BSM searches (SUSY and Exotic) from ATLAS

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Searches for new physics beyond the Standard Model (SM) at the LHC are mainly driven by two approaches: a signature-based search where one looks for a deviation from the SM prediction in event yield or kinematic properties, and a more theory-oriented approach where the search is designed to look for specific signatures/topologies predicted by certain beyond standard model (BSM) scenarios. Typical examples for the latter are searches for Supersymmetry and other BSM theories with extended symmetries. Supersymmetry predicts a new partner for every SM particle. An extension to the SM by introducing new gauge or global symmetries (including in Hidden Sector) usually leads to the presence of new heavy gauge bosons. Extensive searches for such particles have been performed in ATLAS at LHC in the context of Supersymmetry, Extended Gauge models, Technicolor, Little Higgs, Extra Dimensions, Left-Right symmetric models, and many other BSM scenarios. Highlights from these searches are presented.
1. Introduction

The Standard Model (SM) of elementary particles and their interactions successfully describes a wide range of phenomena that can be investigated experimentally with the current generation of particle accelerators. It is a general opinion between physicists that the SM is only an effective theory that must break down above a certain energy scale. There are strong theoretical arguments to believe that it breaks down at the electroweak scale. The unexplained phenomena and problems like the nature of dark matter and dark energy, matter-antimatter asymmetry, neutrino oscillations, inconsistency with the general relativity and hierarchy problem, suggests that the universe we observe requires theoretical developments beyond the Standard Model (BSM). Supersymmetry (SUSY) is proposed as a simple and elegant extension of the SM. Other theoretical approaches providing solutions to some of the problems mentioned above, and often offering a rich phenomenology, are grouped under the term of exotic physics. The ATLAS experiment [1] at the Large Hadron Collider (LHC) has run extensive physics searches to cover as many scenarios as possible. These proceedings review a selection of results among the many searches for supersymmetry and exotic signatures based on the LHC proton-proton collision data collected in Run 1 at $\sqrt{s} = 7$ and 8 TeV.

2. ATLAS detector and data taking

The ATLAS detector consists of four major parts: the Inner Detector to track precisely charged particles and reconstruct common vertices; the Calorimeter system to measure the energy of easily stopped particles; the muon system to make additional standalone measurements of highly penetrating muons; the two magnet systems to bend charged particles in the Inner Detector and in the Muon Spectrometer, allowing their momenta to be measured.

The detector operates with close to 100% efficiency and provides performance characteristics slightly better than its design values. A three level trigger system provides information to identify, in real time, the most interesting events to retain for detailed analysis. Figure 1 shows the total integrated luminosity recorded in 2011 ($\sqrt{s} = 7$ TeV) and 2012 ($\sqrt{s} = 8$ TeV).

![Figure 1: Cumulative luminosity as function of time delivered to (green), recorded by (yellow) and good for physics for (blue) ATLAS during stable beams for LHC proton-proton collisions in 2011 and 2012. Taken from [https://twiki.cern.ch/twiki/bin/view/AtlasPublic].](image-url)
3. Searches for SUSY physics signals

The collider experiments can give the direct confirmation of the existence of the superpartners of bosons and fermions predicted by SUSY theory [2, 3, 4]. The sparticle searches are generally conducted by selecting promising and as clear as possible signature of interest expected from a SUSY model. The signal selection is made choosing good discriminant kinematics variables able to disentangle the signal events from the SM background. If agreement is seen between the SM prediction and the observed data, 95% CL exclusion limits are set, ruling out scenarios that are incompatible with observations. These limits are usually given as a function of parameters in the model. The searches covered in these proceedings refer to a selection of sparticles production both via strong and electroweak interactions. A complete list of public results on SUSY searches are reported in [5].

3.1 Electroweak produced SUSY

In the limit where the strongly produced sparticles are most often produced off-shell, production of the electroweakinos may be the dominant SUSY process at the LHC, and will most likely be found via multilepton final states. Direct production of charginos ($\tilde{\chi}^\pm$) and neutralinos ($\tilde{\chi}_i^0$), considering the $\tilde{\chi}_1^0$ as LSP, is expected to have a clean signature due to the presence of SM bosons and leptons in the decay chains. Depending on the mass splitting, a heavier neutralino can decay to the LSP via a $Z$ or the SM Higgs, and the charginos via a $W$. The final states in direct pair production of charginos and neutralinos are characterized by a large lepton multiplicity ($\geq 2$). Depending on the decay, a dilepton invariant mass compatible with the $Z$ mass can be vetoed or required. Chargino masses below 350 GeV are excluded for the decay via SM bosons and 700 GeV for the decays via sleptons [6, 7]. The summary of all ATLAS electroweakinos searches can be seen in Figure 2. The analysis uses 20.3 fb$^{-1}$ of $\sqrt{s} = 8$ TeV pp collision data recorded in 2012.

3.2 Strongly produced SUSY

Direct production of gluinos and first and second generation squarks have high cross-sections for masses up to around 1 TeV. The majority of models consider the decay of these SUSY particles to the LSP ($\tilde{\chi}_1^0$). This will escape the experiment undetected, provided it is stable. In these cases, the LSP provides a good candidate for a weakly interacting dark matter particle. The decay chain leading from the strongly produced sparticles to the LSP will involve the production of a number of SM particles, predominantly hadronic jets and, depending on the scenario, sometimes leptons. The escaping LSP provides a source of missing transverse energy, a requirement on which is also commonly included in searches. Results of the ATLAS searches [8, 9, 10, 11] are summarized in the two plots of Figure 3. On the left are shown the limits for the photon + $j$ analysis set in the two-dimensional plane of the general-gauge-mediated supersymmetry breaking model (GGM) [12, 13] parameters $\mu$ and M3 for the higgsino-bino GGM model with a positive value of the $\mu$ parameter. On the right are shown the exclusion limits in simplified models with squark-pair production and subsequent direct squark decays to a quark and the lightest neutralino.
Figure 2: Summary of ATLAS search for electroweak production of charginos and neutralinos. Limits are set in the chargino/neutralino mass planes. The dashed and solid lines show the expected and observed limits, respectively, including all uncertainties except the theoretical signal cross section uncertainties. Taken from [7].

3.3 Third generation produced SUSY

Direct production of the third generation strongly-interacting sparticles, i.e. the stops and sbottoms, are considered separately from other SUSY ATLAS searches [14, 15, 16]. They have a more moderate production cross-section than the gluinos and first and second generation squarks, up to masses of around 0.5 TeV. The decays of these particles also produce a large number of jets, possibly leptons, and missing transverse energy. Figure 4 summarises ATLAS results from a number of analyses in the $\tilde{\chi}_0^1$ mass versus $\tilde{t}_1$ mass parameter space. Different regions of this space are accessed using different decay modes of the stop, as these are dependent on the mass difference between the $\tilde{t}_1$ and $\tilde{\chi}_0^1$. Lines are included to mark the limits of a given decay mode, as labelled. The analysis contributes to three regions of the parameter space via these different decay modes, as can be seen by the three distinct exclusion regions displayed. At stop mass values below 210 GeV the use of the azimuthal angle distribution between the two leptons in the dileptonic events helps to probe the difficult region where the mass of the stop is closed to that of the top [17].

3.4 R-parity violating searches

R-parity violating supersymmetry scenarios can lead to long-lived particles (LLPs) if the coupling is weak enough, giving a displaced decay of the metastable LSP. The ATLAS long-lived slepton search [18] for charged LLPs with $c\tau > 1$ m has results interpreted in the context of a $\tilde{\tau}_1$ in models with Gauge Mediated SUSY Breaking [19]. LLPs with $c\tau > 1$ m are likely to decay outside ATLAS and, if charged, leave a track similar to a muon throughout the detector systems. LLPs are differentiated from muons using track $\beta$ values calculated from $dE/dx$ measurements in the Inner Tracker pixel detectors and time-of-flight measurements in the Calorimeters and Muon Spectrometer. Tracks are considered to be LLP candidates if they have transverse momentum > 50 GeV and $\beta < 0.95$. The background to this analysis is overwhelmingly high transverse momentum.
muons with mismeasured $\beta$ values. Background is reduced by requiring two LLP candidates in an event and the signal region is set by calculating candidate masses from their transverse momentum and $\beta$, before applying a model dependant mass cut. For the model parameter range $\tan\beta = 5-50$, limits excluding $m_{\tilde{\tau}_1} < 347-402$ GeV can be set.

4. Searches for Exotic physics signals

As well as for the SUSY searches, the Exotic one are conducted identifying the most promising and as much as possible background free signatures of interest expected from some Exotic models. The data analysis starts from a series of selection criteria able to disentangle the signal events from the SM background. The result of the signal selection is presented using kinematics variables capable to well discriminate the signal from the SM Monte Carlo 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 [20].

4.1 Search for high-mass dilepton resonances

The dilepton final state has been one of the first channel studied at ATLAS because it benefits from a clear signature and a relatively low background. The data analysis has been performed in the cases where the two leptons are well isolated electrons and muons [21], for proton-proton collisions at $\sqrt{s} = 8$ TeV corresponding to an integrated luminosity of about 20 fb$^{-1}$. The main challenge of this analysis is the transverse momentum resolution of the two leptons. Only in the electron case, no charge identification is required. The main backgrounds for dielectron and dimuon final states
originate from Drell-Yan, diboson, top and jet productions. Misidentified jets are an important background for the electron final states for which the fake rate is measured with data.

The dilepton invariant mass distributions are shown in Figure 5. A good agreement between data and SM model predictions is found in all channels. Exclusion limits have been set on various model interpretation like the grand-unification model based on the $E_6$ gauge group [22, 23], $Z'$ bosons, Minimal $Z'$ model, the Sequential Standard Model $Z'_{SSM}$ boson [24], the spin-2 graviton excitation from Randall-Sundrum models [25], quantum black holes and a Minimal Walking Technicolor model with a composite Higgs boson. The narrow resonance with SM $Z$ coupling to fermions is excluded at 95% confidence level for masses less than 2.79 TeV in the dielectron channel, 2.53 TeV in the dimuon channel and 2.90 TeV in the two channels combined. The exclusion limits are shown in Figure 6.

4.2 Search for vector diboson resonances: $WZ$, $WW$, $ZZ$

The search of diboson resonances helps to investigate about the source of electroweak symmetry breaking. Extensions of the SM, like Grand Unified Theory, Technicolor, extra dimensions model, etc., predict diboson resonances at high masses. Diboson searches have been performed in all the possible final states [26, 27] at $\sqrt{s} = 8$ TeV proton-proton collisions for an integrated luminosity of about 20 fb$^{-1}$.

In this proceedings only the $WZ$ diboson resonance search is presented. The fully leptonic channel $lll'$ ($l, l' = e, \mu$), with exactly 3 charged leptons reconstructed at the same primary vertex, is used to search for a new resonance decaying to $WZ$. It shows a better sensitivity at low mass thanks to its higher mass resolution and its smaller backgrounds that come mainly from SM diboson
production as well as top-antitop production associated with a $W$ or a $Z$. The invariant mass of the $WZ \rightarrow l\ell'\ell'$ system is reconstructed from the four-vectors of the candidate $W$ and $Z$ bosons and is used as the discriminating variable for the signal. The main uncertainties are those associated with the PDFs and the normalization and factorization scales for the backgrounds. A good agreement is found between the observed and predicted $WZ$ invariant mass distribution for events in the high-mass signal region, leading to the exclusion limits on the Extended Gauge Model (EGM) $W'$ below 1.52 TeV and on the Heavy Vector Triplet (HVT) \cite{28} benchmark models, as shown in Figure 7.

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

Many new-physics scenarios propose the existence of new high mass states like the additional heavy gauge bosons \cite{24} proposed by the SSM (the charged ones are denoted $W'$), the electroweak doublet vectors ($Z', W'$) predicted by theories \cite{29} based on the existence of $U(3)_W = SU(3)_W \times U(1)_W$ gauge extension of the $SU(2)_W \times U(1)_Y$ electroweak group which is spontaneously broken down to TeV scale and the direct production of weakly interacting candidate dark matter particles \cite{30}. This proceedings describe such a search \cite{31} in events containing only one lepton (muon...
or electron) and missing transverse momentum using 8 TeV \( pp \) collision data corresponding to a total integrated luminosity of 20.3 fb\(^{-1}\). The kinematic variable used to identify the signal is the transverse mass \( m_T = \sqrt{2p_T E_{miss}^T (1 - \cos \phi_{p_T})} \) where \( p_T \) is the lepton transverse momentum, \( E_{miss}^T \) is the missing transverse momentum and \( \phi_{p_T} \) is the angle between the \( p_T \) and \( E_{miss}^T \) vectors. The main background comes from the so called electroweak background (\( W \rightarrow l \nu \), \( W \) and \( Z \) production with decays to \( \tau \rightarrow \nu \tau l \nu \), diboson production). The data distributions of \( p_T \), \( E_{miss}^T \) and \( m_T \) after selection well agree with the expected background and the exclusion limits on the high mass states predicted by the considered theoretical models are set.

4.4 Non-prompt lepton jets

Several models of physics beyond the Standard Model predict neutral particles called \( \gamma_d \) (dark-photons) that decay into final states consisting of collimated jets of light leptons and hadrons (so-called "lepton jets"). These particles can also be long-lived with decay length comparable to, or even larger than, the LHC detectors’ linear dimensions. ATLAS has searched for non-prompt muonic lepton jets at \( \sqrt{s} = 7 \) TeV [32] and for lepton jets in all the possible final states: \( \geq 2 \mu \) and no \( e \), \( \geq 2(e/\pi) \) and no \( \mu \), \( \geq 2 \mu \) and \( \geq 2(e/\pi) \) at \( \sqrt{s} = 8 \) TeV [33]. The high-resolution, high-granularity measurement capability of the ATLAS Muon Spectrometer is crucial for this type of search. In addition, the ATLAS Inner Detector can be used to define isolation criteria to significantly reduce, for decay vertices far from the interaction point, the otherwise overwhelming SM background from proton-proton collisions. No excess of events has been observed over the estimated background level, and limits have been set on the Falkowski-Ruderman-Volansky-Zupan (FRVZ) benchmark models [34] which predict non-SM Higgs boson decays to lepton jets. The limits are set on the Higgs boson decay branching fraction to lepton jets as a function of the dark photon mean lifetime. In the case of a dark photon which kinetically mixes with the SM photon, these limits can be converted into exclusion limits on the kinetic mixing parameter \( \epsilon \). For \( H \rightarrow 2 \gamma_d + X \) with a dark photon mass = 0.4 GeV, the interval that is excluded at 95% CL is \( 7.7 \times 10^{-7} \leq \epsilon \leq 2.7 \times 10^{-6} \). The final results of the search and their contribution to the parameter space exclusion plot for dark
photons are shown in Figure 8.

**Figure 8**: Parameter space exclusion plot for dark photons as a function of the $\gamma_d$ mass and of the kinetic mixing parameter $\gamma$. Shown are existing 90% CL exclusion regions from beam dump experiments E137, E141, and E774, Orsay, U70, CHARM, LSND, A1, the electron and muon anomalous magnetic moment, HADES, KLOE, the test run results reported by APEX, an estimate using a BaBar result, and constraints from astrophysical observations. The 90% CL exclusion limits from the ATLAS search, assuming the FRVZ model $H \rightarrow 2\gamma_d + X$ with decay branching fraction to dark photon of 5/10/20/40% and the NNLO gluon fusion Higgs production cross section, are shown. Taken from [33].

5. Conclusions

ATLAS is conducting a wide range of searches for SUSY particles and other exotic new particles, exploiting different signatures and using various detection techniques. These proceedings give a summary of the results of some of these searches. Despite a huge effort, no new signal has been observed in the data to date and exclusion limits on cross sections and masses are given, continuing to constrain the parameter space of many physics models. While the Run 1 physics program is being completed, the emphasis on the data at $\sqrt{s} = 13$ TeV grows more and more.

References


