Review and partial combination of searches for vector-like quarks

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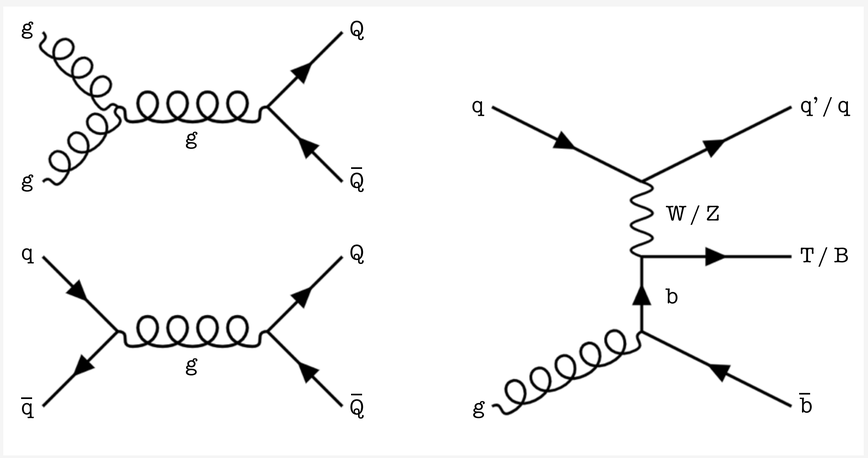
Introduction

- The standard model (SM) of particle physics is well established with the discovery of Higgs boson (H) at LHC in 2012.
- However, the stability of Higgs boson mass at electroweak scale is unexplained within SM, since higher order loop correction leads to divergence
- To address the hierarchy and naturalness problems of SM, several extensions [1, 2, 3] postulates vector-like quarks (VLQs)
- These hypothetical spin-$\mathbf{1/2}$ particles are vector-like, i.e. their left- and right-handed components transform in the same way under the electroweak gauge symmetry group.
- As singlets, the VLQ T and B are introduced with electrical charges of $\mathbf{+2/3}$ and $\mathbf{-1/3}$, respectively.
- At the LHC, VLQs can be pair and singly produced via strong and weak interactions, respectively.



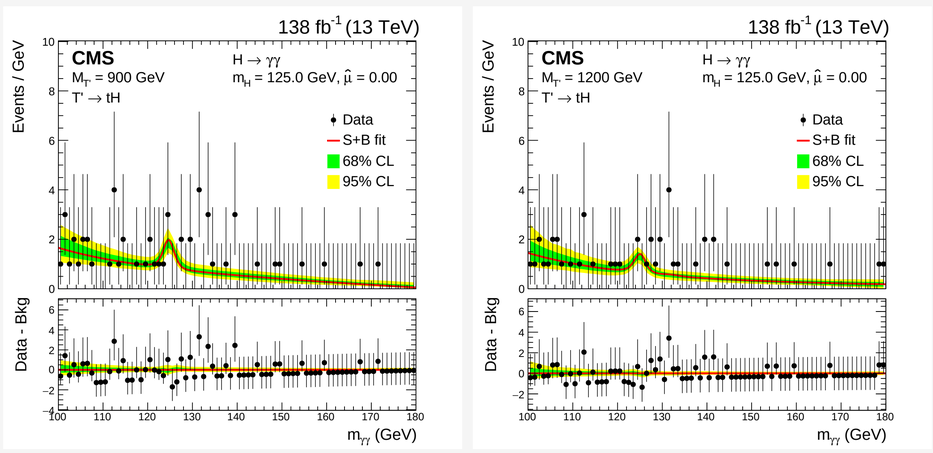
Representative leading-order Feynman diagrams for pair (left) and single (right) production of VLQ. Here Q stands for either VLQ flavour.

- The allowed decay modes for the VLQ are:

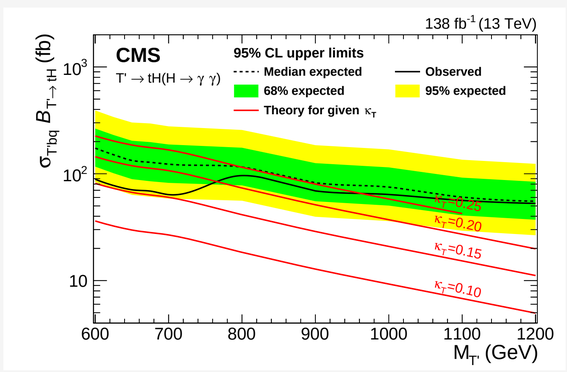
$$T \rightarrow bW,\ T \rightarrow tZ,\ T \rightarrow tH$$
$$B \rightarrow tW,\ B \rightarrow bZ,\ B \rightarrow bH$$

Single production T → tH

- The search is designed to utilize the high-resolution reconstruction of the Higgs boson mass in diphoton decay.
- Aim is to detect two photons originating from the decay of H from the decay of T quark.
- Event selection involves the use of diphoton triggers with $m_{\gamma\gamma} > \mathbf{90}$ GeV and MVA for the efficient selection of photons with primary vertex
- To separate overlapping T signal from SM H process and non-resonant background process, BDTs are used.
- Furthermore, the events are separated into leptonic and hadronic categories for higher sensitivities.



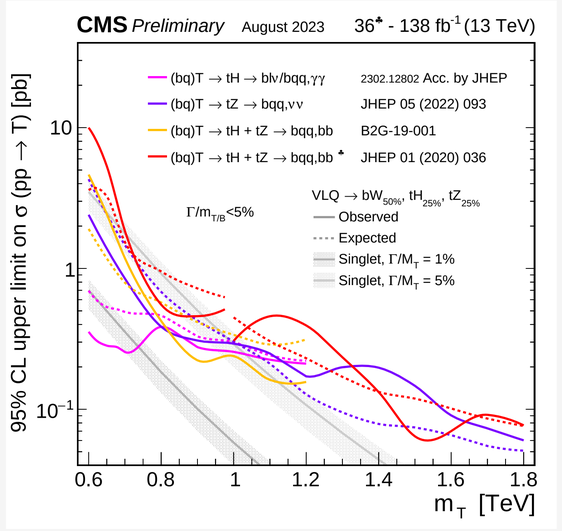
(Ref. [4]) The combined, leptonic plus hadronic, distributions for data (black dots) and $m_{\gamma\gamma}$ signal-plus-background model fits (red line) for a VLQ signal with m_T of 900 (left) and 1200 GeV (right). The green (yellow) band represents the 68% (95%) CL in the background component of the fit. The peak in the background component shows the considered irreducible SM Higgs boson (ggH, VBF, VH, $t\bar{t}H$ and tH) contribution. Here, $\hat{\mu}$ is the best fit value of the signal strength parameter μ, which is zero for the two m_T values considered. The lower panel shows the residuals after the subtraction of the background component.



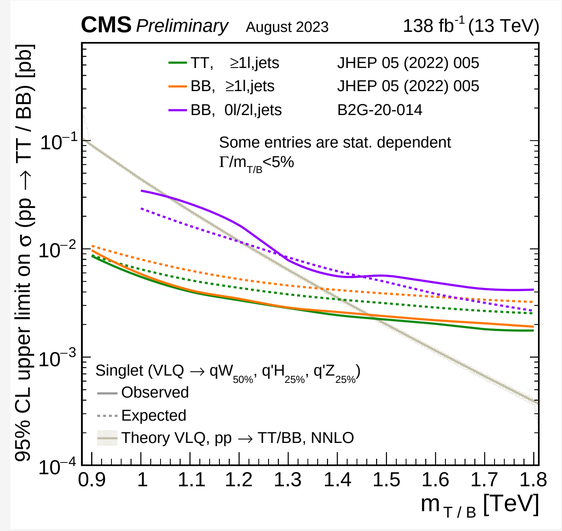
(Ref. [4]) The combined, leptonic plus hadronic, expected (dotted black) and observed (solid black) upper limits at 95% CL on $\sigma_{Tbq}\mathcal{B}_{T\rightarrow tH}$ are displayed as a function of m_T. The green (yellow) band represents the 68% (95%) of the limit values expected under the background-only hypothesis. The theoretical cross sections for the singlet T production with representative κ_T-values fixed at 0.1, 0.15, 0.2 and 0.25 (for $\Gamma/m_T < \mathbf{5\%}$) are shown as red lines.

- Assuming a coupling to third generation quarks of $\kappa_T = \mathbf{0.25}$ and a relative decay width of $\Gamma/m_T < \mathbf{5\%}$, the electroweak production of a singlet T quark is excluded up to a mass of 960 GeV at 95% confidence level.

Summary of VLQ searches



Observed and expected 95% CL upper limits on the production cross section of a single T VLQ, versus its mass obtained by different analyses. Two theory predictions corresponding to different VLQ widths of the singlet model are superimposed.

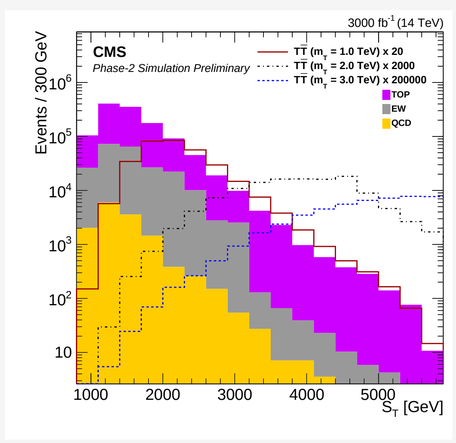


Observed and expected 95% CL upper limits on the production cross section of a pair of TT/BB VLQs, versus its mass obtained by different analyses. A theory prediction corresponding to the singlet, NNLO pair production, with a narrow width is superimposed.

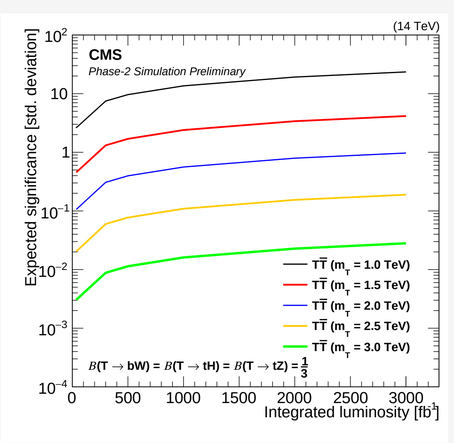
LHC future prospects for VLQs

- After high luminosity (HL) upgrades to LHC, integrated luminosity will be increased to 3000 fb^{-1}.
- This projection study is search for a vector-like quark T decaying to bW, tZ, tH in the single lepton final state at the HL-LHC
- The study targets three decay modes of T involving a single electron or muon and jets in the final state.
- Events are further divided into eight different signal regions based on the number of b-tagged jets, W-tagged jets and single, doubly b-tagged H jets for better sensitivity.
- The upper limits on the $T\bar{T}$ production are computed using a simultaneous maximum likelihood fit of the S_T distributions.

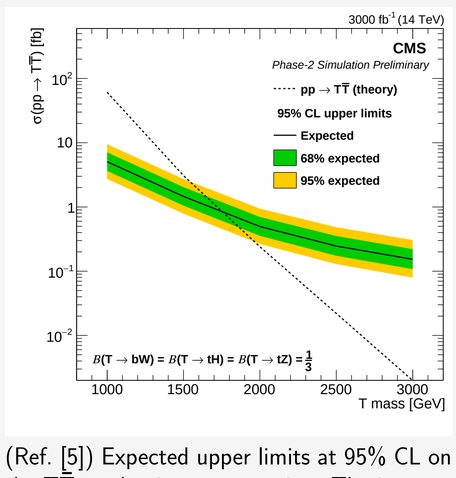
$$S_T = \sum_{jets} |\vec{p}_T^{\,jets}| + p_T^{miss} + p_T^{lepton}$$



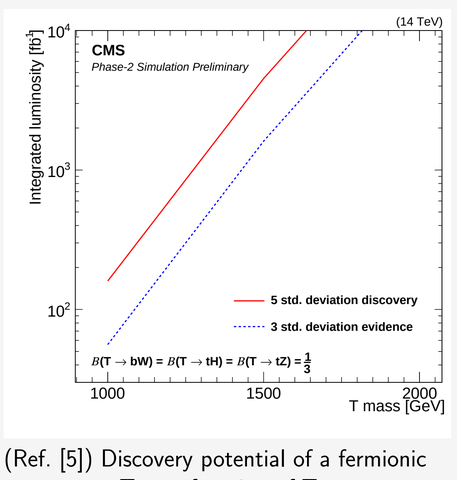
(Ref. [5]) Distributions in S_T for signal and background processes.



(Ref. [5]) The expected discovery significances as a function of integrated luminosity at the HL-LHC.



(Ref. [5]) Expected upper limits at 95% CL on the $T\bar{T}$ production cross section. The inner (green) and the outer (yellow) bands indicate the regions containing 68 and 95%, respectively, of the distribution of limits expected under the background-only hypothesis.



(Ref. [5]) Discovery potential of a fermionic top partner T as a function of T mass versus integrated luminosity. The blue dashed and red solid lines represent discoveries at expected significances of three and five standard deviations, respectively.

- T quark with m_T <1750 GeV is expected to be excluded at 95% CL
- T quark with m_T <1440 GeV can be discovered at the HL-LHC with a significance of five std. deviations.

References

[1] K. Agashe, R. Contino, and A. Pomarol, "The minimal composite higgs model," *Nucl. Phys. B*, vol. 719, p. 165, 2005.

[2] M. Perelstein, "Little higgs models and their phenomenology," *Prog. Part. Nucl. Phys.*, vol. 58, p. 247, 2007.

[3] S. P. Martin, "Extra vector-like matter and the lightest Higgs scalar boson mass in low-energy supersymmetry," *Phys. Rev. D*, vol. 81, p. 035004, 2010.

[4] A. M. Sirunyan *et al.*, "Search for a vector-like quark T → tH via the diphoton decay mode of the Higgs boson in proton-proton collisions at $\sqrt{s} = 13$ TeV," *JHEP*, vol. 09, p. 057, 2023.

[5] CMS Collaboration, "Search for a vector-like quark T decaying to bW, tZ, tH in the single lepton final state at the HL-LHC," CMS-PAS-FTR-22-002, CERN, Geneva, 2022.