Laboratory of Fundamental and Applied Physics
Cadi Ayyad University, Safi, Morocco

Probing Charged Higgs Bosons In The 2HDM Type-II With Vector-Like Quarks

Mohammed Boukidi

in collaboration with: R. Benbrik and S.Moretti

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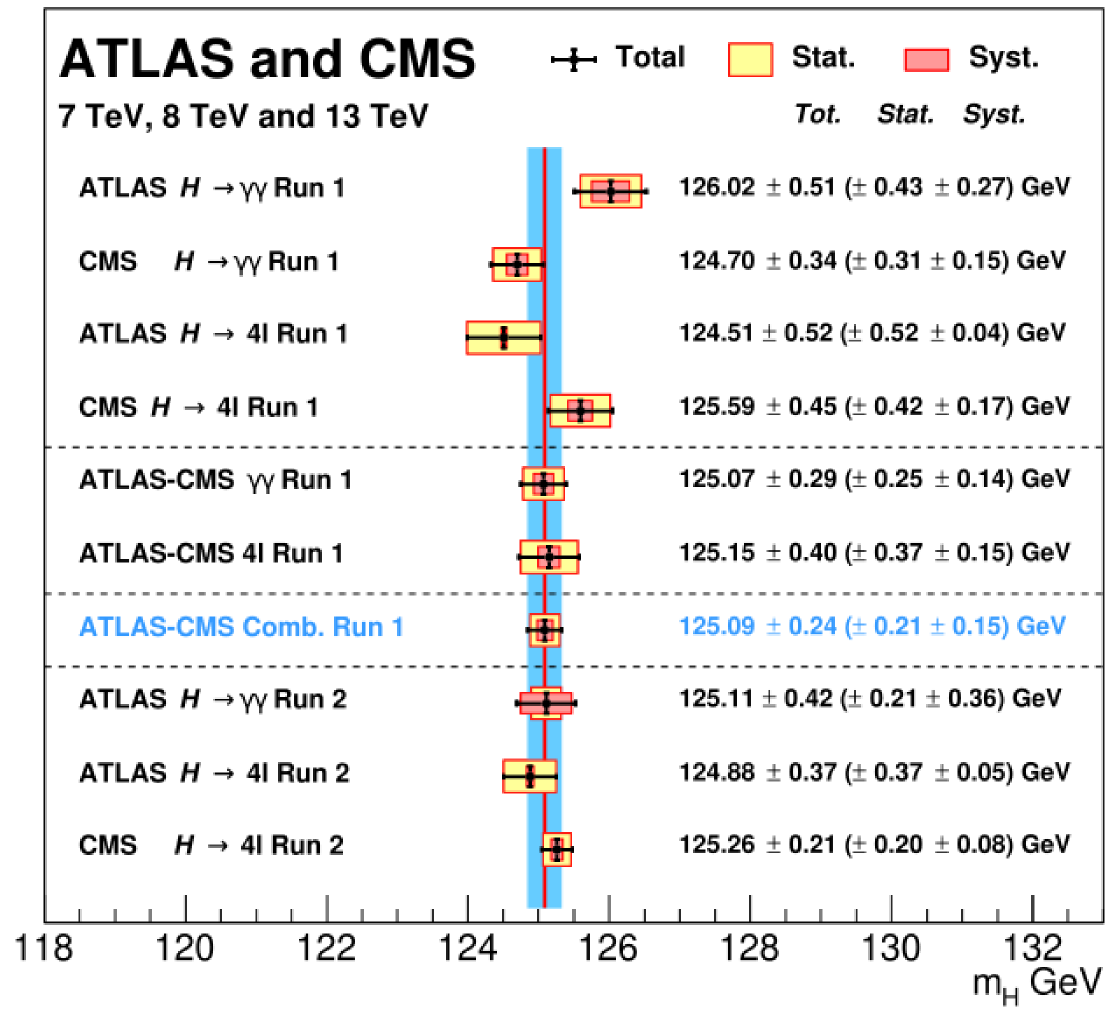
OUTLINE

Motivation

- Higgs properties measurements at run 1 and run 2 are in a good agreement with the SM
- Perhaps other scalars are not yet discovered
- Two Higgs Doublet Model (2HDM)
  - Minimal extension to the SM
  - Rich collider phenomenology
  - LHC benchmark mode
    - Benchmarks for light/heavy charged Higgs
    - Benchmarks for light/heavy neutral Higgses



C. Patrignani et al., Particle Physics Group, Chin. Phys. C, 40 100001

Motivation

- ✩ **LH and RH same $SU(2)_L$ transformation.**
- ✩ **VLQs don't get their mass from the Higgs: $m\psi\bar{\psi}$.**
- ✩ **VLQs can mix with SM quarks and 2HDM Higgses.**
- ✩ **VLQs are the simplest type of colored fermions still experimentally allowed.**
- ✩ **VLQs could be singlet, doublet or triplet under $SU(2)_L$.**

Component fields	T	B	TB	XT	BY	TBY	XTB
$U(1)_Y$	2/3	-1/3	1/6	7/6	-5/6	-1/3	2/3
$SU(2)_L$	1	1	2	2	2	3	3
$SU(3)_C$	3	3	3	3	3	3	3

- ✩ **VLQs have the electric charges: $Q_T = \frac{2}{3}, Q_B = -\frac{1}{3}, Q_X = \frac{5}{3}$, and $Q_Y = -\frac{4}{3}$.**

2HDM PARAMETRIZATION

The most general scalar potential of the 2HDM [Branco, G. et al. Phys.Rept. 516 (2012)] :

$$V(\Phi_1\Phi_2) = m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - \left[m_{12}^2\Phi_1^\dagger\Phi_2 + \text{h.c.}\right]$$
$$+ \frac{\lambda_1}{2}\left(\Phi_1^\dagger\Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_2^\dagger\Phi_2\right)^2 + \lambda_3\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right) + \lambda_4\left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_2^\dagger\Phi_1\right)$$
$$+ \left\{\frac{\lambda_5}{2}\left(\Phi_1^\dagger\Phi_2\right)^2 + \left[\lambda_6\left(\Phi_1^\dagger\Phi_1\right) + \lambda_7\left(\phi_2^\dagger\Phi_2\right)\right]\Phi_1^\dagger\Phi_2 + \text{h.c.}\right\} \quad (1)$$

with :

$$\Phi_{1,2} = \begin{pmatrix} \phi_{1,2}^+ + i\varphi_{1,2}^+ \\ \frac{1}{\sqrt{2}}\left(v_{1,2} + \rho_{1,2} + i\eta_{1,2}\right) \end{pmatrix} \quad (2)$$

✦ The 10 independent parameters ($m_{11}^2,\ m_{22}^2,\ m_{12}^2,\ \lambda_{1,\ldots,7}$) are assumed to be real.

2HDM PARAMETRIZATION

- Introduced to avoid flavor-changing neutral currents (FCNCs) at tree level.
- Each Higgs doublet transforms under Z_2: $\Phi_1 \to \Phi_1$, $\Phi_2 \to -\Phi_2$.
  - **Type I**: One doublet couples to all fermions.
  - **Type II**: One doublet couples to up-type quarks, the other to down-type quarks and leptons.
  - **Lepton-specific (Type X)**: One doublet couples to quarks, the other to leptons.
  - **Flipped (Type Y)**: One doublet couples to up-type quarks and leptons, the other to down-type quarks.
- 2 minimization conditions and the combination $v_1^2 + v_2^2 = v^2 \implies$ **7** free parameters:

$\boldsymbol{m_h,\ m_H,\ m_A,\ m_{H^\pm},\ s_{\beta-\alpha},\ \tan\beta = \frac{v_2}{v_1}}$ and $\boldsymbol{m_{1,2}^2}$.

VLQ PARAMETRIZATION

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

$$-\mathcal{L} \supset y^u \bar{Q}_L^0 \tilde{H}_2 u_R^0 + y^d \bar{Q}_L^0 H_1 d_R^0 + M_u^0 \bar{u}_L^0 u_R^0 + M_d^0 \bar{d}_L^0 d_R^0 + h.c.$$

- When only the top quark “mixes” with T:

$$\begin{pmatrix} t_{L,R} \\ T_{L,R} \end{pmatrix} = U_{L,R}^u \begin{pmatrix} t_{L,R}^0 \\ T_{L,R}^0 \end{pmatrix} = \begin{pmatrix} \cos\theta_{L,R}^u & -\sin\theta_{L,R}^u e^{i\phi_u} \\ \sin\theta_{L,R}^u e^{-i\phi_u} & \cos\theta_{L,R}^u \end{pmatrix} \begin{pmatrix} t_{L,R}^0 \\ T_{L,R}^0 \end{pmatrix},$$

- In the weak eigenstate basis the diagonalisation of the mass matrices makes the Lagrangian of the third generation and heavy quark mass terms such that:

$$\begin{aligned} \mathcal{L}_{\text{mass}} &= -\left(\bar{t}_L^0 \;\; \bar{T}_L^0\right) \begin{pmatrix} y_{33}^u \frac{v}{\sqrt{2}} & y_{34}^u \frac{v}{\sqrt{2}} \\ y_{43}^u \frac{v}{\sqrt{2}} & M^0 \end{pmatrix} \begin{pmatrix} t_R^0 \\ T_R^0 \end{pmatrix} \\ &\quad -\left(\bar{b}_L^0 \;\; \bar{B}_L^0\right) \begin{pmatrix} y_{33}^d \frac{v}{\sqrt{2}} & y_{34}^d \frac{v}{\sqrt{2}} \\ y_{43}^d \frac{v}{\sqrt{2}} & M^0 \end{pmatrix} \begin{pmatrix} b_R^0 \\ B_R^0 \end{pmatrix} + \text{h.c.}, \end{aligned}$$

M^0 is a bare mass and the y_{ij}'s are Yukawa couplings. While $y_{43} = 0$, for the singlet and $y_{34} = 0$, for the doublet.

- Using standard techniques of diagonalisation, the mixing matrices are obtained by

$$U_L^q \, \mathcal{M}^q \, (U_R^q)^\dagger = \mathcal{M}_{\text{diag}}^q,$$

- Using the above equation and depending on the VLQs representation one can find:

$$\tan\theta_R^q = \frac{m_q}{m_Q} \tan\theta_L^q \quad \text{(singlet)},$$

$$\tan\theta_L^q = \frac{m_q}{m_Q} \tan\theta_R^q \quad \text{(doublet)},$$

CONSTRAINTS

Theoretical

- **Unitarity** The variety of scattering process must be unitary.
- **Perturbativity** constraints impose the following condition on the quartic couplings of the scalar potential: $|\lambda_i| < 8\pi$
- **Vacuum stability** constraints require the potential be bounded from below and positive in any direction of the fields Φ_i, consequently, the parameter space must satisfy the following conditions:

$$\lambda_1 > 0, \quad \lambda_2 > 0, \quad \lambda_3 > -\sqrt{\lambda_1\lambda_2},$$
$$\lambda_3 + \lambda_4 - |\lambda_5| > -\sqrt{\lambda_1\lambda_2}.$$

`2HDMC-1.8.0` (D. Eriksson, J. Rathsman and O. Stal [0902.0851])

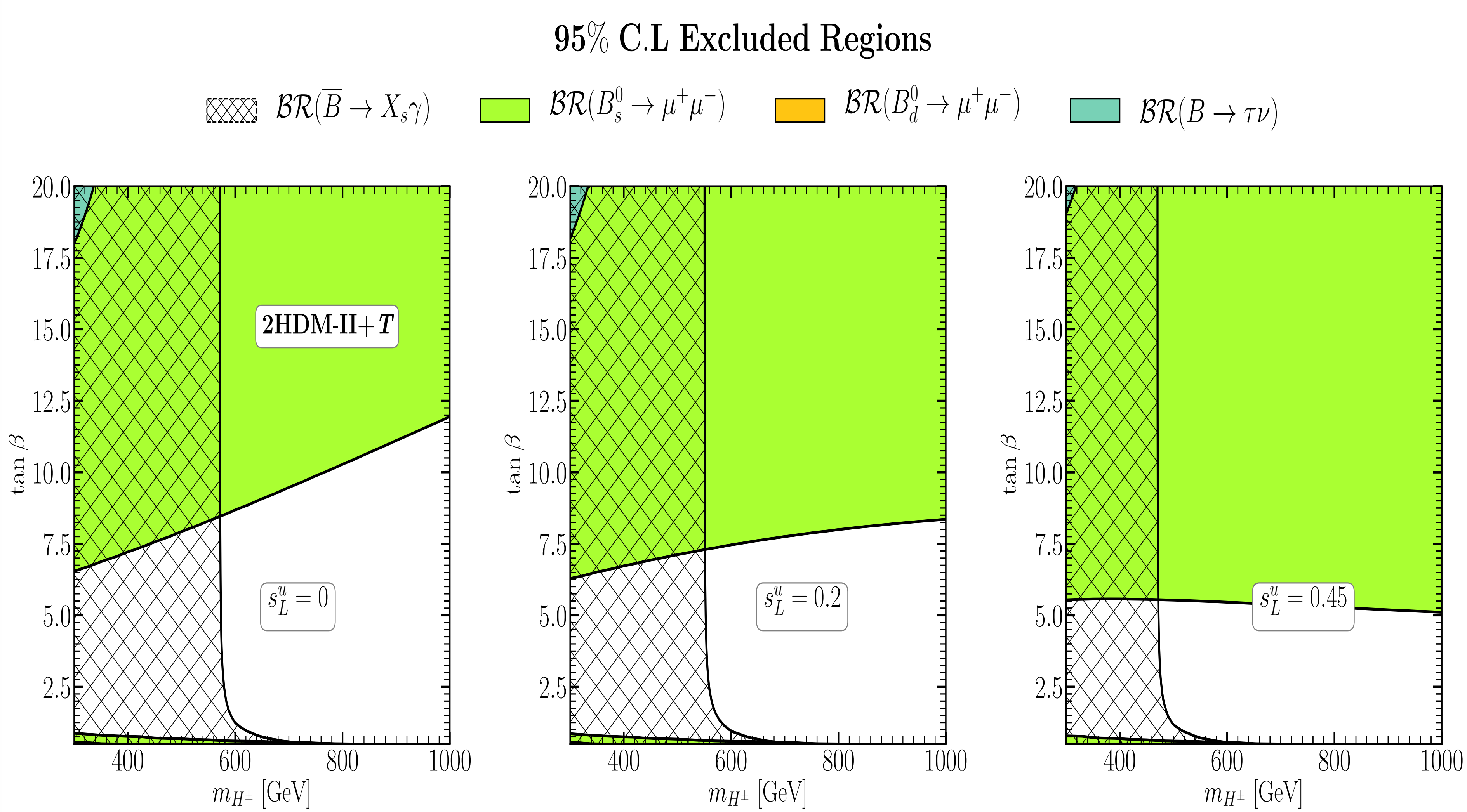
Experimental

- **EWPOs**, implemented through the EW oblique parameters S, T, we require $\Delta\chi^2(S^{VLQ} + S^{2HDM}, \; T^{VLQ} + T^{2HDM}) \leq 6.18$.
- **SM-like Higgs boson discovery**: an agreement between selected points in parameter space and the current measurements of the properties of the discovered Higgs boson at 125 GeV is enforced by means of the publicly available cod `HiggsSignals-3` via `HiggsTools`.
- **Non-SM-like Higgs boson exclusions**: to check the parameter space points against the exclusion limits from null Higgs boson searches at LEP, Tevatron and, in particular, the LHC, we apply the public code `HiggsBounds-6` via `HiggsTools` .
- **B-physics observables** are tested against data by resorting to the public code `SuperIso_v4.1`, (mainly $B \to X_s\gamma, \; B_{s,d} \to \mu^+\mu^-$ and $B_s \to \tau\nu$).

2HDM-II+T Singlet Scenario

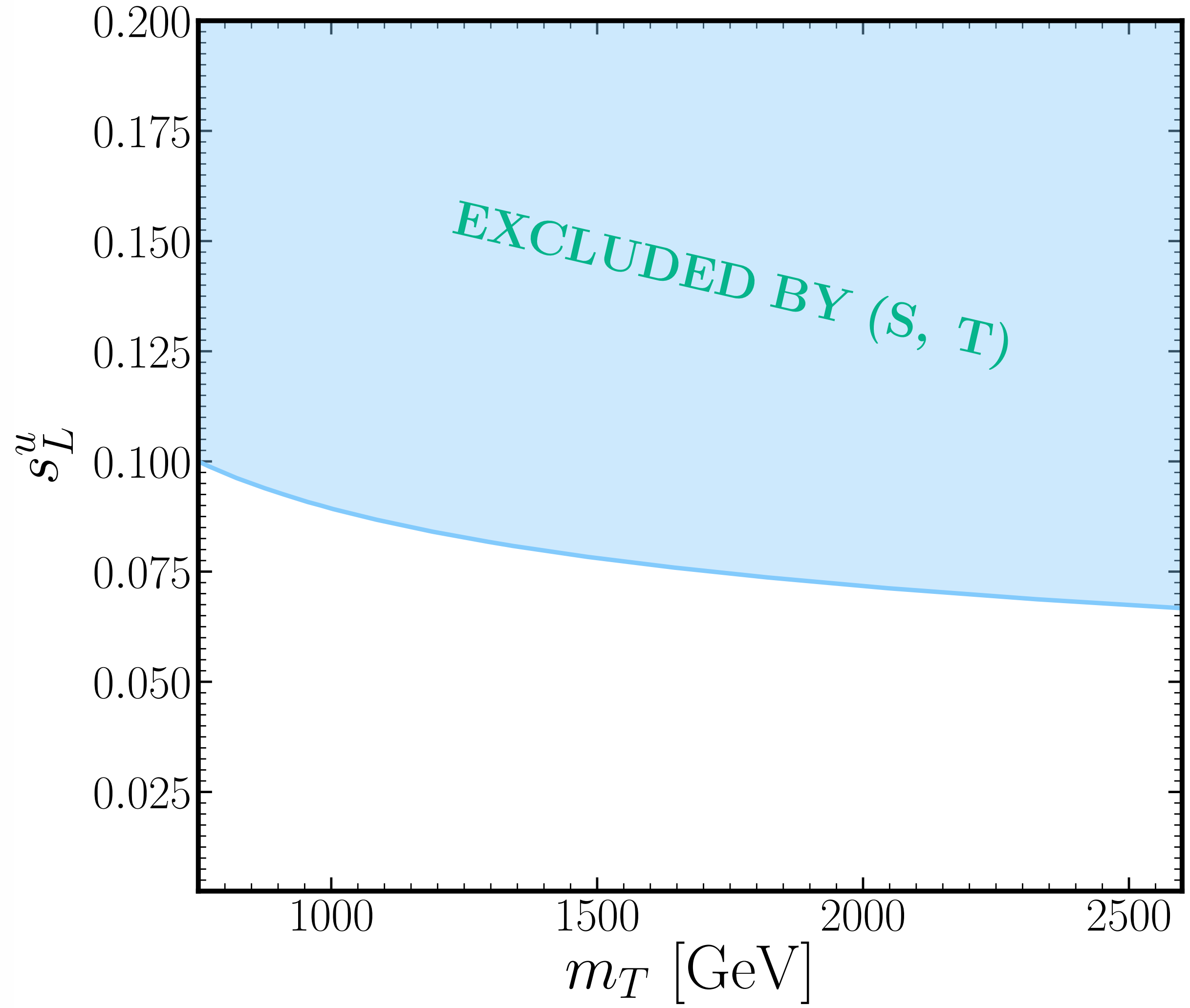
$$-\mathcal{L}_{H^+} \quad = \quad \frac{\sqrt{2}}{v}\bar{t}\left(\kappa_t m_t P_L - \kappa_b m_b P_R\right) b H^+ + h.c., \qquad (3)$$

Models	κ_t	κ_b
2HDM-II	$\cot\beta$	$-\tan\beta$
2HDM-II+(T)	$c_L \cot\beta$	$-c_L \tan\beta$



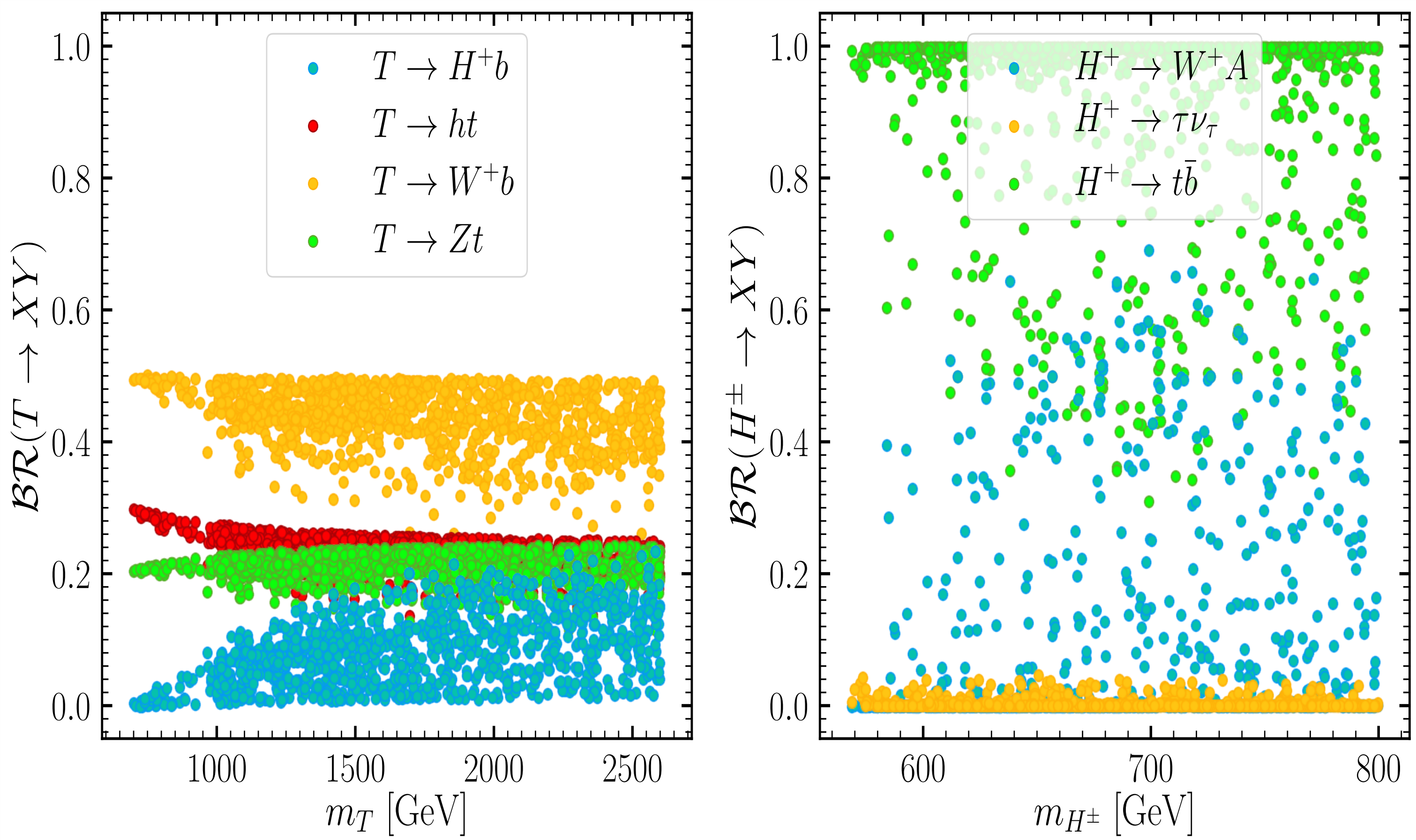
2HDM-II+T Singlet Scenario

- Fixed parameters: $m_H = 532.80$ GeV, $m_A = 524.26$ GeV and $m_{H^\pm} = 588.02$ GeV, with $\tan\beta = 5.19$.



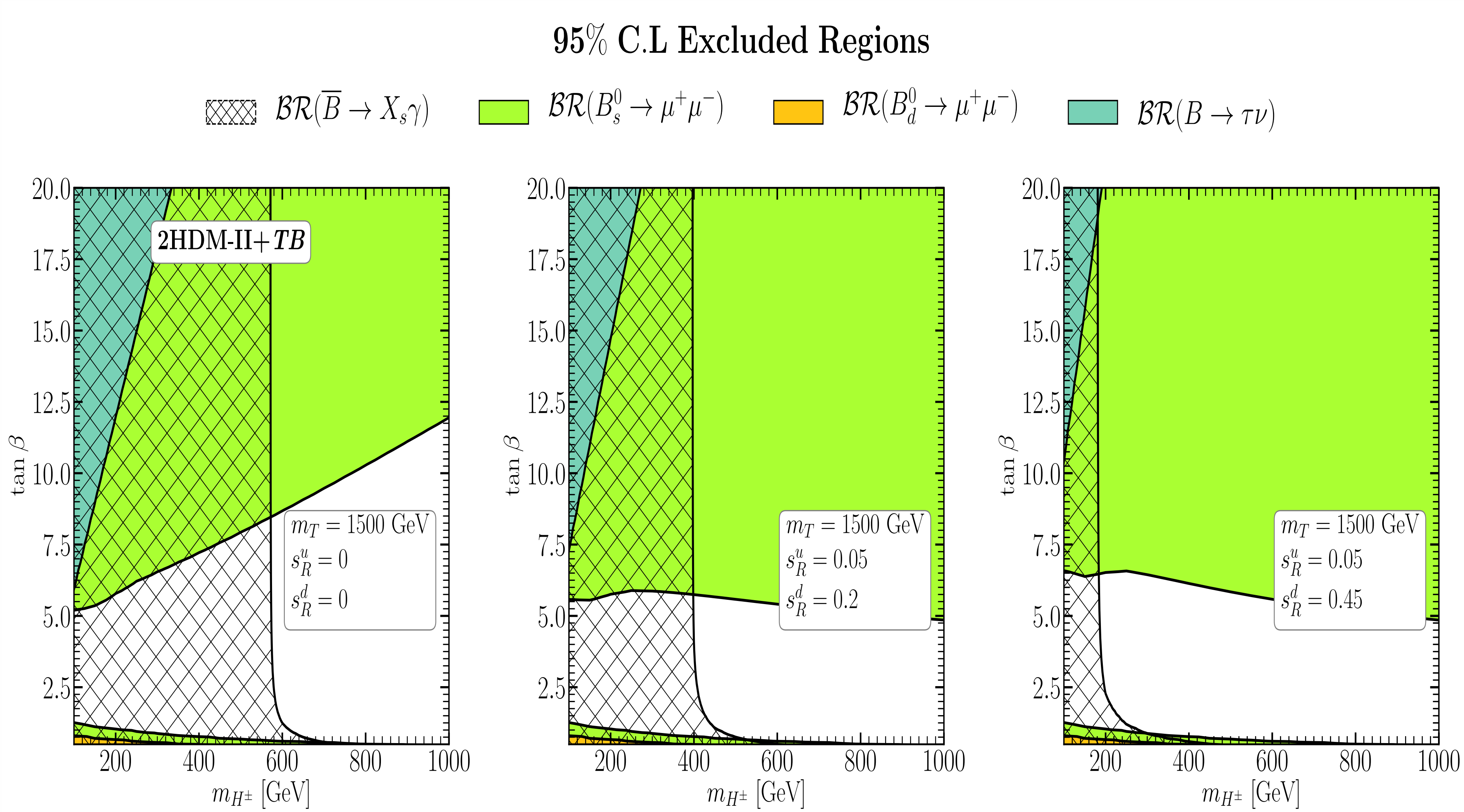
2HDM-II+T Singlet Scenario

Parameters	Scanned ranges
2HDM	
m_H	[130, 800]
m_A	[80, 800]
$m_{H^\pm}$	[80, 800]
$\tan\beta$	[0.5, 20]
$\sin(\beta-\alpha)$	1
2HDM-II+(T)	
s_L	[−0.5, 0.5]
m_T	[750, 2600]

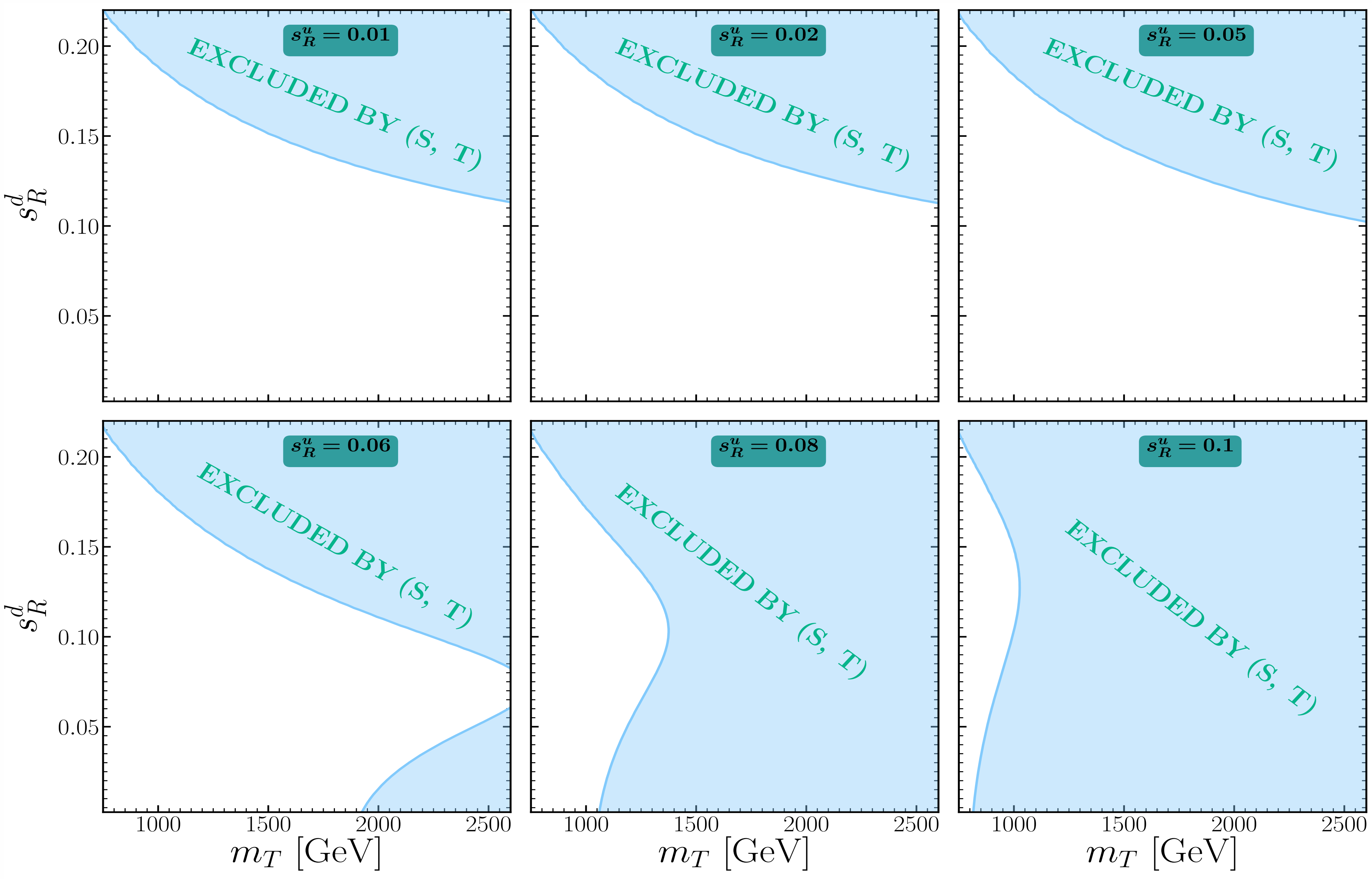


2HDM-II+TB Doublet Scenario

Models	κ_t	κ_b
2HDM-II	$\cot\beta$	$-\tan\beta$
2HDM-II+(TB)	$\cot\beta\left[c_L^d c_L^u + \frac{s_L^d}{s_L^u}({s_L^u}^2 - {s_R^u}^2)e^{i(\phi_u-\phi_d)}\right]$	$-\tan\beta\left[c_L^u c_L^d + \frac{s_L^u}{s_L^d}({s_L^d}^2 - {s_R^d}^2)e^{i(\phi_u-\phi_d)}\right]$

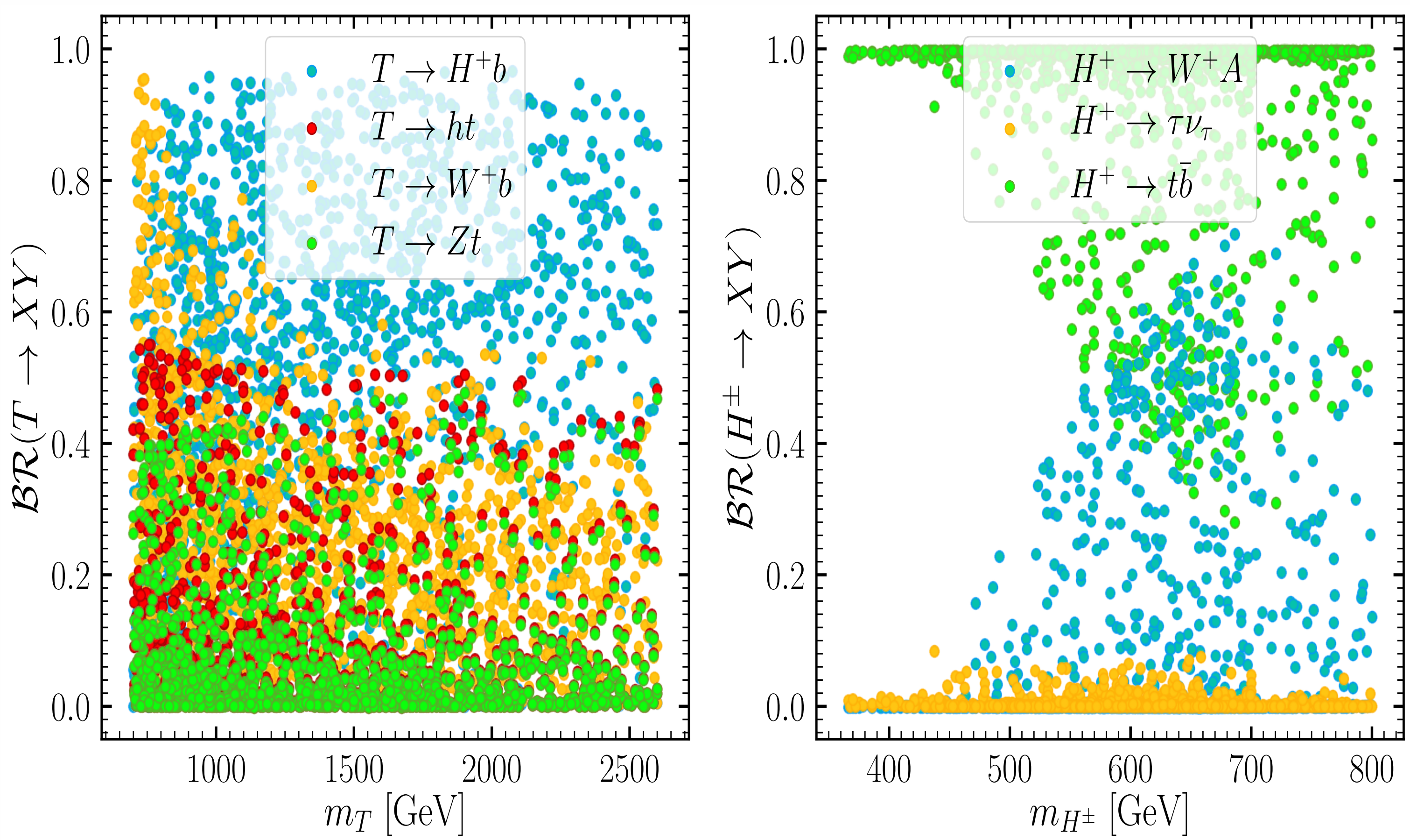


2HDM-II+TB Doublet Scenario

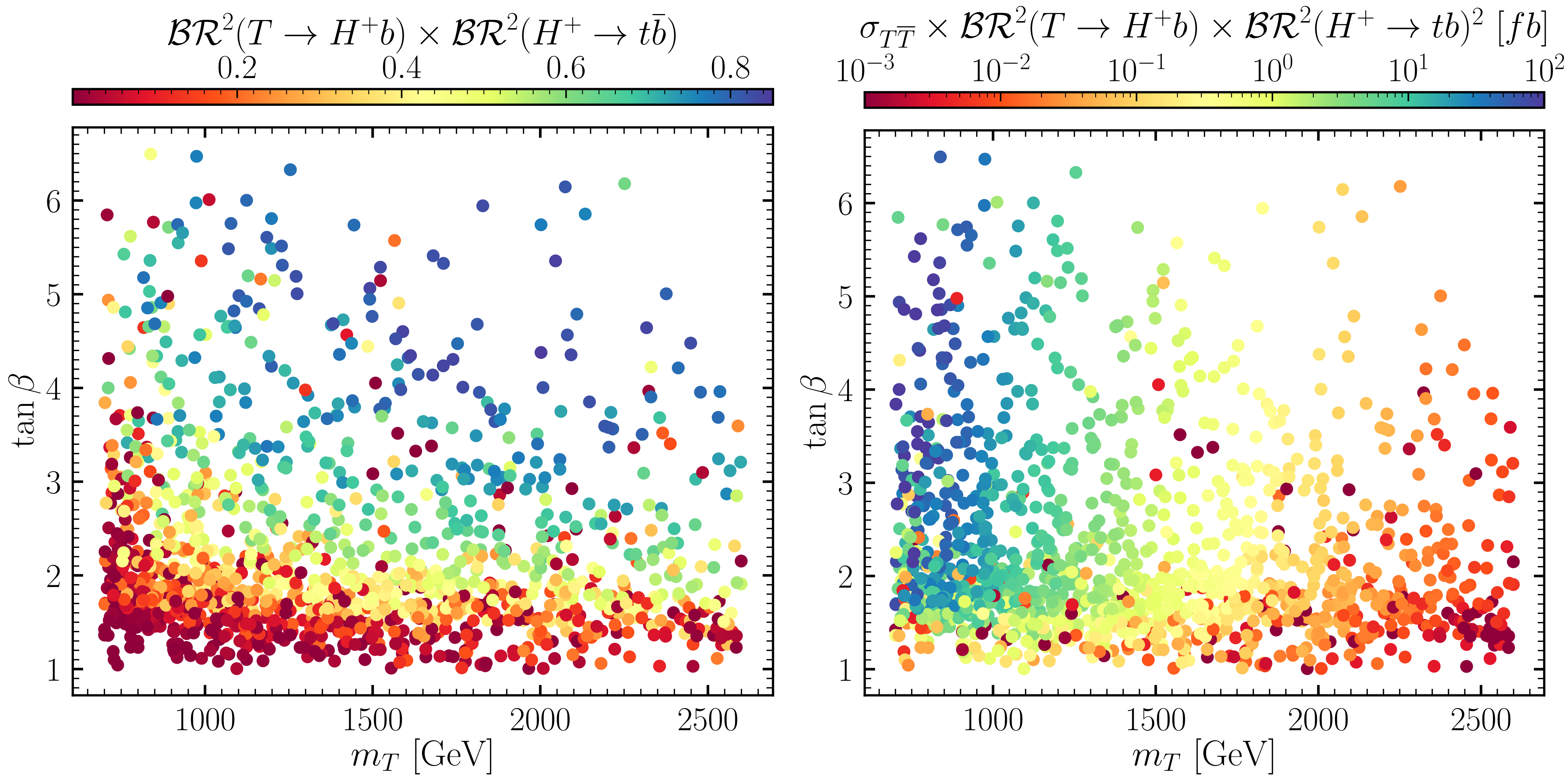


2HDM-II+TB Doublet Scenario

Parameters	Scanned ranges
2HDM	
m_H	$[130, 800]$
m_A	$[80, 800]$
$m_{H^\pm}$	$[80, 800]$
$\tan\beta$	$[0.5, 20]$
$\sin(\beta-\alpha)$	1
2HDM-II+(TB)	
$s_R^{u,d}$	$[-0.5, 0.5]$
m_T	$[750, 2600]$



2HDM-II+TB Doublet Scenario



✦ The signal $(4b2t)$ can exceed 100 fb for $m_T <= 1000$ GeV.

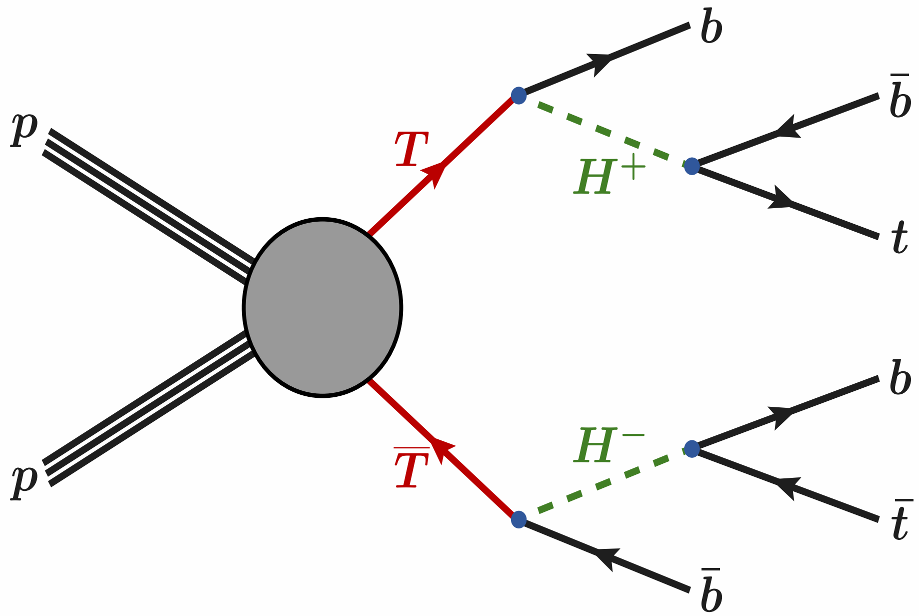
Conclusion

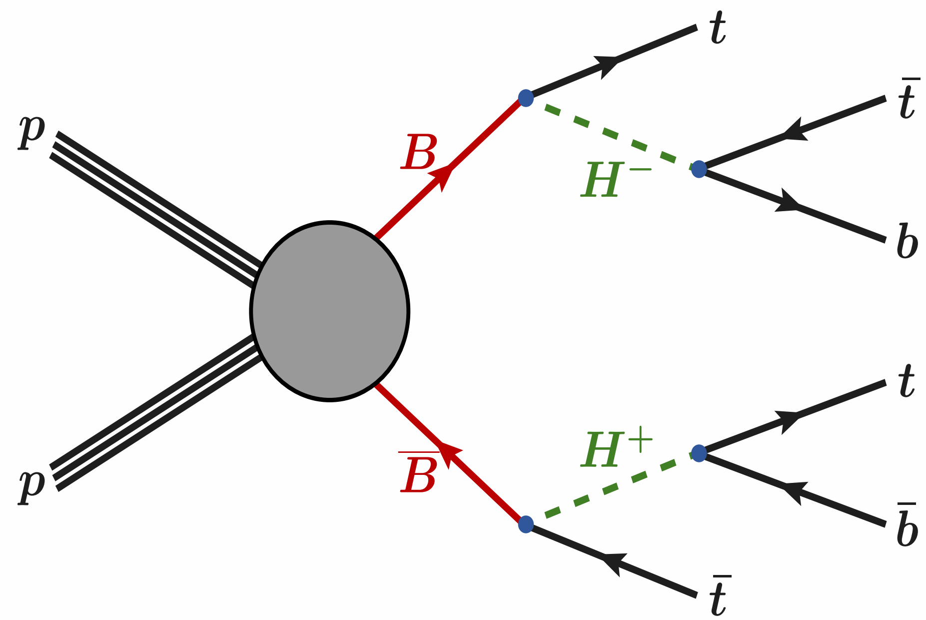
- In the doublet scenario (2HDM-II+(TB)), the charged Higgs mass limit is reduced to approximately 200 GeV (and 360 GeV after including EWPOs constraint).
- In the 2HDM-II+(TB) model, the branching ratio of $T \to H^+b$ is nearly 100%, while in the 2HDM-II+(T) model, it is only 25%.
- The decay of $H^\pm \to tb$ results in a final state with two top and four bottom quarks ($2t4b$), with the signal rate reaching up to 100 fb in the 2HDM-II+(TB) scenario.

Backup

VLT pair production at the LHC

A.Arhrib, R. Benbrik, M.Berrouj, M.B, B. Manaut [arXiv:2407.01348]





$pp \to T\bar{T} \to H^+ bH^- \bar{b} \to 2t4b,$ $\quad pp \to B\bar{B} \to H^- \bar{b}H^+ b \to 4t2b$

VLT pair production at the LHC

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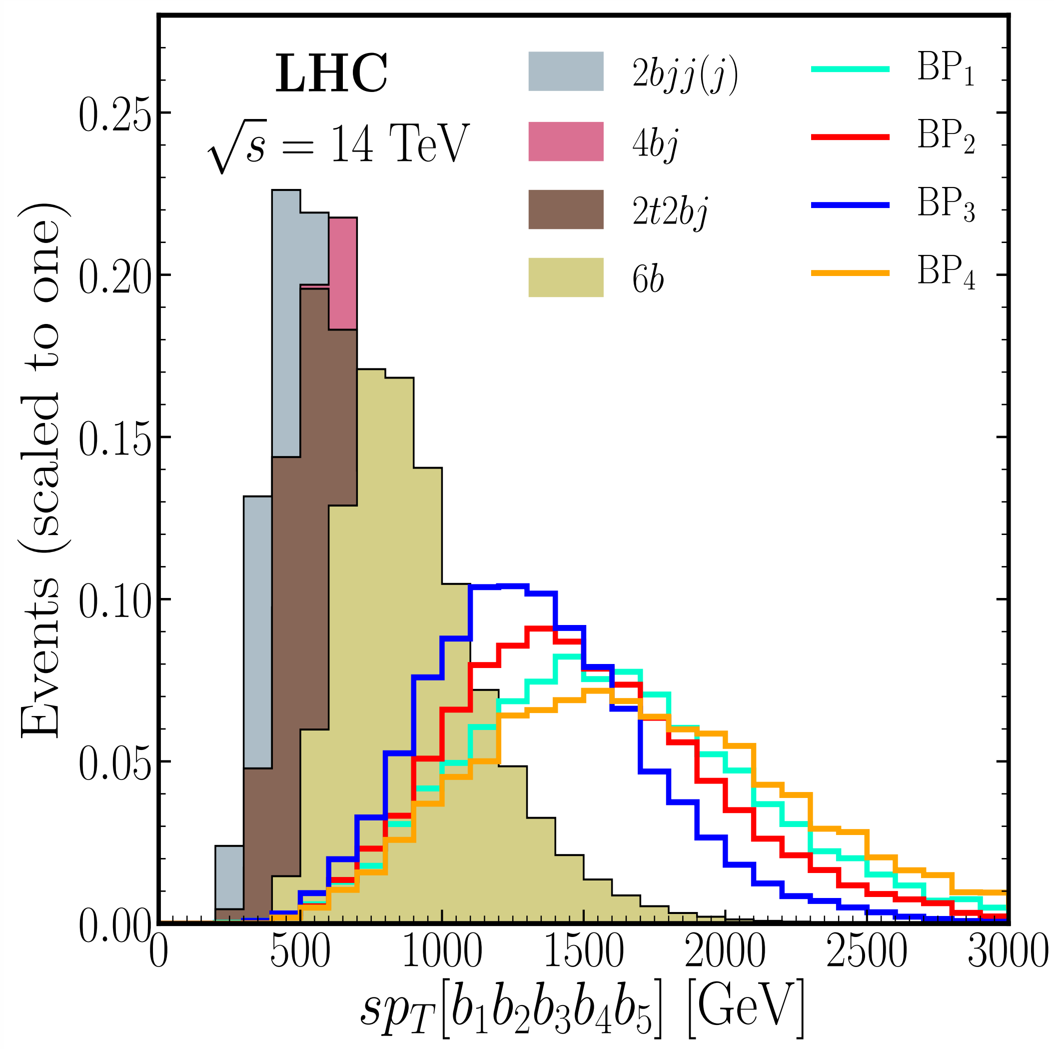


Cuts	Definition
Cut 1	$\Delta R(b,b) > 0.4 \quad , \quad \eta(b) < 2.5$
Cut 2	$sp_T > 1500$ GeV
Cut 3	$p_T^{b_4} > 120$ GeV

MC: VLT pair production at the LHC

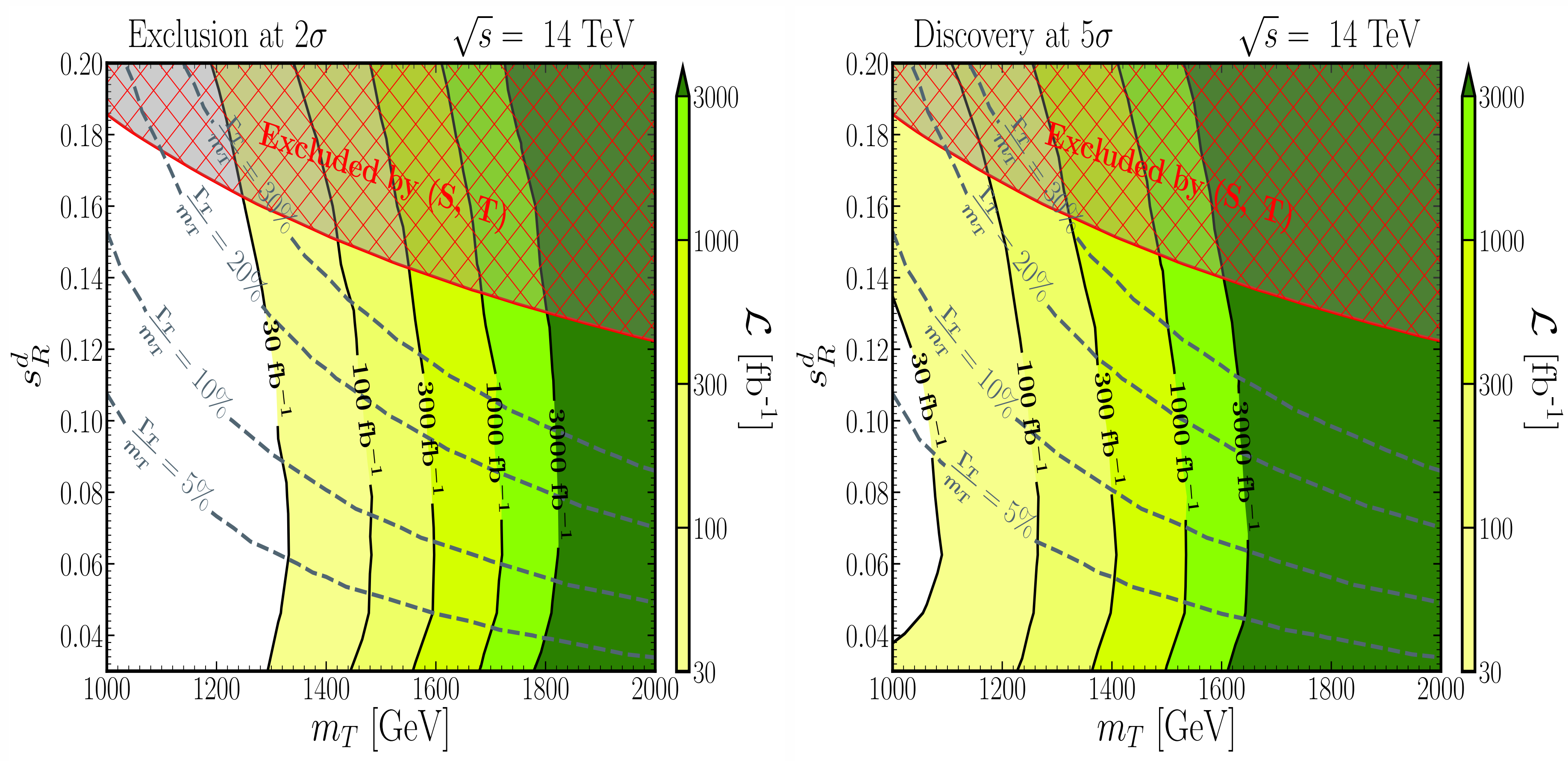
A.Arhrib, R. Benbrik, M.Berrouj, M.B, B. Manaut [arXiv:2407.01348]

$$\mathcal{Z}_{disc} = \sqrt{2\left[(s+b)\ln\left(\frac{(s+b)\left(1+\delta^2 b\right)}{b+\delta^2 b\,(s+b)}\right) - \frac{1}{\delta^2}\ln\left(1+\delta^2\frac{s}{1+\delta^2 b}\right)\right]}.$$

$$\mathcal{Z}_{excl} = \sqrt{2\left[s - b\ln\left(\frac{s+b+x}{2b}\right) - \frac{1}{\delta^2}\ln\left(\frac{b-s+x}{2b}\right)\right] - (b+s-x)\left(1+\frac{1}{\delta^2 b}\right)}.$$

with $x = \sqrt{(s+b)^2 - 4\delta^2 s b^2/\left(1+\delta^2 b\right)}$., In the limit of $\delta \to 0$, these expressions simplify to:

$$\mathcal{Z}_{disc} = \sqrt{2\left[(s+b)\ln\left(1+s/b\right) - s\right]}, \qquad \mathcal{Z}_{excl} = \sqrt{2\left[s - b\ln\left(1+s/b\right)\right]}.$$



MC: VLT pair production at the LHC

A.Arhrib, R. Benbrik, M.Berrouj,M.B, B. Manaut [arXiv:2407.01348]