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Search for long-lived neutral particles decaying into lepton-jets in 20.3 fb^{-1} proton-proton collisions at $\sqrt{s}$ = 8 TeV with the ATLAS detector

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Abstract. Several models of elementary particle physics beyond the Standard Model, predict the existence of neutral particles that can decay in jets of leptons and light hadrons (lepton-jets). The present contribution collects the results about the lepton-jet search with the ATLAS experiment at the proton-proton LHC collider at $\sqrt{s}$=8 TeV during the entire 2012 data taking (20 fb^{-1}). No excess of events have been observed over the expected background and the exclusion limits for two different models, that predict the Higgs boson to decay in lepton-jets, have been computed. A new lepton-jet search is underway for the new LHC era at ($\sqrt{s}$=13 TeV).

ATL-PHYS-PROC-2015-195
22/12/2015

1 Introduction

The Standard Model (SM) of particle physics and its mutual interactions has proven up to now extremely successful, but despite that it still remains incomplete, e.g. it does not explain the nature of dark matter. New long lived light particles are predicted in several extensions of the SM, such as hidden sector scenarios. If the mass of these particles is in the MeV to GeV range, they would decay mainly to leptons and light mesons [1]. One of the most promising model is that in which the hidden sector and the visible one are coupled via the vector portal: a light hidden photon (γ_d) mixes kinetically with the SM photon. If the γ_d is the lightest state of the hidden sector, it decays back to SM particles. Due to the small mass of the γ_d and the size of the kinetic mixing parameter (that control both the BR and lifetime of the γ_d) these particles are produced with a large boost. As a consequence the decay products of the γ_d are collimated jets of pairs of electrons and/or muons and or pions that can be produced far from the IP of the event (displaced lepton-jet). The high resolution and high granularity measurement capability of the ATLAS air-core muon-spectrometer (MS) [2] is ideal for this kind of search. This note refers to the full dataset collected by ATLAS during the 2012 run at $\sqrt{s}$ = 8 TeV, corresponding to an integrate luminosity of 20.3 fb^{-1} as reported in [3]. Search for non-prompt muonic lepton-jet has been performed at ATLAS during the 2011 data taking at $\sqrt{s}$ = 7 TeV as reported in [4].

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2 Lepton-jet definition and selection

The search adopts a generic definition of lepton-jet in order to make the analysis as model-independent as possible. The lepton-jet contains at least one γ_d highly isolated in the inner detector, contained in a narrow angular cone (ΔR) and decaying far from the primary vertex to pairs of electrons/muons/pions. A lepton-jet gun Monte Carlo generator has been developed to optimize search criteria and to produce detection efficiency curves. This MC allows to study the response of the detector to lepton-jets and guide their characterization and the identification of the variables useful for the selection of signal. Only three topologies of lepton-jets are considered: TYPE0, TYPE1 and TYPE2. The first one is a cluster of only muons identified into the MS and no jets in a cone opening ΔR=0.5. It is the signature of a lepton-jet with all γ_d decaying to muon pairs. The second one is a cluster of two muons and jets in a cone opening ΔR=0.5. It the signature of one γ_d decaying to muon pair and the other one in electron or pion pair. The third one are jets with low electromagnetic fraction, narrow width and no muons in a cone opening ΔR=0.5. It is the signature of a lepton-jet with one or two γ_d both decaying to electron/pion pairs. Figures 1 shown a sketch of the three lepton-jet types.
The triggers used to select displaced lepton-jets of TYPE0 and TYPE1 is the unprescaled multi-muon trigger with at least three reconstructed muons in the MS with $p_{\mathrm{T}} \geq 6$ GeV. For the TYPE2 lepton-jets the single jet trigger with lo electromagnetic fraction is used.
The events that pass the trigger filters have to satisfy additional requirements. To separate the signal to the background the following major requirements are made: exactly two reconstructed lepton-jets in the event, both lepton-jet are isolated in the ID (the highest ID $\sum p_{\mathrm{T}}$ in the event must be ≤ 3 GeV), the absolute value of the azimuthal angle $\Delta\phi$ between the two lepton-jets must be ≥ 1, the muons must have no ID track match and the jets must be in timing with the bunch crossing ($-1ns \leq t_{jet} \leq 5ns$).

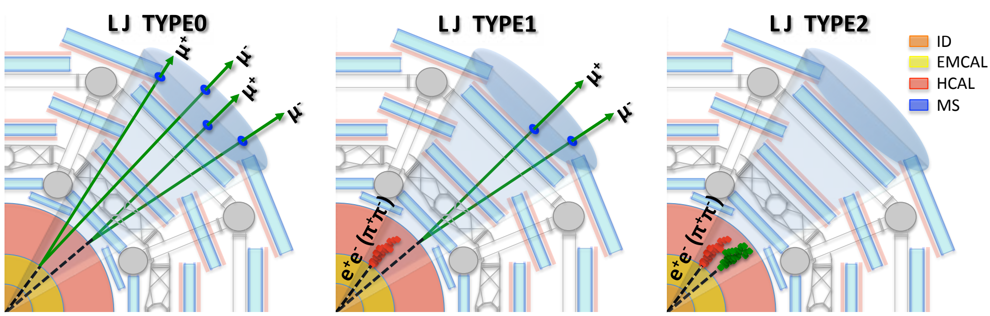

Figure 1. Sketch of the three lepton-jets classification: left TYPE0 lepton-jet (only muons), centre TYPE1 lepton-jet (muons and jets), right TYPE2 lepton-jet (only jets). If the lepton-jet contains only one γ_d it contributes only to TYPE0 and TYPE2.

3 Background

The potential backgrounds in the signal sample include all processes with prompt muons with or without associated jets (e.g. W+jets, Z+jets, ttbar, single-top, etc.), cosmic-rays (e.g. muon bundles in cosmic-ray air showers), beam induced background.
The cosmic-ray events are reduced using jet timing. For muons there is an additional requirement: the perigee to the beam line of the extrapolated MS track has to be close to the PV. For the evaluation of the remain CR contribution the triggers have been used in empty bunches of 2012 data. QCD multi-jet

is reduced using isolation in the ID (less dependent to pile-up) and jet EM fraction/width cuts. The isolation variable is the p_{T} of the ID tracks associated to the PV in a cone ΔR=0.5 around the lepton-jet line of flight ($p_T^{track} \geq 0.5$ GeV). Figure 2-left shows the ID isolation distribution in the control sample of the 2012 data selected by single-jet triggers. The ID isolation is validated using the muons from Z$\rightarrow \mu\mu$ decays. The remain QCD multi-jet background is evaluated using a data-driven matrix method. As uncorrelated variables the $|\Delta\phi|$ and max$\{\sum p_T\}$ are used. The signal region is defined as $|\Delta\phi| \geq$1rad and max$\{\sum p_{\mathrm{T}}\} \leq 3$ GeV. Figure 2-right shows the event distribution in this plane before the requirements on $|\Delta\phi|$ and max$\{\sum p_{\mathrm{T}}\}$. Indicating with "A" the signal region, the residual background in A can be predicted from the population of the other three regions: $N_A = N_B$ x N_D/N_C.

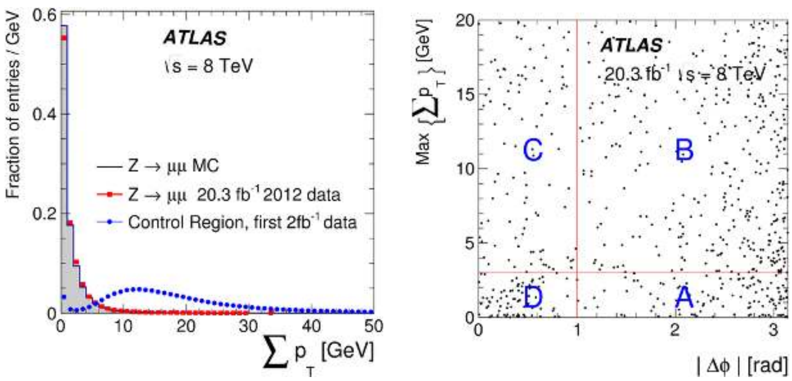

Figure 2. Left plot is the distribution of $\sum p_{\mathrm{T}}$: (filled dot) control sample of the first 2 fb^{-1} of 2012 data, (filled square) $Z \rightarrow \mu\mu$ in 2012 data and (solid line) $Z \rightarrow \mu\mu$ MC sample. All distributions are normalized to unit area. Right plot is the distribution of lepton-jet events in the ABCD plane before the requirements max$\{\sum p_{\mathrm{T}}\} \leq 3$ GeV and $|\Delta\phi| \geq 1$. Taken from [3].

4 Lepton-jet benchmark models

The performance of the lepton-jets search criteria are evaluated setting limits on two Falkowski-Ruderman-Volansky-Zupan (FRVZ) models [5] which predict non-SM Higgs boson decays to lepton-jets. Figure 3 shows the diagrams for the decay of the Higgs to lepton-jets in the two models. The two diagrams refer to the production of $2\gamma_d$ and $4\gamma_d$ respectively. In both models the decay chain contain two lighter hidden fermions HLSP (Hidden Lightest Stable Particle) that escape to the detection.

5 Results

Table 1 summarizes the data and background results of the search for lepton-jets in the 2012 data sample. Both for all lepton-jet pair events and for the case where the TYPE2-TYPE2 lepton-jets are excluded, the data agree with the background expectation.
The results of the lepton-jets search are used to set upper limits on the Higgs boson decay branching fraction to lepton-jets as a function of the γ_d mean lifetime, according to the FRVZ models. The resulting exclusion limits on the σ x BR, assuming the Higgs boson SM gluon fusion production cross section $\sigma_{SM} = 19.2$ pb, are shown in figure 4 as a function of the γ_d mean lifetime (expressed as $c\tau$) for the two benchmark models and for the cases in which all the lepton-jet type events are included

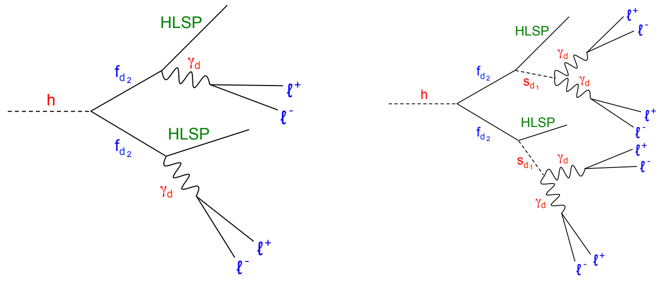

Figure 3. Diagrams of the two FRVZ models used as benchmarks in this search. l^+ l^- corresponds to electron/muon/pion pair decay in the final state.

Table 1. Summary of the lepton-jet (LJ) selection applied to data and background in the full 2012 data sample. The first uncertainty is statistical, while the second is systematic.

	All LJ pair types	TYPE2-TYPE2 LJs excluded
Data	119	29
Cosmic-rays	40 ± 11 ± 9	29 ± 9 ± 29
Multi-jets	70 ± 58 ± 11	12 ± 9 ± 2
Total background	110 ± 59 ± 14	41 ± 12 ± 29

(top plots) and for those in which the TYPE2-TYPE2 events are excluded. The corresponding limits with TYPE2-TYPE2 events excluded are shown in table 2. For the case of a hidden photon which kinetically mixes with the SM photon, these limits can be converted into exclusion limits on the kinetic mixing parameter ϵ. These results are also interpreted in the context of the Vector portal model as exclusion contours in the kinetic mixing parameter ϵ vs γ_d mass plane as shown in figure 5.

Table 2. Ranges of γ_d lifetime $c\tau$ excluded at 95% CL for $H \rightarrow 2\gamma_d + X$ and $H \rightarrow 4\gamma_d + X$, assuming 10% BR and the Higgs boson SM gluon fusion production cross section. The events TYPE2-TYPE2 are not used.

FRVZ model	Expected $c\tau$ [mm] BR(100%)
Higgs $\rightarrow 2\gamma_d$ + X	14<$c\tau$<140
Higgs $\rightarrow 4\gamma_d$ + X	15<$c\tau$<260

6 To be continue with Run II data

The opportunity offered by LHC in the era at highest energy ($\sqrt{s}$ = 13 TeV) and high luminosity was caught and a new lepton-jet search is started. An ambitious physics program for this new work is underway. It will include new triggers (e.g. single muon trigger), new TYPEs with EM clusters, the RPC timing for cosmic-rays rejection, the lepton-jet vertex search and the harmonization with prompt-lepton-jet search and extend the analysis to other lepton-jet production mechanisms (e.g. associated production with vector bosons W and Z).

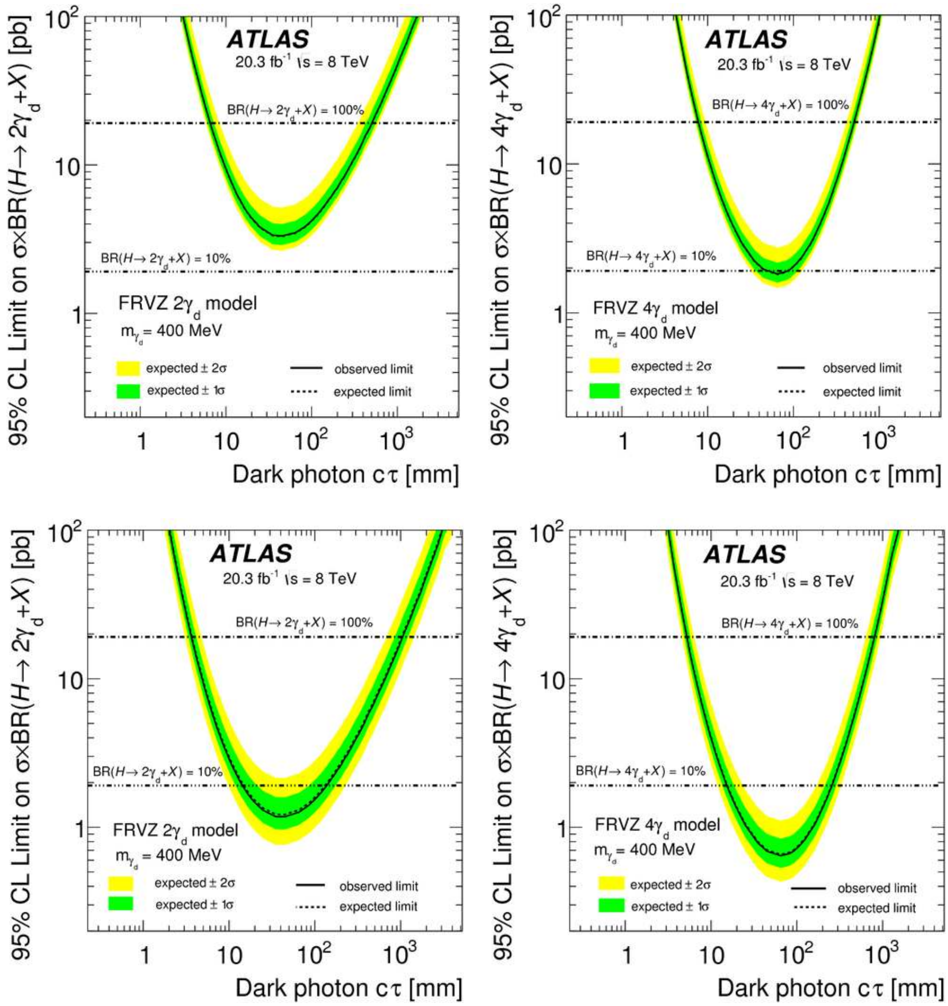

Figure 4. Top plots: 95% upper limits on the σ x BR for the processes $H \rightarrow 2\gamma_d + X$ (left) and $H \rightarrow 4\gamma_d + X$ (right), as a function of the γ_d lifetime ($c\tau$) for the FRVZ benchmark samples. Bottom plots: 95% upper limits excluding the TYPE2-TYPE2 events. The expected limit is shown as the dashed curve and the almost identical solid curve shows the observed limit. The horizontal lines correspond to σ x BR for two values of the BR of the Higgs boson decay to dark photons. Taken from [3].

7 Conclusions

The search for new phenomena beyond the Standard Model is a very active field at the ATLAS experiment. Recent results for lepton-jet search at ATLAS are presented in this note. No excess over the Standard Model expectation has been observed and limits are placed on the two FRVZ benchmark models.

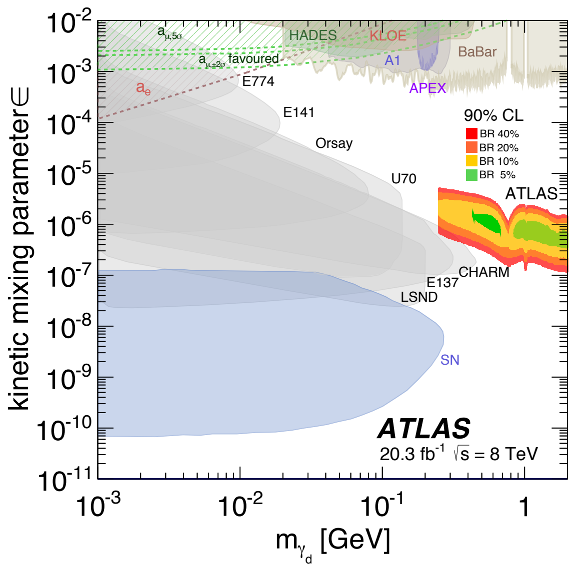

Figure 5. Parameter space exclusion plot for γ_d as a function of its mass and of the kinetic mixing parameter ϵ. The 90% CL exclusion limits are presented assuming the FRVZ model $H \rightarrow 2\gamma_d + X$ with decay branching fraction to γ_d of 5/10/20/40% and the NNLO gluon fusion Higgs production cross section. There are shown the existing 90% CL exclusion regions from other experiments like beam dump, electron and muon anomalous magnetic moment, constraints from astrophysical observations. Taken from [3].

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