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Searches for unconventional signatures with the ATLAS detector at 13 TeV

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A review of exotic unconventional detector-signatures searches performed by the ATLAS experiment is presented. General introduction to unconventional searches is included, as well as selected detailed results based on data collected during early $\sqrt{s}$ = 13 TeV pp collisions at the LHC.

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1. Introduction

Many of the new physics scenarios predict the existence of new particles with relatively long lifetime, a feature that can enable a direct measurement. The new particles might differ from the Standard-Model (SM) ones in the way they interact with the detector, producing *"unconventional"* signatures. For instance, a particle that is predicted to be massive is expected to travel at lower velocities than the speed-of-light, and if electrically charged it might be highly ionizing.

The features of the detector signature which categorize it as unconventional, depend a lot on the new particle degree of stability. In general, a particle is considered as a *'long-lived particle'* (LLP) if it can be measured directly by the detector, yet there can be a distinction between two types: stable and meta-stable LLPs.

An LLP is considered as stable if it has long enough lifetime to cross the entire detector, i.e. pass through all detector layers without decaying into other particles. Such particles, if electrically charged are expected to leave a signal in all detector stations [1][2][3]. A non-SM particle can be referred to as a meta-stable LLP with a lifetime sufficient to decay within the detector, and since the exact decay location of the particle cannot be predicted in advance, a range of possible lifetimes will be studied.

Such particles decaying in the detector can exhibit a variety of signatures, depending on their electric charge. If the particle is produced as electrically charged and is not the lightest BSM particle, it can decay into a neutral BSM particle and low-momentum SM one. This final state will be reflected in the detector as an amputated track, and is referred to as a *'disappearing track'* [1][2][4]. In case the particle is produced neutral, the decay inside the detector would result in a vertex appearing in one of the detector stations with no trails leading to the interaction-point (IP). These studies are referred to as *'displaced vertices'*[1][2][5] searches, and are the main focus of this summary.

2. ATLAS unconventional signature searches

Unconventional detector signature searches are performed within ATLAS [6] in both the Supersymmetry (SUSY)[1] and Exotic[2] communities, and include studies of all LLP categories.

In most of the cases, the main strategy is to search for a specific detector signature, and rely on the way the LLP interacts with the detector in order to distinguish the SM background from possible signal. Yet most of the currently available trigger chains are not designed to detect these types of unusual objects and therefore the existing trigger chains are creatively exploited to eliminate non-relevant events from the studied sample. Also, the common analysis tools are not entirely suitable for these kinds of searches and hence search teams are required to develop new or modified object reconstruction and analysis tools, as well as custom made Monte-Carlo (MC) simulations for signal samples. The background estimation is in most of the cases data driven, i.e. using control data samples where the main source for background originate from badly reconstructed or mis-measured objects as well as beam-halo and instrumental noise.

3. Displaced vertices searches

Searches for displaced vertices in early $\sqrt{s}$ = 13 TeV pp collisions data have been performed. These studies carry-out model-independent searches which are interpreted using several simplified versions of Hidden-sector predictions, and rely on detector signature reflecting a neutral LLP decay in the detector with no trails leading to the IP. The studies considered here are a search for displaced jets [7] and for displaced leptonic-jets (LJs) [8]. In both cases the main source of background originates from multi-jet production and Non-Collision Background (NCB), where the latter includes cosmic muons and beam halo (also referred to as Beam Induced Background (BIB)). The ABCD data-driven method is used for background estimation, using two discriminating variables. The results published are based on data sample of $\sim$3fb^{-1} collected during 2015 run.

3.1 Displaced jets in the calorimeter

The theoretical prediction for Hidden Sectors (HS) suggests a new sector, weakly coupled to the SM one via a communicator particle, where the HS particles may decay to SM particles via the communicator. The search described here [7] considers a simplified interpretation to the HS model, in which the SM sector and the HS are connected via a heavy neutral boson Φ. If produced, the Φ is expected to decay into two long-lived neutral scalars s ($\Phi \to ss$), which eventually decay into a pair of SM fermions f ($s \to f\bar{f}$). In the current study s is predicted to decay in the hadronic calorimeter and will result in a narrow jet.

The detector signature will include two displaced vertices, atypical and narrow jets (mainly composed of $b\bar{b}$-quarks), with no Inner-Detector (ID) tracks and small energy deposition in the electromagnetic calorimeter, i.e. high CalRatio-jet ($\frac{E_{HCal}}{E_{EM}}$). The mass ranges studied included a heavy boson Φ of masses: $m_\Phi = 400$ GeV $\to$ 1 TeV and a neutral scalar s of: $m_s = 50 \to 400$ GeV. The main online selection was done by the CalRatio signature-driven trigger, and the offline selection included mainly the BIB removal algorithm in order to eliminate background jets and Boosted Decision Tree (BDT) plus p_T cuts based on the study results shown in Fig. 1.

The final background rejection step include cuts on the BDT value within time window, p_T for soft NCB jets rejection and angle separation between the two jets $\Delta\Phi(jet_1^{CalRatio}, jet_2^{CalRatio})$.

A data driven ABCD method was used for background estimation, with the two discriminating variables (Fig. 1) $\Sigma\Delta R_{min(jet,tracks)}$ (the minimum distance between a jet and all tracks with $p_T \leq 2$ GeV, summed for all jets with $p_T \leq 50$ GeV) and ΣBDT (the sum of the BDT values of the two jets with the highest BD values in the event).

Consistency between the number of predicted background events (18.4 $\pm$ 6.3 (stat) $\pm$ 6.6 (syst)) and number of observed events (24) was found. Limits were set on $\sigma \times BR$ of the signal as a function of the proper lifetime of the LLP. For the heaviest scalar boson explored with mass m_Φ = 1 TeV, the limits were set at 1pb σ assuming BR=100%, with the s decay length range excluded between 0.05 m $\to$ 16 m (Fig. 1).

3.2 Displaced lepton-jets

Models that include a hidden photon, γ_d, mixed kinetically with the SM photon predict the new photon to have small mass. These hidden photons are highly boosted and can be relatively long lived depending on the kinetic mixing parameter. The lightest hidden photon is expected to

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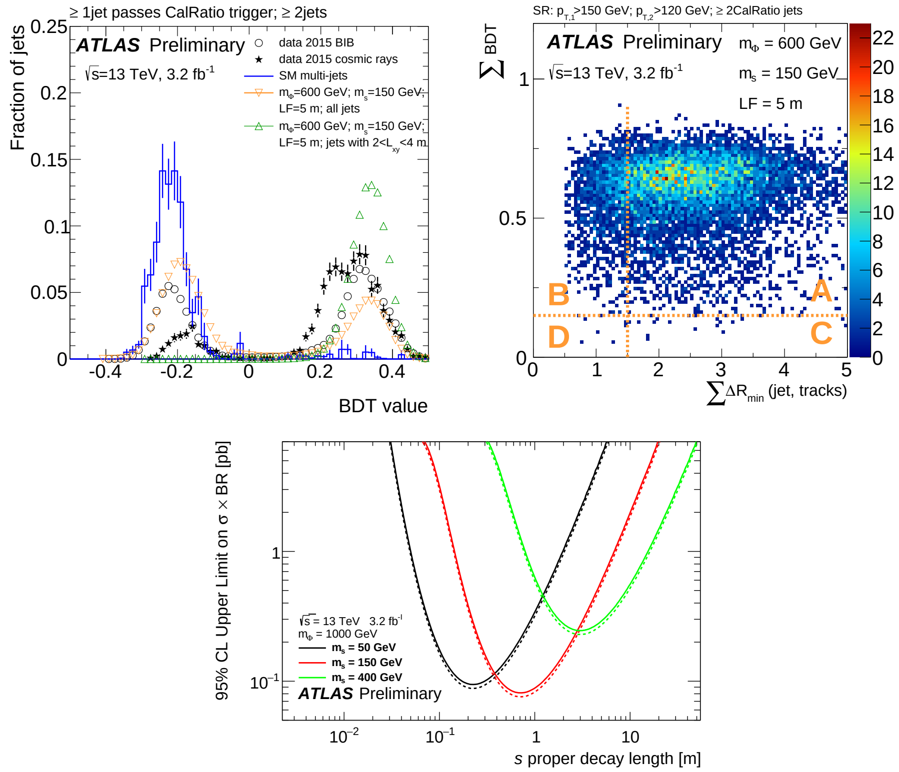

Figure 1: Top left: BDT value distribution of jets with pT > 40 GeV in events passing the CalRatio trigger, for beam induced background taken from data (BIB), cosmic-ray muons, SM multi-jets MC, signal including all jets (orange upside-down triangles) and signal including only jets with 2 < Lxy < 4 m (green triangles). The error bars account for statistical uncertainties only. Top right: Σ Δ Rmin (jet, tracks) vs. Σ BDT distribution after the final selection for signal MC events containing two CalRatio jets. Bottom: The observed 95% CL upper limits on the $\sigma \times BR$ for the signal samples with Φ mass of 1000 GeV as a function of the s proper decay length. The dashed line is the expected limit, and the solid line is the observed limit for each labeled mass.

decay to SM particles, mainly leptons and mesons. The study shown here [8] considers two FRVZ models as benchmarks, where in both cases the hidden sector is communicating with the SM one through the Higgs portal, i.e. the Higgs boson decays into a pair of hidden fermions f_{d2}. In the first model the dark fermion f_{d2} decays into a dark photon γ_d and a Hidden-Lightest-Stable-Particle (HLSP) f_{d1}. In the second, the dark fermion f_{d2} decays into a dark scalar s_{d1} and an HLSP, and the scalar s_{d1} is then expected to decay into a pair of dark photons. Each dark photon is expected to decay into two Lepton-Jets (LJs) produced back-to-back in the azimuthal plane.

The detector signature type depends on the LJs, which are defined and classified according to their muon/jet content found within a cone of opening: $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

Three types of signatures are studied : Type0 - Muons only - at least two muons, no jets. Type1 - Muons + jet - at least two muons and only one jet. And type2 - Jets only - no muons, only jets.

The study considered both cases of either 2 or 4 dark photons produced with mass of: $m_{\gamma_d} =$ 0.4 GeV, and two possible Higgs scenarios: SM-Higgs of m_H = 125 GeV and non-SM Higgs of mass: m_H = 800 GeV. Online selection of events included an 'OR' combination of 3 trigger chains: Narrow scan (scan for muon objects in a narrow cone), Tri-muon Muon-Spectrometer (MS) only (events with at least 3 muons and no Inner-Detector (ID) information) and CalRatio (isolated jets with low energy deposition in the electromagnetic calorimeter). The background rejection depends on the type of detector signature studied as detailed in [8].

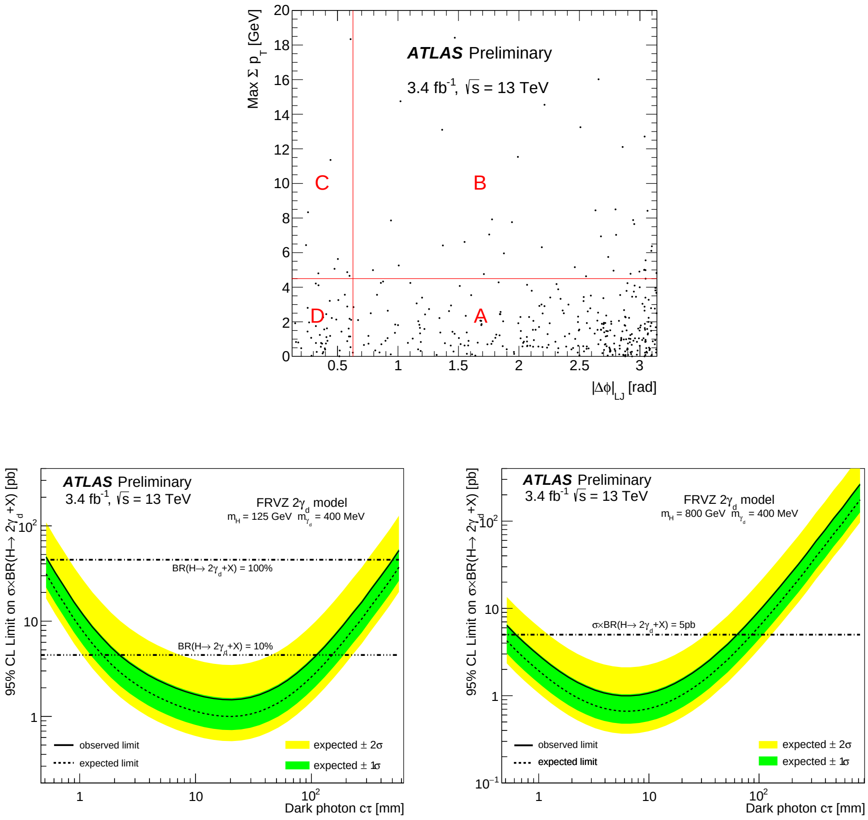

Figure 2: Top: Schematic of the ABCD method in the ($|\Delta\Phi|_{LJ}$, Max Σp_T) plane with the definition of the ABCD regions. Left: The 95% upper limits on the $\sigma \times BR$ for the FRVZ 125 GeV Higgs $\to 2\gamma_d + X$ benchmark models as a function of the γ_d lifetime ($c\tau$). The horizontal lines correspond to $\sigma \times BR$ for two values of the BR of the Higgs boson decay to dark photons. Right: The 95% upper limits on the $\sigma \times BR$ for the FRVZ 800 GeV $\to 2\gamma_d + X$ benchmark models as a function of the γ_d lifetime ($c\tau$). The horizontal lines correspond to a $\sigma \times BR$ of 5 pb.

Final offline selection of events required two LJ objects that passed the background rejection criteria, ID-track isolation and $\Delta\phi$ separation between the two LJs.

The background was estimated using a data-driven ABCD method with two discriminating variables (as demonstrated in Fig. 2): maxΣp_T (the maximum value of Σp_T^{ID} amongst all LJs in a given event) and $|\Delta\phi|_{LJ}$ (the angle separation between the two LJs).

The number of observed events (285) was found to be consistent with the number of expected background events (231 $\pm$ 12 (stat) $\pm$ 62 (syst)), therefore limits were set on both Higgs scenarios decaying into LJs (Fig. 2). For the case of SM-Higgs decaying into dark photons, the BR was found to be lower than 10% and the following dark-photon decay-lengths were excluded: $H \to 2\gamma_d + X$

for γ_d with $2.2mm \leq c\tau \leq 111.3mm$, and $H \rightarrow 4\gamma_d + X$ for γ_d with $3.8mm \leq c\tau \leq 163mm$. In the case σxBR of 5.0 pb for non-SM Higgs, with mass of m_H = 800 GeV, decaying into dark-photons the excluded decay-lengths were: $H \rightarrow 2\gamma_d + X$ for γ_d with $0.6mm \leq c\tau \leq 63mm$ and $H \rightarrow 4\gamma_d + X$ for γ_d with $0.8mm \leq c\tau \leq 186mm$.

4. Summary

Many BSM scenarios predict unconventional final-state detector signatures. Customized analysis tools achieve the sensitivity needed to either detect or set limits on their production. Studies of meta-stable LLPs forming a displaced vertices type of detector signature were presented based on early 13 TeV data runs, with no evidence for the existence of new physics and limits were set at 95% CL on the new particles decay-length.

The current LLP triggers are being updated and new ones designed for both Phase-I and Phase-II ATLAS upgrades. New triggers will address more LLP scenarios, using new and improved technologies for running more sophisticated algorithms online. The new technological phase, together with the increase in luminosity will allow for higher sensitivity for unconventional signature searches [9].

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