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Searches for BSM physics using challenging and long-lived signatures with the ATLAS detector

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Various theories beyond the Standard Model predict new, long-lived particles with unique signatures which are difficult to reconstruct and for which estimating the background rates is also a challenge. Signatures from exotic heavy particles, or long-lived particles decaying in the inner detector, as well as those from particles with a charge larger than the elementary unit charge, are all examples of experimentally demanding signatures. Four recent results using 13 TeV proton-proton collision data collected by the ATLAS detector are presented here.

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1. Unconventional and long-lived signatures at ATLAS

Since the beginning of its first data-taking campaign, the ATLAS Collaboration [1] has published numerous studies that search for Beyond-Standard Model (BSM) physics in hadronic collisions. In the following, four different recent searches for BSM physics are summarised. These exploit proton-proton collision data at $\sqrt{s} = 13\,\mathrm{TeV}$, collected between 2015 and 2018, corresponding to an integrated luminosity of $139\,\mathrm{fb}^{-1}$. Although multiple search channels and different benchmark models are tested, all these searches are united by the idea that BSM physics processes can originate unusual signatures such as anomalous energy deposits, long time-of-flights or displaced vertices due to Long-Lived Particle (LLP) decays. Searches based on unconventional signatures can be highly sensitive to BSM physics, but very often rely on dedicated reconstruction algorithms or on dedicated strategies for the estimation of the background, which can be due to statistical fluctuations of energy deposits or rare events that are not well reproduced in Monte Carlo simulations.

2. Searches based on highly-ionising particles

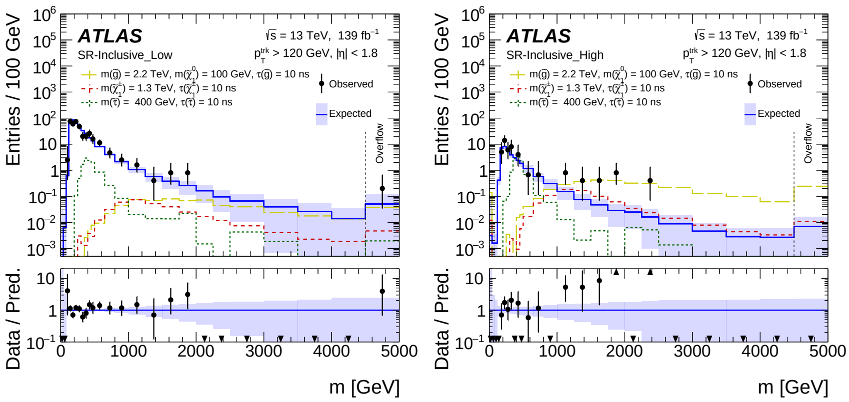
Charged particles with masses between hundreds of GeV and a few TeV can be produced in proton-proton collisions with a significantly low velocity (β), compared to the speed of light. If their mean proper lifetime is long enough, these particles can leave large energy deposits per unit length (dE/dx) in the sensitive material of the detector, compared to Minimum Ionising Particles (MIP).

Search for charged long-lived particles with large ionisation losses in the pixel detector

A recent ATLAS study [2] is based on the measurement of the dE/dx in the pixel detector. The measurement of this quantity is possible starting from the *time-over-threshold* information of the signal produced by the ionising particle, which is proportional to the ionisation charge. A series of corrections and calibration are applied to this variable, taking into account the different conditions of the detector during the data taking and finally the $\beta\gamma$ of the particles is estimated from the Bethe-Bloch relation. This information, combined with the particle momentum determined by the tracker, allows to get a powerful estimator for the mass of slow-moving particles.

The study is optimised on Monte Carlo events containing supersymmetric (SUSY) partners of SM particles such as gluinos, charginos or sleptons. These particles can be pair-produced and, after travelling a macroscopic distance in the detector, decay in SM particles and invisible SUSY partners that remain undetected. This suggests the use of a trigger based on missing transverse momentum ($E_{\mathrm{T}}^{\mathrm{miss}}$) as a generic feature-less trigger for this search. The event selection exploits quality requirements on the events and on the track associated with large dE/dx, in order to reject common SM backgrounds. Events are classified according to their dE/dx, if between 1.8 and $2.4\,\mathrm{MeV\,cm^{-2}\,g^{-1}}$ or if $dE/dx > 2.4\,\mathrm{MeV\,cm^{-2}\,g^{-1}}$. A total of 8 Signal Regions (SRs) are defined, targeting different values of particle lifetimes and masses (e.g. by requiring hits in the muon system or large ionization released in a single pixel layer). Background contributions to these SRs are due to SM processes that yield mis-identified tracks with large dE/dx, due to statistical fluctuations. The amount of background is estimated thanks to generated SR-like events, where the track kinematics and dE/dx are extracted from dedicated control regions.

Observed data agree with the predicted background for the four regions with $dE/dx \in [1.8, 2.4]$ MeV cm^{-2} g^{-1}, as well for three of the four regions with $dE/dx > 2.4$ MeV cm^{-2} g^{-1}. A likelihood fit of the particle mass distribution is used to put limits on the production of gluinos, charginos or sleptons in a lifetime range above 1 ns. One of the SRs with $dE/dx > 2.4$ MeV cm^{-2} g^{-1} shows an excess of 7 events observed over the expected background of 0.7 ± 0.4 events, corresponding to a local (global) excess of $3.6\,\sigma$ $(3.3, \sigma)$. Figure 1 shows the mass distribution of candidate tracks entering two signal regions of this search. The time-of-flight information of these candidate tracks has been further inspected, using the information from the calorimeter and the muon spectrometer, which both found that the velocity of these particles is compatible with $\beta = 1$, thus rejecting the hypothesis of heavy slow-moving particles.



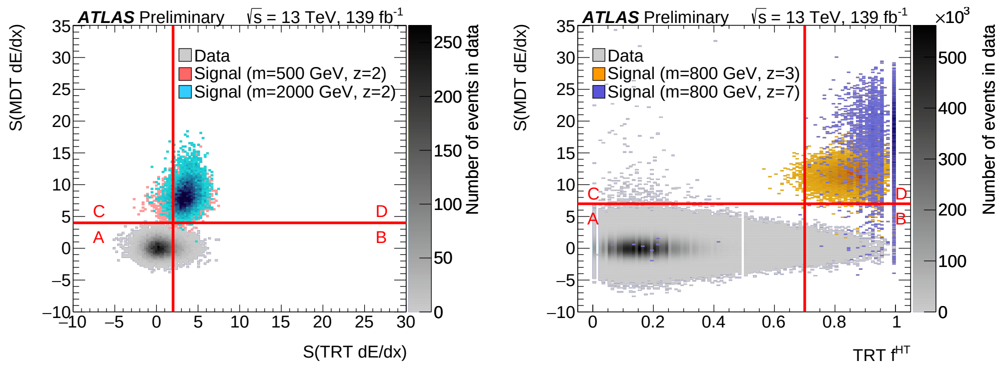
(a) **(b)**

Figure 1: Mass distribution reconstructed for candidate tracks with dE/dx ranging between 1.8 and 2.4 MeV cm^{-2} g^{-1} (a) and with $dE/dx > 2.4$ MeV cm^{-2} g^{-1} (b). Figures from Ref. [2].

Search for Multi-Charged Particles

Another ATLAS recent result [3] reports a search for massive Multi-Charged Particles (MCPs). MCPs are heavy fermions with mass ranging between 0.5 and 2 TeV, which can have an electric charge up to $|z| = 7\,e$ (e denotes the absolute value of the charge of the electron). In this search, MCPs are assumed to have a long decay lifetime, such that the majority of them escape the detector before any decay process occur. Given their large electric charge, MCPs are highly-ionising particles and they leave hits in the pixel detector, in the Transition Radiation Tracker (TRT) and in the Monitored Drift Tube (MDT) chambers. The presence of hits in the muon spectrometer allows to reconstruct MCP tracks as muons, motivating the use of muon triggers in the first stage of the event selection. Late-muon and $E_{\mathrm{T}}^{\mathrm{miss}}$ triggers are also used, to recover the efficiency for slow-moving MCPs.

The dE/dx significance, S, represents a powerful discriminant when selecting events containing candidate MCPs, and is defined as the difference from the average muon dE/dx, measured in $Z \to \mu\mu$ events, divided by its root-mean-square. Another useful discriminant for the identification of MCPs comes from the TRT. Signals in the straw tubes of the detector are compared with a low threshold and a high threshold, where the latter correspond to a ionisation that is at least three times larger than the one of a MIP. Multi-Charged Particles can leave many High-Threshold (HT) hits, so that the fraction of them among the total (f_{HT}) is more than 70%. A selection based on the dE/dx significance and on the f_{HT} defines two search regions, optimised for MCP with charge $|z| = 2$ and $|z| > 2$, respectively. Background events in these SRs originate from random fluctuations of the energy loss distribution and are estimated via a data-driven "ABCD" method. The ABCD planes, where region D is the SR, are shown in Figure 2. No deviation from the expected number of events is observed, so the results are used to calculate limits on the production cross section of Multi-Charged Particles with charge $2 \leq |z| \leq 7$, which are excluded at 95% CL for masses up to 1.7 TeV.



(a) **(b)**

Figure 2: ABCD planes used for the background estimation in the Multi-Charged Particle search. Figure (a) corresponds to the search region for $|z| = 2$, while Figure (b) corresponds to the region for which $|z| > 2$. Figures from Ref. [3].

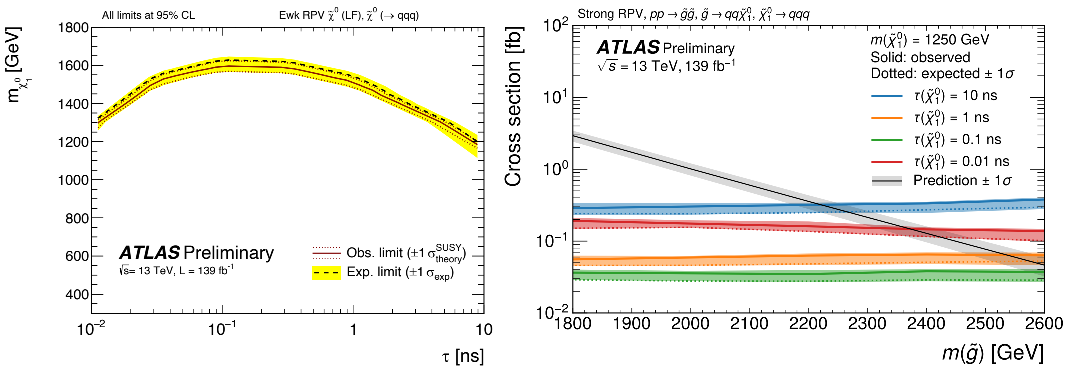
3. Searches based on the reconstruction of displaced vertices

Many searches targeting the production of LLPs that decay in the Inner Detector (ID) rely on dedicated algorithms for the identification of their decay vertices. In the following, two analysis cases that exploit special criteria for the identification of Displaced Vertices (DVs) are discussed.

Search for massive long-lived particles in events with jets and displaced vertices

Long-lived SUSY particles such as neutralinos or charginos, with mean proper lifetimes greater than ~ 10 ps, are predicted by some R-Parity Violating (RPV) models. Such particles can be pair-produced in LHC collisions and can decay to pairs of SM quarks after travelling a macroscopic distance in the ID. A search targeting this scenario has been recently published by the ATLAS Collaboration and is based on the identification of events with a large number of hadronic jets (between four and seven) and at least one DV [4]. Track reconstruction in the ID is performed with the *Large Radius Tracking* [5], which has an efficiency more than 6 times larger than conventional tracking algorithms for radii (r) above 20 mm. This allows to reconstruct DV with an efficiency greater than

60% for LLP decays that occur at $r < 250$ mm. Events are selected with jet-based triggers and are classified in two signal regions, defined in terms of the jet multiplicity and momentum. In both cases, at least one DV with mass larger than 10 GeV is required in each event, to reduce the contribution from heavy hadron decays. The signal regions of this search are affected by backgrounds which do not originate from SM processes, as there are no known high-mass particles giving rise to displaced decay vertices. Accidental crossing of tracks, of close-by secondary vertices, as well as events with hadronic jets are the only non-negligible source of background in the SR. These are estimated evaluating the probability of finding mis-reconstructed DV in a statistically independent sample. No excess of events is observed over the expected background, which is predicted to be less than one event in each SR. These results are used to set 95% CL upper limits on SUSY models where long-lived gluinos or neutralino pairs are produced and are shown in Figure 3.



(a) **(b)**

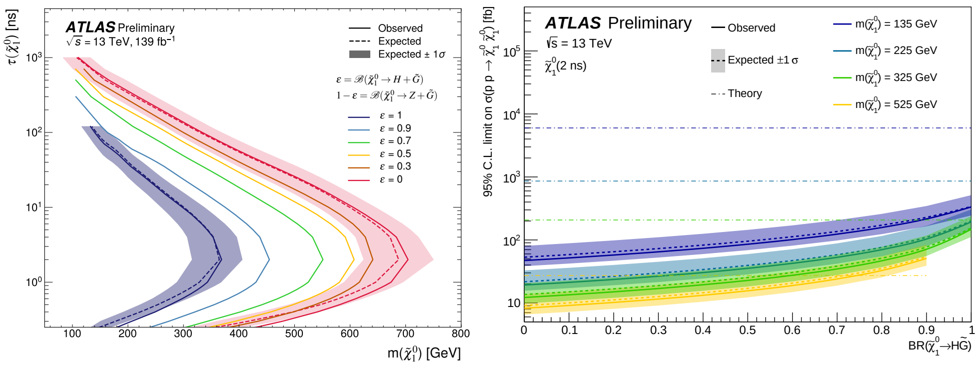
Figure 3: Upper limits at 95% CL on the neutralino mass, reported as function of (a) its mean proper lifetime, and (b) on the production cross section of gluino pairs for several mean proper lifetime hypotheses. Figures reported from Ref. [4].

Search for displaced di-photon vertices

Displaced production of H or Z boson can produce secondary di-photon or di-electron vertices, resulting in a pair of electromagnetic (EM) showers that are not pointing to the primary vertex. This peculiar signature is exploited in Ref. [6], which considers a SUSY benchmark model in which displaced Z or H bosons are produced in each event by an in-flight decay of neutralinos.

Timing and directionality of the EM shower are two key variables exploited by this search. The former is used to obtain the average timing of the EM shower (t_{avg}) and the latter is used to identify the position of the displaced vertex, allowing to estimate the distance (ρ) travelled by the LLP before decaying. This search does not rely on any information from the ID, in order to treat EM showers from photons and electrons in the same way.

Events are initially selected by triggers that require the presence of two photons, which is followed by the requirement of at least one di-photon vertex in each event. Additional selections are applied to ensure that the triggers are fully efficient and to select events consistent with a displaced decay of a H or Z boson, including a requirement on the combined mass of di-photon pair, required to range between 60 and 135 GeV. No known SM process can cause high-mass di-photon vertices and the only non-negligible source of background in the SR of the analysis is due to mis-reconstructed photons passing the criteria for the DV reconstruction. A data-driven background estimation is performed to predict the shape and the normalisation of the distribution of t_{avg} in several bins of ρ. No disagreement is observed from the SM predictions and a likelihood fit is performed to place 95% CL limits on the masses and lifetimes of the neutralino, which are reported in Figure 4. This search was possible thanks to the high granularity of the ATLAS LAr calorimeter and represents the first study performed at the LHC based on the identification of displaced di-photon vertices.



(a) **(b)**

Figure 4: Exclusion limits at 95% CL on (a) the neutralino lifetime as function of its mass, for different assumptions on its decay branching ratio, and on (b) the production cross section of neutralinos for different masses and branching ratio hypotheses. Figures adapted from Ref. [6].

References

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[4] ATLAS Collaboration, *Search for long-lived, massive particles in events with displaced vertices and multiple jets in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector*, ATLAS-CONF-2022-054 (2022).

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