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Search for long-lived neutral particle decays with first 1.9 fb^{-1} of 2011 data collected with the ATLAS detector at the LHC

D. Salvatore[1,a] On behalf of the ATLAS Collaboration

[1] *University of Calabria, ponte P. Bucci, 87036 Rende (CS), Italy*

Abstract. Many extensions of the Standard Model (SM) include neutral weakly-coupled particles that can be long-lived. These long-lived particles occur in many models, included gauge-mediated extensions of the Minimal Supersymmetric Model (MSSM), MSSM with R-parity violation, inelastic dark matter and the Hidden Valley (HV) scenario. Results are presented on the first ATLAS searches at the LHC for possible rare Higgs boson decays to pair of neutral, long-lived hidden-sector particles that lead to final states containing fermion anti-fermion pairs or pairs of collimated lepton jets. No excess of events above the expected background has been observed for 1.9 fb^{-1} of data collected in 2011 at a center of mass energy of 7 TeV. Limits are presented as a function of the proper lifetime of the long-lived neutral particle.

1 Introduction: the Hidden Valley scenario

Several models of physics beyond the SM predict the existence of Hidden Sectors able to comunicate to the SM through several portals (Higgs, Z', loop of SUSY particles). A light Higgs boson can decay to particles of the hidden sector [1] such as the long-lived pseudo-scalar v-pion (π_v) or scalar hidden fermions. These HV particles can decay back in the standard sector to fermion anti-fermion pairs or collimated lepton-jets [2]. Lifetimes can be comparable to ATLAS [3] dimensions, leading to displaced decays far from the interaction point. Dedicated trigger algorithms [4] and reconstruction techniques have been developed.

2 Displaced π_v decays in the Muon Spectrometer

This analysis describes the first ATLAS search for the Higgs decay to two identical neutral particles (π_v) that have displaced decay $b\bar{b}$, $c\bar{c}$, $\tau^+\tau^-$ in the ratio 85:5:8 [5]. Four datasets have been simulated with Higgs masses 120 and 140 GeV and π_v masses 20 and 40 GeV. Both π_v decays are required to occur near the outer radius of the hadronic calorimeter (HCAL) (~4 m) or in the muon spectrometer (MS). Such decays give a (η,ϕ) cluster of charged and neutral hadrons in the MS. Requiring both $\pi_v's$ to have this topology improves background rejection.

A dedicated signature-driven trigger, the muon Region Of Interests (RoI) cluster trigger [4], was developed to trigger on events with a π_v decaying in the MS. It selects events with a cluster of three or more muon RoIs in a ΔR=0.4 cone in the MS barrel trigger chambers. This trigger configuration implies that one π_v must decay in the barrel, while the second π_v may decay either in the barrel or the forward spectrometer. The background of punch-through jets is suppressed by requiring no calorimeter jets with $E_T > 30$ GeV in a ΔR=0.7 cone and no ID tracks with $p_T > 5$ GeV within a region of $\Delta\eta\times\Delta\phi$=0.2×0.2 around the RoI cluster center. These isolation criteria result in a negligible loss in the simulated signal while significantly reducing the backgrounds. Monte Carlo (MC) studies show the RoI cluster trigger is 30-50% efficient in the region from 4 m to 7 m. The $\pi_v's$ that decay beyond a radius of 7 m do not leave hits in the trigger chambers located at 7 m, while the π_v decays that occur before 4 m are located in the calorimeter and do not produce sufficient activity in the MS to pass the trigger.

A specialized tracking and vertex reconstruction algorithm was developed to identify $\pi_v's$ that decay inside the MS. Such decays produce a high multiplicity of low p_T particles clustered in a small ΔR region, containing ~10 charged particles and ~5 π_0, resulting in large electromagnetic showers, which confuses standard muon reconstruction. The $\pi_v's$ that decay before the last sampling layer of the HCAL do not produce a significant number of tracks in the MS. Thus, detectable decay vertices must be located in the region between the outer radius of the HCAL and the middle station of the MS.

The separation of the two multilayers inside a single muon chamber provides a powerful tool for track pattern recognition in this busy environment and a momentum measurement with resolution for tracks up to ~10 GeV in the barrel. In the endcap spectrometers, the muon chambers are outside the magnetic field region; therefore it is not possible to measure the track momentum inside of a single chamber. The MS vertex algorithm begins by

[a] e-mail: daniela.salvatore@cern.ch

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grouping the track segments formed out of hits in single muon chambers using a simple cone algorithm with ΔR=0.6. In the barrel the vertex is reconstructed as the point in (r,z) that uses the largest number of track segments to reconstruct a vertex with a χ^2 probability greater than 5%, while in the forward spectrometer, the vertex is found using a least squares regression, that assumes the track segments are straight lines. A vertex is reconstructed using at least three track segments. After requiring the MS vertex to be separated from ID tracks with $p_T \geq 5$ GeV and jets with $E_T \geq 15$ GeV by ΔR=0.4 and 0.7, respectively, the algorithm has an efficiency of ~40% in signal MC events throughout the barrel region ($4 \leq r \leq 7.5$ m) (Figure 1) and a resolution of 20 cm in z, 32 cm in r and 50 mrad in ϕ. In the forward spectrometer, the algorithm is 40% efficient in the region $8 \leq |z| \leq 14$ m. The MC description of hadrons and photons in the MS was validated on a sample of events containing a punch-through jet, which are similar to signal events as they contain both low energy photons and charged hadrons in a localized region of the MS.

The final event selection requires two isolated MS vertices separated by ΔR > 2. The background is calculated using a fully data-driven method by measuring the probability for a random event to contain an MS vertex (P_{vertex}) and the probability of reconstructing a vertex given the event passed the trigger (P_{reco}). Because P_{vertex} and P_{reco} are measured in data, they incorporate backgrounds from cosmic showers, beam halo and detector noise. The background is calculated to be 0.03 ± 0.02 events from:

$$N_{Fake}\,(2\text{ MS vertex}) = N(\text{MS vertex},1\text{ trig})*P_{vertex} + N(\text{MS vertex},2\text{ trig})*P_{reco}$$

N(MS vertex,1 trig) is the number of events with a single trigger object and an isolated MS vertex; N(MS vertex, 2 trig) is the number of events with an isolated vertex and a second trigger object. P_{vertex} was measured using events selected by a random generator in coincidence with the bunch crossing and P_{reco} was measured on collision data from events that pass the trigger.

No events in the data sample pass the selection requiring two isolated, back-to-back vertices in the MS. Since no significant excess over the background prediction is found, exclusion limits for $\sigma_H \times BR(H \to \pi_v\, \pi_v)$ are set by rejecting the signal hypothesis at the 95% confidence level (CL) using the CLs [7] procedure. Figure 2 shows the 95% CL upper limit on $\sigma_H \times BR(H \to \pi_v\, \pi_v)/\sigma_{SM}$ as a function of the π_v proper decay length ($c\tau$) in multiples of the SM Higgs cross section, σ_{SM}.

3 Displaced muon-jet search

The benchmark model for this analysis [6] is a simplified scenario where the Higgs boson decays to a pair of neutral hidden fermions (f_{d2}) each decaying to one long-lived dark photon (γ_d) and one stable neutral hidden fermion (f_{d1}) that escapes the detector unnoticed, resulting in two muon jets (MJ) from the γ_d decays in the final state. Parameters for MC simulations are given in table 1.

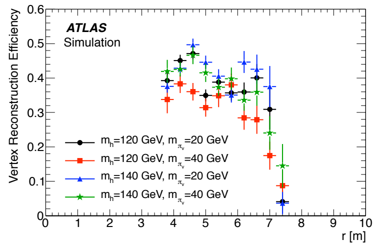

Figure 1. Vertex reconstruction efficiency as a function of the radial decay position of the π_v [5].

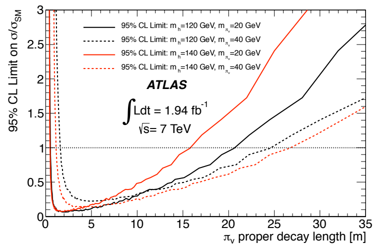

Figure 2. Observed 95% upper limits on the process $H \to \pi_v\, \pi_v$ vs. the π_v proper decay length [5].

Since signal events are characterized by a four-muon final state with relatively low p_T, a low p_T multi-muon trigger with muons reconstructed only in the MS is needed. In order to have an acceptably low trigger rate, at least three muons are required. Candidate events are collected using an unprescaled high level trigger with three reconstructed muons of $p_T \geq 6$ GeV, seeded by a Level 1 trigger with three different muon RoIs. These muons are reconstructed using the tracking at the trigger level only in the MS, since muons originating from a neutral particle decaying outside the pixel detector will not have a matching track in the ID tracking system. The trigger efficiency for the MC signal samples, defined as the fraction of events passing the trigger requirement with respect to the events satisfying the analysis selection criteria is $0.32 \pm 0.01_{stat}$ for m_H = 100 GeV and $0.31 \pm 0.01_{stat}$ for m_H = 140 GeV. The main reason for the relatively low trigger efficiency is the small opening angle (ΔR) between the two muons of the γ_d decay, which is often smaller than the Level 1 trigger granularity.

MJs are identified by a clustering algorithm that associates all the muons in ΔR=0.2 cones, starting with the muon with highest p_T. The MJ direction and momentum are obtained from the vector sum over all muons in the

m_H (GeV)	m_{fd1} (GeV)	m_{fd2} (GeV)	$m_{\gamma d}$ (GeV)	$c\tau$ (mm)
100	5.0	2.0	0.4	47
140	5.0	2.0	0.4	36

Table 1. Parameters for the MC simulation [6].

cut	cosmic-rays	multi-jet	total background	m$_H$=100 GeV	m$_H$=140 GeV	data
N_{MJ} = 2	3.0 ± 2.1	N/A	N/A	$135{\pm}11^{+29}_{-21}$	$90{\pm}9^{+17}_{-13}$	871
$E_T^{\rm isol} \leq 5$ GeV	3.0 ± 2.1	N/A	N/A	$132{\pm}11^{+28}_{-21}$	$88{\pm}9^{+17}_{-13}$	219
$\|\Delta\phi\| \geq 2$	1.5 ± 1.5	153 ± 18 ± 9	155 ± 18 ± 9	$123{\pm}11^{+26}_{-19}$	$81{\pm}9^{+15}_{-12}$	104
Q$_{MJ}$ = 0	1.5 ± 1.5	57 ±15±22	59 ± 15 ± 22	$121{\pm}11^{+26}_{-19}$	$79{\pm}8^{+15}_{-12}$	80
$\|d_0\|$, $\|z_0\|$	$0^{+1.64}_{-0}$	111±39±63	111±39±63	$105{\pm}10^{+22}_{-16}$	$66{\pm}8^{+12}_{-10}$	70
$\Sigma p_T^{ID} < 3$ GeV	$0^{+1.64}_{-0}$	$0.06{\pm}0.02^{+0.66}_{-0.06}$	$0.06^{+1.64+0.66}_{-0.02-0.06}$	$75{\pm}9^{+16}_{-12}$	$48{\pm}7^{+9}_{-7}$	0

Table 2. Cut flow for the signal selection of $H \to \gamma_d\, \gamma_d$ +X on signal MC, the corresponding cosmic-ray background, the multi-jet background estimation from the ABCD method and the data [6].

MJ. Only events with two MJs separated with $|\Delta\phi| \geq 2$ and each containing two reconstructed muons of opposite charge, are kept for the analysis. The main background contribution is expected from processes giving a high production rate of secondary muons which do not point to the primary vertex, such as decays in flight of K/π and heavy flavour decays in multi-jet processes, or muons due to cosmic rays.

The calorimetric isolation variable $E_T^{\rm isol}$ has been defined as the difference between the E_T in a ΔR=0.4 cone around the highest p_T muon and the E_T in a 0.2 cone; a cut $E_T^{\rm isol} \leq 5$ GeV keeps almost all the signal and significantly reduce the background. The isolation modelling is validated with a sample of $Z \to \mu\mu$ decays.

The scalar sum of the p$_T$ of the tracks measured in the ID ($\Sigma_{p_T}^{\rm ID}$), inside a ΔR=0.4 cone around the direction of the MJ, is requested to be < 3 GeV. The muon tracks of the MJ in the ID, if any, are not removed from the isolation sum; as a consequence, the $\Sigma_{p_T}^{\rm ID}$ cut will remove prompt MJs or MJs with very short decay length.

For the cosmic-ray muon background, we require the transverse and longitudinal impact parameters of the muons with respect to the primary vertex to be $|d_0| < 200$ mm and $|z_0| < 270$ mm. The γ_d reconstruction efficiency for the lifetimes used in this simulation, defined as the number of γ_d passing the offline selection divided by the number of γ_d in the spectrometer acceptance ($|\eta| < 2.4$) with both muons having $p_T \geq 6$ GeV, is around 35%.

To estimate the multi-jet background contamination in the signal region we use a data-driven ABCD method, slightly modified in order to cope with the low statistics: the two relatively uncorrelated variables used to separate signal and background are the MJ $E_T^{\rm isol}$ and $\Delta\phi$. The final yields for the signal samples, for the data and for the different background sources nomalized at the integrated luminosity of 1.9 fb^{-1} are summarized in Table 2; no events in the data sample pass the selection with an expected total background of $0.06 \pm 0.02_{\rm stat}\ {}^{+0.66}_{-0.6}{}_{\rm syst}$ events.

The efficiency of the selection criteria is evaluated for the simulated signal samples as a function of the mean lifetime of the γ_d, so the expected number of signal events is predicted in a $c\tau$ up to 700 mm. These numbers, together with the expected number of background events (multi-jet and cosmic rays) and taking into account the zero data events surviving the selection criteria in 1.9 fb^{-1} and all the systematic uncertainties, are used as input to obtain limits at the 95% CL on the cross section times branching ratio ($\sigma\times$BR) for the process $H \to \gamma_d\, \gamma_d$ +X through the CLs method.

4 Conclusions

In 1.9 fb^{-1} of p-p collision data at a center-of-mass energy of 7 TeV there is no evidence of an excess of events containing two isolated, back-to-back vertices in the ATLAS MS. Assuming 100% branching ratio for $H \to \pi_v\, \pi_v$, a wide range of π_v proper decay length can be excluded (0.5 m - 25 m depending on the masses). Also, no excess has been observed for the process $H \to \gamma_d\, \gamma_d$ +X: assuming the SM production rate for a 140 GeV Higgs boson, its branching ratio to two γ_d is found to be below 10%, at 95% CL, for hidden photon $c\tau$ in the range 7 mm - 82 mm. Bounds on the BR of a 126 GeV Higgs boson can be infered by interpolating between the 100 (120) GeV and 140 GeV curves for the MJ (π_v) cases.

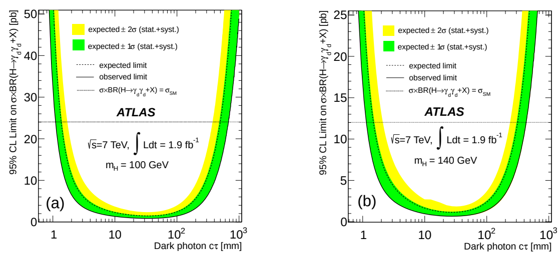

Figure 3. The expected 95% upper limits on the $\sigma \times BR$ as function of the $\gamma_d\ c\tau$ [6].

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