SEARCHES FOR NEW PHYSICS WITH DISPLACED VERTEX SIGNATURES AT THE ATLAS EXPERIMENT IN LHC RUN 1*

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Results from a selection of $\sqrt{s} = 8$ TeV ATLAS searches for new physics with displaced signatures are presented. Displaced decays are reconstructed in either the inner detector, hadronic calorimeter, or muon spectrometer. No events over the expected background were observed, and limits as a function of proper lifetime are set.

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1. Introduction

Most ATLAS searches focus on looking for new particles that are produced and decay at the interaction point (IP). However, there is nothing that requires any undiscovered particles to decay promptly. Instead, they could be neutral and long-lived, decaying a macroscopic distance from the IP but still inside the detector. If they decay back to Standard Model (SM) particles, they will leave a displaced vertex signature, with no detector activity upstream from the particle decay. Models predicting long-lived particles (LLPs) can arise naturally, or simply be a possibility that has not yet been ruled out.

Three searches for displaced objects using the ATLAS detector [1] are discussed in this proceedings. The first is a SUSY search looking for displaced inner detector (ID) vertices in conjunction with muons, electrons, jets, or missing transverse energy ($E_{\mathrm{T}}^{\mathrm{miss}}$). The second is an analysis searching

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for two displaced vertices in the same event: two ID vertices, one ID and one muon spectrometer (MS) vertex, or two MS vertices. The third analysis searches for two displaced calorimeter jets, defined by a low electromagnetic energy fraction.

2. Inner detector vertex reconstruction

Default tracking in the ATLAS inner detector (ID) only reconstructs tracks with a transverse impact parameter (d_0) less than 10 cm. When a LLP decays, it will leave ID pixel and SCT hits just like any other particles, but many will be from high-d_0 tracks and thus not reconstructed into tracks. In order to have enough tracks to reconstruct a vertex, another tracking step is needed. The default tracking quality criteria linked to prompt, low-d_0 tracks are loosened, and tracking is rerun with any hits not used in the initial default track reconstruction.

There are two standard inner detector vertex reconstruction algorithms used by ATLAS: one for reconstructing primary vertices from the hard scatter, and the other for reconstructing secondary vertices used primarily for b-tagging. Both of these algorithms have been successfully adapted for reconstructing vertices from displaced decays, with Ref. [2] using a modified primary vertex reconstruction and Ref. [3] using modified secondary vertex reconstruction. Once a vertex is formed, any tracks that have a hit before the vertex position are removed, and the vertex is refit with the remaining tracks.

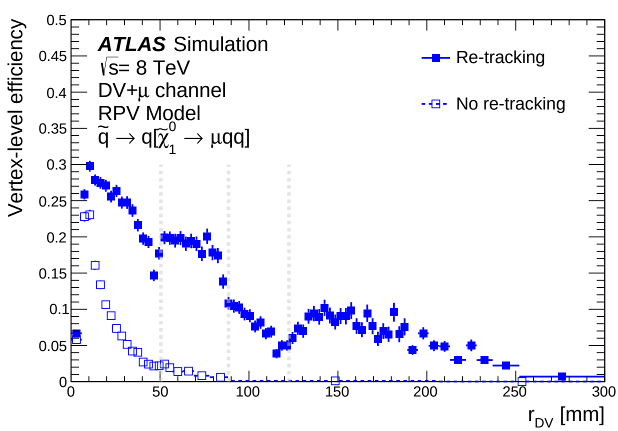


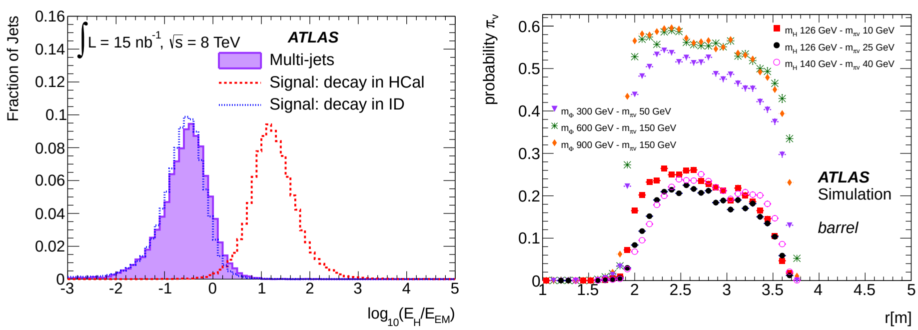
Fig. 1. Efficiency of reconstructing a displaced vertex (DV) as a function of the vertex radial position r_{DV} for an RPV SUSY model with long-lived 494 GeV neutrinos. The vertical grey lines show the position of the first, second and third pixel layers. All selection criteria are applied, except for the material veto [3].

A set of *good vertex criteria* (GVC) are determined to distinguish background vertices from vertices characteristic of signal. Since different signal models can leave different vertex signatures, different criteria and values are used for each model. The criteria include the number of tracks contributing to the vertex, the ΔR between the vertex and the nearest calorimeter jet, and the vertex χ^2 probability of fit. An example of the reconstruction efficiency for one of the models used in the SUSY analysis is shown in Fig. 1; the improvement gained from the additional tracking step is clear.

Additionally, a material veto is applied to ensure none of the vertices are from hadronic interactions with the material. Details on the material map construction are given in Ref. [3].

3. Displaced jets in the hadronic calorimeter

When a long-lived particle decays near the end of the electromagnetic calorimeter (ECAL) or in the hadronic calorimeter (HCAL), it will be reconstructed as a narrow jet with a very low electromagnetic fraction (EMF). To more clearly visually separate signal-like low-EMF jets from the QCD multi-jet background, the variable $\log_{10}(E_{\mathrm{HAD}}/E_{\mathrm{EM}})$ is used, where E_{H} is the energy deposited in the HCAL, and E_{EM} is the energy deposited in the ECal. A plot of the discriminating power of this variable between signal decays in the HCAL and the multi-jet background is shown in Fig. 2 (a).



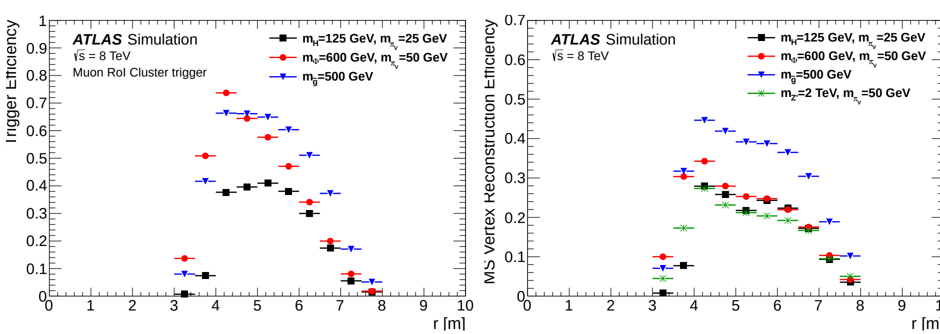
(a) (b)

Fig. 2. (a) Distribution of jet $\log_{10}(E_{\mathrm{HAD}}/E_{\mathrm{EM}})$ with jet $|\eta| < 2.5$ and $p_{\mathrm{T}} > 40$ GeV, comparing displaced calorimeter jets from signal (dashed), signal jets decaying in the ID (dotted), and the multi-jet data sample used to evaluate the multi-jet contribution to the background (filled). (b) The probability for a single LLP (π_{v}) to pass the CalRatio trigger as a function of the π_{v} radial decay length for several scalar boson (Φ) and π_{v} masses, for decays in the barrel HCAL ($|\eta| < 1.7$) [4].

A dedicated, unprescaled trigger (*CalRatio trigger*) selects events with at least one jet with $\log_{10}(E_{\mathrm{HAD}}/E_{\mathrm{EM}}) > 1.2$, and no tracks with $p_{\mathrm{T}} > 1$ GeV within $(\Delta\phi \times \Delta\eta) = (0.2 \times 0.2)$ of the jet centre [4, 5]. Off-line, these jets are required to have $E_{\mathrm{T}} > 60$ GeV. The trigger efficiency is shown in Fig. 2 (b) for a range of benchmark models used in the analysis, for decays in the barrel. Higher mass benchmark models are more likely to pass the trigger because the LLPs are more likely to have enough energy to pass the jet energy thresholds. Additionally, higher energy jets from LLPs tend to have a larger $\log_{10}(E_{\mathrm{HAD}}/E_{\mathrm{EM}})$ value, because there is more hadronic energy deposited to counteract any EM deposits from pileup or noise.

4. Displaced decays in the muon spectrometer

In the muon spectrometer, an LLP decay leaves a shower of muon drift tube (MDT) and trigger (RPC, TGC) hits. Normally, a muon would leave a single line of hits, and thus the level-1 (L1) muon trigger reports an LLP decay as a collection of L1 muon regions of interest (RoIs). The Muon RoI Cluster trigger [5] selects events with localised clusters of L1 Muon RoIs. Clusters of at least three (four) muon RoIs in the barrel (endcaps) are then required to be isolated from calorimeter jets and ID tracks, reducing the background from prompt jets whose energy the calorimeters do not fully absorb (punch-through jets). The efficiency of this trigger in the MS barrel ($\eta < 1.0$) is shown in Fig. 3 (a). Once the LLP decay occurs beyond the first RPC trigger plane (at $R \sim 6.5$ m for large sectors and $R \sim 7.8$ m for small sectors), the efficiency drops to zero. The effects of collimated decays are



(a) (b)

Fig. 3. Barrel efficiency as a function of the radial decay position of the long-lived particle for (a) the Muon RoI Cluster trigger and (b) MS vertex reconstruction for scalar boson, for a selection of simulated benchmark signal samples [2].

visible in the $m_{\Phi} = 600$ GeV, $m_{\pi_{\rm v}} = 50$ GeV curve, where the efficiency drops as the decay approaches the first RPC plane, since the decay products will not be sufficiently wide to create enough L1 muon RoIs.

The identification of a displaced muon spectrometer decay is further refined at the off-line selection level with a custom algorithm that reconstructs tracks, then vertices, from the MDT hits [6]. A separate set of good vertex criteria for MS vertices are developed that include isolation criteria ensuring that the vertex is not caused by punch-through jets. The efficiency for reconstructing a good MS vertex in the barrel is shown in Fig. 3 (b) for a selection of benchmark signal samples.

5. Event selection and exclusion limits

No excess of events over the expected background was observed in any of the analyses. In all cases, limits were set using $\mathrm{CL_S}$ [7], and presented as upper limits at 95% confidence level.

The SUSY analysis searched for events with a single ID vertex with $m_{\rm vertex} > 10$ GeV in the four channels summarised in Table I. Zero events were observed in all the signal regions. Exclusion limits for a Split SUSY model (Fig. 4 (a)) with neutralino of mass 100 GeV and four different gluino masses are shown in Fig. 5 (a).

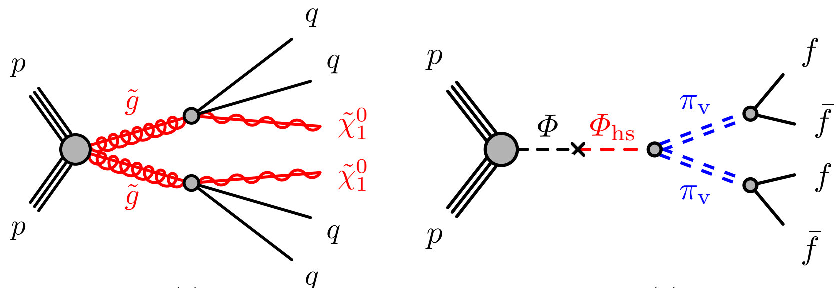
TABLE I

The topologies considered in the SUSY ID vertex analysis.

Channel	Criteria
ID vertex + muon	muon: $p_{\rm T} > 55$ GeV, $\lvert\eta\rvert < 1.07$, $d_0 > 1.5$ mm
ID vertex + electron	electron: $p_{\rm T} > 125$ GeV, $d_0 > 1.5$ mm
ID vertex + $E_{\rm T}^{\rm miss}$	$E_{\rm T}^{\rm miss} > 180$ GeV
ID vertex + jets	4 jets with $p_{\rm T} > 90$ GeV, 5 jets with $p_{\rm T} > 65$ GeV, or 6 jets with $p_{\rm T} > 55$ GeV

Proper lifetimes of the gluino are excluded when the observed limit curve dips below the horizontal grey gluino production cross section at the corresponding mass. A range of proper lifetimes are excluded, even for gluino masses of 1.4 TeV.

There are two searches in three search channels that require two displaced objects [2, 4]. The model they share in common is a scalar boson (Φ) (Higgs boson (h) if $m_{\Phi} = 125$ GeV) that decays to two neutral, long-lived (pseudo-) scalars $\pi_{\rm v}$, which subsequently decay into fermion pairs, as shown

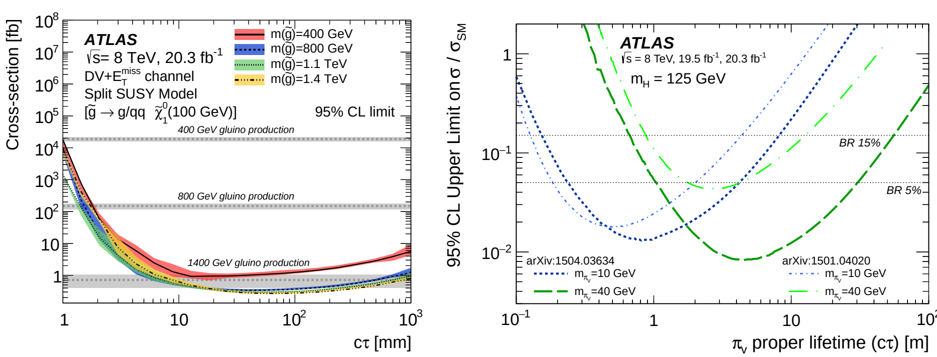


(a) (b)

Fig. 4. Effective diagrams for (a) long-lived R-hadron decay in a split-supersymmetry scenario; the quarks and leptons shown may have different flavours [3] and (b) scalar mixing with a hidden sector to produce neutral, long-lived scalars decaying to heavy fermion pairs [2]. Filled circles indicate effective interactions.

in Fig. 4 (b). The primary decay products are b-quarks, since the π_{v} decays via a Yukawa coupling. The channels applicable to the shared model are summarised in Table II.

Full selection criteria are detailed in Refs. [2] and [4]. Exclusion limits are shown in Fig. 5 (b). A proper lifetime is excluded for a given $H \to \pi_{\mathrm{v}}\pi_{\mathrm{v}}$ branching ratio if the observed limit curve dips below the horizontal branching ratio line. A wide range of proper lifetimes are excluded for LLP branching ratios lower than 5%.



(a) (b)

Fig. 5. Observed 95% C.L. limits on (a) the production cross section for gluino pair production in the split-supersymmetry model, with the gluino decaying to a neutralino plus either a gluon or a light-quark pair [3], and (b) $\sigma \times \mathrm{BR}/\sigma_{\mathrm{SM}}$ for the 125 GeV Higgs boson decaying to π_{v} pairs for $m_{\pi_{\mathrm{v}}} = 10$ and 40 GeV [2, 4].

TABLE II

The topologies considered in the two displaced object analyses.

Channel	Criteria
Muon Cluster	Event passes Muon RoI Cluster trigger One ID vertex and one MS Vertex or two MS Vertices Vertices pass GVC, separated by $\Delta R > 2.0$
Two low-EMF jets	Event passes CalRatio trigger Two jets with $\log_{10}(E_{\mathrm{HAD}}/E_{\mathrm{EM}}) > 1.2$

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