

# Beyond Standard Model searches by ATLAS and CMS

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**Abstract.** An overview of recent searches for physics beyond the Standard Model with the ATLAS and CMS experiments is given. The presented searches use data taken in 13 TeV proton–proton collisions at the LHC with an integrated luminosity of up to  $80 \text{ fb}^{-1}$ .

## 1. Introduction

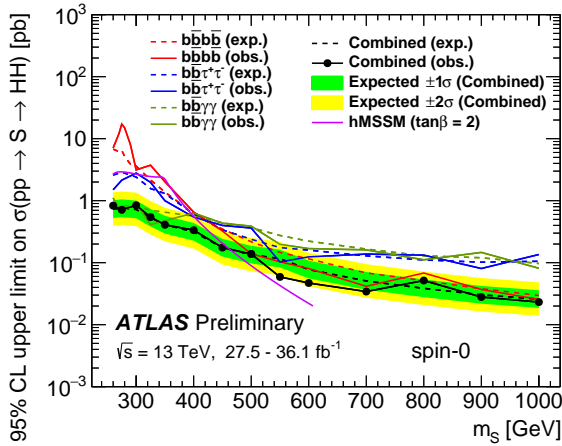
A selection of recent searches for physics beyond the Standard Model (BSM) is discussed. The analyzed data were recorded in proton–proton collisions at the LHC at a center-of-mass energy of 13 TeV with the ATLAS [1] and CMS [2] detectors. Ten results by the ATLAS and ten results by the CMS Collaboration are chosen, which were released no longer than four months before the start of the conference. No attempt is made to either cover the full status of BSM searches or to make a thorough comparison of the presented results with previously published results. The different analyses are grouped into six categories based on their signatures, covering boson–boson resonances, boson–quark resonances (vector-like quarks), mono-object signatures, quark–quark/quark–gluon/gluon–gluon resonances, new particles that directly decay into charged leptons, and searches for supersymmetry (SUSY). No significant excess above the Standard Model (SM) background was found and exclusion limits were set on the parameters of benchmark models.

## 2. Searches for diboson resonances

Three searches for resonances that decay into two Higgs bosons were combined [3]. The searches were carried out in the final states  $b\bar{b}b\bar{b}$ ,  $b\bar{b}\tau^+\tau^-$  and  $b\bar{b}\gamma\gamma$  and used up to  $36.1 \text{ fb}^{-1}$  of data. Upper limits at 95% confidence level (CL) were set on the cross section times branching ratio (BR) into two Higgs bosons for spin-0 (Figure 1) and spin-2 resonances in the range of 260–1000 GeV for the mass of the resonance. At low resonance masses the  $b\bar{b}\gamma\gamma$  analysis dominates the sensitivity, at intermediate masses the  $b\bar{b}\tau^+\tau^-$  analysis has very good sensitivity, and at high masses the  $b\bar{b}b\bar{b}$  is most sensitive.

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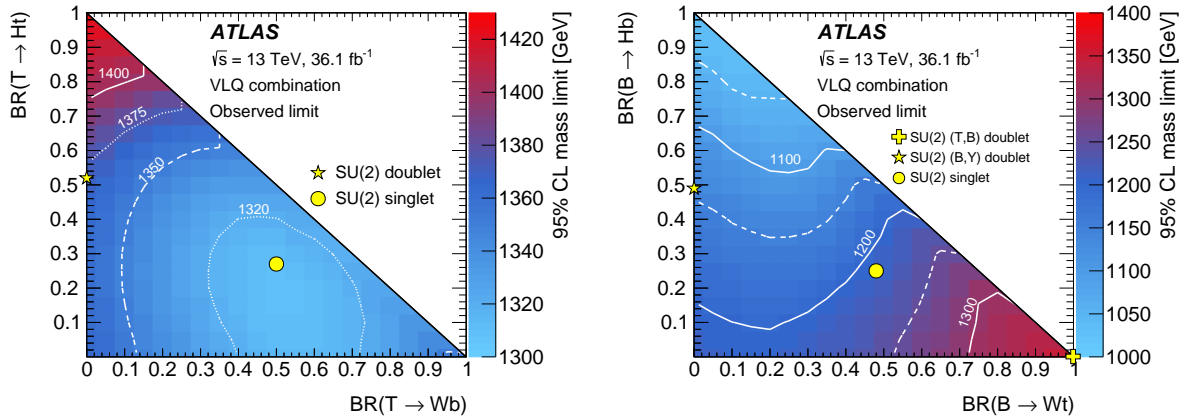
**Figure 1.** Upper limits at 95%CL on the cross section times BR into two Higgs bosons for the production of a scalar particle as a function of its mass for the combination of analyses in the  $b\bar{b}b\bar{b}$ ,  $b\bar{b}\tau^+\tau^-$  and  $b\bar{b}\gamma\gamma$  channels [3].

### 3. Searches for vector-like quarks

Pair-production of vector-like quarks (VLQ) was searched for in final states with at least two leptons, requiring either two leptons of the same flavor and opposite electric charge that have an invariant mass close to the  $Z$ -boson mass [4] or two leptons with the same electric charge [5] using  $36.1 \text{ fb}^{-1}$  of data. While the former analysis is particularly sensitive to decays of vector-like  $T$ - and  $B$ -quarks that decay into  $Zt$  or  $Zb$ , respectively, the latter analysis is sensitive to many combinations of VLQ pair-production final states, such as  $W^-tW^+\bar{t}$  or  $W^+bH\bar{t}$ . Pair-production of VLQs was also searched for in all-hadronic final states [6] using  $36.1 \text{ fb}^{-1}$ , where the large background from multijet production was suppressed by tagging hadronic resonance decays with a multi-class deep neural network based on variable- $R$  jets, and with the matrix-element method. The analysis is especially sensitive to the decays of vector-like  $T$ - and  $B$ -quarks to  $Ht$  or  $Hb$ , respectively. These analysis were combined with other searches for VLQ pair production [7] using the same dataset, setting lower limits on the masses of vector-like  $T$ - and  $B$ -quarks, assuming that only decays to  $W$ ,  $Z$  and Higgs bosons together with third-generation SM quarks are allowed (Figure 2). Vector-like  $T$ -quarks ( $B$ -quarks) with masses smaller than 1.31 TeV (1.03 TeV) were excluded at 95% CL for all possible combinations of the BRs.

Single-production of VLQs was searched for in the decay modes  $B \rightarrow Hb$ , using the  $H \rightarrow \gamma\gamma$  decay and  $79.8 \text{ fb}^{-1}$  of data [8], and the decay mode  $B \rightarrow W^-t$  in the lepton+jets final state using  $35.9 \text{ fb}^{-1}$  of data [9]. The latter analysis is also sensitive to the single production of vector-like  $X$ -quarks that decay via  $X \rightarrow W^+t$ . Both analyses set 95% CL upper limits on the single-production cross section times BR into the analyzed decay mode as a function of the vector-like  $B$ -quark mass. In the  $B \rightarrow Hb$  analysis a benchmark value of the coupling of the VLQ to SM quarks was assumed, and in the  $B \rightarrow W^-t$  analysis the limits were presented for different values of the intrinsic width of the vector-like  $B$ - or  $X$ -quarks, which can be translated to different values of the coupling to SM quarks.

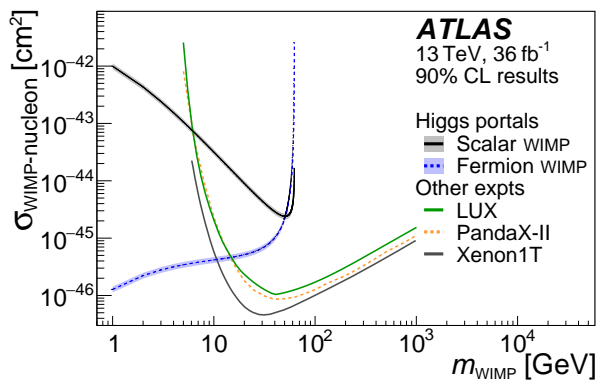
Pair production of vector-like  $X$ -quarks was searched for in the lepton+jets final state and in final states with two leptons of the same electric charge using  $35.9 \text{ fb}^{-1}$  of data [10]. The results from both channels were combined, where the same-sign analysis is more sensitive at low values of the mass of the vector-like  $X$ -quark, and the lepton+jets analysis is more sensitive for high values. Vector-like  $X$ -quarks with masses smaller than 1.33 TeV (1.30 TeV) were excluded at 95% CL in the case of a purely right-handed (left-handed) coupling to the  $W$  boson.



**Figure 2.** Lower limits at 95% CL on the mass of (left) vector-like  $T$ -quarks and (right) vector-like  $B$ -quarks as a function of their BRs to  $Wb$  and  $Ht$  or  $Wt$  and  $Hb$ , respectively, for a combination of six searches for  $T$ -quark pair production and four searches for  $B$ -quark pair production [7]. The BR to  $Zt$  or  $Zb$ , respectively, is inferred by assuming that the BRs for the three decay modes add up to unity.

#### 4. Searches for mono signatures

Signatures with a single object recoiling against objects that are invisible in the detector, also called “mono signatures”, are sensitive to the pair production of weakly-interacting massive particles (WIMP) together with one or several visible objects. In particular, such WIMPs are candidates for dark-matter particles. These searches can be interpreted in so-called “simplified models”, for example with a high-mass mediator particle that couples to SM particles as well as to WIMPs. A search was performed for vector-boson fusion production of the SM Higgs boson, which acts as mediator and decays to two WIMPs using  $36.1 \text{ fb}^{-1}$  of data [11]. The signature is given by two distinct high- $p_T$  jets and large missing transverse momentum. An upper limit at 90% CL was set on the BR of the Higgs boson to invisible particles of 32%, which was translated to model-dependent 90% CL upper limits on the spin-independent WIMP-nucleon cross section as a function of the WIMP mass in a Higgs-portal model (Figure 3).

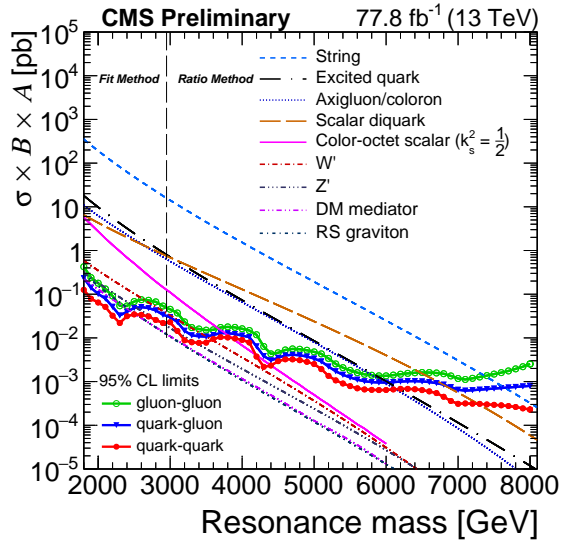


**Figure 3.** Upper limits at 95%CL on the spin-independent WIMP-nucleon cross section as a function of the WIMP mass in a Higgs-portal model for the analysis in Ref. [11] in comparison to other experiments.

#### 5. Searches for resonances that decay into two color-charged particles

Resonant dijet production is sensitive to many extensions of the SM that predict particles that decay into two quarks, two gluons, or a quark and a gluon. A search for dijet resonances was

performed using  $77.8 \text{ fb}^{-1}$  of data [12]. In this search, two high- $p_T$  jets were used as seeds, and additional jets within a radius of 1.1 in  $\eta$ - $\phi$  space were added in order to build “wide jets”, which include final-state radiation and improve the mass resolution of the dijet system. Upper limits at 95% CL were set on the production cross section times BR times acceptance as a function of the resonance mass, setting lower limits on the mass in a variety of benchmark models (Figure 4), as well as on the coupling of a leptophobic  $Z'$  boson as a function of its mass, which can be interpreted as limits on the production of a mediator in the decay into two quarks instead of the decay into two WIMPs.



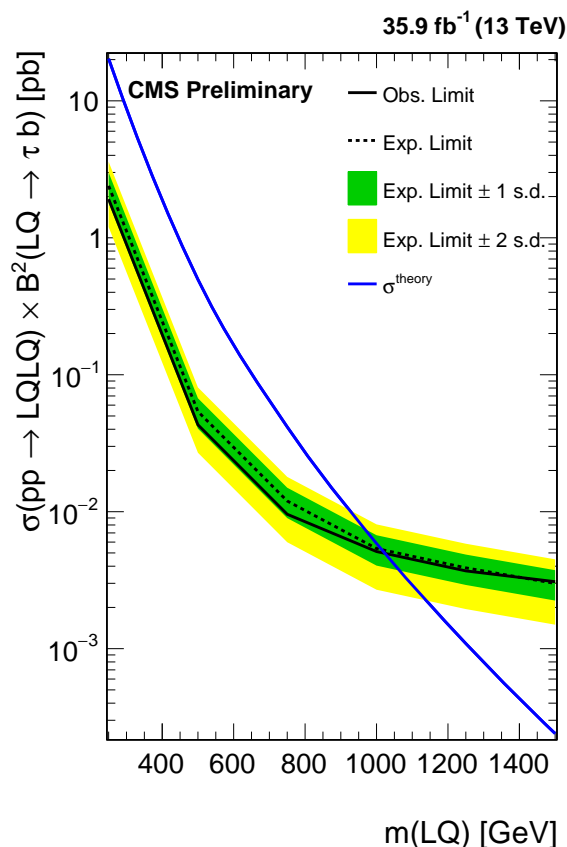
**Figure 4.** Upper limits at 95% CL on the cross section for the production of a resonance times BR to two partons times acceptance as a function of the mass of the resonance [12].

The search for dijet resonances with low masses is challenging, because jet triggers are strongly prescaled at low jet  $p_T$  due to the large rate of multijet production at the LHC, so that only a small fraction of the events needed for the analysis is recorded. By selecting events with a high- $p_T$  jet from initial-state radiation (ISR), a larger fraction of events can be selected. This strategy was used to search for a resonance that decays to two  $b$ -quarks using  $35.9 \text{ fb}^{-1}$  of data [13]. As the resonance recoils against the ISR jet, the angle between the two  $b$ -quarks from its decay is small, and the resonance is captured with a single jet with large radius parameter, which is required to be double- $b$ -tagged. Substructure variables are used to discriminate two-prong signal jets from background jets that originate from the hadronization of quarks or gluons. As these variables are designed to be uncorrelated to the mass of the jet, a resonance would show up as a peak in the jet-mass spectrum. Upper limits at 95% CL were set on the production cross section times BR for scalar and pseudo-scalar resonances and on the coupling of these resonances to SM quarks.

Charged vector resonances ( $W'$  bosons) that decay into a vector-like  $T$ - or  $B$ -quark and a SM  $b$  or top quark, respectively, were searched for using the decay modes  $T \rightarrow Ht$  and  $B \rightarrow Hb$  using  $35.9 \text{ fb}^{-1}$  of data [14]. Hence, the final state consists of a  $b$ -quark, a top quark, and a Higgs boson. The searches was performed in the all-hadronic channel, and the large background from multijet production was suppressed by using  $b$ -tagging and the identification of hadronically decaying top quarks and Higgs bosons based on the substructure of jets with a large radius parameter. Upper limits at 95% CL were set on the  $W'$  production cross section times BR to  $btH$  as a function of the  $W'$  mass for benchmark choices for the parameters of the model.

## 6. Searches for resonances that decay into charged leptons

Pair production of leptoquarks (LQ) was searched for in final states with two hadronically decaying  $\tau$ -leptons and two jets using  $35.9 \text{ fb}^{-1}$  of data [15]. No  $b$ -tagging requirement was made on the two jets, so that the analysis is sensitive to LQs that decay into a  $\tau$ -lepton and first- or second-generation quark, but also to LQs that decay into a  $\tau$ -lepton and a  $b$ -quark. The results were interpreted as upper limits at 95% CL on the LQ production cross section times BR to a  $\tau$ -lepton and a  $b$ -quark as a function of the LQ mass, setting a lower limit at 95% CL of 1.02 TeV on the LQ mass in the case of a BR of 100% (Figure 5).



**Figure 5.** Upper limit at 95% CL on the pair-production cross section for LQs times BR to a  $\tau$ -lepton and a  $b$ -quark as a function of the LQ mass [15].

Pair production of LQs was also searched for in a mono-LQ-like analysis, where one LQ decays to a charm quark and a muon, and the other LQ decays into a WIMP and a high-mass co-annihilation partner,  $X$ , using  $77.4 \text{ fb}^{-1}$  of data [16]. The co-annihilation partner then decays via a virtual LQ to a WIMP, a charm quark and a muon. The mass difference between  $X$  and the WIMP is assumed to be small, so that the charm quark and the muon from the decay of  $X$  have low momentum and, hence, a low probability to be measured in the detector. Thus, the signature consists of a charm quark and a muon with an invariant mass that is distributed around the mass of the LQ, and missing transverse momentum. Upper limits at 95% CL were set as a function of the WIMP mass and the LQ mass, using benchmark values for the residual parameters of the model.

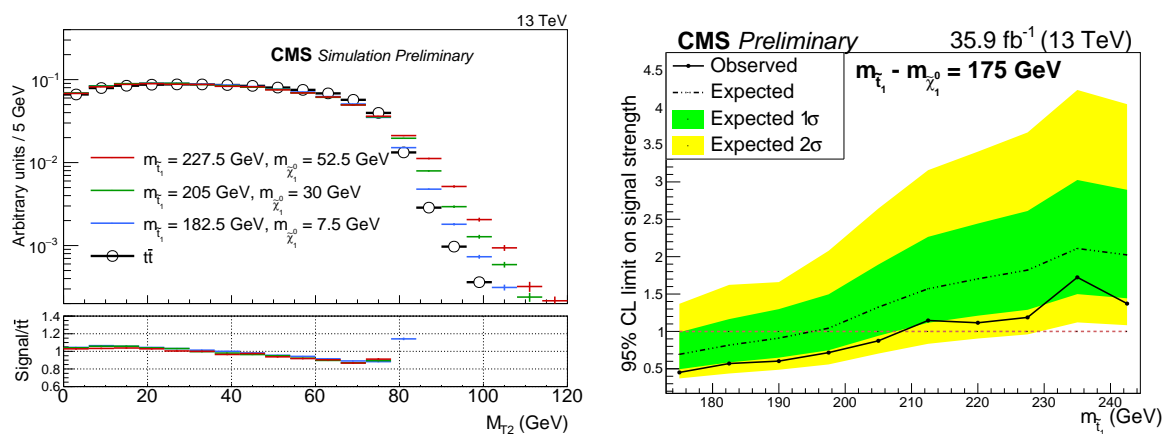
Heavy neutrinos were searched for in final states with two jets and two leptons with either opposite or the same electric charge using  $36.1 \text{ fb}^{-1}$  of data [17]. The heavy neutrino could be a Majorana particle or a pseudo-Dirac particle, and it was assumed to be produced via resonant or virtual production of a high-mass right-handed  $W$  boson, depending on whether the  $W$ -boson

mass is larger or smaller than the mass of the heavy neutrino. In case the neutrino is a pseudo-Dirac particle, only events with oppositely-charged leptons are expected to be present. In case it is a Majorana particle, opposite and same charges are expected with the same probability. Lower limits at 95% CL were set on the  $W$ -boson and the heavy-neutrino masses—separately for Majorana and pseudo-Dirac neutrinos, and for the  $e^+e^-$  and  $\mu^+\mu^-$  final states. The left- and right-handed coupling constants were assumed to be equal, and it was assumed that there is no mixing between lepton flavors. For Majorana neutrinos, the same-sign analysis dominates the sensitivity for the case that the produced  $W$  boson is virtual, and both analyses contribute to the combined sensitivity for the case of resonant  $W$ -boson production.

## 7. Searches for supersymmetry

Although SUSY can produce signatures that partially or strongly overlap with the signatures discussed in the previous sections, the search for SUSY is discussed separately, as SUSY provides a unique framework for the interpretation of searches.

Stop quarks,  $\tilde{t}$ , were searched for in pair production, where the stop quark was assumed to decay into a SM top quark and the lightest neutralino,  $\tilde{\chi}_1^0$ , here assumed to be the lightest supersymmetric particle (LSP), using  $36.9 \text{ fb}^{-1}$  of data [18]. Hence, the signature is similar to  $t\bar{t}$  production, but with an additional source of missing transverse momentum, and discriminating the signal from background is particularly challenging in the case that the mass difference between  $\tilde{t}$  and  $\tilde{\chi}_1^0$  is close to the top-quark mass. The search uses the dileptonic  $t\bar{t}$  decay with an electron and a muon in the final state, and signal and background are separated by the use of the  $M_{T2}$  variable, which has a kinematic endpoint for the background but not for the signal, given the additional missing transverse momentum of the neutralinos in the final states (Figure 6 (left)). Upper limits at 95% CL were set on the signal strength for stop-quark pair production for the cases that the mass difference is either 175 GeV, 167.5 GeV, or 182.5 GeV. If the mass difference is 175 GeV, stop-quark masses below 210 GeV were excluded at 95% CL (Figure 6 (right)).



**Figure 6.** (left) Normalized distribution of  $M_{T2}$  for  $t\bar{t}$  production and for stop-quark pair production for different values of the masses of the stop-quark and the LSP mass with a mass difference,  $m_{\tilde{t}} - m_{\tilde{\chi}_1^0}$ , of 175 GeV. (right) Upper limit at 95% CL on the signal strength of stop-quark pair production with  $m_{\tilde{t}} - m_{\tilde{\chi}_1^0} = 175 \text{ GeV}$  as a function of  $m_{\tilde{t}}$  [18].

Sbottom-quark pair production was searched for in the decay into the second-lightest neutralino,  $\tilde{\chi}_2^0$ , and a SM  $b$ -quark, where the second-lightest neutralino decays to the lightest neutralino—assumed to be the LSP—and a Higgs boson, using  $79.8 \text{ fb}$  of data [19]. As the

Higgs boson decays to  $b\bar{b}$  with a large BR, the final state is characterized by the presence of many  $b$ -jets and missing transverse momentum. The analysis was optimized for sensitivity to two benchmark scenarios, where either the mass difference between  $\tilde{\chi}_2^0$  and  $\tilde{\chi}_1^0$  is 130 GeV, or where the LSP mass is 60 GeV. Lower limits at 95% CL were set as a function of the  $\tilde{\chi}_2^0$  mass and the mass of the sbottom quark.

Gluginos were searched for using  $35.9 \text{ fb}^{-1}$  of data in final states with a high- $p_T$  photon, motivated by gauge-mediated SUSY breaking with the gravitino as the LSP [20], and with razor variables in zero- and one-charged-lepton final states [21]. The results of the two analyses were interpreted by setting lower limits at 95% CL on the mass of the  $\tilde{\chi}_1^0$  and the gluino in several benchmark scenarios for the gluino decay chain. The results of the analysis using razor variables were also interpreted as lower 95% CL limits on the  $\tilde{\chi}_1^0$  and stop-quark masses.

The pair production of charginos was searched for assuming that the chargino decays to the lightest neutralino as the LSP and a  $W$  boson using  $80.5 \text{ fb}^{-1}$  of data [22]. Events with  $W$ -boson decays to an electron or muon and a neutrino were used, and lower limits at 95% CL were set on the  $\tilde{\chi}_1^0$  mass and the chargino mass.

## 8. Conclusions

A selection of recent searches for physics beyond the Standard Model with the ATLAS and CMS experiments at the LHC was discussed. No significant deviations from the background from Standard Model processes were found, and limits were set on the parameters of benchmark models, strongly constraining the phase space of these parameters.

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