PROCEEDINGS OF SCIENCE

Searches for displaced hadronic and lepton jets at ATLAS

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Results of searches for long-lived particles that decay to either pairs of hadronic jets or lepton-jets in proton-proton collisions with the ATLAS experiment at the LHC with center-of-mass energies of 8 and 13 TeV are described. The results are interpreted in the context of several models, including hidden valleys with high-mass scalars, baryogenesis models, stealth SUSY, and models with QCD-like dark hadronization.

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1. Introduction

There are many theories which predict the existence of 'long-lived' particles, which are weakly coupled to the standard model.

Here two existing ATLAS [1] 8 TeV results taken are reported, firstly covering long-lived, weakly interacting particles decaying to hadronic jets [2] and secondly pair produced, long-lived neutral particles decaying to hadronic jets [3].

One new result is also presented, which consists of a search for long-lived neutral particles decaying into 'lepton-jets' [4]. This search uses pp collisions at $\sqrt{s} = 13$ TeV, corresponding to an integrated luminosity of 3.4 fb^{-1} collected in 2015.

2. Hadronic jets

The so-called 'hidden–valley' refers to a general class of models in which a hidden sector (v-sector) is added to the standard-model (SM). The v–particles, such as π_v, don't couple directly to SM particles, so need communicator particles. Depending on the strength of the coupling, this can lead to long lifetimes for the lightest v-particles and with a large detector such as ATLAS, it is therefore possible to detect their decays.

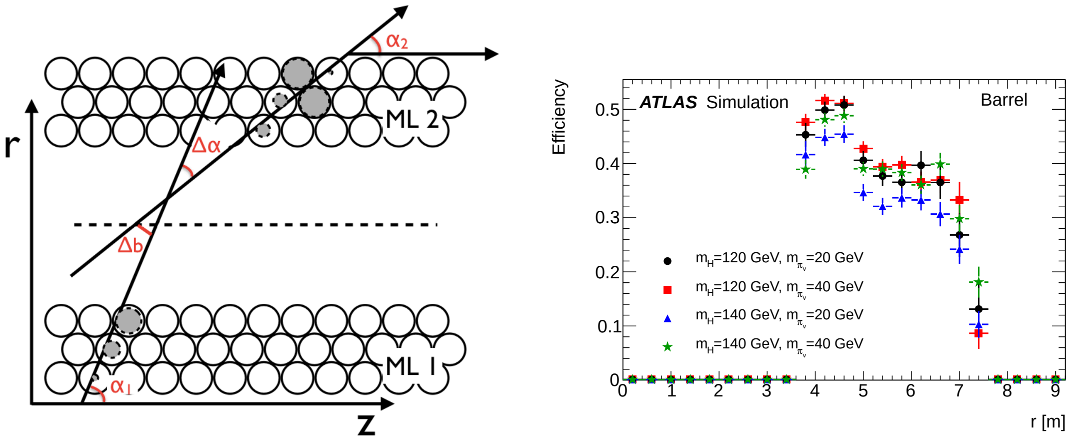
The first challenge is how to trigger on such events; most standard triggers are linked to the primary vertex, and are so very inefficient to detect displaced decays. Instead several specialised triggers are used by the various searches including: a 'Calo-Ratio' trigger, which looks for greater than one narrow jet with relatively little energy deposited in the EM calorimeter, and no charged tracks pointing towards to the jet; and a 'Muon-RoI-Cluster' trigger which looks for decays of neutral particles in the muon spectrometer [6].

Another challenge is reconstructing the events, which have unusual topologies and so require innovative approaches. For instance, as shown in Figure 1(a) the spatial separation between the two multilayers inside a single MDT chamber provides a powerful tool for pattern recognition.'Tracklets' can be formed inside a single chamber and a specialised algorithm is then used to reconstruct straight line segments in multilayers, and finally match these segments using two parameters [5] :

- Δb the minimum distance between segments at centre of chamber
- $\Delta\alpha$ angle between segments (can measure momenta for low p_{T} muons)

From these tracklets it is possible to reconstruct vertices. Figure 1(b) shows the resultant efficiency for reconstructing a vertex for barrel π_v decays that pass the trigger. The efficiency is zero until the outer layers of the calorimeter, at around $r = 4$ m, due to the low p_{T} of the decay products. The efficiency then rapidly increases, only to decrease again toward the radii of the middle MDT stations, at about $r = 7$m. This is because of decreasing spatial separation of the charged hadrons and photons (and their corresponding EM showers) in the MDT chambers.

No significant excess of events is observed over the background estimate in 20.3 fb^{-1} of p-p collision data, and so limits are set on the π_v proper decay lengths for different scalar boson and π_v mass combinations. Table 1 shows the results for various values of m_H and m_{π_v}, whilst other results for various Φ masses can be found in Ref. [3].



(a) (b)

Figure 1: (a) Schematic of a MS barrel chamber with one segment in multilayer 1 and one in multilayer 2. The variable $\alpha 1(2)$ is defined as the angle with respect to the z-axis of the segment in multilayer 1(2). The parameter $\Delta\alpha$ is defined as $\Delta\alpha = \alpha 1 - \alpha 2$ and Δb is defined to be the distance of closest approach between the pair of segments at the middle plane of the MDT chamber. The middle plane of the chamber is the plane equidistant from multilayers 1 and 2, represented here by the dashed line. (b) Efficiency for reconstructing a vertex for π_v decays in the barrel muon spectrometer as a function of the radial decay position of the π_v for π_v decays that satisfy the Muon RoI Cluster trigger [5].

Table 1: Ranges of π_v proper decay lengths excluded at 95% CL assuming a 30% and a 10% BR for a $m_H = 126$ GeV [3].

MC sample m_H, m_{π_v} [GeV]	Excluded range 30% BR $H \to \pi_v\pi_v$ [m]	Excluded range 10% BR $H \to \pi_v\pi_v$ [m]
126, 10	0.10 – 6.08	0.14–3.13
126, 25	0.30–14.99	0.41–7.57
126, 40	0.68–18.50	1.03–8.32

Similarly, no significant excess is observed with 19.5 fb^{-1} (Muon RoI cluster trigger) and 20.3 fb^{-1} (Jet + missing ET trigger). In Table 2 limits are shown for various values of $m_{\pi v}$, whilst other results for various Φ and gluino masses can be found in Ref. [2].

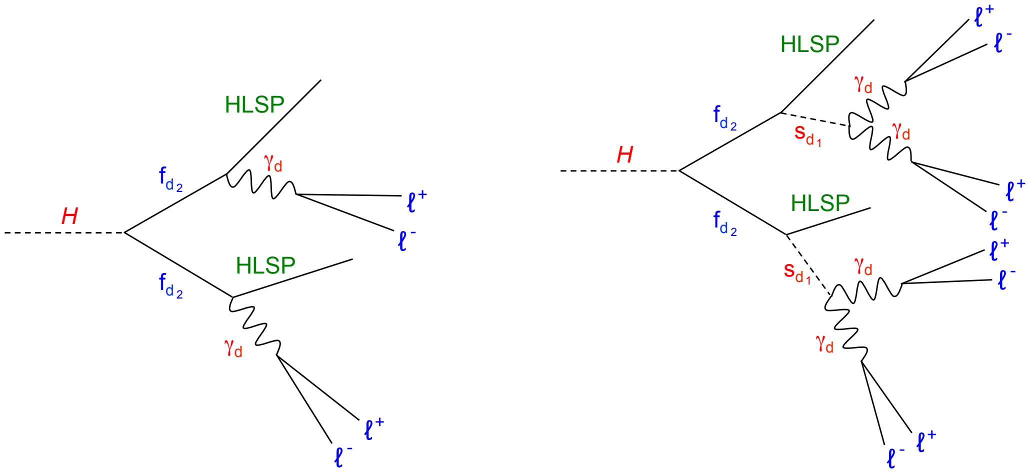
3. Lepton Jets

The signal for this analysis follows the prediction of the Falkowsky-Ruderman-Volansky-Zupan (FRVZ) where Higgs boson decays to pairs of hidden fermions. In the first benchmark model, as shown in Figure 2(a), the dark fermion decays to a dark photon γ_d and a lighter dark

Table 2: Ranges of π_v proper decay lengths excluded at 95% CL assuming a 30%, 15%, 5%, or 1% BR for m_H = 125 GeV [2].

m_{π_v}	Excluded $c\tau$ range [m]			
[GeV]	1% BR	5% BR	15% BR	30 % BR
10	no limit	0.24−4.2	0.16−8.1	0.12−11.8
25	1.10−5.35	0.43−18.1	0.28−32.8	0.22−46.7
40	2.82−7.45	1.04−30.4	0.68−55.5	0.52−79.2

fermion f_{d1}, or HLSP (Hidden Lightest Stable Particle). In the second model, as shown in Figure 2(b), the dark fermion f_{d2} decays to an HLSP and a dark scalar s_{d1} that in turn decays to pairs of dark photons.



(a) (b)

Figure 2: The two FRVZ models used as benchmarks in the analysis. In the first model (left), the dark fermion decays to a γ_d and a HLSP. In the second model, the dark fermion f_{d2} decays to an HLSP and a dark scalar s_{d1} that in turn decays to pairs of dark photons.

These dark photons are typically produced with a large boost, which, together with their low mass, leads to collimated jet-like structures containing pairs of muons/electrons and/or pions, which are known as ‘lepton-jets’. The limited granularity of the detectors makes resolving the lepton-jet constituents challenging.

The integrated luminosity for this search is 3.57 fb^{-1}, which is lower than for the 2012 dataset at 8 TeV, however the sensitivity remains comparable, due to improvements in trigger sensitivity and reconstruction efficiency for close-by muons, and a higher cross section for Higgs production at 13 TeV.

At detector level, lepton-jets are categorised into three types according to content, as shown in Figure 3, and different techniques are used depending on the type. For example, muonic lepton-jets are reconstructed by ‘clustering’ all muon tracks within a cone (seeded from highest-pT muon

Table 3: Results of the ABCD compared with the observed events on data after all selection requirements are applied [4].

Category	Observed events	Expected background
All events	285	$231 \pm 12(\text{stat}) \pm 62(\text{syst})$
Type2–Type2 excluded	46	$31.8 \pm 3.8(\text{stat}) \pm 8.6(\text{syst})$
Type2–Type2 only	239	$241 \pm 41(\text{stat}) \pm 65(\text{syst})$

track), whilst for type 2 lepton-jets, an anti-k_t calorimetric jet search algorithm is used to select γ_d decaying into an electron or pion pair. The dominant background is from time-coincident cosmic-rays, and this can be studied using events collected in empty bunch crossings. They are rejected using a combination of the muon track impact parameter $|z_0|$ and jet-timings (i.e. the difference between calorimeter cell timing, and the bunch crossing time).

In order to extract the signal yield, taking into account the multijet and the cosmic-ray background residual contaminations, a data-driven likelihood-based ABCD method is used, the results of which are shown in Table 3.

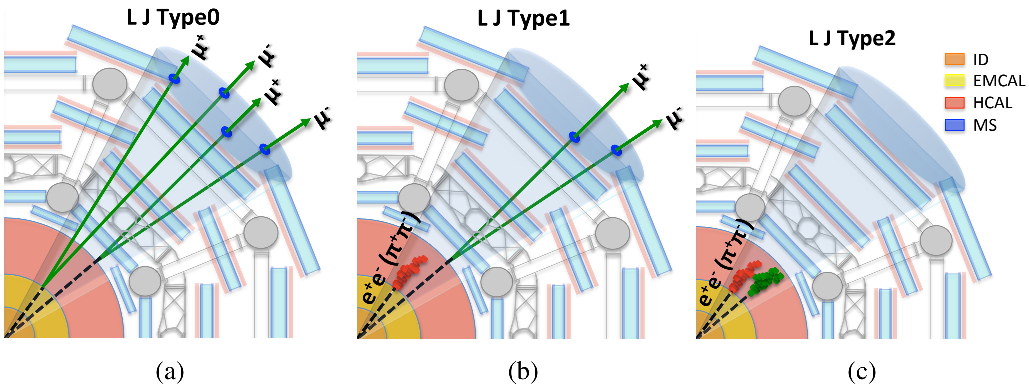


Figure 3: Schematic picture of the lepton-jet (LJ) classification according to the γ_d decay final states. Electrons and pions originating from γ_d decay appear as jets. Type0 LJ is composed of only muons (left). Type1 LJ is composed of muons and a jet (centre). Type2 LJ is composed of only jets (right)

No signal is found, so limits are set (excluding the Type2-Type2 channel, which has low efficiency and high background). For example, Figure 4 shows the resulting exclusion limits on the $\sigma\times$ BR as a function of the γ_d proper decay length, for a 125 GeV Higgs boson.

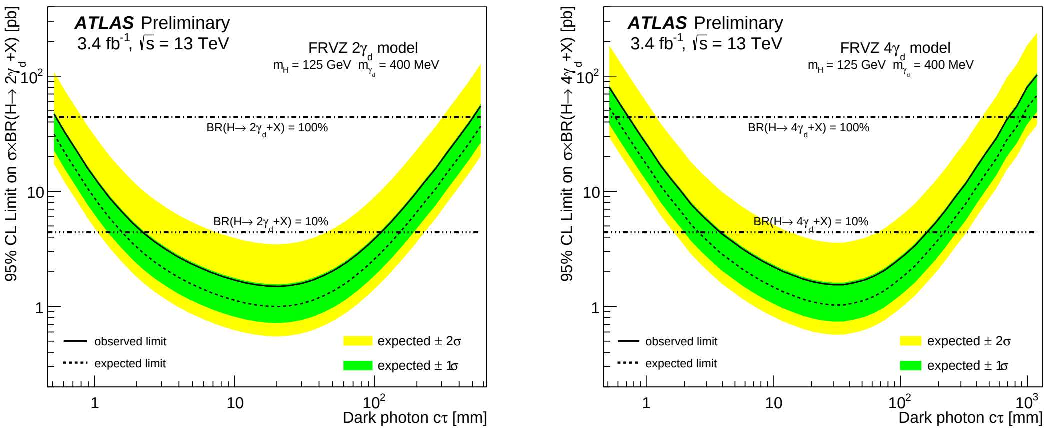


Figure 4: The 95% upper limits on the $\sigma\times$ BR for the FRVZ 125 GeV Higgs $\rightarrow 2\gamma_d + X$ (left) and Higgs $\rightarrow 4\gamma_d + X$ (right) benchmark models as a function of the γ_d lifetime ($c\tau$). The horizontal lines correspond to $\sigma\times$ BR for two values of the BR of the Higgs boson decay to dark photons [4].

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