Prospects for SUSY discovery based on inclusive searches with the ATLAS detector

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Abstract. The search for Supersymmetry (SUSY) among the possible scenarios of new physics is one of the most relevant goals of the ATLAS experiment running at CERN’s Large Hadron Collider. In the present work the expected prospects for discovering SUSY with the ATLAS detector are reviewed, in particular for the first fb$^{-1}$ of collected integrated luminosity. All studies and results reported here are based on inclusive search analyses realized with Monte Carlo signal and background data simulated through the ATLAS apparatus.

1. Introduction

Among the different proposed theoretical models of physics beyond the Standard Model (SM), Supersymmetry (SUSY) is expected to be one of the most promising. In this work generic SUSY models with $R$ parity conserved are considered: this implies that SUSY particles are produced in pairs and determine decay chains ending with the Lightest Supersymmetric Particle (LSP), a neutral and stable particle which could be a good candidate for cold dark matter.

If squarks and gluinos have masses of the order of a TeV, the Large Hadron Collider (LHC) will be able to observe them thanks to its multipurpose experiments, like ATLAS (A Toroidal LHC Apparatus) [1]. A few different benchmark points ($SU_n$ [2]) have been considered within the framework of the Minimal Supergravity model (mSUGRA) [3] in the analyses shown in the following: $SU1$ and $SU8.1$ points in the coannihilation region, $SU2$ in the focus point region, $SU3$ in the bulk region, $SU4$ in the low mass region and $SU6$ in the funnel region.

Two approaches have been used here for inclusive SUSY searches. Firstly, various signatures have been studied on a selected number of fully simulated $SU_n$ points and relevant SM background sources, involving the typical experimental evidence expected for $R$-parity conserving scenarios: large missing transverse energy ($E_{T}^{\text{miss}}$), jets with high transverse momentum ($p_T$), presence of 0, 1, 2 or 3 electrons and/or muons, decays of $\tau$ leptons or of $b$ quarks. Secondly, several scans have been carried out over subsets of the SUSY parameter space, with the goal to verify the ATLAS sensitivity to SUSY discovery with early LHC data at 14 TeV center-of-mass energy over a wide range of models.

2. Zero-lepton mode

At the LHC the typical SUSY event topology is dominated by high-$p_T$ jets coming from the production of squark and gluino decays, together with large $E_{T}^{\text{miss}}$ from undetected LSPs at the end of each sparticle decay chain. This provides the least model-dependent search for SUSY events. The basic selection cuts required for this channel are:
• at least 4 jets with $p_T > 50$ GeV and at least one with $p_T > 100$ GeV;
• $E_T^{\text{miss}} > 100$ GeV and $E_T^{\text{miss}} > 0.2 M_{\text{eff}}$;
• transverse sphericity $S_T > 0.2$;
• $\Delta \phi (\text{jet}_i - E_T^{\text{miss}}) > 0.2$, $i = 1, 2, 3$;
• no reconstructed electrons or muons;
• $M_{\text{eff}} > 800$ GeV,

where $M_{\text{eff}}$ is defined as the sum of $E_T^{\text{miss}}$ and of $p_T$ of the leading four jets. From here on, this set of basic standard cuts will be referred to as BSC. The cuts on jet multiplicity mostly reject the main SM background, i.e. QCD events with relatively large $E_T^{\text{miss}}$ due to energy measurement fluctuations or real decays with neutrinos. The requirement on sphericity aims at exploiting the typically isotropic shape expected for SUSY events, while the $\Delta \phi$ cut is optimized against QCD events in which $b$ decays produce missing energy in the direction of jets. In Figures 1 and 2 the effective mass distributions are shown after all the cuts for various SUSY benchmark points and for the most relevant sources of SM background.

The main background is represented by multi-jet QCD (especially in the low-$M_{\text{eff}}$ region) and by $t\bar{t}$ events with an unidentified lepton, but also $W$+jets and $Z$+jets give significant contributions at large $M_{\text{eff}}$. The statistical significances $Z_n$ [2] for 1 fb$^{-1}$ have been computed taking also into account uncertainties on the background sources as expected from data-driven methods with that integrated luminosity: 50% for QCD multijet events and 20% for $t\bar{t}$, $W$+jets, $Z$+jets and $W/Z$ pairs. The values of $Z_n$ are larger than 5 for all the considered SUSY points [2], except for $SU2$ in which direct gaugino production is dominant.

Analyses based on less than 4 jets in the final state impose higher $p_T$ requirements to reduce the resulting larger QCD background. These cuts are summarized as follows:

• at least 2 (3) jets with $p_T > 100$ GeV and at least one with $p_T > 150$ GeV;
• $E_T^{\text{miss}} > 100$ GeV and $E_T^{\text{miss}} > 0.3 (0.25) M_{\text{eff}}$;
• $\Delta \phi (\text{jet}_i - E_T^{\text{miss}}) > 0.2$, $i = 1, 2, 3$;
• no reconstructed electrons or muons;
• $M_{\text{eff}} > 800$ GeV,
where $M_{\text{eff}}$ is here defined as the sum of $E_T^{\text{miss}}$ and of $p_T$ of the 2 (3) jets in the analysis.

After all cuts, the different background contributions ($t\bar{t}$, $W+$jets, $Z+$jets and QCD) are roughly comparable among each other, as can be observed in Fig. 3. With respect to the 4-jet analysis, the number of surviving events are approximately doubled for both signal and background (except for the low-mass $SU_4$ point, see Fig. 4), while the expected values of significance with 1 fb$^{-1}$ don’t change significantly.

Figure 3. $M_{\text{eff}}$ distribution for the 0-lepton plus 2-jet analysis: $SU3$ signal (open circles) is compared with the main sources of SM background.

Figure 4. $M_{\text{eff}}$ distributions for the 0-lepton plus 2-jet analysis for various $SUn$ points compared with the expected total SM background.

3. One-lepton mode

A strong reduction of wrongly selected background from QCD multi-jet events can be obtained by requiring one lepton in addition to multiple jets and $E_T^{\text{miss}}$. As will be discussed in the following, the reach in the 1-lepton mode is comparable to that of the 0-lepton mode: this is true especially in $SU1$ and $SU3$ points where the significant amount of $\tau$’s from gaugino decays can then produce leptonic decays.

The cuts used in this case are the same as BSC, together with the following requirements:

- exactly one isolated $e/\mu$ with $p_T > 20$ GeV;
- no additional leptons with $p_T > 10$ GeV;
- $M_T > 100$ GeV,

where the cut on the transverse mass $M_T$, formed by the lepton and $E_T^{\text{miss}}$, aims at suppressing $t\bar{t}$ and $W+$jets backgrounds.

In Fig. 5 the $M_{\text{eff}}$ distribution is shown for the SUSY benchmark points compared to the sum of the expected SM background. The QCD background is reduced to a negligible level by the $E_T^{\text{miss}}$ and the lepton requirements.

Although the background rejection is better with respect to the 0-lepton analysis, the reach seems to be worse as the statistical significances $Z_n$ with 1 fb$^{-1}$ are in average lower [2].

Other analyses, not shown here, can be also very effective by requiring a smaller number of jets with harder cuts.

4. Two-lepton modes

Events with two leptons in the final state can be very relevant for inclusive searches and can be also exploited for exclusive studies involving measurement of SUSY parameters.
4.1. Opposite-sign dileptons
The case of two leptons (electrons or muons) with opposite sign and same flavour can arise from neutralino decays, such as $\chi_2^0 \rightarrow \ell^+ \ell^- \chi_1^0$, directly or mediated by a slepton. Leptons can also come from independent decays, thus giving rise to dilepton pairs having same or different flavours.

The opposite-sign dilepton analysis is based on BSC (except those on $S_T$ and $M_{\text{eff}}$) plus the requirement of exactly two isolated, opposite-sign leptons with $p_T > 10$ GeV and $|\eta| < 2.5$. The presence of two leptons efficiently suppresses SM background, so that additional cuts can just reduce statistics with no relevant gain in the signal to background ratio. The significances $Z_n$ as functions of $E_T^{\text{miss}}$ are shown in Fig. 6 for four different $SU_n$ points: while very high discovery potentials are found for $SU_3$ and $SU_4$, the case of $SU_1$ is much more problematic owing to the presence of low-$p_T$ leptons (therefore harder to select) produced by the small mass gaps between the involved SUSY particles. The $SU_2$ point can only be discovered in the two-lepton mode with significantly more than 1 fb$^{-1}$ of data.

A clear evidence of new physics in this channel would be given by an excess of events containing same-flavour dileptons with respect to events with different flavour leptons (mostly coming from $t\bar{t}$ and $W$ events): in this case, the statistical significance computed for points $SU_1$-$4$ provides the values 2.63, 0.22, 4.80 and 4.27, respectively.

4.2. Same-sign dileptons
Events with two prompt same-sign leptons are quite rare in SM, but in SUSY they should normally occur since the gluino is a Majorana particle. They represent a very clear event signature, but very small rates are expected (from 10 to 100 events/fb$^{-1}$). The cuts for their
selection are $BSC$ (without requirements on $S_T$ and $M_{eff}$) plus exactly two isolated, same-sign leptons with $p_T > 10$ GeV and $|\eta| < 2.5$.

As shown in Fig. 7, all the considered $SU_n$ signals should be visible, with significance values going from $\sim 2$ (in $SU_2$) to $\sim 20$ (in $SU_4$).

![Figure 7](image.png)

**Figure 7.** Distribution of transverse missing energy for same-sign dilepton events after all cuts except $E_T^{miss}$.

The main SM backgrounds are $t\bar{t}$, $W$+jets and $Z$+jets, though they are almost negligible.

5. **Three-lepton mode**

Trilepton production from all sources (not only direct gaugino production) is studied in ATLAS following two approaches. After asking for (at least) 3 isolated $e$ or $\mu$ with $p_T > 10$ GeV, the first strategy is based on the presence of at least one jet with $p_T > 100$ GeV (aiming at removing the huge QCD background), while the second strategy is optimized with the additional requirements:

- there must be one same-flavour dilepton pair with invariant mass $> 20$ GeV;
- lepton track isolation: maximum $p_T$ of additional tracks in a cone $\sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.2$ around the lepton: $p_{T,\text{trk}} < 1(2)$ GeV for muons (electrons);
- $E_T^{miss} > 30$ GeV;
- all same-flavour dilepton pairs must have invariant mass less than $M_Z - 10$ GeV.

In the latter case, the goal of these cuts is to reject background sources coming from: $WZ$, $J/\Psi$, photon conversion and residual $b$, $c$ and $Z$ decays. The significances are shown in Table 1 together with the number of events after the final selection for 1 fb$^{-1}$ of data. By considering a 20% background systematic uncertainty, only $SU_4$ gives a signal with $Z_n > 5$.

6. **$\tau$ mode**

Signatures with $\tau$’s can be relevant in SUSY for large values of $\tan \beta$, where $e/\mu/\tau$ universality is expected to be widely violated. Events with leptonic $\tau$ decays, being indistinguishable from prompt leptons, are already included in the previous analyses. Cuts proposed for this analysis are based on $BSC$ (except for what concerns $S_T$ and $M_{eff}$) plus the requirements:

- no isolated lepton with $p_T > 10$ GeV;
- at least one $\tau$ with $p_T > 40$ GeV and $|\eta| < 2.5$;
- $M_T > 100$ GeV (using visible momentum of hardest $\tau$ and $E_T^{miss}$).

The most favoured points for this analysis are $SU_3$ and $SU_6$ (see Fig. 8), for which the significances $Z_n$ for 1 fb$^{-1}$ are equal to 12 and 6.8, respectively (having assumed a 20% systematic uncertainty on background estimates). The reconstructed tau’s have a purity of about 80% due to the relatively large probability for a jet to fake a tau. The dominant background is given by $t\bar{t}$, $W$+jets and QCD.
Table 1. Expected events, signal over square root of background and significance for 3-leptons + $E_T^{miss}$ analysis with 1 fb$^{-1}$.

| Point | Events | $S/\sqrt{B}$ | $Z_n$ |
|-------|--------|--------------|-------|
| SU1   | 24.1   | 2.8          | 1.3   |
| SU2   | 17.6   | 2.1          | 1.0   |
| SU3   | 63.9   | 7.5          | 3.5   |
| SU4   | 544.9  | 63.5         | 16.4  |
| SU8   | 5.3    | 0.6          | 0.3   |

$WZ$ 22.8
ZZ 1.6
$Zb$ 0
WW 0
$tt$ 0

Figure 8. $M_{\text{eff}}$ distribution for SUSY signals and SM background in the $\tau$ analysis with 1 fb$^{-1}$ of data.

7. $b$-jet mode

Depending on SUSY parameters, the SUSY signal may be rich in jets from $b$ quarks (since $\tilde{b}$ and $\tilde{t}$ are lighter than the other squarks). The cuts included in this analysis, apart from $BSC$, are:

- at least two jets tagged as $b$-jets: $p_T > 20$ GeV and specific $b$-tagging cuts on vertex and impact parameter;
- $M_{\text{eff}} > 600, 800$ or 1000 GeV.

The background is mostly dominated by $tt$ and QCD, while $W$, $Z$ and diboson sources are essentially negligible. The effective mass distribution for signal and all SM backgrounds is shown in Fig. 9. By using the hardest $M_{\text{eff}}$ cut and assuming uncertainties of 50% for QCD and of 20% for the other backgrounds, the statistical significance with 1 fb$^{-1}$ is found to be larger than 5 for all considered benchmark points.

8. Discovery reach

The $SU\eta$ points studied in these analyses cannot be representative of all possible SUSY-breaking scenarios to be found at the LHC. In order to efficiently perform a wide scan of the allowed parameter space with adequate statistics, a fast parameterized simulation of the ATLAS detector (ATLFAST [4]) has been adopted instead of running a fully detailed simulation with Geant 4 code [5]. Cross sections used for SUSY signals are here at leading order, while background
samples have been calculated at next-to-leading order: for this reason, generally, conservative estimates are obtained for discovery reach with a given integrated luminosity.

Scans over mSUGRA parameter space have been performed with different approaches, both running on fixed grids (with given values of parameters tan $\beta$, $A_0$, $\mu$) or moving on a random grid with specific experimental constraints such as leading to a dark matter relic density in agreement with observations [2]. Also grids for other R-parity conserving scenarios have been considered in the following, i.e. Non Universal Higgs Model (or NUHM), where the Higgs masses are not assumed to unify with squark and slepton masses at the GUT scale, and Gauge Mediated Symmetry Breaking (or GMSB), in which the next-to-lightest SUSY particle is assumed to be a slepton decaying promptly to leptons.

All the reach plots shown in this section are based on the cuts previously described and represent the $5\sigma$ discovery reach in each of the discussed analyses with 1 fb$^{-1}$ of collected data. In Fig. 10 and 11 the contour plots of the analyses with 0 and 1 leptons are shown, respectively.

In both cases the scans (as functions of $m_0$ and $m_{1/2}$ in mSUGRA with tan $\beta$=10, $A_0$=0 and $\mu >0$) have been performed by requiring 2, 3 or 4 jets, producing the best reach for the case of

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**Figure 9.** $M_{\text{eff}}$ distribution for SUSY signal and for total SM backgrounds in the $b$-jet analysis.

**Figure 10.** The 1 fb$^{-1}$ 5$\sigma$ contours for the 0-lepton analysis with various jet requirements as functions of $m_0$ and $m_{1/2}$ in mSUGRA. The straight and curved lines indicate $m_{\tilde{g}}$ and $m_{\tilde{q}}$ in steps of 500 GeV.

**Figure 11.** The 1 fb$^{-1}$ 5$\sigma$ contours for the 1-lepton analysis with various jet requirements as functions of $m_0$ and $m_{1/2}$ in mSUGRA. The straight and curved lines indicate $m_{\tilde{g}}$ and $m_{\tilde{q}}$ in steps of 500 GeV.
4 jets. The 0-lepton mode has the best discovery reach, close to 1.5 TeV for the smaller of \(m_{\tilde{g}}\) and \(m_{\tilde{q}}\), but the 1-lepton mode is expected to be more robust against QCD background. Owing to lower efficiency and purity, the \(\tau\)-mode, even if enhanced for high \(\tan \beta\) models, has always worse reach than the 0- and 1-lepton modes, and similarly the 2-lepton modes.

Also performing random scans in mSUGRA with low-energy constraints (scatter plot in Fig. 12) the reach is found to be compatible with those obtained for the single \(S\tilde{u}n\) points. Exploring other SUSY-breaking mechanisms, the NUHM model is characterized by different spectra of masses and decay modes, but has qualitatively similar topology. As shown in Fig. 13, the reach with 0 and 1 lepton is essentially the same as for mSUGRA in the \(m_0-m_{1/2}\) plane. Models in the GMSB scan considered here have at least two leptons in the final state, so they are quite easy to distinguish from SM backgrounds. It is observed that, in this case, the 3-lepton search has much better reach than the 2-lepton and extends well beyond 2 TeV for gluinos at large \(\tan \beta\) [2].

9. Conclusions
The analyses presented in this work, both in fully simulated benchmark points and in fast simulated scans over different scenarios, show that ATLAS is able to discover signals of \(R\)-parity conserving SUSY with masses of the order of 1 TeV, after having collected \(\sim 1 \text{ fb}^{-1}\) of understood data. In some favourable case the mass reach could be even higher. Anyway, if SUSY should not be found with such little integrated luminosity, it could still be possible to discover it at the LHC, but more detailed studies would be required.

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