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Searches for Vector-Like Quarks at CMS experiment(*)

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Summary. — This work aims to present recent results in the searches for a specific type of candidates of new physics Beyond Standard Model, the so-called Vector-Like Quarks, with the CMS detector at the LHC. Searches for the single production of the Vector-Like Quark T in tH decay channel and the pair production of T and B in leptonic final states will be described. The results are based on the proton-proton collisions reaching up to $\sqrt{s} = 13$ TeV in the centre-of-mass and an integrated luminosity of 138 fb^{-1}.

1. – Introduction

Although the Standard Model (SM) of particle physics boasts a large number of experimental evidences over the years, it is still far from being complete. Its first obvious limitation is that the gravity has not yet been described using a quantum field theory. Among other issues, we can list the baryonic asymmetry, the impossibility to provide a description of Dark Matter, the hierarchy problem, and the Higgs mass fine-tuning.

Many model classes provide answers to problems such as the ones listed above by expanding the SM, and are therefore referred to as "Beyond the Standard Model" (BSM) theories. We can mention several classes of models, among which Composite Higgs (CHM), Extra-dimensions and non-minimal SUSY extensions like Two-Higgs-Doublet Model (2HDM).

These models predict the presence of candidates of new physics at TeV scale, so the Compact Muon Solenoid [1] (CMS) experiment at Large Hadron Collider (LHC), with possibility to reach 13.6 TeV by p-p collisions in the centre-of-mass is among the candidate experiments for the possible observation of such particles.

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TABLE I. – *Main features of the VLQs T and B* [2].

VLQ	Electric charge	Decay channels
T	$+\frac{2}{3}$	tZ, bW^{+}, tH
B	$-\frac{1}{3}$	bZ, bH, tW^{-}

2. – Vector-Like Quarks

The Vector-Like Quarks (VLQs) [2] are supposed to be coloured fermions with spin $\frac{1}{2}$ and mass of the order of TeV. The origin of their name lies in the fact that their left- and right-handed components have the same colour and electroweak quantum numbers. This phenomenology allows them to admit mass as a free parameter of the model.

The VLQs can be produced in p-p collision with two distinct mechanisms: the single production, via electroweak interaction, and pair production, via strong interaction.

Different VLQs are theorized to have various electric charges and can generally be grouped into SU(2) multiplets (singlets, doublets, or also triplets considering exotic extensions). We briefly summarize the main features in table I

The analyses carried out have mainly assumed that VLQs decay exclusively into Standard Model particles with varying branching ratios that sum to 100%, depending also on their multiplet representation.

This paper will present the results of two searches: the first searches for VLQ T in one of its decay channels under the single production hypothesis, while the second searches for both VLQs T and B but considering the pair production hypothesis.

2·1. *Search for a vector-like quark* $T' \to tH$ *via the diphoton decay mode of the Higgs boson in proton-proton collisions at* $\sqrt{s} = 13$ *TeV*. – The analysis reported in [3] searches for the single production of a VLQ T, reconstructed in the decay channel tH, where H further cascades into a pair of photons $H \to \gamma\gamma$. The Feynman diagram of the process is shown in fig. 1.

This study considers the narrow width approximation (NWA) to parametrize VLQ production and decay, assuming that $\Gamma_T/M_T \sim 1\%$, where Γ_T is the natural width of the resonance T. However, the analysis is so sensitive that it also extends to scenarios in which $\Gamma_T/M_T \sim 5\%$.

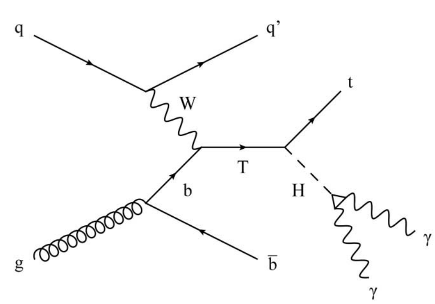

Fig. 1. – Leading-order Feynman diagram for single T production via Wb fusion and its subsequent decay into tH ($H \to \gamma\gamma$) [3].

The analysis divides the events into two main categories, leptonic and hadronic, according to the decay modes of the top quark.

In the leptonic events ($t \to bW \to bl\nu$) are required two photons, at least an electron or a muon and a b-tagged jet to target $t \to bW$, while in the hadronic events ($t \to bW \to b\bar{q}q'$), in addition to the two prompt photons, three jets and at least one b-tagged are required, and events are vetoed if one lepton (muon or electron) is present.

The major background for leptonic events is made up by Drell-Yan processes. The QCD, γ + jets, and $\gamma\gamma$ + jets processes make up approximately 25% of the background for events belonging to the leptonic category, whereas the same processes make up approximately 95% of the total background.

The SM Higgs Boson production (SMH) processes constitute a background for both categories of events, and in particular the one with the largest contribution is $\bar{t}tH$ with $H \to \gamma\gamma$.

A Boosted Decision Tree (BDT-SMH) was implemented for the rejection of the SMH background in both the leptonic and hadronic categories. A further Boosted Decision Tree was implemented for the rejection of non-resonant background in the hadronic event category (BDT-NRB).

Previous searches utilized the reconstructed T invariant mass or transverse mass as the primary observable. This analysis takes advantage of the 1-2% resolution for the reconstructed H mass in the diphoton decay channel, aiming to identify a signal indicated by a peak in the H mass above the smoothly falling diphoton mass distribution characteristic of non-resonant background processes($m_{\gamma\gamma}$).

A simultaneous fit to the extended maximum likelihood of $m_{\gamma\gamma}$ at different m_T hypotheses is performed, and in absence of evidence for a signal, an upper limits at 95% CL on the signal strength is derived and converted to the cross section $\sigma_{T'bq}\mathcal{B}_{T'\to tH}$.

The upper limit on the cross section compared with the theoretical cross section at different values of the coupling parameter k_T of T with SM particles is shown in fig. 2.

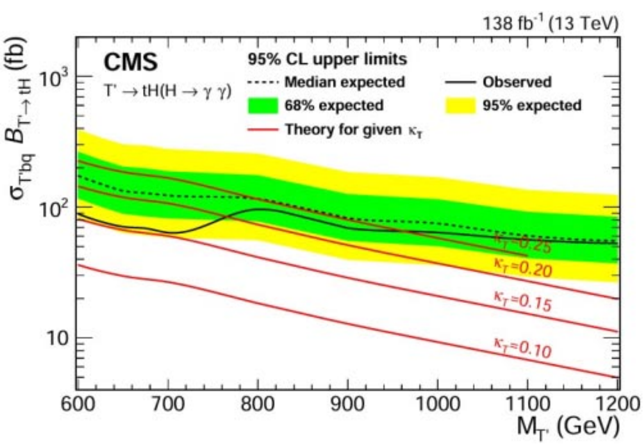

Fig. 2. – The combined, leptonic plus hadronic, expected (dotted black) and observed (solid black) upper limits at 95% CL on $\sigma_{T'bq}\mathcal{B}_{T'\to tH}$ are displayed as a function of $M_{T'}$. The green (yellow) band represents the 68% (95%) of the limit values expected under the background-only hypothesis. The theoretical cross sections for the singlet T production with representative k_T values fixed at 0.1, 0.15, 0.2 and 0.25 (for $\Gamma/M_T < 5\%$) are shown as red lines [3].

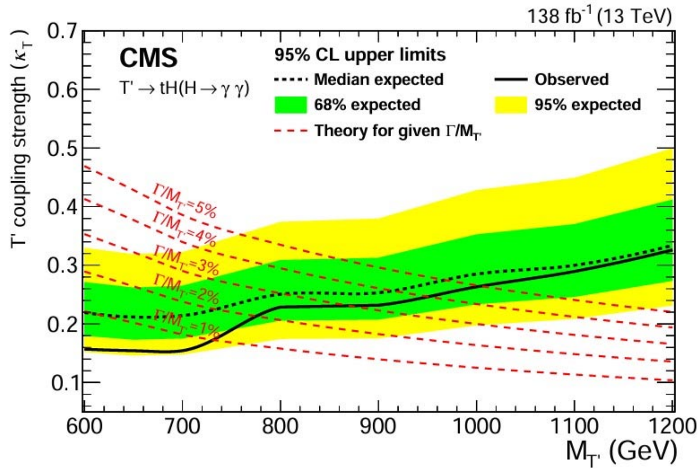

Fig. 3. – The combined, leptonic plus hadronic, expected (dotted black) and observed (solid black) upper limits at 95% CL on the T coupling to third-generation quarks, k_{T}, under the narrow width approximation displayed as a function of M_{T}. The green (yellow) band represents the 68% (95%) of the limit values expected under the background-only hypothesis. The theoretical k_{T} values corresponding to the $\Gamma/M_{\mathrm{T}'}$-values fixed at 1, 2, 3, 4, and 5% are shown as red dashed lines [3].

The analysis also establishes the upper limits to the coupling constant k_{T} considering the NWA with its theoretical previsions at different hypotheses of Γ/M_{T} equal to 1, 2, 4 and 5%. These are in fig. 3.

2·2. *Search for pair production of Vector-Like Quarks in leptonic final states in proton-proton collisions at* $\sqrt{s} = 13$ *TeV*. – In this analysis [4] is presented a search for VLQs T and B in the pair production (fig. 4) hypothesis, reconstructed in three possible final states containing charged leptons.

The first category is the single-lepton channel, characterized by the presence of one charged lepton and a neutrino, manifesting as missing energy, both considered as stem-

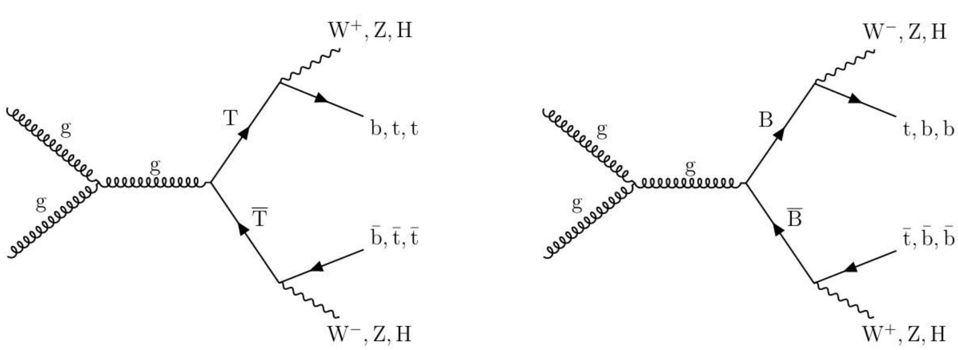

Fig. 4. – Representative Feynman diagrams of the pair production of TT (left) and BB (right), with decays to third generation quarks and SM bosons [4].

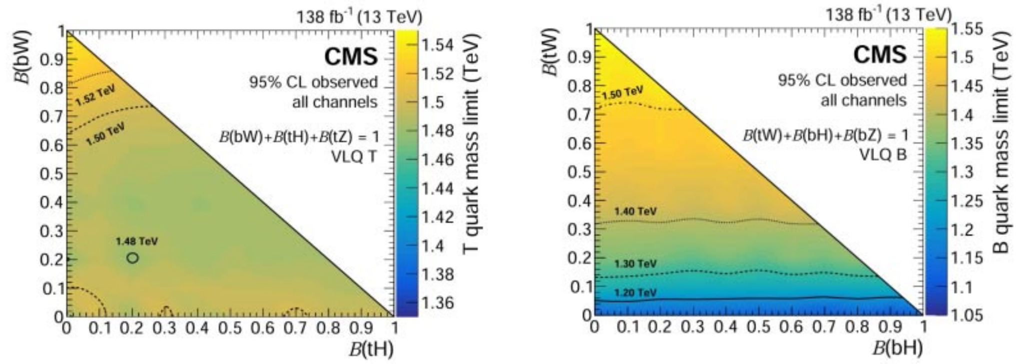

Fig. 5. – The 95% CL observed lower mass limits on pair-produced T (left) and B (right) quark masses, from the combined fit to all channels, as functions of their branching ratios to H and W bosons. Mass contours are also shown [4].

ming from the decay of a W boson or a top quark; for the other three objects in the final state their fully hadronic decay mode is considered, so they are reconstructed as large-radius hadronic jets. The single-lepton channel is sensitive to all the $T\bar{T}$ decays and to tW channel decay for the VLQ B. The second event category is the same-sign charge dilepton channel, sensitive to $T \rightarrow tH$ and $B \rightarrow tW$ decays. The third category is the multilepton channel, in which events with three or more leptons are selected. This final state is rare for the SM processes, and it is sensitive to $T \rightarrow tZ$ and $B \rightarrow tW$ decays. In the single-lepton channel analysis, a multilayer neural network and jet identification algorithms are used to select signal events. Meanwhile, the same-sign dilepton and multilepton channels use the high-energy signature of the signal to differentiate it from SM backgrounds.

Evaluating a simultaneous binned maximum likelihood fit on the three event categories, the analysis provides upper limits at 95% CL on the cross sections of $T\bar{T}$ and $B\bar{B}$ productions; in addition, the analysis is able to provide exclusion of mass scenarios in different branching ratio hypotheses (fig. 5).

3. – Conclusions

An overview of the VLQ searches at the CMS Experiment was presented. In particular, the search for VLQ T in single production in the $T \rightarrow tH \rightarrow t\gamma\gamma$ channel excludes mass up to 1.1 TeV.

The search for VLQs T and B in pair-production in leptonic final states, instead, excludes T with a mass $m_T < 1.48$ TeV while for B $m_B < 1.12$ TeV. The limits obtained in the search for pair-production $T\bar{T}$ are the strongest to date for pair production with all VLQ decay modes.

Searches to date are based solely on the hypothesis that VLQs only decay in SM objects. However, the possibility that they can decay into further BSM objects (non-minimal decay channels) [5] opens the door to further research scenarios for similar new physics candidates.

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