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Exploring LHC Constraints on VLBs within the 2HDM Framework

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Plan

1. Introduction
2. 2HDM+VLQ
3. Results and Discussion
4. Conclusions and perspectives

Introduction

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.
- They have not been detected at the LHC. Current searches exclude VLQ masses up to m_{VLQ} 1.7 TeV.
- 2HDMs extended by VLQs predict new BSM decay channels that can dominate over SM channels.

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:

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

2HDM Theory

2HDM potential under Z_2 symmetry:

$$V_{\text{2HDM}}^{Z_2} = m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + \text{h.c}) + \frac{1}{2}\lambda_1|\Phi_1|^4 + \frac{1}{2}\lambda_2|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \frac{1}{2}\lambda_5\left[(\Phi_1^\dagger\Phi_2)^2 + \text{h.c.}\right]$$

Higgs doublets in 2HDM framework:

$$\Phi_1 = \begin{pmatrix} \Phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \rho_1 + i\eta_1) \end{pmatrix}, \qquad \Phi_2 = \begin{pmatrix} \Phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \rho_2 + i\eta_2) \end{pmatrix}, \qquad \tan\beta = \frac{v_2}{v_1}.$$

- Existence of two CP-even Higgs bosons H, h.
- Existence of a CP-odd Higgs boson A.
- Existence of charged Higgs bosons $H^\pm$.

Parametrization & Yukawa Sector

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

$$-\mathcal{L} \supset y^u\, \bar{Q}^0_L\, \tilde{H}_2\, u^0_R + y^d\, \bar{Q}^0_L\, H_1\, d^0_R + M^0_u\, \bar{u}^0_L\, u^0_R + M^0_d\, \bar{d}^0_L\, d^0_R + \text{h.c.}$$

- Mixing in the up sector (top–T):

$$\begin{pmatrix} t_{L,R} \\ T_{L,R} \end{pmatrix} = U^u_{L,R} \begin{pmatrix} t^0_{L,R} \\ T^0_{L,R} \end{pmatrix} = \begin{pmatrix} \cos\theta^u_{L,R} & -\sin\theta^u_{L,R}\, e^{i\phi_u} \\ \sin\theta^u_{L,R}\, e^{-i\phi_u} & \cos\theta^u_{L,R} \end{pmatrix} \begin{pmatrix} t^0_{L,R} \\ T^0_{L,R} \end{pmatrix}$$

- Mixing in the down sector (bottom–B):

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

From these relations, one obtains the link between left- and right-handed mixings:

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

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

LHC VLQ Bounds

Considering only the SM+VLQ, the Q quark decays via three channels:

$$Q \to Wq, \quad Q \to Zq, \quad Q \to hq$$

These satisfy:

$$\mathrm{BR}(Q \to Wq) + \mathrm{BR}(Q \to Zq) + \mathrm{BR}(Q \to hq) = 1$$

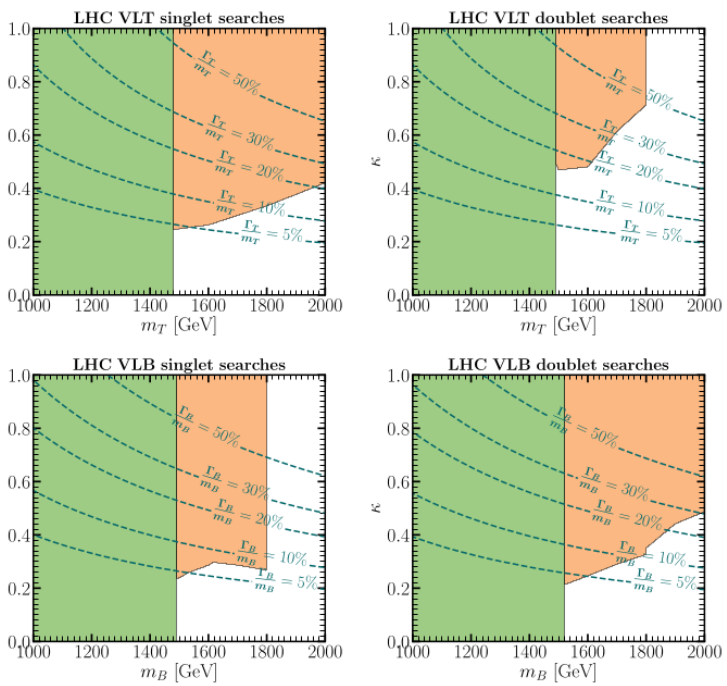
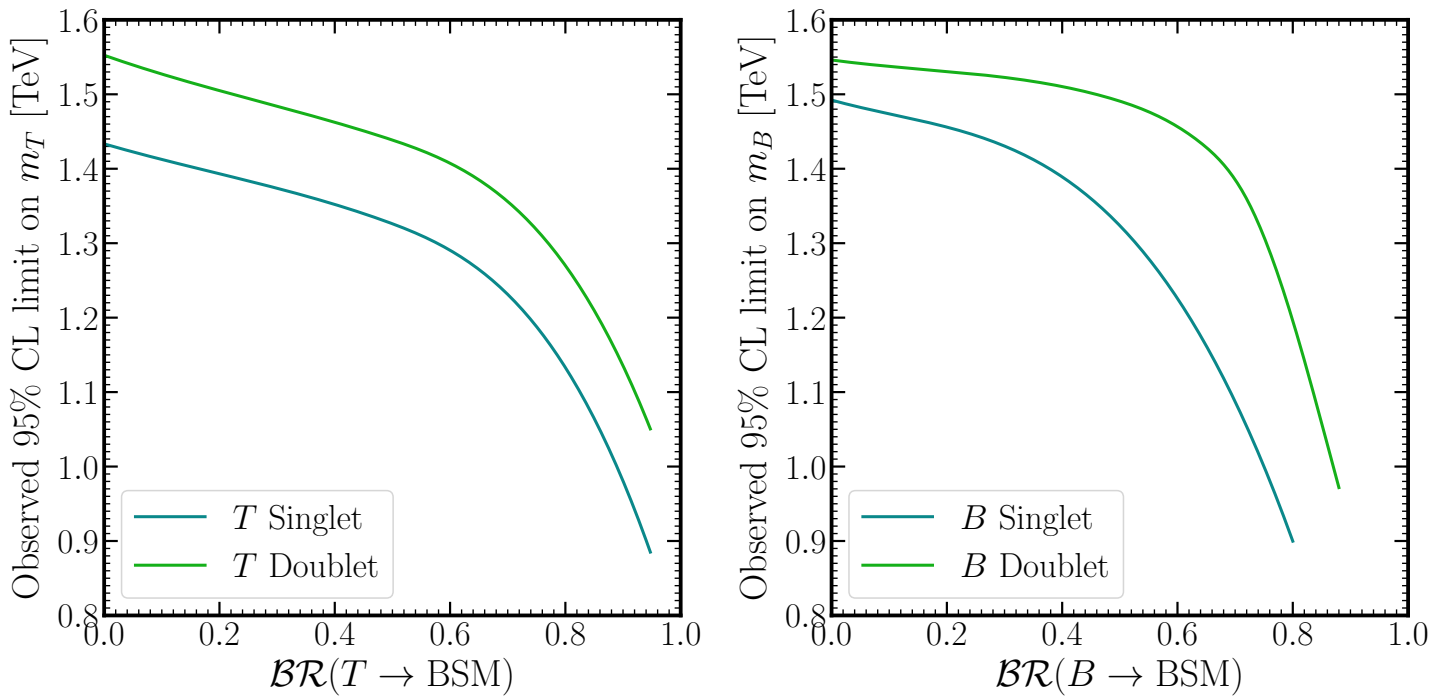


Figure: LHC 95% CL exclusion limits in the (m_Q, κ) plane. Green: pair production limits. Orange: single production limits. *R. Benbrik et al., JHEP 03 (2025) 020*

Recasted VLQ Bounds

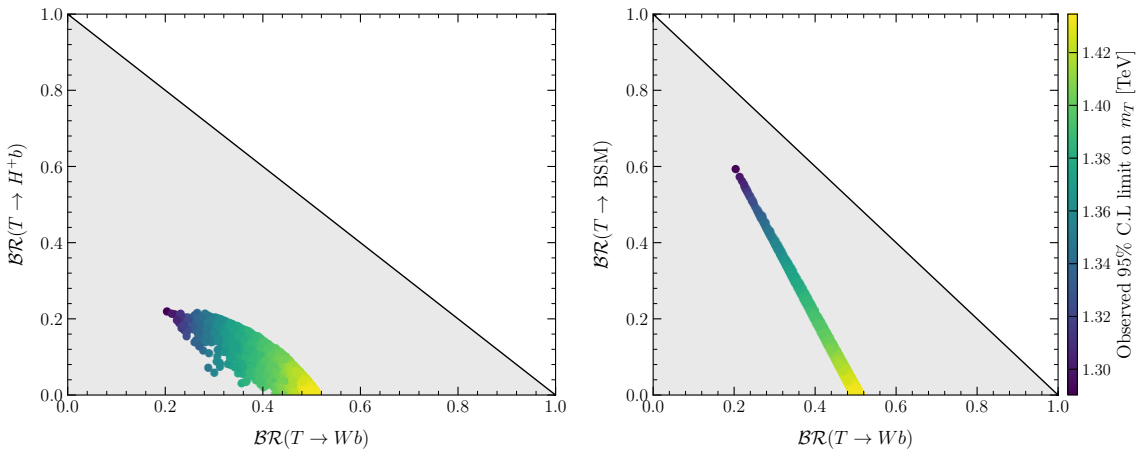
If VLQ decays to BSM final states, we get a new constraint:

$$\mathrm{BR}(Q \to Wq) + \mathrm{BR}(Q \to Zq) + \mathrm{BR}(Q \to hq) + \mathrm{BR}(Q \to \mathrm{BSM}) = 1.$$



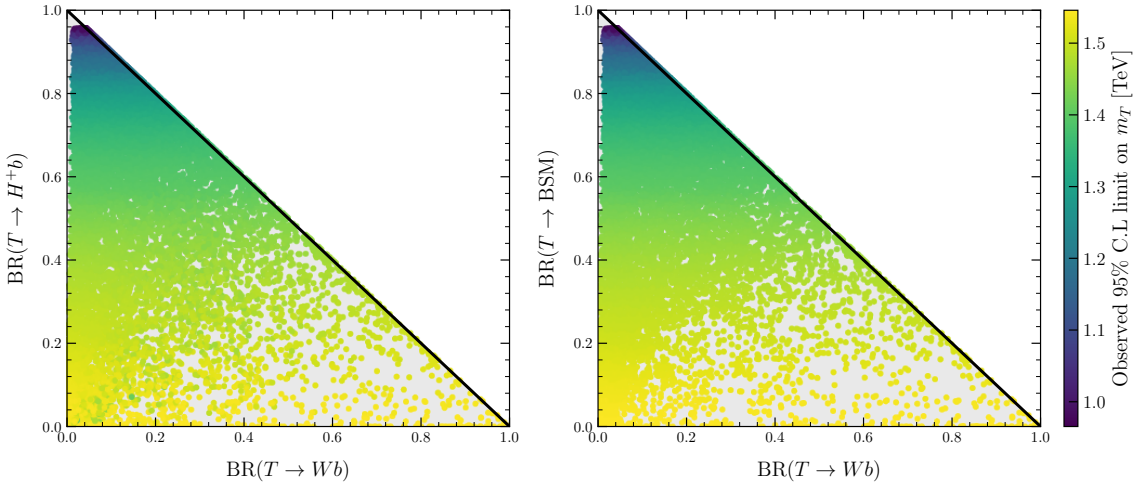
Observed LHC upper limits as a function of the branching ratio into BSM Higgs bosons

2HDM-II + VLT Singlet



- Increasing BR(T $\to$ H$^+$b) and BR(T $\to$ BSM) leads to a significant reduction of the excluded m_T limit.
- The exclusion weakens and reaches **1.28 TeV** for:
  - BR(T $\to$ H$^+$b) $\simeq 24\%$
  - BR(T $\to$ BSM) $\simeq 60\%$

2HDM-II + TB Doublet

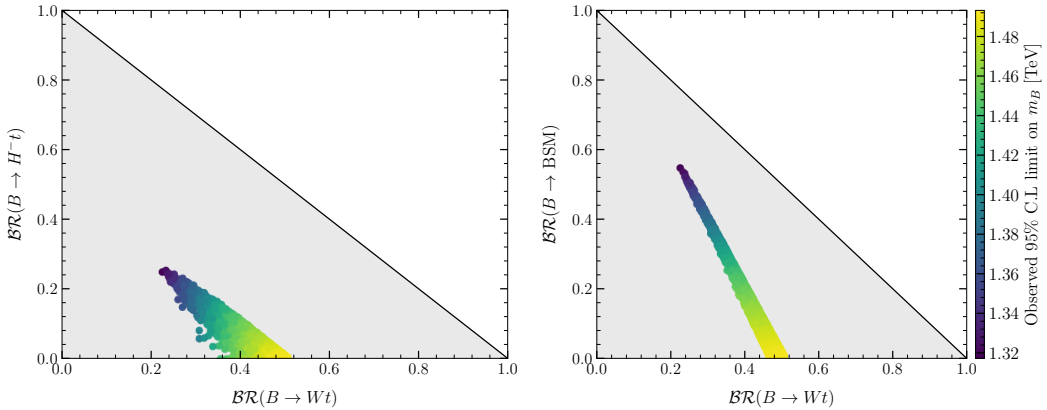


- Observed m_T upper limit scatter in the planes:
  - $(\mathrm{BR}(T \to H^+b), \mathrm{BR}(T \to Wb))$
  - $(\mathrm{BR}(T \to \mathrm{BSM}), \mathrm{BR}(T \to Wb))$
- $\mathrm{BR}(T \to \mathrm{BSM}) = \mathrm{BR}(T \to H^+b) \approx 96\%$
- $\mathrm{BR}(T \to \mathrm{BSM})$ is mainly driven by $\mathrm{BR}(T \to H^+b)$
- Observed m_T can reach ~ 0.98 TeV

2HDM-II + VLB Singlet

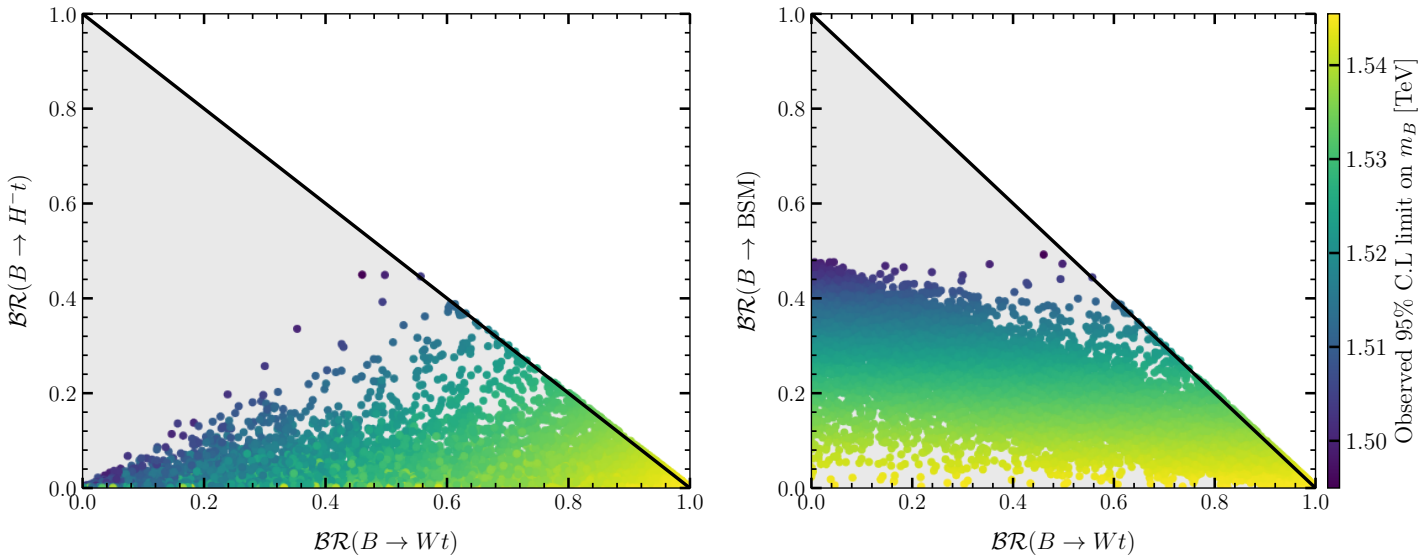
Parameter	Range
m_B	$[800, 2000]$
m_A	$[100, 800]$
m_H	$[130, 800]$
m_{H^-}	$[600, 1000]$
$\sin(\beta - \alpha)$	1
m_{12}^2	$\cos\beta \, \sin\beta \, m_H$
$\tan\beta$	$[0.5, 60]$
$s_L^{u,d}$	$[-0.25, 0.25]$
$s_R^{u,d}$	$[-0.25, 0.25]$

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



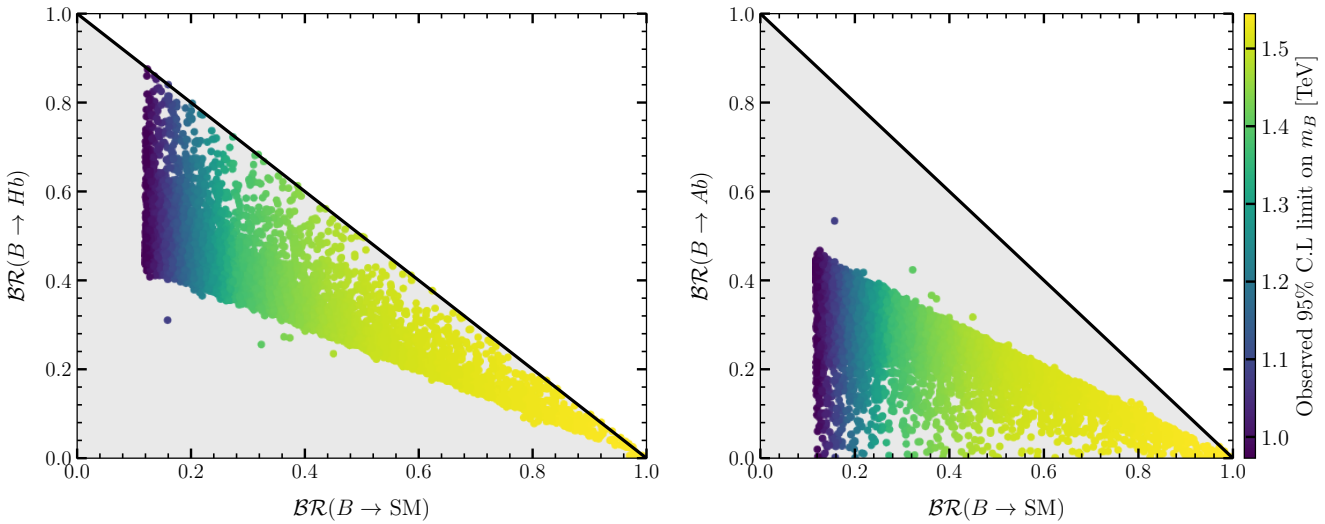
- The **color bar** highlights the excluded m_B values.
- The region outside the gray area corresponds to **unphysical configurations**, where $\sum_i \mathrm{BR}_i > 1$.

2HDM-II + TB



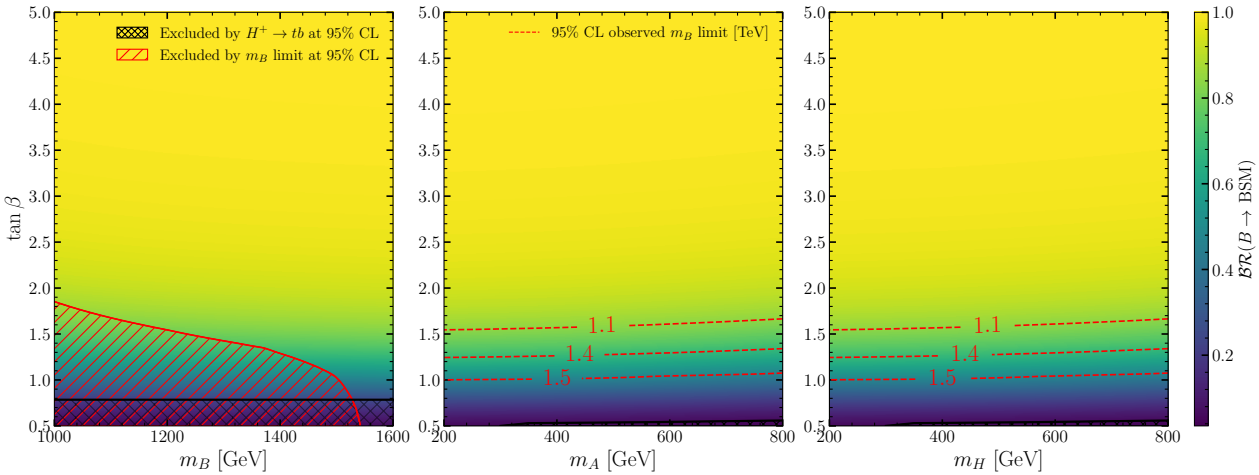
- $\mathcal{BR}(B \to H^- t) \approx 45\%$ and $\mathcal{BR}(B \to \text{BSM}) \approx 50\%$.
- The VLB mass bound relaxes from 1.55 TeV to about 1.49 TeV.

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 $\tan\beta \sim 1.57$.
- Beyond $\tan\beta > 1.57$, $\mathcal{BR}(B \to \text{BSM}) > 90\%$, SM decays negligible, m_B becomes unconstrained.
- Middle and right panels: m_A and m_H show minimal variation. Contours relax only with increasing $\tan\beta$.

Conclusions and perspectives

- 2HDM-II with singlet T : $\mathcal{BR}(T \to \text{BSM})$ up to 60% $\Rightarrow$ exclusion weakens from ~ 1.45 to ~ 1.3 TeV.
- 2HDM-II with singlet B : the exclusion limit drops to **1.3 TeV**.
- 2HDM-II with doublet (TB) :
  - BR$(T \to \text{BSM})$ up to 100% $\Rightarrow$ weakening limit from ~ 1.55 to ~ 0.98 TeV.
  - Dominated by $T \to H^+ b$, which is promising for searches at low m_T.
  - For the B partner: only mild weakening (**1.55 $\to$ 1.49 TeV**) since BR$(B \to \text{BSM}) \sim 49\%$.
- 2HDM-II + doublet (BY) : exclusion decreases to **0.98 TeV**, driven by:
  - $\mathcal{BR}(B \to Hb) \approx 85\%$
  - $\mathcal{BR}(B \to Ab) \approx 50\%$ at high $\tan\beta$

Thanks for listening