SEARCHES FOR SUPERSYMMETRY AND EXOTIC PHENOMENA WITH THE ATLAS DETECTOR*

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Weak-scale supersymmetry is one of the best motivated and studied extensions of the Standard Model and it is explored, together with other new physics scenarios, exploiting the recent increase in the center-of-mass energy of proton–proton collisions at the Large Hadron Collider. This paper summarizes the searches performed with the ATLAS detector in the first Run 2 data using 3.2 fb^{-1} at 13 TeV.

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1. Introduction

The Standard Model (SM) of elementary particles has had enormous phenomenological success during the past half century. However, it is generally believed that it is a low-energy limit of a more general theory, and numerous theoretical scenarios are studied in order to address at least some of the open issues such as the unification of forces, the existence of dark matter or the hierarchy problem. Many of these models indicate that new phenomena are likely to appear at the TeV-scale, the direct probe of which is possible with the Large Hadron Collider (LHC) [1] at CERN. Supersymmetry (SUSY) is most commonly invoked to address the open questions of the SM, but there are a large number of important and well-motivated theoretical models that seek to answer some or all of the fundamental questions. These, non-SUSY phenomena are often collectively referred to as exotic physics.

The ATLAS experiment [2] explores TeV-scale territory performing a large number of searches for beyond the Standard Model (BSM) physics. The emphasis in this conference report is placed on the recent results, based on the LHC proton–proton collision data collected in Run 2 at $\sqrt{s} = 13$ TeV.

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2. Searches for SUSY physics signals

SUSY [3–8] is a symmetry which transforms bosonic states into fermionic states, and *vice versa*. SUSY models can provide solutions to many of the known shortcomings of the SM, most notably the hierarchy or fine-tuning problem [9–12]. The minimal supersymmetric extension to the SM (MSSM) [13, 14] predicts a supersymmetric partner ("sparticle"), which differs in spin by $1/2$ from its SM counterpart. In order to satisfy baryon (B) and lepton number (L) conservation, a new parity is introduced for SUSY models, called R-parity. If R-parity is conserved [15], each supersymmetric interaction involves an even number of "sparticles", and as a result, there exists a Lightest Supersymmetric Particle (LSP), which must be stable and is typically the lightest neutralino[1] ($\tilde{\chi}_1^0$) which escapes detection. The escaping LSP provides a source of missing transverse momentum, $\boldsymbol{p}_{\mathrm{T}}^{\mathrm{miss}}$, with magnitude $E_{\mathrm{T}}^{\mathrm{miss}}$. In many SUSY models, the LSP serves as a viable candidate for non-baryonic dark matter [16]. SUSY production is characterized by pair-produced "sparticles", which then decay via cascades into final states involving LSPs.

Several classes of phenomenological and simplified models covering different combinations of physics objects in the final state have been studied in ATLAS with the LHC Run 2 data. A complete list of public results on SUSY searches are reported in [17].

2.1. Inclusive strong production searches

The majority of models consider the decay of these SUSY particles to the LSP. A multitude of signal regions have been designed to probe different parts of the phase space using different cuts on the number of jets, the number of charged light leptons (electrons or muons), and the transverse momenta of all particles and jets in the event.

Search for gluino ($\tilde{g}$) and squark ($\tilde{q}$) pair production

A search for $\tilde{q}$ and $\tilde{g}$ in final states containing jets (≥ 2 to ≥ 6 jets), $E_{\mathrm{T}}^{\mathrm{miss}}$ and no electrons or muons have been performed [18]. Good agreement is seen between the number of events observed in the data and the numbers of events expected from SM processes. For a massless $\tilde{\chi}_1^0$, gluino masses ($m_{\tilde{g}}$) below 1520 GeV are excluded at the 95% C.L. in a simplified model with only $\tilde{g}$ and the $\tilde{\chi}_1^0$, extending the region of supersymmetric parameter space excluded by previous ATLAS searches.

[1] The SUSY partners of the Higgs and electroweak gauge bosons mix to form the mass eigenstates known as charginos ($\tilde{\chi}_l^{\pm}$, $l = 1, 2$ ordered by increasing mass) and neutralinos ($\tilde{\chi}_m^0$, $m = 1, \ldots, 4$ ordered by increasing mass).

Search for gluino pair ($\tilde{g}\tilde{g}$) production with complex decay chains

This analysis concerns searches for gluinos in final states with large jet multiplicities and $E_{\mathrm{T}}^{\mathrm{miss}}$ [19]. Events with various jet multiplicities (from ≥ 7 to ≥ 10 jets) and with various b-jet multiplicity requirements (≥ 0, ≥ 1 and ≥ 2 b-tagged jets) are selected to enhance the sensitivity. No excess above SM expectations is observed. The results are interpreted in the context of a simplified SUSY model, and a slice of the pMSSM [20, 21] each of which predicts cascade decays of "sparticles" and hence large jet multiplicities. The data exclude $m_{\tilde{g}}$ up to 1400 GeV at the 95% C.L. in these models, significantly extending previous bounds, as one can see in Fig. 1.

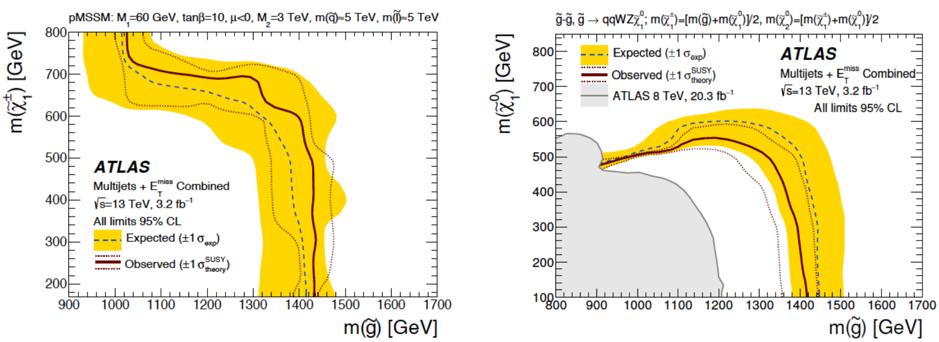


Fig. 1. 95% C.L. exclusion limits for direct production of $\tilde{g}\tilde{g}$ decaying via the cascade for pMSSM (left) with respect to the gluino mass ($m_{\tilde{g}}$) and to the chargino mass ($m_{\tilde{\chi}_1^\pm}$), and for simplified model (right) with respect to the gluino mass and to the neutralino mass ($m_{\tilde{\chi}_1^0}$) [19].

Search for $\tilde{g}$ (or $\tilde{q}$) pair production with a Z-boson in the decay chains

Another of the many interesting searches performed in the frame of the strong production searches is the $Z + E_{\mathrm{T}}^{\mathrm{miss}}$ analysis [22], where events are required to contain at least two the same-flavoured leptons (electrons or muons), with opposite charge, coming from the decay of a Z-boson, at least two jets and high $E_{\mathrm{T}}^{\mathrm{miss}}$. After using data-driven methods to estimate all major backgrounds, the total background estimated in signal region is 10.3 ± 2.3 events, whereas the observed number of events is 21. This excess corresponds to a significance of 2.2 standard deviations (σ). More LHC Run 2 data is necessary in order to answer the question if this excess was a hint of new physics or a statistical fluctuation.

Gluino-mediated sbottom pair production

The next analysis concerns the search for pair production of gluinos decaying via sbottom ('Gbb model') and stop ('Gtt model') to the lightest neutralino [23]. The sbottom and stop are assumed to be produced off-shell such that the gluinos undergo a three-body decay and that the only parameters of the simplified models are the gluino and neutralino masses. The signal is searched for in events containing several energetic jets, of which at least three must be identified as b-jets, large $E_{\mathrm{T}}^{\mathrm{miss}}$ and potentially isolated charged electrons or muons. The data are found to be in good agreement with the predicted background yield. For $\tilde{\chi}_1^0$ masses below approximately 700 GeV, $m_{\tilde{g}}$ less than 1780 GeV and 1675 GeV are excluded at the 95% C.L. in simplified models of the pair production of gluinos decaying via sbottom and stop, respectively.

2.2. Third generation squark direct production searches

A search for pair production of the supersymmetric partner of the SM bottom quark ($\tilde{b}_1$) has been performed in events containing large $E_{\mathrm{T}}^{\mathrm{miss}}$ and up to four jets, exactly two of which have been identified as b-jets [24]. No excess above the expected SM background yield is found.

Exclusion limits at 95% C.L. on the mass of the bottom squark are derived in phenomenological supersymmetric R-parity-conserving (RPC) models in which the $\tilde{b}_1$ is the lightest squark and is assumed to decay via $\tilde{b}_1(\rightarrow b\tilde{\chi}_1^0)$. The results extend the constraints on bottom squark masses by more than 150 GeV with respect to Run 1 searches despite the lower integrated luminosity because of the increase in centre-of-mass energy of the LHC.

2.3. Search for gluino-pair production in final states with one lepon, jets and E_T^{miss}

This section considers a SUSY-inspired model where pair-produced gluinos decay via the lightest chargino ($\tilde{\chi}_1^{\pm}$) to the LSP. The three-body decay of the gluino to the chargino proceeds via $\tilde{g} \rightarrow q\bar{q}'\tilde{\chi}_1^{\pm}$. The chargino decays to the LSP by emitting an on- or off-shell W boson, depending on the available phase space. The experimental signature characterising this search consists of a lepton (electron or muon), several jets, and $E_{\mathrm{T}}^{\mathrm{miss}}$ from the undetectable neutralinos and neutrino(s). The analysis is based on two complementary sets of search channels (gluino simplified models). Details about the analyses can be found in [25]. Figure 2 shows the combined 95% C.L. exclusion limits in the simplified models with gluino production using for each model point the signal region with the best expected sensitivity.

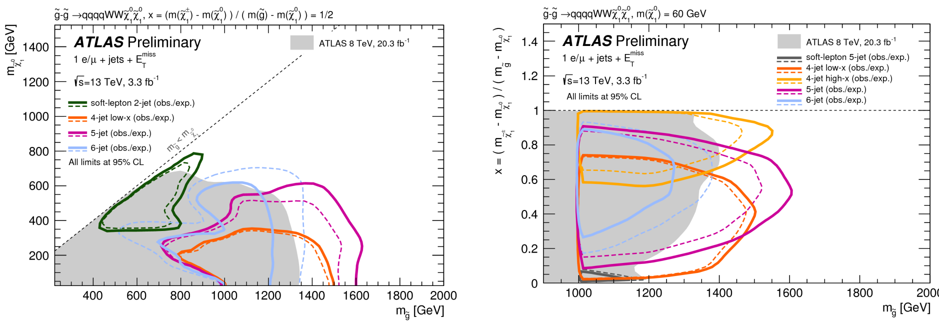


Fig. 2. Combined 95% C.L. exclusion limits in the two gluino simplified models using for each model point the signal region with the best expected sensitivity. The limits are presented in the $(m_{\tilde{g}}, m_{\tilde{\chi}_1^0})$ mass plane (left) for the scenario, where the mass of the chargino $\tilde{\chi}_1^{\pm}$ is fixed to $x = (m_{\tilde{\chi}_1^{\pm}} - m_{\tilde{\chi}_1^0})/(m_{\tilde{g}} - m_{\tilde{\chi}_1^0}) = 1/2$ and in the $(m_{\tilde{g}}, x)$ plane (right) for the $m_{\tilde{\chi}_1^0} = 60$ GeV models. The exclusion limits by previous ATLAS analyses are shown as the grey area.

2.4. Search for strongly produced superpartners in final states with the same-sign leptons or three leptons and jets

A search for supersymmetry in events with exactly two the same-sign leptons or at least three leptons, multiple jets, b-jets and $E_{\mathrm{T}}^{\mathrm{miss}}$ is presented [26]. In this analysis, events containing multiple jets and either two leptons (electrons or muons) of the same electric charge (same-sign leptons, SS) or at least three leptons (3L) are used to search for strongly produced supersymmetric particles. Signatures with SS or 3L are predicted in many SUSY scenarios. Gluinos produced in pairs or in association with a squark can lead to SS signatures when decaying to any final state that includes leptons because gluinos are Majorana fermions. Squark production, directly in pairs or through $\tilde{g}\tilde{g}$ or $\tilde{g}\tilde{q}$ production with subsequent $\tilde{g} \to q\tilde{q}$ decay, can also lead to SS or 3L signatures when the squarks decay in cascades involving top quarks (t), charginos, neutralinos or sleptons, which subsequently decay as $t \to bW$, $\tilde{\chi}_i^{\pm} \to W^{\pm(*)}\tilde{\chi}_j^0$, $\tilde{\chi}_i^0 \to h/Z^{(*)}\tilde{\chi}_j^0$, or $\tilde{\ell} \to \ell\tilde{\chi}_1^0$, respectively. With no significant excess over the SM expectation observed, results are interpreted in the framework of simplified models featuring gluino and bottom squark production. These results are complementary to those of previous searches and extend the exclusion limits they set.

3. Searches for exotic physics signals

As well as for the SUSY searches, the exotic searches are conducted identifying the most promising and as much as possible background-free signatures of interest expected from some exotic models. The data analyses start from a series of selection criteria able to disentangle the signal events from the SM background. The result of the signal selections is presented using kinematics variables capable to well discriminate the signal from the SM background. If data are in good agreement with the MC background, the exclusion limits are set on the parameters of the benchmark models. A complete list of public results on exotic searches are reported in [27].

3.1. Searches in the dijet final state

Any new particle that can be created at the LHC must couple to quarks or gluons and, therefore, searches using the dijet final state have broad sensitivity to new physics. Two variables are used for these searches [28]: *(i)* the dijet invariant mass m_{jj} which is sensitive to new particles in the s-channel, and *(ii)* $\chi = e^{|y_1 - y_2|}$, where y_1 and y_2 are the rapidities of the jets, which is sensitive to new particles in the t-channel. The m_{jj} distribution is shown in Fig. 3. In all cases, good agreement with the SM expectation is observed, and limits on the cross section for a generic Gaussian dijet resonance are shown in Fig. 3.

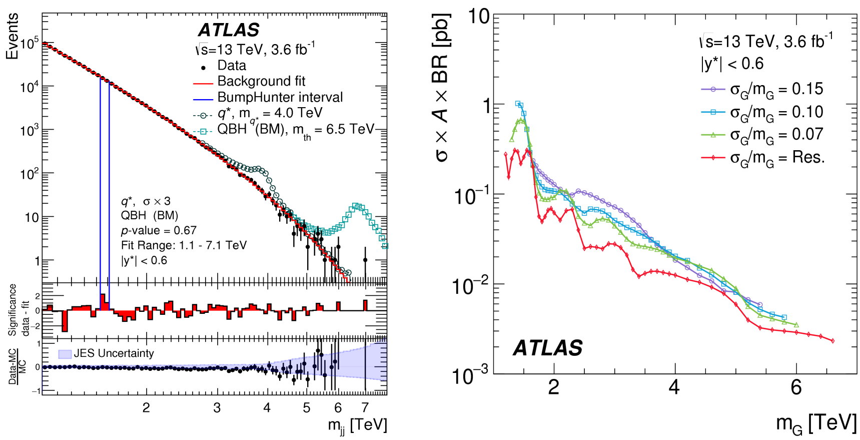


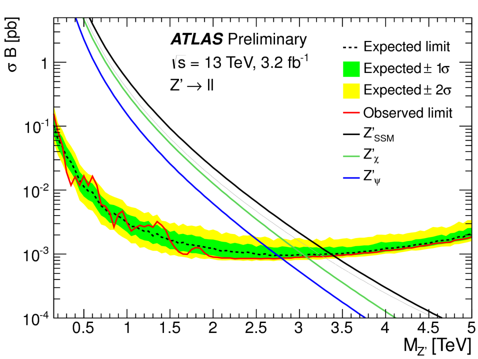
Fig. 3. Left: The reconstructed dijet mass distribution (filled points) for events with $|y^{\star}| < 0.6$ and $p_{\mathrm{T}} > 440(50)$ GeV for the leading (subleading) jets. The solid line depicts the fit to an empirical background distribution function. Predictions for an excited quark and a quantum black hole are also shown. Right: The 95% C.L. upper limits obtained from the m_{jj} distribution on cross section times acceptance times branching ratio to two jets for a hypothetical signal that is Gaussian in m_{jj}, with various widths, as a function of the mean mass of the Gaussian distribution, m_{G} [28].

3.2. Searches with leptonic final states

The final set of searches reported here are those that look for new phenomena in fully leptonic final states. A typical model to which these searches are sensitive is that of a new heavy vector boson, but in some cases, the searches are sensitive to non-resonant (*i.e.* t-channel) effects too.

Search for high-mass dilepton resonances

The $\ell^+\ell^-$ final state signature is a key search channel for a host of different new phenomena expected in theories that go beyond the SM. The $\ell^+\ell^-$ invariant mass ($m_{\ell\ell}$) distribution could deviate from the SM expectation either due to the presence of a Z' resonance [29], or the presence of new non-resonant couplings [30]. A search for these effects was performed in both the electron and muon channels, with the $m_{\ell\ell}$ distributions compared to the SM prediction [31]. This search channel benefits from high signal selection efficiencies and relatively small, well-understood backgrounds. No significant deviations are observed, and the resulting limits on the cross section times branching ratio for a Z' boson as a function of mass are shown in Fig. 4 (left). The lower 95% C.L. exclusion limits on the energy scale Λ for various $\ell\ell qq$ contact interaction models range between 16.7 TeV and 20.0 TeV (Fig. 4 (right)).



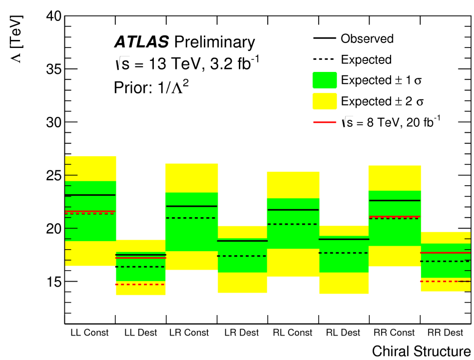


Fig. 4. Left: Upper 95% C.L. limits for Z' production cross section times branching ratio to two leptons. Right: Lower 95% C.L. limits on the contact interaction (CI) scale Λ for different chiral coupling and both constructive and destructive interference scenarios using a uniform positive prior in $1/\Lambda^2$.

Search for high mass states in events with one lepton and missing energy

The search is conducted in the $W' \to \ell\nu$ channel, where $\ell = e$ or μ. The signature is a single high-p_{T} isolated lepton and substantial missing transverse momentum $E_{\mathrm{T}}^{\mathrm{miss}}$ due to the undetected neutrino. The signal discriminant is the transverse mass of the lepton and neutrino ($m_{\mathrm{T}} = \sqrt{2p_{\mathrm{T}}E_{\mathrm{T}}^{\mathrm{miss}}(1-\cos\varphi_{\ell\nu})}$) which is compared to the expectation from SM processes. Good agreement is observed, as shown in Fig. 5 (left). The resulting limits on the cross section times branching ratio for a W' boson as a function of mass are shown in Fig. 5 (right). The results of this search [32] are interpreted in the context of the benchmark Sequential Standard Model (SSM) [33], where the couplings of the W' to fermions are assumed to be identical to those of the SM W boson. Interference between the SSM W' and the SM W boson and the decay into other bosons is neglected.

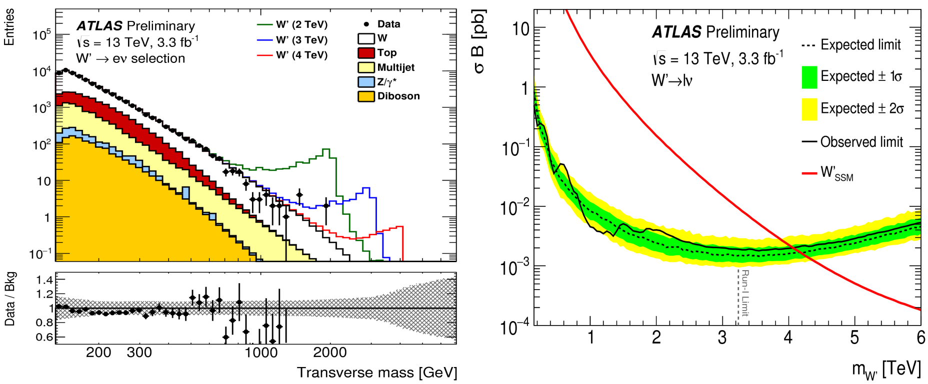


Fig. 5. (Colour on-line) Left: Transverse-mass distributions for events satisfying all selection criteria in the electron channel. The distributions are compared to the sum of all expected backgrounds with three selected W'_{SSM} signals overlaid. The band in the ratio plot shows the systematic uncertainty [32]. Right: Median expected (dashed black line) and observed (solid black line) 95% C.L. upper limits on cross section times branching ratio. The predicted σB for W'_{SSM} production is shown as a (red) solid line [32].

Search in the $e\mu$ final state

Within the SM, direct production of lepton pairs with different flavour is forbidden due to lepton flavour conservation (LFC). However, lepton flavour violation (LFV) is allowed in many extensions of the SM such as Arkan–Dimopoulos–Dvali (ADD) [34] and Randall–Sundrum (RS) [35] models for extra dimensions. A search for such resonance was carried out by comparing the $e\mu$ invariant mass distribution to the SM expectation [36]. Good agreement is observed, and the resulting limits on the cross section times branching ratio for a LFV Z' as a function of the Z' mass are shown in Fig. 6.

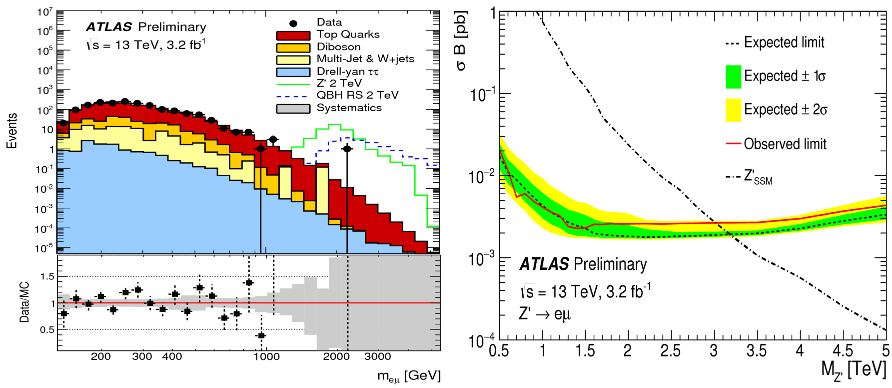


Fig. 6. Left: The invariant mass distribution of selected electron–muon pairs for data and MC expectation. The errors show the statistical uncertainty on the observed yields, while the systematic band includes the addition in quadrature of all systematic uncertainties. Right: The expected and observed 95% C.L. lower mass limits on the Z' production cross section in decays to an $e\mu$ final state [36].

4. Conclusion

The search for new phenomena beyond the Standard Model is a very active field within the ATLAS experiment, of which only a subset of results is presented here. An impressive variety of supersymmetry and exotics models have been carried out using 3.2 fb^{-1} of pp collisions at $\sqrt{s} = 13$ TeV recorded by the ATLAS experiment at the LHC. No evidence of new physics was revealed in these searches, but in 2016, it is expected that ≈ 30 fb^{-1} will be recorded and will shed more light on the high energy regime of particle physics.

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