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STUDY ON THE DISCOVERY POTENTIAL OF ALL-HADRONIC SEARCHES FOR VECTOR-LIKE QUARKS AT FUTURE COLLIDERS

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Introduction and Aim. The discovery of a 125 GeV scalar boson at the Large Hadron Collider (LHC) with the ATLAS and CMS experiments in 2012 is a resounding success of modern particle physics. However, our current understanding of the Standard Model is incomplete; some of its weaknesses include the lack of explanation of the various energy hierarchies in the theory, as well as a self-consistent explanation of the mass of the newly discovered particle. The 125 GeV scalar boson, so far, is compatible with the electroweak symmetry breaking properties of the Brout-Englert-Higgs mechanism, and no significant evidence of physics beyond the Standard Model has been observed to-date. Yet, the question regarding the fundamental nature of the particle remains unanswered.[1, 2]

Many extensions of the Standard Model predict the 125 GeV scalar boson is a composite particle, more specifically a pseudo-Nambu-Goldstone boson, of a symmetry broken at a higher energy than currently accessible to LHC data. Vector-like-quarks (VLQs: T/B/Y/X) are an immediate consequence of composite-Higgs models whose masses are not derived from its interactions with the Higgs field, and hence are not excluded from current measurements of the 125 GeV scalar boson. Evidence of VLQs would imply structure of the newly discovered 125 GeV scalar boson and would lead the field into a new direction of exploration, and a deeper understanding of the natural world.[3]

The LHC, as a hadron collider, generates an enormous hadronic background, making leptonic tagging attractive for cleaner event selection. However, doing so leaves out the large hadronic branching fraction of the decaying particles (T/B $\rightarrow$ W/Z/H+t/b). These channels are complementary to each other, and all should be investigated. For this Letter of Interest we will focus on motivating the fully hadronic channel, which benefits from a large production cross section, but suffers from large QCD backgrounds. To distinguish the signatures from light jet backgrounds, we use jet substructure identification with artificial intelligence tools that we are currently utilizing in the CMS experiment.

Context and Past Searches. At the Tevatron, searches for new quarks focused mainly on massive 4th generation chiral-type quarks, with similar decay channels to T and B VLQs. Before the Higgs discovery, there was quite some interest in new, massive quarks.[4][5] With the discovery of the Higgs, however, the parameter space for a 4th generation has been severely restricted.

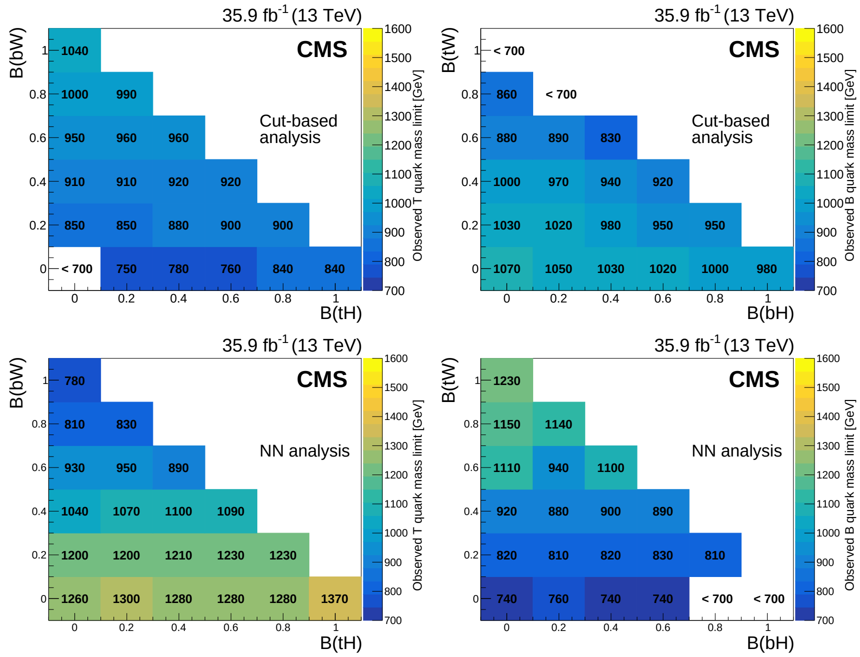

FIGURE 1. Observed mass exclusion limits at 95% confidence level for example combinations of T (left) and B (right) quark branching fractions, in a cut-based analysis (upper) and a neural-network-based analysis (lower).[7]

At the LHC, both ATLAS and CMS have dedicated searches for VLQs in all-hadronic channels, as well as with single and two leptons.[6, 7] The search strategies in both LHC collaborations have evolved since Run 1: early results relied on cut-and-count analyses characterized by a series of physically motivated selections (cuts) to define kinematic regions where the observed data (count) was expected to be signal-rich, later results (including those currently under development) use more aggressive boosted-object tagging techniques that utilizes the performance gains of Machine Learning (ML) algorithms, such as boosted decision trees and neural-networks, to identify possible signal.

Looking Forward to Future Colliders. The future of the energy frontier will bring higher luminosities to LHC energies and with it more data, but the possibilities of higher energy colliders such as the Super Proton Proton Collider (SPPC) and Future Circular Collider (FCC) are possibly more exciting. VLQ searches not only benefit from an increase in luminosity/data, but their pair-production cross-section are significantly enhanced by an increase in center-of-mass collision energy.[8] We propose to study the discovery potential of all-hadronic searches for VLQs at various center-of-mass energies of future colliders in order to better understand the impact of the colliding energy choices on the future of particle physics.

Study Strategy and Resources Needed. To evaluate the reach of future colliders, we propose to extrapolate current CMS-style searches to the HL-LHC. If possible, we would also propose to contrast analyses at the various FCC and SPPC energy benchmarks, as well as to use simple cut-and-count methods to compare against more sophisticated ML approaches. Comparing the former informs us of baseline improvements due to the colliding environment, whereas the latter can help illustrate the potential gains that can be achieved by investing in novel algorithm development to use in analyses. Since the authors of this Letter are developers of the Boosted Event Shape Tagger algorithm, we will likely use this approach as a guideline for our Snowmass tagger.[9]

In order to perform the studies, we will need to generate MC samples of VLQ benchmarks (T/B $2-10\ TeV$) and the typical background processes at a hadron collider (high-pT QCD, V+jets, ttbar, ttH). In order to train a ML-based tagger for the study, we would need additional, independent simulations of processes enriched in the boosted-objects tagged: Z'→bb/tt/WW/ZZ, high-pt QCD. For the training, the production mechanism is of secondary importance; what is crucial is that there are enough statistics to fit a robust ML-model (~1M jets with pT of $2-10\ TeV$ per object type would be ideal). In terms of the event information needed, we ask to have jets and their constituent information (Particle-Flow candidates, or truth particle ID + eta/phi/pt), as well as secondary-vertex information of the jet constituents for b-hadron tagging.

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