Model-independent study of vector-like quarks scenarios

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27th of June, 2015
Erice

Introduction

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- **Goal:** From a model-independent analysis, we want to obtain constraints on a general model featuring one or several VLQs.

1. Introduction to vector-like quarks
   - Presentation of VLQ
   - Phenomenology of VLQ

2. Visible decay
   - The XQCAT program
   - Study of the interferences
   - Offshellness analysis

3. Invisible decay (preliminary results)
   - Presentation of the project
   - Relic density

Vector-like quark (VLQ)

Definition

A *vector-like quark* (VLQ) is a quark whose left- and right-handed chiralities belong to the same representation of the symmetry group G of the underlying theory. For the Standard Model (SM), $G = SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$.

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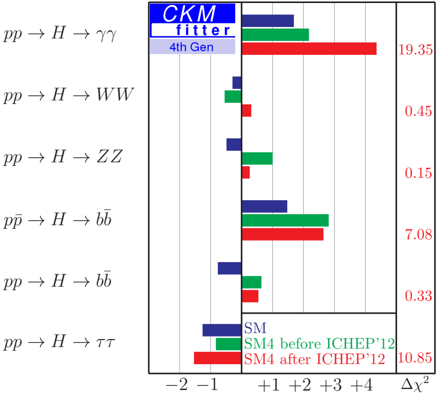
For VLQs, we have *both* left-handed and right-handed charged currents

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

while for the SM chiral quarks we *only* have left-handed charged currents

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

Moreover, since a 4th generation of chiral quarks is excluded at 4.8σ by LHC Higgs data ([1209.1101]), searches for VLQs will acquire high priorities experimentally.



Quantum numbers

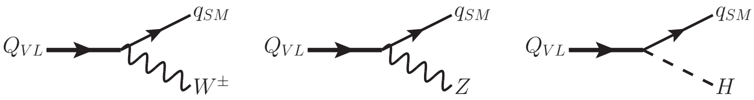
	SM quarks	Singlets	Doublets	Triplets
	$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$	$\begin{pmatrix} T \end{pmatrix} \begin{pmatrix} B \end{pmatrix}$	$\begin{pmatrix} X \\ T \end{pmatrix} \begin{pmatrix} T \\ B \end{pmatrix} \begin{pmatrix} B \\ Y \end{pmatrix}$	$\begin{pmatrix} X \\ T \\ B \end{pmatrix} \begin{pmatrix} T \\ B \\ Y \end{pmatrix}$
$SU(2)_L$	$q_L = 2$ $q_R = 1$	1	2	3
Y	$Y_{q_L} = 1/6$ $Y_{u_R} = 2/3$ $Y_{d_R} = -1/3$	2/3 -1/3	7/6 1/6 -5/6	2/3 -1/3
$\mathcal{L}_m$	forbidden[1]	$-M\bar{\psi}\psi$	$-M\bar{\psi}\psi$	$-M\bar{\psi}\psi$

[1] The Higgs mechanism is needed.

Visible and invisible decays

Two kinds of model:

- VLQ decaying to visible particles: the possibilities of decay for a VLQ T are $Z\,u_i$, $H\,u_i$ and $W^+\,d_i$.



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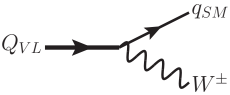
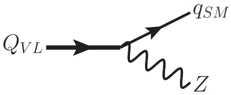
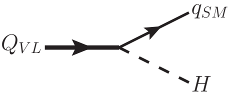
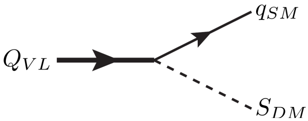
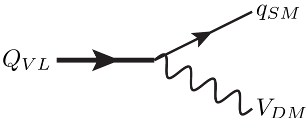






- VLQ decaying to invisible particles (Dark Matter): the only possibility of decay for a VLQ T is $\chi\,u_i$, where χ is a DM particle (scalar or vector) made stable by a $\mathbb{Z}_2$ symmetry imposed to the Lagrangian.





Presentation of the project

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)

2) D. Barducci, A. Belyaev, M. Buchkremer, J. Marrouche, S. Moretti and **LP**, *XQCAT: eXtra Quark Combined Analysis Tool*, **arXiv:1409.3116 [hep-ph]** (to be submitted to CPC)

INPUT

- Mass
- Branching ratios to SM states
- Dominant chirality of couplings to SM

For each heavy quark

Pre-simulated
DATABASE OF EFFICIENCIES
per bin, per mass, per channel
For each implemented search
(ATLAS, CMS)

CROSS-SECTIONS
WEIGHTED WITH EFFICIENCIES AND BRs
and therefore
NUMBER OF SIGNAL EVENTS
For each implemented search

OUTPUT
Exclusion confidence level

$$eCL \equiv 1 - CL_s$$

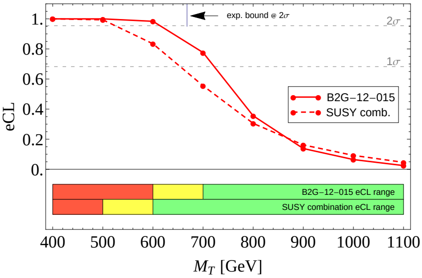
For each implemented search
or for searches **in combination**

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



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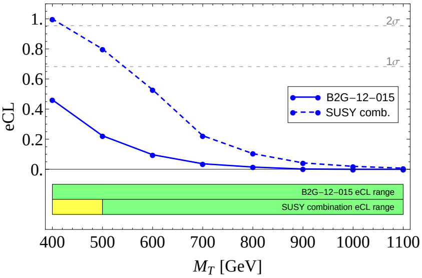

- Stronger bounds when mixing with 3rd generation.
- Mixing with light generation: SUSY searches are more sensitive than direct searches.

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- Cross section: $\sigma \propto (\mathcal{A}_{T_1} + \mathcal{A}_{T_2})^2 \propto \underbrace{\mathcal{A}_{T_1}^2 + \mathcal{A}_{T_2}^2}_{\sigma_1 + \sigma_2} + \underbrace{2\,\mathrm{Re}(\mathcal{A}_{T_1} \mathcal{A}_{T_2}^*)}_{\text{interference term}}$

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- We can show using the narrow-width approximation (NWA) that $\sigma_i \propto g_{i+}^2 g_{i-}^2 \left(\int \frac{\mathrm{d}q^2}{2\pi}\mathcal{P}_i^0\mathcal{P}_i^{0*}\right)^2$, i.e. that the cross section is proportional to the squared couplings times the integral of the BW propagators.

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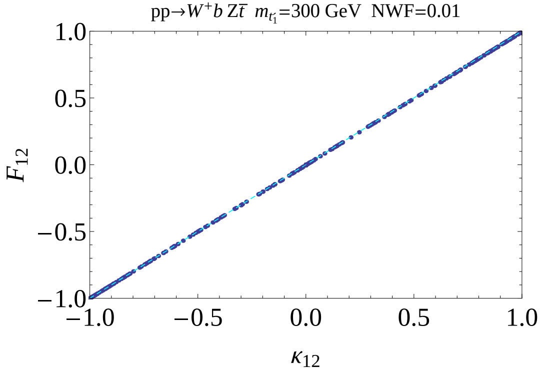
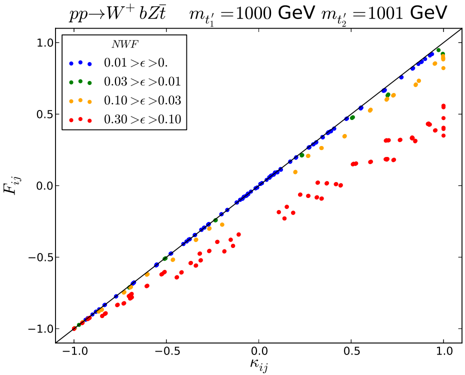
$$\Rightarrow \text{ Ansatz: } \sigma_{\text{int}} \propto 2 g_{1+} g_{1-} g_{2+} g_{2-}\ \mathrm{Re}\left\{ \left(\int \frac{dq^2}{2\pi} \mathcal{P}^0_1 \mathcal{P}^{0*}_2 \right)^2 \right\}$$

Interference plot



$$F_{12} = \frac{\sigma_{\text{int}}}{\sigma_1 + \sigma_2} \simeq \frac{2\ g_{1+}g_{1-}g_{2+}g_{2-}\ \mathrm{Re}\left\{\left(\int \frac{\mathrm{d}q^2}{2\pi}\mathcal{P}_1^0\mathcal{P}_2^{0*}\right)^2\right\}}{g_{1+}^2 g_{1-}^2 \left(\int \frac{\mathrm{d}q^2}{2\pi}\mathcal{P}_1^0\mathcal{P}_1^{0*}\right)^2 + g_{2+}^2 g_{2-}^2 \left(\int \frac{\mathrm{d}q^2}{2\pi}\mathcal{P}_2^0\mathcal{P}_2^{0*}\right)^2} = \kappa_{12}$$

Limits of our ansatz



Interference effects cannot be well-treated for large Γ/M $\rightarrow$ let's explore in a quantitative way the deviations from NWA.

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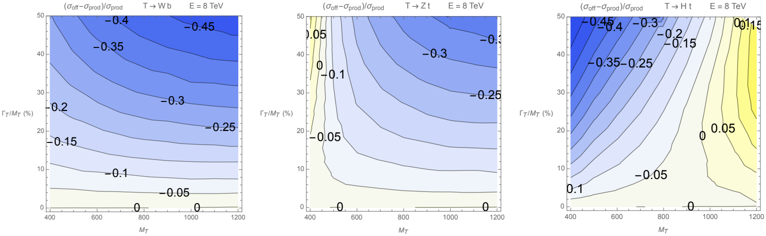

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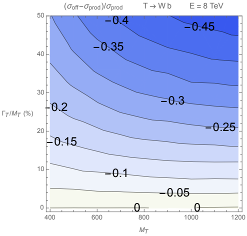

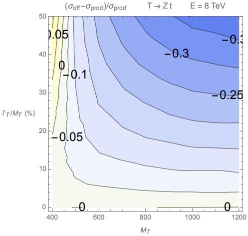

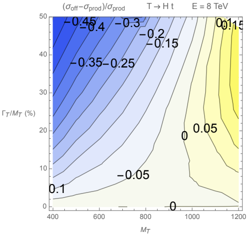

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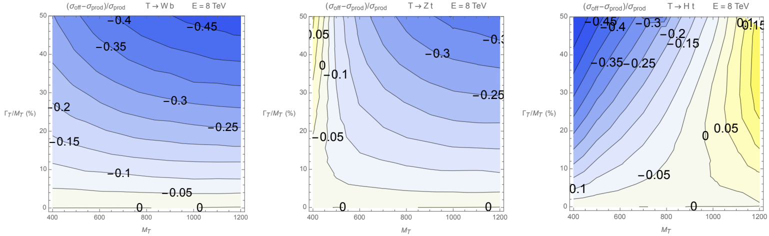

- *Wb* and *Zt* channels: the offshell contribution is more important when Γ/M is large.
- *Ht* channel: different behaviour due to the fact that the coupling to the Higgs is proportional to the mass M_T → study of the differential distributions needed.

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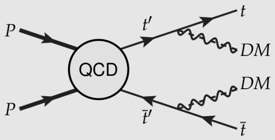
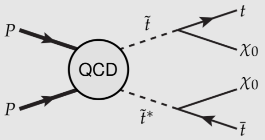
- Interesting analogy with SUSY searches (same final state)

Decay into Dark Matter and top quarks

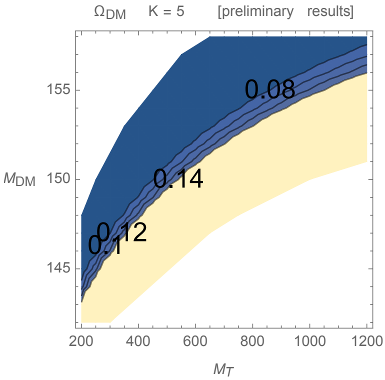




If a signal is observed, it may be possible to distinguish a VLQ signal from a SUSY signal from the different kinematics of the events!

By computing the relic density of DM in a model featuring a VLQ *T* decaying to a scalar DM particle we can impose strong constraints on the value of the masses and coupling.

$$\Omega_{DM} \sim \frac{1}{< \sigma v >}$$



These preliminary results still have to be checked using micrOMEGAs.

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  - It may be possible to distinguish the origin of a signal by studying the *kinematics* of the event.

Thank you for your attention.

Backup slides

Dimension of representation

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$\Rightarrow$ $\bar{q}HQ$ is a singlet

In term of representation of $SU(2)_L$ we have

1. $q_R \otimes H \otimes Q = 1 \otimes 2 \otimes n = 1 \oplus \ldots$

   or

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$\Rightarrow$ ***Q* can only be a singlet, a doublet or a triplet.**

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2. $q_L \otimes H \otimes Q = 2 \otimes 2 \otimes n = 1 \oplus \ldots$

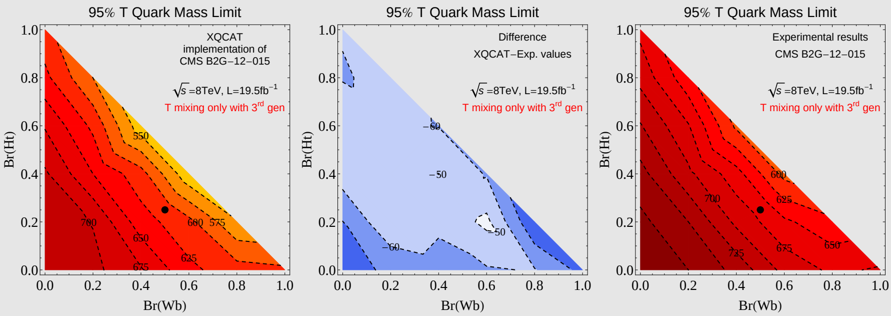
   - 1st case: $n = 2$
   - 2nd case: $n = 1$ or $n = 3$

$\Rightarrow$ ***Q* can only be a singlet, a doublet or a triplet.**

Remark: We can also have higher representations for VLQs by considering model with more than one VLQ.

Validation of XQCAT: 1 T singlet

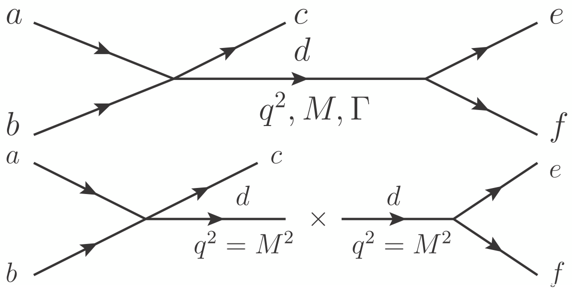
Validation plots: T mixing only with 3^{rd} generation



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

Presentation of the NWA

The Narrow-Width Approximation (NWA) allows us to simplify the computation of complex processes → very useful and used in theoretical physics.
Basic idea: factorise the whole process into the on-shell production and the subsequent decay



Proof of the NWA

$$\mathcal{M} = \mathcal{M}_P \frac{1}{q^2 - M^2 - iM\Gamma} \mathcal{M}_D$$

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With $\sigma = \frac{1}{F} \int \mathrm{d}\Phi \left|\bar{\mathcal{M}}\right|^2$, $\mathrm{d}\Phi = \mathrm{d}\Phi_P \frac{\mathrm{d}q^2}{2\pi} \mathrm{d}\Phi_D$ and our approximation $\frac{1}{(q^2-M^2)^2+(M\Gamma)^2} \xrightarrow[\Gamma \ll M]{} \frac{\pi}{M\Gamma} \cdot \delta(q^2 - M^2)$, we find

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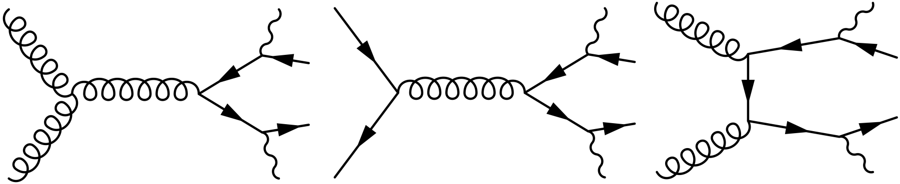
$$\boxed{\sigma \simeq \sigma_P \cdot \frac{\Gamma_D}{\Gamma} \simeq \sigma_P \cdot BR}$$

Generalisation



+ crossed

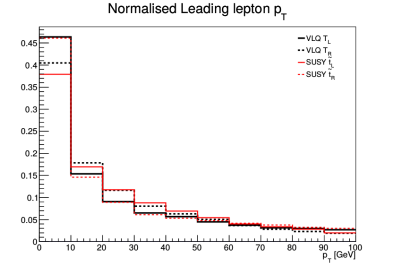
2 to 4 processes with fermionic propagators.

$$\boxed{\sigma = \sigma_P \frac{\Gamma_{D^+}}{\Gamma_+}\frac{\Gamma_{D^-}}{\Gamma_-} = \sigma_P \cdot BR_+ \cdot BR_-}$$

Comparison VLQ-SUSY [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 missing transverse energy in the final state.

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



$$m_{t'/\tilde{t}} = 600GeV$$
$$m_{S_{DM}/\chi_0} = 10GeV$$

CheckMATE results: the SUSY point is excluded, but not the VLQ point!

The preliminary results looks promising.