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Probing Single Production of Vector-Like T Quarks through the $T \to H^+ b$ Decay Mode with $H^+ \to tb$ at the HL-LHC

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We study the single production and decay of a vector-like top quark (T) (VLT) with charge +2/3 in the context of the Two Higgs Doublet Model Type II (2HDM-II), extended by a vector-like quark (VLQ) doublet (TB). Our focus is on the decay mode where the T quark decays into a charged Higgs boson (H^+) and a bottom quark, followed by the subsequent decay of H^+ into a top and bottom quark. We specifically examine the collider process $pp \to qg \to T^+\bar{b}j \to H^+b\bar{b}j \to W^+b\bar{b}j \to 1\ell + 4b + 1j + \not{E}_T$, resulting in final states with multiple bottom quarks, a single jet, one lepton, and missing transverse energy. Our results demonstrate that this channel offers a promising opportunity for discovering both the VLT and the charged Higgs boson, providing strong detection potential across a broad parameter space.

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1. Introduction

The discovery of vector-like quarks (VLQs), heavy spin-1/2 fermions that share identical electroweak quantum numbers for their left- and right-handed couplings, would provide compelling evidence for physics beyond the Standard Model (BSM). Although absent in the Standard Model (SM), VLQs naturally arise in many BSM scenarios and are pivotal in extending our understanding of fundamental interactions.

Another cornerstone of BSM physics is the search for charged Higgs bosons ($H^\pm$), which are predicted by extended Higgs sectors such as the Two Higgs Doublet Model Type II (2HDM-II). Despite extensive efforts by the ATLAS and CMS experiments at the Large Hadron Collider (LHC), direct evidence for $H^\pm$ remains elusive. However, substantial regions of the parameter space have been excluded, maintaining the search for $H^\pm$ as an active frontier of exploration.

Previous works [1–3] have established a comprehensive framework for analyzing VLQs, including the vector-like top (T), bottom (B), and exotic X and Y quarks, within the 2HDM-II. These studies have focused on their decays into exotic scalar bosons (H, A, $H^\pm$) and their impact on B-physics observables [4]. Additionally, production mechanisms for VLQs have been extensively studied, ranging from pair production at the LHC [5] to single production at $e\gamma$ colliders [6].

In this work, we investigate the single production of the vector-like top quark (VLT) at the High-Luminosity LHC (HL-LHC). Specifically, we analyze the process $pp \to qg \to T^+b\bar{b}j \to H^+b\bar{b}j \to W^+b\bar{b}j \to 1\ell + 4b + 1j + \not{E}_T$ [7], demonstrating its potential as a discovery channel for $H^\pm$ via VLQ decays and its capacity to probe new regions of the parameter space in BSM physics.

2. The 2HDM-II with (TB) Framework

We consider the 2HDM-II framework extended by a vector-like quark doublet (TB), where the charged Higgs boson ($H^\pm$) interacts with the vector-like top quark (T) and the W boson. The detailed Yukawa Lagrangian and associated interactions governing this framework are provided in Refs. [3, 4].

3. Numerical Analysis

We perform a detailed numerical scan of the parameter space to analyze the final state $W^+b\bar{b}b\bar{b}j$. The methodology follows Ref. [7], and all parameter points are validated against theoretical and experimental constraints, including electroweak precision observables (EWPOs) [4, 8]. This allows us to identify regions of parameter space with substantial signal cross sections while remaining consistent with current experimental data.

Figure 1 highlights the branching ratios ($\mathcal{BR}$) of $H^\pm \to tb$ and $T \to H^\pm b$. At low $\tan\beta$, $\mathcal{BR}(H^\pm \to tb)$ reaches nearly 100%, indicating that the charged Higgs predominantly decays into a top quark and a bottom quark. Similarly, $\mathcal{BR}(T \to H^\pm b)$ can reach up to 80% for intermediate $\tan\beta$, enhancing the overall signal cross section and enabling a deeper exploration of BSM physics.

To illustrate the potential for discovery, we select three benchmark points (BPs) with notable cross sections for different m_T values. Using Monte Carlo simulations, we evaluate the signal against

SM backgrounds and calculate the expected discovery (5σ) and exclusion (2σ) significances, as detailed in Ref. [7].

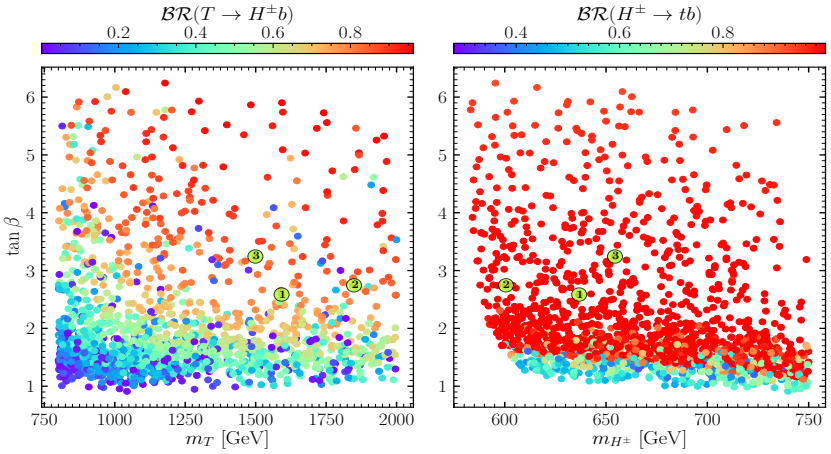

Figure 1: Branching ratios $\mathcal{BR}(T \to H^+ b)$ as a function of m_T and $\tan\beta$ (left) and $\mathcal{BR}(H^{\pm} \to tb)$ (right) plotted over the ($m_{H^{\pm}}$, $\tan\beta$) plane.

Table 1 summarizes the HL-LHC's potential to exclude or discover T quarks across a mass range of $[1000\ \text{GeV}, 2000\ \text{GeV}]$, showcasing the collider's sensitivity to VLQ properties and their interactions with $H^{\pm}$.

HL-LHC $\sqrt{s}$ = 14 TeV, s_R^u = 0.05			
$s_R^d(\mathcal{L}\ \text{fb}^{-1})$	2σ Exclusion	$s_R^d(\mathcal{L}\ \text{fb}^{-1})$	5σ Discovery
$s_R^d(200)$	$[0.16, 0.2]$	$s_R^d(800)$	$[0.165, 0.2]$
$s_R^d(500)$	$[0.12, 0.2]$	$s_R^d(1000)$	$[0.155, 0.2]$
$s_R^d(1000)$	$[0.10, 0.16]$	$s_R^d(2000)$	$[0.125, 0.2]$
$s_R^d(2000)$	$[0.08, 0.13]$	$s_R^d(3000)$	$[0.11, 0.19]$

Table 1: Exclusion and discovery potential for T quarks at the HL-LHC.

4. Conclusion

This study identifies the decay channel $T \to H^{\pm} b$ as a promising probe of BSM physics within the 2HDM-II+TB framework. Our analysis demonstrates the HL-LHC's significant sensitivity to the properties of VLQ T quarks and charged Higgs bosons $H^{\pm}$, enabled by enhanced cross sections and branching ratios.

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