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Dark Sector searches in final states with prompt neutral particles with the ATLAS detector

E. POMPA PACCHI(1)(2) on behalf of the ATLAS COLLABORATION

(1) *INFN, Sezione di Roma - Roma, Italy*
(2) *Dipartimento di Fisica, Università di Roma La Sapienza - Roma, Italy*

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Summary. — This work investigates the possibility that dark matter could be produced at the LHC, under the assumption that it is weakly coupled to the ordinary matter via a mixing parameter ε and that it constitutes a new sector of particles. Under the assumption of a neutral mediator, the dark photon, that decays promptly inside the ATLAS innermost detector volume, the lepton-jet signature, in which collimated leptons are reconstructed as a single object, is exploited. This work, based on the full Run-2 dataset, aims at extending the sensitivity of the previous Run-1 search to smaller branching ratios of the Higgs boson decaying to dark photons and to a wider dark photon mass range in the $\varepsilon > 10^{-5}$ region.

1. – Motivations and dark sector signal models

This work investigates the possibility that dark matter could be produced in ATLAS with the Higgs boson acting as a portal to a dark sector. The dark sector minimal model foresees an interaction similar to the electromagnetic one, mediated by the dark photon γ_d, which is assumed to be massive and to decay into Standard Model (SM) particles via the vector portal, where γ and γ_d mix kinematically with a mixing coupling strength ε. Small values of ε for $m_{\gamma_d} \in O(10\text{ MeV–}10\text{ GeV})$ can be probed only at accelerator facilities. To investigate the possibility that dark photons could be produced at the ATLAS detector, the signature predicted by the Falkowski-Ruderman-Volansky-Zupan (FRVZ) model [1] (fig. 1) is investigated, where the Higgs boson decays into a pair of dark fermions f_d. The process results into decays into Hidden Lightest Stable Particles (HLSPs), undetected, and γ_d decaying into a pair of light SM fermions f. The mass of the HLSPs and of the f_d are tuned to produce the same kinematics for the different m_{γ_d} hypotheses tested ($m_{\gamma_d} \in [0.017, 6]$ GeV). According to its mass, the γ_d can decay into a pair of electrons, muons or light hadrons with different BRs. The mixing coupling ε determines the dark photon mean proper lifetime, τ_{γ_d}: the smaller is ε, the larger is τ_{γ_d}. Different values of ε lead to different signatures in the detector, thus

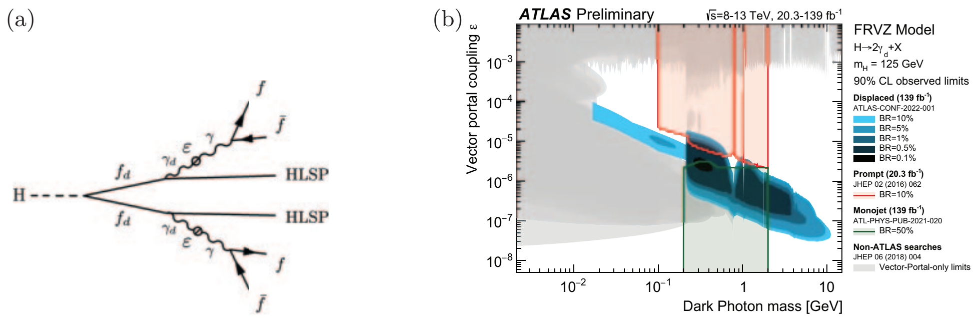

Fig. 1. – (a) Higgs decay chain predicted by the FRVZ model. The blobs represent the mixing, governed by ε, between γ_d and γ, f_d the intermediate states coupled to the Higgs, HLSP the non-interacting Hidden Lightest Stable Particle, and f the SM fermions produced in the off-shell γ decay. (b) 90% CL exclusion area in the $(\varepsilon, m_{\gamma_d})$ plane from ATLAS prompt (red) [2] search is compared with excluded areas for ATLAS displaced (azure) [3] and monojet (green) search [4], assuming different $BR(H \to 2\gamma_d + X)$.

different analysis techniques to address them properly are deployed. In ATLAS there are three γ_d searches: the prompt search [2], looking for promptly decaying γ_d resulting into collimated particles inside ATLAS Inner Detector (ID), the displaced search [3], which searches for γ_d decaying with macroscopic lifetimes inside ATLAS and leaving late calorimetric releases and/or displaced vertices, and the *mono-jet* search [4], which can be reinterpreted in terms of γ_d escaping outside the ATLAS detector before decaying because of their long lifetime and that result in missing transverse momentum. Figure 1 shows current bounds ([2-4]) for these ATLAS γ_d searches in the $(\varepsilon, m_{\gamma_d})$ plane, for different $BR(H \to 2\gamma_d + X)$ hypotheses (here X stands for undetected particles, in this context the HLSP).

Whilst published searches for displaced γ_d are based on the full Run-2 dataset, the search for promptly decaying γ_d is based on the Run-1 dataset. In this work, an ongoing search for prompt dark photon decays in the Inner Detector (ID), based on the full Run-2 sample, is described. This analysis aims at extending the sensitivity of the previous searches to smaller $BR(H \to 2\gamma_d)$ and to a wider m_{γ_d} range in the region with $\varepsilon > 10^{-5}$.

2. – Signature and analysis strategy

The Higgs production mechanism considered in this work is the gluon-gluon fusion, as it is the most likely one (whilst other ATLAS and CMS analyses have considered other production mechanisms too). In the m_{γ_d} mass range considered, dark photons decay into leptons or light-hadrons. However, since events with light-hadrons produced in the ID would be completely indistinguishable from multi-jet events, only γ_d decays into leptons are considered. Since γ_d are boosted, they produce collimated pairs of leptons: for this reason, they are reconstructed as a single object, referred to as *Lepton Jet* (LJ). There are two kinds of LJs, according to their content: the *muonic-LJ*, μLJ (bottom-left cone in fig. 2) and the *electronic-LJ*, eLJ (upper-right cone in fig. 2). In the μLJ, at least two *combined* muons (*i.e.*, whose associated track is reconstructed in the ID as well as in the Muon Spectrometer, MS) and no electrons are found within the same cone of opening angle $\Delta R = 0.4$. Since electrons produced in γ_d decays are so collimated that they are often reconstructed as a single electron, with one electromagnetic

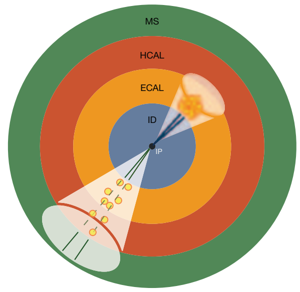

Fig. 2. – μLJ (lower-left cone) and eLJ (upper-right cone) inside the ATLAS barrel transverse plane. The outer circle represents the Muons Spectrometer (MS), the red circle the Hadronic CALorimeter (HCAL), the orange circle the Electromagnetic CALorimeter (ECAL), the blue circle the Inner Detector (ID). The black dot is the Interaction Point (IP), the yellow circles are energy releases, and continuous lines are tracks.

(EM) cluster and two tracks associated to it, an eLJ is reconstructed when at least one EM cluster with two associated tracks and no muons are found within the same cone of opening angle $\Delta R = 0.4$. Three analysis channels, depending on the LJs type, are investigated: the muonic channel (2μLJs are reconstructed), the electronic channel (2eLJs are reconstructed) and the mixed channel (1μLJ and 1 eLJ are reconstructed). All channels follow the same analysis strategy: a combination of lepton triggers is required, at least two LJs must be reconstructed and trigger matching is requested for the leptons making up the LJs. eLJ can be mimicked either by jets containing collimated tracks pointing to the same calorimetric release or by events where a real lepton is very close to a random track; electroweak production of muon pairs or the production of light resonances can instead account for events where μLJs are produced. Tables I, II show the event yield for the 2μLJ channel and the 2eLJ channel, respectively, after each of the requirements described above, assuming a $BR(H \rightarrow 2\gamma_d + X) = 5\%$. Two signal models and two of the largest background contributions are reported. The signal models here chosen are the ones with the largest (400 MeV and 17 MeV for the 2μLJ and the 2eLJ channel respectively) and smallest (6 GeV and 100 MeV for the 2μLJ and the 2eLJ channel respectively) acceptance times efficiency, $\mathcal{A}$, in the γ_d mass range where the channels are most sensitive, that is $m_{\gamma_d} < (\geq)$ 240 MeV for the 2eLJ (2μLJ) channel. The 2μLJ channel is almost background free requiring 2μLJ to be reconstructed, while the same does not hold for the 2eLJ channel, where additional quality requirements on eLJs are needed in order to suppress the background. To suppress the background due to the associated production of a Z boson and jets ($Z + jets$), the invariant mass of the eLJ is requested to be different from the Z mass. To suppress the multi-jet background the eLJ isolation $iso^{e\mathrm{LJ}} = \frac{\sum^i p_{\mathrm{T}}^i}{p_{\mathrm{T}}^{e\mathrm{LJ}}}$, where i ranges over all the tracks that have not been used to build the eLJ, is required to be null. To suppress all the backgrounds where a random track, not associated to any electron, is used to build the eLJ, the eLJ charge (*i.e.*, the sum of the charges of all the tracks inside the eLJ) is requested to be zero. Finally, a selection on the p_T imbalance, defined as $p_{\mathrm{T}}^{imb} = \frac{p_{\mathrm{T}}^{lead} - p_{\mathrm{T}}^{sub-lead}}{p_{\mathrm{T}}^{lead} + p_{\mathrm{T}}^{sub-lead}}$, is optimised to reject most of the residual background contributions maintaining a good efficiency for signal events. As the Monte Carlo (MC) simulation might not be fully reproducing the data for such unconventional signatures, MC predictions must be cross-checked with

TABLE I. – *$2\mu LJ$ channel event yields for the largest background contributions (W + jets and diboson) and for the signal points with the largest* (400 *MeV*) *and smallest* (6 *GeV*) $\mathcal{A}$*, assuming a $BR(H \to 2\gamma_d + X) = 5\%$.*

Selection cuts	$m_{\gamma_d} = 400$ MeV	$m_{\gamma_d} = 6$ GeV	*diboson*	$W + jets$
Preselection	337900 ± 700	337900 ± 700	14650 ± 35	254300 ± 2500
Trigger	45280 ± 240	23350 ± 150	9207 ± 26	11300 ± 400
2μLJ	8350 ± 100	482 ± 13	14.4 ± 0.7	1.69 ± 1.2
Trigger matching	3940 ± 70	398 ± 12	10.4 ± 0.3	1.1 ± 1.1

TABLE II. – *$2eLJ$ channel event yields for the largest background contribution (Z + jets and $t\bar{t}$) and for the signal points with the largest* (17 *MeV*) *and smallest* (100 *MeV*)$\mathcal{A}$*, assuming a $BR(H \to 2\gamma_d + X) = 5\%$.*

Selection cuts	$m_{\gamma_d} = 17$ MeV	$m_{\gamma_d} = 0.$ GeV	$Z + jets$	$t\bar{t}$
Preselection	337900 ± 660	337900 ± 700	210000 ± 1000	4700 ± 24
Trigger	82000 ± 330	70000 ± 90	180000 ± 900	4000 ± 21
$2e$LJ	15000 ± 140	5700 ± 90	180000 ± 900	3700 ± 20
Trigger matching	13000 ± 130	2400 ± 60	180000 ± 900	3600 ± 20
eLJ quality cuts	13000 ± 130	790 ± 30	90 ± 19	4.2 ± 0.7

data-driven methods. For this analysis, the so-called ABCD method will be used, and the expectation of backgrounds in each signal region will be derived from control regions defined by orthogonal selections on two uncorrelated observables. The results obtained will be interpreted in the framework of the dark sector model described above. In case no excess will be observed in the ATLAS full Run-2 data-set, these results will allow setting competitive exclusion limits for light, promptly-decaying dark photons produced by the decay of the Higgs boson. This search is expected to extend the excluded area to a m_{γ_d} range [17 MeV, 6 GeV] in the $\varepsilon > 10^{-5}$, assuming a $BR(H \to 2\gamma_d) \leq 1\%$.

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