Top-partners in composite models: status & perspectives

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Outline

- Motivations
- Bounds & Mixing structures
- Model independent framework
- Conclusions

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
- “common” theoretical expectation in Composite Higgs EFT is a not too heavy mass scale M (∿TeV) and mainly coupling to the 3rd generation - but not a general statement!
- Present LHC mass bounds ∿ 800 GeV
- Mixings bounded by EWPT, flavour…

Simplest multiplets (and SM quantum numbers)

	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	1	2	3
$U(1)_Y$	$q_L = 1/6$ $u_R = 2/3$ $d_R = -1/3$	2/3 -1/3	1/6 7/6 -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 $M + 3 \times \lambda^i$

Embeddings in $SU(2)_L \times U(1)_Y$

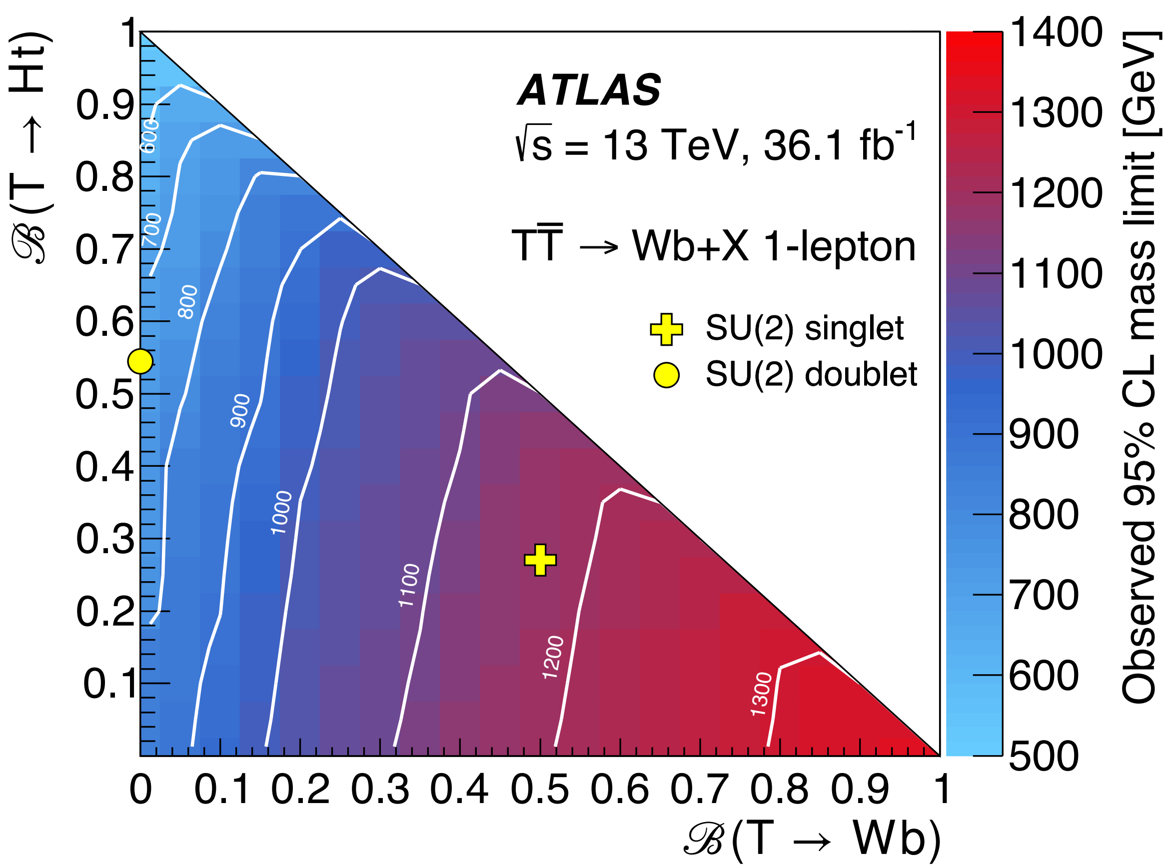
List of vector-like multiplets forming mixed Yukawa terms with the SM quark representations and a SM or SM-like Higgs boson doublet

ψ	$(SU(2)_L, U(1)_Y)$	T_3	Q_{EM}
U	$(\mathbf{1}, 2/3)$	0	$+2/3$
D	$(\mathbf{1}, -1/3)$	0	-1/3
$\begin{pmatrix} X^{8/3} \\ X^{5/3} \\ U \end{pmatrix}$	$(\mathbf{3}, 5/3)$	$+2$ $+1$ 0	$+8/3$ $+5/3$ $+2/3$
$\begin{pmatrix} X^{5/3} \\ U \\ D \end{pmatrix}$	$(\mathbf{3}, 2/3)$	$+1$ 0 -1	$+5/3$ $+2/3$ $-1/3$
$\begin{pmatrix} U \\ D \\ Y^{-4/3} \end{pmatrix}$	$(\mathbf{3}, -1/3)$	$+1$ 0 -1	$+2/3$ $-1/3$ $-4/3$

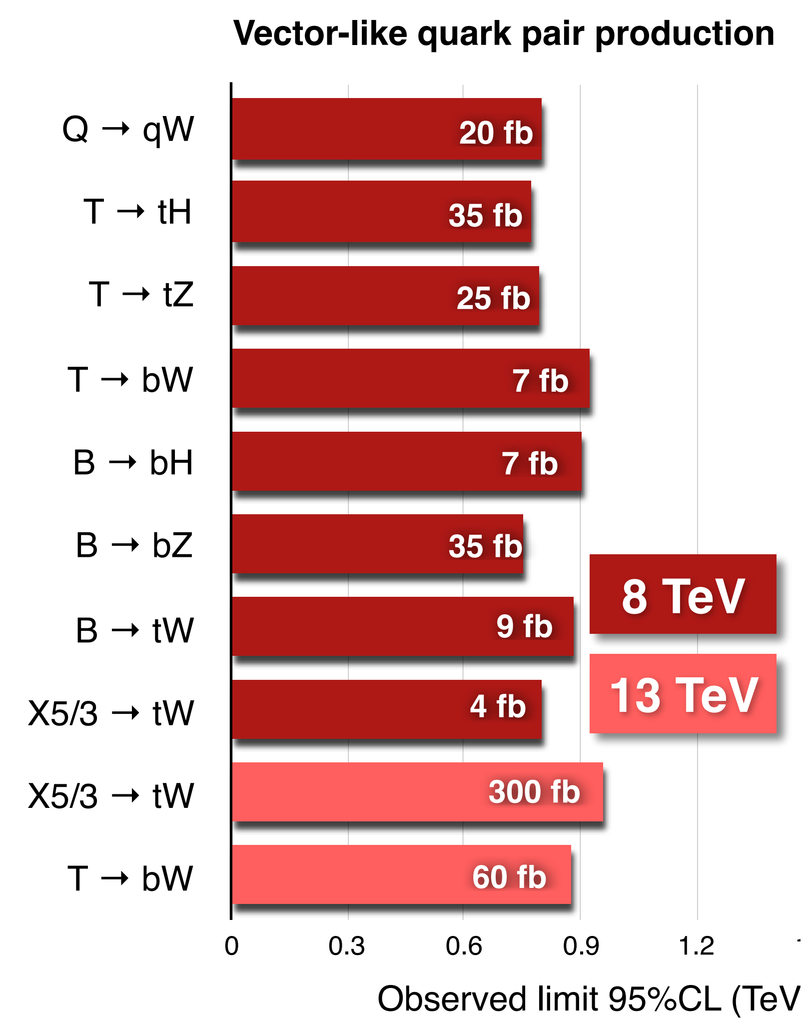
ψ	$(SU(2)_L, U(1)_Y)$	T_3	Q_{EM}
$\begin{pmatrix} U \\ D \end{pmatrix}$	$(\mathbf{2}, 1/6)$	$+1/2$ $-1/2$	$+2/3$ $-1/3$
$\begin{pmatrix} X^{5/3} \\ U \end{pmatrix}$	$(\mathbf{2}, 7/6)$	$+1/2$ $-1/2$	$+5/3$ $+2/3$
$\begin{pmatrix} D \\ Y^{-4/3} \end{pmatrix}$	$(\mathbf{2}, -5/6)$	$+1/2$ $-1/2$	$-1/3$ $-4/3$
$\begin{pmatrix} X^{8/3} \\ X^{5/3} \\ U \\ D \end{pmatrix}$	$(\mathbf{4}, 7/6)$	$+3/2$ $+1/2$ $-1/2$ $-3/2$	$+8/3$ $+5/3$ $+2/3$ $-1/3$
$\begin{pmatrix} X^{5/3} \\ U \\ D \\ Y^{-4/3} \end{pmatrix}$	$(\mathbf{4}, 1/6)$	$+3/2$ $+1/2$ $-1/2$ $-3/2$	$+5/3$ $+2/3$ $-1/3$ $-4/3$
$\begin{pmatrix} U \\ D \\ Y^{-4/3} \\ Y^{-7/3} \end{pmatrix}$	$(\mathbf{4}, -5/6)$	$+3/2$ $+1/2$ $-1/2$ $-3/2$	$+2/3$ $-1/3$ $-4/3$ $-7/3$

LHC VLQ searches

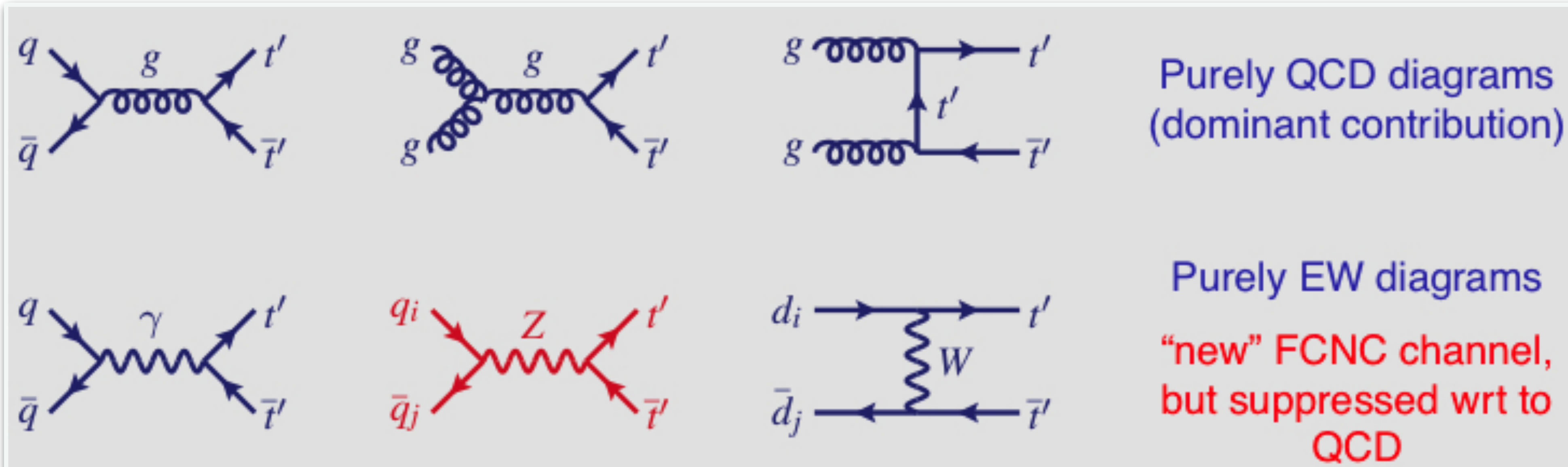
- Currents searches assume: Br(T' → Zt,ht,Wb) = 1, Br(B' → Zb,hb,Wt) = 1, Br($X^{5/3}$ →Wt)=1, Br($Y^{4/3}$ →Wb)=1
  - pair produced (QCD) ⇒ ~ model-independent
  - singly produced (EW) ⇒ depends on mixing with SM quarks

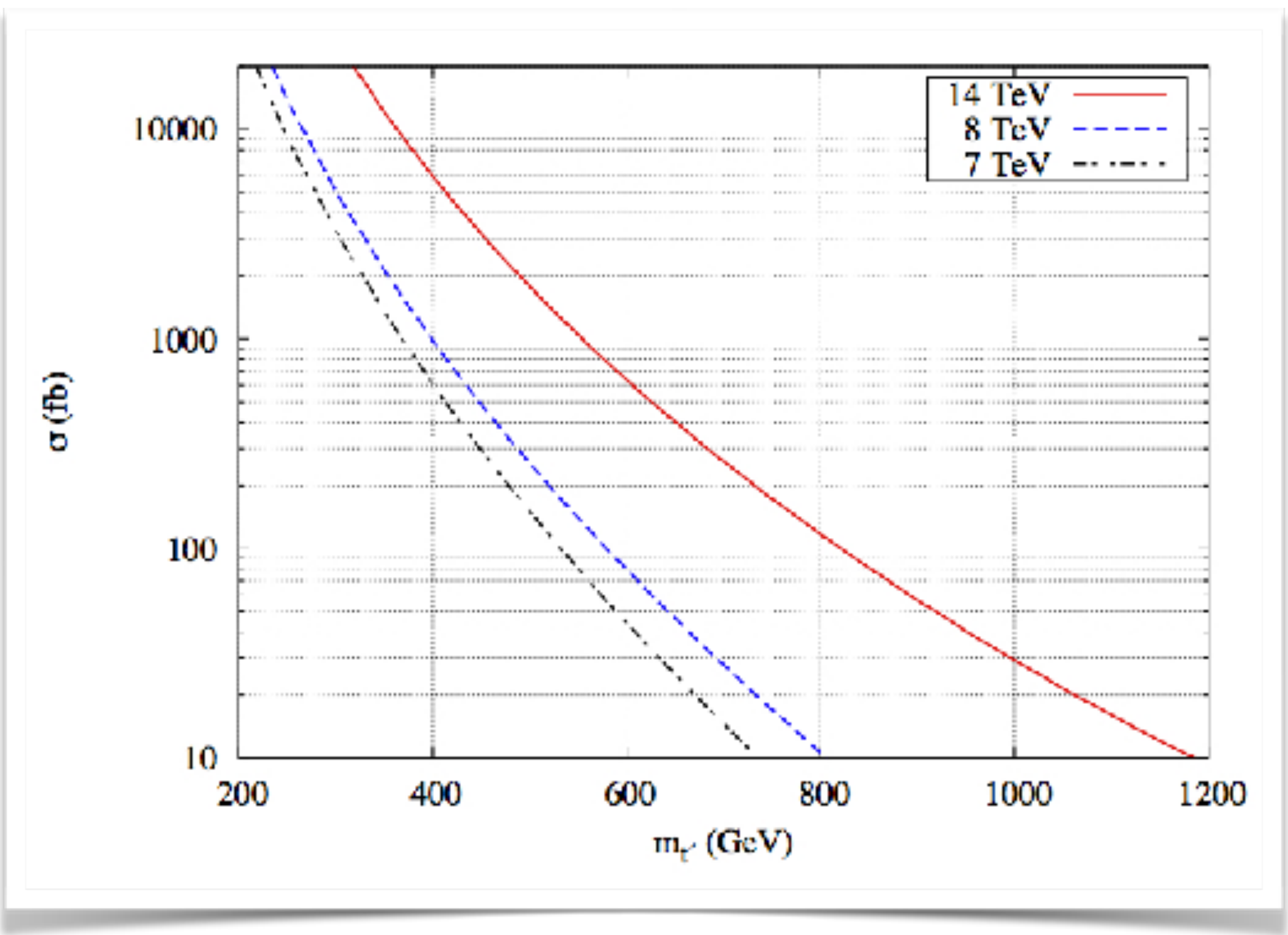


CMS



Pair production LO





Pair production for T’ of the non-SM doublet pp → T’T’ @ LHC at LO

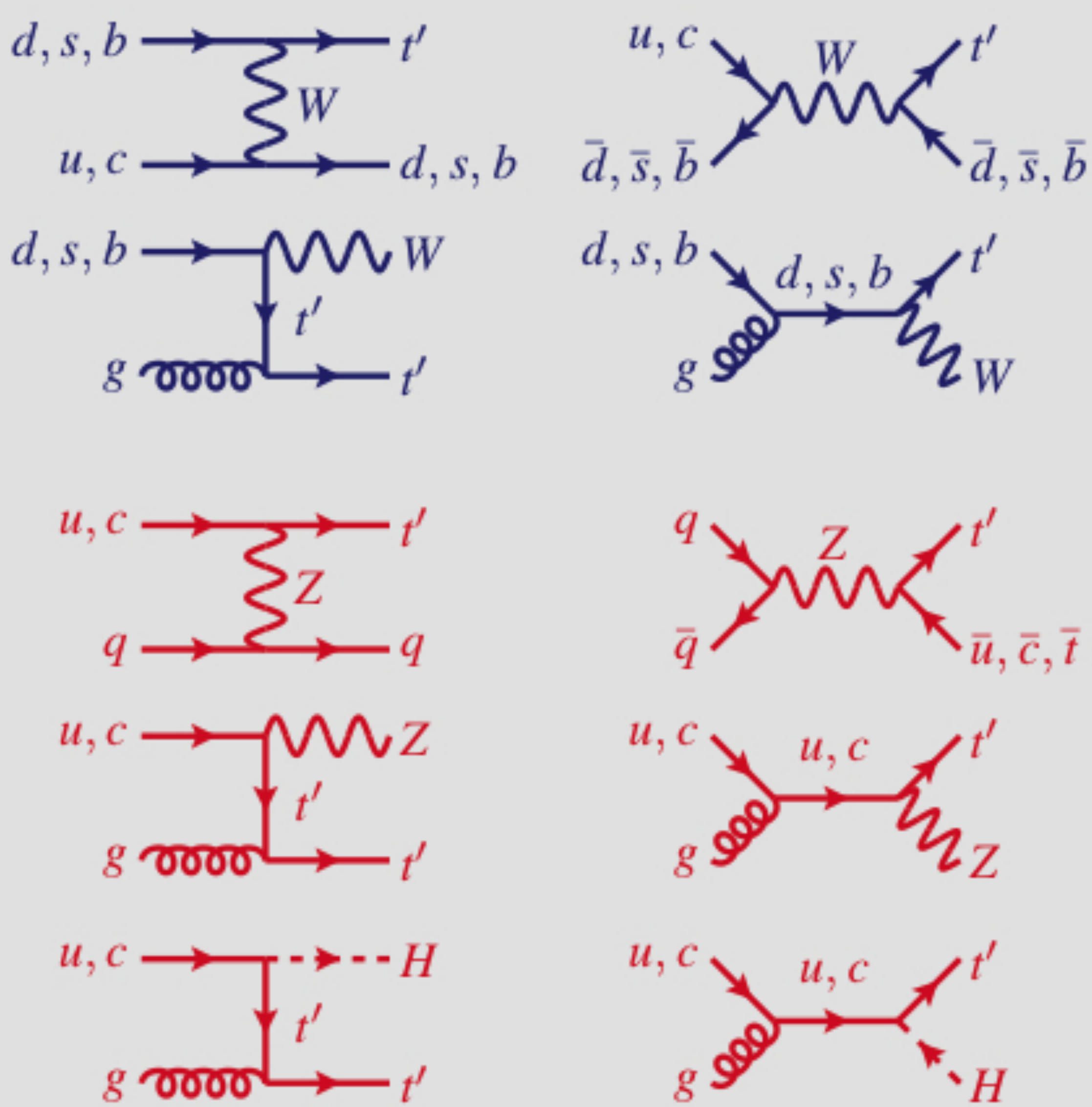
Pair production NLO

m_T [GeV]	Scenario	$\sigma_{\rm LO}$ [pb]	$\sigma_{\rm NLO}$ [pb]
400	QCD	$(7.069\ 10^{0})^{+32.0\%+2.7\%}_{-22.6\%-2.7\%}$	$(1.004\ 10^{1})^{+9.4\%\ +2.5\%}_{-11.3\%-2.5\%}$
	TH1	$(7.022\ 10^{0})^{+30.2\%+1.2\%}_{-23.8\%-4.1\%}$	$(9.980\ 10^{0})^{+8.0\%\ +1.2\%}_{-12.5\%-3.8\%}$
800	QCD	$(1.261\ 10^{-1})^{+33.2\%+3.8\%}_{-23.2\%-3.8\%}$	$(1.733\ 10^{-1})^{+8.5\%\ +4.4\%}_{-11.1\%-4.4\%}$
	TH1	$(1.244\ 10^{-1})^{+18.8\%+-7.3\%}_{-31.2\%-14.0\%}$	$(1.702\ 10^{-1})^{+-2.3\%+-6.0\%}_{-20.0\%\ -13.9\%}$
1200	QCD	$(7.685\ 10^{-3})^{+34.0\%+5.8\%}_{-23.7\%-5.8\%}$	$(1.061\ 10^{-2})^{+8.8\%\ +5.8\%}_{-11.4\%-5.8\%}$
	TH1	$(1.053\ 10^{-2})^{+-1.7\%+-18.4\%}_{-36.7\%\ -25.8\%}$	$(1.372\ 10^{-2})^{+-16.6\%+-18.2\%}_{-29.0\%\ -25.8\%}$
1600	QCD	$(7.477\ 10^{-4})^{+34.9\%+8.5\%}_{-24.2\%-8.5\%}$	$(1.030\ 10^{-3})^{+9.0\%\ +8.6\%}_{-11.6\%-8.6\%}$
	TH1	$(3.395\ 10^{-3})^{+-3.3\%+-13.3\%}_{-27.0\%\ -19.9\%}$	$(4.117\ 10^{-3})^{+-14.6\%+-14.4\%}_{-21.8\%\ -20.9\%}$
2000	QCD	$(8.980\ 10^{-5})^{+35.5\%+18.3\%}_{-24.5\%-18.3\%}$	$(1.260\ 10^{-4})^{+8.7\%\ +17.8\%}_{-11.7\%-17.8\%}$
	TH1	$(1.563\ 10^{-3})^{+4.2\%\ +-5.4\%}_{-20.0\%-13.0\%}$	$(1.960\ 10^{-3})^{+-6.3\%+-6.0\%}_{-14.0\%\ -13.6\%}$

T'T' production @ 13 TeV from 1610.04622 Fuks & Shao. QCD scenario: only QCD diagrams, EW contribution typically small; TH1 scenario: mixing with 1st generation enhance production rate

NLO effect: ~50% enhancement, reduce scale uncertainty

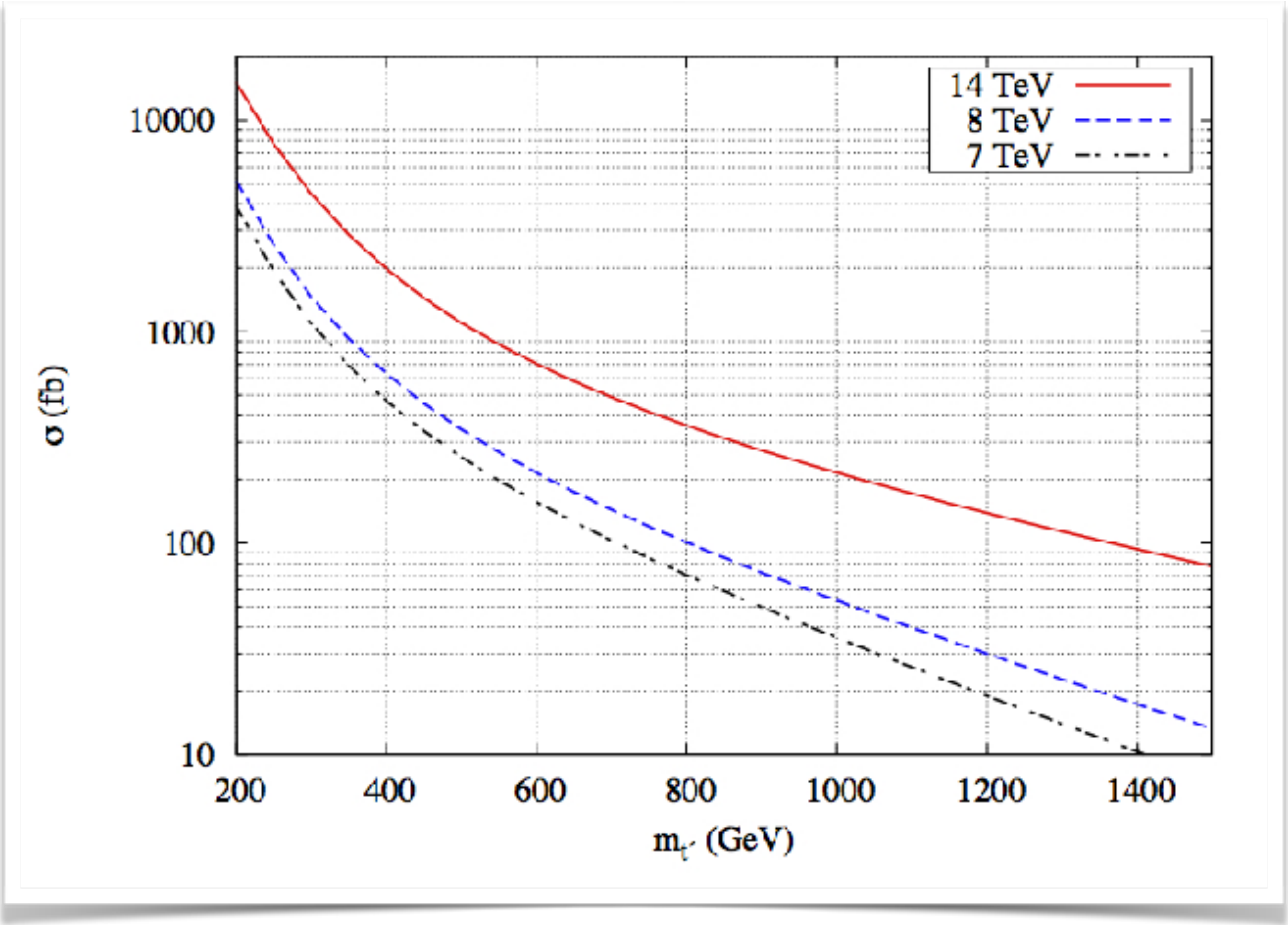
Single production



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 LO



Non-SM doublet single t' production cross section as function of the t' mass (LO)

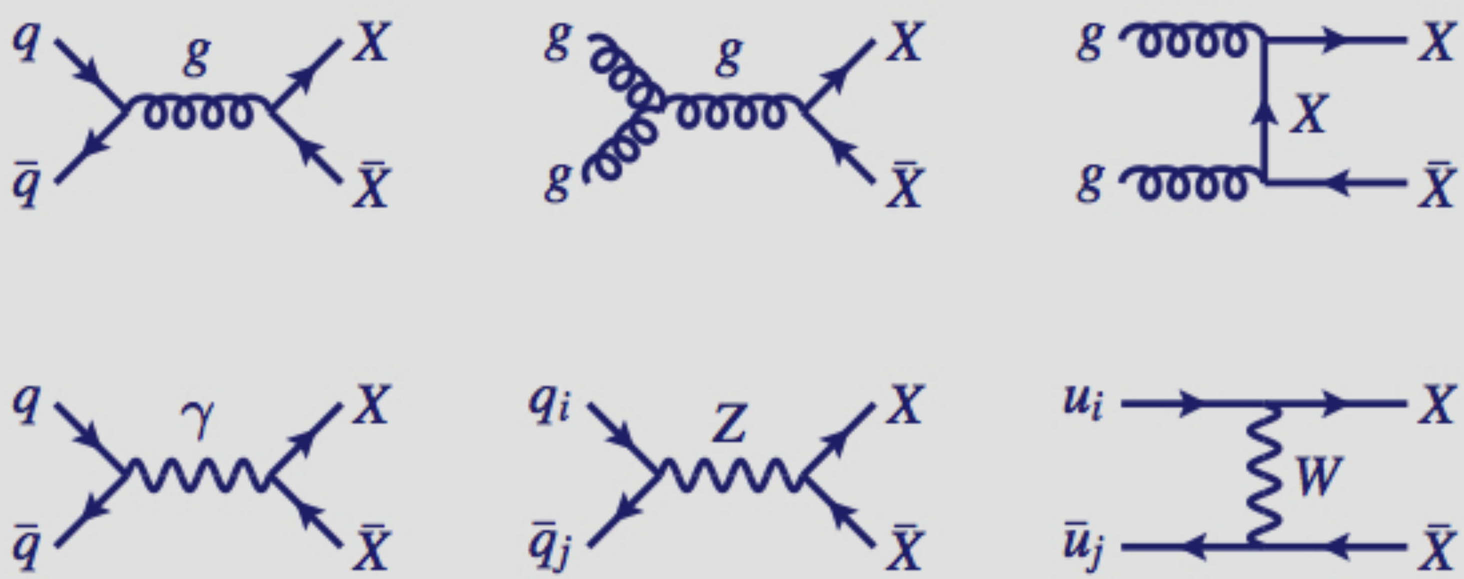
Single production NLO

m_T [GeV]	Scenario	$\sigma_{\rm LO}$ [pb]	$\sigma_{\rm NLO}$ [pb]
400	**TZ1**	$(1.995\ 10^{0})^{+2.6\%+1.6\%}_{-2.7\%-1.6\%}$	$(1.987\ 10^{0})^{+0.8\%+1.7\%}_{-0.6\%-1.7\%}$
	TZ2	$(2.613\ 10^{0})^{+0.1\%+1.2\%}_{-1.0\%-1.2\%}$	$(2.685\ 10^{0})^{+1.1\%+1.2\%}_{-0.6\%-1.2\%}$
	TW1	$(1.541\ 10^{0})^{+3.4\%+2.4\%}_{-3.3\%-2.4\%}$	$(1.575\ 10^{0})^{+0.9\%+2.4\%}_{-0.2\%-2.4\%}$
	TW2	$(4.229\ 10^{0})^{+1.1\%+4.5\%}_{-1.5\%-4.5\%}$	$(4.392\ 10^{0})^{+1.1\%+4.4\%}_{-0.3\%-4.4\%}$
1200	**TZ1**	$(2.214\ 10^{-1})^{+8.2\%+1.9\%}_{-7.1\%-1.9\%}$	$(2.483\ 10^{-1})^{+1.4\%+2.0\%}_{-1.9\%-2.0\%}$
	TZ2	$(1.168\ 10^{-1})^{+5.6\%+3.2\%}_{-5.3\%-3.2\%}$	$(1.348\ 10^{-1})^{+1.6\%+2.9\%}_{-1.6\%-2.9\%}$
	TW1	$(1.572\ 10^{-1})^{+8.9\%+3.5\%}_{-7.6\%-3.5\%}$	$(1.812\ 10^{-1})^{+1.9\%+3.5\%}_{-2.4\%-3.5\%}$
	TW2	$(2.476\ 10^{-1})^{+7.3\%+12.0\%}_{-6.5\%-12.0\%}$	$(2.878\ 10^{-1})^{+2.0\%+11.3\%}_{-2.2\%-11.3\%}$
2000	**TZ1**	$(4.721\ 10^{-2})^{+10.9\%+2.4\%}_{-9.2\%\ -2.4\%}$	$(5.771\ 10^{-2})^{+2.9\%+2.4\%}_{-3.5\%-2.4\%}$
	TZ2	$(1.277\ 10^{-2})^{+8.7\%+7.0\%}_{-7.8\%-7.0\%}$	$(1.600\ 10^{-2})^{+3.0\%+6.6\%}_{-3.1\%-6.6\%}$
	TW1	$(3.105\ 10^{-2})^{+11.5\%+5.0\%}_{-9.7\%\ -5.0\%}$	$(3.899\ 10^{-2})^{+3.5\%+4.7\%}_{-4.0\%-4.7\%}$
	TW2	$(3.725\ 10^{-2})^{+10.1\%+24.7\%}_{-8.7\%\ -24.7\%}$	$(4.653\ 10^{-2})^{+3.2\%+23.1\%}_{-3.6\%-23.1\%}$

NLO effect: k-factor increase with mT (table from 1610.04622 Fuks & Shao)

$X^{5/3}$ production

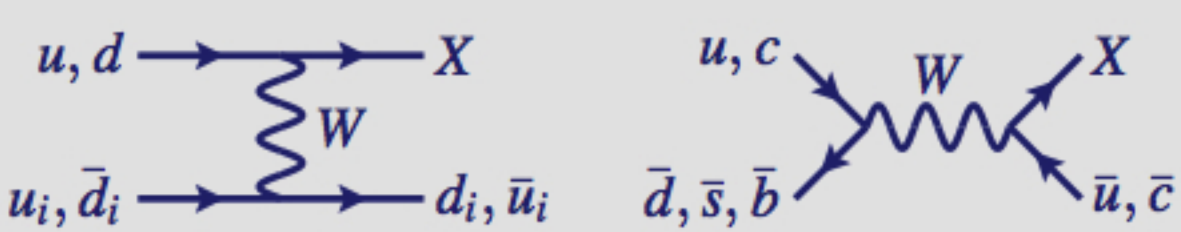
Pair production



Purely QCD diagrams (dominant contribution)

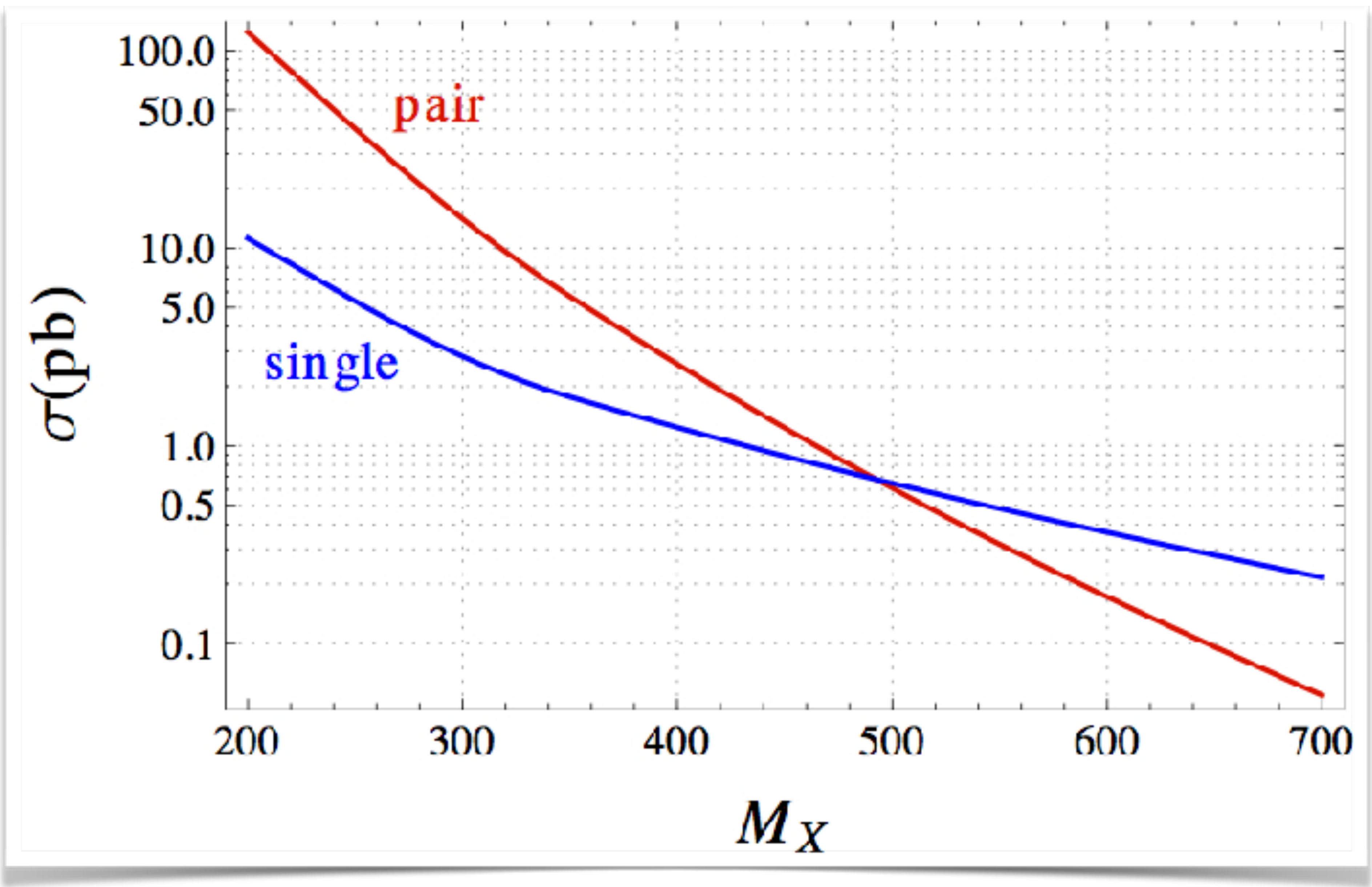
Purely EW diagrams

Single production



Charged current channels are suppressed in doublets, non-suppressed in singlet and triplets

$X^{5/3}$ production



pNGB Higgs & top partners

- Two species of fundamental fermions needed to build top partners (see 1311.6562 Barnard, Gherghetta, Ray)
- EW sector (Higgs sector): fermions ψ
- Spontaneous symmetry breaking should deliver at least 4 pNGBs associated to Higgs doublet: H ~ ($\psi\psi$)
- Coloured sector: fermions χ
- Bound states ($\psi\psi\,\chi$) or ($\psi\,\chi\,\chi$) with quantum numbers of SM top quark
- Additional coloured pNGBs ($\chi\,\chi$) ~ πc are present

Additional EW pNGBs

- Smallest cosets:
- SU(4)/Sp(4): 5 of Sp(4) ≡ A2 = (2,±1/2) + (1,0) (H, η)
- SU(5)/SO(5): 14 of SO(5) ≡ S2 = (3,±1) + (3,0) + (2,±1/2) + (1,0) (Φ±, Φ0, H, η)
- SU(4)×SU(4)/SU(4): 15 of SU(4) ≡ Ad = (3,0) + (2,±1/2) + (2,±1/2) + (1,±1) + (1,0) +(1,0) (Φ0, H1, H2, $N^{\pm}$, N^{0}, η)
- ⇒ Always SM-like singlet, η ⇒ Sometimes triplets or second Higgs doublet

Additional coloured pNGBs

- SU(6)/SO(6) ⊃ SU(3)c : 20′ of S0(6) ≡ A2 = (8,0) + (6,4/3) + (6,−4/3)   (π_8, π_6, π_6^c)

- SU(6)/Sp(6) ⊃ SU(3)c : 14 of Sp(6) ≡ S2 = (8,0) + (3,−4/3) + (3,4/3)   (π_8, π_3, π_3^c)

- SU(3) × SU(3)/SU(3)c : 8 of SU(3) ≡ Ad = (8,0) (π_8)

- Always a coloured octet π_8 ⇒ Sometimes coloured triplets or sextets (see 1507.02283)

Extra decay modes

- Fermionic UV "completion" of CHMs including top partners is non-minimal wrt CHM SO(5)/SO(4) description

  → presence of additional light states (pNGBs) that are involved in VLQs decays (Serra 1506.05110 and Bizot, Cacciapaglia, Flacke in preparation)

- EW-singlet: T → ηt with η = EW pNGB like Higgs

- U(1): T → at with a = pNGB of non-anomalous U(1)

- Coloured: X5/3 → $\pi_6 b$ with π_6 = Coloured pNGB

- Charged : X5/3 → $\phi^+ t$ with ϕ^+ = EW pNGB

- Consequences: possible large branching ratios in these modes, reduced experimental bound on VLQs masses

Mixing effects

- 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 ψ = (1, 2/3) = U : only a top partner is present
  - triplet ψ = (3, 2/3) = {X, U, D} , the new fermion contains a partner for both top and bottom, plus X with charge 5/3
  - triplet ψ = (3, −1/3) = {U, D, Y} , the new fermions are a partner for both top and bottom, plus Y with charge −4/3

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

$$\begin{pmatrix} \cos\theta_u^L & -\sin\theta_u^L \\ \sin\theta_u^L & \cos\theta_u^L \end{pmatrix} \begin{pmatrix} \frac{y_u v}{\sqrt{2}} & x \\ 0 & M \end{pmatrix} \begin{pmatrix} \cos\theta_u^R & \sin\theta_u^R \\ -\sin\theta_u^R & \cos\theta_u^R \end{pmatrix}$$

Mixing effects

- Type 2 : new doublets couple to SM R-singlet
- SM doublet case ψ = (2, 1/6) = {U, D} , the vector-like fermions are a top and bottom partners
- non-SM doublets ψ = (2, 7/ 6) = {X, U} , the vector-like fermions are a top partner and a fermion X with charge 5/3
- non-SM doublets ψ = (2, -5/ 6) = {D,Y} , the vector-like fermions are a bottom partner and a fermion Y with charge -4/3

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

$$\begin{pmatrix} \cos\theta_u^L & -\sin\theta_u^L \\ \sin\theta_u^L & \cos\theta_u^L \end{pmatrix} \begin{pmatrix} \frac{y_u v}{\sqrt{2}} & 0 \\ x & M \end{pmatrix} \begin{pmatrix} \cos\theta_u^R & \sin\theta_u^R \\ -\sin\theta_u^R & \cos\theta_u^R \end{pmatrix}$$

Mixing with more VL multiplets

integer isospin multiplets

$$\mathcal{L}_{\rm mass} = \bar{q}_L \cdot \left(\begin{array}{ccc|ccc|ccc}
\mu_1 & 0 & 0 & 0 & \dots & 0 & x_{1,n_d+4} & \dots & x_{1,N} \\
0 & \mu_2 & 0 & 0 & \dots & 0 & x_{2,n_d+4} & \dots & x_{2,N} \\
0 & 0 & \mu_3 & 0 & \dots & 0 & x_{3,n_d+4} & \dots & x_{3,N} \\
\hline
y_{4,1} & y_{4,2} & y_{4,3} & M_4 & 0 & 0 & & & \\
\vdots & \vdots & \vdots & 0 & \ddots & 0 & & \omega_{\alpha\beta} & \\
y_{n_d+3,1} & y_{n_d+3,2} & y_{n_d+3,3} & 0 & 0 & M_{n_d+3} & & & \\
\hline
0 & 0 & 0 & & & & M_{n_d+4} & 0 & 0 \\
\vdots & \vdots & \vdots & & \omega'_{\alpha\beta} & & 0 & \ddots & 0 \\
0 & 0 & 0 & & & & 0 & 0 & M_N
\end{array}\right) \cdot q_R + h.c.$$

semi-integer isospin multiplets

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_α are the VL masses of the new representations
- $n_d \times n_s$ matrix ω and $n_s \times n_d$ matrix ω' contain the Yukawa couplings among VL representations
- ω' couplings correspond to the “wrong” (opposite) chirality configuration with respect to SM Yukawa couplings

Bounds

- LHC searches (already mentioned)
- Tree-level bounds
  - FCNC effects at tree level due to mixing
  - Z → b b +1% → -0.2% in the left coupling and +20% → -5% in the right coupling (L and R are correlated)
  - Atomic parity violation (weak charge affected by FCNC of Z → 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 (via mixing) CMS PRL112 (2014), 7 and 8 TeV data:

$$\frac{\Gamma(t \to Zu) + \Gamma(t \to Zc)}{\Gamma(t \to Wb)} < 0.18\% \quad at \quad 2\sigma$$

implies : $$|V_R^{t't}|\sqrt{|V_R^{t'u}|^2 + |V_R^{t'c}|^2} < 0.06\ |V^{tb}|$$

- Z → 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 :

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

for Cesium:

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

- at 3 sigmas this implies :

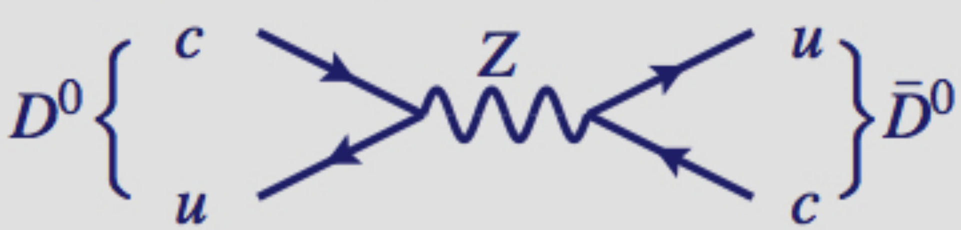
$$\delta Q_W = -(2Z+N)|V_R^{t'u}|^2 \qquad |V_R^{t'u}| < 7.8 \times 10^{-2}$$

FCNC tree level (if no b')

- D-Dbar mixing and D → l+l- :

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

Mixing ($\Delta C = 2$):



$$\delta x_D = f(m_D, \Gamma_D, m_c, m_Z)(g_{ZR}^{uc})^2$$

Decay ($\Delta C = 1$):

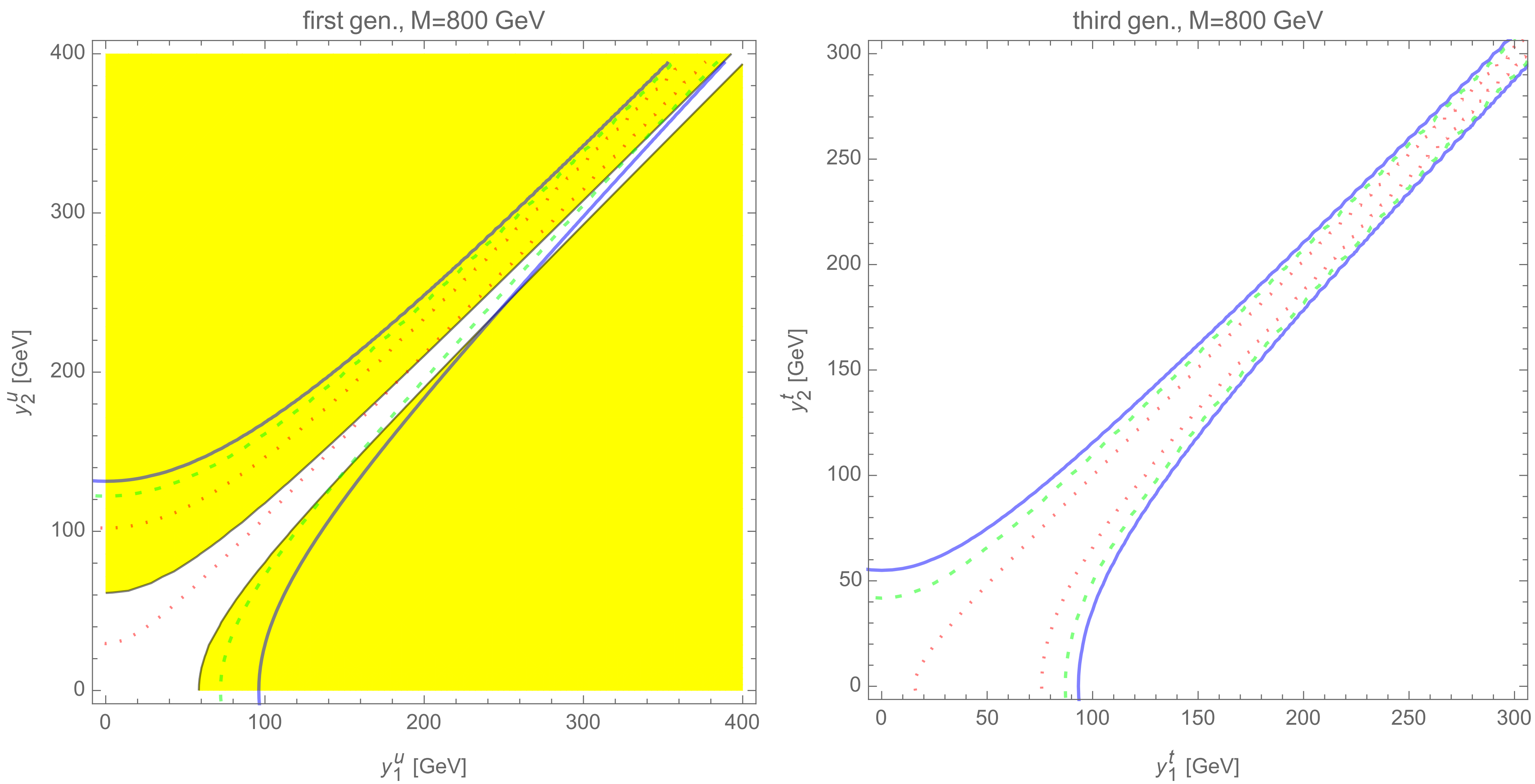
$$\delta BR = g(m_D, \Gamma_D, m_l, m_Z)(g_{ZR}^{uc})^2$$

- strongest bound from xD :

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

$$(g_{ZR}^{uc})^2 = \frac{\pi\alpha}{c_W^2 s_W^2}|V_R^{t'u}|^2|V_R^{t'c}|^2 \quad \Longrightarrow \quad |V_R^{t'u}||V_R^{t'c}| < 3.2\times 10^{-4} \quad @3\sigma$$

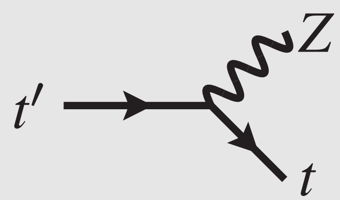
Interplay of VLQ multiplets in bounds



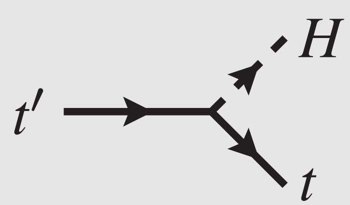
Doublet Y = 1/6 and Doublet Y = 7/6 : EWP bounds at 1σ (red- dashed), 2σ (green-dashed) and 3 σ (blue) for VL quarks coupling with the first (left panel) and third (right panel) SM generations, compared with the region excluded at 3σ by tree-level bounds (yellow region in the left panel). M = 800 GeV, ω = ω′ = 0. (from 1502.00370)

T’ decays

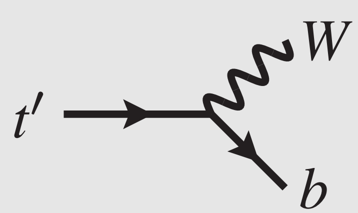
Different possibilities for t' decay ($\sin\theta_R = 0.3$, i.e. mixing with top dominates)



$$pp \to j\,(t' \to t\,Z) \to j\,(t \to b\,l^+\,\nu)\,(Z \to \nu\,\bar{\nu}) \to j\,b\,l^+\,\not{E}_T$$
$$\to j\,(t \to b\,l^+\,\nu)\,(Z \to l^+\,l^-) \to j\,b\,l^+\,l^+\,l^-\,\not{E}_T$$
$$\to j\,(t \to b\,l^+\,\nu)\,(Z \to j\,j) \to j\,j\,j\,b\,l^+\,\not{E}_T$$

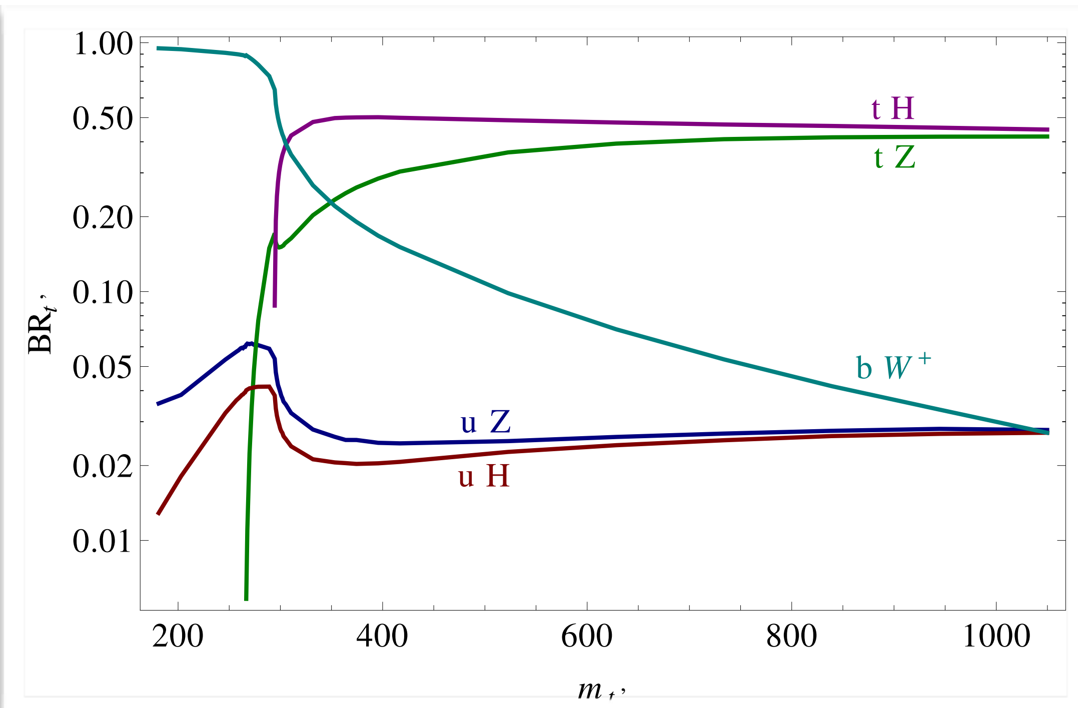


$$pp \to j\,(t' \to t\,H) \to j\,(t \to b\,l^+\,\nu)\,(H \to b\,\bar{b}) \to b\,\bar{b}\,b\,l^+\,\not{E}_T$$



$$pp \to j\,(t' \to b\,W) \to j\,b\,(W \to l^+\,\nu) \to j\,b\,l^+\,\not{E}_T$$

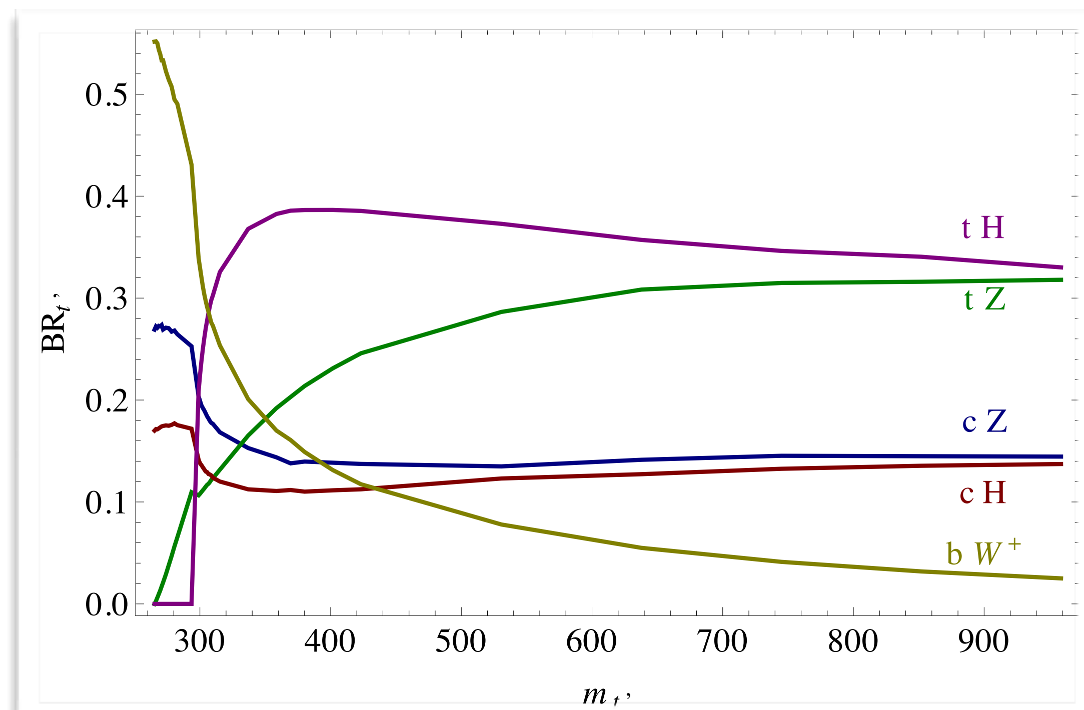
T’ decays ($X^{5/3}$,T’) multiplet



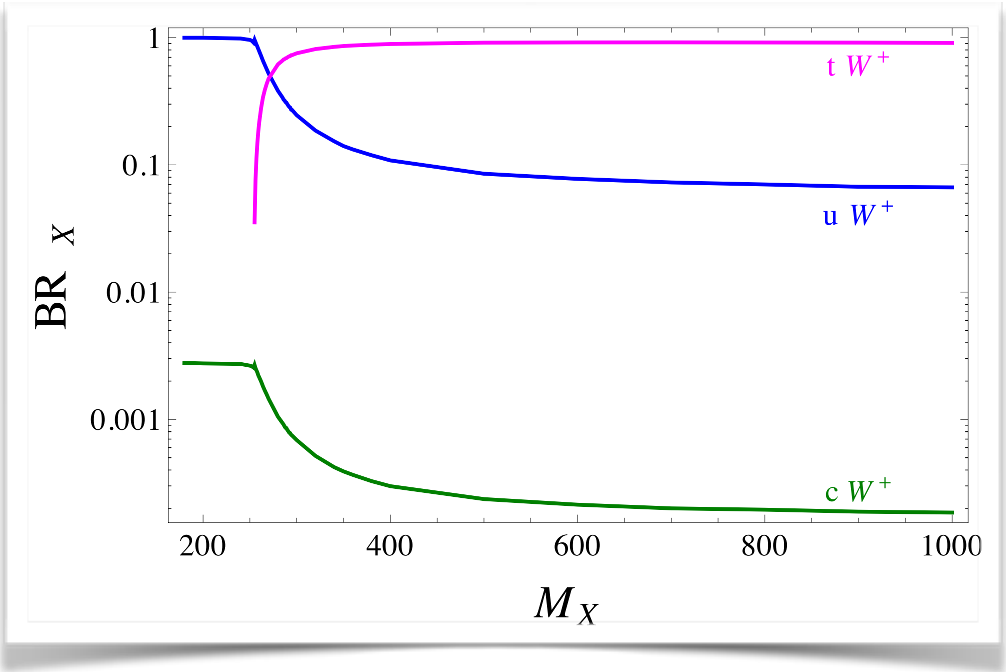
Mixing mostly with top
V_R^{41} maximal

Mixing mostly with top
V_R^{42} maximal

In all cases T' → bW
NOT dominant for allowed masses

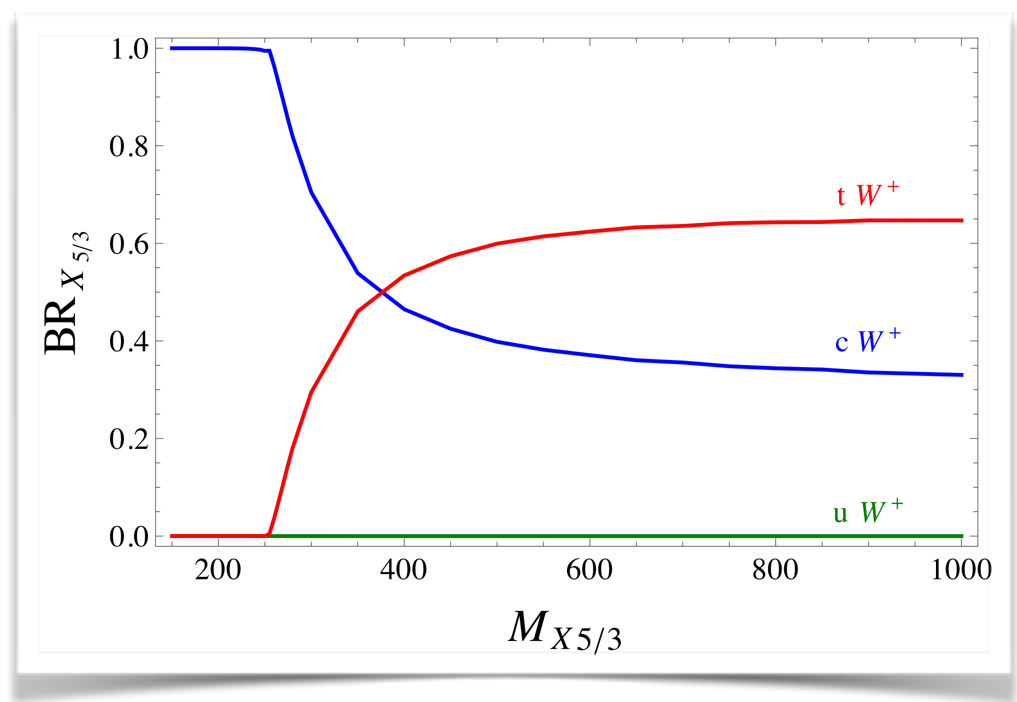


$X^{5/3}$decays ($X^{5/3}$,T') multiplet



Mixing mostly with top
V_R^{41} maximal

Mixing mostly with top
V_R^{42} maximal



General parameterisation (example with a T')

- T' assumed to couple with Wq, Zq, hq here
- it is more physical to consider observables (BRs, cross-sections) rather than Lagrangian parameters
- Neglect SM quark masses here (full case in 1305.4172)

$$BR(T \to V q_i) = \frac{\kappa_V^2 |V_{L/R}^{4i}|^2 \Gamma_V^0}{\left(\sum_{j=1}^3 |V_{L/R}^{4j}|^2\right)\left(\sum_{V'=W,Z,H} \kappa_{V'}^2 \Gamma_{V'}^0\right)}$$

$$\zeta_i = \frac{|V_{L/R}^{4i}|^2}{\sum_{j=1}^3 |V_{L/R}^{4j}|^2}, \quad \sum_{i=1}^3 \zeta_i = 1,$$

$$\xi_V = \frac{\kappa_V^2 \Gamma_V^0}{\sum_{V'=W,Z,H} \kappa_{V'}^2 \Gamma_{V'}^0}, \quad \sum_{V=W,Z,H} \xi_V = 1;$$

$$BR(T \to V q_i) = \zeta_i \xi_V$$

$$\zeta_{jet} = \zeta_1 + \zeta_2 = 1 - \zeta_3$$

- Only 5 independent parameters, M, ξ_W, ξ_Z, ζjet , κ
- Choosing multiplet fixes ξ_W, ξ_Z

NLO extension

Example with T, B, X, Y VLQs

$$\mathcal{L}_{\rm VLQ} = i\bar{Y}\not{D}Y - m_{Y}\bar{Y}Y + i\bar{B}\not{D}B - m_{B}\bar{B}B + i\bar{T}\not{D}T - m_{T}\bar{T}T + i\bar{X}\not{D}X - m_{X}\bar{X}X$$
$$- h\left[\bar{B}\Big(\hat{\kappa}^{B}_{L}P_{L} + \hat{\kappa}^{B}_{R}P_{R}\Big)q_{d} + \bar{T}\Big(\hat{\kappa}^{T}_{L}P_{L} + \hat{\kappa}^{T}_{R}P_{R}\Big)q_{u} + {\rm h.c.}\right]$$
$$+ \frac{g}{2c_{W}}\left[\bar{B}\not{Z}\Big(\tilde{\kappa}^{B}_{L}P_{L} + \tilde{\kappa}^{B}_{R}P_{R}\Big)q_{d} + \bar{T}\not{Z}\Big(\tilde{\kappa}^{T}_{L}P_{L} + \tilde{\kappa}^{T}_{R}P_{R}\Big)q_{u} + {\rm h.c.}\right]$$
$$+ \frac{\sqrt{2}g}{2}\left[\bar{Y}\not{W}\Big(\kappa^{Y}_{L}P_{L} + \kappa^{Y}_{R}P_{R}\Big)q_{d} + \bar{B}\not{W}\Big(\kappa^{B}_{L}P_{L} + \kappa^{B}_{R}P_{R}\Big)q_{u} + {\rm h.c.}\right]$$
$$+ \frac{\sqrt{2}g}{2}\left[\bar{T}\not{W}\Big(\kappa^{T}_{L}P_{L} + \kappa^{T}_{R}P_{R}\Big)q_{d} + \bar{X}\not{W}\Big(\kappa^{X}_{L}P_{L} + \kappa^{X}_{R}P_{R}\Big)q_{u} + {\rm h.c.}\right]$$

similar to the previous, one more parameter to satisfy the renormalisation conditions

see Fuks & Shao 1610.04622; Cacciapaglia, Cai, Carvalho, AD, Flacke, Fuks, Majumder & Shao (1703.10614)

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, and decays beyond W, Z, h should be included.
- 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
- Present bounds start probing the interesting mass range for VL relevant in BSM model building
- A general parameterisation, useful for LHC searches and NLO tool for detailed calculations are available