XQCAT: Model independent analysis of heavy vector-like top partners

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XQCAT in a nutshell

XQCAT = eXtra Quark Combined Analysis Tool
https://launchpad.net/xqcat

1) 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 [hep-ph]** (submitted to JHEP)

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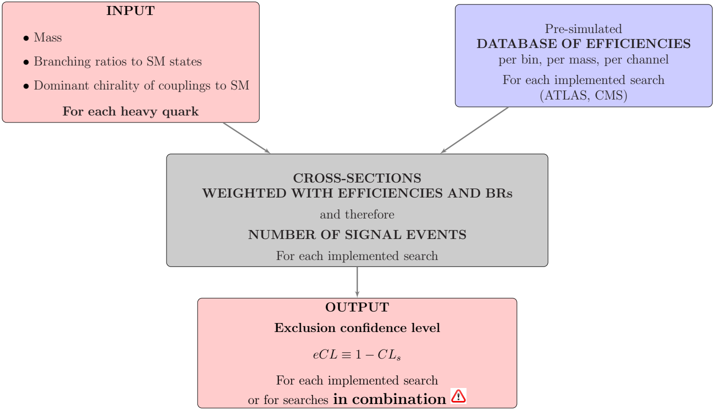

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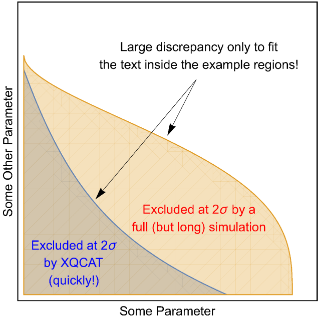
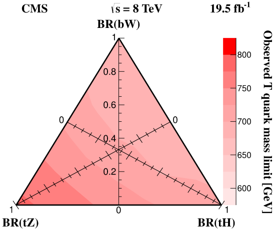


Searches at the LHC

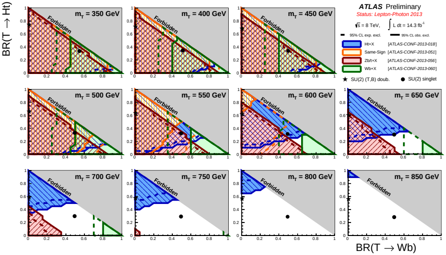
CMS (t')

Phys. Lett. B 729 (2014) 149



ATLAS (t')

ATLAS twiki: summary plots



Bounds from **pair production** in the 600-800 GeV range
depending on the extra quark and on its decay channels

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

Few exceptions to the common assumptions to date:

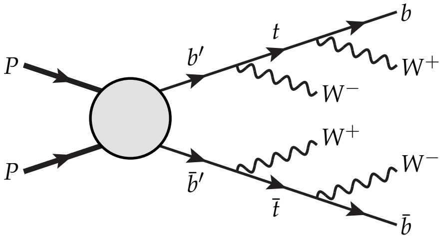
- ATLAS-CONF-2012-137: single production, mixing with first generation only (bounds above the TeV, but coupling-dependent)
- ATLAS-CONF-2014-036: pair+single production, mixing with third generation only (bounds still in the 600-800 GeV range)

XQCAT motivations

1 New physics may be hidden where we haven't searched it yet: extra quarks may have different **mixing patterns**

Allowing general mixing

b' pair production



Searches in the
same-sign dilepton channel
with one or more b-jets

Allowing general mixing

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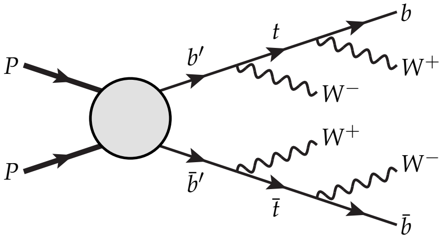

Searches in the
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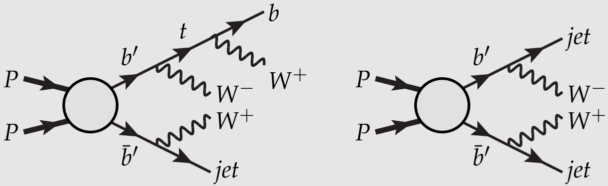
If the b' decays both into Wt and Wq



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

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1 New physics may be hidden where we haven't searched it yet: extra quarks may have different **mixing patterns**

If extra quarks interact also (or only) with light generations can I derive bounds on their masses from experimental data?

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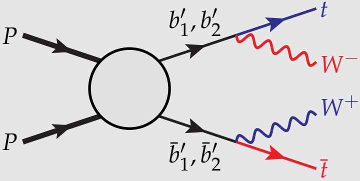
2 Theoretical models predict in general **multiple new quarks**, which may have similar masses, but different charges and different mixing properties

Allowing more than one VLQ

Case 1: two extra quarks of the <u>same</u> species



Different kinematics
if quark masses are different

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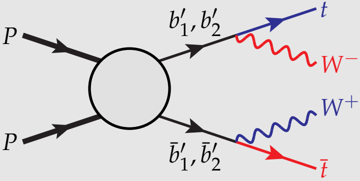

Different kinematics
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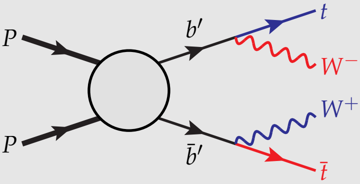
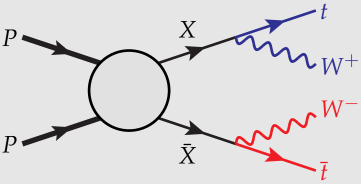
Case 2: two extra quarks of <u>different</u> species





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

XQCAT motivations

1

New physics may be hidden where we haven't searched it yet:
extra quarks may have different **mixing patterns**

If extra quarks interact also (or only) with light generations
can I derive bounds on their masses from experimental data?

2

Theoretical models predict in general **multiple new quarks**, which may have similar masses, but different charges and different mixing properties

How can I estimate the excluded regions of parameter space of a model which contains more than one extra quark?

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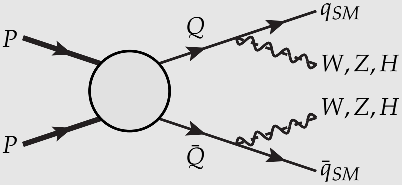
Straightforward answer to both questions

Perform a complete simulation for each scenario that we want to test
and apply the selection and kinematical cuts of the experimental searches

Time consuming ✗ Model dependent ✗ Not efficient for scans ✗

XQCAT approach

QCD pair production + decay



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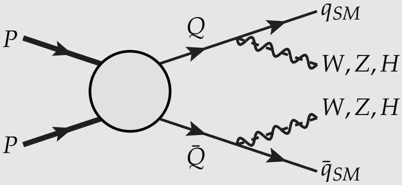

- The production process depends only on the **mass** of the extra quark

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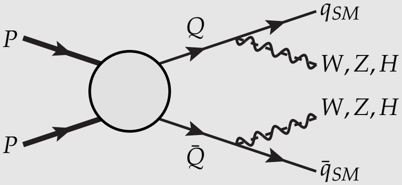

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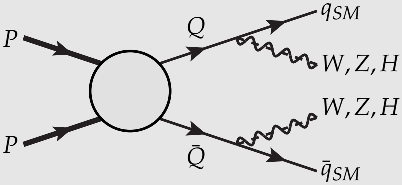

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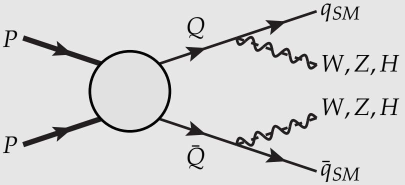
- The **number of decay channels is limited** (and reasonably small) and they all have **different kinematics**
- If one determines the **efficiencies** associated to specific **selection and kinematical cuts** for all decay channels the number of **signal events** for any spectrum can be derived through **simple algebra!**

$$N_S = L_{exp} \sum_Q \sigma_{QCD}(m_Q) \sum_{ij} BR_i(Q) BR_j(\bar{Q}) \epsilon_{ij}$$

XQCAT approach

QCD pair production + decay



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- Knowing (from experiment!) the **background and observed events** it is possible to determine the likelihood of the signal, and therefore its **exclusion confidence level**

$$eCL \equiv 1 - CL_s$$

Counting the final states

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

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

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

each one with its peculiar kinematics

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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!

Generation of the efficiency database

Numerical Simulation

$PP \rightarrow Q\bar{Q} \rightarrow q_{SM}, V_{SM}, H_{SM}$ MadGraph $\longrightarrow$ Hadronization and PS Pythia $\longrightarrow$ Detector Simulation Delphes

Signal

$\downarrow$

1st search

bin 1 $\rightarrow$ ϵ_1, bin 2 $\rightarrow$ ϵ_2, bin n_1 $\rightarrow$ ϵ_{n_1}

2nd search

bin 1 $\rightarrow$ ϵ_1, bin 2 $\rightarrow$ ϵ_2, bin n_2 $\rightarrow$ ϵ_{n_2}

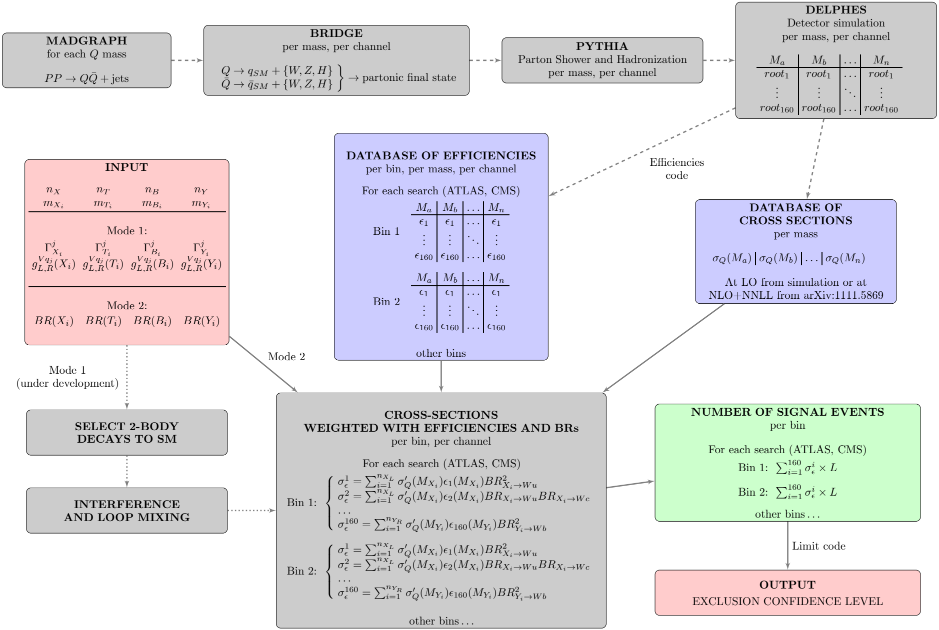
...

Nth search

bin 1 $\rightarrow$ ϵ_1, bin 2 $\rightarrow$ ϵ_2, bin n_N $\rightarrow$ ϵ_{n_N}

$\downarrow$

Database of Efficiencies


MADGRAPH
for each Q mass
$PP \to Q\bar{Q} + \text{jets}$
BRIDGE
per mass, per channel
$Q \to q_{SM} + \{W, Z, H\}$
$\bar{Q} \to \bar{q}_{SM} + \{W, Z, H\}$
→ partonic final state
PYTHIA
Parton Shower and Hadronization
per mass, per channel
DELPHES
Detector simulation
per mass, per channel
M_a | M_b | ... | M_n
$root_1$ | $root_1$ | ... | $root_1$
$root_{160}$ | $root_{160}$ | ... | $root_{160}$
Efficiencies
code
INPUT
n_X n_T n_B n_Y
m_{X_i} m_{T_i} m_{B_i} m_{Y_i}
Mode 1:
$\Gamma^j_{X_i}$ $\Gamma^j_{T_i}$ $\Gamma^j_{B_i}$ $\Gamma^j_{Y_i}$
$g^{Vq_j}_{L,R}(X_i)$ $g^{Vq_j}_{L,R}(T_i)$ $g^{Vq_j}_{L,R}(B_i)$ $g^{Vq_j}_{L,R}(Y_i)$
Mode 2:
$BR(X_i)$ $BR(T_i)$ $BR(B_i)$ $BR(Y_i)$
DATABASE OF EFFICIENCIES
per bin, per mass, per channel
For each search (ATLAS, CMS)
Bin 1
M_a | M_b | ... | M_n
ϵ_1 | ϵ_1 | ... | ϵ_1
ϵ_{160} | ϵ_{160} | ... | ϵ_{160}
Bin 2
M_a | M_b | ... | M_n
ϵ_1 | ϵ_1 | ... | ϵ_1
ϵ_{160} | ϵ_{160} | ... | ϵ_{160}
other bins
DATABASE OF
CROSS SECTIONS
per mass
$\sigma_Q(M_a) \mid \sigma_Q(M_b) \mid \ldots \mid \sigma_Q(M_n)$
At LO from simulation or at
NLO+NNLL from arXiv:1111.5869
Mode 2
Mode 1
(under development)
SELECT 2-BODY
DECAYS TO SM
INTERFERENCE
AND LOOP MIXING
CROSS-SECTIONS
WEIGHTED WITH EFFICIENCIES AND BRs
per bin, per channel
For each search (ATLAS, CMS)
Bin 1:
$\sigma^1_\epsilon = \sum_{i=1}^{n_{X_L}} \sigma'_Q(M_{X_i})\epsilon_1(M_{X_i})BR^2_{X_i \to Wu}$
$\sigma^2_\epsilon = \sum_{i=1}^{n_{X_L}} \sigma'_Q(M_{X_i})\epsilon_2(M_{X_i})BR_{X_i \to Wu}BR_{X_i \to Wc}$
...
$\sigma^{160}_\epsilon = \sum_{i=1}^{n_{Y_R}} \sigma'_Q(M_{Y_i})\epsilon_{160}(M_{Y_i})BR^2_{Y_i \to Wb}$
Bin 2:
$\sigma^1_\epsilon = \sum_{i=1}^{n_{X_L}} \sigma'_Q(M_{X_i})\epsilon_1(M_{X_i})BR^2_{X_i \to Wu}$
$\sigma^2_\epsilon = \sum_{i=1}^{n_{X_L}} \sigma'_Q(M_{X_i})\epsilon_2(M_{X_i})BR_{X_i \to Wu}BR_{X_i \to Wc}$
...
$\sigma^{160}_\epsilon = \sum_{i=1}^{n_{Y_R}} \sigma'_Q(M_{Y_i})\epsilon_{160}(M_{Y_i})BR^2_{Y_i \to Wb}$
other bins...
NUMBER OF SIGNAL EVENTS
per bin
For each search (ATLAS, CMS)
Bin 1: $\sum_{i=1}^{160} \sigma^i_\epsilon \times L$
Bin 2: $\sum_{i=1}^{160} \sigma^i_\epsilon \times L$
other bins...
Limit code
OUTPUT
EXCLUSION CONFIDENCE LEVEL

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)

See Gerrit's talk for more details about this search

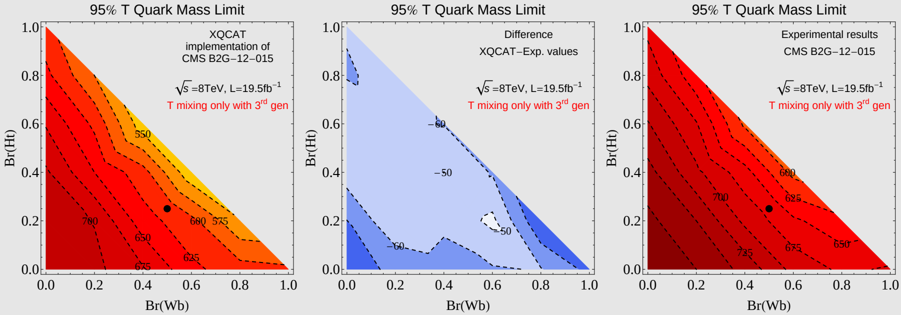
- SUSY searches (in combination!)

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: 1 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 **(including their combination!)** has been validated in

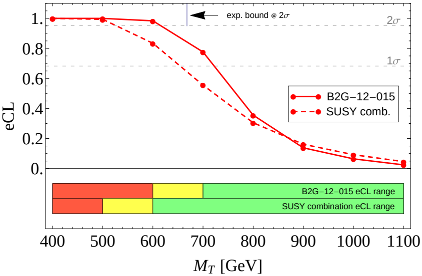
O. Buchmuller and J. Marrouche, Int.J.Mod.Phys. A29 (2014) 1450032, arXiv:1304.2185

First results of XQCAT: 1 T singlet

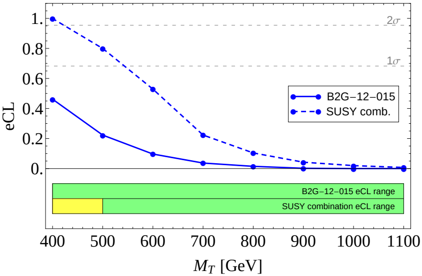
but with different mixing structure

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

T singlet mixing with 3[rd] generation

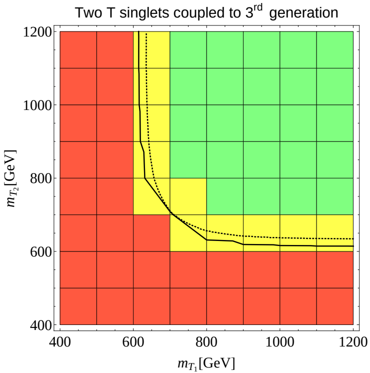


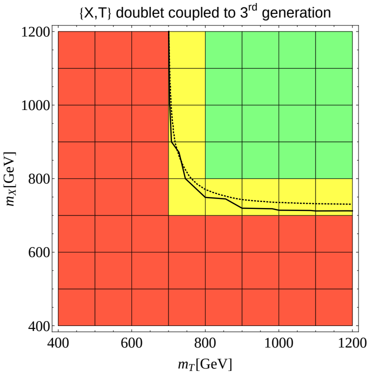
T singlet mixing with 1[st] generation



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 quarks





Bounds obtained using the direct VLQ search B2G-12-015

General conclusions

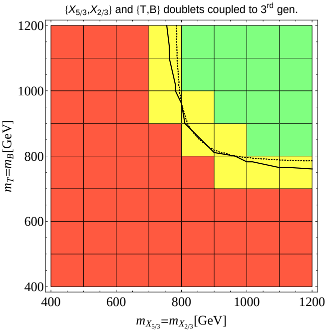
1. The presence of multiple extra quarks can give heavier mass bounds
2. Dedicated searches for a given quark species may constrain other ones

First results of XQCAT: multiple quarks

Considering physically motivated scenarios

Composite (pseudo) Goldstone boson Higgs model
De Simone et al., *A first top partner hunters guide*, arXiv:1211.5663 [hep-ph]

SO(4) quadruplet $\begin{pmatrix} X_{5/3} & t' \\ X_{2/3} & b' \end{pmatrix}$ $\begin{cases} BR(X_{5/3} \to Wb) = BR(b' \to Wt) = 100\% \\ BR(X_{2/3} \to Zt) = BR(X_{2/3} \to Ht) = 50\% \\ BR(t' \to Zt) = BR(t' \to Ht) = 50\% \end{cases}$



General conclusions

1. The presence of multiple extra quarks raises the bounds to the 900-1000 GeV range
2. Models with extra content can be more constrained

Bounds obtained using the direct VLQ search B2G-12-015

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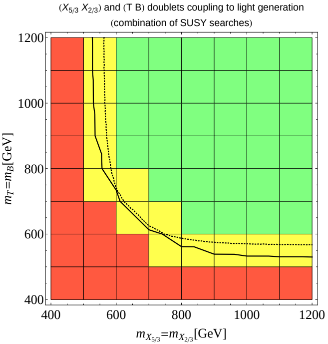
Considering physically motivated scenarios

Composite (pseudo) Goldstone boson Higgs model

De Simone et al., *A first top partner hunters guide*, arXiv:1211.5663 [hep-ph]

But now let's assume mixing only with light generation!

SO(4) quadruplet $\begin{pmatrix} X_{5/3} & t' \\ X_{2/3} & b' \end{pmatrix}$ $\begin{cases} BR(X_{5/3} \to Wj) = BR(b' \to Wj) = 100\% \\ BR(X_{2/3} \to Zj) = BR(X_{2/3} \to Hj) = 50\% \\ BR(t' \to Zj) = BR(t' \to Hj) = 50\% \end{cases}$



General conclusions

1. Models with multiple extra quarks but non-standard mixing patterns can already be constrained even if no dedicated searches are available
2. Reinterpretation of searches not designed for extra quarks can be a powerful instrument to help designing future searches

Bounds obtained using a combination of SUSY searches

A digression on interpolation

- The simulation has **discrete steps**: the mass of the extra quarks runs from 400 GeV to 2 TeV **steps of 100 GeV**
- **Information** on the efficiencies for points not simulated is **missing**
- A generic spectrum contains extra quarks with values of masses that **have not been simulated**

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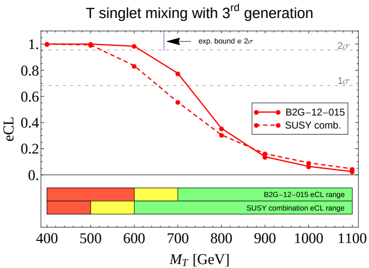
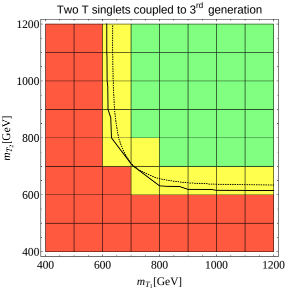
How does XQCAT interpolate?

A digression on interpolation

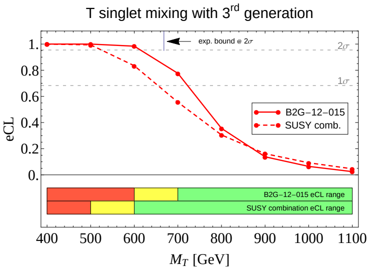


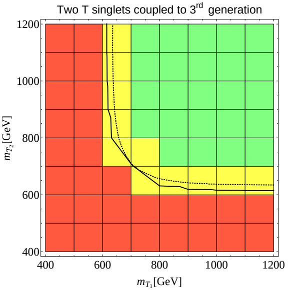


1. **Interpolation of efficiencies:** run XQCAT for the given spectrum, with the exact values of the extra quark masses. The code interpolates between the efficiencies of the nearest simulated masses. Quick but **fluctuations** in the efficiencies have to be **small** between the simulated values!

$$\epsilon(k, m_Q) = \epsilon(k, m^{\downarrow}) \frac{m^{\uparrow} - m_Q}{m^{\uparrow} - m^{\downarrow}} + \epsilon(k, m^{\uparrow}) \frac{m_Q - m^{\downarrow}}{m^{\uparrow} - m^{\downarrow}}$$

A digression on interpolation





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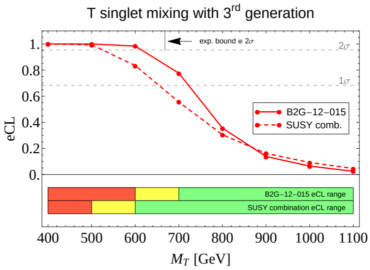
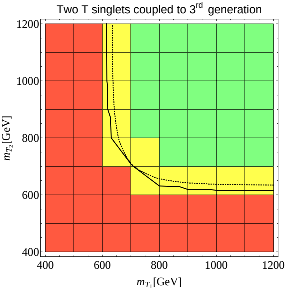
2. **Determination of a range for the exclusion confidence levels:** for a given spectrum with N extra quark, compute the eCLs in all the vertices of the N-dimensional cube, corresponding to the closest simulated masses. Longer, but the most conservative approach!

A digression on interpolation





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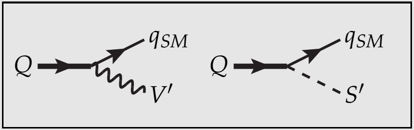
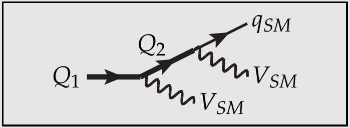
3. **Interpolation of the exclusion confidence levels**: the same as before, but the eCL of the test-point is the interpolation of the eCLs in the vertices of the N-dimensional cube. Longer, and **fluctuations** in the efficiencies have to be **small**!

Remarks and subtleties

Chain decays

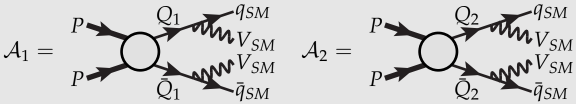


Other new sectors besides the VLQs



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

Conclusions and Outlook

- **XQCAT** (eXtra Quark Combined Analysis Tool) is a tool aimed to determine **exclusion Confidence Levels** for scenarios with the presence of **one or multiple extra extra quarks** which interact through Yukawa couplings with **any** of the Standard Model quarks.
- The code exploits a **database of efficiencies** for pre-simulated processes of QCD pair production and decays of the extra quarks.

https://launchpad.net/xqcat

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- **XQCAT** (eXtra Quark Combined Analysis Tool) is a tool aimed to determine **exclusion Confidence Levels** for scenarios with the presence of **one or multiple extra extra quarks** which interact through Yukawa couplings with **any** of the Standard Model quarks.
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What's next (in pseudo-random order)

- Upgrade to **Delphes 3** and implementation of **further experimental searches**
- Inclusion of decays into **Dark Matter** particles
- Inclusion of **interference and loop effects in pair production**
- Inclusion of **single production** processes in the simulation (see Mathieu's talk)
  - ⟶ check if couplings comply with **flavour bounds**, **EWPT**. . .)
  - ⟶ inclusion of **interference and loop effects in single production**
- (Possibly) Inclusion of **chain decays** between VLQs
- Generalisation of the procedure for **different states** (extra vectors, extra scalars, . . .)

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

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

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

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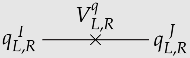
Mixing in left- and right-handed sectors behave differently

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



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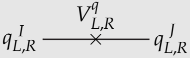

Singlets and triplets (case of up-type quarks)

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

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

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

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

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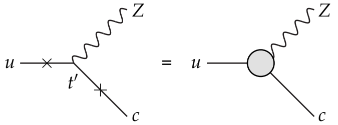
FCNC, are induced by the mixing with vector-like quarks!

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

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



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

Couplings

With $W^{\pm}$

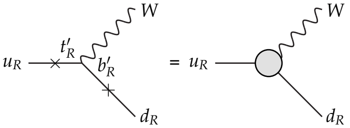
$$\mathcal{L}_{W^\pm} = \frac{g}{\sqrt{2}} (\bar{u}\ \bar{c}\ \bar{t}\ |\bar{t}')_L\ (V_L^u)^\dagger \left(\begin{array}{c|c} \tilde{V}_L^{CKM} & \\ \hline & 1 \end{array}\right) \gamma^\mu V_L^d \begin{pmatrix} d \\ s \\ b \\ \hline b' \end{pmatrix}_L W_\mu^+$$

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

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

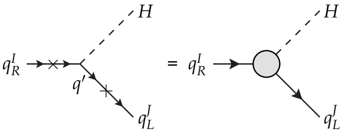
$$\mathcal{L}_h = \frac{1}{v}\,(\bar{q}_1\;\bar{q}_2\;\bar{q}_3\;\bar{q}'_1)_L\,(V_L^q)^\dagger \left[\mathcal{M}_q - M\begin{pmatrix}0 & & & \\ & 0 & & \\ & & 0 & \\ & & & 1\end{pmatrix}\right](V_R^q)\begin{pmatrix}q_1\\ q_2\\ q_3\\ q'\end{pmatrix}_R h + h.c.$$

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

310 events

Background

300 events

The exclusion confidence level

Observation

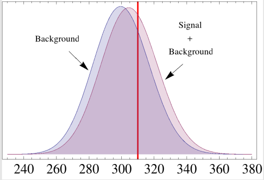
310 events

Background

300 events

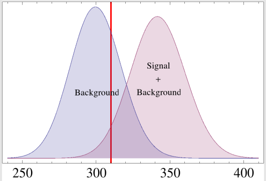
Signal

Case I: 5 events



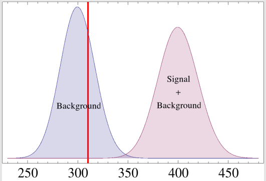
Exclusion CL $\simeq$ 14%

Case II: 42 events



Exclusion CL $\simeq$ 94%

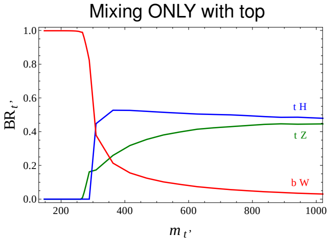
Case III: 100 events



Exclusion CL $\simeq$ 99.99%

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

Decays of t'



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

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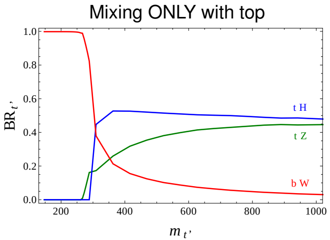

Equivalence theorem at large masses:
$BR(qH) \simeq BR(qZ)$

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