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Prospects for detecting long-lived supersymmetric particles with ATLAS

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Abstract. In certain Supersymmetry (SUSY) breaking scenarios, characteristic signatures can be expected which would not necessarily be found in generic SUSY searches for events containing high- p_T multi-jets and large missing transverse energy. In this document, the expected response of the ATLAS detector to signatures involving high- p_T photons which may or may not appear to point back to the primary collision vertex and long-lived charged sleptons and R-hadrons is presented. Such processes often have the advantage of small Standard Model backgrounds and their observation could provide unique constraints on the different SUSY breaking scenarios. Using these signatures, discovery potentials are estimated for either Gauge-Mediated Supersymmetry Breaking or Split-Supersymmetry scenarios. These studies have been performed using Monte Carlo samples of SUSY and background processes corresponding to integrated luminosity of about 1 fb⁻¹ and $\sqrt{s} = 14$ TeV.

1. Introduction

Many scenarios beyond the Standard Model (SM) predict the existence of particles whose lifetime is long enough to be directly detected in the ATLAS detector. These are long-lived particles [1] whose specific final-state topology may not be observed by generic Supersymmetry (SUSY) searches which include high- p_T multi-jets and missing transverse energy [2–5]. Besides these and depending on their identity, long-lived particles can show non-pointing photons or high- p_T muon-like tracks with longer time-of-flight than muons.

Although several models allow different kinds of long-lived particles, many of them have a common feature: their velocity is significantly lower than the speed of light. Most of the algorithms developed in ATLAS for detection and reconstruction assume that particles have a velocity near the speed of light, $\beta \sim 1$. Therefore, slow particles will not be necessarily detected using these algorithms and a method for reconstructing slower particles is needed. In the method reviewed here, a particle with $\beta < 1$ can be identified and its mass directly determined, without needs of knowing details of the model that predicts this new particle. Thus, it is model-independent.

One of the scenarios where long-lived particles are predicted is the Gauge Mediated Supersymmetry Breaking (GMSB) model [6–8], that can give rise to long-lived neutralinos or sleptons. Detection of long-lived neutralinos is reviewed in section 3 and that of sleptons in section 4. Other relevant models are the Split-SUSY [9, 10], where long-lived $R_{\tilde{g}}$ -hadrons are predicted and those with a gravitino being the lightest supersymmetric particle (LSP) and a stop the next-to-LSP (NLSP) [11], allowing long-lived $R_{\tilde{f}}$ -hadrons. These two are discussed in

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section 6. Also some R-Parity Violating (RPV) scenarios can give rise, for example, to long-lived stops [12].

There are many analyses involving long-lived particles with relatively small Standard Model background that can be performed at the LHC and the current exclusion limits set by Tevatron [13, 14] point out that they are ideal first-data searches. The observation (or not) of such particles can set tight constraints on specific SUSY breaking scenarios. Although the work presented here is performed within the framework of SUSY searches, the techniques which have been developed are applicable to searches in other New Physics scenarios.

This paper is a review of studies on the detection of long-lived particles, performed at $\sqrt{s} = 14 \text{ TeV}$, carried out by the ATLAS Collaboration and documented in refs [15, 16].

2. SUSY Examples

There are several possibilities for a particle to become stable or meta-stable such as the conservation of a quantum number due to a symmetry, a small phase space in the decay of the particle or a small coupling constant. Many beyond the Standard Model scenarios predict new particles fulfilling one or more of those conditions and become stable or meta-stable. We are interested about scenarios allowing long-lived particles within SUSY and we hereby briefly present some examples of such models.

2.1. Gauge Mediated Supersymmetry Breaking (GMSB)

In this scenario the gravitino is very light ($M_{\tilde{G}} \leq 1 \text{ GeV}$) and hence is the LSP for any relevant set of model parameters. It is characterised by six parameters namely $\tan\beta$; $\operatorname{sgn}(\mu)$, the Higgsino mass parameter; C_{grav} , controlling the gravitino mass; Λ , the effective SUSY-breaking scale; $M < 10^{15} \text{ GeV}$, scale for the messenger generators; N_5 , number of messenger generators added to the theory at a scale M. SUSY breaking takes place in a hidden sector and it is transmitted to Minimal Supersymmetric fields through this messenger sector. When the number of messenger generators is $N_5 = 1$ the NLSP is the lightest neutralino which decays to a gravitino and a photon. If the number of messenger generators is larger than one, the NLSP is a slepton decaying to a gravitino and a SM lepton.

When the coupling is soft the NLSP lifetime becomes large, so we have either a long-lived neutralino or a long-lived slepton.

2.2. Split - Supersymmetry

The name of this model indicates the big difference between scalar masses (except for the ordinary Higgs), near the GUT scale, and gaugino and higgsino masses which are of the order of the weak scale. In a hard collision, two gluinos are formed whose decay proceed via internal heavy squark lines, so they are meta-stable. As they are coloured particles, they hadronise to form $R_{\tilde{g}}$ -hadrons.

2.3. Gravitino LSP / stop NLSP

It is similar to the Split-SUSY, but here the NLSP is the stop \tilde{t}_1 , which forms bound states called $R_{\tilde{t}}$ -hadrons.

3. Long-lived Neutralinos

We consider first the case of reconstructing long-lived neutralinos in the GMSB model in which we have chosen $\Lambda = 90 \text{ TeV}$, $M_{\text{mess}} = 500 \text{ TeV}$. The LSP is the gravitino and the NLSP is the lightest neutralino $\tilde{\chi}_1^0$, with a branching ratio to gravitino plus photon of 97%. In a typical event, the signature has some standard Supersymmetry features, such as high- p_T multi-jets and a high missing transverse energy coming from the gravitinos and possibly from lost photons. But it also

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has some specific and exclusive characteristics. As the neutralino is long-lived, its decay will not take place near the primary vertex so, as seen in Figure 1 on the right, the reconstructed photon will have a direction which will not point to the center of the transversal plane of the detector. These are called non-pointing photons. From Figure 1 on the left and because SUSY particles are produced in pairs, it is clear that the event may also have one or two pairs of leptons with the same flavour but different sign of the charge.



Figure 1. Left: Feyman representation of a typical event. For each $\tilde{\chi}_2^0$ there can be a pair of leptons with opposite sign and same flavour. Right: Schematic diagram of the transversal view of the event in the ATLAS detector with the Inner Detector in the center, surrounded with the Calorimetres and the Muon System.

In Table 1 the result is shown of a study for an integrated luminosity of 1 fb^{-1} . The selection of events has been done after applying a standard preselection for SUSY-like signatures in order to separate the signal from the Standard Model background [15]:

- At least four jets must be found with $p_T > 50 \text{ GeV}$ ($p_T > 100 \text{ GeV}$ for the leading jet).
- Missing transverse energy $E_T^{\text{miss}} > 100 \,\text{GeV}$ and $E_T^{\text{miss}} > 0.2 \cdot M_{\text{eff}}$, where the effective mass M_{eff} is defined as the scalar sum of E_T^{miss} and the transverse momenta of the four leading jets.
- A cut on the number of reconstructed photons with $p_T > 20 \text{ GeV}$ and $|\eta| < 2.5$ provides an effective way to further suppress the backgrounds.

Several cuts in the number of non-pointing photons and in the number of pairs of leptons with opposite sign, same flavour (OSSF) have been done. Requiring one non-pointing photon and one pair of OSSF leptons, the significance defined as $\text{Sig} = \text{S}/\sqrt{\Sigma B}$, where S is the number of signal events passing the cuts and ΣB is the sum of background events passing the cuts, increases by a factor 2. In the calculation of the significance it is assumed that there is at least one background event left.

4. Sleptons

We consider now another GMSB point: $\Lambda = 30 \text{ TeV}$, $M_{\text{mess}} = 250 \text{ TeV}$. The LSP is the gravitino, NLSP is a slepton with $M_{\tilde{\tau},\tilde{\ell}} \sim 100 \text{ GeV}$. The lightest neutralino, with a mass $M_{\tilde{\chi}_1^0} = 114 \text{ GeV}$, decays to a SM lepton and to NLSP slepton which decays to LSP gravitino and a lepton. This last coupling is weak, so the slepton is long-lived and, in principle, it can be detected as a muon. If its velocity is near the speed of light, $\beta \sim 1$, it will be indistinguisible from a muon. However, as shown in Figure 2, the velocity distribution is such that most of the sleptons have $\beta < 1$. In

Table 1. Number of signal and background events passing the preselection mentioned above for several cuts on number of non-pointing photons and OSSF lepton pairs. The significance is defined as $\text{Sig} = \text{S}/\sqrt{\text{B}}$ [15].

N_{γ}	$\mathbf{N}_{\mathbf{OSSF}}$	Signal	Σ Background	Sig	N_W	$N_{\rm Z}$	N_{tt}
0	0	825.2	929.6	27.1	274.4	21.0	632.8
0	1	265.2	73.0	33.2	8.7	1.4	63.0
1	0	255.8	51.7	35.7	19.5	2.0	30.1
1	1	68.6	1.4	58.6	0.2	0.0	1.2
2	0	12.5	0.1	12.5	0.0	0.0	0.1
2	1	4.7	0.0	4.7	0.0	0.0	0.0

this case, the slepton can be identified and with a measure of β , its mass can be determined [17]. The Resistive Plate Chambers (RPC) in the muon system has an excellent time resolution of ~ 3 ns which provides a very precise time of flight measurement ($\sigma_{tof} \sim 0.7 \text{ ns}$) [18] and hence a good mass measurement for slow particles is possible.

As it is explained in the next section, the efficiency of labelling particles with the correct bunch crossing identifier (BCID) is high for particles with $\beta > 0.7$. This is the case in most of the events for at least one of the sleptons. If it is labelled with the correct BCID, the triggers have a good efficiency.



Figure 2. Transverse momenta and β distribution for sleptons in blue dashed line and muons in red full line. Most muons have small p_T and $\beta = 1$ whilst sleptons have extended distributions [15].

To be able to identify a particle inside the ATLAS detector, a reconstruction algorithm is needed. The signature of sleptons in the detector is similar to that of muons so in principle muon reconstruction algorithms could be used to identify sleptons. Nevertheless, these muon algorithms assume muons to have $\beta = 1$, what makes the efficiency of reconstructing sleptons with muon reconstruction algorithms be lower for particles with $\beta < 1$. In Figure 3 this efficiency is represented for two different muon algorithms developed in ATLAS, called Muid and Staco. For $\beta \sim 1$ the reconstruction is good, but as β decreases, the efficiency falls down rapidly.

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Therefore a specialised algorithm to reconstruct slow particles is needed. In Figures 4, 5 the resolution in β and in reconstructed mass are shown, respectively, for one of these specialised algorithms, muGirl [19]. Estimating the velocity and mass muGirl avoids reconstructing sleptons as muons.



Figure 3. Efficiency of reconstructing slow particles with two different muon reconstruction packages as a function of β [15].

It is worth mentioning that this mechanism of reconstructing slow particles is also valid for other models besides GMSB, for example Lepton Flavour Violating SUSY [12].



Figure 4. β resolution of sleptons (left) and β resolution of R-Hadrons with a mass of 300 GeV (right) [16] using the new muGirl algorithm, as mentioned above.

5. Matching to the correct Bunch Crossing

In ATLAS, event fragments from different parts of the detector, originating from the interaction point and traveling at the speed of light, are assigned to a particular bunch crossing (BC) using a bunch crossing identifier (BCID). The maximum path a particle can cover from the interaction point until it leaves the detector is about 20 metres. Taking into account that the bunch crossing period is 25 ns, there can coexist 3 events at the same time in the detector. As BCIDs are assigned considering $\beta = 1$ particles, hits from slower particles may be lost or labelled with a wrong BCID. Figure 6 shows the efficiency for all slepton hits in the muon trigger



Figure 5. Reconstructed mass of GMSB5 sleptons generated with masses of 100.2 and 102.3 GeV (left) and R-Hadrons generated with a mass of 300 GeV (right) [16] using the new muGirl algorithm, as mentioned above.

chambers to be included in the same bunch crossing as a function of β . The efficiency decreases rapidly for $\beta < 0.7$ so for slower particles data from next BCs should be kept



Figure 6. Efficiency of associating the correct BCID to sleptons as a function of β for the trigger in the endcap muon system (left) and for the trigger in the barrel muon system (right). [15]

6. R-Hadrons

R-hadrons are meta-stable hadrons formed by meta-stable gluinos $(R_{\tilde{g}})$ or stops $(R_{\tilde{t}})$. One of the models presenting these particles is Split-SUSY. In this scenario, two gluinos are formed in the hard scattering which will decay into a squark and an antiquark (or an anti-squark and a quark). The amplitude of the favoured decay of these gluinos is small because the squark is very heavy, so the gluino becomes meta-stable. As it is a coloured particle, it hadronises to form a meta-stable hadron.

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Figure 7. Gluino decay through heavy squark internal line.

In principle, these particles will give high- p_T slow muon-like tracks but the energy deposition in the detector is supposed to be small, since only quarks(lighter than sparticles) will interact with matter, but not squarks or gluinos. Therefore, R-hadrons will not be stopped in their way through the detector, and they will not be confused with jets.

A typical R-hadron has between 10 and 20 nuclear interactions before it leaves the detector (for a description of interactions of coloured heavy stable particles with matter, see for example [20]). An important feature of these particles is that in these interactions, the R-hadron can flip its charge through reactions like

$$R^+n \longrightarrow R^- p \pi^+$$

Because of the large number of interactions with matter, a high probability is expected to have tracks of particles that have changed their electric charge. If the R-hadron goes from one sign of the charge to the opposite, there will be a track in the ID corresponding to a track in the muon system with the opposite charge. If the particles goes from charged to neutral, there will be a track in the Inner Detector (ID) with non matching track in the muon system and vice versa.

Figure 8 shows the charge (q_{ID}) and transverse momentum (p_{ID}) measured in the ID divided by charge (q_{μ}) and transverse momentum (p_{μ}) measured in the muon system. For non-flipping particles this plot should be centered at 1 and empty in the negative zone. The peak in the negative section means one track in the ID corresponding to a track in the muon system with similar p_T and different sign of the charge.



Figure 8. Distribution of the variable $\frac{q_{ID} \cdot p_{ID}}{q_{\mu} \cdot p_{\mu}}$ for $R_{\tilde{g}}$ -hadrons (left) and $R_{\tilde{t}}$ -hadrons (right) [15]. The small peak in the negative zone of $R_{\tilde{g}}$ -hadrons shows particles flipping the sign of the charge. There are no expected flippers for $R_{\tilde{t}}$ -hadrons as explained in ref. [11] and references therein.

It is a great challenge for the reconstruction to match tracks with possibly different sign of the charge in the ID and in the muon system, but these would be very useful observables for the discovery of R-hadrons. In addition to this distinctive quality, R-hadrons have a transverse momenta distribution that makes them have a small SM background as seen in Figure 9. There, the p_T distributions are plotted for hard tracks ($p_T > 50 \,\text{GeV}$) as reconstructed in the ID (left column) and muon system (right column) corresponding to $R_{\tilde{g}}$ -hadrons with different masses (top), $R_{\tilde{t}}$ -hadrons with different masses (middle) and background (bottom).



Figure 9. Reconstructed transverse momenta distributions of $R_{\tilde{g}}$ -hadrons, several masses (top); $R_{\tilde{t}}$ -hadrons, several masses (middle), and SM background (bottom). The left column corresponds to ID measurements and the right column to muon system measures [15].

Some selection criteria have been applied to separate R-hadrons from background [15].

- No hard muon-like track $(p_T > 250 \text{ GeV})$ can come within a distance R < 0.36 of a hard jet $(p_T > 100 \text{ GeV})$ where $R = (\Delta \eta^2 + \Delta \phi^2)^{1/2}$.
- A candidate R-hadron must satisfy at least one of the following conditions:
 - (i) The event contains at least one hard muon track with no linked inner detector track. A linked track is defined such that the distance R between the measurements in the ID and muon systems is less than 0.1.
 - (ii) The event contains two hard back-to-back ID tracks with the transition radiation tracker (TRT) hit distribution satisfying $HT/LT < 0.05^{1}$. A back-to-back configuration is defined such that the cosine of the angle between the two muon tracks is less than -0.85.
 - (iii) The event contains two hard back-to-back (as defined above) like-sign muon tracks.

¹ The ATLAS TRT registres a number of high-threshold (HT) and low-threshold (LT) hits to each track. A high HT indicates the passage of a particle with high Lorentz factor $\gamma = \frac{1}{1-\beta^2}$

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(iv) The event contains at least one hard muon track with a hard matching ID track of opposite charge fulfilling the condition $p_{T,ID} > 0.5 p_{T,\mu}$.

The rates of accepted events within $1 \, \text{fb}^{-1}$ is shown in Table 2. As backgrounds rates are negligible for R-hadrons above $1 \, \text{TeV}$, a discovery window is open with low luminosity searches for stop and gluino R-hadrons with masses greater than several hundred GeV. (Backgrounds not shown here are rejected by the above criteria.)

Table 2. Rate of accepted events in the R-hadrons analysis within 1 fb^{-1} by the above criteria. [15]

Sample	Rate (Events/fb ^{-1})
300 GeV gluino	6.44×10^3
600 GeV gluino	2.70×10^3
1000 GeV gluino	10.7
1300 GeV gluino	1.22
1600 GeV gluino	0.147
2000 GeV gluino	$1.26 imes 10^{-2}$
$300 {\rm ~GeV stop}$	70.0
$600 {\rm GeV} {\rm stop}$	3.9
$1000 {\rm ~GeV stop}$	0.1
QCD	0.895
$Z \longrightarrow \mu \mu$	0.776

7. Conclusions

Some search strategies have been developed at ATLAS for a range of long-lived particles within certain Supersymmetry scenarios like neutralinos and sleptons in GMSB or R-hadrons in Split-SUSY.

Analyses for an integrated luminosity of about 1 fb^{-1} of LHC data have been performed with promising results. In the case of long-lived neutralinos it has been shown that non-pointing photons coming from their decay provide a good trigger and can give a good significance together with lepton pairs with same flavour but different sign of the electric charge.

For charged long-lived heavy particles, the general ATLAS muon reconstruction algorithms are not very efficient, so new specific software has been developed. The efficiency of reconstructing slow particles with such algorithms is shown to be good for sleptons and Rhadrons although it depends on collecting data from several bunch crossings for slower particles. In addition, R-hadrons may present changes in their electric charge, which gives a useful observable for their identification.

In general, there is a discovery window opened in ATLAS for the above particles: long-lived neutralinos within GMSB with non-pointing photons signature and R-hadrons with muon-like and charge exchange signature even for first LHC data with an integrated luminosity of about 1 fb^{-1} .

The techniques used here are model-independent so, although these studies have been performed within Supersymmetry, these techniques can be applied to searches in other scenarios.

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References

- M. Fairbairn, A. C. Kraan, D. A. Milstead, T. Sjostrand, P. Skands and T. Sloan, "Stable massive particles at colliders," Phys. Rept. 438 (2007) 1 [arXiv:hep-ph/0611040].
- [2] H.P. Nilles, Phys. Rept. 110 (1984) 1
- [3] H.E. Haber and G.L. Kane, Phys. Rept. 117 (1985) 75263.
- [4] J. Wess and J. Bagger, Princeton, USA: Univ. Pr. (1992) 259 p.
- [5] S. P. Martin, "A Supersymmetry Primer," arXiv:hep-ph/9709356.
- [6] M. Dine, W. Fischler and M. Srednicki, Nucl. Phys. B189 (1981) 575593.
- [7] S. Dimopoulos and S. Raby, Nucl. Phys. B192 (1981) 353.
- [8] L. Alvarez-Gaume, M. Claudson and M.B.Wise, Nucl. Phys. B207 (1982) 96.
- [9] N. Arkani-Hamed, S. Dimopoulos, G.F. Giudice and A. Romanino, Nucl. Phys. B709 (2005) 346.
- [10] G.F. Giudice, and A. Romanino, Nucl. Phys. B699 (2004) 6589.
- [11] J.L. Diaz-Cruz, J.R. Ellis, K.A. Olive. and Y. Santoso, JHEP 05 (2007) 003.
- [12] S. Kaneko, J. Sato, T. Shimomura, O. Vives and M. Yamanaka, "Measuring Lepton Flavour Violation at LHC with Long-Lived Slepton in the Coannihilation Region," Phys. Rev. D 78 (2008) 116013 [arXiv:0811.0703 [hep-ph]].
- [13] T. Aaltonen *et al.* [CDF Collaboration], "Search for Heavy, Long-Lived Neutralinos that Decay to Photons at CDF II Using Photon Timing," Phys. Rev. D 78, 032015 (2008) [arXiv:0804.1043 [hep-ex]].
- [14] V. M. Abazov et al. [D0 Collaboration], "Search for long-lived particles decaying into electron or photon pairs with the D0 detector," Phys. Rev. Lett. 101 (2008) 111802 [arXiv:0806.2223 [hep-ex]].
- [15] G. Aad *et al.* [The ATLAS Collaboration], "Expected Performance of the ATLAS Experiment Detector, Trigger and Physics," arXiv:0901.0512 [CERN-OPEN-2008-020].
- [16] S. Tarem, S. Bressler, H. Nomoto, A. Dimattia. Scientific Note SN-ATLAS-2008-071. Trigger and Reconstruction for a heavy long-lived charged particles with the ATLAS detector.
- [17] ATLAS Collaboration, ATLAS High-Level Trigger, Data Acquisition and Controls Technical Design 9 Report, ATLAS TDR-016 (2003).
- [18] G. Aad *et al.* [ATLAS Collaboration], "The ATLAS Experiment at the CERN Large Hadron Collider," JINST 3 (2008) S08003.
- [19] S. Tarem, Z. Tarem, N. Panikashvili, O. Belkind, MuGirl Muon identification in ATLAS from the inside out, Nuclear Science Symposium Conference Record, 2006. IEEE Volume 1, May 2007, Pages 617 - 621.
- [20] R. Mackeprang and A. Rizzi, "Interactions of coloured heavy stable particles in matter," Eur. Phys. J. C 50 (2007) 353 [arXiv:hep-ph/0612161].