Non-standard decays of vectorlike quarks

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Where I belong

Discussion based on

I was interested in VECTORLIKE QUARKS from my PhD days!

For their exotic decays, the credit goes to SHIFt

1. **A roadmap to explore the vector-like quarks decaying to a new (pseudo)scalar**
   *A. Bhardwaj, **TM**, S. Mitra, C. Neeraj*
   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, **TM**, S. Mitra, C. Neeraj*
   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, **TM**, S. Mitra, C. Neeraj*
   Phys. Rev. D 107 (2023) 11, 115001 [arXiv:2212.02442]
4. **Machine learning tagged boosted dark photon: A signature of fermionic portal matter at the LHC**
   *S. Verma, S. Biswas, **TM**, S. Mitra*
   Under review in PRD [arXiv:2410.06925]
5. **Tagging fully hadronic exotic decays of the vectorlike quark using a graph neural network**
   *J. Bardhan, **TM**, S. Mitra, C. Neeraj, M. Rawat*
   Submitted to PRD [arXiv:2505.07769]

What is vectorlike quark?

- A fermion is vectorlike if its left- and right-handed chiralities belong to the same representation of the symmetry group.
  SM quarks are vectorlike under $SU(3)_C$ but are chiral under $SU(2)_L \times U(1)_Y$.
- Charged current Lagrangian in SM: $\mathscr{L} \supset \frac{g_w}{\sqrt{2}} j^\mu W_\mu$

SM Chiral fermions (V-A form)

$$j_L^\mu = \bar{\psi}_L \gamma^\mu \psi'_L; \qquad J_R^\mu = 0$$

$$j^\mu = j_L^\mu + j_R^\mu = \bar{\psi}\gamma^\mu(1-\gamma^5)\psi$$

Vectorlike fermions (V form)

$$j_L^\mu = \bar{\psi}_L \gamma^\mu \psi'_L; \quad J_R^\mu = \bar{\psi}_R \gamma^\mu \psi'_R$$

$$j^\mu = j_L^\mu + j_R^\mu = \bar{\psi}\gamma^\mu\psi$$

- Appelquist-Carazzone decoupling theorem is violated for the chiral fourth-generation quarks. They heavily contribute to the Higgs production/decay. Hence, ruled out.
- Vectorlike fermions decouple easily from the SM in the high-mass. A $\sim$ TeV VLQ is allowed by the current data.

Quantum numbers of VLQs

- VLQs transform as triplets under $SU(3)$ and whose left- and right-handed components have the same electroweak quantum numbers.

They can transform as singlets, doublets or triplets under the weak $SU(2)_L$.

	SM quarks	Singlets		Doublets			Triplets	
	$\begin{pmatrix} u \\ d \end{pmatrix}$ $\begin{pmatrix} c \\ s \end{pmatrix}$ $\begin{pmatrix} t \\ b \end{pmatrix}$	(U)	(D)	$\begin{pmatrix} X \\ U \end{pmatrix}$	$\begin{pmatrix} U \\ D \end{pmatrix}$	$\begin{pmatrix} D \\ Y \end{pmatrix}$	$\begin{pmatrix} X \\ U \\ D \end{pmatrix}$	$\begin{pmatrix} U \\ D \\ Y \end{pmatrix}$
$SU(2)_L$	$q_L = 2$ $q_R = 1$	1		2			3	
$U(1)_Y$	$q_L = 1/6$ $u_R = 2/3$ $d_R = -1/3$	$2/3$	$-1/3$	$7/6$	$1/6$	$-5/6$	$2/3$	$-1/3$
$\mathcal{L}_Y$	$-y_u^i \bar{q}_L^i H^c u_R^i$ $-y_d^i \bar{q}_L^i V_{CKM}^{i,j} H d_R^j$	$-\lambda_u^i \bar{q}_L^i H^c U_R$ $-\lambda_d^i \bar{q}_L^i H D_R$		$-\lambda_u^i \psi_L H^{(c)} u_R^i$ $-\lambda_d^i \psi_L H^{(c)} d_R^i$			$-\lambda_i \bar{q}_L^i \tau^a H^{(c)} \psi_R^a$	
$\mathcal{L}_m$	not allowed	$-M\bar{\psi}\psi$						

Okada, Panizzi '12

Why we love VLQs?

- TeV-scale VLQs are an essential ingredient of many new physics models - extra-dimension, composite Higgs, GUT etc.
- $M\,\overline{Q}Q$ – gauge invariant bare mass term is allowed; Higgs mechanism is not required.
- Vectorlike fermions do not contribute to gauge anomalies.
- Unique signatures: unlike chiral quarks, they induce FCNC decays. Branching rations are comparable.
  $T \to bW, tZ, th$
  $B \to tW, bZ, bh$
  Not detected at LHC yet in the "standard" decay modes—mass limits are as high as ≈ 1.6 TeV
- Possibly they are decaying dominantly to non-standard decay modes – VLQ $\to$ SM-Q + BSM (scalar or vector)

  Recent interest in literature as well: See "Vectorlike quarks: Status and new directions at the LHC (SciPost Phys. Core 7 (2024) 079)"

A theory motivation: VLQ in WED

- A warped-space ED (RS model) proposed as a solution to the gauge hierarchy problem of the SM Randall, Sundrum '99
- Original RS setup: an extra spatial dimension is confined between two branes (TeV and Planck) and only gravity can propagate into the bulk
  - Gauge hierarchy problem can be solved
  - Flavor hierarchy problems can't be addressed
- Allowing SM gauge fields in the bulk could possibly yield unification of gauge couplings Randall, Schwartz '01
- Allowing SM fermions to propagate in the bulk – flavor hierarchy problems can be addressed
- We have to check experimental constraints such as Peskin-Takauchi parameters (S and T) and $Z\bar{b}_L b_L$ coupling

Original Randall-Sundrum model

- One compact spatial dimension on $S_1/\mathbb{Z}_2$. Warped 5D metric in RS

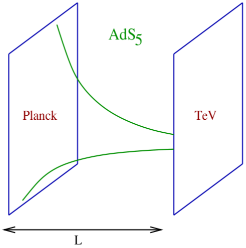
$$ds^2 = e^{-2\kappa|\phi|}\eta_{\mu\nu}dx^\mu dx^\nu - d\phi^2$$

Curvature scale, $\kappa/M_{\rm Planck} \lesssim 0.1$

Davoudiasl, Hewett, Rizzo '00

- Non-trivial metric induces TeV scale from Planck scale

k



$k e^{-k L}$

- Geometry of extra dimension solves hierarchy

$$\boxed{\Lambda_{\rm TeV} \sim M_{\rm Planck}\, e^{-\kappa L}} \quad \text{with } \kappa L \sim 35$$

Fermions in the bulk

- 5D warped space fermionic action

$$S = \int d^4x \int_0^{\pi R} dy \sqrt{-G} \left[\frac{1}{2} \bar{\psi} \left(i\Gamma^M (\partial_M + \omega_M) - ck \right) \psi \right]$$

- EOM of bulk fermions using $\delta S = 0$

$$\left[-e^{2ky} \eta^{\mu\nu} \partial_\mu \partial_\nu + e^{ky} \partial_5 \left(e^{-ky} \partial_5 \right) - c(c \pm 1) k^2 \right] \left(e^{-2ky} \Psi_{L/R}(x,y) \right) = 0$$

$$\boxed{\Psi_{L/R} = \frac{e^{2ky}}{\sqrt{\pi R}} \sum_n \psi_{L/R}^{(n)}(x) f^{(n)}(y)}$$

- Fermionic profiles can be obtained from the following 2nd order diff. equations

$$\boxed{\left[\partial_5^2 - k\partial_5 - (c(c \pm 1)k^2 - e^{2ky} m_n^2) \right] f^{(n)}(y) = 0}$$

...continued

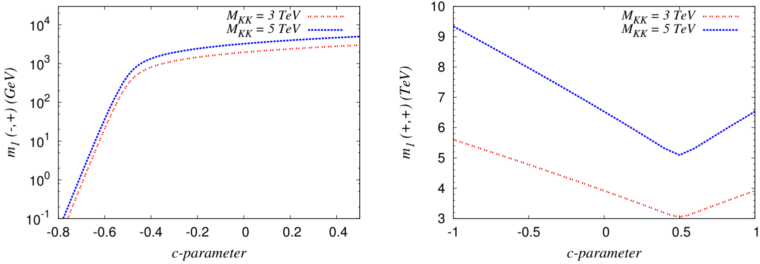
- Fermionic profiles

$$f^{(0)}_{\Psi_L}(y) = \sqrt{\frac{(1-2c)k\pi R}{e^{(1-2c)k\pi R}-1}}\, e^{-cky}$$

$$f^{(n)}_{\Psi_L}(y) = \frac{e^{ky/2}}{N_n}\left[J_\alpha\left(\frac{m_n}{k}e^{ky}\right) + b_\alpha(m_n)\, Y_\alpha\left(\frac{m_n}{k}e^{ky}\right)\right]$$

  where $\alpha = |c + 1/2|$; J_α and Y_α are the Bessel functions of order α of first and second kind respectively
- Boundary conditions to solve the diff. eq. of fermionic profiles
  - Dirichlet $(-)$ BC : $f^{(n)}(y)|_{y=\text{brane}} = 0$
  - Neumann $(+)$ BC : $(\partial_y \pm ck) f^{(n)}_{L/R}(y)|_{y=\text{brane}} = 0$
- $(-,+)$ BCs: no zero mode but light first KK mode possible
- $(+,+)$ BCs: zero mode but first KK mode heavier than M_{KK}

First Kaluza-Klein excitation



Fermions with $(-,+)$ BCs could be light

Interesting for phenomenology at the LHC

Bulk gauge group

- Bulk group: $SU(2)_L \otimes U(1)_Y$ (SM gauge bosons in bulk, SM fermions, H on TeV brane)
  - T parameter is not protected (EW radiative corrections)
  - S parameter is enhanced
  - $M_{KK} \gtrsim 10$ TeV introduces little hierarchy

Csaki, Erlich, Terning '02

- Enhanced bulk group: $SU(2)_L \otimes SU(2)_R \otimes U(1)_X$ (only H on TeV brane)
  - Offers a custodial symmetry: T parameter is protected
  - Correction to the T parameter satisfies EWPT data even for $M_{KK} \gtrsim 3$ TeV but $Z\bar{b}_L b_L$ coupling is in conflict with data

Agashe *et. al.* '03

- To protect $Z\bar{b}_L b_L$ coupling:
  - 3rd gen. quarks in bidoublet $(2,2)_{2/3}$ representation
  - $\mathbb{Z}_2$ symmetry interchanges $SU(2)_L \longleftrightarrow SU(2)_R$

Agashe *et. al.* '06

Quark representations

Bulk group: $SU(2)_L \otimes SU(2)_R \otimes U(1)_X$

- A simple representation
  - $Q_L \equiv (\mathbf{2},\mathbf{1})_{1/6} = (t_L, b_L)$
  - $Q_{t_R} \equiv (\mathbf{1},\mathbf{2})_{1/6} = (t_R, b')$
  - $Q_{b_R} \equiv (\mathbf{1},\mathbf{2})_{1/6} = (t', b_R)$

  T parameter is protected but $Z\bar{b}_L b_L$ coupling is shifted
- To protect $Z\bar{b}_L b_L$: $Q_L \equiv (\mathbf{2},\mathbf{2})_{2/3} = \begin{pmatrix} t_L & \chi \\ b_L & t' \end{pmatrix}$
- To write an invariant top Yukawa - two possible representations for t_R
  - $Q_{t_R} \equiv (\mathbf{1},\mathbf{1})_{2/3} = t_R$
  - $Q_{t_R} \equiv (\mathbf{1},\mathbf{3})_{2/3} \oplus (\mathbf{3},\mathbf{1})_{2/3} = \begin{pmatrix} \chi' \\ t_R \\ b' \end{pmatrix} \oplus \begin{pmatrix} \chi'' \\ t'' \\ b'' \end{pmatrix}$
- Higgs is in $(\mathbf{2},\mathbf{2})_0$: $\Sigma = \begin{pmatrix} \phi_0^* & \phi^+ \\ -\phi^- & \phi_0 \end{pmatrix}$

Redundant parameter

A singlet VLQ F'

$$\mathscr{L} \supset -\left\{\tilde{\lambda}_q \left(\bar{Q}_L H_F\right) q_R + \omega_F \left(\bar{Q}_L H_F\right) F'_R + \tilde{\omega}_F m_F \bar{F}'_L q_R + M_F \bar{F}'_L F'_R + \mathrm{h}.c.\right\}$$

After EWSB, the above terms in a matrix form

$$\mathscr{L}_{\text{mass}} = -\left(\bar{q}_L\ \bar{F}'_L\right) \begin{pmatrix} \tilde{\lambda}_q \frac{v}{\sqrt{2}} & \omega_F \frac{v}{\sqrt{2}} \\ \tilde{\omega}_F m_F & m_F \end{pmatrix} \begin{pmatrix} q_R \\ F'_R \end{pmatrix} + h.c.$$

The red-colored term is redundant. Can be removed by the following field redefinition

$$F'_L \to F_L, \quad F'_R \to F_R - \frac{\tilde{\omega}_F m_F}{M_F} q_R$$

After the above transformation, the Lagrangian in the un-primed basis

$$\mathscr{L} \supset -\left\{\lambda_q \left(\bar{Q}_L H_F\right) q_R + \omega_F \left(\bar{Q}_L H_F\right) F_R + M_F \bar{F}_L F_R + \mathrm{h}.c.\right\}$$

The redefined Yukawa coupling is : $\lambda_q = \tilde{\lambda}_q - \omega_F \tilde{\omega}_F \frac{m_F}{M_F}$

VLQ $\leftrightarrow$ SM-Q mixing: singlet T

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

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

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

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

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

- These mixing matrices can be determined by:

$$O_L^T \mathscr{M} O_R = \mathscr{M}_{\text{diag}}$$

Eigenvalues of $\mathscr{M}$ 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

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

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

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

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

Interactions with SM fields

- Interactions with the Higgs boson

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

- Interactions with W, Z bosons

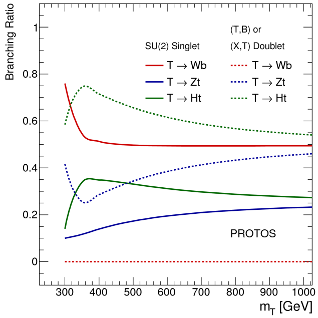
$$\mathscr{L} \supset \frac{g}{\sqrt{2}} s_L\, \bar{b}_L \gamma^\mu\, t_{2L} W^-_\mu + \frac{2g\mathbb{T}^t_3}{\cos\theta_W} c_L s_L\, \bar{t}_L \gamma^\mu\, t_{2L} Z_\mu + h.c.$$

  where $\mathbb{T}^t_3 = 1/2$ is the weak isospin of t_L

- These couplings go as $\sim \frac{1}{M}$ for large M. Essentially decouple and can easily satisfy the experimental constraints.
- These interactions lead to branching ratios of T to $bW : tZ : th = 2:1:1$

Branching ratios

arXiv:1409.5500



- VLQs are searched for in the channels,

$$T \to bW, tZ, th \qquad B \to tW, bZ, bh$$

- 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)

Exotic decays of VLQs

- In composite Higgs models, VLQs are accompanied with additional scalars (hyper-mesons).
- In extradimensional models, KK excitations are vectorlike. There are scalars like radion, dilaton etc. are also present.
- In simple gauge extensions, Z', W' can contribute to the VLQ production
- In these non-minimal set-up VLQs can be produced through and decayed into new scalars/vectors.
  - Lighter than VLQ: $T, B \to q\Phi, q\Phi^{\pm}, qZ', qW'$
    $\Phi \to WW, Zh, hh, gg, \gamma\gamma, tt$; $\Phi^{\pm} \to WZ, Wh, tb$
    $Z' \to WW, Zh, tt$; $W' \to WZ, Wh, tb$
  - Heavier than VLQ: contributes in the production
    $\Phi \to TT, Tt, BB, Bb$ (this could be KK graviton)

Some exotic decay modes

$T_{2/3} \to \Phi t$; $T_{2/3} \to \Phi^{+} b$; $B_{-1/3} \to \Phi b$; $B_{-1/3} \to \Phi^{-} t$

$X_{5/3} \to \Phi^{+} t$; $X_{5/3} \to \Phi^{++} b$; $Y_{-4/3} \to \Phi^{-} b$; $Y_{-4/3} \to \Phi^{--} t$

Singlet T + singlet Φ: branching ratios

- Interactions with Φ

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

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

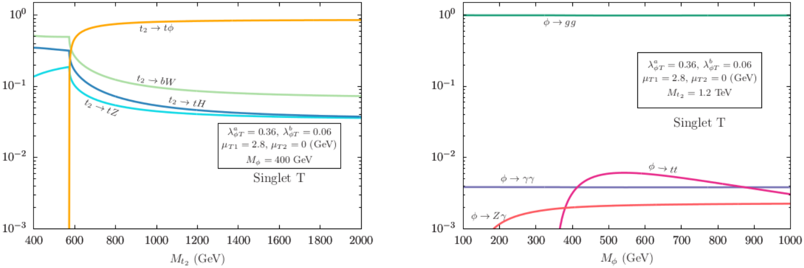


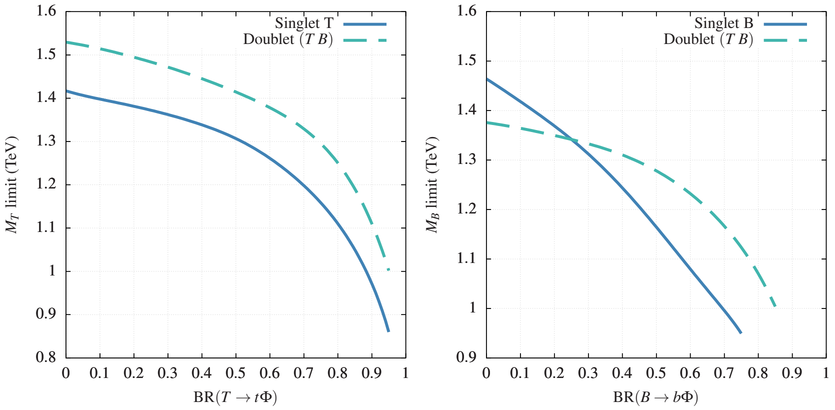
Figure: Branching ratios of (a) T quark and (b) Φ.

Rescaled mass limits

- Adding the new decay mode, the BR constraint becomes

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

- 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)

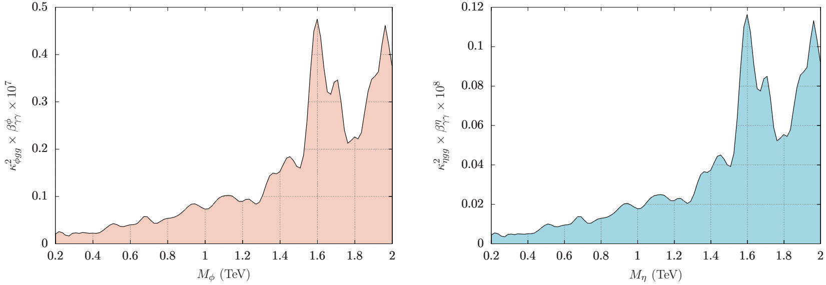


Limits on Φgg coupling

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

$$\kappa^2_{\Phi gg} \times \sigma_{pp\to\Phi} \times \beta_{\Phi\to\gamma\gamma} < \sigma_{\text{meas}} \times \varepsilon$$

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



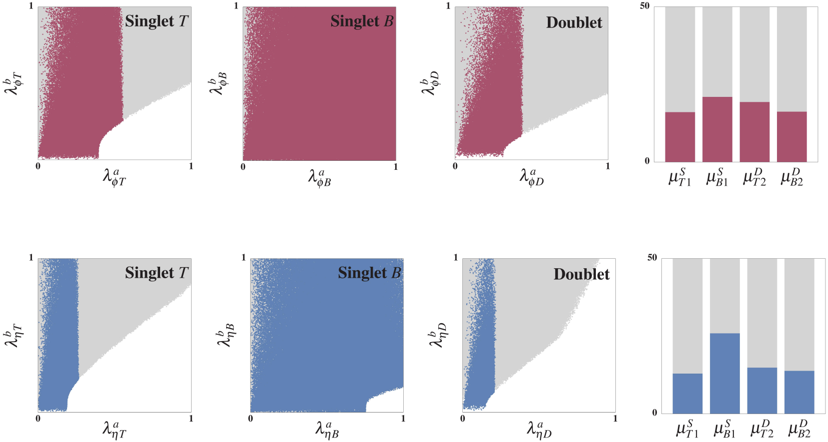
The white regions are excluded.

arXiv:2203.13753

$q_2 \to q_1\Phi$ 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: $\lambda^i \in [-1.0, 1.0]$, $\mu \in [0, 50]$
- Demands:
  - $\text{BR}(q_2 \to q\Phi)$ 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

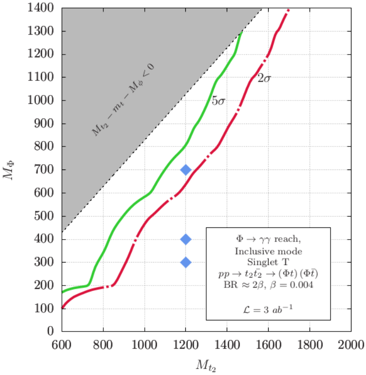


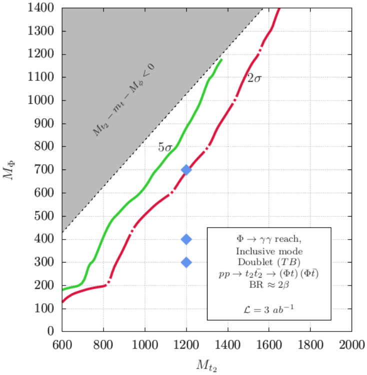
Pair-production of VLQs revisited

$q_2\bar{q}_2$ decay	Possible final states: $q_2 = t_2$	Possible final states: $q_2 = b_2$
$q\Phi\ q\Phi$	$2t + 4j$	$2b + 4j$
	$2t + 2\gamma + 2j$ [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 $b\Phi\ tW$	$t + b + 4j$	$t + b + 4j$
	$t + b + 2\gamma + 2j$	$t + b + 2\gamma + 2j$
	$t + b + 2j + \ell + \not{E}$	$t + b + 2j + \ell + \not{E}$
	$t + b + 2\gamma + \ell + \not{E}$	$t + b + 2\gamma + \ell + \not{E}$
	$3t + b + 2j$	$3b + t + 2j$
	$3t + b + \ell + \not{E}$	$3b + t + 2\gamma + \ell + \not{E}$
$q\Phi\ q_1Z$ or $q\Phi\ q_1h$	$2t + 4j$	$2b + 4j$
	$2t + 4\gamma$	$2b + 4\gamma$
	$2t + 2b + 2j$	$2b + 2j + 2\gamma$
	$2t + 2b + 2\gamma$	$2b + 2j + 2\ell$
	$2t + 2j + 2\gamma$	$2b + 2\ell + 2\gamma$
	$2t + 2\ell + 2j$	$2b + 2t + 2j$ (#)
	$2t + 2\ell + 2\gamma$	$4b + 2j$
	$2t + 4b$ (#)	$4b + 2\gamma$
	$4t + 2\gamma$	$4b + 2\ell$
	$4t + 2b$	$4b + 2t$ (#)
	$4t + 2j$	$6b$
	$4t + 2\ell$	

$pp \to TT \to (t\Phi)(t\Phi) \to 2t + 4\gamma$

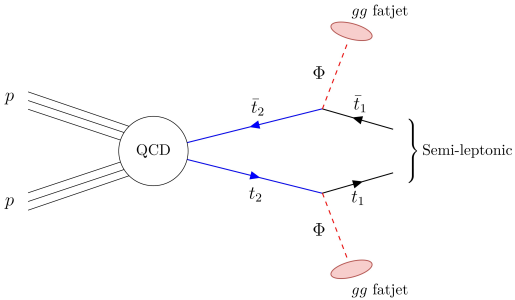
- Pros: a very clean channel for discovery.
- Cons: hard to achieve substantial branching in $\Phi \to \gamma\gamma$ mode in realistic models





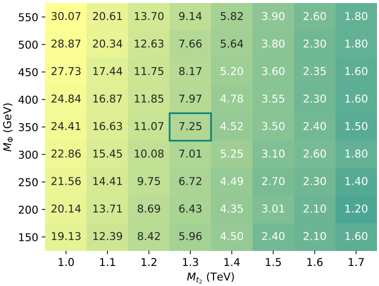
HL-LHC prospects of singlet T

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



- Semileptonic mode $\implies$ 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.

HL-LHC reach

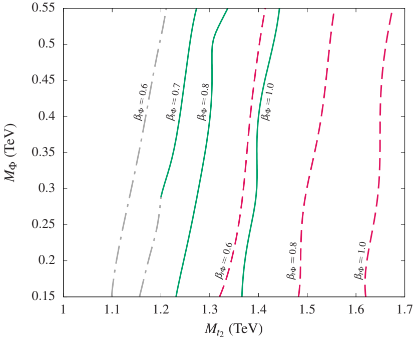


- We use a boosted decision tree (BDT) model to separate pair produced t_2 signal from the backgrounds.
- The significance formula use

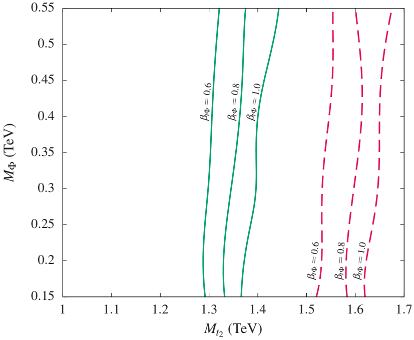
$$\mathscr{Z} = \frac{N_S}{\sqrt{N_S + N_B}}$$

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

Exclusive & inclusive modes



(a)



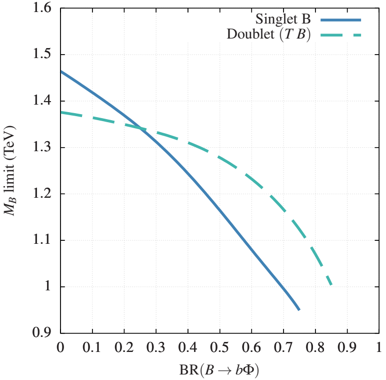
(b)

(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: $\beta_{t\Phi}\,(2 - \beta_{t\Phi})$

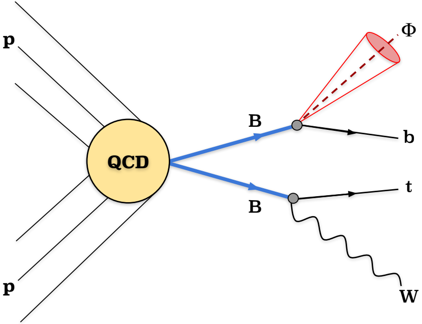
HL-LHC prospects of singlet B

- When $B \to b\Phi$ mode is dominant $B\bar{B} \to (bgg)\,(\bar{b}gg)$ / $(bb\bar{b})\,(\bar{b}b\bar{b})$ **Fully hadronic!**
- Singlet B, rescaled limits relax faster $\Longrightarrow$ **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)**



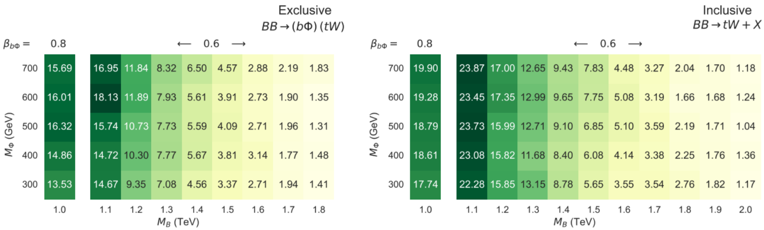
Asymmetric pair production of singlet B

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



- Semileptonic mode $\implies$ 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 $M_J > 300$ GeV, separated from b jet

LHC reach

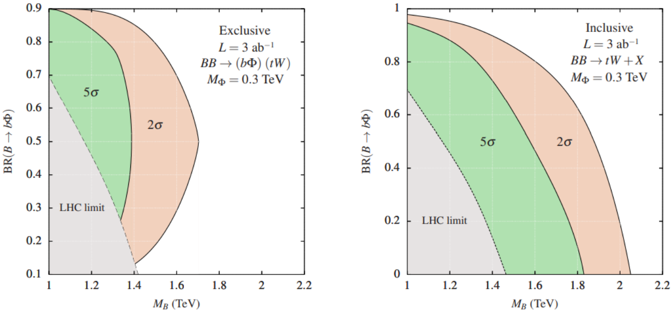


- We use a simple deep neural network (DNN) with weighted loss for classification.
- The significance formula use

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

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

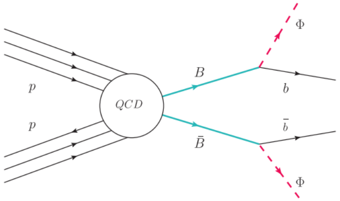
Discovery and exclusion regions

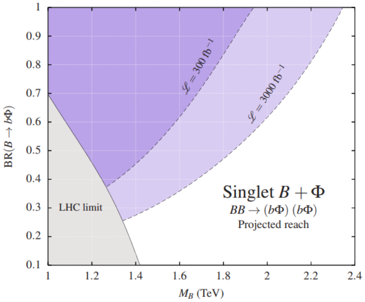


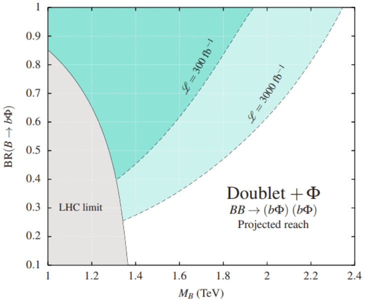
- For every mass point, we search over $\beta_{b\Phi} \in [0.1, 0.9]$ to find the maximum and minimum values for $\mathscr{Z} = 5$ and 2.
- For singlet model, signal yield scales as $2\beta_{b\Phi}(1 - \beta_{b\Phi})$ and becomes maximum for 0.5.

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

Singlet/doublet B in fully hadronic mode







Maverick top-partners

J. H. Kim et. al. '19

$$\mathscr{G} \equiv \mathscr{G}_{\rm SM} \times U(1)_d$$

	$SU(3)$	$SU(2)_L$	Y	Y_d
t_{1R}	3	1	2/3	0
b_R	3	1	−1/3	0
$Q_L = \binom{t_{1L}}{b_L}$	3	2	1/6	0
Φ	1	2	1/2	0
t_{2L}	3	1	2/3	1
t_{2R}	3	1	2/3	1
H_d	1	1	0	1

$$\Gamma(T\to tZ) \approx \Gamma(T\to th_1) \approx \frac{1}{2}\Gamma(T\to bW) \approx \frac{1}{32\pi}\frac{M_T^3}{v_{\rm EW}{}^2}\sin^2\theta_L^t$$

$$\Gamma(T\to t\gamma_d) \approx \Gamma(T\to th_2) \approx \frac{1}{32\pi}\frac{M_T^5}{M_t^2 v_d^2}\frac{\sin^2\theta_L^t}{1+\frac{M_T^2}{M_t^2}\sin^2\theta_L^t}$$

$$\frac{\Gamma(T\to t+\gamma_d/h_2)}{\Gamma(T\to t/b+W/Z/h_1)} \approx \left(\frac{M_T}{M_t}\right)^2\left(\frac{v_{\rm EW}}{v_d}\right)^2\frac{1}{1+\frac{M_T^2}{M_t^2}\sin^2\theta_L^t}$$

$$\varepsilon = \left(\frac{7}{R(M_{\gamma_d}) + \sum_{\ell=e,\mu,\tau}\theta(M_{\gamma_d}-2M_\ell)}\right)^{1/2}\left(\frac{M_T}{1\ \text{TeV}}\right)^{1/2}\left(\frac{1\ \text{GeV}}{M_{\gamma_d}}\right)$$

$$\times\begin{cases} \gtrsim 1\times 10^{-3} & \text{for prompt decays} \\ 2.4\times 10^{-6} - 7.6\times 10^{-5} & \text{for displaced vertices} \\ 7.6\times 10^{-7} - 2.4\times 10^{-6} & \text{for decays in detector} \\ \lesssim 7.6\times 10^{-7} & \text{for decays outside the detector} \end{cases}$$

- Decays outside the detector: PRD 107 (2023) 11, 115024
- Prompt decays: submitted to PRD (S. Verma, S. Biswas, **TM**, S. Mitra)
- Displaced vertices: ongoing (S. Verma, S. Biswas, **TM**, S. Mitra, N. Reule)

Interesting facts and future investigations

- Considered only statistical uncertainty. Will inclusion of systematic uncertainty wash out the reach? Median Z-score will reduce the significance a lot - underestimated.

$$\mathscr{Z} = \sqrt{2}\left((N_S + N_B) \ln\left[\frac{(N_S + N_B)(N_B + \sigma_B^2)}{N_B^2 + (N_S + N_B)\sigma_B^2} \right] - \left(\frac{N_B}{\sigma_B^2} \right)^2 \ln\left[1 + \frac{\sigma_B^2 N_S}{N_B(N_B + \sigma_B^2)} \right] \right)^{1/2}$$

- **Liptak-Stouffer (weighted) Z-score** might be a remedy We used in 2106.07605

$$\mathscr{Z} = \frac{\sum_{i=1}^{N} w_i \mathscr{Z}_i}{\sqrt{\sum_{i=1}^{N} w_i^2}} \qquad w_i^{-1} = N_B^i + (\sigma_B^i)^2$$

- Is the standard cross-entropy loss function used in neural network good? Can we do better? **We found a mathematically derived loss-function which can give better Z-score.** arXiv:2412.09500
- What is the best discovery channel for a doublet B that decays to $B \to b\Phi$? How to discover B that decays dominantly to $B \to b\Phi$? **A multi-prong 'vectorlike quark' tagger can help.**

Take away

- Searches for VLQs are null. But, we are optimistic, perhaps **decaying to non-standard decay modes**.
- Mass limits on VLQs **relax significantly** in the presence of new $Q \to q\Phi$ decay mode.
- 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 region of available parameter space.**
- $\Phi \to gg$ decays is dominant as well (even above tt-threshold) in large part of the parameter space - **not fine-tuned.**
- 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!