Testing Vector-like Quarks via Higgs Pair Production at NLO

Haiying Cai

IPNL, Universite Lyon 1

Work in preparation

Higgs Couplings, 09-12 November, 2016
Motivation for VLQs

Vector-Like Quarks exist in several BSM scenarios: Little Higgs Models, Extra Dimensions, Strong dynamics and so on.

In Little Higgs model and Composite Higgs Model, vector-like top partners play the role of stabilising the Electroweak symmetry breaking.

Vector-like quarks may interplay with new coloured scalars, heavy vectors, possible to generate rich phenomenology.

The simplest scenario is vector-like quark mix with light SM quarks via Yukawa interaction, thus contribute to exotic Higgs pair production.
### Types of VLQ and Yukawa Interactions

[Aguila, Victoria and Santiago, 2000]

<table>
<thead>
<tr>
<th></th>
<th>Singlet</th>
<th>Doublet</th>
<th>Triplet</th>
</tr>
</thead>
<tbody>
<tr>
<td>$SU(2)_L$</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>$U(1)_Y$</td>
<td>2/3</td>
<td>1/6</td>
<td>7/6</td>
</tr>
<tr>
<td></td>
<td>-1/3</td>
<td>-5/6</td>
<td>2/3</td>
</tr>
<tr>
<td></td>
<td>-1/3</td>
<td>-1/3</td>
<td></td>
</tr>
</tbody>
</table>

$\mathcal{L}_Y$

- $-\frac{\lambda_u v}{\sqrt{2}} u_L T_R$
- $-\frac{\lambda_d v}{\sqrt{2}} d_L B_R$
- $-\frac{\lambda_u v}{\sqrt{2}} T_L u_R$
- $-\frac{\lambda_d v}{\sqrt{2}} B_L d_R$
- $-\lambda_u v d_L B_R$
- $-\lambda_u v d_L B_R$

Yukawa mixing of T/B and SM quark

\[
\begin{pmatrix}
\cos \theta_u^L & -\sin \theta_u^L \\
\sin \theta_u^L & \cos \theta_u^L
\end{pmatrix}
\begin{pmatrix}
\frac{y_u v}{\sqrt{2}} x \\
0
\end{pmatrix}
\begin{pmatrix}
\cos \theta_u^R & \sin \theta_u^R \\
-\sin \theta_u^R & \cos \theta_u^R
\end{pmatrix}
= 
\begin{pmatrix}
m_u & 0 \\
0 & m_T
\end{pmatrix}
\]

$M$ is the Dirac mass for vector-like quark
Mixing Patterns

Singlet/Triplet VLQ mixing

\[ x \quad m_u \quad x \]
\[ t_L \quad T_R \quad T_L \quad t_R \quad t_L \quad T_R \]
\[ \sim \frac{x^2}{M^2} \quad \sim \frac{m_u}{M} \quad \frac{x}{M} \]

(Non) SM Doublet VLQ mixing

\[ m_u \quad x \quad M \]
\[ t_L \quad t_R \quad T_L \quad t_R \quad T_L \]
\[ \sim \frac{m_u}{M} \quad \frac{x}{M} \quad \frac{x}{M} \]

\[ \sin \theta_u^L = \frac{Mx}{\sqrt{(M^2 - m_u^2)^2 + M^2x^2}} \]
\[ \sin \theta_u^R = \frac{m_u}{M} \sin \theta_u^L \]

mainly left handed mixing

\[ \sin \theta_u^L = \frac{Mx}{\sqrt{(M^2 - m_u^2)^2 + M^2x^2}} \]
\[ \sin \theta_u^R = \frac{m_u}{M} \sin \theta_u^R \]

mainly right handed mixing

Haiying CAI  (IPNL, France)
Interplay of 2 VLQs

Case A: 2 doublets mixing

\[
\begin{pmatrix}
m_u \\
m_c \\
y_1^1 & y_1^2 & y_1^3 & M_1 \\
y_2^1 & y_2^2 & y_2^3 & M_2
\end{pmatrix}
\]

Case B: 2 singlets/triplets mixing

Left and right rotations exchanged

\[
\begin{pmatrix}
m_u & x_1^1 & x_2^1 \\
m_c & x_1^2 & x_2^2 \\
y_1^1 & y_1^2 & y_1^3 & M_1 \\
y_2^1 & y_2^2 & y_2^3 & M_2
\end{pmatrix}
\]

Case C: 1 singlet/triplet and 1 doublet mixing

\[
\begin{pmatrix}
m_u \\
m_c & x_1^1 & x_2^1 \\
y_1^1 & y_1^2 & y_1^3 & M_1 \\
y_2^1 & y_2^2 & y_2^3 & \omega' & M_2
\end{pmatrix}
\]

[Cacciapaglia, Deandrea, Gaur, Harada, Okada, Panizzi 2015]
Degenerate Bi-doublet Model

[Atre, Carena, Han and Santiago, 2000]

One special case is 2 vector-like quark $SU(2)_L$ doublets with hypercharges $1/6$ and $7/6$.

$$Q^{(0)}_{L,R} = \begin{pmatrix} T_{L,R}^1 \\ B_{L,R} \end{pmatrix}_{1/6}, \quad \chi^{(0)}_{L,R} = \begin{pmatrix} X_{L,R} \\ T_{L,R}^2 \end{pmatrix}_{7/6},$$

Defining $T = \frac{1}{\sqrt{2}}(T^1 + T^2)$ and $T' = \frac{1}{\sqrt{2}}(T^1 - T^2)$

$$\mathcal{L}_m = \begin{pmatrix} \bar{u}_L & \bar{T}_L & \bar{T'}_L \end{pmatrix} \begin{pmatrix} \lambda_u \frac{\sqrt{2}}{\sqrt{2}} & 0 & 0 \\ \lambda_Q \sqrt{2} & m_Q & 0 \\ 0 & 0 & m_Q \end{pmatrix} \begin{pmatrix} u_R \\ T_{L,R}^+ \\ T_{L,R}^{'+} \end{pmatrix} + h.c.$$

This model gives one heavy Top mainly couple to Higgs and another heavy Top mainly couple to Z-boson. **Due to sole mixing with u-quark**

Maximise the branching ratio of $T$ decay into Higgs plus jet!
Effective Lagrangian

\[ \mathcal{L}_{\text{eff}} = \frac{\sqrt{2}g}{2} \left[ \bar{Y} \bar{\mathcal{W}} \left( \kappa_L^Y P_L + \kappa_R^Y P_R \right) d + \bar{B} \bar{\mathcal{W}} \left( \kappa_L^B P_L + \kappa_R^B P_R \right) u \right] \\
+ \bar{T} \mathcal{W} \left( \kappa_L^T P_L + \kappa_R^T P_R \right) d + \bar{X} \mathcal{W} \left( \kappa_L^X P_L + \kappa_R^X P_R \right) u \\
+ \frac{g}{2c_W} \left[ \bar{B} \bar{Z} \left( \kappa_L^B P_L + \kappa_R^B P_R \right) d + \bar{T} \bar{Z} \left( \kappa_L^T P_L + \kappa_R^T P_R \right) u \right] \\
- h \left[ \bar{B} \left( \kappa_L^B P_L + \kappa_R^B P_R \right) d + \bar{T} \left( \kappa_L^T P_L + \kappa_R^T P_R \right) u \right] + \text{h.c.} \]

For $H-T-u$ and $H-B-d$, we parameterize $\kappa_{L,R}^T = \kappa \frac{M_T}{v}$ and $\kappa_{L,R}^B = \kappa' \frac{M_B}{v}$, to characterize the linear mass dependence of the couplings.
Bounds on Kappa in Bi-doublet

Yellow band excluded by atomic parity violation

EWPT bound is more stringent

\[ \kappa \sim \sqrt{2} \frac{y}{M_T} \] constrained to be \( \lesssim 1.0 \) with only mild dependence on \( M_T \)

EW process competitive with QCD process!
The NLO cross section at LHC Run II

VLQ induced di-Higgs production, $Q(\bar{Q}) \rightarrow h + jet$

Very small compared with VLQ induced signals

PDF uncertainty and scale uncertainty added in quadrature

QCD and EW interference effect in $q\bar{q} \rightarrow T\bar{T}$ ignored.
2b 2\(\gamma\) Channel

This channel benefits both from large \(B(h \to b\bar{b})\) and the clean di-photon signal, since the signal \(m_{\gamma\gamma}\) will peak on top of a continuum spectrum.

2b 2\(\gamma\) is promising to explore the non-linear coupling from composite Higgs model. [Contino, Ghezzi, Moretti, Panico, Piccinini and Wulzer, 2000]

VLQ model induce larger di-Higgs signals, at high luminosity LHC, for \(m_T < 1\) TeV 2b 2\(\gamma\) channel is more sensitive to BSM effects than other channels.

We generate signal events at QCD NLO by Madgraph5 and interface with pythia8 for parton shower, then use Fastjet package for jet clustering.
Signal vs. BKG I

<table>
<thead>
<tr>
<th>$m_T = 500$ GeV, $20.0$ fb$^{-1}$</th>
<th>$TT$ (QCD)</th>
<th>$QQ$ (EW)</th>
<th>$TH + TH$</th>
<th>$gg \to HH$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2b -$ tagged, $</td>
<td>\eta^b</td>
<td>&lt; 2.5$</td>
<td>46.8</td>
<td>1.28</td>
</tr>
<tr>
<td>$p_T^{b_1(b_2)} &gt; 55(35)$ GeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$2\gamma$, $</td>
<td>\eta^\gamma</td>
<td>&lt; 2.37$</td>
<td>34.3</td>
<td>0.94</td>
</tr>
<tr>
<td>$E_T^{\gamma(1\gamma)} / m_{\gamma\gamma} &gt; 0.35(0.25)$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$95 &lt; m_{bb} &lt; 135$ GeV</td>
<td>23.74</td>
<td>0.68</td>
<td>4.75</td>
<td>0.087</td>
</tr>
<tr>
<td>$105 &lt; m_{\gamma\gamma} &lt; 160$ GeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acceptance</td>
<td>15.6%</td>
<td>16.9%</td>
<td>13.1%</td>
<td>11.7%</td>
</tr>
</tbody>
</table>

Table: The significance of $S/\sqrt{B}$ at NLO with $\kappa = 0.2$, given for an integrated luminosity of $\int L dt = 20.0$ fb$^{-1}$ at a $\sqrt{s} = 13$ TeV LHC. The b-tag efficiency is set to be $\epsilon_b = 70\%$ and $\epsilon_{c\to b} = 10\%$. 

Haiying CAI (IPNL, France)
The cut efficiency is optimised at $m_T = 1000$ GeV.
The direct search (3 $\sigma$ exclusion) puts a stronger bound than EWPT.
Kinematic distributions

The $m_{hh}$ distribution at NLO peaks between $m_T$ and $2 \ m_T$

Additional cut $p^{h1}_T > 200$ GeV and $p^{h2}_T > 150$ GeV is imposed
4b Channel

The channel has the largest branching ratio around 33%, yielding more events than other channels, but there is overwhelming b-enriched QCD backgrounds.

Higgs is decayed from a heavy VLQ, the b quark-antiquark pair collimates into a cone size of $R \sim 2 m_H/p_T$; for $m_T < 1$ TeV, ATLAS resolved analysis is applicable.

- 4 b-tagged R=0.4 jets with $p_T > 40$ GeV and $\eta < 2.5$, the b-tag efficiency is set to be 0.7.
- 2 di-bjets need to be reconstructed to be di-Higgs candidates, for the signal selection, we require $X_{hh} < 1.6$.
- $\Delta R_{bb} < 1.5$ and $p_{T}^{h1} > 200$ GeV, $p_{T}^{h2} > 150$ GeV.

$$X_{hh} = \sqrt{\frac{(m_{h1} - 124 \text{ GeV})}{0.1 m_{h1}}^2 + \frac{(m_{h2} - 115 \text{ GeV})}{0.1 m_{h2}}^2}$$
Signal vs. BKG II

Madgraph5 @ NLO / pythia8 / Fastjet

<table>
<thead>
<tr>
<th>$M_T = 500$ GeV, 1.0fb$^{-1}$</th>
<th>$T\bar{T}$ (QCD)</th>
<th>$QQ$ (EW)</th>
<th>$TH + \bar{T}H$</th>
<th>$gg \to HH$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$4b$ – tagged</td>
<td>78.1</td>
<td>2.01</td>
<td>14.5</td>
<td>0.19</td>
</tr>
<tr>
<td>$p_T^b &gt; 40$ GeV, $</td>
<td>\eta^b</td>
<td>&lt; 2.5$</td>
<td>37.7</td>
<td>1.22</td>
</tr>
<tr>
<td>$\Delta R_{bb(h)} &lt; 1.5$</td>
<td>20.3</td>
<td>0.67</td>
<td>4.65</td>
<td>0.045</td>
</tr>
<tr>
<td>$p_T^{h1(h2)} &gt; 200(150)$ GeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$x_{hh} &lt; 1.6$</td>
<td>2.1%</td>
<td>2.6%</td>
<td>2.0%</td>
<td>1.0%</td>
</tr>
<tr>
<td>Acceptance</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table: The significance of $S/\sqrt{B}$ at NLO with $\kappa = 0.2$, given for an integrated luminosity of $\int L\,dt = 3.2$ fb$^{-1}$ at a $\sqrt{s} = 13$ TeV LHC. The $b$-tag efficiency is set to be $\epsilon_b = 70\%$. 

Haiying CAI (IPNL, France)
Boost search

For large mass VLQ, the boost analysis is optimised, jet substructure technique
is employed to reduce the QCD contamination.

The definition of N-subjettiness: [Thaler and Tilburg, JHEP 03 (2011)]

\[ \tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min \{ \Delta R_{1,k}, \Delta R_{2,k}, \ldots, \Delta R_{N,k} \} \]

This quantity measures how close a fat-jet to be N-prong
For a fat-jet contains 2-prong, the ratio of \( \tau_{21} = \tau_2/\tau_1 \) is small.

H. Cai, A.Carvalho, D.Majumder, work in progress

Following the large-R ATLAS analyses, we define a Higgs fat-jet \( J_H \) as anti-Kt
jet with \( R = 0.8 \) that passes the following basic selection:

\[ \eta_{J_H} < 2.4; \quad 250 < p_T < 2500 \text{ GeV}; \quad m_{J_H} > 50 \text{ GeV} \]
Large-R jet analysis

Madgraph5 @NLO, pythia8 and Delphes.

Using the ATLAS reconstruction

- 2 large-R jets satisfying ATLAS Higgs-jet pre-selection
- $\Delta \eta_{JJ} < 1.7$ as the Higgs-jet is mostly central production
- $\tau_{21} = \tau_2/\tau_1 < 0.6$, with 2-subjets
- $X_{hh} < 1.6$ as the signal region condition

Assume each Large-R jet contains 2 b-jets, with b-tag efficiency set to be 0.7
The Signal is compared with ATLAS BKG analysis in PRD. 94. 052002
Leading H-Jet Pt distribution

The single VLQ + H EW production is important for large kappa value

Leading H-jet pT > 350 GeV
Conclusions

- We explore exotic di-Higgs production induced by vector-like quark (VLQ) mixing with light SM quarks, where the EW contribution can play an important role.

- For $m_T \sim 500$ GeV, the $2b \ 2$ gamma channel has larger sensitivity than other channels due to the clean diphoton signal, putting stronger exclusion limit on VLQ models than the EWPT constraint.

- For the 4b channel, the resolved analysis is applicable to the small VLQ mass region; while for high VLQ mass, boost effects make events have simple topology, we can use jet substructure for an effective analysis.

- The boost analysis applies to other processes, e.g. single VLQ plus jet production.