Model independent analysis of heavy vector-like top partners

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Based on:

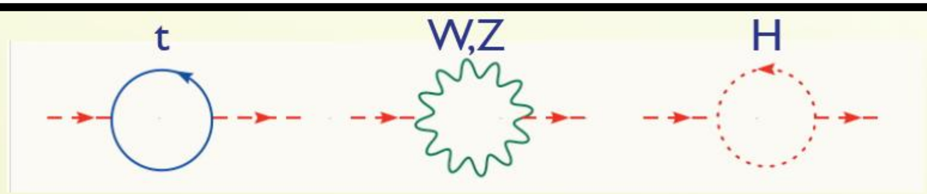
1. M. B., G. Cacciapaglia, A. Deandrea, L. Panizzi, Model Independent Framework for Searches of Top Partners, Nucl.Phys. B876 (2013) 376-417, arXiv:1305.4172 [hep-ph] .

2. D. Barducci, A. Belyaev, M. B., G. Cacciapaglia, A. Deandrea, S. De Curtis, J. Marrouche, S. Moretti, L. Panizzi, Model Independent Analysis of Scenarios with Multiple Vector-like Quarks, **in preparation**.

Naturalness argument in crisis ?

Let us assume that the SM remains valid up to a cut-off scale Λ ($\simeq$ 10 TeV)

➡ The top quark dramatically affects the stability of the scalar boson mass !



$$m_H^2 = m_{H0}^2 \quad - \frac{3}{8\pi^2} y_t \Lambda^2 \quad + \frac{1}{16\pi^2} g^2 \Lambda^2 \quad + \frac{1}{16\pi^2} \lambda^2 \Lambda^2$$

- Can we avoid fine-tuning in the Standard Model ?
- (In)stability at Planck scale ?
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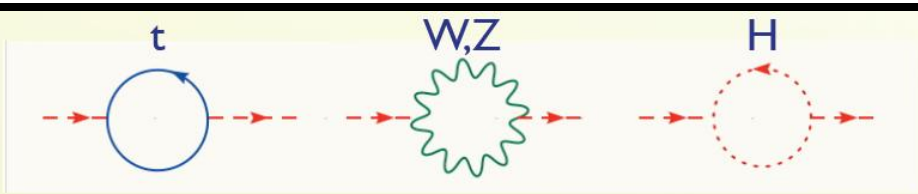

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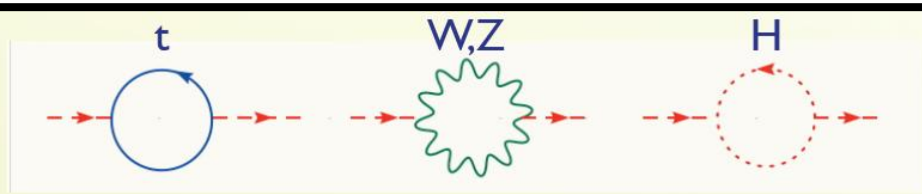

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Top Partners appear in many New Physics models !

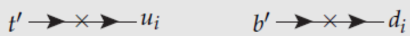
- Warped or universal **extra-dimensions** : as KK excitations of bulk fields,
- **Composite Higgs** models : as excited resonances of the bounded states,
- **Little Higgs** models : as partners of SM fermions embedded in larger group representations (e.g., SO(10)/SO(5)^2 ...),
- **Gauge-flavoured** groups : as required for anomaly cancellation or mass generation,
- ...

provide smoking gun signatures as a common ingredient !

Model-independent parametrization

- Top partners = Vector-like quarks = coloured spin 1/2 particles
- Vector-like quarks get their masses independently from electroweak symmetry breaking
- Vector-like quarks can couple to SM fermions via Yukawa interactions

They can mix with SM quarks



Many open channels for **production** and **decay** of heavy fermions

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$t' \rightarrow \times \rightarrow u_i$ $\quad$ $b' \rightarrow \times \rightarrow d_i$

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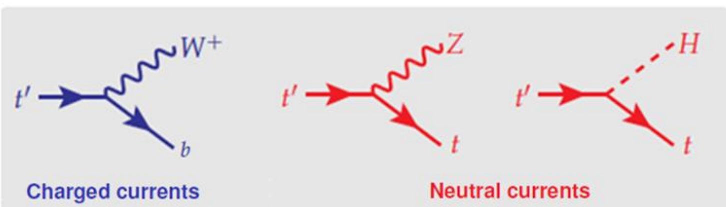
Exemple: Decays of a t' partner



t'	Wb	Zt	ht
Singlet	50%	25%	25%
Doublet	~ 0%	50%	50%

Remarks

1. Branchings are never 100% in one channel.
2. VLQ interactions are allowed through *arbitrary* Yukawa couplings.

$\Longrightarrow$ Multiple decay modes (Wb, Wj, Zt, Zj, Ht, Hj) contribute to the signal region.

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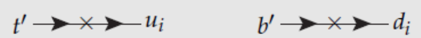

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Charged currents

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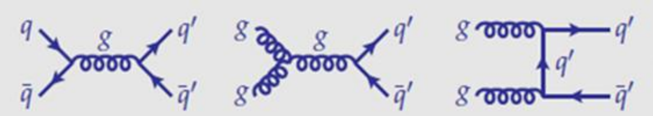
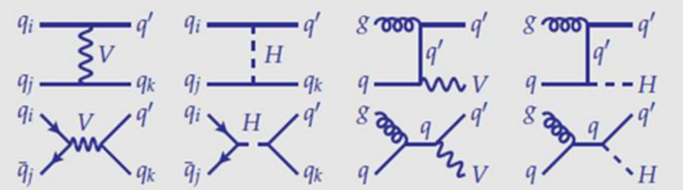
Pair production: $pp \to q'\bar{q}'$ (Purely QCD diagrams)



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

EW+QCD diagrams + potentially relevant FCNC channel



- **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

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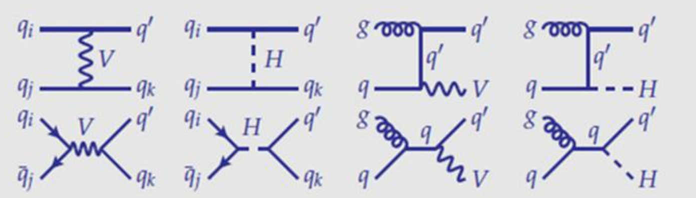

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Reinterpretation of the searches for models with multiple top partners

Experimental limits (pair-production only):

- **ATLAS-CONF-2013-018,-051,-056,-060**: lower 95% CL limit on $m_{t'}$ between 670 and 790 GeV.
- **ATLAS-CONF-2013-051,-056:** lower 95% CL limit on $m_{b'}$ between 645 and 725 GeV.
- **CMS-B2G-12-015**: lower 95% CL limit on $m_{t'}$ between 687 and 782 GeV.
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- ... they only consider exclusive couplings to a single family (3^{rd} generation).
- ... they neglect potentially large loop effects (e.g., mixing, interferences, ...).
- ... they assume that only one new state beyond the Standard Model is present.

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Project: design a NLO tool extracting reliable bounds on realistic NP scenarios

- for any number of top partners.
- for any assumption on their mixing and branching ratio parameters.
- from any (available) search (SUSY, direct, ...), or combination thereof.

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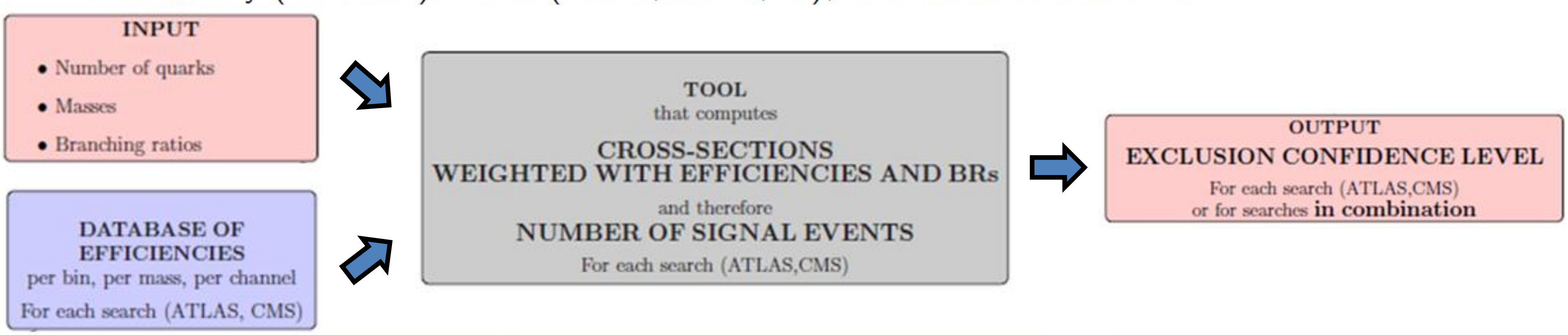


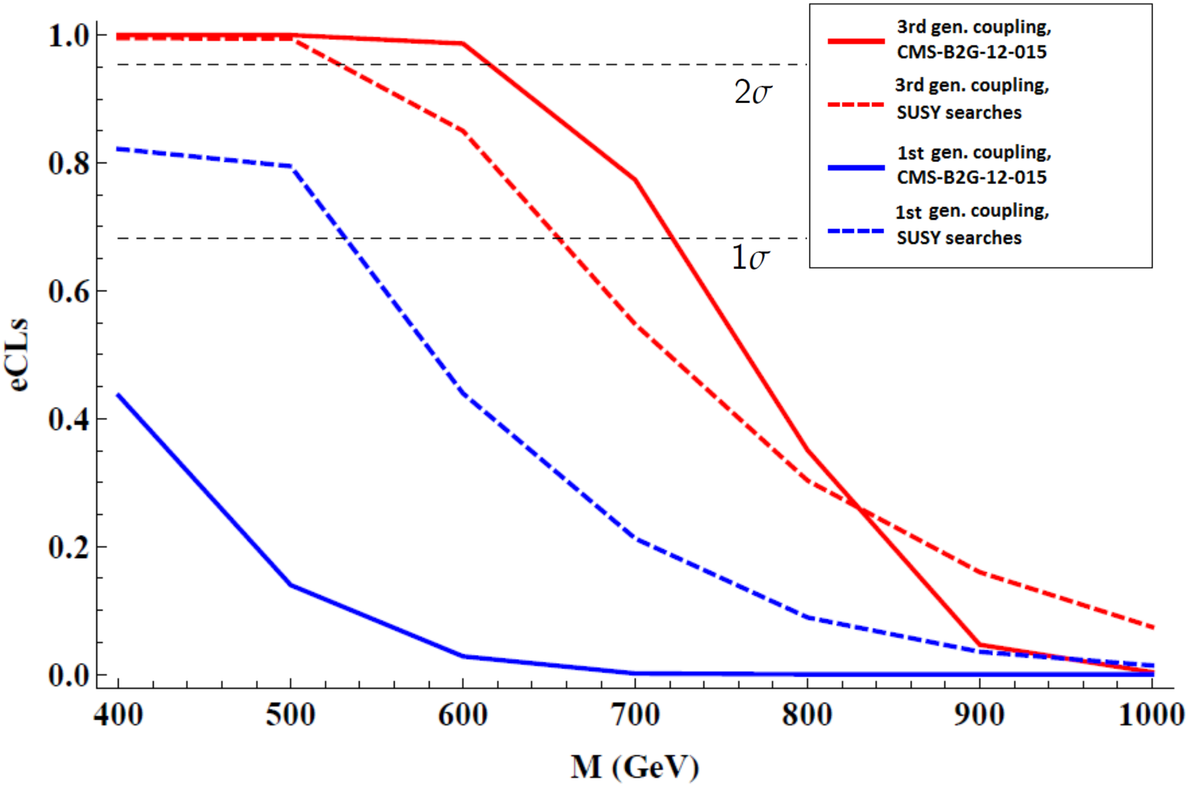
Exemple: SUSY searches vs. direct searches (CMS-B2G-12-015) for a T singlet

Implemented searches (only CMS temporarily) $(*)$

α_T 7 and 8 TeV	L_P (monolepton) 7 TeV	SS dileptons 7 and 8 TeV	OS dileptons 7 TeV

- T with exclusive 3^{rd} gen. coupling:
  $\mathbf{BR}(T \rightarrow Wb)$: $\mathbf{BR}(T \rightarrow Zt)$: $\mathbf{BR}(T \rightarrow Ht)$ $\sim$ **50% : 25% : 25%**

- T with exclusive 1^{st} gen. coupling:
  $\mathbf{BR}(T \rightarrow Wj)$: $\mathbf{BR}(T \rightarrow Zj)$: $\mathbf{BR}(T \rightarrow Hj)$ $\sim$ **50% : 25% : 25%**



We observe that :

1. the limits directly depend on the coupling assumptions
2. assuming exclusive 3^{rd} generation coupling, the combination $(*)$ set constraints in the same ballpark as CMS-B2G-12-015.
3. assuming exclusive 1^{st} generation coupling, the combination $(*)$ set more stringent constraints than CMS-B2G-12-015.

Summary

- Vector-like quarks offer a rich phenomenology, with many channels left to explore at the LHC.
- The current bounds on vector-like quark masses are around 600-800 GeV, but scenarios with general mixing assumptions and multiple top partners are still unconstrained.
- Tool development for model-independent reinterpretations is ongoing, NLO results will soon be publicly available.
- Strong potential to improve the forthcoming analyses and exploit other BSM-inspired searches to test New Physics scenarios.

Stay tuned !

Backup

Experimental limits (CMS)

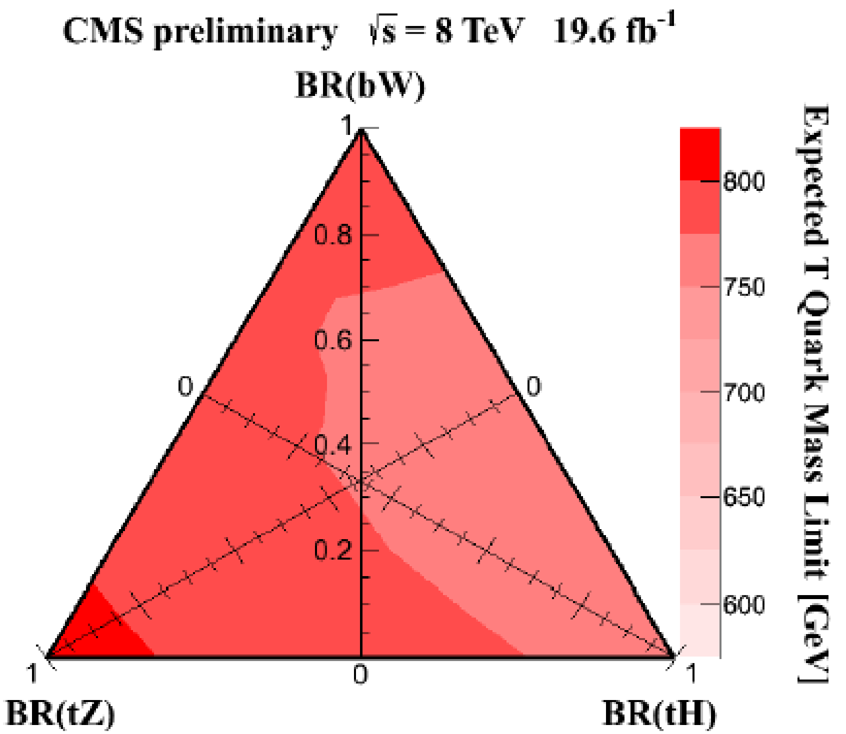
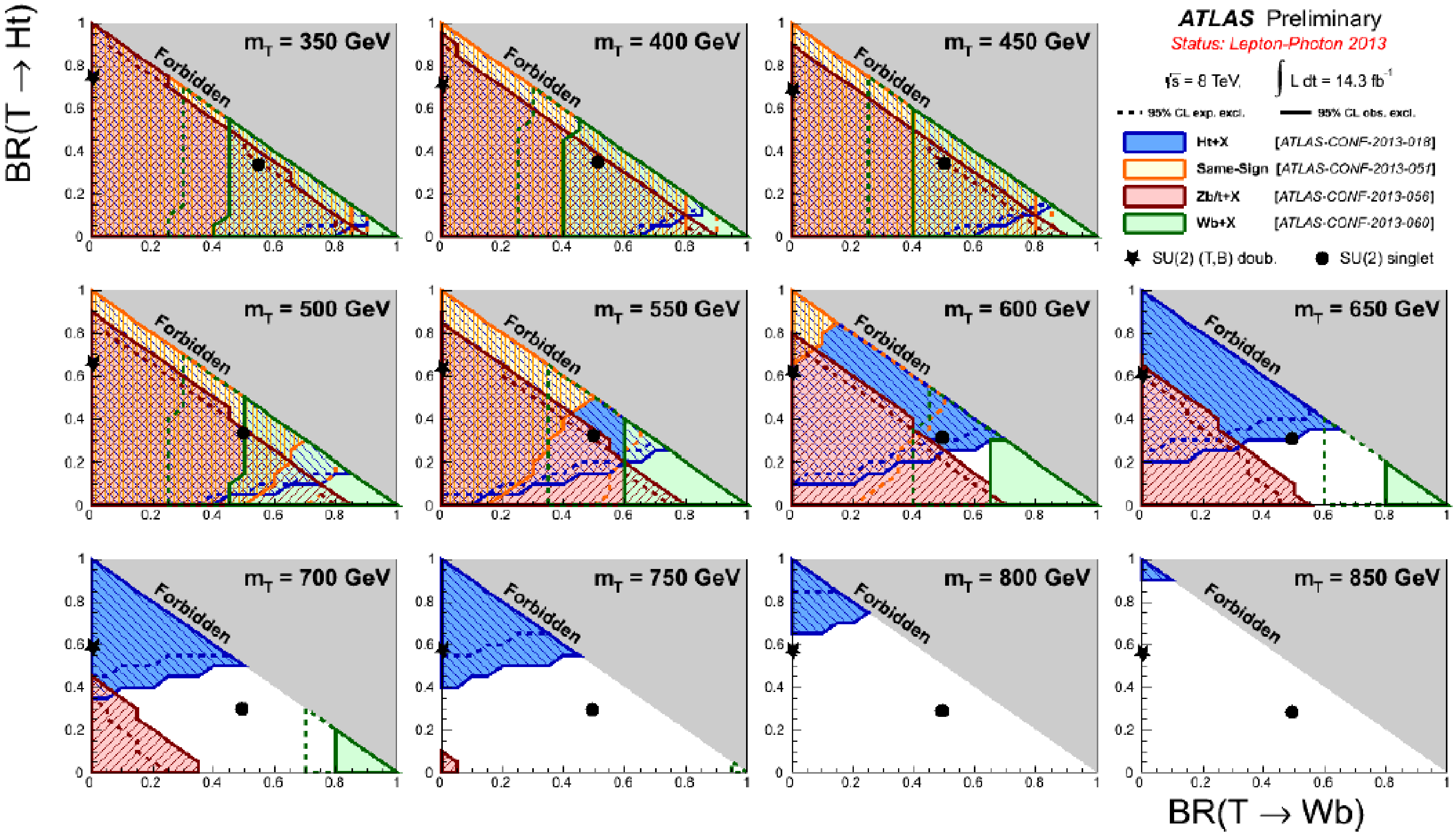


Figure 7: Branching fraction triangle with expected limits (left) and observed limits (right) for the T quark mass. Every point in the triangle corresponds to a particular set of branching fraction values subject to the constraint that all three add up to one. The branching fraction for each mode decreases from one at the corner labeled with the decay mode to zero at the opposite side of the triangle.

CMS PAS B2G-12-015

Experimental limits (ATLAS)



Vector-Like Quark representations

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 $M + 3 \times \lambda^i$

Vector-Like Quark representations

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

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

They can mix with SM quarks

$t' \rightarrow\times\rightarrow u_i$ $b' \rightarrow\times\rightarrow d_i$

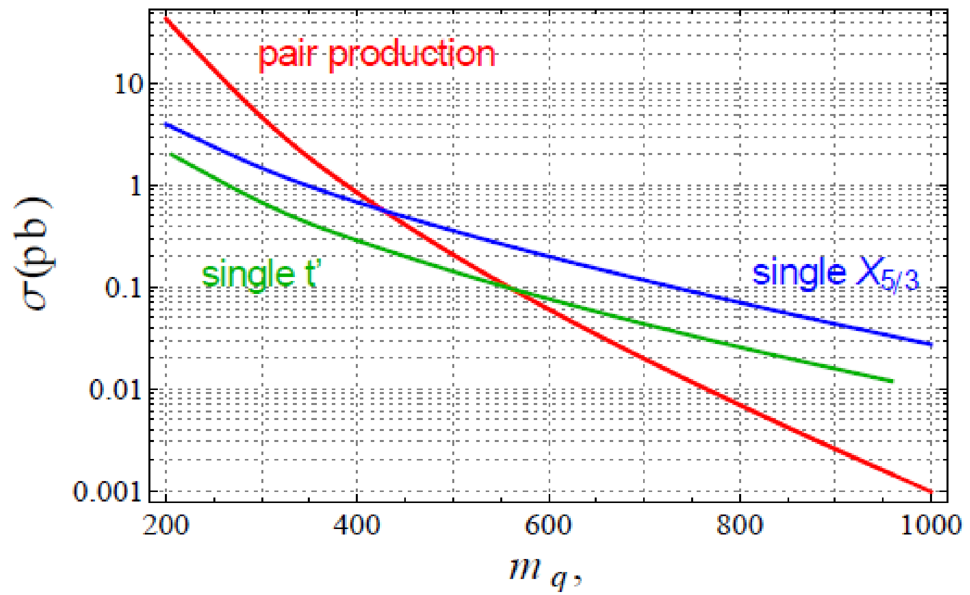
Many open channels for **production** and **decay** of heavy fermions

BR

Q_q	$(T_{2/3})$	$(B_{-1/3})$	$\begin{pmatrix} X_{5/3} \\ T_{2/3} \end{pmatrix}$	$\begin{pmatrix} T_{2/3} \\ B_{-1/3} \end{pmatrix}$	$\begin{pmatrix} B_{-1/3} \\ Y_{-4/3} \end{pmatrix}$	$\begin{pmatrix} X_{5/3} \\ T_{2/3} \\ B_{-1/3} \end{pmatrix}$	$\begin{pmatrix} T_{2/3} \\ B_{-1/3} \\ Y_{-4/3} \end{pmatrix}$
T_{3q}	0	0	1/2	1/2	1/2	1	1
Y	2/3	-1/3	7/6	1/6	-5/6	2/3	-1/3
$T \to Wb$	50%	-	0%	0%	-	50%	0%
$T \to Zt$	25%	-	50%	50%	-	25%	50%
$T \to Ht$	25%	-	50%	50%	-	25%	50%
$B \to Wt$	-	50%	-	100%	0%	0%	50%
$B \to Zb$	-	25%	-	0%	50%	50%	25%
$B \to Hb$	-	25%	-	0%	50%	50%	25%

Production channels

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



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

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

Full Lagrangian:

$$\mathcal{L} = \kappa_T \left\{ \sqrt{\frac{\zeta_i \xi_W^T}{\Gamma_W^0}} \frac{g}{\sqrt{2}} [\bar{T}_L W_\mu^+ \gamma^\mu d_L^i] + \sqrt{\frac{\zeta_i \xi_Z^T}{\Gamma_Z^0}} \frac{g}{2c_W} [\bar{T}_L Z_\mu \gamma^\mu u_L^i] - \sqrt{\frac{\zeta_i \xi_H^T}{\Gamma_H^0}} \frac{M}{v} [\bar{T}_R H u_L^i] - \sqrt{\frac{\zeta_3 \xi_H^T}{\Gamma_H^0}} \frac{m_t}{v} [\bar{T}_L H t_R] \right\}$$
$$+ \kappa_B \left\{ \sqrt{\frac{\zeta_i \xi_W^B}{\Gamma_W^0}} \frac{g}{\sqrt{2}} [\bar{B}_L W_\mu^- \gamma^\mu u_L^i] + \sqrt{\frac{\zeta_i \xi_Z^B}{\Gamma_Z^0}} \frac{g}{2c_W} [\bar{B}_L Z_\mu \gamma^\mu d_L^i] - \sqrt{\frac{\zeta_i \xi_H^B}{\Gamma_H^0}} \frac{M}{v} [\bar{B}_R H d_L^i] \right\}$$
$$+ \kappa_X \left\{ \sqrt{\frac{\zeta_i}{\Gamma_W^0}} \frac{g}{\sqrt{2}} [\bar{X}_L W_\mu^+ \gamma^\mu u_L^i] \right\} + \kappa_Y \left\{ \sqrt{\frac{\zeta_i}{\Gamma_W^0}} \frac{g}{\sqrt{2}} [\bar{Y}_L W_\mu^- \gamma^\mu d_L^i] \right\} + h.c.$$

$$\mathrm{BR}(Q \to Vq_i) = \xi_V \, \zeta_i$$

Mass +

- T : 4 parameters
- B : 4 parameters
- X : 2 parameters
- Y : 2 parameters

$$\sum_{i=1}^{3} \zeta_i = 1 \qquad \sum_{V=W,Z,H} \xi_V = 1$$

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http://feynrules.irmp.ucl.ac.be/wiki/VLQ

Model Independent Framework for Single VLQ Production

$m = 600$ GeV

Compendium of cross-sections & distributions for all the allowed production channels

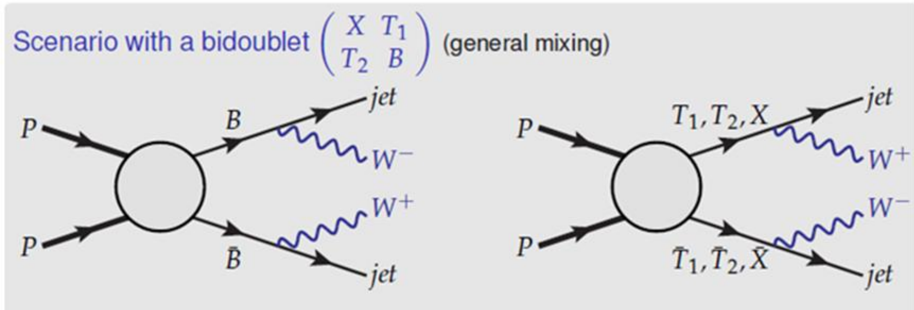
	(fb)	7 TeV $i=1$	7 TeV $i=2$	7 TeV $i=3$	8 TeV $i=1$	8 TeV $i=2$	8 TeV $i=3$	14 TeV $i=1$	14 TeV $i=2$	14 TeV $i=3$
Q+t	$\bar\sigma^{T\bar t}_{W_i}$	893	68.4	20.7	1441	123	39.1	7580	985	373
	$\bar\sigma^{T\bar t}_{Z_i}$	–	–	4.22	–	–	6.28	–	–	2.47
	$\bar\sigma^{Bt}_{W_i}$	2314	34.5	–	3605	64.5	–	16700	588	–
	$\bar\sigma^{B\bar t}_{W_i}$	–	–	2.04	–	–	3.14	–	–	13.8
	$\bar\sigma^{X\bar t}_{W_i}$	2277	33.9	7.01	3546	63.2	10.0	16640	578	33.6
	$\bar\sigma^{Yt}_{W_i}$	936	71.2	22.3	1507	128	42.7	7911	1021	405
Q+j	$\bar\sigma^{Tj}_{W_i}$	34150	4943	1906	45420	7316	2957	125000	29400	13970
	$\bar\sigma^{Tj}_{Z_i}$	48000	1770	–	63200	2760	–	171000	13400	–
	$\bar\sigma^{Bj}_{W_i}$	39500	1140	–	53000	2090	–	152000	10800	–
	$\bar\sigma^{Bj}_{Z_i}$	22500	3030	1130	30400	4550	1790	91000	19600	9080
	$\bar\sigma^{Xj}_{W_i}$	72900	2950	–	94000	4520	–	232000	20400	–
	$\bar\sigma^{Yj}_{W_i}$	18600	2290	831	25600	3510	1340	80500	16200	7250
Q+V	$\bar\sigma^{TW}_{W_i}$	1300	106	32.9	2070	187	60.9	10700	1420	545
	$\bar\sigma^{BW}_{W_i}$	3270	53.5	–	5040	97.9	–	23400	840	–
	$\bar\sigma^{XW}_{W_i}$	3270	53.5	–	5040	97.9	–	23400	840	–
	$\bar\sigma^{YW}_{W_i}$	1300	106	33.0	2070	187	60.9	10700	1420	545
	$\bar\sigma^{TZ}_{Z_i}$	3370	55.0	–	5200	101	–	24200	869	–
	$\bar\sigma^{BZ}_{Z_i}$	1340	109	33.9	2130	193	62.6	11100	1470	563
	$\bar\sigma^{TH}_{H_i}$	2460	34.5	–	3610	64.5	–	16900	588	–
	$\bar\sigma^{BH}_{H_i}$	965	74.1	22.5	1560	133	42.4	8560	1090	409

The cross section for pair production is 170 fb

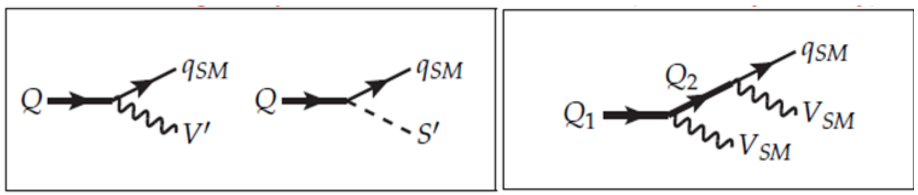
M. B., G. Cacciapaglia, A. Deandrea, L. Panizzi, *Model Independent Framework for Searches of Top Partners*, Nucl.Phys. B876 (2013) 376-417, arXiv:1305.4172

NLO results & other challenges

- A given final state can be feeded by different channels



- Model-dependent decay chains must to be included

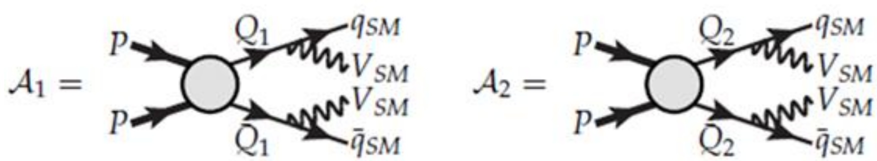


Other new sectors besides the VLQs

Chain decays between VLQs

A dedicated simulation is required for these channels

- Role of interferences is to be accounted for



$$\sigma \propto |\mathcal{A}_1|^2 + |\mathcal{A}_2|^2 + 2Re\,[\mathcal{A}_1 \mathcal{A}_2^*]$$

- Quantum mixing has to be treated properly