# Highlights of ATLAS Search Results

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Searching for beyond standard model (BSM) physics has been one of the primary goals of the Large Hadron Collider (LHC). The LHC delivered 140 $\text{fb}^{-1}$ data of high quality in Run 2, allowing the ATLAS experiment to expand and improve its search programme. The recent development in detector performance and analysis techniques have brought significant boosts to the search sensitivities. In this article, highlights of recent ATLAS search results are discussed and summarised.

## 1 Introduction

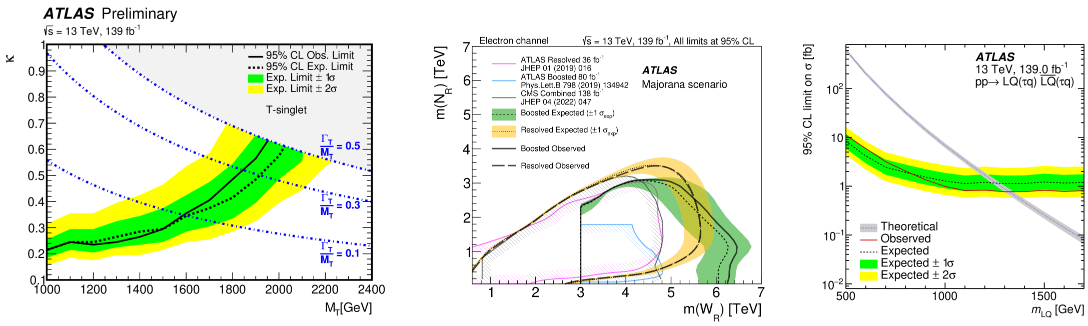
Many mysteries in particle physics, such as the hierarchy problem, the origin of dark matter (DM) and neutrino masses are still waiting for answers or hints from the Large Hadron Collider (LHC). ATLAS is a general purpose detector at the LHC that is capable of searching for beyond standard model (BSM) physics via various approaches. ATLAS has conducted a comprehensive set of searches in the past years. Even though no evidence of BSM physics has been reported, those searches excluded a large part of the phase space for many models. The ATLAS Run 2 data-taking is a great success, and a huge investment. Therefore, it is imperative to maximise its physics return. Recent ATLAS searches are featured with upgrading previous iterations using cutting-edge analysis techniques or detector performance development, filling the gaps between explored regions of phase space and considering challenging, completely uncovered signatures.

## 2 Full Run 2 Upgrades

The detector performance in ATLAS is continuously improving, thanks to the diligent work carried out in the relevant areas. For instance, the performance of bottom- and top-tagging has advance significantly in the past few years. In addition, the application of machine learning techniques have become very mature in physics analyses, enhancing the sensitivities. Even though previous analyses have explored similar final states, taking advantage of the above facts and more data, the full Run 2 upgrades of those searches will push the exclusion limits further.

In the full Run 2 ATLAS vector-like quark search, the top partner masses with 50% decay width are excluded up to 1975 GeV for the singlet representation, considering $B(T \to Wb) = 0.5$, as shown in Figure 1a. Compared to the previous analysis probing the same final state, this analysis adopted an updated top-tagger and more optimised selections, achieving greatly improved sensitivities [1]. The ATLAS full Run 2 right-handed neutrino search sets the most stringent limits on the Keung-Senjanović process in the TeV $W$ partner ($W_{\mathrm{R}}$) mass region. This search considers both the “resolved” and “merged” cases, depending on the mass split between the $W_{\mathrm{R}}$ and the heavy neutrino ($N_{\mathrm{R}}$). For Majorana neutrinos, in the muon channel, the limit on $m(W_{\mathrm{R}})$ reaches 6.4 TeV for $m(N_{\mathrm{R}}) = 1$ TeV, and the limit on $m(N_{\mathrm{R}})$ extends to 3.6 TeV for $m(W_{\mathrm{R}}) = 4.8$ TeV, as shown in Figure 1b [2].

Combination of different analyses offers a powerful way to constrain a given type of model. A recent ATLAS search is concentrated on final states with $\tau$ leptons and hadronic jets, providing interpretation including both the leptoquark and excited $\tau$ models. In particular, it is sensitive to $LQ \to c\tau^-$ ($\overline{LQ} \to \bar{c}\tau^+$) decays, as the analysis does not enforce any jets to be $b$-tagged. It comprises a critical piece in the leptoquark combination given this unique feature of the signal region selection. As seen in Figure 1c, $LQ$ masses below 1.3 TeV are excluded, assuming the branching ratio of their decays to the $c$-quark$\tau$-lepton pair is equal to one [3].




(a) (b) (c)

Figure 1: (a): Observed (solid line) and expected (dashed line) limits on the singlet representation of a vector like top-quark[1]. (b): Exclusion contour of the Majorana heavy neutrino on the $m(W_{\mathrm{R}}) - m(N_{\mathrm{R}})$ mass plane[2]. (c): Observed (solid line) and expected (dashed line) limits on LQ pair production where the LQ decays to a $\tau$ lepton and a charm quark[3].

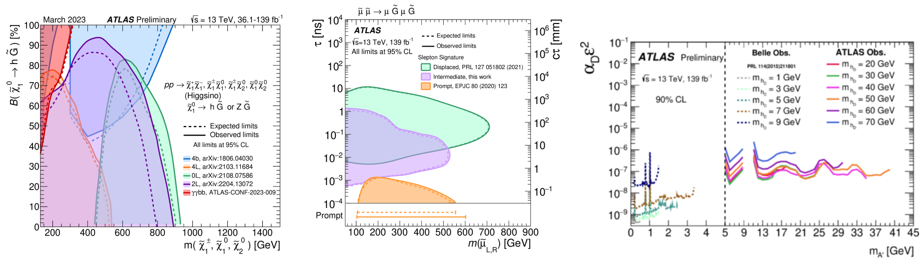
## 3 Filling the Gap

There have been many BSM models proposed by the theory community in the past decades. The number of free parameters in those models can be so large that a single search can only probe a subset of the parameter space, a particular combination of masses and couplings. Naturally, there are gaps between existing searches, and they need to be explored. The gap regions are usually hard to study so that special analysis strategies are essential.

Supersymmetry has been searched extensively at the LHC by a comprehensive programme. However various uncovered corners have been present on specific parameter planes. A recent ATLAS search for higgsinos considers the $b\bar{b}\gamma\gamma$ final state, taking advantage of the excellent mass resolution of the photons and the large $H \rightarrow b\bar{b}$ branching ratio. It successfully fills the gap in the low mass region, as seen in Figure 2a [4].

The gap between dedicated long-lived particle (LLP) searches and conventional searches is becoming increasingly important. A recent ATLAS search for micro-displaced muons is focused on this region using muons reconstructed by the standard algorithms, requiring the impact parameter ($|d_0|$) of the muons to be between 0.1 and 3 mm. Control regions, validation regions, and signal regions are constructed using the muon $|d_0|$ and muon-pair mass. In the context of a smuon pair production, the smuon lifetimes down to 1 $ps$ and smuon masses up to 520 GeV are excluded, as shown in Figure 2b [5].

Searching for BSM is a primary goal for many experiments. It is pivotal to make the most of LHC's higher collision energy and large integrated luminosity, in order to complete the picture. A recent ATLAS search looks for dark photons in the $4l + X$ final state, where the four leptons are from two dark photons ($A'$). The average invariant mass of the two lepton pairs is used as the main observable. The four lepton mass is used to construct signal and control regions, while the lepton pair mass is used to suppress quarkonia background. This search excludes a much wider mass region compared to the results from the Belle collaboration, as shown in Figure 2c [6].



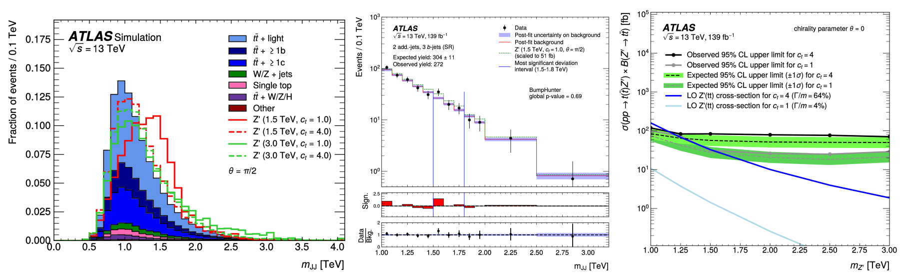

(a) (b) (c)

Figure 2: (a): Exclusion contour of the higgsino pair production on the mass and branching ratio 2D plane[4]. (b): Exclusion contour of the smuon pair production on the mass and lifetime 2D plane[5]. (c): Exclusion limits on the dark sector couplings as a function of dark photon mass[6].

## 4 New and Challenging Signatures

ATLAS is capable of studying an impressive amount of signatures, but there are signatures known to be very challenging. For instance, searches for LLPs usually need to develop dedicated triggering or reconstruction algorithms. Besides less optimal detector performance in certain regions, a signature can be strenuous because the traditional analysis techniques are not suitable. Analyses challenging those signatures can greatly broaden the ATLAS search programme.

ATLAS has searched for heavy particles produced in association with two top-quarks, decaying to two top-quarks, i.e., top-philic heavy particles. The previous search considered the non-resonant production as the reconstructed $t\bar{t}$ mass is very broad as seen in Figure 3a. A recent ATLAS analysis takes the resonant production channel into account. A hybrid background estimation method is developed to overcome the difficulties in dealing with broad signals. A background template is obtained in an inclusive region first and then propagated to the signal region via simulation, in order to minimize the biases introduced by the broad signals. A global deviation scan is done first in a model agnostic way, observing no significant deviations from the background in data, presented in Figure 3b. The observed (expected) limits range from 21 (14) fb to 119 (86) fb depending on the choice of model parameters, shown in Figure 3c. The results are limited by the modeling uncertainties [7].

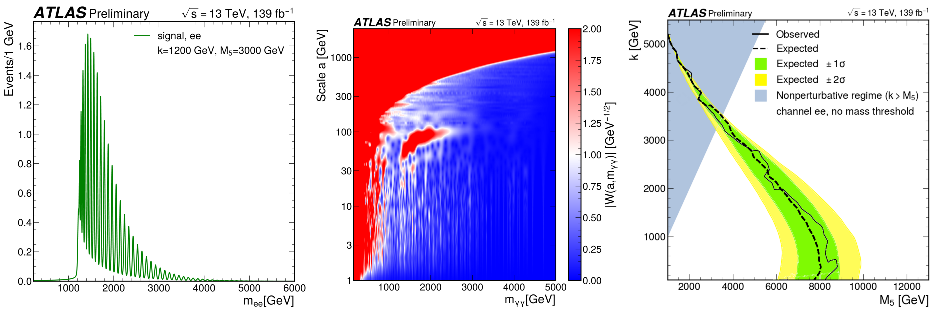



(a) (b) (c)

Figure 3: (a): Invariant mass distributions of the two large-R jets for different backgrounds and signal points. (b): Global deviation scan of the invariant mass spectrum. No significant deviations are observed. (c): Observed (solid line) and expected (dashed line) limits on the top-philic heavy particles as a function of mass[7].

Searches are typically performed using intuitive observables such as the invariant mass as the one discussed above. A recent ATLAS search explores periodic signals for the first time.

Such a signal is predicted in the ClockWork (CW) or LinearDilation (LD) framework. Instead of having one peak in the invariant mass spectrum, a periodic signal predicts continuous narrow peaks, as illustrated in Figure 4a. The analysis applied a “continuous wavelet” transformation to separate the signal events from the background in a scalogram more efficiently, depicted in Figure 4b. Limits are set for the gravity scale, $M_5$, and the turn-on mass scale, $k$, shown in Figure 4c [8]. This search has not only pioneered this intriguing signature, but also demonstrated that the data can be analyzed in a non-traditional space.




(a) (b) (c)

Figure 4: (a): The di-electron mass spectrum of a periodic signal. (b): Scalogram of a signal + background sample. (c): Observed (solid line) and expected (dashed line) limits on the model parameters, $M_5$ and $k$ [8].

## 5 Summary

The search programme at ATLAS is expanding in multiple fronts. Advanced detector performance and modern analysis techniques allow us to greatly enhance the sensitivities to a variety of BSM models. The unexplored regions and the gaps are being filled with new searches applying unique search strategies. Last but not the least, ATLAS is pioneering brand new signatures that challenge traditional methods vastly, motivating us to think out of the box and experiment fresh new methodologies. In addition, more effective theory interpretations are carried out in precision SM measurements such as the lepton flavour violating top measurement [9]. There are many interesting ongoing searches besides the ones covered in this article, including exciting Run 3 results. More highlights are coming.

## References

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