Search for long-lived, heavy particles in final states with a muon and multi-track displaced vertex in proton-proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector


Published in:
Physics Letters B

DOI:
10.1016/j.physletb.2013.01.042

Citation for published version (APA):

General rights
It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).

Disclaimer/Complaints regulations
If you believe that digital publication of certain material infringes any of your rights or (privacy) interests, please let the Library know, stating your reasons. In case of a legitimate complaint, the Library will make the material inaccessible and/or remove it from the website. Please Ask the Library: https://uba.uva.nl/en/contact, or a letter to: Library of the University of Amsterdam, Secretariat, Singel 425, 1012 WP Amsterdam, The Netherlands. You will be contacted as soon as possible.
UvA-DARE is a service provided by the library of the University of Amsterdam (http://dare.uva.nl)
Search for long-lived, heavy particles in final states with a muon and multi-track displaced vertex in proton–proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector

ATLAS Collaboration

ARTICLE INFO

Article history:
Received 28 October 2012
Received in revised form 21 December 2012
Accepted 19 January 2013
Available online 26 January 2013
Editor: H. Weerts

ABSTRACT

Many extensions of the Standard Model posit the existence of heavy particles with long lifetimes. In this Letter, results are presented of a search for events containing one or more such particles, which decay at a significant distance from their production point, using a final state containing charged hadrons and an associated muon. This analysis uses a data sample of proton–proton collisions at $\sqrt{s} = 7$ TeV corresponding to an integrated luminosity of 4.4 fb$^{-1}$ collected in 2011 by the ATLAS detector operating at the Large Hadron Collider. Results are interpreted in the context of R-parity violating supersymmetric scenarios. No events in the signal region are observed and limits are set on the production cross section for pair production of supersymmetric particles, multiplied by the square of the branching fraction for a neutralino to decay to charged hadrons and a muon, based on the scenario where both of the produced supersymmetric particles give rise to neutralinos that decay in this way. However, since the search strategy is based on triggering on and reconstructing the decay products of individual long-lived particles, irrespective of the rest of the event, these limits can easily be reinterpreted in scenarios with different numbers of long-lived particles per event. The limits are presented as a function of neutralino lifetime, and for a range of squark and neutralino masses.

© 2013 CERN. Published by Elsevier B.V. All rights reserved.

1. Introduction

Several extensions to the Standard Model predict the production of heavy particles with lifetimes that may be of order picoseconds up to about a nanosecond [1], at the Large Hadron Collider (LHC). One such scenario is gravity-mediated supersymmetry (SUGRA [2]) with R-parity violation (RPV) [3,4]. If the results of R-parity conserving supersymmetry searches at the LHC (see, for example, Refs. [5,6]) continue to disfavour light superpartners, then scenarios in which R-parity is violated may be required if supersymmetry is the solution to the hierarchy problem [7]. The present (largely indirect) constraints on RPV couplings [3,4] would allow the decay of the lightest supersymmetric particle as it traverses a particle detector at the LHC. Signatures of heavy, long-lived particles also feature in models of gauge-mediated supersymmetry breaking [8], split-supersymmetry [9], hidden-valley [10], dark-sector gauge bosons [11] and stealth supersymmetry [12] though some of these models are disfavoured [13] by the recent results on the search for the Higgs boson [14,15].

This Letter presents the results of a search for the decay of a heavy particle, producing a multi-track vertex that contains a muon with high transverse momentum ($p_T$) at a distance between millimetres and tens of centimetres from the $pp$ interaction point. As in the earlier ATLAS work [16], the results are interpreted in the context of an R-parity violating supersymmetric scenario. In this model, the signature under consideration corresponds to the decay of the lightest supersymmetric particle, resulting in a muon and many high-$p_T$ charged tracks originating from a single displaced vertex (DV). This can arise from a diagram such as that shown in Fig. 1, where the decay occurs due to the non-zero RPV coupling $\lambda^{ij}_{21}$.

The CMS Collaboration has performed a search for a related signature, where a long-lived neutral particle decays to a final state containing two leptons, using 5 pb$^{-1}$ of $pp$ collisions at $\sqrt{s} = 7$ TeV [17]. Similar searches have also been performed by the DØ Collaboration at the Tevatron with $\sqrt{s} = 1.96$ TeV $p\bar{p}$ collisions [18], who also study decays to a $b\bar{b}$ pair [19], and at LEP [20]. The result reported here improves on the previous ATLAS search for this signature [16] in several ways. The dataset is around 100 times larger, corresponding to an integrated luminosity of 4.4 fb$^{-1}$ [21]. Furthermore, the signal efficiency is increased by improving the reconstruction efficiency for reconstructing tracks...
that do not originate from the primary vertex. The dependence on simulation to estimate background levels is also removed. Finally, while the previous analysis did not require muons to be associated vertices, this association requirement is now imposed, which greatly simplifies both the analysis itself, and also the reinterpretation of these results for scenarios containing different numbers of long-lived particles.

2. The ATLAS detector

The ATLAS detector [22] is a multipurpose apparatus at the LHC. The detector consists of several layers of subdetectors. From the interaction point (IP) outwards there is an inner detector (ID), measuring the tracks of charged particles, electromagnetic and hadronic calorimeters, and an outer muon spectrometer (MS).

The ID is immersed in a 2 T axial magnetic field, and extends from a radius\(^2\) of about 45 mm to 1100 mm and to \(\eta > 4\) is additionally covered by separate trigger chambers, used by the hardware trigger for the first level of triggering (level-1). The MS is immersed in a magnetic field which is produced by a set of toroid magnets, one for the barrel and one each for the two end-caps. Online event selection is performed with a three-level trigger system. It comprises a hardware-based level-1 trigger, which uses information from the MS trigger chambers and the calorimeters, followed by two software-based trigger levels.

\(\eta \equiv -\ln \tan(\theta/2)\)

Fig. 1. Diagram of the massive lightest neutralino state decaying into a muon and two jets via a virtual smuon, with lepton-number and \(R\)-parity violating coupling \(\lambda_{211}\).

The calorimeter provides coverage over the pseudorapidity range \(\eta < 4.9\). It consists of a lead/liquid-argon electromagnetic calorimeter, a hadronic calorimeter comprising a steel and scintillator-tile system in the barrel region and a liquid-argon system with copper and tungsten absorbers in the end-caps.

Muon identification and momentum measurement is provided by the MS. This device has a coverage in pseudorapidity of \(|\eta| < 2.7\) and is a three-layer system of gas-filled precision-tracking chambers. The pseudorapidity region \(4 < \eta < 2.4\) is additionally covered by separate trigger chambers, used by the hardware trigger for the first level of triggering (level-1). The MS is immersed in a magnetic field which is produced by a set of toroid magnets, one for the barrel and one each for the two end-caps. Online event selection is performed with a three-level trigger system. It comprises a hardware-based level-1 trigger, which uses information from the MS trigger chambers and the calorimeters, followed by two software-based trigger levels.

The data used in this analysis were collected between March and October, 2011. After the application of beam, detector, and data-quality requirements, the integrated luminosity considered corresponds to 4.4 fb\(^{-1}\), with an uncertainty of \(\pm 3.9\%\) [21].

Signal Monte Carlo (MC) events are generated with Pythia 6 [23], using the MRST LO\(^+\) [24] set of parton distribution functions (PDFs). Processes are simulated in which a \(qq, \bar{q}q\), or \(q\bar{q}\) pair is produced in the \(pp\) collision, with each squark (antisquark) decaying into a long-lived lightest neutralino and a quark (antiquark). Degeneracy of the first and second generations and for the left-handed and right-handed squarks is assumed. The masses of the gluino, sleptons and third-generation squarks are set at such a high value (5 TeV) that they are not directly produced in the supersymmetry scenario considered here.

The parameter settings for the samples of signal MC events are summarised in Table 1. The chosen values of squark and neutralino masses correspond to a wide range in the quantities to which the signal efficiency is most sensitive: neutralino speed and final-state multiplicities (see Section 5). The Higgsino-gaugino mixing determines the neutralino mass values. The signal MC samples are labelled in Table 1 according to the squark mass and neutralino mass, respectively: MH (medium-mass squark, heavy neutralino), ML (medium-mass squark, light neutralino), and HH (heavy squark and heavy neutralino). It is assumed that all RPV couplings other than \(\lambda_{211}\) are zero. This leads to each neutralino decaying to \(\mu^+\mu^-\) (or the charge-conjugate state), Decays of neutralinos to a neutrino and jets final state, which would also occur via a non-zero \(\lambda_{211}\), are not considered in this work.

The PROSPINO [25] program is used to calculate the signal cross section (hereafter referred to as the supersymmetry production cross section) at next-to-leading order; cross section values are listed in Table 1. The CTEQ6.6 PDF set [26] is used. Owing to differences in the predicted cross sections for the \(\tilde{q}\tilde{q}\) and \(\tilde{q}\tilde{q}\) processes from Pythia and PROSPINO, and the possible sensitivity of the neutralino-speed distribution to the assumed process, signal samples are generated for each process separately with Pythia and reweighted according to the relative cross sections of the two processes as estimated with PROSPINO. The reweighting procedure, however, has a minimal effect on the distributions of physical quantities used in this work and typically leads to changes of much less than 1%.

3. Data and simulation

The parameter values for the three signal MC samples used in this work: the assumed squark mass, production cross section (calculated with PROSPINO), neutralino mass, average value of the Lorentz boost factor (from Pythia), average proper decay length, and value of \(\lambda_{211}\) coupling used in the generation of the signal MC samples.

<table>
<thead>
<tr>
<th>Sample</th>
<th>(m_q) [GeV]</th>
<th>(\sigma) [fb]</th>
<th>(m_{\tilde{\chi}^0_1}) [GeV]</th>
<th>(\langle y_p \rangle_{\tilde{\chi}^0_1})</th>
<th>(c_{\text{unc}}) [mm]</th>
<th>(\lambda_{211}) (\times 10^{-5})</th>
</tr>
</thead>
<tbody>
<tr>
<td>MH</td>
<td>700</td>
<td>66.4</td>
<td>494</td>
<td>1.0</td>
<td>78</td>
<td>0.3</td>
</tr>
<tr>
<td>ML</td>
<td>700</td>
<td>66.4</td>
<td>108</td>
<td>3.1</td>
<td>101</td>
<td>1.5</td>
</tr>
<tr>
<td>HH</td>
<td>1500</td>
<td>0.2</td>
<td>494</td>
<td>1.9</td>
<td>82</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Table 1
4. Vertex reconstruction and event selection

It is required that the trigger identifies a muon candidate with transverse momentum $p_T > 40$ GeV and $|\eta| < 1.07$, i.e., in the barrel region of the MS. The latter selection is necessary since there is no ID track requirement in the trigger, and the trigger rate arising from muons with badly measured momenta in the (larger $|\eta|$) end-cap region, where the magnetic field is highly complex, would have consumed too much bandwidth to be viable in the 2011 running conditions.

Owing to the higher instantaneous luminosity of the LHC in 2011 compared to that in 2010, most events contain more than one primary vertex (PV). The PV with the highest sum of $\sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$ is selected, where $\Delta\phi$ and $\Delta\eta$ are the azimuthal angles and pseudorapidities of the two reconstructed muons.

A muon candidate is required to have been reconstructed in both the MS and the ID with transverse momentum $p_T > 50$ GeV (which is well into the region where the trigger efficiency is approximately independent of the muon momentum) and $|\eta| < 1.07$. The impact parameter relative to the transverse position of the primary vertex ($d_0$) is required to satisfy $|d_0| > 1.5$ mm. To ensure that the muon candidate is associated with the muon that satisfied the trigger requirement, the selection $\sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} < 0.15$ is imposed, where $\Delta\phi$ ($\Delta\eta$) is the difference between the azimuthal angle (pseudorapidity) of the reconstructed muon and that of the muon identified by the trigger. The ID track associated with the muon candidate is required to have at least six SCT hits, and at most one SCT hit that is expected but not found, i.e., in an active detector element with no known read-out problems. Furthermore, the track must satisfy an $|\eta|$-dependent requirement on the number of TRT hits. No pixel-hit requirements are applied to the muon track. The combination of requirements described above is referred to as the muon-selection criteria.

In order to reconstruct a DV it is first necessary to select high quality tracks. This is done by requiring that candidate tracks have two or more associated SCT hits and a value of $|d_0|$ greater than 2 mm. Studies made with the MC simulation show that 98% of all tracks originating from the primary $pp$ interaction are rejected by the selection on $|d_0|$. Standard ATLAS tracking [22] is based on three passes in which the initial track candidates are formed in different ways: initially found in the silicon detectors, initially found in the TRT detector, and only found in the TRT detector. The algorithms all assume that tracks originate from close to the PV, and hence have reduced reconstruction efficiency for signal tracks which originate at a DV. To counter this problem and recover some of these lost tracks, the silicon-seeded tracking algorithm is re-run with looser requirements on the radial and $z$ impact parameters, and on the number of detector hits that can be shared among more than one seed track. To reduce the rate of false seed tracks, it is required that these additional tracks have $p_T > 1$ GeV, which is greater than the standard-tracking requirement of $p_T > 400$ MeV. This procedure is termed “re-tracking”. Fig. 2 shows the efficiency for vertex reconstruction (described later) as a function of the radial position of the vertex $r_{DV}$ when using standard tracking and re-tracking for sample MH. As can be seen, there is a substantial improvement due to re-tracking at values of $r_{DV}$ greater than about 10 mm. The dips in the plot correspond to losses in efficiency for decays immediately before a pixel layer, where many tracks from the vertex have shared pixel hits and therefore fail the selection.

Using an algorithm based on the incompatibility-graph approach [29], DVs are sought with the selected tracks. The method adopted is similar to that used in Ref. [30]. The algorithm starts by finding two-track seed vertices from all pairs of tracks; those that have a vertex-fit $\chi^2$ of less than 5.0 per degree of freedom are retained. A seed vertex is rejected if at least one of its tracks has hits between the vertex and the PV. Multi-track vertices are formed from combinations of seed vertices in an iterative process. The following method is used to do this. If a track is assigned to two different vertices, the action taken depends on the distance $D$ between the vertices. If $D < 3\sigma_D$, where $\sigma_D$ is the estimated uncertainty on $D$, a single vertex is formed from the tracks of the two vertices. Otherwise, a track is associated with that vertex for which the track has the smaller $\chi^2$ value. In the event of the $\chi^2$ of a track relative to the resulting vertex exceeding 3.0 per degree of freedom, the track is removed from the vertex, and the vertex is refitted. This process continues until no track is associated with more than one vertex. Finally, vertices are combined and refitted if they are separated by less than 1 mm.

To ensure a good quality DV fit, the $\chi^2$ per degree of freedom of the fit must be less than 5. Furthermore, the DV position is required to be in the fiducial region, defined as $|z_{DV}| < 300$ mm and $r_{DV} < 180$ mm, where $r_{DV}$ and $z_{DV}$ are the radial and longitudinal vertex positions with respect to the origin. To minimise background coming from the PVs, the transverse distance $\sqrt{(x_{DV} - x_{PV})^2 + (y_{DV} - y_{PV})^2}$ between any of the PVs and the DV must be at least 4 mm. Here $x$ and $y$ are the transverse coordinates of a given vertex, with the subscripts PV and DV denoting the type of vertex. The number of tracks $N_{DV}$ associated with the DV is required to be at least five. This reduces background from random combinations of tracks and from material interactions. Background due to particle interactions with material is suppressed by requiring $m_{DV} > 10$ GeV. Here, $m_{DV}$ is the invariant mass of the set of tracks associated with the DV, using the charged-pion mass hypothesis for each track. Candidate vertices which pass (fail) the $m_{DV} > 10$ GeV requirement are hereafter referred to as being high-$m_{DV}$ (low-$m_{DV}$) vertices.

The typical position resolution of the DV in the signal MC samples is tens of microns for $r_{DV}$ and about 200 $\mu$m for $z_{DV}$ near the interaction point. For vertices beyond the outermost pixel layer, which is located at a radius of 122.5 mm, the typical resolution is several hundred microns for both coordinates. Low-$m_{DV}$ ($m_{DV} < 4$ GeV) vertices from particle–material interactions are abundant in regions in which the detector material is dense. High-$m_{DV}$ background may arise from the random
spatial coincidence of a material-interaction vertex with a high-\(p_T\) track, especially when this track and the particle that initiated the material-interaction vertex originate from different primary interactions, resulting in a large angle between their momentum vectors.

To reduce this source of background, vertices that are reconstructed in regions of high-density material are removed. The high-density material was mapped using low-\(m_{\text{DV}}\) material-interaction candidate vertices in data and true material-interaction vertices in minimum-bias MC events. The \(z_{\text{DV}}\) and \(r_{\text{DV}}\) positions of these vertices are used to make a two-dimensional material-density distribution with a bin size of 4 mm in \(z_{\text{DV}}\) and 1 mm in \(r_{\text{DV}}\). It has been demonstrated [30] that the detector simulation describes the positions of pixel layers and associated material reasonably well, while the simulated position of the beampipe is shifted with respect to the actual position. The use of data events to construct the material map therefore ensures that the beampipe material is correctly mapped, while the use of the simulation provides a high granularity of the map at the outer pixel layers, where material-interaction vertices in the data are comparatively rare. Material-map bins with vertex density greater than an \(r_{\text{DV}}^\text{-}\text{and } z_{\text{DV}}\)-dependent density criterion are characterised as high-density-material regions. These make up 34% of the volume at \(|z_{\text{DV}}| < 300\) mm, \(r_{\text{DV}} < 180\) mm.

To ensure that the muon candidate is associated with the reconstructed DV, the distance of closest approach of the muon with respect to the DV is required to be less than 0.5 mm. This requirement ensures that the vertex that we reconstruct gave rise to the muon that triggered the event, and so the selection efficiency for each neutralino decay is independent of the rest of the event. This facilitates a straightforward calculation of the event selection efficiency for scenarios with different numbers of long-lived neutralinos in the event. The aforementioned selections are collectively referred to as the vertex-selection criteria. Events containing one or more vertices passing these criteria are accepted.

5. Signal efficiency

The signal efficiency depends strongly on the efficiencies for track reconstruction and track selection, which are affected by several factors: (1) The number of tracks originating from the DV and their total invariant mass increase with the neutralino mass. (2) More tracks fail the \(|d_0| > 2\) mm requirement for small \(r_{\text{DV}}\) or if a neutralino with large \(p_T\) has a small decay length, thereby leaving its daughters pointing back closer to the PV. (3) The efficiency for reconstructing tracks decreases with increasing values of \(|d_0|\). Because the MH and HH samples have the same neutralino mass, but different boosts, a cross-check of the efficiency estimation procedure can be made. The HH sample is reweighted vertex-by-vertex such that the \(\beta\gamma\) versus \(\eta\) distributions match the MH sample. It was checked that they have the same efficiency as a function of decay position.

The total efficiency for each of the signal MC samples is shown in Fig. 3 as a function of \(c_T\). This is an overall event efficiency, derived from the determination of (the single) vertex efficiency, and is based on having two displaced vertices per event in the signal MC. This efficiency as a function of \(c_T\) is calculated from the samples generated with a single-c\(c_T\) value (see Table 1) using a two-dimensional map in \((|z_{\text{DV}}|, r_{\text{DV}})\) (Fig. 4) and distributions of decay positions for different values of \(c_T\). Events are reweighted according to their probability of being found at different positions in the map, where the probability depends on \(c_T\). Fig. 3 includes systematic corrections and uncertainties that are discussed in Section 7.

6. Background estimation

Spurious high-\(m_{\text{DV}}\), high-multiplicity vertices in non-material regions could come from one of two sources: (1) Purely random combinations of tracks (real or fake). This type of background is expected to form the largest contribution at small radii where the track density is highest. (2) Vertices from real hadronic interactions with gas molecules. Although most of these events will have masses below the 10 GeV requirement, the high-mass tail of the distribution indicates a potential background, in particular if the vertex is crossed by a random track (real or fake) at large crossing angle.

The first source of background mentioned above gives rise to displaced vertices inside the beampipe (where there are few real hadronic interactions due to the good vacuum, but where random combinations are expected to dominate). The expected contribution from this source of background is evaluated using a large sample of jet-triggered events, and examining the ratio of the number of vertices with \(m_{\text{DV}} > 10\) GeV to the number in a mass control region, \(4\) GeV < \(m_{\text{DV}}\) < \(10\) GeV. Since the number of random combinations of tracks depends primarily on the pile-up conditions, and is therefore independent of the type of event that fired the trigger, this ratio can also be applied to the number of vertices in
the mass control region in muon-triggered events. All of this information is used as input to a simple maximum likelihood fit, which yields a background expectation of $(0.00\pm0.06)$ vertices passing our cuts, that arise from random combinations of tracks.

To estimate the second source of background i.e. vertices arising from real hadronic interactions, including those crossed by tracks from different PVS, two $m_{PV}$-distributions are constructed. One distribution is formed from vertices which do not include a so-called large-angle track, i.e. the average angle between a constituent track and the rest of the tracks in the vertex must be less than one radian. The four-momentum of a randomly-selected track in the event is added to the vertex to build the second distribution. Both of these distributions are taken from a large control sample of jet-triggered events. The relative normalisations of these distributions are determined using an estimate of the “crossing probability”. This is obtained by fitting a function representing a $K_S$ mass peak to the invariant mass distribution of all two-track combinations within three-track vertices, and comparing the integral of this function (which is a measure of how many real $K_S$ were crossed by a random track to form a three-track vertex), to the number of two-track $K_S$ mesons observed.

With the shape of the $m_{PV}$-distribution determined in this manner, the absolute normalisation for the muon-triggered sample can be found. It is extracted from a maximum likelihood fit, which takes as input the numbers of vertices in each material layer (i.e., the beam pipe and three pixel detector layers$^3$), and the numbers of low-track-multiplicity vertices in the regions in which there is no material, which are termed “air gaps”. It has been empirically observed that in each material layer or air gap, the relation between the numbers of $n$-track, $(n+1)$-track, $(n+2)$-track vertices etc., is well modelled by an exponential function. Furthermore, the ratio of the number of $n$-track vertices in a material layer to the number in the air gap immediately outside it, is consistent between several different control samples. These relations can therefore be used in the fit to predict the number of vertices with at least five tracks in the air gaps. This procedure was tested on various control samples, giving consistent results for the $m_{PV} < 10$ GeV control region in all cases. For instance, in events that fail the muon trigger requirement, the fit predicted $105.4\pm5.7$ events, whereas 110 events were observed. The $m_{PV}$ distribution, scaled by the prediction, is then integrated to obtain an estimate of the number of vertices with $m_{PV} > 10$ GeV, and a final scale factor is applied, based on the fraction of events in our muon-triggered sample that pass the offline muon requirements. Systematic uncertainties are evaluated by varying the relevant input parameters (the crossing probability, the parameters of the exponential function and material-to-airgap ratio, and the final scale factor) within their respective uncertainties, and taking the largest deviation. Finally, the background from hadronic interactions in the air gaps is estimated to be $3.7^{+4.7}_{-3.3} \times 10^{-3}$ vertices. Note that this is somewhat conservative, as the “crossing probability” used here is derived from tracks crossing $K_S$ vertices, which have worse position resolution than vertices with four or more tracks.

The total background estimate is therefore taken to be $4.5^{+6.0}_{-4.4} \times 10^{-3}$ vertices.

7. Systematic corrections and uncertainties

Several categories of uncertainties and corrections are considered. The values of the uncertainties depend on the neutralino lifetime and the signal sample under investigation. However, they can be ordered in approximately decreasing size. Uncertainties on the muon reconstruction efficiency are largest (typically $\approx 7\%$), followed by trigger ($\approx 6\%$) and tracking ($\approx 4\%$) efficiency uncertainties. The relative luminosity uncertainty is $3.9\%$, while the uncertainty due to limited numbers of events in the signal samples is around $1.5\%$. Other systematic effects, such as the uncertainty on the modelling of pile-up, contribute less than $1\%$ to the total uncertainty. The effect on the efficiency associated with PDF uncertainties is negligible.

To estimate the uncertainty on the efficiency as a function of $c_t$ (Fig. 3) from finite MC sample size, the efficiency in each bin of the two-dimensional efficiency map (Fig. 4) was varied randomly within its statistical uncertainty and the total efficiency was repeatedly re-measured. The spread in those results is taken as the contribution to the systematic uncertainty on the efficiency at each $c_t$ value.

To compensate for the different $z$-distributions of the primary vertices in data and MC simulation, a weight is applied to each simulated event such that the reweighted $z_{PV}$ distribution matches that in data. This weight is applied to both the numerator and denominator in the efficiency calculation.

Similarly, a weight is applied to each simulated event such that the distribution of $(\mu)$, the average number of interactions per bunch-crossing, matches that in data. An uncertainty associated with this procedure is estimated by scaling the $(\mu)$ values used as input to this correction calculation by a factor 0.9 (motivated by the difference between scaling the MC simulation by $(\mu)$ calculated from luminosity measurements and by using the number of reconstructed PVs in data and MC simulation). The difference in the efficiency is evaluated as a function of $c_t$, and is applied as a symmetric systematic uncertainty.

A trigger efficiency correction and its associated systematic uncertainty are derived from a study of $Z \rightarrow \mu^+\mu^-$ events in which at least one of the muons was selected with a single-muon trigger. The trigger efficiency for selecting a signal event is about 90%. The ratio of the trigger efficiencies in data and simulation is applied as a correction factor. Furthermore, the statistical uncertainty on this ratio is added in quadrature to the differences in trigger efficiency between the $Z \rightarrow \mu^+\mu^-$ sample and the signal samples to estimate a systematic uncertainty.

The modelling of track reconstruction efficiency for prompt tracks has been extensively studied in ATLAS [31]. In order to estimate the systematic uncertainty on the track reconstruction for secondary tracks, a study is performed where the number of $K_S$ vertices in data and simulation are compared over a range of radii and $\eta$-values. Based on the outcome of this study, some fraction of tracks in the signal MC are randomly removed from the input to the vertexing algorithm, and the same procedure is used to obtain efficiency-vs-$c_t$ is performed. The difference between this and the nominal efficiency at each $c_t$ point is taken as the systematic uncertainty.

Since the distribution of the true values of $d_0$ for cosmic-ray muons is flat over the limited $d_0$ range considered here, as predicted by cosmic-ray simulation, the shapes of the measured (and simulated) $d_0$-spectra of such muons are used to determine the accuracy to which the simulation reproduces the muon-finding efficiency as a function of $d_0$. The ratio of the number of observed cosmic-ray muons (recorded during 2011) and the simulated muon-finding efficiency is studied as a function of $d_0$. The degree to which the distribution is not flat is used to estimate the $d_0$-dependent muon-finding efficiency, which is used for the results in Figs. 3 and 4. The uncertainties on the efficiency (largely due to the limited statistical precision of the cosmic-ray background sample) are propagated to uncertainties of between $\pm3.5\%$.

$^3$A detailed study of the material distribution within the ID is provided in Ref. [30].
(MH) and ±8% (ML) on the signal reconstruction efficiency, depending on the signal sample.

8. Results

Fig. 5 shows the distribution of $m_{DV}$ vs. $N_{DV}^{trk}$ for vertices in the selected data events, including vertices that are rejected by the selection on $m_{DV}$ and $N_{DV}^{trk}$. The signal distribution for the MH sample is also indicated. The signal region, corresponding to a minimum number of five tracks in a vertex and a minimum vertex mass of 10 GeV, is also shown. No events are observed in the signal region.

Given the lack of candidate events in data, upper limits are evaluated on the supersymmetry production cross section ($\sigma$) times the square of the branching ratio (BR$^2$) for produced squarks to decay via long-lived neutralinos to muons and quarks. The limits are presented for different assumed values of squark and neutralino mass and $\tau$, where $\tau$ is the neutralino lifetime. Based on the efficiency, background estimate, and luminosity of 4.4 fb$^{-1}$, the limits are presented at 95% confidence level on $\sigma \cdot \text{BR}^2$ versus $\tau$. The resulting limits are shown in Fig. 6, with the PROSPINO-calculated cross sections for squark masses of 700 GeV and 1500 GeV. The PROSPINO predictions are shown as a band which represents the variation in predicted cross section when using two different sets of PDFs (CTEQ6.6 and MSTW2008NLO) and varying the factorisation and renormalisation scales each up and down by a factor of two. Since essentially no background is expected and no events are observed, the expected and observed limits are indistinguishable. Based on the observation of no signal events in a data sample of 4.4 fb$^{-1}$, a 95% confidence-level upper limit of 0.68 fb is set on $\sigma \cdot \text{BR}^2$ multiplied by the detector acceptance and the reconstruction efficiency for any signal vertex.

9. Summary and conclusions

An improved search is presented for new, heavy particles that decay at radial distances between 4 mm and 180 mm from the pp interaction point, in association with a high-transverse-momentum muon. This search is based on data collected by the ATLAS detector at the LHC at a centre-of-mass energy of 7 TeV. Fewer than 0.06 background events are expected in the data sample of 4.4 fb$^{-1}$, and no events are observed. Limits are derived on the product of di-squark production cross section and decay chain branching fraction squared, in a SUGRA scenario where the lightest neutralino produced in the primary-squark decay undergoes an $R$-parity violating decay into a muon and two squarks. The limits are reported as a function of the neutralino lifetime and for a range of neutralino masses and velocities, which are the factors with greatest impact on the reconstruction efficiency. Limits for a variety of other models can thus be approximated from these results, based on the neutralino mass and velocity distribution in a given model. Comparing to the results of the previous analysis reported in [16], for lifetimes $\tau < 100$ mm, the limits presented here are somewhat less stringent than what less stringent than could be expected from the factor $\approx 130$ increase in integrated luminosity, as a result of tighter trigger and offline muon selection requirements. For longer lifetimes, these factors are more than outweighed by the increase in efficiency afforded by re-tracking, so the limits are somewhat better than would be expected by simple scaling according to the integrated luminosity of the data samples.

Acknowledgements

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently.

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; CONICYT, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF, DNSRC and Lundbeck Foundation, Denmark; EPLANET and ERC, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; CNR, Georgia; BMBF, DFG, HGF, MPG and AvH Foundation, Germany; GSRT, Greece; ISF, INERVA, GIF, DIP and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; RCN, Norway; MNiSW, Poland; GRICES and FCT, Portugal; MERSYS (MECTS), Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTD, Serbia; MSSR, Slovakia; ARRS and MVZT, Slovenia; DST/NRF, South Africa; MICINN, Spain; SRC and Wallenberg Foundation, Sweden; SER, SNSF and Cantons of Bern and Geneva, Switzerland; NSC, Taiwan; TAEK, Turkey; STFC, the Royal Society and Leverhulme Trust, United Kingdom; DOE and NSF, United States of America.
The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN and the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA) and in the Tier-2 facilities worldwide.

Open access

This article is published Open Access at sciencedirect.com. It is distributed under the terms of the Creative Commons Attribution License 3.0, which permits unrestricted use, distribution, and reproduction in any medium, provided the original authors and source are credited.

References


ATLAS Collaboration


V.V. Ammosov 128

121 Petersburg Nuclear Physics Institute, Gatchina, Russia
122 INFN Sezione di Pisa; (b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
123 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA, United States
124 Laboratorio de Instrumentacion e Fisica Experimental de Particulas – LIP, Lisboa, Portugal; (b) Departamento de Fisica Teorica y del Cosmos and LAFPE, Universidad de Granada, Granada, Spain
125 Instituto of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
126 Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
127 Czech Technical University in Prague, Praha, Czech Republic
128 State Research Center Institute for High Energy Physics, Protvino, Russia
129 Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
130 Physics Department, University of Regina, Regina, SK, Canada
131 Ritsumeikan University, Kusatsu, Shiga, Japan
132 INFN Sezione di Roma I; (b) Dipartimento di Fisica, Università La Sapienza, Roma, Italy
133 INFN Sezione di Roma Tor Vergata; (b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
134 INFN Sezione di Roma Tre; (b) Dipartimento di Fisica, Università Roma Tre, Roma, Italy
135 Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies – Université Hassan II, Casablanca; (b) Centre National de l'Energie des Sciences Techniques Nucléaires, Rabat; (c) Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA, Marrakech; (d) Faculté des Sciences, Université Mohamed Premier and LPIPM, Oujda; (e) Faculté des sciences, Université Mohammed V-Agdal, Rabat, Morocco
136 DSM/IRFU (Institut de Reccherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat a l'Energie Atomique), Gif-sur-Yvette, France
137 Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, CA, United States
138 Department of Physics, University of Washington, Seattle, WA, United States
139 Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
140 Department of Physics, Shinshu University, Nagano, Japan
141 Fachbereich Physik, Universität Siegen, Siegen, Germany
142 department of Physics, Simon Fraser University, Burnaby, BC, Canada
143 CAC National Accelerator Laboratory, Stanford, CA, United States
144 Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; (b) Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
145 Department of Physics, University of Johannesburg, Johannesburg; (b) School of Physics, University of the Witwatersrand, Johannesburg, South Africa
146 Department of Physics, Stockholm University; (b) The Oskar Klein Centre, Stockholm, Sweden
147 Physics Department, Royal Institute of Technology, Stockholm, Sweden
148 Departments of Physics & Astronomy, University of Sussex, Brighton, United Kingdom
149 School of Physics, University of Sydney, Sydney, Australia
150 Institute of Physics, Academia Sinica, Taipei, Taiwan
151 Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
152 Raymond and Beverly Sacker School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
153 Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
154 International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
155 Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
156 Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
157 Department of Physics, University of Toronto, Toronto, ON, Canada
158 TRIUMF, Vancouver, BC, (b) Department of Physics and Astronomy, York University, Toronto, ON, Canada
159 Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan
160 Department of Physics and Astronomy, Tufts University, Medford, MA, United States
161 Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
162 Department of Physics and Astronomy, University of California Irvine, Irvine, CA, United States
163 INFN Gruppo Collegato di Udine; (b) ICP, Trieste; (c) Dipartimento di Chimica, Fisica e Ambienti, Università di Udine, Udine, Italy
164 Department of Physics, University of Illinois, Urbana, IL, United States
165 Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
166 Instituto de Físico Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain
167 Department of Physics, University of British Columbia, Vancouver, BC, Canada
168 Department of Physics and Astronomy, University of Victoria, Victoria, BC, Canada
169 Department of Physics, University of Warwick, Coventry, United Kingdom
170 Waseda University, Tokyo, Japan
171 Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
172 Department of Physics, University of Wisconsin, Madison, WI, United States
173 Fachhochshule für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
174 Fachbereich Physik, Bergische Universität Wuppertal, Wuppertal, Germany
175 Physics Department, Yale University, New Haven, CT, United States
176 Yerevan Physics Institute, Yerevan, Armenia
177 Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France

* Also at Laboratory of Instrumentacacao e Fisica Experimental de Particulas – LIP, Lisboa, Portugal.
* Also at Faculdade de Ciencias and CFNUL, Universidade de Lisboa, Lisboa, Portugal.
* Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.
* Also at TRIUMF, Vancouver, BC, Canada.
* Also at Department of Physics, California State University, Fresno, CA, United States.
* Also at Novosibirsk State University, Novosibirsk, Russia.
* Also at Department of Physics, University of Coimbra, Coimbra, Portugal.
* Also at Department of Physics, UASLP, San Luis Potosi, Mexico.
* Also at Università di Napoli Parthenope, Napoli, Italy.
* Also at Institute of Particle Physics (IPP), Canada.
* Also at Department of Physics, Middle East Technical University, Ankara, Turkey.
* Also at Louisiana Tech University, Ruston, LA, United States.
* Also at Dep Fisica and CEFITEC de Faculdade de Ciencias e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal.
n Also at Department of Physics and Astronomy, University College London, London, United Kingdom.

o Also at Department of Physics, University of Cape Town, Cape Town, South Africa.

p Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.

q Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.

r Also at Manhattan College, New York, NY, United States.

s Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.

t Also at School of Physics and Engineering, Sun Yat-sen University, Guanzhou, China.

u Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.

v Also at School of Physics, Shandong University, Shandong, China.

w Also at Dipartimento di Fisica, Università La Sapienza, Roma, Italy.

x Also at DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat a l’Energie Atomique), Gif-sur-Yvette, France.

y Also at Section de Physique, Université de Genève, Geneva, Switzerland.

z Also at Departamento de Física, Universidade de Minho, Braga, Portugal.

aa Also at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, United States.

ab Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.

ac Also at California Institute of Technology, Pasadena, CA, United States.

ad Also at Institute of Physics, Jagiellonian University, Krakow, Poland.

ae Also at LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France.

af Also at Nevis Laboratory, Columbia University, Irvington, NY, United States.

ag Also at Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom.

ah Also at Department of Physics, Oxford University, Oxford, United Kingdom.

ai Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.

aj Also at Department of Physics, The University of Michigan, Ann Arbor, MI, United States.

ak Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa.

* Deceased.