Next-to-minimal vectorlike quark models at the LHC

Bounds and Prospects

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Based on

1. **A roadmap to explore the vector-like quarks decaying to a new (pseudo)scalar**
   A. Bhardwaj, T. Mandal, S. Mitra, ***C.N.***
   Phys.Rev.D 106 (2022) 9, 095014 [arXiv:2203.13753]
2. **Discovery prospects of a vectorlike top partner decaying to a singlet boson**
   A. Bhardwaj, K. Bhide, T. Mandal, S. Mitra, ***C.N.***
   Phys. Rev. D 106 (2022) 7, 075024 [arXiv:2204.09005]
3. **Machine-learning enhanced search for a vectorlike singlet B quark decaying to a singlet scalar or pseudoscalar**
   J. Bardhan, T. Mandal, S. Mitra, ***C.N.***
   Phys.Rev.D 107 (2023) 11, 115001 [arXiv:2212.02442]

Outline

1. Motivations
2. VLQ searches: current limits, possible gap
3. Quantifying the gap
4. Roadmap: Signatures, benchmarks for LHC
5. HL-LHC Prospects: Singlet T, B models
6. Conclusions

Motivations

- Vectorlike quarks (VLQs) are hypothetical spin-$\frac{1}{2}$ particles that transform as triplets under the colour gauge group and whose left- and right-handed components have the same electroweak quantum numbers.
  They can transform as singlets, doublets or triplets under the weak $SU(2)$ group.
- TeV-scale VLQs are essential ingredients in many new physics models (models with extra dimensions, 2HDMs, composite higgs models, etc.).
  Not detected at LHC yet—mass limits are as high as ≈ 1.6 TeV.
- We look at how to tag non-standard decays of VLQs to a new spinless singlet state and a 3rd gen. quark ($Q \to q\Phi$), in a model-independent manner.
  Some interest in literature as well: 1504.01074, 1606.09013, 1612.01909, 1907.05929, 2005.07222, 2007.09722

VLQ $\leftrightarrow$ SM quark mixing: Singlet T example

Assumption: before EWSB, Φ mostly couples to only the vectorlike quarks.

- After EWSB, mass terms (for t, T) in the SM + Singlet T model can be written as:

$$\mathcal{L}_{\text{mass}} = -\begin{pmatrix} \bar{t}_L & \bar{T}_L \end{pmatrix} \begin{pmatrix} m_t & y_{tT} \frac{v}{\sqrt{2}} \\ 0 & m_T \end{pmatrix} \begin{pmatrix} t_R \\ T_R \end{pmatrix} + h.c.$$

- Weak eigenstates $\rightarrow$ Mass eigenstates = bi-orthogonal rotation.

$$\begin{pmatrix} t_{L/R} \\ T_{L/R} \end{pmatrix} = U_{L/R} \begin{pmatrix} t_{1\,L/R} \\ t_{2\,L/R} \end{pmatrix} = \begin{pmatrix} \cos\theta_{L/R} & -\sin\theta_{L/R} \\ \sin\theta_{L/R} & \cos\theta_{L/R} \end{pmatrix} \begin{pmatrix} t_{1\,L/R} \\ t_{2\,L/R} \end{pmatrix} \tag{1}$$

t_1, t_2 are the physical SM top quark and T VLQ respectively.

- These mixing matrices can be determined by:

$$U_L \mathcal{M} U_R = \mathcal{M}_{\text{diag}} \tag{2}$$

Eigenvalues of $\mathcal{M}$ is the physical top (m_{t_1}) and T VLQ mass (M_{t_2}), $m_{t_1} < M_{t_2}$

Mixing Parameters

We can express the left and right mixing angles as

$$\tan\left(2\theta_{F_L}\right) = \frac{2\left(m_q\,\mu_{F2} + M_F\,\mu_{F1}\right)}{\left(m_q^2 + \mu_{F1}^2\right) - \left(M_F^2 + \mu_{F2}^2\right)}, \tag{3}$$

$$\tan\left(2\theta_{F_R}\right) = \frac{2\left(m_q\,\mu_{F1} + M_F\,\mu_{F2}\right)}{\left(m_q^2 + \mu_{F2}^2\right) - \left(M_F^2 + \mu_{F1}^2\right)}. \tag{4}$$

The mass eigenvalues m_{q_1,q_2} are given by

$$m_{q_1,q_2}^2 = \frac{1}{2}\Bigg[\mathrm{Tr}\left(\mathcal{M}^{\mathrm{T}}\mathcal{M}\right) \mp \sqrt{\left[\mathrm{Tr}\left(\mathcal{M}^{\mathrm{T}}\mathcal{M}\right)\right]^2 - 4\left(\mathrm{Det}\ \mathcal{M}\right)^2}\Bigg]. \tag{5}$$

We identify q_1 with the physical SM quark. The above expressions indicate for a very heavy F, i.e., when $M_F \gg m_q, \mu_{F1}, \mu_{F2}$, the SM quark and the VLQ effectively decouple.

- Interactions with the Higgs boson (h)

$$\mathcal{L} \supset \frac{1}{v}\Big[(m_t\, c_L s_R + \mu_{T1}\, c_L c_R)\,\bar{t}_L t_{2R} + (m_t\, s_L c_R - \mu_{T1}\, s_L s_R)\,\bar{t}_R t_{2L}\Big] h + h.c. \quad (6)$$

- Interactions with W, Z bosons

$$\mathcal{L} \supset \frac{g}{\sqrt{2}} s_L\, \bar{b}_L \gamma^\mu t_{2L}\, W_\mu^- + \frac{2g\mathbb{T}_3^t}{\cos\theta_W} c_L s_L\, \bar{t}_L \gamma^\mu t_{2L} Z_\mu + h.c. \quad (7)$$

where $\mathbb{T}_3^t = 1/2$ is the weak isospin of t_L

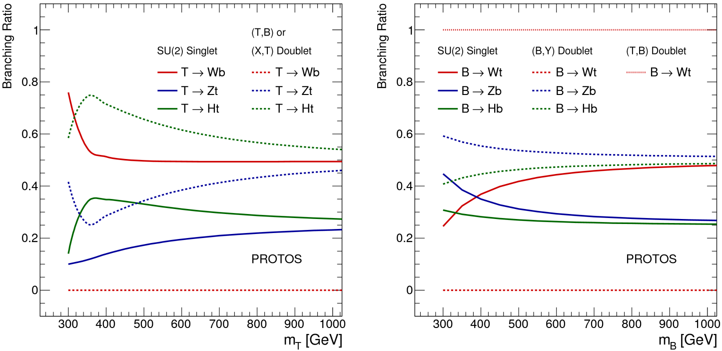
- Interactions with Φ

$$\begin{aligned}\mathcal{L} \supset &- \lambda^a_{\Phi T} \Phi \left(c_L \bar{t}_{2L} - s_L \bar{t}_L\right) \Gamma\, (c_R t_{2R} - s_R t_R) \\ &- \lambda^b_{\Phi T} \Phi \left(c_L \bar{t}_{2L} - s_L \bar{t}_L\right) \Gamma\, (c_R t_R + s_R t_{2R}) + h.c. \quad (8)\end{aligned}$$

where $\Gamma = \{1, i\gamma_5\}$ for $\Phi = \left\{\phi, \eta\right\}$.

LHC Searches

[arXiv:1409.5500]



- VLQs are searched for in the channels,

$$t_2 \to bW, tZ, th \qquad b_2 \to tW, bZ, bh \tag{9}$$

- For $M_{q_2} \gtrsim$ TeV, $\beta_{q_1' W} \approx 2\beta_{q_1 Z} \approx 2\beta_{q_1 h}$ (Singlet)
  $\beta_{q_1 Z} \approx \beta_{q_1 h},\ \beta_{q_1' W} \approx 0$ (Doublet)

Model	Obs. Mass Limits (TeV)
Singlet $T\bar{T}$	1.27
Doublet $T\bar{T}$	1.46
100% $T \to Zt$	1.60
Singlet $B\bar{B}$	1.20
Doublet $B\bar{B}$	1.32
100% $B \to Zb$	1.42

- ATLAS VLQ pair-production (inclusive) search — Run 2 (139 fb^{-1})

$$pp \to T\bar{T} \to tZ + X$$

[arXiv:2210.15413]

$$pp \to b\bar{B} \to bZ + X$$

Rescaled Mass limits [arXiv:2203.13753]

- Adding the new decay mode, the BR constraint becomes

$$\beta_{q_1 H} + \beta_{q_1 Z} + \beta_{q' W} = 1 \to \left(1 - \beta_{q_1 \Phi}\right) \quad (10)$$

- For $M_{q_2} \gtrsim$ TeV, $\beta_{q_1' W} \approx 2\beta_{q_1 Z} \approx 2\beta_{q_1 h}$ (Singlet)
  $\beta_{q_1 Z} \approx \beta_{q_1 h},\ \beta_{q_1' W} \approx 0$ (Doublet)

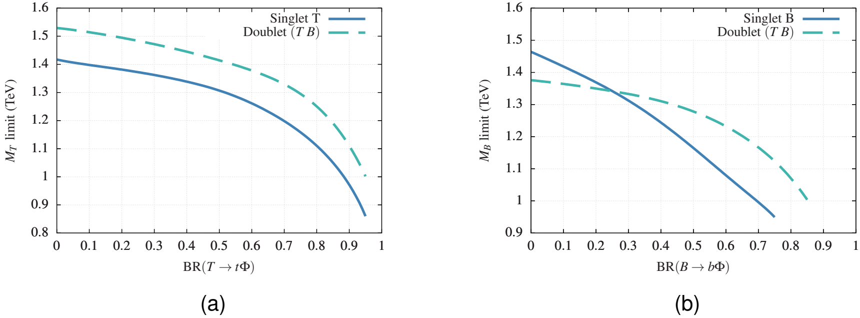


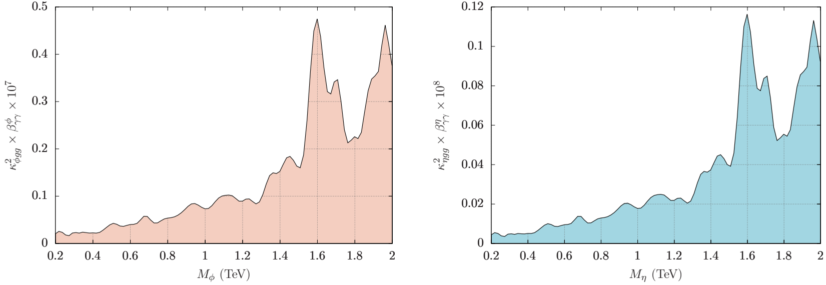
Figure: LHC exclusion limits on (a) T-type and (b) B-type VLQs as a function of BR in the new mode.

Limits on $\kappa_{\Phi gg}$

We recast latest ATLAS study [2102.13405] of a heavy resonance decaying to photon pairs using the following constaint:

$$\kappa_{\Phi gg}^2 \times \sigma_{pp\to\Phi} \times \beta_{\Phi\to\gamma\gamma} < \sigma_{\text{meas}} \times \epsilon$$

where, β is BR of the diphoton mode, $\sigma_{\text{meas}}, \epsilon$ are the cross-section and efficiency from the study.



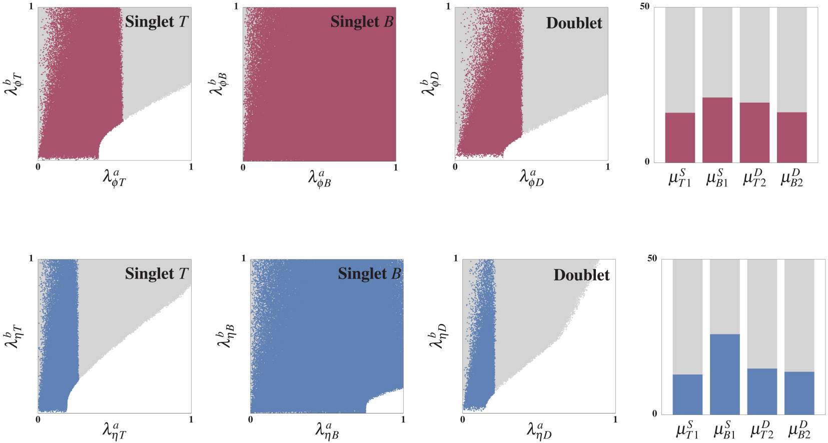
[arXiv:2203.13753]

The white regions are excluded.

$q_2 \to q_1\Phi$ decay dominant parameter space

- Singlet models have 3 independent parameters
  1 off-diagonal mass term, λ^a, λ^b
- Doublet models have 4 independent parameters
  2 off-diagonal mass terms, λ^a, λ^b
- We pick a benchmark mass for VLQ and Φ
  $M_{q_2} = 1.2, M_\Phi = 0.4$ **TeV**
- Ranges for parameters: $\lambda^i \in [0.0, 1.0]$, $\mu \in [0, 50]$
- Demands:
  - BR($q_2 \to q\Phi$) should be greater than the rescaled experimental limits for $M_{q_2} = 1.2$ TeV
  - The effective coupling $\kappa_{\Phi gg} \leq$ the recast limits
  - $\Phi \to gg$ branching, $\beta^\Phi_{gg} \geq 50\%$

Parameter Scans

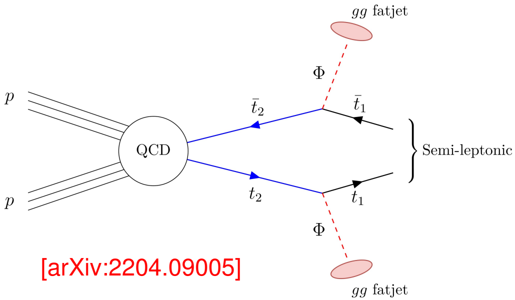


Pair-production signatures of VLQs revisited

$q_2\bar{q}_2$ decay	Possible final states	
	$q_2 = t_2$	$q_2 = b_2$
$q\Phi\ q\Phi$	$2t + 4j$	$2b + 4j$
	$2t + 2\gamma + 2j$ [37]	$2b + 2\gamma + 2j$
	$2t + 4\gamma$ [37]	$2b + 4\gamma$
	$2t + 2b + 2j$ (#)	$2b + 2t + 2j$ (#)
	$2t + 2b + 2\gamma$ (#)	$2b + 2t + 2\gamma$ (#)
	$2t + 4b$ (#)	$2b + 4t$ (#)
	$4t + 2j$	$4b + 2j$
	$4t + 2\gamma$ [37]	$4b + 2\gamma$
	$4t + 2b$ (#)	$4b + 2t$ (#)
	$6t$ [33]	$6b$
$t\Phi\ bW$ or $b\Phi\ tW$	$t + b + 4j$	$t + b + 4j$
	$t + b + 2\gamma + 2j$	$t + b + 2\gamma + 2j$
	$t + b + 2j + \ell + \not{E}$	$t + b + 2j + \ell + \not{E}$
	$t + b + 2\gamma + \ell + \not{E}$	$t + b + 2\gamma + \ell + \not{E}$
	$3t + b + 2j$	$3b + t + 2j$
	$3t + b + \ell + \not{E}$	$3b + t + 2\gamma + \ell + \not{E}$
$q\Phi\ q_1 Z$ or $q\Phi\ q_1 h$	$2t + 4j$	$2b + 4j$
	$2t + 4\gamma$	$2b + 4\gamma$
	$2t + 2b + 2j$	$2b + 2j + 2\gamma$
	$2t + 2b + 2\gamma$	$2b + 2j + 2\ell$
	$2t + 2j + 2\gamma$	$2b + 2\ell + 2\gamma$
	$2t + 2\ell + 2j$	$2b + 2t + 2j$ (#)
	$2t + 2\ell + 2\gamma$	$4b + 2j$
	$2t + 4b$ (#)	$4b + 2\gamma$
	$4t + 2\gamma$	$4b + 2\ell$
	$4t + 2b$	$4b + 2t$ (#)
	$4t + 2j$	$6b$
	$4t + 2\ell$	

HL-LHC prospects of Singlet T in the new mode

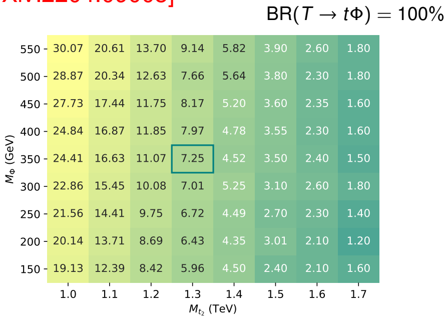
Pair production of t_2, dominantly decaying to $t\Phi$; $\Phi \to gg$



[arXiv:2204.09005]

- Semileptonic mode ⇒ one of tops, $t \to bW \to b\ell\nu_\ell$
- Therefore, we demand $t_2\bar{t}_2$ event must have
  - *Exactly* 1 lepton
  - *At least* 2 $b-$quark jets (from the tops).
  - *At least* 2 fat jets for Φ
- We identify other (SM) processes that can pass the same demands; then see if its possible to see the identify the signal from those backgrounds.

LHC reach [arXiv:2204.09005]

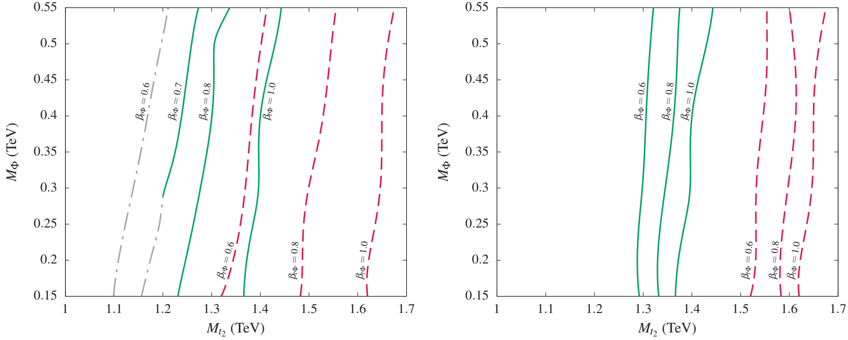


- We use a boosted decision tree (BDT) model to separate pair produced t_2 signal from the backgrounds.
- The significance formula use

$$\mathcal{Z} = \frac{N_S}{\sqrt{N_S + N_B}}$$

where, N_S, N_B are signal and background events after BDT cut, at HL-LHC luminosity $\mathcal{L} = 3\text{ab}^{-1}$

Exclusive, Inclusive Mode Reach



(a) [arXiv:2204.09005] (b)

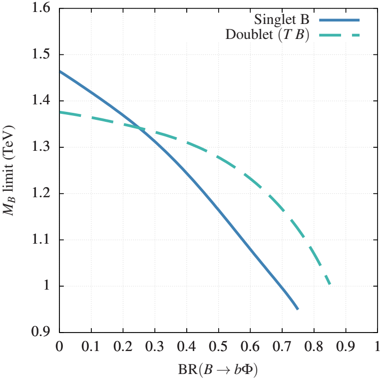
(a) Exclusive Mode: $pp \to t_2\, \bar{t}_2 \to t\Phi\; \bar{t}\Phi$, Scaling factor: $\beta_{t\Phi}^2$

(b) Inclusive Mode: $pp \to t_2\, \bar{t}_2 \to t\Phi + X$, $(X \in \{t\Phi, bW, tZ, tH\})$
Scaling factor: $\beta_{t\Phi}\,(2 - \beta_{t\Phi})$

HL-LHC prospects of Singlet B

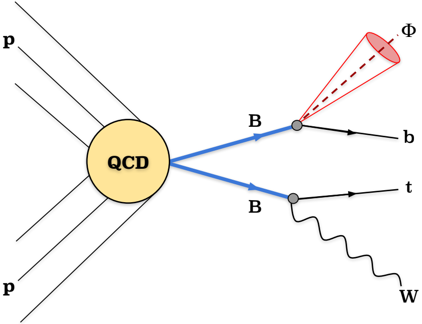
[arXiv:2212.02442]

- When $B \to b\Phi$ mode is dominant $B\bar{B} \to (bgg)\left(\bar{b}gg\right) / \left(bb\bar{b}\right)\left(\bar{b}b\bar{b}\right)$ **Fully hadronic!**
- Singlet B, rescaled limits relax faster $\Rightarrow$ **Decays to SM bosons are not insignificant.**
- We look for monoleptonic signatures of a pair produced B. **(Highest branching is for $B \to tW$ mode)**



Monoleptonic signatures of Singlet B

Pair production of B: $pp \to B\bar{B} \to (b\Phi)\ (t^+W^-)$



- Semileptonic mode $\Rightarrow$ either the top or W decays leptonically
- Therefore, we demand $B\bar{B}$ event must have
  - *Exactly* 1 lepton.
  - *At least* 3 AK4 jets
  - *At least* 1 high-p_T b jet.
  - *At least* 1 fat jet (Φ) with $M_J > 250$ GeV, separated from b jet

LHC reach [arXiv:2212.02442]

Exclusive
$BB \to (b\Phi)\,(tW)$

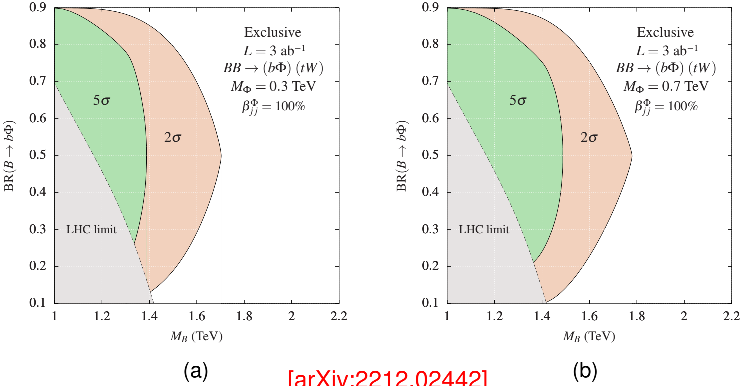
$\beta_{b\Phi} =$	0.8	⟵ 0.6 ⟶							
M_Φ (GeV) \ M_B (TeV)	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8
700	15.69	16.95	11.84	8.32	6.50	4.57	2.88	2.19	1.83
600	16.01	18.13	11.89	7.93	5.61	3.91	2.73	1.90	1.35
500	16.32	15.74	10.73	7.73	5.59	4.09	2.71	1.96	1.31
400	14.86	14.72	10.30	7.77	5.67	3.81	3.14	1.77	1.48
300	13.53	14.67	9.35	7.08	4.56	3.37	2.71	1.94	1.41

- We use a simple deep neural network (DNN) with weighted loss for classification.
- The significance formula we use

$$\mathcal{Z} = \sqrt{2\,(N_S + N_B)\ln\left(\frac{N_S + N_B}{N_B}\right) - 2N_S}$$

where, N_S, N_B are signal and background events after DNN cut, at HL-LHC luminosity $\mathcal{L} = 3\text{ab}^{-1}$

Discovery (5σ) and 2σ Regions



[arXiv:2212.02442]

- For every mass point, we search over $\beta_{b\Phi} \in [0.1, 0.9]$ to find the maximum and minimum values for $\mathcal{Z} = 5$ and 2.
- For singlet model, signal yield scales as $\beta_{b\Phi}(1 - \beta_{b\Phi})$ and becomes maximum for 0.5.

  (BR constraint: $\beta_{bH} + \beta_{bZ} + \beta_{tW} = 1 - \beta_{b\Phi}$)

Conclusions

- Mass limits on VLQs relax significantly in the presence of $Q \to q\Phi$ decay.
- Taking into account rescaled mass limits on VLQs and limits on Φ, we see that $Q \to q\Phi$ mode can dominate in a large amount of available parameter space.
- $\Phi \to gg$ decays is dominant as well in large part of the parameter space, especially in singlet VLQ models.
- Pair production signatures in the presence of the new decay mode can act as a discovery channel even when $Q \to q\Phi$ dominates.

Thank you for your attention!