



Letter

Search for massive, long-lived particles in events with displaced vertices and displaced muons in pp collisions at $\sqrt{s} = 13.6$ TeV with the ATLAS experiment

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ABSTRACT

A search is presented for massive long-lived particles in events featuring at least one displaced vertex and at least one displaced muon, using proton–proton collision data collected by the ATLAS detector at the Large Hadron Collider from 2022 to 2024 at a centre-of-mass energy of 13.6 TeV. The data sample corresponds to an integrated luminosity of 164 fb^{−1}. The analysis targets scenarios in which long-lived particles decay inside the ATLAS inner detector, resulting in a topology of at least one massive, displaced vertex (DV) with multiple associated tracks, and at least one muon with a large transverse impact parameter relative to the primary interaction point. The muon is not required to be associated with the DV. Two signal regions are defined by the transverse distance of the reconstructed DV from the interaction point. Background contributions are estimated by using fully data-driven techniques. No significant excess above the expected background is observed. Upper limits at 95% confidence level are set on the visible cross-section and on the production cross-sections of several benchmark models of R -parity-violating supersymmetry.

1. Introduction

The Standard Model (SM) of particle physics is a remarkably successful framework, yet it leaves several fundamental questions unanswered. It does not provide an explanation for the nature of dark matter, the observed matter–antimatter asymmetry in the Universe, or the origin of neutrino masses. These and other shortcomings strongly motivate the existence of beyond-Standard Model (BSM) physics. The Large Hadron Collider (LHC) [1] at CERN is a powerful tool to probe BSM scenarios through high-energy proton–proton (pp) collisions, enabling searches for new particles and interactions. While most BSM searches at the LHC have targeted promptly decaying particles, many extensions of the SM predict long-lived particles (LLPs) that travel measurable distances before decaying, giving rise to distinctive signatures such as a displaced vertex (DV) [2]. This Letter presents a search for LLPs using pp collision data in events with a DV and a displaced muon. BSM models resulting in DVs include various supersymmetry (SUSY) models addressing the hierarchy problem like minisplit SUSY [3,4], gauge-mediated SUSY breaking [5], R -parity-violating (RPV) SUSY [6–14], Stealth SUSY [15,16], and neutral naturalness [17–20], as well as hidden valley models [21,22] and others addressing dark matter [23–27] and the matter–antimatter asymmetry of the Universe [28–30]. Many

such models predict final states with displaced muons, which facilitate efficient triggering and provide powerful background suppression.

The results are presented with a model-independent interpretation on the visible cross-section for events with a DV and a displaced muon, and with interpretations in the context of SUSY models with RPV interactions. Under the RPV assumption, the lightest supersymmetric particle (LSP) is no longer stable and may decay into SM particles via lepton-number-violating (L -violating) or baryon-number-violating (B -violating) interactions. If the corresponding couplings are small, the decays can be significantly suppressed, leading to displaced signatures. Higgsinos and top squarks ($\tilde{t}$) are common candidates for an unstable LSP, usually produced in pairs at the LHC, and can decay into final states containing muons and quarks in various RPV scenarios. If the LSP is a higgsino, its RPV decay proceeds via a virtual sfermion mediator. If the sfermion mass is assumed to be much heavier than the higgsino mass, this leads to three-body decays in which the virtual sfermion is far off-shell and effectively decouples from the decay kinematics. In this regime, the higgsino lifetime depends only on the higgsino mass and the RPV coupling strength divided by the square of the mediator sfermion mass. If the LSP is the top squark, it decays directly into SM particles via the RPV coupling. This two-body decay results in a lifetime that depends on the top-squark mass and the RPV coupling strength.

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Both the ATLAS and CMS Collaborations have conducted searches for long-lived higgsinos and top squarks in RPV SUSY [31–37]. Using Run-1 data at $\sqrt{s} = 8$ TeV, ATLAS searched for higgsino-like neutralinos ($\tilde{\chi}_1^0$) produced via heavier squarks and decaying through $\tilde{\chi}_1^0 \rightarrow \mu^- u \bar{d}$ (and charge conjugate (c.c.)), excluding neutralino masses under this production assumption between 100 and 500 GeV for mean proper lifetimes, τ , between 3 ps and 10 ns [32]. Using Run-2 data at $\sqrt{s} = 13$ TeV, CMS searched for higgsino-like neutralinos with $\tilde{\chi}_1^0 \rightarrow t b s$ (and c.c.) decays in events with two DVs, excluding neutralino masses up to 1100 GeV for lifetimes between 2 ps and 230 ps [36]. For $\tilde{t}\bar{\tilde{t}}$ production, ATLAS placed limits on $\tilde{t} \rightarrow b \mu$ decays in topologies with a DV and a displaced muon track using Run-2 data at $\sqrt{s} = 13$ TeV [35]. Top-squark masses up to 1.7 TeV were excluded for $\tau = 0.1$ ns, and masses below 1.3 TeV were excluded for lifetimes between 0.01 ns and 30 ns. Most recently, CMS searched for $\tilde{t}\bar{\tilde{t}}$ production in RPV $\tilde{t} \rightarrow d \ell$ and $\tilde{t} \rightarrow b \ell$ decays, where ℓ denotes an electron or a muon, using Run-2 data at $\sqrt{s} = 13$ TeV [37]. This excluded top-squark masses between 100 GeV and at least 460 GeV for $0.3 \text{ ps} < \tau < 30 \text{ ns}$, with a maximum exclusion of 1500 GeV at $\tau = 70 \text{ ps}$.

Data from pp collisions at $\sqrt{s} = 13.6$ TeV collected by the ATLAS detector between 2022 and 2024 of the LHC Run 3 are used. The selected data sample corresponds to an integrated luminosity of 164 fb^{-1} [38]. Several techniques novel to Run 3 are employed, including a dedicated displaced-muon trigger [39] extending sensitivity to muon transverse momenta as low as 20 GeV, thereby improving the reach for lower-mass LLPs, and specialised tracking and vertexing algorithms [40] for reconstructing displaced decay signatures across a broad lifetime range. The background contributions are estimated by using fully data-driven techniques, and the results are extracted via a profile likelihood fit in a binned observable distribution that separates signal and background. The results are expressed as model-independent upper limits on the visible cross-section for processes yielding a DV and a displaced muon, and are further interpreted in three representative RPV SUSY scenarios involving higgsino pair production and $\tilde{t}\bar{\tilde{t}}$ production.

2. ATLAS detector

The ATLAS experiment [41,42] at the LHC is a multipurpose particle detector with a forward-backward symmetric cylindrical geometry and a near 4π coverage in solid angle.¹ It consists of an inner tracking detector (ID) surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic (EM) and hadronic calorimeters, and a muon spectrometer (MS). The ID covers the pseudorapidity range $|\eta| < 2.5$. It consists of silicon pixel, silicon microstrip (SCT), and transition radiation tracking (TRT) detectors. Lead/liquid-argon (LAr) sampling calorimeters provide EM energy measurements with high granularity within the region $|\eta| < 3.2$. A steel/scintillator-tile hadronic calorimeter covers the central pseudorapidity range ($|\eta| < 1.7$). The endcap and forward regions are instrumented with LAr calorimeters for EM and hadronic energy measurements up to $|\eta| = 4.9$. The MS surrounds the calorimeters and is based on three large superconducting air-core toroidal magnets with eight coils each. The field integral of the toroids ranges between 2.0 and 6.0 T m across most of the detector. The MS includes three precision layers, each consisting of layers of monitored drift tubes, covering the region $|\eta| < 2.7$, except in the innermost layer of the endcap region, where layers of small thin-gap and Micromegas chambers provide both precision tracking in the re-

gion $1.3 < |\eta| < 1.7$. The muon trigger system, covering $|\eta| < 2.4$, uses various detectors including resistive-plate chambers in the barrel region, thin-gap chambers in the endcaps, and small-strip thin-gap chambers together with Micromegas detectors in the innermost endcap layer. The luminosity is measured mainly by the LUCID-2 detector [43], which is located close to the beam pipe. A two-level trigger system was used to select events [39]. The first-level trigger is implemented in hardware and uses a subset of the detector information to accept events at a rate close to 100 kHz. This is followed by a software-based high level trigger (HLT) that reduces the accepted rate of complete events to 3 kHz on average, depending on the data-taking conditions. A software suite [44] is used in data simulation, in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment.

3. Samples of simulated events

Monte Carlo (MC) simulation samples are used to study the event selection acceptance and the reconstruction efficiency for benchmark signals. The effect of multiple interactions in the same and neighbouring bunch crossings (pile-up) is modelled by overlaying [45] the simulated hard-scattering event with inelastic pp events generated from a mix of EPOS 2.0.1.4 [46] and PYTHIA 8.308 [47,48]. The detector response to each simulated event was modelled using GEANT4 [49]. Correction factors are applied to account for differences between data and simulation in the pile-up, the trigger, reconstruction, and identification efficiencies of muons [39,50], and for the track reconstruction efficiency [40].

Samples of simulated long-lived higgsino pairs are used as benchmarks to set limits on the visible cross-section for higgsino pair production. The following production modes are considered: $\tilde{\chi}_1^0 \tilde{\chi}_2^0$, $\tilde{\chi}_1^0 \tilde{\chi}_1^\pm$, $\tilde{\chi}_2^0 \tilde{\chi}_1^\pm$, and $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$, where $\tilde{\chi}_1^0$ is the LSP, and $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm$ are the next-to-lightest neutralino and the lightest chargino, respectively. A nearly mass-degenerate spectrum is assumed, with mass splittings of 1 GeV between $\tilde{\chi}_1^0$ and $\tilde{\chi}_1^\pm$, and $\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0$ [51,52]. All other supersymmetric particles are assumed to be heavy and decoupled.

Two RPV decay scenarios are considered, where the higgsinos are assumed to decay through interactions that are either L -violating or B -violating [13]. These interactions arise from additional terms in the supersymmetric superpotential of the form $\lambda'_{ijk} L_i Q_j D_k^c$ and $\lambda''_{ijk} U_i^c D_j^c D_k^c$, where λ'_{ijk} and λ''_{ijk} are the coupling strengths and i, j , and k are generation indices. Here, L and Q denote the lepton and quark $SU(2)$ doublet superfields, while U^c and D^c are the up- and down-type quark $SU(2)$ singlet superfields. Under the decoupling assumption, the masses of the sfermions that mediate the higgsino decays are much larger than the higgsino masses. Thus, the higgsino decays are modelled as effective three-body decays via a contact interaction, with the higgsino mass and decay width treated as independent simulation parameters, without resolving the underlying dependence on the RPV coupling strength and mediator sfermion mass. The following two higgsino benchmark scenarios were simulated, both assuming that all other RPV terms are zero:

- L -violating: λ'_{211} , leading to decays $\tilde{\chi}_1^0, \tilde{\chi}_2^0 \rightarrow \mu^- u \bar{d}$ (+ c.c.), and $\tilde{\chi}_1^\pm \rightarrow \mu^\pm d \bar{d}$.
- B -violating: λ''_{323} , leading to decays $\tilde{\chi}_1^0, \tilde{\chi}_2^0 \rightarrow t s b$ (+ c.c.), and $\tilde{\chi}_1^\pm \rightarrow \bar{b} s \bar{b}$, $\tilde{\chi}_1^\mp \rightarrow b s b$. Sensitivity for this scenario depends on neutralino production and the subsequent semileptonic decay of the resulting top quark, leading to a lower muon multiplicity and reduced signal acceptance with respect to the L -violating benchmark.

The decay modes are illustrated in Fig. 1(a) and (b). The hard interaction was generated with up to two additional partons with the MADGRAPH5_AMC@NLO 3.5.7 [53] generator at leading order (LO) in perturbative quantum chromodynamics (QCD), using the NNPDF3.0NLO parton distribution function (PDF) set [54]. The parton shower and hadronisation were simulated with PYTHIA 8.308 using the A14 set of tuned parameters [55] and the NNPDF2.3LO PDF set [56]. The decays of

¹ ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (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 upwards. Polar coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z -axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln \tan(\theta/2)$ and is equal to the rapidity $y = \frac{1}{2} \ln \left(\frac{E+p_z}{E-p_z} \right)$ in the relativistic limit. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta y)^2 + (\Delta \phi)^2}$.

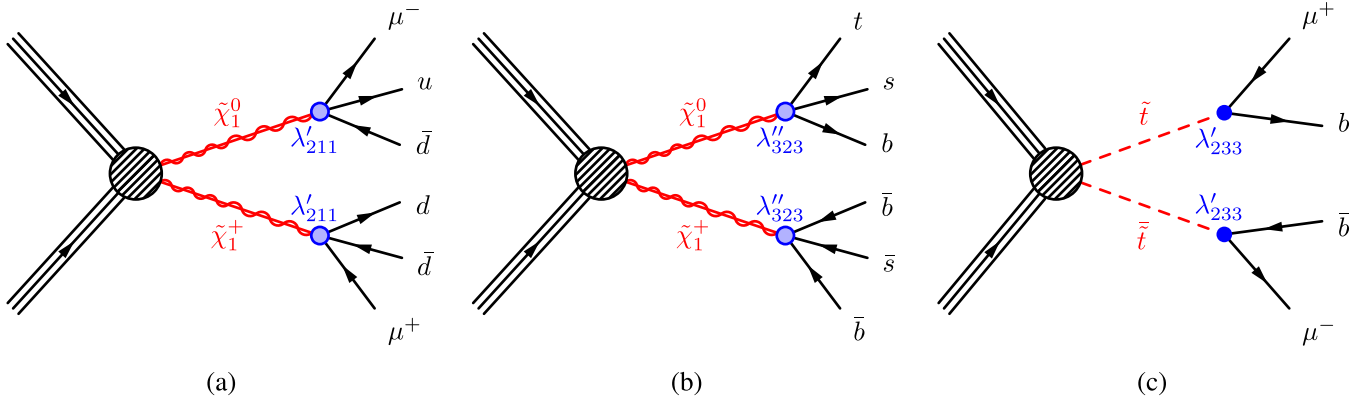


Fig. 1. Illustrative diagrams for the three considered R -parity-violating (RPV) SUSY simplified benchmark models, each assuming a single non-zero RPV term: (a) higgsino pair production with λ'_{211} decays, (b) higgsino production with λ''_{323} decays, and (c) top-squark-anti-squark pair production with λ'_{233} decays. Equivalent diagrams with charge-conjugate processes are also considered.

bottom and charm hadrons were simulated by EVTGEN 1.6.0 [57]. The L -violating (B -violating) decay mode was generated for higgsino lifetimes between 3 ps and 100 ns for a range of mass values of 100–1900 GeV (200–1500 GeV). The generated sets of events were scaled to cross-sections at approximate next-to-next-to-leading order (NNLO) accuracy in QCD with threshold resummation of the next-to-next-to-leading logarithms (NNLLs) [58], as computed with the RESUMMINO package [59,60]. The resulting production cross-sections decrease rapidly with increasing higgsino mass, from 19.5 pb at $m = 100$ GeV to $\mathcal{O}(10^{-2})$ fb at $m = 1900$ GeV, with scale uncertainties of a few percent and PDF uncertainties increasing from a few percent at low masses to $\mathcal{O}(50\text{--}100\%)$ at the largest masses considered. Interactions of charginos with the detector material were found to have a negligible impact on the signal yields and were not simulated in the MC samples.

Using the same MADGRAPH5_AMC@NLO+PYTHIA generator, $\tilde{t}\tilde{t}$ production samples were generated at LO QCD with up to two additional partons. The other top-squark mass eigenstate and all other supersymmetric particles are assumed to be heavy and decoupled. The squarks are assumed to decay exclusively via L -violating couplings to a muon and a b -quark, $\tilde{t} \rightarrow \mu b$, given by a non-zero λ'_{233} coupling term. The diagram for this process is illustrated in Fig. 1(c). Different samples were generated with $3\text{ ps} < \tau < 100\text{ ns}$ for a range of mass values between 700 GeV and 2100 GeV. The generated sets of events were scaled to cross-sections computed at approximate NNLO accuracy in QCD. The production cross-section decreases rapidly with increasing top-squark mass, from about 0.1 pb at $m_{\tilde{t}} = 700$ GeV to about 10^{-2} fb at $m_{\tilde{t}} = 2100$ GeV, with associated theoretical uncertainties increasing from roughly 6% to about 36%. Since the top squarks carry colour charge and all simulated proper lifetimes are far longer than the hadronisation timescale in QCD, they were hadronised in PYTHIA to form colour-singlet states with SM quarks, called R -hadrons. The top squarks primarily form meson-like states ($\tilde{t}q$), but approximately 10% of them form baryon-like states ($\tilde{t}qq$). About half of the R -hadrons carry non-zero electric charge. Interactions of the R -hadrons with the detector material were not simulated in the MC samples.

4. Reconstruction

Charged-particle trajectories (tracks) are reconstructed in two passes using *hits* (individual detector measurement points) found in the ID. The primary pass reconstructs tracks with transverse impact parameter (d_0) relative to the interaction point (IP) of $|d_0| < 5$ mm and a minimum transverse momentum (p_T) of 500 MeV [61]. A large-impact-parameter pass uses left-over hits from the primary pass to increase the acceptance up to $|d_0| < 300$ mm and a minimum p_T of 1 GeV [40]. All tracks are passed through an ambiguity resolution step to resolve overlaps and remove

fake tracks before being re-fit using a global χ^2 method [40]. The tracks from the silicon pixel and SCT sub-detectors may then be extended into the TRT [61]. The pp vertex with the highest sum of squared transverse momenta of associated tracks is taken as the primary interaction vertex (PV).

Muons are reconstructed using the standard ATLAS reconstruction suite [61] by combining both primary and large-impact-parameter ID tracks with track segments reconstructed in the MS within $|\eta| < 2.5$; the performance of this combined approach under the 2022 and 2023 Run 3 data-taking conditions was studied in a previous ATLAS analysis [62]. If an MS track segment is matched to both a primary and large-impact-parameter track, the combined track with the best combined fit quality for the given MS track is retained. If they have the same quality, the muon with the smallest $\Delta\eta$ between the MS and ID tracks is kept [61]. Muons must satisfy a modified version of the *Medium* identification criteria as defined in ref. [50], where the requirements on the number of pixel and SCT hits are omitted if reconstructed from large-impact-parameter tracks. Only muons with $p_T > 25$ GeV, $2\text{ mm} < |d_0| < 300$ mm, a transverse-displacement significance $|d_0|/\sigma_{d_0} > 150$, and a longitudinal displacement relative to the PV of $|z_0| < 500$ mm are considered.

To reconstruct the vertex of the LLP decay, primary and large-impact-parameter tracks are passed to a modified version of the DV reconstruction algorithm described in ref. [63]. The vertex reconstruction first forms two-track vertices from a set of *seed tracks*. These seed tracks are selected following the criteria in ref. [63], but with the requirement for at least one track in the seed pair to have $|d_0| > 2$ mm relaxed to $|d_0| > 1$ mm, improving efficiency for LLP decays whose decay products – particularly in models with short lifetimes – tend to point back towards the PV and have small $|d_0|$. Two-track vertices are combined to form multi-track vertices and tracks not initially preselected for vertex seeding are attached to compatible vertices.

Candidate DVs are required to be within the fiducial volume of the ID, with a transverse distance from the beamline of $R_{xy} < 300$ mm and a longitudinal position of $|z| < 300$ mm, but with a minimum transverse distance from the PV of $d_T(\text{PV}, \text{DV}) > 1$ mm. They are further required to fulfil a vertex quality requirement of $\chi^2_{\text{red}} < 5$, where ‘red’ in the subscript indicates division by the number of degrees of freedom of the vertex fit, to suppress vertices formed from random track crossings. Additional background rejection is achieved using two angular requirements that exploit the expected topology of displaced decays. These requirements suppress backgrounds in which tracks are misassociated with the DV or arise from random crossings or back-to-back configurations. First, a minimum azimuthal angle between the DV displacement vector and any of its associated tracks is required, $\cos_{\min} \phi(\text{DV}, \text{track}) > -0.995$, rejecting vertices containing tracks that point nearly opposite to the DV displacement direction. Second, among all tracks forming an acute

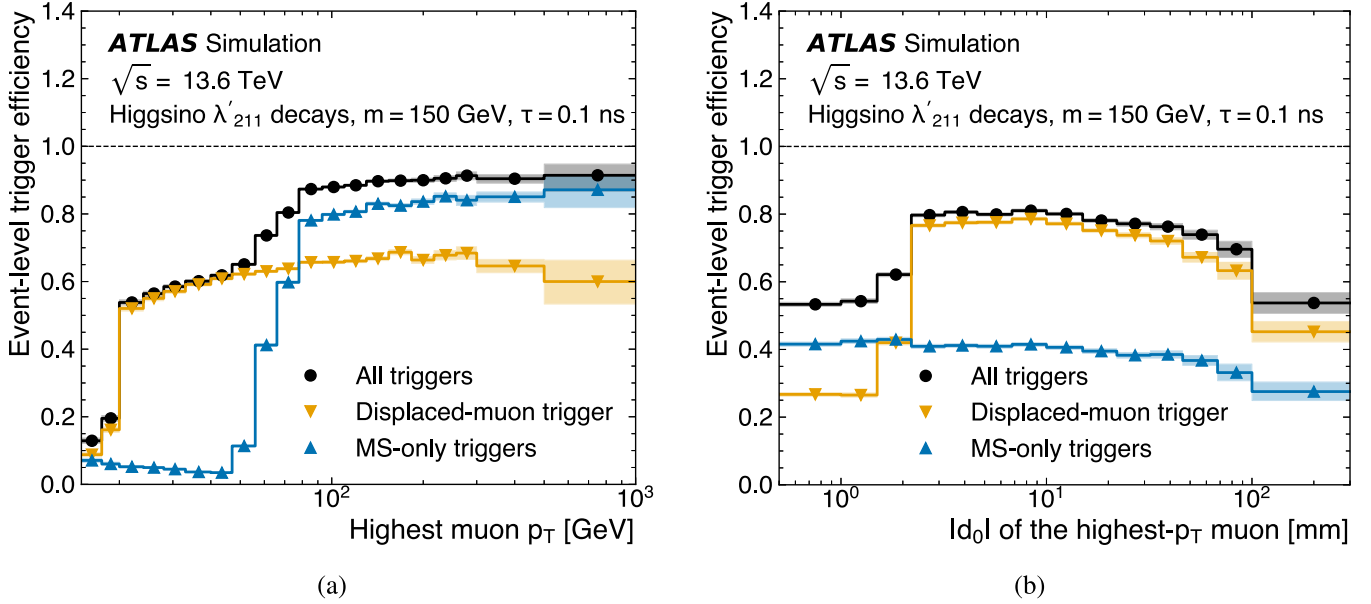


Fig. 2. Event-level trigger efficiency for the triggers used in this analysis. The plots show separate curves for the MS-only triggers and the displaced-muon trigger, which exploits the dedicated large-impact-parameter track reconstruction introduced in the HLT in Run 3, and their combination. The efficiencies are evaluated as a function of (a) the highest muon p_T in the event, and (b) the transverse impact parameter, $|d_0|$, of that muon. The benchmark sample used here consists of higgsino pair-production events with L -violating λ'_{211} decays ($m = 150$ GeV, $\tau = 0.1$ ns). For the MS-only triggers, the trigger plateau criteria are applied to the highest- p_T muon in the event (63 GeV for the $p_T > 60$ GeV, $|\eta| < 1.05$ trigger and 84 GeV for the $p_T > 80$ GeV, $|\eta| < 2.4$ trigger with additional requirement of three hits in precision tracking layers for $|\eta| > 1.05$). The muon p_T plot shows the combined trigger efficiency turn-on behaviour. The $|d_0|$ distribution reflects the $|d_0| > 2$ mm requirement of the displaced-muon trigger, with reduced efficiency at large $|d_0|$ due to the limited tracking efficiency for highly displaced muons.

angle with the DV displacement direction, at least one must have a sufficiently large angle, $\cos_{\min} \phi(\text{DV, acute-angle track}) < 0.97$. This requirement suppresses backgrounds where tracks are nearly collinear with the displacement direction, while retaining signal-like decays with a broader angular spread.

5. Event selection

Events are selected using two MS-only triggers and a novel displaced-muon trigger introduced in Run 3 [39]. The MS-only triggers accept events based on muon tracks reconstructed in the MS without requiring a matching ID track. The first MS-only trigger selects muon track segments with transverse momentum of $p_T > 60$ GeV for $|\eta| < 1.05$, while the second requires $p_T > 80$ GeV over the full pseudorapidity range in the muon trigger system of $|\eta| < 2.4$, with an additional requirement of three hits in precision tracking layers for $|\eta| > 1.05$. The displaced-muon trigger selects events containing at least one muon candidate reconstructed in the HLT with $p_T > 20$ GeV, $|\eta| < 2.4$, and $|d_0| > 2$ mm. It exploits the dedicated large-impact-parameter track reconstruction introduced in the HLT in Run 3, which is designed to suppress incorrectly reconstructed displaced tracks and enables lower p_T thresholds than in Run 2. Fig. 2 shows the trigger efficiency as a function of the highest muon p_T in the event and of its transverse impact parameter, $|d_0|$, evaluated using simulated higgsino pair-production events with L -violating λ'_{211} decays, $m = 150$ GeV and $\tau = 0.1$ ns. The combination of these triggers achieves high efficiency across a broad range of muon p_T and $|d_0|$ values.

Events selected in the analysis must contain at least one muon candidate that either is spatially matched to the HLT muon that fired the displaced-muon trigger, or has p_T at least 5% above the relevant MS-only trigger threshold (63 GeV and 84 GeV) to operate on the trigger-efficiency plateau [62].

If present, DVs are categorised as ‘far’ or ‘near’ by their transverse distance from the PV, $d_T(\text{PV, DV})$. Far DVs have $d_T(\text{PV, DV}) \geq 4$ mm and near DVs have $1 \text{ mm} < d_T(\text{PV, DV}) < 4$ mm. A DV is considered *signal-like*

if it has at least four associated tracks ($n_{\text{track}} \geq 4$) and if the invariant mass of all DV-associated tracks fulfils $m_{\text{DV}} \geq 20$ GeV for far DVs and $m_{\text{DV}} \geq 40$ GeV for near DVs. Signal-like DVs are also required to be outside the material layers defined by a map described in ref. [64] to veto potential hadronic interactions between particles and the detector material. This material-map veto removes 42% of the fiducial volume. The presence of far or near signal-like DVs is used to categorise events as detailed in Section 6.

Three primary muon background sources are considered: muons from heavy-flavour decays, cosmic-ray muons, and algorithmic fakes. Heavy-flavour backgrounds are suppressed by requiring candidates to satisfy the *Tight VarRad* isolation criteria described in ref. [50], hereafter referred to as the *heavy-flavour veto*. This requirement eliminates approximately 98.9% of heavy-flavour muons and provides an optimal balance between background rejection and signal efficiency. Cosmic-ray rejection is performed by requiring $|\eta_\mu + \eta_{\text{MS}}| > 0.014$ and $|\phi_\mu - \phi_{\text{MS}}| - \pi > 0.25$, where the μ (MS) subscripts refer to the reconstructed muon (MS track segment). This rejects muon candidates with an MS track segment on the opposite side of the detector. A geometric correction is applied so that the muon direction is expressed in the detector reference frame for comparison with the MS track segment. The η and ϕ requirements are optimised using a dedicated cosmic-ray data sample recorded in 2023. Additionally, a muon-material-map veto described in ref. [62] is applied to account for detector inefficiencies in regions where MS track segment reconstruction is not possible. The combined *cosmic-ray veto* achieves a rejection of approximately 97.5% for cosmic-ray muons. Algorithmic fakes – reconstructed muon candidates that do not originate from real muons – are suppressed by requiring a high-quality match between the ID and MS tracks: the combined fit must satisfy $\chi^2_{\text{red}} < 3$ and have at least three precision layer hits, achieving rejection rates of approximately 97.4% and 99.7% in the barrel and endcap regions, respectively. The combination of these matching requirements is referred to as the *algorithmic-fake veto*.

Events are considered to contain a signal-like muon if the muon with the highest p_T in the event passes the heavy-flavour, cosmic-ray, and

algorithmic-fake vetoes. No association between the signal-like muon and the DV is required to preserve model independence. Two signal regions, denoted SR_{far} and SR_{near} , are defined and correspond to events with a signal-like muon and at least one far or near signal-like DV, respectively. Only a single DV is required to retain sensitivity for long lifetimes, including cases where one decay occurs outside the ID, while preserving a model-independent interpretation. Events in which either the muon or the vertex is not signal-like are placed in validation regions for the background estimate.

6. Background estimate

Background contributions arise from events with displaced muons from heavy-flavour decays, cosmic rays, or algorithmic fakes, and from DVs produced by hadronic interactions or random crossings of tracks in the detector. These backgrounds are efficiently suppressed by the muon-veto requirements and by the requirements on m_{DV} and n_{track} in the signal regions. To predict the event yields from these sources in the signal regions, a fully data-driven transfer factor method is employed. In this approach, separate transfer factors are derived for each muon background source i . The muon-veto requirements and the DV selection criteria are used to define exclusive regions in data: region A, where both the muon-veto and DV selection are applied (the signal region); regions B_i and C, where exactly one criterion is inverted; and region D_i , where both criteria are inverted. Here, i denotes the specific muon background type. This corresponds to separate ABCD constructions for each background source, which share the same regions A and C, but have distinct regions B_i and D_i . The background estimate relies on the fact that the variables used to reject displaced muons from background sources are uncorrelated with the variables used to reject DVs from background. The event yields in region A for source i can then be estimated from the observed yields in region B_i and the ratio of yields in regions C and D_i , where region C is common to all background sources, via $N_{A,i} = N_{B_i} \cdot N_C / N_{D_i}$. The ratio $f_i = N_C / N_{D_i}$ is referred to as the TF for background source i . For background events, the probabilities to satisfy the DV and muon selection criteria were validated to be independent in data by confirming that the shapes of the muon observables are unchanged under varying DV selections. Any residual correlations are measured and treated as a systematic uncertainty in the background prediction, as described in Section 6.2.

Potential signal contamination in regions B_i , C, and D_i is evaluated using simulated signal samples. The expected signal yields are normalised to values consistent with existing exclusion limits [62]. Under

this assumption, the fraction of signal events entering these regions is found to be negligible compared to the background yields.

TFs are derived separately for each muon background source i , with algorithmic fakes further split into barrel and endcap categories with a transition at $|\eta| = 1.2$ to account for different fake rates in the two MS regions, yielding four muon background sources in total. Events are categorised based on the highest- p_T muon: if this muon fails exactly one of the three vetoes (heavy-flavour, cosmic-ray, or algorithmic-fake), it is considered to be of that background type and the event enters region B_i or D_i ; for algorithmic fakes, the $|\eta|$ of the muon is used to determine the barrel/endcap category. Regions A or C consist of events where the highest- p_T muon passes all vetoes. Events where the highest- p_T muon fails two or more vetoes are discarded. A schematic overview of the constructed regions is shown in Fig. 3.

For the DV selection criterion, events are assigned to categories following a fixed sequence: events with no reconstructed DV enter the zero-DV category; if a DV is present, those failing to meet the m_{DV} requirement are considered first, followed by those obtained by dropping the m_{DV} requirement and selecting $n_{\text{track}} < 4$, with far DVs given precedence over near ones at both steps; events with DVs rejected by the material-layer map, referred to as *material-map-vetoed* DVs, are further divided into those with $n_{\text{track}} \geq 4$ and $n_{\text{track}} < 4$.

While material-map-vetoed DVs originate from hadronic interactions and differ from signal-like DVs, the efficiency of the muon vetoes in these events is expected to be uncorrelated with whether a DV occurs in the detector material or in the fiducial volume. Consequently, events with material-map-vetoed DVs and those with no DVs are used to populate the regions C and D_i , providing high-statistics samples. These regions contain an admixture of the muon background sources, thus, the TFs are derived from subsets of these regions, with additional muon requirements to enhance the purity for specific backgrounds, as detailed in Section 6.1. The remaining DV categories are used to define validation regions and the signal regions SR_{far} and SR_{near} . The total predicted background yield in SR_{far} (SR_{near}) is obtained as $N_A^{\text{pred}} = \sum_{i=1}^4 f_i N_{B_{\text{far},i}}$ ($N_{B_{\text{near},i}}$), where the sum runs over the four muon background sources i . To obtain a prediction in SR_{far} and SR_{near} for a binned observable, the TFs are multiplied by the corresponding binned yields in $B_{\text{far},i}$ and $B_{\text{near},i}$, respectively.

6.1. Transfer-factor derivation

Zero-DV events and those with material-map-vetoed DVs are highly enriched in background muons, but the TF derivation requires sets of events dominated by a single source of muon background. Thus, addi-

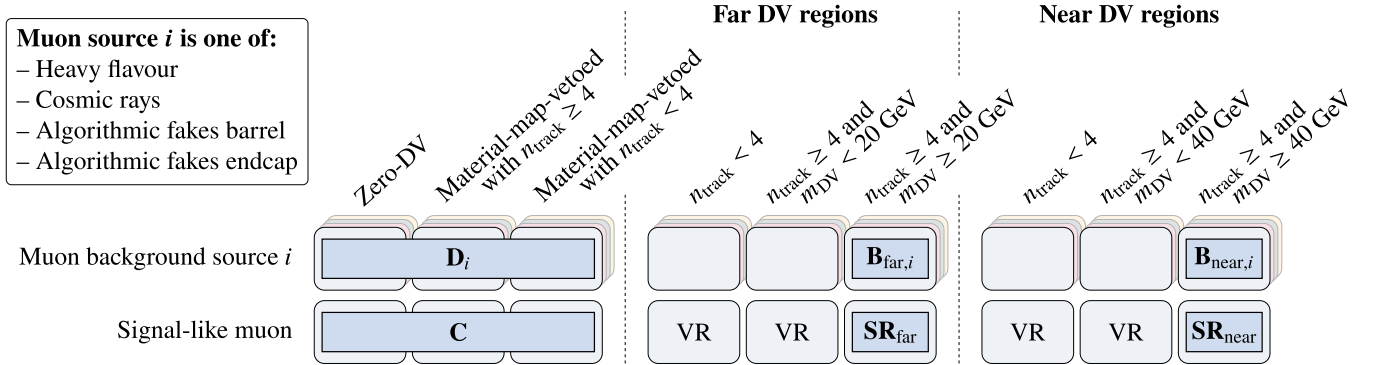


Fig. 3. Categorisation of events based on the presence and quality of displaced vertices (DV) (horizontal axis) and the background source i of the highest- p_T muon (vertical axis). The schematic is compressed vertically for simplicity. If a muon fails the veto for a specific muon background source, it is assigned that background category; if it passes all muon requirements, it is considered signal-like. The signal regions, SR_{far} and SR_{near} , require at least one signal-like muon and at least one signal-like far or near DV, respectively. Additional validation regions are defined by dropping or inverting the n_{track} and m_{DV} requirements for signal-like DVs. The regions C and D_i consist of the zero-DV and material-map-vetoed DV classes; the transfer factors (TFs) are derived from subsets of these regions by applying additional muon selections to enhance the purity for each source. The background predictions for SR_{far} and SR_{near} are then obtained by applying the TFs to the $B_{\text{far},i}$ and $B_{\text{near},i}$ regions, respectively.

tional muon selection criteria are applied to the highest- p_T muon in the event when defining regions C and D_i for the TF calculation:

1. Muons from heavy-flavour decays dominate at small displacement, so a requirement of $|d_0(\mu)| < 3$ mm is imposed when deriving the heavy-flavour TF; for the other three background TFs, $|d_0(\mu)| > 15$ mm is required to remove heavy-flavour contributions. These requirements are applied in addition to the overall muon selection criterion of $2 \text{ mm} < |d_0(\mu)| < 300$ mm.
2. Cosmic-ray muons predominantly occur in the central detector and enter from one side in azimuth; therefore, $|\eta| < 1.05$ and $\phi < 0$ are required to isolate a pure sample for the cosmic-ray TF derivation.
3. Muons from algorithmic fakes are treated separately in the barrel ($|\eta| \leq 1.2$) and endcap ($|\eta| > 1.2$) regions; to avoid cosmic-ray contamination, an additional $\phi > 0$ requirement is applied for the barrel.

The derived TFs are of the order of $\mathcal{O}(10^{-2})$, reflecting the strong suppression of the background muon sources by the muon-veto requirements. Statistical uncertainties from the finite event yields in the TF derivation regions range between 2% and 6%.

6.2. Systematic uncertainties in the transfer factors

Multiple uncertainties are assigned to the TFs to account for potential residual correlations in the probabilities for background events to satisfy the muon and DV selection criteria, for residual correlations between the TFs and the muon properties, and for possible contamination of the TF derivation regions by other muon background sources.

Potential residual correlations between the DV and muon selection criteria are assessed by recomputing the TFs individually for zero-DV events and for events with DVs rejected by the material-map veto. As the latter are enriched in background DVs from hadronic interactions with detector material, comparing these TFs provides a test of whether the probabilities to satisfy the muon and DV selection criteria are independent for background events. The largest relative difference between the nominal and recomputed TFs is assigned as a systematic uncertainty for each muon background class. These uncertainties range between 8% and 35% and are largest for the heavy-flavour and the algorithmic fake barrel TFs.

To account for residual dependencies of the TF values on the muon $|d_0|$, the chosen $|d_0|$ ranges are split into two subregions at midpoint values that balance the statistical uncertainties on either side. The TFs are recomputed independently in these subregions and compared with the nominal values. This comparison provides a check for unmodelled $|d_0|$ dependencies given the available data, without attempting to model a detailed functional dependence. The largest relative differences between the nominal and recomputed TFs are assigned as a systematic uncertainty for each background class. The computed midpoints are $|d_0| = 2.3$ mm for muons from heavy-flavour decays, $|d_0| = 85$ mm for cosmic-ray muons, $|d_0| = 130$ mm for algorithmic fakes in the barrel, and $|d_0| = 102.5$ mm for algorithmic fakes in the endcap. The d_0 uncertainties range between 3% for cosmic-ray muons and 21% for algorithmic fakes in the endcap.

Additional sources of systematic uncertainty are considered for the cosmic-ray, algorithmic-fake barrel and algorithmic-fake endcap TFs to account for residual dependencies of the TF values on the muon η and ϕ coordinates, and for possible contamination of the TF derivation regions by other muon background sources. For all three TFs, the ϕ regions are split in half to compute separate TFs, and the largest relative differences between the original and recomputed TFs are taken as systematic uncertainties. For the cosmic-ray and algorithmic-fake barrel TFs, the midpoint is picked so that the statistical uncertainty is minimal on either side, while for the algorithmic-fake endcap TF, a split at $\phi = 0$ is used to account for possible residual cosmic-ray contamination in the negative- ϕ region. The cosmic-ray and algorithmic-fake barrel ϕ uncertainties amount to approximately 4%, while the algorithmic-fake endcap

Table 1

Predicted background event yields and expected signal yields for three representative benchmark models in the two signal regions. The background uncertainties include the statistical and systematic uncertainties in the transfer factors (TFs), and statistical uncertainties reflecting the finite event yields in the regions to which the TFs are applied. An additional uncertainty is included for the heavy-flavour background in SR_{far} , derived from an observed discrepancy between predicted and observed event yields in the $m_{\text{DV}} < 20$ GeV validation region (see Section 6.3).

Process	SR_{far}	SR_{near}
Heavy flavour	1.2 ± 1.0	2.3 ± 0.8
Cosmic rays	0.18 ± 0.10	0.23 ± 0.13
Algorithmic fakes barrel	0.31 ± 0.15	0.31 ± 0.15
Algorithmic fakes endcap	0.11 ± 0.06	0.06 ± 0.04
Total background	1.8 ± 1.1	2.9 ± 0.8
Higgsino, λ'_{211} decays, $m = 1500$ GeV		
$\tau = 1$ ns	3.4 ± 0.5	0.153 ± 0.027
$\tau = 0.1$ ns	4.5 ± 0.7	0.66 ± 0.06
$\tau = 0.01$ ns	0.55 ± 0.17	0.64 ± 0.15

ϕ uncertainty is as high as 49%. For the cosmic-ray TF, an additional midpoint split in $|\eta|$ that minimises the statistical uncertainties on either side is performed, yielding an additional $|\eta|$ uncertainty of 42%.

Table 1 lists the predicted event yields for each background category in SR_{far} and SR_{near} , including all uncertainties in the TFs. In both regions, muons from heavy-flavour decays dominate the background estimate.

6.3. Validation

The TFs are validated in the zero-DV and material-map-vetoed DV selections, but without applying the restrictive muon selection criteria used for the TF derivation in Section 6.1. This provides a direct check that these criteria do not bias the TFs, and that the systematic uncertainties cover potential residual correlations between the muon-veto requirements and the DV selection criteria, and residual background contamination of the TF derivation regions. Good agreement is observed, with all data yields within 1σ uncertainty of the predictions, demonstrating the robustness of the background estimate. The agreement between predicted and observed event yields in these validation regions is shown in Fig. 4.

Further validation is performed by applying the TFs to the other validation regions outlined in Fig. 3, namely events with DVs that fail to meet one or multiple signal DV criteria: events with a far DV with $n_{\text{track}} < 4$, events with a far DV with $m_{\text{DV}} < 20$ GeV, events with a near DV with $n_{\text{track}} < 4$, and events with a near DV with $m_{\text{DV}} < 40$ GeV. Good agreement is observed for all but the far $m_{\text{DV}} < 20$ GeV region: while the TF method predicts 16 ± 4 events, only six are observed. Although no physical source for a systematic bias was identified, as supported by the good agreement observed in the corresponding near DV region with $m_{\text{DV}} < 40$ GeV, a conservative approach is adopted and a non-closure uncertainty is derived for the heavy-flavour background, which dominates this selection. This uncertainty of approximately 77% is then applied to the heavy-flavour estimate in this region and propagated to SR_{far} . Fig. 4 also shows the agreement between predicted and observed event yields in these validation regions, with the non-closure uncertainty included where applicable. Fig. 5 shows the distributions of the predicted background yields and the observed data for events with a far DV with $n_{\text{track}} < 4$ and a near DV with $n_{\text{track}} < 4$ as a function of the $|d_0|$ of the highest- p_T muon and the p_T of the highest- p_T muon, respectively.

7. Signal systematic uncertainties

Several sources of systematic uncertainty are evaluated for the predicted yields from the signal benchmark models. These include modelling and instrumental uncertainties, affecting both overall event yields

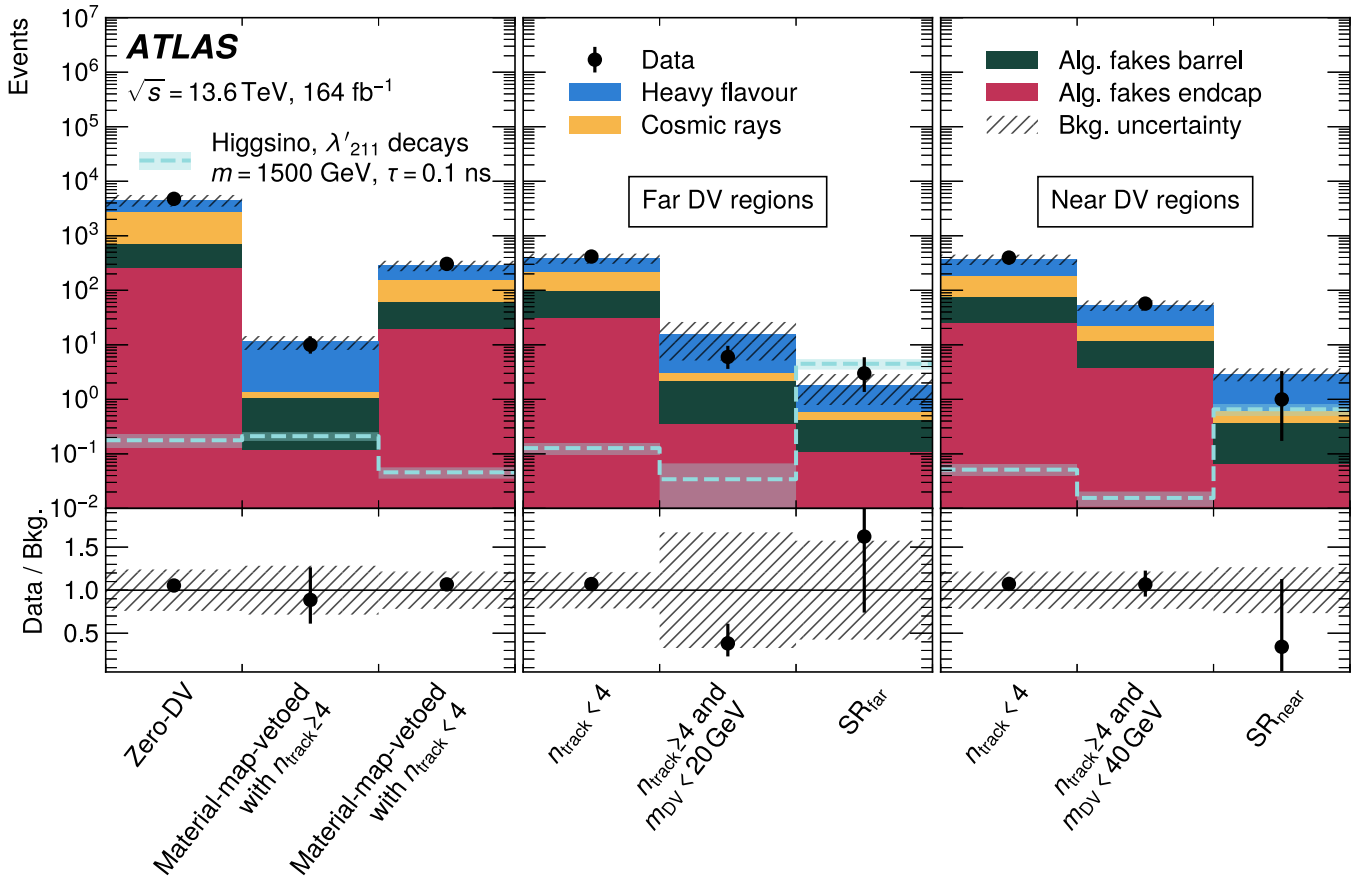


Fig. 4. Overview of the analysis regions with varying displaced vertex (DV) selection criteria. The predicted background yields are obtained via the transfer factor method from the zero-DV and material-map-vetoed DV selections, with additional muon selection criteria to enhance the purity for each background. Good agreement is observed in all validation regions, except the far $n_{\text{track}} \geq 4, m_{\text{DV}} < 20 \text{ GeV}$ region. An additional non-closure uncertainty is applied to the heavy-flavour estimate in that region and in SR_{far} . The hatched band represents the total uncertainty in the prediction. The predictions are overlaid with one representative higgsino pair production benchmark model, with $m = 1500 \text{ GeV}$ and $\tau = 0.1 \text{ ns}$, and lepton-number-violating decays via the λ'_{211} coupling. The uncertainty in the signal prediction includes statistical and systematic uncertainties.

and shapes of distributions used in the statistical analysis described in Section 8. Summing all individual contributions in quadrature, the average total systematic uncertainty in the signal selection efficiency is 24% and 20% for SR_{near} and SR_{far} , respectively.

For all considered signal modelling uncertainties, differences between the overall signal normalisation are removed, such that the quoted uncertainties reflect only acceptance effects. Uncertainties from missing higher orders in QCD in the simulation are evaluated by varying the renormalisation and factorisation scale by factors 0.5 and 2. The variations are done both simultaneously and independently, and the largest deviation from the nominal prediction in each direction is taken as the uncertainty. The average variation over the considered signal samples is 3% for SR_{near} and 2% for SR_{far} . The maximal variations are 13% and 9%, respectively. Uncertainties owing to the choice of the PDF set are evaluated following ref. [65] by reweighting the simulated events to the 100 replica sets of the NNPDF PDF set and taking the standard deviation of the resulting event yields as the uncertainty. The average effect on the signal predictions is observed to be 3% and 5% in SR_{near} and SR_{far} , respectively.

The uncertainty in the efficiency for the reconstruction of primary and large-impact-parameter tracks is derived and propagated to the vertexing efficiency, following the methods described in ref. [66]. The average effect on the event yields for the different benchmark models is around 2% and 3% in SR_{near} and SR_{far} , respectively.

Uncertainties in the muon reconstruction, isolation and identification efficiencies are computed following the method described in ref. [50]; additional uncertainties in the background veto efficiencies

are evaluated. A dedicated efficiency correction is applied for the identification of displaced muons. Uncertainties are derived combining two terms: one associated with the reconstruction of the ID track, and one associated with the reconstruction in the MS segments. Overall, these correspond to a signal uncertainty between 0.1% and 2%. Uncertainties in the simulation-to-data trigger scale factors are considered for standard prompt muons, and the impact varies between 0.2% and 8%; an additional 3% uncertainty accounts for the displaced-muon trigger efficiency, computed by comparing the trigger tracking efficiency relative to offline tracks in data and MC simulation, as done in ref. [39].

The uncertainty associated with the pile-up reweighting procedure [67], averaged over the signal simulations considered, is 3% and 2% for SR_{near} and SR_{far} , respectively.

Furthermore, the expected number of signal events depends on the total integrated luminosity of the data sample. The combined integrated 2022–2024 luminosity has an uncertainty of 1.9%, determined using the LUCID-2 detector [43], which provides the primary luminosity measurement, complemented by measurements using the ID and the calorimeters.

8. Results

Three events are observed in SR_{far} and one event is observed in SR_{near} , fully consistent with the combined background predictions, as summarised in Table 2.

A statistical analysis is performed to derive upper limits on the visible cross-section of final states with DVs and displaced muons, and to

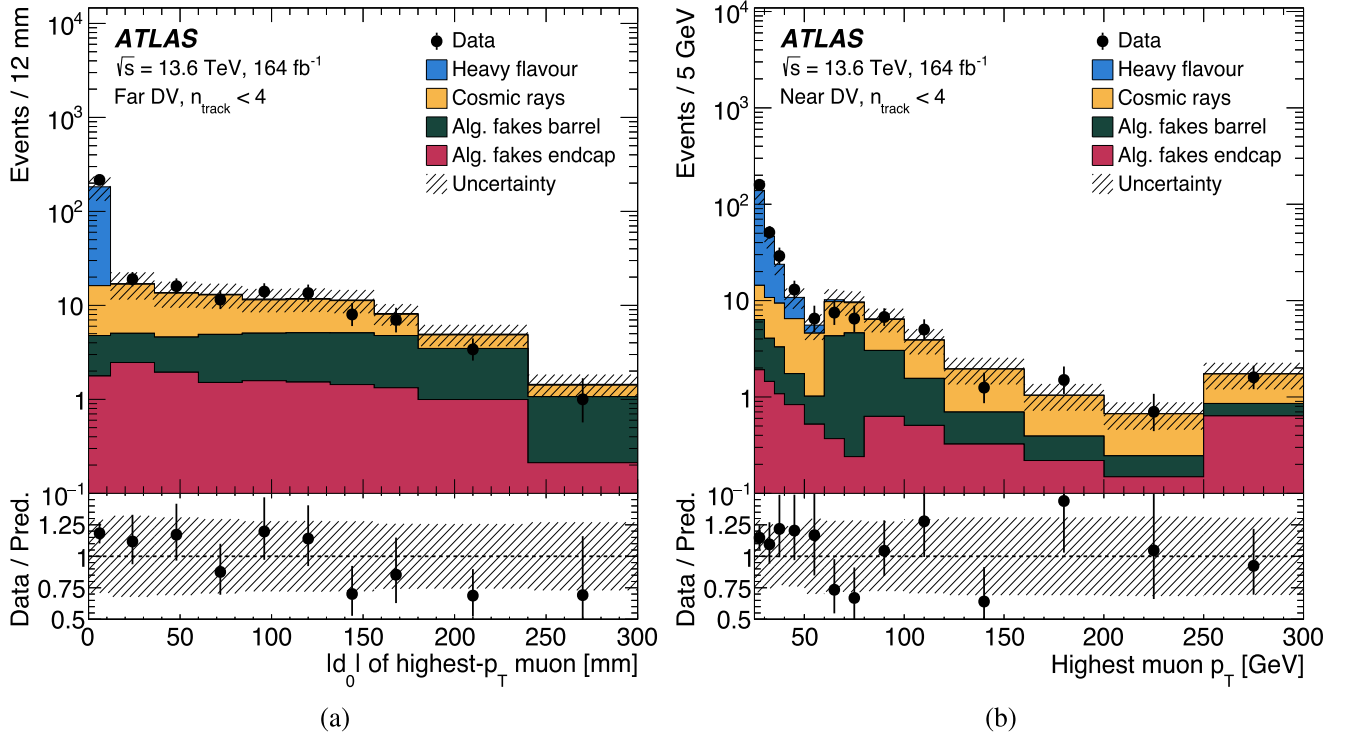


Fig. 5. Distributions of the predicted background yields and the observed data for events with (a) a far displaced vertex (DV) with a transverse distance from the primary vertex larger than 4 mm and $n_{\text{track}} < 4$ as a function of the $|d_0|$ of the highest- p_T muon, and (b) a near DV with a transverse distance from the primary vertex between 1 mm and 4 mm and $n_{\text{track}} < 4$ as a function of the p_T of the highest- p_T muon. The hatched band represents the total uncertainty in the prediction. Overflow events are included in the last bins. Good agreement is observed in both regions.

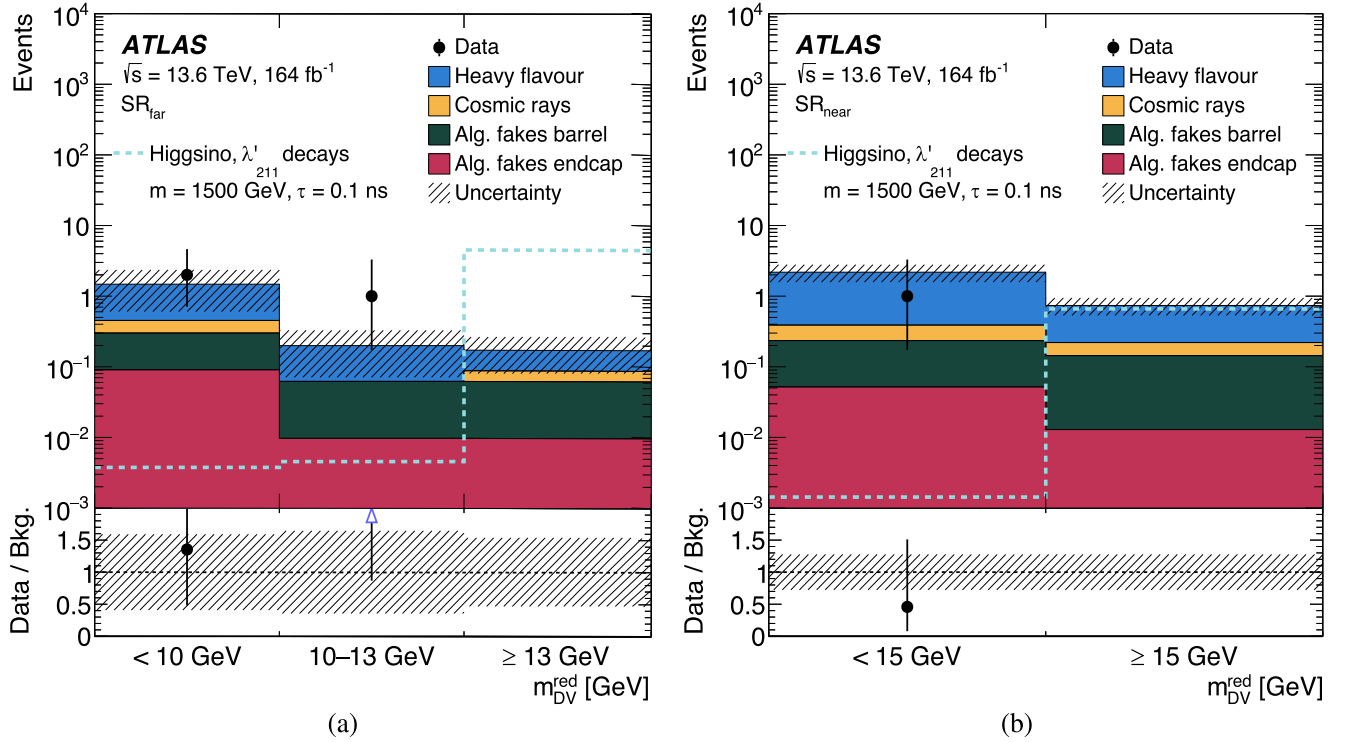


Fig. 6. Distributions of the largest reduced invariant mass of any displaced vertex, $m_{\text{DV}}^{\text{red}}$, in the two signal regions: (a) SR_{far} and (b) SR_{near} . In both signal regions, no events are observed in data in the two highest $m_{\text{DV}}^{\text{red}}$ bins. The background predictions derived using the data-driven transfer factor method are shown, along with an example signal benchmark (higgsino pair production with λ'_{211} decays, $m = 1500$ GeV and $\tau = 0.1$ ns) overlaid for illustration. The lower panels show the ratio of observed data to the total background prediction.

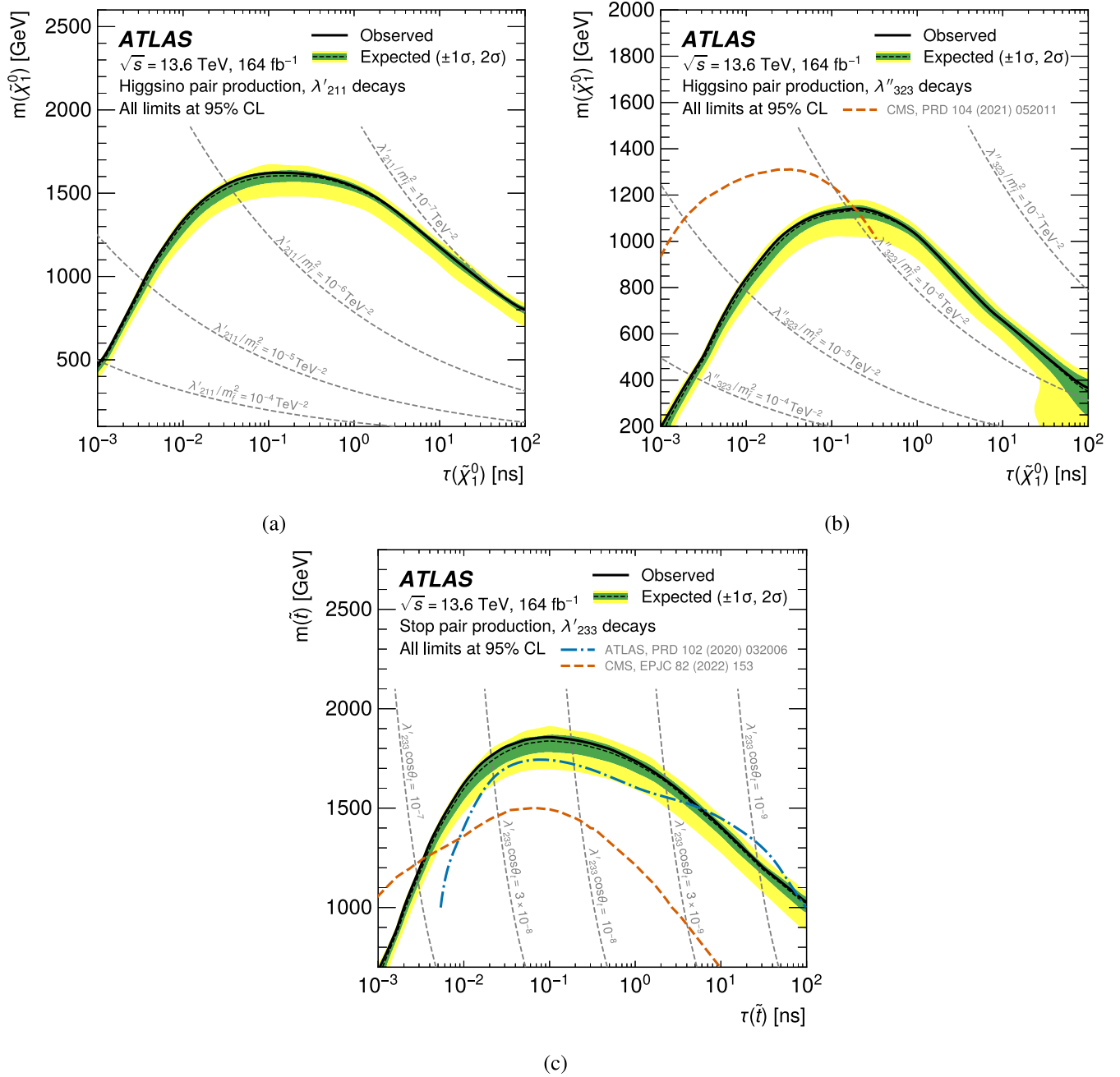


Fig. 7. Expected and observed exclusion contours at 95% confidence level in the plane of the long-lived particle's mass and proper lifetime, for the three considered benchmark models: higgsino pair production with (a) L -violating λ'_{211} and (b) B -violating λ''_{323} decays, and (c) $t\bar{t}$ pair production with L -violating λ'_{233} decays. A triangular interpolation scheme between simulated and lifetime-reweighted points is used to obtain a smooth contour. The triangulation is done linearly in mass, and logarithmically in lifetime and signal strength. Additional smoothing using a Gaussian kernel is applied to the observed limit contour to reduce artifacts from the interpolation. The contours are overlaid with isocontours of the R -parity-violating (RPV) SUSY coupling strength. In the top-squark model, these isocontours correspond to the coupling strength $\lambda'_{233} \cos \theta_i$, where θ_i is the mixing angle between left- and right-handed top squarks. In the higgsino models, the values are given for the coupling strengths λ/m_f^2 , where m_f is the mass of the virtual sfermion mediating the RPV decay (with the assumption that $m_f \gg m_{\tilde{\chi}_1^0}$). The contours in (b) and (c) are overlaid with results from previous searches for similar models [35–37].

interpret the results in terms of upper limits on the production cross-sections of the benchmark models described in Section 3. The reduced invariant mass of the DV, $m_{\text{DV}}^{\text{red}} = m_{\text{DV}}/\Delta R_{\text{max}}$, where ΔR_{max} is the largest angular separation between any pair of DV-associated tracks, is used as the fitting observable. The average angular separation is typically smaller for signal than for background events, providing additional discrimination over m_{DV} alone. In events with more than one signal-like DV, only the vertex with the highest $m_{\text{DV}}^{\text{red}}$ value is considered. The best sensitivity to a broad range of signal benchmark models is achieved with

three bins in SR_{far} , with boundaries at $m_{\text{DV}}^{\text{red}} = 10$ GeV and $m_{\text{DV}}^{\text{red}} = 13$ GeV, and two bins in SR_{near} , with a boundary at $m_{\text{DV}}^{\text{red}} = 15$ GeV. The $m_{\text{DV}}^{\text{red}}$ distributions with this binning in the two signal regions are shown in Fig. 6, overlaid with one example signal benchmark.

The limit extraction is done with the profile likelihood method as implemented in the ROOFIT, HISTFACTORY and TREXFITTER frameworks [68–71]. The signal strength serves as the parameter of interest, while nuisance parameters account for systematic uncertainties in the signal and background predictions and are constrained by Gaussian

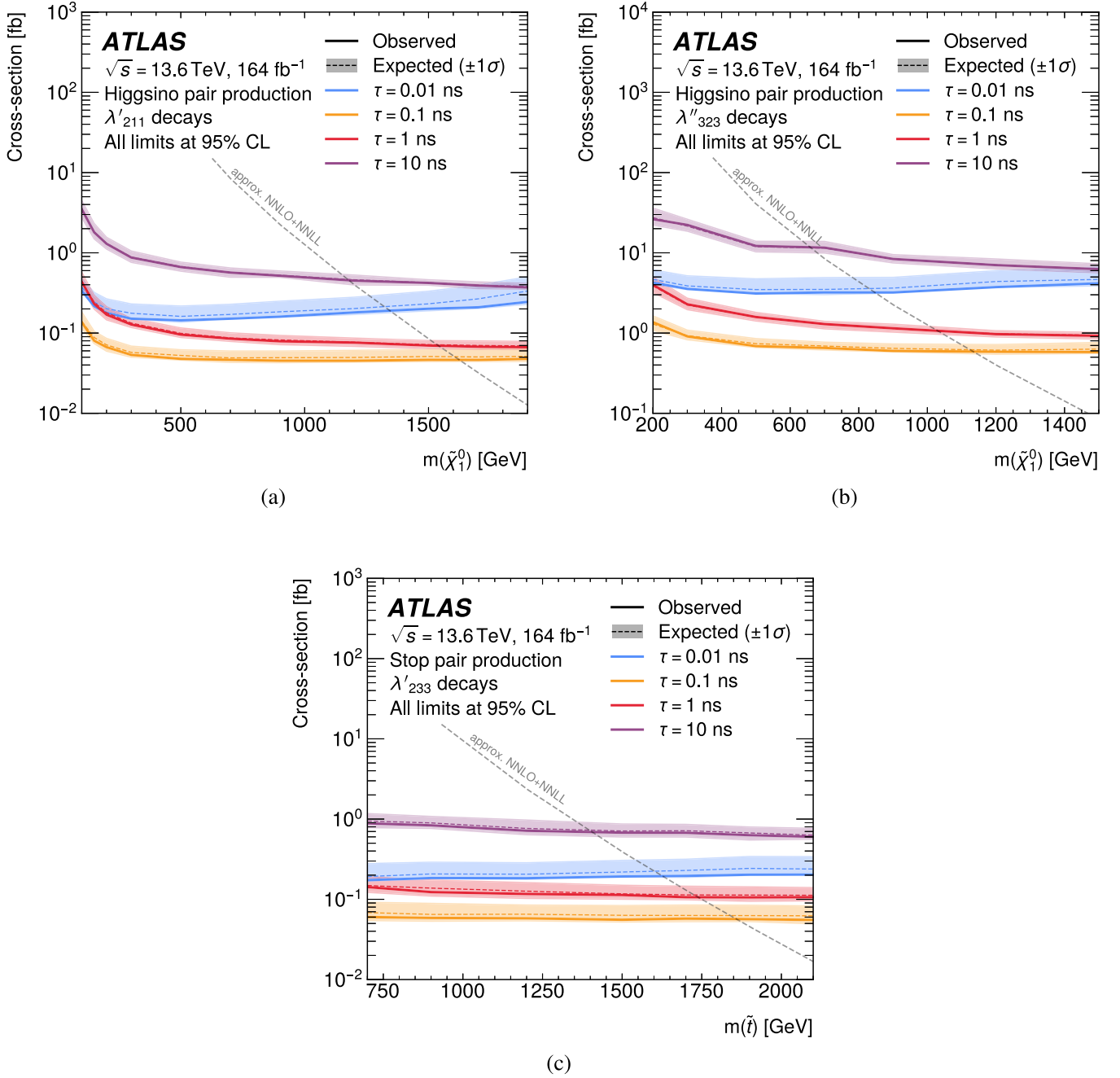


Fig. 8. Expected and observed 95% confidence level upper limits on the production cross-section for four representative lifetime values, shown as a function of the long-lived particle mass in the higgsino pair production benchmark model with decays via (a) the λ'_{211} coupling and (b) the λ'_{323} coupling, and (c) the top-squark mass in the top-squark model with decays via the λ'_{233} coupling. The expected limits are shown with their one standard deviation uncertainty bands. The plots are overlaid with the approximate NNLO + NNLL cross-section curves for higgsino and top-squark pair production [58–60]. Good sensitivity is achieved across the entire mass ranges, with the best sensitivity for lifetimes of 0.1 ns.

priors. The likelihood combines Poisson terms for the event yields in the signal regions and in the regions used to derive the background estimates, to which the TFs are applied. The sensitivity of the analysis is primarily limited by the available data statistics, with systematic uncertainties having a subdominant impact. Consequently, any potential residual mismodelling effects between data and simulation for these exotic signatures have a very limited influence on the final results. Upper limits at 95% confidence level (CL) are derived using the CL_s method [72,73], profiling the nuisance parameters to obtain limits on the signal strength. For the RPV interpretations, the likelihood fit incorporates the binned

distributions of the discriminating variable, $m_{\text{DV}}^{\text{red}}$, to enhance sensitivity across the benchmark models.

Model-independent 95% CL upper limits on the visible cross-section, $\langle \sigma A \epsilon \rangle$, for final states containing at least one DV and at least one displaced muon are obtained from counting experiments performed separately in SR_{far} and SR_{near} . In each region, progressively tighter selections are formed by increasing the minimum $m_{\text{DV}}^{\text{red}}$ threshold through the exclusion of one bin at a time. Limits are derived from ensembles of pseudo-experiments using the CL_s method. Table 2 summarises the total background predictions, observed yields, and the resulting $\langle \sigma A \epsilon \rangle_{\text{obs}}^{95}$

Table 2

Model-independent upper limits at 95% confidence level on the visible cross-section, $\langle\sigma A\epsilon\rangle_{\text{obs}}^{95}$, in the two signal regions. The limits are derived using the CL_s method [72,73] and include the effect of systematic uncertainties as nuisance parameters in the statistical analysis. The limits are given for three different minimum requirements on the reduced invariant mass of the displaced vertex, $m_{\text{DV}}^{\text{red}}$, in SR_{far} and two different minimum requirements in SR_{near} . *Total predicted* lists the total background prediction in each selection, with uncertainties including both statistical and systematic components. *Observed* lists the number of events observed in data for each selection. The $\langle\sigma A\epsilon\rangle_{\text{obs}}^{95}$ column lists the observed upper limits on the visible cross-section; the S_{obs}^{95} and S_{exp}^{95} columns list the observed and expected upper limits on the number of signal events, respectively.

	Total predicted	Observed	$\langle\sigma A\epsilon\rangle_{\text{obs}}^{95}$ [fb]	S_{obs}^{95}	S_{exp}^{95}
$\text{SR}_{\text{far}}, m_{\text{DV}}^{\text{red}} \text{ inclusive}$	1.8 ± 1.1	3	0.038	6.2	4.9
$\text{SR}_{\text{far}}, m_{\text{DV}}^{\text{red}} \geq 10 \text{ GeV}$	0.37 ± 0.20	1	0.023	3.8	3.1
$\text{SR}_{\text{far}}, m_{\text{DV}}^{\text{red}} \geq 13 \text{ GeV}$	0.17 ± 0.09	0	0.018	3.0	3.0
$\text{SR}_{\text{near}}, m_{\text{DV}}^{\text{red}} \text{ inclusive}$	2.9 ± 0.8	1	0.021	3.5	4.7
$\text{SR}_{\text{near}}, m_{\text{DV}}^{\text{red}} \geq 15 \text{ GeV}$	0.73 ± 0.20	0	0.018	3.0	3.0

for each selection, and the corresponding observed and expected upper limits on the number of signal events. The most stringent cross-section limits are obtained when only the highest- $m_{\text{DV}}^{\text{red}}$ bin of SR_{far} or SR_{near} is considered. The limits on the visible cross-section are of the same order of magnitude as those obtained in the ATLAS Run-2 search for DVs and displaced muon tracks [35], but derived in a different fiducial volume.

Model-dependent 95% CL upper limits on the production cross-sections of the benchmark models described in Section 3 are obtained from ensembles of pseudo-experiments following a simultaneous fit to SR_{far} and SR_{near} , using a one-sided profile-likelihood ratio test statistic [74] within the CL_s framework. The signal acceptance times efficiency ($A \times \epsilon$) reaches peak values of approximately 38% (31%) for the L -violating higgsino (top-squark) model for a proper lifetime of 0.1 ns, while being about one order of magnitude lower for the B -violating higgsino model where muons only arise from top-quark decays. Fig. 7 shows the expected and observed exclusion contours in the plane of the LLP mass and proper lifetime for the three considered benchmark models: higgsino pair production with (a) L -violating λ'_{211} and (b) B -violating λ''_{323} couplings, and (c) $t\bar{t}$ production with L -violating λ'_{233} couplings. The contours are overlaid with isocontours of the RPV SUSY coupling strength for each model. For the top-squark model, these isocontours correspond to the coupling strength $\lambda'_{233} \cos \theta_t$, where θ_t is the mixing angle between left- and right-handed top squarks, calculated following the expression provided in ref. [75]. In the higgsino models, the values are given for the coupling strengths $\lambda/m_{\tilde{f}}^2$, where $m_{\tilde{f}}$ is the mass of the virtual sfermion mediating the RPV decay, following the parameterisation in ref. [76]. Upper limits on the production cross-sections are also derived for four representative lifetime values, shown as a function of the LLP mass in Fig. 8.

Limits on higgsino masses up to 1600 GeV (1150 GeV) are placed for proper lifetimes of 0.1 ns for λ'_{211} (λ''_{323}) decays, and higgsino masses between 100 GeV and at least 450 GeV are excluded for proper lifetimes between 1 ps and 100 ns for λ'_{211} decays. Compared with the λ'_{211} limits set by the ATLAS Run-1 search for higgsino-like neutralinos [32], the reach is significantly extended in both mass and proper lifetime while placing fewer assumptions on the production mechanism. On average, the limits on the production cross-sections for higgsino-like neutralinos with λ'_{211} decays are improved by approximately two orders of magnitude. For λ''_{323} decays, the proper lifetime reach is extended up to 100 ns, providing complementary coverage to the CMS Run-2 search for hadronic DV pairs [36]. Optimised for vertex pairs within the beam pipe radius of 22 mm, the CMS search sets tighter limits at proper lifetimes below 0.1 ns, whereas this result provides unique sensitivity at larger displacements.

Top-squark masses of up to 1850 GeV are excluded for proper lifetimes of 0.1 ns, and any values between 700 GeV and 1500 GeV are ex-

cluded for proper lifetimes between 10 ps and 5 ns. This improves upon the limits set by the previous ATLAS search for DVs and displaced muon tracks using Run-2 data [35], particularly for proper lifetimes below 5 ns, highlighting the enhanced sensitivity provided by the new dedicated muon triggers and improved reconstruction techniques employed. For longer lifetimes, the Run-2 search retains more stringent limits due to the usage of missing transverse momentum triggers, which were not considered in this Letter.

9. Conclusion

A search for LLPs decaying into a DV and a muon is presented, using 164 fb^{-1} of $\sqrt{s} = 13.6 \text{ TeV}$ pp collision data collected by the ATLAS detector at the LHC between 2022 and 2024. The search targets events with a DV with at least four associated tracks and an invariant mass above 20 GeV, along with at least one muon with a transverse impact parameter $|d_0| > 2 \text{ mm}$. A data-driven TF method is employed to estimate the background contributions from heavy-flavour decays, cosmic-ray muons, and algorithmic fakes. Two signal regions are defined based on the transverse distance between the DV and the primary interaction vertex; in both regions, the background is dominated by muons from heavy-flavour decays. No significant excess above the expected background is observed. The results are interpreted in terms of upper limits on the visible cross-section for final states with at least one DV and at least one displaced muon, and as upper limits on the production cross-sections of benchmark models involving LLPs from RPV SUSY. The sensitivity is significantly enhanced over previous searches: cross-section limits for higgsino-like neutralinos with L -violating λ'_{211} decays are improved by approximately two orders of magnitude relative to Run-1 measurements, and the reach for B -violating λ''_{323} decays is extended to proper lifetimes of 100 ns. For top squarks, the dedicated Run-3 muon triggers and refined reconstruction techniques lead to better sensitivity to $\lambda'_{233} \cos \theta_t$ for proper lifetimes below 5 ns than achieved in prior ATLAS results.

Data availability

The public release of data supporting the findings of this article will follow the CERN Open Data Policy.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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