



# 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<sup>☆</sup>

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## 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  $4.4 \text{ fb}^{-1}$  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.

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## 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

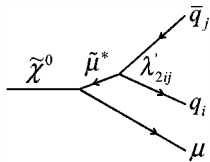
a muon with high transverse momentum ( $p_T$ ) at a distance between millimetres and tens of centimetres from the  $pp$  interaction point. As in the earlier ATLAS work [16], the results are interpreted in the context of an  $R$ -parity violating supersymmetric scenario. In this model, the signature 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  $\lambda'_{2ij}$ .

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  $5 \text{ pb}^{-1}$  of  $pp$  collisions at  $\sqrt{s} = 7$  TeV [17].<sup>1</sup> 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  $4.4 \text{ fb}^{-1}$  [21]. Furthermore, the signal efficiency is increased by improving the reconstruction efficiency for reconstructing tracks

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<sup>1</sup> Following submission of our Letter, this paper was submitted addressing the same physics, but for a different final state.



**Fig. 1.** Diagram of the massive lightest neutralino  $\tilde{\chi}^0$  decaying into a muon and two jets via a virtual smuon, with lepton-number and  $R$ -parity violating coupling  $\lambda'_{2ij}$ .

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 re-interpretation 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<sup>2</sup> of about 45 mm to 1100 mm and to  $|z|$  of about 3100 mm. It provides tracking and vertex information for charged particles within the pseudorapidity region  $|\eta| < 2.5$ . At small radii, silicon pixel layers and stereo pairs of silicon microstrip detectors provide high resolution pattern recognition. The pixel system consists of three barrel layers, and three forward disks on either side of the interaction point (the beam pipe envelope is at a radius of about 30 mm). The barrel pixel layers, which are positioned at radii of 50.5 mm, 88.5 mm, and 122.5 mm are of particular relevance to this work. The silicon microstrip tracker (SCT) comprises four double layers in the barrel, and nine forward disks on either side. A further tracking system, a transition-radiation tracker (TRT), is positioned at larger radii. This device is made of straw-tube elements interleaved with transition-radiation material; it provides coverage within the region  $|\eta| < 2.0$ .

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  $|\eta| < 2.4$  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.

<sup>2</sup> ATLAS uses a right-handed coordinate system with its origin at the nominal IP in the centre of the detector and the  $z$ -axis along the beam pipe. The  $x$ -axis points from the IP to the centre of the LHC ring, and the  $y$ -axis points upward. Cylindrical coordinates  $(r, \phi)$  are used in the transverse plane,  $\phi$  being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle  $\theta$  as  $\eta = -\ln \tan(\theta/2)$ .

**Table 1**

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.

Sample	$m_{\tilde{q}}$ [GeV]	$\sigma$ [fb]	$m_{\tilde{\chi}^0_1}$ [GeV]	$\langle \gamma\beta \rangle_{\tilde{\chi}^0_1}$	$c\tau_{\text{MC}}$ [mm]	$\lambda'_{211} \times 10^{-5}$
MH	700	66.4	494	1.0	78	0.3
ML	700	66.4	108	3.1	101	1.5
HH	1500	0.2	494	1.9	82	1.5

## 3. Data and simulation

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  $4.4 \text{ fb}^{-1}$ , 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  $\tilde{q}\tilde{q}$ ,  $\tilde{q}\tilde{\bar{q}}$ , or  $\tilde{q}\tilde{q}$  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  $\mu^- u \bar{d}$  (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  $\tilde{q}\tilde{\bar{q}}$  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%.

Each generated event in the signal samples is processed with the GEANT4-based [27] ATLAS detector simulation [28] and treated in the same way as the collision data. The samples include a realistic modelling of the effects of multiple  $pp$  collision per bunch crossing (pile-up) observed in the data, obtained by overlaying simulated Minimum Bias events generated using PYTHIA, on top of the hard scattering events, and reweighting events such that the distribution of the number of interactions per bunch crossing matches that in the data.

#### 4. Vertex reconstruction and event selection

It is required that the trigger identifies a muon candidate with transverse momentum  $p_T > 40$  GeV and  $|\eta| < 1.05$ , 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  $p_T^2$  of the tracks associated to it is required to have at least five tracks and a  $z$  position in the range  $|z_{PV}| < 200$  mm. In order to reduce cosmic-ray background, events are rejected if they contain two muons which appear back-to-back. A selection  $\sqrt{(\pi - (\phi_1 - \phi_2))^2 - (\eta_1 + \eta_2)^2} > 0.1$  is applied where  $\phi_1$ ,  $\phi_2$ ,  $\eta_1$  and  $\eta_2$  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.

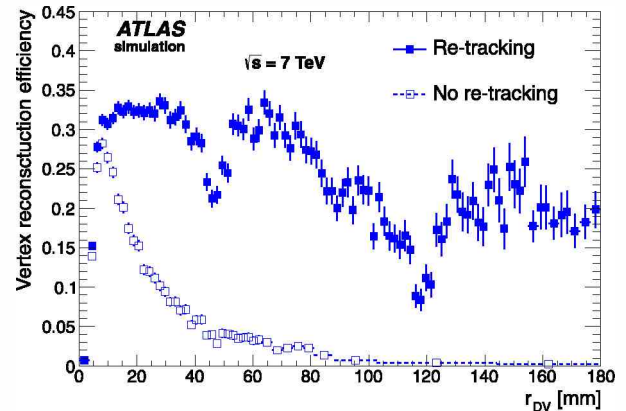


Fig. 2. The vertex reconstruction efficiency as a function of  $r_{DV}$  for the MH sample, with and without re-tracking. All selection criteria, except for the material veto, have been applied.

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  $N_{DV}^{\text{trk}}$  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  $\mu\text{m}$  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- $m_{DV}$  material-interaction candidate vertices in data and true material-interaction vertices in minimum-bias MC events. The  $z_{DV}$  and  $r_{DV}$  positions of these vertices are used to make a two-dimensional material-density distribution with a bin size of 4 mm in  $z_{DV}$  and 1 mm in  $r_{DV}$ . 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  $r_{DV}$ - and  $z_{DV}$ -dependent density criterion are characterised as high-density-material regions. These make up 34% of the volume at  $|z_{DV}| < 300$  mm,  $r_{DV} < 180$  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  $r_{DV}$  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  $c\tau$ . 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  $c\tau$  is calculated from the samples generated with a single- $c\tau$  value (see Table 1) using a two-dimensional map in  $(|z_{DV}|, r_{DV})$  (Fig. 4) and distributions of decay positions for different values of  $c\tau$ . Events are reweighted according to their probability of being found at different positions in the map, where the probability depends on  $c\tau$ . Fig. 3 includes systematic corrections and uncertainties that are discussed in Section 7.

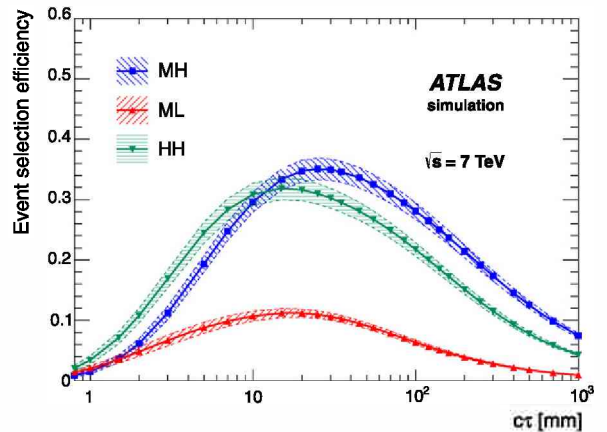


Fig. 3. The event selection efficiency as a function of  $c\tau$  for the three signal samples. The total uncertainties on the efficiency are shown as bands; the estimation of the uncertainties is discussed in Section 7.

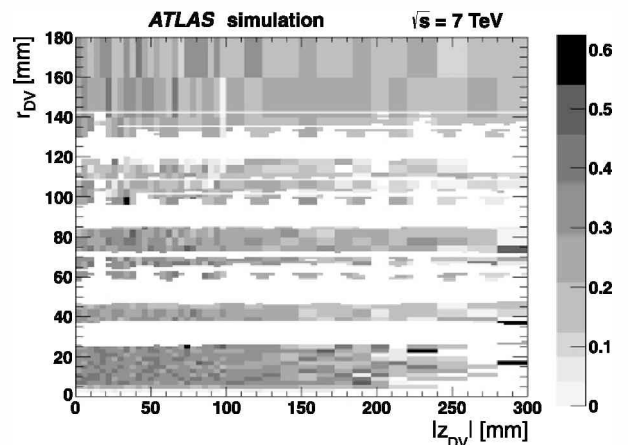


Fig. 4. The efficiency as a function of  $r_{DV}$  and  $z_{DV}$  for vertices in the signal MC sample MH. The blank areas represent regions of dense material which are not considered when looking for DVs. Bin-to-bin fluctuations due to limited MC sample size are compensated for by recalculating this map many times, varying each bin content within its statistical uncertainty.

## 6. Background estimation

Spurious high- $m_{DV}$ , 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  $m_{DV} > 10$  GeV to the number in a mass control region,  $4 \text{ GeV} < m_{DV} < 10 \text{ GeV}$ . 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  $0.00_{-0}^{+0.06}$  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  $m_{DV}$ -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  $m_{DV}$ -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<sup>3</sup>), 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  $m_{DV} < 10$  GeV control region in all cases. For instance, in events that fail the muon trigger requirement, the fit predicted  $105.4 \pm 5.7$  events, whereas 110 events were observed. The  $m_{DV}$  distribution, scaled by the prediction, is then integrated to obtain an estimate of the number of vertices with  $m_{DV} > 10$  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  $3.7_{-3.7}^{+4.4} \times 10^{-3}$  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  $4_{-4}^{+60} \times 10^{-3}$  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  $c\tau$  (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  $c\tau$  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.

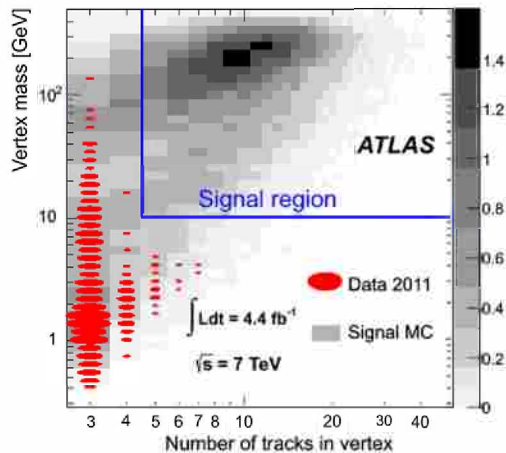
Similarly, a weight is applied to each simulated event such that the distribution of  $\langle\mu\rangle$ , the average number of interactions per bunch-crossing, matches that in data. An uncertainty associated with this procedure is estimated by scaling the  $\langle\mu\rangle$  values used as input to this correction calculation by a factor 0.9 (motivated by taking the difference between scaling the MC simulation by  $\langle\mu\rangle$  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  $c\tau$ , 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- $c\tau$  is performed. The difference between this and the nominal efficiency at each  $c\tau$  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  $\pm 3.5\%$

<sup>3</sup> A detailed study of the material distribution within the ID is provided in Ref. [30].



**Fig. 5.** Vertex mass ( $m_{DV}$ ) vs. vertex track multiplicity ( $N_{DV}^{\text{trk}}$ ) for DVs in events with no muon requirements other than the trigger, and all other selection criteria except the  $m_{DV}$  and  $N_{DV}^{\text{trk}}$  requirements. Shaded bins show the distribution for the signal MC MH sample (see Table 1), and data are shown as filled ellipses, with the area of the ellipse proportional to the number of vertices in the corresponding bin.

(MH) and  $\pm 8\%$  (ML) on the signal reconstruction efficiency, depending on the signal sample.

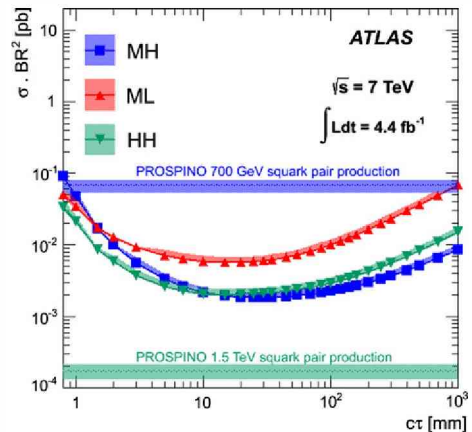
## 8. Results

Fig. 5 shows the distribution of  $m_{DV}$  vs.  $N_{DV}^{\text{trk}}$  for vertices in the selected data events, including vertices that are rejected by the selection on  $m_{DV}$  and  $N_{DV}^{\text{trk}}$ . 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 ( $\text{BR}^2$ ) 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  $c\tau$ , where  $\tau$  is the neutralino lifetime. Based on the efficiency, background estimate, and luminosity of  $4.4 \text{ fb}^{-1}$  (with the uncertainties on each of these treated as nuisance parameters), the  $CL_s$  method [32] is used to set limits on the plane of  $\sigma \cdot \text{BR}^2$  versus  $c\tau$ . 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 [33]) 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  $4.4 \text{ fb}^{-1}$ , a 95% confidence-level upper limit of  $0.68 \text{ fb}$  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  $4.4 \text{ fb}^{-1}$ , and no events are observed. Limits are derived on the product of di-squark production cross section and decay chain branching frac-



**Fig. 6.** Upper limits at 95% confidence level on  $\sigma \cdot \text{BR}^2$  vs. the neutralino lifetime for different combinations of squark and neutralino masses, based on the observation of zero events satisfying all criteria in a  $4.4 \text{ fb}^{-1}$  data sample. The shaded areas around these curves represent the  $\pm 1\sigma$  uncertainty bands on the expected limits. The horizontal lines show the cross sections calculated from PROSPINO for squark masses of 700 GeV and 1500 GeV. The shaded regions around these lines represent the uncertainties on the cross sections obtained from the procedure described in the text.

tion 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 quarks. 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  $c\tau < 100 \text{ mm}$ , the limits presented here are somewhat 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.

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