Vector-like quarks
\( t' \) and partners

Luca Panizzi

University of Southampton, UK
Outline

1. Motivations and Current Status
2. Couplings and constraints
3. Signatures at LHC
1 Motivations and Current Status

2 Couplings and constraints

3 Signatures at LHC
What are vector-like fermions?
and where do they appear?

The left-handed and right-handed chiralities of a vector-like fermion $\psi$
transform in the same way under the SM gauge groups $SU(3)_c \times SU(2)_L \times U(1)_Y$. 
What are vector-like fermions? and where do they appear?

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Why are they called “vector-like”?
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Why are they called “vector-like”?

$$\mathcal{L}_W = \frac{g}{\sqrt{2}} \left( J^\mu_+ W^\mu_+ + J^\mu_- W^\mu_- \right)$$

Charged current Lagrangian
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$$\mathcal{L}_W = \frac{g}{\sqrt{2}} \left( J_{\mu}^+ W_{\mu}^+ + J_{\mu}^- W_{\mu}^- \right)$$

Charged current Lagrangian

SM chiral quarks: ONLY left-handed charged currents

$$J_{\mu}^+ = J_{L\mu}^+ + J_{R\mu}^+$$

with

$$\begin{cases} 
J_{L\mu}^+ = \bar{u}_L \gamma^\mu d_L = \bar{u} \gamma^\mu (1 - \gamma^5) d = V - A \\
J_{R\mu}^+ = 0 
\end{cases}$$
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$$\mathcal{L}_W = \frac{g}{\sqrt{2}} \left( J_{\mu}^+ W^+_{\mu} + J_{\mu}^- W^-_{\mu} \right)$$

Charged current Lagrangian

- SM chiral quarks: ONLY left-handed charged currents

$$J_{\mu}^+ = J_{\mu}^L + J_{\mu}^R$$

with

$$\begin{cases} J_{\mu}^L = \bar{u}_L \gamma^\mu d_L = \bar{u} \gamma^\mu (1 - \gamma^5) d = V - A \\ J_{\mu}^R = 0 \end{cases}$$

- vector-like quarks: BOTH left-handed and right-handed charged currents

$$J_{\mu}^+ = J_{\mu}^L + J_{\mu}^R = \bar{u}_L \gamma^\mu d_L + \bar{u}_R \gamma^\mu d_R = \bar{u} \gamma^\mu d = V$$
What are vector-like fermions?
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The left-handed and right-handed chiralities of a vector-like fermion $\psi$ transform in the same way under the SM gauge groups $SU(3)_c \times SU(2)_L \times U(1)_Y$.

Vector-like quarks in many models of New Physics

- Warped or universal **extra-dimensions**
  KK excitations of bulk fields

- **Composite Higgs** models
  VLQ appear as excited resonances of the bounded states which form SM particles

- **Little Higgs** models
  partners of SM fermions in larger group representations which ensure the cancellation of divergent loops

- **Gauged flavour group** with low scale gauge flavour bosons
  required to cancel anomalies in the gauged flavour symmetry

- **Non-minimal SUSY extensions**
  VLQs increase corrections to Higgs mass without affecting EWPT
SM and a vector-like quark

\[ \mathcal{L}_M = -M \bar{\psi} \psi \]  
Gauge invariant mass term without the Higgs
SM and a vector-like quark

\[ \mathcal{L}_M = -M \bar{\psi} \psi \]  
Gauge invariant mass term without the Higgs

Charged currents both in the left and right sector

\[ \psi_L \rightarrow W \]  
\[ \psi_L' \rightarrow W \]  
\[ \psi_R \rightarrow W \]  
\[ \psi_R' \rightarrow W \]
SM and a vector-like quark

\[ \mathcal{L}_M = -M \bar{\psi} \psi \]  
Gauge invariant mass term without the Higgs

Charged currents both in the left and right sector

\[ \psi_L \xrightarrow{W} \psi'_{L,R} \]

They can mix with SM quarks

\[ t' \xrightarrow{W} u_i \quad b' \xrightarrow{W} d_i \]

Dangerous FCNCs \( \rightarrow \) strong bounds on mixing parameters

BUT

Many open channels for production and decay of heavy fermions

Rich phenomenology to explore at LHC
Bounds from pair production between 600 GeV and 800 GeV depending on the decay channel

Common assumption: mixing with third generation only
Example: $b'$ pair production

Common assumption
CC: $b' \rightarrow tW$

Searches in the same-sign dilepton channel (possibly with b-tagging)
Example: $b'$ pair production

$P b' \rightarrow tW$  

Common assumption  
$CC: b' \rightarrow tW$  

Searches in the  
same-sign dilepton channel  
(possibly with b-tagging)

If the $b'$ decays both into $Wt$ and $Wq$

There can be less events in the same-sign dilepton channel!
Representations and lagrangian terms

**Assumption:** vector-like quarks couple with SM quarks through Yukawa interactions
### Representations and Lagrangian Terms

**Assumption:** vector-like quarks couple with SM quarks through Yukawa interactions

<table>
<thead>
<tr>
<th></th>
<th>SM</th>
<th>Singlets</th>
<th>Doublets</th>
<th>Triplets</th>
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<tbody>
<tr>
<td></td>
<td>$(u\ d\ c\ s\ t\ b)$</td>
<td>$(U)$</td>
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<tr>
<td>$SU(2)_L$</td>
<td>2 and 1</td>
<td>1</td>
<td>2</td>
<td>3</td>
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<td>$U(1)_Y$</td>
<td>$q_L = 1/6$</td>
<td>2/3</td>
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<tr>
<td></td>
<td>$u_R = 2/3$</td>
<td>-1/3</td>
<td>1/6</td>
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<td>$d_R = -1/3$</td>
<td></td>
<td>-5/6</td>
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<tr>
<td>$L_Y$</td>
<td>$-y_u^i \bar{q}_L^i H^c u_R^i$</td>
<td>$-\lambda_u^i \bar{q}_L^i H^c U_R$</td>
<td>$-\psi_L H^{(c)} u_R$</td>
<td>$-\bar{q}_L^i \tau^a H^{(c)} \psi_R^a$</td>
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|                  |             |          |          |          |
|                  |             | 2/3 -1/3 | 7/6 1/6 -5/6 |    2/3   -1/3 |

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<thead>
<tr>
<th>( \mathcal{L}_Y )</th>
<th>(- \frac{\mathcal{y}_{lv}}{\sqrt{2}} \bar{u}^i_L u^i_R )</th>
<th>(- \frac{\mathcal{y}_{lv}}{\sqrt{2}} \bar{t}^i_L t^i_R )</th>
<th>(- \frac{\mathcal{y}_{lv}}{\sqrt{2}} \bar{d}^i_L d^i_R )</th>
<th>(- \frac{\mathcal{y}_{iv}}{\sqrt{2}} \bar{u}^i_L u^i_R )</th>
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$$U(1)_Y$$
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- -1/3
- 7/6
- 1/6
- -5/6
- 2/3
- -1/3

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<td>$$-\frac{y_i^u v}{\sqrt{2}} \bar{u}^i_L u^i_R$$</td>
<td>$$-\frac{\lambda^i_{u}}{\sqrt{2}} \bar{u}^i_L U^i_R$$</td>
<td>$$-\frac{\lambda^i_{d}}{\sqrt{2}} \bar{d}^i_L D^i_R$$</td>
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<tr>
<td>$$-\frac{y_i^d v}{\sqrt{2}} \bar{d}^i_L V^{ij}_{\text{CKM}} d^j_R$$</td>
<td>$$-\frac{\lambda^i_{d}}{\sqrt{2}} \bar{d}^i_L D^i_R$$</td>
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<tr>
<td></td>
<td>$$-M\bar{\psi}\psi$$</td>
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(gauge invariant since vector-like)

<table>
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<tr>
<th>Free parameters</th>
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<tr>
<td></td>
<td>4</td>
<td>4 or 7</td>
<td>4</td>
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<tr>
<td></td>
<td>$$M + 3 \times \lambda^i$$</td>
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Outline

1. Motivations and Current Status
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3. Signatures at LHC
Flavour changing neutral currents in the SM

$$u \times t' \times c = u$$

and flavour conserving neutral currents receive a contribution

$$u_R \times t' \times c_L = u_R$$
Couplings
Major consequences

Flavour changing neutral currents in the SM

$u \times t' = u \times Z$

$Z \times c_L = H$

and flavour conserving neutral currents receive a contribution

Charged currents between right-handed SM quarks

$u_R \times t' = u_R \times W$

$u_R \times d_R = u_R \times W$

and charged currents between left-handed SM quarks receive a contribution
Flavour changing neutral currents in the SM

\[ u \times t' \times c = u \times Z \times c, \]

and flavour conserving neutral currents receive a contribution

Charged currents between right-handed SM quarks

\[ u_R \times t' \times b' \times d_R = u_R \times W \times d_R, \]

and charged currents between left-handed SM quarks receive a contribution

All proportional to combinations of mixing parameters
**FCNC constraints**

**Rare top decays**

\[ BR(t \rightarrow Zq) = \mathcal{O}(10^{-14}) \]

SM prediction

\[ BR(t \rightarrow Zq) < 0.24\% \]

measured at CMS @ 5 fb\(^{-1}\)

**Meson mixing and decay**

\[ D^0 \{ c \quad d_i \quad d_i \quad u \} \rightarrow \bar{D}^0 \]

\[ D^0 \{ c \quad u \} \rightarrow \bar{D}^0 \]

\[ D^0 \{ c \quad d_i \quad v_i \quad u \} \rightarrow l^+ \quad l^- \]

\[ D^0 \{ c \quad u \} \rightarrow l^+ \quad l^- \]
Flavour conserving NC constraints

**Zc\bar{c} and Zb\bar{b} couplings**

- **Direct coupling measurements:** $g_{ZL,ZR}^q = (g_{ZL,ZR}^q)^{SM}(1 + \delta g_{ZL,ZR}^q)$
- **Asymmetry parameters:** $A_q = \frac{(g_{ZL}^q)^2 - (g_{ZR}^q)^2}{(g_{ZL}^q)^2 + (g_{ZR}^q)^2} = A_q^{SM}(1 + \delta A_q)$
- **Decay ratios:** $R_q = \frac{\Gamma(Z\rightarrow q\bar{q})}{\Gamma(Z\rightarrow\text{hadrons})} = R_q^{SM}(1 + \delta R_q)$

**Atomic parity violation**

Weak charge of the nucleus

$$Q_W = \frac{2c_W}{g} \left[ (2Z + N)(g_{ZL}^u + g_{ZR}^u) + (Z + 2N)(g_{ZL}^d + g_{ZR}^d) \right] = Q_W^{SM} + \delta Q_W^{VL}$$

Most precise test in Cesium $^{133}\text{Cs}$:

$$Q_W^{(133}\text{Cs})|_{exp} = -73.20 \pm 0.35 \quad Q_W^{(133}\text{Cs})|_{SM} = -73.15 \pm 0.02$$
Constraints from EWPT and CKM

EW precision tests

Contributions of new fermions to S,T,U parameters

CKM measurements

- Modifications to CKM relevant for singlets and triplets because mixing in the left sector is NOT suppressed
- The CKM matrix is not unitary anymore
- If BOTH $t'$ and $b'$ are present, a CKM for the right sector emerges
Higgs coupling with gluons/photons

Production and decay of Higgs at the LHC

New physics contributions mostly affect loops of heavy quarks $t$ and $q'$:

$$\kappa_{gg} = \kappa_{\gamma\gamma} = \frac{v}{m_t} g_{ht\bar{t}} + \frac{v}{m_{q'}} g_{hq'\bar{q}'} - 1$$

The couplings of $t$ and $q'$ to the higgs boson are:

$$g_{ht\bar{t}} = \frac{m_t}{v} + \delta g_{ht\bar{t}} \quad g_{hq'\bar{q}'} = \frac{m_{q'}}{v} + \delta g_{hq'\bar{q}'}$$

In the SM: $\kappa_{gg} = \kappa_{\gamma\gamma} = 0$

The contribution of just one VL quark to the loops turns out to be negligibly small

Result confirmed by studies at NNLO
Outline

1. Motivations and Current Status
2. Couplings and constraints
3. Signatures at LHC
Production channels

Vector-like quarks can be produced in the same way as SM quarks plus FCNCs channels.

- **Pair production**, dominated by QCD and sensitive to the $q'$ mass independently of the representation the $q'$ belongs to.
- **Single production**, only EW contributions and sensitive to both the $q'$ mass and its mixing parameters.
Production channels

Pair vs single production, example with non-SM doublet ($X_{5/3} t'$)

pair production depends only on the mass of the new particle and decreases faster than single production due to different PDF scaling

current bounds from LHC are around the region where (model dependent) single production dominates
Decays

SM partners

Neutral currents

Charged currents

Exotics

Not all decays may be kinematically allowed
it depends on representations and mass differences
Decays of $t'$

Equivalence theorem at large masses: $BR(qH) \simeq BR(qZ)$

Decays are in different channels (BR=100% hypothesis now relaxed in exp searches)
Decays of $t'$

Equivalence theorem at large masses: $\text{BR}(qH) \sim \text{BR}(qZ)$

Decays are in different channels (BR=100% hypothesis now relaxed in exp searches)

Still, current bounds assume mixing with third generation only!
Decays of $t'$

Equivalence theorem at large masses: $BR(qH) \simeq BR(qZ)$
Decays are in different channels (BR=100% hypothesis now relaxed in exp searches)

Still, current bounds assume mixing with third generation only!

Decay to lighter generations can be sizable even if Yukawas are small!
Single Production

From couplings to BRs

Charged current of T ($t'$)

$$\mathcal{L} \supset \kappa_W V_{L/R}^{4i} \frac{g}{\sqrt{2}} \left[ \bar{T}_{L/R} W_{\mu}^+ \gamma^\mu d^i_{L/R} \right]$$
From couplings to BRs

Charged current of $T (t')$

$$\mathcal{L} \supset \kappa_W V_{4i}^{L/R} \frac{g}{\sqrt{2}} \left[ \bar{T}_{L/R} W_{\mu}^{+} \gamma^{\mu} d_{L/R}^{i} \right]$$

Partial Width

$$\Gamma(T \rightarrow Wd_{i}) = \kappa_W^2 |V_{4i}^{L/R}|^2 \frac{M^3 g^2}{64 \pi m_W^2} \Gamma_W^0 (M, m_W, m_d = 0)$$

Assumption: massless SM quarks, corrections for decays into top (see 1305.4172)
From couplings to BRs

Charged current of $T$ ($t'$)

$$\mathcal{L} \supset \kappa_W V_{L/R}^{4i} \frac{g}{\sqrt{2}} [T_{L/R} W_+^\mu \gamma^\mu d_{L/R}^i]$$

Partial Width

$$\Gamma(T \rightarrow Wd_i) = \kappa_W^2 |V_{L/R}^{4i}|^2 \frac{M_W^3 g^2}{64 \pi m_W^2} \Gamma_W^0 (M, m_W, m_{d_i} = 0)$$

Assumption: massless SM quarks, corrections for decays into top (see 1305.4172)

Branching Ratio

$$BR(T \rightarrow Wd_i) = \frac{|V_{L/R}^{4i}|^2}{\sum_{j=1}^{3} |V_{L/R}^{4j}|^2} \cdot \frac{\kappa_W^2 \Gamma_W^0}{\sum_{V'=W,Z,H} \kappa_{V'}^2 \Gamma_{V'}^0} \equiv \zeta_i \xi_W$$
From couplings to BRs

Charged current of T ($t'$)

$$\mathcal{L} \supset \kappa_W V_{L/R}^{4i} \frac{g}{\sqrt{2}} [\bar{T}_{L/R} W^+_\mu \gamma^\mu d^i_{L/R}]$$

Partial Width

$$\Gamma(T \to Wd_i) = \kappa_W^2 |V_{L/R}^{4i}|^2 \frac{M_W^3 g^2}{64 \pi m_W^2} \Gamma_0^W (M, m_W, m_{d_i} = 0)$$

Assumption: massless SM quarks, corrections for decays into top (see 1305.4172)

Branching Ratio

$$BR(T \to Wd_i) = \frac{|V_{L/R}^{4i}|^2}{\sum_{j=1}^3 |V_{L/R}^{Aj}|^2} \cdot \frac{\kappa_W^2 \Gamma_0^W}{\sum_{V'=W,Z,H} \kappa_{V'}^2 \Gamma_{V'}^0} \equiv \zeta_i \xi_W$$

Re-expressing the Lagrangian

$$\mathcal{L} \supset \kappa_T \sqrt{\frac{\zeta_i \xi_W}{\Gamma_0^W}} \frac{g}{\sqrt{2}} [\bar{T}_{L/R} W^+_\mu \gamma^\mu d^i_{L/R}] \quad \text{with} \quad \kappa_T = \sqrt{\sum_{i=1}^3 |V_{L/R}^{4i}|^2} \sqrt{\sum_V \kappa_V^2 \Gamma_V^0}$$
The complete Lagrangian

\[ \mathcal{L} = \kappa_T \left\{ \sqrt{\frac{\zeta_i T^{\dagger}}{\Gamma_W^0}} \frac{g}{\sqrt{2}} [\bar{T}_L W^+_{\mu} \gamma^\mu u^i_L] + \sqrt{\frac{\zeta_i Z}{\Gamma_Z^0}} \frac{g}{2 c_W} [\bar{T}_L Z_{\mu} \gamma^\mu u^i_L] - \sqrt{\frac{\zeta_i H}{\Gamma_H^0}} \frac{M}{v} [\bar{T}_R u^i_L] - \sqrt{\frac{\zeta_3 H}{\Gamma_H^0}} \frac{m_t}{v} [\bar{T}_L h_t] \right\} \\
+ \kappa_B \left\{ \sqrt{\frac{\zeta_i B^{\dagger}}{\Gamma_W^0}} \frac{g}{\sqrt{2}} [\bar{B}_L W^-_{\mu} \gamma^\mu u^i_L] + \sqrt{\frac{\zeta_i Z}{\Gamma_Z^0}} \frac{g}{2 c_W} [\bar{B}_L Z_{\mu} \gamma^\mu d^i_L] - \sqrt{\frac{\zeta_i H}{\Gamma_H^0}} \frac{M}{v} [\bar{B}_R d^i_L] \right\} \\
+ \kappa_X \left\{ \sqrt{\frac{\zeta_i X^{\dagger}}{\Gamma_W^0}} \frac{g}{\sqrt{2}} [\bar{X}_L W^+_{\mu} \gamma^\mu u^i_L] \right\} \\
+ \kappa_Y \left\{ \sqrt{\frac{\zeta_i Y^{\dagger}}{\Gamma_W^0}} \frac{g}{\sqrt{2}} [\bar{Y}_L W^-_{\mu} \gamma^\mu d^i_L] \right\} \\
+ h.c. \]


\[ \sum_{i=1}^{3} \zeta_i = 1 \quad \sum_{V=W,Z,H} \xi_V = 1 \]

- \(T\) and \(B\): NC+CC, 4 parameters each (\(\zeta_{1,2}\) and \(\xi_{W,Z}\))
- \(X\) and \(Y\): only CC, 2 parameters each (\(\zeta_{1,2}\))
Cross sections (example with $T$)

In association with top

\[ \sigma(T\bar{t}) = \kappa_T^2 \left( \xi_Z \zeta_3 \bar{\sigma}^{T \bar{t}}_{Z3} + \xi_W \sum_{i=1}^{3} \zeta_i \bar{\sigma}^{T \bar{t}}_{Wi} \right) \]

In association with light quark

\[ \sigma(Tj) = \kappa_T^2 \left( \xi_W \sum_{i=1}^{3} \zeta_i \bar{\sigma}^{Tj} \bar{\sigma}^{Tj}_{Wi} + \xi_Z \sum_{i=1}^{3} \zeta_i \bar{\sigma}^{Tj} \bar{\sigma}^{Tj}_{Zi} \right) \]

In association with gauge or Higgs boson

\[ \sigma(T\{W, Z, H\}) = \kappa_T^2 \left( \xi_W \sum_{i=1}^{3} \zeta_i \bar{\sigma}^{TW} + \xi_Z \sum_{i=1}^{3} \zeta_i \bar{\sigma}^{TZ} + \xi_H \sum_{i=1}^{3} \zeta_i \bar{\sigma}^{TH} \right) \]

The \( \bar{\sigma} \) are model-independent coefficients: the model-dependency is factorised!
### Cross sections

Coefficients (in fb) for $T$ and $\bar{T}$ with mass 600 GeV

<table>
<thead>
<tr>
<th></th>
<th>with top $\sigma_{Zi}^{T\bar{T}+Tt}$</th>
<th>with light quark $\sigma_{Zi}^{Tj+T\bar{t}}$</th>
<th>with gauge or Higgs $\sigma_{i}^{TZ+\bar{T}Z}$</th>
<th>$\sigma_{i}^{TH+\bar{T}H}$</th>
<th>$\sigma_{i}^{TW+\bar{T}W}$</th>
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<tr>
<td>$\zeta_1 = 1$</td>
<td>- 1690</td>
<td>69200 51500</td>
<td>5480 3610 2430</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\zeta_2 = 1$</td>
<td>- 247</td>
<td>5380 10700</td>
<td>202 133 374</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\zeta_3 = 1$</td>
<td>12.6 78.2</td>
<td>- 4230</td>
<td>-</td>
<td>-</td>
<td>122</td>
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The cross section for pair production is 170 fb
Cross sections

Embed the model-dependency into a consistent framework

<table>
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<tr>
<th>(1,2/3)</th>
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Flavour bounds are necessary to get the inclusive cross sections
Flavour vs direct search

ATLAS search in the CC and NC channels

Assumptions: mixing only with 1st generation and coupling strength $\kappa = \frac{v}{M_{VL}}$
Flavour vs direct search

Comparison with flavour bounds

Assumptions: mixing only with 1st generation and coupling strength saturating flavour bounds

Flavour bounds are competitive with current direct searches
Conclusions and Outlook

- After Higgs discovery, **Vector-like quarks** are a very promising playground for searches of new physics.
- **Fairly rich phenomenology at the LHC** and many possible channels to explore:
  - Signatures of single and pair production of VL quarks are **accessible at current CM energy and luminosity** and have been explored to some extent.
  - Current bounds on masses around 600-800 GeV, but searches are not fully optimized for general scenarios.
- **Model-independent studies** can be performed for **pair** and **single production**, and also to analyze scenarios with **multiple vector-like quarks** (work in progress, results very soon!)