, has a significantly larger cross section for a given mass than the stop because it is a color octet instead of a triplet, and because it is a fermion rather than scalar. Therefore, for a fixed LHC energy and luminosity, the mass reach is much higher for gluinos than stops. Furthermore, in a “natural SUSY” scenario [3, 4], the stop is (one of) the only squarks lighter than the gluino, so the gluino will have a large branching fraction to a top and a stop $\tilde{g} \to t\tilde{t}$, where, of course, the top and stop have opposite electric charges. In this final section, we will briefly discuss the current searches in this scenario.

In the scenario we are considering, the stop decays to top + LSP, so the final state from gluino pair production is $t\bar{t}t\bar{t}\chi^0\chi^0$. This leads to various spectacular signatures such as events with large numbers ($\geq 8$) of jets, same sign-leptons, and three or more leptons. The limits on these models will be relatively insensitive to the stop mass. They will depend dominantly on the mass of the gluino because that sets the total production rate, and on the mass difference between the gluino and the LSP because that sets the typical missing energy in the event. If the stop is heavier than the gluino but lighter than the other squarks, the gluino will decay via off-shell stop to $t\bar{t}\chi^0$, a final state which looks experimentally very similar to the cascade decay of a gluino through a stop. One could also consider a long-lived gluino, if all squarks are very heavy and above around 100 TeV [26]. Many experimental results present limits in this simplified model whose only two parameters are gluino and LSP masses. We present some of the recent 8 TeV bounds on this scenario. All gluino bounds presented here are for massless LSP, but are generally independent of the LSP mass as long as $m_{\tilde{g}} - m_{\chi^0} > 4m_t$.

- ATLAS search [27] for $\geq 6$ jets and missing energy with 5.8 fb$^{-1}$. Places the bound $m_{\tilde{g}} > 1080$ GeV for an off-shell intermediate stop.
• CMS search [9] for $\geq 3$ $b$-jets and missing energy with 11.7 fb$^{-1}$ using the $\alpha_T$ variable places a bound of $m_{\tilde{g}} > 1000$ GeV.

• CMS search [28] for same sign leptons and $b$-jets with 10.5 fb$^{-1}$ $m_{\tilde{g}} > 1000$ GeV.

• CMS search [29] for three leptons with 9.2 fb$^{-1}$ $m_{\tilde{g}} > 950$ GeV.

• ATLAS search [30] for same sign leptons, jets and missing energy with 5.8 fb$^{-1}$. Places the bound $m_{\tilde{g}} > 920$ GeV for an off-shell intermediate stop.

Theory studies of this channel can be found in [31–34].

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