

Nonstandard decays of vectorlike top partners in a two-Higgs-doublet model at the HL-LHC

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Extensions of the Standard Model featuring both an enlarged scalar sector and vector-like fermions arise naturally in a wide class of well-motivated theoretical frameworks. In such scenarios, vectorlike quarks (VLQs) can exhibit nonstandard decay modes involving additional Higgs states, giving rise to distinctive collider signatures that remain largely unexplored by existing experimental searches. We investigate the prospects of probing this possibility at the high-luminosity Large Hadron Collider (HL-LHC) through the decay of vector-like top partner (T) to charged Higgs ($H^\pm$) followed by the decay, $H^\pm \rightarrow \tau\nu$, producing a final state containing two tau leptons, two b jets, and missing transverse energy. A model-independent collider analysis is performed using global kinematic observables constructed from visible objects and the missing transverse momentum vector to suppress the dominant backgrounds. Polarization-sensitive observables built from the hadronic τ decay products are also examined as complementary probes of the spin-0 origin of the τ leptons. The expected discovery sensitivity is evaluated using the Asimov significance for an integrated luminosity of 3 ab^{-1} at $\sqrt{s} = 14 \text{ TeV}$. Our results demonstrate that the $2\tau + 2b + \cancel{E}_T$ (where $\cancel{E}_T$ is the missing transverse energy) channel provides a promising and largely orthogonal avenue to search for non-standard VLQ decays in extended Higgs sectors, with discovery-level sensitivity achievable for VLQ masses up to approximately 1.9 TeV.

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I. INTRODUCTION

The discovery of the Higgs boson at the Large Hadron Collider (LHC) [1,2] has established the Brout–Englert–Higgs mechanism as the origin of electroweak symmetry breaking (EWSB). Yet the precise structure of the Higgs sector remains only partially explored, and there is no compelling theoretical reason for it to be minimal. Extensions of the Standard Model (SM) Higgs sector provide a well-motivated framework for probing deviations from the SM predictions and for addressing open questions, such as the origin of fermion mass hierarchies, the stability of the electroweak vacuum, and the possibility of a strong first-order electroweak phase transition relevant to baryogenesis.

Among the simplest and most thoroughly studied SM extensions is the 2-Higgs Doublet Model (2HDM) [3,4],

which augments the SM by a second $SU(2)_L$ doublet while preserving consistency with the precision data through the alignment limit [5]. Beyond the SM-like Higgs boson h , the physical spectrum of the 2HDM contains two additional neutral states—a CP -even scalar H and a CP -odd pseudoscalar A —and a pair of charged Higgs bosons $H^\pm$. The charged Higgs state is of particular phenomenological interest because it has no SM analogue and its observation would constitute unambiguous evidence for physics beyond the SM (BSM).

Vectorlike quarks (VLQs) are a theoretically natural and well-motivated extension of the SM fermion sector. Their gauge-invariant masses are not generated by Yukawa couplings and are therefore free from the fine-tuning constraints that afflict chiral fermion masses. VLQs arise ubiquitously in many extensions of the SM such as composite Higgs models, little Higgs models, extradimensional scenarios, etc. [6–12], and their mixing with the SM quarks can substantially modify the phenomenology of the Higgs sector. Importantly, when VLQs couple to an extended Higgs sector, new decay channels open up that have no analog in the minimal setup [13–42]. Such exotic VLQ decays—proceeding through additional neutral or charged Higgs states—have been the subject of growing

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theoretical interest [43–47], yet current experimental searches remain largely insensitive to them.

Current LHC searches constrain the mass of the lightest VLQ partner of the top-quark (denoted by T) up to approximately 1.3–1.5 TeV under SM-like decay assumptions [48,49], i.e., decays into Wb , Zt , and ht . When such a VLQ couples appreciably to a charged scalar, the exotic decay mode $T \rightarrow H^\pm b$ can become comparable to or dominant over the SM-like channels across broad regions of parameter space, rendering the above exclusion limits inapplicable. This motivates a dedicated study of VLQ signatures (of a top-quark companion) mediated by extended Higgs sector states. (See [23] for the case of neutral Higgs bosons.)

In this work, we investigate the $2\tau + 2b + E_T$ final state arising from pair-produced T in a type-II 2HDM. The topology proceeds through the cascade decay, $T\bar{T} \rightarrow (H^+b)(H^-\bar{b}) \rightarrow (\tau^+\nu_\tau b)(\tau^-\bar{\nu}_\tau \bar{b})$ (hereafter $\nu_\tau \equiv \nu$), exploiting the enhanced $H^\pm \rightarrow \tau\nu$ branching ratio (BR) characteristic of large $\tan\beta$ (defined in Sec. II) in type-II models. The analysis is formulated in a model-independent manner. The signal yield is factorized as the product of the $pp \rightarrow T\bar{T}$ production cross section and the effective cascade decay rate $\mathcal{B} \equiv \text{BR}(T \rightarrow H^\pm b) \times \text{BR}(H^\pm \rightarrow \tau\nu)$, so that results can be interpreted in any scenario involving a heavy colored fermion decaying through a charged Higgs state. The signal process is illustrated in Fig. 1.

To the best of our knowledge, the $2\tau + 2b + E_T$ final state arising from the cascade $T\bar{T} \rightarrow (H^+b)(H^-\bar{b}) \rightarrow (\tau^+\nu_\tau b)(\tau^-\bar{\nu}_\tau \bar{b})$ has not been previously studied in the context of VLQ pair production, and the present work constitutes the first dedicated collider analysis of this topology at the HL-LHC. The results are presented in a model-independent framework, enabling direct reinterpretation in any scenario involving a heavy colored fermion decaying through a charged scalar state.

We assess the discovery and exclusion reach of the above-mentioned process at the high-luminosity LHC

(HL-LHC) ($\mathcal{L} = 3 \text{ ab}^{-1}$, $\sqrt{s} = 14 \text{ TeV}$) through a cut-based analysis employing global kinematic observables. The complementary role of τ polarization properties in distinguishing the signal from the SM backgrounds is also discussed.

The paper is organized as follows. The theoretical framework is described in Sec. II. The collider analysis strategy is presented in Sec. III. The τ lepton polarization observables are discussed in Sec. IV. The main results are presented in Sec. V while conclusions are given in Sec. VI.

II. THEORETICAL FRAMEWORK

A. The 2HDM

We consider a CP -conserving 2HDM with a softly broken discrete $\mathbb{Z}_2$ symmetry. The scalar potential involving the two $SU(2)_L$ doublets (Φ_1, Φ_2) reads [3,4],

$$V(\Phi_1, \Phi_2) = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 (\Phi_1^\dagger \Phi_2 + \text{H.c.}) + \frac{\lambda_1}{2} (\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2} (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1) (\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2) (\Phi_2^\dagger \Phi_1) + \frac{\lambda_5}{2} [(\Phi_1^\dagger \Phi_2)^2 + \text{H.c.}], \quad (1)$$

where all parameters are real. Each doublet acquires a vacuum expectation value (VEV), $\langle \Phi_i \rangle = (0, v_i/\sqrt{2})^T$ for $i = 1, 2$, with v_1 and v_2 the VEVs of Φ_1 and Φ_2 , respectively. Working in the Higgs basis (H_1, H_2) in which only one doublet acquires a nonzero VEV,

$$H_1 = \begin{pmatrix} G^+ \\ \frac{v + \phi_1^0 + iG^0}{\sqrt{2}} \end{pmatrix}, \quad H_2 = \begin{pmatrix} H^+ \\ \frac{\phi_2^0 + iA}{\sqrt{2}} \end{pmatrix}, \quad (2)$$

where $G^{0,\pm}$ are the Goldstone bosons absorbed by the Z and $W^\pm$ whereas $H^\pm$ is the physical charged Higgs state and A is the CP -odd neutral one. The physical CP -even states arise from the mixing

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} \sin(\beta - \alpha) & \cos(\beta - \alpha) \\ \cos(\beta - \alpha) & -\sin(\beta - \alpha) \end{pmatrix} \begin{pmatrix} \phi_1^0 \\ \phi_2^0 \end{pmatrix}, \quad (3)$$

where $\tan\beta = v_2/v_1$ with v_1 and v_2 the VEVs of Φ_1 and Φ_2 defined above, with $v = \sqrt{v_1^2 + v_2^2} = 246 \text{ GeV}$, and the mixing angle α diagonalizes the CP -even mass matrix. In the alignment limit, $\sin(\beta - \alpha) \rightarrow 1$, the lighter state h reproduces the SM Higgs couplings, consistent with current LHC measurements [50,51]. In the type-II 2HDM, down-type quarks and charged leptons couple exclusively to Φ_1 whereas up-type quarks couple to Φ_2 . As a consequence, the $H^\pm \tau\nu$ Yukawa coupling is proportional to $m_\tau \tan\beta$, making $\text{BR}(H^\pm \rightarrow \tau\nu)$ particularly large at high $\tan\beta$ —a regime that is phenomenologically well

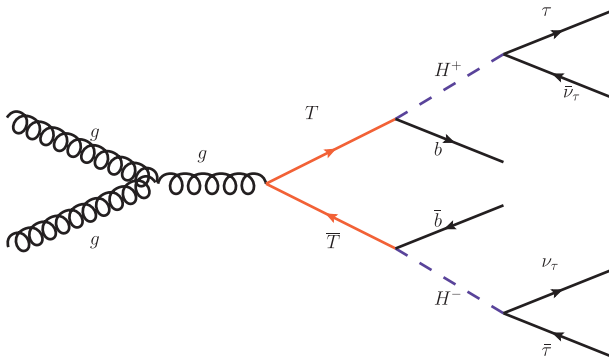


FIG. 1. Representative Feynman diagram for the signal process $pp \rightarrow T\bar{T} \rightarrow (H^+b)(H^-\bar{b}) \rightarrow (\tau^+\nu_\tau b)(\tau^-\bar{\nu}_\tau \bar{b})$, yielding the $2\tau + 2b + E_T$ final state studied in this work.

motivated and experimentally less constrained for $M_{H^\pm}$ above the top-quark threshold.

B. VLQs as top partners

We extend the type-II 2HDM by a singlet up-type VLQ pair (T_L, T_R) with electric charge $Q = 2/3$ (henceforth, top-VLQ). The most general renormalizable Yukawa Lagrangian involving the third-generation quark sector is

$$-\mathcal{L}_Y^\Pi \supset \{y_t \bar{Q}_L^0 \tilde{H}_2 t_R^0 + y_T \bar{Q}_L^0 \tilde{H}_2 T_R^0 + \xi_T \bar{Q}_L^0 \tilde{H}_1 T_R^0 + \tilde{\omega}_T M_T \bar{T}_L^0 t_R^0 + M_T \bar{T}_L^0 T_R^0 + \text{H.c.}\}, \quad (4)$$

where $Q_L^0 = (t_L^0, b_L^0)^T$, t_R^0 is the third-generation SM up-type singlet, and $\tilde{H}_i = i\tau_2 H_i^*$. The off-diagonal mass term $\tilde{\omega}_T$ can be removed by a field redefinition in the right-handed sector, leaving Eq. (4) with adjusted parameters [52]. After EWSB, the top-VLQ mass matrix in the weak-interaction basis (t_L^0, T_L^0) is

$$\mathcal{M} = \begin{pmatrix} \frac{y_t v}{\sqrt{2}} & \frac{\xi_T v}{\sqrt{2}} \\ 0 & M_T \end{pmatrix}, \quad (5)$$

which is diagonalized by a biunitary transformation $U_L \mathcal{M} U_R^\dagger = \mathcal{M}_d$, yielding the physical mass eigenstates

$$\begin{pmatrix} t \\ T \end{pmatrix}_{L,R} = \begin{pmatrix} \cos \theta_{L,R} & -\sin \theta_{L,R} \\ \sin \theta_{L,R} & \cos \theta_{L,R} \end{pmatrix} \begin{pmatrix} t^0 \\ T^0 \end{pmatrix}_{L,R}. \quad (6)$$

The left- and right-handed mixing angles are given by,

$$\tan(2\theta_L) = \frac{4m_t M_T}{2M_T^2 - 2m_t^2 - \xi_T^2 v^2}, \quad (7)$$

$$\tan(2\theta_R) = \frac{2\sqrt{2}\xi_T m_t v}{2M_T^2 + 2m_t^2 - \xi_T^2 v^2}. \quad (8)$$

After diagonalization, the physical T state couples to the charged Higgs boson through a mixing-angle-suppressed $TbH^\pm$ vertex. The standard decay channels $T \rightarrow Wb$, $T \rightarrow Zt$, $T \rightarrow ht$ are always present. The same mixing also generates the nonstandard neutral-scalar modes $T \rightarrow Ht$ and $T \rightarrow At$, which compete with $T \rightarrow H^\pm b$ for the branching ratio. However, these neutral-scalar channels do not contribute to the $2\tau + 2b + E_T$ final state under study: the subsequent top decay $t \rightarrow Wb$ introduces additional jets or leptons from the W , populating busier final states distinct from our signal region. Any such competition for the BR is automatically absorbed into our model-independent treatment, since $\text{BR}(T \rightarrow H^\pm b)$ is kept as a free parameter within $\mathcal{B}$ rather than fixed to unity except in the optimistic $\mathcal{B} = 1$ benchmark of Sec. V. The nonstandard mode $T \rightarrow H^\pm b$ can become the dominant decay for sizable ξ_T and moderate $M_{H^\pm}/M_T$ ratio.

C. Model-independent signal parametrization

The signal cross section in the $2\tau + 2b + E_T$ channel can be parametrized as

$$\sigma_{\text{sig}} = \sigma(pp \rightarrow T\bar{T}) \times \text{BR}(T \rightarrow H^\pm b)^2 \times \text{BR}(H^\pm \rightarrow \tau\nu)^2. \quad (9)$$

Since the intermediate particles are not individually reconstructible at the detector level, the analysis is sensitive only to the product $\mathcal{B}^2 \equiv [\text{BR}(T \rightarrow H^\pm b) \times \text{BR}(H^\pm \rightarrow \tau\nu)]^2$. We therefore present results as contours of constant Asimov significance in the planes of $\{M_T, \mathcal{B}\}$ and $\{M_{H^\pm}, M_T\}$ (at $\mathcal{B} = 1$), enabling reinterpretation in any scenario in which a heavy color-triplet fermion (Q) undergoes the specific cascade $Q \rightarrow H^\pm q \rightarrow \tau\nu q$. We note that values of $\mathcal{B}$ approaching unity are realizable in well-defined regions of the Type-II 2HDM + VLQ parameter space. The standard decay channels $T \rightarrow Wb$, $T \rightarrow Zt$, $T \rightarrow ht$ arise from t - T mixing and are suppressed by $\sin^2 \theta_{L,R} \propto m_t^2/M_T^2$ at large M_T , whereas the $TbH^\pm$ coupling contains an independent Yukawa coupling ξ_T [Eq. (4)] that is a free parameter and can be large, making $\text{BR}(T \rightarrow H^\pm b)$ dominant for sizable ξ_T with $M_{H^\pm} < M_T - m_b$. For $\text{BR}(H^\pm \rightarrow \tau\nu)$: the $H^\pm \tau\nu$ Yukawa coupling is proportional to $m_\tau \tan\beta$ while the competing $H^\pm \rightarrow tb$ mode is proportional to $m_t \cot\beta$; for $\tan\beta \gtrsim 5$ –10, the tau mode dominates even above the top threshold [4], consistent with current LHC and Large Electron-Positron Collider (LEP) constraints [53–55]. The full $\mathcal{B}$ -plane results of Fig. 4 provide the sensitivity at all values $\mathcal{B} \in (0, 1]$, so the $\mathcal{B} = 1$ contour serves as an upper benchmark rather than the sole quoted result.

The leptonic decay $H^\pm \rightarrow \tau\nu$ is a distinctive feature of the type-II 2HDM at large $\tan\beta$, where the $H^\pm \tau\nu$ Yukawa coupling is enhanced by $m_\tau \tan\beta$, and this mode dominates over $H^\pm \rightarrow tb$ once $\tan\beta \gtrsim 2$ –3 for charged Higgs masses above the top-quark threshold [4]. The same topology can arise in other extended scalar sectors with a similar Yukawa structure, such as the type-X or flipped 2HDM variants, or in supersymmetric models where the lightest chargino decays through a stau. In scenarios where $H^\pm \rightarrow tb$, $W^{(*)}h$ and/or $W^{(*)}A$ dominate instead, the present results do not directly apply, and a dedicated analysis in those decay channels would be required.

III. COLLIDER ANALYSIS

A. Signal and background processes

The signal topology we consider here is as follows,

$$pp \rightarrow T\bar{T} \rightarrow (H^+ b)(H^- \bar{b}) \rightarrow (\tau^+ \nu_\tau b)(\tau^- \bar{\nu}_\tau \bar{b}). \quad (10)$$

This yields the $2\tau + 2b + E_T$ final state (Fig. 1). Both tau leptons are required to decay hadronically ($\tau \rightarrow \text{hadrons} + \nu_\tau$), giving two reconstructed hadronic

tau candidates τ_h in the detector. This mode has a combined BR of approximately 42% and benefits from efficient hadronic tau identification and b tagging at the LHC detectors. Signal samples are generated for a grid of benchmark mass points spanning $M_T \in [600, 2200]$ GeV and $M_{H^\pm} \in [200, 800]$ GeV. The $T\bar{T}$ production cross sections are evaluated at next-to-leading order (NLO) in QCD, consistent with available higher order calculations [56].

The dominant SM background processes considered are:

- (i) $t\bar{t}$ + jets, where each top decays as $t \rightarrow Wb$ with both W bosons decaying to $\tau\nu$, directly supplying the two b -jets, the two taus, and the missing energy that define the signal topology; this is the dominant background in the analysis.
- (ii) $t\bar{t}V$ associated production ($V = W, Z, H$), where the $t\bar{t}$ system already supplies the $2\tau + 2b + \cancel{E}_T$ topology while V contributes additional jets or missing energy; this constitutes the second-largest background.
- (iii) Single vector boson production ($Z \rightarrow \tau^+\tau^-$ or $W \rightarrow \tau\nu$) accompanied by jets. Despite the large inclusive cross section, the requirement of two genuine b -tagged jets strongly suppresses this background, owing to the small b -tagging and tau-misidentification rates for light- and heavy-flavor jets; this background is found to be negligible after selection.
- (iv) tW associated single-top production, where the b -jet from top decay and a second b -jet from gluon splitting, together with $\tau\nu$ from the W decays, can mimic the signal topology at a smaller rate than $t\bar{t}$.
- (v) tb associated single-top production, which naturally supplies two b -jets but only a single tau from $t \rightarrow Wb \rightarrow (\tau\nu)b$, making it subdominant relative to $t\bar{t}$ and tW .
- (vi) Diboson production (WW, ZZ) with jets, where $WW \rightarrow \tau^+\nu_\tau\tau^-\bar{\nu}_\tau$ or $ZZ \rightarrow \tau^+\tau^-\nu\bar{\nu}$ directly yield the $2\tau + \cancel{E}_T$ topology, with the two b -jets arising from gluon splitting. WZ + jets is omitted since it cannot efficiently populate the exactly-two- τ_h signal region: the accompanying W decay yields either an extra isolated lepton (rejected by the lepton veto) or a third tau (rejected by the exactly-two- τ_h requirement).

The higher-order cross sections used to derive K factors for each background are listed in Table I. All backgrounds are normalized to these higher-order predictions throughout the analysis. The K factors account for the ratio of the higher-order cross sections to the corresponding leading-order (LO) predictions and are applied uniformly after event selection.

B. Event generation and preselection cuts

Signal and background events are generated with MadGraph5_aMC [62] at LO accuracy in QCD,

TABLE I. Higher-order inclusive cross sections for the dominant SM background processes at $\sqrt{s} = 14$ TeV, prior to decay and event selection. The QCD accuracy of each calculation is indicated in the final column. These values are used to derive the K -factors applied to the cross section obtained at the LO.

Background process	σ (pb)	Order
VV + jets [57]		
WW + jets	124.31	NLO
ZZ + jets	17.72	NLO
Single top [58]		
tW	83.10	N ² LO
$t\bar{t}$ [59]		
$t\bar{t}$ + jets	988.57	N ³ LO
$t\bar{t}V$ [60,61]		
$t\bar{t}Z$	1.05	NLO + N ² LL
$t\bar{t}W$	0.65	NLO + N ² LL
$t\bar{t}H$	0.64	NNLO + NNLL + EW

interfaced with Pythia 8 [63] for parton showering, hadronization, and underlying-event modeling. Jets are clustered with the anti- k_T algorithm [64] using radius parameter $R = 0.4$ as implemented in FastJet [65]. Detector effects are modelled with Delphes3 [66] using the ATLAS detector card.

The baseline object selection requires exactly two hadronic tau candidates (τ_h) satisfying $p_T > 30$ GeV and $|\eta| < 2.5$, and at least two b -tagged jets with $p_T > 30$ GeV and $|\eta| < 2.5$. Tau candidates overlapping with b jets within $\Delta R < 0.4$ are discarded. Events containing isolated electrons or muons with $p_T > 20$ GeV are vetoed to suppress the dileptonic $t\bar{t}$ contribution.

C. Kinematic observables and event selection

Invariant-mass variables involving missing transverse energy require special care at a hadron collider, since the longitudinal momentum of the neutrino system is unmeasured and a fully Lorentz-invariant four-momentum cannot be assigned to E_T on an event-by-event basis. We resolve this by constructing an effective four-vector,

$$p_{\cancel{E}_T}^\mu = (\cancel{E}_x, \cancel{E}_y, 0, \cancel{E}_T), \quad (11)$$

where $\cancel{E}_{x,y}$ are the Cartesian components of the missing momentum and $\cancel{E}_T = |\vec{p}_T|$. This vector is combined with the four-momenta of visible objects to define multi-body effective invariant masses $\text{IM}(\cancel{E}_T, X_1, X_2, \dots)$. Although these quantities are not strictly Lorentz-invariant, they are well-defined and experimentally computable, and are found to provide strong signal-to-background discrimination.

The primary kinematic discriminants employed in the analysis are:

- (i) $\cancel{E}_T$: missing transverse energy, sensitive to the energetic neutrinos from $H^\pm \rightarrow \tau\nu$;
- (ii) S_T : scalar sum of the transverse momenta of all reconstructed objects including $\cancel{E}_T$, characterizing the overall event energy scale;

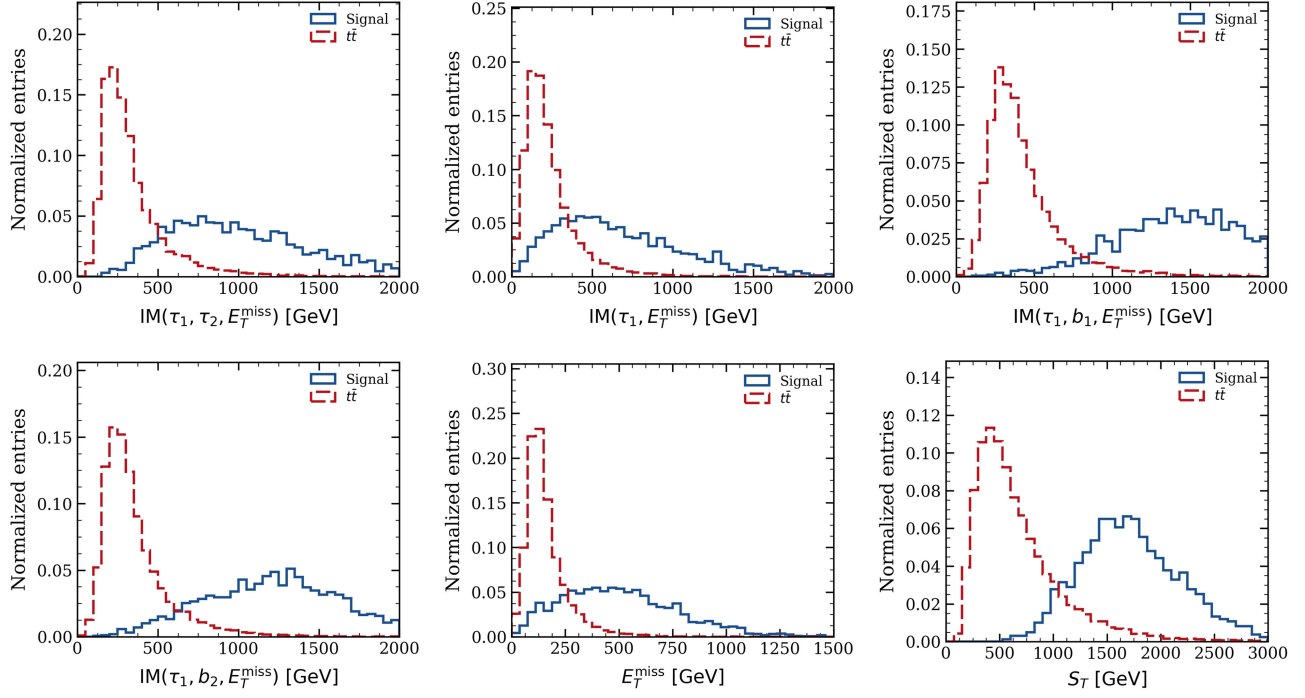


FIG. 2. Normalized distributions of the primary kinematic discriminants for the signal benchmark with $M_T = 1500$ GeV and $M_{H^\pm} = 500$ GeV, and for the dominant $t\bar{t}$ background. *Top row* (left to right): $\text{IM}(E_T, \tau_{j1}, \tau_{j2})$, $\text{IM}(E_T, \tau_{j1})$, and $\text{IM}(E_T, \tau_{j1}, b_{j1})$. *Bottom row*: $\text{IM}(E_T, \tau_{j1}, b_{j2})$, E_T , and S_T . The missing transverse energy four-vector entering all $\text{IM}(E_T, \dots)$ variables is constructed using the effective four-vector of Eq. (11). Signal distributions exhibit considerably harder spectra than the $t\bar{t}$ background across all observables, driven by the large invariant mass scales of the cascade decay.

- (iii) $\text{IM}(\cancel{E}_T, \tau_{j1}, \tau_{j2})$: effective invariant mass of the two leading tau jets combined with $\cancel{E}_T$;
- (iv) $\text{IM}(E_T, \tau_{j1}, b_{j1})$ and $\text{IM}(\cancel{E}_T, \tau_{j1}, b_{j2})$: three-body invariant masses sensitive to the cascading mass scale of the signal;
- (v) $\text{IM}(\cancel{E}_T, \tau_{j1})$: two-body transverse masslike observable.

We emphasize that every invariant-mass variable of the form $\text{IM}(\cancel{E}_T, \dots)$ listed above, both in the selection criteria and in the distributions shown below, is constructed using the effective missing-momentum four-vector defined in Eq. (11).

Normalized distributions of these observables are shown in Fig. 2 for the signal benchmark with $M_T = 1500$ GeV, $M_{H^\pm} = 500$ GeV, and for the dominant $t\bar{t}$ background. The signal exhibits consistently harder spectra across all variables, driven by the large invariant mass scales M_T and $M_{H^\pm}$ of the cascade. This kinematic separation provides the basis for the cut-based selection described below.

Based on the discriminating power of the observables described above, a sequential cut-based selection is applied, optimized to maximize the Asimov significance for a benchmark signal with $M_T = 1500$ GeV and $M_{H^\pm} = 500$ GeV. The selection criteria are summarized in Table II. The global $\cancel{E}_T$ and S_T requirements (C1 and C2) efficiently reduce the multijet and low-mass

TABLE II. Sequential event selection criteria applied in the cut-based analysis. The invariant-mass variables involving $\cancel{E}_T$ are constructed using the effective four-vector of Eq. (11). Cuts are ordered by their approximate discriminating power, progressing from global energy-scale requirements (C1, C2) to topology-specific invariant-mass requirements (C3).

Label	Selection criterion
C1	$\cancel{E}_T > 350$ GeV
C2	$S_T > 1200$ GeV
C3	$\text{IM}(\cancel{E}_T, \tau_{j1}, \tau_{j2}) > 500$ GeV $\text{IM}(\cancel{E}_T, \tau_{j1}, b_{j1}) > 1100$ GeV $\text{IM}(\cancel{E}_T, \tau_{j1}, b_{j2}) > 700$ GeV $\text{IM}(\cancel{E}_T, \tau_{j1}) > 300$ GeV

backgrounds, while the multibody invariant-mass cuts (C3) further exploit the distinctive heavy-particle topology of the signal. The invariant-mass variables in C3 are constructed using the effective four-vector of Eq. (11).

D. Statistical analysis

The expected discovery significance is evaluated using the Asimov formalism [67]. The Asimov Z score is computed from the profile likelihood ratio including a Gaussian constraint on the background normalization,

$$Z_A = \left[2(s+b) \ln \left(\frac{(s+b)(b+\sigma_b^2)}{b^2 + (s+b)\sigma_b^2} \right) - \frac{2b^2}{\sigma_b^2} \ln \left(1 + \frac{s\sigma_b^2}{b(b+\sigma_b^2)} \right) \right]^{1/2}, \quad (12)$$

where s and b are the total expected numbers of signal and background events surviving all selections, respectively, and σ_b is the absolute systematic uncertainty on the background normalization. A flat uncertainty of $\sigma_b/b = 10\%$ is assumed throughout, reflecting the combined effect of theoretical uncertainties on the background cross sections as well as experimental uncertainties on tau identification and b -tagging efficiencies. A significance of $Z_A \geq 5(2)$ is adopted as the discovery (exclusion) threshold.

IV. TAU POLARIZATION AS A COMPLEMENTARY PROBE

The polarization state of the tau leptons encodes information about the spin of their parent particle that is not captured by the kinematic observables used in the event selection. In the present signal, taus originate from the decay of the spin-0 charged Higgs boson, $H^\pm \rightarrow \tau^\pm \nu_\tau$. The chiral structure of the $H^\pm \tau \nu$ Yukawa coupling implies that τ^+ (τ^-) produced in this decay are in right-handed (left-handed) helicity eigenstates, i.e., $\mathcal{P}_\tau = +1$. This is opposite to the case of $W^\pm \rightarrow \tau^\pm \nu_\tau$ decays via the transverse gauge component, where the purely $V-A$ electroweak coupling forces τ^+ into a left-handed state ($\mathcal{P}_\tau = -1$). We note that the longitudinal (Goldstone) component of the W boson couples to $\tau \nu$ through a scalar Yukawa-type vertex of the same chiral structure as the $H^\pm \tau \nu$ coupling, and would therefore yield $\mathcal{P}_\tau = +1$ like the signal. However, this contribution to $\Gamma(W \rightarrow \tau \nu)$ is suppressed relative to the transverse gauge contribution by $(m_\tau/M_W)^2 \sim 5 \times 10^{-4}$, and is therefore entirely negligible. The dominant $t\bar{t}$ background thus produces taus with $\mathcal{P}_\tau = -1$ via the transverse W component, opposite to the signal, providing a powerful handle for discrimination that is absent from the kinematic selection of Sec. III.

The polarization of the tau can be accessed experimentally through the energy and angular distributions of its visible hadronic decay products. For one-prong decays through the π and ρ modes, we construct the polarization-sensitive variables R_1 and R_2 , defined as normalized ratios of visible momenta of the decay products [68,69]. These variables are directly accessible from the reconstructed constituents of the tau jet, making them suitable for use in an experimental analysis.

The two-dimensional distributions in the (R_1, R_2) plane for the signal and the dominant backgrounds are shown in Fig. 3, in both 3D histograms and 2D heatmap representations. The signal accumulates preferentially at high values of R_1 , consistent with the right-handed polarization from scalar $H^\pm$ decay. The $t\bar{t}$ background, where taus are

produced via left-handed W decays, is concentrated at low R_1 . The $Z(\rightarrow \tau\tau) + \text{jets}$ background falls between the two, as the Z boson couples to both tau helicity states. The clear separation visible in both representations confirms that R_1 and R_2 carry discriminating power that is complementary to the kinematic observables.

Although R_1 and R_2 are not incorporated into the cut-based selection of Sec. III, the clear separation visible in Fig. 3 demonstrates that they carry independent discriminating power. We do not include them in the baseline selection because the kinematic cuts already reduce the background to $\mathcal{O}(30)$ events, leaving the analysis signal-limited where additional background rejection yields diminishing returns. However, these observables become particularly valuable if hints of a signal are observed: since R_1 and R_2 encode the spin-0 origin of the taus, they can serve as a powerful tool for validating the signal hypothesis and distinguishing it from backgrounds with different polarization structure. Their inclusion in a future multivariate analysis could further improve the discovery reach, particularly at large M_T where kinematic discrimination alone may be insufficient.

V. RESULTS

We present the expected discovery and exclusion reach of the HL-LHC in the $2\tau + 2b + \cancel{E}_T$ channel, evaluated from the Asimov significance of Eq. (12) after applying the full event selection of Table II. The event yields in Table III correspond to two representative mass points within this reach. Results are expressed as 2σ (exclusion) and 5σ (discovery) contours in two complementary planes of the parameter space, shown in Fig. 4.

A. The M_T - $\mathcal{B}$ plane

The left panel of Fig. 4 shows significance contours in the plane of M_T versus the effective cascade decay rate $\mathcal{B} \equiv \text{BR}(T \rightarrow H^\pm b) \times \text{BR}(H^\pm \rightarrow \tau \nu)$, for a fixed charged Higgs mass of $M_{H^\pm} = 500$ GeV. The light-blue band between the two contours identifies the parameter region observable at 2σ but not yet at the 5σ discovery threshold; the red region lying below the 2σ contour is not accessible at this luminosity. Both contours terminate at $\mathcal{B} = 1$, which corresponds to the physical upper bound of the BR product.

The 5σ discovery contour reaches $M_T \approx 1.9$ TeV for $\mathcal{B} = 1$, while the 2σ exclusion extends to $M_T \approx 2.05$ TeV. For moderate BRs, the required $\mathcal{B}$ rises steeply with M_T as the $T\bar{T}$ production cross section falls, so the channel retains sensitivity primarily for $M_T \lesssim 1.9$ TeV at 5σ and $M_T \lesssim 2.0$ TeV at 2σ .

B. The $M_{H^\pm}$ - M_T mass plane

The right panel of Fig. 4 shows the reach in the $(M_{H^\pm}, M_T)$ mass plane under the assumption $\mathcal{B} = 1$, representing the optimistic scenario in which the full signal

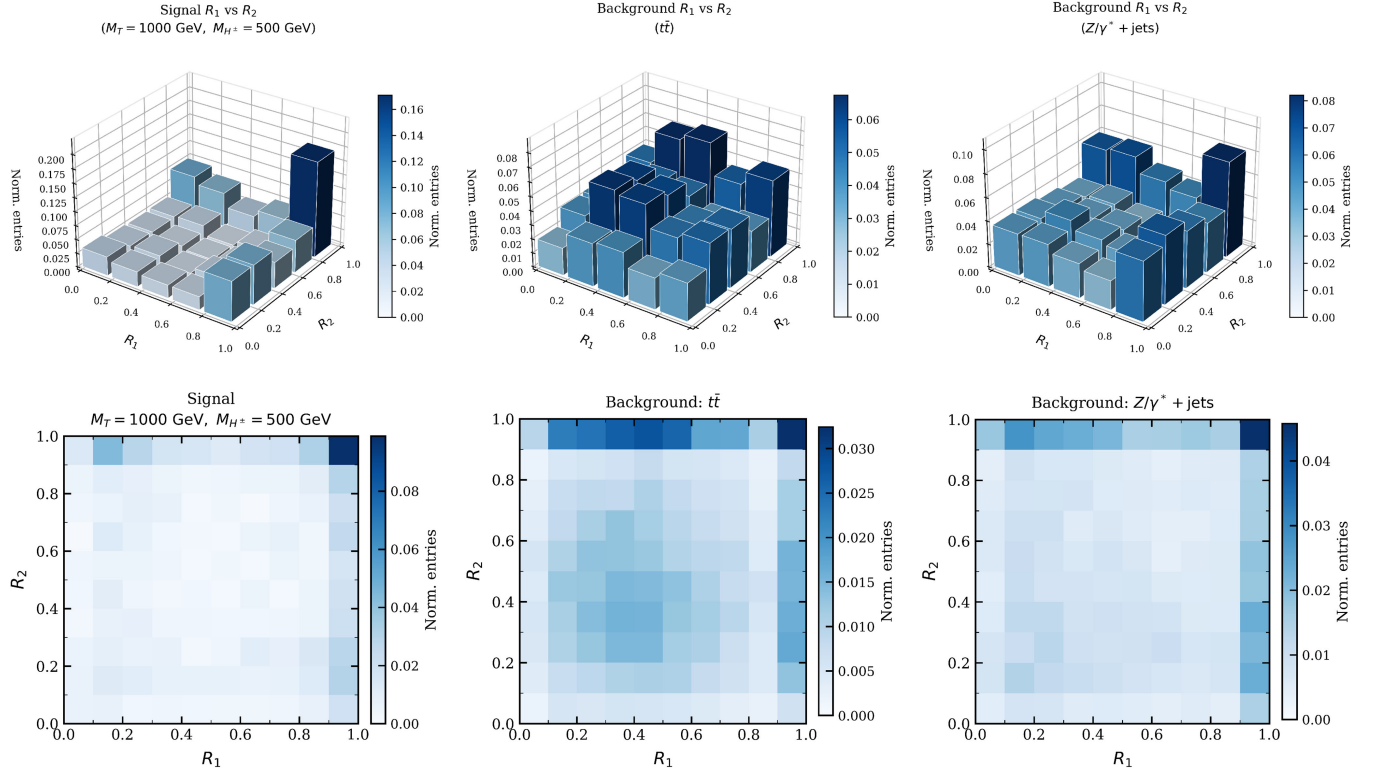


FIG. 3. Distributions of the tau polarization-sensitive variables R_1 and R_2 for the signal ($M_T = 1000$ GeV, $M_{H^\pm} = 500$ GeV), the $t\bar{t}$ background, and the $Z(\rightarrow \tau\tau) + \text{jets}$ background (left, center, and right columns, respectively). *Top row*: three-dimensional histogram representations. *Bottom row*: corresponding 2D heatmaps of normalized event fractions per bin. The signal accumulates at high R_1 , consistent with the right-handed tau polarization from scalar $H^\pm$ decay, while the $t\bar{t}$ background populates the low- R_1 region associated with left-handed taus from W decays. These observables are not included in the baseline cut-based selection, but the clear separation demonstrated here motivates their use in future multivariate or machine-learning analyses.

TABLE III. Cut-flow table showing the number of expected events surviving each successive selection requirement for the dominant SM backgrounds and for two representative signal benchmarks, normalized to an integrated luminosity of 3 ab^{-1} at $\sqrt{s} = 14$ TeV. All numbers are rounded to the nearest integer except entries below unity, which are quoted to one decimal place. The signal benchmark labels denote $(M_T, M_{H^\pm})$ in GeV.

Process	C1	C2	C3
$t\bar{t}$	1517	943	33
$t\bar{t}H$	3	1	<1
$t\bar{t}Z$	11	3	<1
Total background	1531	947	33
Signal (1500, 500)	160	142	94
Signal (2000, 500)	12	12	9

rate flows into the $2\tau + 2b + E_T$ channel. The 5σ discovery contour spans $M_T \approx 1.90\text{--}1.97$ TeV across the full $M_{H^\pm}$ range considered, while the 2σ exclusion reaches $M_T \approx 2.12\text{--}2.18$ TeV. The mild dependence on $M_{H^\pm}$ reflects the relatively flat signal efficiency as a function of the charged Higgs mass once the kinematic selection requirements are satisfied.

A modest reduction in sensitivity is observed near the kinematically compressed region $M_T - M_{H^\pm} \sim m_b$, where the b -jet from T decay becomes insufficiently energetic to pass the p_T threshold. This loss could be partially recovered through a dedicated soft- b selection strategy, which we leave as a direction for future work.

C. Discussion

The results presented above demonstrate that the $2\tau + 2b + \cancel{E}_T$ channel provides discovery-level sensitivity to nonstandard VLQ decays for $M_T \lesssim 1.9$ TeV at the HL-LHC, assuming order-unity cascade BRs. This reach is complementary to, and largely orthogonal from, existing top-VLQ searches, which assume exclusive decays into Wb , Zt , and ht , thereby not efficiently generating the $2\tau + 2b + \cancel{E}_T$ final state. The present analysis therefore fills a significant gap in the existing top-VLQ search program.

After the full event selection, the residual background is dominated by $t\bar{t}$ production, which contributes the bulk of the surviving noise, followed by $Z(\rightarrow \tau\tau) + \text{jets}$ as a subdominant but non-negligible contribution at lower S_T values. For our cut-based analysis, the invariant-mass variables are good enough to suppress the background.

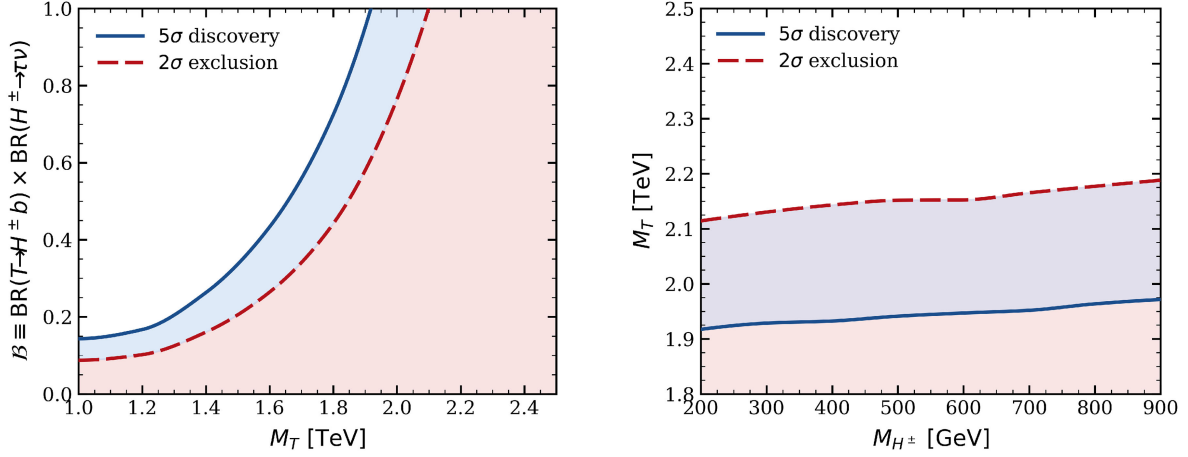


FIG. 4. Expected 2σ (dashed, red) and 5σ (solid, blue) significance contours at the HL-LHC ($\mathcal{L} = 3 \text{ ab}^{-1}$, $\sqrt{s} = 14 \text{ TeV}$) for the $2\tau + 2b + E_T$ channel. *Left*: Contours in the M_T - B plane with $M_{H^\pm} = 500 \text{ GeV}$ fixed, where $B \equiv \text{BR}(T \rightarrow H^\pm b) \times \text{BR}(H^\pm \rightarrow \tau\nu)$. The blue shaded band denotes the region observable at 2σ but below the 5σ discovery threshold; the red shaded region is not significant at the 2σ level. *Right*: Contours in the $M_{H^\pm}$ - M_T mass plane for $B = 1$, with the same shading convention. A flat systematic uncertainty of 10% on the total background normalization is assumed throughout.

However, the inclusion of the tau polarization observables R_1 and R_2 discussed in Sec. IV into a multivariate discriminant might provide additional rejection of the $t\bar{t}$ background, since signal and $t\bar{t}$ events populate opposite ends of the R_1 spectrum. We also leave the development of such a multivariate strategy as a direction for future work.

The assumed 10% systematic uncertainty on the background normalization is conservative relative to what could be achieved in a full experimental analysis. In practice, dedicated control regions enriched in $t\bar{t}$ (e.g., an $e\mu + \geq 2b$ region) and in $Z \rightarrow \tau\tau$ (e.g., a $Z \rightarrow ee$ region) can typically constrain the background normalization to the few-percent level. Given the small number of residual background events after the full selection (~ 33), Table III, the analysis is signal-limited, and the significance contours are not visibly affected by varying σ_b/b between 5% and 10%.

VI. CONCLUSIONS

We have investigated the prospects for observing non-standard decay modes of VLQs partners to top-quarks at the HL-LHC, in the context of a type-II 2HDM augmented by a singlet VLQ. The signal topology $pp \rightarrow T\bar{T} \rightarrow (H^\pm b)(H^\mp \bar{b}) \rightarrow 2\tau + 2b + \cancel{E}_T$ is distinctive, experimentally clean, and largely orthogonal to the standard VLQ search channels targeting Wb , Zt , and ht final states.

A model-independent, cut-based analysis has been performed using global kinematic observables constructed from the final-state visible objects and the missing transverse momentum vector. The sequential event selection—comprising requirements on $\cancel{E}_T$, the scalar sum S_T , and several multi-body effective invariant masses built from an auxiliary missing-momentum four-vector—suppresses the dominant $t\bar{t}$ and $Z(\rightarrow \tau\tau) + \text{jets}$ backgrounds by several

orders of magnitude while maintaining good signal efficiency across the mass range considered. The results are expressed as model-independent contours in the M_T - B and $M_{H^\pm}$ - M_T planes, enabling direct reinterpretation in other BSM scenarios with analogous cascade topologies.

Using the Asimov significance formalism with a conservative 10% systematic uncertainty on the background normalization, we find that the HL-LHC with 3 ab^{-1} can achieve 5σ discovery sensitivity for $M_T \lesssim 1.9 \text{ TeV}$, and can exclude at 2σ up to $M_T \approx 2.1 \text{ TeV}$, assuming $B = \text{BR}(T \rightarrow H^\pm b) \times \text{BR}(H^\pm \rightarrow \tau\nu) = 1$. These results establish the $2\tau + 2b + E_T$ final state as a well-motivated and sensitive probe of nonstandard top-VLQ decays at the HL-LHC.

We have also shown that the tau polarization variables R_1 and R_2 , which encode the helicity of the parent particle through the kinematics of hadronic tau decay products, provide a natural complement to the kinematic event selection. The opposite polarizations of signal taus (from $H^\pm$) and dominant background taus (from $W^\pm$) manifest as a clear separation in the (R_1, R_2) plane (Fig. 3), offering additional discriminating power that could be harnessed in a future multivariate or machine-learning analysis to extend the discovery reach beyond what is achievable with the cut-based approach alone.

Taken together, these findings motivate dedicated experimental searches for nonstandard top-VLQ decay modes at the HL-LHC and underscore the importance of considering extended Higgs sector signatures when interpreting the results of VLQ searches, in the spirit of Refs. [38,70].

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DATA AVAILABILITY

There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

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