Search for displaced vertices arising from decays of new heavy particles in 7 TeV pp collisions at ATLAS

The ATLAS Collaboration

Abstract

We present the results of a search for new, heavy particles that decay at a significant distance from their production point into a final state containing charged hadrons in association with a high-momentum muon. The search is conducted in a pp-collision data sample with a center-of-mass energy of 7 TeV and an integrated luminosity of 33 pb$^{-1}$ collected in 2010 by the ATLAS detector operating at the Large Hadron Collider. Production of such particles is expected in various scenarios of physics beyond the standard model. We observe no signal and place limits on the production cross-section of supersymmetric particles in an R-parity-violating scenario as a function of the neutralino lifetime. Limits are presented for different squark and neutralino masses, enabling extension of the limits to a variety of other models.

1. Introduction

Various scenarios of physics beyond the standard model predict the production at the Large Hadron Collider (LHC) of heavy particles with lifetimes that may be of order picoseconds to about a nanosecond. An example of such a scenario is gravity-mediated supersymmetry (SUGRA) with $R$-parity violation (RPV), where current limits on RPV couplings allow for the decay vertex of the lightest supersymmetric particle to be within the range accessible to collider-based particle detectors. In gauge-mediated supersymmetry models, the next-to-lightest supersymmetric particle may be long lived due to suppression of its decay by the large supersymmetry-breaking scale. Additional scenarios allowing for such a signature include split-supersymmetry, hidden-valley, dark-sector gauge bosons, stealth supersymmetry, or a meta-stable supersymmetry-breaking sector.

Searches for related signatures have been performed at the Tevatron with $\sqrt{s} = 1.96$ TeV pp collisions. The D0 collaboration has searched for a long-lived neutral particle decaying into a final state containing two muons or a $b\bar{b}$ pair. No signal was observed, and limits were computed in the context of RPV and hidden-valley model scenarios.

In this letter, we report the results of a search for a heavy particle decaying into several charged particles at a distance of order millimeters to tens of centimeters from the $pp$ interaction point, in events containing a muon with high transverse momentum ($p_T$). We report the results of the search in terms of limits within the SUGRA scenario, where this signature corresponds to the decay of the lightest supersymmetric particle due to non-zero RPV couplings $\lambda'_{2ij}$, via a diagram such as the one shown in Fig. 1. However, it may also be the result of other models with heavy, long-lived particles that decay into or are produced in association with a high-$p_T$ muon.

2. The ATLAS detector

The ATLAS detector comprises a tracking inner detector (ID) system, a calorimeter system, and an extensive muon spectrometer (MS).

The ID operates in a 2 T magnetic field and provides tracking and vertex information for charged particles in the pseudorapidity range $|\eta| < 2.5$, where $\eta \equiv \ln \tan(\theta/2)$ and $\theta$ is the polar angle, defined with respect to the cylindrical symmetry axis (the $z$ axis) of the detector. At small radii, high-resolution pattern recognition capability is obtained using silicon pixel layers and stereo pairs of silicon microstrip layers. The pixel system comprises three barrel layers, and three forward disks on each side of the interaction point. Of particular significance to this analysis are the barrel pixel layers, which are positioned at radii of 50.5, 88.5, and 122.5 mm. The silicon microstrip tracker (SCT) has four barrel layers, and nine forward disks on each side.
At larger radii, a transition-radiation tracker (TRT) composed of straw-tube elements interleaved with transition-radiation material contributes to track reconstruction up to $|\eta| = 2.0$ and improves electron identification.

The calorimeter system covers the pseudorapidity range $|\eta| < 4.9$. It includes a lead/liquid-argon electromagnetic calorimeter and a hadronic calorimeter comprising a steel/scintillating-tile barrel system and a liquid-argon endcap system with copper and tungsten absorbers.

The MS provides muon identification and momentum measurement in the pseudorapidity range $|\eta| < 2.7$ using a 3-layer system of gas-filled precision-tracking chambers. The $|\eta| < 2.4$ range is covered by separate trigger chambers, which are used for the level-1 hardware trigger. The MS operates in a toroidal magnetic field generated by a barrel toroid and two endcap toroids.

A three-level trigger system is used for online event selection. 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.

### 3. Data and simulation

The data used in this analysis were collected between June and October 2010. Basic requirements on stable beam, detector, and trigger conditions are applied, resulting in a total integrated luminosity of 33 pb$^{-1}$.

Monte Carlo (MC) simulated event samples are used to study possible sources of background, evaluate acceptance and signal efficiency, and for systematic-uncertainty studies. For this purpose, we use minimum-bias, QCD-dijet, W+ jets, and Z+ jets samples produced with the PYTHIA MC generator, and $t\bar{t}$ samples generated with MC@NLO.

We use PYTHIA to generate signal events, where a pair of primary squarks or a squark-antisquark pair is produced in the $pp$ collision, and each squark (antisquark) decays into a neutralino and a quark (antiquark). The signal events are generated with a gluino mass of 5 TeV, so that the cross-section for gluino-pair production is small, and this process is not considered.

The parameters of the different signal MC samples are shown in Table 1. The generated values of squark and neutralino masses are chosen so as to provide a broad range of neutralino velocities and daughter-particle multiplicities, which are the quantities that have the greatest impact on the signal efficiency (see discussion in Section 8). The signal MC samples are labeled in Table 1 according to the squark mass and neutralino mass, respectively: MH (medium-mass squark, heavy neutralino), ML (medium-mass squark, light neutralino), LL (light squark and light neutralino), and HH (heavy squark and heavy neutralino).

### Table 1: Parameters of the four signal MC samples used in the analysis

<table>
<thead>
<tr>
<th>Sample</th>
<th>$m_{\tilde{q}}$ [GeV]</th>
<th>$\sigma$ [fb]</th>
<th>$m_{\tilde{\chi}^0_1}$ [GeV]</th>
<th>$\langle \gamma \beta \rangle_{\tilde{\chi}^0_1}$</th>
<th>$c_{\tau_{\text{MC}}}$ [mm]</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>
</tr>
<tr>
<td>ML</td>
<td>700</td>
<td>66.4</td>
<td>108</td>
<td>3.1</td>
<td>101</td>
</tr>
<tr>
<td>LL</td>
<td>150</td>
<td>$539 \times 10^3$</td>
<td>108</td>
<td>1.5</td>
<td>196</td>
</tr>
<tr>
<td>HH</td>
<td>1500</td>
<td>0.2</td>
<td>494</td>
<td>1.9</td>
<td>82</td>
</tr>
</tbody>
</table>

The RPV coupling $Y_{211}$ is set to a non-zero value, so that each neutralino decays to $\mu^- \nu_d$ (or the charge-conjugate state). The value of $Y_{211}$ for each sample is chosen so that a significant fraction of neutralino decays takes place throughout the pixel region, and the resulting average neutralino proper flight distances ($c_{\tau_{\text{MC}}}$, where $c_{\tau_{\text{MC}}}$ is the generated neutralino lifetime) are given in Table 1. We note that while the MC distributions shown in Figs. 3, 4, and 7 depend on $c_{\tau_{\text{MC}}}$, the results of the analysis, presented in Section 8, are independent of the values of $Y_{211}$ and $c_{\tau_{\text{MC}}}$ with which the signal MC samples are generated.

The signal cross-section values listed in Table 1 are obtained from PROSPINO, which performs a next-to-leading-order calculation. We observe that the cross-sections for $\tilde{q}\tilde{q}$ and $\bar{q}\bar{q}$ events are significantly different between PYTHIA and PROSPINO, and that the neutralino-velocity distributions generated by PYTHIA for these two types of events are different, especially in the 150-GeV squark case. To take this into account, $\tilde{q}\tilde{q}$ and $\bar{q}\bar{q}$ events signal samples are generated separately with PYTHIA, and reweighted according to the relative cross-sections of the two event types in PROSPINO.

The background and signal MC samples are generated with an average of $\langle \mu \rangle = 2.2$ interactions per event, corresponding to $\langle \mu \rangle$ for data taken in 2010. An additional sample, otherwise identical to the MH sample in Table 1, is produced with $\langle \mu \rangle = 5$. Each simulated event is passed through the GEANT4-based ATLAS detector simulation and processed in the same way as the data.

### 4. Vertex reconstruction and event selection

We select events that pass an MS level-1 single-muon trigger, where the muon candidate has transverse momentum $p_T > 40$ GeV, as determined in the MS. We require the primary vertex (PV) originating from the $pp$ collision to have at least five tracks and a $z$ position in the range $|z_{\text{PV}}| < 200$ mm. In events with multiple interactions, the PV with the highest scalar sum of the $p_T$ of its tracks is used.

Reconstruction of a displaced vertex (DV) begins with the selection of tracks with $p_T > 1$ GeV formed with at least two SCT hits. For each track we require $|d_0| > 2$ mm.
where $|d_0|$ is the impact parameter of the track with respect to the transverse position of the PV, $(x_{\text{PV}}, y_{\text{PV}})$. In the MC, this requirement rejects 98% of all tracks originating from the primary $pp$ interaction.

The selected tracks are used to search for displaced vertices using an algorithm based on the incompatibility-graph approach, similar to that used in Ref. [10]. The algorithm begins by reconstructing 2-track seed vertices from all track pairs, and keeping those that have a vertex-fit $\chi^2$ less than 5. A seed vertex is rejected if one of its tracks has hits between the vertex and the PV. Seed vertices are combined into multi-track vertices in an iterative process, as follows. If a track is used in 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 $D$, then the tracks of the two vertices are combined and refitted to a single vertex; otherwise, the track is associated with only the vertex relative to which it has the smaller $\chi^2$. If the $\chi^2$ of a track relative to the resulting vertex is greater than 6, the track is removed from the vertex, and the vertex is refitted. The process continues until no tracks are shared among different vertices. Finally, vertices that are separated by less than 1 mm are combined and refitted. Events containing at least one such displaced vertex are said to satisfy the event selection criteria.

The typical position resolution of the DV in the signal MC samples is tens of microns for $r_{\text{DV}}$ and about 200 microns for $y_{\text{DV}}$ 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.

To ensure the quality of the DV fit, we require the $\chi^2$ per degree of freedom (DOF) of the fit to be less than 5. The DV position is required to be within the barrel pixel fiducial region, defined by the longitudinal and transverse ranges $|z_{\text{DV}}| < 300$ mm, $r_{\text{DV}} < 180$ mm, respectively. To suppress background from tracks that originate from the PV, we require the transverse distance $\sqrt{(x_{\text{DV}} - x_{\text{PV}})^2 + (y_{\text{DV}} - y_{\text{PV}})^2}$ between the primary and the displaced vertices to be at least 4 mm. We require the number of tracks $N_{\text{DV}}$ in the DV to be at least four, to suppress background from random combinations of tracks and from material interactions. Background due to particle interactions with material is further suppressed by requiring $m_{\text{DV}} > 10$ GeV, where $m_{\text{DV}}$ is the invariant mass of the tracks originating from the DV. We refer to vertex candidates that satisfy (fail) the $m_{\text{DV}} > 10$ GeV requirement as high-$m_{\text{DV}}$ (low-$m_{\text{DV}}$) vertices.

Low-$m_{\text{DV}}$ vertices from particle-material interactions are abundant in regions of high-density detector material. High-$m_{\text{DV}}$ background may arise from random spatial coincidence of such a vertex with a high-$p_T$ track, especially when this track and the particle that created the material-interaction vertex originate from different primary interactions, which may result in a large angle between their momentum vectors. An example of such a random combination of a material-interaction vertex with a high-$p_T$ track is shown in Fig. 2.

To suppress this type of background, we veto vertices that are reconstructed within regions of high-density material, mapped using low-$m_{\text{DV}}$ material-interaction candidate vertices in data and true material-interaction vertices in minimum-bias MC events. We use the $z_{\text{DV}}$ and $r_{\text{DV}}$ positions of these vertices to form a 2-dimensional material-density map with a bin size of 4 mm in $z_{\text{DV}}$ and 1 mm in $r_{\text{DV}}$. Studies have shown [10] that the positions of pixel layers and associated material are well simulated in the MC detector model, while the simulated beampipe position is shifted with respect to the actual position. Thus, the use of data events to construct the material map ensures the correct mapping of the beampipe material, while MC events make possible the high granularity of the map at the outer pixel layers, where material-interaction vertices in the data are relatively rare due to the low density of primary particles. Material-map bins with vertex density greater than an $r_{\text{DV}}$ and $z_{\text{DV}}$-dependent density criterion are designated as high-density-material regions, which constitute 34.4% of the fiducial volume $|z_{\text{DV}}| < 300$ mm, 4 < $r_{\text{DV}} < 180$ mm. High-$m_{\text{DV}}$ vertices reconstructed within these bins are rejected. We refer to the combination of all the requirements above as the vertex-selection criteria.

In addition to the vertex-selection criteria, events are required to contain a muon candidate reconstructed in both the MS and the ID with $p_T > 45$ GeV, which is well into the efficiency plateau of the 40 GeV level-1 trigger. The muon candidate must satisfy $\sqrt{\Delta \phi^2 + \Delta \eta^2} < 0.1$, where $\Delta \phi$ ($\Delta \eta$) is the difference between the azimuthal angle (pseudorapidity) of the reconstructed muon candidate 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, with at most one SCT hit that is expected but not found, and must satisfy an $|\eta|$-dependent requirement on the number of TRT hits. No pixel-hit re-
requirements are applied to the muon track. The muon track is not required to originate from a DV, in order to maintain high signal efficiency and sensitivity to scenarios where the muon may originate from the PV rather than from the DV, such as supersymmetry with longer decay chains involving prompt smuons. The combination of requirements above is referred to as the muon-selection criteria.

5. Signal efficiency

The efficiency for signal MC vertices is shown in Fig. 3 as a function of $r_{DV}$ for the different selection criteria and two representative signal MC samples – sample MH of Table 1 where the neutralino is heavy and slow moving, and sample ML, where it is light and highly boosted. The efficiency presented in Fig. 3 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 the neutralino is highly boosted. (3) Track-finding algorithms used in track reconstruction are not optimized for tracks with large values of $|d_0|$, resulting in decreased efficiency for large $r_{DV}$. (4) One of the track-quality requirements applied by standard ID tracking is that tracks share no more than one hit in the pixel and SCT layers. As a result, the efficiency is low when $r_{DV}$ is slightly smaller than the radial position $r_{pixel}$ of a pixel layer and increases again for $r_{DV} > r_{pixel}$.

We observe in MC studies that the vertex-efficiency dependence on $z_{DV}$ is, to a good accuracy, uncorrelated with its $r_{DV}$ dependence. Therefore, we parametrize the efficiency function $\epsilon(r_{DV}, z_{DV})$ as a histogram in $r_{DV}$ and a fourth-order polynomial in $z_{DV}$, with parameters obtained from a fit to the MC. An example of the resulting efficiency function, after including the effect of the material veto, is shown in Fig. 4.

Fig. 5 shows comparisons between data and background MC distributions of $m_{DV}$ and $N_{DV}$ for selected events in the control region, $m_{DV} < 10$ GeV and before applying the material veto. Overall, good agreement between data and MC is observed. As we show in Section 6, the level of background contamination in our sample is estimated to be very small. Therefore, small discrepancies between the data and MC distributions do not have significant impact on the final results. Additional studies comparing MC and control-sample data are described in Section 7.

6. Background estimation

As we show later in this section, the probability for background events to satisfy all the selection criteria is extremely low. Therefore, in order to obtain enough events for background estimation, we study the efficiency of the

![Figure 3: The efficiency as a function of $r_{DV}$ for vertices in the signal MC samples MH (top) and ML (bottom) of Table 1. In each plot, the top histogram (circles) is the efficiency for the event selection criteria, the middle histogram (squares) shows the efficiency when also requiring one vertex to satisfy the vertex-selection criteria, and the bottom histogram (triangles) includes the muon-selection criteria. The material veto is not applied when making these plots.](image1)

![Figure 4: The efficiency as a function of $r_{DV}$ and $z_{DV}$ for vertices in the signal MC sample ML of Table 1. High-density material regions that are vetoed are shown in white. The four major vetoed regions surround the beampipe wall, at radii of about 25 – 37 mm, and the three barrel pixel layers.](image2)
background to satisfy the muon-selection criteria separately from the efficiency to satisfy the other selection criteria. We then combine the results assuming that the two efficiencies are uncorrelated.

We use the background MC samples (see Section 3) to estimate the number of data events of each background type that are expected to satisfy the selection criteria, without applying any trigger requirements or the muon-selection criteria. Multiplying this number by the probability for each MC event type to satisfy the muon-trigger and the offline muon-selection criteria yields the expected background for each sample. The \( W^- \rightarrow \mu^- \bar{\nu}_\mu \) sample yields no selected vertices, but has high efficiency for satisfying the muon requirements. As a result, for this background we find the highest upper limit of all the other samples. Given 0 observed \( W^- \rightarrow \mu^- \bar{\nu}_\mu \) MC events and the luminosities of the data and of the MC sample, we find the expected \( W^- \rightarrow \mu^- \bar{\nu}_\mu \) background yield to be \( N_{\text{bkg}} < 0.03 \) events at 90\% confidence level. The expected background yield from \( Z \), \( t\bar{t} \), and dijet events is at least an order of magnitude smaller.

We validate the use of MC to estimate the background by comparing displaced-vertex yields in a sample of non-diffractive MC events and data collected with minimum-bias triggers. For this study, we select vertices with \( m_{\text{DV}} < 10 \) GeV and reject vertices with \( m_{\text{DV}} \) corresponding to \( K_S^0 \) or \( \Lambda^0 \) decays or to photon conversions, in order to increase the purity of material-interaction vertices with high position resolution. From MC, we determine \( N_{\text{int}}(r_{\text{DV}}) \), the radius-dependent fraction of vertices that are due to particle interactions with material. This fraction is close to unity in detector material and much smaller than unity in gap regions between material layers, which are filled with \( N_2 \) gas. Using \( N_{\text{int}}(r_{\text{DV}}) \) and the number of 2-track vertices in a pixel layer and in the adjacent gap, we determine an effective pixel-layer-to-gas mass-density ratio \( \rho \). From \( \rho \), \( N_{\text{int}}(r_{\text{DV}}) \), and the number of \( N_{\text{DV}} > 2 \) vertices seen in each pixel layer, we predict the expected number of such vertices in the adjacent gap. Comparing this with the number of vertices actually observed, we find the prediction to be accurate within expected statistical variations in both MC and data.

As a further cross-check of the estimated background level in the muon-trigger sample, we study a control sample of events selected with jet-based triggers and which fail the \( p_T > 45 \) GeV muon trigger. These events are required to satisfy all the selection criteria, except the muon-selection and \( m_{\text{DV}} > 10 \) GeV requirements. We denote with \( N_{\text{jet}}^{\text{pass}} \) the number of control-sample events containing a vertex that satisfies the \( m_{\text{DV}} > 10 \) GeV requirement. Then an estimate for the \( m_{\text{DV}} > 10 \) GeV background yield in the muon-trigger sample is \( N_{\text{bkg}} = N_{\text{jet}}^{\text{pass}} A_{\text{fail}}^{\text{jet}} / A_{\text{fail}} = 0.003 \pm 0.002 \) events, where \( N_{\text{fail}}^{\text{jet}} = 3 \) (\( N_{\text{fail}}^{\text{jet}} = 4170 \)) is the number of selected muon-trigger (control-sample) events with no vertices that pass the \( m_{\text{DV}} > 10 \) GeV requirement, and \( N_{\text{pass}}^{\text{jet}} = 4 \). We perform

Figure 5: Comparison of the \( m_{\text{DV}} \) (top), \( N_{\text{DV}}^{\text{trk}} \) (center), and \( r_{\text{DV}} \) (bottom) distributions of data and MC events in the control region \( m_{\text{DV}} < 10 \) GeV. Other than the material veto and the \( N_{\text{DV}}^{\text{trk}} > 4 \) and \( m_{\text{DV}} > 10 \) GeV requirements, all selection criteria are applied. In addition, the \( N_{\text{DV}}^{\text{trk}} \) and \( r_{\text{DV}} \) distributions include a veto on \( K_S^0 \) decays. The MC histograms are normalized to the integrated luminosity of the data, with the MC cross-section given by PYTHIA [11].
variations of this estimate to account for some differences in the track-momentum spectrum and in \( N_{\text{bgd}} \) between the muon-trigger and control-sample events, and obtain consistent results.

We observe that the data-driven background-yield estimate is consistent with the MC-based upper limit of \( N_{\text{bgd}} < 0.03 \) events. In Section 8, we conservatively use the MC-based upper limit when calculating upper limits on the signal yield.

7. Systematic uncertainties

We study several sources of systematic uncertainties on the signal reconstruction efficiency. These include uncertainties due to the trigger efficiency, the \( |d_0| \) dependence of muon- and hadron-reconstruction efficiencies, the performance of the vertex-reconstruction algorithm, the uncertainty on the integrated luminosity, and the effect of multiple pp interactions per LHC bunch crossing. These studies and the resulting systematic uncertainties are briefly described below. We estimate that systematic uncertainties associated with the background estimate have a negligible impact on the limits obtained in Section 8, since the conservatively estimated background yield is far less than one event.

The efficiency of the trigger used in this analysis has been studied using \( Z^0 \to \mu^+\mu^- \) events. Based on that study, we correct the MC-estimated efficiency by an overall factor of 0.91, and assign to it a relative uncertainty of 0.043. Although \( Z^0 \) bosons are produced at the interaction point, the trigger uses only MS hits, so it is not strongly dependent on the true \( |d_0| \) value. We find good agreement between MC and data in terms of the dependence of the efficiency on the \( |d_0| \) measured by the MS.

We test the MC simulation of the \( |d_0| \) dependence of the offline muon-reconstruction efficiency using cosmic-ray muons found in pp-collision events. A downward-going cosmic-ray muon is reconstructed by the tracking algorithm as two separate tracks, one above the interaction point and one below. To identify cosmic-ray muons, we select muon-candidate pairs that are back-to-back to within 0.03 in \( \phi \) and 0.01 in \( \eta \), and reject beam-produced muons by requiring \( |d_0| > 2 \) mm for both candidates. The difference \( \Delta p_T \) between the \( p_T \) of the upper candidate and that of the lower candidate peaks at around 6 GeV, due to muon energy loss in the calorimeters, and the fact that for high-\( p_T \) muons the \( p_T \) measurement is dominated by the MS. From the distribution of \( \Delta p_T \) we find that the purity of the cosmic-ray sample is greater than 95%.

Since the true-\( |d_0| \) distribution for cosmic-ray muons is flat over the small \( |d_0| \) range used in the analysis, as verified by cosmic-ray simulation, the measured \( |d_0| \) distribution of cosmic-ray muons yields the \( |d_0| \) dependence of the efficiency. Fig. 6 shows the ratio between the number of cosmic muons and the MC muon efficiency as a function of \( |d_0| \), normalized to unity in the range 2 < \( |d_0| < 4 \) mm.

The ratio shown is for sample HH of Table 1 but is similar for the other MC samples. All deviations from unity appearing in Fig. 6 (and in the corresponding distributions for the other signal samples) are taken into account in the calculation of the signal efficiency in each \( d_0 \) bin, and are reflected in Figs. 7 and 8. The statistical uncertainties shown in Fig. 6 are propagated to uncertainties of between 3.5% and 8% on the signal reconstruction efficiency, depending on the signal sample.

![Figure 6: The ratio between the \( |d_0| \) distribution of cosmic-ray muons and the \( |d_0| \)-dependence of the signal MC muon reconstruction efficiency, shown as an example for sample HH of Table 1. The ratio is normalized to unity in the range 2 < \( |d_0| < 4 \) mm.](image_url)

We estimate a systematic uncertainty on the inner-detector track reconstruction efficiency as a function of the radial position of the vertex by comparing the \( r_{\text{DV}} \) distributions of \( K^0_S \) mesons in minimum-bias MC and in data events collected with a minimum-bias trigger. We find that the \( K^0_S \) momentum distributions in data and MC are in good agreement, and hence expect the \( r_{\text{DV}} \) distributions to agree as well. To test this, we compute the ratio \( R_{K^0_S} \equiv \kappa_{\text{data}}(r_{\text{DV}})/\kappa_{\text{MC}}(r_{\text{DV}}) \), where \( \kappa_{\text{data}}(r_{\text{DV}}) \) is the ratio between the number of \( K^0_S \) mesons reconstructed in sample \( i \) in a radial range around \( r_{\text{DV}} \) and the number reconstructed inside the beampipe. Based on the largest deviation of \( R_{K^0_S} \) from unity, we determine a systematic uncertainty of 3% for tracks with \( |\eta| < 1 \) and 4.3% for tracks with \( |\eta| > 1 \). This track-reconstruction uncertainty is propagated to an uncertainty on the vertex-reconstruction efficiency by random removal of tracks from the signal MC samples prior to vertex reconstruction and generation of alternative versions of the efficiency function \( \epsilon(r_{\text{DV}}, z_{\text{DV}}) \).

A data-MC difference in the vertex-reconstruction ef-
iciency is difficult to distinguish from an effect due to tracking-reconstruction efficiency. A vertex-reconstruction efficiency difference is likely to lead to differences in the vertex-fit $\chi^2$/DOF. Comparing the fraction of vertices for which the $\chi^2$/DOF is below 2.5 in data and MC, we estimate a systematic uncertainty of 0.7%.

We take the systematic uncertainty on the luminosity to be 3.4% [17].

The impact of multiple $pp$ interactions per bunch crossing on the level of background is studied with jet-trigger events with multiple primary vertices, and is determined to be negligible. The impact on signal efficiency, studied with the ($\mu$) = 5 signal MC sample, is negligible as well. Therefore, no systematic uncertainties are assigned due to multiple interactions.

Propagation of the systematic uncertainties to the final results of the analysis is described in the following section.

8. Results

Figure 7 shows the distribution of $m_{\text{DV}}$ vs. $N_{\text{trk}}^{\text{DV}}$ for vertices in the selected data events, including vertices that fail the requirements on $m_{\text{DV}}$ and $N_{\text{trk}}^{\text{DV}}$, overlaid with the signal distribution for the MH sample. We observe no events that satisfy all the selection criteria.

Based on this null observation, we set upper limits on the supersymmetry production cross-section $\sigma$ times the branching fraction $B$ of the complete simulated signal decay chain for different combinations of squark and neutralino masses and for different values of $c\tau$, where $\tau$ is the neutralino lifetime.

The limits are determined in the following way. For each value of $c\tau$, we use the two-dimensional rapidity-vs.-velocity distribution of the generated neutralinos in each signal MC sample to produce a distribution of DV positions with respect to the PV. This distribution is convolved with a Gaussian representing the $z$ distribution of the PV, and then multiplied by the 2-dimensional efficiency map for vertices in that signal MC sample, obtaining the expected distribution of $r_{\text{DV}}$ vs. $z_{\text{DV}}$. This distribution is generated separately for two cases. In the first case the reconstructed DV and muon originate from the same neutralino, and in the second they originate from different neutralinos. This allows us to correctly account for the muon-reconstruction efficiency for the desired value of $c\tau$, despite the fact that the signal MC is produced with a different lifetime, $c\tau_{\text{MC}}$. Integrating over the $r_{\text{DV}}$ vs. $z_{\text{DV}}$ distributions, we obtain the total efficiency for reconstructing at least one vertex and one muon in the event given our selection criteria and the value of $c\tau$. From the efficiency and luminosity, we obtain the expected average signal-event yield for any value of the signal production cross-section. The expected background yield is taken to be zero with a conservative uncertainty of 0.03 events, which is the 90% CL upper limit on the background (see Section 6). The upper limit on $\sigma B$ is then calculated using the CL$_{s}$ method [18], where signal-only and signal-plus-background $p$-values are evaluated using pseudo-experiments generated from distributions based on counting statistics. The uncertainties on luminosity, efficiency, and background are treated as nuisance parameters.

The systematic uncertainty on the track-reconstruction efficiency is taken into account in the limit calculation by use of the alternative efficiency functions described in Section 7. All other efficiency systematic uncertainties are used when converting the limit on the number of signal events to the limit on $\sigma B$.

The resulting limits are shown in Figure 8 with the PROSPINO-calculated cross-sections for squark masses of 150 GeV and 700 GeV. Since no background is expected, the expected and observed limits are indistinguishable. In addition, based on the observation of no signal events in a data sample of 33 pb$^{-1}$, we set a 95% confidence-level upper limit of 0.09 pb on the cross-section times the detector acceptance times the reconstruction efficiency for any signal vertex.

9. Summary and conclusions

We have searched for new, heavy particles with lifetimes and velocities such that they decay at radial distances between 4 mm and 180 mm from the $pp$ interaction.
Figure 8: Upper limits at 95% CL on the production cross-section times branching fraction vs. the neutralino lifetime times the speed of light for different combinations of squark and neutralino masses, based on the observation of zero events satisfying all criteria in a 33 pb$^{-1}$ data sample. The horizontal lines show the cross-sections calculated from PROSPINO for squark masses of 700 GeV and 150 GeV.

point, in association with a high-transverse-momentum muon. Fewer than 0.03 background events are expected in the data sample of 33 pb$^{-1}$, and no events are observed. We present limits on the product of di-squark production cross-section and decay-chain branching fraction in a SUGRA scenario where the lightest neutralino produced in the primary-squark decay undergoes $R$-parity-violating decay into a muon and two quarks. 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 limit. Limits for a variety of other models can thus be approximated from our results, based on the neutralino mass and velocity distribution in a given model.

10. Acknowledgements

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References

<table>
<thead>
<tr>
<th>Name</th>
<th>Affiliation</th>
</tr>
</thead>
<tbody>
<tr>
<td>J. Weingarten</td>
<td>Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan</td>
</tr>
<tr>
<td></td>
<td>Physics Department, National Technical University of Athens, Zografou, Greece</td>
</tr>
<tr>
<td></td>
<td>Physics Department, University of Athens, Athens, Greece</td>
</tr>
<tr>
<td>H. Wang</td>
<td>Department of Physics, The University of Texas at Arlington, Arlington TX, United States of America</td>
</tr>
<tr>
<td>W. Walkowiak</td>
<td>High Energy Physics Division, Argonne National Laboratory, Argonne, IL, United States of America</td>
</tr>
<tr>
<td>W. Walker</td>
<td>Department of Physics, Boston University, Boston MA, United States of America</td>
</tr>
<tr>
<td>C. Wang</td>
<td>School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom</td>
</tr>
<tr>
<td>H. Wang</td>
<td>Turkish Atomic Energy Authority, Ankara, Turkey</td>
</tr>
<tr>
<td>J. Walbersloh</td>
<td>Institute of Physics, University of Belgrade, Belgrade; Physics Engineering, Gaziantep University, Gaziantep, Turkey</td>
</tr>
<tr>
<td>A.M. Zaitsev</td>
<td>Department of Physics, Gazi University, Ankara; Turkish Atomic Energy Authority, Ankara, Turkey</td>
</tr>
<tr>
<td>Y. Yasu</td>
<td>Department of Physics, Ankara University, Ankara; Turkish Atomic Energy Authority, Ankara, Turkey</td>
</tr>
<tr>
<td>H. Wang</td>
<td>Department of Physics, Dumlupinar University, Kutahya; Turkish Atomic Energy Authority, Ankara, Turkey</td>
</tr>
<tr>
<td>J. Walder</td>
<td>Department of Physics, University of Alberta, Edmonton AB, Canada; Turin, Italy</td>
</tr>
<tr>
<td>R. Walker</td>
<td>Department of Physics, University of Belgrade, Belgrade; Vinca Institute of Nuclear Sciences, Belgrade, Serbia</td>
</tr>
<tr>
<td>W. Walkowiak</td>
<td>Department of Physics, University of California, Berkeley CA, United States of America</td>
</tr>
<tr>
<td>C. Wang</td>
<td>Department of Physics, Humboldt University, Berlin, Germany</td>
</tr>
<tr>
<td>H. Wang</td>
<td>Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland</td>
</tr>
<tr>
<td>J. Walker</td>
<td>School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom</td>
</tr>
<tr>
<td>W. Walker</td>
<td>Department of Physics, Brandeis University, Waltham MA, United States of America</td>
</tr>
<tr>
<td>W. Walkowiak</td>
<td>University at Albany, Albany NY, United States of America</td>
</tr>
<tr>
<td>H. Wang</td>
<td>Department of Physics, Physics Division, Lawrence Berkeley National Laboratory and Laboratory for High Energy Physics, University of California, Berkeley CA, United States of America</td>
</tr>
<tr>
<td>J. Walbersloh</td>
<td>Department of Physics, Physics Division, Lawrence Berkeley National Laboratory and Laboratory for High Energy Physics, University of California, Berkeley CA, United States of America</td>
</tr>
<tr>
<td>A. M. Zaitsev</td>
<td>Department of Physics, Brandeis University, Waltham MA, United States of America</td>
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<tr>
<td>Y. Yasu</td>
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<tr>
<td>J. Walbersloh</td>
<td>Department of Physics, University of California, Berkeley CA, United States of America</td>
</tr>
</tbody>
</table>
Universidade de Sao Paulo, Sao Paulo, Brazil
24 Physics Department, Brookhaven National Laboratory, Upton NY, United States of America
25 (a)National Institute of Physics and Nuclear Engineering, Bucharest; (b)University Politehnica Bucharest, Bucharest;
(c)West University in Timisoara, Timisoara, Romania
26 Departamento de F´ısica, Universidad de Buenos Aires, Buenos Aires, Argentina
27 Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
28 Department of Physics, Carleton University, Ottawa ON, Canada
29 CERN, Geneva, Switzerland
30 Enrico Fermi Institute, University of Chicago, Chicago IL, United States of America
31 (a)Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; (b)Departamento de Física,
Universidad Técnica Federico Santa Maria, Valparaíso, Chile
32 (a)Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; (b)Department of Modern Physics,
University of Science and Technology of China, Anhui; (c)Department of Physics, Nanjing University, Jiangsu; (d)High
Energy Physics Group, Shandong University, Shandong, China
33 Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3,
Aubiere Cedex, France
34 Nevis Laboratory, Columbia University, Irvington NY, United States of America
35 Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
36 (a)INFN Gruppo Collegato di Cosenza; (b)Dipartimento di Fisica, Università della Calabria, Arcavata di Rende, Italy
37 Faculty of Physics and Applied Computer Science, AGH-University of Science and Technology, Krakow, Poland
38 The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
39 Physics Department, Southern Methodist University, Dallas TX, United States of America
40 Physics Department, University of Texas at Dallas, Richardson TX, United States of America
41 DESY, Hamburg and Zeuthen, Germany
42 Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
43 Institut für Kern- und Teilchenphysik, Technical University Dresden, Dresden, Germany
44 Department of Physics, Duke University, Durham NC, United States of America
45 SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
46 Fachhochschule Wiener Neustadt, Johannes Gutenbergstrasse 3, 2700 Wiener Neustadt, Austria
47 INFN Laboratori Nazionali di Frascati, Frascati, Italy
48 Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg i.Br., Germany
49 Section de Physique, Université de Genève, Geneva, Switzerland
50 (a)INFN Sezione di Genova; (b)Dipartimento di Fisica, Università di Genova, Genova, Italy
51 Institute of Physics and HEP Institute, Georgian Academy of Sciences and Tbilisi State University, Tbilisi, Georgia
52 II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
53 SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
54 II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
55 Laboratoire de Physique Subatomique et de Cosmologie, Université Joseph Fourier and CNRS/IN2P3 and Institut
National Polytechnique de Grenoble, Grenoble, France
56 Department of Physics, Hampton University, Hampton VA, United States of America
57 Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States of America
58 (a)Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (b)Physikalisches Institut,
Ruprecht-Karls-Universität Heidelberg, Heidelberg; (c)ZITI Institut für technische Informatik,
Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
59 Faculty of Science, Hiroshima University, Hiroshima, Japan
60 Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
61 Department of Physics, Indiana University, Bloomington IN, United States of America
62 Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
63 University of Iowa, Iowa City IA, United States of America
64 Department of Physics and Astronomy, Iowa State University, Ames IA, United States of America
65 Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
66 KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
67 Graduate School of Science, Kobe University, Kobe, Japan
68 Faculty of Science, Kyoto University, Kyoto, Japan
69 Kyoto University of Education, Kyoto, Japan
70 Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
71 Physics Department, Lancaster University, Lancaster, United Kingdom
INFN Sezione di Lecce; Dipartimento di Fisica, Università del Salento, Lecce, Italy

Department of Physics, Józef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia

Department of Physics, Queen Mary University of London, London, United Kingdom

Department of Physics, Royal Holloway University of London, Surrey, United Kingdom

Department of Physics and Astronomy, University College London, London, United Kingdom

Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France

Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom

Department of Physics, McGill University, Montreal QC, Canada

School of Physics, University of Melbourne, Victoria, Australia

Department of Physics, The University of Michigan, Ann Arbor MI, United States of America

Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America

INFN Sezione di Milano; Dipartimento di Fisica, Università di Milano, Milano, Italy

B.I. Stepnov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus

National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus

Department of Physics, Massachusetts Institute of Technology, Cambridge MA, United States of America

Group of Particle Physics, University of Montreal, Montreal QC, Canada

P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia

Department of Physics, Northern Illinois University, DeKalb IL, United States of America

Budker Institute of Nuclear Physics (BINP), Novosibirsk, Russia

Department of Physics, New York University, New York NY, United States of America

Ohio State University, Columbus OH, United States of America

Faculty of Science, Okayama University, Okayama, Japan

Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States of America

INFN Sezione di Napoli; Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy

Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America

INFN Sezione di Pisa; Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy

Petersburg Nuclear Physics Institute, Gatchina, Russia

INFN Sezione di Pavia; Dipartimento di Fisica Nucleare e Teorica, Università di Pavia, Pavia, Italy

Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America

Laboratorio de Instrumentación e Física Experimental de Partículas - LIP, Lisboa, Portugal; Dipartimento di Fisica Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain

INFN Sezione di Milano; Dipartimento di Fisica, Università di Milano, Milano, Italy

Department of Physics, McGill University, Montreal QC, Canada

School of Physics, University of Melbourne, Victoria, Australia

Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America

INFN Sezione di Milano; Dipartimento di Fisica, Università di Milano, Milano, Italy

B.I. Stepnov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus

National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus

Department of Physics, Massachusetts Institute of Technology, Cambridge MA, United States of America

Group of Particle Physics, University of Montreal, Montreal QC, Canada

P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia

Department of Physics, Northern Illinois University, DeKalb IL, United States of America

Budker Institute of Nuclear Physics (BINP), Novosibirsk, Russia

Department of Physics, New York University, New York NY, United States of America

Ohio State University, Columbus OH, United States of America

Faculty of Science, Okayama University, Okayama, Japan

Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States of America

INFN Sezione di Napoli; Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy

Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America

INFN Sezione di Pisa; Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy

Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America

Laboratorio de Instrumentación e Física Experimental de Partículas - LIP, Lisboa, Portugal; Dipartimento de Fisica Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain
Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
Czech Technical University in Prague, Praha, Czech Republic
State Research Center Institute for High Energy Physics, Protvino, Russia

Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom

Physics Department, University of Regina, Regina SK, Canada
Ritsumeikan University, Kusatsu, Shiga, Japan

INFN Sezione di Roma I; Dipartimento di Fisica, Università La Sapienza, Roma, Italy
INFN Sezione di Roma Tor Vergata; Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
INFN Sezione di Roma Tre; Dipartimento di Fisica, Università Roma Tre, Roma, Italy
Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca;
Centre National de l’Énergie des Sciences Techniques Nucléaires, Rabat; Université Cadi Ayyad, Faculté des sciences Semlalia Département de Physique, B.P. 2390 Marrakech 40000;
Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda;
Faculté des Sciences, Université Mohammed V, Rabat, Morocco

DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat a l’Énergie Atomique), Gif-sur-Yvette, France
Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United States of America

Department of Physics, University of Washington, Seattle WA, United States of America
Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
Department of Physics, Shinshu University, Nagano, Japan
Fachbereich Physik, Universität Siegen, Siegen, Germany
Department of Physics, Simon Fraser University, Burnaby BC, Canada
SLAC National Accelerator Laboratory, Stanford CA, United States of America
Department of Physics, University of Johannesburg, Johannesburg;
School of Physics, University of the Witwatersrand, Johannesburg, South Africa
Department of Physics, Stockholm University;
The Oskar Klein Centre, Stockholm, Sweden
Physics Department, Royal Institute of Technology, Stockholm, Sweden
Department of Physics and Astronomy, Stony Brook University, Stony Brook NY, United States of America
Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
School of Physics, University of Sydney, Sydney, Australia
Institute of Physics, Academia Sinica, Taipei, Taiwan
Department of Physics, Technion: Israel Inst. of Technology, Haifa, Israel
Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
Department of Physics, University of Toronto, Toronto ON, Canada
TRIUMF, Vancouver BC; Department of Physics and Astronomy, York University, Toronto ON, Canada
Institute of Pure and Applied Sciences, University of Tsukuba, Ibaraki, Japan
Science and Technology Center, Tufts University, Medford MA, United States of America
Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America
INFN Gruppo Collegato di Udine; ICTP, Trieste; Dipartimento di Fisica, Università di Udine, Udine, Italy
Department of Physics, University of Illinois, Urbana IL, United States of America
Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNMI), University of Valencia and CSIC, Valencia, Spain
Department of Physics, University of British Columbia, Vancouver BC, Canada
Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada
Waseda University, Tokyo, Japan
Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel