PROCEEDINGS OF SCIENCE

Search for new resonances coupling to third generation quarks at CMS

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Recent results of searches for heavy resonances decaying to third generation quarks are presented. The searches use proton-proton collision data with a center-of-mass energy of 13 TeV, collected during LHC Run-2 with the CMS experiment and corresponding to an integrated luminosity of 138 fb^{-1}. A variety of jet tagging techniques is used to identify boosted particles, exploiting jet substructure and novel machine-learning based algorithms. No significant deviations from the Standard Model predictions have been observed and stringent exclusion limits on new physics models have been set.

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1. Introduction

Many theories of physics Beyond the Standard Model (BSM) predict the existence of new heavy particles decaying to top and bottom quarks. The searches described in this report focus on heavy resonances at the TeV scale. The decay products of such heavy particles are Lorentz boosted, meaning that they are collimated and can be reconstructed in single, large-radius jets. The hadronic decays of top quarks and Higgs/Z/W bosons present characteristic signatures that can be exploited to identify them and distinguish them from the multijet background that is largely present in physics analyses at the LHC. Jet substructure techniques are unique tools to identify the origin of these jets [1].

2. Jet tagging techniques

Jet substructure is fundamental for the identification (tagging) of top quark, Higgs (H) and weak vector-boson (Z/W) jets. In CMS, jets are typically reconstructed with the anti-k_T algorithm [2] and have a radius parameter of 0.4 or 0.8. The Pile Up Per Particle Identification (PUPPI) [3] algorithm is applied on large-radius jets to mitigate the effects of pileup, the multiple *pp* collisions that happen in the same bunch crossing. The most important observables used for tagging are the jet soft-drop mass m_{SD} [4], the *N-subjettiness* variables and their ratios (τ_{21}, τ_{32}) [5] and the jet flavour content (b and c quark tagging). Recently, sophisticated jet taggers have been developed for the identification of hadronic decays of heavy objects. Examples of such algorithms are the *Heavy Object Tagger with Variable R* (HOTVR) [10], a jet clustering and identification algorithm with variable jet radius, and machine learning based techniques, like DeepAK8 and ImageTop [6]. The performance of these algorithms is shown in Fig. 1 for top quark identification.

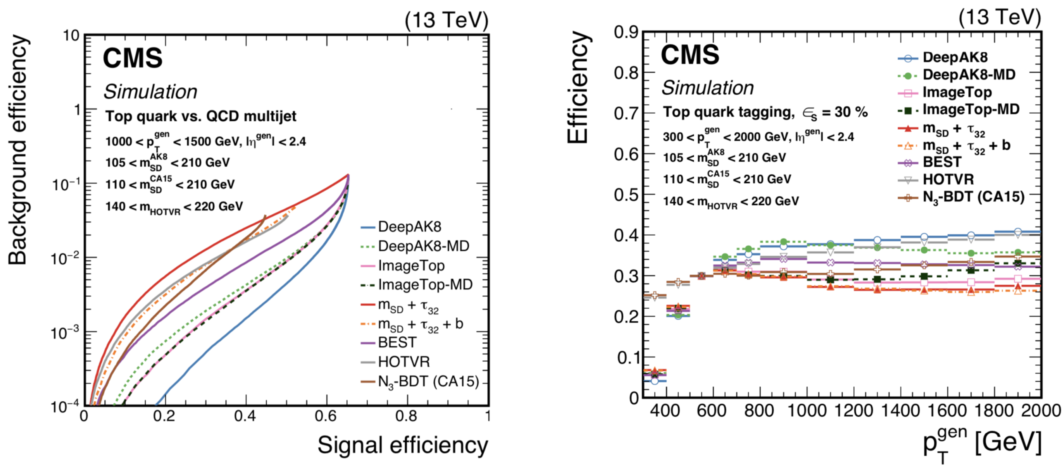

Figure 1: (Left) The top tagging performance comparison in terms of the receiver operating characteristic (ROC) curve. (Right) The efficiency as a function of the generated particle transverse momentum p_T for top quark identification [6].

3. Results with the CMS experiment

In the following, the latest results of searches for new resonances with top and bottom quarks in the final state are presented. The searches are performed on *pp* collision data with a center-of-mass energy of 13 TeV recorded with CMS experiment [7] at the LHC during 2016-2018, corresponding to an integrated luminosity of 138 fb^{-1}.

3.1 Search for heavy resonances decaying to tW in the all-hadronic final state

A search for a heavy resonance b^* decaying to a t quark and a W boson in the all-hadronic final state is presented in this analysis [8]. Back-to-back dijet events are selected where both the t quark and the W boson are reconstructed with large-radius AK8 jets. The substructure variables m_{SD}, τ_{21} and τ_{32} are used to tag the jets. By inverting the tagging requirements, control regions are defined to estimate the contribution of the main SM backgrounds: the QCD multijet background is estimated from data, while the $t\bar{t}$ background from simulation.

The 2D distribution (m_t, m_{tW}) is used for the statistical analysis. Exclusion limits are placed on the product of cross section and branching ratio for the b^* resonance with right-handed (RH), left-handed (LH) and Vector-Like (VL) chiralities. The results are also interpreted in the hypothesis of a vector-like quark B, produced via electroweak interaction in association with a t or b quark. Given the smaller cross-section for this signal hypothesis, no mass limit is set.

3.2 Search for heavy resonances decaying to tW in the lepton+jets final state

In this analysis [9] another search for a heavy resonance b^* decaying to a t quark and a W boson is performed, similar to the analysis presented in the previous section 3.1, but the lepton+jets final state is considered. Events are selected with one isolated lepton and missing transverse momentum from the W boson decay, and a jet from the hadronic decay of the t quark. The HOTVR [10] algorithm is used for the first time in an LHC search to reconstruct and tag the t quark jet. The distance parameter of the HOTVR jets is not fixed, as in the majority of jet clustering algorithms, but it is adapted dynamically with the jet transverse momentum p_T. In this way a high tagging efficiency is obtained both in the low and high p_T regimes. The sensitive variable is the mass of the tW system and it is shown in Fig. 2 (left). Different categories are constructed based on the number of b jets, and they are used to define the signal region and control regions from which the SM backgrounds are estimated.

The results are combined with the analysis targeting the all-hadronic final state [8]. Since no excess over the SM prediction is found, upper limits on the production cross section of a b^* resonance are set and they are shown in Fig. 2 (right) for the VL hypothesis. It is possible to exclude b^* quarks up to 2.95(LH), 3.03(RH) and 3.22(VL) TeV. The analysis in the lepton+jets final state with the HOTVR algorithm extends the reach from 1.4 TeV to 0.7 TeV, compared to the analysis in the all-hadronic final state.

3.3 Search for a W′ boson decaying to tb in the all-hadronic final state

A W′ boson, heavy partner of the W boson, that decays into a t and a b quark in the all-hadronic final state is probed in this analysis [11]. Both the right-handed (RH) and left-handed (LH) charged current interaction hypothesis are considered and the LH hypothesis includes the interference with

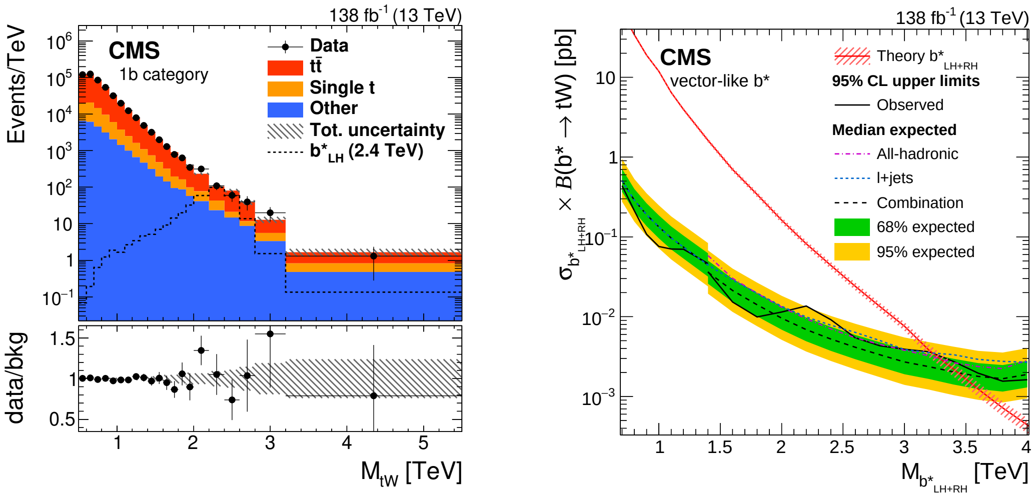

Figure 2: (Left) The mass of the reconstructed tW system in the 1b category. (Right) Upper limits on the production cross section and branching fraction of the Vector-Like b* hypothesis. The combination of the lepton+jets and all-hadronic analyses is performed. [9].

SM single top production. The final state presents a back-to-back topology, with a small-radius jet originating from the b quark and a large-radius jet from the t quark. The b quark jet is identified with the DeepJet [12] algorithm, while the t quark jet is identified with the DeepAK8 tagger [6]. DeepAK8 is a multi-classifier able to identify the hadronic decays of t/H/Z/W and their various decay channels (e.g. $Z \to b\bar{b}$, $Z \to c\bar{c}$, $Z \to q\bar{q}$). It is based on a neural network that takes as inputs jet constituents and secondary vertex information. A mass-decorrelated (MD) version of the tagger has been developed, to prevent the algorithm from learning the jet mass and suppress mass-sculpting effects. The MD version of DeepAK8 is used in this analysis. Events are categorized into regions based on the tagging requirements. In particular, a control region is used for the QCD multijet background estimation from data. The sensitive variable is the mass of the tb system m_{tb}. No excess over the SM background is found and upper limits are set on the cross section and branching fraction for the RH and LH W′ boson, as shown in Fig. 3. It is possible to exclude $m_{W'_{L,R}}$ up to 3.4 TeV, resulting in the most stringent limits to date.

3.4 Search for a W′ boson and a VLQ in the all-hadronic final state

A search for a W′ resonance decaying to a T or B vector-like quark (VLQ) and a b or t quark, respectively, is presented [13] ($W' \to Tb/Bt$). The T VLQ decays then to a H or Z boson and a t quark, while the B VLQ decays to a H or Z boson and a b quark, resulting in two possible final states: tHb or tZb. The all-hadronic decays of all particles are considered. The small-radius jet originating from the b quark is tagged with the DeepJet algorithm. The t quark and the H and Z bosons are reconstructed with AK8 jets and the soft-drop mass m_{SD} is used as a discriminant. The hadronic decay of the Z boson is selected through a cut on the τ_{21} variable and the m_{SD}. The Higgs boson decaying into $b\bar{b}$ is identified with the double-b tagger (Dbtag) [12]. The t quark jet is identified with ImageTop, a machine-learning based algorithm used here for the first time in a CMS search. ImageTop uses image recognition to distinguish t quark jets from QCD jets, by pixelizing

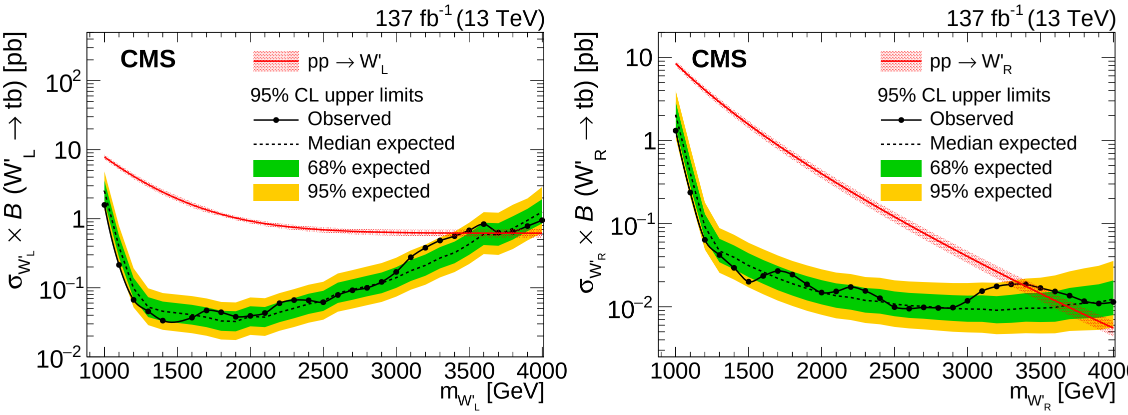

Figure 3: Upper limits on the cross section times branching fraction for a LH (left) and RH (right) W′ boson decaying to tb. The LH hypothesis includes the interference with SM single top production [11].

jet energy deposits. The tagger is decorrelated both from the jet p_T and mass by reweighing the QCD multijet distributions to match the ones from the t quark jets.

The QCD background is estimated from data with a transfer function in a control region, defined by inverting the tagging requirements. The sensitive variable is the invariant mass of the three final state jets, namely m_{tHb} or m_{tZb}. This variable for the tZb final state is shown in Fig 4 (left). Exclusion limits are set on the W′ production cross section for different values of the VLQ masses. The W′ boson with mass up to 3.1 TeV is excluded for a VLQ with mass $m_{\mathrm{VLQ}} = 2/3\, m_{\mathrm{W'}}$. The exclusion limit for this benchmark is presented in Fig 4 (right). The sensitivity for other VLQ masses, $m_{\mathrm{VLQ}} = 1/2\, m_{\mathrm{W'}}$ and $m_{\mathrm{VLQ}} = 3/4\, m_{\mathrm{W'}}$, is not reached yet.

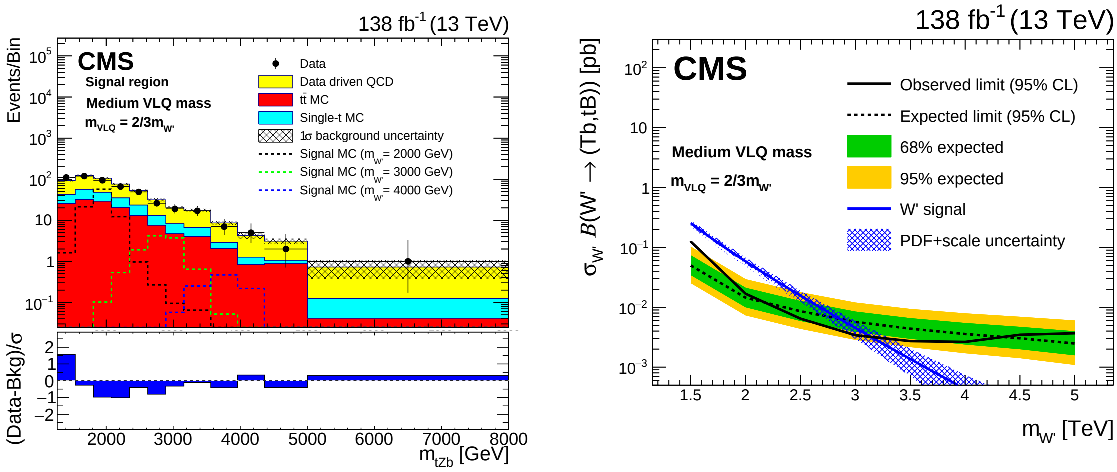

Figure 4: (Left) The invariant mass distribution of the tZb system. (Right) Upper limit on the W′ production cross section and branching fraction for the VLQ mass $m_{\mathrm{VLQ}} = 2/3\, m_{\mathrm{W'}}$ [13].

3.5 Summary

In conclusion, different searches for new physics coupling to third generation quarks are presented, including b* resonances, W′ bosons and vector-like quarks. A variety of novel tagging techniques are employed, crucial for the identification of the hadronic decays of boosted objects. The latest results using data recorded during LHC Run-2 with the CMS experiments at 13 TeV are presented. No deviations from the SM predictions have been reported at ICHEP and stringent exclusion limits are set.

References

[1] R. Kogler, *Advances in Jet Substructure at the LHC*, Springer Tracts Mod. Phys. 284 (2021).

[2] M. Cacciari, G. P. Salam, G. Soyez *The anti-k_T jet clustering algorithm* *JHEP* **04** (2008) 063 [hep-ph/0802.1189].

[3] D. Bertolini, P. Harris, M. Low et al., *Pileup per particle identification*, *JHEP* **2014** 59 (2014) [hep-ph/1407.6013].

[4] A. J. Larkoski, S. Marzani, G. Soyez, J. Thaler, *Soft drop*, *JHEP* **05** (2014) 146 [hep-ph/1402.2657].

[5] J. Thaler, K. Van Tilburg, *Identifying boosted objects with N-subjettiness*, *JHEP* **03** (2011) 15 [hep-ph/1011.2268].

[6] CMS Collaboration, *Identification of heavy, energetic, hadronically decaying particles using machine-learning techniques*, *JINST* **15** (2020) P06005 [hep-ex/2004.08262].

[7] CMS Collaboration, *The CMS experiment at the CERN LHC*, *JINST* **3** (2008) S08004.

[8] CMS Collaboration, *Search for a heavy resonance decaying to a top quark and a W boson at $\sqrt{s}$ = 13 TeV in the fully hadronic final state*, *JHEP* **12** (2021) 106 [hep-ex/2104.12853].

[9] CMS Collaboration, *Search for a heavy resonance decaying into a top quark and a W boson in the lepton+jets final state at $\sqrt{s}$ = 13 TeV*, *JHEP* **04** (2022) 048 [hep-ex/2111.10216].

[10] T. Lapsien, R. Kogler, J. Haller, *A new tagger for hadronically decaying heavy particles at the LHC*, *Eur. Phys. J. C* **76**, 600 (2016) [hep-ph/1606.04961].

[11] CMS Collaboration, *Search for W' bosons decaying to a top and a bottom quark at $\sqrt{s}$ = 13 TeV in the hadronic final state*, *Phys. Lett. B* **820** (2021) 136535 [hep-ex/2104.04831].

[12] CMS Collaboration, *Identification of heavy-flavour jets with the CMS detector in pp collisions at 13 TeV*, *JINST* **13** (2018) P05011 [physics.ins-det/1712.07158].

[13] CMS Collaboration, *Search for a W' boson decaying to a vector-like quark and a top or bottom quark in the all-jets final state at $\sqrt{s}$ = 13 TeV*, *JHEP* **09** (2022) 088 [hep-ex/2202.12988].