Searches for Supersymmetry and Exotics phenomena with the ATLAS detector

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Abstract. Searches for new physics beyond the Standard Model are performed using the p-p LHC data collected with the ATLAS detector in 2011 at 7 TeV and in 2012 at 8 TeV centre-of-mass energy. Various production modes for supersymmetric (SUSY) particles are considered: strong production of squarks and gluinos, weak production of sleptons and gauginos, R-parity violating decays and long-lived particles. No significant deviation from the Standard Model processes is observed and limits are set on different flavours of SUSY, such as cMSSM/mSUGRA, pMSSM, GMSB and AMSB. Searches for exotic models for BSM physics are performed, probing for a large variety of well-motivated models, such as heavy gauge resonances, excited fermions, extra-dimensions, exotic Higgs models and new quarks. As in the case of SUSY searches, no excess is observed above the SM background and limits are obtained for the models mentioned above.

1. Introduction

The Standard Model of particle physics is still to this day the best description of matter and forces in our universe. With the recent discovery of a new Higgs-like boson at the LHC [1], the Standard Model is closer to being completely experimentally verified. It is however an incomplete theory and many new models are currently being developed to overcome the Standard Model’s missing ingredients, such as a dark matter candidate particle. Precision measurements of various parameters of the Standard Model, which are more sensitive to new physics phenomena, continue to orient the searches for physics beyond the Standard Model (BSM).

Among the theories currently envisaged as BSM candidates, one theory is of particular interest, Supersymmetry (SUSY). Developed in the 1960s, it introduces new particles, one superpartner (or sparticle) for each existing SM particle. As no SUSY particles have been observed yet, SUSY is believed to be spontaneously broken and consequently, the masses of the superpartners are believed to be higher than their SM counterparts. SUSY is believed to solve several of the current problems with the Standard Model: the hierarchy problem, by cancelling loop contributions to the Higgs mass, as well as providing a dark matter candidate.

In the following, highlights from the searches for SUSY are presented, followed by results from a wide variety of BSM searches in ATLAS [2].

2. Supersymmetry searches

In order to include the SUSY breaking into the observable world, various models are developed, among which the simplest one consistent with the Standard Model is known as
the Minimal SuperSymmetric Model (MSSM). The MSSM contains 105 parameters to be determined experimentally, which allows for a large tuning. To make it more manageable, models can be derived from the MSSM with extra constraints to reduce the number of free parameters. This can be achieved by specifying the mechanisms for SUSY breaking, leading to models such as the Gravity-Mediated Supersymmetry Breaking (mSUGRA), also known as the cosmological MSSM (cMSSM), the Gauge Mediated Supersymmetry Breaking (GMSB) and the Anomaly Mediated Supersymmetry Breaking (AMSB). More recently, a new approach was used and phenomenological constraints were added to the MSSM, based on current experimental observations, leading to the phenomenological MSSM (pMSSM). In order to satisfy baryon and lepton number conservation, a new parity is introduced for SUSY models, called R-parity. It assigns a quantum number of 1 for SM particle and -1 for SUSY particles, hence creating a new parity that also conserve baryon and lepton numbers.

The searches for SUSY in ATLAS are divided into main categories: strong production, searching for squarks and gluinos, weak production, looking for sleptons and gauginos; long-lived particles, which are stable massive particles that cross the detector at a low velocity, and RPV production, where the LSP is allowed to decay to SM particles. Several of these searches were recently updated with 8 TeV results, as pointed out in the following.

A search for coloured sparticles is performed using 8 TeV data [3] looking for squarks and gluinos decaying to SM particles and the LSP, in this case the neutralino, as described in Eq. 1.

$$\tilde{q} \rightarrow q \tilde{\chi}_1^0, \tilde{g} \rightarrow q\bar{q} \tilde{\chi}_1^0$$  \hspace{1cm} (1)

Events are required to have greater or equal to 2-6 jets and missing transverse energy ($E_T^{miss}$), while excluding leptons. The Standard Model processes which could fake this signature come from the production of vector bosons with jets ($W \rightarrow \ell\nu, Z \rightarrow \nu\bar{\nu}$), top pair production ($tt\bar{t}$) associated with jets and QCD multijets. The analysis is divided into 12 signal regions covering 5 jet multiplicities. No signal is observed outside the bounds of the SM, and limits on the mSUGRA model are set. The squarks and gluinos mass is set to be greater than 1500 GeV. In the case of simplified models [4] where the LSP is massless, limits of $m_{\tilde{q}} > 1100$ GeV and $m_{\tilde{g}} > 730$ GeV are determined.

Events with coloured sparticles are also looked for in the high jet multiplicity region for models where $m_{\tilde{q}} > m_{\tilde{g}}$ [5], using 8 TeV data. In this case, the events are selected using $E_T^{miss}/\sqrt{p_T} > 4$ GeV in 6 signal regions based on jet multiplicity (from $\geq 6$ to $\geq 9$ jets) and jet transverse momentum ($p_T$). The main background events are produced by QCD multijets, $tt\bar{t}$ decaying leptonically and $W/Z$ associated with jets. Exclusion limits are determined as no signal is distinguishable from the background, with $m_{\tilde{q}} > 1.0$ TeV for a simplified model where $m_{\tilde{\chi}_1^0} > 300$ GeV.

In models with small fine-tuning, the stop mass is expected to be close to the top mass. The discovery of a low mass Higgs boson has direct consequences on the scale of the MSSM Higgs mass parameter, better known as the “μ term”. It is therefore expected that μ should be close to the electroweak scale, with the direct consequence that Higgsinos, Gauginos, and third generations squarks should be light. Searches for these sparticles are then a direct measure of SUSY naturalness.

A search for direct production of sbottom quarks is performed [6], where the bottom quarks are expected to decay to a $b$-quark and the LSP. Events with 2 $b$-tagged jets and $E_T^{miss}$ are searched in 7 TeV data. The contransverse mass ($m_{CT}$), as defined in Eq. 2, is used to control the $tt\bar{t}$ background. Other backgrounds are the vector boson production with associated heavy flavour jets. No deviation from the SM background is observed, and exclusion limits are set.
on simplified models, such that $m_b > 490 \text{ GeV}$ for a massless LSP and $m_{\tilde{\chi}^1_0} < 180 \text{ GeV}$ for $m_{\tilde{b}} = 400 \text{ GeV}$.

$$m_{CT} = \sqrt{(E_T(b_1) + E_T(b_2))^2 - (p_T(b_1) - p_T(b_2))^2}$$  \hspace{1cm} (2)

Similarly, searches for direct stop production are conducted and combined to form a common exclusion in the $m_{\tilde{\chi}^0_1}$-$m_{\tilde{t}}$ plane. Five searches, completed using the 7 TeV dataset, look for stop decay, either through $\tilde{t} \rightarrow t \tilde{\chi}^0_1$ or $\tilde{t} \rightarrow b \tilde{\chi}^\pm_1$ and their several decay channels [7–11]. The combined exclusion limits are shown in Fig. 1. A mixing angle $\theta_t = 0.985^1$ is considered for the signal model generation.

![Figure 1](image_url)  \hspace{1cm} Figure 1. Combined exclusion limits for the direct stop production using 7 TeV data [12].

Third generation squarks can also be produced through decays of directly pair-produced gluinos. The gluino-mediated stop production is tested by four different analyses [5, 13–15] using the 8 TeV dataset and is summarized in a common exclusion limit in the $m_{\tilde{\chi}^0_1}$-$m_{\tilde{g}}$ plane, as shown in Fig. 2.

The gluino-mediated sbottom production can be probed likewise in 8 TeV data using events with three $b$-tagged jets [14]. The reach in the $m_{\tilde{\chi}^0_1}$-$m_{\tilde{g}}$ plane is improved significantly from the 7 TeV analysis, represented by the green solid line in Fig. 3. New exclusions of $m_{\tilde{g}} < 1240 \text{ GeV}$ for $m_{\tilde{\chi}^0_1} < 200 \text{ GeV}$ and $m_{\tilde{\chi}^0_1} < 570 \text{ GeV}$ for $m_{\tilde{g}} = 1100 \text{ GeV}$ are obtained.

Searches for directly produced weak production are also performed using the 7 TeV dataset. Decays of directly produced left-handed sleptons ($\tilde{\ell}^\pm \rightarrow \ell^\pm \tilde{\chi}^0_1$) are probed for in events with two leptons and $E_T^{\text{miss}}$ in the final state [16]. Significant improvement is obtained over LEP limits obtained for right-handed smuons, as shown in Fig. 4. Using the same signature, direct production of gauginos are searched for, focusing on the LSP and $\tilde{\chi}^\pm_1$. These gauginos decay through intermediate particles, either vector bosons or sleptons. Depending on the decay channel that the intermediate particles take, these processes can lead to higher multiplicity of leptons for which specific searches are designed [17]. For the $\geq 3$ leptons searches, the production of $\tilde{\chi}^\pm_2$ is also considered. The main backgrounds for direct gauginos searches are $t\bar{t}$, $W/Z$ associated with jets, diboson production and non-isolated leptons. The results for two lepton multiplicities are shown in Fig. 5.

Models with RPV terms added to the Lagrangian [18] allow for LSP decays, thus creating event signatures with large lepton multiplicities as well as fully hadronic three-jet resonances

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1 Corresponding to a mixing matrix of $\begin{pmatrix} \tilde{\ell}_1 \\ \tilde{\ell}_2 \end{pmatrix} = \begin{pmatrix} 0.55 & -0.83 \\ 0.83 & 0.55 \end{pmatrix} \begin{pmatrix} \tilde{\ell}_R \\ \tilde{\ell}_L \end{pmatrix}$, resulting in a mostly right handed mixture.
3. Exotic phenomena searches

Although SUSY is well motivated, other models are developed to account for missing pieces of the Standard Model and describe the physics beyond the SM. There is a large variety of models tested using LHC data. In the following, a selection of interesting results is presented, including searches done using the 8 TeV dataset, testing production of heavy gauge bosons ($Z', W'$), excited fermions ($f^* \rightarrow f\gamma$), extra-dimensions (ADD, UED, RS), exotic Higgs models ($H^{++}$) and new quarks (fourth generation, vector-like quarks), among others.

A search for heavy resonances, here $Z'$, is performed in the dilepton channel using 8 TeV data [20]. The search is performed for both electron and muon channels. No significant excess is observed over the dilepton invariant mass background. Limits are set on various E6 $Z'$ models.
Figure 4. Exclusion limits for direct left-handed sleptons production using 7 TeV data [16].

Figure 5. Exclusion limits for direct gaugino production in (a) the two lepton channel [16] and (b) the three inclusive lepton channel [17] using 7 TeV data.

For all models, a $Z'$ with a mass below 2 TeV is excluded. In the special case of the Sequential Standard Model (SSM), the $Z'$ mass is restricted to be greater than 2.49 TeV, as shown in Fig. 6. Data events considered in this analysis include the highest energy dimuon event, with an invariant mass of 1.258 TeV, the two back-to-back muons entering the detector with a $p_T$ of 289 and 274 GeV respectively.

New heavy resonances can also arise in highly energetic dijet events. In this case, the analysis is used to test quark compositeness, by searching for decays of excited quarks through a gluon ($q^* \rightarrow q\gamma$) in 7 [21] and 8 TeV [22] data. The data is observed to be consistent with the expected background for the dijet invariant mass distribution. Exclusion limits are set on the excited quark masses, of 3.84 TeV, as shown in Fig. 7. The highest energy event recorded by the ATLAS detector in 8 TeV data was found in this analysis, with an invariant mass of 4.69 TeV for...
two back-to-back jets of $p_T = 2.19$ and 2.29 TeV respectively. This event had $E_T^{miss} = 47$ GeV.

The LHC is a $t\bar{t}$ factory, which is also a good channel to look for heavy resonances. A search for $Z'$ and Randall-Sundrum (RS) Kaluza-Klein (KK) gluons using the leptons+jets decay channel for top decay, $t\bar{t} \rightarrow W(\ell\nu)bW(qq)b$ is done using 7 TeV data [23] (a search for fully hadronic top decays [24] is also used but not presented here). The analysis is performed using two complementary reconstruction schemes. The resolved reconstruction looks for the individual hadronic jets from the top quark decay, each with small radius, while the boosted reconstruction searches for one large radius jets, as the hadronic top decay products are expected to be collimated for highly-boosted top quarks. The combination of these two schemes allows for an extended reach in $t\bar{t}$ invariant mass. No significant fluctuation above the predicted background is observed. Exclusion limits for the production of leptophobic topcolor $Z'$ with mass $< 1.7$ TeV

Figure 6. Combined dielectron and dimuon exclusion limits for the cross-section times branching fraction $\sigma \times B$ using 8 TeV data [20].

Figure 7. Exclusion limits on the cross-section times acceptance $\sigma \times A$ for excited quarks production using 8 TeV data [22].
and of RS KK gluon excitation with mass < 1.9 TeV are set, as shown in Fig. 8.

\[ \sigma \times \mathcal{B}(g_{\text{KK}}) < 1.9 \text{ TeV} \]

**Figure 8.** Exclusion limits on $\sigma \times \mathcal{B}$ for KK gluon production using 7 TeV data [23].

Leptons, just like quarks, are theorised to exhibit compositeness. A search in 8 TeV ATLAS data is performed to probe for lepton compositeness [25] with scale $\Lambda$ in decays through photons, $\ell^* \rightarrow \ell \gamma$. The analysis is performed for both electron and muon channels, looking for excess in the $m_{\ell\ell\gamma}$ distribution, which is sensitive to all $\ell^*$ possible widths. No significant departure from the expected background is recorded. For a value of $\Lambda = m_{\ell^*}$, an exclusion limit of $m_{\ell^*} < 2.2$ TeV is determined.

Diboson resonances can be used to probe for bulk RS models by looking for the decay of a spin-2 RS graviton ($G^*$). This analysis [26] searches through 8 TeV data for $ZZ$ decays to $\ell^+\ell^- qq$, which provides better rejection of the QCD multijets background than the fully hadronic channel. In the high mass regime, events are selected with one large jet resulting from the merging of the two boosted jets from the $Z$ decay. No resonant feature is observed on top of the smoothly decreasing background. Exclusion limits of $m_{G^*} < 850$ GeV for a dimensionless coupling parameter $\kappa/\bar{m}_{PL} = 1.0$ is obtained.

Large extra-dimensions, in their ADD flavour, can leave a striking signature in the ATLAS detector by means of an energetic monojet and $E_T^{miss}$ emerging from the decay of KK gravitons. This event topology can also be used to search for dark matter candidates, or WIMPs arising from a GMSB scenario. A search for such event signatures [27] is performed using the 8 TeV data and good agreement is observed between the experimental measurements and the Standard Model background expectation. An exclusion limit is set on the fundamental Planck scale $M_D < 2.5$ TeV for various number of extra-dimensions $n$. For a GMSB scenario where $m_{\tilde{q}} = m_{\tilde{g}}$, the best gravitino limits to date are obtained for various values of the squark mass, as shown in Fig. 9.

Searches for ADD extra-dimension models are also performed in electromagnetic channels, such as $\ell^+\ell^-$ and $\gamma\gamma$ [28, 29]. In the dileptonic channel, a non-resonant search (using the total observed number of events) is performed using a similar selection as for the heavy resonances search while in the diphoton case, two isolated $\gamma$ are required. Since no deviation from the Standard Model background is observed, the two channels are combined to obtain more stringent limits for the string scale $M_S > 2.6-4.2$ TeV and for the mass of the lightest graviton $M_G < 1.03(2.23)$ TeV for $\kappa/\bar{m}_{PL} = 0.01 \ (0.1)$.

A search for top+jet resonance is performed using 7 TeV ATLAS data in the $t\bar{t}$+jets channel [30]. The lepton+jets mode is used for the $t\bar{t}$ decay. While the Tevatron observed a $3.4\sigma$ deviation in the $t\bar{t}$ forward-backward asymmetry $A_{FB}$ [31, 32], ATLAS measures no
deviation from the Standard Model expectations. An exclusion limit on the mass of the new resonance (for both $\phi$ and $W'$ and coupling parameter $g_R=1$) of 430 GeV is determined.

Exotic models which include a Higgs triplet can lead to the production of doubly charged Higgs ($H^{\pm\pm}$). They are searched for using 7 TeV ATLAS data in their decay to two pairs of same-sign-same-flavour leptons $\ell^{\pm\pm}\ell'^{\pm\pm}$ ($ee, e\mu, \mu\mu$) [33]. Background processes include both prompt ($tt+W/Z, W/Z$) and non-prompt (Heavy Flavour production, conversion) sources of leptons. No excess is measured on top of the background and decay-channel dependent limits are set. Masses for doubly charged Higgs of $m_{H^{\pm\pm}} < 409$ (398, 375) GeV for $ee$ ($\mu, \mu, e\mu$) are excluded.

Finally, a search for heavy quarks is performed using 7 TeV ATLAS data [34], probing for pair production of $b'$ and $T_{5/3}$ heavy quarks. A complex signature is considered ($t^+\ell^+b\bar{b}q\bar{q}q$) and is searched for in events with two same-sign leptons, one $b$-tagged jet and two light jets. After selection 5.6 events are expected and four are measured, therefore exclusion limits are computed. Masses for $b'$ and $T_{5/3} < 0.67$ TeV are excluded. A search for the 4th generation top partner, $t'$, is performed with the same dataset [35]. The $t'$ is looked for in its $t'\bar{t}' \to WbWb$ decay channel. The lepton+jets final state is used to perform this measurement, where no deviation is observed from the Standard Model background. An exclusion limit of 656 GeV is obtained for the mass of the $t'$, when considering $\text{BR}(t' \to Wb) = 1$.

4. Conclusion
The search for new phenomena beyond the Standard Model is a very active field at the ATLAS experiment, of which only a subset of results is presented here. An impressive variety of Supersymmetry and Exotics models have been considered for searches, amounting to 23 (10) public conference notes with 7 (8) TeV data, and 49 papers with the 2010-2011 dataset for SUSY searches and 48 (6) public conference notes with 7 (8) TeV data, and 52 papers with the 2010-2011 dataset for Exotics searches. These results allowed us to push the masses of the 1st and 2nd generation squarks and gluinos even further above the TeV mark while naturalness arguments are driving the searches for 3rd generation squarks and gauginos. At the same time, the limits on exotic particle masses, coupling parameters and cross-sections are being pushed higher than ever. So far, the data is very much still agreeing with the Standard Model, but this is just the beginning. While the analyses presented above and many more are being updated to 8 TeV, new results with the upgraded LHC energy of 13 TeV will shed more light on the high energy regime of particle physics.
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