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

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LHC HWG For BSM Higgs (WG3)
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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 $Q_Y = -\frac{4}{3}$.**

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:

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

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:

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

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

2HDM PARAMETRIZATION

- The most general scalar potential of the 2HDM :

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

with :

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

- Adopting the $\mathcal{CP}$-conserving, the 10 independent parameters ($m_{11}^2,\ m_{22}^2,\ m_{12}^2,\ \lambda_{1,\ldots,7}$) are assumed to be real.
- $\mathbb{Z}_2$ (Softly broken): Avoid the tree-level FCNCs $\Longrightarrow$ $\lambda_6 = \lambda_7 = 0$.
- After EWSB $\rightarrow$ 7 free parameters:
  - 4 Scalar physical states: $m_h,\ m_H,\ m_A,\ m_{H^\pm}$.
  - 2 mixing angels α, β, and m_{12}^2, (with $\tan\beta = \frac{v_2}{v_1}$ and $v^2 = v_1^2 + v_2^2 = (246\ \text{GeV})^2$).

ALIGNMENT LIMIT

- In the Higgs-basis the alignment limit is most clearly exhibited :

$$H_1 = \begin{pmatrix} H_1 \\ H_2 \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix} \Longrightarrow \langle H_1^0 \rangle = v/\sqrt{2},\ \langle H_2^0 \rangle = 0.$$

  with $\langle \Phi_i \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_i. \end{pmatrix}$

- The 2 physical Higgs states h et H are as follows:

$$\begin{aligned} H &= (\sqrt{2}\mathrm{Re}H_1^0 - v)\cos(\beta-\alpha) + \sqrt{2}\mathrm{Re}H_2^0\sin(\beta-\alpha) \\ h &= (\sqrt{2}\mathrm{Re}H_1^0 - v)\sin(\beta-\alpha) + \sqrt{2}\mathrm{Re}H_2^0\cos(\beta-\alpha) \end{aligned}$$

- $\cos(\beta-\alpha) \to 0$, $h \equiv H_{SM}$. (Standard hierarchy) [J. Bernon, J. F. Gunion, H. E. Haber, Y. Jiang and S. Kraml, Phys. Rev. D 92 (2015) no.7, 075004].
- $\sin(\beta-\alpha) \to 0$, $H \equiv H_{SM}$. (Inverted hierarchy) [J. Bernon, J. F. Gunion, H. E. Haber, Y. Jiang and S. Kraml, Phys. Rev. D 93 (2016) no.3, 035027].

CONSTRAINTS

Theoretical

- **Unitarity** constraints require a variety of scattering process to be unitary: specifically, the tree-level 2-to-2 body scattering matrix involving scalar-scalar, gauge–gauge and/or scalar-gauge initial and/or final states must have eigenvalues e_i's such that $|e_i| < 8\pi$.
- **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-2.6.1` [2012.09197] (P. Bechtle et al).
- **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-5.10.1` [2006.06007] (P. Bechtle et al).
- **B-physics observables** are tested against data by resorting to the public code `SuperIso_v4.1` (F. Mahmoudi [0808.3144]), (mainly $B \to X_s\gamma$, $B_{s,d} \to \mu^+\mu^-$ and $B_s \to \tau\nu$).

- The Lagrange density which defines the interactions of the charged Higgs boson with third generation of fermions can be written as:

$$-\mathcal{L}_{H^+} = \frac{\sqrt{2}}{v}\overline{U}\left(\kappa_U m_U V_{CKM} P_L - \kappa_D m_D V_{CKM} P_R\right) D H^+ + h.c. \quad (1)$$

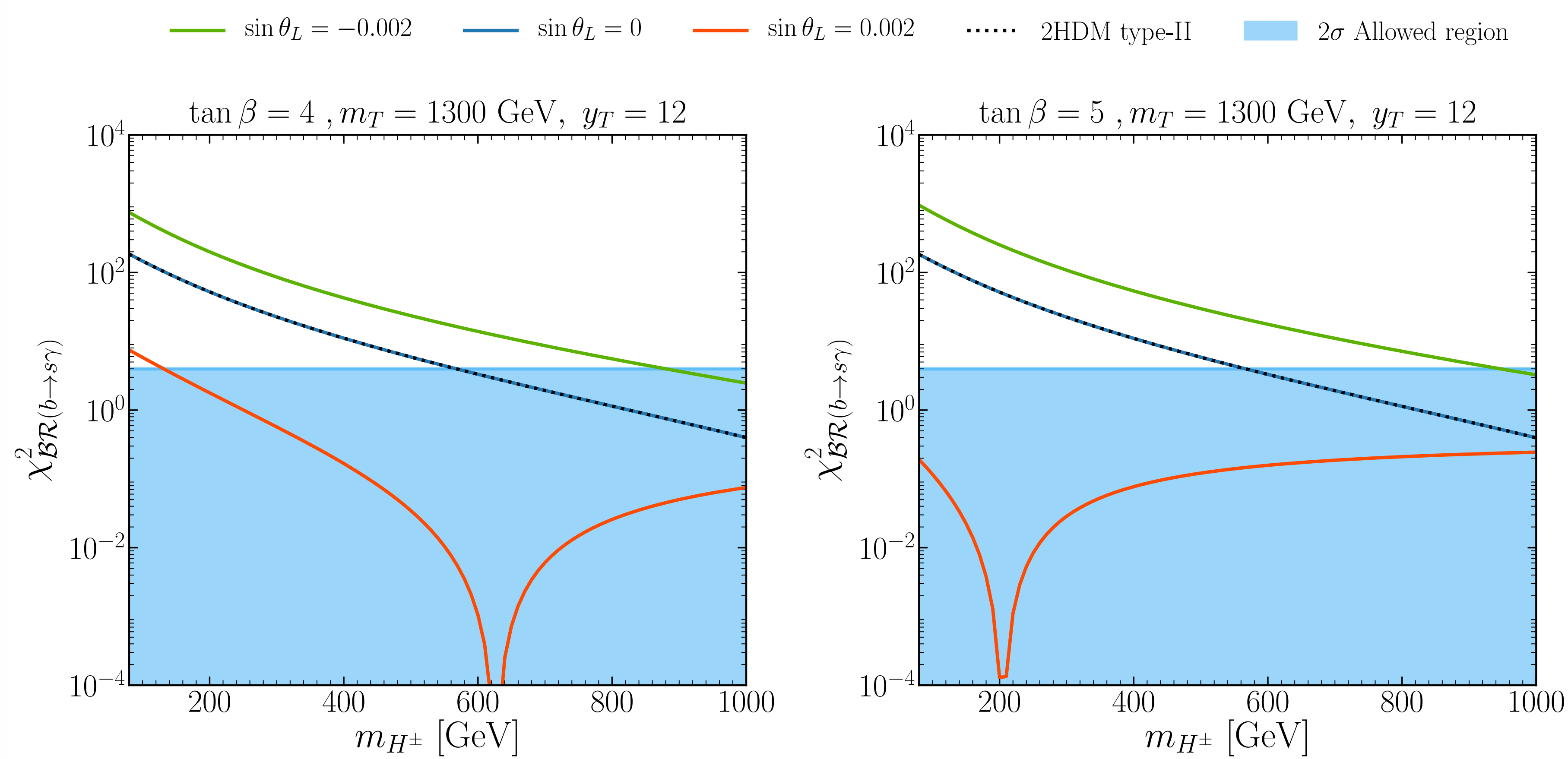
where $P_{L/R} = (1 \pm \gamma^5)/2$ are the chiral projection operators, U and D are the up- and down-type quarks with masses m_U and m_D while V_{CKM} represents the relevant Cabibbo-Kobayashi-Maskawa matrix element.

- For the 2HDM-II, 2HDM-II+T, and 2HDM-II+TB cases, the couplings κ_U and κ_D take the values:

Models	κ_U	κ_D
2HDM-II	$\cot\beta$	$-\tan\beta$
2HDM-II + T	$c_R c_L \cot\beta - s_R c_L \frac{y_T \times v}{\sqrt{2} m_t}$	$-\tan\beta$
2HDM-II + TB	${c_R^u}^2 \cot\beta$	$-{c_R^d}^2 \tan\beta$

Numerical results

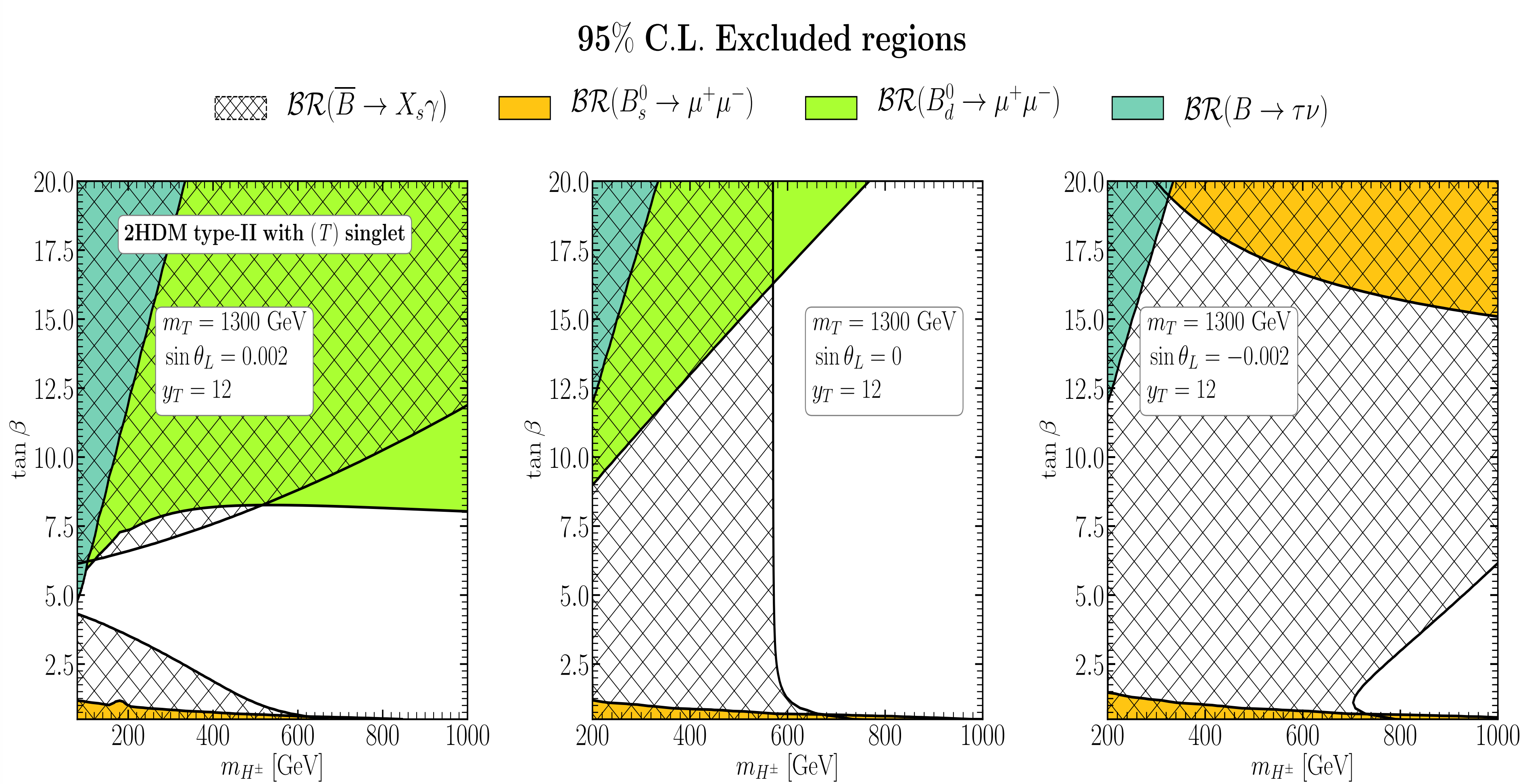
2HDM-II+ (T)



- For $4.5 \leq \tan\beta \leq 6$ and with $m_T = 1300,\ y_T = 12$ and $\sin\theta_L = 0.002$, the limit on $m_{H^\pm}$ can be reduced to something as light as $m_{W^\pm}$.

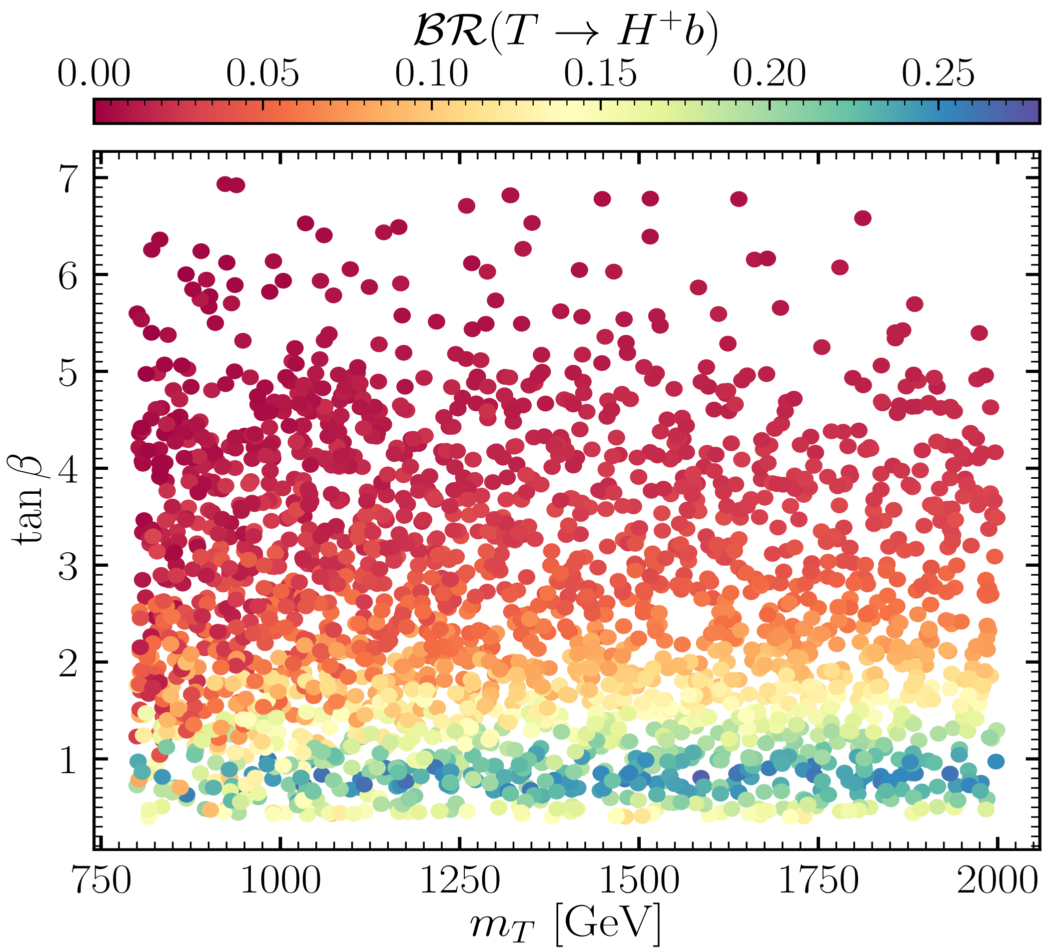
The full analytic calculation of VLQ contribution to the $b \to s\gamma$ transitions is in progress

2HDM-II+ (T)



✦ In the limit $\sin\theta_L = 0$, we recover the 2HDM framework.

2HDM-II+ (T)

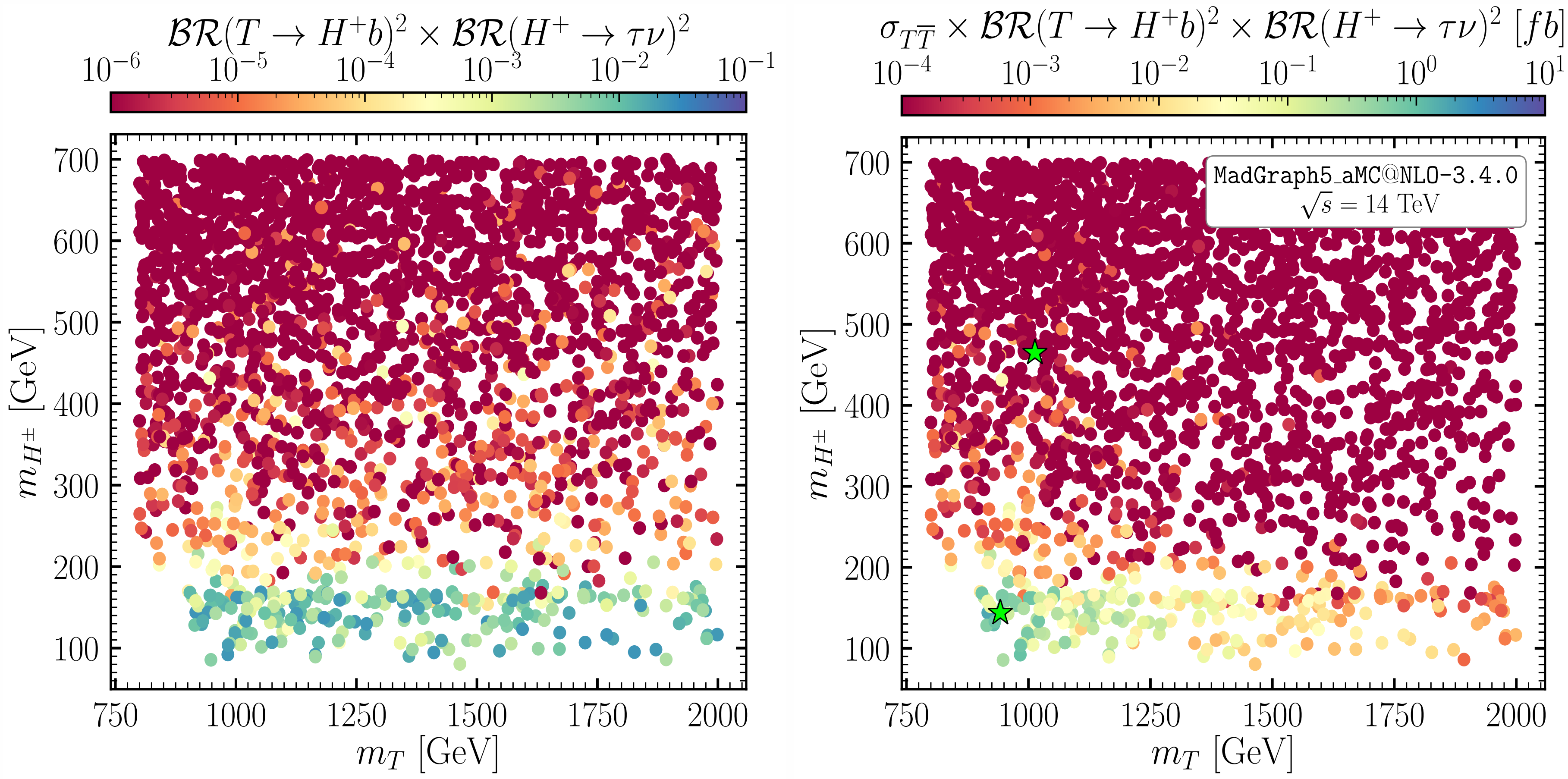


- $\mathcal{L}_{H^+} = -\frac{g m_T}{\sqrt{2} M_W} \overline{T} (\cot\beta Z^L_{Tb} P_L + \tan\beta Z^R_{Tb} P_R) b H^+ + H.c.$, with $Z^L_{Tb} = s^u_L$ and $Z^R_{Tb} = 0$.
- $\mathcal{BR}(T \to H^+ b)$ could reach 28% for small $\tan\beta$ values.

For more details on the T decay channels see Abdesslam's talk

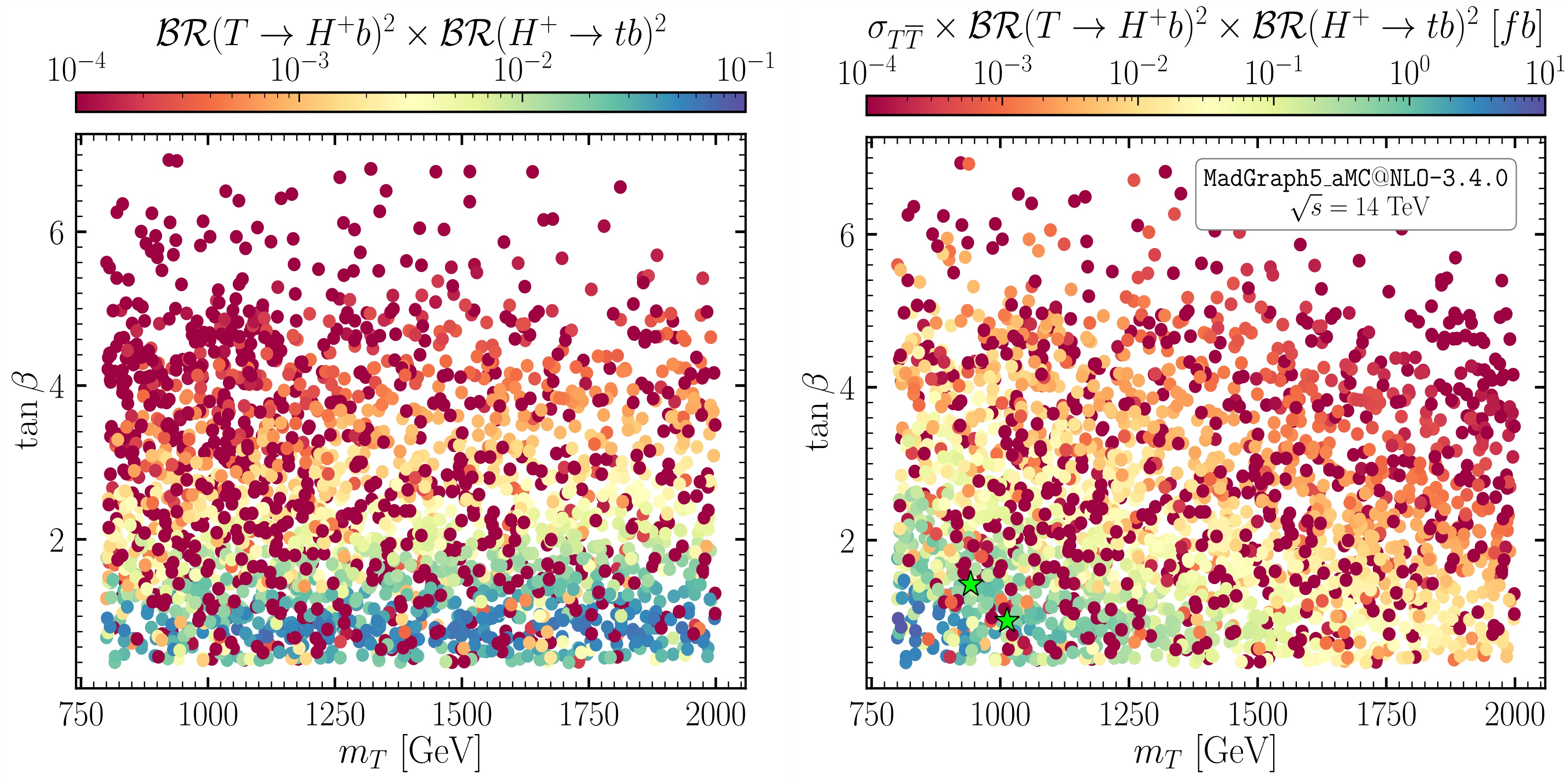
[A. Arhrib, R. Benbrik, MB, R. Enberg, B. Manaut, S. Moretti, L. Panizzi and S. Taj] Work in progress

2HDM-II+ (T)



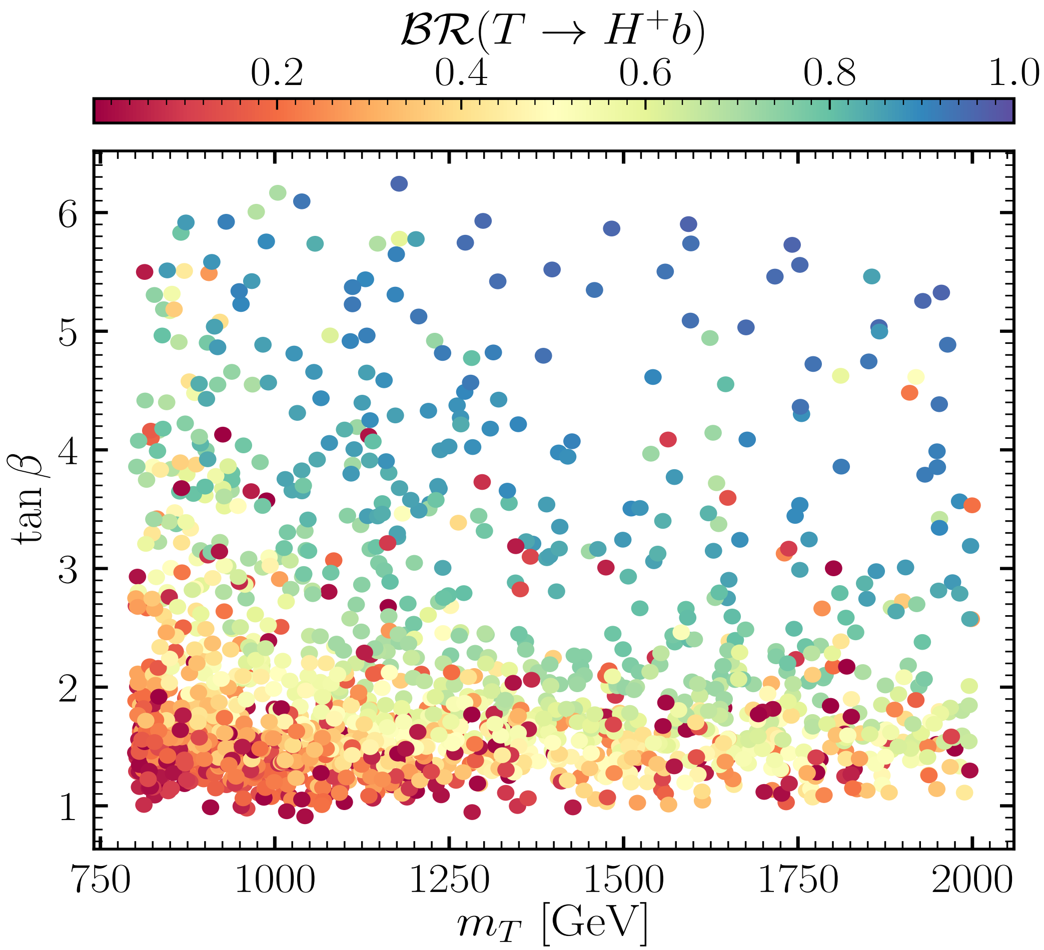
✦ The signal $(\tau\tau\nu\nu + X)$ can enjoy a cross section of the order 1–8 fb for $m_T < 1200$.

2HDM-II+ (T)



✦ The signal $(ttbb + X)$ can exceed 10 fb for $m_T < 1000$ GeV and for small $\tan\beta$ values.

2HDM-II+ (TB)

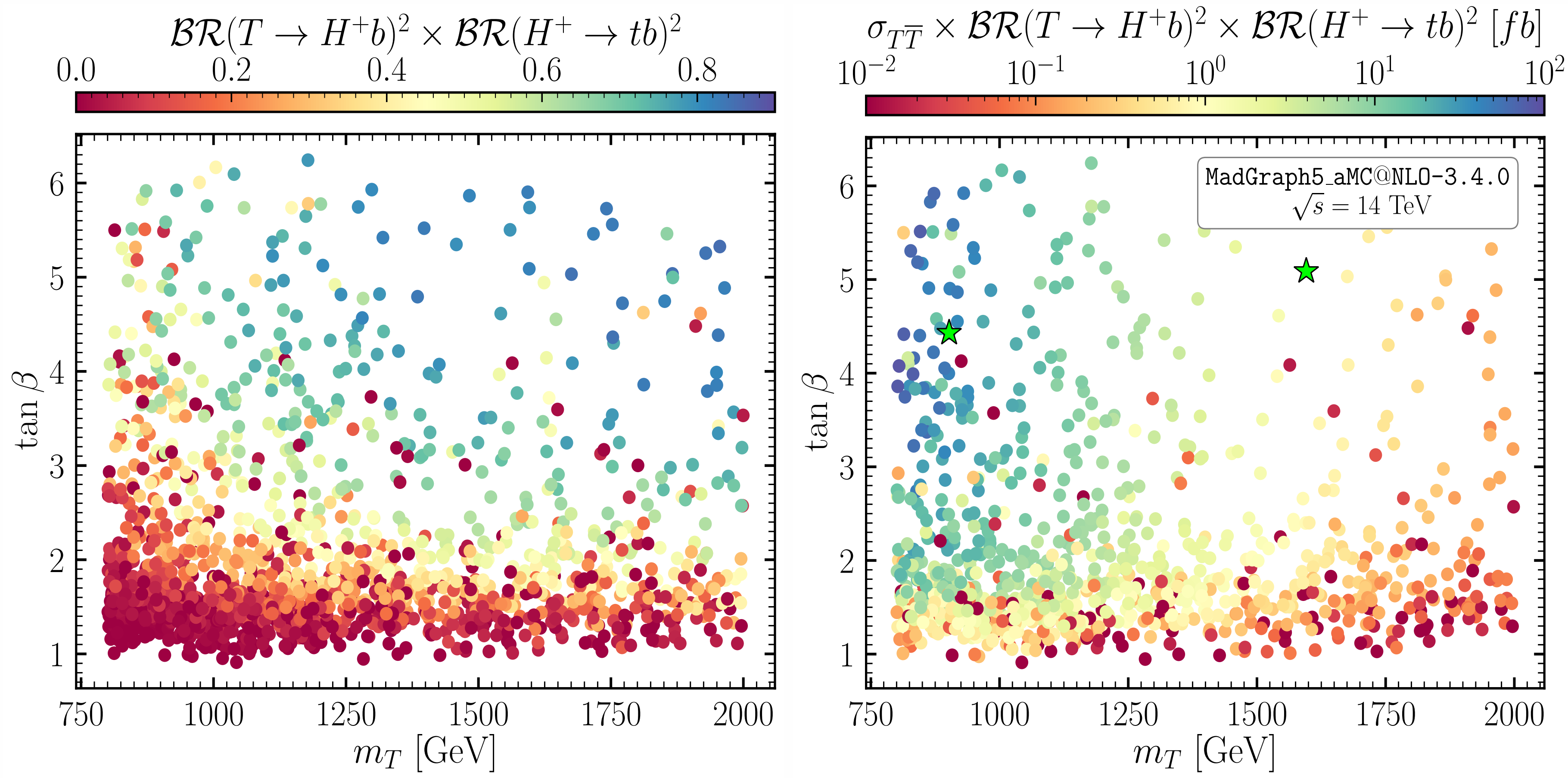


- $\mathcal{L}_{H^+} = -\frac{g m_T}{\sqrt{2} M_W} \overline{T} (\cot\beta Z^L_{Tb} P_L + \tan\beta Z^R_{Tb} P_R) b H^+ + H.c.,$

  with: $Z^L_{Tb} = c^d_L s^u_L e^{-i\phi_u} + ({s^u_L}^2 - {s^u_R}^2) \frac{s^d_L}{c^u_L} e^{-i\phi_d}$ and $Z^R_{Tb} = \frac{m_b}{m_T} \left[c^d_L s^u_L e^{-i\phi_u} + ({s^d_R}^2 - {s^d_L}^2) \frac{c^u_L}{s^d_L} e^{-i\phi_d} \right]$

- $\mathcal{BR}(T \to H^+ b)$ could reach 100% for medium $\tan\beta$ values.

2HDM-II+ (TB)



✦ The signal $ttbb + X$ could reach values up to 100 fb for medium $\tan\beta$ and for $m_T \leq 1000$ GeV.

BENCHMARK POINTS

Parameters	2HDM-II+T BP$_1$	2HDM-II+T BP$_2$	2HDM-II+TB BP$_1$	2HDM-II+TB BP$_2$
m_h	125	125	125	125
m_H	208.74	451.66	593.30	582.40
m_A	186.93	565.47	582.15	574.28
$m_{H\pm}$	143.95	464.90	596.13	647.32
$\tan\beta$	1.42	0.95	4.43	5.09
m_T	942.33	1013.28	902.07	1595.80
m_B	–	–	913.55	1602.35
$\sin(\theta)^u_L$	-0.0272	0.0520	0.0141	-0.0037
$\sin(\theta)^d_L$	–	–	-0.0009	-0.0003
$\sin(\theta^u)_R$	–	–	0.0737	-0.0345
$\sin(\theta^d)_R$	–	–	-0.1735	-0.0966
y_T	-4.92	3.66	–	–
$\mathcal{BR}(H^\pm \to XY)$ in %				
$\mathcal{BR}(H^+ \to t\bar{b})$	0.21	98.34	98.01	96.12
$\mathcal{BR}(H^+ \to \tau\nu)$	83.97	0.88	1.79	3.03
$\mathcal{BR}(T \to XY)$ in %				
$\mathcal{BR}(T \to W^+b)$	36.86	29.33	13.59	5.21
$\mathcal{BR}(T \to Zt)$	16.62	13.39	1.09	0.32
$\mathcal{BR}(T \to ht)$	20.67	16.19	1.38	0.35
$\mathcal{BR}(T \to Ht)$	4.74	13.44	–	–
$\mathcal{BR}(T \to At)$	3.72	7.19	–	–
$\mathcal{BR}(T \to H^+b)$	17.39	20.45	83.94	94.12
Γ in GeV				
$\Gamma(T)$	0.55	3.15	53.43	238.85
σ [fb]				
$\sigma_{T\overline{T}} \times \mathcal{BR}(T \to H^+b)^2 \times \mathcal{BR}(H^+ \to \tau\nu)^2$	0.00	1.44	0.02	0.00
$\sigma_{T\overline{T}} \times \mathcal{BR}(T \to H^+b)^2 \times \mathcal{BR}(H^+ \to t\bar{b})^2$	1.23	0.00	51.18	1.08

Conclusion

- Contrary to the SM+VLQ, the $\mathcal{BR}$ of new top T may decay into $H^{\pm}b$.
- The presence of Vector-Like Quarks with quantum numbers identical to the top-quark ones alongside the 2-Higgs Doublet Model Type-II allow the charged Higgs boson $H^{\pm}$ to be very light .
- Search for new exotic quark can be done via charged Higgs.

Thank You For Listening!