Vector like Quark multiplets

Naveen Gaur

Dyal Singh College (University of Delhi),
Lodhi Road, New Delhi - 110003

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Fundamental Composite Dynamics

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- "Vector like multiplets: constraints and LHC potential" arXiv:1806.01024
- "Interplay of vector-like top partner multiplets in a realistic mixing set-up ", arXiv:1502.00370.
- "XQCAT: eXtra Quark Combined Analysis Tool", arXiv:1409.3116.
- "Framework for Model Independent Analyses of Multiple Extra Quark Scenarios", arXiv:1405.0737.
- "Heavy Vector-like Top Partners at the LHC and flavour constraints", arXiv:1108.6329.
- "Bounds and Decays of New Heavy Vector-like Top Partners", arXiv:1007.2933.

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What is Vector Like (VL) quark

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- They have Diract mass without the Higgs

$$\mathcal{L}_{mass} = M \left(\bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L \right)$$

- They couple to SM quarks via Yukawa-type interactions

$$\mathcal{L}_{Yuk} = -\frac{\lambda v}{\sqrt{2}} \left(\bar{q}_L \psi_R + \bar{\psi}_R q_L \right) \quad or \quad \left(\bar{\psi}_L q_R + \bar{q}_R \psi_L \right)$$

Charged current interactions :

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

SM Chiral quarks :

$$J^{\mu +} = J^{\mu +}_L + J^{\mu +}_R$$

with $J^{\mu +}_L = \bar{u}_L \gamma^{\mu} d_L = \bar{u} \left(1 - \gamma^5 \right) d = (V - A), \qquad J^{\mu +}_R = 0.$

What is Vector Like (VL) quark

In VL quarks we have both left and right handed charged currents

$$\begin{aligned} J^{\mu+} &= J_L^{\mu+} + J_R^{\mu+} \\ &= \bar{U}_L \gamma^\mu D_R + \bar{D}_L \gamma^\mu U_R \\ &= U \gamma^\mu D = V \end{aligned}$$

Left and right hand chiralities of VL fermion (ψ) transforms in the same way in SM gauge group $SU(3)_c \times SU(2)_L \times U(1)_Y$

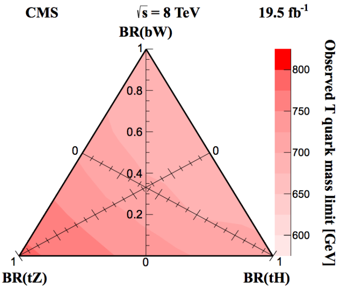
VL quarks appear in many new physics models :

- Warped or universal extra dimension models
- Composite Higgs models
- Little Higgs models
- ....

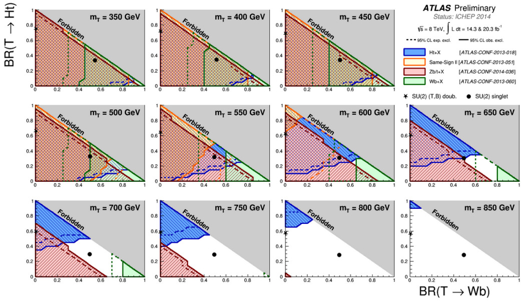
Searches at LHC (t')

Bounds from pair production of VL top quark in range 600-800 GeV

CMS



ATLAS



Assumption: Mixing with only third generation only.

Catalogue of representations, Lagrangian ....

Top type multiplets

Multiplet	ψ	$(SU(2)_L, U(1)_Y)$	T_3	Q_{EM}	Yuk. SM
Singlet 2/3	U	$(\mathbf{1}, 2/3)$	0	$+2/3$	Yes
Doublet 7/6	$\begin{pmatrix} X^{5/3} \\ U \end{pmatrix}$	$(\mathbf{2}, 7/6)$	$+1/2$ $-1/2$	$+5/3$ $+2/3$	Yes
Triplet 5/3	$\begin{pmatrix} X^{8/3} \\ X^{5/3} \\ U \end{pmatrix}$	$(\mathbf{3}, 5/3)$	$+2$ $+1$ 0	$+8/3$ $+5/3$ $+2/3$	No

arXiv:1502.00370

Doublet 7/6

- U mixes with SM top.
- New exotic quark (X) with EM charge 5/3.

arXiv:1108.6329

Bottom type multiplets

Multiplet	ψ	$(SU(2)_L, U(1)_Y)$	T_3	Q_{EM}	Yuk. SM
Singlet-1/3	D	$(\mathbf{1}, -1/3)$	0	-1/3	Yes
Doublet 5/6	$\begin{pmatrix} D \\ Y^{-4/3} \end{pmatrix}$	$(\mathbf{2}, -5/6)$	$+1/2$ $-1/2$	$-1/3$ $-4/3$	Yes
Triplet 4/3	$\begin{pmatrix} D \\ Y^{-4/3} \\ Y^{-7/3} \end{pmatrix}$	$(\mathbf{3}, -4/3)$	0 -1 -2	$-1/3$ $-4/3$ $-7/3$	No

arXiv:1502.00370

Mixed type multiplets

Multiplet	ψ	$(SU(2)_L, U(1)_Y)$	T_3	Q_{EM}	Yuk. SM
Doublet 1/6	$\begin{pmatrix} U \\ D \end{pmatrix}$	$(\mathbf{2}, 1/6)$	$+1/2$ $-1/2$	$+2/3$ $-1/3$	Yes*
Triplet 2/3	$\begin{pmatrix} X^{5/3} \\ U \\ D \end{pmatrix}$	$(\mathbf{3}, 2/3)$	$+1$ 0 -1	$+5/3$ $+2/3$ $-1/3$	Yes
Triplet 1/3	$\begin{pmatrix} U \\ D \\ Y^{-4/3} \end{pmatrix}$	$(\mathbf{3}, -1/3)$	$+1$ 0 -1	$+2/3$ $-1/3$ $-4/3$	Yes

arXiv:1502.00370

Simplifying assumption (right now) : Mixing only in third generation.

Singlet, $\psi = (1, \frac{2}{3}) = U$

$$\begin{aligned} \mathcal{L}_{\rm Yuk} &= -y_u\, \bar{q}_L H^c u_R - \lambda\, \bar{q}_L H^c U_R - M\, \bar{U}_L U_R + h.c. \\ &= -\frac{y_u v}{\sqrt{2}}\, \bar{u}_L u_R - \frac{\lambda v}{\sqrt{2}}\, \bar{u}_L U_R - M\, \bar{U}_L U_R + h.c.\,. \end{aligned}$$

Triplet, $\psi = (3, \frac{2}{3}) = (X^{5/3}, U, D)^T$

$$\begin{aligned} \mathcal{L}_{\rm Yuk} &= -y_u\, \bar{q}_L H^c u_R - \lambda\, \bar{q}_L \tau^a H^c \psi^a_R - M\, \bar{\psi}_L \psi_R + h.c. \\ &= -\frac{y_u v}{\sqrt{2}}\, \bar{u}_L u_R - \frac{\lambda v}{\sqrt{2}}\, \bar{u}_L U_R - \lambda v\, \bar{d}_L D_R - M\, (\bar{U}_L U_R + \bar{D}_L D_R + \bar{X}_L X_R) + h.c.\,. \end{aligned}$$

Top sector mixing matrix :

$$\begin{pmatrix} \frac{y_u v}{\sqrt{2}} & x \\ 0 & M \end{pmatrix}$$

$$q = (u, d)^T$$

$$V_u^{L,R} = \begin{pmatrix} \cos\theta_u^{L,R} & \sin\theta_u^{L,R} \\ -\sin\theta_u^{L,R} & \cos\theta_u^{L,R} \end{pmatrix},$$

$$\begin{pmatrix} \cos\theta_u^{L} & -\sin\theta_u^{L} \\ \sin\theta_u^{L} & \cos\theta_u^{L} \end{pmatrix} \begin{pmatrix} \frac{y_u v}{\sqrt{2}} & x \\ 0 & M \end{pmatrix} \begin{pmatrix} \cos\theta_u^{R} & \sin\theta_u^{R} \\ -\sin\theta_u^{R} & \cos\theta_u^{R} \end{pmatrix} = \begin{pmatrix} m_t & 0 \\ 0 & m_{t'} \end{pmatrix},$$

with $m_{t'} \geq M \geq m_t$

$$\frac{y_u^2 v^2}{2} = m_t^2 \left(1 + \frac{x^2}{M^2 - m_t^2}\right), \qquad m_{t'}^2 = M^2 \left(1 + \frac{x^2}{M^2 - m_t^2}\right),$$

$$\sin\theta_u^L = \frac{Mx}{\sqrt{(M^2 - m_t^2)^2 + M^2 x^2}}, \qquad \sin\theta_u^R = \frac{m_t}{M} \sin\theta_u^L .$$

For $M \gg v \sim m_t \sim x$:

$$\frac{y_u v}{\sqrt{2}} \sim m_t, \quad m_{t'} \sim M, \quad \sin\theta_u^L \sim \frac{x}{M}, \quad \sin\theta_u^R \sim \frac{m_t x}{M^2}.$$

Strongly constrained

$$sin\theta_u^L \gg sin\theta_u^R$$

Doublet 1/6, $\psi = (2, \frac{1}{6}) = (U, D)^T$

$$\begin{aligned}
\mathcal{L}_{\rm Yuk} &= -y_u\, \bar{q}_L H^c u_R - \lambda_u\, \bar{\psi}_L H^c u_R - \lambda_d\, \bar{\psi}_L H d_R - M\, \bar{\psi}_L \psi_R + h.c. \\
&= -\frac{y_u v}{\sqrt{2}}\, \bar{u}_L u_R - \frac{\lambda_u v}{\sqrt{2}}\, \bar{U}_L u_R - \frac{\lambda_d v}{\sqrt{2}}\, \bar{D}_L d_R - M\,(\bar{U}_L U_R + \bar{D}_L D_R) + h.c..
\end{aligned}$$

Doublet 7/6, $\psi = (2, \frac{7}{6}) = (X^{5/3}, U)^T$

$$\begin{aligned}
\mathcal{L}_{\rm Yuk} &= -y_u\, \bar{q}_L H^c u_R - \lambda\, \bar{\psi}_L H u_R - M\, \bar{\psi}_L \psi_R + h.c. \\
&= -\frac{y_u v}{\sqrt{2}}\, \bar{u}_L u_R - \frac{\lambda v}{\sqrt{2}}\, \bar{U}_L u_R - M\,(\bar{U}_L U_R + \bar{X}_L X_R) + h.c..
\end{aligned}$$

Top sector mixing matrix :

$$\begin{pmatrix} \frac{y_u v}{\sqrt{2}} & 0 \\ x & M \end{pmatrix}$$

Catalogue of representations, Lagrangian ....

Top sector mixing (Doublet)

The diagonalization can be carried out in same way to give.

$$\sin\theta_u^R = \frac{Mx}{\sqrt{(M^2 - m_t^2)^2 + M^2x^2}}\,, \quad \sin\theta_u^L = \frac{m_t}{M}\sin\theta_u^R\,.$$

Singlet, Triplet	Doublet
$\sin\theta_u^R = \frac{Mx}{\sqrt{(M^2-m_t^2)^2+M^2x^2}}$ $\sin\theta_u^L = \frac{m_t}{M}\sin\theta_u^R$	$\sin\theta_u^R = \frac{m_t}{M}\sin\theta_u^R$ $\sin\theta_u^R = \frac{Mx}{\sqrt{(M^2-m_t^2)^2+M}}$
$\sin\theta_u^L \gg \sin\theta_u^R$	$\sin\theta_u^R \gg \sin\theta_u^L$

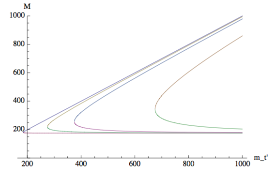


Figure 1: *Plot of M as a function of $m_{t'}$ for different values of x (from left to right: 10, 100, 200 and 500 GeV). In the limit case $x \to 0$, the two straight lines correspond to $M = m_{t'}$, and $M = m_t$ (with $m_{t'} = \frac{y_u v}{\sqrt{2}}$).*

- Constraints on singlet and triplet multiplets are stronger
- Doublet 1/6 is also constrained due to bottom partner that is in same multiplet.

Generalized mixing: Doublet 7/6 : $\psi = (2, \frac{7}{6}) = (X, U)^T$

$$\mathcal{L}_{\rm yuk} = -y_u^{i,j}\,\bar{Q}_L^i H^c u_R^j - y_d^{i,j}\,\bar{Q}_L^i H d_R^j - \lambda^j\,\bar{\psi}_L H u_R^j\,. \quad i,j = 1,2,3, \quad Q = (u,d)^T$$

where $\tilde{m}_x = \frac{y_x v}{\sqrt{2}}$ and $x_i = \frac{\lambda^i v}{\sqrt{2}}$.

$$\begin{aligned}
\mathcal{L}_{\rm mass} &= -(\bar{d}_L, \bar{s}_L, \bar{b}_L)\cdot \tilde{V}_{CKM}\cdot \begin{pmatrix} \tilde{m}_d & & \\ & \tilde{m}_s & \\ & & \tilde{m}_b \end{pmatrix}\cdot\begin{pmatrix} d_R \\ s_R \\ b_R \end{pmatrix} \\
&- (\bar{u}_L, \bar{c}_L, \bar{t}_L, \bar{U}_L)\cdot \begin{pmatrix} \tilde{m}_u & & & 0 \\ & \tilde{m}_c & & 0 \\ & & \tilde{m}_t & 0 \\ x_1 & x_2 & x_3 & M \end{pmatrix}\cdot\begin{pmatrix} u_R \\ c_R \\ t_R \\ U_R \end{pmatrix} - M\,\bar{X}_L X_R + h.c.
\end{aligned}$$

M_u can be diagonalised by bi-unitary matrices (V_L, V_R)

$$M_u = V_L \cdot \begin{pmatrix} m_u & & & \\ & m_c & & \\ & & m_t & \\ & & & m_{t'} \end{pmatrix}\cdot V_R^\dagger\,.$$

$\tilde{V}_{CKM}$ is the misalignment between left-handed ups and downs and it would correspond to the Cabibbo-Kobayashi-Maskawa matrix in the absence of the new fermion.

LH mixing : V_L diagonalises following :

$$M_u \cdot M_u^\dagger = \begin{pmatrix} \tilde{m}_u^2 & 0 & 0 & x_1^* \tilde{m}_u \\ 0 & \tilde{m}_c^2 & 0 & x_2^* \tilde{m}_c \\ 0 & 0 & \tilde{m}_t^2 & x_3 \tilde{m}_t \\ x_1 \tilde{m}_u & x_2 \tilde{m}_c & x_3 \tilde{m}_t & M^2 + |x_1|^2 + |x_2|^2 + x_3^2 \end{pmatrix}.$$

LH mixing suppressed by light quark masses (first two generations)

RH mixing : V_R diagonalises following :

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

RH mixing possibly large with suppression coming from small $x's$.

Generalized mixing: Doublet 7/6 : $\psi = (2, \frac{7}{6}) = (X, U)^T$

The left handed coupling of Z can be written as :

$$\mathcal{L}_Z = \frac{g}{c_W} \left(\bar{u}_L, \bar{c}_L, \bar{t}_L, \bar{U}_L\right) \cdot \left[\left(\frac{1}{2} - \frac{2}{3} s_W^2\right) \begin{pmatrix} 1 & & & \\ & 1 & & \\ & & 1 & \\ & & & 1 \end{pmatrix} - \begin{pmatrix} & & & \\ & & & \\ & & & \\ & & & 1 \end{pmatrix} \right] \gamma^\mu \cdot \begin{pmatrix} u_L \\ c_L \\ t_L \\ U_L \end{pmatrix} Z_\mu \, .$$

In the mass eigenstate basis, the coupling becomes

$$g_{ZL}^{IJ} = \frac{g}{c_W} \left(\frac{1}{2} - \frac{2}{3} s_W^2\right) \delta^{IJ} - \frac{g}{c_W} V_L^{*,4I} V_L^{4J} \, ;$$

where $I, J = 1, 2, 3, 4$. Flavour violation is governed by V_L^{4i} elements!
Analogously for the right-handed couplings we obtain

$$g_{ZR}^{IJ} = \frac{g}{c_W} \left(-\frac{2}{3} s_W^2\right) \delta^{IJ} - \frac{1}{2} \frac{g}{c_W} V_R^{*,4I} V_R^{4J} \, .$$

$\boxed{\text{Large flavour violation only in RH Z sector and results in milder flavour constraints}}$

Generalized mixing: Doublet 7/6 : $\psi = (2, \frac{7}{6}) = (X, U)^T$

Evaluated constraints coming from :

- $Z \to b\bar{b}$, $W - t - b$ coupling
- Precision data (S, T parameters)
- Direct bounds
- FCNC constraints : $D - \bar{D}$, rare D-decays, Top FCNC ($t \to Zc, Zu$)
- Atomic parity violation.
- Charm Couplings at LEP

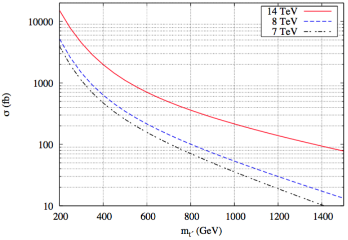
Identified parameter space consistent with all the above constraints

arXiv:1108.6329

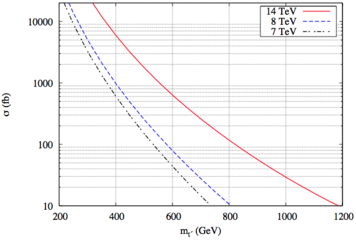
Generalized mixing: Doublet 7/6 : $\psi = (2, \frac{7}{6}) = (X, U)^T$

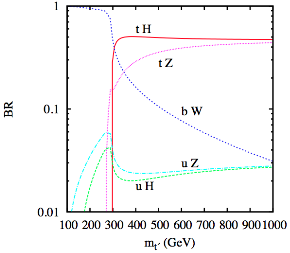
LHC

$pp \to t'j$

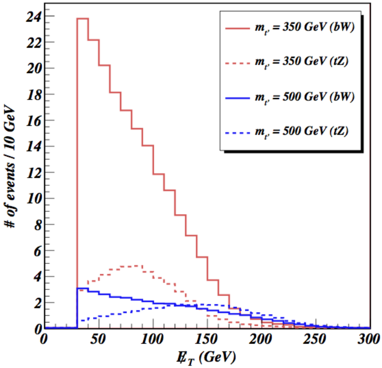


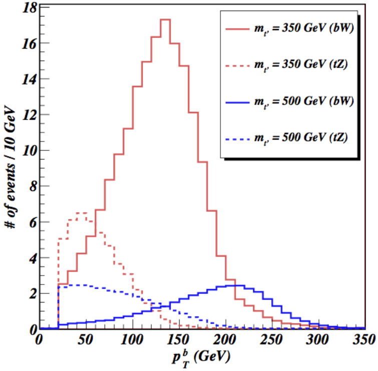
$pp \to t'\bar{t}'$





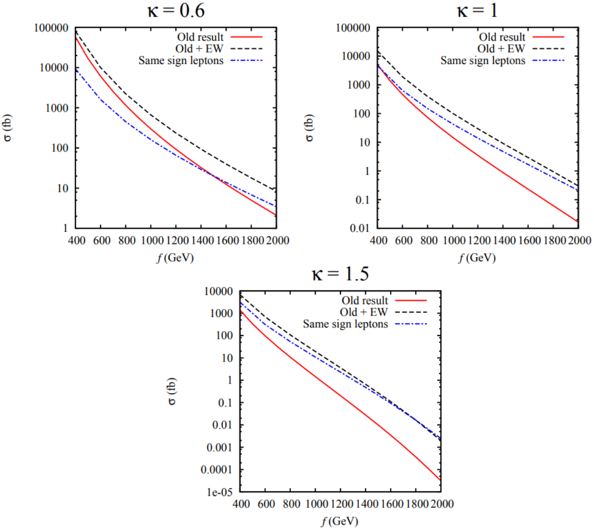
$$pp \to t'j, \qquad t' \to t(\to b\ell^{\pm}\nu)Z(\to \nu\bar{\nu}) \to b\ell^{\pm} \not{E}_T$$
$$t' \to bW(\to \ell\nu) \to b\ell^{\pm} \not{E}_T$$



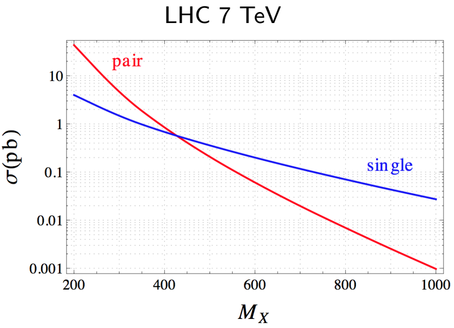


Little Higgs Model with T-parity

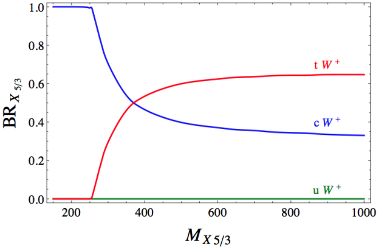
Instances when EW production can dominate over QCD production. $pp \to T\bar{T}$



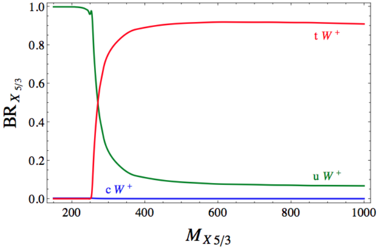
Exotic : $(X^{5/3})$



LHC 7 TeV
pair
single
σ(pb)
10
1
0.1
0.01
0.001
200
400
600
800
1000
M_X



$BR_{X\,5/3}$
$t\,W^+$
$c\,W^+$
$u\,W^+$
$M_{X\,5/3}$



$BR_{X\,5/3}$
$t\,W^+$
$u\,W^+$
$c\,W^+$
$M_{X\,5/3}$

- The two multiples are not of same hyper charge.
- there must be two VL top quarks.
- eventual VL bottom quarks do not mix with SM bottom sector, *i.e.* we can take the mixing to be zero without affecting the top sector, to ensure that the model is not constrained too much by the stringent flavour physics and Zbb coupling bounds from the bottom sector.

Combinations

- Singlet ($Y = 2/3$) + Doublet ($Y = 7/6$);
- Doublet ($Y = 7/6$) + Triplet ($Y = 5/3$);
- Singlet ($Y = 2/3$) + Doublet ($Y = 1/6$);
- Doublet ($Y = 1/6$) + Doublet ($Y = 7/6$).

$\psi_1 = (\mathbf{2}, \frac{7}{6}) = \left(X_1^{5/3} \;\; U_1\right)^T$ and $\psi_2 = (\mathbf{1}, \frac{2}{3}) = U_2$.

$$\begin{aligned}
\mathcal{L}_{V-SM} &= -\lambda_1^k \,\bar{\psi}_{1L} H u_R^k - \lambda_2^k \bar{Q}_L \tilde{H} \psi_{2R} + h.c.\,, \\
\mathcal{L}_{V-V} &= -\xi_1 \,\bar{\psi}_{1L} H \psi_{2R} - \xi_2 \,\bar{\psi}_{1R} H \psi_{2L} + h.c.\,,
\end{aligned}$$

$$\begin{aligned}
\mathcal{L}_{\rm mass} &= -y_1^k \,\bar{U}_{1L} u_R^k - x_2^k u_L^k U_{2R} - \omega \bar{U}_{1L} U_{2R} - \omega' \,\bar{U}_{1R} U_{2L} - M_1 \,\bar{U}_{1L} U_{1R} \\
&\quad - M_2 \,\bar{U}_{2L} U_{2R} - M_1 \,\bar{X}_{1L}^{5/3} X_{1R}^{5/3} + h.c.\,.
\end{aligned}$$

$$M_u = \begin{pmatrix} (\tilde{m}^{up})_{3\times 3} & 0_{3\times 1} & \left(x_2^k\right)_{3\times 1} \\ \left(y_1^k\right)_{1\times 3} & M_1 & \omega \\ 0_{1\times 3} & \omega' & M_2 \end{pmatrix}, \quad M_{X_1^{5/3}} = M_1\,,$$

$$\psi_1 = (\mathbf{2}, \tfrac{7}{6}) = \begin{pmatrix} X_1^{5/3} & U_1 \end{pmatrix}^T \text{ and } \psi_2 = (\mathbf{3}, \tfrac{5}{3}) = \begin{pmatrix} X_2^{8/3} & X_2^{5/3} & U_2 \end{pmatrix}^T .$$

$$\begin{aligned} \mathcal{L}_{V-SM} &= -\lambda_1^k \, \bar{\psi}_{1L} H u_R^k + h.c. \, , \\ \mathcal{L}_{V-V} &= -\xi_1 \, \bar{\psi}_{1L} \tau^a \tilde{H} (\psi_{2R})^a - \xi_2 \, \bar{\psi}_{1R} \tau^a \tilde{H} (\psi_{2L})^a + h.c. \, , \end{aligned}$$

$$\begin{aligned} \mathcal{L}_{\rm mass} = & -y_1^k \bar{U}_{1L} u_R^k - \sqrt{2}\, \omega \bar{U}_{1L} U_{2R} - \omega \bar{X}_{1L}^{5/3} X_{2R}^{5/3} - \sqrt{2}\, \omega' \bar{U}_{1R} U_{2L} - \omega' \bar{X}_{1R}^{5/3} X_{2L}^{5/3} \\ & - M_1 \, \bar{U}_{1L} U_{1R} - M_1 \, \bar{X}_{1L}^{5/3} X_{1R}^{5/3} - M_2 \, \bar{U}_{2L} U_{2R} - M_2 \, \bar{X}_{2L}^{5/3} X_{2R}^{5/3} - M_2 \, \bar{X}_{2L}^{8/3} X_{2R}^{8/3} + h.c \end{aligned}$$

$$M_u = \begin{pmatrix} (\tilde{m}^{up})_{3\times 3} & 0_{3\times 1} & 0_{3\times 1} \\ (y_1^k)_{1\times 3} & M_1 & \sqrt{2}\,\omega \\ 0_{1\times 3} & \sqrt{2}\,\omega' & M_2 \end{pmatrix}, \quad M_{X^{5/3}} = \begin{pmatrix} M_1 & \omega \\ \omega' & M_2 \end{pmatrix}, \quad M_{X^{8/3}} = M_2 \, .$$

$\psi_1 = (\mathbf{2}, \frac{1}{6}) = (U_1 \;\; D_1)^T$ and $\psi_2 = (\mathbf{1}, \frac{2}{3}) = U_2$

$$
\begin{aligned}
\mathcal{L}_{V-SM} &= -\lambda_1^k \, \bar{\psi}_{1L} \tilde{H} u_R^k - \lambda_{1d}^k \, \bar{\psi}_{1L} H d_R^k - \lambda_2^k \bar{Q}_L^k \tilde{H} \psi_{2R} + h.c. \, , \\
\mathcal{L}_{V-V} &= -\xi_1 \, \bar{\psi}_{1L} \tilde{H} \psi_{2R} - \xi_2 \, \bar{\psi}_{1R} \tilde{H} \psi_{2L} + h.c. \, ,
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{L}_{\rm mass} &= -y_1^k \bar{U}_{1L} u_R^k - x_2^k u_L^k U_{2R} - \omega \bar{U}_{1L} U_{2R} - \omega' \bar{U}_{2L} U_{1R} \\
&\quad - M_1 \, \bar{U}_{1L} U_{1R} - M_2 \, \bar{U}_{2L} U_{2R} - M_1 \, \bar{D}_{1L} D_{1R} + h.c. \, .
\end{aligned}
$$

$$
M_u = \begin{pmatrix} (\tilde{m}^{up})_{3\times 3} & 0_{3\times 1} & (x_2^k)_{3\times 1} \\ (y_1^k)_{1\times 3} & M_1 & \omega \\ 0_{1\times 3} & \omega' & M_2 \end{pmatrix}, \quad M_d = \begin{pmatrix} (\tilde{m}^{down})_{3\times 3} & 0_{1\times 3} \\ (0)_{3\times 1} & M_1 \end{pmatrix} .
$$

$\psi_1 = (\mathbf{2}, \frac{1}{6}) = (U_1 \;\; D_1)^T$ and $\psi_2 = (\mathbf{2}, \frac{7}{6}) = \left(X_2^{5/3} \;\; U_2\right)^T$.

$$\mathcal{L}_{V-SM} = -\lambda_1^k \, \bar{\psi}_{1L} \tilde{H} u_R^k - \lambda_{1d}^k \, \bar{\psi}_{1L} H d_R^k - \lambda_2^k \, \bar{\psi}_{2L} H u_R^k + h.c. \, ,$$

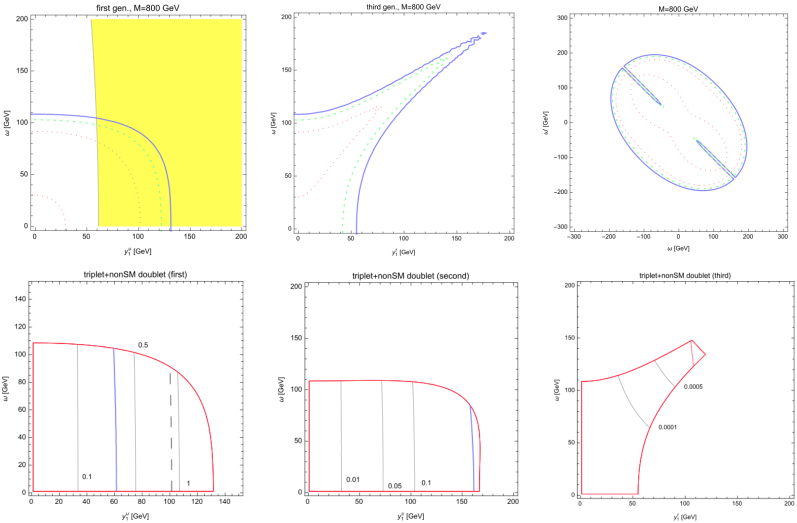
$$\begin{aligned} \mathcal{L}_{\rm mass} \;\; = \;\; & -y_{1u}^k \bar{U}_{1L} u_R^k - y_{1d}^k \bar{D}_{1L} d_R^k - y_2^k U_{2L} u_R^k \\ & -M_1 \, \bar{U}_{1L} U_{1R} - M_1 \, \bar{D}_{1L} D_{1R} - M_2 \, \bar{U}_{2L} U_{2R} - M_2 \, \bar{X}_{2L}^{5/3} X_{2R}^{5/3} + h.c. \, , \end{aligned}$$

$$M_u = \begin{pmatrix} (\tilde{m}^{up})_{3\times 3} & 0_{3\times 1} & 0_{3\times 1} \\ (y_1^k)_{1\times 3} & M_1 & 0 \\ (y_2^k)_{1\times 3} & 0 & M_2 \end{pmatrix}, \quad M_d = \begin{pmatrix} (\tilde{m}^{down})_{3\times 3} & 0_{3\times 1} \\ (0)_{1\times 3} & M_2 \end{pmatrix}, \quad M_{X^{5/3}} = M_2 \, .$$

$$M_u^{(A)} = \begin{pmatrix} \tilde{m}_u & & & 0 & 0 \\ & \tilde{m}_c & & 0 & 0 \\ & & \tilde{m}_t & 0 & 0 \\ y_1^1 & y_1^2 & y_1^3 & M_1 & 0 \\ y_2^1 & y_2^2 & y_2^3 & 0 & M_2 \end{pmatrix}, \quad M_u^{(B)} = \begin{pmatrix} \tilde{m}_u & & & x_1^1 & x_2^1 \\ & \tilde{m}_c & & x_1^2 & x_2^2 \\ & & \tilde{m}_t & x_1^3 & x_2^3 \\ 0 & 0 & 0 & M_1 & 0 \\ 0 & 0 & 0 & 0 & M_2 \end{pmatrix}$$

$$M_u^{(C)} = \begin{pmatrix} \tilde{m}_u & & & 0 & x_2^1 \\ & \tilde{m}_c & & 0 & x_2^2 \\ & & \tilde{m}_t & 0 & x_2^3 \\ y_1^1 & y_1^2 & y_1^3 & M_1 & \omega \\ 0 & 0 & 0 & \omega' & M_2 \end{pmatrix}$$

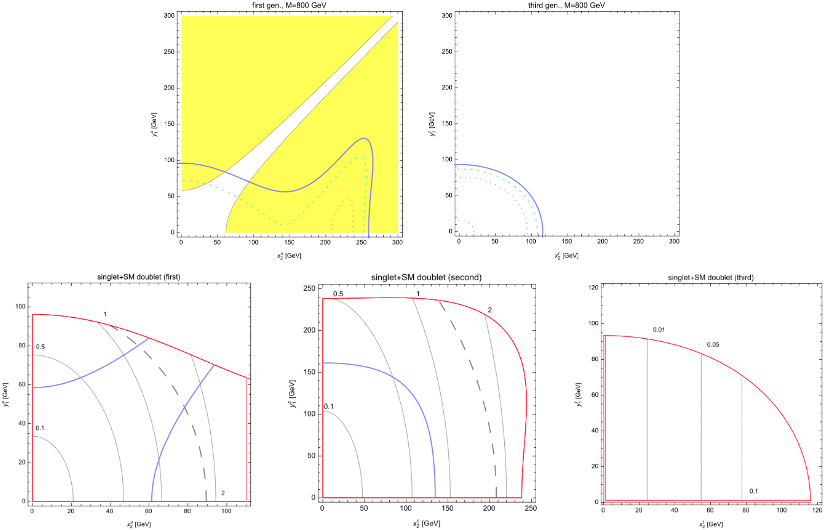
2nd $\downarrow$ 1st $\rightarrow$	Singlet $Y = \frac{2}{3}$	Doublet $Y = \frac{1}{6}$	Doublet $Y = \frac{7}{6}$	Triplet $Y = \frac{5}{3}$
Singlet $Y = \frac{2}{3}$	case B	**case C**	**case C**	case B
Doublet $Y = \frac{1}{6}$		case A	**case A**	case C
Doublet $Y = \frac{7}{6}$			case A	**case C**
Triplet $Y = \frac{5}{3}$				case B



arXiv:1502.00370

Interplay of vector like quark multiplets (Degenerate)

Singlet $Y = 2/3$ and Doublet $Y = 1/6$

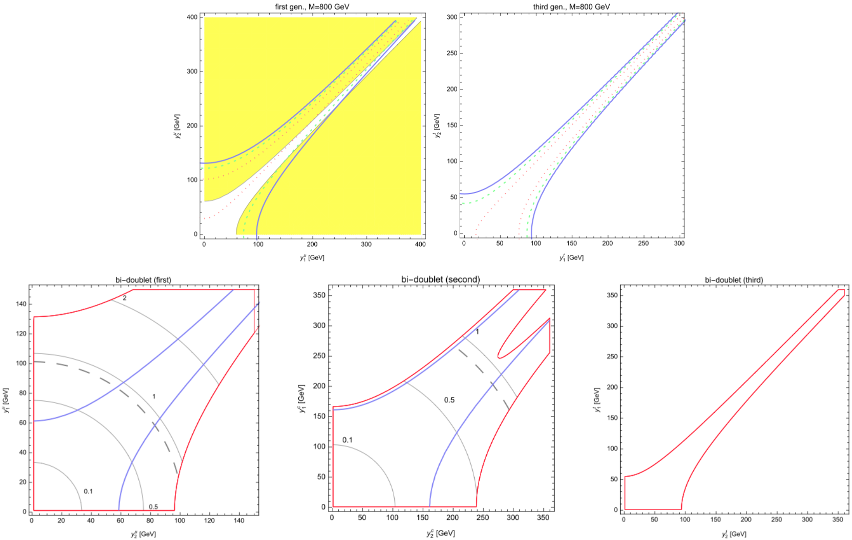


arXiv:1502.00370

Interplay of vector like quark multiplets

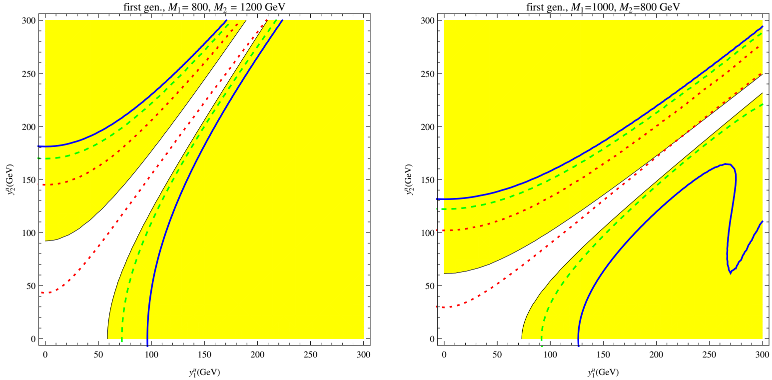
Doublet $Y = 1/6$ and Doublet $Y = 7/6$

arXiv:1502.00370



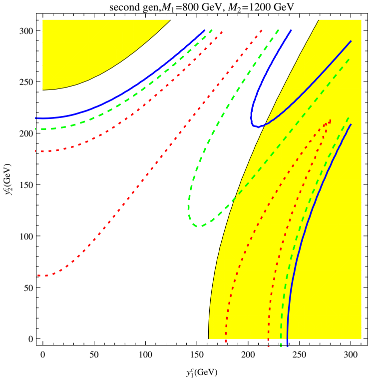
arXiv:1502.00370

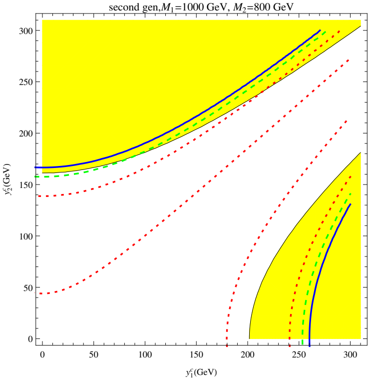
First generation mixing



under prep

Second generation mixing

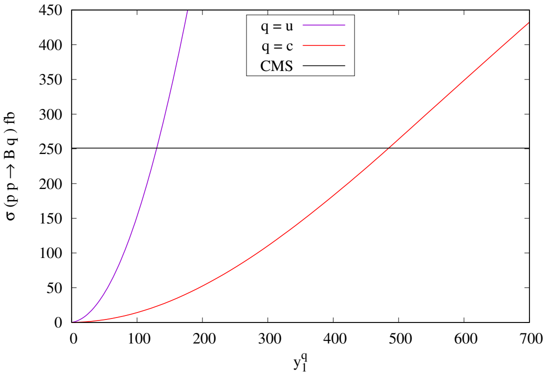




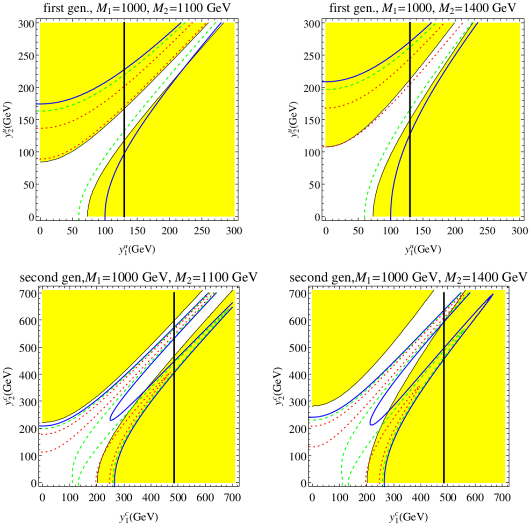
under prep

Non-Degenerate case ($M_1 \neq M_2$)

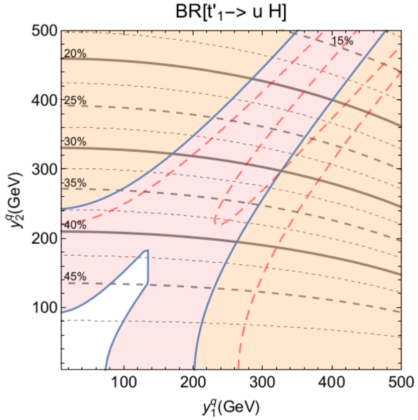
Considered following doublets $\begin{pmatrix} U_1 \\ D_1 \end{pmatrix}_{1/6}$ and $\begin{pmatrix} X_2^{5/3} \\ U_2 \end{pmatrix}_{7/6}$

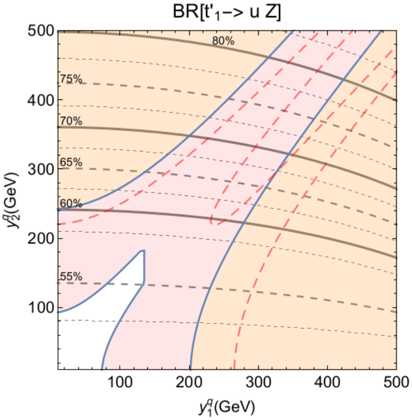


Non-Degenerate case ($M_1 \neq M_2$)

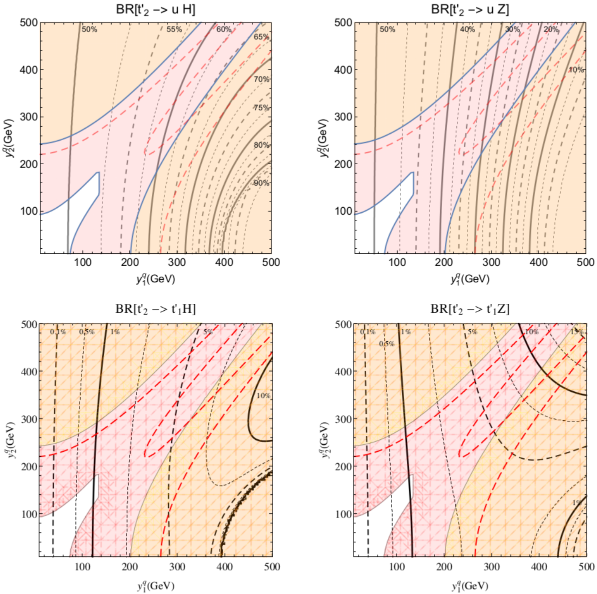


Non-Degenerate case ($M_1 \neq M_2$)

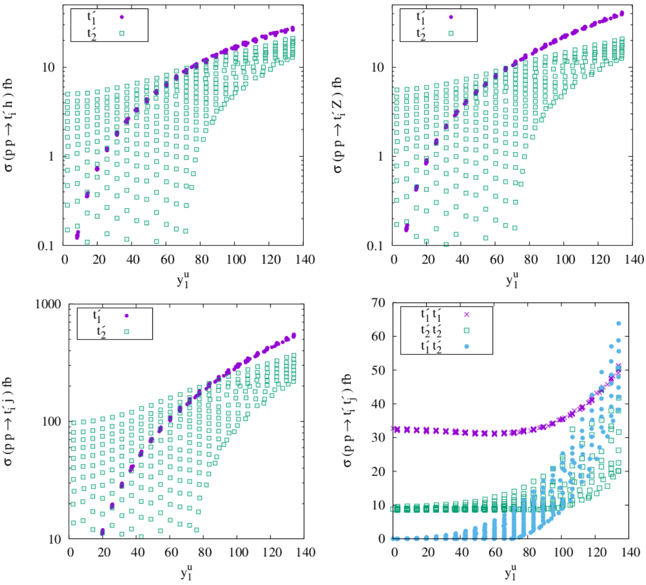




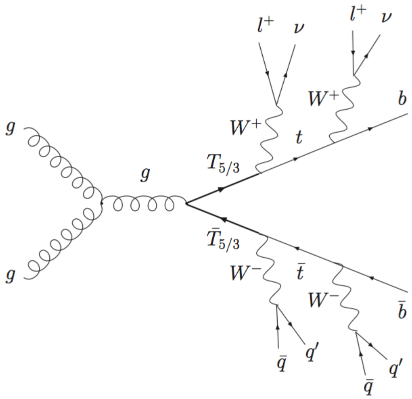
Non-Degenerate case ($M_1 \neq M_2$)

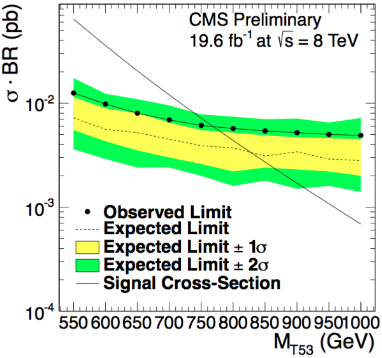


Non-Degenerate case ($M_1 \neq M_2$)



Same sign dilepton

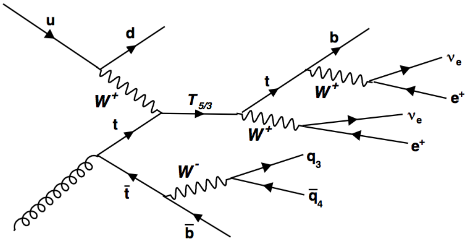




Assuming Br$(T^{5/3} \to bW) = 100\%$ mass upto 770 GeV excluded.

CMS PAS B2G-12-012

Same sign dilepton



Constrained parameter	95% C.L. limits Expected	Observed
b' / $T_{5/3}$ pair production		
b' mass or $T_{5/3}$ mass for $\lambda \ll 1$	> 0.64 TeV	> 0.67 TeV
$T_{5/3}$ single and pair production		
$T_{5/3}$ mass for $\lambda = 1$	> 0.64 TeV	> 0.68 TeV
$T_{5/3}$ mass for $\lambda = 3$	> 0.66 TeV	> 0.70 TeV
Four top quark event production		
Four top quark production cross-section	< 90 fb	< 61 fb

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Some possible extensions :

- Have been able to develop (to a fairly good extent) a general framework for arbitrary number of vector like quark multiples.
- Can possibly be replicated in leptonic sector (there are already some works).
- Can possibly be extended for more interesting case single VL quark production.
- Needs more exploration specially exotic sector.