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ATLAS Searches with Unconventional Signatures

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Many theories beyond the Standard Model have been proposed to address several of its shortcomings. Some of these beyond-the-Standard-Model extensions predict new particles or interactions directly accessible at the Large Hadron Collider, but which would leave unconventional signatures in the ATLAS detector. These unconventional signatures require special techniques and reconstruction algorithms that, once developed, enable analysers to perform unique searches for new physics. These proceedings cover several such searches using the Run-2 dataset.

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1. Introduction

Unconventional signatures observed with the ATLAS experiment [1] at the Large Hadron Collider are used in searches that aim at verifying many models possibly extending the Standard Model (SM). These searches often use non-standard reconstruction methods, which can be based on specific detectors or use specific triggers or are designed to exploit special reconstruction algorithms. Recent searches with the ATLAS detector using unconventional signatures based on the inner detector (ID) are presented in Section 2, while searches using unconventional signatures based on the calorimeters and the muon spectrometer are presented in Section 3.

2. Signatures in the inner detector

Several unconventional tracking variables have been used aiming at the detection of heavy slow particles eventually decaying inside the tracker.

Disappearing track signatures are produced by charged long-lived particles (LLPs), like sleptons and charginos, produced in proton-proton collisions or from prompt decays of unstable particles with lifetimes O(0.1-10) ns that decay into stable neutral particles and low momentum charged particles inefficiently reconstructed. Hence, the LLP's track is typically reconstructed in the ID up to its decays point, with no matching tracks outgoing. In some analyses, the selection of additional objects (e.g. large missing transverse energy) can be used to improve the sensitivity. The disappearing track signature is exploited in Ref. [2] to search for charginos, that excluded pure-wino charginos with masses up to about 850 GeV for lifetimes of about 1 ns.

The *large radius tracking* (LRT) is a specialised track reconstruction algorithm developed for tracks with large impact parameter. The algorithm reconstructs charged particles with transverse impact paramater d_0 of approximately 10 mm<$|d_0|$<300 mm and it exploits hits not used by standard tracking. It was initially run on O(1%) of data samples [3], and later re-run on the entire Run2 data sample thanks to improved processing time and disk space usage [4]. The LRT is very efficient for decays within the pixel detector and out to the first semiconductor tracker layer with enough detector hits.

A *displaced vertex* (DV) in the ID is identified by tracks pointing back to a common vertex far from the interaction point and is caused by the decay of long-lived neutral particles to charged (and neutral) particles in a sensitivity range complementary to the prompt-decay searches. In the case of SUSY particles decays, the large invariant mass makes them easily distinguishable from standard model particles decays. In Ref. [5] displaced vertices are used to search for long-lived, massive particles in events with multiple jets from DVs, targeting zero background events (only one background event observed). In Ref. [6] LLPs with mass between 5-55 GeV that decay hadronically in the ID are searched for, considering three benchmark models: the Higgs exotic decay to a pair of neutral spin-0 bosons s that decay to SM quarks ($H \to ss \to 4q$), the production of axion-like particles (ALPs) a in association with W/Z bosons and from the exotic decay of the top quark to an ALP and a u/c quark ($t \to ac/au$).

A *large impact parameter* is instead exploited in searches like in Ref. [7], based on the signature of two displaced leptons with a large impact parameter ($|d_0|$>3 mm) from the decay of a slepton pair. In Ref. [8], a pair of micro-displaced leptons (0.1 mm<$|d_0|$<3 mm) with high invariant mass are looked for with standard tracking algorithms, targeting an intermediate sensitivity range between long-lived and promptly decaying sleptons with lifetimes of $O(10^{-3} - 10^{-2})$ ns.

Charged and massive LLPs are searched for in Ref. [9]. Such particles must also be slow, hence due to the Bethe-Bloch relation they must feature a *high ionization energy loss* ($\mathrm{d}E/\mathrm{d}x$) that can be measured in the pixel detector. The search is model-independent and is sensitive to lifetimes ranging from approximately 0.3 ns to stable, a range complementary to those of the disappearing-track and DV signatures, and masses from approximately 100 GeV to 3 TeV. A 3.3σ excess was observed in the mass window [1.1,2.8] TeV corresponding to a mass of 1.4 TeV, but the time-of-flight (ToF) measurement of the calorimeter and of the muon system did not confirm that the tracks in the excess were slow. Results were interpreted for pair-production of R-hadrons, charginos and staus in supersymmetric scenarios, extending the mass limits beyond those from previous analyses in a broad range of lifetimes. A new version of this analysis was also performed in Ref. [10], that also includes the $\beta\gamma$ measurement from the ToF measurement done with the hadronic calorimeter. The calorimeter $\beta\gamma$ and pixel $\mathrm{d}E/\mathrm{d}x$ measurement lead to two independent measurements of the mass required to be compatible, allowing to an improved background reduction. This second version of the analysis has a sensitivity for lifetimes exceeding 3 ns and data were found compatible with the background prediction.

3. Signatures in the calorimeters and the muon spectrometer

Unconventional signatures based on energy deposits in the calorimeters and mouns reconstructed in the muon spectrometer have also been explored.

A displaced collimated group of standard model fermions reconstructed in the calorimeter or in the muon spectrometer with a structure similar to a jet is the signature of a *dark photon jet*. It is used in Ref. [11], where the search of dark photons from the exotic decays of the Higgs boson produced from vector boson fusion allowed to reduce background and to make the search for one dark photon feasible, and to extend to sensitivity to shorter and longer lifetimes.

Highly ionizing particles (HIPs) like magnetic monopoles and high-electric-charge objects (HECOs) up to $|z| \approx 100$, instead, are searched for in Ref. [12]. Their interaction in matter produces small radiation losses (<5%) and a large number of δ-rays. Hence the resulting signature features, in addition to an high-threshold (HT) hit in the transition radiation tracker (TRT) produced by the HIP, additional HT hits in neighbouring TRT straws produced by δ-rays, aligned with a narrow high-energy deposit in the liquid argon electromagnetic calorimeter. The search in Ref. [12] improved by approximately a factor of three the previous cross-section limits on the Drell-Yan production of magnetic monopoles and HECOs, and set the first ATLAS limits on the their photon-fusion pair production.

Out-of-time energy deposits are represented by hadronic activity detected in the calorimeter in absence of collisions, as a consequence of LLPs that stop in the calorimeter and may decay at a much later time. This signature is exploited in Ref. [13] to search for R-hadrons stopped in the calorimeter decaying from 100 ns to one year later. The lifetime sensitivity covers a broad spectrum of several orders of magnitude from 10^{-5} s to 10^{3} s. This search set lower limits on the mass of gluino R-hadrons, assuming gluinos $\tilde{g}$ decaying to the lightest neutralino $\tilde{\chi}_1^0$ and quarks with a

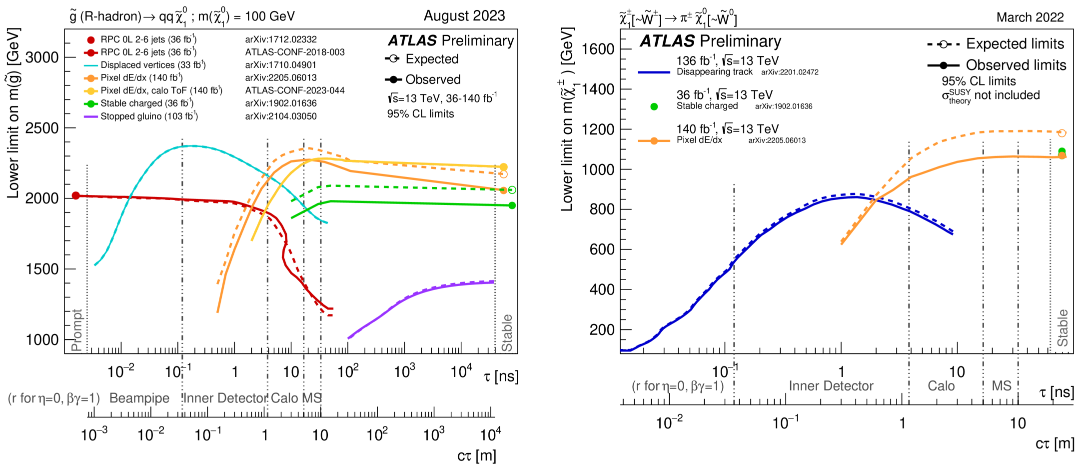

Figure 1: Constraints on the gluino mass-lifetime plane (left) for a split-supersymmetry model with the gluino R-hadron decaying into a gluon or light quarks and a neutralino with mass of 100 GeV, and constraints on the chargino mass-lifetime plane (right) for an AMSB model with $\tan\beta$=5 and μ>0. The wino-like chargino is pair-produced and decays to the wino-like neutralino and a very soft charged pion. Solid lines indicate the observed limits, dashed lines indicate the expected limits. The area below the curves is excluded. The dots represent results for which the particle is assumed to be prompt or stable [16].

branching fraction of $B(\tilde{g} \to q\bar{q}\tilde{\chi}_1^0)$=100%, excluding masses of up to 1.4 TeV for gluino lifetimes of 10^{-5} to 10^3 s.

A photon detected the electromagnetic calorimeter not pointing back to the interaction point is called a *non-pointing photon*. Its reconstruction doesn't use tracking information, but is based on the longitudinal shape of the shower to reconstruct the displaced vertex to which it points, and delayed timing. Two non-pointing photons forming a high-mass displaced vertex are used in Ref. [14] to search for displaced decays of neutral LLP into H, Z bosons reconstructed in the decay modes $H \to \gamma\gamma$ and $H \to ee$. In Ref. [15] delayed non-pointing photons are used to search for the displaced decay of a neutral LLP. Results were interpreted in the scenario of NLSP pair-production from exotic decays of the Higgs boson, each decaying into a photon and a LSP escaping detection. No excess was observed and upper limits on the branching ration of Higgs boson exotic decay were set.

4. Conclusion

Different unconventional measurements based on different detectors and reconstruction techniques were presented, together with the most recent analyses that target several models beyond the standard model. Different signatures allow to explore complementary regions of particles' mass-lifetime plane. For example, Figure 1 left shows that displaced vertex signatures are sensitive to gluino lifetimes approximately in the range (0.02-40) ns, the pixel detector dE/dx (and calorimeter ToF) is sensitive to lifetimes down to 0.5 (2) ns, and out-of-time energy deposits approximately from 100 ns to 11 hours. Figure 1 right similarly shows that the disappearing track signature is sensitive to chargino lifetime <10 ns, while the pixel detector dE/dx is sensitive to lifetimes exceeding 1 ns.

References

[1] ATLAS Collaboration, *The ATLAS Experiment at the CERN Large Hadron Collider*, JINST 3 (2008) S08003

[2] ATLAS Collaboration, *Search for long-lived charginos based on a disappearing-track signature using 136 fb^{-1} of pp collisions at $\sqrt{s}$=13 TeV with the ATLAS detector*, Eur. Phys. J. C 82 (2022) 606

[3] ATLAS Collaboration, *Performance of the reconstruction of large impact parameter tracks in the ATLAS inner detector*, ATL-PHYS-PUB-2017-014

[4] ATLAS Collaboration, *Performance of the reconstruction of large impact parameter tracks in the inner detector of ATLAS*, Eur. Phys. J. C 83 (2023) 1081

[5] 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*, JHEP 06 (2023) 200

[6] ATLAS Collaboration, *Search for light long-lived particles in pp collisions at $\sqrt{s}$=13 TeV using displaced vertices in the ATLAS inner detector*, arXiv:2403.15332

[7] ATLAS Collaboration, *Search for displaced leptons in $\sqrt{s}$=13 TeV pp collisions with the ATLAS detector*, Phys. Rev. Lett. 127 (2021) 051802

[8] ATLAS Collaboration, *Search for pairs of muons with small displacements in pp collisions at $\sqrt{s}$=13 TeV with the ATLAS detector*, Phys. Lett. B 846 (2023) 138172

[9] ATLAS Collaboration, *Search for heavy, long-lived, charged particles with large ionisation energy loss in pp collisions at $\sqrt{s}$=13 TeV using the ATLAS experiment and the full Run 2 dataset*, JHEP 06 (2023) 158

[10] ATLAS Collaboration, *Search for heavy, long lived charged particles with large specific ionisation and low-beta in 140 fb^{-1} of p-p collisions at $\sqrt{s}$ = 13 TeV using the ATLAS experiment*, ATLAS-CONF-2023-044

[11] ATLAS Collaboration, *Search for light long-lived neutral particles from Higgs boson decays via vector-boson-fusion production from pp collisions at $\sqrt{s}$=13 TeV with the ATLAS detector*, arXiv:2311.18298

[12] ATLAS Collaboration, *Search for magnetic monopoles and stable particles with high electric charges in $\sqrt{s}$=13 TeV pp collisions with the ATLAS detector*, JHEP 11 (2023) 112

[13] ATLAS Collaboration, *A search for the decays of stopped long-lived particles at $\sqrt{s}$=13 TeV with the ATLAS detector*, JHEP 07 (2021) 173

[14] ATLAS Collaboration, *Search in diphoton and dielectron final states for displaced production of Higgs or Z bosons with the ATLAS detector in $\sqrt{s}$=13 TeV pp collisions*, Phys. Rev. D 108 (2023) 012012

[15] ATLAS Collaboration, *Search for displaced photons produced in exotic decays of the Higgs boson using 13 TeV pp collisions with the ATLAS detector*, Phys. Rev. D 108 (2023) 032016

[16] ATLAS Collaboration, *SUSY August 2023 Summary Plot Update*, ATL-PHYS-PUB-2023-025