Searches for other non-SUSY new phenomena at the LHC

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The ATLAS and CMS collaborations collected datasets of approximately 20 fb\(^{-1}\) of \(pp\) collisions at \(\sqrt{s} = 8\) TeV produced by the LHC during the Run-1 period. The collaborations performed a thorough analysis of these datasets searching for physics phenomena beyond the Standard Model. These conference proceedings summarize the results of a selection of searches targeting non-Supersymmetry phenomena.

1 Introduction

The substantial dataset of approximately 20 fb\(^{-1}\) of \(pp\) collisions at \(\sqrt{s} = 8\) TeV collected by the ATLAS\(^1\) and CMS\(^2\) collaborations during the Run-1 period of the LHC provided an unprecedented opportunity to search for phenomena beyond the Standard Model (SM). A thorough signature-driven search program targeting non-Supersymmetry extensions to the SM was executed by both collaborations. The collaborations used phenomenological models as benchmarks to optimize the event selection criteria and to interpret the data. These conference proceedings summarize the results of a selection of these searches, including searches for new massive resonances decaying to SM particles, searches for vector-like partners of the third generation quarks, and searches for heavy neutrinos.

2 Searches for heavy resonances

Several extensions to the SM predict the existence of new resonances with masses at the TeV scale, for example, models with an extended gauge sector, models with warped extra dimensions, models with excited quarks, and compositeness models.

The CMS Collaboration searched for new phenomena in the invariant mass distribution of dijet events\(^3\). In this search, jets were constructed with the “wide-jet” technique that aims to include the complete radiation pattern of gluons by seeding the jet building with narrow jets and including objects within a distance of \(\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2} < 1\) of the narrow jet seeds, where \(\eta\) is the pseudo-rapidity, and \(\phi\) is the azimuthal angle. To improve the sensitivity of the search to signals decaying to final states including bottom quarks, the selected events were classified according to their \(b\)-tag multiplicity. The background of this search was estimated using an empirical parametric model that assumes a smoothly and steeply falling dijet mass distribution for background events. The search was sensitive not only to new narrow resonances, but also to wide resonances and quantum blackholes. No significant discrepancies with respect to the SM background were observed and exclusion limits were set in the context of specific models,
excluding string resonances with masses below 5.0 TeV; excited quarks below 3.5 TeV; scalar diquarks below 4.7 TeV; $W'$ bosons below 1.9 TeV or between 2.0 and 22 TeV; $Z'$ bosons below 1.7 TeV; Randall-Sundrum gravitons below 1.6 TeV; excited bottom quarks, with masses below 1.2 or 1.6 TeV depending on their decay properties; axigluons and colorons with masses below 3.6 TeV; color-octet scalars with a mass below 2.5 TeV, and lower bounds between 5.0 and 6.3 TeV are set on the masses quantum black holes depending on the fundamental Planck scale and the number of extra dimensions of the quantum black hole production model.

CMS also searched for new physics in the dilepton mass spectra with $\mu\mu$ and $ee$ final states$^6$. The search was sensitive to resonant and non-resonant new phenomena. The resonant analysis used an unbinned maximum likelihood analysis, while the non-resonant analysis used cut-and-count approach. The dominant background to this search was Drell-Yan $Z/\gamma$ production. The backgrounds were estimated using Next to Leading Order (NLO) simulation to determine the shape of the spectrum, and a data Control Region (CR) to determine the overall normalization. No significant deviations with respect to the SM were observed and exclusion limits were set on Sequential Standard Model $Z'$ resonances lighter than 2.9 TeV, a superstring-inspired $Z'$ lighter than 2.57 TeV, and Randall-Sundrum Kaluza-Klein gravitons with masses below 2.7, 2.4, and 1.3 TeV for couplings of 0.10, 0.05, and 0.01, respectively. Within the non-resonant analysis lower limits were established on $M_{S}$, the scale characterizing the onset of quantum gravity, which range from 3.3 to 4.9 TeV when the number of additional spatial dimensions varies from 3 to 7, and lower limits on $A$, the energy scale parameter for a contact interaction within the left-left isoscalar model; for dimuons the limits were set at 12.0 (15.2) TeV for destructive (constructive) interference, and for dielectrons the limits were set at 13.5 (18.3) TeV for destructive (constructive) interference.

ATLAS searched for high mass resonances in the invariant mass spectra of $\tau\tau$ final states$^7$, motivated by the possibility of lepton-flavor dependent new phenomena. This search used both leptonically and hadronically decaying $\tau$ leptons. A kinematic variable based on the transverse mass of the reconstructed $\tau$'s and missing transverse momentum, $E_{T}^{miss}$, was used as a proxy to the actual invariant mass of the $\tau\tau$ system. A cut-and-count approach was followed where the cut values were optimized for different sought after signals. No significant discrepancies with respect to the SM were observed and limits on the inclusive production cross section times branching ratio of a new $Z'$ decaying to $\tau\tau$ were set as a function of the $Z'$ mass, excluding new $Z'$ with SM couplings decaying to $\tau\tau$ with masses up to 2 TeV.

CMS and ATLAS also searched for new heavy resonances decaying to a vector boson and a Higgs boson. ATLAS searched for these resonances using the decay of the Higgs boson to bottom quarks and non-hadronic decays of the vector bosons$^8$ targeting resonance masses between 0.3 and 1.9 TeV. In this search the data were classified according to the lepton and $b$-tagging multiplicity in the selected events. CMS searched for these resonances focus in a higher resonance mass regime covering from 0.8 to 2.5 TeV, and used the decays of the Higgs boson to $\tau$ leptons in conjunction with the hadronic decay of a $Z$ boson$^9$, or the decay of the Higgs boson to $b$ quarks and the leptonic decay a $W$ boson$^{10}$. To reconstruct and select hadronically decaying $Z$ bosons, CMS used large-$R$ jets, groomed to discard jet components from pileup and underlying event interactions, their mass and jet sub-structure properties. For the reconstruction and selection of the hadronically decaying Higgs bosons CMS also used large-$R$ groomed jets in conjunction with the $b$-tagging multiplicity of associated narrow jets, and to reconstruct and select Higgs bosons decaying to $\tau$ leptons both leptonic and hadronic $\tau$ lepton decay modes were used. No significant deviations with respect to the SM prediction were observed by any of the analyses, and the results of these searches were interpreted with the Heavy Vector Triplet$^{11}$ phenomenological model as a benchmark. Under this model, ATLAS and CMS excluded minimal composite Higgs models (model B) with new resonance masses up to 1.5 TeV.
3 Searches in the angular distributions of dijet events

The angular distribution of jets relative to the beam axis in events with high dijet invariant mass are sensitive to the presence of new forces interacting with quarks and to the existence of internal structure for quarks. CMS\textsuperscript{12} and ATLAS\textsuperscript{13} searched for new physics in dijet angular distributions analyzing the distribution of $\chi = e^{y_1-y_2}$, where $y_i$ is the rapidity of the leading or sub-leading jet in the event in bins of dijet mass. Both collaborations compared the data to NLO SM model predictions including electroweak (EW) corrections and no significant deviations with respect to these predictions were observed. The results by ATLAS and CMS were interpreted as 95% CL lower limits on the scale of a new contact interaction between 8 and 12 TeV depending on the interaction model. CMS also interpreted the results as 95% CL lower limits on the scale of a virtual graviton exchange in the Arkani-Hamed-Dimopolous-Dvali (ADD)\textsuperscript{14,15} model of extra dimensions between 6 and 8 TeV depending on the number of extra dimensions.

4 Searches for vector-like quarks

Several extensions to the SM introduce new fermion partners to the third generation quarks for which both chiralities transform in the same way under the SM gauge groups as a means to explain the lightness of the Higgs boson mass. These new states, commonly referred to as vector-like quarks (VLQ), could be produced at the LHC; light VLQs would be produced dominantly in pairs in strong interaction processes, while heavy VLQs would be produced singly in weak interaction processes. The decays products of the VLQs can involve top and bottom quarks, and Higgs and vector bosons, depending on the flavor, mass, and couplings of these new quarks.

ATLAS and CMS searched for VLQ in different final states. ATLAS used events with $b$-tagged jets, and two same sign leptons or three leptons\textsuperscript{16}. The analysis defined eight different signal regions optimized according to the lepton multiplicity, number of $b$-tagged jets, $E_T^{\text{miss}}$, and the scalar sum of transverse momenta of the different objects reconstructed in the event. The signal regions were optimized for different VLQ signals, and were also sensitive to the presence of other non-VLQ new phenomena such as four-top production, chiral bottom quarks, and flavor changing Higgs couplings. CMS searched for VLQ partners of the bottom quark in events with at least three leptons\textsuperscript{17}. In this analysis, the events were classified according to the lepton multiplicity and flavor, including $T$ leptons, $b$-tagging multiplicity, and kinematic quantities. ATLAS searched for VLQ partners of the $b$ quark in events with an isolated lepton, large $E_T^{\text{miss}}$, and at least one $b$-tagged jet\textsuperscript{18}. The analysis targeted the decay of the new VLQ to a top quark and a $W$ boson using multivariate analysis methods, but had sensitivity to other VLQ signatures. CMS searched for VLQ partners of the top quarks decaying to a top quark and a Higgs boson in the fully hadronic channel\textsuperscript{19}. In this analysis, boosted decays of the top quark and the Higgs boson were reconstructed and tagged using large-$R$ jets, $b$-tagging and jet sub-structure information, and the analysis proceeded using a likelihood constructed from the mass of the Higgs boson candidate and a kinematic variable that characterized the hadronic activity in the event. No significant deviations with respect to the SM predictions were observed by ATLAS or CMS and both collaborations set lower limits on the mass of VLQ and their couplings to the Higgs, and vector bosons.

5 Searches for heavy neutrinos

The observation of neutrino oscillations has provided evidence that neutrinos have masses. The “seesaw” mechanism can explain the smallness of the SM neutrino masses. In the simplest “seesaw” model, the mass of the SM neutrinos is given by $m_{\nu} \sim y^2 v^2/m_N$, where $y_{\nu}$ is a Yukawa coupling between the SM neutrino and the Higgs field, $v$ is the Higgs vacuum expectation value, and $m_N$ is the mass of a new heavy neutrino state, $N$. In this model, $N$ is a Majorana particle, and hence processes that violate lepton number are possible. At the LHC, these heavy neutrino
states, $N$, could be produced through the charged weak interaction together with a charged lepton, and decay to a $W$ and a lepton.

CMS and ATLAS searched for heavy neutrinos in events with leptons and jets. The CMS search used events with two same sign muons and jets\textsuperscript{20}. In this search, the hadronic decay mode of the $W$ resulting from the $N$ decay was chosen to increase the signal selection efficiency. No significant deviation with respect to the SM expectation was observed, and heavy Majorana neutrinos with masses between 40 and 500 GeV were excluded depending on their coupling with the $\mu$ lepton. ATLAS searched for heavy neutrinos in events with two same sign leptons and two jets\textsuperscript{21}. In this search, no significant deviation from the SM expectation was observed, and exclusion limits on heavy neutrinos between 100 and 500 GeV were set depending on the coupling between the heavy neutrino and the SM charged leptons.

6 Summary

These proceedings presented a selection of signature driven searches for physics beyond the SM performed with approximately 20 fb$^{-1}$ of $pp$ collisions at $\sqrt{s} = 8$ TeV, collected during the Run-1 period of the LHC, by ATLAS and CMS collaborations. In the searches presented no significant deviations with respect to the SM expectation were observed, and exclusion limits were set on different benchmark models.

References

10. CMS Collaboration, CMS-PAS-EXO-14-010
17. CMS Collaboration, CMS-PAS-B2G-13-003