Recent results from SUSY searches with ATLAS and prospects for the HL-LHC

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Abstract. Even if no experimental evidence has been found so far, TeV-scale supersymmetry is still one of the most popular extensions of the Standard Model. This work summarizes some of the most recent results on inclusive searches obtained with the ATLAS detector using about 80 fb\(^{-1}\) of data collected in 2015-2017 at a center-of-mass energy \(\sqrt{s} = 13\) TeV. Also prospects on the HL-LHC discovery potential are presented assuming an integrated luminosity of 3000 fb\(^{-1}\) at \(\sqrt{s} = 14\) TeV.

1. Introduction
Supersymmetry (SUSY) \(^1\) is one of the best motivated extensions of the Standard Model (SM). It predicts new bosonic partners for the existing fermions and fermionic partners for the known bosons. In the framework of a generic R-parity \(^3\) conserving SUSY model, supersymmetric particles (or sparticles) are produced in pairs and the lightest supersymmetric particle (LSP) is stable and provides a possible dark matter candidate. Different kinds of sparticles are searched at the LHC (Large Hadron Collider) in Geneva \(^2\). Strong production (squarks and gluinos) is the most favoured scenario, owing to the higher expected cross-sections. Electroweakinos (Higgsinos, winos and bino) mix to form neutralino (\(\tilde{\chi}_i^0\), \(i=1,2,3,4\)) and chargino (\(\tilde{\chi}_i^\pm\), \(i=1,2\)) eigenstates. In case strong coloured sparticles have much heavier masses than electroweakinos, then SUSY would be mainly produced at the LHC via direct electroweak production. In this work results for a few SUSY searches in R-parity conserving (RPC) scenarios are presented. All searches have been carried out using up to 80 fb\(^{-1}\) of data collected at the LHC for 2015 to 2017 at \(\sqrt{s} = 13\) TeV.

2. The ATLAS experiment
ATLAS \(^3\) is a multi-purpose detector situated at the LHC. It consists of three main subsystems organized in a cylindrical symmetry. The inner detector (ID) reconstructs tracks of charged particles within the pseudorapidity range \(|\eta| < 2.5\) by means of silicon pixel and strip detectors, and a transition radiation tracker providing a large number of hits in the outermost layers. The ID is immersed in a 2 T axial magnetic field produced by a barrel

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\(^3\) For each particle R-parity is defined as \(R = (-1)^{3(B-L)+2S}\), where \(B\) is the barionic number, \(L\) is the leptonic number and \(S\) is the spin. \(R\) is +1 for SM particles and −1 for their SUSY partners.
solenoid, inside which an electromagnetic calorimeter and a hadronic calorimeter provide energy measurements within $|\eta| < 4.9$. The outermost subdetector, the muon spectrometer (MS), allows accurate reconstruction for all muons up to $|\eta| < 2.7$: it consists of one barrel and two end-cap superconducting toroidal magnets around which precision chambers provide spatial and momentum measurements, together with separate trigger chambers allowing online selection of event with muons characterized by $|\eta| < 2.4$. In order to perform physics analyses starting from the huge LHC rate (40 MHz), the ATLAS trigger is implemented with a two-level selection system: the hardware-based Level-1 trigger reduces the rate down to $\sim 100$ kHz by putting together a subset of available detector information; the software-based High Level Trigger subsequently reduces the rate to $\sim 1$ kHz, which is definitively saved for physics studies.

2.1. Upgrades for HL-LHC

The HL-LHC (High-Luminosity LHC) will operate at an instantaneous luminosity up to $7.5 \times 10^{34}$ cm$^{-2}$ s$^{-1}$, corresponding to an average number of inelastic p-p collisions per bunch-crossing ($\mu$) of 200. A target integrated luminosity of 3000 fb$^{-1}$ is foreseen for the HL-LHC. These conditions will demand a performance from the ATLAS detector that goes well beyond the original design. Major upgrades will be needed for all sub-detectors to cope with the high-radiation environment and the large increase in pileup. The new Inner Tracker (ITk) [4, 5] will cover track reconstruction up to $|\eta| < 4.0$. The upgraded Muon Spectrometer [6] with a forward muon tagger included is designed to provide lepton identification capabilities up to $|\eta| < 4.0$. The construction of a new high granularity timing detector (HGT D) [7] is also planned with the purpose to mitigate the pileup effects in the forward region of $2.4 < |\eta| < 4.0$. The electronics of both LAr and Tile calorimeters [8, 9] will be upgraded to cope with the harsher pileup conditions. A study of the expected performance of the ATLAS upgraded detectors for the HL-LHC is shown in Ref. [10].

3. Searches with gluinos and squarks

ATLAS searches for strong SUSY production are based on a large number of dedicated analyses with a wide variety of Signal Regions (SRs). Results are represented in terms of exclusion contours placed on benchmark simplified models (defined by making specific assumptions on SUSY parameters), for what concerns both gluino pair production (Fig. 1) and squark pair production (Fig. 2) [11]. No evidence of SUSY is found and, depending on the considered analysis and on the possible decays, masses are excluded at 95% confidence level (C.L.) up to more than 2 TeV for gluinos and around 1.8 TeV for squarks. Such limits highly depend on the considered model: all the analysis details in these searches may be found in their respective publications, as reported on the figures.

As an example of search for SUSY strong production scenario, the production of gluino pairs decaying via third-generation squarks into the lightest neutralino [12] is considered here. The search is performed on an integrated luminosity of 79.8 fb$^{-1}$. The event selection is based on large missing transverse energy ($E_{\text{T}}^{\text{miss}}$) and on the presence of many energetic jets, at least 3 of which are tagged as $b$-jets. Several SRs are defined in the analysis, also depending on the presence of 0 or 1 lepton ($\ell^{\pm} = e^{\pm}$ or $\mu^{\pm}$). In Fig. 3 the event yields in the SRs are represented for the benchmark scenario in which each gluino decays in the $\tilde{g} \rightarrow t \tilde{\chi}^{0}_1$ mode. No excess is found above the expected SM background. For $\tilde{\chi}^{0}_1$ masses below about 800 GeV, gluinos with less than 2.23 TeV (2.19) TeV masses are excluded at 95 % C.L. in simplified models in which the gluino pair decays via top (bottom) squarks.

4. Direct pair production of 3rd generation squarks

Many sophisticated analyses aim at the observation of direct production of bottom or top squark pairs. In a typical natural SUSY spectrum, the supersymmetric partners of the 3rd generation
Figure 1. Exclusion limits at 95% C.L. based on 13 TeV data in the \((\tilde{g}, \chi^0_1)\) mass plane for different models featuring the decay of the gluino to the LSP [11].

Figure 2. Exclusion limits at 95% C.L. based on 13 TeV data in the \((\tilde{q}, \chi^0_1)\) mass plane for different models featuring the decay of the squark to the LSP [11].

Figure 3. Results of the background-only fit extrapolated to the SRs for the multi-bin search for gluino pair production scenarios in which the gluino decays into \(t\bar{t}\chi^0_1\). The upper panel shows the observed number of events and the predicted background yield. The lower panel shows the pull in each SR [12].

SM quarks are expected to be the lightest coloured SUSY particles. This scenario represents a good possibility to discover SUSY in case gluinos are too heavy to be produced at the LHC. Much lower cross-sections with respect to \(\tilde{g}\tilde{g}\) production are expected in this case. Due to the large top mass, the phenomenology of top squark decays can be more or less complex, with 2-, 3-, 4-body decays. Analyses targeting to 3\(^{rd}\) generation squarks are usually divided in different categories according to the number of leptons (0, 1, 2 or more) in the final state. Figure 4 summarizes all results in terms of the observed 95% C.L. exclusion limits in models considering the pair production of 3\(^{rd}\) generation squarks. The lower limit on the top squark mass is about 1.0 TeV for a massless neutralino, while for \(m(t\bar{t}) - m(\chi^0_1) \sim m(t)\) the range 230 GeV < \(m(t\bar{t}) < 580\) GeV is excluded. Similar limits have also been set by ATLAS for bottom squarks, consistently
with the expectation of many SUSY models, that predict a top and a bottom squark to have similar masses [11].

Dedicated studies have been performed to quantify the possible extension of the excluded regions in the \((\tilde{t}_1, \chi_1^0)\) mass plane at the HL-LHC. Expected limits at an integrated luminosity of 3000 fb\(^{-1}\) are shown in Ref. [13], with \(\tilde{t}_1\) masses excluded up to 1.7 TeV for a massless \(\chi_1^0\).

5. Electroweak production of gauginos

Despite the lower cross-sections than strong processes, electroweak (EW) production represents the most promising discovery channel for SUSY if coloured sparticles have mass above 3-4 TeV. SUSY decays via EW interaction can take place through direct production of charginos, neutralinos or sleptons.

Results on the search of chargino pair production via the target process \(\tilde{\chi}_1^± \tilde{\chi}_1^± \rightarrow WW\tilde{\chi}_1^0\tilde{\chi}_1^0\) [14] are presented here for an integrated luminosity of 80.5 fb\(^{-1}\). Since only the leptonic decay mode of the W-boson is taken into account in this analysis, charginos are searched for in final states with two isolated leptons with opposite charge and \(p_T > 25\) GeV, \(E_T^{\text{miss}} > 110\) GeV and at most one light jet in the final state. Events are also required to have no b-jets, in order to suppress contributions of processes containing top quarks. The dominant backgrounds are the SM diboson production and the dilepton \(tt\) and \(Wt\) processes. Events with same flavor lepton pairs are asked to have di-lepton invariant mass outside the \(Z\)-mass window \((|m_{ll} - m_Z| > 30\) GeV).

In Fig. 5 the results of the analysis are shown in terms of the observed and expected exclusion limits as a function of the \(\tilde{\chi}_1^±\) and the \(\chi_1^0\) masses. Thanks to the increased luminosity and energy with respect to Run-1 and to improved analysis techniques (including the use of \(E_T^{\text{miss}}\) significance and of shape fits in the transverse mass \(m_T^{\tilde{t}\tilde{t}}\) [14]), exclusion limits have been largely extended and chargino masses are excluded at 95% C.L. up to 410 GeV for a massless neutralino.

6. Long-lived particles

In highly compressed mass scenarios, SUSY models can foresee the existence of long-lived particles. An example is given by a disappearing track search, which looks for the production
of charginos decaying via a neutralino and a very soft pion, which is not reconstructed [15]. A small mass \( \tilde{\chi}_1^\pm - \tilde{\chi}_1^0 \) splitting implies that the chargino has a significantly long lifetime and decays within the innermost region of the tracking detector. This search, already performed using 36 fb\(^{-1}\) Run-2 data [16], is presented here at the high-luminosity LHC assuming an integrated luminosity of 3000 fb\(^{-1}\) with \( \sqrt{s} = 14 \) TeV. Selection is based on the \( E_T^{\text{miss}} \) trigger, on a lepton veto, and on the presence of a high-\( p_T \) jet and an isolated pixel tracklet, which is required to have small azimuthal angular distance (\(< 0.5\)) with respect to the \( E_T^{\text{miss}} \) direction. The minimum azimuthal angular distance between the transverse missing momentum and each of the first four jets (ordered in \( p_T \)) is required to be greater than 1, in order to reject events with mis-measured \( E_T^{\text{miss}} \). Background estimates are performed via data-driven templates on Run-2 and extrapolated for the high luminosity case.

Results in Fig. 6 are shown in terms of expected exclusion limits as a function of the chargino mass and lifetime for both \( \tilde{\chi}_1^+ \tilde{\chi}_1^- \) and \( \tilde{\chi}_1^\mp \tilde{\chi}_1^0 \) production cases. Using the full expected HL-LHC dataset, lifetimes of light chargino (with mass of 100 GeV) will be excluded at 95% C.L. in the range between 7 ps and 4 \( \mu \)s assuming a wino-like LSP. In the hypothesis of a higgsino-like LSP, such range is found to go from 10 ps to 1.5 \( \mu \)s.
7. Conclusions
A representative selection of recent searches for supersymmetric scenarios with the ATLAS experiment at the LHC has been introduced and discussed, also in connection with the future perspectives at the HL-LHC. Still no significant deviations from the Standard Model background processes have been found, and limits have been set on the SUSY scenarios in different benchmark models, constraining more and more the phase space of the corresponding parameters.

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