Exotic searches with the ATLAS detector

Harinder Singh Bawa
California State University Fresno
E-mail: <harinder.singh.bawa@gmail.com>

Abstract. The summary is given for the exotic, non-SUSY searches for new physics with the ATLAS detector at Large Hadron Collider (LHC). The results presented use data collected at center-of-mass energies of $\sqrt{s}=13$ TeV, for data sets corresponding to a variety of integrated luminosities. Searches using leptons, photons, missing transverse energy, and jets are performed, as well as searches requiring custom jet and track reconstruction, and searches for so-called lepton jets. No deviations from Standard Model expectations are observed, hence constraints are placed on the phase space of available theoretical models.

1. Introduction
The Standard Model (SM) remains a remarkably successful theory of Physics, withstanding tests of unprecedented precision. Recent discovery of a Higgs boson, reported by the ATLAS and CMS collaborations [1] has revealed the last missing component of the SM, the scalar field which is predicted in the SM and which is responsible for the fact the fundamental particles in the SM obtain their mass. While the observation of the Higgs boson would explain the electroweak (EW) symmetry breaking in the Standard Model (SM), it still leaves many unexplained fundamental problems such as the hierarchy problem, the fermion mass hierarchy, dark matter, the baryon asymmetry of the Universe, etc. Many models have been proposed over the past decades which address the issues above and motivate a wide range of searches by the ATLAS experiment.

This document covers a variety of searched performed with the ATLAS detector at the Large Hadron Collider (LHC), interpreted in the context of ‘exotic’ model predictions, including theories with extra spatial dimensions, Hidden Sector theories, vector-like quark models, and seesaw neutrino mass models. Supersymmetry (SUSY) is not considered, except for cases where SUSY is part of a larger extension to the SM, such as the Hidden Sector scenario. Many exotica searches are signature based so that different models can be studied in the same final state. In such a signature, even never thought-of signals may show up unexpectedly. Analyses presented in this paper are public results of the ATLAS experiment at CERN. A detailed description of the ATLAS detector can be found elsewhere [2]. It is impossible to cover all ATLAS exotic analyses in the brief conference proceedings. Therefore, only those ATLAS exotic searches that the author finds most relevant are considered below.

2. Dark Matter searches
The search for Dark Matter (DM) is a fundamental part of the physics programme of the Large Hadron Collider (LHC). The LHC has the ability to produce DM in pp-collisions and will be able to probe all basic interactions. The simplest realistic models consist of a DM particle and
a so-called mediator, which connects the Standard Model (SM) to the dark sector [3, 4, 5, 6]. Recently, searches for these simplified models have become very popular at the LHC following two strategies. The first strategy looks for DM itself, while the second strategy searches for the mediator particle. Since in the first case the invisible DM particles will escape the detector undetected, the DM particles needs to be boosted opposite to the direction of visible particles, leading to the "mono-X" signatures. Therefore, all those signatures are characterized by a large amount of missing transverse momentum. At the LHC a wide range of final states can be investigated, reaching from mono-photon to mono-Higgs signatures.

2.1. Searches for Dark Matter with jets
The search for DM in final states with an energetic jet and large missing transverse momentum ($E_T^{miss}$) has the largest $E_T^{miss} + X$ cross-section and includes searches with jets from the hadronic decay of W and Z bosons. The search has been performed using proton-proton collision data corresponding to an integrated luminosity of 36 $fb^{-1}$ at a centre-of-mass energy of 13 TeV collected in 2015 and 2016 [7]. Events are required to have at least one high momentum jet, large missing transverse energy and no leptons. The dominant background contributions originate from $Z(\rightarrow \nu\nu)$ and $W+jets$ processes, which have been constrained using MC samples normalized using data in dedicated control regions (CR), seperately for the mono-jet and mono-V channel. The $V+jets$ MC predictions are reweighted to account for higher-order QCD and electroweak corrections, following the recommendations described in Ref. [8]. Fig. 1 shows the missing transverse energy distribution in data and MC simulation in the signal region (SR).

![Figure 1](image)

**Figure 1.** Measured distributions of the $E_T^{miss}$ compared to the SM predictions. The error bands in the ratios shown in the lower panels include both the statistical and systematic uncertainties in the background predictions.

No significant deviation from SM has been observed. The results are therefore interpreted in terms of simplified models with an axial-vector, vector, pseudoscalar or scalar mediator. Fig. 2 show the 95% CL exclusion contours for the axial-vector and vector mediator model.

2.2. Search for Dark Matter in visible final states
The second option is to probe the interaction between dark matter and SM particles. As an example of such a strategy, the most relevant interactions at LHC energy scales can be
represented by a simplified model of dark matter production with a mediator particle \( Z' \) between quarks and dark matter. One can then search for this \( Z' \) directly, through its decays back to quarks that yield resonant signatures in the dijet invariant mass. Such a \( Z' \) particle can also, in more complicated models, be produced along with a dark matter pair: such a scenario is covered in Ref. [9]. The simplified dark matter model mentioned above has two key parameters: the mass of the mediator \( m_{Z'} \) and its coupling to quarks \( g_q \). In simple dijet resonance interpretations the dark matter mass \( m_{DM} \) is set very high such that it is kinematically inaccessible, in order to factorise the visible and invisible decays of the \( Z' \), and its coupling to the \( Z' \), \( g_{DM} \) is therefore of limited relevance.

2.2.1. ATLAS resonance search limits and constraints: The limits from dijet resonance searches to such \( Z' \) models from dijet resonance searches in 2013 is shown in fig. 3. Here \( Z_B \) is identified as the mediator \( Z' \) and \( g_B \) is six times the coupling of the mediator to quarks \( g_q \). The red line is the exclusion limit from an ATLAS dijet resonance search with 20.3 \( fb^{-1} \) of 8 TeV data collected in 2012 [10]. The equivalent run 2 ATLAS search [11], with 37 \( fb^{-1} \) of 13 TeV data collected in 2015 and 2016 is shown in fig. 4. It excludes values \( g_q \) below 0.07 for \( m_{Z'} = 1.5 \) TeV, compared to around 0.15 for the run 1 result [11]. However it does not set limits below \( m_{Z'} = 1.5 \) TeV, due to trigger constraints,
which are also why the run 1 result starts becoming weaker below 1 TeV. Below this mass the search used prescaled triggers (only a fraction of events accepted by a trigger are recorded) and a delayed stream (events accepted by some triggers were written to a separate stream that was not reconstructed until computing resources became available over the 2013-2014 shutdown). The ATLAS trigger system [12] consists of two parts: a first level (L1) to reduce the event rate from the 30 MHz delivered by the LHC 2 to the $\sim 100$ kHz that the subdetectors can be read out at, and a ‘high level trigger’ (HLT) that reduces this to $\sim 1–1.5$ kHz for offline storage, limited by the total storage and processing cost. Of this, $\sim 20–40$ Hz is dedicated to the single jet trigger used by this dijet resonance search [15]. Since this rate constraint is fixed, the jet trigger $p_T$ threshold must be raised as instantaneous luminosity increases (it is observed that the trigger rate is proportional to $p_T^{-5}$). In 2016, the trigger selected events containing a jet with $E_T > 380$ GeV, which was fully efficient in selecting jets with $p_T > 440$ GeV offline, and it is this which sets the lower bound on $Z'$ mass sensitivity.

2.2.2. Overcoming trigger limitations: Trigger-Level Analysis The main driver of the 1.5 kHz limit on the HLT output rate is the offline storage and processing cost. Hence it is more strictly a bandwidth limit rather than a pure rate limit. Since a dijet resonance search only requires jets (and not e.g. leptons), and since jets are well reconstructed in the trigger, a new data stream can be provided that contains only trigger jets (0.5% of normal event size) at a high rate (1-3 kHz) with minimal bandwidth impact. This idea was pioneered at the LHC by CMS [13], [14] and LHCb [15], and was first implemented for ATLAS in 2015 under the name ‘trigger-level analysis’ (TLA) [16].

This new data stream allowed all events with leading jet $p_T$ above 220 GeV to be included in the search, meaning that the mass spectrum analyses started at 531 GeV rather than 1100 GeV for the offline search (fig. 5).

In addition to trigger jet four-momenta, the trigger-level analysis stream contains sufficient information to be able to redo jet calibration. The procedure followed is as close as possible to that for offline jets [17], with some parts re-derived since TLA data lacks track information, as shown in fig. 6. The result of this specific calibration is excellent agreement between offline and recalibrated trigger dijet mass $m_{jj}$ (the mean difference is less than 0.5% for all $m_{jj}$ considered).

The search is performed through fitting a smooth functional form to the data. However, the unprecedented amount of data in the $m_{jj}$ spectrum meant that the known functions could not adequately describe the data over the whole mass range. Thus the background estimation at each mass was obtained by fitting a subrange of the spectrum around that mass. Following
Figure 5. Comparison between the number of dijet events in the data used by the TLA (black points), the number of events selected by any single-jet trigger (thicker, blue line), and the events selected by singlejet triggers but corrected for the trigger prescale factors (thinner, red line) as a function of $m_{jj}$ [16]

Figure 6. Calibration stages for trigger-level jets, each applied to the four-momentum of the jet [16]

This procedure, no significant excesses were observed, and the limits shown in blue in fig. 4 above were obtained. The TLA greatly improves sensitivity over dijet+ISR, despite the lower mass TLA signal region (using data collected with a lower threshold trigger at the beginning of the 2016 data-taking period, and a tighter selection to lower the $Z'$ mass cutoff) using far less integrated luminosity. The higher mass TLA signal region fills in the gap in ATLAS run 2 sensitivity to these $Z'$ models and ensures ATLAS run 2 limits (fig. 4) now surpass pre-LHC ones (fig 3) everywhere.

2.2.3. Complementarity: As can be seen in fig. 7, monoX and resonance searches complement each other to cover a wide range of the $m_{DM} - m_{Z'}$ plane, with mono-X searches being more sensitive for low masses. There is also complementarity between both sets of collider searches and direct detection. In both cases the interplay between different searches strongly depends on the model considered, see ref. [18] for other models and continually updated versions of these
plots.

Figure 7. Regions in a dark matter mass-mediator mass plane excluded at 95% CL by a selection of ATLAS dark matter searches, for one possible interaction between the Standard Model and dark matter, the leptophobic axial-vector mediator [19]

3. Search for extended gauge groups

The existence of heavy resonances is predicted by a variety of BSM models which are alternatives to SUSY in the explanation of the electroweak symmetry breaking. They are heavy new states with integer spin. Left-right symmetric and Extended Gauge models predict spin-1 states [20] while Randall-Sundrum models predict heavy spin-2 states [21].

In general, the analysis basically consists of searching for a bump in the two-body invariant mass spectra. The background is either small or could be modelled from the data control samples. ATLAS have searched for dilepton (including lepton+\(\nu\)), diphoton, dijet and jet+\(\gamma\) resonances. Relatively simple topologies allow for a robust analysis to be done rapidly. The most recent searches focused on fully hadronic signatures such as \(W' \rightarrow tb \rightarrow qqb\bar{b}\) [22]. The specific search for a \(W'\) boson decaying into \(tb\) allows for a right-handed \(W'\) boson (\(W'_R\)) in models in which the right-handed neutrino’s mass is assumed to be much higher than that of the \(W'\) boson (\(m_{\nu_R} > m_{W'}\)), which the leptonic decay mode cannot access. In such a model, the branching ratio for a \(W'_R\) boson decaying into \(tb\) is \(O(10\%)\) higher relative to that for a \(W'_L\) boson that can decay into quarks or leptons. Limits on a SSM left-handed \(W'\) boson (\(W'_L\)) decaying into a lepton and a neutrino have been set previously [23],[24].

This analysis searches for a \(W'\) boson decaying into \(tb\) with a mass in the range of 1-5 TeV, in the invariant mass spectrum of the top quark and bottom quark (\(m_{tb}\)) reconstructed in the fully hadronic channel. This includes a \(W'_R\) boson that is not kinematically allowed to decay into a lepton and neutrino and a \(W'_L\) boson that can decay into quarks or leptons. The large \(W\) mass results in a top quark and a b-quark that have high transverse momentum (\(p_T\)). The decay products of the top quark become more collimated as the top-quark increases, and their showers partially overlap [25]. This high- \(p_T\) topology is referred to as boosted. The boosted top-quark decay is reconstructed as a single jet. The shower deconstruction (SD) algorithm [26, 27] is employed to select, or tag, jets from boosted top-quark decays. A signal would be reconstructed as a localised excess in the \(m_{tb}\) distribution rising above the smoothly falling background originating mostly from jets created by the strong interaction described by quantum
chromodynamics (QCD). This analysis represents an improvement on the previous ATLAS analysis in this channel due to a higher centre-of-mass energy, higher integrated luminosity, and better top-tagging techniques, understanding of systematic uncertainties, and statistical treatment.

Fig. 8 shows the distributions in the three signal regions and the validation region after the fit to data. The fit in VR is done independently to test the post-fit agreement of the prediction with data.

![Figure 8](image)

**Figure 8.** Reconstructed mtb distributions in data and for the background after the fit to data in the three signal regions and in the multi-jet validation region: (a) SR1, (b) SR2, (c) SR3, and (d) VR. The top panel shows the total-background mtb distribution before the fit to data as the narrow dotted line and the 3 TeV -boson signal mtb distribution as the dashed line. The “non all-had ” label refers to events in which the W boson from one or both top quarks decays leptonically. The bottom panel of the plot shows the ratio of data to prediction and the hatched band includes the systematic uncertainties after the fit to data.

The maximum value of observed in data is 5.8 TeV. The hatched band in the bottom panel includes the systematic uncertainties after the fit to data. The most discrepant region, at 2.25 TeV, has a local significance of 2.0 $\sigma$ for the combined fit in the three Signal regions (SRs), consistent with the background-only hypothesis. In the absence of any significant excess over the background-only hypothesis, 95% CL limits are derived on the cross-section times branching ratio of W$'$ to $t\bar{b}$ decay, as shown in Fig. 9, for the right-handed and left-handed couplings. The observed and expected limits are derived using a linear interpolation between simulated signal mass hypotheses. They translate to observed (expected) lower limits on the mass of a W$'$ boson, with the same coupling to fermions as the SM W boson, of 3.0 (3.0) TeV and 2.9 (2.8) TeV in the right- and left-handed models, respectively [28].
Figure 9. Observed and expected 95% CL limits on the $W'_R$-boson cross-section times branching ratio of $W'$ to $t\bar{b}$ decay as a function of the corresponding $W'$-boson mass. The expected 95% CL limits are shown with $\pm 1$ and $\pm 2$ standard deviation bands. The narrow dotted curves show the theoretical cross-section predictions and the bands around them show the uncertainties in the predictions for the corresponding $W'$-boson signal.

3.1. Combining searches for new heavy resonances

The ATLAS and CMS collaborations had previously combined searches for new particles decaying to pairs of W or Z bosons, or to a W/Z boson with a Higgs boson. The ATLAS experiment extends these combinations to include – for the first time – decay channels to pairs of light leptons [29]. The new result spans a total of 14 individual analyses of different final states, all using 2015-2016 data of 13 TeV proton-proton collisions taken at CERN’s Large Hadron Collider (LHC). In each analysis, physicists searched for a narrow resonant peak over smooth background indicative of new physics. Careful consideration was required in the combination: the event selections of the individual analyses were designed to avoid events appearing in more than one analysis channel and correlations between channels were taken into account in the statistical analysis.

The new combination places constraints on three new physics models: one postulates a new heavy Higgs-like particle; another a new heavy W/Z boson, based on a Heavy Vector Triplet (HVT) model invoking an extended electroweak sector; and the third, the excitation of a graviton in models with extra spatial dimensions. Constraints obtained by the combination are improved significantly over the most sensitive individual channels. For example, the lower mass limit on graviton excitations increases from 1.7 TeV to 2.3 TeV, and that on new heavy W/Z bosons in a weakly coupled HVT model increases from 4.6 TeV to 5.5 TeV. In the HVT model, the couplings of new particles to quarks and leptons are free parameters. Individual analyses only constrain a subset of these coupling parameters or have a limited sensitivity to them, but together they lead to much stronger simultaneous constraints, exploiting their complementarity. The new combination also improves existing constraints that used precision electroweak measurements, which are only indirectly sensitive to the new heavy particles (see Figure 10).

In the future, this combination programme could be further extended. A particularly promising prospect is the inclusion of channels with pairs of light quarks or top quarks. These channels more precisely probe the coupling of new particles to quarks, which complement the sensitivity of current channels and also provide a probe for new physics coupling more strongly...
Figure 10. Constraints on the coupling strength between either the Higgs boson and W/Z bosons (horizontal axis), or fermions (vertical axis) with a new heavy W/Z boson with masses of 3, 4 and 5 TeV. The area outside of the contours is excluded. Curves correspond to the result of the resonance search combination whereas the filled areas correspond to the constraints from precision electroweak measurements.

4. Vector-like quarks (VLQ)
While a fourth generation of chiral fermions may exist, there are actually strong constraints on it from EW measurements. Vector-like (VL) fermions escape these constraints, and are predicted by many extensions of the SM. They would be a novel form of matter. In certain scenarios, e.g. extra-dimensions, VL quarks Q could couple sizeably to the light generation of quarks, leading to a strong signal at the LHC. For single production of such quarks, the t-channel, is dominant.

A combination of the searches for pair-produced vector-like partners of the top and bottom quarks in various decay channels (T→Zt / Wb / Ht, B→Zb / Wt / Hb) is performed using 36.1 fb$^{-1}$ of pp collision data at $\sqrt{s}$=13 TeV with the ATLAS detector at the Large Hadron Collider[30]. The observed data are found to be in good agreement with the Standard Model background prediction and upper limits are set at 95% confidence level on the production cross-section for a range of vector-like quark scenarios, significantly extending the reach of the individual searches. Observed and expected upper limits on the $T\bar{T}$ cross-sections as a function of mass are shown in Figure 11 for the benchmark scenarios of an isospin singlet or doublet T. A singlet T is excluded for masses below 1.31 TeV and a singlet B is excluded for masses below 1.22 TeV. Assuming a weak isospin (T,B) doublet, T masses below 1.37 TeV and B masses below 1.37 TeV are excluded.

In addition, model-independent lower limits are set on the VLQ mass also for all combinations of branching ratios, assuming $B(T\rightarrow Ht)+ B(T\rightarrow Zt)+ B(T\rightarrow W b) = 1$ and $B(B\rightarrow Hb)+ B(B\rightarrow Zb)+ B(B\rightarrow Wt) = 1$. The resulting lower limits on the VLQ mass as a function of branching ratio are presented in Figure 12. Limits corresponding to $B(T\rightarrow W b) = 1$ and $B(B\rightarrow Wt) = 1$ are found to also be applicable to $Y\bar{Y}\rightarrow WbWb$ and $XX \rightarrow WtWt$, respectively. The high degree of complementarity between the analyses is clearly demonstrated in Figure 12. For any combination of branching ratios, the combination leads to observed (expected) lower mass limits of 1.31 (1.22) TeV for T and 1.03 (0.98) TeV for B.
Figure 11. Observed (solid line) and expected (dashed line) 95% CL upper limits on the $T\bar{T}$ cross-section versus mass for the combination and the standalone analyses for the (left) singlet and (right) doublet scenarios. The shaded bands correspond to ±1 and ±2 standard deviations around the combined expected limit. The thin red line and band show the theory prediction and corresponding uncertainty, respectively.

Figure 12. Observed lower limits at 95% C.L. on the mass of the (a) T and (b) B as a function of branching ratio assuming $B (T \rightarrow Ht) + B (T \rightarrow Zt) + B (T \rightarrow Wh) = 1$ and $B (B \rightarrow Hb) + B (B \rightarrow Zb) + B (B \rightarrow Wt) = 1$. The yellow markers indicate the branching ratios for the SU(2) singlet and doublet scenarios where the branching ratios become approximately independent of the VLQ mass [31].

5. Summary
While there is still no direct evidence of new phenomena at the LHC, the ATLAS Collaboration has set very stringent limits on many exotic models, analysing 36.1 fb$^{-1}$ of the LHC data. Some
of these limits are the most stringent to date, or are novel models never tested by any other experiment. With new techniques, like Machine Learning, Jet Imaging, Complicated FPGA based trigger like Boost data-taking, FastTracker and full Run-2 data been used in more and more analysis teams, we expect to have improved results in next years and are looking forward to see new signals.

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