Experimental interplay between the top quark and Supersymmetry at the LHC and Tevatron

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Abstract. The search for Supersymmetry is of highest priority for the physics programs of the LHC and Tevatron experiments. The top quark plays an important role in this quest, both as a dominant background and as a key signature for the signal, in particular in the decay of third generation squarks. We review the latest status of the interplay of top quark and SUSY at hadron colliders.

1. Introduction

Supersymmetry (SUSY) [1–9] is often considered the favorite extension of the Standard Model (SM). It solves several of its limitations such as fixing the fine-tuning problem of the Higgs boson, providing a viable dark matter candidate and unifying the coupling constants at the Grand Unification scale. Supersymmetry implies that each SM particle will have one or two supersymmetric partners, with a spin differing from the associated SM particle by one half. For example the top quark will have two scalar top “squark” partners (\(\tilde{t}_1\) and \(\tilde{t}_2\)).

Supersymmetry must be broken since the SUSY partners have not been observed to date. A subset of them need to be light to solve the fine-tuning problems of the SM Higgs and thus are expected to be accessible by the Tevatron and/or LHC experiments. In most searches R-parity conservation is assumed, which implies that the number of SUSY particles is conserved. The typical SUSY phenomenology involves strongly produced particles, such as gluinos (\(\tilde{g}\), the partner of the gluon) and squarks, which produce a decay chain involving several jets and leptons of high transverse momentum (\(p_T\)), and missing transverse energy (\(E_T^{miss}\)) due to the lightest SUSY particle (LSP), which must be stable by R-parity conservation.

The top quark plays an important role in the search for SUSY at hadron colliders for two main reasons. Firstly its experimental signature is similar to the ones described above for SUSY. It typically constitutes a dominant background for these searches. Secondly its SUSY partners, the two top squarks, are required to be two of the lightest SUSY particles in order to solve the hierarchy problem. In this document we will explore these two aspects of the interplay between top quark and SUSY in more details. The presented analyses utilize the ATLAS [10], CDF, CMS [11] and DØ detectors, analysis selections and identification algorithms which are described in detail elsewhere in these TOP2012 workshop proceedings.

1 Fermions have two scalar partners to conserve the number of degrees of freedom.
2. The top quark as a background to SUSY searches

The pair production of top quarks tends to be a dominant background to SUSY searches because of a combination of factors. Firstly the top quark is the most massive SM particle, and thus closest in energy scale to the new particles that are presumably more massive. Secondly its pair production has a high cross-section since it is mediated by the strong interaction, e.g. \( \sigma_{\bar{t}t} \approx 165 \text{ pb} \) at \( \sqrt{s} = 7 \text{ TeV} \). Finally the decay products involve several high-\( p_T \) jets, lepton(s) and \( E_T^{\text{miss}} \), and can thus mimic the typical decay chains from SUSY particles. In fact it constitutes the single largest background for several inclusive searches for strongly produced SUSY (a few recent examples can be found in Ref. [12–20]), in particular those involving leptons and/or \( b \)-jets.

The details of the method used to estimate the \( t\bar{t} \) background are analysis-dependent but a few general principles apply. The estimates are purely or partially data-driven because the SUSY background consists of events in the high-\( p_T \) tails of the \( t\bar{t} \) events that suffer from larger theoretical, experimental and MC statistical uncertainties than typical \( t\bar{t} \) events. A top-enriched control region is employed, which, on one hand, is designed to be as free as possible of SUSY signal and other SM backgrounds. On the other hand it is devised to be kinematically as close as possible to the signal region(s) in order to reduce extrapolation uncertainties. An extrapolation to the signal region is then performed to predict the \( t\bar{t} \) background, either to correct the MC prediction for the signal region, or by using only data for purely data-driven background estimates.

One example is a CMS analysis that uses a lepton \( p_T \) spectrum method to predict the semi-leptonic \( t\bar{t} \) background in an inclusive SUSY search with one high-\( p_T \) lepton, for which the details of the analysis are provided in Ref. [13]. This method is almost entirely data-driven. It employs the fact that, in a \( t\bar{t} \) event, the charged lepton \( p_T \) spectrum can be used to predict the neutrino momentum, and thus \( E_T^{\text{miss}} \). Corrections need to be applied to account for the slightly different \( \ell^\pm \) and \( \nu \) spectrum from \( W \) boson decays (due to \( W \) polarization), the lepton \( p_T \) threshold in the selections and the different lepton \( p_T \) and \( E_T^{\text{miss}} \) resolutions. Excellent agreement is obtained between the data and predicted \( E_T^{\text{miss}} \) spectra as shown in Fig. 1.

![Figure 1.](image1.png)

**Figure 1.** Data and predicted \( E_T^{\text{miss}} \) distribution for the \( t\bar{t} \) background of the CMS 1-lepton SUSY search described in Ref. [13].

In general the ATLAS collaboration uses a transfer factor method for estimating its \( t\bar{t} \) background in SUSY searches. The signal region prediction is obtained by using a MC-based transfer factor translating the number of events from a top-enriched control region to the signal region. This transfer factor is applied to the number of events in the control region in data which is corrected for the number of background events. One example is a recent search requiring exactly one isolated lepton. The details of the analysis are provided in Ref. [18]. The signal
region requires at least four jets with $p_T > 80$ GeV, a muon or an electron with $p_T > 25$ GeV, the transverse mass between the lepton and $E_T^{miss}$, $m_{T}$, greater than 100 GeV, as well as $E_T^{miss} > 250$ GeV. Also the inclusive transverse mass $m_{inc}^{eff}$, defined as the total transverse energy of the selected objects and of all jets with $p_T > 40$ GeV, is required to be greater than 800 GeV.

The $t\bar{t}$ control region utilizes the same selections except that at least one jet is required to be $b$-tagged, $100 < E_T^{miss} < 180$ GeV and $500 < m_{inc}^{eff} < 1300$ GeV. The distribution of $m_{inc}^{eff}$ for the $t\bar{t}$ control region is shown in Fig. 2 before applying the $m_{inc}^{eff}$ cut. The region is pure in $t\bar{t}$ events and the signal contamination, illustrated by a low-mass SUSY point, is negligible.

3. Searches for third generation squarks

The ATLAS and CMS collaborations have increased their focus on more specific signatures as inclusive searches for SUSY have yet to uncover a signal. Only a few SUSY particles need to be relatively light for SUSY to cancel the large corrections to the Higgs boson mass [21, 22], and thus be “natural”. At the one loop level, only $\tilde{t}_1$, $\tilde{t}_2$ and $\tilde{b}_1$ are required to be less than a TeV or so. The gluino, which appears at the two loop level in the Higgs boson mass corrections, should also be relatively light. A natural decay chain for SUSY thus involves the pair production of $\tilde{g}$, each decaying to the lightest top squark $\tilde{t}_1$, as illustrated in Fig. 3. Another example is the direct pair production of $\tilde{t}_1$ which is illustrated in Fig. 4. The inclusive searches discussed in Sec. 2 are generally not optimized to observe these processes. We describe in this section the search for third generation squarks at LHC and the Tevatron. For these proceedings to the TOP2012 workshop, we concentrate on searches with final states involving $\tilde{t}_1$ and top quarks. All quoted limits are at the 95% confidence level.

3.1. Searches for the gluino-mediated production of top squarks

The process described in Fig. 3 has a spectacular signature consisting of four top quarks as well as two $\tilde{\chi}^0_1$’s, resulting in high $E_T^{miss}$. Since each top quark decays approximately 100% of the time to a $W$ boson and a $b$-quark, each event will contain at least four $b$-jets, up to 12 jets from decays and up to four leptons from $W$ boson decays. Several searches have been designed and we describe them below in the order defined by the increasing number of isolated leptons required. In this document we only quote limits on a four-top simplified model (FTS), where the $\tilde{t}_1$ is assumed to be heavier than the $\tilde{g}$, in which case each $\tilde{g}$ decays directly to $t\bar{t}$ (via a virtual $\tilde{t}_1$) and $\tilde{\chi}^0_1$. This model has the advantage that the limits depend solely on the $\tilde{g}$ and the $\tilde{\chi}^0_1$ masses. Limits on the full process in Fig. 3 can be found in the references provided. The exclusion limits obtained in the FTS model are summarized in Fig. 5 (CMS) and Fig. 6 (ATLAS).

ATLAS has searched for gluino-mediated top squarks production in events with zero isolated electrons or muons and at least three $b$-jets in 4.7 fb$^{-1}$ of $\sqrt{s}$=7 TeV data [23]. Several signal regions are devised with varying requirements on the number of jets, $E_T^{miss}$, $b$-tagging and $m_{eff}$.
where \( m_{\text{eff}} \) is defined as the total transverse energy of the selected objects. No excess is found and limits are obtained that span \( \tilde{g} \) masses up to 0.94 TeV and \( \tilde{\chi}^0_1 \) masses up to 300 GeV in the FTS model. ATLAS has also searched for this process in events with zero leptons with no \( b \)-jet requirements but with high jet multiplicity requirements, i.e. between six and nine jets with \( p_T > 55 \) to 80 GeV [24]. The search is performed in 5.8 fb\(^{-1}\) of \( \sqrt{s}=8 \) TeV data and limits are set in the FTS model for \( \tilde{g} (\tilde{\chi}^0_1) \) mass up to 1.0 (0.36) TeV. CMS performed a search in this channel that uses 3.9 fb\(^{-1}\) of \( \sqrt{s}=8 \) TeV data and exploits the \( \alpha_T \) variable [12] to discriminate between events with real and fake \( E_T^{\text{miss}} \). At least two jets are required with \( p_T > 100 \) GeV. Several signal regions are designed with varying requirements on the total transverse energy of selected objects (\( H_T \)) and the number of \( b \)-jets. Limits in the FTS model are obtained that span \( \tilde{g} \) \( \tilde{\chi}^0_1 \) mass up to 0.85 (0.25) TeV. Several other recent searches in the zero-lepton channel have been performed at CMS and interpreted as searches for gluino-mediated top squarks [25–29].

CMS also performed a search [30] in which one isolated lepton with \( p_T > 20 \) GeV is required in addition to at least three jets with \( H_T > 40 \) GeV, \( H_T > 350 \) GeV and \( E_T^{\text{miss}} > 100 \) GeV. Limits up to approximately 0.9 TeV and 200 GeV in the \( \tilde{g} \) and \( \tilde{\chi}^0_1 \) mass, respectively, are obtained.

Since four top quarks are present, there is a significant probability that two leptons carry the same electric charge in the same event, a signature which suffers little background from SM processes. CMS has performed such a search in 3.95 fb\(^{-1}\) of \( \sqrt{s}=8 \) TeV data by requiring two same-sign leptons with \( p_T > 20 \) GeV, at least two jets with \( p_T > 40 \) GeV, of which at least two must be \( b \)-tagged [14]. Several signal regions are devised with varying requirements on \( E_T^{\text{miss}} \), \( H_T \), and the number of jets and \( b \)-jets. No excess is observed in data and limits are obtained on the \( \tilde{g} \) and \( \tilde{\chi}^0_1 \) masses up to 0.9 TeV and 450 GeV, respectively. ATLAS has performed a similar search which sets comparable limits on gluino-mediated production of top squarks [33]. ATLAS also performed a search in which at least three isolated leptons (\( p_T > 15 \) GeV) are required [34].

Figures 5 and 6 summarize the limits in the \( \tilde{g} \) and \( \tilde{\chi}^0_1 \) mass plane of the FTS model for CMS [31].

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig5.png}
\caption{Exclusion limits in the \( \tilde{g} \) and \( \tilde{\chi}^0_1 \) mass plane of the FTS model for CMS [31].}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig6.png}
\caption{Exclusion limits in the \( \tilde{g} \) and \( \tilde{\chi}^0_1 \) mass plane of the FTS model for ATLAS [32].}
\end{figure}

3.2. Searches for direct production of top squarks

Searches for the process in Fig. 4 are important to cover the possibility that the \( \tilde{g} \) is too massive to be (yet) observable at the LHC. The experimental signature is the same as for \( t\bar{t} \) events but with additional \( E_T^{\text{miss}} \) due to the presence of two \( \tilde{\chi}^0_1 \)'s.
At the time of this workshop, the CMS collaboration did not have public dedicated searches for this process. However, the searches have been re-interpreted for direct stop production and yield limits on the $\tilde{t}_1$ mass between approximately 325 and 475 GeV for light $\tilde{\chi}_1^0$'s, and up to 150 GeV in $\tilde{\chi}_1^0$ [26, 35, 36].

ATLAS has performed a dedicated search in the zero-lepton channel [37], in which at least six high-$p_T$ jets are required and $E_T^{\text{miss}} > 150$ GeV. The reconstruction of the two top quarks in the event is attempted and topological cuts are applied to reduce the multi-jets background. No excess is observed and limits are obtained on the $\tilde{t}_1$ mass between 370 and 465 GeV for massless $\tilde{\chi}_1^0$, and up to $m_{\tilde{\chi}_1^0} \approx 50$ GeV. An analysis is also performed in the one-lepton channel [38]. Stringent selections on $E_T^{\text{miss}}$, $m_T$ and the reconstructed top quark mass are applied to reject the dominant $t\bar{t}$ background. The limits on $m_{\tilde{t}_1}$ span 230–440 GeV for massless $\tilde{\chi}_1^0$ and reach up to $m_{\tilde{\chi}_1^0} \approx 125$ GeV. Other dedicated searches for $\tilde{t}_1$ have been performed by ATLAS that include the other possible decay channel $\tilde{t}_1 \to b\tilde{\chi}_1^\pm$ [39–41]. The limits from ATLAS in the $\tilde{t}_1$ and $\tilde{\chi}_1^0$ mass plane are summarized in Fig. 7.

The top squark has also been searched for at the Tevatron. The searches have focused on low $m_{\tilde{t}_1}$ decays such as $\tilde{t}_1 \to c\tilde{\chi}_1^0$ [42] and $\tilde{t}_1 \to bl\tilde{\nu}$ [43, 44].

![Figure 7. Exclusion limits in the $\tilde{t}_1$ and $\tilde{\chi}_1^0$ mass plane of the FTS model for ATLAS [32].](image)

4. Conclusions
The top quark plays an important role in the search for Supersymmetry at hadron colliders. We have provided an overview of the techniques performed to estimate the $t\bar{t}$ background, which is often dominant. Top quarks can also be part of the signal, in particular as the decay product of third generation squarks. We have summarized the searches for the top squark. Increased luminosity and $\sqrt{s}$ will substantially improve the sensitivity of future searches.

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