Search for Decays of Stopped, Long-Lived Particles from 7 TeV pp Collisions with the ATLAS Detector

The ATLAS Collaboration

Abstract New metastable massive particles with electric and colour charge are features of many theories beyond the Standard Model. A search is performed for long-lived gluino-based $R$-hadrons with the ATLAS detector at the LHC using a data sample corresponding to an integrated luminosity of 31 pb$^{-1}$. We search for evidence of particles that have come to rest in the ATLAS detector and decay at some later time during the periods in the LHC bunch structure without proton-proton collisions. No significant deviations from the expected backgrounds are observed, and a cross-section limit is set. It can be interpreted as excluding gluino-based $R$-hadrons with masses less than 341 GeV at the 95% C.L., for lifetimes from $10^{-5}$ to $10^{3}$ seconds and a neutralino mass of 100 GeV.

1 Introduction

The search for exotic massive long-lived particles (LLPs) is an important component of the early data exploration program of the Large Hadron Collider (LHC) experiments. LLPs are predicted in supersymmetry (SUSY) models, such as split-SUSY \[1,2\] and gauge-mediated SUSY breaking \[3\], as well as other exotic scenarios, e.g. universal extra dimensions \[4\]. If LLPs carried colour charge, as predicted in a variety of Standard Model (SM) extensions \[5\], they would hadronise with quarks and gluons to form colour-singlet states before interacting with the detector. $R$-parity conserving split-SUSY presents such a model since the gluino ($\tilde{g}$) decay—$\tilde{g} \rightarrow g\tilde{\chi}_{0}^{2}_{1}$, or $\tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_{0}^{2}_{1}$—is suppressed by small coupling to the gravitino LSP or very large squark ($\tilde{q}$) mass\[6\]. The possibility of direct pair production of coloured particles through the strong nuclear force implies a large production cross-section at the LHC. The search described herein is particularly sensitive to such a scenario, and results are interpreted in the context of split-SUSY.

During the hadronisation process, long-lived gluinos bind with SM quarks and gluons from the vacuum to produce “$R$-hadrons”\[1\]—a new heavy composite state \[7\]. When $R$-hadrons scatter via the nuclear force, they can transform their internal state by exchanging partons with the detector material (e.g. $\tilde{g}qq \rightarrow \tilde{g}qqq$). Depending on the mass hierarchy of $R$-hadron states and the matter interaction model, these particles traverse the detector flipping between electrically neutral, singly- and doubly-charged states. Several properties of the $R$-hadron, such as mass and lifetime\[2\], are primarily determined by properties of the constituent gluino. Other properties, such as hadronic matter interactions, are dominated by the constituent quarks and gluons.

Since $R$-hadrons may be produced near threshold in LHC collisions, they are expected to be slow ($\beta$ significantly below 1) and have large ionisation energy loss. At LHC energies, some fraction (typically several per cent) of $R$-hadrons, produced with low kinetic energy, would lose sufficient energy to come to rest inside the dense detector materials of the ATLAS calorimeter. These stopped $R$-hadrons may have lifetimes spanning many orders of magnitude, and may decay with significant delay after the collision that created them. It is possible to more easily detect these decays by searching for calorimeter energy deposits during the so-called empty bunch crossings \[8\] when there is less background, as described in detail in Section 3. Since this sample has a very low proton-proton collision rate, the dominant backgrounds to this search are cosmic 

1 The term $R$-hadron has its origin in the $R$-parity quantum number in supersymmetry theories.
2 Lifetime refers to the gluino decays, not the $R$-hadron transition from one hadronic state to another.
ray muons, beam-related backgrounds and instrument-
tional noise. Similar searches for out-of-time decays have 
previously been performed by other experiments [9,10].

This analysis complements previous ATLAS searches 
for long-lived particles [11,12] which are less sensitive 
to particles with initial $β < 1$. By relying primarily 
on calorimetric measurements, this analysis is also sensi-
tive to events where $R$-hadron charge-flipping may 
make reconstruction in the inner tracker and the muon 
system impossible. A potential detection of stopped $R$-hadrons 
could also lead to a measurement of their lifetime and decay properties. Moreover, the search is 
sensitive to any potential new physics scenario produc-
ing large out-of-time energy deposits in the calorime-
ter with minimal additional detector activity. The data 
analysed in this Letter were recorded by the ATLAS 
experiment between April and November 2010, exploit-
ing proton-proton collisions at a centre-of-mass energy 
of 7 TeV.

2 The ATLAS detector

The ATLAS detector [13] consists of an inner track-
ing system (ID) surrounded by a thin superconduct-
ing solenoid, electromagnetic and hadronic calorime-
ters and a muon spectrometer (MS). The ID consists 
of pixel and silicon microstrip detectors, surrounded by 
a transition radiation tracker. The calorimeter system is 
based on two active media for the electromagnetic and 
hadronic calorimeters: liquid argon (LAr) in the inner 
and forward regions, and scintillator-tiles (TileCal) in 
the outer barrel region. The absorber materials are lead 
and either steel, copper, or tungsten. The calorimeters 
are segmented in cells which have typical size 0.1 by 0.1 
in $η-φ$ space in the TileCal section. The MS, capable 
of reconstructing tracks within $|η| < 2.7$, uses toroidal 
bending fields generated by three large superconducting 
magnet systems.

Jets are constructed using the anti-$k_t$ jet algorithm [14] 
with a radius parameter (in $η-φ$ space) set to $R = 0.4$, 
which assumes the energetic particles originated from 
nominal interaction point. This assumption, while in-
correct, still accurately quantifies the energy released 
from the stopped $R$-hadron decays occurring in the 
calorimeter; the associated systematic uncertainty is 

discussed in Section 7. The inputs to the jet algorithm 
described in this paper are calorimeter energy deposits. 
Jet energy is quoted without applying a hadronic cal-
ibration; only jets with energy above 10 GeV are con-
sidered in this search. ATLAS jet reconstruction algo-
ritms are described in more detail elsewhere [15].

3 LHC bunch structure and trigger strategy

The LHC accelerates two counter-rotating proton beams, 
each divided into 3564 25 ns bunch slots. When protons 
are injected into the LHC not every slot is filled. In 
late 2010 running, slots that were filled typically had 
$10^{11}$ protons. Unfilled slots could contain protons due 
to diffusion from filled slots, but this was typically be-
low $5 \times 10^8$ protons per slot.

The filled and unfilled slots can be combined to 
make three different “bunch crossing” scenarios. A paired 
crossing consists of a filled bunch from each beam col-
liding in ATLAS and is by far the most likely to produce 
$R$-hadrons. An unpaired crossing has a filled bunch from 
one beam and an unfilled slot from the other. Finally, 
in an empty crossing the slots from both beams are un-
filled. Empty crossings typically had a proton-proton 
collision rate less than one-millionth the rate in paired 
crossings[16]. In the search sample, described in Sec-

ion 5, there are approximately 350 paired bunch cross-
ings organized in groups of eight. Inside a group, paired 
bunch crossings occurred every 150 ns or longer, while 
the gaps between groups are longer. Most ATLAS anal-
yses use data collected from the paired crossings; this 
analysis instead searches for physics signatures of LLPs 
in the empty crossings. This is accomplished with a set 
of dedicated low-threshold calorimeter triggers which 
may fire only in the empty or unpaired crossings where 
the background to this search is much lower.

ATLAS has a three-level trigger system consisting of 
one hardware and two software levels [17]. Signal can-
didates for this analysis are collected using a hardware 
trigger requiring localised calorimeter activity with a 
10 GeV transverse energy threshold. This trigger could 
fire only during an empty crossing at least 125 ns af-

ter the most recent paired bunch crossing. By waiting 
to collect data only during the empty crossings many 
signal decays are lost; however, this provides a sample 
nearly free of all collision backgrounds. Although the 
$R$-hadrons decay at a time randomly distributed with 
respect to the bunch-crossing clock (which has a 25 ns 
period), this does not cause any loss of efficiency as the 
calorimeter response is longer than 25 ns. A sideband 
region to study beam-halo muons is collected with a 
similar trigger that fired in the unpaired crossings. Both 
samples are collected with only a hardware-level trigger
and without further requirement at the higher trigger levels.

4 Simulation of $R$-hadrons

Monte Carlo simulations are used primarily to determine the reconstruction efficiency and stopping fraction of the $R$-hadrons, and to study associated systematic uncertainties on the quantities used in the selections. The simulated samples have gluino masses in the range 200–600 GeV, to which the present analysis is sensitive. Furthermore, a detailed simulation incorporating gluino generation, stopping and decay steps provides a modular approach for signal production. The Pythia program [15] is used to simulate gluino-gluino pair production events. The string hadronisation model [19], incorporating specialised hadronisation routines [5] for $R$-hadrons, is used inside Pythia to produce final states containing two $R$-hadrons.

Table 1 Signal Monte Carlo stopping fractions for various gluino mass values with their statistical uncertainties. Each efficiency is the number of $R$-hadrons that stop anywhere in the detector divided by the number of produced $R$-hadrons events. Some $R$-hadrons stop in parts of the detector where there is little sensitivity to detect their decay. This is accounted for in the reconstruction efficiency in Table 2.

<table>
<thead>
<tr>
<th>$m_{\tilde{g}}$ (GeV)</th>
<th>Generic (%)</th>
<th>Regge (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>11.5±0.7</td>
<td>5.7±0.5</td>
</tr>
<tr>
<td>300</td>
<td>13.1±0.7</td>
<td>4.7±0.5</td>
</tr>
<tr>
<td>400</td>
<td>12.4±0.7</td>
<td>6.5±0.5</td>
</tr>
<tr>
<td>500</td>
<td>13.2±0.7</td>
<td>4.5±0.5</td>
</tr>
<tr>
<td>600</td>
<td>11.8±0.7</td>
<td>5.6±0.5</td>
</tr>
</tbody>
</table>

To compensate for the fact that $R$-hadron scattering is not strongly constrained by SM analogues, the simulation of $R$-hadron interactions in matter is handled by a special detector response simulation [20] using Geant4 [21,22] routines based on two rather different scattering models with different sets of assumptions: the Generic [20,23] and Regge [24,25] models. Each model makes different assumptions about the $R$-hadron nuclear cross-section and mass spectra of various internal states. Briefly, the phenomenologies of the two models are described as follows:

Generic : Limited constraints on allowed stable states permit the occurrence of doubly charged $R$-hadrons and a wide variety of charge-exchange scenarios. The scattering model is purely phase space driven. This model is chosen as the nominal signal model for gluino $R$-hadrons.

Regge : Only one (electrically neutral) baryonic state is allowed. The scattering model employs a triple-Regge formalism. This is expected to result in a lower stopping fraction than the Generic scenario.

If an $R$-hadron comes to rest in ATLAS, its location is recorded. Table 1 shows the probability for an $R$-hadron to stop as a function of the generated gluino mass for the two models considered. The stopping fraction shows no significant dependence on the gluino mass within the available simulation statistics.

These stopping locations are used as input into a second step of Pythia where the decays of the $R$-hadrons are simulated. Different models allow the gluinos to decay via the radiative process, $\tilde{g} \rightarrow g\tilde{\chi}_1^0$, or via $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$. The reconstruction efficiencies are comparable for both decay modes however, the results are interpreted assuming a 100% branching ratio to $g\tilde{\chi}_1^0$ in accordance with previous results [20,21]. In all simulations the neutralino mass, $m_{\tilde{\chi}_1^0}$, is fixed to 100 GeV. Interactions of the decay products with the detector are simulated with Geant4. These events then follow the standard ATLAS reconstruction which outputs signal candidates.

Fig. 1 Percentage timing efficiency as a function of gluino lifetime. The region $10^{-5}$ to $10^3$ seconds has the highest efficiency, approximately 37%. For shorter lifetimes many $R$-hadrons decay in paired bunch crossings while for longer lifetimes many decay when ATLAS is not taking data. The solid line is calculated with the assumption that no $R$-hadron survived from one run to the next (allowing a per run analysis for shorter lifetimes). The dashed line is calculated after averaging over bunch structure but does allow $R$-hadrons to decay in a run they are not produced in.

An additional inefficiency arises because only a fraction of the stopped $R$-hadrons decay in an empty crossing, while ATLAS is taking data. This inefficiency is a function of the gluino lifetime, and is calculated from
a detailed knowledge of the bunch structure across different LHC fills (relevant for short lifetimes) and the ATLAS data acquisition schedule (relevant for long lifetimes). The timing efficiency versus lifetime is shown in Figure 1; the plateau corresponds to 37% efficiency for lifetimes from $10^{-5}$ to $10^3$ seconds. These lifetimes are long enough to survive until an isolated empty crossing which may be many microseconds after the production event. However, these lifetimes are short enough so that most of the $R$-hadrons do not decay outside of an ATLAS data-taking run, which is typically ten to twenty hours.

5 Data samples

As discussed in Section 3, data are collected with calorimeter-based triggers in the empty and unpaired crossings. To construct two sidebands and a signal search sample, the data from empty bunch crossings are separated into early, middle and late 2010 subsets, respectively. The total integrated luminosity in paired crossings concurrent with these three empty-crossing samples is $34 \text{pb}^{-1}$. Each sample has a different signal to background ratio due to the rapidly increasing instantaneous luminosity of the LHC during 2010.

To predict the number of cosmic ray muons—the dominant background—both the amount of time and varying number of empty bunches per beam revolution in each data-taking run must be accounted for. The trigger live-time (in units of crossing-hours) is quantified by taking the product of the number of hours the trigger is active and the number of empty bunch crossings per beam revolution in that LHC filling scheme.

The first data sample, the background sample, had low beam current and corresponds to a trigger live-time of $1.07 \times 10^6$ crossing-hours and $0.26 \text{pb}^{-1}$ of integrated luminosity; it is used to estimate the background from cosmic ray muons. A second sample, the control sample, corresponds to $0.55 \times 10^6$ crossing-hours, and an integrated luminosity of $2.6 \text{pb}^{-1}$. This sample has different beam conditions, and acts as a cross-check for the cosmic ray muon background estimate. The signal search is performed in the search sample, which corresponds to $0.32 \times 10^6$ crossing-hours. Data collected in the search sample reflect an integrated luminosity of $31 \text{pb}^{-1}$ with a peak instantaneous luminosity of approximately $2.1 \times 10^{32} \text{cm}^{-2} \text{s}^{-1}$. The probability of producing an $R$-hadron in either the background or control sample is small compared to the search sample.

Finally a small sample from the unpaired crossings is used to quantify the background induced by beam-halo muons.

6 Candidate selection

In addition to the signal candidates, several background processes survive the trigger: beam-halo muons, proton-proton collisions, proton-gas collisions, calorimeter noise and cosmic ray muons. The first three of these processes arise from the non-zero proton population in the empty bunches, as described in Section 5. Beam-halo muons are produced when a stray $3.5 \text{TeV}$ proton collides with a collimator or residual gas many metres away from ATLAS. The subsequent shower decays or is blocked by shielding, but occasionally a muon survives to traverse the detector.

The search and sideband samples are divided into two exclusive channels based on the number of reconstructed jets with energy over $10 \text{GeV}$, $N_{\text{jets}}$. Lower energy $R$-hadron decays tend to be reconstructed as a single jet, but very energetic ones may be reconstructed as multiple jets due to their larger spatial extent. The two channels, denoted single jet and multi-jet, differ primarily in their respective noise rejection criteria, labelled as “jet cleaning”. Without requirements on a second jet to reject background, the single jet channel, $N_{\text{jets}} = 1$, uses a more demanding calorimeter selection. Selection criteria described below that are not specifically mentioned in the event yield summary (Table 2) fall under the jet cleaning label for either the single or multi-jet channel.

6.1 Criteria common to both channels

All events in the three empty-crossing data samples, described in Section 5, must pass basic beam, detector and data quality requirements. Events with proton-proton collisions or proton-gas collisions, which happen at a very low rate in empty crossings, are rejected by requiring no reconstructed tracks in the ID. Additionally, events where the missing transverse momentum is less than half of the leading jet transverse momentum are vetoed. The criterion on missing transverse momentum removes the rare collision events since they tend to produce jets with balanced transverse momentum. A signal event, however, produces only one localised energy deposit, since even if both $R$-hadrons stop in the detector they are likely to decay at times separated by more than $25 \text{ns}$. The trigger system would identify these decays as separate events because its timing resolution is significantly smaller than $25 \text{ns}$.

To reduce the contribution from calorimeter noise, the most energetic jet must have an energy greater than $50 \text{GeV}$, and be in the central region ($|\eta| < 2.2$). Furthermore, $n_{90}$, the minimum number of calorimeter cells
Table 2 Event yield at various levels of the selection for the single jet (top) and multi-jet (bottom) channels. The yields of the background and control samples are scaled by detector live-time to the search sample. The background and control samples agree well in the bottom three rows for both channels, showing the live-time scaling works after detector noise is removed (via jet cleaning). Agreement is not expected before jet cleaning due to the sporadic nature of calorimeter noise across 2010. Since the rate of beam-halo muons scales with beam current it only contributes significantly to the search sample as discussed in Section 3. Only statistical uncertainties are shown in the table.

<table>
<thead>
<tr>
<th>Selection criterion</th>
<th>Background sample</th>
<th>Control sample</th>
<th>Search sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data Quality</td>
<td>1119200 ± 600</td>
<td>1038600 ± 800</td>
<td>1579949</td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
<td>&lt; 1.2$</td>
<td>875600 ± 500</td>
</tr>
<tr>
<td>$N_{\text{jets}} = 1$</td>
<td>71800 ± 200</td>
<td>72800 ± 200</td>
<td>1089374</td>
</tr>
<tr>
<td>Jet Cleaning</td>
<td>5860 ± 40</td>
<td>5860 ± 60</td>
<td>5615</td>
</tr>
<tr>
<td>Muon Segment Veto</td>
<td>4 ± 1</td>
<td>5 ± 2</td>
<td>9</td>
</tr>
<tr>
<td>Jet Energy &gt; 100 GeV</td>
<td>0.3 ± 0.3</td>
<td>0.6 ± 0.6</td>
<td>0</td>
</tr>
</tbody>
</table>

| Data Quality              | 1119200 ± 600     | 1038600 ± 800  | 1579949       |
| $|\eta| < 2.2$                | 1093300 ± 600     | 1012400 ± 800  | 1507017       |
| $1 < N_{\text{jets}} < 10$| 22480 ± 80        | 22700 ± 100    | 24902         |
| Jet Cleaning              | 8650 ± 50         | 8310 ± 70      | 8036          |
| Muon Segment Veto         | 1 ± 0.6           | 4 ± 2          | 3             |
| Jet Energy > 100 GeV      | 0.6 ± 0.4         | 0.6 ± 0.6      | 1             |

that collectively contain 90% of the jet energy, must be greater than three.

Cosmic ray and beam-halo muons are vetoed by requiring the absence of a muon segment anywhere in the MS. A muon segment is formed when there is correlated activity in a single detector station of the MS, and serves as input to more sophisticated track finding algorithms. This presents the common selection in the different jet channels and is used to study the data sample. In the final search only events with leading jet energy over 100 GeV are considered. This threshold optimises the search reach while maintaining sensitivity to lighter gluino models.

6.2 Single jet criteria

To remove effects from the noisier calorimeter endcaps, the leading jet must be within the barrel region ($|\eta| < 1.2$). Jets must have at least half of their energy in the TileCal ($f_{\text{Tile}} > 50\%$) to reject beam-halo muons, which occur more frequently closer to the beam pipe. The energy weighted transverse size of the jet, in $\eta-\phi$ space, must be greater than 0.04.

6.3 Multi-jet criteria

The requirement of a second jet in the multi-jet channel, $1 < N_{\text{jets}} < 10$, strongly suppresses the noise and beam-halo contributions, allowing for looser jet cleaning cuts. The energy of the sub-leading jet must be at least 15 GeV to ensure it is well reconstructed; requiring $N_{\text{jets}} < 10$ vetoes several events with bursts of calorimeter noise. In this channel, there is no jet transverse size requirement; however, one of the two leading jets must have $f_{\text{Tile}} > 10\%$.

6.4 Data sample consistency

A very small fraction of the cosmic ray muons incident on the ATLAS detector deposit sufficient energy in the calorimeters to mimic the $R$-hadron signal. This is the dominant background in all data samples prior to applying the muon segment veto. Figures 2(a) and 2(b) show the jet energy distributions, scaled to live-time, of the events selected in the single and multi-jet channels, respectively. The distributions show the event populations after applying the jet cleaning criteria but prior to the muon segment veto. Agreement among the three empty-crossing data samples is found, demonstrating that cosmic ray muons dominate the background at this point.

6.5 Signal efficiency

The same selection criteria are applied to both the data and the signal sample; their affect on signal efficiency is calculated using the simulation. There is an additional small signal loss when a muon segment is reconstructed in the same event as the signal decay. Muon segments due to cosmic rays or noise would cause the event to be vetoed but they are not included in the simulation, unlike those due to signal decays. Using data from the empty bunches acquired with a random trigger, it is estimated that 93% of decays would pass the muon segment veto and remain in the search sample.
Fig. 2 Distributions of jet energy for the single jet (a) and multi-jet (b) channel. Events are plotted for the three empty-crossing data samples considered in the analysis, scaled to the detector live-time of the search sample, prior to applying the muon segment veto. Cosmic ray muons, whose rate is independent of LHC luminosity, dominate the data samples before the muon segment veto is applied.

The reconstruction efficiency is modified by the different stopping models, since they affect the stopping locations of the $R$-hadrons in the calorimeter. Both channels’ signal reconstruction efficiencies are summarised in Table 3. Very energetic $R$-hadron decays are more likely to be reconstructed as several jets, due to their large spatial extent. This causes the single jet channel efficiency to drop slightly, while the multi-jet channel efficiency grows, for heavier $R$-hadrons.

7 Systematic uncertainties on the signal

A variety of systematic uncertainties are investigated; their descriptions and magnitudes are given in the following list. Adding these uncertainties in quadrature yields a total systematic uncertainty of 23% on the predicted number of signal events.

- $R$-hadron Nuclear Interaction (17%): To account for theoretical uncertainties in the interaction model, the cross-section for the quarks in the $R$-hadron to interact with a nucleus is varied up and down by a factor of two. The stopping fraction is recalculated and the largest deviation from the nominal value is taken as the uncertainty. The anticorrelation between the reconstruction efficiency and the stopping efficiency is conservatively not taken into account. This procedure is applied for both stopping models, and the larger deviation is quoted.
- Selection Criteria (9.9%): Each individual selection criterion is varied by ±10% except for the $n_{90}$ requirement which is varied by ±1 cell. The largest difference across all simulated signal samples and selection flow is used as the systematic uncertainty. The 10% variation serves as a conservative estimate of the effects of jet energy scale and resolution uncertainties and other detector effects. This variation includes effects arising from the jets originating inside the calorimeter and propagating in unusual directions. This number also accounts for the uncertainty from the limited Monte Carlo statistics.
- Luminosity (3.4%): This uncertainty is taken directly from Ref. [26].
- Calorimeter Timing (3%): In the signal simulation, each $R$-hadron decay is given a random timing offset between ±50 ns relative to the nominal bunch crossing time. This allows the quantification of the calorimeter response to significantly out-of-time decays. In reality, a signal decay will cause the trigger to be fired in the first 25 ns window in which it deposits enough transverse energy to satisfy the calorimeter trigger threshold (10 GeV); the simulation, however, only models the trigger in one bunch crossing. To take this into account, the signal efficiency is measured in the following windows [–10, 15], [–5, 20] and [0, 25] ns relative to the nominal bunch crossing time. A 3% fractional variation in the efficiency is observed. The window is conservatively varied by 5 ns since the calorimeter channel-to-channel timing uniformity is of order 2 ns.
- Production Cross-Section (10%): The same procedure as in Ref. [11] is used. The production cross-section from Prospino [27] is calculated using the sparticle mass as the renormalisation scale with uncertainties estimated by varying the renormalisation and factorisation scales upward and downward by a factor of two.
Table 3 Signal reconstruction efficiency for various gluino mass values with a fixed $\tilde{\chi}_0^\pm$ mass of 100 GeV. Efficiencies are shown for the single jet (multi-jet) channels and the uncertainties quoted are statistical only. Only the process $\tilde{g} \rightarrow q\tilde{\chi}_1^0$ is considered here. These values do not take into account stopping inefficiencies, timing inefficiency, or losses from random muon segments discussed in Section 4 and Section 5.5.

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<th>Generic (%)</th>
<th>Regge (%)</th>
</tr>
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<tbody>
<tr>
<td>200</td>
<td>0.9±0.3 (0.1±0.1)</td>
<td>1.6±0.3 (0.0±0.0)</td>
</tr>
<tr>
<td>300</td>
<td>8.8±0.6 (4.1±0.4)</td>
<td>10.3±0.8 (6.1±0.6)</td>
</tr>
<tr>
<td>400</td>
<td>9.5±0.8 (6.5±0.7)</td>
<td>13.1±0.9 (8.9±0.7)</td>
</tr>
<tr>
<td>500</td>
<td>8.6±0.8 (9.0±0.8)</td>
<td>9.2±0.8 (12.0±0.8)</td>
</tr>
<tr>
<td>600</td>
<td>8.3±0.7 (9.8±0.8)</td>
<td>9.8±0.7 (14.1±0.8)</td>
</tr>
</tbody>
</table>

8 Background estimation

To quantify the expected number of background events in the search sample we investigate three different sources: cosmic ray muons, beam-halo muons, and calorimeter noise. Since cosmic ray muons occur at a constant rate regardless of LHC conditions their rate is measured using the background sample. From this rate, $0.3\pm0.3$ (0.6±0.4) events are expected to pass the single (multi-) jet selection in the search sample, as shown in Table 2. Here the uncertainties are statistical only.

The rate of beam-halo muons changes with the LHC conditions, most importantly with the beam current. Beam-halo muons should contribute significantly only to the search sample where the beam current is far higher than for the other data samples. The number of beam-halo muons expected to pass the selection is calculated using data collected in the unpaired crossings from the same LHC fills as the empty crossing data. These events have a filled bunch in only one beam and, after requiring a far forward muon segment ($|\eta|>2.2$), correspond to a nearly pure beam-halo sample. Of the beam-halo events that passed the single (multi-) jet criteria, all but $0.6\%$ (0.05\%) leave a muon segment. In the empty bunches there are 83 (531) events with far forward muon segments consistent with beam-halo that otherwise pass the selection. Thus $0.5±0.2$ (0.2±0.2) beam-halo events are expected to pass the selection criteria without leaving a muon segment in the search sample. This expected yield of beam-halo background is added to the final numbers in the background sample of Table 2 to obtain the overall expected background yield shown in Table 3. After the jet cleaning selection much less than 1 event is expected from calorimeter noise in either of the search channels.

9 Results

The leading jet energy distribution of the selected events is shown in Figures 3(a) and 3(b) for the single jet and multi-jet channels respectively. No excess of events is observed in either signal region beyond leading jet energies of 100 GeV.

Limits are set for the single and multi-jet measurements separately; however, since the single jet channel gives an expected limit on the cross-section which is half that of the multi-jet channel, the observed limit from the single jet channel is quoted as the final result. This limit applies to $R$-hadrons decaying to a gluon and lightest supersymmetric particle ($m_{\tilde{g}}=100$ GeV) with a lifetime between $10^{-5}$ to $10^{3}$ seconds as described in Section 4. The limit takes into account systematic uncertainties on the signal cross-section and efficiency as well as on the background estimate, as described above.

Limits are set on the signal cross-section for each gluino mass, $m_{\tilde{g}}$, using a Bayesian method [28] with a uniform prior. Given the expected cross-section as a function of mass, and a limit on the expected number of signal events, gluino $R$-hadrons with a mass $m_{\tilde{g}} < 341$ GeV (294 GeV) are excluded at 95% credibility level (C.L.) for the Generic (Regge) model. Gluino masses $m_{\tilde{g}} < 200$ GeV are not investigated. Figure 4 shows the expected and observed 95% C.L. limit and the ±1 and...
and derived a 95% C.L. limit, excluding $m_{g^0} < m_{\tilde{g}} \pm \sigma_{\text{lifetime}}$ between 10$^{-5}$ and 10$^0$ seconds.

The CMS collaboration used 10 pb$^{-1}$ of proton-proton data collected from collisions at $\sqrt{s} = 7$ TeV. They derived a 95% C.L. limit, excluding $m_{\tilde{g}} < 370$ GeV.

10 Summary

A search is presented for long-lived gluinos which have stopped in the ATLAS detector, using 7 TeV proton-proton collisions at the LHC. No evidence for the subsequent decay of these particles into $g\chi^0$ is found, in a dataset with peak instantaneous luminosity of $2 \times 10^{32}$ cm$^{-2}$ s$^{-1}$ and an integrated luminosity of 31 pb$^{-1}$, during time periods where there are no proton-proton collisions. A dedicated calorimeter trigger is employed, and the observed events are consistent with the background expectation derived from control samples in data. Limits on the gluino pair production as a function of gluino lifetime are derived and exclude 200 $< m_{\tilde{g}} < 341$ GeV at 95% C.L. for lifetimes between $10^{-5}$ to $10^3$ seconds with a fixed neutralino mass of $m_{\chi^0} = 100$ GeV and the Generic matter interaction model.

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