Status of exotic searches at the LHC

Caterina Vernieri for the "Exotica, all searches expt SUSY", ATLAS and CMS collaborations.

Abstract

An overview of the searches for new heavy resonances decaying to standard model (SM) bosons or fermions at the TeV mass scale is presented. Results are based on data corresponding to an integrated luminosity up to about 36 fb\(^{-1}\) recorded in proton-proton collisions at \(\sqrt{s} = 13\) TeV with the CMS and ATLAS detector at the Large Hadron Collider at CERN.

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Searches for Exotica at the LHC

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An overview of the searches for new heavy resonances decaying to standard model (SM) bosons or fermions at the TeV mass scale is presented. Results are based on data corresponding to an integrated luminosity up to about 36 fb$^{-1}$ recorded in proton-proton collisions at $\sqrt{s} = 13$ TeV with the CMS and ATLAS detector at the Large Hadron Collider at CERN.

1 Introduction

The ”hierarchy problem”, meaning the several orders of magnitude discrepancy between the gravitational and the weak forces, is an open question of the standard model (SM) and many theories beyond the SM aim to explain it. We do not know where new physics is and we explore the unknown with comprehensive searches over accessible phase space by combining both signature-based generic and model-driven targeted approaches. Several theories predict the existence of new particles. For example, warped extra dimension models (WED) suggest a solution for the integration of gravity in the SM and to the hierarchy problem. They predict the existence of new particles, such as the spin-0 radion and the spin-2 first Kaluza-Klein excitation of the graviton. Other theories suggest the existence of new gauge bosons $Z'$ or $W'$ which are $Z$ or $W$ like$^2$, where the $Z'$ could serve also as Dark Matter mediator.

Many beyond the SM theories predict new resonances at the TeV mass scale. Heavy, narrow width particles that can couple to a pair of SM fermions, either leptons or quarks, or bosons, specifically the W and Z vector bosons (V) or the Higgs boson (H). This is a summary of the most recent results on searches for dilepton, diboson and dijet resonances. Results are based on the data corresponding to an integrated luminosity up to about 36 fb$^{-1}$ recorded in proton-proton collisions at $\sqrt{s} = 13$ TeV with the CMS$^3$ and ATLAS$^4$ detector at the Large Hadron Collider at CERN.

2 Searches for dilepton resonances

In the search for New Physics carried out at hadron colliders, the study of dilepton final-states provides excellent sensitivity to a large variety of phenomena. Extensions to the SM may include heavy gauge bosons, which are heavier versions of the SM W and Z bosons and are generically referred to as $W'$ and $Z'$ bosons. The Sequential Standard Model (SSM)$^2$ posits $Z'$ and $W'$ SSM boson with couplings to fermions equivalent to those of the SM Z and W bosons respectively.

We report here the result of the search for a $Z'$ and $W'$ bosons conducted in the $Z' \to \ell \ell$ and $W' \to \ell \nu$ channels with the ATLAS experiment$^5,6$. The analyses use events with a high transverse momentum ($p_T$) lepton (an electron or a muon) and significant missing transverse momentum $E_T^{miss}$, which is the measure to infer the presence of the neutrino in the
event as it escapes direct detection. The dilepton signature benefits from a fully reconstructed final state, high signal selection efficiencies and relatively small, well-understood backgrounds, representing a powerful test for a wide range of theories beyond the SM. The search for narrow resonances is performed in the dilepton invariant mass distributions above the SM background, which is shown in Fig 1. In the $\ell\nu$ channel the signal discriminant is the transverse mass, shown in Fig. 1, which is defined as $m_T = \sqrt{2p_T E_T^{\text{miss}}(1 - \cos \phi_{\ell\nu})}$, where $\phi_{\ell\nu}$ is the azimuthal angle between the lepton $p_T$ and the $E_T^{\text{miss}}$ directions in the transverse plane.

As no excess of events above the SM prediction is observed, the results are used to set upper limits on the $Z'$ and $W'$ bosons cross-section as a function of the $Z'$ and $W'$ mass up to 5 TeV, as shown in Fig. 2. Results from searches performed at 7, 8 and 13 TeV center of mass energy are compared. Thanks to the increase of the center of mass energy it has been possible to probe higher mass resonances, while the larger available dataset with the increased luminosity has allowed to probe smaller couplings.

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**Figure 1** – Left, Distributions of dielectron reconstructed invariant mass. Right, Transverse mass distributions for events satisfying $\mu\nu$ selection criteria. The distributions in data are compared to the stacked sum of all expected backgrounds. The middle panels show the ratios of the data to the expected background, with vertical bars representing both data and MC statistical uncertainties. The lower panels show the ratios of the data to the adjusted expected background that results from the statistical analysis.

**Figure 2** – Upper 95% CL limits on the $Z'$ (left) and $W'$ (right) production cross-section as a function of $Z'$ and $W'$ mass respectively.
3 Searches for diboson resonances

Given fairly strong limits set on the masses of such resonances using fermionic decay channels, it is particularly interesting to explore bosonic decay channels, which can dominate if the coupling to fermions is suppressed. The decay of new, heavy particles (X) to pairs of V or H bosons is searched for in the all hadronic final state in multiple searches at CMS and ATLAS. The hadronic final state has the largest branching fraction of V or H decays and thus these searches are the most sensitive at high resonance mass. The topology of the final state is constrained by \( M_X/(M_V(H_1) + M_V(H_2)) \gg 1 \), where \( M_X \) is the mass of the resonant particle, and defines the so-called boosted regime, in which each V or H is produced with a large momentum and its decay products are collimated along its direction of motion. When the \( p_T \) of the boson is greater than \( \sim 250 \) GeV it is more efficient to reconstruct the boson as a fat jet rather than two small-cone jets. Each boson is thus reconstructed as a large cone size jet (fat jet) of \( R = 0.8 \) and 1.0 for CMS and ATLAS respectively. The boson candidates are selected by requiring jet mass compatibility with the V or H hypothesis and by employing jet substructure and b tagging techniques to exploit both the composite nature and the flavor of the jets. Same challenges are solved with different techniques for ATLAS and CMS and they achieve similar performance. Jet substructure measures the degree to which a jet can be considered as composed of two prongs. In CMS the “N-subjettiness” algorithm is used to determine the consistency of the jet with two substructures from the two-pronged V(H) → q\(\bar{q}\)(b\(\bar{b}\)) decay. The ratio of the N-subjettiness observables \( \tau_{21} = \tau_2/\tau_1 \) is found to be a good discriminator between jets with two prongs from jets with a single prong, as can be seen in Figure 3.

![Figure 3 – Distribution of the N-subjettiness \( \tau_{21} \) after the kinematic selections on the two jets, for data, simulated background, and signal. The distributions are normalized to the number of events observed in data.](image)

Grooming techniques are applied to remove soft and wide-angle radiation from the jet cone. Grooming tends to push the jet mass scale of the quark- and gluon-initiated (q/g) jets to lower values while preserving the hard scale of the boson jets. In CMS the soft drop algorithm is used with \( \beta = 1 \), which corresponds to the modified mass drop procedure. The soft drop mass peaks at the V or H boson mass for signal events and reduces the mass of background q/g jets. The distribution is shown in Figure 4 for simulated signal and background events.

In order to identify H or Z decaying to b quarks in CMS the double-b tagger discriminant is employed. The double-b tagger exploits the presence of two hadronized b quarks inside the fat jet and their kinematics in relation to the jet substructure, namely the fact that the B hadron flight directions are strongly correlated with the axes used to calculate the N-subjettiness observables. Several observables exploiting the B hadron lifetime are used as input variables. The distribution of the double-b tagger for simulated signal and background events in Figure 4.
Figure 4 – Distribution of the soft drop jet mass (left) and b tagging discriminator (right) after the kinematic selections on the two jets, for data, simulated background, and signal. The distributions are normalized to the number of events observed in data\textsuperscript{14}.

### 3.1 Searches for X → VV(qqqq)

The search for a heavy resonant particle decaying to a pair of V decaying hadronically is done by selecting events with two fat jets, each of them compatible with the boosted V tagging criteria. Events are selected online with requirements based on the scalar sum of the transverse energy of all jets in the event ($H_T$) or the presence of one of more jets with loose substructure requirements. Online selections are fully efficient for resonance mass above 1 TeV. Then we search for a VV resonance in the dijet invariant mass ($m_{jj}$) spectrum. After all the event selection criteria are applied the dominant background is QCD multijet. The background is directly estimated from data and the search for signal in the dijet mass spectrum is done using a "bump-hunt" approach. It assumes that the SM background is a smooth, monotonically decreasing distribution and any signal will appear as a narrow peak on top of the falling distribution. A continuous function is used\textsuperscript{12} to fit the background and the functions are tested in simulation and data sidebands. The parameters and the normalization of the background are free to float. Systematic uncertainties are treated as nuisance parameters and are profiled in the statistical interpretation. The background-only hypothesis is tested against the X → VV signal as shown in Figure 5 for the CMS result. The results are interpreted in terms of 95\% confidence level (CL) upper limits\textsuperscript{13} on the production cross section of the spin-1 heavy boson and the spin-2 graviton and can be seen in Figure 6.

### 3.2 Searches for X → VH(qqbb)

The strategy to search for a heavy resonant particle decaying to a vector boson and a Higgs boson is very similar to the one presented for VV search, with an additional requirement on the b tagging for the H candidate jet. After the selection criteria are applied, about 90\% of the background in the signal regions originates from multijet events. The remaining 10\% is predominantly $t\bar{t}$ with a small contribution from V+jets. The multijet background is modelled directly from data by combining the information of several control regions, while other backgrounds are estimated from simulation. The reconstructed dijet mass distribution is used to search for a signal as shown in Figure 7. Both for ATLAS and CMS searches\textsuperscript{14,15}, data are found in agreement with the SM expectations, with the largest excess found at a resonance mass of 3.0 TeV with a local (global) significance of 3.3 (2.1)$\sigma$ for ATLAS. The results are interpreted in terms of 95\% CL upper limits on the production cross section times branching ratio for new bosons which decay to a W or Z boson and a Higgs boson and reported in Figure 8.
Figure 5 – Dijet invariant distribution $m_{jj}$ of the two leading jets compatible with the Z mass hypothesis. The preferred background-only fit is shown with an associated shaded band indicating the uncertainty. The differences between the data and the predicted background, divided by the data statistical uncertainty ($\sigma$) are shown in the lower panel.\(^{12}\)

Figure 6 – The combined observed (black solid) and expected (black dashed) 95% CL upper limits for the spin-1 heavy boson (left) and the spin-2 bulk graviton (right).\(^{12}\)
Figure 7 – Dijet invariant distribution $m_{VH}$ of the two leading jets in the Z mass region with b tagging selections. The background prediction is shown along with the data. The expected signal distributions (multiplied by 50) for 2 TeV mass hypothesis is also shown. The ratio between the data and the predicted background is shown in the lower panel$^{15}$.

Figure 8 – The combined observed (black solid) and expected (black dashed) 95% CL upper limits for the $Z'$ heavy boson for ATLAS (left) and CMS (right)$^{14,15}$. 
3.3 Searches for $X \rightarrow HH$

Several hypotheses of physics beyond the standard model posit narrow-width resonances decaying into pairs of Higgs bosons, as for instance WED models. Several searches for HH resonant production have been performed by both ATLAS and CMS collaborations with pp collisions at 8 and 13 TeV. The final states include $bb\bar{b}b$, $b\bar{b}\tau\tau$, $b\bar{b}\gamma\gamma$, $WW\gamma\gamma$ and $b\bar{b}WW$.

The $bb\gamma\gamma$ channel is a promising final state to investigate in the searches for Higgs boson pair production, given the clean diphoton trigger, excellent diphoton invariant mass resolution, and lower background rates compared to the hadronic final states. This channel is particularly important in the search for resonances in the low mass scenario (260,500) GeV. However it is statistical limited because of the very small Higgs branching ratio in the $\gamma\gamma$ channel. The $bb\bar{b}b$ is the most sensitive channel for high mass resonance hypotheses.

![Figure 9](image_url)  
Figure 9 – The expected and observed upper limit of $(X\rightarrow HH)$ at 95% CL provided by the searches performed by ATLAS and CMS experiments looking at the several different final states.

3.4 Searches for $X \rightarrow Z\gamma$

Another important set of decay channels is the one involving photons, i.e. $W\gamma$, $Z\gamma$, and $\gamma\gamma$. Here we report the results of a search for high-mass resonances decaying to a $Z$ boson and a photon performed by the CMS experiment. Both hadronic and leptonic decays of the $Z$ boson are exploited. In the leptonic channel the $Z$ boson candidates are reconstructed using an electron or a muon pair. In the hadronic channel they are identified using a fat jet containing either light-quark or b quark decay products of the $Z$ boson, identified using jet substructure and advanced b tagging techniques. The results in the leptonic and hadronic channels are combined and interpreted in terms of upper limits on the production cross section of narrow and broad spin-0 resonances with masses between 0.3 and 4.0 TeV. These limits are most stringent to date for a wide range of resonance masses, and shown in Figure 10.

4 Searches for dijet resonances

Searches for new particles decaying to pairs of jets have historically been among the first analyses performed at new collision energies. Such searches usually focus on the production of heavy particles inaccessible at lower collision energies, as in the case of recent results from ATLAS and CMS focusing on the mass region above 1 TeV. With the increase in collision energy
and beam intensity at hadron colliders, there has been a loss of search sensitivity for lighter resonances with couplings to quarks and gluons. The main experimental difficulties originate from the large increase in the cross section of multijet backgrounds at small resonance masses, and the more restrictive trigger requirements needed to reduce the data recording rate because of limited resources for event processing and storage. Nevertheless, the region below 1 TeV remains an important target of searches for resonances with lower masses and lower cross-sections, and is challenging to access at the LHC.

The search is performed by selecting events passing the online selections with two energetic jets, reconstructed with cone size of $R = 0.4$. The reconstructed dijet mass distribution is then used to search for a signal as shown in Figure 11 in the mass range between 1.1 and 9 TeV$^{17}$. A similar search performed by CMS extends the mass range down to 600 GeV thanks to lower trigger thresholds, achieved by recording only the information necessary to perform the analysis. SM QCD processes are the dominant background to this search. A data-driven background estimate is derived by fitting a smooth functional form to dijet invariant mass spectrum. The dijet mass spectrum is well described by a smooth parameterization and no significant evidence for the production of new particles is observed$^{18}$. Results are interpreted in terms of upper limits on the universal quark coupling $g_q$ as a function of resonance mass for a leptophobic $Z'$ and shown in Figure 11.

Requiring a hard ISR object in the final state comes at the cost of reduced signal production rates, but allows highly-efficient triggering at much lower masses than typically possible when triggering directly on the resonance decay products. ATLAS has performed a search which require an ISR photon in the final state, allowing to extend the dijet search in the mass region below 200 GeV$^{19}$. Requiring an ISR jet instead benefits from high ISR rate and it still provides enough energy in the event to satisfy the trigger requirements. Background jet combinatorics are reduced by assuming that the diquark resonance is sufficiently boosted, so that the hadronization products merge and are reconstructed within a single massive jet. CMS has performed a search with this strategy and set the first constrains from LHC in the mass region below 200 GeV and down to 50 GeV$^{20}$. The search is performed in the jet mass distribution and uses the W and Z SM processes as standard candles to which correlate some systematics uncertainties with the $Z'$ signal and further constrain them through the presence of those resonant SM processes. Figure 12 shows the jet mass distribution for data and expected background contributions and
the W and Z contributions are clearly visible in the data. A key feature of this analysis is the use of substructure requirements for merged dijet and the decorrelation procedure employed to make jet substructure and mass information orthogonal, allowing to build the prediction of background shape at low mass. Figure 13 reports upper limits on the signal cross-section translated into the coupling ($g_{qg}$) vs $Z'$ mass plane for both CMS and ATLAS recent results. Previous results from UA2 and CDF are also reported.

Figure 11 – Left, The reconstructed dijet mass distribution $m_{jj}$ (filled points) is shown for events with $p_T > 440$ GeV for the leading jet and above $m_{jj} = 1.1$ TeV. The solid line depicts the background prediction. The middle panel shows the bin-by-bin significances of the data-fit differences, considering only statistical uncertainties. Right, The 95% CL upper limits on the universal quark coupling $g_{qg}$ as a function of resonance mass for a leptophobic $Z'$ resonance that only couples to quarks.\cite{17,18}.

Figure 12 – Soft-drop jet mass distribution for the jet $p_T$ range from 900 to 1000 GeV. The multijet background prediction, including uncertainties, is shown by the shaded bands. Contributions from the W and Z boson, and top quark background processes, and a hypothetical $Z'$ boson signal at a mass of 135 GeV are also indicated. In the bottom panel, the ratio of the data to the background prediction, including uncertainties, is shown.\cite{20}.
Figure 13 – The 95% CL upper limits on the quark coupling $g_q$ as a function of resonance mass for a leptophobic $Z'$ resonance that only couples to quarks. Limits from other relevant searches and an indirect constraint on a potential $Z'$ signal from the SM Z boson width are also shown.

5 Summary

An overview of the searches for new heavy resonances decaying to standard model (SM) bosons or fermions at the TeV mass scale is presented. Results are based on data corresponding to an integrated luminosity up to about 36 fb$^{-1}$ recorded in proton-proton collisions at $\sqrt{s} = 13$ TeV with the CMS and ATLAS detector at the Large Hadron Collider at CERN. ATLAS and CMS have well-developed searches in place for new physics. As a function of the resonance mass, high luminosities are necessary to reach low couplings of the order 0.1 to 0.01 for a five sigma discovery. The 13 TeV dataset statistics should increase by a factor three by the end of 2018. With more available data LHC will probe smaller couplings. Improvements are also possible from optimized events selection and improved object reconstruction as well as from more accurate SM theory predictions for the main backgrounds to these searches.


*https://cds.cern.ch/record/2195743

\(^a\)https://cds.cern.ch/record/2264692
\(^b\)https://cds.cern.ch/record/2256873
\(^c\)http://cds.cern.ch/record/2206221
\(^d\)http://cds.cern.ch/record/2206221