Model independent framework for analysis of scenarios with multiple Heavy Extra Quarks

Daniele Barducci

A. Belyaev, M. Buchkremer, G. Cacciapaglia, A. Deandrea, S. De Curtis, J. Marrouche, S. Moretti and L. Panizzi

Based on arXiv:1405.0737 [hep-ph]

NExT Institute (Southampton University and RAL) & CERN

LAPTh
Annecy
12th June 2014

Outline

- Introduction and motivations
- Vector-Like Quarks Properties
- LHC phenomenology of Vector-Like Quarks
- XQCAT: a tool for a model independent approach
- Results
- Conclusions and future development of the tool

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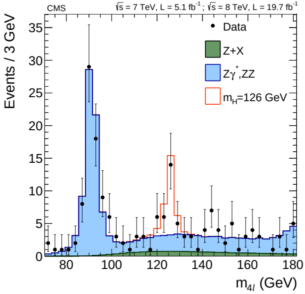

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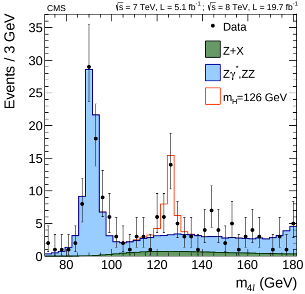

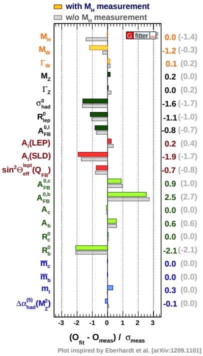

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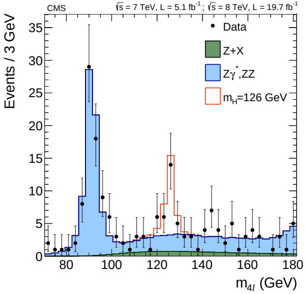

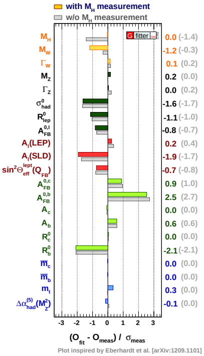

However...

Many problems afflict the Standard Model ✗

Theoretical

- Fine tuning
- Gauge unification

Experimental

- Dark Matter
- Neutrino mass

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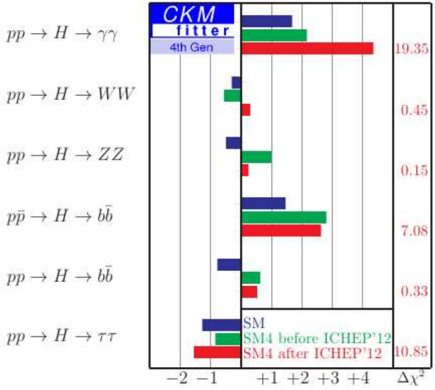
- From a theoretical point of view fine tuning is the main reason for physics beyond the Standard Model
- For naturalness reasons new physics is expected to be at the TeV scale

And with new physics, new particles appear..

A coloured new fermion is the most common new particle

4th generation of quarks

After the Higgs discovery a 4th generation of SM quarks is ruled out



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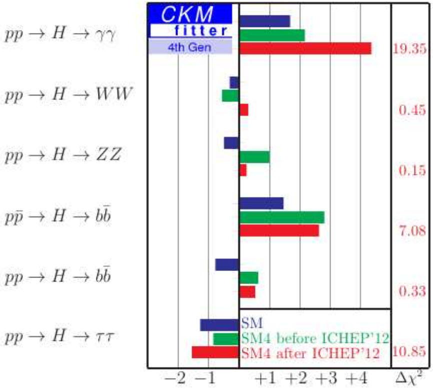

But new quarks can appear in other ways

Vector-Like Quarks (VLQs)

Many BSM models predict the existence of **Vector-Like Quarks**

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

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$$\mathcal{L} \supset \frac{g}{\sqrt{2}}(j^{\mu+}W^+_\mu + j^{\mu-}W^-_\mu) \qquad j^{\mu\pm} = j^{\mu\pm}_L + j^{\mu\pm}_R$$

SM chiral quarks

$$j^\mu_L = \bar{f}_L\gamma^\mu f'_L \qquad j^\mu_R = 0$$

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

$V - A$

VLQs

$$j^\mu_L = \bar{f}_L\gamma^\mu f'_L \qquad j^\mu_R = \bar{f}_R\gamma^\mu f'_R$$

$$j^\mu = j^\mu_L + j^\mu_R = \bar{f}\gamma^\mu f'$$

V

Vector-Like Quarks (VLQs)

They appear in many models of new physics

- Model of **Composite Higgs**
  As excited resonances of bounds states that form the SM particles
- Warped or Universal **Extra Dimensions**
  As KK excitations of bulk fields
- **Little Higgs** models
  As partners of SM in large group representations that ensure cancellations of divergent loops
- Non minimal **Supersymmetric** models
  They can increase corrections to Higgs mass
- Gauged **flavour** groups
  Required to cancel anomalies in the gauged flavour symmetry

Properties of VLQs

Gauge invariant mass term without the Higgs mechanism

$$\mathcal{L} \supset -m(\bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L)$$

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They mix with the SM quarks

$$t' \longrightarrow \times \longrightarrow t$$

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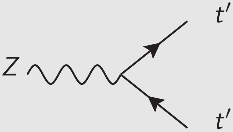
They interact with SM gauge bosons



Properties of VLQs

	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
$\mathcal{L}_Y$	$\bar{q}^i_L H^c u^i_R$ $\bar{q}^i_L V^{i,j}_{CKM} H d^j_R$	$\bar{q}^i_L H^c t'_R$ $\bar{q}^i_L H b'_R$	$\psi_L H^{(c)} u^i_R$ $\psi_L H^{(c)} d^i_R$	$\bar{q}^i_L \tau^a H^{(c)} \psi^a_R$
$\mathcal{L}_m$		$-M\bar{\psi}\psi$ (gauge invariant since vector-like)		

Assumption: VLQ interacts with SM through Yukawa type couplings
Limited number of $SU(2)_L$ representations that can be used

Properties of VLQs

The mixing parameters are constrained by many observables

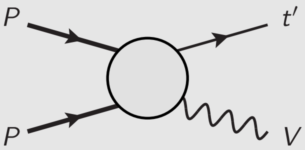
- Flavour Changing Neutral Currents
- Meson's mixing and decays
- Rare top decays
- $Zc\bar{c}$ and $Zb\bar{b}$ couplings
- EW precision tests
- Higgs physics at the LHC

All these constraints are model dependent and have been studied
Cacciapaglia et al., Heavy Vector-like Top Partners at the LHC and flavour constraints, 1108.6329 [hep-ph],
Buchkremer et al., Model Independent Framework for Searches of Top Partners, 1305.4172 [hep-ph],
Aguilar-Saavedra et al, A handbook of vector-like quarks: mixing and single production, 1306.0572 [hep-ph],...

Production modes

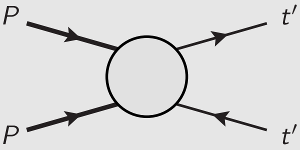
At the LHC VLQs can mainly be produced via

Single production



Also with a SM quark or Higgs

Pair production



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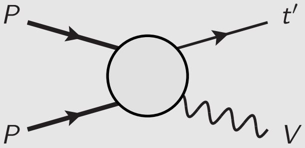

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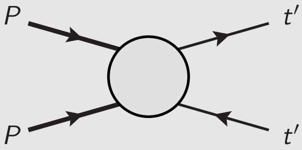

Sensitive to

VLQ mass
Mixing parameters/couplings

Model dependent

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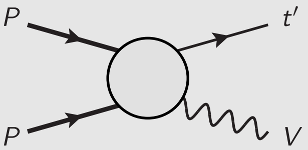

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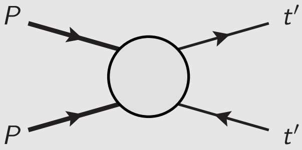
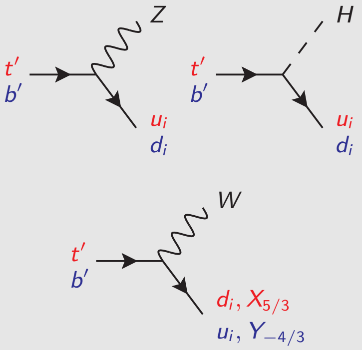


Sensitive to

Single production	Pair production
VLQ mass Mixing parameters/couplings	VLQ mass (QCD process)
Model dependent	Model independent

Decay modes

SM partner



- Both Neutral and Charged Currents

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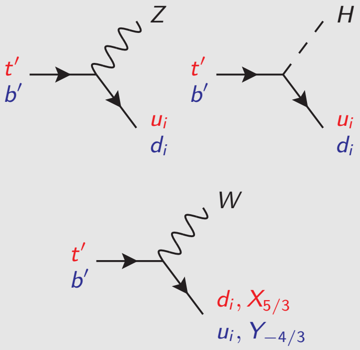

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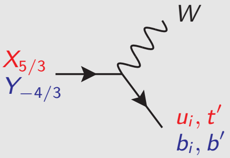

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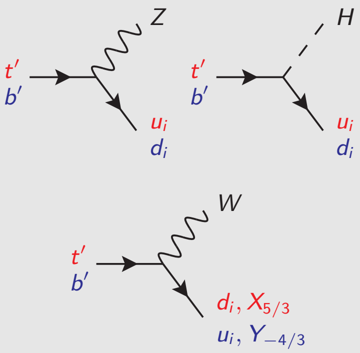

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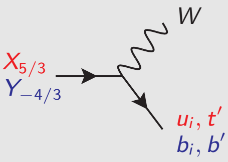

- Only Charged Currents

- Just one VLQ per type
- No extra gauge boson
- No DM candidate

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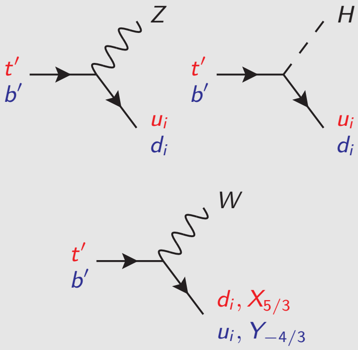

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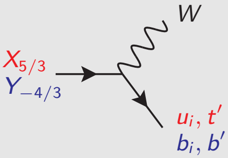

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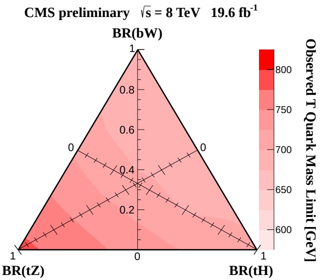
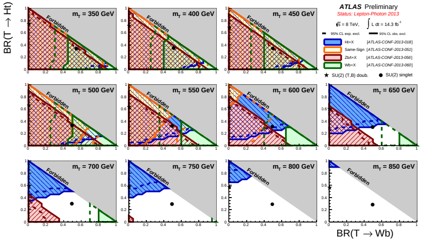
Rich phenomenology to explore at the LHC!!

Experimental status

ATLAS and CMS bounds on VLQ are between 600 and 800 GeV





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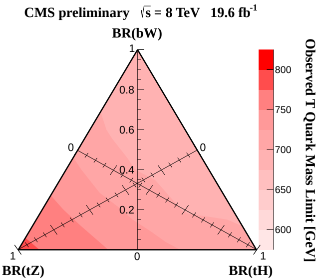

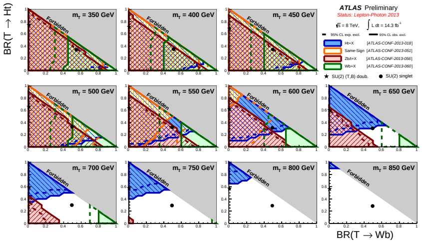

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Assumptions

Just one VLQ in the spectrum

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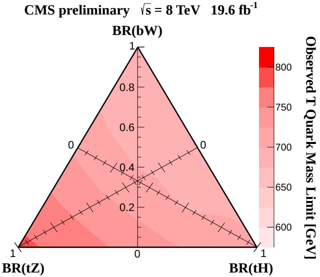

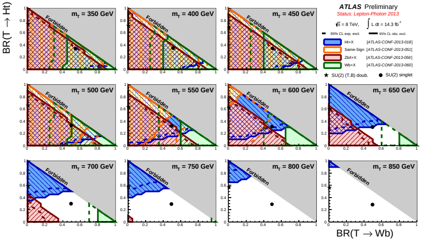

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Reality

Realistic model present a VLQ sector

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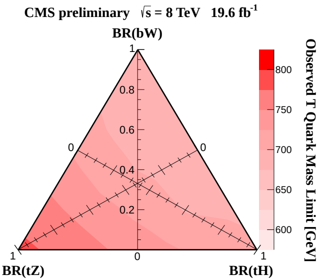

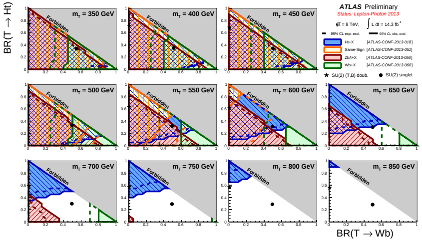

However...

Assumptions	Reality
Just one VLQ in the spectrum	Realistic model present a VLQ sector
Decay just in 3rd generation $t' \to Zt$ $t' \to Ht$ $t' \to W^- t$	

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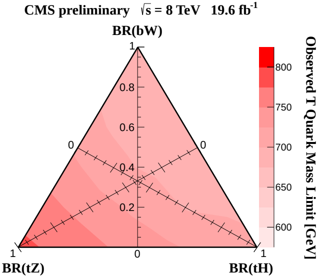

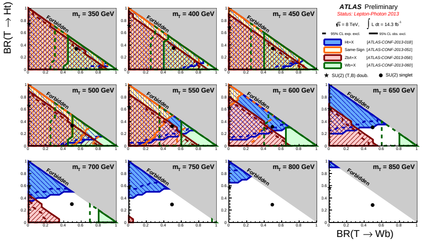

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Assumptions

Just one VLQ in the spectrum

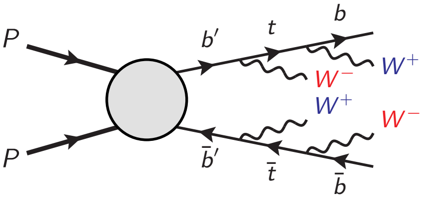
Decay just in 3rd generation
$t' \to Zt \quad t' \to Ht \quad t' \to W^- t$

Reality

Realistic model present a VLQ sector

Decay in light quarks cannot be excluded a priori

Decay also in 1st generation

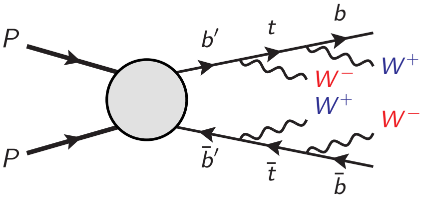


Decay channel: $b' \to Wt$

- Same Sign dilepton channel
- Eventual b-tagging

Relaxing the third generation exclusive decay hypothesis

Decay also in 1st generation



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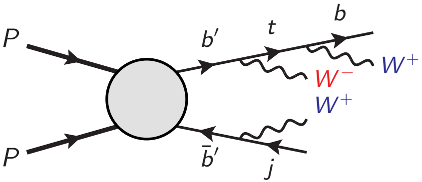
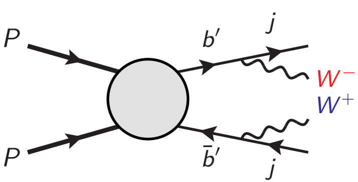
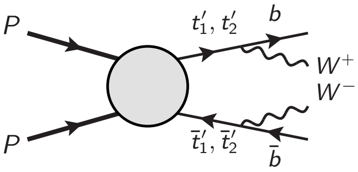




Less events in the Same Sign dilepton channel and less b-jets

More than one VLQ in the spectrum

Case 1: two VLQs of the same specie



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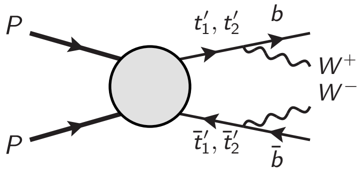
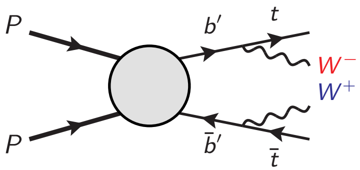
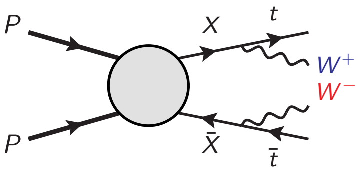


Case 2: two VLQs of different specie





The same final state can be fed by different channels with different kinematics

Question

Is there a way to take in account all these aspects in order to reinterpret the results of one (or more) given experimental search?

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Straightforward and long answer

Perform a complete simulation for each scenario that we want to test and apply the corresponding search

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Yes, taking in account that

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Let's go for an example...

Example

Suppose to have a b' decaying only into $W^- t$ and $W^- u$:
how many possible final state we have?

$$PP \to b'\bar{b}' \to \begin{cases} W^+W^- u\bar{u} \\ W^+W^- u\bar{t} \to W^+W^-W^- u\bar{b} \\ W^+W^- t\bar{u} \to W^+W^+W^- b\bar{u} \\ W^+W^- t\bar{t} \to W^+W^+W^-W^- b\bar{b} \end{cases}$$

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Distinguishing the channel through the W boson multiplicity the relative rates into WW, WWW and WWWW channels are given by

$$Br(b' \to Wu)^2 : 2Br(b' \to Wu)Br(b' \to Wt) : Br(b' \to Wt)^2$$

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Each channel has a different selection efficiency for a given search
However is enough to simulate the channels just once and calculate the total signal as a weighted sum of all channels with the saved efficiencies

Example

Just one bin and integrated luminosity of 5 fb^{-1}

- $\sigma_{QCD}(m_{t'}) = 100$ fb
- $Br(t' \to Wb) = 10\%$
  $Br(t' \to Zt) = 90\%$
- $\epsilon(m_{t'}, WbW\bar{b}) = 1\%$
  $\epsilon(m_{t'}, WbZ\bar{t}) = 2\%$
  $\epsilon(m_{t'}, ZtW\bar{b}) = 3\%$
  $\epsilon(m_{t'}, ZtZ\bar{t}) = 4\%$

- $\sigma_{QCD}(m_X) = 200$ fb
- $Br(X \to Wt) = 100\%$
- $\epsilon(m_X, WtW\bar{t}) = 5\%$

$$N_{ev.} = \mathcal{L} \cdot \Big(\sigma_{QCD}(m_{t'})Br(t' \to Wb)^2\epsilon(m_{t'}, WbW\bar{b}) + \\ + \sigma_{QCD}(m_{t'})Br(t' \to Wb)Br(t' \to Zt)\epsilon(m_{t'}, WbZ\bar{t}) + \ldots\Big) = 68.5$$

The number of signal events has been easily computed knowing the efficiencies for each subprocess with given mass

Total number of channels

t' quark decays: W^+j W^+b Zj Zt Hj Ht

$$PP \to t'\bar{t}' \to \begin{pmatrix} W^+jW^-j & W^+jW^-\bar{b} & W^+jZj & W^+jZ\bar{t} & W^+jHj & W^+jH\bar{t} \\ W^+bW^-j & W^+bW^-\bar{b} & W^+bZj & W^+bZ\bar{t} & W^+bHj & W^+bH\bar{t} \\ ZjW^-j & ZjW^-\bar{b} & ZjZj & ZjZ\bar{t} & ZjHj & ZjH\bar{t} \\ ZtW^-j & ZtW^-\bar{b} & ZtZj & ZtZ\bar{t} & ZtHj & ZtH\bar{t} \\ HjW^-j & HjW^-\bar{b} & HjZj & HjZ\bar{t} & HjHj & HjH\bar{t} \\ HtW^-j & HtW^-\bar{b} & HtZj & HtZ\bar{t} & HtHj & HtH\bar{t} \end{pmatrix}$$

Just 36 possible final state, since light quarks are seen as jets

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b' quark decays: W^-j W^-t Zj Zb Hj Hb
$PP \to b'\bar{b}'$: 36 possible final state into SM states

Total number of channels

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$$PP \to t'\bar{t}' \to \begin{pmatrix} W^+jW^-j & W^+jW^-\bar{b} & W^+jZj & W^+jZ\bar{t} & W^+jHj & W^+jH\bar{t} \\ W^+bW^-j & W^+bW^-\bar{b} & W^+bZj & W^+bZ\bar{t} & W^+bHj & W^+bH\bar{t} \\ ZjW^-j & ZjW^-\bar{b} & ZjZj & ZjZ\bar{t} & ZjHj & ZjH\bar{t} \\ ZtW^-j & ZtW^-\bar{b} & ZtZj & ZtZ\bar{t} & ZtHj & ZtH\bar{t} \\ HjW^-j & HjW^-\bar{b} & HjZj & HjZ\bar{t} & HjHj & HjH\bar{t} \\ HtW^-j & HtW^-\bar{b} & HtZj & HtZ\bar{t} & HtHj & HtH\bar{t} \end{pmatrix}$$

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$PP \to b'\bar{b}'$: 36 possible final state into SM states

X quark decays: W^+j W^+t

4 combinations

Y quark decays: W^-j W^-b

4 combinations

Total number of channels

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$PP \to b'\bar{b}'$: 36 possible final state into SM states

X quark decays: W^+j W^+t

4 combinations

Y quark decays: W^-j W^-b

4 combinations

In total 80 channels for decays of pair produced VLQ into SM particles

Generation of the efficiency database

Numerical Simulation

$pp \to QQ \to V, H, q$ MadGraph $\to$ Hadronization Pythia $\to$ Detector Simulation Delphes

Signal

$\downarrow$

1st search

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

2nd search

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

Nth search

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

Eff. Database

Generation of the efficiencies database

Database of efficiencies

- Per VLQs pair: $t'\bar{t}', b'\bar{b}', X\bar{X}, Y\bar{Y}$

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- Per search: CMS and ATLAS search

Generation of the efficiencies database

Database of efficiencies

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Generation of the efficiencies database

Database of efficiencies

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80 channels $\cdot$ 2 chirality $\cdot$ 17 mass $=$ 2720 simulations

Knowing the efficiencies for all final state it is possible to reconstruct any signal
Any scenario with any number of VLQ with general couplings can be analysed!!!

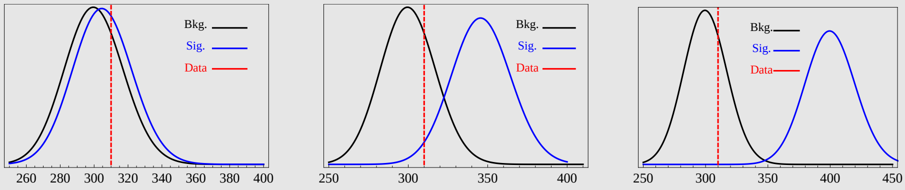
Computing the exclusion confidence level

Suppose to have just one bin

Background: 300 events

Observation: 310 events

$$eCL = 1 - \frac{CL(s+b)}{CL(b)}$$



Signal: 5
eCL=14%

Signal: 46
eCL=96%

Signal: 100
eCL=99.9997%

Flowchart of the project

User's input
N. of VLQ's
Masses of the VLQ's
BR's of the VLQ's

XQCAT database
Database of ϵ

Computing
σ weighted with ϵ and BRs
$\downarrow$
Number of signal events

Output
eCL for a given input

Exclusion confidence level for a give scenario without any simulation!!!

Search implemented in the tool

CMS searches

VLQs direct searches

- B2G-12-015: $t' \to Wb, Zt, Ht$ 8 TeV

SUSY searches

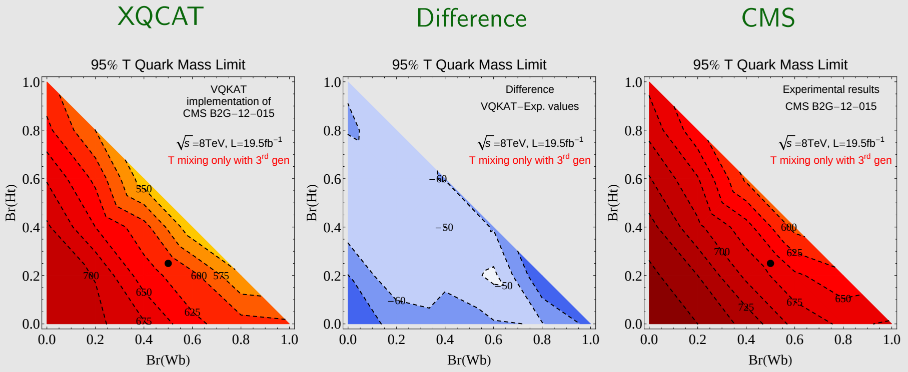
- α_T: 7 and 8 TeV
- L_p: 7 TeV
- SS: 7 and 8 TeV
- OS: 7 TeV

No problem in considering non VLQs searches, since we are only interested in the final state signature!

Validation of the code

The code has been validated against the VLQ direct search B2G-12-015

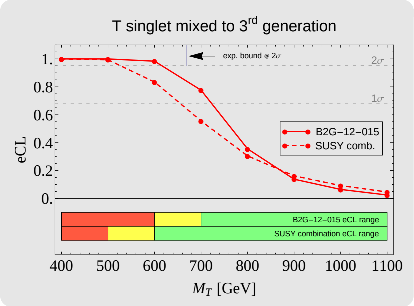
A t' mixing only with W^+b, Zt and Ht decay channels



We reproduce the experimental results within 60 GeV

$$t' \text{ singlet scenario} \begin{cases} Br(Zt) = 25\% \\ Br(Ht) = 25\% \\ BR(Wb) = 50\% \end{cases}$$

Eq. theorem



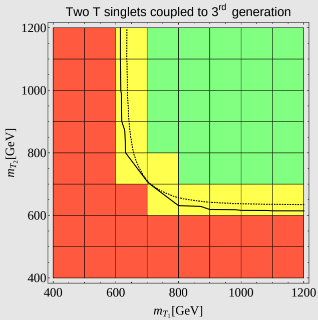
- Direct search more sensitive
- SUSY searches bound not so far from the direct one

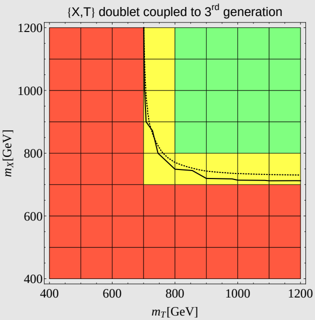
SUSY searches may have a role in scenarios where direct searches are not sensitive!!

Multiple VLQ scenario

Let's have a look at two toy multiple VLQ scenarios

$(t'_1),\ (t'_2)$ $\qquad$ (X, t')





- The presence of a second VLQ gives an higher mass bound
- The t' dedicate search is able to put a bound on the $X_{5/3}$ mass

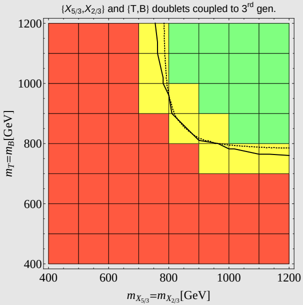
Multiple VLQ scenario

Considering physical motivated scenarios

Model with a Composite (pseudo) Goldstone boson Higgs

De Simone et al., A First top partner hunter guide, arXiv:1211:5663 [hep-ph]

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

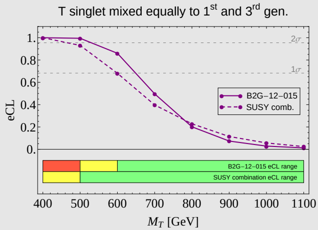


- The presence of extra quarks raises the bound on the VLQs masses to be in the 900-1000 GeV ballpark in the quasi degenerate case
- Model with extra content could be even more constrained

Mixing with light generations of quarks

Back to the t' singlet case, assuming general couplings

$$Br(Zj) = Br(Zt) = 12.5\%$$
$$Br(Hj) = Br(Ht) = 12.5\%$$
$$BR(Wj) = Br(Wb) = 25\%$$



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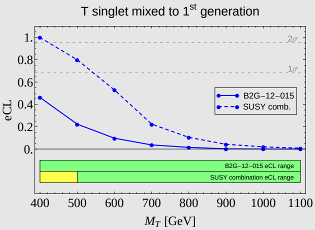
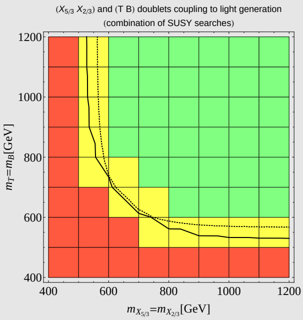


In case of exclusive mixing with 1st generation, SUSY searches can give a bound, while direct searches no!

Multiple VLQ scenario

Considering again the Composite (pseudo) Goldstone boson Higgs model
De Simone et al., A First top partner hunter guide, arXiv:1211:5663 [hep-ph]
But now coupling exclusively to the 1st generation quarks

$SO(4)$ bidoublet: $\begin{pmatrix} X_{5/3} & t' \\ X_{2/3} & b' \end{pmatrix}$ $\left\{ \begin{array}{l} Br(X_{5/3} \to Wj) = Br(B \to Wj) = 100\% \\ Br(X_{2/3} \to Zj) = Br(X_{2/3} \to Hj) = 50\% \\ Br(t' \to Zj) = Br(t' \to Hj) = 50\% \end{array} \right.$



- These kind of models can already be constrained even if no dedicated searches are available
- Reinterpretation of SUSY searches provide indeed a powerful instrument

Conclusion

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The XQCAT code will be soon available for public use!

Future upgrade of the code

- Inclusion of the latest available direct searches
- Inclusion of the EW single production
  Also this can be done in a model independent way
  Buchkremer et al., Model Independent Framework for Searches of Top Partners, arXiv:1305.4172 [hep-ph]
- Inclusion of decay into DM particles
- Inclusion of chain decays between VLQs
- (Possible) generalization to other states
  Heavy vectors, heavy scalars...

Stay tuned!

Thanks for the attention

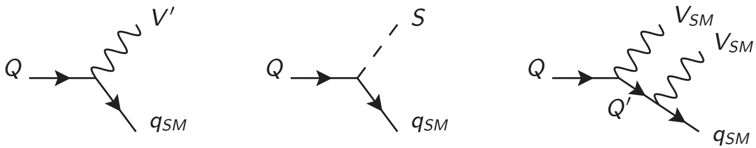
Thanks for the attention

Other decay modes

We want to a conservative bound

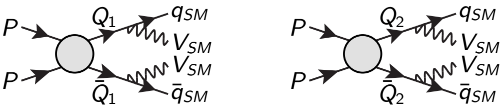
- A non exclusion doesn't mean that the scenario is allowed
- Possible other effect can increase the signal

Other decay modes



Adding new decay channels will only increase the final state signal
An exclusion is therefore robust!

Interference effects



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

Within the NWA is it possible to estimate the interference effects knowing the couplings and the widths

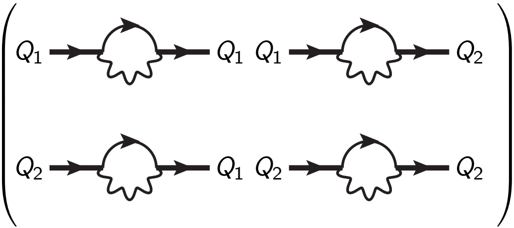
$$\sigma'_Q(M_i) = \sigma_Q(M_i)(1 + \sum_{j\neq i}^{n_Q} y_{ij}) \qquad \text{with} \qquad y_{ij} = \frac{2Re\left[g_a g_b^* g_c g_d^* (\int \mathcal{P}_i \mathcal{P}_j^*)^2\right]}{g_a^2 g_b^2 (\int \mathcal{P}_i \mathcal{P}_i^*)^2 + g_c^2 g_d^2 (\int \mathcal{P}_j \mathcal{P}_j^*)^2}$$

DB et al., Model independent approach for the analysis of interference effects in pair production of new heavy quarks, 1311.3977 [hep-ph]

Quantum mixing between states

- With VLQ (quasi) degenerate in mass the off diagonal propagator effects might be relevant
- Need to diagonalize the matrix of the propagators

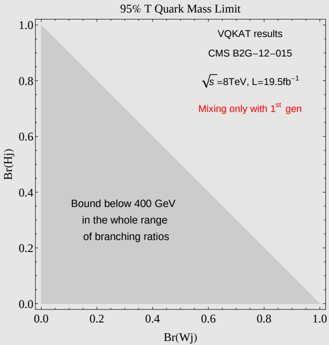
$i\Delta_{ij} =$

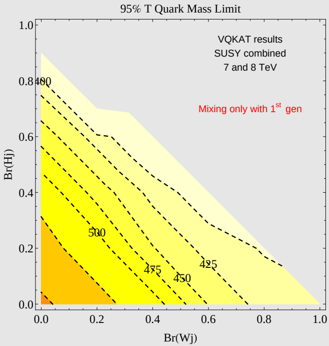


These effects are strongly model dependent

Other results

t' in 1st generation with variable BRs

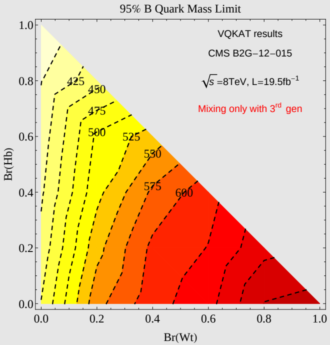


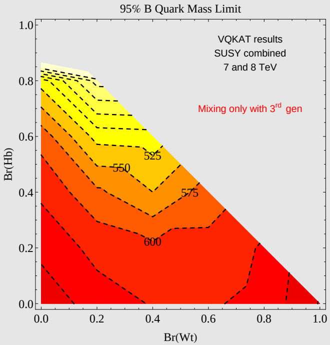


Bounds above 400 GeV in all the range of BRs with SUSY searches

Other results

b' in 3rd generation with variable BRs

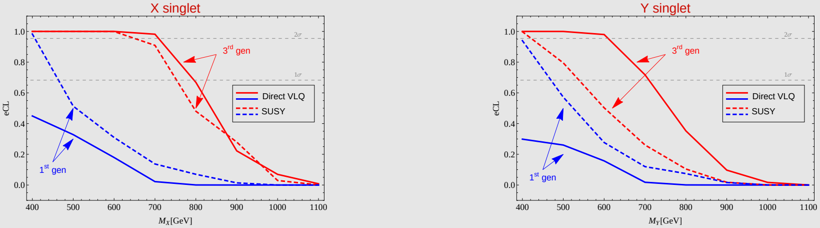




Also quarks for which the direct search are not dedicated can be bounded

Other results

X and Y quarks



Bounds also on quarks with exotic charge