VLQs coupling determination at the LHC and future hadron colliders

Daniele Barducci

with Luca Panizzi

arXiv:1610.02325
Vector-like Quarks

VLQs are new colored states whose left- and right-handed component transform in the same way under the SM gauge group

\[ \mathcal{L} \sim g \, j^\mu, + W^+_\mu + h.c. \]

V-A interaction

\[ j_L^\mu = \bar{f}_L \gamma^\mu f'_L \quad j_R^\mu = 0 \]

\[ j^\mu = j_L^\mu + j_R^\mu = \bar{f} \gamma^\mu (1 - \gamma^5) f' \]

Vector interaction

\[ j_{L,R}^\mu = \bar{f}_{L,R} \gamma^\mu f'_{L,R} \]

\[ j^\mu = j_L^\mu + j_R^\mu = \bar{f} \gamma^\mu f' \]

For VLQs a gauge invariant mass term is allowed

\[ \mathcal{L}_{\text{mass}} = m_{VLQ} \, \bar{Q}_L Q_R + h.c. \]
They appear in many NP models that try to address the SM hierarchy problem.
Vector-like Quarks

They appear in many NP models that try to address the SM hierarchy problem.

- Composite Higgs
- Little Higgs
- Extra dimensions
- Non minimal SUSY
- …

In CHMs they control the level of fine tuning of the theory. They are thus expected to be found around the TeV scale.
Vector-like Quarks

They appear in many NP models that try to address the SM hierarchy problem.

- Composite Higgs
- Little Higgs
- Extra dimensions
- Non minimal SUSY
- ...

In CHMs they control the level of fine tuning of the theory. They are thus expected to be found around the TeV scale.

This has motivated an intense experimental activity.
Vector-like Quarks searches at the LHC

Assuming mixing with only the 3rd generation of SM quarks

\[ T \rightarrow W^+ b, Zt, Ht \quad B \rightarrow W^- t, Zb, Hb \]
\[ X \rightarrow W^+ t \quad Y \rightarrow W^- b \]

All these channels are covered by LHC searches
Vector-like Quarks properties

In the minimal scenario they interact with the SM through Yukawa terms.

D4 interactions can only be written for singlets, doublet and triplets of $SU(2)_L$.

<table>
<thead>
<tr>
<th>$SU(2)_L$</th>
<th>$U(1)_Y$</th>
<th>$\psi$</th>
<th>$L_y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2/3</td>
<td>$T$</td>
<td>$q_L H^c t_R$</td>
</tr>
<tr>
<td></td>
<td>-1/3</td>
<td>$B$</td>
<td>$q_L H b_R$</td>
</tr>
<tr>
<td>2</td>
<td>7/6</td>
<td>$(X, T)$</td>
<td>$\psi_L H t_R$</td>
</tr>
<tr>
<td></td>
<td>1/6</td>
<td>$(T, B)$</td>
<td>$\psi_L H^c t_R, \psi_L H b_R$</td>
</tr>
<tr>
<td></td>
<td>-5/6</td>
<td>$(B, Y)$</td>
<td>$\psi_L H^c b_R$</td>
</tr>
<tr>
<td>3</td>
<td>2/3</td>
<td>$(X, T, B)$</td>
<td>$\bar{q}_L \tau^a H^c \psi_R^a$</td>
</tr>
<tr>
<td></td>
<td>-1/3</td>
<td>$(T, B, Y)$</td>
<td>$\bar{q}_L \tau^a H \psi_R^a$</td>
</tr>
</tbody>
</table>

Left- and right- handed chiral component rotate in a different way

$$\frac{\tan \theta^R}{\tan \theta^L} = \frac{m_q^{SM}}{m_{VLQ}} \quad \text{for} \quad SU(2)_L = 1, 3$$

$$\frac{\tan \theta^L}{\tan \theta^R} = \frac{m_q^{SM}}{m_{VLQ}} \quad \text{for} \quad SU(2)_L = 2$$

$m_{VLQ} \gg m_q^{SM}$: one of the two chiral-coupling is always suppressed.
Vector-like Quarks properties

- The coupling is almost pure Left or Right
- Final state gauge bosons and quarks have a non-zero polarization

A difference in the kinematic of the decay product is expected

Slightly different reach between the two hypotheses
**Gauge boson polarization**

- Gauge bosons tend to have a dominant longitudinal component
- No kinematic difference in the two coupling hypotheses

\[
T \rightarrow Zt \text{ decay}
\]

\[
|M|_L^2 = \frac{g^2}{2} \sin^2 \theta_L^u (m_T^2 - m_W^2) \\
|M|_R^2 = 0 \\
|M|_0^2 = \frac{g^2}{4} \frac{m_T^2}{m_W^2} \sin^2 \theta_L^u (m_T^2 - m_W^2)
\]

\(\mathcal{O}(1\%)\) transverse component

---

Daniele Barducci  
VLQs coupling determination at the LHC and future hadron colliders  
CERN
Top quark polarization

Top quark decay product carry information on its polarization

**Top quark rest frame**

\[
\frac{1}{\Gamma_l} \frac{d\Gamma_l}{d \cos \theta_{f, \text{rest}}} = \frac{1}{2} \left( 1 + \kappa_f P_t \cos \theta_{f, \text{rest}} \right)
\]

Decaying top

Top quark would-be momentum in the lab frame

**Laboratory frame**

Boost to Lab. frame produces harder object for positively polarized top quarks, i.e. right-handed coupling

Easier to pass selection cuts for right-handed VLQs: higher mass reach
Top quark polarization

$p_T$ distribution of the lepton from a polarized top from a VLQ decay

If a VLQ were to be discovered at the LHC can this difference be used to disentangle the two hypotheses?

- Assume we can subtract the SM background

- Test the discrimination power via a $\chi^2$

$$\chi^2 = \sum_{i=1}^{n_{bins}} \frac{(L_i - R_i)^2}{\max(L_i, R_i)}$$
LHC discrimination power

Charged 2/3 VLQ decaying entirely in $Zt$ in the single $\ell$ plus $E_T^{\text{miss}}$ final state

Mostly invisible $Z$ : the lepton comes from the top decay

- The binning impacts the discrimination reach. Optimization possible
- LHC able to discriminate the hypotheses in all the discovery range accessible
HE-LHC discrimination power

Charged 5/3 VLQ decaying entirely in $Wt$ in the same-sing $2\ell$ final state

Must pick the lepton from the top, and from not the $W$ decay

Identification possible: the lepton from the top is always softer

Use the sub-leading lepton distribution to perform the discrimination
HE-LHC discrimination power

LHC-33

\[ XX \rightarrow WtWt, \sqrt{s} = 33 \text{TeV}, \epsilon_{\text{syst}} = 20\% \]

200 GeV binning

\[ m_X \text{ [GeV]} \]

L [1/fb]

LHC-100

\[ XX \rightarrow WtWt, \sqrt{s} = 100 \text{TeV}, \epsilon_{\text{syst}} = 20\% \]

300 GeV binning

\[ m_X \text{ [GeV]} \]

L [1/fb]

High energy hadron collider prototypes are able to discriminate the coupling hypothesis in all their accessible discovery range.
Conclusions

- HL-LHC and HE-LHC will increase the exclusion-discovery reach on the masses of BSM states

- Important to assess whether these machines will be able to discriminate amongst different model hypotheses should NP be found

- Polarized top quarks arising from VLQs decay can be used as a probe to discriminate the coupling structure of the VLQs with SM states

- HL-LHC and HE-LHC will be able to discriminate between left- and right-handed coupling in all their accessible discovery range

Open questions

- Focused on pair-produced VLQs: what about single production?

- What can be said if a VLQ doesn’t decay into a top quark?