# University Sultan Moulay Slimane

Laboratoire Interdisciplinaire de Recherche en Sciences et Techniques

# Phenomenology of Heavy Quarks at the LHC

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**Beyond Standard Model: From Theory To Experiment**
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# Outline


1. Motivation for VLQs
2. Current status
3. Yukawa interactions
4. Production and decay of the heavy quarks
5. Conclusion

# Motivation for VLQs

- Vector-Like Quarks exist in several BSM scenarios: Little Higgs Models N. Arkani-Hamed *et al* JHEP'02, Extra Dimensions I. Antoniadis, PLB'90, Composite Higgs Models J. Serra, JHEP'15, and so on.

- In Little Higgs model and Composite Higgs Model, vector- like top partners play the role of stabilising the Electroweak symmetry breaking.

- Vector-like quarks may interplay with new coloured scalars, heavy vectors, possible to generate rich phenomenology.

Luca Panizzi

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# Motivation for VLQs

- The discovery of a Higgs boson ATLAS,CMS '12 is a good opportunity to search for a possible extended EWSB sector. Indeed, several theoretical models addressing the hierarchy problem, like Supersymmetry or composite Higgs models predict the existence of additional Higgs scalars.
- The underlying idea of these models is to add a second Higgs doublet to the one predicted by the SM.
- Another class of models, called here vector-like quark (VLQ) models, instead, requires the presence of fermionic partners of the top-bottom quarks. Aguilar-Saavedra Juan Antonio

# Current status

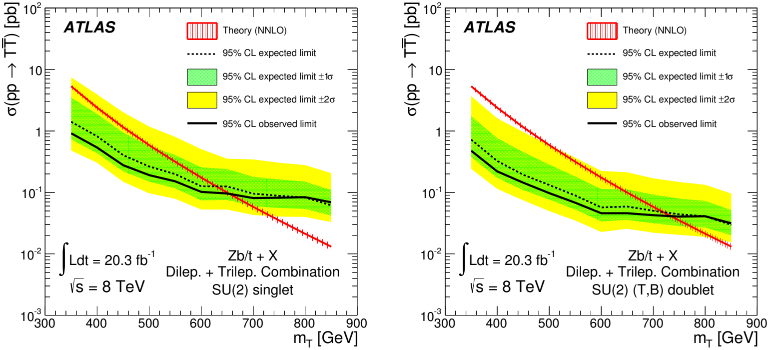


Figure: The upper limit on the pair-production cross section as a function of the heavy quark mass for left an SU(2) singlet (T) quark, and right a T quark forming an SU(2) (T,B) doublet with a charge -1/3 B quark.ATLAS'14 arXiv:1409.5500
left : Observed(expected)=655 GeV(625 GeV)

right : Observed(expected)=735 GeV(720 GeV)

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# Current status

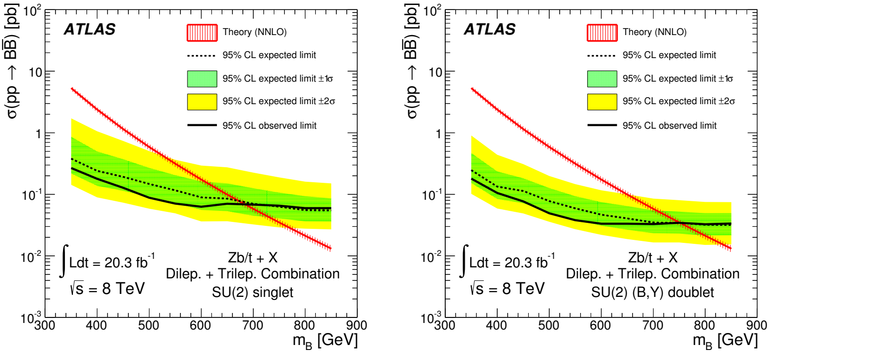


Figure: Predicted pair-production cross section as a function of the heavy quark mass and 95% CL observed and expected upper limits for left an SU (2) singlet B quark, and right a B quark forming an SU (2) (B,Y) doublet with a charge -4/3 Y quark. ATLAS'14 arXiv:1409.5500

left : Observed(expected)=685 GeV(670 GeV) right : Observed(expected)=755

# Current status

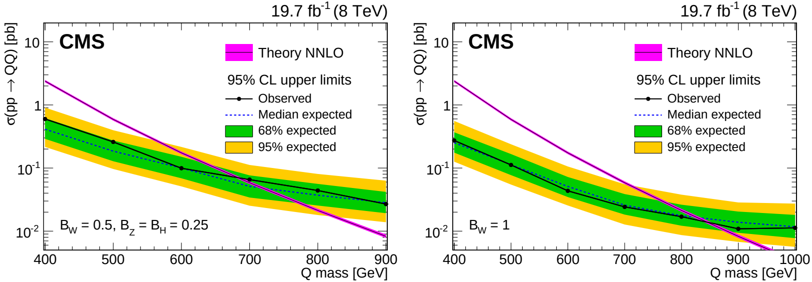


Figure: The 95% CL exclusion limits on the production cross section determined assuming different sets of model parameters ( $B_W = 0.5$, $B_Z = 0.25$ (left), and $B_W = 1$ (right)) as a function of the hypothetical VLQ mass, and for the scenario where only strong pair production of the VLQs is considered.

CMS'17 arXiv:1708.02510

# Models

| | Singlet | | Doublet | | | Triplet | |
|---|---|---|---|---|---|---|---|
| | $T$ | $B$ | $\begin{pmatrix} T \\ B \end{pmatrix}$ | $\begin{pmatrix} X \\ T \end{pmatrix}$ | $\begin{pmatrix} B \\ Y \end{pmatrix}$ | $\begin{pmatrix} X \\ T \\ B \end{pmatrix}$ | $\begin{pmatrix} T \\ B \\ Y \end{pmatrix}$ |
| **SU(2)** | **1** | | **2** | | | **3** | |
| $\mathbf{U(1)_Y}$ | **2/3** | **−1/3** | **1/6** | **7/6** | **−5/6** | **2/3** | **−1/3** |

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

- Spin 1/2 fermions, $SU(3)_c$ triplets;
- Can mix with 2HDM quarks;
- Can be isospin singlets, doublets or triplets;
- Can have SM electric charges (T with $2/3|e|$ and B with $-1/3|e|$) or exotic charges (X with $5/3|e|$ and Y with $-4/3|e|$).

# Yukawa interactions

**2HDM + (T) Singlet :**

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

**2HDM +(B) Singlet :**

$$-\mathcal{L}_Y^{II} \supset y_b \overline{q}_L^0 \Phi_1 b_R^0 - y_b \tan\beta \overline{q}_L^0 \Phi_2 b_R^0 + \xi_B \overline{q}_L^0 \Phi_1 B_R^0 - y_B \overline{q}_L^0 \Phi_2 B_R^0 + m_B \overline{B}_L^0 B_R^0 + h.c$$

**2HDM +(XT) Doublet :**

$$-\mathcal{L}_Y^{II} \supset y_t \overline{q}_L^0 \widetilde{\Phi}_1 t_R^0 + y_t \cot\beta \overline{q}_L^0 \widetilde{\Phi}_2 t_R^0 + \xi_T \overline{Q}_L^0 \Phi_1 t_R^0 + y_T \overline{Q}_L^0 \Phi_2^* t_R^0 + m_T \overline{T}_L^0 T_R^0 + h.c$$

**2HDM +(TB) Doublet :**

$$-\mathcal{L}_Y^{II} \supset y_t \overline{q}_L^0 \widetilde{\Phi}_1 t_R^0 + y_t \cot\beta \overline{q}_L^0 \widetilde{\Phi}_2 t_R^0 + \xi_T \overline{Q}_L^0 \Phi_1 t_R^0 + y_T \overline{Q}_L^0 \Phi_2^* t_R^0 + m_T \overline{T}_L^0 T_R^0 + y_b \overline{q}_L^0 \Phi_1 b_R^0 - y_b \tan\beta \overline{q}_L^0 \Phi_2 b_R^0 + \xi_B \overline{Q}_L^0 \Phi_1 b_R^0 - y_B \overline{Q}_L^0 \Phi_2 b_R^0 + m_B \overline{B}_L^0 B_R^0 + h.c$$

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# Yukawa interactions

**2HDM +(BY) Doublet :**

$$-\mathcal{L}_Y^{II} \supset y_b \overline{q}_L^0 \Phi_1 b_R^0 - y_b \tan\beta \overline{q}_L^0 \Phi_2 b_R^0 + \xi_B \overline{Q}_L^0 \widetilde{\Phi}_1 b_R^0 + y_B \overline{Q}_L^0 \widetilde{\Phi}_2 b_R^0 + m_B \overline{B}_L^0 B_R^0 + h.c$$

**2HDM +(XTB) Triplet :**

$$\begin{aligned} -\mathcal{L}_Y^{II} \supset\ & y_t \overline{q}_L^0 \widetilde{\Phi}_1 t_R^0 + y_t \cot\beta \overline{q}_L^0 \widetilde{\Phi}_2 t_R^0 + \xi_T \overline{Q}_L^0 \Phi_1 T_R^0 + y_T \overline{Q}_L^0 \Phi_2^* T_R^0 + M^0 \overline{T}_L^0 T_R^0 \\ & + y_b \overline{q}_L^0 \Phi_1 t_R^0 + y_b \tan\beta \overline{q}_L^0 \Phi_2 t_R^0 + \xi_B \sqrt{2} \overline{Q}_L^0 \widetilde{\Phi}_1 B_R^0 + y_B \sqrt{2}\, \overline{Q}_L^0 \widetilde{\Phi}_2 B_R^0 + M^0 \overline{B}_L^0 B_R^0 \\ & + h.c \end{aligned}$$

**2HDM +(TBY) Triplet :**

$$\begin{aligned} -\mathcal{L}_Y^{II} \supset\ & y_t \overline{q}_L^0 \widetilde{\Phi}_1 t_R^0 + y_t \cot\beta \overline{q}_L^0 \widetilde{\Phi}_2 t_R^0 + \xi_T \overline{Q}_L^0 \widetilde{\Phi}_1 T_R^0 + y_T \overline{Q}_L^0 \widetilde{\Phi}_2 T_R^0 + M^0 \overline{T}_L^0 T_R^0 \\ & + y_b \overline{q}_L^0 \Phi_1 t_R^0 + y_b \tan\beta \overline{q}_L^0 \Phi_2 t_R^0 + \xi_B \sqrt{2} \overline{Q}_L^0 \Phi_1 B_R^0 + y_B \sqrt{2}\, \overline{Q}_L^0 \Phi_2 B_R^0 + M^0 \overline{B}_L^0 B_R^0 \\ & + h.c \end{aligned}$$

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# Mixing with vector-like quarks

The relation between weak eigenstates and mass eigenstates write as

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

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

with $t^0_{L,R} \equiv u^0_{L3,R3}, \quad b^0_{L,R} \equiv d^0_{L3,R3}$.

And : $\tan\theta^q_R = \frac{m_q}{m_Q} \tan\theta^q_L$ (singlets, triplets)
$\tan\theta^q_L = \frac{m_q}{m_Q} \tan\theta^q_R$ (doublets)

# Production of the heavy quarks

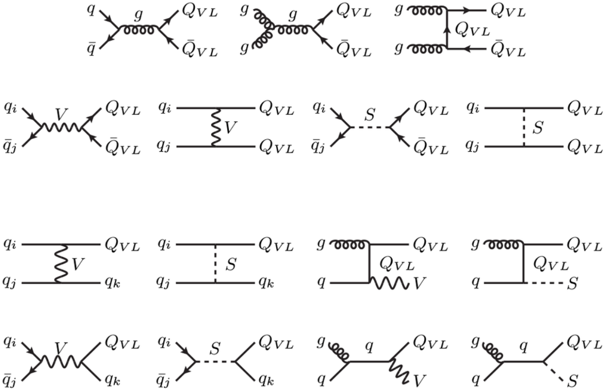


Figure: Feynman diagrams for pair and single production of a generic VLQ.

Yasuhiro Okada and Luca Panizzi Adv.HEP'13

# Decay of the heavy quarks

Scenario :

| | |
|---|---|
| $2HDM + (T)$ | $V^L_{Tb} = X^L_{tT} = Z^L_{Tb} = Y^R_{tT} = 0.0086,\ Y^L_{tT} = 0.00149$<br>$V^R_{Tb} = X^R_{tT} = Z^R_{Tb} = 0$ |
| $2HDM + (B)$ | $V^L_{tB} = X^L_{bB} = Z^L_{tB} = 0.00024,\ Y^L_{bB} = 7.10^{-7}$<br>$V^R_{tB} = X^R_{bB} = Z^R_{tB} = 0,\ Y^R_{bB} = 0.00024$ |
| $2HDM + (XT)$ | $V^L_{Tb} = 0.0086, X^L_{tT} = 0.0172, Z^L_{Tb} = 0$<br>$V^R_{Tb} = X^R_{tT} = Z^R_{Tb} = 0 Y^L_{tT} = 0.05,\ Y^R_{tT} = 0.008664$ |
| $2HDM + (BY)$ | $V^L_{tB} = 0.00024, X^L_{bB} = 0.00048, Z^L_{tB} = 0$<br>$V^R_{tB} = X^R_{bB} = Z^R_{tB} = 0,\ Y^L_{bB} = 0.05,\ Y^R_{bB} = 0.000159,$ |
| $2HDM + (TB)$ | $V^L_{Tb} = 0.0084, X^L_{tT} = 0, Z^L_{Tb} = 0.0086,\ Y^L_{tT} = 0.05,\ Y^R_{tT} = 0.0086,$<br>$V^R_{Tb} = X^R_{tT} = -Z^R_{Tb} = -0.05,\ V^L_{tB} = -0.0084, X^L_{bB} = 0, Z^L_{tB} = 0.0048,$<br>$V^R_{tB} = X^R_{bB} = -0.05, Z^R_{tB} = 0.00022,\ Y^L_{bB} = 0.05,\ Y^R_{bB} = 0.00024,$ |
| $2HDM + (XTB)$ | $X^R_{tT} = Z^R_{Tb} = Z^R_{tB} = Z^L_{tB} = 0, Z^L_{Tb} = 0.05,\ V^R_{Tb} = V^R_{tB} = -0.07062,$<br>$V^L_{Tb} = -0.01192,\ Y^L_{tT} = 0.00149,\ V^L_{tB} = -0.01192, X^R_{bB} = -0.09987,$<br>$Y^L_{bB} = 0.0000275,\ Y^R_{bB} = -X^L_{bB} = -Y^R_{tT} = -X^L_{tT} = -0.0086$ |
| $2HDM + (TBY)$ | $V^L_{Tb} = -X^L_{tT} = Y^R_{tT} = 0.0086, Z^L_{Tb} = V^R_{Tb} = Z^R_{Tb} = 0, X^R_{tT} = -0.09987,$<br>$Y^L_{tT} = 0.00149,\ V^L_{tB} = X^L_{bB} = Z^L_{tB} = 0.00024,\ V^R_{tB} = X^R_{bB} = Z^R_{tB} = 0,$<br>$Y^L_{bB} = 7.68 \times 10^{-7},\ Y^R_{bB} = 0.00024$ |

with $s_{\beta\alpha} = 1, c_{\beta\alpha} = 0,\ s^u_R = 0.05,\ s^d_R = 0.05,\ m_{T,B} = 1$ TeV.

# Decay of the heavy quarks

## The singlet (T) & (B)

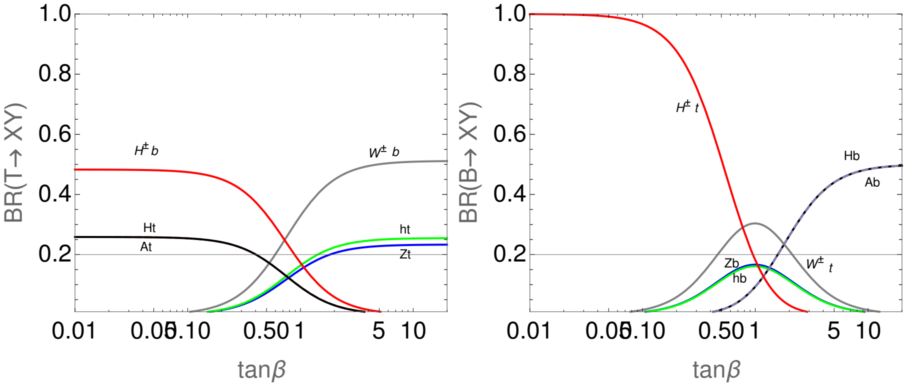


Figure: BRs of the T in the 2HDM+singlet (T) (left), and the B state in the 2HDM+singlet (B) (right), as a function of tan $\beta$

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# Decay of the heavy quarks

## The doublet (XT) & (BY)

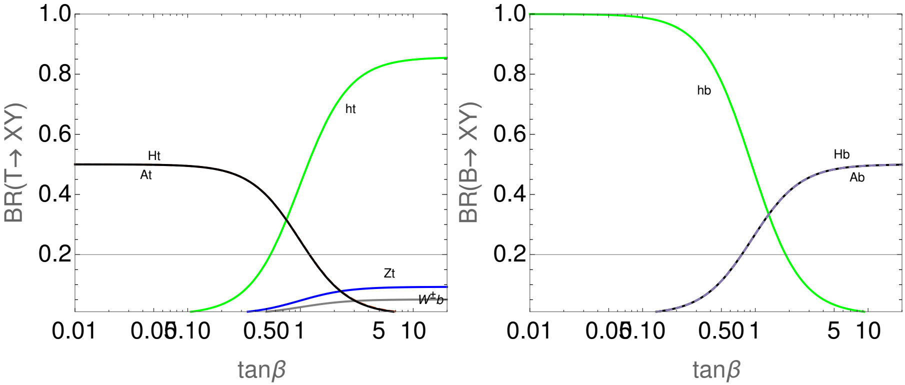


Figure: BRs of the T in the 2HDM+doublet (XT) (left), and the B state in the 2HDM+doublet (BY) (right), as a function of $\tan\beta$

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# Decay of the heavy quarks

## The doublet (TB)

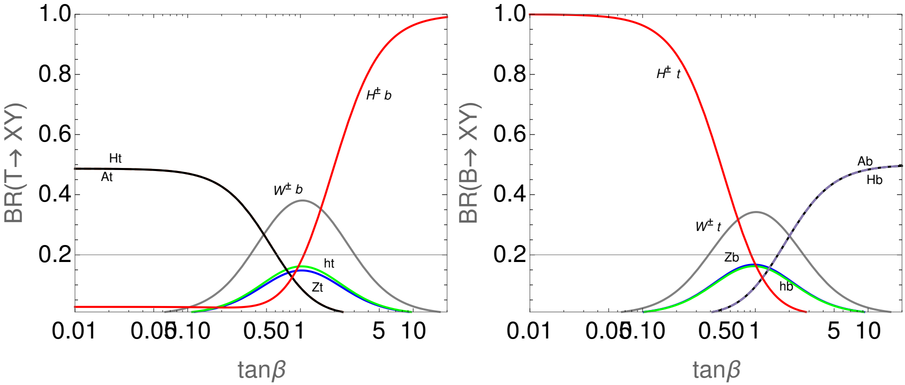


Figure: BRs of the T state (left), and the B state (right), in the 2HDM+doublet (TB) as a function of $\tan\beta$

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# Decay of the heavy quarks

## The triplet (XTB)

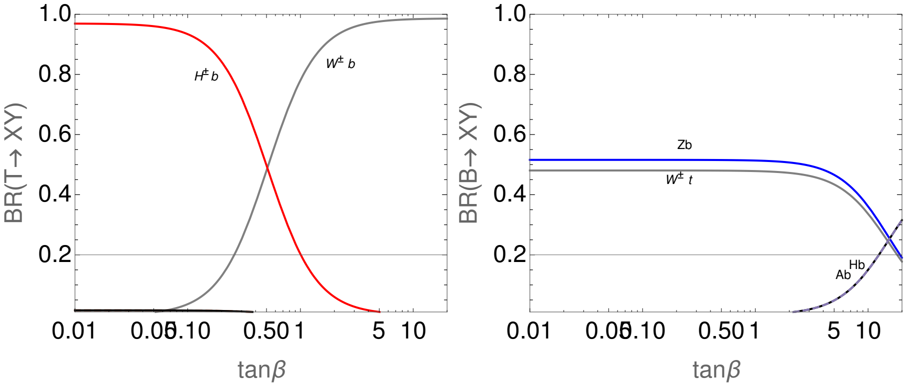


Figure: BRs of the T state (left), and the B state (right), in the 2HDM+triplet (XTB) as a function of $\tan\beta$

# Decay of the heavy quarks
## The triplet (TBY)

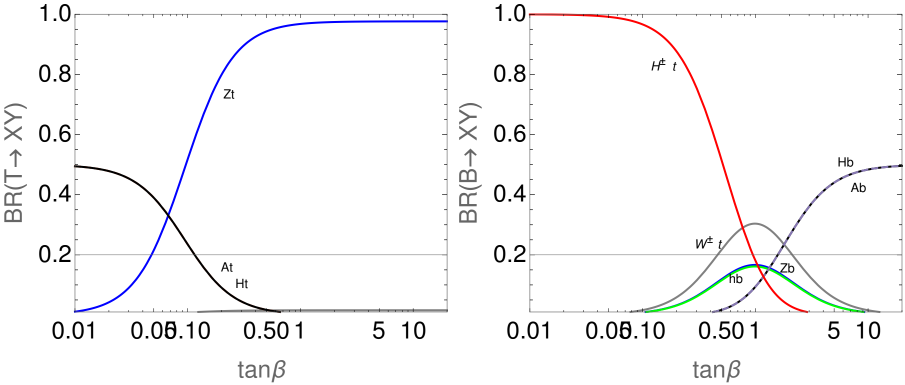


Figure: BRs of the T state (left), and the B state (right), in the 2HDM+triplet (TBY) as a function of tan $\beta$

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# Conclusion

- In this talk, we have extended the ordinary 2HDM-II by a singlet, doublet and triplet 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 600 - 800 GeV, at present.
- This work complements the study of heavy quark pair production in J. A. Aguilar-Saavedra, JHEP 0911 (2009) and single production in J. A. Aguilar-Saavedra, R. Benbrik, S. Heinemeyer, and M. Perez-Victoria, Phys. Rev. D 88 (2013) 094010 , by refining predictions for the heavy quark decays. Together, these works provide a comprehensive guide for the LHC phenomenology of minimal extensions of the SM with vector-like quarks.

**End**

**Thank!**

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