Highlights from Searches at ATLAS

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A selection of recent results from the ATLAS Collaboration on searches for physics beyond the Standard Model has been presented. The covered signatures are: searches for Dark Matter either in final states with large amounts of missing transverse energy or via the resonant production of new heavy mediators, signatures of long-living particles, searches for new gauge bosons or heavy mediators in final states with many-lepton or boosted di-Higgs signatures. All shown results use the full Run 2 data set corresponding to an integrated luminosity of $140\,\mathrm{fb}^{-1}$ delivered by the LHC.

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0.1 Introduction

Although the Standard Model (SM) of particle physics is an extremely successful theory, a number of fundamental open questions are not addressed by it, such as the nature and origin of Dark Matter (DM) and Dark Energy, the hierarchy problem, or the strong CP problem, to just name a few. The LHC [1] and its detectors, with ATLAS [2] being one of the two large scale multi-purpose experiments, are the optimal place to search for new phenomena at the high energy frontier. So far, the wealth of results from Run 1 and Run 2 show no conclusive deviation from the SM predictions and inspired significant evolution of the search strategies, such as new analysis and trigger strategies, usage of machine learning to improve performance of reconstructed particles and overall sensitivity, as well as searches with signatures that have not been targeted yet.

0.2 Searches for Dark Matter and Heavy Mediators

One possibility for the DM particle χ to obtain its mass is through a Higgs-like mechanism, with a new scalar "Dark Higgs" s that mixes to the SM-like Higgs with the mixing angle θ. The coupling of the DM to the SM sector happens through a new U(1)' gauge symmetry via the corresponding vector Z' boson and the coupling g_χ and g_q to the DM particle and quarks, respectively. In this model, the coupling of Z' to leptons is suppressed. The presented search [3] targets signatures with resolved di-b jets at low values of missing transverse energies ($E_{\mathrm{T}}^{\mathrm{miss}}$) and merged di-$b$ tagged jets at large $E_{\mathrm{T}}^{\mathrm{miss}}$ values. No excess beyond the SM expectation are found and limits are set in different mass planes: $m_{Z'}$-m_s with m_χ set to 200 GeV and g_q, g_χ and $\sin\theta$ set to fixed values. While this scenario is chosen for comparison with previous searches, two more scenarios are used for the interpretation of the results. One in the $m_{Z'}$-m_s mass plane and another in the $m_{Z'}$-m_χ mass plane, but in both cases with g_χ adjusted such that the relic density Ωh^2 takes a value of 0.12. Exclusion limits in those scenarios are reaching $m_{Z'}$ values of up to 4.5 TeV.

Another approach to search for DM is to not directly target the $E_{\mathrm{T}}^{\mathrm{miss}}$ signature of the DM particle itself, but instead to search for the mediator that couples the SM to the dark sector. If this coupling exists, i.e. if g_q is non-zero, the produced mediator should also decay back into quarks, resulting in a resonant feature in the di-jet mass spectrum. A search [4] has been presented that triggers on either a photon or a jet with large transverse momentum (p_{T}) from a hard initial state radiation (ISR). This allows to reach significantly lower mediator masses. The search is performed in three different channels, di-jet or di-b-jet with either an ISR photon or jet. In the three-jet channel the ambiguity of which jets originate from the decay of the mediator is resolved by choosing the pair with the lowest azimuthal angular difference $\Delta\phi$ between them. After a background fit with an analytic function, no significant resonant features are observed in either of the channels resulting in limits on the coupling strength g_q as a function of the mediator mass in the range from 200 to 600 GeV. To further improve the sensitivity the γjj and jjj channels are combined.

Another promising category to search for new physics is in final states with top quarks. When searching for a di-top resonance, the interference of signal and background processes have to be taken into account. The interference term can be significant and results in such cases in a characteristic peak-dip structure. A dedicated analysis [5] has been presented combining searches with boosted and resolved topologies. Since no significant deviation has been observed, limits are set in various models, like for example in two-Higgs-doublet models with or without an additional pseudo scalar. Further, a model independent interpretation is provided with $m_{t\bar{t}}$ templates for the signal and the signal+interference terms that are derived as a function of mass and width of the heavy mediator.

0.3 Searches with Displaced Jets or Tracks

A long-time favourite class of models that provide a DM candidate, while also addressing some other open questions of the SM, is supersymmetry (SUSY). In models with R-parity conservation the lightest SUSY particle (LSP) is stable, and if not charged under electromagnetic and strong interactions it acts as a perfect DM candidate. However, in scenarios where the next-to-lightest SUSY particle (NLSP) is close in mass with the LSP, the decay of the NLSP is suppressed by a small phase space, resulting in live times that can lead to a measurable displacement of the decay with respect to the primary vertex. For very small mass gaps ($\sim\ 250-400$ MeV), the NLSP could have large enough life times to leave a signature of a disappearing track in the detector, while for mass gaps of 2 GeV and beyond the decay would be indistinguishable from a prompt decay and hence the standard searches with leptons+$E_{\mathrm{T}}^{\mathrm{miss}}$ signatures would be sensitive. For the first time, a search for mildly displaced soft tracks with a hit in the first layer of the pixel detector and a p_{T} in the range from 2–5 GeV is carried out to target the range of mass gaps in between the two above mentioned scenarios, i.e. from 0.3–1 GeV [6]. Tracks that are compatible with originating from a K_s or Λ decay are excluded from the selection. Since no significant excess is observed, limits are set in the targeted mass range for NLSP masses of up to 170 GeV, exceeding for the first time the limits from LEP2 [7].

In the previously discussed search the heavy (meta-)stable charged particle decayed to a single lepton and invisible particles. Alternatively, the long-lived particle can also decay into a hadronic final state and result in a signature of a jet with a displaced vertex (DV) [8]. This search makes for the first time use of a new large radius tracking [9]. The search strategy is to train a boosted decision tree (BDT) to discriminate prompt against displaced jets. A final discriminator d is then defined as the product of the BDT values of the two highest scoring jets. The probability of a jet to be associated to a DV is measure in a control region at lower values of d (< 0.7) in bins of p_{T}, the jets flavour tagging score (DL1r) and the jets BDT score. From the "per jet" probabilities the "per event" probabilities are calculated to have either one or two and or more DVs. The method is successfully tested in validation regions for d in the range from 0.7–0.9 and further in a event selection with a photon. The signal region ($d > 0.9$ for $n_{\mathrm{DV}} = 1$ and $d > 0.7$ for $n_{\mathrm{DV}} > 1$) is further sub-divided into selections with either one lepton, two leptons, or no leptons and a Vector-Boson-Fusion signature of a two forward jets in opposite detector hemispheres. Since no significant deviation from the expected background prediction is seen, limits are set in various different scenarios: Firstly, a Higgs portal model with the decay of H to a pair of light scalars ss which then each subsequently decay to $q\bar{q}$. Previous limits on this model are improved by this search by roughly an order of magnitude. Secondly, limits are set for the first time on models with axion-like particles (ALPs): once for the associated production of an ALP with a W or Z boson, and once for the case of a top-quark decaying into a light quark and an ALP. In all case, best sensitivity is obtained for $c \cdot \tau$ values of approximately 1 cm.

0.4 Searches for Exotic Gauge Bosons and Heavy Scalars

Searches for new gauge bosons are motivated by many new physics models. However, if the Z' couples to light quarks most models are strongly constrained because the large production cross section at the LHC. But if the coupling is suppressed like in the case of a new gauge group $U(1)_{B-L}$ that gauges the difference of lepton numbers, e.g. $L_\mu - L_\tau$, limits are significantly weaker. A search for such models has been performed in the channel with three muons and one neutrino [10]. For this final state the dominant SM background arises from WZ and $W\gamma^*$ production. The search strategy uses a single paramterised deep neural network, which is trained to discriminate simultaneously against signal models with different Z' masses. Since no excess beyond the expectation is observed, limits on the production cross section of the Z' boson in the three-muon channel are set in the range of 10 fb at masses of 8 GeV down to 1 fb for masses around 80 GeV. The new result is combined with a search in the four-muon channel [11], which exhibits slightly better sensitivity for Z' masses below 65 GeV. This combination results in the most stringent limits on $U(1)_{B-L}$ models for Z' masses in the range from 5 to 80 GeV.

The final analysis that has been presented is a search for di-Higgs production. In the SM, the di-Higgs production is sensitive to various couplings, represented by the coupling modifiers κ_{2V}, κ_V, κ_λ, and κ_t. A dedicated search has been performed to obtain the best sensitivity to $\kappa_2 V$ as well as to new heavy scalars X' decaying into a pair of Higgs bosons [12]. This search is using a novel neural network double-b tagger to efficiently identify $H(b\bar{b})$ candidates. The background estimation is fully data-driven: While for the signal two double-b tags are expected with both $b\bar{b}$ masses close to m_H of 125 GeV, the single double-b tag selection is dominated by background events that follow a rather smoothly falling distribution for the two $b\bar{b}$ masses. The background sample is obtained by the events with one double-b tag, which are then normalised to a control region defined by both $b\bar{b}$ masses being sufficiently away from 125 GeV, i.e. a ring-like selection in the mass plane of the two candidate masses. A BDT is then trained to separate the background events against signal events defined by $\kappa_{2V} = 0$. This choice is made as it ensures a sensitivity to anomalous di-Higgs events. No deviation from the background expectation has been observed (see Figure 1, left). The results are combined with a search in the resolved four b-jet final state [13] resulting in the exclusion of the $\kappa_{2V} = 0$ hypothesis with 3.8 σ observed while 3.3 σ was expected. Furthermore, heavy X' mediators are excluded in the range from 1 to 5 TeV with limits on the production cross sections between 0.7 and 5 fb (see Figure 1, right).

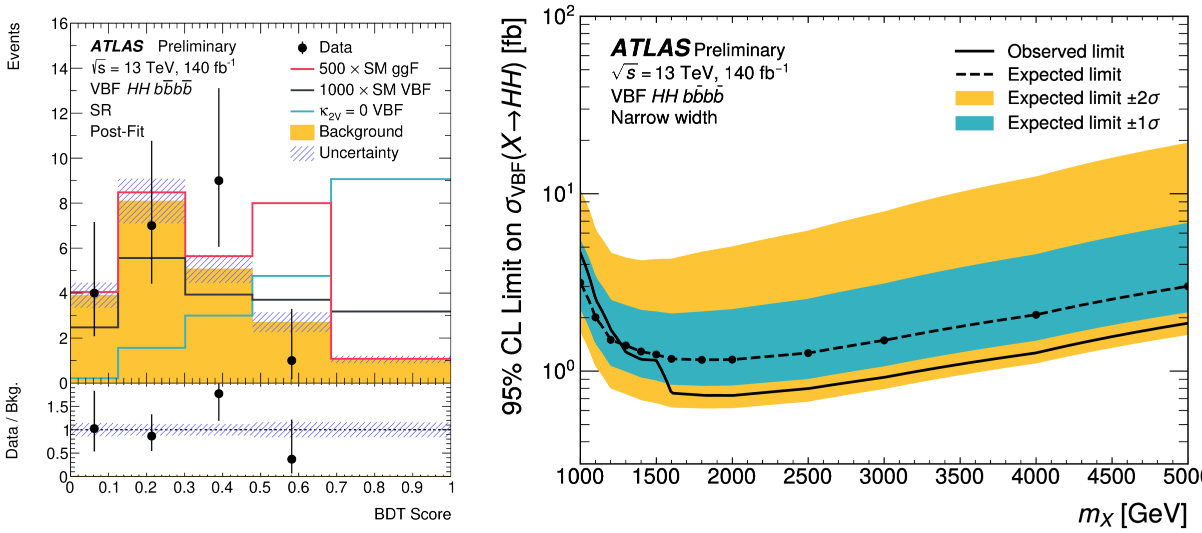

Figure 1 – The left figure shows the BDT score distribution in the signal region of the di-Higgs search for data in comparison with the background expectation. Individual contributions from gluon-gluon Fusion (red), Vector-Boson fusion (black) and anomalous di-Higgs ($\kappa_{2V} = 0$) are overlaid non-stacked. The right hand side figure shows the limit on the production cross section of a heavy X' mediator as a function of its mass. Figures are taken from reference [12].

0.5 Conclusion

In summary, the ATLAS Collaboration is continuing to improve the sensitivity of their searches at the LHC to more and more challenging phase spaces, while any conclusive evidence for physics beyond the Standard Model remains to be established. But with more search results from Run 2 still in preparation, and many more analyses expected from Run 3, as well as from the HL-LHC, searches for new physics remain a very interesting field with surprises left to be uncovered.

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