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Third generation SUSY searches in ATLAS

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Supersymmetry (SUSY) is one of the most popular and promising extensions to the Standard Model (SM) of particle physics. It predicts partner particles for all SM particles with a spin difference of $1/2$. These SUSY partners, if they exist within a reachable energy scale, should be produced at the Large Hadron Collider (LHC). The events are usually characterized by high missing transverse energy and can have varying jet and lepton multiplicities, depending on the model used. Searches for partners of third generation squarks are of special interest because of their special event topologies.

Many searches have been performed in proton-proton collisions at $\sqrt{s} = 13$ TeV at the LHC with the ATLAS detector, using an integrated luminosity of 3.2 fb^{-1}. Several of these will be presented in these proceedings.

No significant deviations from the SM expectations have been observed and exclusion limits have been set for the respective models. Most analysis already exceed the sensitivity achieved with Run1 analysis.

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1. Introduction

Supersymmetry is one of the most popular and promising extensions to the Standard Model of particle physics. It solves problems within the Standard Model, as for instance the absence of a dark matter candidate or the hierarchy problem, by introducing new partner particles to the existing ones. The partners have exactly the same quantum numbers, except for the spin, which differs by $1/2$. Since no SUSY particles have been observed, the mass of the SUSY partners must be higher, thus the symmetry must be broken.
The partner particles of the third generation quarks, scalar top (stop) and scalar bottom (sbottom) quarks, are of particular interest. The stop is the most important part for the solution of the hierarchy problem, because of its large Yukawa coupling. Third generation squarks can have many different decay modes, depending on the exact mass hierarchy of the SUSY particles (see Figure 1), so inclusive searches for scalar quarks of the first and second generation are usually not as sensitive as dedicated searches.
The searches presented here use simplified models as benchmarks for their optimizations, which implies that a branching ratio of 100% is assumed for the decays of interest and that no other SUSY particle interferes with the process. Most of the searches target R-parity conserving models, which means that the SUSY particles are produced in pairs and that a SUSY particle always has a SUSY particle in its decay products. This leads to a stable lightest SUSY particle (LSP), which is in the searches presented here assumed to be the lightest neutralino. It participates in the weak interaction only, so it is a candidate for dark matter, and leaves the detector without any energy deposition. This leads to missing transverse energy $E_{\mathrm{T}}^{\mathrm{miss}}$, one of the key characteristics of events containing SUSY particles. The stops and sbottoms are assumed to be the (next-to-)next-to-lightest SUSY particle (N)NLSP. In the NNLSP case, a chargino is assumed to have a mass in between the stop/sbottom mass and the neutralino mass.

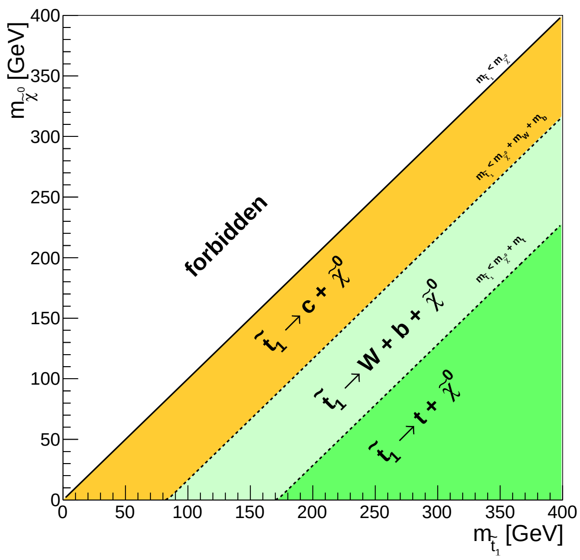

Figure 1: Example of possible decay modes of the scalar top quark in a simplified model, where the Neutralino $\tilde{\chi}_1^0$ is the lightest super symmetric particle and the scalar top quark $\tilde{t}_1$ is the next heavier particle.

2. Background estimation

All analyses use data driven approaches for the estimation of the main backgrounds (see Figure 2):
Besides the signal regions (SRs), which are optimized for a high signal sensitivity, control regions (CRs) are defined, such that they have a high purity of events for a given background. These regions are orthogonal to the SRs, but have a similar topology for the targeted process. This usually leads to unique CRs for each main background of each signal region. The CRs are used to extract information about the backgrounds and extrapolate them to the SRs. This is done using various methods including jet smearing, the matrix method, the ABCD method or simply an extraction of the normalization factor.
In order to validate the procedure, validation regions (VRs) may be defined, which are again orthogonal to the signal and control regions, but show sensitivity for the extrapolations from the CRs to the SRs.

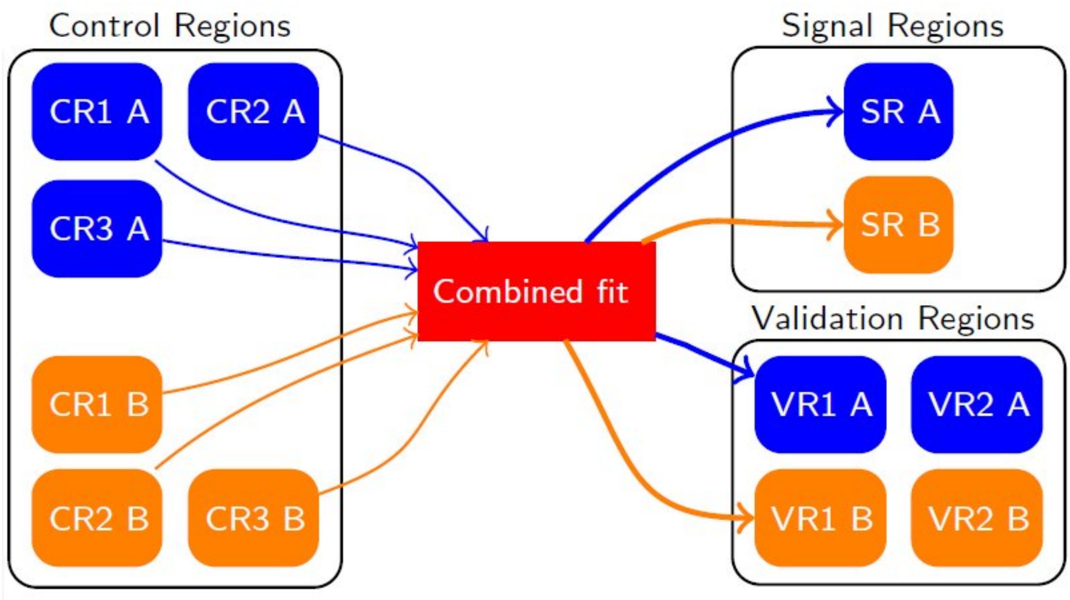

Figure 2: Schematic visualisation of the fit procedure.

3. Existing limits from 8 TeV analysis

During the 2012 data taking period, searches targeting third generation squarks were performed. No significant excesses over the SM expections were observed and exclusion limits were set for all searches. An overview over the existing limits for scalar top quarks is shown in Figure 3. The exact limits depend on the mass hierarchies of the SUSY particles, and the resulting decay modes. In the case where the scalar top quark is the NLSP, masses up to $m_{\tilde{t}_1} \approx 700$ GeV were excluded for high mass differences $\Delta m = m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0}$, while $m_{\tilde{t}_1} \approx 300$ GeV were reached for smaller Δm. In the NNLSP case, the limits reach up to $m_{\tilde{t}_1} \approx 500 - 600$ GeV.

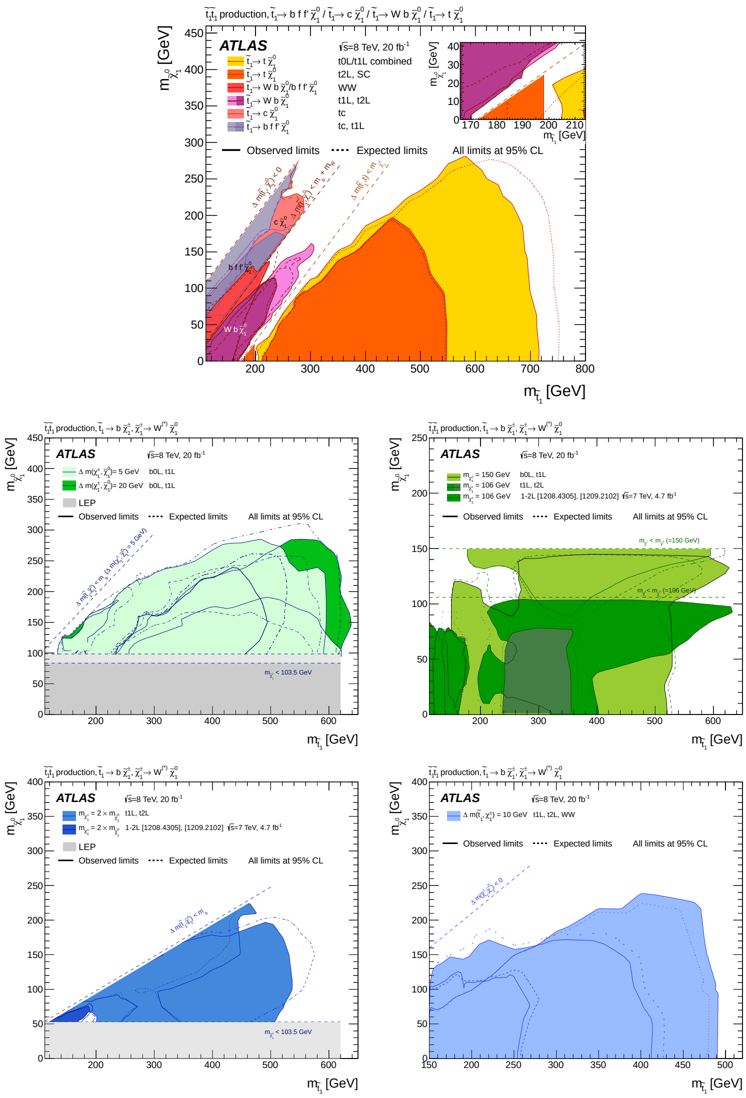

Figure 3: Exclusion limits for scalar top quarks in various simplified models [1]. The upper (lower) plot shows scenarios where the scalar top quark is the NLSP (NNLSP). The searches targeting individual decay modes are represented by a color code.

4. Analysis at $\sqrt{s} = 13$ TeV

4.1 Sbottom 2b + $E_{\mathrm{T}}^{\mathrm{miss}}$

This search targets a scenario where the sbottom is the NLSP. The event selection requires two b-tagged jets and vetos events with leptons. The signal topology depends on the mass difference between sbottom and neutralino $\Delta m = m_{\tilde{b}_1} - m_{\tilde{\chi}_1^0}$, thus two types of SRs are defined.

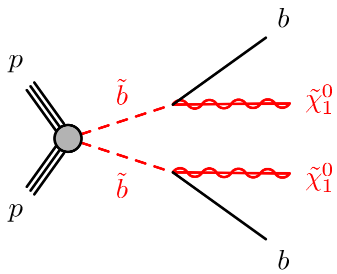

Figure 4: Feynman diagram of the benchmark model.

SR A: High Δm

A high mass difference leads to high-p_T b-jets and large $E_{\mathrm{T}}^{\mathrm{miss}}$. In addition to requirements on these variables, the contransverse mass

$$m_{\mathrm{CT}}^2 = [E_{\mathrm{T}}(b_1) + E_{\mathrm{T}}(b_2)]^2 - [\vec{p}_{\mathrm{T}}(b_1) - \vec{p}_{\mathrm{T}}(b_2)]^2$$

is used to enhance signal purity. The main backgrounds are W- and Z-boson production in association with heavy flavor. The softest signal region of this type is shown in Figure 5.

SR B: Low Δm

A low mass difference leads to low-p_T b-jets and small $E_{\mathrm{T}}^{\mathrm{miss}}$. In order to suppress the background events, events containing high p_T initial state radiation (ISR) jets are selected, which boost the sbottom system. This results in even tighter requirements on $E_{\mathrm{T}}^{\mathrm{miss}}$ and jet p_T than in SR A. The main background is from top pair production.

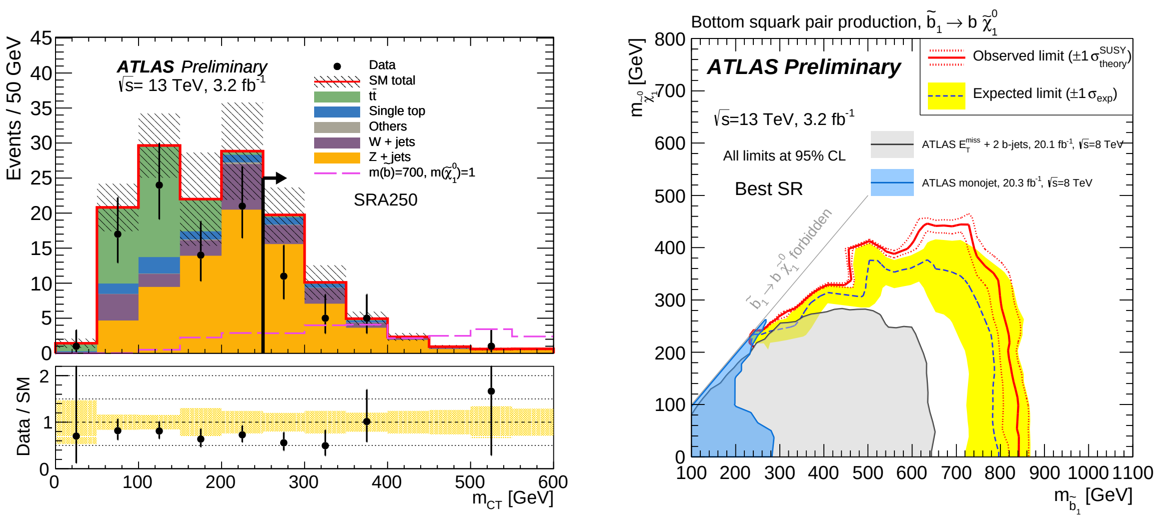

Figure 5: Left: m_{CT} distribution in a SR of type A. No excess over the SM expectation is observed. Right: Exclusion limit for this Sbottom 2b + $E_{\mathrm{T}}^{\mathrm{miss}}$ analysis. For high Δm sbottoms with masses up to ≈ 840 GeV can be excluded. The 8 TeV sensitivity (grey area) was exceeded by this analysis. [2]

4.2 Stop 2 lepton search

This search targets a scenario where the stop is the NNLSP. The event selection requires two opposite sign leptons, which do not originate from a Z-boson. In addition the stransverse mass m_{T2} and the kinematic variable R1 are used to suppress the backgrounds. The signal regions are split into events with same or different flavor leptons.

$$m_{T2} = \min_{\vec{q}_T^{\,1}+\vec{q}_T^{\,2}=\vec{p}_T^{\,\text{miss}}} \left(\max \left[m_T(\vec{p}_T^{\,\ell_1}, \vec{q}_T^{\,1}), m_T(\vec{p}_T^{\,\ell_2}, \vec{q}_T^{\,2}) \right] \right)$$

$$R1 = \frac{E_T^{\text{miss}}}{m_{\text{eff}}}$$

The analysis is interpreted for two signal models

$$m_{\tilde{\chi}_1^\pm} = 2 \times m_{\tilde{\chi}_1^0} \qquad \text{and} \qquad m_{\tilde{t}_1} - m_{\tilde{\chi}_1^\pm} = 10 \text{ GeV}.$$

The highest sensitivity is reached for compressed spectra, where the b-jets have low p_T, thus no tagging requirement is applied.

Since no significant excess over the SM is observed, exclusion limits are set. These are shown in Figure 7.

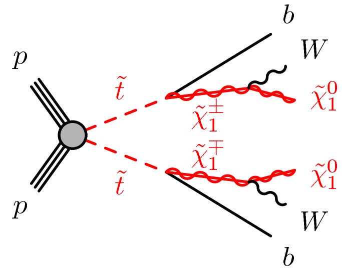

Figure 6: Feynman diagram of the benchmark model.

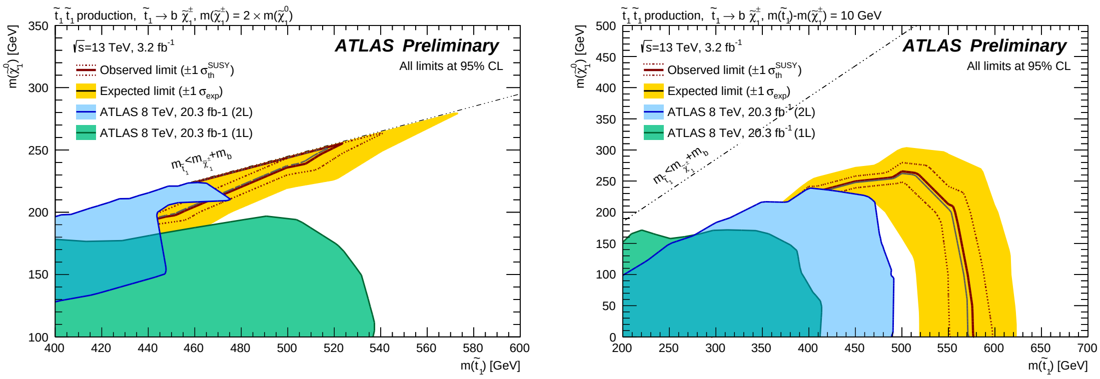

Figure 7: Exclusion limits for the 2L Stop analysis. Left: Exclusion limit for the scenario where $m_{\tilde{\chi}_1^\pm} = 2 \times m_{\tilde{\chi}_1^0}$. For small $\Delta m = m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0}$ stops with masses up to ≈ 525 GeV can be excluded. Right: Exclusion limit for the scenario where $m_{\tilde{t}_1} - m_{\tilde{\chi}_1^\pm} = 10$ GeV. For high Δm stops with masses up to ≈ 575 GeV can be excluded. [3]

4.3 Stop 1 lepton search

This search targets two different scenarios: In scenario 1 the stops are directly produced and decay into a top quark and a W-boson, while in scenario 2 the stops are decay products of the directly produced gluinos. Furthermore the mass difference $\Delta m = m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0}$ is assumed to be very small, thus the decay products of the stops are soft and can not be reconstructed. However the top quarks, which also originate from the gluinos, are produced on-shell.
The event selection requires one lepton and one b-tagged jet. Additionally the variables

$$m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\ell} E_{\mathrm{T}}^{\mathrm{miss}} \left(1 - \cos(\Delta\Phi(\vec{p}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\ell}))\right)}$$

m_{top}^{χ}: best top mass from jets

am_{T2} and m_{T2}^{τ}: variations of m_{T2}

are used to enhance the sensitivity. The main backgrounds are top pair production and top pair production in association with a Z-boson that decays into two neutrinos.
In one of the signal regions of scenario 1 a 2.2σ [4] excess is observed, which leads to the unusual form of the exclusion limit.

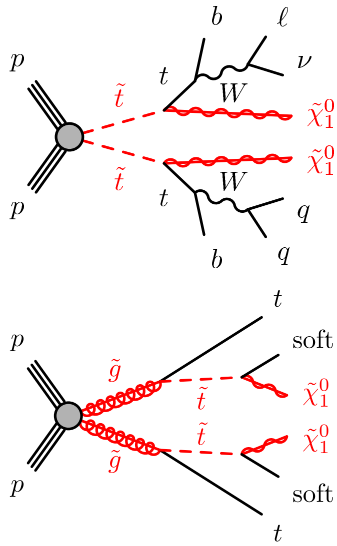

Figure 8: Feynman diagrams of the benchmark models.

No significant excess over the SM is observed, exclusion limits are set. These are shown in Figure 9.

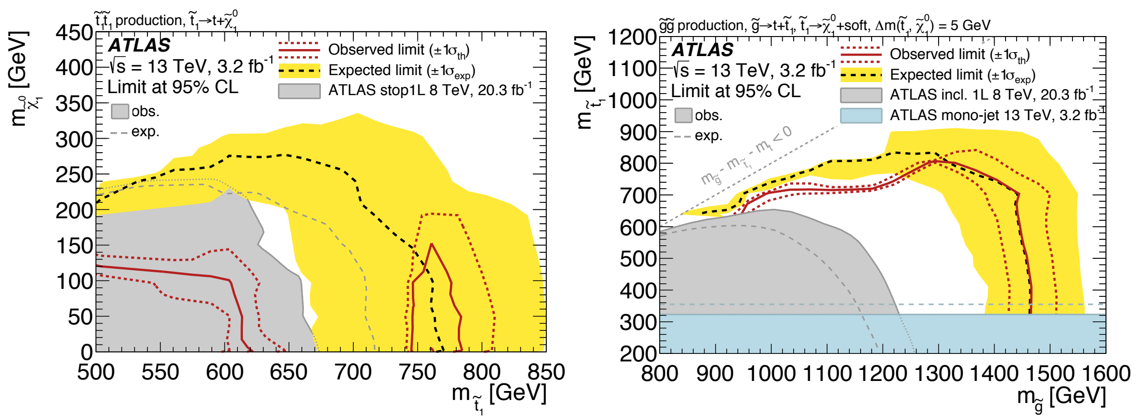

Figure 9: Exclusion limits for the 1L Stop analysis. Left: Exclusion limit for scenario 1. The SR which is used for the final sensitivity in this plot is the one with the best expected sensitivity. In the region dominating in the central region, a 2.2σ excess is observed, leading to the gap in the exclusion limit. In the other regions no excess is observed. Right: Exclusion limit for scenario 2. For high $\Delta m = m_{\tilde{g}} - m_{\tilde{t}_1}$ gluinos with masses up to ≈ 1.47 TeV can be excluded. [4]

4.4 RPV Stop: UDD

This search targets a R-parity violating model with a UDD-type coupling. The stops are produced in pairs, but decay each into a bottom and a strange quark. This leads to a final state without leptons or invisible particles. However the events should contain at least four jets, with two pairs that have an invariant mass m^{jj} close to the stop mass. Additionally each pair should contain a b-tagged jet.
The main background for this analysis is the multijet production, which is derived completely from data. The shape of the distributions is extracted from b-veto regions, while the normalization is being determined using the ABCD method. For the definition of these four regions, the variables

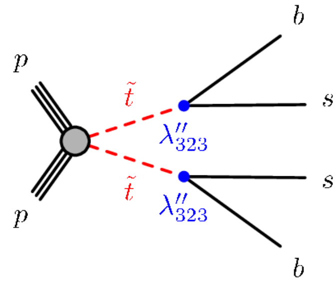

Figure 10: Feynman diagram of the benchmark model.

$$\mathscr{A} = \frac{|m_1^{jj} - m_2^{jj}|}{m_1^{jj} + m_2^{jj}} \qquad \text{and}$$

$$\cos(\theta^*) = (\vec{p}_{\tilde{t}_1^1} + \vec{p}_{\tilde{t}_1^2}) \cdot \vec{x}_{\text{beam pipe}} \text{ in center of mass frame}$$

are used.
The SRs are defined as windows around the benchmark stop mass in the average mass of the two jet pairs

$$m_{\text{avg}} = (m_1^{jj} + m_2^{jj})/2.$$

A small excess is observed in the SR for $m_{\tilde{t}_1} = 350$ GeV with a local p-value of $p_0 = 0.07$ [5]. Since this is not significant, exclusion limits are set. These are shown in Figure 11.

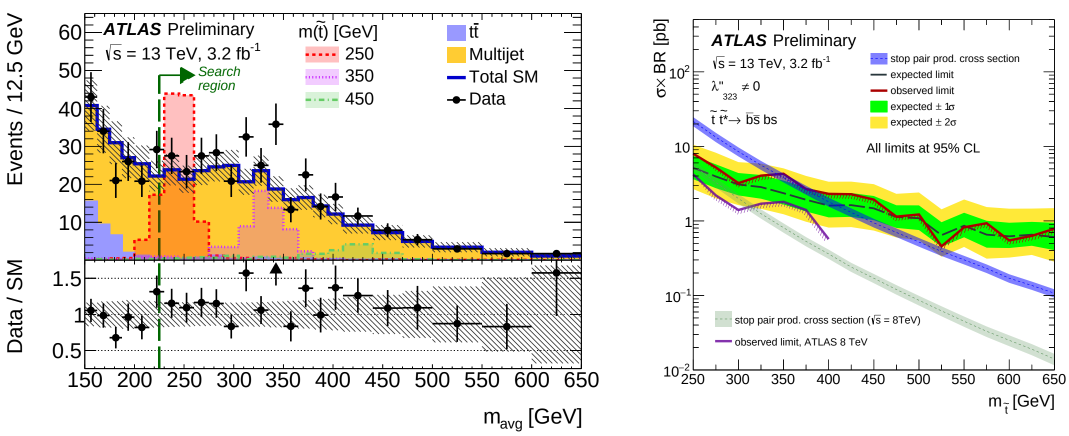

Figure 11: Results of the RPV Stop analysis. Left: m_{avg} distribution in the signal enhanced region. No significant excess is observed. Right: The final exclusion limit. Stop masses up to ≈ 375 GeV can be excluded. [5]

5. Conclusions

Many searches for SUSY, and in particular searches for third generation squarks, have already been performed with ATLAS at 13 TeV. No significant deviations from the SM expectation have been observed so far, so exclusion limits have been set. Many searches have an increased sensitivity compared to the 8 TeV analysis, so despite the much smaller integrated luminosity, the exclusion limits already exceed the existing limits (see Figure 12).

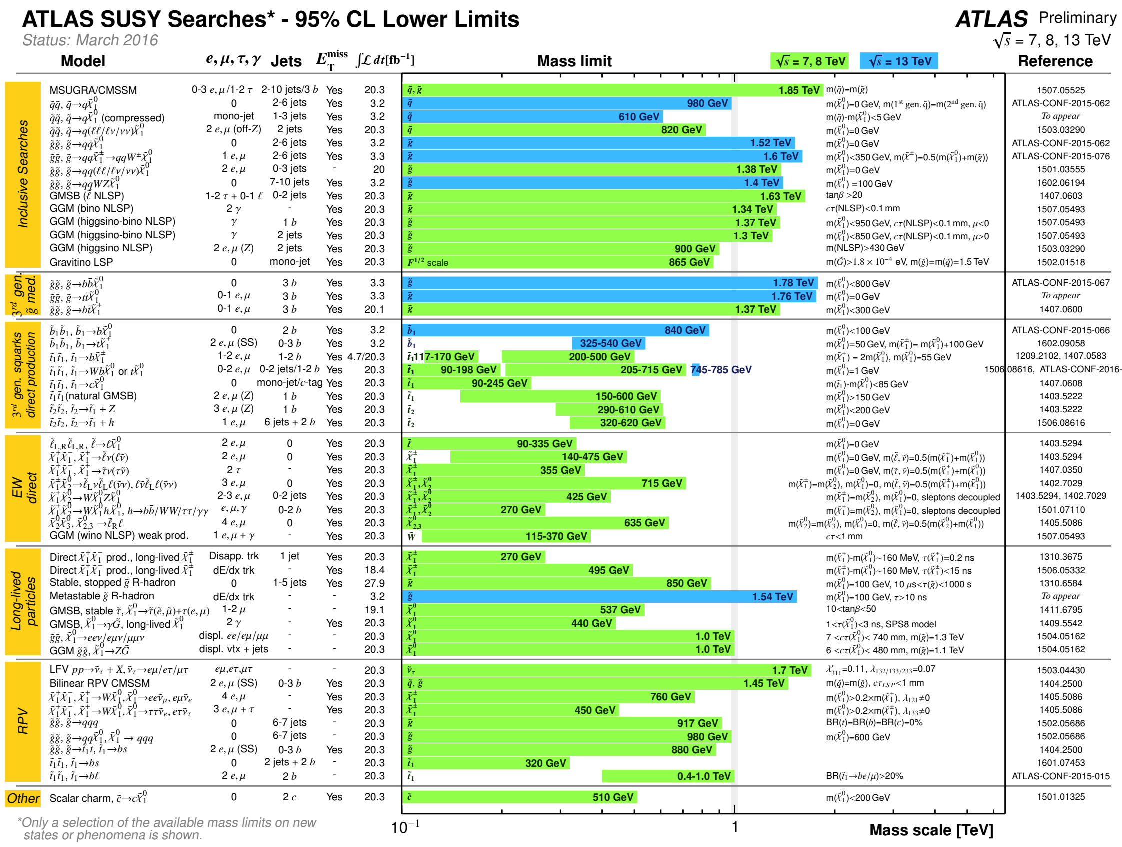

Figure 12: Summary plot including 7, 8 and 13 TeV limits of ATLAS searches for Supersymmetry. Only a representative selection of the available results is shown. [6]

References

[1] ATLAS Collaboration, *ATLAS Run 1 searches for direct pair production of third-generation squarks at the Large Hadron Collider*, [arXiv:1506.08616].

[2] ATLAS Collaboration, *Search for Bottom Squark Pair Production with the ATLAS Detector in proton-proton Collisions at $\sqrt{s} = 13$ TeV*, [ATLAS-CONF-2015-066], http://cds.cern.ch/record/2114833/files/ATLAS-CONF-2015-066.pdf

[3] ATLAS Collaboration, *Search for direct top squark pair production in final states with two leptons in $\sqrt{s} = 13$ TeV pp collisions using 3.2 fb^{-1} of ATLAS data*, [ATLAS-CONF-2016-009], http://cds.cern.ch/record/2139643/files/ATLAS-CONF-2016-009.pdf

[4] ATLAS Collaboration, *Search for top squarks in final states with one isolated lepton, jets, and missing transverse momentum in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector*, [arXiv:1606.03903].

[5] ATLAS Collaboration, *A search for R-parity violating decays of the top squark in four-jet final states with the ATLAS experiment at $\sqrt{s} = 13$ TeV*, [ATLAS-CONF-2016-022], http://cds.cern.ch/record/2152392/files/ATLAS-CONF-2016-022.pdf

[6] ATLAS Collaboration, *SUSY summary plot*, [https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SUSY/index.html].