New Phenomenology of Vector-Like Fermions

Felix Yu
JGU Mainz

Based in part on [1612.01909] with Bogdan A. Dobrescu

IAS Program on High Energy Physics
HKUST Jockey Club Institute for Advanced Study, January 11, 2018

Motivation

- New particle searches share historical motivation from naturalness constructions
- Bottom-up constructions provide new phenomenology
  - Can reveal new patterns for searches
  - Null results in standard channels leaves open possibility for exotic decays
    - a la R-parity violating SUSY
- Will mainly focus on vector-like quarks (largest rate)

Outline

- Brief recap: Current LHC status of VLQ searches
- New collider phenomenology for VLQs
  - 3-body decays via heavy leptoquark
  - 3-body decays via heavy diquark
- Phenomenology of vector-like fermions from gauged U(1)'
- Conclusions

Vector-like quarks

- Canonically arise many BSM constructions with Higgs as PNGB
- (Colored) Top-partners generally mix with SM top quark, lowering cutoff scale of Higgs
  - Top partner inherits coupling of SM top to Higgs and longitudinal modes of W, Z
  - Predicts decay pattern of t' → bW, tZ, tH at 2:1:1 ratio as t' mass grows
  - e.g. VL pair of RH top quark partners, χ_L and χ_R

$$\mathcal{L} \supset -m_\chi \bar{\chi}\chi - \overline{q}_L^j H \left(y_{j\chi}\chi_R + y_{ji}u_R^i\right) + \text{H.c.}$$

Vector-like quarks

- Mixing angle between χ_L and t_L is

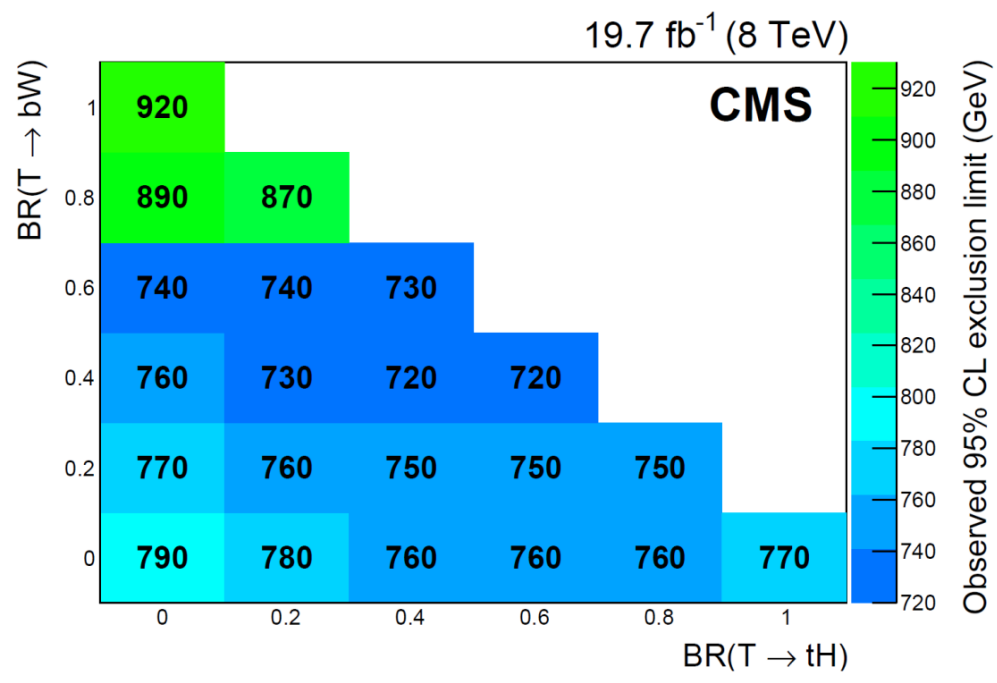
$$s_L \equiv \sin\theta_L \simeq y_{3\chi}\frac{v_H}{m_\chi}$$

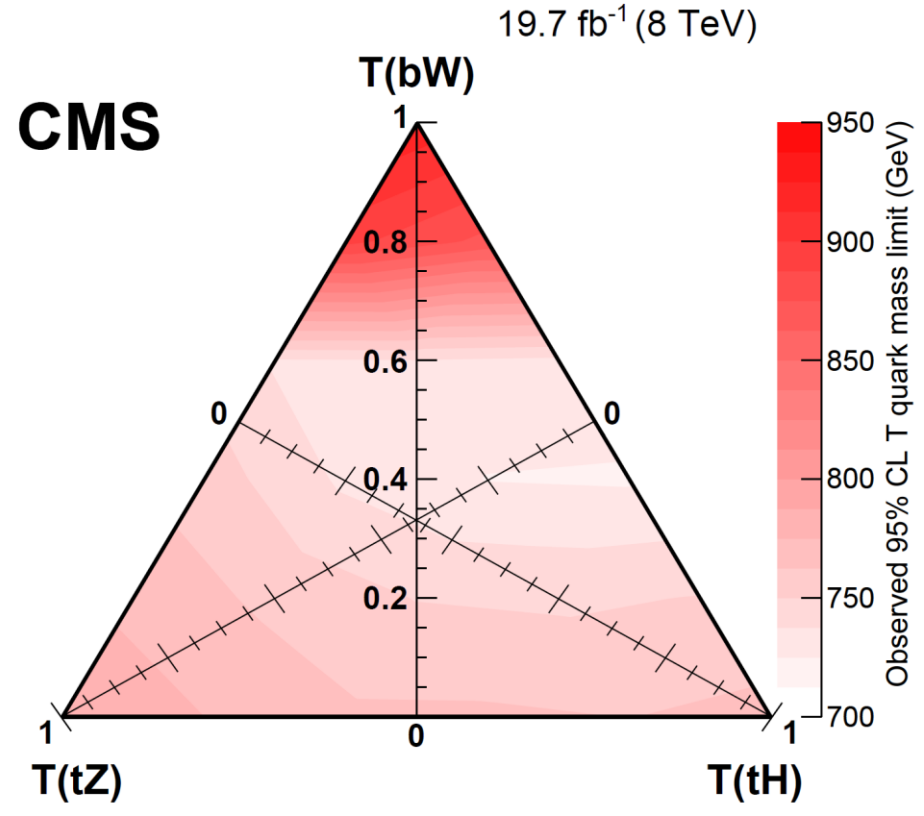
- Decay width for t' (combining standard decays) is

$$\Gamma(t' \to Wb, Zt, ht) = \frac{s_L^2(2-s_L^2)}{32\pi v_H^2} m_{t'}^3 \left[1 + O\left(\frac{m_t^2}{m_{t'}^2}\right)\right]$$

VLQ searches – Standard decays

- Most recent combined analysis of standard channels is still 8 TeV data

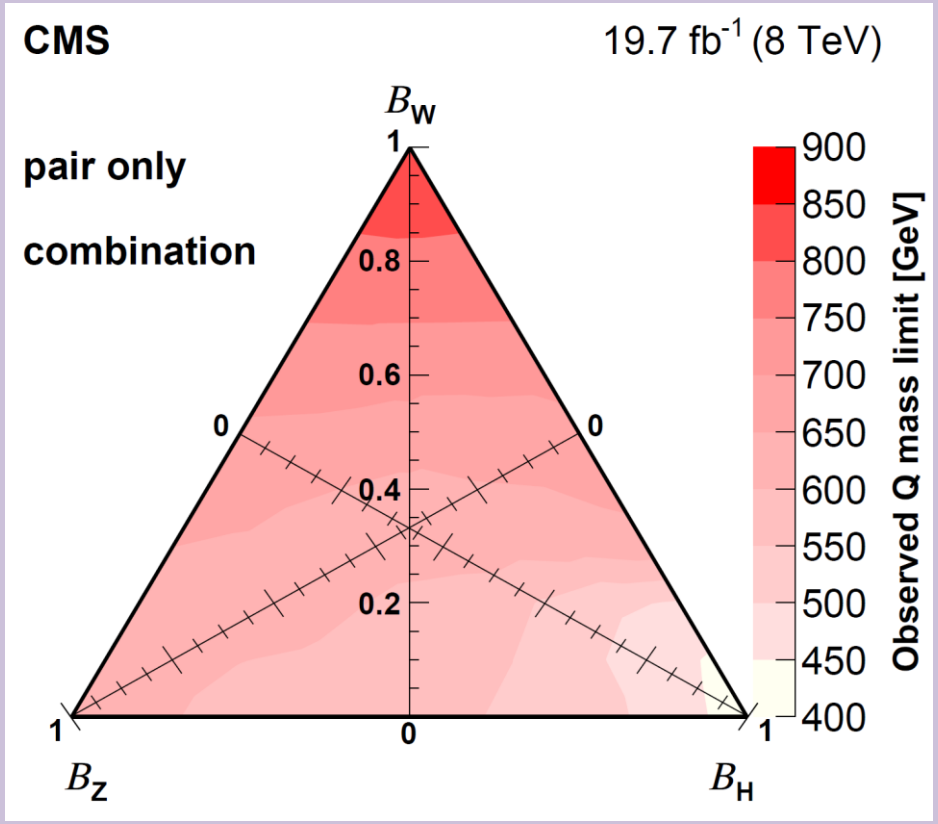




CMS [1509.04177]

VLQ searches – Standard decays

- Also expand to non-heavy flavor decays
  - Remove heavy flavor tagging on associated jets



CMS [1708.02510]

Collider phenomenology of VLQs

- For $s_L \to 0$, obvious Z_2 symmetry restored, preventing t' decay
  - Vector-like mass disconnected from Yukawa interactions
  - Pair production is model-independent, decays are model-dependent
- Consider $y_{3\chi}$ vanishing at tree level, and other NP particles mediate t' decays
  - Construct possible sets of t' decays from dimension-6 four fermion operators
  - Mediators can be out of reach of LHC

Scenario 1: t' and new leptoquark

- Four-fermion operator

$$\mathcal{O}_6 = \frac{\lambda_\chi \lambda_q}{M_\xi^2}(\overline{\chi}_R l_L^3)\, i\sigma_2(\overline{\tau}_R q_L^3) + \text{H.c.}$$

- UV completion is a tree-level LQ exchange

$$\mathcal{L} = \lambda_\chi(\bar{\chi}_R l_L^3) i\sigma_2 \xi + \lambda_q \chi^\dagger(\bar{\tau}_R q_L^3) + \lambda_t \xi^\dagger i\sigma_2(\bar{l}_L^3 u_R^3)$$

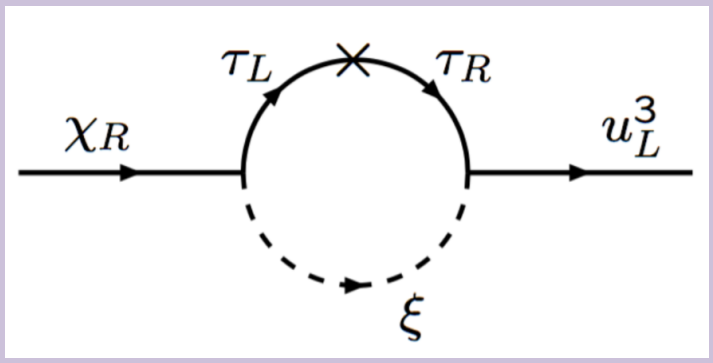
- Operator induced t' decay width

$$\Gamma(t' \to \tau^+\tau^- t) = \frac{\lambda_\chi^2(\lambda_q^2+\lambda_t^2)}{6144\pi^3 M_\xi^4} m_{t'}^5 \left[1 + O\left(\frac{m_t^2}{m_{t'}^2}\right)\right]$$

Scenario 1: t' and new leptoquark

- Setting / tuning $y_{3\chi} = 0$ at UV scale is not protected by RGEs
- Reintroduce s_L from LQ-induced vertex correction

$$s_L = \frac{y_\tau \lambda_\chi \lambda_q v_H}{8\pi^2 m_\chi} \ln \frac{\Lambda}{M_\xi}$$

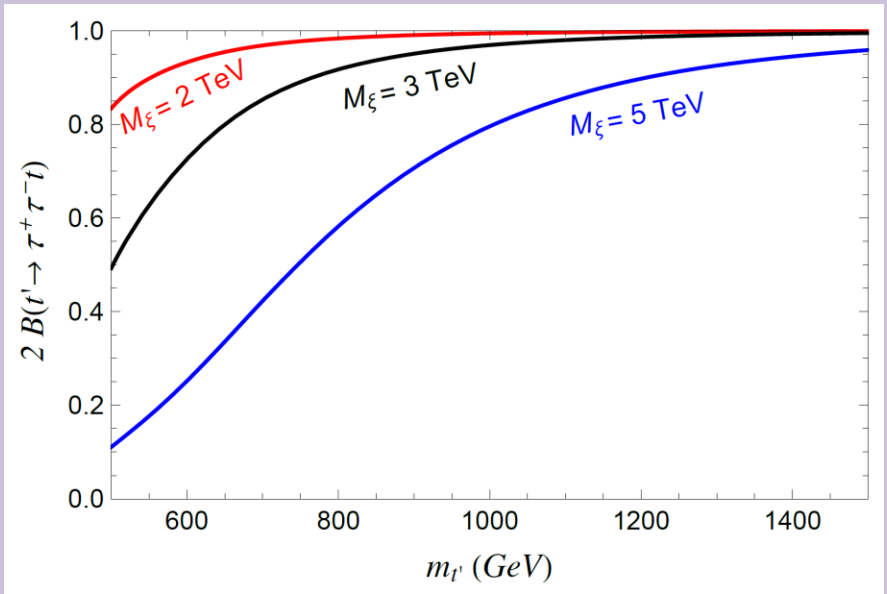


- Decays remain prompt for very heavy LQs

$$L_{t'} = \frac{1.9\ \mu\text{m}}{\lambda_\chi^2(\lambda_q^2 + \lambda_t^2)} \left(\frac{M_\xi}{100\ \text{TeV}}\right)^4 \left(\frac{1\ \text{TeV}}{m_{t'}}\right)^5$$

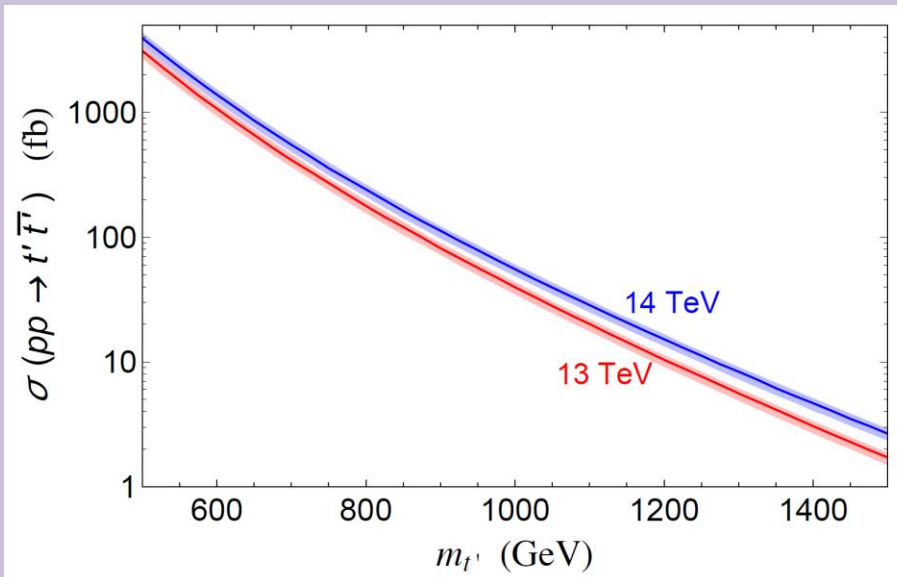
Scenario 1: t' and new leptoquark

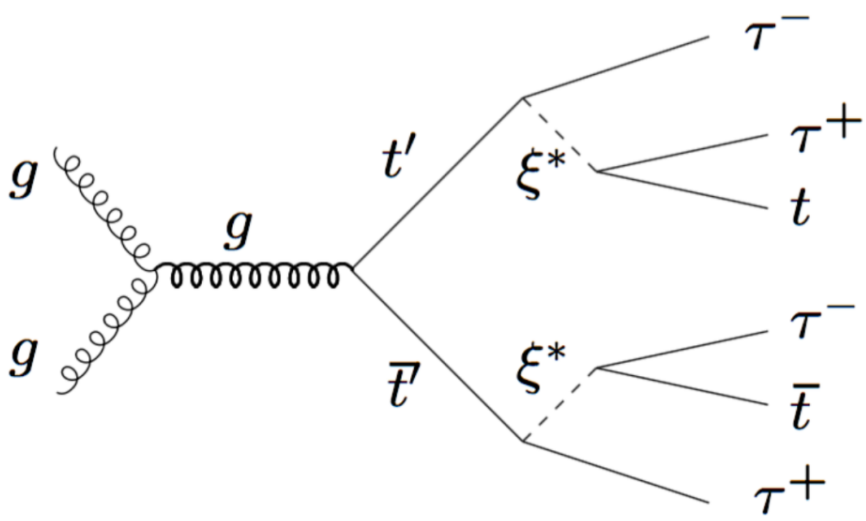
- Overall exotic decay width from dimension-6 operator competes
  - Exotic branching fraction includes t' → ττt and t' → τνb
  - Rates in standard search channels generally suppressed, even for LQs at O(TeV) scale



Scenario 1: Collider phenomenology

- Non-resonant structure make it more difficult to optimize
  - Tau identification not extensively used in current standard searches
- Exotic decay kinematically similar to t' -> tZ, Z -> ττ and t' -> tH, H -> ττ decays
  - Rates in primary Z and Higgs channels depleted
  - Detailed phenomenology study ongoing





Scenario 2: t' and new diquark

- Four-fermion operator

$$\mathcal{O}_6 = \frac{\kappa_\chi \kappa_t}{M_\zeta^2}(\overline{\chi}_R^c d_R^3)(\overline{d}_R^3 u_R^{3c}) + \text{H.c.}$$

- UV completion is a diquark, Y = -1/3

$$\mathcal{L} = \kappa_\chi \zeta \bar{\chi}_R^c d_R^3 + \kappa_t \zeta^\dagger \bar{d}_R^3 u_R^{3c}$$

- Jet-rich, heavy flavor-rich exotic decay

$$\Gamma(t' \to b\bar{b}t) = \frac{(\kappa_\chi \kappa_t)^2}{2048\pi^3 M_\zeta^4} m_{t'}^5 \left[1 + O\left(\frac{m_t^2}{m_{t'}^2}\right)\right]$$

Scenario 2: t' and new diquark

- Four-fermion operator

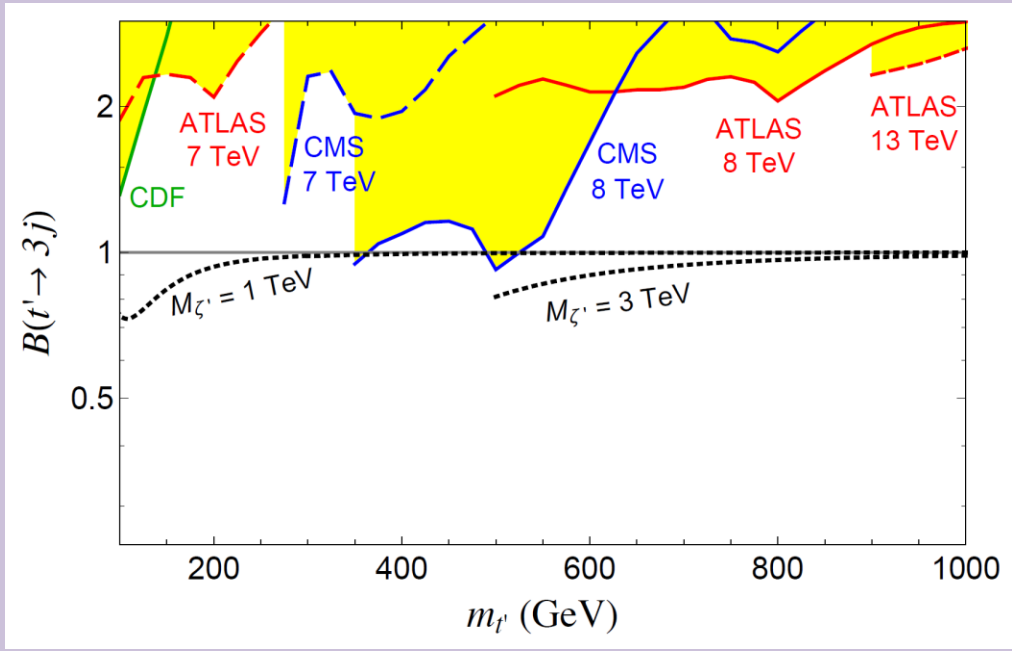
$$\mathcal{O}_6 = \frac{\kappa'_\chi \kappa'_t}{M^2_{\zeta'}} (\overline{\chi}^c_R u^2_R)(\overline{u}^2_R u^{2c}_R) + \text{H.c.}$$

- UV completion is a diquark, Y = -4/3
- Flavor structure of LQ imprints on exotic decay of t'

$$\Gamma(t' \to c\bar{c}c) = \frac{(\kappa'_\chi \kappa'_t)^2}{2048\pi^3 M'^4_\zeta} m^5_{t'} \left[1 + O\left(\frac{m^2_t}{m^2_{t'}}\right)\right]$$

Scenario 2: Collider phenomenology

- For t' → 3c, current searches are largely unconstraining
  - Recast from RPV gluino searches



- Can also extend idea to bottom partners, b'

Revisiting vector-like fermions

- Gauge-invariant mass term admittedly unattractive
- More compelling: ascribe chiral symmetry to generate mass scale for VL fermions
  - Should distinguish from SM fermions by some new gauge charge, e.g. U(1)'
- Two possibilities

See, e.g. Lu, Morrissey, Wijangco [1705.08896]

  - Reuse SM chiral symmetry, vector-like under U(1)'
    - Do not have to add complete generation to cancel anomalies
  - Vector-like under SM gauge group, chiral under U(1)'
    - e.g. $U(1)_B$ or $U(1)_L$: Cancellation of mixed anomalies introduces new VL matter charged under $SU(2)_L$, $U(1)_Y$

Revisiting vector-like fermions

- Following the second possibility, new gauged U(1)' built from global SM flavor symmetries introduce new EW-charged states, possibly within reach of LHC
  - Straightforward models copy structural elements of SM: new Higgs boson, Z' boson, and anomalons
  - Model can exhibit non-SM hierarchies in masses by reshuffling λ, g_X, and y_f
  - Concrete model framework for connecting beam dump experiment searches for light Z' bosons, LHC searches for new EW states, and exotic Higgs phenomenology

Conclusions

- Vector-like matter well-probed in standard decays
- Exotic decay patterns are immediately realized if leading interaction with SM occurs at high scale
  - Explicitly not naturalness-motivated top-partners
  - Can connect to flavor structure of LQs inspired by B-meson anomalies See Buttazzo, Greljo, Isidori, Marzocca [1706.07808]
- EW vector-like fermions necessary in UV completions of new chiral U(1)' models
  - Connect beam dump probes with LHC direct searches and Higgs physics – can also connect to DM

Scenario 3: b' and new LQ

- Four-fermion operator

$$\mathcal{O}_6 = \frac{\lambda'_\chi}{M^2_{\xi'}}(\overline{\omega}_R \tau^c_R)\left(\lambda'_q\, \bar{l}^{3c}_L i\sigma_2 q^3_L + \lambda'_t\, \overline{\tau}^c_R d^3_R\right) + \text{H.c.}$$