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ATLAS Collaboration

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 [1] 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 [2]. Additional scenarios allowing for such a signature include split-supersymmetry [3], hidden-valley [4], dark-sector gauge bosons [5], stealth supersymmetry [6], or a meta-stable supersymmetry-breaking sector [7].

Searches for related signatures have been performed at the Tevatron with $\sqrt{s} = 1.96$ TeV $p\bar{p}$ collisions. The D0 Collaboration has searched for a long-lived neutral particle decaying into a final state containing two muons [8] or a $b\bar{b}$ pair [9]. 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 [10] 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 is the barrel pixel
The signal MC samples are labeled in Table 1 that have the greatest impact on the signal efficiency (see discussions and daughter-particle multiplicities, which are the quantities in Table 1. The generated values of squark and neutralino masses is small, and this process is not considered.

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 [14] ATLAS detector simulation [15] 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. [16]. 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 only with 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 merged 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 $r_{90}$ and about 200 microns for $z_{90}$ 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.

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1. The final neutralino mass values are the result of Higgsino–gaugino mixing.
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 [16] 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, $r_{\text{DV}} < 180$ 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 $\Delta \phi^2 + \Delta \eta^2 < 0.1$, 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 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 $r_{\text{DV}}$ 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 $r_{\text{DV}}$ 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 $r_{\text{pixel}}$ of a pixel layer and increases again for $r_{DV} > r_{\text{pixel}}$.

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 $N_{\text{trk}}^{DV}$ 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 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 $W^- \rightarrow \mu^- \nu_{\mu}$ 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
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 $m_{PV} < 10$ GeV and reject vertices with $m_{DV}$ corresponding to $K^0_S$ or $Λ^0$ decays or to photon conversions, in order to increase the purity of material-interaction vertices with high position resolution. From MC, we determine $R_{int}(t_{DV})$, 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 $R_{int}(t_{DV})$ 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 $ρ$. From $ρ$, $R_{int}(t_{DV})$, and the number of $κ_{DV}^2 > 2$ 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 $p_T > 10$ GeV muon trigger. These events are required to satisfy all the selection criteria, except the muon-selection and $m_{DV} > 10$ GeV requirements. We denote with $N_{PV}$ the number of control-sample events containing a vertex that satisfies the $m_{PV} > 10$ GeV requirement. Then an estimate for the $m_{DV} > 10$ GeV background yield in the muon-trigger sample is

$$N_{bgd} = N_{PV} η_{PV} / η_{FAIL} = 0.003 ± 0.002$$

events, where $N_{FAIL} = 3 (N_{FAIL} = 4170)$ is the number of selected muon-trigger (control-sample) events with no vertices that pass the $m_{DV} > 10$ GeV requirement, and $N_{FAIL} = 2$. We perform variations of this estimate to account for some differences in the track-momentum spectrum and in $N_{DV}$ 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 $N_{bgd} < 0.03$ 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, as the conservatively estimated background yield is far less than one event.

The efficiency of the trigger used in this analysis has been studied using $Z^0 → μ^+μ^-$ events. Based on that study, we correct the MC-evaluated 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 $φ$ and 0.01 in $η$, and reject beam-produced muons by requiring $|d_0| > 2$ mm for both candidates. The difference $Δp_T$ 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 $Δp_T$ 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 reconstruction efficiency as a function of $|d_0|$, normalized to unity in the range $2 < |d_0| < 4$ mm.

![Fig. 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)
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 $\epsilon(r_{DV}, z_{DV})$.

A data-MC difference in the vertex-reconstruction efficiency 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 on signal efficiency, studied with the $\langle \mu \rangle = 5$ 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

Fig. 7 shows the distribution of $m_{DV}$ vs. $N_{trk}^{DV}$ for vertices in the selected data events, including vertices that fail the requirements on $m_{DV}$ and $N_{trk}^{DV}$, 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 $cT$, where $\tau$ is the neutralino lifetime.

The limits are determined in the following way. For each value of $cT$, 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 average signal-event yield for any value of $cT$, despite the fact that the signal MC is produced with a different lifetime, $cT_{MC}$. Integrating over the $r_{DV}$ vs. $z_{DV}$ 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 $cT$. 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 $C_L$ 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 Fig. 8, with the PROSPINO-calculated cross-sections for squark masses of 150 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 and 180 mm from the pp interaction 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.

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