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Search for single production of vector-like top partner $T \to H^+b$ and $H^\pm \to t\bar{b}$ at the LHC Run-III

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Introduction

Experimental data has not ruled out the existence of additional Higgs bosons or gauge sectors. Several models propose heavy vector-like partner quarks with vector-axial (V-A) coupling at the TeV scale. This study focuses on the decays of the heavy quark T into $H^\pm b$, which may compete with $W^\pm b$ decays, potentially opening new discovery channels at the LHC. Through Monte Carlo simulations, we analyze both signal and background processes to assess the LHC's sensitivity to the masses of T and $H^\pm$ in the 2HDM + VLQ model. This work introduces a novel strategy for identifying VLQs at the LHC by exploring these new channels.

Framework

In the Two-Higgs-Doublet Model (2HDM), the Yukawa interaction couples the Higgs boson to fermions, and for vector-like quarks (VLQs), it couples VLQs to the Higgs boson. The interaction in 2HDM is described by:

$$\mathcal{L}_Y = -Y_u H_u q_L u_R - Y_d H_d q_L d_R - Y_e H_d l_L e_R + h.c. \tag{1}$$

where Y_u, Y_d, and Y_e are Yukawa coupling matrices; H_u and H_d are Higgs doublets; and q_L, u_R, d_R, l_L, and e_R are Standard Model (SM) fields.

Extending 2HDM with VLQs involves introducing doublets like T and B, partners of the top and bottom quarks, respectively. These doublets have different hypercharge values ($Y = 2/3$ for T and $Y = -1/3$ for B). The Yukawa interaction with VLQs is:

$$\mathcal{L}_Y = -Y_u H_u Q_L U_R - Y_d H_d Q_L D_R + M_u \bar{U}_L U_R + M_d \bar{D}_L D_R + h.c. \tag{2}$$

Here, Q_L, U_R, and D_R are VLQ fields, and Y_u and Y_d describe the mixing between VLQs and SM quarks.

In 2HDM with VLQs, VLQs can affect Higgs phenomenology, leading to new Higgs production channels. VLQs' properties and their interactions with the Higgs boson provide insights into electroweak symmetry breaking and new physics beyond the SM.

To define the relevant Yukawa interactions for our signal, we use:

$$\begin{aligned}\mathcal{L}_{H^+} = &-\frac{gm_t}{\sqrt{2}M_W}\bar{t}(\cot\beta Z^L_{tb}P_L + \tan\beta Z^R_{tb}P_R)bH^+ \\ &-\frac{gm_T}{\sqrt{2}M_W}\overline{T}(\cot\beta Z^L_{Tb}P_L + \tan\beta Z^R_{Tb}P_R)bH^+ + h.c.\end{aligned} \tag{3}$$

with

$$\begin{aligned} Z^L_{tb} &= c^d_L c^u_L + \frac{s^d_L}{s^u_L}({s^u_L}^2 - {s^u_R}^2)e^{i(\phi_u-\phi_d)}, \\ Z^R_{tb} &= \frac{m_b}{m_t}\left[c^u_L c^d_L + \frac{s^u_L}{s^d_L}({s^d_L}^2 - {s^d_R}^2)e^{i(\phi_u-\phi_d)}\right], \\ Z^L_{Tb} &= c^d_L s^u_L e^{-i\phi_u} + ({s^u_L}^2 - {s^u_R}^2)\frac{s^d_L}{c^u_L}e^{-i\phi_d}, \\ Z^R_{Tb} &= \frac{m_b}{m_T}\left[c^d_L s^u_L e^{-i\phi_u} + ({s^d_R}^2 - {s^d_L}^2)\frac{c^u_L}{s^d_L}e^{-i\phi_d}\right].\end{aligned} \tag{4}$$

Additionally:

$$\mathcal{L}_W = -\frac{g}{\sqrt{2}}\overline{T}\gamma^\mu(V^L_{Tb}P_L + V^R_{Tb}P_R)bW^+_\mu + h.c. \tag{5}$$

with

$$\begin{aligned} V^L_{Tb} &= s^u_L c^d_L e^{-i\phi_u} - c^u_L s^d_L e^{-i\phi_d}, \\ V^R_{Tb} &= c^u_R s^d_R e^{-i\phi_d}.\end{aligned} \tag{6}$$

1 Numerical Analysis

We performed a numerical scan over the parameter space shown in Table 1 to identify scenarios with significant cross sections for $W^+b\bar{b}b\bar{b}j$. Points were checked for consistency with theoretical and experimental constraints (see Refs. [1]).

Parameters	Scanned ranges
m_h	125
m_A	[300, 800]
m_H	[300, 800]
$m_{H^\pm}$	[590, 800]
$\tan\beta$	[0.5, 20]
$\sin\theta^{u,d}_R$	[−0.5, 0.5]
m_T	[700, 2000]

Table 1: 2HDM & VLQs parameters with their scanned ranges. Masses are in GeV.

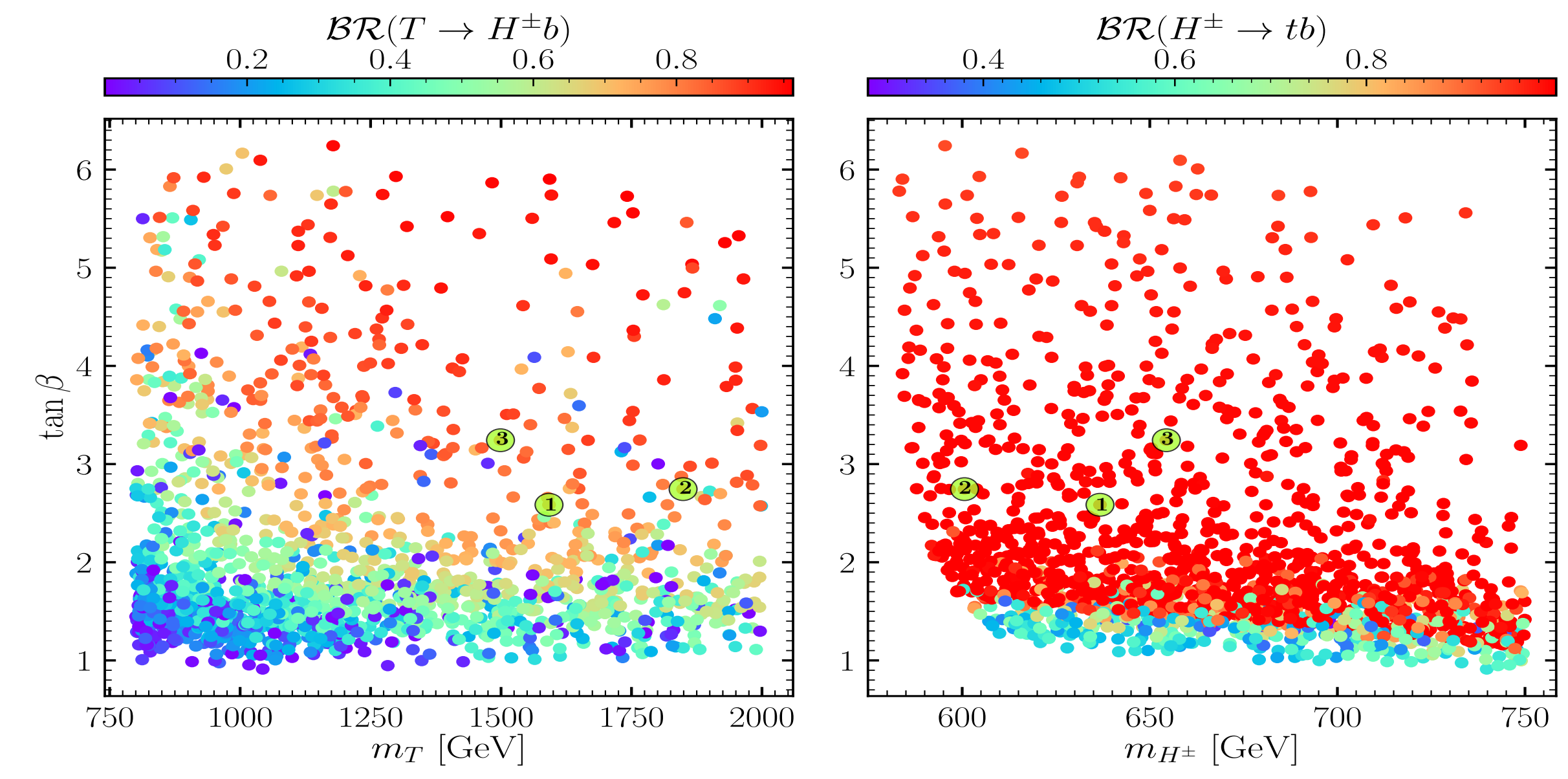

Figure 1: $\mathcal{BR}(T \to H^+b)$ as a function of m_T and $\tan\beta$ (left) and $\mathcal{BR}(H^\pm \to t\bar{b})$ (right) plotted over the $(m_{H^\pm}, \tan\beta)$ plane.

Analyzed process:

$$pp \to qg \to T\bar{b}j \to H^+b\bar{b}j \to t\bar{b}b\bar{b}j \to W^+b\bar{b}b\bar{b}j \to 1\ell + 4b + 1j + \not{E}_T \tag{7}$$

Discovery and exclusion significance calculated using median significance approach:

$$\mathcal{Z}_{\text{disc}} = \sqrt{2\left[(s+b)\ln(1+s/b) - s\right]} \tag{8}$$
$$\mathcal{Z}_{\text{excl}} = \sqrt{2\left[s - b\ln(1+s/b))\right]} \tag{9}$$

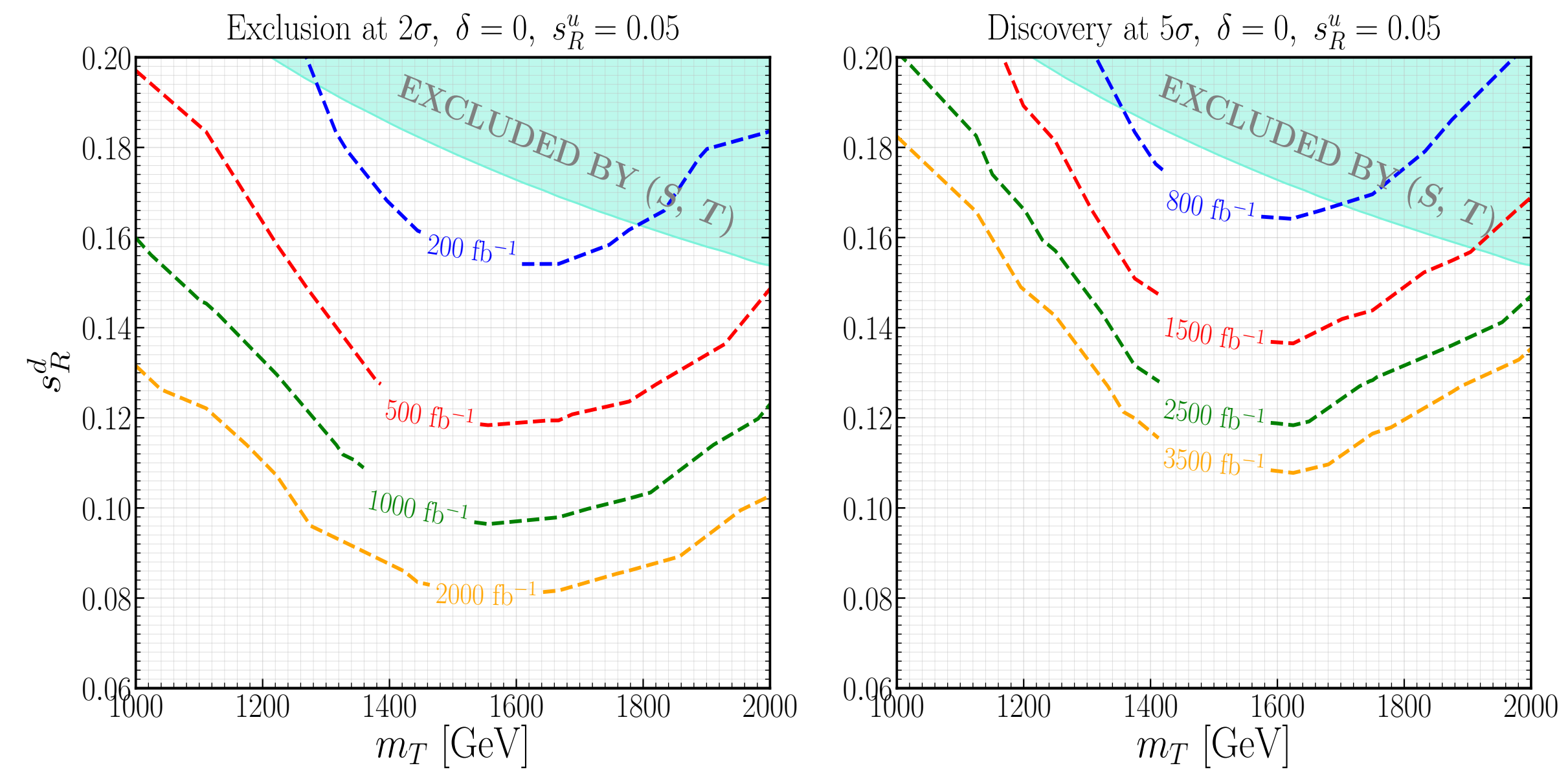

Figure 2: Discovery prospects (5σ) and exclusion limit (2σ) for $m_T - \sin\theta^u_R$ at $\sqrt{s} = 14$ TeV LHC for different integrated luminosities.

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

Table 2: Exclusion and discovery capability on T at LHC and HL-LHC.

References

[1] R. Benbrik, M. Berrouj, M. Boukidi, A. Habjia, E. Ghourmin, and L. Rahili. Search for single production of vector-like top partner T→H+b and H±→tb¯ at the LHC Run-III. *Phys. Lett. B*, 843:138024, 2023.