LP2EA
Laboratoire de Physique, Énergie, Environnement et ses Applications

Polydisciplinary Faculty of Safi
Cadi Ayyad University

MARRAKECH
جامعة القاضي عياض
UNIVERSITÉ CADI AYYAD

Vector-like Quark B Bounds at the LHC: Impact of 2HDM

Khawla Salime
In collaboration with:
R.Benbrik, M. Boukidi, M. Berrouj, S.Moretti, M. Ech-chaouy

arXiv:2512.xxxxx

Scalars 2025

September 24, 2025

Plan

Motivation: Vector-like Quarks

The left- and right-handed chiralities of a vector-like fermion transform in the same way under the Standard Model gauge groups:

$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

- Vector-like quarks are spin 1/2 colored fermions.
- Adding vector-like quarks to the Standard Model is the simplest way to break the Glashow–Iliopoulos–Maiani mechanism.
- They can mix with SM and 2HDM Higgses.

Vector-Like Quark Models

Examples of Beyond the Standard Model Scenarios

- **Composite Higgs models**
- **Little Higgs models**
- **Extra dimensions**
- **Non-minimal SUSY extensions**

The canonical representation of vector-like quarks includes one of the following seven multiplets: two singlets, three doublets, and two triplets.

	Singlet		**Doublet**			**Triplet**	
Q	(T)	(B)	$\begin{pmatrix} T \\ B \end{pmatrix}$	$\begin{pmatrix} X \\ T \end{pmatrix}$	$\begin{pmatrix} B \\ Y \end{pmatrix}$	$\begin{pmatrix} X \\ T \\ B \end{pmatrix}$	$\begin{pmatrix} T \\ B \\ Y \end{pmatrix}$
Isospin	0	0	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	1
Hypercharge	$\frac{2}{3}$	$-\frac{1}{3}$	$\frac{1}{6}$	$\frac{7}{6}$	$-\frac{5}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$

- The electric charges of the new VLQs are:

$$Q_T = \frac{2}{3}, \quad Q_B = -\frac{1}{3}, \quad Q_X = \frac{5}{3}, \quad Q_Y = -\frac{4}{3}.$$

2HDM Potential

The Higgs Lagrangian, contains the kenitic terms and a potential V,

$$\mathcal{L}_{\textbf{Higgs}} = \sum_{i=1,2} (D_\mu \Phi_i)^\dagger (D^\mu \Phi_i) - V(\phi_1, \phi_2)$$

The most general, renormalizable two doublet scalar potential is:

$$\begin{aligned} V(\Phi_1,\Phi_2) &= m_{11}^2\, \Phi_1^\dagger \Phi_1 + m_{22}^2\, \Phi_2^\dagger \Phi_2 - m_{12}^2 \left(\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1\right) \\ &+ \frac{\lambda_1}{2}\left(\Phi_1^\dagger \Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_2^\dagger \Phi_2\right)^2 \\ &+ \lambda_3 \left(\Phi_1^\dagger \Phi_1\right)\left(\Phi_2^\dagger \Phi_2\right) + \lambda_4 \left|\Phi_1^\dagger \Phi_2\right|^2 \\ &+ \frac{\lambda_5}{2}\left[\left(\Phi_1^\dagger \Phi_2\right)^2 + \text{h.c.}\right], \end{aligned} \quad (1)$$

The two complex scalar doublets, Φ_1 and Φ_2, with identical hypercharge $Y = +1$.

$$\Phi_i = \begin{pmatrix} \phi_i^+ \\ \frac{1}{\sqrt{2}}\left(v_i + \eta_i^0 + i a_i\right) \end{pmatrix}, \qquad i = 1, 2 \quad (2)$$

Parametrization & Yukawa Sector

In the Higgs basis, the Yukawa Lagrangian can be written as:

$$-\mathcal{L} \supset y^u\, \bar{Q_L}^0\, \tilde{H}_2\, u_R^0 + y^u\, \bar{Q_L}^0\, H_1\, u_R^0 + M_u^0\, \bar{u_L}^0\, u_R^0 + M_d^0\, \bar{d_L}^0 d_R^0 + \text{h.c.}$$

- The bottom quark mixes with B as follows:

$$\begin{pmatrix} b_{L,R} \\ B_{L,R} \end{pmatrix} = U_{L,R} \begin{pmatrix} b^0_{L,R} \\ B^0_{L,R} \end{pmatrix} = \begin{pmatrix} \cos\theta^d_{L,R} & -\sin\theta^d_{L,R} e^{i\phi_d} \\ \sin\theta^d_{L,R} e^{-i\phi_d} & \cos\theta^d_{L,R} \end{pmatrix} \begin{pmatrix} b^0_{L,R} \\ B^0_{L,R} \end{pmatrix}$$

For the diagonalization of the mass matrices, the Lagrangian of the third generation and the VLQ mass terms is written as:

$$\mathcal{L}_{\text{mass}} = -\begin{pmatrix} \bar{t}^0_L & \bar{T}^0_L \end{pmatrix} \begin{pmatrix} \frac{y^u_{33} v}{\sqrt{2}} & \frac{y^u_{34} v}{\sqrt{2}} \\ \frac{y^u_{43} v}{\sqrt{2}} & M^0 \end{pmatrix} \begin{pmatrix} t^0_R \\ T^0_R \end{pmatrix}$$

$$-\begin{pmatrix} \bar{b}^0_L & \bar{B}^0_L \end{pmatrix} \begin{pmatrix} \frac{y^d_{33} v}{\sqrt{2}} & \frac{y^d_{34} v}{\sqrt{2}} \\ \frac{y^d_{43} v}{\sqrt{2}} & M^0 \end{pmatrix} \begin{pmatrix} b^0_R \\ B^0_R \end{pmatrix} + \text{h.c.}$$

where M^0 is a bare mass term and y_{ij} are Yukawa couplings. For the singlet case, $y_{13} = 0$, while for the doublet case, $y_{34} = 0$.

Using the standard diagonalization procedure, the mixing matrices satisfy:

$$U_L^\dagger M^u U_R = M^u_{\text{diag}}$$

From this relation, one obtains:

$$\tan\theta^q_R = \frac{m_q}{m_Q} \tan\theta^q_L \quad \text{(singlet)},$$

$$\tan\theta^q_L = \frac{m_q}{m_Q} \tan\theta^q_R \quad \text{(doublet)}.$$

2HDM + VLB Interactions

The interactions between the **vector-like** B **quark** and the extended Higgs sector are:

$$\mathcal{L}_H = -\frac{g\, m_B}{2M_W}\, \bar{b}\left(Y^L_{HbB} P_L + Y^R_{HbB} P_R\right) B\, H + \text{h.c.}, \tag{3}$$

$$\mathcal{L}_A = i\, \frac{g\, m_B}{2M_W}\, \bar{b}\left(Y^L_{AbB} P_L - Y^R_{AbB} P_R\right) B\, A + \text{h.c.}, \tag{4}$$

$$\mathcal{L}_{H^-} = -\frac{g\, m_B}{\sqrt{2}M_W}\, \overline{B}\left(\cot\beta\, Z^L_{Bt} P_L + \tan\beta\, Z^R_{Bt} P_R\right) b\, H^- + \text{h.c.}, \tag{5}$$

- H, A, H^- = BSM Higgs bosons.
- $Y^{L,R}, Z^{L,R}$ = Yukawa-like couplings.

Light-heavy coupling to BSM Higgses

Scenario	Y^L_{HbB}	Y^L_{AbB}
(B)	$\left(c_{\beta\alpha} + s_{\beta\alpha} \tan\beta\right) \frac{m_b}{m_B} c_L s_L e^{i\phi}$	$\tan\beta \frac{m_b}{m_B} c_L s_L e^{i\phi}$
(TB)	$\left(c_{\beta\alpha} + s_{\beta\alpha} \tan\beta\right) s^d_R c^d_R e^{i\phi_d}$	$\tan\beta s^d_R c^d_R e^{i\phi_d}$
(BY)	$\left(c_{\beta\alpha} + s_{\beta\alpha} \tan\beta\right) c_R s_R e^{i\phi}$	$\tan\beta c_R s_R e^{i\phi}$

Table: Light-heavy **left** couplings of bottom quarks to the **neutral Higgses**.

Scenario	Y^R_{HbB}	Y^R_{AbB}
(B)	$(c_{\beta\alpha} + s_{\beta\alpha} \tan\beta) c_L s_L e^{i\phi}$	$\tan\beta c_L s_L e^{i\phi}$
(TB)	$(c_{\beta\alpha} + s_{\beta\alpha} \tan\beta) \frac{m_b}{m_B} s^d_R c^d_R e^{i\phi_d}$	$\tan\beta \frac{m_b}{m_B} s^d_R c^d_R e^{i\phi_d}$
(BY)	$(c_{\beta\alpha} + s_{\beta\alpha} \tan\beta) \frac{m_b}{m_B} c_R s_R e^{i\phi}$	$\tan\beta \frac{m_b}{m_B} c_R s_R e^{i\phi}$

Table: Light-heavy **right** couplings of bottom quarks to the **neutral Higgses**.

Scenario	Z^L_{Bt}	Z^R_{Bt}
(B)	s_L	0
(TB)	$\frac{m_t}{m_B}\left[c^u_L s^d_L e^{i\phi_d} + ({s^u_R}^2 - {s^u_L}^2)\frac{c^d_L}{s^u_L} e^{i\phi_u}\right]$	$c^u_L s^d_L e^{i\phi_d} + ({s^d_L}^2 - {s^d_R}^2)\frac{s^u_L}{c^d_L} e^{i\phi_u}$
(BY)	0	0

Table: Heavy-light couplings to the charged Higgs.

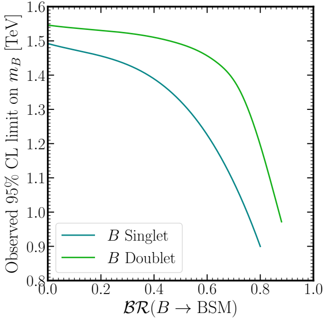
Recasted VLB Bounds

$$\mathcal{BR}_{\text{SM}} = 1 - \mathcal{BR}_{\text{BSM}}$$

with:

$$\mathcal{BR}_{\text{BSM}} \equiv \mathcal{BR}(B \to Hb) + \mathcal{BR}(B \to Ab) + \mathcal{BR}(B \to H^- t)$$

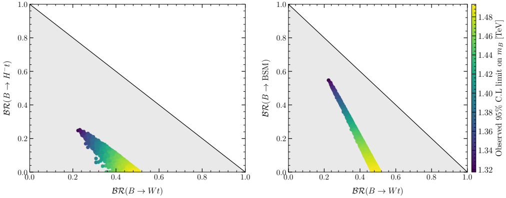
$$\mathcal{BR}_{\text{SM}} \equiv \mathcal{BR}(B \to hb) + \mathcal{BR}(B \to Zb) + \mathcal{BR}(B \to Wt)$$



2HDM-II + VLB Singlet

Parameter	Range
m_B	$[800,\ 2000]$
m_A	$[100,\ 800]$
m_H	$[130,\ 800]$
m_{H^-}	$[600,\ 1000]$
$\sin(\beta-\alpha)$	1
m_{12}^2	$\cos\beta\ \sin\beta\, m_H$
$\tan\beta$	$[0.5,\ 60]$
$s_L^{u,d}$	$[-0.25,\ 0.25]$
$s_R^{u,d}$	$[-0.25,\ 0.25]$

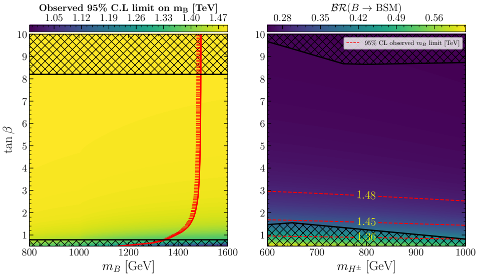
Table: Scan ranges in 2HDM-II + VLB scenarios



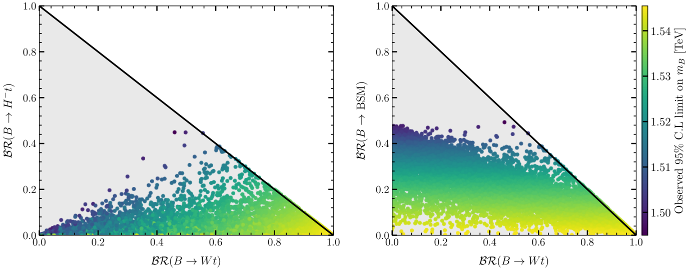
- The **color bar** highlights the excluded m_B values.
- The region outside the gray area corresponds to **unphysical configurations**, where $\sum_i \mathrm{BR}_i > 1$.

2HDM-II + B Singlet

* **Left panel:**
  - At $\tan\beta \sim 1$: **exclusion reaches $m_B \sim 1.4$ TeV**.
  - Upper shaded region: excluded by ATLAS $\tau\tau$.
  - Lower shaded region: excluded by ATLAS $H^+ \to tb$.
  - At larger $\tan\beta$, SM branching ratios dominate, stabilizing m_B at approximately 1.48 TeV
* **Right panel:**
  - The exclusion similarly weakens for $\tan\beta \lesssim 1$ due to enhanced BSM branching ratios, with minimal dependence on $m_{H^\pm}$.

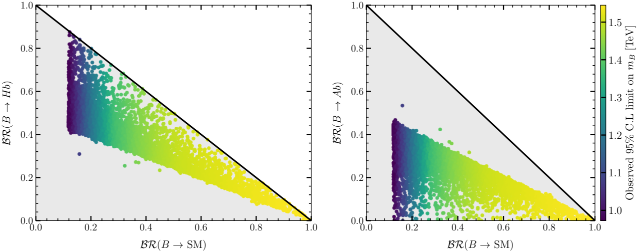


2HDM-II + TB



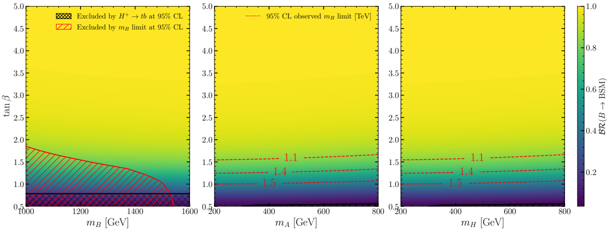
- $\mathcal{BR}(B \to H^- t) \approx 45\%$ and $\mathcal{BR}(B \to \text{BSM}) \approx 50\%$.
- The VLB mass bound relaxes from 1.55 TeV to about 1.49 TeV.

2HDM-II + YB



- The colour scale indicates the m_B exclusion limit.
- $\mathcal{BR}(B \to Hb)$ and $\mathcal{BR}(B \to Ab)$ can reach up to 84% and 57%.
- Relaxed m_B limit below 1 TeV

2HDM-II + YB



- Left panel: Red-hatched region shows the recast m_B exclusion. Weakens for $\tan\beta > 1$, reaching $m_B \approx 1$ TeV at $\tan\beta \sim 1.57$.
- For $\tan\beta > 1.57$: $\mathcal{BR}(B \to \text{BSM}) > 90\%$, SM decays negligible, m_B becomes unconstrained.
- Middle and right panels: m_A and m_H show minimal variation. Contours relax only mildly with increasing $\tan\beta$.
- Overall: Relaxation of m_B limit correlates with the growth of $\mathcal{BR}(B \to \text{BSM}) \sim m_B^3 \tan^2\beta$.

Conclusions and perspectives

- For the singlet case (2HDM-II$+B$), the exclusion limit drops to approximately 1.3 TeV.
- In the (TB) doublet exhibits minimal weakening of the exclusion limit, shifting from 1.55 TeV to 1.49 TeV, as the branching ratio to BSM Higgses, $\mathcal{BR}(B \to \text{BSM})$, reaches only $\sim$ 49%.
- The (BY) doublet representation, the limit further decreases to about 0.98 TeV, driven by high branching ratios of $\mathcal{BR}(B \to Hb) \approx 85\%$ and $\mathcal{BR}(B \to Ab) \approx 50\%$ at large $\tan\beta$.

Thanks for listening