Exotic decays of top partner in 2HDM

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Outline

Motivation for VLQs

- The discovery of the Higgs boson by both ATLAS and CMS in 4th July 2012 is a good opportunity to search for a possible extended EW Syemmetry Breaking sector. Indeed, several theoretical models addressing the hierarchy problem, like Supersymmetry or composite Higgs models which predict the existence of additional Higgs scalars.
- So far, various measurements from experimentals side looks in a very good agreements with the SM predictions. The SM provides an excellent description of fundamental physics at the electroweak scale. It may persist as a good effective field theory.
- Another class of models, called vector-like quark (exotic), requires the presence of fermionic partners of the top-bottom quarks. Aguilar Juan Antonio et al. ,2013

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The Higgs sector beyond the Standard Model

ρ parameter can be computed easily for any set of complex scalar multiplets with vev v_i, isospins I_i and hypercharges Y_i.

$$\rho = \frac{\sum_i v_i^2 \left(4I_i(I_i+1) - |Y_i|^2\right)}{2\sum_i v_i^2 |Y_i|^2} = 1. \tag{1}$$

$$(2I_i+1)^2 - 3|Y_i|^2 = 1. \quad \forall i. \tag{2}$$

- Neutral singlet : $(I_i, Y) = (0{,}0)$
- Doublet : $(1/2, \pm 1)$ (doublet)
- There are other solutions.

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Two Higgs Doublets Model (2HDM)

We consider two complex doublets Φ_1 and Φ_2 with the same hypercharge $Y = +1$.

$$\Phi_i = \begin{pmatrix} \phi_i^+ \\ \phi_i^0 \end{pmatrix} = \begin{pmatrix} \phi_i^+ \\ \frac{1}{\sqrt{2}}\left(v_i + \eta_i^0 + i a_i\right) \end{pmatrix} \; ; \quad i = 1, 2 \tag{3}$$

The most general potential for 2HDM:

$$\begin{aligned} V(\Phi_1, \Phi_2) &= m_1^2 \Phi_1^\dagger \Phi_1 + m_2^2 \Phi_2^\dagger \Phi_2 + (m_{12}^2 \Phi_1^\dagger \Phi_2 + \mathrm{h.c}) \\ &+ \frac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2 \\ &+ \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \\ &+ \frac{1}{2}[\lambda_5 (\Phi_1^\dagger \Phi_2)^2 + (\lambda_6 \Phi_1^\dagger \Phi_1 + \lambda_7 \Phi_2^\dagger \Phi_2)\Phi_1^\dagger \Phi_2 + \mathrm{h.c.}], \end{aligned} \tag{4}$$

- m_{12}^2 and λ_5 could be complex.
- $\mathbb{Z}_2$: $\Phi_i \to (-)^i \Phi_i \Leftrightarrow \lambda_{6,7} = 0$ (No FCNC at the tree-level)

Two Higgs Doublets Model (2HDM)

The two complex scalar doublets $\Phi_{1,2}$ may be rotated into a basis, $H_{1,2}$, where only one obtains a Vacuum Expectation Value (VEV) :

$$H_1 = \begin{pmatrix} G^+ \\ \frac{v+\phi_1^0+iG^0}{\sqrt{2}} \end{pmatrix} \quad ; \quad H_2 = \begin{pmatrix} H^+ \\ \frac{\phi_2^0+iA}{\sqrt{2}} \end{pmatrix} \tag{5}$$

where $\phi_{1,2}^0$ may be rotated as:

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} s_{\beta-\alpha} & c_{\beta-\alpha} \\ c_{\beta-\alpha} & -s_{\beta-\alpha} \end{pmatrix} \begin{pmatrix} \phi_1^0 \\ \phi_2^0 \end{pmatrix} \tag{6}$$

We left with two CP-even (h, H) one CP-odd (A) and a pair of charged Higgs ($H^\pm$). In addition, we used as input parameter $\tan\beta$, $\sin(\beta-\alpha)$ and m_{12}^2.

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Models

	Singlet		Doublet			Triplet	
	T	B	$\begin{pmatrix} T \\ B \end{pmatrix}$	$\begin{pmatrix} X \\ T \end{pmatrix}$	$\begin{pmatrix} B \\ Y \end{pmatrix}$	$\begin{pmatrix} X \\ T \\ B \end{pmatrix}$	$\begin{pmatrix} T \\ B \\ Y \end{pmatrix}$
Q	$\mathbf{2/3}$	$\mathbf{-1/3}$	$\mathbf{1/6}$	$\mathbf{7/6}$	$\mathbf{-5/6}$	$\mathbf{2/3}$	$\mathbf{-1/3}$

Francisco del Aguila *et al* JHEP 0009 (2000)

- They have spin $1/2$ and belong into $SU(3)_c$;
- They can mix with 2HDM Higgses;
- They can be isospin singlets, doublets or triplet.
- The electric charges of the new VLQs are $Q_T = 2/3$, $Q_B = -1/3$, $Q_X = 5/3$ and $Q_Y = -4/3$

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Yukawa interactions

2HDM + (T) Singlet :

$$-\mathcal{L}_Y^{II} \supset y_t \overline{q}_L^0 \widetilde{\Phi}_1 t_R^0 + y_t \cot\beta \overline{q}_L^0 \widetilde{\Phi}_2 t_R^0 + \xi_T \overline{q}_L^0 \widetilde{\Phi}_1 T_R^0 + y_T \overline{q}_L^0 \widetilde{\Phi}_2 T_R^0 + M \overline{T}_L^0 T_R^0 + h.c \quad (7)$$

These parameters are not physical, we rotate them into physical basis and we get :

$$\tan(2\theta_L) = \frac{\sqrt{2} M v \xi_T}{M^2 - \frac{y_T^2 v^2}{2} - \frac{\xi_T^2 v^2}{2}} \quad ; \quad \tan(2\theta_R) = \frac{y_T \xi_T v^2}{M^2 - \frac{y_T^2 v^2}{2} - \frac{\xi_T^2 v^2}{2}} \quad (8)$$

$$m_T^2 + m_t^2 = M^2 + \frac{y_t^2 v^2}{2} + \frac{\xi_T^2 v^2}{2} \quad ; \quad \frac{y_t^2 v^2 M^2}{2} = m_t^2 m_T^2 \quad (9)$$

$$M^2 = m_t^2 \sin^2(\theta_L) + m_T \cos^2(\theta_L), \quad (10)$$

$$\tan(\theta_L) = \frac{m_t}{m_T} \tan(\theta_R) \quad ; \quad \frac{\xi_t}{y_t} = s_L c_L \frac{m_T^2 - m_t^2}{m_T m_t}, \quad (11)$$

Results and discussion

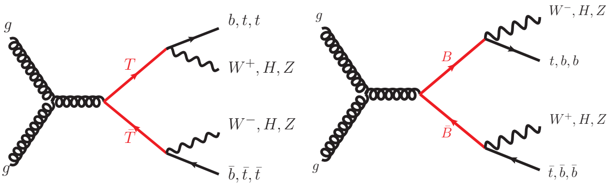

Figure: 1 Pair production of VLQs at LHC at tree-level

- In the SM with additional singlet top : $T \to W^+b$, $T \to tH$, $T \to tZ$

$BR(T \to W^+b) + BR(T \to tH) + BR(T \to tZ) =: 50\% : 25\% : 25\%$

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Results and discussion

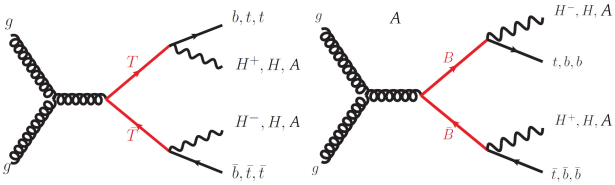

Figure: 2 Pair production of VLQs at LHC at tree-level

- In 2HDM, $T \to H^+ b,\ T \to t\phi : (\phi = H, A)$

$$BR(T \to SM) + BR(T \to 2HDM) = 100\%$$

with

$$BR(T \to 2HDM) = BR(T \to bH^+) + BR(T \to tH) + BR(T \to tA)$$

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Results and discussion

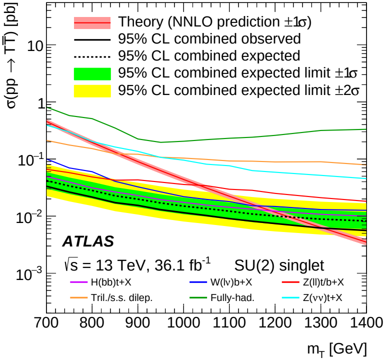

Figure: 3 Limits from ATLAS at run 2 on VLQ mass

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Results and discussion

In this talk, we will study the phenomenological decay of new top T in the alignement limit ($\cos(\beta - \alpha)=0$)

$$\kappa^{h}_{Tt} = \frac{c_L s_L}{m_T}(m_t P_L + m_T P_R)$$

$$\kappa^{H}_{Tt} = \frac{c_L s_L \cot\beta}{m_T}(m_t P_L + m_T P_R)$$

$$\kappa^{A}_{Tt} = -\frac{c_L s_L \cot\beta}{m_T}(m_t P_L + m_T P_R)$$

It is clear that when $s_L \to 0$, all those coupllings vanish and we recover 2HDM framework.

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Results and discussion

We have used the following public codes which respect most of the theoretical and experiemtal constraints, that are:

- 2HDMC-1.7.0 (BFB, Unitarity, Vacuum stability)
- HiggsBounds-5 and HiggsSignals-2 (Run 2)
- S, T and U oblique parameters
- $B \to X_s \gamma$ constraint

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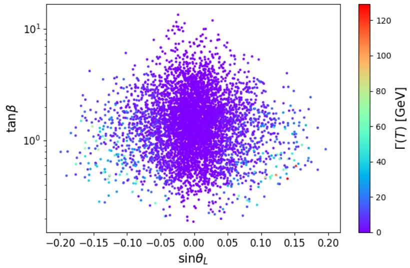
Results and discussion



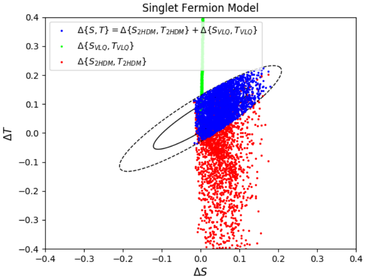


Figure: 4 Results in $(s_L, \tan\beta)$ plane.

- Right plot: blue points are the allowed region by imposing S, T parameters.
- Left plot: the surviving points in $(s_L, \tan\beta)$ plane, mapped with total $\Gamma(T)$ of the new top.
- It is clear that the points with small $\Gamma(T)$ are the most dominate.

Results and discussion

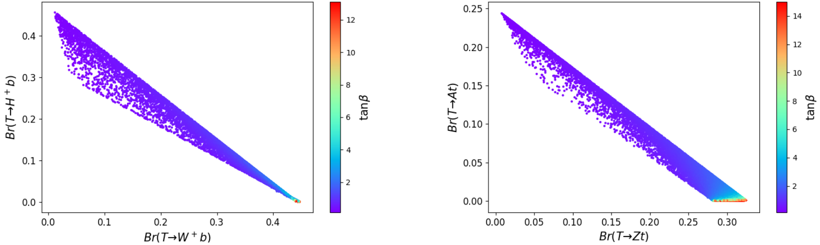


Figure: 5 Correlations between W^+b and H^+b in the left and Zt with At in the T-singlet model

- For $\tan\beta \geq 10$, $BR(T \to W^+b)$ is about 50%
- However, for $\tan\beta < 4$: when $BR(T \to H^+b)$ increases the $BR(T \to W^+b)$ decreases.

Results and discussion

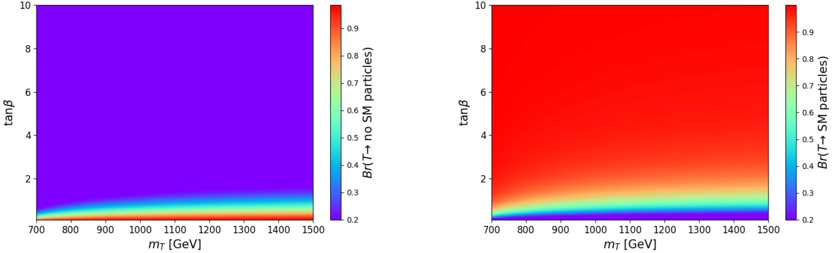


Figure: 6 Complementary regions of $BR(T \to SM)$ and $BR(T \to 2HDM)$ in the T-singlet

- For low $\tan\beta$, the channel in witch new T decays into 2HDM particles is dominate.

Results and discussion

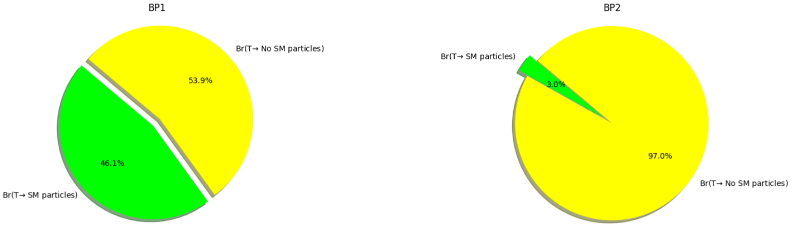


Figure: 7 Two benchmark points for looking T decays into SM and 2HDM particles.

	m_h	m_H	m_A	$m_{H^\pm}$	m_{12}	$\tan\beta$	$\sin(\beta-\alpha)$	y_T	m_T	$\sin\theta_L$
BP1	125.0	588.11	548.85	603.20	376.84	0.707	0.998	19.81	1454.86	-0.108
BP2	125.0	637.91	634.53	635.40	234.31	0.139	1.0	0.233	1477.71	-0.021

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Conclusion

- In this talk, we have extended the ordinary 2HDM-II by a singlet heavy VLQ .
- New vector-like quarks can naturally have masses above the electroweak symmetry breaking scale.
- They are being searched for at the LHC, with lower limits on their masses in the range 1100 - 1300 GeV, at present.
- This work complements the study of heavy top decays in SM.

Thanks for listening

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