Exotic searches by ATLAS and CMS

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Abstract. ATLAS and CMS are two general-purpose detectors setting almost opposite to each other at the LHC ring. Both detectors resulted in the discovery of Higgs Boson in 2012. With successful data taking during Run-II, ATLAS and CMS recorded up to $139 \text{ fb}^{-1}$ of integrated luminosity and probes for rare and exotic decays and sets exclusion limits on various models searching beyond standard model physics.

1. Introduction
The standard model (SM) of particle physics successfully explains the structure of matter and forces acting between them but still, it fails (i) to include the fourth fundamental force i.e. gravitational force (ii) to explain matter-antimatter in the universe (iii) to explain the 95% dark energy and dark matter forming the universe and so on.

There are several models evolved with time to explain the physics beyond the standard model and are known as ”Beyond Standard Model (BSM)”. Some examples of these models are Sequential-SM, $E_6$ model, Grand Unified Theories (GUT). Different search strategies have been incorporated at the LHC to find answers to the above questions.

LHC successfully recorded data up to December, 2018 around $\sim 139 \text{ fb}^{-1}$ of integrated luminosity from p-p collisions at 13 TeV as shown in figure 1.

This marks the end of Run-II. The luminosity obtained at the LHC helps to investigate the different extensions of the Standard Model. The biggest challenge due to this large instantaneous

Figure 1. Luminosity recorded by the ATLAS experiment.

Figure 2. Mean number of interactions per bunch crossing.
luminosity is the number of simultaneous collisions (called pile-up events) which increase the background and complicates the reconstruction as shown in figure 2.

Due to space constraints, we are providing a snapshot of the latest results recorded by ATLAS and CMS detectors and are classified into four major categories: heavy resonances, new leptons and quarks, dark matter, and new leptons and quarks based on theoretical motivations.

2. Heavy resonances
The most striking signature for the existence of new physics beyond the standard model is the existence of heavy resonance such as excited quarks, new heavy gauge bosons, gravitons or dark matter which eventually decay to standard model particles giving pairs of jets, leptons, photons, or more complicated objects like W and Z bosons and top quarks as the possible final states. Dedicated reconstructions mechanisms and background estimation methods have been utilized by both ATLAS and CMS to search for such kind of signatures.

2.1. Dijet resonance search
The dijet resonance search is the best approach to search for extremely high masses due to large production cross-section of jet final states. But, with the large sensitivity towards the signal, the biggest challenge in these searches is the handling of QCD or other jet backgrounds.

In this search [1] carried out by CMS, a new data-driven method is introduced for $m_{jj} > 2.4$ TeV which predicts the background from a control region where the pseudorapidity separation of the two jets ($|\Delta \eta|$) is large. This new method termed as ”ratio method” leads to improvement in the sensitivity for broad resonances by a factor of two depending on the resonance width and mass. Also, to reduce analysis sensitivity to final state radiations (FSR), two close-by jets are combined forming a wide jet with a cone size of 0.8 as shown in figure 3.

Due to better data-driven background estimate from ”ratio method” than the traditional ”fit method”, larger signal significance has been observed with the ratio method. With this search, limits are improved by 200 GeV TO 800 GeV for narrow resonances relative to those reported in previous CMS dijet resonance searches. Figure 4 describes the exclusion limits for various models predicting new resonances.

Another benchmark was set with analyzing data collected at high-level trigger (HLT) level to get sensitivity in lower masses. With this technique called Data Scouting, events containing three jets are reconstructed, selected, and recorded in a compact form with lower thresholds using only calorimeter information by the high-level trigger. The spectrum of the dijet invariant mass, calculated from the two jets with the largest transverse momenta in the event, is used to search for resonance. No significant excess has been observed over a smoothly falling background. This search [2] presents the most stringent upper limits in the mass range between 350 and 450 GeV as shown in figure 5.
Another search [3] for $t\bar{t}$ resonance decaying to fully hadronic final states has been carried out by ATLAS experiment exploiting an advanced top-tagger based on deep neural network (DNN) technique. In this technique, a single large-R jet captures the top-quark decay products and accordingly multiple jet-level discriminants are used as input to the DNN tagger such as jet transverse momentum and mass, information about the dispersion of the jet constituents, splitting scales and energy correlation functions. The signal region is further divided into two regions containing 1b or 2b jets tagged as variable radius (VR) track jets containing b-hadrons identified using multivariate classification technique with an artificial deep neural network to combine track information within a jet. A parametric fit has been performed over data and no significant excess has been observed. Upper limits are set on the production cross-section times branching fraction for $Z'$ in the topcolor-assisted-technicolor model, resulting in the exclusion up to 3.9 and 4.7 TeV for decay widths of 1% and 3%, respectively as shown in the figure 6.

**Figure 4.** The observed 95% CL upper limits on the product of the cross-section, branching fraction, and acceptance for quark-quark, quark-gluon, and gluon-gluon type dijet resonances.

**Figure 5.** Upper limits at 95% CL on the product of the cross-section, branching fraction, and acceptance as a function of resonance mass for a narrow resonance decaying into a pair of quark jets using data-scouting technique.

**Figure 6.** Observed and expected upper limits on the cross-section times branching fraction of the $Z' \rightarrow t\bar{t}$ as function of $Z'$ mass.
However, improved analysis techniques have provided 65% improvement in the expected cross-section limit at 4 TeV with the same data set.

2.2. Diboson resonance search

For the diboson resonance searches, the search becomes more challenging. Due to the production of heavy bosons in the TeV scale, the decay products produced are generally boosted and hence it becomes critical to combine the calorimeter information with the tracker angular information. ATLAS and CMS have extensive search strategies to search for diboson resonances. With the increasing centre of mass energy, the novel techniques have been developed such as 3D likelihood fits and anomaly detection techniques for broadening the scope of these searches. Both ATLAS and CMS search for diboson resonances \[4\] \[5\] with all possible final states i.e. 0-lepton, 2-lepton final state with associated jet from H decay. ATLAS also considered the fully hadronic decay \[6\] of the diboson resonance. Whereas, to enhance sensitivity for the search, CMS considered the VBF production mechanism of the ZH resonance. As no significant excess has been observed, upper limits with 95% CL are set on masses for \(Z'\) for 0-lepton, 2-lepton channel and in fully hadronic final states by ATLAS and is shown in figure 7. Similarly, CMS sets exclusion limits for VBF 0-lepton and 2-lepton final state with 95% confidence level for the HVT benchmark Model C where \(Z'\) couples only to the SM bosons as shown in figure 9.

**Figure 7.** Upper limits at the 95% CL on the product of the cross section for \(pp \rightarrow Z'\) and their respective branching fraction to ZH from the combination of the 0-lepton and 2-lepton channels.

**Figure 8.** Upper limits at the 95% CL on the product of the cross section for \(pp \rightarrow Z'\) and their respective branching fraction to ZH for fully hadronic channel.

**Figure 9.** Upper limits at the 95% CL on the product of the cross section for \(pp \rightarrow Z'\) and their respective branching fraction to ZH from the combination of the 0-lepton and 2-lepton channels with VBF signal.
3. New leptons and quarks

One of the biggest questions remains unanswered by the standard model theory is the symmetry between the quarks and lepton families. Several models such as Grand unified theories, technicolor models etc foresee new particles that carry both lepton and baryon number and are known as ‘Leptoquarks (LQ)’. Recently, LQ search gained more importance because it may explain B-meson anomalies.

ATLAS probes for the LQ with two search categories: LQ decaying to $\tau$ lepton and top quark [8] and to $e$ (or $\mu$) and top quark [9]. In the former case, five final states, based on the multiplicity and flavour of lepton candidates, are considered and each of them is divided into several event categories to constrain several leading background in each final state. No significant excess above the Standard Model expectation is observed and 95% CL upper limits are set on the production cross section as a function of the LQ mass, under different assumptions for the branching fractions into $t\tau$ and $b\nu$ as shown in figure 10.

For the scalar LQ decaying to a top quark and either an electron or a muon, the normalization of dominant backgrounds such as $Z+jets$ and $t\bar{t}$ is determined with profile likelihood fit to a binned BDT in the signal region and two dedicated control regions. The observed data distributions are compatible with the expected Standard Model background and lower limits on the production cross-section are set at 1.48 TeV and 1.47 TeV for the electron and muon channels, respectively as shown in figure 11.

![Figure 10](image1.png)

**Figure 10.** Observed (solid line) and expected (dashed line) 95% CL upper limits on the $LQ^d_3$ pair production cross-section as a function of $m_{LQ^d_3}$.

![Figure 11](image2.png)

**Figure 11.** Observed (solid line) and expected (dashed line) 95% CL upper limits on the cross section of LQ pair production as a function of LQ mass assuming $B(LQ \rightarrow t\ell\nu) = 1$, for muon channels.

Recently, CMS considered the search for LQ [9] in which LQ may couple to a top quark plus a $\tau$ lepton ($t\tau$) or a bottom quark plus a neutrino ($b\nu$, scalar LQ), or else to $bt\nu$ (vector LQ), leading to the final states $t\tau\nu b$ and $t\tau\nu$. The channel in which both the top quark and the $\tau$ lepton decay hadronically is investigated, including the case of a large LQ-t mass splitting giving rise to a boosted top quark whose decay products may not be separated on the scale of the spatial resolution of the jet. Such a signature has not been previously examined in searches for physics beyond the standard model. The observations are found to be in agreement with the standard model prediction. Exclusion limits are given in the plane of the LQ-lepton-quark vertex coupling $\lambda$ and the LQ mass for scalar and vector LQ. The range of lower limits on the
LQ mass, at 95% CL, is 0.98-1.73 TeV, depending on $\lambda$ and the LQ spin as shown in figure 12.

Figure 12. The observed and expected (solid and dotted lines) 95% CL LQ exclusion limits in the plane of the LQ-lepton-quark vertex coupling and the mass of the LQ for single (brown lines), pair (blue lines) production, and considering their sum (black lines).

4. Dark matter searches

Gravitational effects on astrophysical scale provide convincing evidence for the existence of non-luminous and Weakly interacting matter which constitutes up to 26% of the matter-energy content of the Universe. At hadron colliders, searches for this weakly interacting DM have to rely on one or more visible particles being produced in association with the invisible DM candidate. Large missing energy in the collision events is the only experimental signature for the DM search.

Several models populate the “theory space” of all possible realizations of physics beyond the SM with a particle that is a viable DM candidate. A common model to interpret the observations known as “simplified DM model” assumes a vector, axial-vector, scalar, or pseudoscalar mediator, which decays into a pair of fermionic DM particles and interacts with SM particles. More complete models involve a 2HDM+a model (or two-Higgs-doublet) in which the pseudoscalar mediator coupling to DM also couples to Higgs boson. ATLAS and CMS have an extensive search program to search physics beyond standard model after the discovery of Higgs boson.

ATLAS presents its first measurements [10] for processes where the pseudo-scalar mediator is produced in association with a single top quark. Several final states are considered, including either one or two charged leptons (electrons or muons) and a significant amount of missing transverse momentum. No significant excess is found with respect to Standard Model predictions. The results are expressed as 95% confidence level limits on the 2HDM+a signal models as shown in figure 13.

Figure 13. The expected and observed cross-section exclusion limits as a function of $m_{H^\pm}$ for signal models with $m_a = 250$ GeV.

Also, a search [11] with an energetic jet and large missing transverse momentum is reported by ATLAS. Compared to previous publications, in addition to an increase of almost a factor of
four in the data size, the analysis implements several improvements in the signal selection and the background estimation leading to enhanced sensitivity. Events are required to have at least one jet with transverse momentum above 150 GeV and no reconstructed leptons (e, µ or τ) or photons. Several signal regions are considered with increasing requirements on the missing transverse momentum starting at 200 GeV. An overall agreement is observed between the number of events in data and Standard Model predictions. Model-independent 95% confidence level limits on visible cross sections for new processes are obtained in the range between 861 fb and 0.3 fb as shown in figure 14.

Another pioneering search [12] is performed by ATLAS for dark matter particles produced in association with a Dark Higgs boson decaying to VV where V = W±, Z. The s → V(qq)V(qq) decays are reconstructed with a novel technique using reclustered jets with a cone parameter R=0.8 based on R=0.4 calorimeter jets and tracking information. The observed data are found to agree with Standard Model predictions. The results provide exclusions in the previously uncharted parameter space of the Dark Higgs model for ms >160 GeV as shown in figure 15.

![Figure 14](image1.png)  
**Figure 14.** 95% CL exclusion contours in the mZA–mA parameter plane for the axial-vector mediator model.

![Figure 15](image2.png)  
**Figure 15.** Observed excluded σ(pp → sχχ) × B(s → VV) for the Dark Higgs model at a 95 C.L., compared to the SM-only expectation.

CMS presents a search [13] for a scalar boson H produced in the Vector Boson Fusion (VBF) production mode and decaying to an undetected particle and a photon. Such Higgs boson decays are predicted by several BSM models. In this search, the target final state is qqH(→ γγD), where the final state quarks (q) arise from the VBF process and γD is a massless dark photon that couples to the Higgs boson through a charged dark sector. The dark photon escapes the CMS detector undetected. No significant excess of events above the expectation from the standard model background is found. The results are used to place limits on the product of the signal cross section for VBF production and the branching fraction for such decays of the Higgs boson, in the context of a theoretical model where the undetected particle is a massless dark photon as shown in figure 16.

5. Unconventional signatures

The existence of long-lived particles and unconventional signatures are features of both standard model (SM) and beyond standard model (BSM) scenarios and are predicted by many extensions of the SM, like several SUSY scenarios (e.g. Gauge Mediated Supersymmetry Breaking or
scenarios with mass-degenerate gauginos) and in models where there is a hidden sector that couples very weakly to visible sector fields. These new long-lived particles would show up in several different topologies in detectors: delayed photons, displaced track vertexes, displaced jets and leptons, disappearing tracks, almost stable charged particles, particles stopped in the detector, and emerging jets. The LHC detectors were not originally intended to detect particles that decay further than a few centimeters from the beamline and the original focus for displaced signature was only on detecting jets containing bottom or charm quarks, which decay a few hundred micrometers from the beam axis.

CMS has presented results for long-lived particles decaying into jets. The analysis [14] examines the distinctive topology of displaced tracks and displaced vertices within a dijet system. To discriminate against SM backgrounds such as QCD, a multivariate discriminant is constructed based on variables such as: Vertex track multiplicity, Vertex $L_{xy}$ significance, Cluster RMS and $\kappa$. For the multivariate discriminant, the Gradient Boosted Decision Trees (GBDT) is utilized and due to insufficient statistics of simulated QCD, data is used for the training and testing. The signal yields in the final signal region are used to set limits on a variety of models. The expected and observed 95% CL upper limits on the branching fraction of the SM Higgs boson to decay to two long-lived scalars, assuming the gluon-gluon fusion SM Higgs production cross section of 49 pb at 13 TeV with $m_H=125$ GeV, shown in figure 17 at different masses and $c_{\tau_0}$ for the scalar S.

Talking of unconventional signatures comes the violation of the assumption that the number of leptons in each family is conserved in interactions known as Lepton Flavour Violation (LFV). LFV is not possible in the SM, even though no fundamental principles forbid it. The observation
of neutrino oscillations, where neutrinos (the neutral leptons) of one flavour transform into that of another, indicates that LFV processes do occur in Nature. It reveals that neutrinos have mass, and this constitutes the first experimental evidence of new phenomena beyond those originally predicted by the SM. The ATLAS experiment sets a new strong constraint on Lepton Flavour Violation effects in weak interactions, searching for $Z$ boson decays into a $\tau$-lepton and another lepton of a different flavour ($e$ or $\mu$) with opposite electric charge [5]. Only events with a $\tau$-lepton that decays hadronically are considered. Neural network classifiers are used in a novel way for optimal discrimination of signal from backgrounds and improved sensitivity in the measurement of LFV effects from the data using a binned maximum-likelihood statistical fit. The LHC Run 2 result is combined with a previous LHC Run 1 result to further improve sensitivity. These results set stringent constraints on LFV $Z$ decays involving $\tau$-leptons, superseding the otherwise most stringent ones set by the LEP experiments. Using a combination of LHC Run 1 and Run 2 proton-proton collision data, the branching fractions for these decays are now measured by the ATLAS experiment to be less than $9.5 \times 10^{-6}$ ($\mu\tau$) and $8.1 \times 10^{-6}$ ($e\tau$) at 95% confidence level as shown in figure [18].

| Experiment, polarization assumption | Observed (expected) upper limit on $BR(Z \to \ell\ell') \times 10^{-6}$ |
|-----------------------------------|--------------------------------------------------|
| ATLAS Run 1, unpolarized $r$      | 9.4                                              |
| ATLAS Run 1, unpolarized $\tau$  | 17                                               |
| ATLAS Run 2, left-handed $r$      | 9.4                                              |
| ATLAS Run 2, right-handed $r$     | 9.4                                              |
| ATLAS Run 1, unpolarized $\ell$  | 17                                               |
| ATLAS Run 1 and Run 2, unpolarized $r$ | 9.4                                |
| LEP OPHEL, unpolarized $r$ [30]  | 9.4                                              |
| LEP DELPHI, unpolarized $r$ [11] | 22                                               |

Figure 18. The expected (median) and observed upper limits on the signal branching fraction at 95% CL.

6. Conclusion

The outstanding performance of the LHC led to $\sim 140 fb^{-1}$ of data accumulated at $\sqrt{s} = 13$ TeV, exceeding the expectations. This large amount of data has allowed for a multitude of searches for beyond Standard Model scenarios involving striking new signatures, like heavy resonances, new leptons and quarks, long-lived particles, and dark matter. Unfortunately, no significant excess of events has been observed above standard model expectations and the measurements are consistent with the Standard Model. While moderate improvements for extremely high mass searches are expected in future, there are several new approaches, targeting low and intermediate-mass regions and using novel experimental techniques, which will explore new territories during next years.

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