Heavy vector-like quarks

Constraints and phenomenology at the LHC

Luca Panizzi

IPN Lyon

Outline

Outline

What are vector-like fermions?

and where do they appear?

The left-handed and right-handed chiralities of a vector-like fermion ψ
transform in the same way under the SM gauge groups $SU(3)_c \times SU(2)_L \times U(1)_Y$

What are vector-like fermions?

and where do they appear?

The left-handed and right-handed chiralities of a vector-like fermion ψ
transform in the same way under the SM gauge groups $SU(3)_c \times SU(2)_L \times U(1)_Y$

Why are they called “vector-like”?

What are vector-like fermions?

and where do they appear?

The left-handed and right-handed chiralities of a vector-like fermion ψ
transform in the same way under the SM gauge groups $SU(3)_c \times SU(2)_L \times U(1)_Y$

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

What are vector-like fermions?

and where do they appear?

The left-handed and right-handed chiralities of a vector-like fermion ψ
transform in the same way under the SM gauge groups $SU(3)_c \times SU(2)_L \times U(1)_Y$

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

$$J^{\mu +} = J_L^{\mu +} + J_R^{\mu +} \quad \text{with} \quad \begin{cases} J_L^{\mu +} = \bar{u}_L \gamma^\mu d_L = \bar{u} \gamma^\mu (1 - \gamma^5) d = V - A \\ J_R^{\mu +} = 0 \end{cases}$$

What are vector-like fermions?

and where do they appear?

The left-handed and right-handed chiralities of a vector-like fermion ψ transform in the same way under the SM gauge groups $SU(3)_c \times SU(2)_L \times U(1)_Y$

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

$$J^{\mu +} = J^{\mu +}_L + J^{\mu +}_R \quad \text{with} \quad \begin{cases} J^{\mu +}_L = \bar{u}_L \gamma^\mu d_L = \bar{u} \gamma^\mu (1 - \gamma^5) d = V - A \\ J^{\mu +}_R = 0 \end{cases}$$

- 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 ψ 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

$\mathcal{L}_M = -M\bar{\psi}\psi$ Gauge invariant mass term without the Higgs

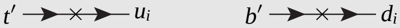
Charged currents both in the left and right sector

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

They can mix with SM quarks



Dangerous FCNCs $\longrightarrow$ strong bounds on mixing parameters
BUT
Many open channels for **production** and **decay** of heavy fermions

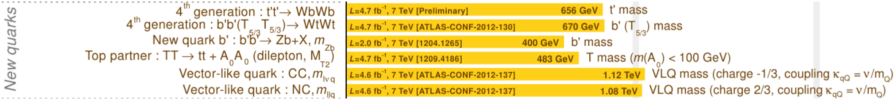
Rich phenomenology to explore at LHC

Searches at the LHC

Overview of ATLAS searches

from ATLAS Twiki page

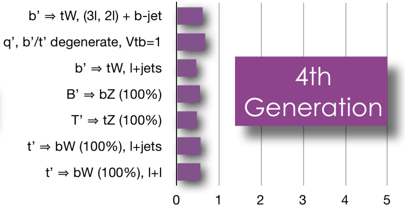
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/CombinedSummaryPlots



Overview of CMS searches

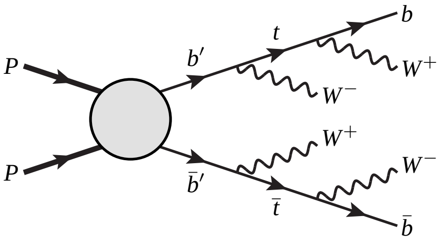
from CMS Twiki page

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO



But look at the hypotheses . . .

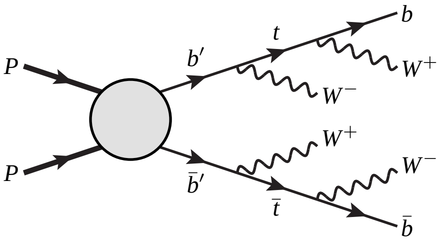
Example: b' pair production



Common assumption
$BR(b' \to tW) = 100\%$

Searches in the
same-sign dilepton channel
(possibly with b-tagging)

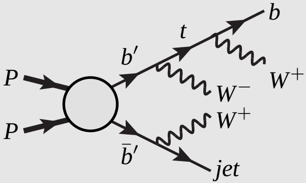
Example: b' pair production

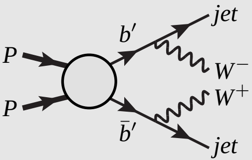


Common assumption
$BR(b' \to tW) = 100\%$

Searches in the
same-sign dilepton channel
(possibly with b-tagging)

If the b' decays both into Wt and Wq





There can be less events in the same-sign dilepton channel!

Representations and lagrangian terms

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

	SM	Singlets		Doublets			Triplets	
	$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$	(U)	(D)	$\begin{pmatrix} X \\ U \end{pmatrix}$	$\begin{pmatrix} U \\ D \end{pmatrix}$	$\begin{pmatrix} D \\ Y \end{pmatrix}$	$\begin{pmatrix} X \\ U \\ D \end{pmatrix}$	$\begin{pmatrix} U \\ D \\ Y \end{pmatrix}$
$SU(2)_L$	2 and 1	1		2			3	
$U(1)_Y$	$q_L = 1/6$ $u_R = 2/3$ $d_R = -1/3$	2/3	-1/3	7/6	1/6	-5/6	2/3	-1/3
$\mathcal{L}_Y$	$-y_u^i \bar{q}_L^i H^c u_R^i$ $-y_d^i \bar{q}_L^i V_{CKM}^{i,j} H d_R^j$	$-\lambda_u^i \bar{q}_L^i H^c U_R$ $-\lambda_d^i \bar{q}_L^i H D_R$		$-\lambda_u^i \psi_L H^{(c)} u_R^i$ $-\lambda_d^i \psi_L H^{(c)} d_R^i$			$-\lambda_i \bar{q}_L^i \tau^a H^{(c)} \psi_R^a$	

Representations and lagrangian terms

Assumption: vector-like quarks couple with SM quarks through Yukawa interactions

	SM	Singlets		Doublets			Triplets	
	$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$	(t')	(b')	$\begin{pmatrix} X \\ t' \end{pmatrix}$	$\begin{pmatrix} t' \\ b' \end{pmatrix}$	$\begin{pmatrix} b' \\ Y \end{pmatrix}$	$\begin{pmatrix} X \\ t' \\ b' \end{pmatrix}$	$\begin{pmatrix} t' \\ b' \\ Y \end{pmatrix}$
$SU(2)_L$	2 and 1	1		2			3	
$U(1)_Y$	$q_L = 1/6$ $u_R = 2/3$ $d_R = -1/3$	2/3	-1/3	7/6	1/6	-5/6	2/3	-1/3
$\mathcal{L}_Y$	$-\frac{y_u^i v}{\sqrt{2}} \bar{u}_L^i u_R^i$ $-\frac{y_d^i v}{\sqrt{2}} \bar{d}_L^i V_{CKM}^{i,j} d_R^j$	$-\frac{\lambda_u^i v}{\sqrt{2}} \bar{u}_L^i U_R$ $-\frac{\lambda_d^i v}{\sqrt{2}} \bar{d}_L^i D_R$		$-\frac{\lambda_u^i v}{\sqrt{2}} U_L u_R^i$ $-\frac{\lambda_d^i v}{\sqrt{2}} D_L d_R^i$			$-\frac{\lambda_i v}{\sqrt{2}} \bar{u}_L^i U_R$ $-\lambda_i v \bar{d}_L^i D_R$	

Representations and lagrangian terms

Assumption: vector-like quarks couple with SM quarks through Yukawa interactions

	SM	Singlets	Doublets	Triplets
	$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$	(t') (b')	$\begin{pmatrix} X \\ t' \end{pmatrix}$ $\begin{pmatrix} t' \\ b' \end{pmatrix}$ $\begin{pmatrix} b' \\ Y \end{pmatrix}$	$\begin{pmatrix} X \\ t' \\ b' \end{pmatrix}$ $\begin{pmatrix} t' \\ b' \\ Y \end{pmatrix}$
$SU(2)_L$	2 and 1	1	2	3
$U(1)_Y$	$q_L = 1/6$ $u_R = 2/3$ $d_R = -1/3$	2/3 -1/3	7/6 1/6 -5/6	2/3 -1/3
$\mathcal{L}_Y$	$-\frac{y_u^i v}{\sqrt{2}} \bar{u}_L^i u_R^i$ $-\frac{y_d^i v}{\sqrt{2}} \bar{d}_L^i V_{CKM}^{i,j} d_R^j$	$-\frac{\lambda_u^i v}{\sqrt{2}} \bar{u}_L^i U_R$ $-\frac{\lambda_d^i v}{\sqrt{2}} \bar{d}_L^i D_R$	$-\frac{\lambda_u^i v}{\sqrt{2}} U_L u_R^i$ $-\frac{\lambda_d^i v}{\sqrt{2}} D_L d_R^i$	$-\frac{\lambda_i v}{\sqrt{2}} \bar{u}_L^i U_R$ $-\lambda_i v \bar{d}_L^i D_R$
$\mathcal{L}_m$		$-M\bar{\psi}\psi$ (gauge invariant since vector-like)		
Free parameters		4 $M + 3 \times \lambda^i$	4 or 7 $M + 3\lambda_u^i + 3\lambda_d^i$	4 $M + 3 \times \lambda^i$

Outline

Mixing between VL and SM quarks

Flavour and mass eigenstates

$$\begin{pmatrix} \tilde{u} \\ \tilde{c} \\ \tilde{t} \\ U \end{pmatrix}_{L,R} = V^u_{L,R} \begin{pmatrix} u \\ c \\ t \\ t' \end{pmatrix} \quad \text{and} \quad \begin{pmatrix} \tilde{d} \\ \tilde{s} \\ \tilde{b} \\ D \end{pmatrix}_{L,R} = V^d_{L,R} \begin{pmatrix} d \\ s \\ b \\ b' \end{pmatrix}$$

The exotics $X_{5/3}$ and $Y_{-4/3}$ do not mix $\rightarrow$ no distinction between flavour and mass eigenstates

$$\mathcal{L}_{y+M} = \left(\bar{\tilde{u}} \; \bar{\tilde{c}} \; \bar{\tilde{t}} \; \bar{U} \right)_L \mathcal{M}_u \begin{pmatrix} \tilde{u} \\ \tilde{c} \\ \tilde{t} \\ U \end{pmatrix}_R + \left(\bar{\tilde{d}} \; \bar{\tilde{s}} \; \bar{\tilde{b}} \; \bar{D} \right)_L \mathcal{M}_d \begin{pmatrix} \tilde{d} \\ \tilde{s} \\ \tilde{b} \\ D \end{pmatrix}_R + h.c.$$

Mixing between VL and SM quarks

Flavour and mass eigenstates

$$\begin{pmatrix} \tilde{u} \\ \tilde{c} \\ \tilde{t} \\ U \end{pmatrix}_{L,R} = V^u_{L,R} \begin{pmatrix} u \\ c \\ t \\ t' \end{pmatrix} \quad \text{and} \quad \begin{pmatrix} \tilde{d} \\ \tilde{s} \\ \tilde{b} \\ D \end{pmatrix}_{L,R} = V^d_{L,R} \begin{pmatrix} d \\ s \\ b \\ b' \end{pmatrix}$$

The exotics $X_{5/3}$ and $Y_{-4/3}$ do not mix $\rightarrow$ no distinction between flavour and mass eigenstates

$$\mathcal{L}_{y+M} = \left(\bar{\tilde{u}}\ \bar{\tilde{c}}\ \bar{\tilde{t}}\ \bar{U}\right)_L \mathcal{M}_u \begin{pmatrix} \tilde{u} \\ \tilde{c} \\ \tilde{t} \\ U \end{pmatrix}_R + \left(\bar{\tilde{d}}\ \bar{\tilde{s}}\ \bar{\tilde{b}}\ \bar{D}\right)_L \mathcal{M}_d \begin{pmatrix} \tilde{d} \\ \tilde{s} \\ \tilde{b} \\ D \end{pmatrix}_R + h.c.$$

Mixing matrices depend on representations

- Singlets and triplets:

$$\mathcal{M}_u = \begin{pmatrix} \tilde{m}_u & & & x_1 \\ & \tilde{m}_c & & x_2 \\ & & \tilde{m}_t & x_3 \\ & & & M \end{pmatrix} \qquad \mathcal{M}_d = \left(\begin{array}{c|c} \tilde{V}_L^{CKM} \begin{pmatrix} \tilde{m}_d & & \\ & \tilde{m}_s & \\ & & \tilde{m}_b \end{pmatrix} \tilde{V}_R^{CKM} & \begin{matrix} x_1 \\ x_2 \\ x_3 \end{matrix} \\ \hline & M \end{array}\right)$$

- Doublets: $\mathcal{M}^{4I}_{u,d} \leftrightarrow \mathcal{M}^{I4}_{u,d}$

Mixing matrices

$$\mathcal{L}_m = \left(\bar{u}\,\bar{c}\,\bar{t}\,\bar{t}'\right)_L (V_L^u)^\dagger \mathcal{M}_u (V_R^u) \begin{pmatrix} u \\ c \\ t \\ t' \end{pmatrix}_R + \left(\bar{d}\,\bar{s}\,\bar{b}\,\bar{b}'\right)_L (V_L^d)^\dagger \mathcal{M}_d (V_R^d) \begin{pmatrix} d \\ s \\ b \\ b' \end{pmatrix}_R + h.c.$$

$$(V_L^u)^\dagger \mathcal{M}_u (V_R^u) = diag\,(m_u, m_c, m_t, m_{t'}) \qquad (V_L^d)^\dagger \mathcal{M}_d (V_R^d) = diag\,(m_d, ms, m_b, m_{b'})$$

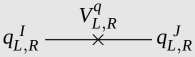
Mixing matrices

$$\mathcal{L}_m = \left(\bar{u}\ \bar{c}\ \bar{t}\ \bar{t}'\right)_L (V_L^u)^\dagger \mathcal{M}_u (V_R^u) \begin{pmatrix} u \\ c \\ t \\ t' \end{pmatrix}_R + \left(\bar{d}\ \bar{s}\ \bar{b}\ \bar{b}'\right)_L (V_L^d)^\dagger \mathcal{M}_d (V_R^d) \begin{pmatrix} d \\ s \\ b \\ b' \end{pmatrix}_R + h.c.$$

$$(V_L^u)^\dagger \mathcal{M}_u (V_R^u) = diag\,(m_u, m_c, m_t, m_{t'}) \qquad (V_L^d)^\dagger \mathcal{M}_d (V_R^d) = diag\,(m_d, ms, m_b, m_{b'})$$

Mixing in left- and right-handed sectors behave differently

$$\begin{cases} (V_L^q)^\dagger (\mathcal{M}\mathcal{M}^\dagger)(V_L^q) = diag \\ (V_R^q)^\dagger (\mathcal{M}^\dagger\mathcal{M})(V_R^q) = diag \end{cases}$$



Mixing matrices

$$\mathcal{L}_m = \left(\bar{u}\;\bar{c}\;\bar{t}\;\bar{t}'\right)_L (V_L^u)^\dagger \mathcal{M}_u (V_R^u) \begin{pmatrix} u \\ c \\ t \\ t' \end{pmatrix}_R + \left(\bar{d}\;\bar{s}\;\bar{b}\;\bar{b}'\right)_L (V_L^d)^\dagger \mathcal{M}_d (V_R^d) \begin{pmatrix} d \\ s \\ b \\ b' \end{pmatrix}_R + h.c.$$

$$(V_L^u)^\dagger \mathcal{M}_u (V_R^u) = diag\,(m_u, m_c, m_t, m_{t'}) \qquad (V_L^d)^\dagger \mathcal{M}_d (V_R^d) = diag\,(m_d, ms, m_b, m_{b'})$$

Mixing in left- and right-handed sectors behave differently

$$\begin{cases} (V_L^q)^\dagger (\mathcal{M}\mathcal{M}^\dagger)(V_L^q) = diag \\ (V_R^q)^\dagger (\mathcal{M}^\dagger\mathcal{M})(V_R^q) = diag \end{cases}$$

$$q^I_{L,R} \;\overset{V^q_{L,R}}{\text{———}\times\text{———}}\; q^J_{L,R}$$

Singlets and triplets (case of up-type quarks)

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

mixing in the left sector present also for $\tilde{m}_q \to 0$

flavour constraints for q_L are relevant

$$V_R^u \implies \mathcal{M}_u^\dagger \cdot \mathcal{M}_u = \begin{pmatrix} \tilde{m}_u^2 & & & x_1^* \tilde{m}_u^2 \\ & \tilde{m}_c^2 & & x_2^* \tilde{m}_c^2 \\ & & \tilde{m}_t^2 & x_3 \tilde{m}_t^2 \\ x_1 \tilde{m}_u & x_2 \tilde{m}_c & x_3 \tilde{m}_t & \sum_{i=1}^3 |x_i|^2 + M^2 \end{pmatrix}$$

$m_q \propto \tilde{m}_q$

mixing is suppressed by quark masses

Doublets: other way round

Now let's check how **couplings** are modified

this will allow us to identify which observables
can constrain masses and mixing parameters

Couplings

With Z

$$\mathcal{L}_Z = \frac{g}{c_W} \left(\bar{q}_1\ \bar{q}_2\ \bar{q}_3\ \bar{q}_1'\right)_L (V_L^q)^\dagger \left[\left(T_3^q - Q^q s_w^2\right) \begin{pmatrix} 1 & & & \\ & 1 & & \\ & & 1 & \\ & & & 1 \end{pmatrix} + \left(T_3^{q'} - T_3^q\right) \begin{pmatrix} 0 & & & \\ & 0 & & \\ & & 0 & \\ & & & 1 \end{pmatrix} \right] \gamma^\mu (V_L^q) \begin{pmatrix} q_1 \\ q_2 \\ q_3 \\ q' \end{pmatrix}_L Z_\mu$$

$$+ \frac{g}{c_W} \left(\bar{q}_1\ \bar{q}_2\ \bar{q}_3\ \bar{q}_1'\right)_R (V_R^q)^\dagger \left[\left(-Q^q s_w^2\right) \begin{pmatrix} 1 & & & \\ & 1 & & \\ & & 1 & \\ & & & 1 \end{pmatrix} + T_3^{q'} \begin{pmatrix} 0 & & & \\ & 0 & & \\ & & 0 & \\ & & & 1 \end{pmatrix} \right] \gamma^\mu (V_R^q) \begin{pmatrix} q_1 \\ q_2 \\ q_3 \\ q' \end{pmatrix}_R Z_\mu$$

Couplings

With Z

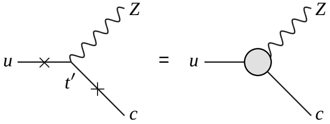
$$\mathcal{L}_Z = \frac{g}{c_W} \left(\bar{q}_1\ \bar{q}_2\ \bar{q}_3\ \bar{q}'_1\right)_L (V_L^q)^\dagger \left[\left(T_3^q - Q^q s_w^2\right) \begin{pmatrix} 1 & & & \\ & 1 & & \\ & & 1 & \\ & & & 1 \end{pmatrix} + \left(T_3^{q'} - T_3^q\right) \begin{pmatrix} 0 & & & \\ & 0 & & \\ & & 0 & \\ & & & 1 \end{pmatrix} \right] \gamma^\mu (V_L^q) \begin{pmatrix} q_1 \\ q_2 \\ q_3 \\ q' \end{pmatrix}_L Z_\mu$$

$$+ \frac{g}{c_W} \left(\bar{q}_1\ \bar{q}_2\ \bar{q}_3\ \bar{q}'_1\right)_R (V_R^q)^\dagger \left[\left(-Q^q s_w^2\right) \begin{pmatrix} 1 & & & \\ & 1 & & \\ & & 1 & \\ & & & 1 \end{pmatrix} + T_3^{q'} \begin{pmatrix} 0 & & & \\ & 0 & & \\ & & 0 & \\ & & & 1 \end{pmatrix} \right] \gamma^\mu (V_R^q) \begin{pmatrix} q_1 \\ q_2 \\ q_3 \\ q' \end{pmatrix}_R Z_\mu$$

FCNC, are induced by the mixing with vector-like quarks!

$$g_{ZL}^{IJ} = \frac{g}{c_W} \left(T_3^q - Q^q s_w^2\right) \delta^{IJ} + \frac{g}{c_W} (T_3^{q'} - T_3^q)(V_L^*)^{q'I} V_L^{q'J}$$

$$g_{ZR}^{IJ} = \frac{g}{c_W} \left(-Q^q s_w^2\right) \delta^{IJ} + \frac{g}{c_W} T_3^{q'} (V_R^*)^{q'I} V_R^{q'J}$$



$$\propto (V_{L,R}^*)^{t'u} V_{L,R}^{t'c}$$

Couplings

With $W^{\pm}$

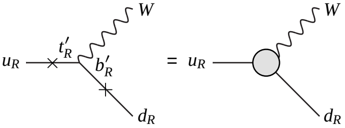
$$\mathcal{L}_{W^\pm} = \frac{g}{\sqrt{2}} \left(\bar{u}\ \bar{c}\ \bar{t}\ |\bar{t'}\right)_L (V_L^u)^\dagger \left(\begin{array}{c|c} \tilde{V}_L^{CKM} & \\ \hline & 1 \end{array}\right) \gamma^\mu V_L^d \begin{pmatrix} d \\ s \\ b \\ \hline b' \end{pmatrix}_L W_\mu^+$$

$$+ \frac{g}{\sqrt{2}} \left(\bar{u}\ \bar{c}\ \bar{t}\ |\bar{t'}\right)_R (V_R^u)^\dagger \left(\begin{array}{ccc|c} 0 & & & \\ & 0 & & \\ & & 0 & \\ \hline & & & 1 \end{array}\right) \gamma^\mu V_R^d \begin{pmatrix} d \\ s \\ b \\ \hline b' \end{pmatrix}_R W_\mu^+ + h.c.$$

CKM matrices for left and right handed sector:

$$g_{WL} = \frac{g}{\sqrt{2}} (V_L^u)^\dagger \left(\begin{array}{c|c} \tilde{V}_{CKM} & \\ \hline & 1 \end{array}\right) V_L^d \equiv \frac{g}{\sqrt{2}} V_L^{CKM} \qquad g_{WR} = \frac{g}{\sqrt{2}} (V_R^u)^\dagger \left(\begin{array}{ccc|c} 0 & & & \\ & 0 & & \\ & & 0 & \\ \hline & & & 1 \end{array}\right) V_R^d \equiv \frac{g}{\sqrt{2}} V_R^{CKM}$$

If BOTH t' and b' are present $\longrightarrow$ CC between right-handed quarks



$$\propto (V_R^{u*})^{t'I} (V_R^d)^{b'J}$$

Couplings

With Higgs

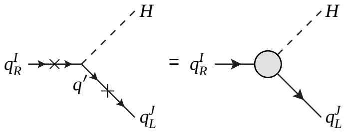
$$\mathcal{L}_h = \frac{1}{v} \left(\bar{q}_1 \ \bar{q}_2 \ \bar{q}_3 \ \bar{q}'_1\right)_L (V_L^q)^\dagger \left[\mathcal{M}_q - M \begin{pmatrix} 0 & & & \\ & 0 & & \\ & & 0 & \\ & & & 1 \end{pmatrix}\right] (V_R^q) \begin{pmatrix} q_1 \\ q_2 \\ q_3 \\ q' \end{pmatrix}_R h + h.c.$$

The coupling is:

$$C = \frac{1}{v}(V_L^q)^\dagger \mathcal{M}_q (V_R^q) - \frac{M}{v}(V_L^q)^\dagger \begin{pmatrix} 0 & & & \\ & 0 & & \\ & & 0 & \\ & & & 1 \end{pmatrix} (V_R^q) = \frac{1}{v} \begin{pmatrix} m_{q_1} & & & \\ & m_{q_2} & & \\ & & m_{q_3} & \\ & & & m_{q'} \end{pmatrix} - \frac{M}{v}(V_L^q)^\dagger \begin{pmatrix} 0 & & & \\ & 0 & & \\ & & 0 & \\ & & & 1 \end{pmatrix} (V_R^q)$$

FCNC induced by vector-like quarks are present in the Higgs sector too!

$$C^{IJ} = \frac{1}{v} m_I \delta^{IJ} - \frac{M}{v} (V_L^*)^{q' I} V_R^{q' J}$$

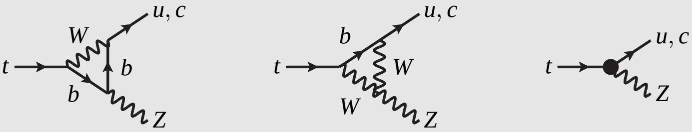


$$\propto (V_L^*)^{q' I} V_R^{q' J}$$

Outline

Rare FCNC top decays

Suppressed in the SM, tree-level with t'

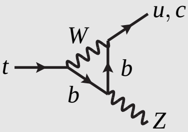


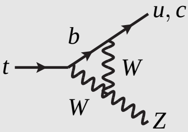
$BR(t \to Zq) = \mathcal{O}(10^{-14})$
SM prediction

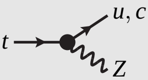
$BR(t \to Zq) < 0.24\%$
measured at CMS @ $5\ fb^{-1}$

Rare FCNC top decays

Suppressed in the SM, tree-level with t'



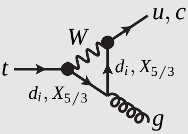


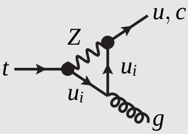


$BR(t \to Zq) = \mathcal{O}(10^{-14})$
SM prediction

$BR(t \to Zq) < 0.24\%$
measured at CMS @ $5\ fb^{-1}$

Loop decays with both SM and vector-like quarks



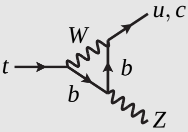


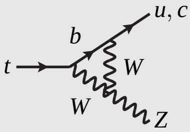
$BR(t \to Zq) = \mathcal{O}(10^{-12})$ SM prediction

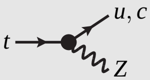
$BR(t \to gu) < 5.7 \times 10^{-5}$
$BR(t \to gc) < 2.7 \times 10^{-4}$
ATLAS @ $2.5\ fb^{-1}$

Rare FCNC top decays

Suppressed in the SM, tree-level with t'



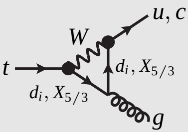


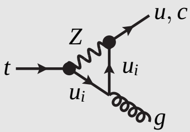


$BR(t \to Zq) = \mathcal{O}(10^{-14})$
SM prediction

$BR(t \to Zq) < 0.24\%$
measured at CMS @ $5\ fb^{-1}$

Loop decays with both SM and vector-like quarks





$BR(t \to Zq) = \mathcal{O}(10^{-12})$ SM prediction

$BR(t \to gu) < 5.7 \times 10^{-5}$
$BR(t \to gc) < 2.7 \times 10^{-4}$
ATLAS @ $2.5\ fb^{-1}$

Bound on mixing parameters $\Longrightarrow$ $BR(t \to Zq, gq) = f(V_{L,R}^{q'u}, V_{L,R}^{q'c}, V_{L,R}^{q't}) \leq BR^{exp}$

$Zc\bar{c}$ and $Zb\bar{b}$ couplings

Coupling measurements

$$\begin{cases} g^c_{ZL} = & 0.3453 \pm 0.0036 \\ g^c_{ZR} = & -0.1580 \pm 0.0051 \end{cases} \begin{cases} g^b_{ZL} = & -0.4182 \pm 0.00315 \\ g^b_{ZR} = & 0.0962 \pm 0.0063 \end{cases}$$

data from LEP EWWG

$$g^q_{ZL,ZR} = (g^q_{ZL,ZR})^{SM}(1 + \delta g^q_{ZL,ZR})$$

$$\begin{cases} g^c_{ZL} = & 0.34674 \pm 0.00017 \\ g^c_{ZR} = & -0.15470 \pm 0.00011 \end{cases} \begin{cases} g^b_{ZL} = & -0.42114^{+0.00045}_{-0.00024} \\ g^b_{ZR} = & 0.077420^{+0.000052}_{-0.000061} \end{cases}$$

SM prediction

$Zc\bar{c}$ and $Zb\bar{b}$ couplings

Coupling measurements

$$g^q_{ZL,ZR} = (g^q_{ZL,ZR})^{SM}(1 + \delta g^q_{ZL,ZR})$$

$$\begin{cases} g^c_{ZL} = 0.3453 \pm 0.0036 \\ g^c_{ZR} = -0.1580 \pm 0.0051 \end{cases} \quad \begin{cases} g^b_{ZL} = -0.4182 \pm 0.00315 \\ g^b_{ZR} = 0.0962 \pm 0.0063 \end{cases}$$

data from LEP EWWG

$$\begin{cases} g^c_{ZL} = 0.34674 \pm 0.00017 \\ g^c_{ZR} = -0.15470 \pm 0.00011 \end{cases} \quad \begin{cases} g^b_{ZL} = -0.42114^{+0.00045}_{-0.00024} \\ g^b_{ZR} = 0.077420^{+0.000052}_{-0.000061} \end{cases}$$

SM prediction

Asymmetry parameters

$$A_q = \frac{(g^q_{ZL})^2 - (g^q_{ZR})^2}{(g^q_{ZL})^2 + (g^q_{ZR})^2} = A_q^{SM}(1 + \delta A_q)$$

$$\begin{cases} A_c = 0.670 \pm 0.027 \\ A_b = 0.923 \pm 0.020 \end{cases}$$

PDG fit

$$\begin{cases} A_c = 0.66798 \pm 0.00055 \\ A_b = 0.93462^{+0.00016}_{-0.00020} \end{cases}$$

SM prediction

$Zc\bar{c}$ and $Zb\bar{b}$ couplings

Coupling measurements

$$g^q_{ZL,ZR} = (g^q_{ZL,ZR})^{SM}(1+\delta g^q_{ZL,ZR})$$

$$\begin{cases} g^c_{ZL} = & 0.3453 \pm 0.0036 \\ g^c_{ZR} = & -0.1580 \pm 0.0051 \end{cases} \quad \begin{cases} g^b_{ZL} = & -0.4182 \pm 0.00315 \\ g^b_{ZR} = & 0.0962 \pm 0.0063 \end{cases}$$

data from LEP EWWG

$$\begin{cases} g^c_{ZL} = & 0.34674 \pm 0.00017 \\ g^c_{ZR} = & -0.15470 \pm 0.00011 \end{cases} \quad \begin{cases} g^b_{ZL} = & -0.42114^{+0.00045}_{-0.00024} \\ g^b_{ZR} = & 0.077420^{+0.000052}_{-0.000061} \end{cases}$$

SM prediction

Asymmetry parameters

$$A_q = \frac{(g^q_{ZL})^2 - (g^q_{ZR})^2}{(g^q_{ZL})^2 + (g^q_{ZR})^2} = A^{SM}_q(1+\delta A_q)$$

$$\begin{cases} A_c = & 0.670 \pm 0.027 \\ A_b = & 0.923 \pm 0.020 \end{cases}$$

PDG fit

$$\begin{cases} A_c = & 0.66798 \pm 0.00055 \\ A_b = & 0.93462^{+0.00016}_{-0.00020} \end{cases}$$

SM prediction

Decay ratios

$$R_q = \frac{\Gamma(Z \to q\bar{q})}{\Gamma(Z \to hadrons)} = R^{SM}_q(1+\delta R_q)$$

$$\begin{cases} R_c = & 0.1721 \pm 0.0030 \\ R_b = & 0.21629 \pm 0.00066 \end{cases}$$

PDG fit

$$\begin{cases} R_c = & 0.17225^{+0.00016}_{-0.00012} \\ R_b = & 0.21583^{+0.00033}_{-0.00045} \end{cases}$$

SM prediction

Atomic Parity Violation

Atomic parity is violated through exchange of Z between nucleus and atomic electrons

Weak charge of the nucleus

$$Q_W = \frac{2c_W}{g}\left[(2Z+N)(g^u_{ZL}+g^u_{ZR}) + (Z+2N)(g^d_{ZL}+g^d_{ZR})\right] = Q_W^{SM} + \delta Q_W^{VL}$$

From Z couplings
$$\begin{cases} \frac{2c_W}{g} g^{qq}_{ZL} = 2(T_3^q - Q^q s_W^2) \; +2(T_3^{q'} - T_3^q)|V_L^{q'q}|^2 \\ \frac{2c_W}{g} g^{qq}_{ZR} = 2(-Q^q s_W^2) \; +2(T_3^{q'})|V_R^{q'q}|^2 \end{cases}$$

Atomic Parity Violation

Atomic parity is violated through exchange of Z between nucleus and atomic electrons

Weak charge of the nucleus

$$Q_W = \frac{2c_W}{g}\left[(2Z+N)(g^u_{ZL}+g^u_{ZR})+(Z+2N)(g^d_{ZL}+g^d_{ZR})\right] = Q_W^{SM} + \delta Q_W^{VL}$$

From Z couplings
$$\begin{cases} \frac{2c_W}{g} g^{qq}_{ZL} = 2(T_3^q - Q^q s_W^2) \; +2(T_3^{q'} - T_3^q)|V_L^{q'q}|^2 \\ \frac{2c_W}{g} g^{qq}_{ZR} = 2(-Q^q s_W^2) \; +2(T_3^{q'})|V_R^{q'q}|^2 \end{cases}$$

$$\delta Q_W^{VL} = 2\left[(2Z+N)\left((T_3^{t'}-\frac{1}{2})|V_L^{t'u}|^2 + T_3^{t'}|V_R^{t'u}|^2\right) + (Z+2N)\left((T_3^{b'}+\frac{1}{2})|V_L^{b'd}|^2 + T_3^{b'}|V_R^{b'd}|^2\right)\right]$$

Atomic Parity Violation

Atomic parity is violated through exchange of Z between nucleus and atomic electrons

Weak charge of the nucleus

$$Q_W = \frac{2c_W}{g}\left[(2Z+N)(g^u_{ZL}+g^u_{ZR})+(Z+2N)(g^d_{ZL}+g^d_{ZR})\right] = Q_W^{SM} + \delta Q_W^{VL}$$

From Z couplings
$$\begin{cases} \frac{2c_W}{g} g^{qq}_{ZL} = 2(T_3^q - Q^q s_W^2) \; +2(T_3^{q'} - T_3^q)|V_L^{q'q}|^2 \\ \frac{2c_W}{g} g^{qq}_{ZR} = 2(-Q^q s_W^2) \; +2(T_3^{q'})|V_R^{q'q}|^2 \end{cases}$$

$$\delta Q_W^{VL} = 2\left[(2Z+N)\left((T_3^{t'} - \frac{1}{2})|V_L^{t'u}|^2 + T_3^{t'}|V_R^{t'u}|^2\right) + (Z+2N)\left((T_3^{b'} + \frac{1}{2})|V_L^{b'd}|^2 + T_3^{b'}|V_R^{b'd}|^2\right)\right]$$

Bounds from experiments

Most precise test in Cesium ^{133}Cs:

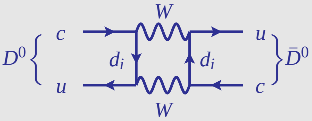
$$Q_W(^{133}\text{Cs})|_{exp} = -73.20 \pm 0.35 \qquad Q_W(^{133}\text{Cs})|_{SM} = -73.15 \pm 0.02$$

Flavour constraints

example with $D^0 - \bar{D}^0$ mixing and $D^0 \to l^+ l^-$ decay

In the SM

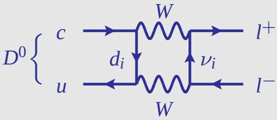
Mixing ($\Delta C = 2$):



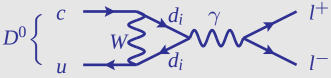
$$x_D = \frac{\Delta m_D}{\Gamma_D} = 0.0100^{+0.0024}_{-0.0026}$$

$$y_D = \frac{\Delta \Gamma_D}{2\Gamma_D} = 0.0076^{+0.0017}_{-0.0018}$$

Decay ($\Delta C = 1$):



$$BR(D^0 \to e^+ e^-)_{exp} < 1.2 \times 10^{-6}$$



$$BR(D^0 \to \mu^+ \mu^-)_{exp} < 1.3 \times 10^{-6}$$
$$BR(D^0 \to \mu^+ \mu^-)_{th,SM} = 3 \times 10^{-13}$$

Flavour constraints

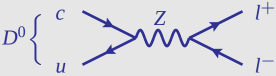
example with $D^0 - \bar{D}^0$ mixing and $D^0 \to l^+ l^-$ decay

Contributions at tree level

Mixing ($\Delta C = 2$):

$$\delta x_D = f(m_D, \Gamma_D, m_c, m_Z, g_{ZL}^{uc}, g_{ZR}^{uc})$$

Decay ($\Delta C = 1$):



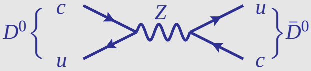
$$\delta BR = g(m_D, \Gamma_D, m_l, m_Z, g_{ZL}^{uc}, g_{ZR}^{uc})$$

Flavour constraints

example with $D^0 - \bar{D}^0$ mixing and $D^0 \to l^+ l^-$ decay

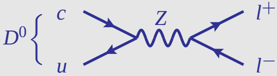
Contributions at tree level

Mixing ($\Delta C = 2$):



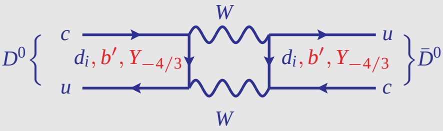
$$\delta x_D = f(m_D, \Gamma_D, m_c, m_Z, g_{ZL}^{uc}, g_{ZR}^{uc})$$

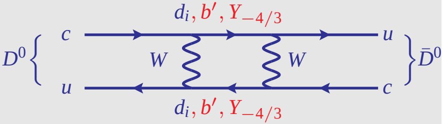
Decay ($\Delta C = 1$):



$$\delta BR = g(m_D, \Gamma_D, m_l, m_Z, g_{ZL}^{uc}, g_{ZR}^{uc})$$

Contributions at loop level

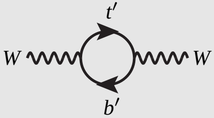




- Relevant only if tree-level contributions are absent
- Possible sources of CP violation

EW precision tests and CKM

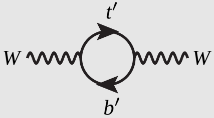
EW precision tests



Contributions of new fermions
to S,T,U parameters

EW precision tests and CKM

EW precision tests



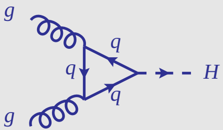
Contributions of new fermions
to S,T,U parameters

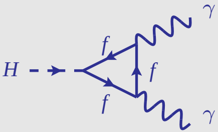
CKM measurements

- Modifications to CKM relevant for singlets and triplets because mixing in the left sector is NOT suppressed
- The CKM matrix is not unitary anymore
- If BOTH t' and b' are present, a CKM for the right sector emerges

Higgs coupling with gluons/photons

Production and decay of Higgs at the LHC



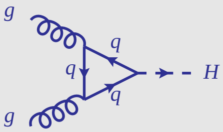


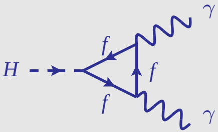
The dominant contributions to the loop come from heavy quarks t and q':

$$\kappa_{gg} = \kappa_{\gamma\gamma} = \frac{v}{m_t} g_{ht\bar{t}} + \frac{v}{m_{q'}} g_{hq'\bar{q}'} - 1$$

Higgs coupling with gluons/photons

Production and decay of Higgs at the LHC





The dominant contributions to the loop come from heavy quarks t and q':

$$\kappa_{gg} = \kappa_{\gamma\gamma} = \frac{v}{m_t} g_{ht\bar{t}} + \frac{v}{m_{q'}} g_{hq'\bar{q}'} - 1$$

The couplings of t and q' to the higgs boson are:

$$g_{ht\bar{t}} = \frac{m_t}{v} - \frac{M}{v} V_L^{*,t't} V_R^{t't} \qquad g_{hq'\bar{q}'} = \frac{m_{q'}}{v} - \frac{M}{v} V_L^{*,q'q'} V_R^{q'q'}$$

The contribution of just one VL quark to the loops turns out to be negligibly small

Result confirmed by studies at NNLO

Outline

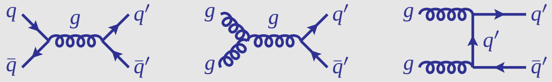
Production channels

Vector-like quarks can be produced
in the same way as SM quarks **plus** FCNCs channels

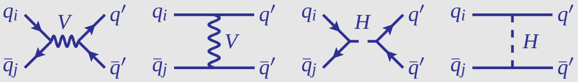
- **Pair production**, dominated by QCD and sentitive to the q' mass independently of the representation the q' belongs to
- **Single production**, only EW contributions and sensitive to both the q' mass and its mixing parameters

Production channels

Pair production: $pp \to q'\bar{q}'$



Purely QCD diagrams (dominant contribution)

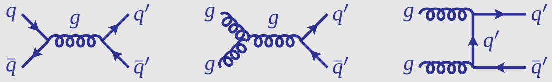


Purely EW diagrams

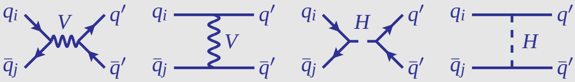
FCNC channels, but suppressed wrt to QCD

Production channels

Pair production: $pp \to q'\bar{q}'$



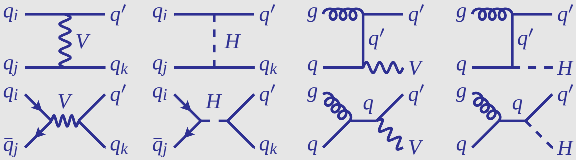
Purely QCD diagrams (dominant contribution)



Purely EW diagrams

FCNC channels, but suppressed wrt to QCD

Single production: $pp \to q' + \{q, V, H\}$

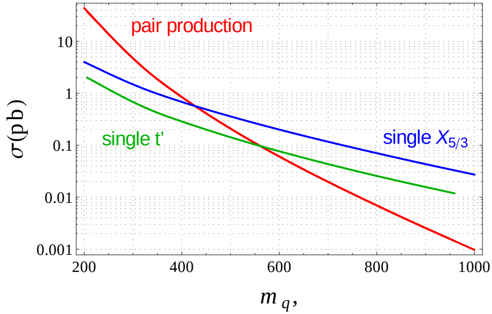


EW+QCD diagrams

potentially relevant FCNC channel

Production channels

Pair vs single production, example with non-SM doublet $(X_{5/3}\ t')$

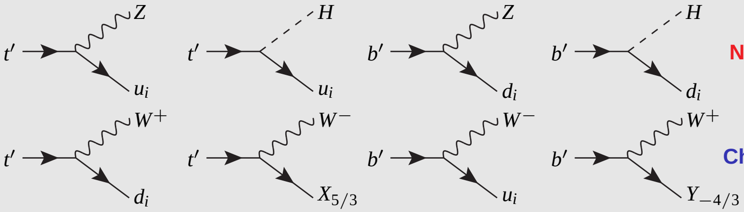


pair production depends only on the mass of the new particle and **decreases faster** than single production due to different **PDF scaling**

current **bounds from LHC** are around the region where (model dependent) **single production dominates**

Decays

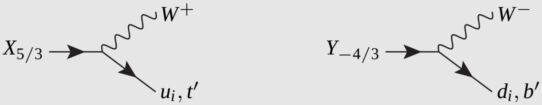
SM partners



Neutral currents

Charged currents

Exotics



Only Charged currents

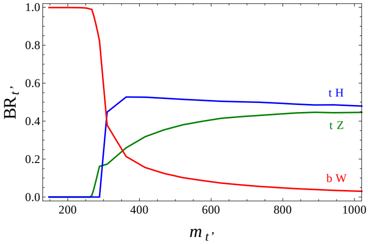
Not all decays may be kinematically allowed

it depends on **representations** and **mass differences**

Decays of t'

Examples with non-SM doublet $(X_{5/3}\ t')$

Mixing ONLY with top



Bounds at ∼600 GeV assuming

$$BR(t' \to bW) = 100\%$$

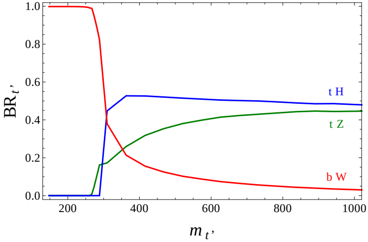
or

$$BR(t' \to tZ) = 100\%$$

Decays of t'

Examples with non-SM doublet $(X_{5/3}\ t')$

Mixing ONLY with top



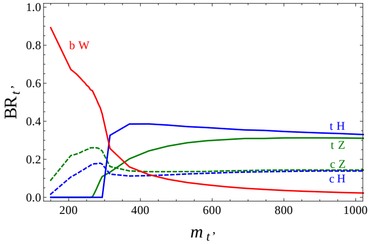
Bounds at ∼600 GeV assuming

$$BR(t' \to bW) = 100\%$$

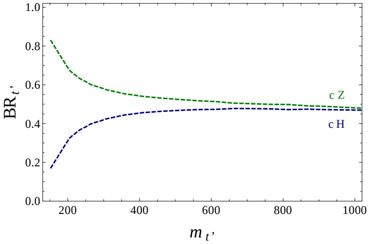
or

$$BR(t' \to tZ) = 100\%$$

Mixing ALSO with charm



Mixing ONLY with charm



Charge	Resonant state	After t' decay
0	$t'\bar{t}'$	$t\bar{t} + \{ZZ, ZH, HH\}$ $tj + \{ZZ, ZH, HH\}$ $jj + \{ZZ, ZH, HH\}$ $tW^- + \{b, j\} + \{Z, H\}$ $W^+W^- + \{bb, bj, jj\}$
	$t'\bar{u}_i \quad t'\bar{t}$	$t\bar{t} + \{Z, H\}$ $tj + \{Z, H\}$ $jj + \{Z, H\}$ $tW^- + \{b, j\}$ $W^\pm + \{bj, jj\}$
1/3	$t'd_i \quad t'b$	$t + \{b, j\} + \{Z, H\}$ $\{bj, jj\} + \{Z, H\}$ $W^\pm + \{bb, bj, jj\}$
	$W^+\bar{t}'$	$tW^- + \{Z, H\}$ $jW^- + \{Z, H\}$ $W^+W^- + \{b, j\}$
2/3	$t'Z \quad t'H$	$t + \{ZZ, ZH, HH\}$ $W^\pm + \{b, j\} + \{Z, H\}$
1	$t'\bar{d}_i \quad t'\bar{b}$	$t + \{b, j\} + \{Z, H\}$ $\{bj, jj\} + \{Z, H\}$ $W^\pm + \{bb, bj, jj\}$
4/3	$t't'$	$tt + \{ZZ, ZH, HH\}$ $tj + \{ZZ, ZH, HH\}$ $jj + \{ZZ, ZH, HH\}$ $tW^+ + \{b, j\} + \{Z, H\}$ $W^\pm W^\pm + \{bb, bj, jj\}$
	$t'u_i \quad t't$	$tt + \{Z, H\}$ $tW^+ + \{b, j\}$ $tj + \{Z, H\}$ $W^\pm + \{bj, jj\}$

Possible final states from pair and single production of t' in general mixing scenario

only 2 effectively tested since now

Conclusions and Outlook

- **Vector-like quarks** are a very promising playground for searches of new physics
- Fairly **rich phenomenology at the LHC** and many possibile channels to explore
  - $\rightarrow$ Signatures of single and pair production of VL quarks are **accessible at current CM energy and luminosity** and have been explored to some extent
  - $\rightarrow$ Current bounds on masses around **500-600 GeV**, but searches are not fully optimized for **general scenarios**.