Model-independent analysis of scenarios with vector-like quarks

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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 $SU(3)_c \times SU(2)_L \times U(1)_Y$. 
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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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Why are they called “vector-like”?

\[ \mathcal{L}_W = \frac{g}{\sqrt{2}} \left( J_{\mu}^+ W_{\mu}^+ + J_{\mu}^- W_{\mu}^- \right) \]

\[ J_{\mu}^{\pm} = J_{L}^{\mu} \pm J_{R}^{\mu} \quad \text{with} \quad \begin{cases} J_{L}^{\mu} = \bar{u}_L \gamma^\mu d_L = \bar{u}_L \gamma^\mu (1 - \gamma^5) d = V - A \\ J_{R}^{\mu} = 0 \end{cases} \]

SM chiral quarks: ONLY left-handed charged currents.
What are vector-like fermions?
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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

- 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?

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 $SU(3)_c \times SU(2)_L \times U(1)_Y$.

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

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

Charged currents both in the left and right sector

\[ \psi_L \quad \psi'_L \quad W \quad \psi_R \quad \psi'_R \quad W \]
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

There can be partners of top and bottom or quarks with exotic charges (5/3, -4/3...)

$$\psi_L \to \to W$$  
$$\psi'_L \to \to W$$  
$$\psi_R \to \to W$$  
$$\psi'_R \to \to W$$
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

There can be partners of top and bottom or quarks with exotic charges \((5/3, -4/3 \ldots)\)

They can mix with SM quarks

\[
\begin{align*}
t' &\rightarrow \times \rightarrow u_i \\
b' &\rightarrow \times \rightarrow d_i
\end{align*}
\]

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
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>SM</th>
<th>Singlets</th>
<th>Doublets</th>
<th>Triplets</th>
</tr>
</thead>
</table>
| \[
\begin{pmatrix}
u \\ d \\ c \\ s \\ t \\ b
\end{pmatrix}
| \[
\begin{pmatrix}
t' \\ b'
\end{pmatrix}
| \[
\begin{pmatrix}
X \\ t' \\ b' \\ b'
\end{pmatrix}
| \[
\begin{pmatrix}
t' \\ b'
\end{pmatrix}
|

**SU(2)\(_L\)**

<table>
<thead>
<tr>
<th>2 and 1</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
</table>

**U(1)\(_Y\)**

| q\(_L\) = 1/6 | 2/3 | 7/6 | 2/3 |
| u\(_R\) = 2/3 | -1/3 | 1/6 | -1/3 |
| d\(_R\) = -1/3 | |

\[
\mathcal{L}_Y = -y_u^i \bar{q}_L^i H^c u_R^i + y_d^i \bar{q}_L^i V_{\text{CKM}}^{ij} H d_R^j
\]

\[
\begin{array}{c}
-\lambda_u^i \bar{q}_L^i H c t'_R \\
-\lambda_d^i \bar{q}_L^i H b'_R
\end{array}
\]

\[
\begin{array}{c}
-\lambda_u^i \psi_L H^{(c)} u_R^i \\
-\lambda_d^i \psi_L H^{(c)} d_R^i
\end{array}
\]

\[
-\lambda_i \bar{q}_L^i \tau^a H^{(c)} \psi_R^a
\]

\[
\mathcal{L}_m = -M \bar{\psi} \psi
\] (gauge invariant since vector-like)

**Free Parameters**

<table>
<thead>
<tr>
<th>4</th>
<th>4 or 7</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>(M + 3 \times \lambda^i)</td>
<td>(M + 3 \lambda_u^i + 3 \lambda_d^i)</td>
<td>(M + 3 \times \lambda^i)</td>
</tr>
</tbody>
</table>
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
Bounds from pair production between 600 GeV and 800 GeV depending on the decay channel

Common assumption
only one vector-like quark mixing only with third generation

While most theoretical models predict a new quark sector
and, in principle, mixing can be with all families
General mixing: $b'$ pair production

Common assumption CC: $b' \rightarrow tW$

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

$$ b'b' \rightarrow tW^{-}W^{+} \quad b'b' \rightarrow \bar{t}W^{-}W^{+} $$

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 $Wq$

$$ b'b' \rightarrow tW^{-}W^{+} \quad b'b' \rightarrow \bar{t}W^{-}W^{+} $$

There can be less events in the same-sign dilepton channel!
Multiple vector-like quarks

Scenario with $X$ and $B$ (decaying to third generation only)
Multiple vector-like quarks

Scenario with $X$ and $B$ (decaying to third generation only)

$P \rightarrow B \rightarrow t$

$P \rightarrow \bar{B} \rightarrow \bar{t}$

$W^- \rightarrow W^-$

$W^+ \rightarrow W^+$

Scenario with a bidoublet $\left( \begin{array}{c} X \\ T_1 \\ T_2 \\ B \end{array} \right)$ (general mixing)

$P \rightarrow B \rightarrow \text{jet}$

$P \rightarrow \bar{B} \rightarrow \text{jet}$

$W^- \rightarrow W^-$

$W^+ \rightarrow W^+$

$X \rightarrow \text{jet}$

$T_1, T_2, X \rightarrow \text{jet}$

$\bar{T}_1, \bar{T}_2, \bar{X} \rightarrow \text{jet}$
Multiple vector-like quarks

Scenario with $X$ and $B$ (decaying to third generation only)

\[ P \rightarrow B \rightarrow t, \bar{t}, W^-, W^+ \]

Scenario with a bidoublet \( \left( \begin{array}{cc} X & T_1 \\ T_2 & B \end{array} \right) \) (general mixing)

\[ P \rightarrow B \rightarrow jet, W^-, W^+ \]

A given final state can be fed by different channels!
(with different kinematics)
Counting the final states

\[ T \text{ pair production} \rightarrow 6 \text{ possible decays: } W^+ j \quad W^+ b \quad Z_j \quad Z_t \quad H_j \quad H_t \]
Counting the final states

$T$ pair production $\rightarrow$ 6 possible decays: $W^+ j$ $W^+ b$ $Zj$ $Zt$ $Hj$ $Ht$

$$PP \rightarrow T\bar{T} \rightarrow \begin{pmatrix}
W^+ jW^- j & W^+ jW^- \bar{b} & W^+ jZj & W^+ jZ\bar{t} & W^+ jHj & W^+ jH\bar{t} \\
W^+ bW^- j & W^+ bW^- \bar{b} & W^+ bZj & W^+ bZ\bar{t} & W^+ bHj & W^+ bH\bar{t} \\
ZjW^- j & ZjW^- \bar{b} & ZjZj & ZjZ\bar{t} & ZjHj & ZjH\bar{t} \\
ZtW^- j & ZtW^- \bar{b} & ZtZj & ZtZ\bar{t} & ZtHj & ZtH\bar{t} \\
HjW^- j & HjW^- \bar{b} & HjZj & HjZ\bar{t} & HjHj & HjH\bar{t} \\
HtW^- j & HtW^- \bar{b} & HtZj & HtZ\bar{t} & HtHj & HtH\bar{t}
\end{pmatrix}$$

(only) 36 possible combinations of decays into SM particles!

each one with its peculiar kinematics
Counting the final states

**T pair production** $\rightarrow$ 6 possible decays: $W^+ j$ $W^+ b$ $Z_j$ $Z_t$ $H_j$ $H_t$

$$PP \rightarrow T\bar{T} \rightarrow \begin{pmatrix} W^+ jW^- j & W^+ jW^- \bar{b} & W^+ jZ_j & W^+ jZ\bar{t} & W^+ jH_j & W^+ jH\bar{t} \\ W^+ bW^- j & W^+ bW^- \bar{b} & W^+ bZ_j & W^+ bZ\bar{t} & W^+ bH_j & W^+ bH\bar{t} \\ Z_jW^- j & Z_jW^- \bar{b} & Z_jZ_j & Z_jZ\bar{t} & Z_jH_j & Z_jH\bar{t} \\ Z_tW^- j & Z_tW^- \bar{b} & Z_tZ_j & Z_tZ\bar{t} & Z_tH_j & Z_tH\bar{t} \\ H_jW^- j & H_jW^- \bar{b} & H_jZ_j & H_jZ\bar{t} & H_jH_j & H_jH\bar{t} \\ H_tW^- j & H_tW^- \bar{b} & H_tZ_j & H_tZ\bar{t} & H_tH_j & H_tH\bar{t} \end{pmatrix}$$

(only) 36 possible combinations of decays into SM particles!
each one with its peculiar kinematics

**B pair production** $\rightarrow$ 6 possible decays: $W^- j$ $W^- t$ $Z_j$ $Z_b$ $H_j$ $H_b$

36 possible combinations of decays into SM particles
Counting the final states

\( T \) pair production \( \rightarrow \) 6 possible decays: \( W^{+}j \quad W^{+}b \quad Zj \quad Zt \quad Hj \quad Ht \)

\[ PP \rightarrow T\bar{T} \rightarrow \begin{pmatrix}
W^{+}jW^{-}j & W^{+}jW^{-}\bar{b} & W^{+}jZj & W^{+}jZ\bar{t} & W^{+}jHj & W^{+}jH\bar{t} \\
W^{+}bW^{-}j & W^{+}bW^{-}\bar{b} & W^{+}bZj & W^{+}bZ\bar{t} & W^{+}bHj & W^{+}bH\bar{t} \\
ZjW^{-}j & ZjW^{-}\bar{b} & ZjZj & ZjZ\bar{t} & ZjHj & ZjH\bar{t} \\
ZtW^{-}j & ZtW^{-}\bar{b} & ZtZj & ZtZ\bar{t} & ZtHj & ZtH\bar{t} \\
HjW^{-}j & HjW^{-}\bar{b} & HjZj & HjZ\bar{t} & HjHj & HjH\bar{t} \\
HtW^{-}j & HtW^{-}\bar{b} & HtZj & HtZ\bar{t} & HtHj & HtH\bar{t} \\
\end{pmatrix} \]

(only) 36 possible combinations of decays into SM particles!

each one with its peculiar kinematics

\( B \) pair production \( \rightarrow \) 6 possible decays: \( W^{-}j \quad W^{-}t \quad Zj \quad Zb \quad Hj \quad Hb \)

36 possible combinations of decays into SM particles

\( X \) pair production \( \rightarrow \) \( W^{+}j \quad W^{+}t \)

4 combinations

\( Y \) pair production \( \rightarrow \) \( W^{-}j \quad W^{-}b \)

4 combinations
Counting the final states

**T** pair production $\rightarrow 6$ possible decays: $W^+j \ W^+b \ Zj \ Zt \ Hj \ Ht$

$$
\begin{pmatrix}
W^+jW^-j & W^+jW^-\bar{b} & W^+jZj & W^+jZ\bar{t} & W^+jHj & W^+jH\bar{t} \\
W^+bW^-j & W^+bW^-\bar{b} & W^+bZj & W^+bZ\bar{t} & W^+bHj & W^+bH\bar{t} \\
ZjW^-j & ZjW^-\bar{b} & ZjZj & ZjZ\bar{t} & ZjHj & ZjH\bar{t} \\
ZtW^-j & ZtW^-\bar{b} & ZtZj & ZtZ\bar{t} & ZtHj & ZtH\bar{t} \\
HjW^-j & HjW^-\bar{b} & HjZj & HjZ\bar{t} & HjHj & HjH\bar{t} \\
HtW^-j & HtW^-\bar{b} & HtZj & HtZ\bar{t} & HtHj & HtH\bar{t}
\end{pmatrix}
$$

(only) 36 possible combinations of decays into SM particles! each one with its peculiar kinematics

**B** pair production $\rightarrow 6$ possible decays: $W^-j \ W^-t \ Zj \ Zb \ Hj \ Hb$

36 possible combinations of decays into SM particles

**X** pair production $\rightarrow W^+j \ W^+t$

4 combinations

**Y** pair production $\rightarrow W^-j \ W^-b$

4 combinations

There are 80 combinations of decays of (pair produced) VLQs into SM! each one with its kinematic properties!
Efficiencies of searches

Numerical Simulation

MadGraph, CalcHEP, ... → $PP \rightarrow Q\bar{Q} \rightarrow$ final state → Pythia hadronization → Delphes detector simulation → signal
Efficiencies of searches

Numerical Simulation

MadGraph, CalcHEP, ... → Pythia → Delphes

$PP \rightarrow Q\bar{Q} \rightarrow \text{final state}$ → hadronization → detector simulation → signal

Efficiencies

\[\text{signal} \rightarrow \begin{cases} \text{Search 1} & \rightarrow \begin{cases} \text{bin 1} & \rightarrow \text{efficiency 1} \\ \text{bin 2} & \rightarrow \text{efficiency 2} \\ \vdots & \rightarrow \vdots \\ \text{bin n} & \rightarrow \text{efficiency n} \end{cases} \\ \text{Search 2} & \rightarrow \text{Efficiencies for search 2} \\ \vdots & \rightarrow \vdots \\ \text{Search N} & \rightarrow \text{Efficiencies for search N} \end{cases}\]
Efficiencies of searches

Numerical Simulation

\[ PP \rightarrow Q\bar{Q} \rightarrow \text{final state} \rightarrow \text{hadronization} \rightarrow \text{detector simulation} \rightarrow \text{signal} \]

Efficiencies

\[
\begin{align*}
\text{signal} & \rightarrow \begin{cases} 
\text{Search 1} & \rightarrow \text{Efficiencies for search 1} \\
\text{Search 2} & \rightarrow \text{Efficiencies for search 2} \\
\vdots & \\
\text{Search N} & \rightarrow \text{Efficiencies for search N}
\end{cases}
\end{align*}
\]

Knowing the efficiencies for all combinations of final states it is possible to reconstruct any signal. Any model containing any number of VLQs can be analysed in a single framework!
The exclusion confidence level
Example with a fictional search

<table>
<thead>
<tr>
<th>Observation</th>
<th>Background</th>
</tr>
</thead>
<tbody>
<tr>
<td>310 events</td>
<td>300 events</td>
</tr>
</tbody>
</table>
The exclusion confidence level

Example with a fictional search

Observation
310 events

Background
300 events

Signal

Case I: 5 events
Exclusion CL $\simeq 14\%$

Case II: 42 events
Exclusion CL $\simeq 94\%$

Case III: 100 events
Exclusion CL $\simeq 99.99\%$

Exclusion CL
$= 1 - \frac{\text{CL}(s+b)}{\text{CL}(b)} = 1 - \frac{\text{p-value}(s+b)}{1 - \text{p-value}(b)}$
Select a benchmark, i.e. number of VLQs of each charge, masses and BRs
Exclusion confidence level of the benchmark against data from searches (any search!) using only one simulation
(Very) Preliminary results
Degenerate \((T \ b)\) doublet

Implemented searches (only CMS temporarily)

<table>
<thead>
<tr>
<th>(\alpha_T)</th>
<th>(L_P) (monolepton)</th>
<th>SS dileptons</th>
<th>OS dileptons</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 and 8 TeV</td>
<td>7 TeV</td>
<td>7 and 8 TeV</td>
<td>7 TeV</td>
</tr>
</tbody>
</table>

All these searches are SUSY-inspired, but it is ok since we only care about final states!

1. Stronger bounds when mixing with 3rd generation
2. Bounds in the ballpark of those obtained with direct searches of VLQs
3. Potential to improve direct searches and to exploit other BSM-inspired searches to test scenarios with VLQ
Remarks and subtleties

This is a conservative result: a “non-exclusion” result does not mean that the benchmark is allowed. We are neglecting other potentially relevant decays!
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We only consider these topologies

\[ Q \rightarrow q_{SM} \]

\[ Q \rightarrow V_{SM} \]

\[ Q \rightarrow q_{SM} \]

\[ Q \rightarrow H_{SM} \]
Remarks and subtleties

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*We only consider these topologies*

\[ Q \rightarrow q_{SM} \]

\[ Q \rightarrow q_{SM}, V_{SM} \]

The following decays have not been considered (model-dependency)

\[ Q \rightarrow q_{SM}, V' \]

\[ Q \rightarrow q_{SM}, S' \]

\[ Q_1 \rightarrow Q_2 \rightarrow q_{SM}, V_{SM} \]

*Other new sectors besides the VLQs*  
*Chain decays between VLQs*

*A dedicated simulation is required for these channels*

But if a benchmark is already excluded by this analysis, adding new channels would only increase the exclusion confidence level. The signal of new physics is, at worst, underestimated, therefore an “exclusion” result is **robust**!
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- **Role of interferences:** If there is more than one VLQ with the same charge and with close masses and/or widths, the interference effects at the level of amplitude squared cannot be neglected.
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- **Role of interferences**: if there is more than one VLQ with same charge and with close masses and/or widths, the interference effects at the level of amplitude squared cannot be neglected.

\[
\begin{align*}
\mathcal{A}_1 &= \begin{array}{c}
\text{\includegraphics[width=0.3\textwidth]{diagram1}}
\end{array} \\
\mathcal{A}_2 &= \begin{array}{c}
\text{\includegraphics[width=0.3\textwidth]{diagram2}}
\end{array} \\
\mathcal{A}_3 &= \begin{array}{c}
\text{\includegraphics[width=0.3\textwidth]{diagram3}}
\end{array}
\end{align*}
\]

\[
\sigma \propto |\mathcal{A}_1|^2 + |\mathcal{A}_2|^2 + |\mathcal{A}_3|^2 + 2\text{Re} [\mathcal{A}_1 \mathcal{A}_2^* + \mathcal{A}_1 \mathcal{A}_3^* + \mathcal{A}_2 \mathcal{A}_3^*]
\]

It is possible to estimate the interference effect knowing the total widths and couplings to SM particles!

\[
\sigma'_Q(M_i) = \sigma_Q(M_i) \left(1 + \sum_{j \neq i}^{n_Q} y_{ij}\right) \quad \text{with} \quad y_{ij} = \frac{2\text{Re} \left[ g_a g_b^* g_c g_d^* (\int P_i P_j^*)^2 \right]}{g_a^2 g_b^2 (\int P_i P_i^*)^2 + g_c^2 g_d^2 (\int P_j P_j^*)^2}
\]

This expression describes with remarkable accuracy the interference effects in the NWA approximation.
Remarks and subtleties

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- **Role of interferences:** if there is more than one VLQ with same charge and with close masses and/or widths, the interference effects at the level of amplitude squared cannot be neglected.

- **Role of quantum mixing between states:** if there is more than one VLQ with same charge and with close masses and/or widths, the mixing at loop level can affect the cross-section.
Remarks and subtleties

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**Diagonalisation of the matrix of the propagators**

\[
i \Delta_{ij} = \begin{pmatrix}
Q_1 & Q_1 & Q_2 \\
Q_2 & Q_1 & Q_2 \\
\end{pmatrix}
\]

The matrix is model-dependent: any particle (also new ones) can enter the loops!!
Remarks and subtleties

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  It’s crucial to take into account these issues in order not to overestimate the signal!
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** to analyse scenarios with **multiple vector-like quarks** (work in progress, results very soon!)