Top Partners

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26^{th} Rencontres de Blois, Particle Physics and Cosmology

The Standard Model is complete (or is it?)

observational facts

Dark matter | Baryon asymmetry | Neutrino masses

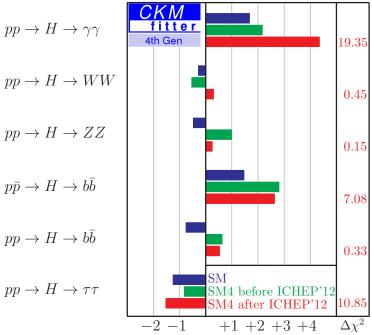
(not to mention) theoretical issues

Hierarchy problem | Origin of families | Gauge couplings unification | . . .

There must be new physics around the corner!

And with new physics, new particles come along. . .

New quarks: the chiral hypothesis



O. Eberhardt, G. Herbert, H. Lacker, A. Lenz, A. Menzel, U. Nierste, M. Wiebusch
Impact of a Higgs boson at a mass of 126 GeV on the standard model with three and four fermion generations
Phys.Rev.Lett. 109 (2012) 241802, arXiv:1209.1101

The SM + a chiral 4th generation is excluded at 4.8σ
(or 5.3σ including $H \to b\bar{b}$ at Tevatron)

Let's go for vector-like quarks

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 $SU(3)_c \times SU(2)_L \times U(1)_Y$

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

Charged current Lagrangian

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- SM chiral quarks: ONLY left-handed charged currents

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

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- vector-like quarks: BOTH left-handed and right-handed charged currents

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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

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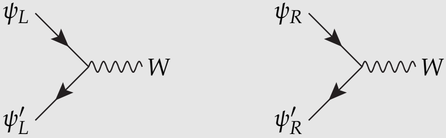
Charged currents both in the left and right sector



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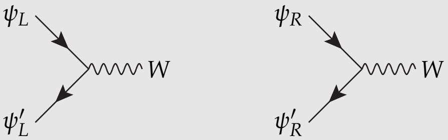

There can be **partners** of top and bottom or quarks with **exotic charges** (5/3,-4/3. . .)

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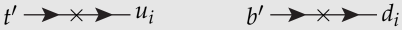
There can be **partners** of top and bottom or quarks with **exotic charges** (5/3,-4/3...)

They can mix through Yukawa couplings 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

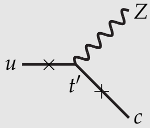
Before jumping to the LHC phenomenology...

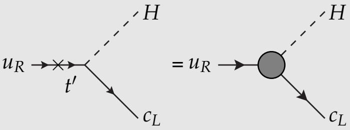
can we put any constraint on the mixing parameters?

Couplings

Major consequences

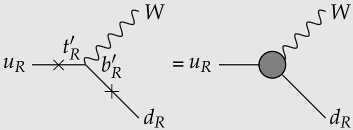
Flavour changing neutral currents in the SM





and flavour conserving neutral currents receive a contribution

Charged currents between right-handed SM quarks



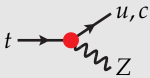
and charged currents between left-handed SM quarks receive a contribution

All proportional to combinations of mixing parameters

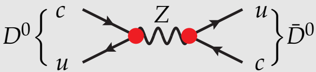
Constraints on mixing

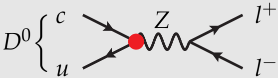
Flavour Changing Neutral Current constraints

Rare top decays



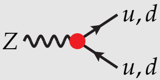
Meson mixing and decay



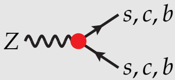


Flavour Conserving Neutral Current constraints

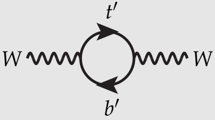
Atomic parity violation



LEP measurements



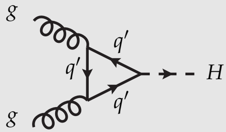
EW precision tests



CKM modifications

$$\begin{pmatrix} 3\times 3 & \cdots \\ \vdots & \ddots \end{pmatrix}_{3+N_{T'},3+N_{B'}}$$

Higgs production and decay



A remark

All these constraints are model dependent!

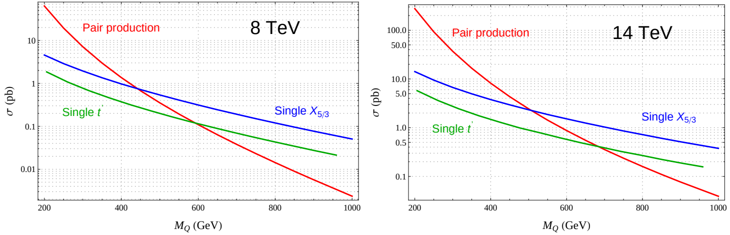
- which species of vector-like quarks are predicted in the model
  top or bottom partners or exotics
- how many vector-like quarks are predicted in the model
  just one or multiple
- which kind of couplings they are allowed to have
  only with third generation, only with light generations, combinations. . .

Searching vector-like quarks at the LHC

Production channels

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

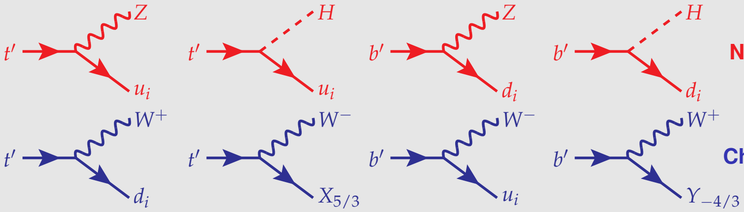
- **Pair production**, dominated by QCD and sentitive to the q' mass independently of the representation the q' belongs to
- **Single production**, only EW contributions and sensitive to both the q' mass and its mixing parameters



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

Decays

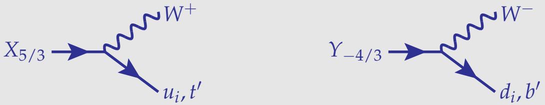
SM partners



Neutral currents

Charged currents

Exotics



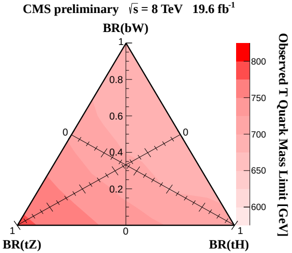
Only Charged currents

Not all decays may be kinematically allowed

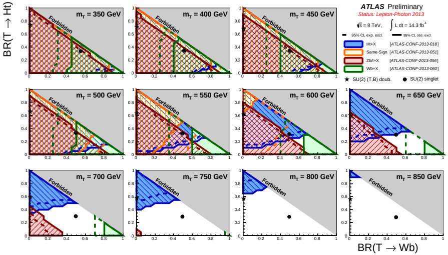
it depends on **representations** and **mass differences**

Searches at the LHC

CMS (t')



ATLAS (t')



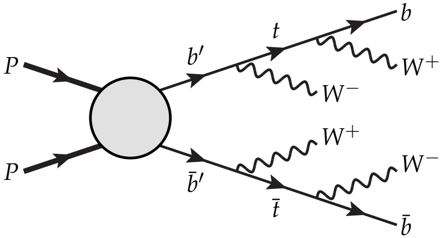
Bounds from pair production between 600 GeV and 800 GeV
depending on the decay channel

Common assumption
only one vector-like quark mixing only with third generation

While most theoretical models predict a new **quark sector**
and, in principle, mixing can be with all families

Allowing general mixing

b' pair production



Common assumption
CC: $b' \to tW$

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

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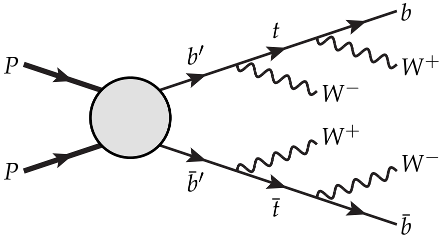

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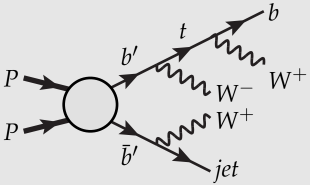
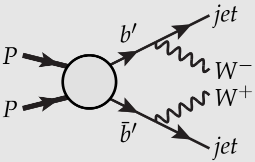
If the b' decays both into Wt and Wq

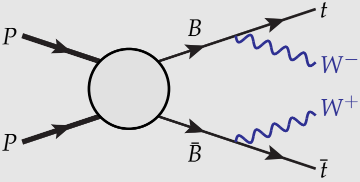


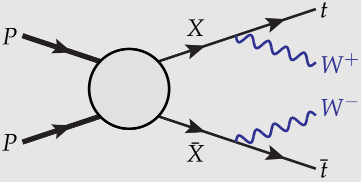


There can be less events in the same-sign dilepton channel!

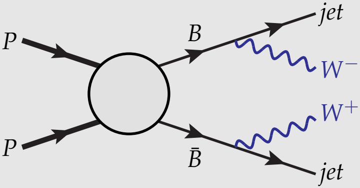
Allowing more than one VLQ

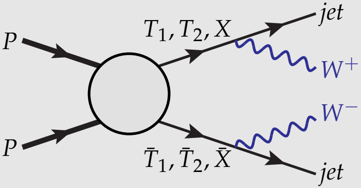
Scenario with X and B (decaying to third generation only)





Scenario with a bidoublet $\begin{pmatrix} X & T_1 \\ T_2 & B \end{pmatrix}$ (general mixing)





A given final state can be fed by different channels!
(with different kinematics)

A plethora of different signatures

Is it possible to develop model-independent approaches?

Pair Production

based on

D. Barducci, A. Belyaev, M. Buchkremer, G. Cacciapaglia,
A. Deandrea, S. De Curtis, J. Marrouche, S. Moretti and **LP**
Model Independent Framework
for Analysis of Scenarios with Multiple Heavy Extra Quarks
arXiv:1405.0737

Counting the final states

T pair production $\longrightarrow$ 6 possible decays: W^+j W^+b Zj Zt Hj Ht

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T pair production $\longrightarrow$ 6 possible decays: $W^+j \quad W^+b \quad Zj \quad Zt \quad Hj \quad Ht$

$$PP \to T\bar{T} \to \begin{pmatrix} W^+jW^-j & W^+jW^-\bar{b} & W^+jZj & W^+jZ\bar{t} & W^+jHj & W^+jH\bar{t} \\ W^+bW^-j & W^+bW^-\bar{b} & W^+bZj & W^+bZ\bar{t} & W^+bHj & W^+bH\bar{t} \\ ZjW^-j & ZjW^-\bar{b} & ZjZj & ZjZ\bar{t} & ZjHj & ZjH\bar{t} \\ ZtW^-j & ZtW^-\bar{b} & ZtZj & ZtZ\bar{t} & ZtHj & ZtH\bar{t} \\ HjW^-j & HjW^-\bar{b} & HjZj & HjZ\bar{t} & HjHj & HjH\bar{t} \\ HtW^-j & HtW^-\bar{b} & HtZj & HtZ\bar{t} & HtHj & HtH\bar{t} \end{pmatrix}$$

(only) 36 possible combinations of decays into SM particles!

each one with its peculiar kinematics

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(only) 36 possible combinations of decays into SM particles!
each one with its peculiar kinematics

B pair production $\longrightarrow$ 6 possible decays: $W^-j \quad W^-t \quad Zj \quad Zb \quad Hj \quad Hb$

36 possible combinations of decays into SM particles

X pair production $\longrightarrow$ $W^+j \quad W^+t$

4 combinations

Y pair production $\longrightarrow$ $W^-j \quad W^-b$

4 combinations

There are 80 combinations of decays of (pair produced) VLQs into SM!
each one with its kinematic properties!

Determination of efficiencies

Numerical Simulation

MadGraph, CalcHEP, ... : $PP \to Q\bar{Q} \to$ final state $\to$ Pythia: hadronization $\to$ Delphes: detector simulation $\to$ signal

Efficiencies

signal $\to$

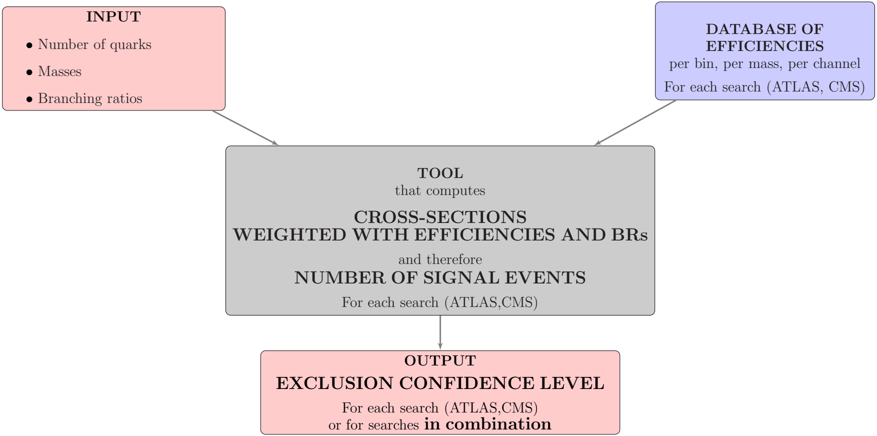
- Search 1 $\to$
  - bin 1 $\to$ efficiency 1
  - bin 2 $\to$ efficiency 2
  - ⋮
  - bin n $\to$ efficiency n
- Search 2 $\to$ Efficiencies for search 2
- ⋮
- Search N $\to$ Efficiencies for search N

Knowing the efficiencies for all combinations of final states it is possible to reconstruct any signal

Any model containing any number of VLQs can be analysed in a single framework!

Flowchart of the XQCAT project

eXtra Quark Combined Analysis Tool



Select a benchmark, i.e. number of VLQs of each charge, masses and BRs

Exclusion confidence level of the benchmark
against data from searches (any search!) using only one simulation

First results of XQCAT

Implemented searches (only CMS temporarily)

- Direct search of vector-like quarks

B2G-12-015 ($t' \to Wb, Zt, Ht$ @ 8 TeV)

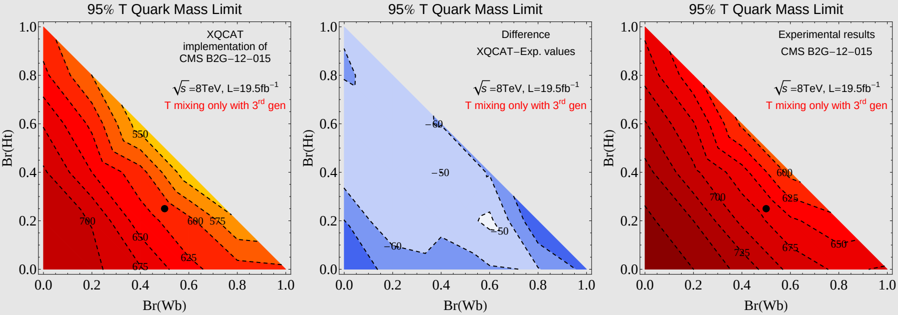
- SUSY searches (in combination!)

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

All these searches are SUSY-inspired, but it is ok: we only care about final states!

First results of XQCAT: T singlet

Validation plots: T mixing only with 3^{rd} generation



We reproduce CMS 95% CL bounds within 50-60 GeV
in the whole BR range

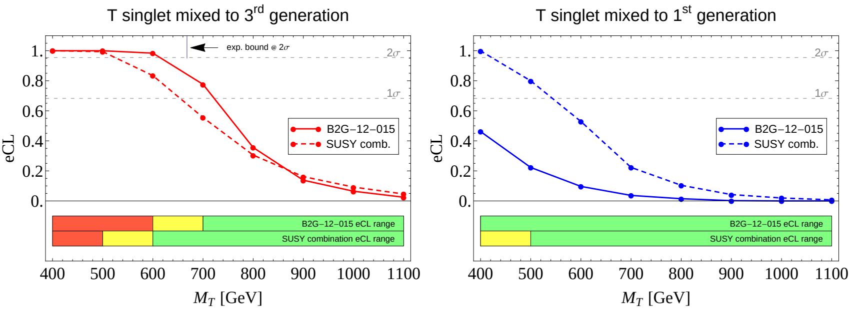
The implementation of SUSY searches has been validated in

O. Buchmuller and J. Marrouche
Universal mass limits on gluino and third-generation squarks
in the context of Natural-like SUSY spectra
Int.J.Mod.Phys. A29 (2014) 1450032, arXiv:1304.2185

First results of XQCAT: T singlet

Comparison of direct and SUSY searches

$$BR(Zq) = BR(Hq) = 25\% \qquad BR(Wq) = 50\%$$

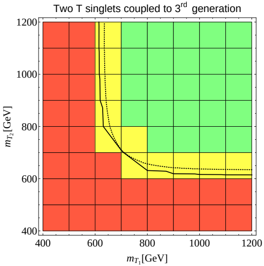


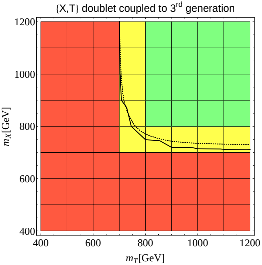
1. **Stronger bounds** when mixing with 3rd generation and in the ballpark of those obtained with **direct search**! N.B. We are not using the same analysis techniques (e.g. no shape analysis), so we cannot perfectly reproduce experimental results!!
2. Assuming **mixing with light generation**, SUSY searches are **more sensitive** than direct searches (on a cut-and-count basis)! This gap will be closed once **new experimental direct searches** of VLQs exploring these scenarios will be available (with more refined analyses)!

First results of XQCAT: multiple VLQs

Coupling with 3^{rd} generation

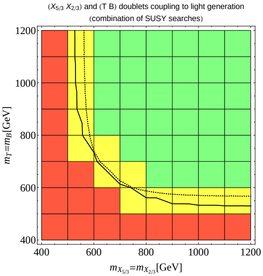
bounds using direct VLQ search





Coupling with 1^{st} generation

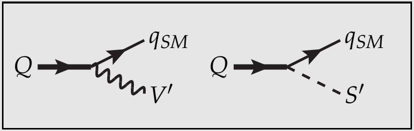
bounds using combination of SUSY searches



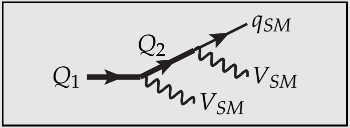
It is possible to use existing data
from **direct VLQ searches** and from **other BSM searches**
to pose conservative bounds on the parameter space
of scenarios with a new heavy quark sector

Remarks and subtleties

Chain decays

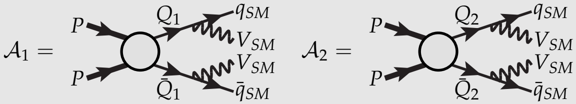


Other new sectors besides the VLQs



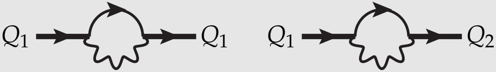
Chain decays between VLQs

Interferences



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

Mixing at loop level



Single Production

based on

M. Buchkremer, G. Cacciapaglia, A. Deandrea and **LP**
Model independent framework for searches of top partners
arXiv:1305.4172, Nucl.Phys. B876 (2013) 376-417

From couplings to BRs

Charged current of T (t')

$$\mathcal{L} \supset \kappa_W V^{4i}_{L/R} \frac{g}{\sqrt{2}} [\bar{T}_{L/R} W^+_\mu \gamma^\mu d^i_{L/R}]$$

Partial Width

$$\Gamma(T \to W d_i) = \kappa_W^2 |V^{4i}_{L/R}|^2 \frac{M^3 g^2}{64\pi m_W^2} \Gamma^0_W(M, m_W, m_{d_i} = 0)$$

Assumption: massless SM quarks, corrections for decays into top (see 1305.4172)

Branching Ratio

$$BR(T \to W d_i) = \frac{|V^{4i}_{L/R}|^2}{\sum_{j=1}^3 |V^{4j}_{L/R}|^2} \cdot \frac{\kappa_W^2 \Gamma^0_W}{\sum_{V'=W,Z,H} \kappa_{V'}^2 \Gamma^0_{V'}} \equiv \zeta_i \xi_W$$

Re-expressing the Lagrangian

$$\mathcal{L} \supset \kappa_T \sqrt{\frac{\zeta_i \xi_W}{\Gamma^0_W}} \frac{g}{\sqrt{2}} [\bar{T}_{L/R} W^+_\mu \gamma^\mu d^i_{L/R}] \quad \text{with} \quad \kappa_T = \sqrt{\sum_{i=1}^3 |V^{4i}_{L/R}|^2 \sqrt{\sum_V \kappa_V^2 \Gamma^0_V}} = \kappa \sqrt{\sum_V \kappa_V^2 \Gamma^0_V}$$

The complete Lagrangian

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

Model implemented and validated in Feynrules: http://feynrules.irmp.ucl.ac.be/wiki/VLQ

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

- T and B: NC+CC, 6 parameters each (M, κ, $\zeta_{1,2}$ and $\xi_{W,Z}$)
- X and Y: only CC, 3 parameters each (κ and$\zeta_{1,2}$)

Simplified models developed in Les Houches and available in the same Feynrules folder

Conclusions and Outlook

- After Higgs discovery, **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
  → Signatures of single and pair production of VL quarks are have been explored to some extent and current bounds on masses are around **600-800 GeV**, but searches are not fully optimized for **general scenarios** with **mixing with light generations** or **multiple vector-like quarks**.
- **Model-independent studies** can be performed for **pair** and **single production**: XQCAT, a tool for analysis of **multiple vector-like quark scenarios** has been developed and will be publicly available very soon!
  → It is possible to exploit different searches to pose bounds on **yet unexplored scenarios**!

Backup

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

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

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Mixing matrices depend on representations

- Singlets and triplets:

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

- 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

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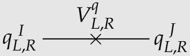
Mixing in left- and right-handed sectors behave differently

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



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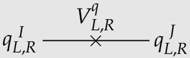

Singlets and triplets (case of up-type quarks)

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

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

Couplings

With Z

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

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

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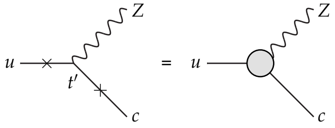
FCNC, are induced by the mixing with vector-like quarks!

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

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



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

Couplings

With $W^{\pm}$

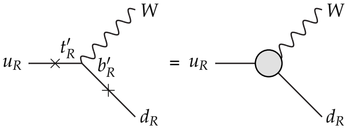
$$\mathcal{L}_{W^\pm} = \frac{g}{\sqrt{2}} (\bar{u}\ \bar{c}\ \bar{t}\ |\bar{t}')_L\, (V_L^u)^\dagger \left(\begin{array}{c|c} \tilde{V}_L^{CKM} & \\ \hline & 1 \end{array}\right) \gamma^\mu V_L^d \begin{pmatrix} d \\ s \\ b \\ \hline b' \end{pmatrix}_L W_\mu^+$$

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

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

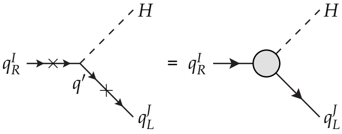
$$\mathcal{L}_h = \frac{1}{v}\,(\bar{q}_1\ \bar{q}_2\ \bar{q}_3\ \bar{q}'_1)_L\,(V_L^q)^\dagger \left[\mathcal{M}_q - M \begin{pmatrix} 0 & & & \\ & 0 & & \\ & & 0 & \\ & & & 1 \end{pmatrix}\right] (V_R^q) \begin{pmatrix} q_1 \\ q_2 \\ q_3 \\ q' \end{pmatrix}_R h + h.c.$$

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!

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



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

The exclusion confidence level

Observation	Background
310 events	300 events

The exclusion confidence level

Observation

310 events

Background

300 events

Signal

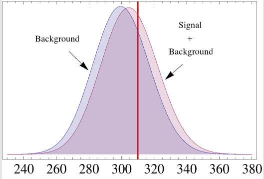
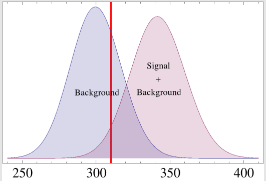
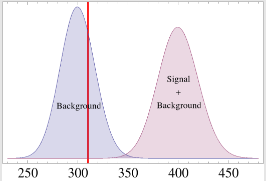
Case I: 5 events	Case II: 42 events	Case III: 100 events
		
Exclusion CL $\simeq$ 14%	Exclusion CL $\simeq$ 94%	Exclusion CL $\simeq$ 99.99%

Chart labels, Case I: Background; Signal + Background; axis 240, 260, 280, 300, 320, 340, 360, 380

Chart labels, Case II: Background; Signal + Background; axis 250, 300, 350, 400

Chart labels, Case III: Background; Signal + Background; axis 250, 300, 350, 400, 450

$$\text{Exclusion CL} = 1 - \frac{\text{CL(s+b)}}{\text{CL(b)}} = 1 - \frac{\text{p-value(s+b)}}{1 - \text{p-value(b)}}$$

Remarks and subtleties

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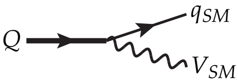
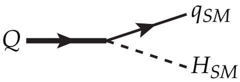
We only consider these topologies





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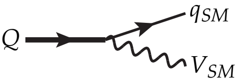
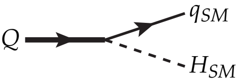
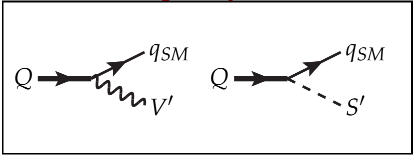
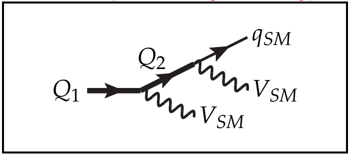




The following decays have not been considered (model-dependency)



Other new sectors besides the VLQs



Chain decays between VLQs

A dedicated simulation is required for these channels

But if a benchmark is already excluded by this analysis, adding new channels would only increase the exclusion confidence level. The signal of new physics is, at worst, underestimated, therefore an “exclusion” result is **robust**!

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- **Role of interferences**: if there is more than one VLQ with same charge and with close masses and/or widths, the interference effects at the level of amplitude squared cannot be neglected.

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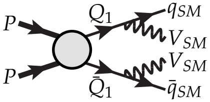
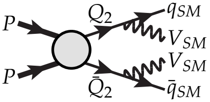
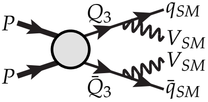
$\mathcal{A}_1 =$ 

$\mathcal{A}_2 =$ 

$\mathcal{A}_3 =$ 

$$\sigma \propto |\mathcal{A}_1|^2 + |\mathcal{A}_2|^2 + |\mathcal{A}_3|^2 + 2Re\left[\mathcal{A}_1\mathcal{A}_2^* + \mathcal{A}_1\mathcal{A}_3^* + \mathcal{A}_2\mathcal{A}_3^*\right]$$

It is possible to estimate the interference effect knowing the total widths and couplings to SM particles!

$$\sigma'_Q(M_i) = \sigma_Q(M_i)\left(1 + \sum_{j\neq i}^{n_Q} y_{ij}\right) \quad \text{with} \quad y_{ij} = \frac{2Re\left[g_a g_b^* g_c g_d^* \left(\int \mathcal{P}_i \mathcal{P}_j^*\right)^2\right]}{g_a^2 g_b^2 \left(\int \mathcal{P}_i \mathcal{P}_i^*\right)^2 + g_c^2 g_d^2 \left(\int \mathcal{P}_j \mathcal{P}_j^*\right)^2}$$

This expression describes with remarkable accuracy the interference effects in the NWA approximation

Remarks and subtleties

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- **Role of interferences**: if there is more than one VLQ with same charge and with close masses and/or widths, the interference effects at the level of amplitude squared cannot be neglected.
- **Role of quantum mixing between states**: if there is more than one VLQ with same charge and with close masses and/or widths, the mixing at loop level can affect the cross-section.

Remarks and subtleties

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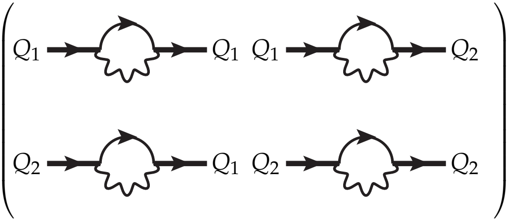
Diagonalisation of the matrix of the propagators

$i\Delta_{ij} =$



The matrix is model-dependent:
any particle (also new ones) can enter the loops!!

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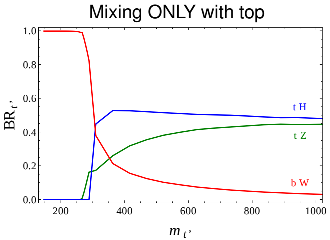
It's crucial to take into account these issues in order not to overestimate the signal!

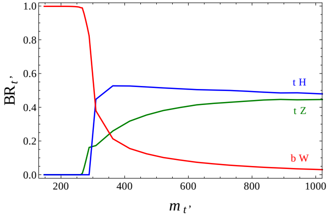
Decays of t'



Equivalence theorem at large masses:
$BR(qH) \simeq BR(qZ)$

Decays of t'

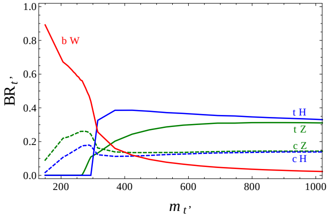
Mixing ONLY with top



Equivalence theorem at large masses:
$BR(qH) \simeq BR(qZ)$

Decay to lighter generations can be sizable even with small Yukawas!

Mixing with top and charm



Mixing ONLY with charm