Vector-Like Top-Quark Models in the Alignment Limit of the 2-Higgs Doublet Model Type-II

Abdesslam Arhrib

Faculté des Sciences et Techniques Tangier, Morocco

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Work in progress in collaboration with
R. Benbrik, M. Boukidi, B. Manaut, R. Enberg, S. Moretti and L. Panizzi

Outlines

- 2HDM+VLQ and EWPT
- New Top decays in 2HDM+VLQ: Singlet T, Doublet TB and TBY triplet
- Conclusions

- Many BSM predicts an extended scalar sector , and also an extended fermion sector.
- Extended scalar sector already extensively studied.
- VLQs are heavy spin 1/2 particles that transform as triplets under colour but, unlike SM quarks, their left- and right-handed components have the same Electro-Weak (EW) quantum numbers.
- Their couplings to Higgs bosons do not participate in the EWSB dynamics onset by the Higgs mechanism, hence they are not of Yukawa type (i.e., proportional to the mass), rather they are additional parameters,

Five Top-Quark Models

$$
\begin{array}{ll}
T^0_{L,R} & \text{(singlet)}\,, \\
(T^0\, B^0)_{L,R}\,, \quad (X^0\, T^0)_{L,R} & \text{(doublets)}\,, \\
(X^0\, T^0\, B^0)_{L,R}\,, \quad (T^0\, B^0\, Y^0)_{L,R} & \text{(triplets)}\,.
\end{array}
$$

- They have spin 1/2 and belong into $SU(3)$,
- They can be isospin singlets, doublets or triplet.
- They can mix with SM fermions and also with 2HDM Higgses,
- They 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 formalism

$$-\mathcal{L} \supset y^u \bar{Q}_L^0 \tilde{H}_2 u_R^0 + y^d \bar{Q}_L^0 H_1 d_R^0 + M_u^0 \bar{u}_L^0 u_R^0 + M_d^0 \bar{d}_L^0 d_R^0 + \mathrm{h.c.} \quad (1)$$

u_R runs over (u_R, c_R, t_R, T_R) and $d_R \to (d_R, s_R, b_R, B_R)$.
In the weak eigenstate basis, the VLQs mass terms

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

- Singlet & Triplets: $y_{43}^q = 0$.
- Doublet $y_{34}^q = 0$.

VLQ formalism

The 2×2 unitary matrices $U^u_{L,R}$ define the relation between the weak and mass eigenstates:

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

- Doublets:

$$(T\ B) : m_T^2 (c_R^u)^2 + m_t^2 (s_R^u)^2 = m_B^2 (c_R^d)^2 + m_b^2 (s_R^d)^2$$

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

- Triplets:

$$(X\ T\ B) : \quad m_X^2 = m_T^2 (c_L^u)^2 + m_t^2 (s_L^u)^2 = m_B^2 (c_L^d)^2 + m_b^2 (s_L^d)^2$$

$$\sin(2\theta_L^d) = \sqrt{2}\frac{m_T^2 - m_t^2}{(m_B^2 - m_b^2)} \sin(2\theta_L^u)$$

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

2HDM formalism

We consider two complex doublets Φ_1 and Φ_2 with the same hyper-charge $Y = +1$.
The most general potential for 2HDM:

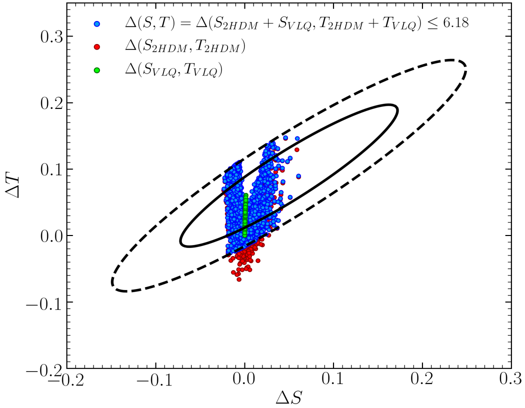
$$\begin{aligned}\mathcal{V} &= m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - \left(m_{12}^2\Phi_1^\dagger\Phi_2 + \mathrm{h.c.}\right) \\ &+\frac{\lambda_1}{2}\left(\Phi_1^\dagger\Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_2^\dagger\Phi_2\right)^2 \\ &+\lambda_3\Phi_1^\dagger\Phi_1\Phi_2^\dagger\Phi_2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

- $\boldsymbol{m_{12}^2}$ and $\boldsymbol{\lambda_5}$ could be complex.
- $\mathbb{Z}_2$ symmetry softy broken by dimension 2 terms (No FCNC at the tree level)
- After **EWSB**: m_h, m_H , m_A, $m_{H^\pm}$, α, $\tan\beta$ and m_{12}^2.

THEORETICAL AND EXPERIMENTAL CONSTRAINTS

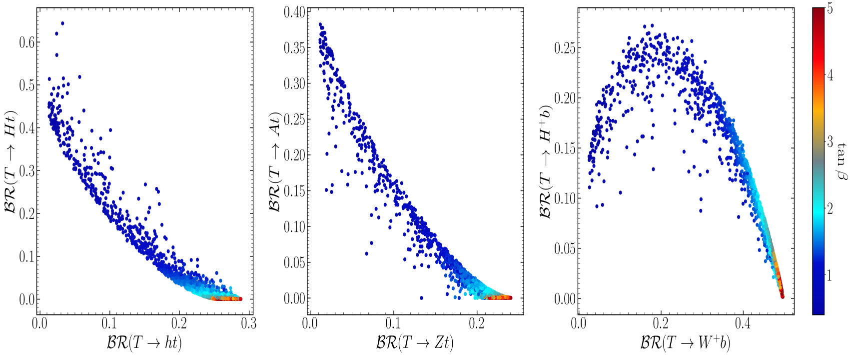
- **2HDMC (D. Eriksson, J. Rathsman and O. Stal)**
  - Unitarity, Perturbativity, Vacuum Stability.
  - EW Precision Observables (S, T) : new calculation $\Delta\chi^2(S_{VLQ} + S_{2HDM},\ T_{VLQ} + T_{2HDM}) \leq 6.18$ is required.
- **HB (P. Bechtle et al), and HS (P. Bechtle et al)**
  - Exclusion limits at 95% Confidence Level (CL) from Higgs searches at colliders (LEP, Tevatron and LHC).
  - Constraints from the Higgs boson signal strength measurements (SM-like Higgs properties).
- **SuperIso (F. Mahmoudi)**
  - Constraints of flavour physics observables ($B \to X_s\gamma,\ B_{s,d} \to \mu^+\mu^-$ and $B_s \to \tau\nu$).

- The Allowed points by all constraints (Blue $\Delta\chi^2(S_{Tot},\ T_{Tot}) \le 6.18$).

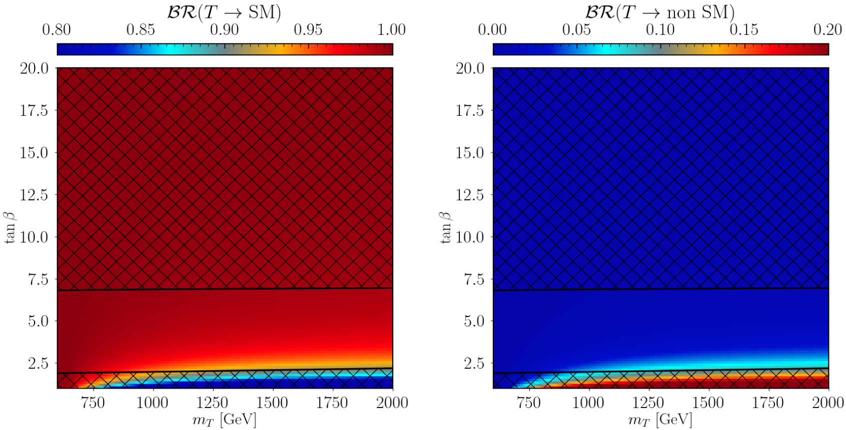


2HDM+T

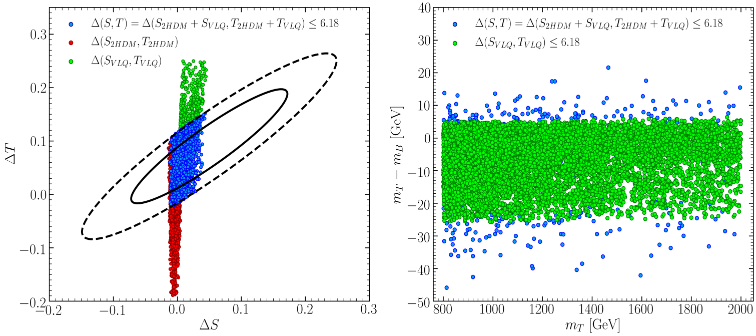
- The BR's of $T \to Wb, Zt, ht$ are approximatively around 50%, 25% and 25%, respectively.
- Recently, a search has been presented by CMS and ATLAS for VLQs from $T\bar{T}$ pair production and masses up to 1.54 TeV are excluded at 95% CL for vector-like T and B quarks.



- For $\tan\beta \geq 2$, $\mathcal{BR}(T \to SM)$ is substantial.

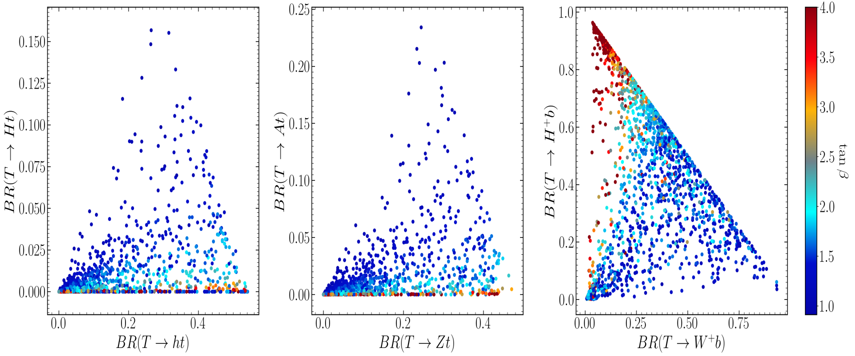


2HDM+TB

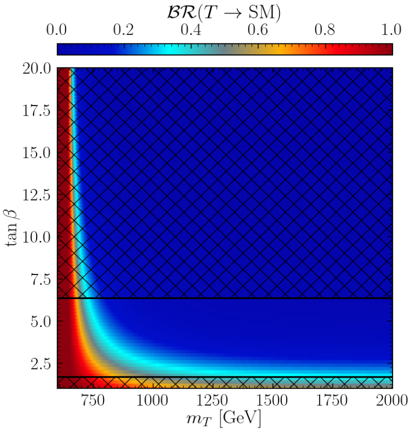


$\Delta(S,T) = \Delta(S_{2HDM} + S_{VLQ}, T_{2HDM} + T_{VLQ}) \le 6.18$
$\Delta(S_{2HDM}, T_{2HDM})$
$\Delta(S_{VLQ}, T_{VLQ})$
ΔT
ΔS
$\Delta(S,T) = \Delta(S_{2HDM} + S_{VLQ}, T_{2HDM} + T_{VLQ}) \le 6.18$
$\Delta(S_{VLQ}, T_{VLQ}) \le 6.18$
$m_T - m_B$ [GeV]
m_T [GeV]

- For medium $\tan\beta$ values, $\mathcal{BR}(T \to H^+ b)$ could reach more than 80%.

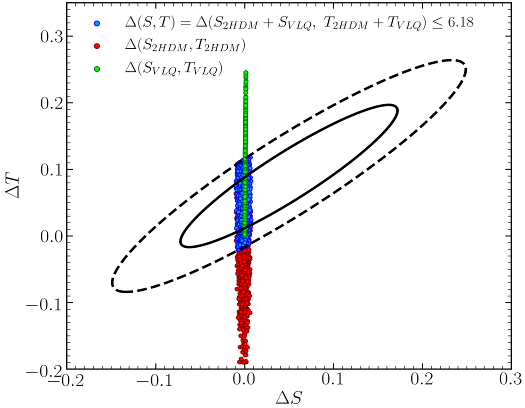


- For $m_T \geq 800$, $\mathcal{BR}(T \to \text{Non SM})$ is substantial.



2HDM+*TBY*

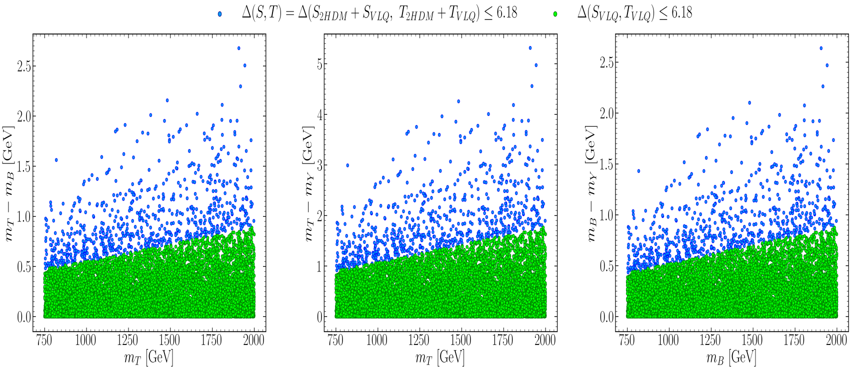
- The Allowed points by all constraints (Blue $\Delta\chi^2(S_{Tot}, \ T_{Tot}) \leq 6.18$)



- m_B and m_Y are derived quantities:

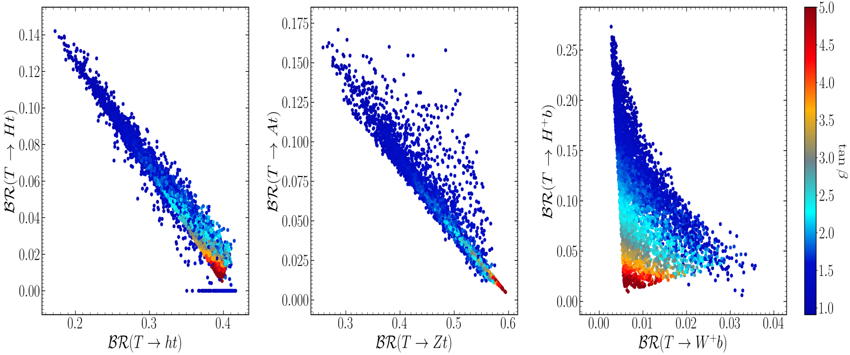
$$m_Y^2 = m_T^2 \cos^2\theta_L^t + m_t^2 \sin^2\theta_L^t$$

$$m_B^2 = \frac{1}{8}\sin^2 2\theta_L^t \frac{(m_T^2 - m_t^2)^2}{m_Y^2 - m_b^2} + m_Y^2.$$



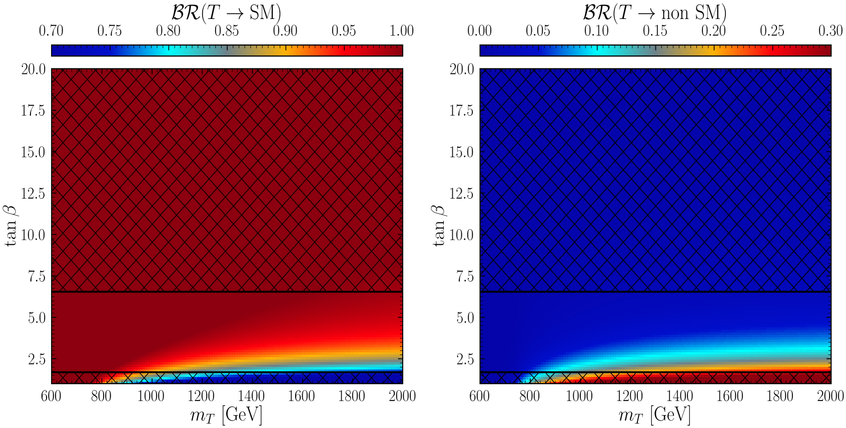
2HDM+*TBY*

- For medium $\tan\beta$ values, $\mathcal{BR}(T \to Zt)$ is about 60%.



2HDM+TBY

- For $\tan\beta \geq 2$, $\mathcal{BR}(T \to SM)$ is substantial.



Conclusions

- we have proceeded to study the standard decays $T \to Wb, Zt, h^0 t$ as well as the exotic ones $T \to H^+ b, A^0 t, H^0 t$ (where H^+,A and H are the heavy Higgs states of the 2HDM).
- EWPOs (i.e., the S, T and U parameters) for 2HDM+VLQ enables one to access a much wider expanse of parameter space than would otherwise be possible with 2HDM alone or VLQ alone.
- This opens up parameter space regions wherein T as well as H^+, A^0 and H^0 particles can be light enough to be pursued in direct searches at the LHC.