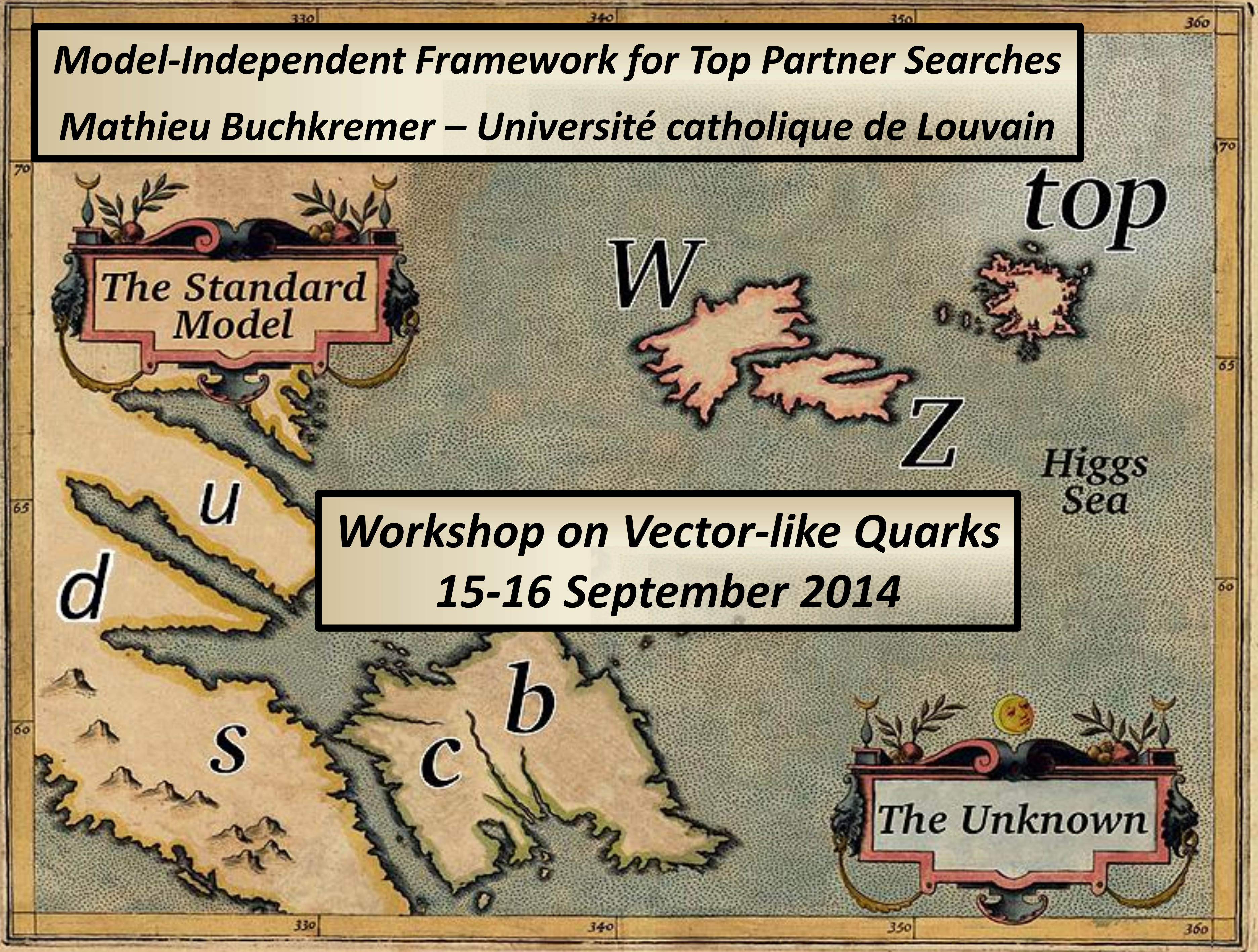
Model-Independent Framework for Top Partner Searches

Mathieu Buchkremer – Université catholique de Louvain



Workshop on Vector-like Quarks
15-16 September 2014

Model Independent Framework for Searches of Top Partners

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Workshop on Vector-like Quarks
15th of September 2014

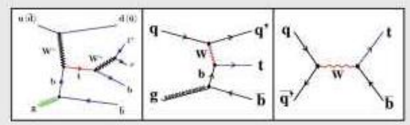
Helmholtz Alliance

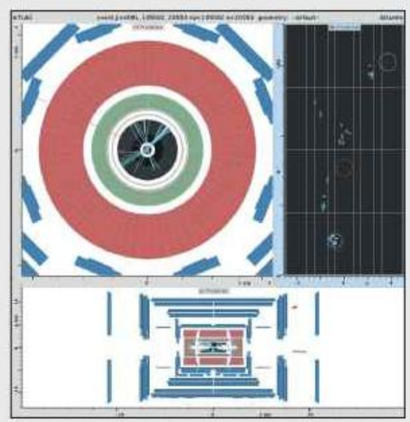
PHYSICS AT THE TERASCALE

2nd Workshop on

Single-top physics and fourth-generation quarks

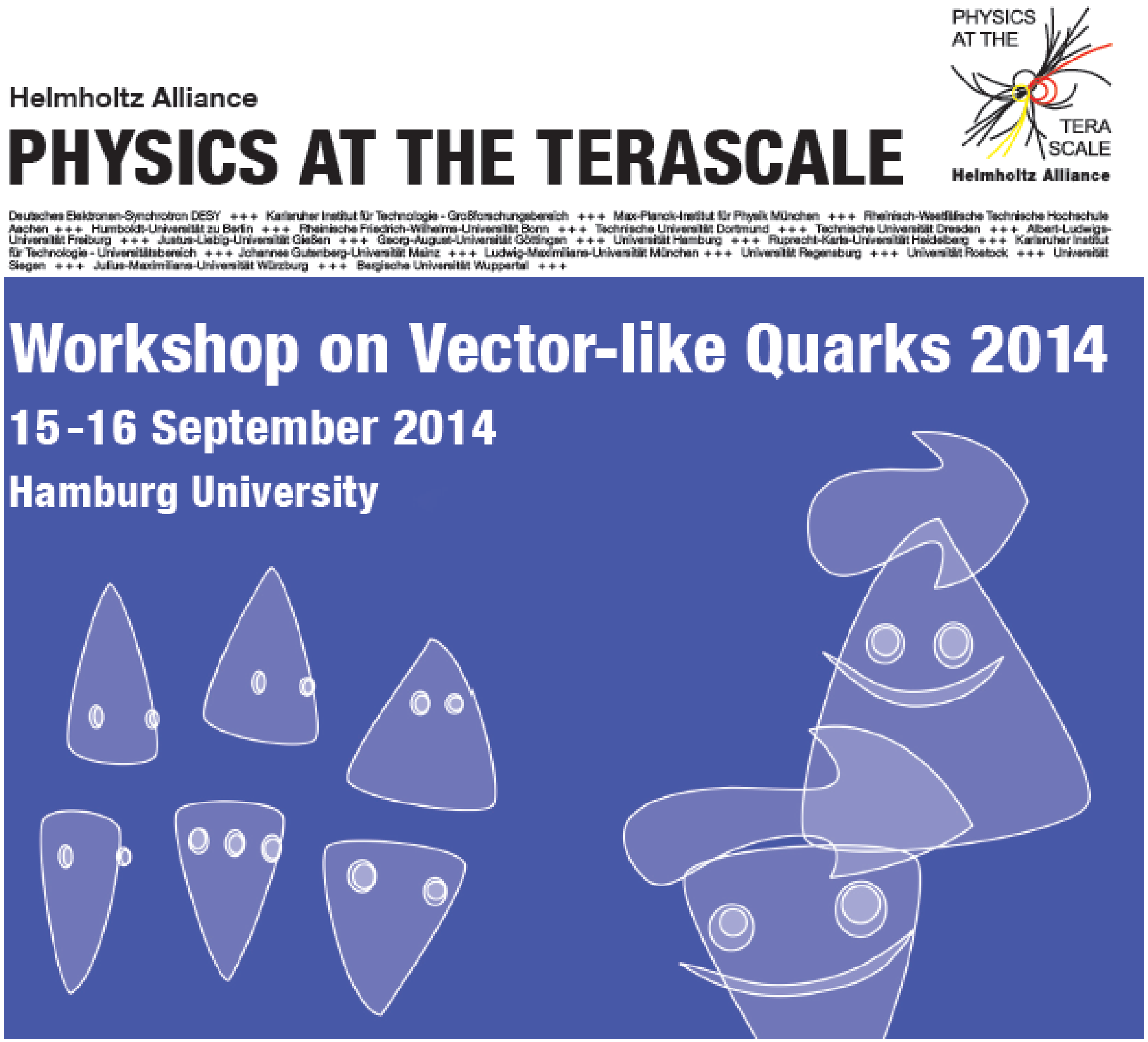
5 - 6 September 2011
DESY, Hamburg





Topics:
- Theoretical and experimental overview of single top and 4th generation quarks
- Single top results from ATLAS and CMS
- Searches for 4th generation quarks at ATLAS and CMS
- Monte Carlo models
- Analysis techniques

2011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Workshop on Vector-like Quarks 2014
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Hamburg University

2014

Outline

1. Introduction.
2. Model-independent framework for VLQ searches.
3. Benchmark scenarios from flavour bounds.
4. Conclusions & prospects.

Based on:

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

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Pedagogy =

Art of repetition

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- Colored Dirac fermions with 1/2 spin
- The right and left handed component of a VLQ transforms in the same way under the SM gauge group $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$

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$$\mathcal{L} \supset \frac{g}{\sqrt{2}}(j^{\mu+}W_\mu^+ + j^{\mu-}W_\mu^-) \qquad j^{\mu\pm} = j_L^{\mu\pm} + j_R^{\mu\pm}$$

SM chiral quarks

$$j_L^\mu = \bar{f}_L\gamma^\mu f_L' \qquad j_R^\mu = 0$$

$$j^\mu = j_L^\mu + j_R^\mu = \bar{f}\gamma^\mu(1-\gamma^5)f'$$

$V - A$

VLQs

$$j_L^\mu = \bar{f}_L\gamma^\mu f_L' \qquad j_R^\mu = \bar{f}_R\gamma^\mu f_R'$$

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V

1. Introduction

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In the Standard Model, quarks are **chiral** under the weak interaction ($SU(2)_L$):

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Mass terms forbidden by gauge invariance !

Fermion masses arise from EWSSB

$$L \supset -M\bar{\psi}\psi$$

$$M_{u,d,e} = \frac{Y_{u,d,e}\ v}{\sqrt{2}}$$

Theoretical Motivations (a selection thereof)

Vector-like quarks:

- may provide a solution to the Hieararchy Problem.
- provide anomaly-free extensions of the SM.
- break the GIM mechanism, allow for non-vanishing FCNCs at tree-level.
- decouple, i.e., do not conflict with the current precision constraints if $M \to \infty$.
- can lead to new sources of CP violations, ...
- appear as a common ingredient of many New Physics models: Composite Higgs/top models, Universal extra-dimensions, Little Higgs models, Gauge flavoured groups, extended gauge symmetries, ... and many more.
- ...

See arXivs [hep-ph]: ⋯, 1004.4895, 1102.1987, 1103.4170, 1106.6357, 1107.1500, 1204.6333, 1205.2378, 1206.3360, 1207.4440, 1211.5663, 1302.0270, 1305.3818, 1306.2656, 1311.5928, 1404.4398, 1409.0100, 1409.0805, ⋯

Properties

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- VLQs can have a gauge invariant mass term independently from the EWSSB mechanism

$$L_{mass} = -M(\bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L)$$

⟶ VLQ masses are not bounded by any symmetries

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- Vector-Like Quarks can couple to the SM Higgs doublet through standard Yukawa couplings

⟶ The VLQ couplings to SM quarks are either left-handed or right-handed.

$$L_{\text{Yukawa}} = -\frac{\lambda v}{\sqrt{2}} \underbrace{(\bar{q}_L \psi_R + \bar{\psi}_R q_L)}_{\text{LH: singlet (triplet)}} \quad \text{or} \quad -\frac{\lambda v}{\sqrt{2}} \underbrace{(\bar{\psi}_L q_R + \bar{q}_R \psi_L)}_{\text{RH: doublet}}$$

⟶ non-chiral quarks decay into a standard quark plus a W, Z, or H boson.

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

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

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

Left-handed

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

Right-handed

Hypothesis:

Vector-Like Quarks belong to complete representations of $SU(2)_L \times U(1)_Y$, with chiral couplings to the SM.

This work → sticks to singlet, doublet and triplet representations under the EW gauge group.

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Q	~~$\begin{pmatrix} t' \\ b' \end{pmatrix}$~~

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Q_q	$T_{\frac{2}{3}}$	$B_{-\frac{1}{3}}$	$\begin{pmatrix} t' \\ b' \end{pmatrix}$
T_3	0	0	
Y	$4/3$	$-2/3$	

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Q_q	$T_{\frac{2}{3}}$	$B_{-\frac{1}{3}}$	$\begin{pmatrix} X_{\frac{5}{3}} \\ T_{\frac{2}{3}} \end{pmatrix}$	$\begin{pmatrix} T_{\frac{2}{3}} \\ B_{-\frac{1}{3}} \end{pmatrix}$	~~$\begin{pmatrix} t' \\ b' \end{pmatrix}$~~	$\begin{pmatrix} B_{-\frac{1}{3}} \\ Y_{-\frac{4}{3}} \end{pmatrix}$
T_3	0	0	$1/2$	$1/2$		$1/2$
Y	$4/3$	$-2/3$	$7/3$	$1/3$		$-5/3$

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Each case leads to a different phenomenology !

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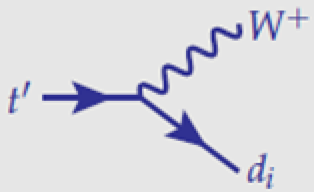
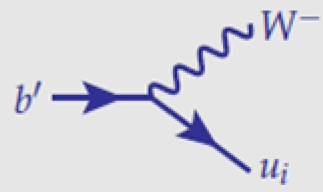
T_3	0	0	$1/2$	$1/2$		$1/2$	1	1
Y	$4/3$	$-2/3$	$7/3$	$1/3$		$-5/3$	$4/3$	$-2/3$

Decays

$i = 1, 2, 3$

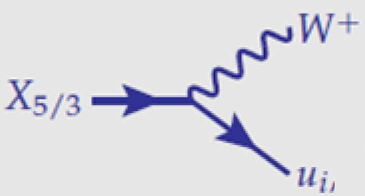
SM partners

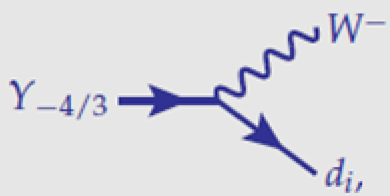




Charged currents

Exotics



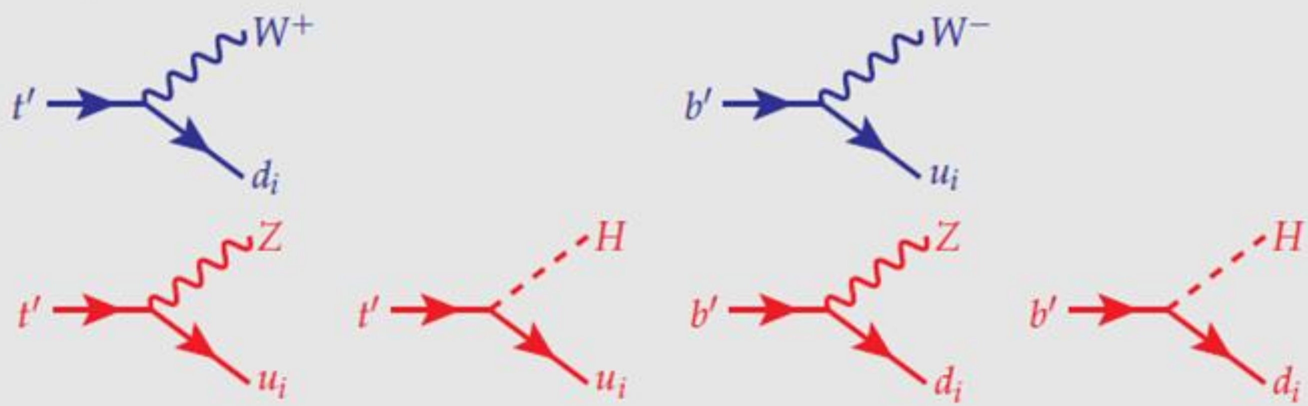


Only Charged currents

Decays

$i = 1, 2, 3$

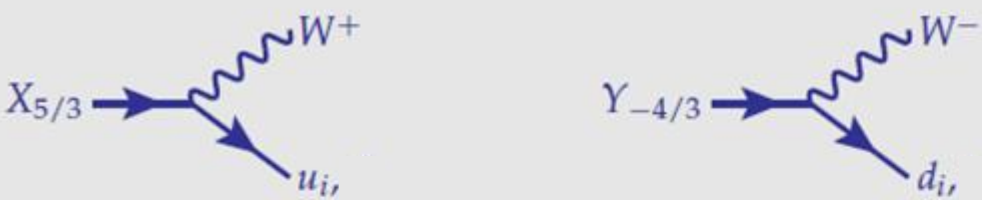
SM partners



Charged currents

Neutral currents

Exotics

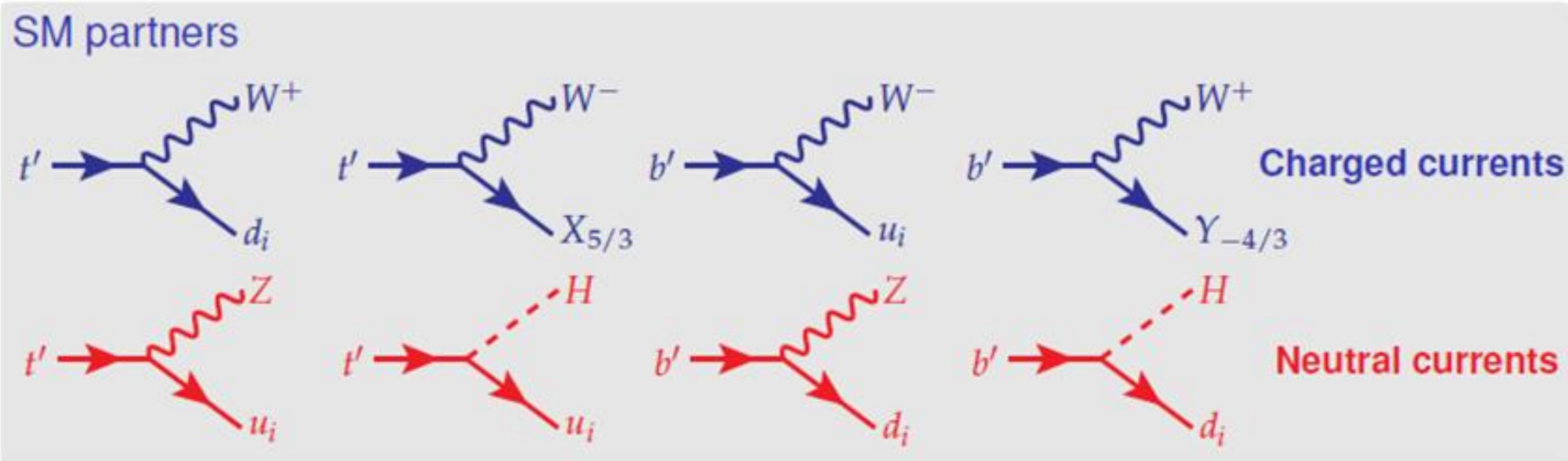


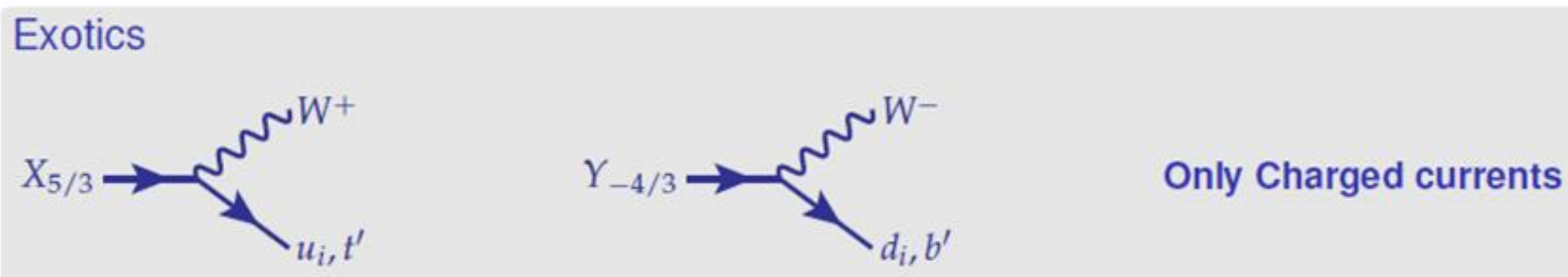
Only Charged currents

2. What is a Vector-Like Quark ?

Decays

$i = 1, 2, 3$



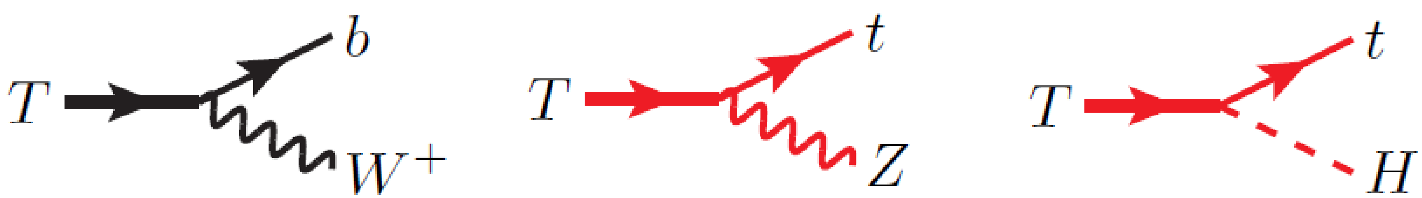


- The branching ratios depend on the VLQ representations and masses
- For $T_{2/3}$ and $B_{-1/3}$ quarks, the Equivalence Theorem requires $\mathrm{BR}(Q \to Zq) \simeq \mathrm{BR}(Q \to Hq) \simeq \mathrm{BR}(Q \to Wq)/2$

Important remarks

1. Branching ratios are never 100% in one channel.

t′	Wb	Zt	ht
Single, Triplet Y=2/3	50%	25%	25%
Doublets, Triplet Y=-1/3	~ 0%	50%	50%



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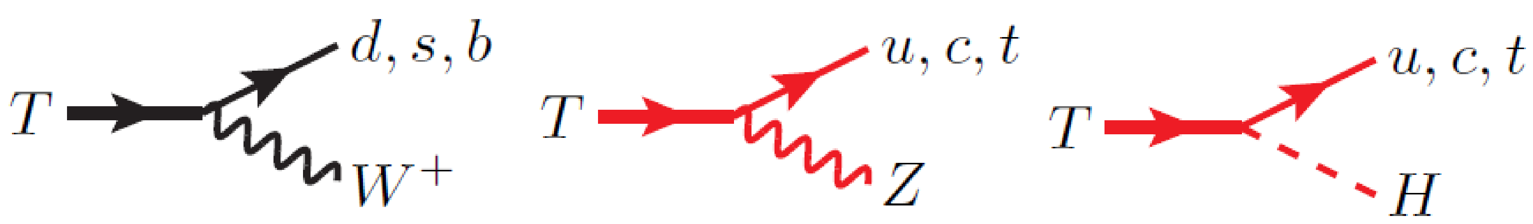

2. VLQ interactions are allowed through arbitrary Yukawa couplings.

   Decays into light quarks may not be negligible

   (The BRs do not directly depend on the Yukawas).

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Vector-like quarks can be produced
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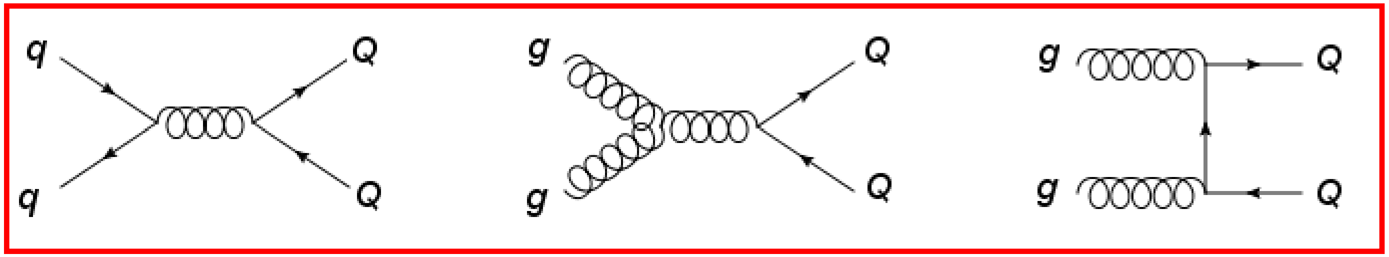
- **Pair production:** dominated by QCD and sensitive to the Q mass (model-independent).



Production

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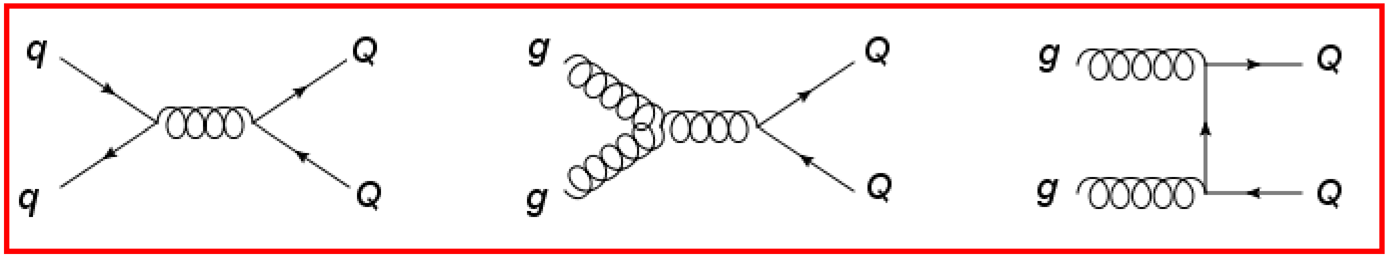
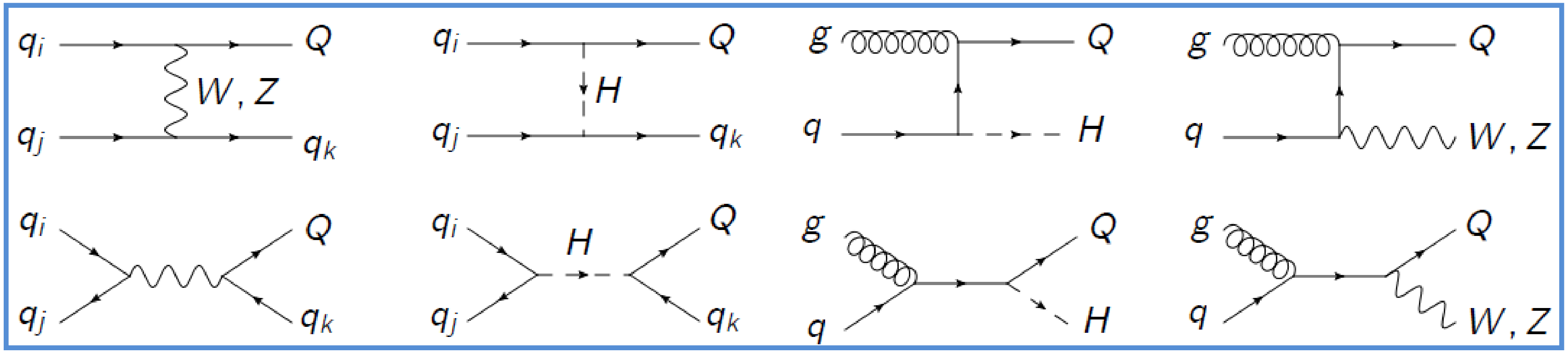
in the same way as SM quarks **plus** FCNCs channels

- **Pair production:** dominated by QCD and sensitive to the Q mass (model-independent).
- **Single production:** EW contributions are sensitive to both the Q mass and its mixing parameters (model-dependent).



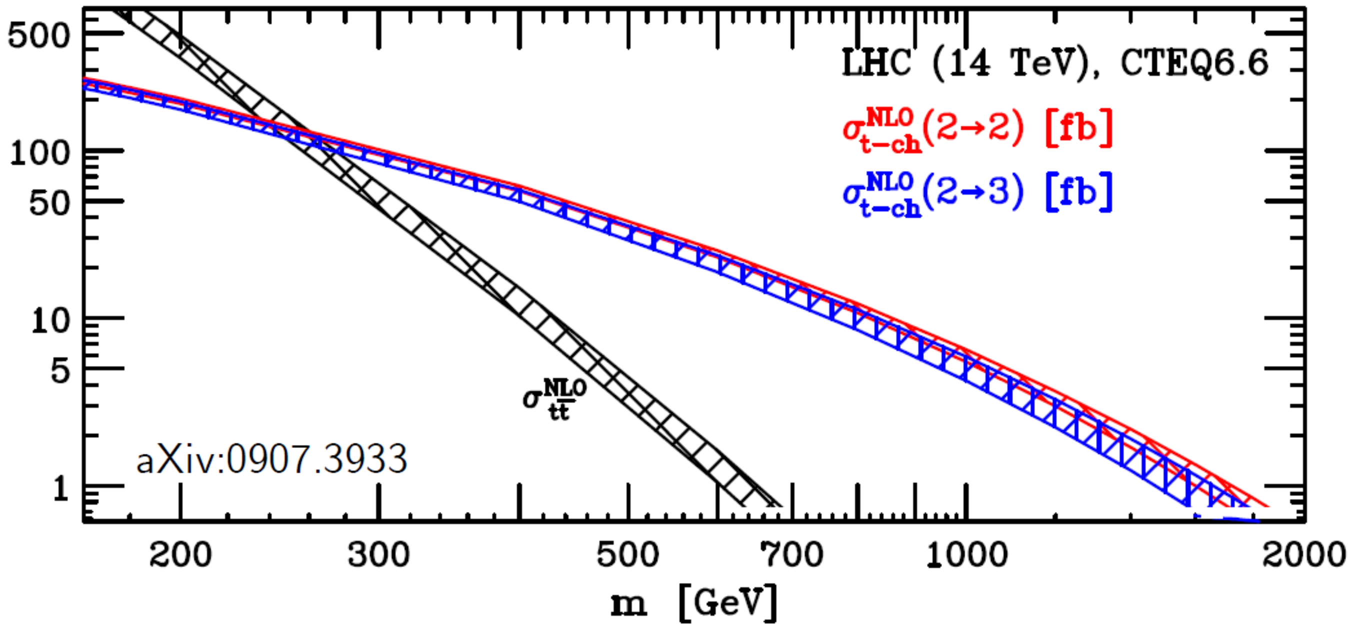


Outline

NLO cross sections (in fb) at the LHC 14 TeV

Pair vs. t-channel single production ($2 \to 2$ and $2 \to 3$ schemes)

T quark with $\mathrm{BR}(T \to Wb) = 1$



QCD pair production decreases faster than EW single production due to different PDF scaling.

Parametrisation: correlates directly the model parameters to the Branching Ratios of the VLQs

↳ Only required inputs

2. Model Independent Framework for VLQ searches

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Example : a $T(t')$ singlet coupling to Wb

$$L \supset \kappa_W V_L^{43} \frac{g}{\sqrt{2}} [\bar{T}_L W_\mu^+ \gamma^\mu b_L]$$

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↓

$$L \sim \kappa_T \sqrt{\xi_W \zeta_b} [\bar{T}_L W_\mu^+ \gamma^\mu b_L]$$

Coupling Strength

$BR(T \to Wb)$

TWb current

Full Lagrangian for $X_{5/3}$, T, B, $Y_{-4/3}$

$$\mathcal{L} = \kappa_T \sqrt{\frac{\zeta_i \xi_W^T}{\Gamma_W^0}} \frac{g}{\sqrt{2}} [\bar{T}_L W_\mu^+ \gamma^\mu d_L^i]$$

Full Lagrangian for $X_{5/3}$, T, B, $Y_{-4/3}$

$$\mathcal{L} = \kappa_T \sqrt{\frac{\zeta_i \xi_W^T}{\Gamma_W^0}} \frac{g}{\sqrt{2}} [\bar{T}_L W_\mu^+ \gamma^\mu d_L^i] + \sqrt{\frac{\zeta_i \xi_Z^T}{\Gamma_Z^0}} \frac{g}{2c_W} [\bar{T}_L Z_\mu \gamma^\mu u_L^i]$$

Full Lagrangian for $X_{5/3}$, T, B, $Y_{-4/3}$

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

Full Lagrangian for $X_{5/3}$, T, B, $Y_{-4/3}$

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$$+ \kappa_B \left\{ \sqrt{\frac{\zeta_i \xi_W^B}{\Gamma_W^0}} \frac{g}{\sqrt{2}} [\bar{B}_L W_\mu^- \gamma^\mu u_L^i] + \sqrt{\frac{\zeta_i \xi_Z^B}{\Gamma_Z^0}} \frac{g}{2c_W} [\bar{B}_L Z_\mu \gamma^\mu d_L^i] - \sqrt{\frac{\zeta_i \xi_H^B}{\Gamma_H^0}} \frac{M}{v} [\bar{B}_R H d_L^i] \right\}$$

Full Lagrangian for $X_{5/3}$, T, B, $Y_{-4/3}$

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

Full Lagrangian for $X_{5/3}$, T, B, $Y_{-4/3}$

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

$$+ \kappa_B \left\{ \sqrt{\frac{\zeta_i \xi_W^B}{\Gamma_W^0}} \frac{g}{\sqrt{2}} [\bar{B}_L W_\mu^- \gamma^\mu u_L^i] + \sqrt{\frac{\zeta_i \xi_Z^B}{\Gamma_Z^0}} \frac{g}{2c_W} [\bar{B}_L Z_\mu \gamma^\mu d_L^i] - \sqrt{\frac{\zeta_i \xi_H^B}{\Gamma_H^0}} \frac{M}{v} [\bar{B}_R H d_L^i] \right\}$$

$$+ \kappa_X \left\{ \sqrt{\frac{\zeta_i}{\Gamma_W^0}} \frac{g}{\sqrt{2}} [\bar{X}_L W_\mu^+ \gamma^\mu u_L^i] \right\} + \kappa_Y \left\{ \sqrt{\frac{\zeta_i}{\Gamma_W^0}} \frac{g}{\sqrt{2}} [\bar{Y}_L W_\mu^- \gamma^\mu d_L^i] \right\} + h.c.$$

Full Lagrangian for $X_{5/3}$, T, B, $Y_{-4/3}$

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

Model-dependency "factored out"

$$BR(Q \to V q_i) = \xi_V \, \zeta_i$$

Full Lagrangian for $X_{5/3}$, T, B, $Y_{-4/3}$

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

Model-dependency "factored out"

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

$$\xi_W + \xi_Z + \xi_H = 1$$

$$\zeta_1 + \zeta_2 + \zeta_3 = 1$$

# of parameters:

- T : 5
- B : 5
- X : 3
- Y : 3

Full Lagrangian for $X_{5/3}$, T, B, $Y_{-4/3}$

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

Model-dependency "factored out"

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

# of parameters:

$$\xi_W + \xi_Z + \xi_H = 1$$

$$\zeta_1 + \zeta_2 + \zeta_3 = 1$$

- T : 5
- B : 5
- X : 3
- Y : 3

Feynrules, MadGraph & CalcHEP public implementations:

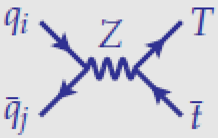
- http://feynrules.irmp.ucl.ac.be/
- http://hepmdb.soton.ac.uk/

(complete model, and specific representations).

Analytical cross-sections for the T quark (leading order)

In association with top

$$\sigma(T\bar{t}) = \kappa_T^2 \; \xi_Z \zeta_3 \; \bar{\sigma}_{Z3}^{T\bar{t}}$$

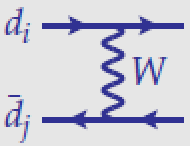


2. Model Independent Framework for VLQ searches

Analytical cross-sections for the T quark (leading order)

In association with top

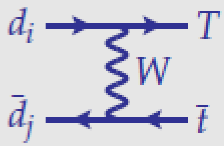
$$\sigma(T\bar{t}) = \kappa_T^2 \left(\xi_Z \zeta_3 \, \bar{\sigma}_{Z3}^{T\bar{t}} + \xi_W \sum_{i=1}^{3} \zeta_i \, \bar{\sigma}_{Wi}^{T\bar{t}} \right)$$



Analytical cross-sections for the T quark (leading order)

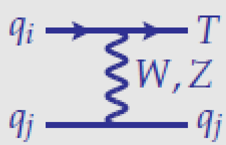
In association with top

$$\sigma(T\bar{t}) = \kappa_T^2 \left(\xi_Z \zeta_3 \, \bar{\sigma}_{Z3}^{T\bar{t}} + \xi_W \sum_{i=1}^{3} \zeta_i \, \bar{\sigma}_{Wi}^{T\bar{t}} \right)$$



In association with light quark

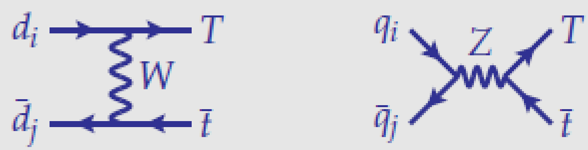
$$\sigma(Tj) = \kappa_T^2 \left(\xi_W \sum_{i=1}^{3} \zeta_i \, \bar{\sigma}_{Wi}^{Tjet} + \xi_Z \sum_{i=1}^{3} \zeta_i \, \bar{\sigma}_{Zi}^{Tjet} \right)$$



Analytical cross-sections for the T quark (leading order)

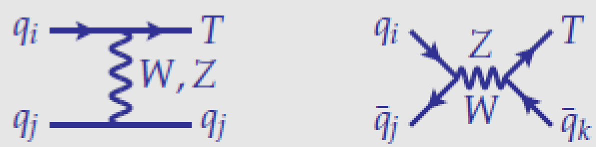
In association with top

$$\sigma(T\bar{t}) = \kappa_T^2 \left(\xi_Z \zeta_3 \, \bar{\sigma}_{Z3}^{T\bar{t}} + \xi_W \sum_{i=1}^{3} \zeta_i \, \bar{\sigma}_{Wi}^{T\bar{t}} \right)$$



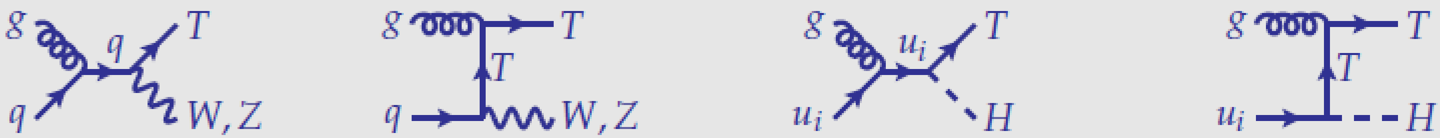
In association with light quark

$$\sigma(Tj) = \kappa_T^2 \left(\xi_W \sum_{i=1}^{3} \zeta_i \, \bar{\sigma}_{Wi}^{Tjet} + \xi_Z \sum_{i=1}^{3} \zeta_i \, \bar{\sigma}_{Zi}^{Tjet} \right)$$



In association with gauge or Higgs boson

$$\sigma(T\{W,Z,H\}) = \kappa_T^2 \left(\xi_W \sum_{i=1}^{3} \zeta_i \, \bar{\sigma}_i^{TW} + \xi_Z \sum_{i=1}^{3} \zeta_i \, \bar{\sigma}_i^{TZ} + \xi_H \sum_{i=1}^{3} \zeta_i \, \bar{\sigma}_i^{TH} \right)$$



The $\bar{\sigma}$ are model-independent coefficients: the model-dependency is factorised!

Leading Order results for $m = 600$ GeV

(fb)	7 TeV			8 TeV			14 TeV		
	$i=1$	$i=2$	$i=3$	$i=1$	$i=2$	$i=3$	$i=1$	$i=2$	$i=3$
$\bar\sigma^{T\bar t}_{W_i}$	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
$\bar\sigma^{B\bar t}_{W_i}$	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
$\bar\sigma^{Y\bar t}_{W_i}$	936	71.2	22.3	1507	128	42.7	7911	1021	405
$\bar\sigma^{Tj}_{W_i}$	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
$\bar\sigma^{TW}_{W_i}$	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

Pair-production: $\sigma^{QCD}_{Q\bar Q} = 109\ (167)$ fb at LO (NLO).

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

2. Model Independent Framework for VLQ searches

Leading Order results for $m = 600$ GeV

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

(fb)		7 TeV			8 TeV			14 TeV	
		$i=1$	$i=2$	$i=3$	$i=1$	$i=2$	$i=3$	$i=1$	$i=2$	$i=3$
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
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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	–
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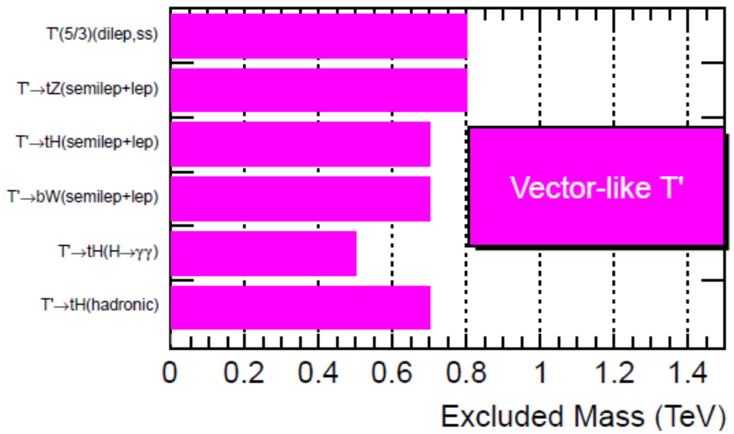
Pair-production: $\sigma^{QCD}_{Q\bar Q}$ = 109 (167) fb at LO (NLO).

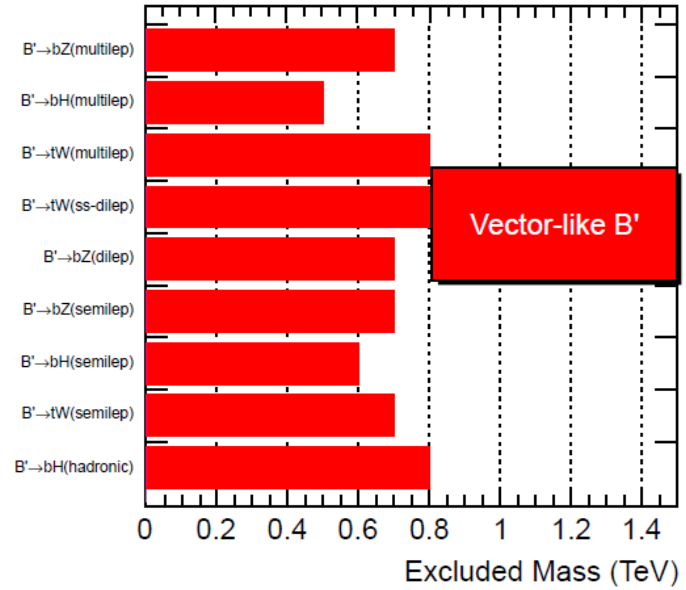
M. B., G. Cacciapaglia, A. Deandrea, L. Panizzi, *Model Independent Framework for Searches of Top Partners*, Nucl.Phys. B876 (2013) 376-417, arXiv:1305.4172

Outline

Current mass limits (direct searches, summer 2014)

- Main assumptions: pair-production + decays to 3^{rd} generation quarks
- Upcoming searches: also single-production + decays to light quarks





CMS

	Model	ℓ, γ	Jets	E_T^{miss}	$\int \mathcal{L} dt [fb^{-1}]$	Mass limit		Reference
Heavy quarks	Vector-like quark $TT \to Ht + X$	1 e, μ	≥ 2 b, ≥ 4 j	Yes	14.3	T mass 790 GeV	T in (T,B) doublet	ATLAS-CONF-2013-018
	Vector-like quark $TT \to Wb + X$	1 e, μ	≥ 1 b, ≥ 3 j	Yes	14.3	T mass 670 GeV	isospin singlet	ATLAS-CONF-2013-060
	Vector-like quark $TT \to Zt + X$	2/≥3 e, μ	≥2/≥1 b	–	20.3	T mass 735 GeV	T in (T,B) doublet	ATLAS-CONF-2014-036
	Vector-like quark $BB \to Zb + X$	2/≥3 e, μ	≥2/≥1 b	–	20.3	B mass 755 GeV	B in (B,Y) doublet	ATLAS-CONF-2014-036
	Vector-like quark $BB \to Wt + X$	2 e, μ (SS)	≥ 1 b, ≥ 1 j	Yes	14.3	B mass 720 GeV	B in (T,B) doublet	ATLAS-CONF-2013-051

ATLAS

Besides the mass limits set from the direct searches, the VLQ parameters are constrained by many observables:

- Flavour Changing Neutral Currents.
- Meson mixing and decays ($\Delta F = 2, 1$).
- Rare top decays.
- $Zu\bar{u}$, and $Zd\bar{d}$ couplings from APV.
- $Zs\bar{s}$, $Zc\bar{c}$, and $Zb\bar{b}$ couplings from LEP.
- EW precision tests.
- Higgs physics at the LHC.

Constraints have been investigated thoroughly in:

- J.A. Aguilar-Saavedra, R. Benbrik, S. Heinemeyer, M. Perez-Victoria, PRD 88 (2013) 094010
- G. Cacciapaglia, A. Deandrea, D. Harada, Y. Okada, JHEP 11 (2010) 159
- G. Isidori, Y. Nir, G. Perez, Ann. Rev. Nucl. Part. Sci. 60 (2010) 355

1. Model-independent bounds from $\Delta F = 2$ operators.

$$(\bar{s}_L\gamma^\mu d_L)^2 \Rightarrow \kappa^4\zeta_1\zeta_2 < 5.5\cdot 10^{-8} \Rightarrow \kappa < \frac{0.015}{\sqrt[4]{\zeta_1\zeta_2}}$$
$$(\bar{b}_L\gamma^\mu d_L)^2 \Rightarrow \kappa^4\zeta_1\zeta_3 < 2.0\cdot 10^{-7} \Rightarrow \kappa < \frac{0.02}{\sqrt[4]{\zeta_1\zeta_3}}$$
$$(\bar{b}_L\gamma^\mu s_L)^2 \Rightarrow \kappa^4\zeta_1\zeta_2 < 4.6\cdot 10^{-6} \Rightarrow \kappa < \frac{0.045}{\sqrt[4]{\zeta_2\zeta_3}}$$
$$(\bar{c}_L\gamma^\mu u_L)^2 \Rightarrow \kappa^4\zeta_1\zeta_2 < 3.4\cdot 10^{-8} \Rightarrow \kappa < \frac{0.014}{\sqrt[4]{\zeta_1\zeta_2}}$$

➡ applies to the product of the coupling to two generations (stronger)

2. Model-independent bounds from SM quarks Z couplings modifications.

$$Z\bar{u}u\,(APV) \Rightarrow |\delta g_{L/R}| < 3\times 0.00069 \to \kappa < 0.074/\sqrt{\zeta_1}$$
$$Z\bar{d}d\,(APV) \Rightarrow |\delta g_{L/R}| < 3\times 0.00062 \to \kappa < 0.07/\sqrt{\zeta_1}$$
$$Z\bar{s}s\,(LEP) \Rightarrow \begin{array}{l} |\delta g_L| < 3\times 0.012 \to \kappa < 0.3/\sqrt{\zeta_2} \\ |\delta g_R| < 3\times 0.05 \to \kappa < 0.6/\sqrt{\zeta_2} \end{array}$$
$$Z\bar{c}c\,(LEP) \Rightarrow \begin{array}{l} |\delta g_L| < 3\times 0.0036 \to \kappa < 0.17/\sqrt{\zeta_2} \\ |\delta g_R| < 3\times 0.0051 \to \kappa < 0.20/\sqrt{\zeta_2} \end{array}$$
$$Z\bar{b}b\,(LEP) \Rightarrow \begin{array}{l} |\delta g_L| < 3\times 0.0015 \to \kappa < 0.11/\sqrt{\zeta_3} \\ |\delta g_R| < 3\times 0.0063 \to \kappa < 0.23/\sqrt{\zeta_3} \end{array}$$
$$Z\bar{t}t\,(T,\ \delta g_{Wtb}) \Rightarrow \kappa < 0.1 \div 0.3/\sqrt{\zeta_3}$$

➡ applies to the coupling to a single generation (milder)

Result: selection of **6** benchmark scenarios, obtained by saturating the couplings with the current Flavour & Electroweak precision bounds.

	Benchmark 1	Benchmark 2	Benchmark 3	Benchmark 4	Benchmark 5	Benchmark 6
	$\kappa = 0.02$	$\kappa = 0.07$	$\kappa = 0.2$	$\kappa = 0.3$	$\kappa = 0.1$	$\kappa = 0.3$
	$\zeta_1 = \zeta_2 = 1/3$	$\zeta_1 = 1$	$\zeta_2 = 1$	$\zeta_3 = 1$	$\zeta_1 = \zeta_3 = 1/2$	$\zeta_2 = \zeta_3 = 1/2$

$\kappa \Longrightarrow$ Max. value of the VLQ coupling strength

$\zeta_{1,2,3} \Longrightarrow$ Branching Ratio to 1^{st}, 2^{nd} and/or 3^{rd} generation quarks

Result: selection of **6** benchmark scenarios, obtained by saturating the couplings with the current Flavour & Electroweak precision bounds.

$M = 600$ GeV ; $\sqrt{s} = 8$ TeV ; $\sigma(Q\bar{Q}) \simeq 109$ (167) fb at LO (NLO)

Inclusive cross-sections (in fb) for EW single production

		Benchmark 1 $\kappa = 0.02$ $\zeta_1 = \zeta_2 = 1/3$	Benchmark 2 $\kappa = 0.07$ $\zeta_1 = 1$	Benchmark 3 $\kappa = 0.2$ $\zeta_2 = 1$	Benchmark 4 $\kappa = 0.3$ $\zeta_3 = 1$	Benchmark 5 $\kappa = 0.1$ $\zeta_1 = \zeta_3 = 1/2$	Benchmark 6 $\kappa = 0.3$ $\zeta_2 = \zeta_3 = 1/2$
$(1,2/3)$	T	15	464	564	399	495	834
$(1,-1/3)$	B	14	455	457	167	-	-
$(2,1/6)$ $\lambda_d = 0$	T B	5.6 10	191 351	114 267	0.6 1.1	195 358	128 301
$(2,1/6)$ $\lambda_u = 0$	T B	9.5 3.7	272 103	451 190	398 166	- -	- -
$(2,1/6)$ $\lambda_d = \lambda_u$	T B	15 14	464 455	564 457	399 167	- -	- -
$(2,7/6)$	X T	15 5.6	528 191	272 114	1.2 0.6	538 195	307 128
$(2,-5/6)$	B Y	3.7 7.6	103 205	190 443	166 388	- -	- -

Result: selection of **6** benchmark scenarios, obtained by saturating the couplings with the current Flavour & Electroweak precision bounds.

$M = 600$ GeV ; $\sqrt{s} = 8$ TeV ; $\sigma(Q\bar{Q}) \simeq 109$ (167) fb at LO (NLO)

Inclusive cross-sections (in fb) for EW single production

		Benchmark 1 $\kappa = 0.02$ $\zeta_1 = \zeta_2 = 1/3$	Benchmark 2 $\kappa = 0.07$ $\zeta_1 = 1$	Benchmark 3 $\kappa = 0.2$ $\zeta_2 = 1$	Benchmark 4 $\kappa = 0.3$ $\zeta_3 = 1$	Benchmark 5 $\kappa = 0.1$ $\zeta_1 = \zeta_3 = 1/2$	Benchmark 6 $\kappa = 0.3$ $\zeta_2 = \zeta_3 = 1/2$
$(1, 2/3)$	T	15	464	564	399	495	834
$(1, -1/3)$	B	14	455	457	167	-	-
$(2, 1/6)$ $\lambda_d = 0$	T B	5.6 10	191 351	114 267	0.6 1.1	195 358	128 301
$(2, 1/6)$ $\lambda_u = 0$	T B	9.5 3.7	272 103	451 190	398 166	- -	- -
$(2, 1/6)$ $\lambda_d = \lambda_u$	T B	15 14	464 455	564 457	399 167	- -	- -
$(2, 7/6)$	X T	15 5.6	528 191	272 114	1.2 0.6	538 195	307 128
$(2, -5/6)$	B Y	3.7 7.6	103 205	190 443	166 388	- -	- -

Observation:

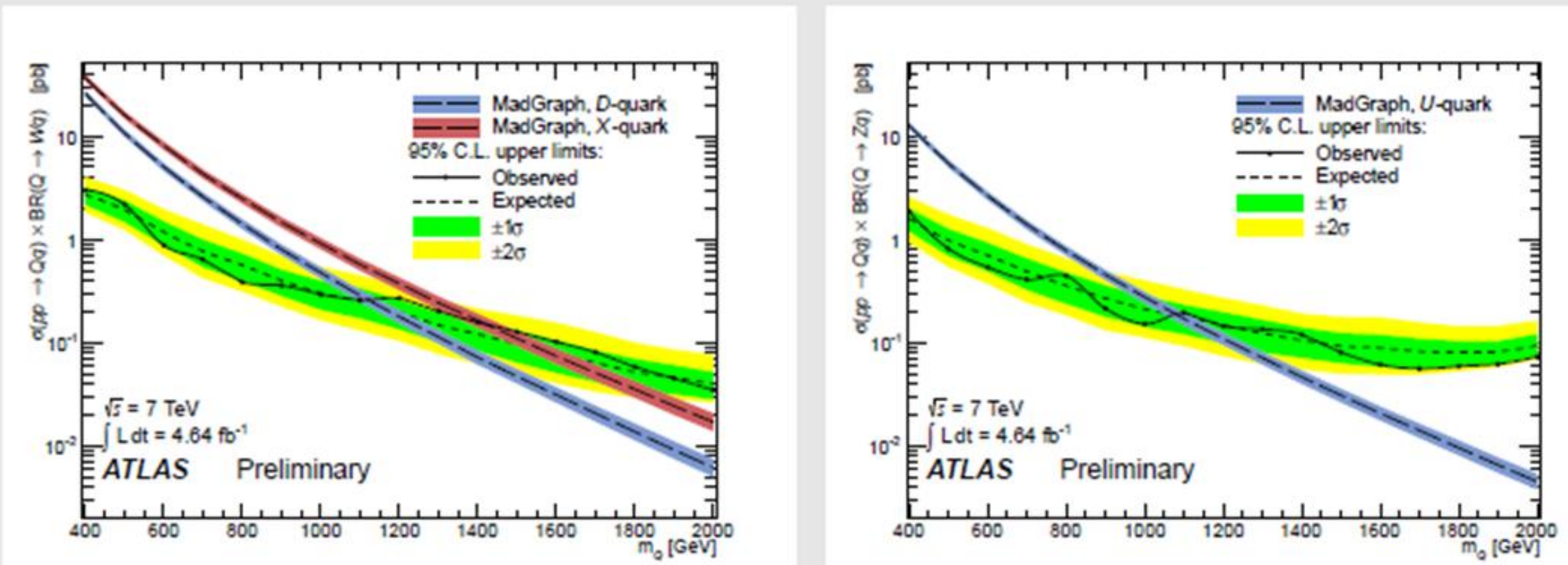
Cross-sections of similar order of magnitude are obtained in most scenarios:

- due to the valence PDFs ($1^{st}/2^{nd}$ generation couplings).
- due to weaker constraints on κ (3^{rd} generation couplings).

3. Benchmark scenarios from flavour bounds

Relevance of single production: the benchmark scenarios obtained by saturating the couplings with the constraints from precision physics indicate that the flavour bounds are competitive with the current direct searches.

ATLAS search in the CC and NC channels



Assumptions: mixing only with 1st generation and coupling strength $\kappa = \frac{v}{M_{VL}}$

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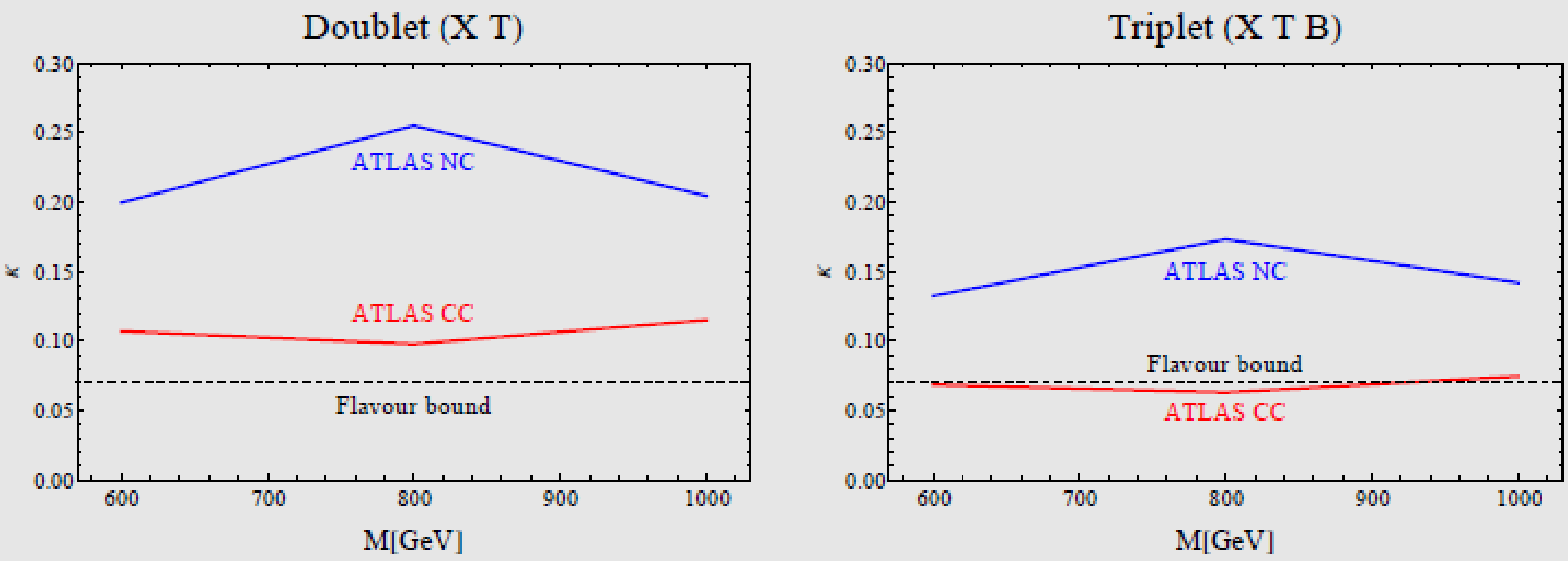
Comparison with flavour bounds



Assumptions: mixing only with 1st generation and coupling strength saturating flavour bounds

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Outline

1. Introduction.
2. Model-independent framework for VLQ searches.
3. Benchmark scenarios from flavour bounds.
4. Conclusions & prospects.

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1. *Relevance of single production:* VLQ production rates are sizeable regardless of their mixing structure with 1^{st}, 2^{nd} or 3^{rd} generation quarks. Single production followed by decays to light and third generations should therefore be considered.

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2. *Exclusive mixing hypotheses:* assuming exclusive (100%) branching ratios may forbid some VLQ single production channels.

	$\mathrm{BR}(Q \to 1^{st}, 2^{nd}) = 1$	$\mathrm{BR}(Q \to 3^{rd}) = 1$
$\mathrm{BR}(Q \to W) = 1$	TZ, TH $B\bar{t}, BZ, BH$	TZ, TH $Bj, B\bar{t}, BW, BZ, BH$
$\mathrm{BR}(Q \to Z) = 1$	$T\bar{t}, TW, TH$ $Bt, B\bar{t}, BW, BH$	Tj, TW, TZ, TH $Bt, B\bar{t}, BW, BH$
$\mathrm{BR}(Q \to H) = 1$	all channels but TH are forbidden all channels but BH are forbidden	all channels are forbidden all channels but BH are forbidden

Forbidden channels for single production with exclusive (100%) mixing patterns.
(E.g., avoid looking for $pp \to TH \to tHH$ with $\mathrm{BR}(T \to tH) = 100$ %)

3. *Relevance of "mixed"* scenarios : many final states provide very interesting, yet uncovered signatures ! Ex : $\zeta_1 = \zeta_3 = 50\%$

$$pp(uu) \rightarrow Tu \rightarrow tZu \rightarrow bWZj$$
$$pp(uu) \rightarrow Tu \rightarrow tHu \rightarrow bWHj$$
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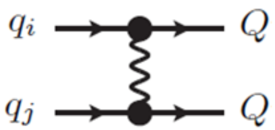
4. *Relevance of "same-sign" pair production signatures* : FCNC allow for largish QQ electroweak pair production (now used to constrain the anomalous tHu & tHc top couplings).

$$\text{Ex}: \ pp(uu) \to TT \to tZtZ \ , \ tHtH \ , \ \ldots$$



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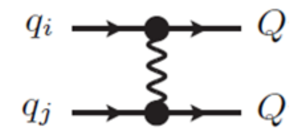

5. *Associated production with top quarks:* $pp \rightarrow Qt$ provides a very interesting final state and is worth exploring even in case of zero 3rd generation mixing.

Conclusions & Prospects

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XQCAT


Top partners ?
top
W
Z
The Standard Model
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c
b
Higgs Sea
Thanks!
The Unknown
330
340
350
360
70
65
60