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Searches for long-lived particles with the ATLAS experiment with proton-proton collisions at $\sqrt{s} = 13$ TeV(*)

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Summary. — Recent results and highlights of long-lived particles (LLP) searches from the ATLAS experiment at the Large Hadron Collider are presented. Analyses are presented with a focus on the signatures used to separate the signal from the Standard Model background. Attention is given to the custom reconstruction requirements and to the control of the background with data driven methods.

1. – Introduction

Long-lived particles (LLPs) are particles beyond the standard model (SM) travelling a substantial distance before decaying within the detector or, if charged, stable within the detector's acceptance. They are predicted by several theoretical models, *e.g.*, supersymmetric models, the hidden sector, multi-Higgs models, the dark matter sector, flavour anomalies and heavy resonances models.

LLPs may have very different properties: they can be either light or massive, slow or fast, decay into detectable SM particles (quarks, leptons, gluons) or not. Hence, LLPs searches can be very different from each other and use specific signatures, for example based on displaced vertices and tracks, lifetime, time of flight, anomalous ionization energy loss, missing transverse energy. As the ATLAS detector at the LHC was not originally designed for the detection of LLPs, searches for LLPs often require to use specific trigger and reconstrunction algorithms, besides ad-hoc simulations or to handle unusual backgrounds. In addition, they are often based on the information from a specific subdetector.

2. – Recent results

The sector of searches for LLPs with the ATLAS detector is very lively. Lots of searches are already performed in the past and many others are ongoing with the Run-2 data. Recent results cover a wide range of processes involving LLPs predicted by several models and update the exclusion limits on their masses, lifetimes and production cross

(*) IFAE 2023 - "Energy Frontier" session sections. Most recent results([1]) include the search for pairs of muons with small displacement targeting supersymmetric partners of the muon ($\tilde{\mu}$) with a lifetime of O(1-10) ps [2], massive LLPs in events with displaced vertices and multiple jets (LLPs decaying into hadrons) [3], diphoton and dielectron final states from displaced production of Higgs or Z bosons [4], heavy long-lived multi-charged particle predicted by several theoretical models [5], displaced photons produced in exotic decays of the Higgs boson [6], heavy, long-lived, charged particles with large ionisation energy loss [7], heavy neutral leptons produced in decays of W bosons using a dilepton displaced vertex [8], neutral long-lived partcles dacaying into displaced hadronic jets [9]. They clearly apply a wide spectrum of signatures and strategies. In the following the main highlights of some of these recent results are summarized, to provide some examples of different signatures and strategies used, selected also considering the presence of signal events.

Events with displaced vertices and multiple jets. In [3] R-parity-violating models are targeted, in which charginos and neutralinos have lifetimes up to O(10) ns thanks to small coupling constants and decay with 100% branching ratio into final states with light flavour quarks (fig. 1). The resulting signature consists in a massive, multi-track displaced vertex and multiple energetic jets. As there are no SM heavy particles producing such a signature, the background is small and predominantly due to low-mass vertices being merged together and misclassified as a high-mass vertex. Hence the strategy applied in this case is to aim for zero background (only 1 background event in the entire data sample). Two mutually exclusive signal regions are used. Both signal regions require a displaced vertex with strict selection criteria to reduce background contamination (minimum distance from the collision vertices, position veto to exclude interactions in the detector material). In addition, to select events with production of a pair of gluinos (*high-p_T jet SR*) at least 3 jets of which at least one or two without track (according to different thresholds in p_T) are required. Alternatively, the *trackless jet SR* collects events failing the high-p_T jet SR and with at least 3 high-p_T jets to select events with chargino or neutralino pair production. The background estimation is based on the probability that a displaced vertex (with the applied selection criteria) is found next to a track jet (jet-DV probability). Such probability is estimated from data in a control region (CR) as a function of the mass of the displaced vertex, the track jet properties and the track multiplicity. The background validation is performed comparing the background distribution to the ones obtained with the same procedure in the validation regions, in which separate jet-DV probabilities are calculated. A second validation is also performed comparing the background distribution to an alternative background estimate obtained with a different procedure, that aims to estimate each source of background independently. The background predictions in the two signal regions are shown in fig. 2. One event was observed in the high-p_T jet SR and zero events were observed in the trackless jet SR (approximately zero events expected in both signal regions). This search set limits in a wide range of the neutralino mass and lifetime and upper limits on the visible cross-section of the searched processes. Some examples are shown in fig. 3.

Heavy LLPs with large ionization energy loss. The search based on high ionization energy loss (dE/dx) [7] targets massive LLPs and is model-independent. It is senstitive to LLPs of lifetimes from approximately 0.3 ns to stable. It is based on the measurement of

([1]) At the time of the IFAE 2023 conference (12-14 April 2023).

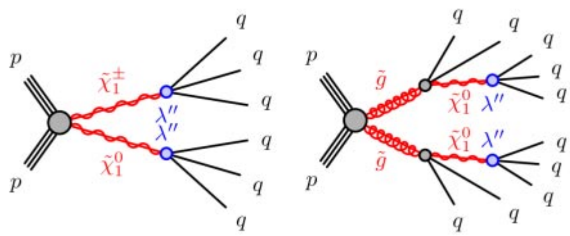

Fig. 1. – Diagrams showing the production of a chargino-neutralino pair (left) and a gluino pair (right), in which each gluino decays into a pair of quarks and a long-lived neutralino. The chargino and neutralino decay into three quarks via the R-parity-violating coupling λ [3].

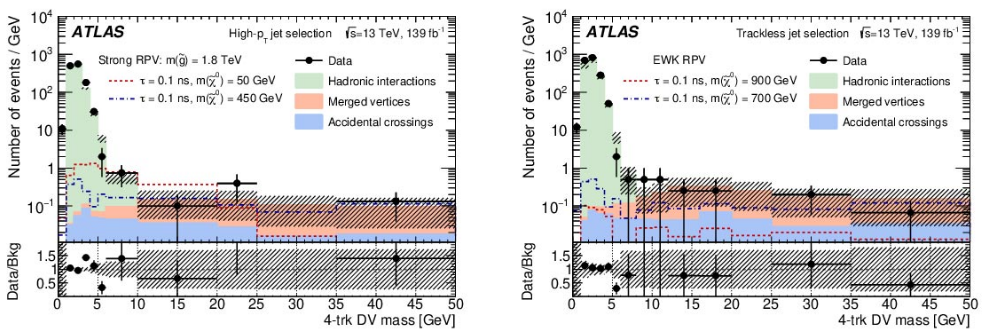

Fig. 2. – Combined background predictions in events passing the high-p_T jet selection and trackless jet selection for displaced vertices with four tracks [3].

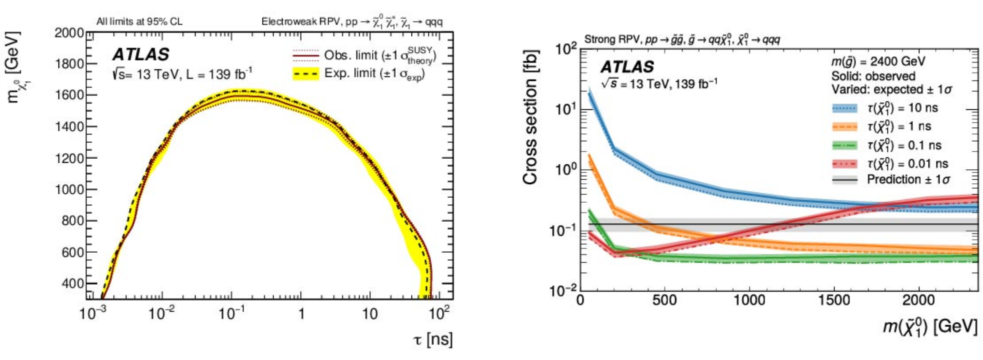

Fig. 3. – Exclusion limits at 95% CL on the lifetime and mass of the neutralino in electroweakino pair production models (left) and and on the production cross section of gluino pairs in the Strong RPV model (right) as a function of the netrualino mass for several values of the neutralino lifetimes [3].

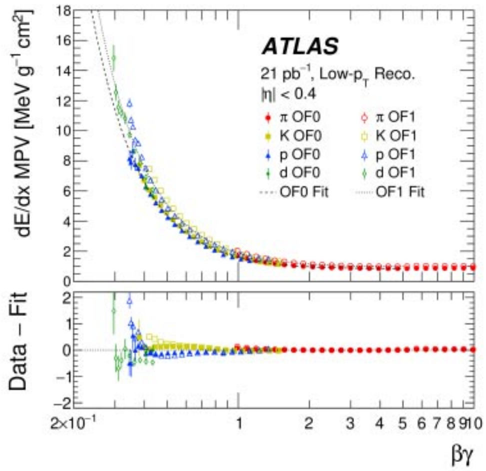

Fig. 4. – Most probable values (MPVs) of dE/dx as a function of particle $\beta\gamma$ for $|\eta|$ <0.4, classified by the presence of the IBL overflow bit (OF0 and OF1) and fitted by a function respecting the Bethe–Bloch formula to obtain the calibration of the Bethe–Bloch relation in [7].

high dE/dx ($>$ 1.8 MeV g^{-1} cm^2) performed with the pixel detector, that according to the Bethe-Bloch relation is an indicator of low $\beta\gamma$. The calibration of the Bethe-Bloch relation from data is shown in fig. 4. The high dE/dx selection, together with the request of high momentum (isolated, central) tracks ($p_T >$ 120 GeV), results in the selection of massive particles. The search uses a high missing energy trigger ($E_T^{miss} >$ 170 GeV). The signal region is further subdivided in 8 regions (inclusive or exclusive with muon match or the overflow of the dE/dx measurement in the insertable B-layer) and in dE/dx bins corresponding to different LLP masses and lifetimes. Also in this case the background estimation is fully data-driven, based on the extraction of the $1/p_T$, η and dE/dx variables from templates obtained from data, and is validated in two regions (one at low p_T and one at high η). Results are compatible with the expected background in most of the signal regions. Notably, an excess with 3.3 σ significance (7 events observed, 0.7 $\pm$ 0.4 expected) was observed in the mass window [1.1,2.8] TeV (visible in fig. 5 left). Some checks were performed to validate the genuineness of the signal events, but no instrumental issue in the tracks and pixel cluster was found and tracks reconstructed in inner detector were found consistent with tracks reconstructed in the muon system. On the other hand, the high-β measurement was not confirmed by the β measurement from the calorimeter and the muon system. This search set new limits on lifetimes of gluinos (fig. 5 right), charginos and staus. A second round of the analysis [11] that includes also the β measurement with time of flight from the hadronic calorimeter was concluded by the time of writing since the IFAE 2023 conference. This approach has the advantage of having less background (and higher sensitivity) thanks to the presence of two independent measurements of the β variable, especially at lifetimes approximately larger than 10 ns.

Heavy neutral leptons in events with dilepton displaced vertex.. Heavy neutral leptons (HNL) searched for in [8] are produced together with a lepton and decay into a pair of

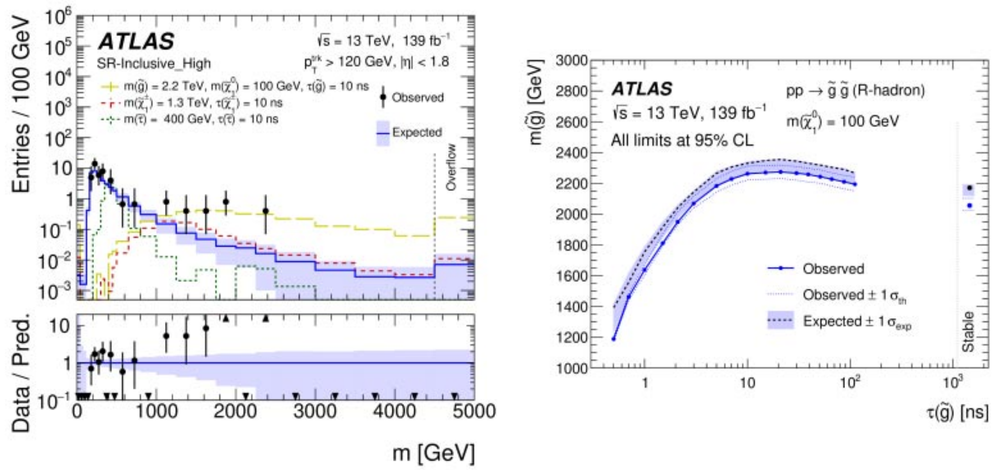

Fig. 5. – Observed mass distribution (left) in the inclusive signal region with $dE/dx > 2.4$ MeV g^{-1} cm^2 (SR-Inclusive_High) with the excess in the mass window [1.1, 2.8] TeV and lower limit on the gluino mass (right) from gluino R-hadron pair production, as a function of gluino lifetime for the neutralino mass assumption of m($\tilde{\chi}_1^0$)=100 GeV [7].

displaced leptons and a neutrino. The signature used in this case is a prompt lepton with two opposite charge leptons from a displaced vertex. The track of displaced leptons is based on a *large radius tracking* (LRT) algorithm [10] to reconstruct tracks with large impact parameter, and the mass of the HNL is obtained from the four-momentum conservation in the W and HNL decay being sensitive to HNLs with masses O(3-20) GeV and lifetimes in the range 1-100 mm. The background consists of random track crossings, estimated with data-driven techniques, but also from displaced vertex from interactions in the detector and the decay of the Z boson, metastable SM particles and cosmic muons, suppressed using mass and geometrical cuts. Results are interpreted both assuming HNL as Dirac or as Majorana particles. No signal was observed, and exclusion limits were set on the mixing coefficients for HNL masses ranging from 3 GeV to 15 GeV, at 95% confidence level. For the first time, limits are evaluated for multi-flavour mixing scenarios that agree with the neutrino flavor oscillation data, for both the normal and inverted neutrino-mass hierarchies (fig. 6).

3. – Conclusions

Long-lived particles are hypothetical, beyond the SM particles that travel a substantial distance before decaying within the detector's acceptance or, if charged, stable within its acceptance. They are foreseen by a variety of theoretical models. Several LLPs searches are already performed with ATLAS detector with a large variety of signatures explored, many other searches are still ongoing. In this paper the most recent results are summarized, covering a wide range of models and applied techniques. LLPs searches often require dedicated trigger and reconstruction algorithms, ad-hoc simulations and the estimation of unusual backgrounds. Some examples among the most recent results were also presented in more detail. Finally, after the LHC Long Shutdown 2 the ATLAS detector was upgraded and Run-3 data are being collected with higher luminosity and

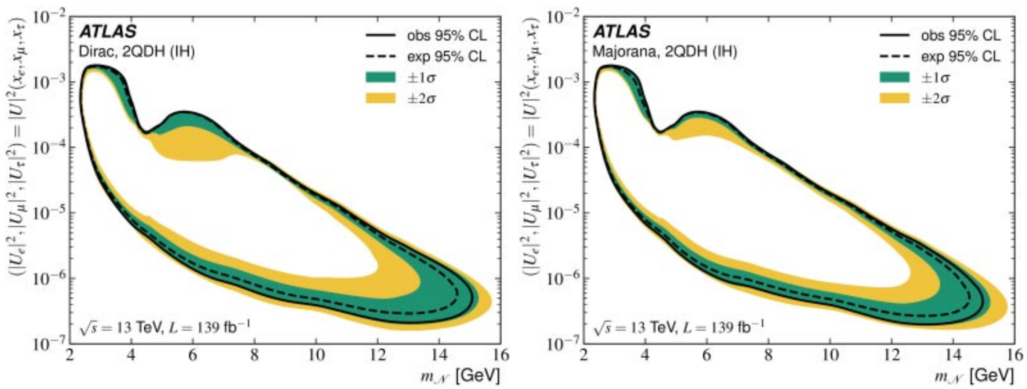

Fig. 6. – Summary plots for two quasi degenerate HNLs (2QDH), inverted neutrino mass hierarchy (IH) mixing model in the Dirac-limit (left) and in the Majorana-limit (right), with the expected and observed 95% CL [8].

with new triggers and data acquisition strategies, and a reach Run-3 program is to be expected.

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