PROCEEDINGS OF SCIENCE

Searches for new heavy fermions in CMS

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We present results for new heavy fermions at CMS. The results include searches for third-generation quark and lepton partners with vector-like properties. The results are based on the large dataset collected during Run 2 of the LHC at a centre-of-mass energy of 13 TeV. We search for these particles in a wide range of masses using several categories of reconstructed objects, from mulit-leptonic to fully-hadronic final states.

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PoS(EPS-HEP2023)448

The presented document focuses on latest results on searches for vector-like quarks (VLQs) using data collected by the CMS detector [1, 2] and their analysis improvements beyond the increase of luminosity, while searches for long lived heavy fermions are presented in other presentations. The presentation is including the latest results and also concentrate on the analysis improvements beyond the increase of luminosity.

1. Production and decay of vector-like quarks

Vector-like quarks appear in many extensions of the standard model (SM) as they provide a solution to the hierarchy problem by protecting the Higgs boson mass from large radiative corrections [3–6]. They typically mix with the third generation SM quarks and in contrast to SM chiral quarks have both vector and axial vector-like couplings.

VLQs can either be produced in pairs via the strong interaction or singly via electroweak interactions in association with additional quarks. There are four kinds of VLQs considered: T/B with respective electric charge of $2/3$ and $-1/3$ and X/Y with more exotic electric charge as $5/3$ and $-4/3$. While pair production cross sections depend only on the VLQ mass and are not model dependent, electroweak production of a single VLQ depends on the initial state coupling. These couplings are typically constrained to small values by precision observables [4], thus resulting in low production cross sections. However, in some models, such as a composite Higgs framework [7], cross sections larger by up to two orders of magnitude are possible.

The VLQ T may decay into a bottom quark and a W boson (bW), a top quark and a Z boson (tZ) or a top quark and a Higgs boson (tH) while B may decay into a top quark and a W boson (tW), a bottom quark and a Z boson (bZ) or a bottom quark and a Higgs boson (bH). The X/Y may decay respectively into a top/bottom quark and a W boson (tW/bW). The branching fractions are model dependent. The singlet/doublet model presented in Ref. [8] predicts branching fractions of 50% for decays to bW/TW, 25% for decays to tZ/bZ or tH/bH for the singlet model, and branching fractions of 50% for decays to tZ/bZ or tH/bH for the doublet scenario.

2. Inclusive T/B pair production

The analysis [9] looks for a pair-produced of T/B in the multi-leptons final state, categorizing events in single-lepton, same-sign dilepton, and trilepton final states.

For the single lepton channel, a large-cone jet identified as a boosted hadronic decay of W/Z/H boson or top quark is requested. A multilayer perceptron neural network is trained to separate the $t\bar{t}$ and W+jets background from the signal. Various categories based on the lepton flavor and the VLQ decay identification coming from the tagging of the large-cone jet are studied.

The same-sign dilepton channel focuses mainly on T decaying to a top quark and a Higgs boson and B decaying to a top quark and a W boson. The background is already reduced with the request of the same-sign dilepton final state and the categories are based on the lepton flavor. The main variable used is the H_T^{lep} corresponding to the sum of the jets transverse momentum (p_T) present in the event and the sum of the p_T of the two leptons.

The last final state studied is the trilepton focusing mainly on T decaying into a top and a Z boson. The search variable is either H_T^{lep} or $S_T = H_T^{lep} + p_T^{miss}$ where the p_T^{miss} represents the missing transverse momentum.

The analysis was already published using only 2016 data in [10]. The luminosity used in this new analysis is increased by a factor 3.5, but additional improvements to the analysis strategy is also included. For the single lepton channel, the usage of the neural network has drastically improved the identification of TT/BB pairs being at a level of 92/89% respectively. In the meantime, the misclassification of $t\bar{t}$ and W+jets as signal is respectively 14% (11% when considering BB pairs) and 2%. In the dilepton and trilepton channels, a standardisation of the non-prompt background allows a better control of it. The improvements allow to push further the observed limits with a 95% confidence level (CL) exclusion of the singlet/doublet model up to mass of T less than 1480/1490 GeV and to mass of B less than 1470/1120 GeV.

Figure 1 presents the 95% CL observed lower mass limits for T/B VLQ as function of branching ratio for the various decay channel.

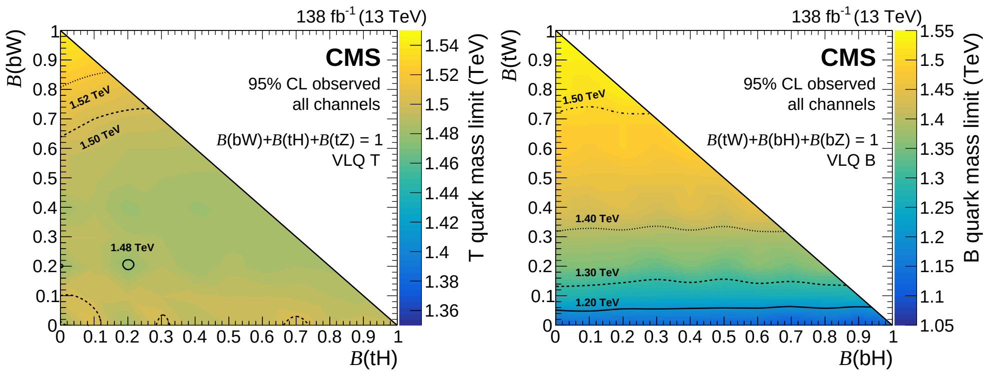

Figure 1: The 95% CL observed lower mass limits on pair-produced T (right) and B (left) quark masses, from the combined fit to all channels, as a function of their branching ratios to H and W bosons. Mass contours are shown with lines of various styles [9].

3. B pair production in all-hadronic and Z in dilepton final state

The second analysis [11] is complimentary to the previous one as it covers the full hadronic channel and the case where a Z boson decay leptonically. For the all-hadronic decay, the small- and large-cone jets are used to cover a wide range of mass. The events are spread in categories depending on the channel and jet multiplicity. In this channel, the jet multiplicity covers from three jets (where jets are W/Z/Higgs boson tagged or top tagged) up to six jets. For the leptonic channel, the multiplicity is reduced to three and four jets and two same flavor leptons with an invariant mass around the Z boson mass is requested. The studied final state does not contain neutrino so the full B candidate invariant mass can be determined. In order to associate the jets to a given decay hypothesis the following χ^2 definition is used:

$$\chi^2 = \frac{(\Delta m_{\mathrm{VLQ}} - \overline{\Delta m}_{\mathrm{VLQ}})^2}{\sigma^2_{\Delta m_{\mathrm{VLQ}}}} + \sum_{i=2}^{n} i \frac{(m_i - \overline{m_i})^2}{\sigma^2_{m_i}} \tag{1}$$

where Δm_{VLQ} is the fractional mass difference of the two reconstructed VLQ candidates in the event, given by $\Delta m_{\mathrm{VLQ}} = 2(m_{\mathrm{VLQ}1} - m_{\mathrm{VLQ}2})/(m_{\mathrm{VLQ}1} + m_{\mathrm{VLQ}2})$, m_i is the mass of a reconstructed resonance (bosons or top quarks), $\overline{m}_i$ and $\overline{\Delta m}_{\mathrm{VLQ}}$ are the average masses of the resonance and Δm_{VLQ}, respectively, taken from simulation, and the σ values are the standard deviations for these average values. The sum depends on the final state, n corresponds to the sum of bosons and top quarks expected. The χ^2 is minimised.

The background is determined from data without any dependency to simulation. Corrections to mimic signal region containing b-tagged jets are applied to the control region made with looser or no b-tagged jet requirement. The improvements with respect to the previous publication [12] is the addition of two channels: Wt as final state and the Z-dileptonic channel. The 95% CL exclusion are given as function of branching ratio for the various decay channel. Considering the singlet/doublet model case, the observed limits on mass of B is lower than 1065/1510 GeV, complementing nicely the inclusive T/B pair production search.

The two searches for pair production are getting combined.

4. Single production of T in all-hadronic final state

The single production is complementary to the pair production as it is sensitive to both VLQ mass and their mixing parameters entering the width hypothesis. The current pair production searches are looking for the narrow-width-approximation (of the order of 1%) while the single production searches study the various width. Nevertheless, new theory developments [13] are introducing some interference in the case of a decay into a top quark and a Higgs boson for width larger than 10%. For this reason, the two presented analyses below are purely considering narrow-width-approximation.

The analysis considers a full hadronic decay for the top quark and H/Z boson ($\rightarrow b\bar{b}$) [14]. Only small-cone jets are considered and the pairing of the jets into W boson, top quark and H/Z boson candidates is performed via a similar χ^2 as presented in Equation 1 removing the Δm_{VLQ} part.

A previous analysis was performed in the same final states using 2016 data [15], where a 3 σ local excess around a VLQ T mass of 700 GeV only in the top+H channel was observed. In the most recent analysis, the selection is performed employing the same variables as in the previous publication but two different categories are identified: below 800 GeV, a selection preserving the falling spectrum is employed, while above 800 GeV the selection designed for the previous publication is kept gaining a few percent on signal efficiency. These two set of selections, using the same criteria but not the same cut value, remove the shaping of the T candidate invariant mass used as the main variable.

The background estimation is data driven and is derived from regions with b-tagged jets using different quality criteria on the three b-tagged jets. The T mass candidate is then corrected by a difference in b-tagging efficiency to navigate from one region to the next one.

The presented analysis, which is based on the Run 2 data (2016+2017+2018), excludes any significant excess as can be seen in Figure 2. The 95% CL exclusion limits obtained are improved with respect to the previous result by at least a factor of three.

PoS(EPS-HEP2023)448

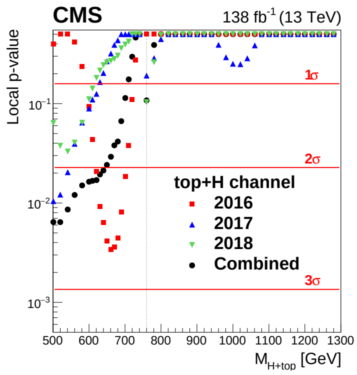

Figure 2: Observed p-values when considering the top+H channel for each year and their combination [14].

5. Single production of T with Higgs boson decaying into a pair of photons

Despite the very low branching ratio of the Higgs boson to a pair of photons, the presented channel gains sensitivity from a very clean final state. Techniques similar to those employed in the SM Higgs analysis [16] are used: the main variable is the photon pair invariant mass. The search [17] looks for hadronic and semi-leptonic decay of the top quark. To constraint the background, a machine learning algorithm based on boosted decision tree is used. For both channels, a first training is made to separate the signal and the SM Higgs boson background processes. For the hadronic channel, a second training is used to distinguish the signal from the gamma+jets background.

As for the SM Higgs analysis, the background is obtained by a fit of the photon pair invariant mass. A reconstruction of the T mass candidate is also achieved to set limits. The 95% CL exclusion limits are set as a function of the T mass but also for various value of the κ parameter. In the model, the κ parameter is linked to the width of the VLQ and its study is made up the detector resolution value as presented in Figure 3.

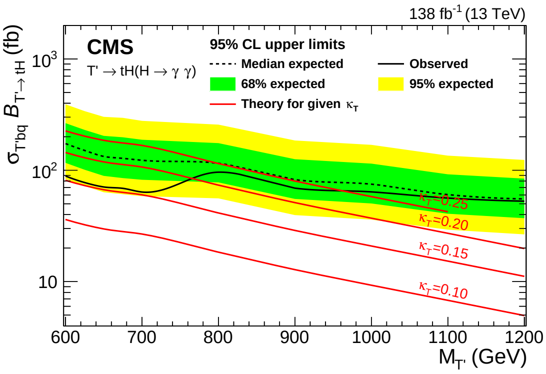

Figure 3: The combined, leptonic plus hadronic, expected (dotted black) and observed (solid black) upper limits at 95% CL on $\sigma_T \mathcal{B}_{T\to t+H}$ are displayed as a function of VLQ T mass (M_T). The green (yellow) band represents the 68% (95%) of the limit values expected under the background-only hypothesis. The theoretical cross sections for the singlet T production with representative κ_T-values fixed at 0.1, 0.15, 0.2 and 0.25 (for $\Gamma/M_T < 5\%$) are shown as red lines [17].

6. Conclusion

In this talk, various searches for new heavy fermions preformed at CMS were presented. While the sensitivity of each analysis gains from the larger data set available from Run 2, many improved techniques also allow further increasing the sensitivity to new physics. Moreover, the background determination technics are moving toward data driven one reducing further the systematics uncertainties. Various combination of the searches are starting, meanwhile, overview of the exclusion limits set by the most recent VLQ searches are visible in figure 4 for both single and pair production.

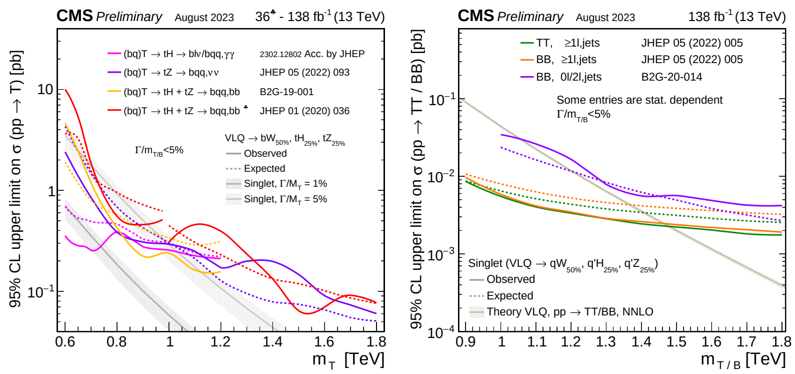

Figure 4: Expected (dotted black) and observed (solid black) upper limits at 95% CL on σ_T (left) and $\sigma_{TT/BB}$ (right) are displayed as a function of $M_{T/B}$. The different color lines represent results from various analysis. Combinations of results are ongoing [18].

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PoS(EPS-HEP2023)448

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