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Search for BSM physics using challenging signatures with the ATLAS detector

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Various theories beyond the Standard Model predict unique signatures which are difficult to reconstruct and for which estimating the background rates is also a challenge. Signatures from displaced decays anywhere from the inner detector to the muon spectrometer, as well as those of new particles with fractional or multiple value of the charge of the electron or high-mass stable charged particles are all examples of experimentally demanding signatures. This review focuses on the most recent results using LHC *pp* collision data at 13 TeV collected by the ATLAS detector.

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1. Introduction

Long-lived particles (LLPs) occur in many extensions to the Standard Model (SM). Most Beyond-the-Standard Model (BSM) searches target promptly decaying particles and have no sensitivity for scenarios involving LLPs. Specially designed searches are hence needed to scrutinize the range of the parameter space where these particles are predicted.

Given the large variety of existing BSM theories, searches for exotic LLPs in the ATLAS experiment [1] are driven by the experimental signature: charged, highly ionizing LLPs with large energy loss in different subdetectors; neutral LLPs leading to displaced objects, divided in different groups depending on where in the detector the LLP decays and what the decay products are: hadrons or leptons in the Inner Detector (ID), creating displaced vertices; hadronic decays in the calorimeter giving rise to displaced jets; hadronic decays in the Muon Spectrometer (MS) producing displaced vertices in the MS; light LLPs decaying after the ID to pairs of collimated leptons or light hadrons; etc. The ATLAS detector is optimized for object identification of prompt particles. Hence, searches for LLPs have to confront several challenges in terms of trigger selection (the first step in data taking), objects reconstruction and background estimation. The lack of efficient triggers for LLPs can risk missing a discovery and specific triggers need to be designed for each unconventional signature. The standard object identification algorithms assume prompt particles and they need to be adapted for the identification of LLPs. The background estimation in LLP searches is done with data-driven methods in most cases, as the main source of background in these analyses usually comes from rare objects from SM processes, instrumental or non-collision backgrounds.

A review of the most recent searches for unconventional signatures from LLPs with the ATLAS detector using Run 2 data of the LHC is presented, where LLPs were looked for in events with displaced jets, collimated pairs of objects, displaced vertices and highly ionizing particles.

2. Searches for displaced jets

Neutral LLPs decaying hadronically within the ATLAS detector give rise to displaced jets (DJs) which can be reconstructed as displaced vertices when they decay in the ID or in the MS or as trackless jets with a characteristic distribution of their energy when they decay in the hadronic calorimeter (HCal). The *CalRatio search* [2] and the *MS search* [3] aim at detecting neutral LLPs decaying in the HCal and in the muon system respectively. One of benchmark models used in these two analyses considers a Hidden Sector where long-lived scalars, produced from decays of heavy bosons, decay to SM fermions.

The CalRatio search looks for pairs of DJs using two triggers specifically designed for this analysis. In the high-E_{T} trigger, an initial energy cluster of $E_{\mathrm{T}} > 60$ GeV is required. The low-E_{T} trigger starts by requiring an energy cluster of $E_{\mathrm{T}} > 30$ GeV fully deposited in the HCal. At a second stage, both triggers select events with at least one narrow jet with no ID-tracks and a large fraction of its energy deposited in the HCal. The high-E_{T} trigger has an efficiency of $> 80\%$ for scalars with $p_{\mathrm{T}} \geq 100$ GeV decaying in the HCal while the low-E_{T} trigger is up to 35% efficient for lower-p_{T} scalars. A per-jet Boosted Decision Tree (BDT) discriminates displaced jets in signal from the main backgrounds: SM multijets and beam-induced-backgrounds. The two jets classified as the most signal-like are used as input to a per-event BDT along with other event variables. A

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final requirement on the p_T of the two most signal-like jets is applied to further reject background. A data driven ABCD method is used for background estimation using the per-event BDTs as one of the discriminating variables. The number of predicted events from backgrounds are consistent with the observation in the 33.0 fb^{-1} of data recorded in 2016 with the ATLAS detector.

The MS search studies three channels: two MS-vertices; one MS-vertex plus missing transverse energy (MET); one MS-vertex plus two prompt jets. A trigger that identifies clusters of muons in the MS is used with an efficiency ranging from 90% in high-p_T jets to 20% in low-p_T jets, for decays at the outer edge of the HCal or within the MS. A dedicated algorithm to reconstruct tracks in busy environments was used to reconstruct displaced MS-vertices. These are required to be isolated from ID-tracks and from jets. The main source of background comes from punch-through jets. In the two-MS-vertices channel (MS2), the background is estimated using data by quantifying the frequency with which an isolated MS vertex is reconstructed for non-signal events. In the MS-vertex plus jets channel, two high-p_T standard jets are required with an angular distance to the vertex greater than 0.7. The MS-vertex plus MET channel is optimized to search for Stealth SUSY where a long-lived singlino decays to a singlet that in turn decays to gluons generating the displaced MS-vertex, along with a gravitino resulting in MET. A minimum MET of 30 GeV is required in a direction close to the MS-vertex. In both single-MS-vertex channels (MS1) the background is estimated with the data-driven ABCD method, using discriminating variables such as the vertex isolation or the number of hits in the MS. The expected background is in good agreement with the observed number of events in 36.1 fb^{-1} of data recorded in 2015 and 2016.

The results from the CalRatio and the MS searches were combined in the interpretation for the Hidden Sector model for long-lived scalars s with masses $5 \leq m_s \leq 400$ GeV and heavy bosons Φ with masses $125 \leq m_\Phi \leq 1000$ GeV. Limits are set on $\sigma \times BR$ as a function of the proper lifetime of the LLP, covering distances from tens of centimeters to hundreds of meters. The MS search is generally more sensitive for low-boosted LLPs and long decay lengths while the CalRatio search sets stronger limits for higher-boost LLPs and shorter decay lengths, as can be seen in Figure 1 showing example limits for (m_Φ, m_s) = (125, 25) GeV and (600, 150) GeV. The MS search reports on limits to the mentioned Stealth SUSY model and in a baryogenesis scenario as well.

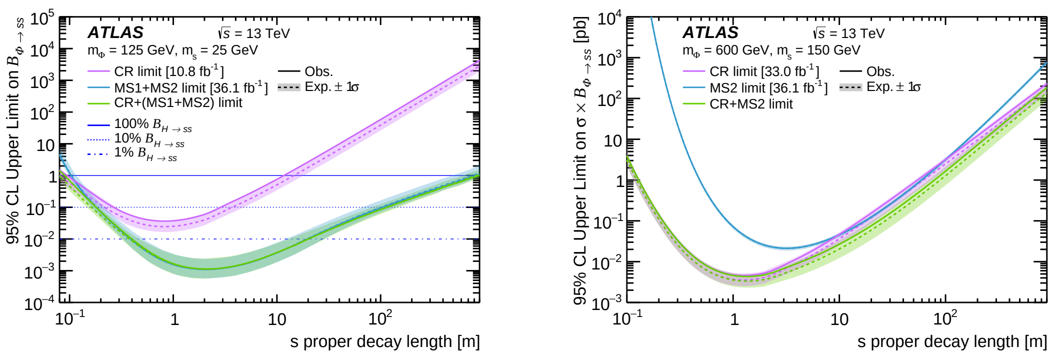

Figure 1: Examples of the combined limits for models with $m_\Phi = 125$ GeV (left) and $m_\Phi = 600$ GeV (right) from the CalRatio (CR) analysis and the MS analysis [2].

3. Displaced dark-photon-jets

Several BSM models predict the existence of a dark sector weakly coupled to the SM. The ATLAS search [4] investigates the case where the two sectors couple via a vector portal, in which a dark photon (γ_d) mixes kinetically with the SM photon and decays into SM leptons and light quarks. For a small kinetic mixing value the γ_d becomes long-lived. Due to their small mass, they are expected to be produced with large boosts, with their decays resulting in collimated groups of leptons and light hadrons in a jet-like structure, referred to as dark-photon jets (DPJs).

The detector signature type depends on the DPJ decay mode. Muonic decays are selected with a logical OR of a dedicated trigger looking for pairs of muons in a narrow cone and a tri-muon trigger. Hadronic decays use the dedicated trigger described in the CalRatio search in Section 2. Per-DPJ BDTs are used to identify these objects. In the muonic case the aim is to separate signal muons from cosmic muons which constitute the main source of background in this channel. For the hadronic case the training is done against SM multijets. The final selection requires a pair of DPJs, with three possible combinations: muonic-muonic, muonic-hadronic, hadronic-hadronic. The background was estimated separately in each of the three channels using the data-driven ABCD method. The number of observed events was in good agreement with the expected backgrounds in the three cases, considering an integrated luminosity of 36.1 fb^{-1} data. A cross section times branching fraction below 4 pb is excluded for a Higgs boson decaying to two dark photons for decay lengths between 1.5 mm and 284 mm. Exclusion limits are also provided for kinetic mixing parameter ε as a function of the dark photon mass as shown in Figure 2.

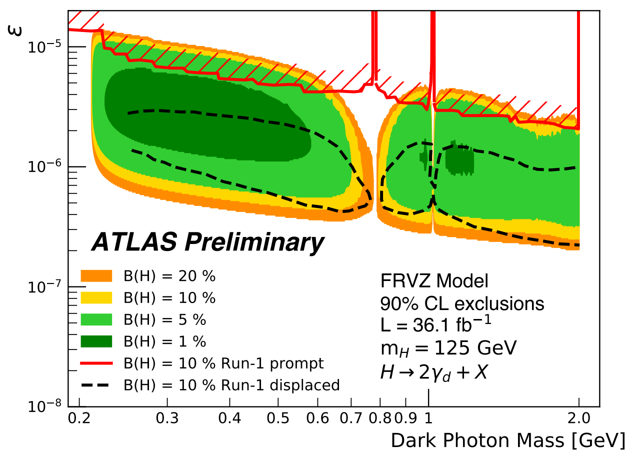

Figure 2: The 90% CL exclusion regions for the decay $H \to 2\gamma_d + X$ of the SM Higgs boson as a function of the γ_d mass and of the kinetic mixing parameter ε [4].

4. Heavy neutral leptons

The problems of neutrino masses, matter-antimatter asymmetry, and dark matter could be addressed by postulating right-handed neutrinos with Majorana masses below the electroweak scale. In [5], leptonic decays of W bosons extracted from 36.1 fb^{-1} of 13 TeV data with the ATLAS detector are used to search for heavy neutral leptons (HNL) produced through mixing with muon or electron neutrinos. Only leptonic decays ($W \to l$ NHL ; NHL $\to lW; W \to l\nu$) are considered.

The search is conducted in both prompt and displaced leptonic decay signatures. Standard lepton triggers are used for selecting the prompt lepton from the W decay. The prompt signature requires three leptons produced at the interaction point (either $\mu\mu e$ or $ee\mu$) with a veto on same-flavour opposite-charge topologies. For HNL masses $m_N < 20$ GeV, as the HNL lifetime gets longer for lower masses and coupling strengths, searches relying on standard prompt objects become highly inefficient. The requirement of a displaced vertex (DV) in the ID detached from the primary interaction eliminates the vast majority of SM backgrounds. In order to recover ID-tracks from DVs, an additional large-radius tracking algorithm was run, using only hits not already associated with tracks reconstructed by the standard ATLAS tracking algorithm. The DV is required to be formed by exactly two tracks with opposite charges from either $\mu\mu$ or μe and must be within the fiducial volume defined as $4 < r_{\mathrm{DV}} < 300$ mm, where r_{DV} is the distance to the beam axis. The overall signal efficiency depends on the HNL mass and lifetime and is typically 1-2%. Possible background sources include hadronic interactions in material, decays of metastable particles such as b- and s-hadrons, accidental crossings of charged particles produced in the collisions, and cosmic-ray muons. The DV invariant mass is required to be higher than 4 GeV to reject low-mass backgrounds, studied using a control data sample. A maximum of 2.3 events are expected in the signal region and 0 events were observed. Limits are set on the coupling strength, $|U_\mu|^2$, as a function of the HNL mass. Figure 3 shows how the prompt signature excludes the regions in $|U_\mu|^2$ above 1.4×10^{-5} in the mass range 20 - 30 GeV. For masses below 10 GeV the displaced signature becomes more sensitive excluding coupling strengths down to $|U_\mu|^2 \sim 2 \times 10^{-6}$ assuming lepton-number violation (LNV) and $\sim 1.5 \times 10^{-6}$ for lepton-number conservation (LNC).

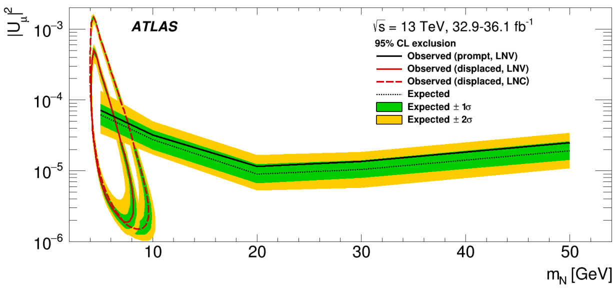

Figure 3: Observed 95% CL exclusion in $|U_\mu|^2$ versus the HNL mass for the prompt and the displaced signatures [5].

5. Highly ionizing particles

The quantum description of the magnetic monopole formulated by Dirac provides a compelling explanation for electric charge quantization. Some extensions of the SM predict monopoles with masses that could be in a range accessible to the LHC. Dirac's fundamental magnetic charge corresponds to $q_m = Ng_Dec$, where $g_D = 1/(2\alpha) = 68.5$ is the Dirac charge, α is the fine structure constant, N is an integer number, e is the unsigned electron charge and c is the speed of light in vacuum. A high-velocity Dirac monopole of magnetic charge g_D would interact with matter like an ion of electric charge $|z| = 68.5e$. Since the energy loss is proportional to the square of the charge, it would deposit 4700 times more energy than a proton. The search presented in [6] considers highly-ionizing particles (HIP) such as magnetic monopoles with $g_D = 1$ or 2 and stable objects with high electric charge (HECO) in the range $20 \leq |z| \leq 100$ and masses ranging from 200 to 4000 GeV, assuming Drell-Yan pair production of these particles.

A dedicated trigger requires an initial energy cluster of $E_{\mathrm{T}} > 18$ GeV in the electromagnetic calorimeter (ECal) with requirements on the number and fraction of high-threshold (HT) hits in the transition radiation tracker (TRT, the outermost part of the inner detector) in a narrow region around the ECal cluster. HT hits correspond to energy deposits in a TRT straw of 6 keV in Xe (2 keV in Ar). The remaining selection uses the fraction of HT hits in an 8-mm-wide rectangular road around the ECal cluster, f_{HT}, and a variable that gives a measure of the energy dispersion of the ECal cluster. Backgrounds sources are random combinations of rare processes such as overlapping charged particles, noise in TRT or in the ECal and high-energy electrons. A final expectation of $0.20 \pm 0.11(stat) \pm 0.40(sys)$ events estimated from data is in agreement with no events observed in 34.4 fb^{-1} of data. Limits are set on production cross sections as a function of HIP mass as shown in Figure 4 for monopoles and HECOs. The search improves by approximately a factor of five the constraints on the direct production of magnetic monopoles and HECOs.

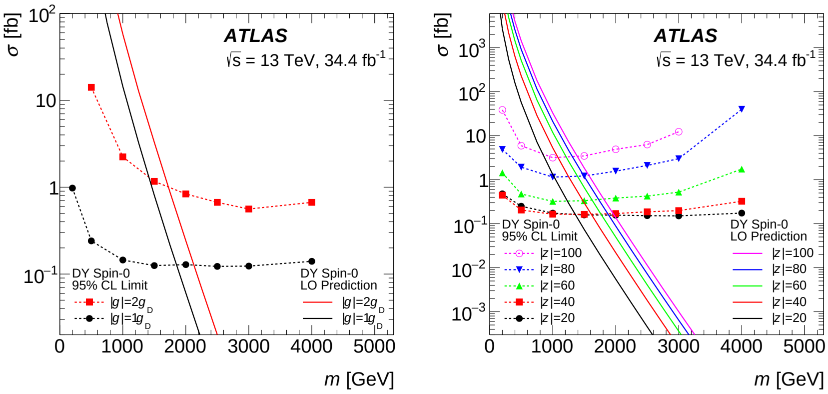

Figure 4: Observed 95% confidence-level upper limits on the cross section for Drell-Yan spin-0 monopole (left) and HECO (right) production and theoretical leading-order cross sections as a function of mass [6].

6. Multicharged particles

Several theoretical models predict heavy multicharged particles (MCP). Doubly charged Higgs bosons are predicted by the left-right symmetric model in Higgs triplets in a model postulating a right-handed version of the weak interaction. The supersymmetric left-right model with lepton number conservation predicts a light $H^{\pm\pm}$ boson with null lepton number, forbidding its decay to two same-sign leptons and making the boson long-lived. In the ATLAS search for MCPs [7], these are assumed to live long enough to traverse the ATLAS detector without decaying, leaving a muon-like signature. As explained in Section 5, particles with large electric charge have high ionizing power, leading to a significant slowdown and to large values of the ionization in the pixel, TRT and monitored-drift-tube (MDT) chambers in the MS systems. The search is performed in the mass range from 50 to 1400 GeV, for electric charges $2 \leq z \leq 7$, assuming Drell-Yan pair production.

A single-muon trigger selects particles with velocity $v/c > 0.6$ due to a timing window within which particles must reach the MS. An additional MET trigger was employed to recover slowly moving particles. A candidate muon track is defined with $p_{\mathrm{T}}^{\mu}/z > 50$ GeV, required to be isolated from other tracks in order to reduce the background from two or more tracks firing the same TRT straws or MDT tubes. The significance of the ionization is defined by comparing the observed signal with the average value for a highly relativistic muon calculated in a data control sample. The significance in the pixel detector is a powerful discriminator for particles with $z = 2$. For higher values of z, the number of overflowing pixel clusters and f_{HT} are used. The significance in the MDT and in the TRT are used for further background rejection. The contribution from remaining backgrounds, estimated from data, turns out to be smaller than 0.16 events for both the $z = 2$ and $z > 2$ cases. No candidate events were found in the 36.1 fb^{-1} of examined data. Figure 5 shows the observed 95% CL cross-section limits as a function of the MCP mass with different charges. MCPs with masses between 50 and 1220 GeV are excluded.

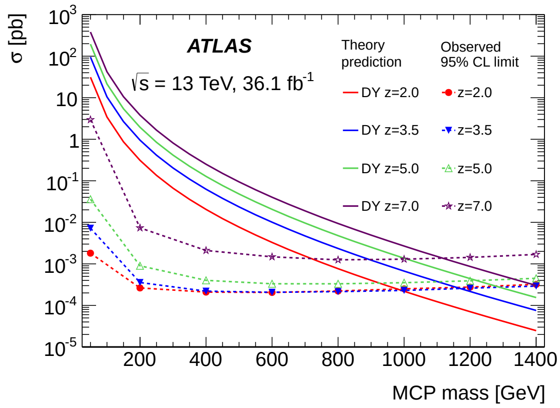

Figure 5: Observed 95% CL cross section upper limits and theoretical cross sections as a function of the MCP mass [7].

7. Summary

Many BSM scenarios predict long-lived particles (LLP) that would leave unconventional detector signatures. Customized analysis are needed to achieve the sensitivity to either detect or set limits on their production. ATLAS has published a large number of searches involving such challenging signatures. Here six searches for exotic LLPs were presented using LHC Run 2 data from 2015 and/or 2016 collected with the ATLAS detector. Many of these searches developed triggers specific for a particular signature and all of them used dedicated techniques to reconstruct objects like displaced jets, displaced vertices in the ID or in the MS and highly ionizing particles. No deviations from the expected backgrounds were found and strong limits were set in the considered models in terms of the production cross-section as a function of the LLP's mass and/or lifetime.

References

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