XQCAT: a model independent analysis of new heavy quarks at the LHC

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Outline

1. Motivations

2. Interactions with Standard Model states

3. Interactions with Dark Matter

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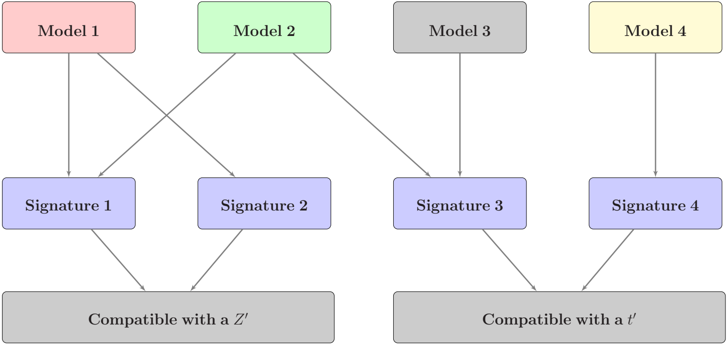
Looking for new physics at the LHC

A bottom-up approach



Model 1

Model 2

Model 3

Model 4

Signature 1

Signature 2

Signature 3

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Compatible with a Z'

Compatible with a t'

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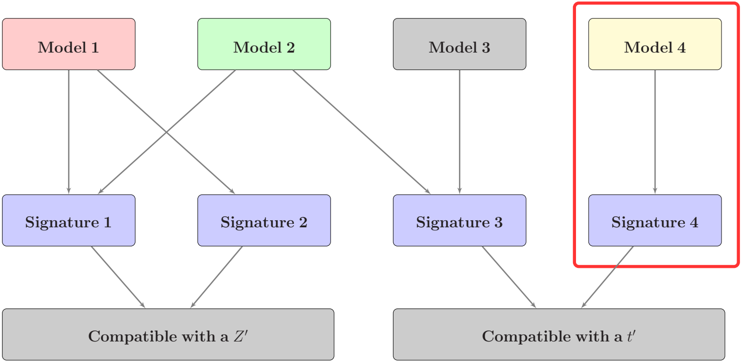

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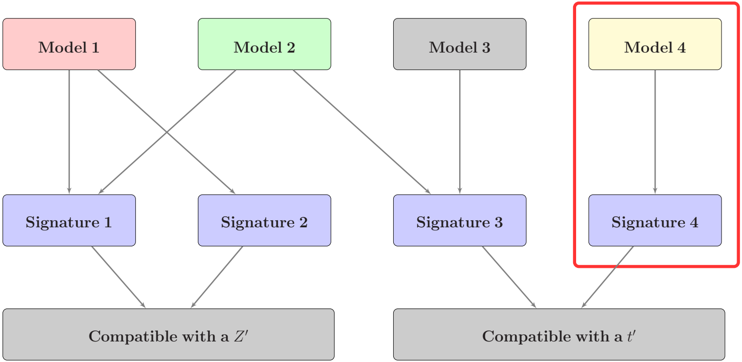

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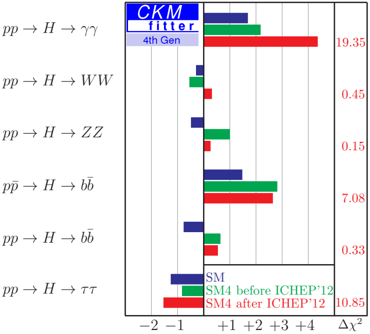
Compatible with a t'

Designing searches or simulating signals to test specific models is a risky bet

Model-independent approach

The LHC is a hadron collider, let's look for new coloured particles!

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

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 quarks?

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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Peculiar Properties

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

Charged currents both in the left and right sector

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Charged current Lagrangian

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- SM chiral quarks: ONLY left-handed charged currents

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

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

$$J^{\mu +} = J^{\mu +}_L + J^{\mu +}_R = \bar{u}_L \gamma^\mu d_L + \bar{u}_R \gamma^\mu d_R = \bar{u} \gamma^\mu d = V$$

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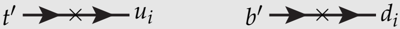
Vector-like quarks in many models of New Physics

- 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 VL quarks

They can mix with SM quarks through Yukawa couplings



Dangerous FCNCs $\longrightarrow$ strong bounds on mixing parameters

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

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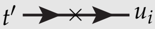
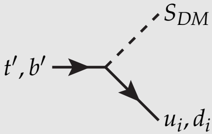


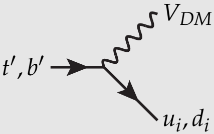
Dangerous FCNCs ⟶ strong bounds on mixing parameters

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

OR (but not both)

They can mediate Dark Matter production





Only **top and bottom partners** are allowed (up to 4-dim operators)

They must be odd under the Z_2 parity of DM ⟶ they **cannot** decay only in SM states

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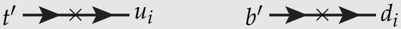

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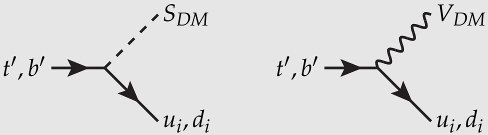

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Many open channels for **production** and **decay** of heavy quarks

Rich phenomenology to explore at LHC

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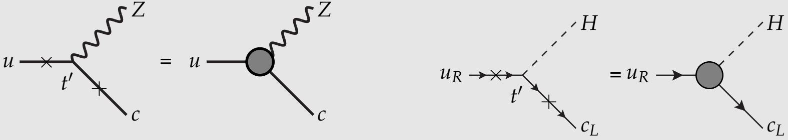
Couplings

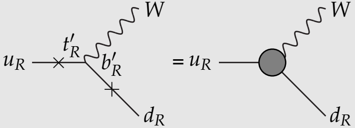
Major consequences

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 parameters

- Flavour changing neutral currents
  - Rare top decays ($t \to Zu$ or $t \to Zc$ at tree level)
  - Meson mixing and decays (e.g. $D^0 \to \bar{D}^0$ at tree level via Z exchange)

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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. . .

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Mixing and number of vector-like quarks as FREE parameters
for **model independent** LHC phenomenology

Signatures at the LHC

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]**, JHEP 1412 (2014) 080

2) D. Barducci, A. Belyaev, M. Buchkremer, J. Marrouche, S. Moretti and **LP**, XQCAT: eXtra Quark Combined Analysis Tool, **arXiv:1409.3116**, submitted to Comp. Phys. Comm.

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- Estimate in a **conservative** and **quick** way the **excluded regions** in the parameter space of models containing **one or multiple** extra quarks

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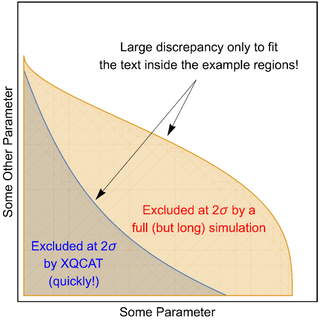
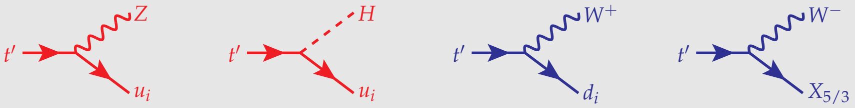


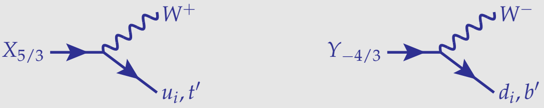
Production and decay channels

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

SM partners



Exotics



Only Charged currents

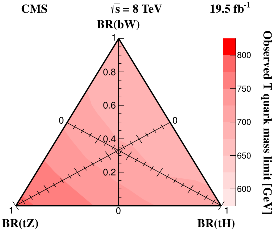
Not all decays may be kinematically allowed

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

Searches at the LHC

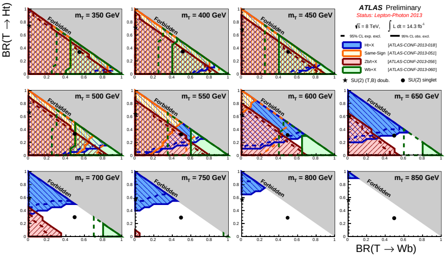
CMS (t')

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 extra 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)
- CMS-PAS-B2G-12-017: pair production, mixing either with 3rd or light gen. (bounds around 800 GeV for the light gen. mixing)

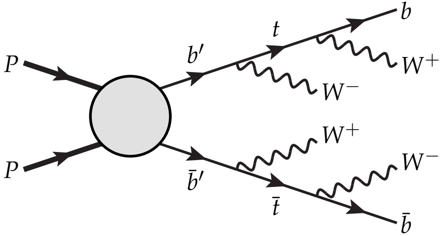
XQCAT motivations

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

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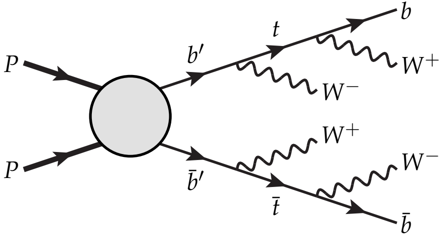

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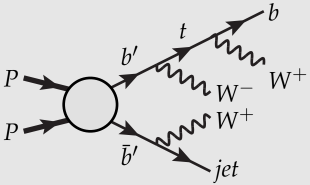
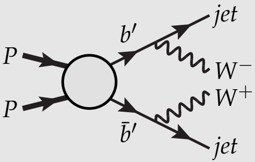
If the b' decays both into Wt and Wq





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

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

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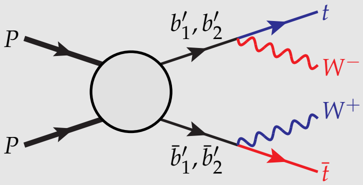
Theoretical models predict in general **multiple new quarks**, which may have similar masses, but different charges and different mixing properties

Allowing more than one VLQ

Case 1: two extra quarks of the same species



Different kinematics
if quark masses are different

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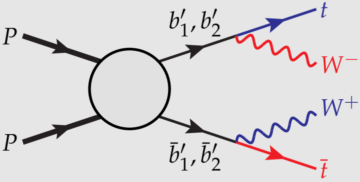

Different kinematics
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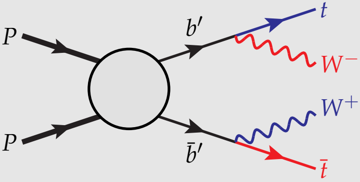
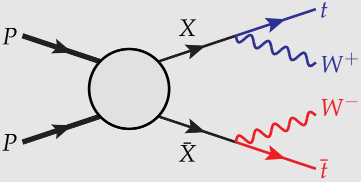
Case 2: two extra quarks of different species





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

XQCAT motivations

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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?

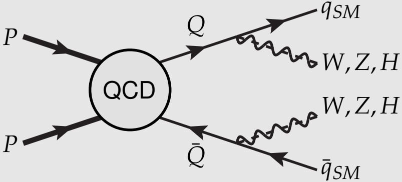
Straightforward answer to both questions

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

Time consuming ✗ Model dependent ✗ Not efficient for scans ✗

XQCAT approach

QCD pair production + decay



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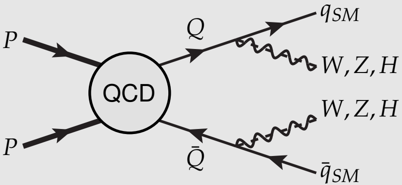
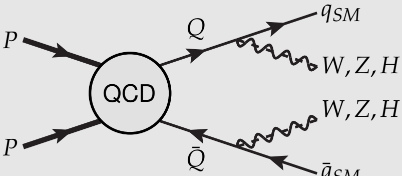


- The production process depends only on the **mass** of the extra quark
- The **number of decay channels is limited** (and reasonably small) and they all have **different kinematics**

XQCAT approach

QCD pair production + decay

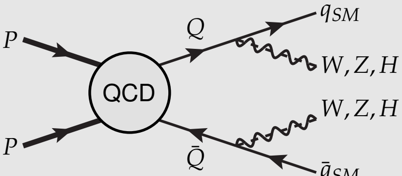


- The production process depends only on the **mass** of the extra quark
- The **number of decay channels is limited** (and reasonably small) and they all have **different kinematics**
- If one determines the **efficiencies** associated to specific **selection and kinematical cuts** for all decay channels 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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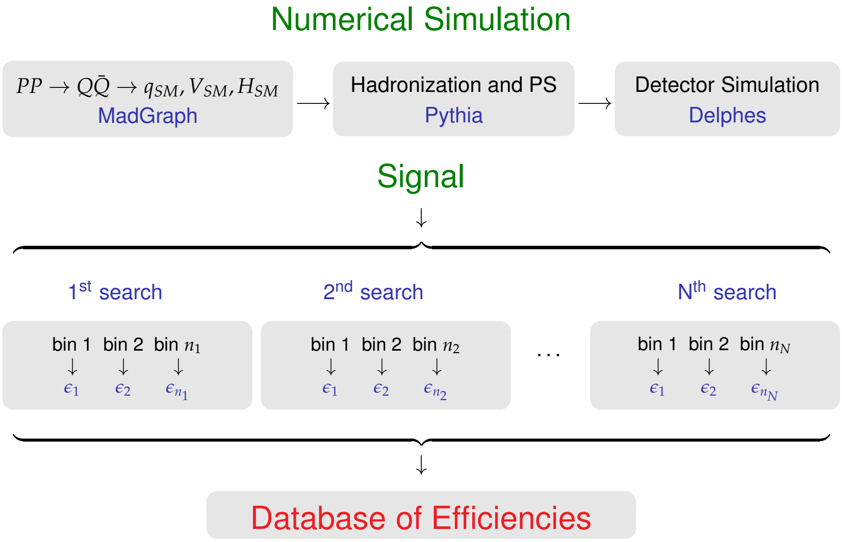
$$N_S = L_{exp} \sum_Q \sigma_{QCD}(m_Q) \sum_{ij} BR_i(Q) BR_j(\bar{Q}) \epsilon_{ij}$$

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

$$eCL \equiv 1 - CL_s$$

Generation of the efficiency database



Numerical Simulation

$PP \to Q\bar{Q} \to q_{SM}, V_{SM}, H_{SM}$
MadGraph

$\longrightarrow$

Hadronization and PS
Pythia

$\longrightarrow$

Detector Simulation
Delphes

Signal

$\downarrow$

1st search

bin 1 $\downarrow$ ϵ_1
bin 2 $\downarrow$ ϵ_2
bin n_1 $\downarrow$ ϵ_{n_1}

2nd search

bin 1 $\downarrow$ ϵ_1
bin 2 $\downarrow$ ϵ_2
bin n_2 $\downarrow$ ϵ_{n_2}

. . .

Nth search

bin 1 $\downarrow$ ϵ_1
bin 2 $\downarrow$ ϵ_2
bin n_N $\downarrow$ ϵ_{n_N}

$\downarrow$

Database of Efficiencies

The exclusion confidence level

Let’s consider a search with one channel

Observation

310 events

Background

300 events

The exclusion confidence level

Let’s consider a search with one channel

Observation

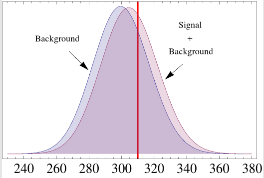
310 events

Background

300 events

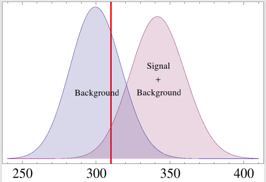
Signal

Case I: 5 events



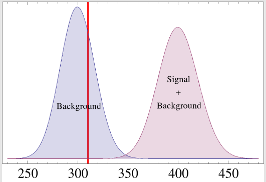
Exclusion CL $\simeq$ 14%

Case II: 46 events



Exclusion CL $\simeq$ 96%

Case III: 100 events



Exclusion CL $\simeq$ 99.9997%

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

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

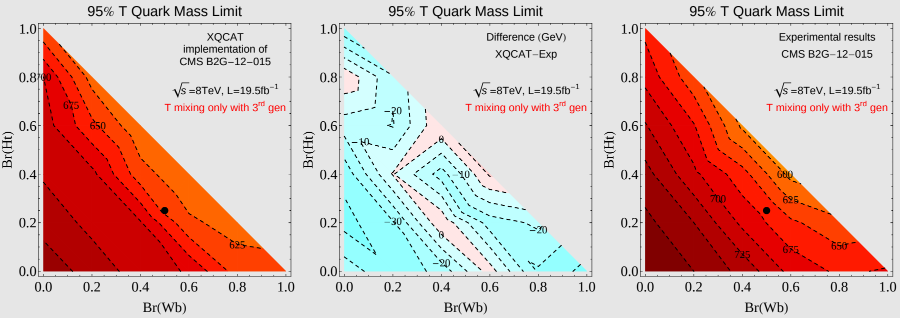
All these searches are SUSY-inspired, but it is ok: we only care about final states!

The next version of the code will be interfaced with CheckMATE[*] and MadAnalysis5[†], to enlarge the database of searches

[*] M. Drees et al, Comput.Phys.Commun. 187 (2014) 227-265, arXiv:1312.2591
[†] E. Conte et al, Eur.Phys.J. C74 (2014) 10, 3103, arXiv:1405.3982

First results of XQCAT: 1 T singlet

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


95% T Quark Mass Limit

95% T Quark Mass Limit

95% T Quark Mass Limit

We reproduce CMS 95% CL bounds within 30-40 GeV
in the whole BR range

The implementation of SUSY searches **(including their combination!)** has been validated in

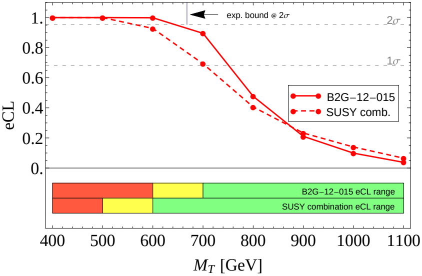
O. Buchmuller and J. Marrouche, Int.J.Mod.Phys. A29 (2014) 1450032, arXiv:1304.2185

First results of XQCAT: 1 T singlet

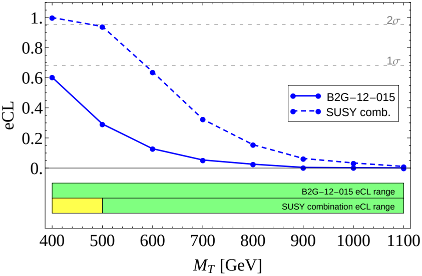
but with different mixing structure

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

T singlet mixing with 3rd generation

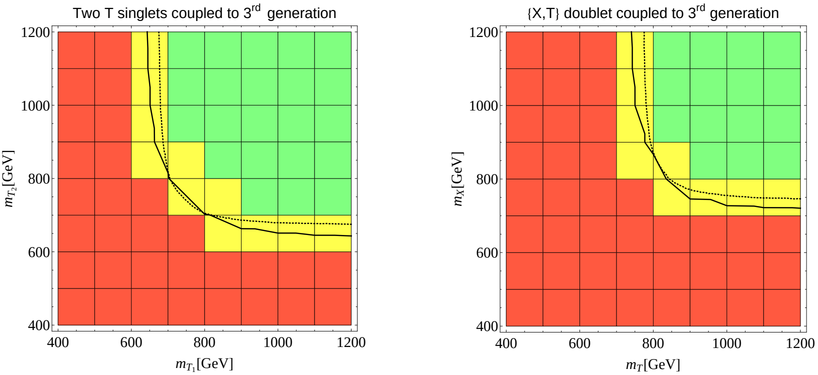


T singlet mixing with 1st gen.



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

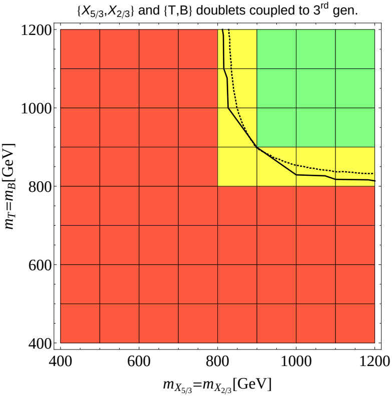
First results of XQCAT: multiple quarks

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

First results of XQCAT: multiple quarks

Considering physically motivated scenarios

Composite (pseudo) Goldstone boson Higgs model

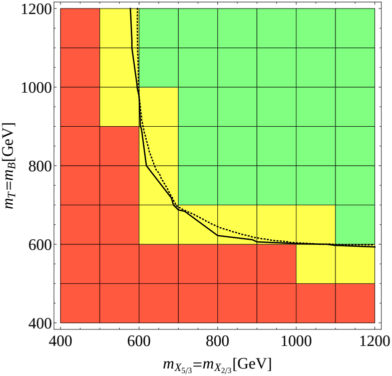
De Simone et al., *A first top partner hunters guide*, arXiv:1211.5663 [hep-ph]

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

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

($X_{5/3}$ $X_{2/3}$) and (T B) doublets coupling to light generation

(combination of SUSY searches)



General conclusions

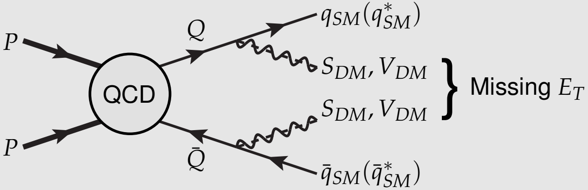
1. Models with multiple extra quarks but non-standard mixing patterns can already be constrained even if no dedicated searches are available
2. Reinterpretation of searches not designed for extra quarks can be a powerful instrument to help designing future searches

Bounds obtained using a combination of SUSY searches

Outline

Final states

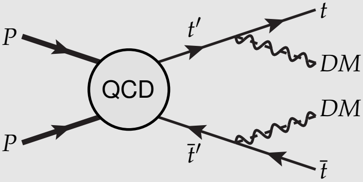
QCD pair production + decay into Dark Matter



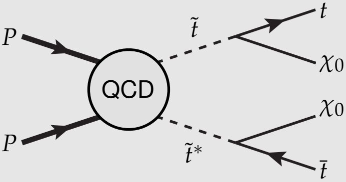
- The kinematics of the final state depends also on the **DM mass, spin and coupling**
- It the mass splitting is small, the **SM quarks may be virtual** (especially in case of top quarks)
- The presence of missing transverse energy makes the **interpretation of signal more difficult**

An interesting analogy

Decay into Dark Matter and top quarks



Heavy quark signal



SUSY signal

If heavy quarks decay into DM, it is possible to reinterpret any SUSY-inspired search
Due to the different nature of the DM particles, the kinematic may be different enough

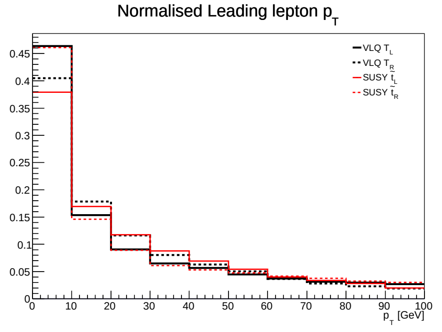
If a signal is observed, it may be possible to distinguish a heavy quark signal from a SUSY signal from the different kinematics of the events!

Preliminary results

Simulation of the process $PP \to t\bar{t} + \not{E}_T$ mediated by pair-produced t' or $\tilde{t}$

Both signals processed through Checkmate on a set of ATLAS searches with $\not{E}_T$ in the final state

One of the searches has a veto on leptons with p_T larger than 10 GeV



$$m_{t'/\tilde{t}} = 600GeV$$

$$m_{S_{DM}/\chi_0} = 10GeV$$

SUSY point excluded

Heavy quark point allowed
(only by LHC data)

Preliminary results look promising

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: a tool for analysis of **multiple vector-like quark scenarios** has been developed (XQCAT) and it is publicly available!
  - → It is possible to exploit different searches to pose bounds on **yet unexplored scenarios**!

What's next

- Inclusion of decays into **Dark Matter** particles
- Inclusion of **single production** processes in the simulation
- (Possibly) Inclusion of **chain decays** between VLQs
- Generalisation of the procedure for **different states** (heavy vectors, heavy scalars, . . .)

Backup

Representations and lagrangian terms

Minimal extension of the SM with **just one** vector-like quark

Representations and lagrangian terms

Minimal extension of the SM with **just one** vector-like quark

	SM	Singlets	Doublets	Triplets
	$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$	(t') (b')	$\begin{pmatrix} X \\ t' \end{pmatrix}$ $\begin{pmatrix} t' \\ b' \end{pmatrix}$ $\begin{pmatrix} b' \\ Y \end{pmatrix}$	$\begin{pmatrix} X \\ t' \\ b' \end{pmatrix}$ $\begin{pmatrix} t' \\ b' \\ Y \end{pmatrix}$
$SU(2)_L$	2 and 1	1	2	3
$U(1)_Y$	$q_L = 1/6$ $u_R = 2/3$ $d_R = -1/3$	2/3 -1/3	7/6 1/6 -5/6	2/3 -1/3
$\mathcal{L}_Y$	$-y_u^i \bar{q}_L^i H^c u_R^i$ $-y_d^i \bar{q}_L^i V_{CKM}^{i,j} H d_R^j$	$-\lambda_u^i \bar{q}_L^i H^c t'_R$ $-\lambda_d^i \bar{q}_L^i H b'_R$	$-\lambda_u^i \psi_L H^{(c)} u_R^i$ $-\lambda_d^i \psi_L H^{(c)} d_R^i$	$-\lambda_i \bar{q}_L^i \tau^a H^{(c)} \psi_R^a$
$\mathcal{L}_m$		$-M\bar{\psi}\psi$ (gauge invariant since vector-like)		
Free parameters		4 $M + 3 \times \lambda^i$	4 or 7 $M + 3\lambda_u^i + 3\lambda_d^i$	4 $M + 3 \times \lambda^i$

Mixing between VL and SM quarks

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

Mass matrices depend on representations

- Singlets and triplets:

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

- Doublets: $\mathcal{M}_{u,d}^{4I} \leftrightarrow \mathcal{M}_{u,d}^{I4}$

Mixing between VL and SM quarks

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

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- Doublets: $\mathcal{M}_{u,d}^{4I} \leftrightarrow \mathcal{M}_{u,d}^{I4}$

Flavour and mass eigenstates

$$\begin{pmatrix} \tilde{u} \\ \tilde{c} \\ \tilde{t} \\ U \end{pmatrix}_{L,R} = V_{L,R}^u \begin{pmatrix} u \\ c \\ t \\ t' \end{pmatrix} \quad \text{and} \quad \begin{pmatrix} \tilde{d} \\ \tilde{s} \\ \tilde{b} \\ D \end{pmatrix}_{L,R} = V_{L,R}^d \begin{pmatrix} d \\ s \\ b \\ b' \end{pmatrix}$$

The exotics $X_{5/3}$ and $Y_{-4/3}$ do not mix → no distinction between flavour and mass eigenstates

Properties of the mixing matrices

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

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

Properties of the mixing matrices

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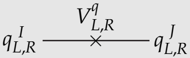
Mixing in left- and right-handed sectors behave differently

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



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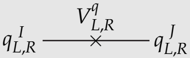


Singlets and triplets (case of up-type quarks)

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

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

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

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

Couplings

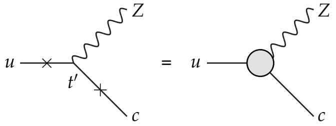
With Z

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

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

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

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



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

Couplings

With $W^\pm$

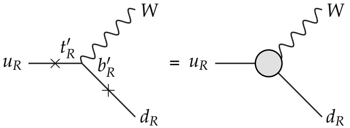
$$\mathcal{L}_{W^\pm} = \frac{g}{\sqrt{2}} \left(\bar{u}\; \bar{c}\; \bar{t}\; |\bar{t}'\right)_L (V_L^u)^\dagger \left(\begin{array}{c|c} \tilde{V}_L^{CKM} & \\ \hline & 1 \end{array}\right) \gamma^\mu V_L^d \begin{pmatrix} d \\ s \\ b \\ \hline b' \end{pmatrix}_L W_\mu^+$$

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

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

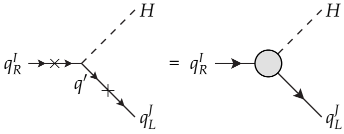
$$\mathcal{L}_h = \frac{1}{v}\,(\bar{q}_1\ \bar{q}_2\ \bar{q}_3\ \bar{q}'_1)_L\,(V_L^q)^\dagger \left[\mathcal{M}_q - M\begin{pmatrix}0&&&\\&0&&\\&&0&\\&&&1\end{pmatrix}\right](V_R^q)\begin{pmatrix}q_1\\q_2\\q_3\\q'\end{pmatrix}_R h + h.c.$$

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!

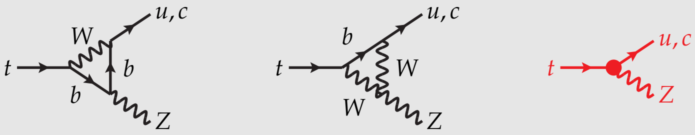
$$C^{IJ} = \frac{1}{v}m_I\delta^{IJ} - \frac{M}{v}(V_L^*)^{q'I}V_R^{q'J}$$



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

Flavour changing NC constraints

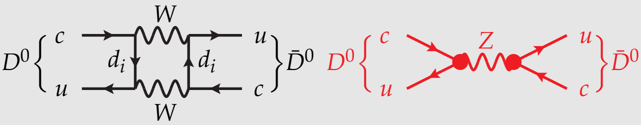
Rare top decays



$BR(t \to Zq) = \mathcal{O}(10^{-14})$
SM prediction

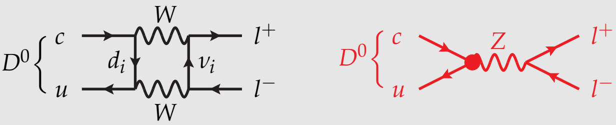
$BR(t \to Zq) < 0.05\%$
measured at CMS @ $19.7\ fb^{-1}$

Meson mixing and decay



$$x_D = \frac{\Delta m_D}{\Gamma_D} = x_D^{SM} + \delta x_D^{VL}$$

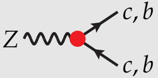
$$y_D = \frac{\Delta \Gamma_D}{2\Gamma_D} = y_D^{SM} + \delta y_D^{VL}$$



$$BR = BR^{SM} + \delta BR^{VL}$$

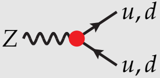
Flavour conserving NC constraints

$Zc\bar{c}$ and $Zb\bar{b}$ couplings



- Direct coupling measurements: $g^q_{ZL,ZR} = (g^q_{ZL,ZR})^{SM}(1 + \delta g^q_{ZL,ZR})$
- Asymmetry parameters: $A_q = \frac{(g^q_{ZL})^2 - (g^q_{ZR})^2}{(g^q_{ZL})^2 + (g^q_{ZR})^2} = A_q^{SM}(1 + \delta A_q)$
- Decay ratios: $R_q = \frac{\Gamma(Z \to q\bar{q})}{\Gamma(Z \to hadrons)} = R_q^{SM}(1 + \delta R_q)$

Atomic parity violation



Weak charge of the nucleus

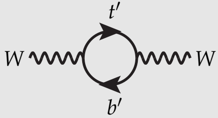
$$Q_W = \frac{2c_W}{g}\left[(2Z + N)(g^u_{ZL} + g^u_{ZR}) + (Z + 2N)(g^d_{ZL} + g^d_{ZR})\right] = Q_W^{SM} + \delta Q_W^{VL}$$

Most precise test in Cesium ^{133}Cs:

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

Constraints from EWPT and CKM

EW precision tests



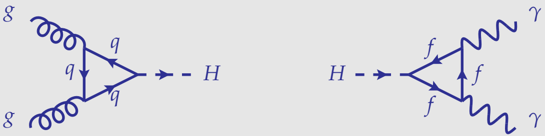
Contributions of new fermions
to S,T,U parameters

CKM measurements

- Modifications to CKM relevant for singlets and triplets because mixing in the left sector is NOT suppressed
- The CKM matrix is not unitary anymore
- If BOTH t' and b' are present, a CKM for the right sector emerges

Higgs coupling with gluons/photons

Production and decay of Higgs at the LHC



New physics contributions mostly affect loops of heavy quarks t and q':

$$\kappa_{gg} = \kappa_{\gamma\gamma} = \frac{v}{m_t} g_{ht\bar{t}} + \frac{v}{m_{q'}} g_{hq'\bar{q}'} - 1$$

G. Cacciapaglia et al., Higgs to Gamma Gamma beyond the Standard Model, JHEP 0906:054,2009, arXiv: 0901.0927 [hep-ph]

The couplings of t and q' to the higgs boson are:

$$g_{ht\bar{t}} = \frac{m_t}{v} + \delta g_{ht\bar{t}} \qquad g_{hq'\bar{q}'} = \frac{m_{q'}}{v} + \delta g_{hq'\bar{q}'}$$

In the SM: $\kappa_{gg} = \kappa_{\gamma\gamma} = 0$

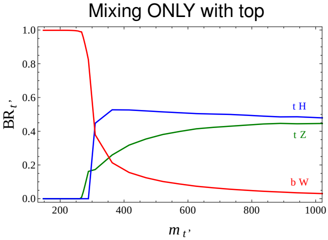
The contribution of just one VL quark to the loops turns out to be negligibly small

Result confirmed by studies at NNLO*

[*] S. Dawson and E. Furlan, A Higgs Conundrum with Vector Fermions, Phys.Rev. D86 (2012) 015021, arXiv:1205.4733 [hep-ph]

Relevance of decays to light gens.

Examples with non-SM doublet $(X_{5/3}\ t')$

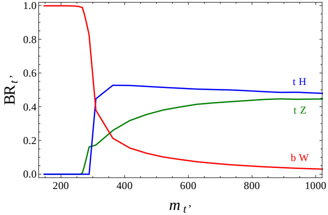


Equivalence theorem at large masses:
$BR(qH) \simeq BR(qZ)$

Relevance of decays to light gens.

Examples with non-SM doublet $(X_{5/3}\ t')$

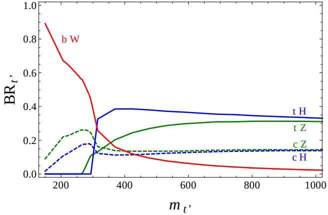
Mixing ONLY with top



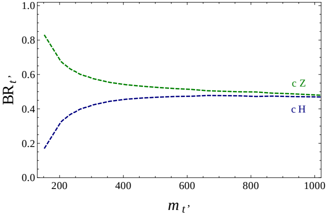
Equivalence theorem at large masses:
$BR(qH) \simeq BR(qZ)$

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

Mixing with top and charm



Mixing ONLY with charm



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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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

Counting the final states

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

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!

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')

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

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)

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Branching Ratio

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

From couplings to BRs

Charged current of T (t')

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Partial Width

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

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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

$$
\begin{aligned}
\mathcal{L} \;=\; & \kappa_T \left\{ \sqrt{\frac{\zeta_i \xi^T_W}{\Gamma^0_W}} \frac{g}{\sqrt{2}} \, [\bar{T}_L W^+_\mu \gamma^\mu d^i_L] + \sqrt{\frac{\zeta_i \xi^T_Z}{\Gamma^0_Z}} \frac{g}{2 c_W} \, [\bar{T}_L Z_\mu \gamma^\mu u^i_L] - \sqrt{\frac{\zeta_i \xi^T_H}{\Gamma^0_H}} \frac{M}{v} \, [\bar{T}_R H u^i_L] - \sqrt{\frac{\zeta_3 \xi^T_H}{\Gamma^0_H}} \frac{m_t}{v} \, [\bar{T}_L H t_R] \right\} \\
+ \; & \kappa_B \left\{ \sqrt{\frac{\zeta_i \xi^B_W}{\Gamma^0_W}} \frac{g}{\sqrt{2}} \, [\bar{B}_L W^-_\mu \gamma^\mu u^i_L] + \sqrt{\frac{\zeta_i \xi^B_Z}{\Gamma^0_Z}} \frac{g}{2 c_W} \, [\bar{B}_L Z_\mu \gamma^\mu d^i_L] - \sqrt{\frac{\zeta_i \xi^B_H}{\Gamma^0_H}} \frac{M}{v} \, [\bar{B}_R H d^i_L] \right\} \\
+ \; & \kappa_X \left\{ \sqrt{\frac{\zeta_i}{\Gamma^0_W}} \frac{g}{\sqrt{2}} \, [\bar{X}_L W^+_\mu \gamma^\mu u^i_L] \right\} \\
+ \; & \kappa_Y \left\{ \sqrt{\frac{\zeta_i}{\Gamma^0_W}} \frac{g}{\sqrt{2}} \, [\bar{Y}_L W^-_\mu \gamma^\mu d^i_L] \right\} \\
+ \; & h.c.
\end{aligned}
$$

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

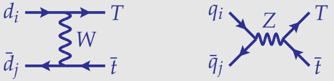
$$
\sum_{i=1}^{3} \zeta_i = 1 \qquad\qquad \sum_{V=W,Z,H} \xi_V = 1
$$

- T and B: NC+CC, 4 parameters each ($\zeta_{1,2}$ and $\xi_{W,Z}$)
- X and Y: only CC, 2 parameters each ($\zeta_{1,2}$)

Cross sections (example with T)

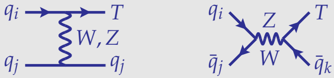
In association with top

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



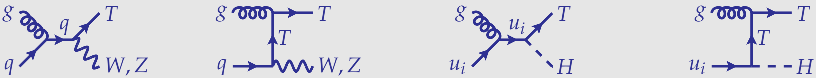
In association with light quark

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



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!

Cross sections

Coefficients (in fb) for T and $\bar{T}$ with mass 600 GeV

	with top		with light quark		with gauge or Higgs		
	$\bar{\sigma}_{Zi}^{T\bar{t}+\bar{T}t}$	$\bar{\sigma}_{Wi}^{T\bar{t}+\bar{T}t}$	$\bar{\sigma}_{Zi}^{Tj+\bar{T}j}$	$\bar{\sigma}_{Wi}^{Tj+\bar{T}j}$	$\bar{\sigma}_{i}^{TZ+\bar{T}Z}$	$\bar{\sigma}_{i}^{TH+\bar{T}H}$	$\bar{\sigma}_{i}^{TW+\bar{T}W}$
$\zeta_1 = 1$	-	1690	69200	51500	5480	3610	2430
$\zeta_2 = 1$	-	247	5380	10700	202	133	374
$\zeta_3 = 1$	12.6	78.2	-	4230	-	-	122

The cross section for pair production is 170 fb

Cross sections (adding flavour constraints)

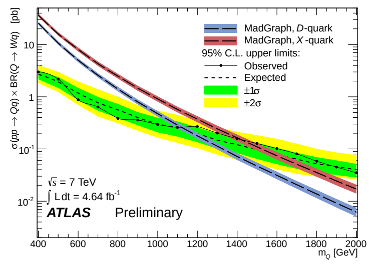
Embed the model-dependency into a consistent framework

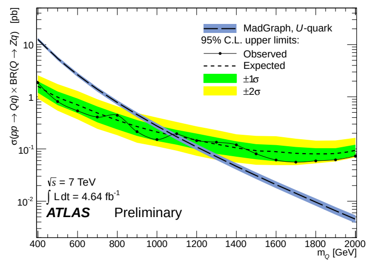
		Benchmark 1 $\kappa = 0.02$ $\zeta_1 = \zeta_2 = 1/3$	Benchmark 2 $\kappa = 0.07$ $\zeta_1 = 1$	Benchmark 3 $\kappa = 0.2$ $\zeta_2 = 1$	Benchmark 4 $\kappa = 0.3$ $\zeta_3 = 1$	Benchmark 5 $\kappa = 0.1$ $\zeta_1 = \zeta_3 = 1/2$	Benchmark 6 $\kappa = 0.3$ $\zeta_2 = \zeta_3 = 1/2$
$(1, 2/3)$	T	15	464	564	399	495	834
$(1, -1/3)$	B	14	455	457	167	-	-
$(2, 1/6)$	T	5.6	191	114	0.6	195	128
$\lambda_d = 0$	B	10	351	267	1.1	358	301
$(2, 1/6)$	T	9.5	272	451	398	-	-
$\lambda_u = 0$	B	3.7	103	190	166	-	-
$(2, 1/6)$	T	15	464	564	399	-	-
$\lambda_d = \lambda_u$	B	14	455	457	167	-	-
$(2, 7/6)$	X	15	528	272	1.2	538	307
	T	5.6	191	114	0.6	195	128
$(2, -5/6)$	B	3.7	103	190	166	-	-
	Y	7.6	205	443	388	-	-
$(3, 2/3)$	X	30.5	1055	545	2.4	-	-
	T	15	464	564	399	-	-
	B	7.4	207	380	332	-	-
$(3, -1/3)$	T	5.6	191	114	0.6	-	-
	B	7.1	227	228	84	-	-
	Y	7.6	205	443	388	-	-

Flavour bounds are necessary to get the inclusive cross sections

Flavour vs direct search

ATLAS search in the CC and NC channels

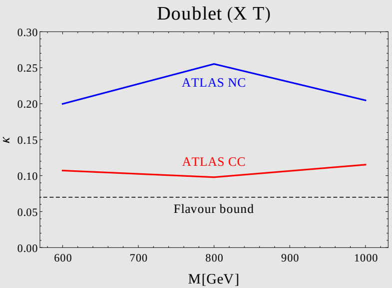


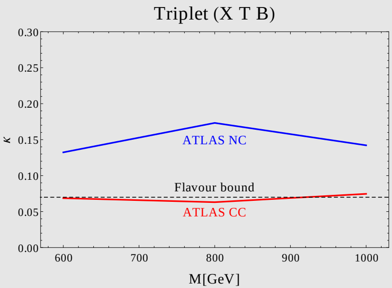


Assumptions: mixing only with 1st generation and coupling strength $\kappa = \frac{v}{M_{VL}}$

Flavour vs direct search

Comparison with flavour bounds





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

Flavour bounds are competitive with current direct searches