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Abstract

The latest results of searches for new heavy resonances decaying in lepton pairs and new physics beyond the Standard Model with multi-lepton final states from the ATLAS and CMS collaborations are presented, based on $\sqrt{s} = 13$ TeV proton-proton collisions data at the LHC. No evidence of new heavy particles is observed and limits are set at the 95 confidence level on various benchmark models.

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Searches for dilepton resonances at high mass ($Z'$, $W'$) and other non hadronic final states with 13 TeV data

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The latest results of searches for new heavy resonances decaying in lepton pairs and new physics beyond the Standard Model with multi-lepton final states from the ATLAS and CMS collaborations are presented, based on $\sqrt{s} = 13$ TeV proton-proton collisions data at the LHC. No evidence of new heavy particles is observed and limits are set at the 95% confidence level on various benchmark models.

1 Introduction

The Standard Model (SM) of particle physics is one of the most successful theories, with experimental results being consistently in agreement with its predictions. It is known however, that the SM does not describe the nature completely and it is usually seen as a low energy approximation of a more general theory. Therefore there exist many theories extending beyond the SM (BSM) which predict new particles at the TeV mass scale. Models with extended gauge groups often feature additional $U(1)$ symmetries with corresponding heavy spin-1 bosons ($W'$, $Z'$). Among the models aimed to justify the neutrino masses, the type-III seesaw mechanism predicts new heavy fermions with multilepton final states. Such new massive particles would appear as a clear excess over a falling SM background in the mass spectrum.

The ATLAS\textsuperscript{1} and CMS\textsuperscript{2} experiments both have a rich program of searches for new exotic phenomena and a complete review of all results can be found in \textsuperscript{3} (ATLAS) and \textsuperscript{4,5} (CMS). Almost any combination of two SM particles can form a resonance in BSM models. This document details several of the most recent ATLAS and CMS searches for heavy particles using $\sqrt{s} = 13$ TeV proton-proton LHC data. In particular, single charged lepton based searches ($W'\to \ell\nu$), charged lepton pair based searches ($Z'\to \ell\ell$, or $Z'\to \ell\ell'$), and multilepton final states searches are described in this document.

2 Charged lepton and neutrino channel

Both ATLAS and CMS collaborations have searched for a heavy charged boson ($W'$) selecting an high-energy isolated electron or muon and missing transverse momentum due to the undetected neutrino using respectively 36.1 fb$^{-1}$ and 2.3 fb$^{-1}$ of data\textsuperscript{6,7}.

Figure 1 displays the transverse mass ($m_T$) distributions in the electron (left) and muon (right) channels observed by ATLAS\textsuperscript{6}. As examples, to the SM prediction were added the expected signal spectra for $W'$ bosons predicted by the benchmark Sequential Standard Model (SSM). The middle panels of figure 1 show the ratio of the data over the SM predictions, and the
lower panels show the ratio of the data to the adjusted background that results from a common fit to the electron and muon channels.

No significant excess of events relative to the SM expectations was observed in the $m_T$ spectra and upper limits at 95% confidence level were set on the product of the production cross-section and branching fraction, as shown in figure 2.

The results were interpreted in the context of the SSM that predicts $W'_{SSM}$ with the same couplings as the SM W boson (figure 2a). Lower limits of 5.1 TeV and 4.1 TeV were established on the $W'_{SSM}$ mass respectively by ATLAS and CMS combining both the electron and muon channels. The CMS transverse mass spectra were used to set model independent limits vs transverse mass as well, as shown in figure 2b.

The CMS collaboration also reported on a search for a $W'$ boson decaying into tau lepton and neutrino, using 2.3 fb$^{-1}$ of data. Only the hadronic decays of the $\tau$ were considered. No deviations from the predicted background was observed on the transverse mass distribution, therefore upper limits were set on the production cross-section times branching fraction, as shown in figure 3, and the results were interpreted in terms of the SSM (left) and model independent (right). A lower limit of 3.3 TeV was established on the $W'_{SSM}$ mass in this channel.

3 Dilepton channel

Both ATLAS and CMS collaborations have searched for heavy neutral new particles selecting high-energy isolated electron or muon pairs.

In addition to the SSM, that predicts the $Z'_{SSM}$ boson with couplings identical to those of the SM Z boson, the Grand Unifies Theories (GUT) inspired models, based on the $E_6$ gauge group, yield $Z'$ signals defined by the two gauge fields associated to two separate $U(1)$ groups resulting from a particular choice of the $E_6$ group symmetry-breaking, and specific values of their mixing angle. ATLAS and CMS collaborations have searched for such heavy spin-1 $Z'$ bosons using approximately 13 fb$^{-1}$ of data.

The CMS collaboration have also searched for the Kaluza-Klein spin-2 graviton ($G_{KK}$) of the extra dimensions Randall-Sundrum (RS) model combining results from the analysis of approximatively 3 fb$^{-1}$ of data collected from proton-proton collisions at $\sqrt{s} = 13$ TeV and results from the previously analyzed 20 fb$^{-1}$ of data collected at $\sqrt{s} = 8$ TeV.

Figure 4 displays the invariant mass distributions in the electron (left) and muon (right) channels observed by ATLAS (figure 4a) and CMS (figure 4b).
Figure 2: Observed and expected 95% confidence level upper limits on the production cross-section times branching fraction of the (a) $W'$ boson using ATLAS (left) and CMS (right) mass spectra interpreted in terms of SSM, and (b) model-independent results from CMS data.

Figure 3: Observed and expected 95% confidence level upper limits on the production cross-section times branching fraction of the $W'$ boson decaying into tau and neutrino interpreted in terms of the SSM (left) and model independent results (right).

No evidence for non-SM physics was found in the invariant mass spectra, either in the 13 TeV data set alone, or in the combined data set. Upper limits at 95% confidence level were set on the product of the production cross-section and branching fraction by the ATLAS collaboration and on the same quantity normalized at the Z peak by the CMS collaboration.

A complete review of all these results is beyond the scope of this document, but can be found in (ATLAS) and (CMS). The most stringent limits on the mass of a spin-1 resonance are shown on figure 5 for the ATLAS (left) and CMS (right) collaborations, combining both the electron and muon channels.
Figure 4: Invariant mass distributions for selected dielectron (left) and dimuon (right) events using data collected by (a) ATLAS\(^9\) and (b) CMS\(^10\). The distributions in data are compared to the stacked sum of all expected backgrounds. Expected signal for three different GUT-inspired Z\('_\chi\) boson masses are added to the SM prediction in (a).

Figure 5: Observed and expected 95% confidence level upper limits on the production cross-section times branching fraction of the Z\('_\psi\) boson using ATLAS mass spectra (left)\(^9\) and on the production cross-section times branching fraction of the Z\('_\psi\) divided by the same quantity at the Z peak using CMS mass spectra (right)\(^10\) interpreted in terms of SSM and GUT-inspired models.

The resulting lower mass limit was of 4.05 TeV for the Z\('_\text{SSM}\) boson. ATLAS excluded the GUT-inspired Z\('_\chi\) and Z\('_\psi\) with masses lower than 3.66 TeV and 3.36 TeV respectively. Other E\(6\) Z\(’\) models mass limits were also constrained in the range between those quoted for the Z\('_\chi\) and Z\('_\psi\). CMS obtained a lower mass limit of 3.5 TeV for the Z\('_\psi\) boson.

The limits on the mass of a RS graviton are shown on figure 6 for different coupling parameters of the extra dimensions theory, combining both the electron and muon channels. The cor-
responding limits for the $G_{KK}$ with coupling parameters 0.01 and 0.10 were 1.46 and 3.11 TeV, respectively.

The ATLAS and CMS collaborations also reported on a search for a $Z'$ decaying into tau lepton pairs, using respectively 3.2 and 2.2 fb$^{-1}$ of data$^{12,13}$. The search is performed selecting high transverse momentum oppositely charged $\tau$ leptons considering both the leptonic and fully hadronic decays of the $\tau$. No deviations from the predicted background was observed on the di-tau mass distribution, therefore upper limits were set on the cross section times branching fraction by ATLAS and to the same quantity normalized at the Z peak by CMS, as shown in figure 7.

The results were interpreted in terms of the SSM and, combining all the final states, the $Z'_{SSM}$ was excluded with masses less than 2.1 TeV. The CMS collaboration interpreted the results also in terms of the topcolor-assisted technicolor (TAT) models aimed to explain the high mass of the top quark and that predict $Z'$ bosons ($Z'_{TAT}$) characterized by a reduced coupling to light fermions and enhanced coupling to heavy third-generation fermions. Combining all the final states, the $Z'_{TAT}$ was excluded with masses less than 1.7 TeV.
4 Lepton flavor violation (LFV) channel

Direct production of lepton pairs with different flavours ($\ell\ell'$) is forbidden within the SM. Models with additional gauge symmetries predicting $Z'$ bosons or low-scale gravity models predicting quantum black holes (QBH) can produce LFV final states.

Both ATLAS and CMS collaborations have searched for heavy particle decaying into different flavour dilepton pairs with approximately $3 \text{ fb}^{-1}$ of data\textsuperscript{14,15}. The selection strategy was very similar as the one used for the same-flavour dilepton channel. The ATLAS collaborations considered the $Z' \rightarrow e\mu$, $e\tau$, $\mu\tau$ decay channels\textsuperscript{14}. The CMS collaboration only reported about the $e\mu$ final state\textsuperscript{15}.

Figure 8a displays the invariant mass distribution in the $e\mu$ channel observed analyzing ATLAS data. No significant excess over the SM prediction was observed in the measured invariant mass spectra. Therefore limits at the 95% confidence level were set on the signal cross section times branching fraction, as shown in figure 8 for the $e\mu$ channel only.

The ATLAS collaboration interpreted the results in terms of a $Z'$ model that has the same fermion couplings as the SM $Z$ boson in the quark sector, but allows only leptonic decays that violate the lepton flavour conservation (figure 8b). The existence of such $Z'$ boson was excluded for masses lower than $\sim 3.0, 2.7,$ and $2.6$ TeV separately for the $e\mu$, $e\tau$ and $\mu\tau$ channels.

Both ATLAS and CMS interpreted the results in terms of QBH theories and set limits on the threshold mass $M_{th}$ for QBH prediction in models with a number $n$ of extra dimensions from
one up to six (figure 8c). The resulting observed limits on the $M_{th}$ were 2.5 TeV and 4.5 TeV respectively for $n = 1$ and $n = 6$, in the $e\mu$ channel. Lower values for the exclusions limits on $M_{th}$ were set considering the $e\tau$ and $\mu\tau$ final states by ATLAS.

5 Search for type-III seesaw heavy fermions

The CMS collaboration has searched for evidence of the heavy Dirac charged leptons $\Sigma^\pm$, and the heavy Majorana neutral lepton $\Sigma^0$, postulated to generate neutrino masses by the type-III seesaw mechanism using 35.9 fb$^{-1}$ of data$^{16}$. Such heavy fermions may be produced both in charged-charged and charged-neutral pairs through electroweak interactions, resulting in multilepton final states due to the following decays $\Sigma^\pm \rightarrow W^\pm \nu$, $\Sigma^\pm \rightarrow Z\ell^\pm$, $\Sigma^\pm \rightarrow H\ell^\pm$, $\Sigma^0 \rightarrow W^\pm \ell^\mp$, $\Sigma^0 \rightarrow Z\nu$, and $\Sigma^0 \rightarrow H\nu$ ($\ell = e, \mu$ or $\tau$). Searches for these signals considering the final states with at least three electrons or muons have been considered. The primary selection was based on the number of leptons and the invariant mass of opposite-sign lepton pairs, and helps discriminate the signal against the standard model background. The final optimization for the type-III seesaw signal was based on the sum of leptonic transverse momenta and missing transverse energy ($L_T + E_{T}^{miss}$), as well as the transverse mass.

No significant excess over the SM expectations was observed in the various signal regions probed. Figure 9a shows the results in the signal region with three charged leptons and one opposite-sign same-flavour lepton pair with mass above the Z peak. Assuming a flavour-democratic scenario, 95% confidence level upper limits were set on the cross-section sum for the production of heavy fermion pairs ($\Sigma^0\Sigma^+, \Sigma^0\Sigma^-, \text{or } \Sigma^+\Sigma^-$). These limits are shown in figure 9b and exclude the production of heavy fermion pairs for masses less than 850 GeV.

6 Conclusions

Searches for physics beyond the standard model are one of the more active areas of both the ATLAS and CMS collaborations. A wide range of searches was performed on data from the
\(\sqrt{s} = 8\) TeV LHC Run 1 and large regions of phase space for new models were excluded. The increased centre-of-mass energy of the LHC Run 2 provides scope for accessing higher mass objects and rarer processes.

In summary, we have shown part of the latest ATLAS and CMS results on the search for heavy new particles with leptons in the final state, using \(\sqrt{s} = 13\) TeV proton-proton collisions delivered by LHC in 2015 and 2016. No significant excess has been observed so far and limits at the 95% confidence level have been set on a variety of models, extending results from the Run 1 analyses. Further searches for new heavy resonances and in more complicated final states are underway.

References

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