PROCEEDINGS OF SCIENCE

Search for direct top squark pair production in the 3-body decay mode with one-lepton final states in $\sqrt{s}$ = 13 TeV pp collisions with the ATLAS detector

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Natural supersymmetry suggests a light top squark, possibly within the discovery reach of the LHC. These proceedings presents the latest result of an analysis targeting a compressed region of the top squark phase space where the mass difference between the top squark and the lightest neutralino is smaller than the top-quark mass, using pp collision data recorded by the ATLAS detector over the full Run 2 of the LHC. A machine learning technique was employed in the analysis to improve the discrimination of signals from backgrounds dominated by the $t\bar{t}$ process. No significant deviation from the predicted Standard Model background is observed, and limits at 95% confidence level on the supersymmetric benchmark model are set, excluding top squark masses up to 720 GeV with neutralino masses up to 580 GeV.

ATL-PHYS-PROC-2019-117
07 October 2019

PoS(EPS-HEP2019)623

European Physical Society Conference on High Energy Physics - EPS-HEP2019 -
10-17 July, 2019
Ghent, Belgium

1. Introduction

Supersymmetry (SUSY) is an extension of the Standard Model (SM) of particle physics which predicts a supersymmetric partner for each particle in the standard model. If R-parity is conserved, then the lightest supersymmetric particle (LSP) is stable and a good dark matter candidate. In many models the LSP is favored to be the lightest neutralino ($\tilde{\chi}_1^0$), and naturalness arguments suggest a relatively light top squark ($\tilde{t}_1$), the SUSY partner of the top quark, assumed to be within reach of the LHC.
A search for direct production of $\tilde{t}_1$ pairs, each decaying exclusively via a 3-body process to a b quark, a W boson, and a $\tilde{\chi}_1^0$ is presented using pp collision data recorded by the ATLAS detector [1]. This analysis considers the final state with exactly one isolated charged lepton (electron or muon) from the decay of one of the W bosons, high-p_T jets, and a significant amount of missing transverse momentum ($E_{\mathrm{T}}^{\mathrm{miss}}$) from the two weakly interacting LSPs that escape detection [2].

2. Analysis Strategy

The general approach is to define an event selection, referred to as the signal region (SR), in order to discriminate between signal and background processes. Two different techniques are developed. The 'cut-and-count' method, which is based on counting events in a single region of phase space and is used for discovery scenarios, and the 'shape-fit' method, where the SR is split into multiple bins in a discriminating variable, used to set exclusion limits.

The SM background after the signal selection is dominated by dileptonic top-quark pair production ($t\bar{t}$2L) where one lepton is 'lost' (meaning either not reconstructed, not identified, or removed when geometrically overlap with another object) or one W boson decays leptonically and the other hadronically via a τ lepton. The $t\bar{t}$2L background is estimated based on a likelihood fit from data in dedicated control regions (CR), and extrapolated to the SR. To evaluate the SM predictions, a validation region (VR) is defined. It is essential that these regions are similar in terms of kinematics to assure a reliable analysis. A signal model with a $\tilde{t}_1$ mass of 450 GeV and a $\tilde{\chi}_1^0$ mass of 300 GeV was chosen as benchmark and used for the SR optimization. The benchmark was defined as a signal point that has not been excluded in the previous search [3] with the same final state.

2.1 Signal Extraction with Machine Learning

A machine learning (ML) approach is used to optimize the SR selection to better discriminate signal from the dominant $t\bar{t}$2L background. The ML classifier maximizes the sensitivity by learning the topological differences between signal and the $t\bar{t}$2L background and then extracting correlations amongst a set of discriminating variables considered as an input to the training.

The size of the training sample is crucial in the performance of any ML approach. As generating samples with full detector simulation containing enough statistics is computationally expensive, only events at generator level were used for training the signal selection. The generated events used

PoS(EPS-HEP2019)623

for the signal were smeared using a dedicated procedure to emulate the effects of the full detector simulation and reconstruction. Kinematic distributions of all input variables after smearing were found to have good agreement with the distributions from the detector simulation. For the SM background this was not a problem because the fully simulated and reconstructed samples already contained enough events for training the classifier.

Two types of jets are of particular interest for the signal model. First, a very hard jet that could boost the $\tilde{t}_1$ system and induce a significant amount of $E_{\mathrm{T}}^{\mathrm{miss}}$, and secondly, softer jets (b-tagged or not) that may arise from the $\tilde{t}_1$ decay or the subsequent W decay since the mass gap between the $\tilde{t}_1$ and $\tilde{\chi}_1^0$ is small. Due to the kinematics of the signal model, the jet multiplicity in final states may vary significantly in the population of signal events. To deal with the jet 4-vectors of the signal jet selection, the first step of the ML architecture applies a recurrent neural network (RNN). The RNN has the ability to extract information from sequences of arbitrary length. In the second step, the output of the RNN is used as an input to a shallow neural network (NN) together with 12 discriminating kinematic variables. The NN contains a single hidden layer with 128 neurons, and two outputs are obtained corresponding to signal and background probabilities.

After the ML classifier is trained, the SR is defined by the classifier output score ($\mathrm{NN}_{\mathrm{bWN}}$) as seen in Figure 1. The shape-fit exploits the shape of the $\mathrm{NN}_{\mathrm{bWN}}$ distribution extending over 10 bins of $\mathrm{NN}_{\mathrm{bWN}}$, from 0.65 to 1. The single-bin SR is defined as the > 0.9 bin.

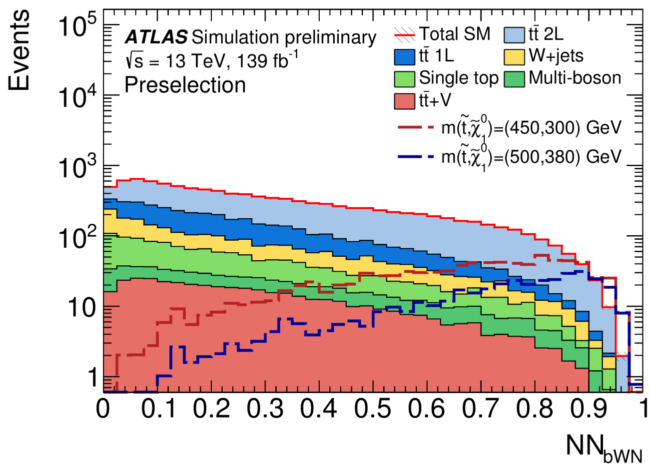

Figure 1: Distribution of the trained ML classifier output after preselection. The $t\bar{t}$ background is not yet normalized to the CR [2].

The $t\bar{t}$2L background process is estimated via a dedicated CR defined by relaxing the selection on the $\mathrm{NN}_{\mathrm{bWN}}$ to 0.40−0.60. The background estimation is then tested using a VR defined in a region between the SR and the CR, so in the 0.60−0.65 bin of $\mathrm{NN}_{\mathrm{bWN}}$. The W+jets and $t\bar{t}$1L background processes are largely suppressed by requiring a transverse mass[1] cut of $m_{\mathrm{T}} > 150$ GeV

[1]The transverse mass is defined as $m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\ell} E_{\mathrm{T}}^{\mathrm{miss}} [1 - \cos(\Delta\phi)]}$, where $\Delta\phi$ is the azimuthal angle between the lepton and $E_{\mathrm{T}}^{\mathrm{miss}}$, and p_{T}^{ℓ} is the transverse momentum of the charged lepton.

in the CR and VR .

3. Results and Conclusion

The presented search is performed on *pp* collision data recorded by the ATLAS experiment at the LHC, at a centre-of-mass energy of $\sqrt{s}$ = 13 TeV corresponding to 139 fb^{-1}. The number of observed events as well as the SM prediction in the VR and SR are illustrated in Figure 2 (left). From left to right, the bins correspond to the CR, VR and the multiple bins of the exclusion SR. Data and SM expectation are in good agreement within statistical and systematic uncertainties. Exclusion limits at 95% CL are obtained based on profile-likelihood fits for the signal model. In a phase space characterized by a mass splitting of $m(W)+m(b) \leq \Delta m(\tilde{t}_1, \tilde{\chi}_1^0) \leq m(t)$, the results improve previous limits by excluding top squark masses up to 720 GeV for an LSP mass of 580 GeV under the assumption of $B(\tilde{t}_1 \to bW\tilde{\chi}_1^0) = 100\%$ as shown in Figure 2 (right).

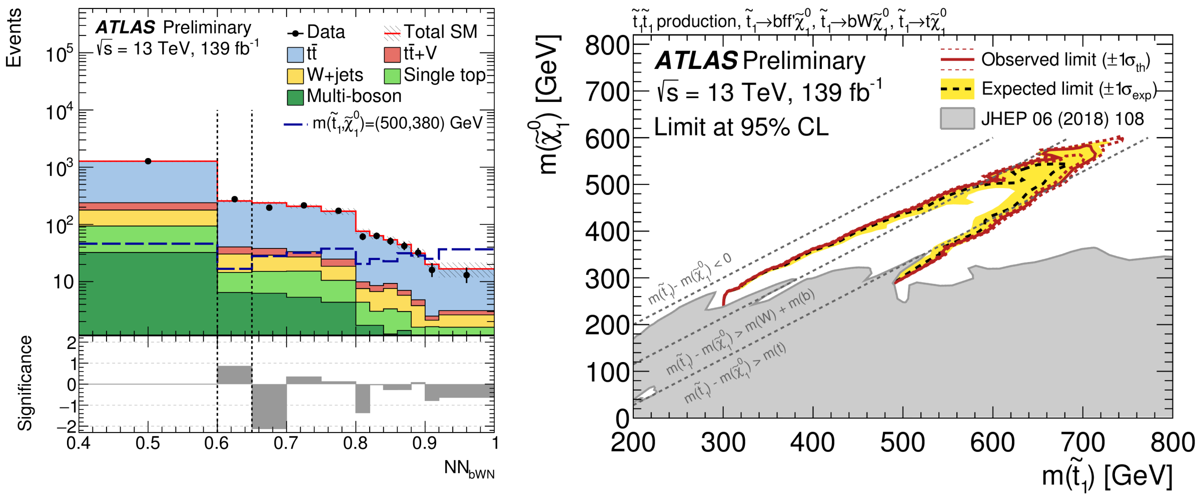

Figure 2: Left: Comparison of observed data with the predicted SM background for the SR. The bottom panel shows the difference between data and the predicted SM background divided by the total uncertainty. Right: Expected (black dashed) and observed (red solid) exclusion limit at 95% confidence level for pure bino LSP models [2]. The grey shaded area denotes the previously excluded regions from [3].

References

[1] ATLAS Collaboration, *The ATLAS Experiment at the CERN Large Hadron Collider*, *JINST* **3** (2008) S08003.

[2] ATLAS Collaboration, *Search for direct top squark pair production in the 3-body decay mode with a final state containing one lepton, jets, and missing transverse momentum in $\sqrt{s}$=13 TeV pp collision data with the ATLAS detector.* ATLAS-CONF-2019-017, http://cdsweb.cern.ch/record/2676594

[3] ATLAS Collaboration, *Search for top-squark pair production in final states with one lepton, jets,and missing transverse momentum using 36 fb^{-1} of $\sqrt{s}$=13 TeV pp collision data with the ATLAS detector*, JHEP **06** (2018) 108, arXiv: 1711.11520 [hep-ex]