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Nuclear Physics B Proceedings Supplement 00 (2014) 1–6
Nuclear Physics B Proceedings Supplement

Searches for direct pair production of third generation squarks with the ATLAS detector

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Abstract

Naturalness arguments for weak-scale supersymmetry favour supersymmetric partners of the third generation quarks with masses not too far from those of their Standard Model counterparts. Top or bottom squarks with masses less than a few hundred GeV can also give rise to direct pair production rates at the LHC proton-proton collisions that can be observed in the data sample recorded by the ATLAS detector. The talk presents recent ATLAS results from searches for direct stop and sbottom pair production.

Keywords: Supersymmetry, Naturalness, stop, sbottom, ATLAS

1. Introduction

Supersymmetry (SUSY) [1, 2] is an extension of the Standard Model (SM) which predicts new bosonic partners for the existing fermions and fermionic partners for the known bosons. In the framework of a generic R-parity conserving minimal supersymmetric extension of the SM (MSSM)[3, 4] SUSY particles are produced in pairs and the lightest supersymmetric particle (LSP) is stable, providing a possible dark matter candidate.

In a large variety of models, the LSP is the lightest neutralino ($\tilde{\chi}_1^0$) which is a mixture of the neutral supersymmetric partners of the gauge and Higgs bosons, known as gauginos and higgsinos. Similarly, charginos are a mixture of the charged gauginos and higgsinos, with the lightest one denoted by $\tilde{\chi}_1^{\pm}$. The scalar partners of right-handed and left-handed quarks, $\tilde{q}_R$ and $\tilde{q}_L$, mix to form two mass eigenstates, $\tilde{q}_1$ and $\tilde{q}_2$, with $\tilde{q}_1$ defined to be the lightest of the two. Naturalness arguments[5] imply that the supersymmetric partners of the top quark (stops) are light, with mass below 1 TeV. A light left-handed top squark also implies that the left-handed bottom squark ($\tilde{b}_L$) may be relatively light due to the SM weak-isospin symmetry.

We report the most recent results for searches of third generation squark direct production, using the ATLAS detector [6], in a variety of final states.

2. Direct top squark production searches

This report summarizes two inclusive searches that are sensitive to the broad $\tilde{t}_1$-$\tilde{\chi}^0$ mass plane. Afterwards we report on two dedicated analyses which target specific regions in this phase space where the mass hierarchy between SUSY particles is such that the inclusive analyses have, a priori, low if any sensitivity. Without detailing we also point out a recent ATLAS analysis [7] of the $t\bar{t}$ production where, by looking for excess with regards to the QCD prediction, limits have been placed on the $\tilde{t}_1$ production. This analysis excludes $\tilde{t}_1$ masses between the top mass and 177 GeV at 95 % C.L. For more details we refer to the report from T. Theveneaux in this conference.

Figure 8 shows the current exclusion limits for the possible ($\tilde{t}_1$, $\tilde{\chi}^0$) masses with a mild assumption on the possible decay modes.

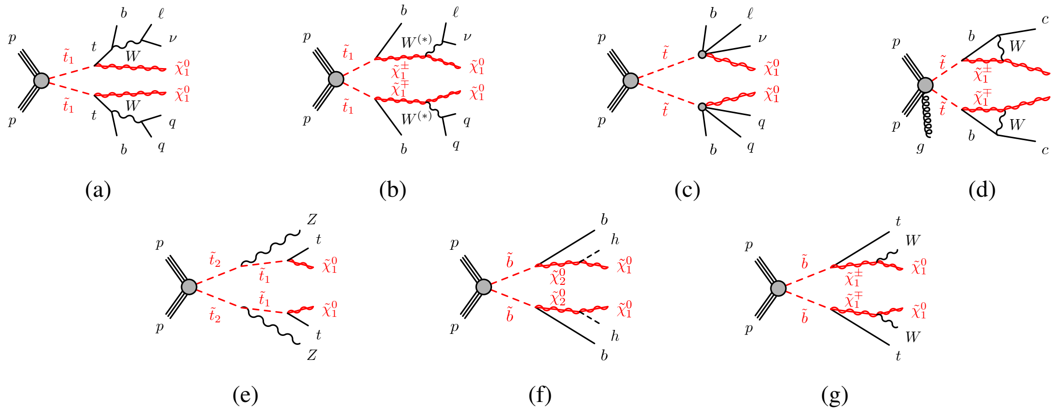


Figure 1: Feynman diagrams of the main processes presented in this report.

2.1. All-hadronic final state searches

These searches target scenarios where the $\tilde{t}_1$ is heavier than the top quark. It is assumed that the $\tilde{\chi}^0$ is the LSP and no mass assumption is made on this particle. It is assumed that the $\tilde{t}_1$ can decay via t $\tilde{\chi}^0$ as shown in Figure 1a or via b $\tilde{\chi}^{\pm}_1$ as presented in Figure 1b (for this analysis we consider the W mesons that decay to quarks for both decay chains).

The analysis [8] targets "fully-resolved" events with six jets (two of them being b-jets). Additionnaly, "partially-resolved" events with four or five jets in the final state are also considered. These events can occur if one or more jets are below the reconstruction threshold or if the decay products of the Lorentz-boosted top quarks are sufficiently collimated. Finally the sensitivity for events where one of the jets of the $W^{(*)}$ decay has low momentum is increased by including events with exactly five jets.

A substantial rejection of the main source of background, $t\bar{t}$ is achieved by requiring that the transverse mass, $m_T^{b,min}$, calculated from the E_T^{miss} and the b-tagged jet closest in ϕ to the missing transverse momentum to be higher than the top mass.

The signal pre-selection distribution, containing at least four jets (and two of them b-tagged), zero leptons and significant missing transverse energy, is presented in Figure 2.

The remaining background processes are dominated by $t\bar{t}$, V+jets and $t\bar{t}$+V (V = W, Z, γ) and are taken from simulation and conveniently normalized with the usage of dedicated control regions.

No significant excess over the Standard Model background prediction is observed, and limits are reported in terms of the $\tilde{t}_1$ and $\tilde{\chi}^0$ masses and as a function of the branching fraction of $\tilde{t}_1 \rightarrow$ t $\tilde{\chi}^0$. For a branching fraction of 100 %, $\tilde{t}_1$ masses ranging from 270 GeV to 645 GeV are excluded for $\tilde{\chi}^0$ masses below 30 GeV. The overall picture, for this branching franction, is shown in Figure 8. For other branching fractions results we refer to the analysis paper.

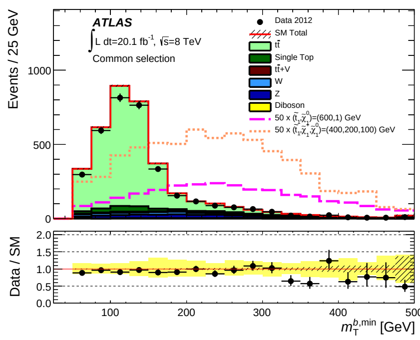


Figure 2: All-hadronic final state searches : The distribution of $m_T^{b,min}$ in events with at least four jets that pass the common pre-selection requirements.

2.2. 1-lepton searches

$\tilde{t}$ decays involving one lepton in the final state are generic enough to target several different processes. The analysis [9] looks for the decays presented in Figures 1a to 1d : $\tilde{t}_1 \rightarrow$ t $\tilde{\chi}^0$, $\tilde{t}_1 \rightarrow$ b $\tilde{\chi}^{\pm}_1$, $\tilde{t}_1 \rightarrow$ b f f' $\tilde{\chi}^0$. This in practice allows to cover scenarios with large mass splitting between the SUSY particles (Figure 1a), scenarios where the difference in mass between the $\tilde{t}_1$ and $\tilde{\chi}^0$ are smaller than the top mass and higher than the W mass (Figure 1b) and even very compressed spectra scenarios (Figures 1c and 1d).

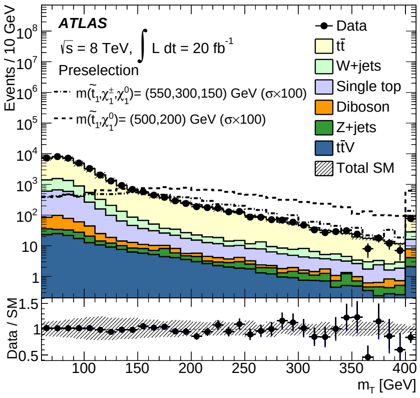


Figure 3: 1-lepton searches : Distribution of the transverse mass, mt, for events that pass the pre-selection and with at least one b-tagged jet.

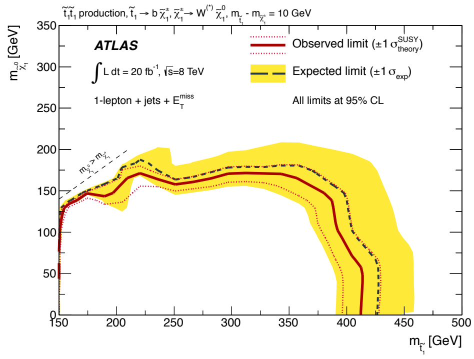


Figure 4: Exclusion limits, for a model similar to the one presented in [10], which would explain the observed excess in W^+W^- production observed by ATLAS and CMS. The prefered region in the model to explain the excess lies around $(m_{\tilde{t}_1}, m_{\tilde{\chi}^0})$≈(220,130) GeV which is excluded by this analysis.

The signal pre-selection consists in events with one isolated lepton, several jets (including two b-tagged jets) and missing transverse energy.
Additional variables, such as the transverse mass, shown in Figure 3 are also used to further suppress the main source of backgrounds. These are di-leptonic $t\bar{t}$ decays where one of the leptons is either not reconstructed or mis-identified as jet and W+jets. Estimations are taken from simulation and properly normalized in dedicated control regions. The analysis results are based on maximum likelihood fits which include the control regions to simultanously normalize the control regions.
No significant excess with regards to the SM prediction is observed. Limits on the $(\tilde{t}_1, \tilde{\chi}^0)$ mass plane are imposed. A $\tilde{t}$ with a mass between 210 and 640 GeV decaying directly to a top quark and a massless LSP is excluded at 95 % CL. A more broader picture of the analysis reach in this plane is shown Figure 8.
This analysis also imposes limits on a variety of other SUSY models. Here we highlight only one of these models [10]. This model explains the WW cross section excess observed by both ATLAS and CMS collaborations. This model is essentially excluded as presented in Figure 4.

2.3. Compressed spectra searches

This analysis [11] targets compressed spectra scenarios where ΔM = m($\tilde{t}_1$) - m($\tilde{\chi}^0$) < m(W) + m(b). There are two competing processes for the decay in these scenarios, the four body decay described in Figure 1c and the loop induced decay to charm shown in Figure 1d. A priori, the signature is caracterized by a low jet multiplicity and moderate missing transverse momentum. This results in a challenge to separate signal from the SM multijet background.
To overcome this obstacle the analysis looks for events that contain initial state radiation (ISR) jets. The interest of the ISR jets is two-folded : it serves as trigger for the interesting events and also permits the $\tilde{t}_1$ pair to be produced with more boost effectively increase the transverse momentum of the decay jets and the missing transverse momentum. c-tagged jets are added also in the signal event definition and result in an improved coverage of the signal phase space where ΔM > 20 GeV.
The main sources of background are V+jets and $t\bar{t}$ production. These are estimated using simulation conveniently normalized in dedicated control regions.
No excess is observed in the signal regions with regards to the SM background estimation. Limits are provided for the studied models as function of the $(\tilde{t}_1,\tilde{\chi}^0)$ mass plane. The mass of the $\tilde{t}_1$ is excluded up to around 240 GeV for any $\tilde{\chi}^0$ mass and even higher for certain $\tilde{\chi}^0$ masses. The limits on the loop induced charm production model are shown in Figure 5.

2.4. Direct searches for $\tilde{t}_2$ production

In cases where the $\tilde{t}_1$ mass is just slightly higher than the sum of the top and $\tilde{\chi}^0$ masses the decay topology is very similar to that of $t\bar{t}$ production. It is very difficult to distinguish the SUSY production from the SM background in this case. The alternative, pursued in this search [12], is to look for the heavier $\tilde{t}_2$. The analysis considers a simplified model where the heavier $\tilde{t}_2$decays either via $\tilde{t}_1$ Z (as shown in Figure 1e or $\tilde{t}_1$ h or top $\tilde{\chi}^0$). If the $\tilde{t}_2$ is not too heavy its decays could be observed. It

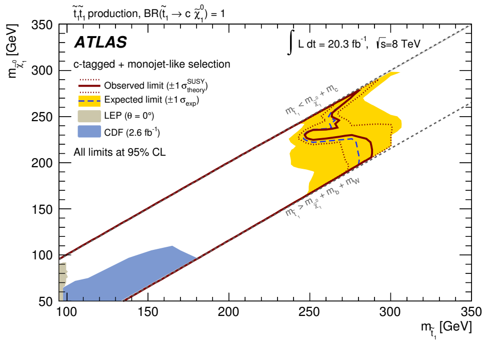


Figure 5: Exclusion plane at 95% C.L. as a function of stop and neutralino masses for the decay channel $\tilde{t}_1 \rightarrow c + \tilde{\chi}^0$(BR=100%).

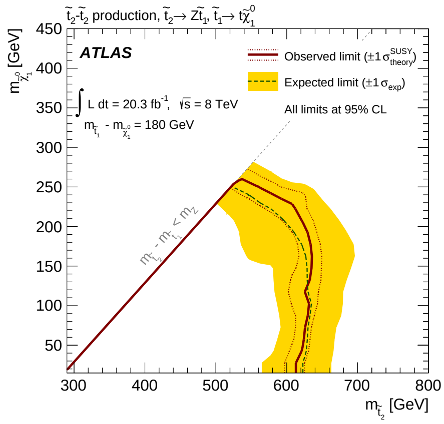


Figure 6: Expected and observed exclusion limits in the m($\tilde{t}_2$)-m($\tilde{\chi}^0$) plane for the direct $\tilde{t}_2$ pair production simplified model with BR($\tilde{t}_2 \rightarrow$ Z $\tilde{t}_1$)=1.

is assumed that the lighter $\tilde{t}_1$ always decays to t $\tilde{\chi}^0$. The mass difference between the $\tilde{t}_1$ and the $\tilde{\chi}^0$ is 180 GeV, slightly above the top mass.
The signal regions used for the search retain events with three leptons ($l = e, \mu$) with two of them compatible with a Z boson decay products, significant missing transverse energy and at least five jets where at least one of them is b-tagged.
The main sources of background come either from events with jets faking leptons, determined with a data-driven method and events originated by the rare $t\bar{t}Z$ SM process which are taken from simulation.
A dedicated validation region, orthogonal to the signal region (essentially with slightly less jets) confirms the good background normalisation.
No excess in the signal regions is observed and limits to the model considered are placed, as shown in Figure 6 for the case where the $\tilde{t}_2$ decays always via $\tilde{t}_1$ Z. In this case the analysis excludes $\tilde{t}_2$mass up to 600 GeV for $\tilde{\chi}^0$ masses up to 200 GeV. Limits for the models assuming the different possible decays of the $\tilde{t}_2$ are also provided in the analysis paper and in this talk.

3. Direct bottom squark production searches

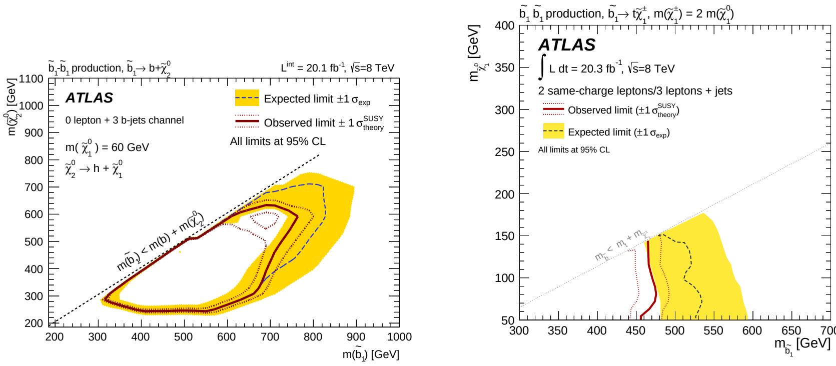
The weak-isospin symmetry correlates the $\tilde{b}$ sector to the $\tilde{t}$ sector. In this sense, the absence of $\tilde{b}$ production up to a given mass range indirectly constraints the possible $\tilde{t}$ masses.
The search for $\tilde{b}$ at the LHC is slightly less challenging than the $\tilde{t}$ searches since for the former's decay topologies are closer to those of the SM $t\bar{t}$ decay topology, the dominant background.
In the past several analyses have looked for $\tilde{b}$ production via $\tilde{g}$ decays. Here we present the results for searches of direct $\tilde{b}$ production.

3.1. 3 b-jet searches

This analysis [13] targets the decay presented in Figure 1f where the $\tilde{b}$ only decays via $\tilde{\chi}^0_2$. A simplified model is used for the signal simulation where it is assumed that the $\tilde{\chi}^0$ mass is 60 GeV.
Given the decay topology on looks for events with four jets, where at least three are b-tagged, and significant missing transverse energy. The main sources of background are $t\bar{t}$ production with c quark initiated jets or hadronic decays of taus miss-identified as b-jets and $t\bar{t}$ production associated with b quarks. The former is controled with dedicated data-driven methods that estimate the mis-tagging rate while the latter is normalized in dedicated control regions.
No excess is observed in the signal region and limits are determined. These are presented in Figure 7a.

3.2. Jets, 2-3 leptons searches

This analysis [14] targets the decay presented in Figure 1g. The signatures used to detect these events consist in events with significant jet multiplicity, high missing transverse energy, effective mass (defined as the sum of the missing transverse energy and of the transverse momentum of leptons and jets) and transverse mass (defined with the lepton with higher transverse momentum and the missing transverse momentum).
The main sources of background come from $t\bar{t}$ production associated with vector bosons, diboson and triboson events and to a minor extent events with jets faking leptons. For the latter process a data-driven method is applied while for the other processes the simulation is used.



(a) (b)

Figure 7: (a) Exclusion limits in the (m($\tilde{b}_1$),m($\tilde{\chi}^0_2$)) plane for the direct–sbottom model tested in the "3 b-jet searches" ,(b) Exclusion limits on direct bottom squark production,for $\tilde{b}\rightarrow$ top $\tilde{\chi}^{\pm}_1$decays with m($\tilde{\chi}^0$)=m($\tilde{\chi}^{\pm}_1$)/2.

No excesses are observed in the signal regions and limits to the $\tilde{b}$ mass are determined in $\tilde{b}$-$\tilde{\chi}^0$ mass plane with two simplified models where either the $\tilde{\chi}^0$ has 60 GeV or the $\tilde{\chi}^{\pm}$has twice the mass of the $\tilde{\chi}^0$ (presented in Figure 7b). For these models one excludes the $\tilde{b}$ mass up to 440 GeV.

4. Summary

Recent results from the searches for third generation squark direct production at the LHC with the ATLAS detector, using the full 8 TeV dataset, have been presented. No excess with respect to the Standard Model predictions have been found and limits on a variety of production modes and mass hierarchies were determined.
The major results presented include : a lower bound on the mass of the lightest stop set to 680 GeV, assuming a direct decay to a massless neutralino; limits to the $\tilde{t}_1$mass of around 250 GeV for very compressed spectra scenarios and the first direct limits on the mass of the $\tilde{t}_2$ at the LHC.

5. Acknowledgments

The author would like to thank the IRFU-Saclay ATLAS group for all the support related with the travel and the preparation of this report.
This report was supported by the ERC, Grant Agreement N 279170 DIBOSON.

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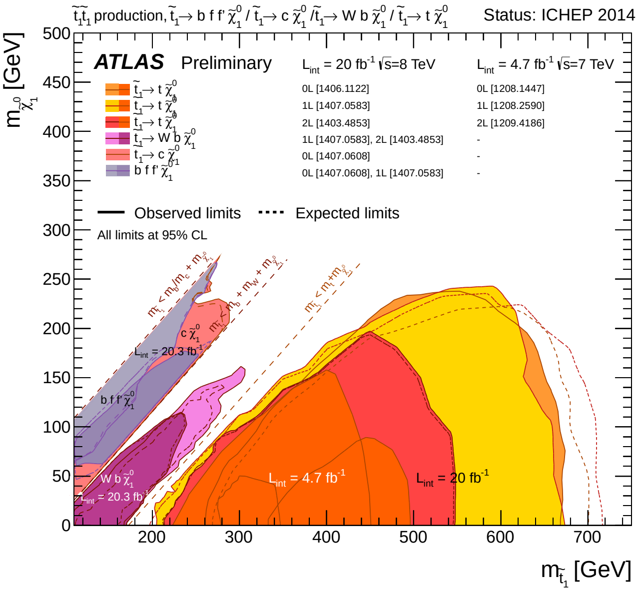

Figure 8: Summary of the dedicated ATLAS searches for $\tilde{t}_1$pair production based on 20 fb^{-1} of pp collision data taken at $\sqrt{s}$ = 8 TeV, and 4.7 fb^{-1} of pp collision data taken at $\sqrt{s}$= 7 TeV. Exclusion limits at 95% CL are shown in the $\tilde{t}_1$-$\tilde{\chi}^0$mass plane. The dashed and solid lines show the expected and observed limits, respectively, including all uncertainties except the theoretical signal cross section uncertainty (PDF and scale). Four decay modes are considered separately with 100% BR: $\tilde{t}_1 \rightarrow$ t $\tilde{\chi}^0$, where the $\tilde{t}_1$is mostly right, $\tilde{t}_1 \rightarrow$ W b $\tilde{\chi}^0$(3- body decay for m($\tilde{t}_1$) < m($\tilde{t}_1$) + m($\tilde{\chi}^0$)), $\tilde{t}_1 \rightarrow$ c $\tilde{\chi}^0$and $\tilde{t}_1 \rightarrow$ f f' b $\tilde{\chi}^0$. The latter two decay modes are superimposed.

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