PROCEEDINGS OF SCIENCE

Status and prospect of LHC BSM searches

Aniello Spiezia on behalf of the ATLAS and CMS Collaborations*
Institute of High Energy Physics and Chinese Academy of Science
E-mail: aniello.spiezia@cern.ch

In the last years, the ATLAS and CMS experiments at LHC have recorded more than 100 fb^{-1} of data that are used to investigate with high precision many aspects of high energy physics. In this conference proceeding, I will review the most recent and interesting results related to the search of new physics at the ATLAS and CMS experiments.

An Alpine LHC Physics Summit (ALPS2018)
15-20 April, 2018
Obergurgl, Austria

*Speaker.

PoS(ALPS2018)025

1. Introduction

The discovery of the Higgs boson at the ATLAS [1] and CMS [2] experiments has been a major milestone in high energy physics, but the solution to remaining problems of the underlying nature of electroweak symmetry breaking still continues to be unknown. Several new theoretical models have been proposed in order to solve this puzzle. In this conference proceeding, I will review the most recent results related to the search of new physics at the ATLAS and CMS experiments.

2. Supersymmetry

Supersymmetry is a theory that is introduced to give a possible solution to the hierarchy problem, while providing a candidate for dark matter. It extends the standard model (SM) by introducing a superpartner for each SM particle, where the new particle differs from its SM counterpart only by the spin quantum number. At the ATLAS and CMS experiments, supersymmetric particles are searched for by using simplified models, i.e. models that use a small set of unambiguous parameters. These models can be grouped in three big families, each considering the following set of new particles:

- gluinos and squarks: produced by strong interaction, they have higher cross sections and final states with jets and missing transverse momentum
- 3rd generation squarks: they are a subset of the previous category, but they are particularly interesting because of the possible role that the 3rd generation could have in new physics; they have intermediate cross sections and final states with b jets and missing transverse momentum
- charginos, neutralinos, and sleptons: low cross sections and final states with leptons and missing transverse momentum

Some of the latest results from the ATLAS and the CMS experiments regarding these three families are shown in the following.

The ATLAS experiment is looking for gluinos and squarks in events containing only hadronic jets and large missing transverse momentum, for example in Ref. [3]. This analysis is using an integrated luminosity of 36.1 fb^{-1}, recorded at 13 TeV during 2015 and 2016. In Fig. 1, examples of pair production of gluinos and squarks are shown, where a number of SM particles are produced in the final state together with the lighest supersymmetric particle (LSP), which is stable and escapes the detector leading to potentially large values of missing transverse momentum. A number of signal regions are defined requiring different cuts on hadronic activity variables and missing transverse momentum, in order to retain sensitivity in different corners of the phase space. Two different approaches are used: effective mass, m_{eff}, uses as discriminant the scalar sum of

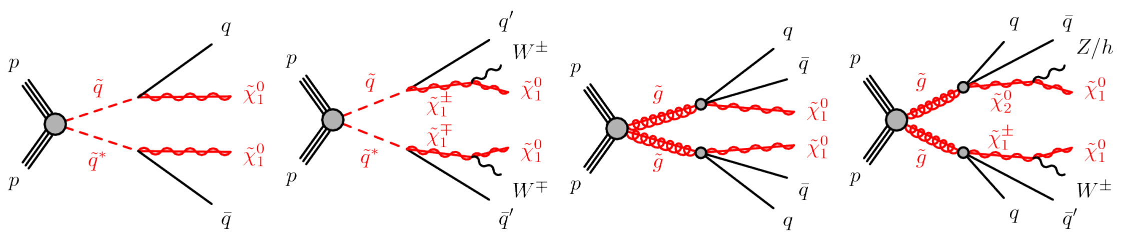

Figure 1: Diagrams for the production of supersymmetric particles, gluinos and squarks [3].

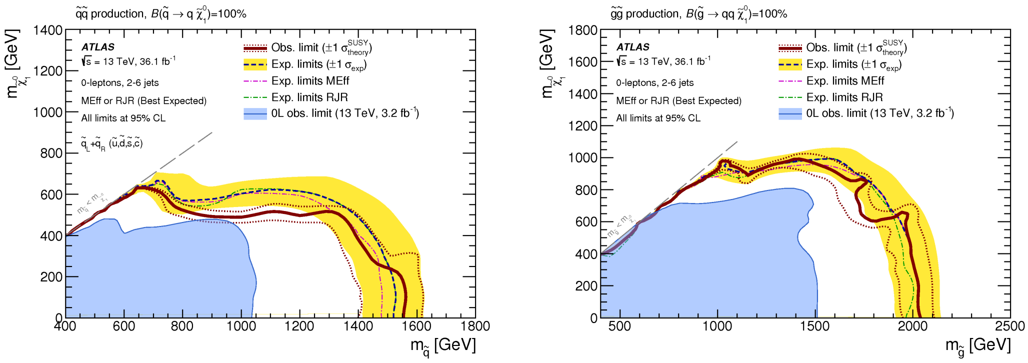

Figure 2: Exclusion limits for pair production of squarks (left) and gluinos (right) by ATLAS [3].

the transverse momenta of the jets and missing transverse momentum of the event; the recursive jigsaw reconstruction uses a transformation to another frame of reference in order to improve the information given by the missing transverse momentum, related to the LSP. An exclusion limit for pair production of squarks and gluinos is shown in Fig. 2, where the squarks are excluded for this particular model for masses up to 1.5 TeV, the gluinos up to 2 TeV, and the LSP up to 1.0 TeV.

The CMS experiment is investigating similar supersymmetric models in Ref. [4]. In this analysis also pair production of 3rd generation squarks is considered. In total 254 categories, depending on the number of jets, b-tagged jets, and the hadronic activity, are considered. In Fig. 3, the exclusion limits are shown for the considered simplified models: the masses of sbottom, stop, and light-flavour squarks are probed up to 1050, 1000, and 1325 GeV, respectively, while the gluino is excluded for masses between 1900 and 1650 GeV, depending on the assumed masses of the intermediate squarks. Finally the LSP is excluded, in these scenarios, for masses up to 1150 (gluinos pair production) and 575 GeV (squarks).

Direct production of charginos and neutralinos or sleptons pairs is studied by both the CMS and ATLAS experiments. In Ref. [5], ATLAS has investigated simplified models by exploring final states involving two or three electrons or muons. As shown in Fig. 4 (left), no significant deviations from the SM expectation are observed. In Ref. [6], CMS probes the production of charginos, neutralinos, and sleptons in different final states in order to target different decay channels of the

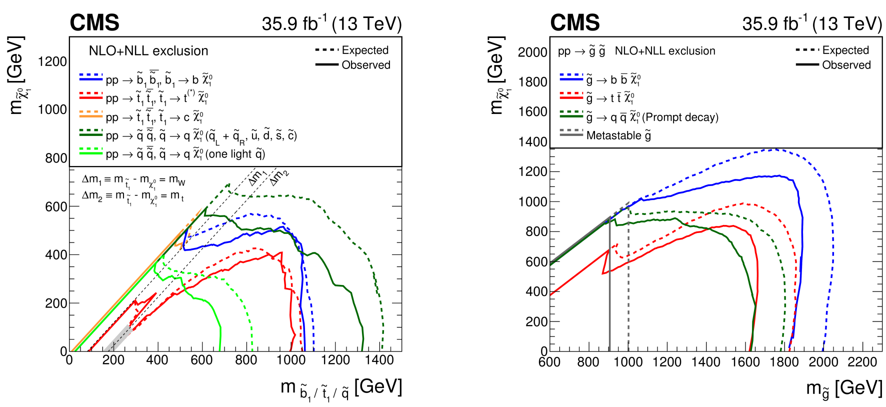

Figure 3: Exclusion limits for pair production of squarks (left) and gluinos (right) by CMS [4].

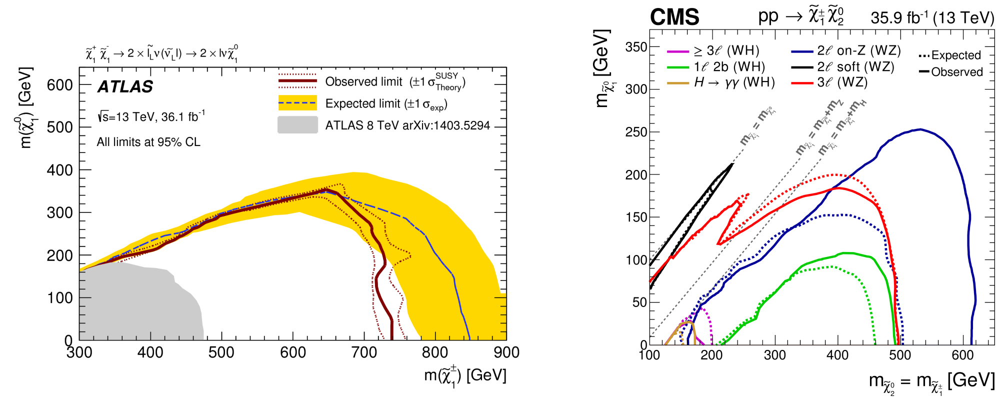

Figure 4: Exclusion limits for pair production of charginos or neutralinos from ATLAS [5] (left) and CMS [6] (right).

W/Z/Higgs (H) bosons that can be produced in the sparticles decays. As shown if Fig. 4 (right), charginos/neutralinos are excluded for masses below 250–660 GeV.

The last supersymmetry result that is presented in this proceeding is covered by an analysis from ATLAS that studies compressed mass spectra [7], i.e., scenarios that involve small mass differences between the new particles. The studied final states consider two low-momentum leptons and missing transverse momentum from the LSP that recoils against a jet from initial state radiation. In Fig. 5 (left), the results for higgsino pair production is shown for this analysis and compared with previous results. In Fig. 5 (right), exclusion limits at 95% CL for higgsino pair production obtained by CMS [8] is shown.

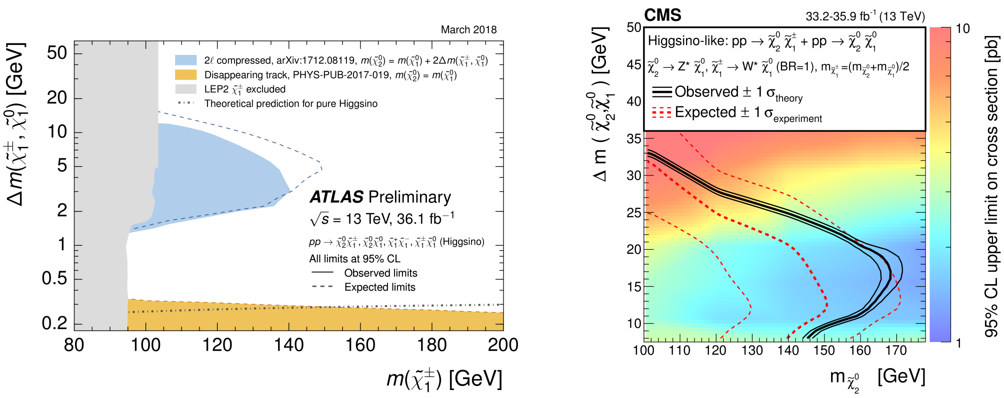

Figure 5: Exclusion limits at 95% CL for higgsino pair production by ATLAS [7] and by CMS [8].

3. Heavy resonances

The search for resonances is one of the simplest way to discover new particles. In fact, possible extensions of the SM introduce new symmetries, and as a consequence new resonances can exist, as for example Z′ and W′. This gives as a result that several final states can be studied: dilepton, diboson, and dijet for example.

The CMS experiment has recently released an analysis based on the combination of the 2016 and 2017 data sets, corresponding to an integrated luminosity of 77.3 fb^{-1} and that is looking for

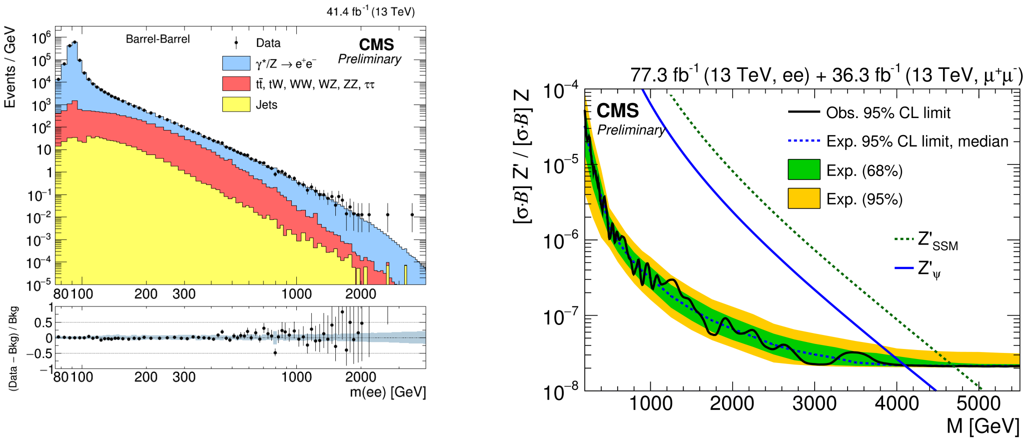

Figure 6: Search for high mass resonances in the dilepton final state using 13 TeV data collected by the CMS experiment at the LHC in 2016 and 2017 [9].

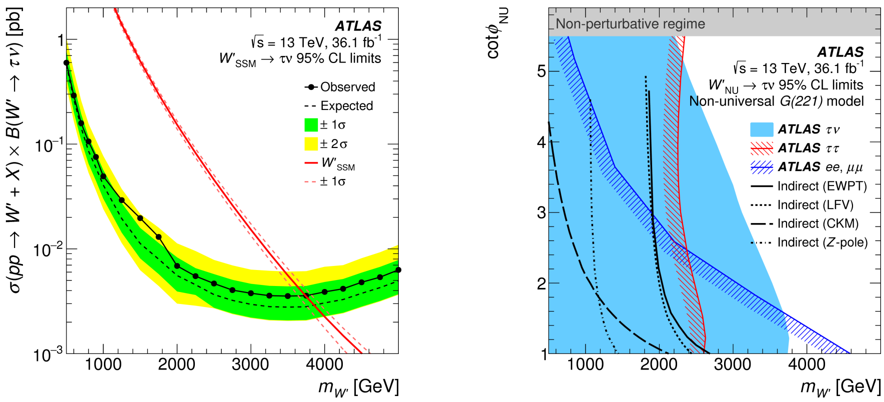

Figure 7: Exclusion limits for W'_{SSM} boson (left) and W'_{NU} boson (right) [10].

a narrow resonance in the invariant mass spectrum of lepton pairs [9]. For 2017, only events with two electrons are considered, while for 2016, both muons and electrons. As shown in Fig. 6, the limits exclude a Z'_{SSM} boson with a mass lower than 4.7 TeV and a Z'_{ψ} boson with a mass less than 4.1 TeV. The limits improve by 200 GeV the 2016 only results. Some final states compatible with the production of a W$'$ boson at the ATLAS and CMS experiments are: $W' \to \tau\nu_\tau$ or $W' \to bt$. In the first case, ATLAS has investigated a non-universal G(221) model (NU) that approaches the SSM model for $\cot\Psi_{NU} \to 1$ [10]. The hadronic decay of the τ lepton is studied and masses below 2.2-3.8 TeV (depending on $\cot\Psi_{NU}$) are excluded, as shown in Fig. 7. Furthermore Fig. 7 (right) shows that this analysis extends the ee, $\mu\mu$, and $\tau\tau$ sensitivities. The decay of the W$'$ in a bottom and a top quarks is accessible when the W$'$ boson is sufficiently heavy and it can directly probe the coupling of this new particle to third generation quarks. Several analyses are looking for this final state at the ATLAS and CMS experiment. The most recent searches involve for CMS events with exactly one electron/muon, missing transverse momentum, and multiple jets [11] and for ATLAS, the fully hadronic channel with the boosted top quark reconstructed as a single jet [12]. The results of these two analyses are shown in Fig. 8.

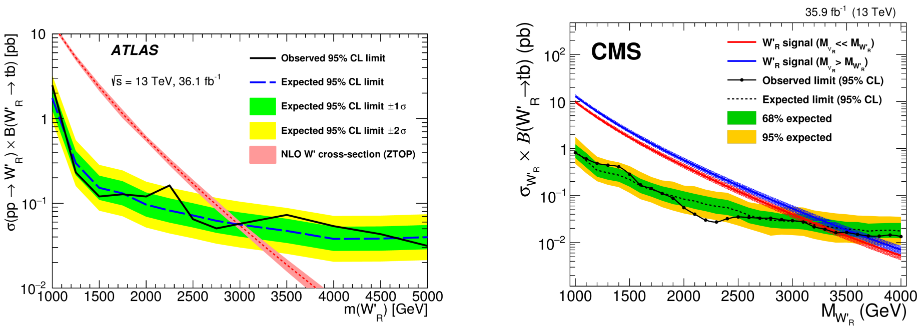

Figure 8: Exclusion limits for W′ boson decaying to a top and a b quarks for the ATLAS [12] (left) and CMS [11] (right) Collaborations..

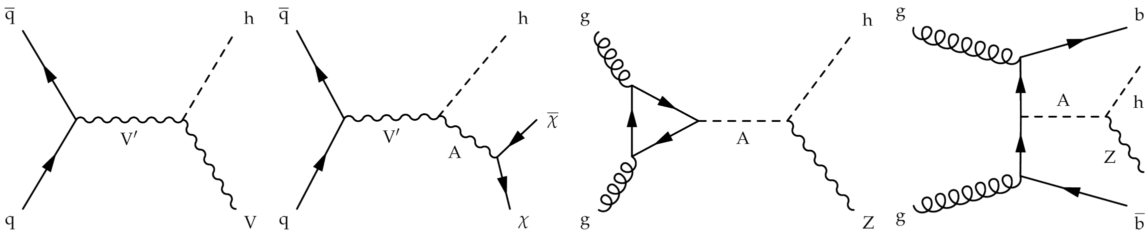

Figure 9: Feynman diagrams for the production of heavy resonances decaying to VH as predicted by the heavy vector triplet model and the 2-Higgs-doublet model with a neutral A boson [13, 14].

Another interesting possible new physics channel is given by a heavy resonance decaying to a vector boson, Z or W, and a Higgs boson. The ATLAS and CMS Collaborations are looking for this signal in the following final states: $W' \to W^{\pm}H \to \ell^{\pm}\nu b\bar{b}$, $Z'/A \to ZH \to \ell^{\pm}\ell^{\mp}b\bar{b}$, and $Z'/A \to ZH \to \nu\bar{\nu}b\bar{b}$ [13, 14]. The interpretation is given in terms of a heavy vector triplet model and the 2-Higgs-doublet model with a neutral A boson, as shown by the Feynman diagram in Fig. 9. Both analysis are using jet substructure techniques that are optimized to select wide jets and categorize them as coming from the hadronic decay of the W/Z/H bosons, reducing at the same time the large contribution from QCD jets. The CMS analysis has three categories: zero leptons and missing transverse momentum, one lepton and missing transverse momentum, or two leptons, while the Higgs boson is reconstructed using jet substructure techniques. The results are given as an exclusion in the $(g_V c_H,\ g^2 c_F/g_V)$ plane for the heavy vector triplet model, i.e. the couplings of

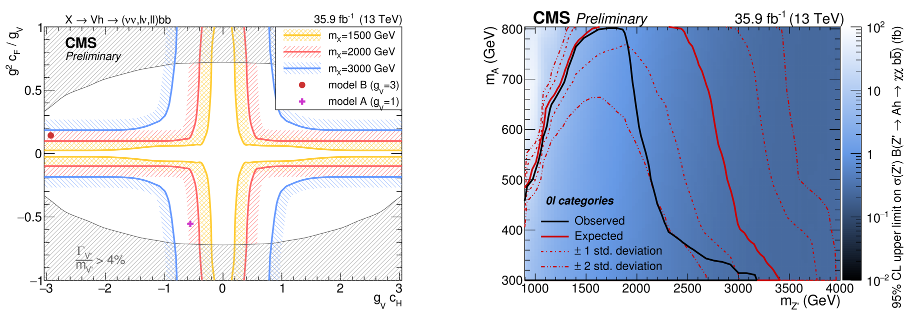

Figure 10: Exclusion limits for the search of a W′ or a Z′ boson, decaying to VH final state from the CMS experiment [13].

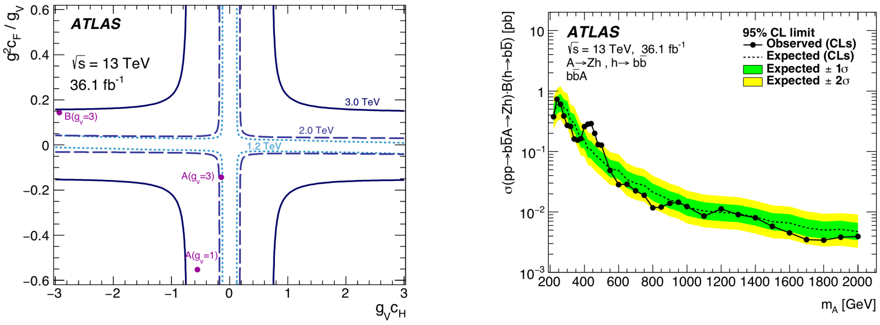

Figure 11: Exclusion limits for the search of a W′ or a Z′ boson, decaying to VH final state from the ATLAS experiment [14].

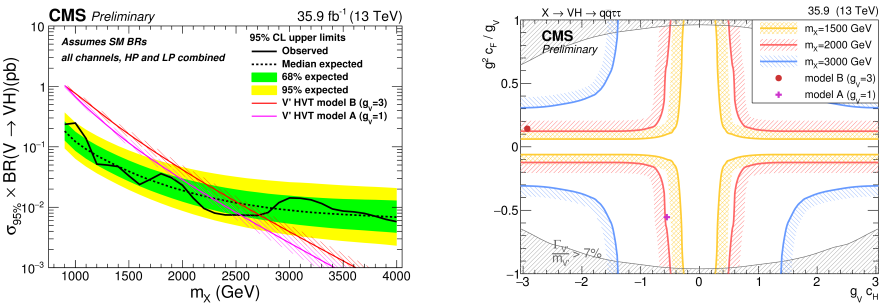

Figure 12: Exclusion limits for the search of new physics in the VH final state from the CMS experiment, with the Higgs boson decaying to τ leptons [15].

the new particles to the SM particles; and in the plane defined by the mass of the Z′ and of the A bosons, as defined in Fig. 9. These results are shown in Fig. 10.
Also the ATLAS collaboration has defined several categories, constructed combining: resolved (2 b jets) or merged (1 wide jet) Higgs boson with zero leptons and missing transverse momentum, one lepton and missing transverse momentum, or two leptons from the vector boson. The results are shown in Fig. 11. The CMS experiment is also looking for W′ or Z′ resonances decaying to VH with one Higgs decaying to τ leptons [15]. The hadronic τ leptons can overlap if coming from a high momentum Higgs, because in this case they are produced close to each other: a dedicated algorithm with jet substructure information used to reconstruct the Higgs boson decaying to τ leptons is used, while for the background estimation, a similar strategy as VH analysis previously

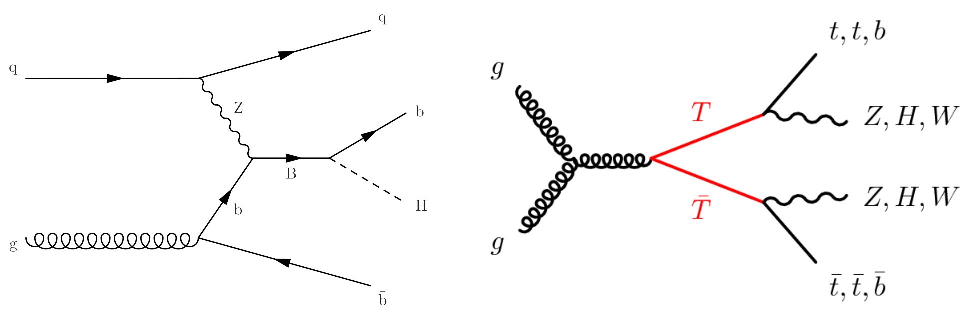

Figure 13: Examples of Feynman diagrams for single (left) and pair (right) production of vector-like quarks.

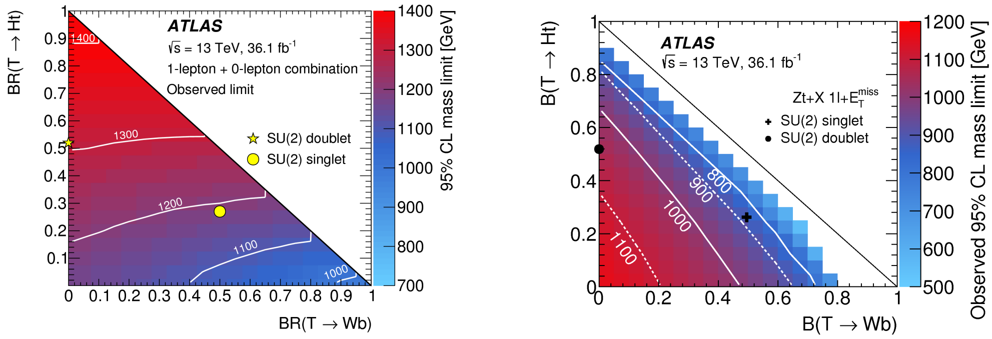

Figure 14: Left: results from $T\bar{T}$ in final states with $H \to bb$ and $Z \to \nu\bar{\nu}$, from the ATLAS experiment [16]. Right: results from $T\bar{T}$ production in the $T \to Zt + X$ final state [17].

described is used. The results are shown in Fig. 12.

4. Vector like quarks

A possible extension of the SM involves heavy particles called vector-like quarks (VLQs). Unlike chiral fermions of the SM, these new particles obtain mass through a direct mass term and as a consequence they are not excluded by precision SM measurements, as it is the case for fourth-generation chiral quarks, instead. The VLQs are expected to couple preferentially to third-generation quarks, so that the following decays are possible: $T \to Wb$, Zt, and Ht, $B \to Wt$, Zb, and Hb. Furthermore, as shown in Fig. 13, they can be produced by pair-production, i.e. strong mechanism and model independent; or by single production, i.e. electroweak mechanism that depends on the couplings with the SM particles.

The ATLAS experiment has focused on the search of pair-produced VLQs. A first analysis [16] is looking for $T\bar{T}$ production with at least one T decaying to a Higgs boson, with $H \to bb$, or with the T decaying to a Z boson, with $Z \to \nu\bar{\nu}$. The final states involve one lepton, the top quark and the Higgs boson decaying hadronically and reconstructed with jet substructure techniques, and missing transverse momentum. After the object reconstruction, several categories are defined depending on the jets, b-jets, W-jets, and top-jets multiplicity. The results are shown in Fig. 14 (left), where several branching fraction of the T quark are tested. A second analysis from ATLAS [17], is looking for $T\bar{T}$ production in the $T \to Zt + X$ final state, with exactly one charged lepton and the Z boson to neutrinos pair decay. Upper limits on T mass are 0.87 (1.05) TeV for the weak-isospin

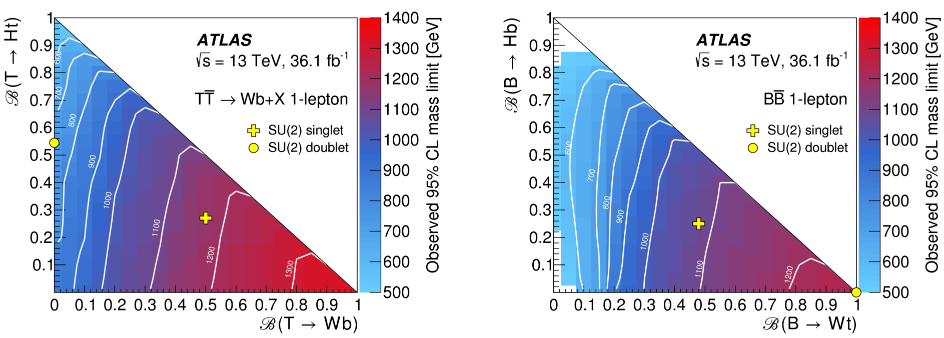

Figure 15: Upper limits on vector-like T (left) and B (right) quarks from the analysis described in Ref. [18].

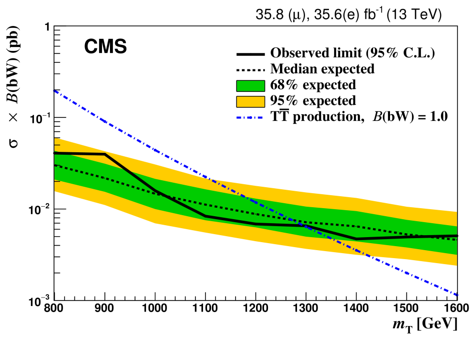

Figure 16: Upper limits on vector-like T quark pair production from the CMS analysis described in Ref. [19].

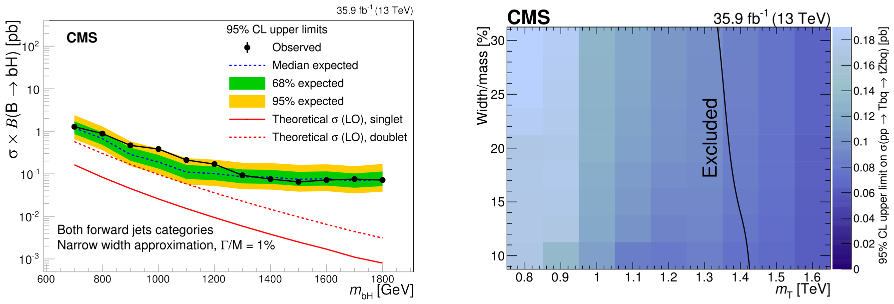

Figure 17: Upper limits on single production of the vector-like B [20] (left) and T [21] (right) quarks.

singlet (doublet) model and 1.16 TeV for the pure Zt decay mode as shown in Fig. 14 (right). Finally, ATLAS looked for the $T\bar{T}$ production with decays to two Wb pairs and with one W boson to leptons and one to quarks [18]. The analysis is also sensitive to the other two decay modes as well as to the vector-like B quarks. As shown in Fig. 15, assuming B(T $\rightarrow$ Wb)=1, the upper limit on the T mass is set to 1.35 TeV, while for the SU(2) singlet T scenario, the upper limit is 1.17 TeV.

The CMS experiment studied both the pair and single production of VLQs. The first analysis described in this proceeding is looking for pair production of T quarks with their subsequent decays to TT $\rightarrow$ bWbW $\rightarrow$ b$\ell\nu$bqq' [19]. A kinematic fit is used to fully reconstruct the mass of the T quark. The results are shown in Fig. 16.

The CMS experiment is also looking for single production of VLQs. One example is the search for the B quark that decays to a Higgs boson and a b quark, with the H $\rightarrow$ $b\bar{b}$ reconstructed as a single collimated jet [20]. A variable width for the B quark is investigated, from negligibly small to 30% of the resonance mass. The result is shown in Fig. 17 (left). Regarding the T quark, the analysis described in Ref. [21] looks for the single production of a vector-like T quark decaying to a Z boson and a top quark, with the Z boson decaying leptonically and the top quark decaying hadronically. Also in this case several width hypotheses are investigated as shown in Fig. 17 (right).

5. Conclusion

The ATLAS and CMS experiments are actively looking for new physics beyond the SM that can explain the current problems of the SM. In this proceeding, some of the most recent searches have been presented. So far, no clear and unambiguous sign of new physics yet from the LHC data has been observed, but LHC will continue to take data until the end of 2018 with more data and improved analysis techniques a larger region of phase space will be probed in the future.

References

[1] ATLAS Collaboration, JINST **3** (2008) S08003. doi:10.1088/1748-0221/3/08/S08003

[2] CMS Collaboration, JINST **3** (2008) S08004. doi:10.1088/1748-0221/3/08/S08004

[3] ATLAS Collaboration, arXiv:1712.02332 [hep-ex].

[4] CMS Collaboration, JHEP **1805** (2018) 025 doi:10.1007/JHEP05(2018)025 [arXiv:1802.02110 [hep-ex]].

[5] ATLAS Collaboration, arXiv:1803.02762 [hep-ex].

[6] CMS Collaboration, JHEP **1803** (2018) 160 doi:10.1007/JHEP03(2018)160 [arXiv:1801.03957 [hep-ex]].

[7] ATLAS Collaboration, Phys. Rev. D **97** (2018) no.5, 052010 doi:10.1103/PhysRevD.97.052010 [arXiv:1712.08119 [hep-ex]].

[8] CMS Collaboration, Phys. Lett. B **782** (2018) 440 doi:10.1016/j.physletb.2018.05.062 [arXiv:1801.01846 [hep-ex]].

[9] CMS Collaboration, CMS-PAS-EXO-18-006 https://cds.cern.ch/record/2308270

[10] ATLAS Collaboration, Phys. Rev. Lett. **120** (2018) no.16, 161802 doi:10.1103/PhysRevLett.120.161802 [arXiv:1801.06992 [hep-ex]].

[11] CMS Collaboration, Phys. Lett. B **777** (2018) 39 doi:10.1016/j.physletb.2017.12.006 [arXiv:1708.08539 [hep-ex]].

[12] ATLAS Collaboration, Phys. Lett. B **781** (2018) 327 doi:10.1016/j.physletb.2018.03.036 [arXiv:1801.07893 [hep-ex]].

[13] CMS Collaboration, CMS-PAS-B2G-17-004 https://cds.cern.ch/record/2309980

[14] ATLAS Collaboration, JHEP **1803** (2018) 174 doi:10.1007/JHEP03(2018)174 [arXiv:1712.06518 [hep-ex]].

[15] CMS Collaboration, CMS-PAS-B2G-17-006, https://cds.cern.ch/record/2296716

[16] ATLAS Collaboration, arXiv:1803.09678 [hep-ex].

[17] ATLAS Collaboration, JHEP **1708** (2017) 052 doi:10.1007/JHEP08(2017)052 [arXiv:1705.10751 [hep-ex]].

[18] ATLAS Collaboration, JHEP **1710** (2017) 141 doi:10.1007/JHEP10(2017)141 [arXiv:1707.03347 [hep-ex]].

[19] CMS Collaboration, Phys. Lett. B **779** (2018) 82 doi:10.1016/j.physletb.2018.01.077 [arXiv:1710.01539 [hep-ex]].

[20] CMS Collaboration, arXiv:1802.01486 [hep-ex].

[21] CMS Collaboration, Phys. Lett. B **781** (2018) 574 doi:10.1016/j.physletb.2018.04.036 [arXiv:1708.01062 [hep-ex]].

PoS(ALPS2018)025