Vector-like quark multiplets, mixings and bounds

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Outline

• Motivations
• Mixing structures
• Bounds (tree and loop level)
• Model independent framework
• Conclusions

Based on:
ArXiv: in preparation

Thanks to all my collaborators on this topic:
M. Buchkremer, G. Cacciapaglia, N. Gaur,
D. Harada, Y. Okada, L. Panizzi.
What is a vector-like fermion?

- VL currents are vectorial (like in QED), so left and right chiralities couple with the same strength

\[ J^\mu = \bar{\Psi} \gamma^\mu \Psi = \bar{\Psi}_L \gamma^\mu \Psi_L + \bar{\Psi}_R \gamma^\mu \Psi_R = J_L^\mu + J_R^\mu \]

- gauge invariant mass terms independent of the Higgs mechanism are allowed and give a new scale \( M \) (L and R are in the same representation)

\[ M \bar{\Psi} \Psi = M(\bar{\Psi}_L \Psi_R + \bar{\Psi}_R \Psi_L) \]

- Coupling to SM fermions and Higgs via Yukawa-type interactions
Where and why (VL quarks)?

- top partners are expected in many extensions of the SM (composite/Little higgs models, Xdim models)
- they come in complete multiplets (not just singlets)
- theoretical expectation is a not too heavy mass scale $M$ ($\sim$ TeV) and mainly coupling to the 3rd generation
- Present LHC mass bounds $\sim$ 700 GeV
- Mixings bounded by EWPT, flavour…(more on this later)
Simplest multiplets (and SM quantum numbers)

<table>
<thead>
<tr>
<th>SM</th>
<th>Singlets</th>
<th>Doublets</th>
<th>Triplets</th>
</tr>
</thead>
<tbody>
<tr>
<td>(u) (d) (c) (s) (t)</td>
<td>(t') (b')</td>
<td>(t') (t') (b')</td>
<td>(t') (b')</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SU(2)_{L}</th>
<th>2</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>q_{L} = 1/6</td>
<td>2/3</td>
<td>-1/3</td>
<td>1/6</td>
<td>7/6</td>
</tr>
<tr>
<td>u_{R} = 2/3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>d_{R} = -1/3</td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

\[
\mathcal{L}_{Y} = -\frac{\lambda_{Y}}{\sqrt{2}} \bar{u}_{L} u_{R} - \frac{\lambda_{Y}}{\sqrt{2}} \bar{d}_{L} d_{R} - \frac{\lambda_{Y}}{\sqrt{2}} U_{L} u_{R} - \frac{\lambda_{Y}}{\sqrt{2}} D_{L} d_{R} - \lambda_{Y} \bar{u}_{L} U_{R} - \lambda_{Y} \bar{d}_{L} D_{R}
\]

\[
\mathcal{L}_{m} = -M \bar{\psi} \psi \quad \text{(gauge invariant since vector-like)}
\]

Free parameters:

\[ M + 3 \times \lambda^{i} \quad M + 3 \lambda^{i}_{u} + 3 \lambda^{i}_{d} \quad M + 3 \times \lambda^{i} \]
Embeddings in SU(2)_{L} \times U(1)_{Y}

Complete list of vector-like multiplets forming mixed Yukawa terms with the SM quark representations and a SM or SM-like Higgs boson doublet

<table>
<thead>
<tr>
<th>Δψ</th>
<th>(SU(2)<em>{L}, U(1)</em>{Y})</th>
<th>T_{3}</th>
<th>Q_{EM}</th>
</tr>
</thead>
<tbody>
<tr>
<td>U</td>
<td>(1, 2/3)</td>
<td>0</td>
<td>+2/3</td>
</tr>
<tr>
<td>D</td>
<td>(1, -1/3)</td>
<td>0</td>
<td>-1/3</td>
</tr>
<tr>
<td>(\frac{X^{5/3}}{U})</td>
<td>(\frac{X^{5/3}}{U})</td>
<td>+2</td>
<td>+8/3</td>
</tr>
<tr>
<td>(\frac{X^{8/3}}{U})</td>
<td>(\frac{X^{8/3}}{U})</td>
<td>+1</td>
<td>+5/3</td>
</tr>
<tr>
<td>(\frac{X^{5/3}}{D})</td>
<td>(\frac{X^{5/3}}{D})</td>
<td>0</td>
<td>+2/3</td>
</tr>
<tr>
<td>(\frac{D}{Y^{-4/3}})</td>
<td>(\frac{D}{Y^{-4/3}})</td>
<td>+1</td>
<td>-1/3</td>
</tr>
<tr>
<td>(\frac{D}{Y^{-7/3}})</td>
<td>(\frac{D}{Y^{-7/3}})</td>
<td>0</td>
<td>-4/3</td>
</tr>
<tr>
<td>(\frac{D}{Y^{-4/3}})</td>
<td>(\frac{D}{Y^{-4/3}})</td>
<td>-1</td>
<td>-4/3</td>
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<td>-4/3</td>
</tr>
<tr>
<td>(\frac{D}{Y^{-7/3}})</td>
<td>(\frac{D}{Y^{-7/3}})</td>
<td>-1</td>
<td>-7/3</td>
</tr>
</tbody>
</table>
Sample effective Lagrangian

Lagrangian with the extra vector-like fermion $\psi = (X \ U)$

\[
\mathcal{L}_m = - (\bar{Q}_L^1 \bar{Q}_L^2 \bar{Q}_L^3) \tilde{V}_{CKM} \begin{pmatrix} y_d \\ y_s \\ y_b \end{pmatrix} H \begin{pmatrix} d_R \\ s_R \\ b_R \end{pmatrix} \\
- (\bar{Q}_L^1 \bar{Q}_L^2 \bar{Q}_L^3) \begin{pmatrix} y_u \\ y_c \\ y_t \end{pmatrix} H^c \begin{pmatrix} u_R \\ c_R \\ t_R \end{pmatrix} \\
- (\lambda_1 \lambda_2 \lambda_3) \bar{\psi}_L H \begin{pmatrix} u_R \\ c_R \\ t_R \end{pmatrix} - M(\bar{U}_L U_R + \bar{X}_L X_R)
\]

SM Yukawa for down-type quarks
$\tilde{V}_{CKM}$ is the modified $V_{CKM}$ due to the presence of $\psi$

SM Yukawa for up-type quarks

$\psi$ mass and mixing with SM quarks

Mass matrices after the Higgs develops a VEV

\[
\mathcal{L}_m = - (\bar{d}_L \bar{s}_L \bar{b}_L) \tilde{V}_{CKM} \begin{pmatrix} \tilde{m}_d \\ \tilde{m}_s \\ \tilde{m}_b \end{pmatrix} \begin{pmatrix} d_R \\ s_R \\ b_R \end{pmatrix} \\
- (\bar{u}_L \bar{c}_L \bar{t}_L \bar{U}_L) \begin{pmatrix} \tilde{m}_u \\ \tilde{m}_c \\ \tilde{m}_t \end{pmatrix} \begin{pmatrix} u_R \\ c_R \\ t_R \end{pmatrix} \\
- M \bar{X}_L X_R
\]

down-type quark masses
$\tilde{m}_i \equiv \frac{\chi_{iv}}{\sqrt{2}} = m_i^{SM}$

mass matrix for up-type quarks
the heavy $U$ induces the mixing

$\chi_i = \frac{\lambda_{1v}}{\sqrt{2}}$

$X$ mass
Simplified Mixing effects (t-T sector only)

• Yukawa coupling generates a mixing between the new state(s) and the SM ones

• Type 1 : singlet and triplets couple to SM L-doublet
  
  • Singlet $\psi = (1, \ 2/3 ) = U$ : only a top partner is present
  
  • triplet $\psi = (3, \ 2/3 ) = \{X, \ U, \ D\}$ , the new fermion contains a partner for both top and bottom, plus X with charge 5/3
  
  • triplet $\psi = (3, \ -1/3 ) = \{U, \ D, \ Y\}$ , the new fermions are a partner for both top and bottom, plus Y with charge −4/3

\[ \mathcal{L}_{mass} = -\frac{yu^2}{\sqrt{2}} \bar{u}_L u_R - x \bar{u}_L U_R - M \bar{U}_L U_R + h.c. \]

\[
\begin{pmatrix}
\cos \theta_u^L & -\sin \theta_u^L \\
\sin \theta_u^L & \cos \theta_u^L
\end{pmatrix}
\begin{pmatrix}
\frac{yu^2}{\sqrt{2}} & x \\
0 & M
\end{pmatrix}
\begin{pmatrix}
\cos \theta_u^R & \sin \theta_u^R \\
-\sin \theta_u^R & \cos \theta_u^R
\end{pmatrix}
\]
Simplified Mixing effects (t-T sector only)

- Type 2: new doublets couple to SM R-singlet

- SM doublet case $\psi = (2, 1/6) = \{U, D\}$, the vector-like fermions are a top and bottom partners

- non-SM doublets $\psi = (2, 7/6) = \{X, U\}$, the vector-like fermions are a top partner and a fermion $X$ with charge $5/3$

- non-SM doublets $\psi = (2, -5/6) = \{D, Y\}$, the vector-like fermions are a bottom partner and a fermion $Y$ with charge $-4/3$

\[
\mathcal{L}_{\text{mass}} = -\frac{y_u v}{\sqrt{2}} \bar{u}_L u_R - x \bar{U}_L u_R - M \bar{U}_L U_R + h.c.
\]

\[
\begin{pmatrix}
\cos \theta_u^L & -\sin \theta_u^L \\
\sin \theta_u^L & \cos \theta_u^L
\end{pmatrix}
\begin{pmatrix}
y_u v \\
x
\end{pmatrix}
\begin{pmatrix}
0 \\
M
\end{pmatrix}
\begin{pmatrix}
\cos \theta_u^R & \sin \theta_u^R \\
-\sin \theta_u^R & \cos \theta_u^R
\end{pmatrix}
\]
Mixing 1VLQ (doublet) with the 3 SM generations

\[ M_u = \begin{pmatrix} \tilde{m}_u & \tilde{m}_c & \tilde{m}_t \\ x_1 & x_2 & x_3 \end{pmatrix} M = V_L \cdot \begin{pmatrix} m_u & m_c & m_t \\ x_1 & x_2 & x_3 \end{pmatrix} \cdot V_R^\dagger \]

\[ V_L \implies M_u \cdot M_u^\dagger = \begin{pmatrix} \tilde{m}_u^2 & \tilde{m}_c^2 & x_1^* \tilde{m}_u^2 \\ x_2 \tilde{m}_c & \tilde{m}_t^2 & x_2^* \tilde{m}_c^2 \\ x_3 \tilde{m}_t & x_3^* \tilde{m}_t & |x_1|^2 + |x_2|^2 + x_3^2 + M^2 \end{pmatrix} \]

\[ m_q \propto \tilde{m}_q \]

Mixing is suppressed by quark masses

\[ V_R \implies M_u^\dagger \cdot M_u = \begin{pmatrix} \tilde{m}_u^2 + |x_1|^2 & x_1^* x_2 & x_1^* x_3 & x_1^* M \\ x_2^* x_1 & \tilde{m}_c^2 + |x_2|^2 & x_2^* x_3 & x_2^* M \\ x_3 x_1 & x_3 x_2 & \tilde{m}_t^2 + x_3^2 & x_3 M \\ x_1 M & x_2 M & x_3 M & M^2 \end{pmatrix} \]

Mixing in the right sector present also for \( \tilde{m}_q \to 0 \)

Flavour constraints for \( q_R \) are relevant
Mixing expansion in $x/M$

$$V_{ij}^R = \begin{pmatrix}
1 - \frac{|x_1|^2}{2m_X^2} & -\frac{x_1^* x_2 m_c^2}{(m_c^2 - m_u^2)m_X^2} & -\frac{x_1^*}{m_X} \\
\frac{x_1 x_2^* m_u^2}{(m_c^2 - m_u^2)m_X^2} & 1 - \frac{|x_2|^2}{2m_X^2} & -\frac{x_2^*}{m_X} \\
0 & 0 & \cos \theta_R + \frac{(m_{t'}^2 + m_{t'}^2)(|x_1|^2 + |x_2|^2) \cos \theta_R \sin^2 \theta_R}{2(m_{t'}^2 - m_{t}^2)m_X^2} \\
V_{41}^R & V_{42}^R & V_{14}^R \\
V_{24}^R & V_{34}^R & V_{44}^R
\end{pmatrix}$$

with:

$$V_{RR}^{u'c} = \frac{x_1^* \cos \theta_R}{m_X}, \quad V_{RR}^{c't'} = \frac{x_2^* \cos \theta_R}{m_X}, \quad V_{RR}^{tt'} = \sin \theta_R - \frac{(m_{t'}^2 + m_{t}^2)(|x_1|^2 + |x_2|^2) \cos^2 \theta_R \sin \theta_R}{2(m_{t'}^2 - m_{t}^2)m_X^2},$$

$$V_{RR}^{t'u} = -\frac{x_1}{m_X}, \quad V_{RR}^{t'c} = -\frac{x_2}{m_X}, \quad V_{RR}^{t't} = -\sin \theta_R + \frac{(|x_1|^2 + |x_2|^2)(3m_{t'}^2 - m_{t}^2 + (m_{t'}^2 + m_{t'}^2) \cos 2\theta_R) \sin \theta_R}{4(m_{t'}^2 - m_{t}^2)m_X^2},$$

$$V_{RR}^{t't'} = \cos \theta_R - \frac{(|x_1|^2 + |x_2|^2)(m_{t'}^2 - 3m_{t'}^2 - (m_{t'}^2 + m_{t}^2) \cos 2\theta_R) \sin \theta_R}{4(m_{t'}^2 - m_{t}^2)m_X^2}.$$
Mixing with more VL multiplets

3.3 Mixed multiplets

Other multiplets contain both a VL top partner and a VL bottom partner. This is a large class of multiplets which have simultaneously mixing effects for the same multiplet both in the up and in the down sector. We shall not discuss in the present paper these cases explicitly, however their mixing structure with the SM and the other VL multiplets can be easily extracted. In order to show as this can be done we consider the general structure in the following.

3.4 General case

In the general case of \( N_3 \) VL quarks mixing via Yukawa interactions to SM quarks, and among themselves, we can consider the general mixing matrix assuming the SM Yukawa matrices already diagonal. The VL masses are also diagonal in our representation. Considering \( n_d \) semi-integer isospin states (doublets, quadruplets, etc.) with possible mixings with the SM right-handed singlets, and \( n_s = N_3 n_d \) integer isospin states (singlets, triplets, etc.) with possible mixings with the SM left-handed doublets, we obtain the following block-diagonal matrix \( [11] \):

\[
\mathcal{L}_{\text{mass}} = \bar{q}_L \cdot \begin{pmatrix}
\mu_1 & 0 & 0 & 0 & \cdots & 0 & x_{1,n_d+4} & \cdots & x_{1,N} \\
0 & \mu_2 & 0 & 0 & \cdots & 0 & x_{2,n_d+4} & \cdots & x_{2,N} \\
0 & 0 & \mu_3 & 0 & \cdots & 0 & x_{3,n_d+4} & \cdots & x_{3,N} \\
y_{4,1} & y_{4,2} & y_{4,3} & M_4 & 0 & 0 & \cdots & 0 & \cdots & 0 \\
\vdots & \vdots & \vdots & 0 & \cdots & 0 & \omega_{\alpha\beta} & \cdots & \cdots & \cdots \\
y_{n_d+3,1} & y_{n_d+3,2} & y_{n_d+3,3} & 0 & 0 & M_{n_d+3} & \cdots & 0 & \cdots & \cdots \\
0 & 0 & 0 & 0 & \cdots & 0 & \omega'_{\alpha\beta} & 0 & \cdots & 0 \\
\vdots & \vdots & \vdots & \vdots & \cdots & 0 & 0 & \cdots & \cdots & \cdots \\
0 & 0 & 0 & 0 & \cdots & 0 & 0 & \cdots & 0 & M_N \\
\end{pmatrix} \cdot q_R + h.c.
\]
Mixing structure

- $n_d \times 3$ matrix $y$ of the Yukawa couplings of the VL doublets (semi-integer isospin)
- $3 \times n_S$ matrix $x$ of the Yukawa couplings of the VL singlets/triplets (integer isospin)
- $M_\alpha$ are the VL masses of the new representations
- $n_d \times n_S$ matrix $\omega$ and $n_S \times n_d$ matrix $\omega'$ contain the Yukawa couplings among VL representations
- $\omega'$ couplings correspond to the “wrong” (opposite) chirality configuration with respect to SM Yukawa couplings
Bounds

- Tree-level bounds
  - FCNC effects at tree level due to mixing
  - $W \rightarrow t\ b$, $\sim \pm 20\%$ variation still allowed (TeVatron data)
  - $Z \rightarrow b\ b$ $+1\% \rightarrow -0.2\%$ in the left coupling and $+20\% \rightarrow -5\%$ in the right coupling ($L$ and $R$ are correlated)
  - Atomic parity violation (weak charge affected by FCNC of $Z \rightarrow$ light quarks)

- Loop level bounds
  - new particles are expected in the loops (not only the new heavy fermions)
  - FCNC effects at loop level
  - Precision EW tests with the T-parameter, but other new particle may affect the result
Tree level bounds

• Rare top decays (induced by mixing)

\[
\frac{\Gamma(t \rightarrow Zu) + \Gamma(t \rightarrow Zc)}{\Gamma(t \rightarrow Wb)} < 0.34\% \quad \text{measured at CMS @ 4.6 fb}^{-1}
\]

implies:

\[
|V_{R}^{t'}| \sqrt{|V_{R}^{t'u}|^2 + |V_{R}^{t'c}|^2} < 0.08|V_{tb}|
\]

• \(Z \rightarrow cc\) coupling from LEP

\[
g_{ZL}^{c} = 0.3453 \pm 0.0036 \\
g_{ZR}^{c} = -0.1580 \pm 0.0051
\]

implies:

\[
|V_{R}^{t'c}| < 0.2
\]
Weak charge of nuclei

• Atomic parity violation, weak charge:

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

for Cesium:

\[ Q_W^{(133\text{Cs})}\big|_{\text{exp}} = -73.20 \pm 0.35 \quad Q_W^{(133\text{Cs})}\big|_{\text{SM}} = -73.15 \pm 0.02 \]

• at 3 sigmas this implies:

\[ \delta Q_W = -(2Z + N)|V_{R}^{t'u}|^2 \quad |V_{R}^{t'u}| < 7.8 \times 10^{-2} \]
FCNC tree level (if no b’)

- D-Dbar mixing and $D \rightarrow l^+l^-$:

  Contribution of the right-handed couplings in the vector-like scenario

  Mixing ($\Delta C = 2$):
  \[
  D^0 \left\{ \begin{array}{c} c \\ u \end{array} \right\} Z \left\{ \begin{array}{c} u \\ c \end{array} \right\} \bar{D}^0 \\
  \delta x_D = f(m_D, \Gamma_D, m_c, m_Z)(g_{ZR}^{uc})^2
  \]

  Decay ($\Delta C = 1$):
  \[
  D^0 \left\{ \begin{array}{c} c \\ u \end{array} \right\} Z \left\{ \begin{array}{c} l^+ \\ l^- \end{array} \right\} \\
  \delta BR = g(m_D, \Gamma_D, m_l, m_Z)(g_{ZR}^{uc})^2
  \]

- strongest bound from $x_D$:

  \[
  x_D = \frac{\Delta m_D}{\Gamma_D} = 0.0100^{+0.0024}_{-0.0026}
  \]

  \[
  (g_{ZR}^{uc})^2 = \frac{\pi \alpha}{c_w^2 s_w^2} |V_R^{u'}|^2 |V_R^{c'}|^2 \quad \Rightarrow \quad |V_R^{u'}| |V_R^{c'}| < 3.2 \times 10^{-4} \quad @3\sigma
  \]
Kaons

- $t'$ in the loop:

$$\Delta m_K \equiv m_{K_L} - m_{K_S} = 2\text{Re } M_{12} \simeq 2|M_{12}|$$

$$\epsilon_K \simeq \frac{e^{i\pi/4}}{\sqrt{2\Delta m_K}} \text{Im } M_{12}$$

$$\Delta m_K|_{exp} = (3.483 \pm 0.006) \times 10^{-15} \text{ GeV} \quad |\epsilon_K|_{exp} = (2.233 \pm 0.015) \times 10^{-3}$$

corrections to $\epsilon_K$ in the 4% range
Kaons

Parameters:

\[ |V_{R}^{\ell^u}| \leq 0.078 \quad |V_{R}^{\ell^c}| \leq 0.2 \quad |V_{R}^{\ell^u^c}||V_{R}^{\ell^c}| \leq 3.2 \times 10^{-4} \]

\[ M_{t'} = 350, 500, 1000 \text{ GeV} \]
Bs-mesons

Effect on phase up to 60% as in many BSM models. To be checked with CPV in $B_s \rightarrow J/\Psi \phi$. 
EW precision tests

Assuming mixing with third family ONLY

Singlet

non-SM doublet
EW precision tests

SM-like doublet

Triplet
EW bounds (2 VL multiplets)

Figure 3: EWP bounds at 1 (red), 2 (green) and 3 (blue) for a Singlet + non-SM Doublet couplings uniquely with the first (left) or second (right) generation, compared with the region allowed at 3 by tree level bounds. Here, $M = 800\, \text{GeV}$.

2.4 Results: Triplet-5/3 + non-SM Doublet

The results are in Figure 4: this case has not been studied by Harada yet.

2.5 Bounds on the third generation mixing

The bounds on the mixing to third generation do not depend on the representation the $T$ belongs to. In Figure 5 we show the allowed region in yellow in the case of a singlet/triplet and doublet. Comparing the regions here to the EWP bounds by Harada-san, we can see that there is no additional bound posed.
Pair production

Pair production for \( t' \) of the non-SM doublet

\[ pp \rightarrow t' \bar{t'} \] @ LHC
Single production

Charged current channels are suppressed in $(X \ t')$ doublet, non-suppressed in singlet and triplets

FCNCs channels can be relevant in single production especially in the singlet $t'$ and $(X \ t')$ doublet
Single production

Non-SM doublet single t' production cross section as function of the t' mass
Decay modes never 100% in one channel, in the limit of the equivalence theorem, dictated by the multiplet representation:

<table>
<thead>
<tr>
<th>t’</th>
<th>Wb</th>
<th>Zt</th>
<th>ht</th>
</tr>
</thead>
<tbody>
<tr>
<td>Singlet, Triplet Y=2/3</td>
<td>50%</td>
<td>25%</td>
<td>25%</td>
</tr>
<tr>
<td>Doublet, Triplet Y=-1/3</td>
<td>~0%</td>
<td>50%</td>
<td>50%</td>
</tr>
</tbody>
</table>
T’ decays

Different possibilities for $t'$ decay ($\sin \theta_R = 0.3$, i.e. mixing with top dominates)

1. $pp \rightarrow j (t' \rightarrow t Z) \rightarrow j (t \rightarrow b l^+ \nu) (Z \rightarrow \nu \bar{\nu}) \rightarrow j b l^+ E_T$
   \[ \rightarrow j (t \rightarrow b l^+ \nu) (Z \rightarrow l^+ l^-) \rightarrow j b l^+ l^+ l^- E_T \]
   \[ \rightarrow j (t \rightarrow b l^+ \nu) (Z \rightarrow j j) \rightarrow j j j b l^+ E_T \]

2. $pp \rightarrow j (t' \rightarrow t H) \rightarrow j (t \rightarrow b l^+ \nu) (H \rightarrow b \bar{b}) \rightarrow b \bar{b} b l^+ E_T$

3. $pp \rightarrow j (t' \rightarrow b W) \rightarrow j b (W \rightarrow l^+ \nu) \rightarrow j b l^+ E_T$

Assuming for example $\kappa = 0.1$ and RL =50% cross-sections are
~500 fb for $t'$ in singlet or non-standard doublet and
~200 fb for $t'$ in standard doublet
Production in association with light quarks is ~ 90%
See table 8 of ArXiv:1305.4172
T’ decays \((X^{5/3}, T')\) multiplet

Mixing mostly with top \(V_{R41}\) maximal

Mixing mostly with top \(V_{R42}\) maximal

In all cases \(T' \rightarrow bW\) NOT dominant for allowed masses
$X^{5/3}$ production

**Pair production**

Purely QCD diagrams (dominant contribution)

Purely EW diagrams

**Single production**

Charged current channels are suppressed in doublets, non-suppressed in singlet and triplets
$X^{5/3}$ production

![Graph showing $\sigma(\text{pb})$ versus $M_X$ with 'pair' and 'single' curves.](image_url)
$X^{5/3}$ decays ($X^{5/3}, T'$) multiplet

Mixing mostly with top $V_{R41}$ maximal

Mixing mostly with top $V_{R42}$ maximal
General parameterisation (example with a t')

- T' will in general couple with Wq, Zq, hq
- It is more physical to consider observables (BRs, cross-sections) rather than Lagrangian parameters
- Neglect SM quark masses here (full case in the paper)

Only 5 independent parameters, M, ς_W, ς_Z, ς_{jet}, κ

Choosing multiplet fixes ς_W, ς_Z
General parameterisation

- **Complete Lagrangian**

\[
\mathcal{L} = \kappa_T \left\{ \sqrt{\frac{\xi_i \xi^T_W}{\Gamma^0_W}} \frac{g}{\sqrt{2}} [\tilde{T}_L W^+_\mu \gamma^\mu d^i_L] + \sqrt{\frac{\xi_i \xi^T_Z}{\Gamma^0_Z}} \frac{g}{2c_W} [\tilde{T}_L Z_\mu \gamma^\mu u^i_L] - \sqrt{\frac{\xi_i \xi^T_H}{\Gamma^0_H}} \frac{M}{v} [\tilde{T}_R H u^i_L] - \sqrt{\frac{\xi^T_i \xi_H}{\Gamma^0_H}} \frac{m_t}{v} [\tilde{T}_L H t_R] \right\}
\]

\[
+ \kappa_B \left\{ \sqrt{\frac{\xi_i \xi^B_W}{\Gamma^0_W}} \frac{g}{\sqrt{2}} [\tilde{B}_L W^-_\mu \gamma^\mu u^i_L] + \sqrt{\frac{\xi_i \xi^B_Z}{\Gamma^0_Z}} \frac{g}{2c_W} [\tilde{B}_L Z_\mu \gamma^\mu d^i_L] - \sqrt{\frac{\xi_i \xi^B_H}{\Gamma^0_H}} \frac{M}{v} [\tilde{B}_R H d^i_L] \right\}
\]

\[
+ \kappa_x \left\{ \sqrt{\frac{\xi_i}{\Gamma^0_W}} \frac{g}{\sqrt{2}} [\tilde{X}_L W^+_\mu \gamma^\mu u^i_L] \right\} + \kappa_y \left\{ \sqrt{\frac{\xi_i}{\Gamma^0_W}} \frac{g}{\sqrt{2}} [\tilde{Y}_L W^-_\mu \gamma^\mu d^i_L] \right\} + h.c.,
\]

- **Parameters**: Mass + 4 (for T and B) or + 2 (for X and Y)
Parameterisation: Montecarlo simulations

- General FeynRules model and MadGraph/CalcHep implementation:

- Specific multiplets (3 parameters)

- M mass of the VL quarks in the multiplet, $g^*$ coupling strength for single production, $R_L$ fraction of decay to light quarks
Analysis tool (data recasting)

- Tool to recast LHC analyses for vector-like quarks (still private as under development)

![Diagram of data recasting process]

**INPUT**
- 

**SCRIPT**
- MG+BRIDGE+PYTHIA+DELPHES

**SIMULATIONS**
- per mass, per channel
- | $M_n$ | $M_b$ | $M_y$ |
- | root | root | root |
- | ... | ... | ... |
- | root | root | root |

**DATABASE OF EFFICIENCIES**
- per bin, per mass, per channel
- For each search (ATLAS, CMS)

**DATABASE OF CROSS SECTIONS**
- per mass
- $\sigma(M_n)\sigma(M_b)\cdots\sigma(M_y)$
- Average of Pythia's log files

**CROSS-SECTIONS**
- WEIGHTED WITH EFFICIENCIES AND BRs
- per bin, per channel

- For each search (ATLAS, CMS)

**SELECT 2-BODY DECAYS TO SM**
- Loop mixing $Q_i \rightarrow \{V,q\} \rightarrow Q_j$
- Non-mixing $\{Q_i', Q_j'\}$

**MIXING OF STATES**
- Loop mixing $Q_i \rightarrow \{V,q\} \rightarrow Q_j$
- Non-mixing $\{Q_i', Q_j'\}$

**INTERFERENCE**
- $y_{ij} = \frac{2\text{Re} [S_{ij} S_{ij}^* (\mathbf{P_P} \cdot \mathbf{P_P})^2]}{g_{ij} S_{ij}^* (\mathbf{P_P} \cdot \mathbf{P_P})^2 + g_{ij} S_{ij}^* (\mathbf{P_P} \cdot \mathbf{P_P})^2}$

**OUTPUT**
- EXCLUSION CONFIDENCE LEVEL

**NUMBER OF SIGNAL EVENTS**
- per bin
- For each search (ATLAS, CMS)

**LIMIT CODE**
- Bin 1: $\sum_{i=1}^{N} \sigma_i \times L$
- Bin 2: $\sum_{i=1}^{N} \sigma_i \times L$
- Other bins...

**EXCLUSION**
- Confidence level

...
Blue, purple, red correspond to $RL = 0, 0.5, \infty$ respectively. Obtained combining SUSY CMS searches ($\alpha_T$, monolepton, OS dileptons, SS dileptons)
Conclusions

• Heavy vector-like fermions are present in many extensions of the SM

• Present constraints can be improved, especially for realistic cases, beyond too simplified assumptions

• Flavour results are helpful to establish the allowed range of mixings

• LHC can produce or bound these particles to a level giving a real feedback on new physics scenarios to theorists

• Present bounds just start probing the interesting mass range for VL relevant in BSM model building

• A general parameterisation, useful for LHC searches is available and an analysis tool is in preparation