NEW PHENOMENOLOGY OF VECTOR-LIKE FERMIONS

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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 $t' \rightarrow bW, tZ, tH$ at 2:1:1 ratio as $t'$ mass grows
  – e.g. VL pair of RH top quark partners, $\chi_L$ and $\chi_R$

$$\mathcal{L} \supset -m_\chi \bar{\chi} \chi - \bar{q}_L^j H (y_j \chi \chi_R + y_{ji} u^i_R) + \text{H.c.}$$

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Vector-like quarks

- Mixing angle between $\chi_L$ 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

$$\Gamma(t' \to Wb, Zt, ht) = \frac{s^2_L (2 - s^2_L)}{32\pi v^2_H} m^3_{t'} \left[ 1 + O\left( \frac{m^2_t}{m^2_{t'}} \right) \right]$$
VLQ searches – Standard decays

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

CMS [1509.04177]

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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 $s_L \rightarrow 0$, 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
  \[ \mathcal{O}_6 = \frac{\lambda \lambda_q}{M_\xi^2} \left( \bar{\chi}_R l^3_L \right) i\sigma_2 \left( \bar{\tau}_R q^3_L \right) + \text{H.c.} \]

- UV completion is a tree-level LQ exchange
  \[ \mathcal{L} = \lambda \chi (\bar{\chi}_R l^3_L)i\sigma_2 \xi + \lambda_q \chi^\dagger (\bar{\tau}_R q^3_L) + \lambda_t \xi \dagger i\sigma_2 (\bar{l}_L^3 u_R^3) \]

- Operator induced $t'$ decay width
  \[ \Gamma(t' \rightarrow \tau^+ \tau^- t) = \frac{\lambda^2 \chi (\lambda_q^2 + \lambda_t^2)}{6144\pi^3 M_\xi^4} m_{t'}^5 \left[ 1 + O \left( \frac{m_t^2}{m_{t'}^2} \right) \right] \]
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
  \[ L_{t'} = \frac{1.9 \, \mu m}{\lambda_\chi^2 (\lambda_q^2 + \lambda_t^2)} \left( \frac{M_\xi}{100 \, \text{TeV}} \right)^4 \left( \frac{1 \, \text{TeV}}{m_{t'}} \right)^5 \]
Scenario 1: t’ and new leptoquark

- Overall exotic decay width from dimension-6 operator competes
  - Exotic branching fraction includes $t' \rightarrow \tau\tau t$ and $t' \rightarrow \tau\nu b$
  - 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 $t' \rightarrow tZ, Z \rightarrow \tau\tau$ and $t' \rightarrow tH, H \rightarrow \tau\tau$ decays
  - Rates in primary $Z$ and Higgs channels depleted
  - Detailed phenomenology study ongoing
Scenario 2: $t'$ and new diquark

- **Four-fermion operator**
  \[ O_6 = \frac{\kappa_X \kappa_t}{M_\zeta^2} (\bar{\chi}_R^c d_R^3)(\bar{d}_R^3 u_R^{3c}) + \text{H.c.} \]

- **UV completion is a diquark, $Y = -1/3$**
  \[ \mathcal{L} = \kappa_X \zeta \chi_R^c d_R^3 + \kappa_t \zeta^\dagger \bar{d}_R^3 u_R^{3c} \]

- **Jet-rich, heavy flavor-rich exotic decay**
  \[ \Gamma(t' \rightarrow b\bar{b}t) = \frac{(\kappa_X \kappa_t)^2}{2048 \pi^3 M_\zeta^4} m_{t'}^5 \left[ 1 + O \left( \frac{m_t^2}{m_{t'}^2} \right) \right] \]
Scenario 2: $t'$ and new diquark

- Four-fermion operator
  \[ O_6 = \frac{\kappa_{\chi}^l \kappa_t^l}{M_{\zeta}^2} \left( \overline{\chi}_R u_R^2 \right) \left( \overline{u}_R u_R^{2c} \right) + \text{H.c.} \]

- UV completion is a diquark, $Y = -4/3$

- Flavor structure of LQ imprints on exotic decay of $t'$
  \[ \Gamma(t' \rightarrow c\overline{c}c) = \frac{(\kappa_{\chi}^l \kappa_t^l)^2}{2048\pi^3 M_{\zeta}^4} m_{t'}^5 \left[ 1 + O\left( \frac{m_t^2}{m_{t'}^2} \right) \right] \]
Scenario 2: Collider phenomenology

• For $t' \rightarrow 3c$, 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
  – 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}

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

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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 \( \lambda, g_X, \) 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

\[ O_6 = \frac{\lambda'_{\chi}}{M^2_{\xi'}} (\bar{\omega}_R \tau^c_R) \left( \lambda'_q \bar{l}_L^3 c \sigma_2 q_L^3 + \lambda'_t \bar{\tau}^c_R d_R^3 \right) + \text{H.c.} \]