Model-independent study of vector-like quarks scenarios

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Erice
Introduction

- **Vector-like quark (VLQ):** particular kind of quarks that are predicted by many scenarios beyond the Standard Model (SM) in different numbers and types:

  - 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
  - Non-minimal SUSY extensions: VLQs increase corrections to Higgs mass without affecting EWPT
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Visible decay

Invisible decay (preliminary results)

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   - 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
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### 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

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

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

$$J^{\mu+} = J^{\mu+}_L + J^{\mu+}_R \text{ with } \begin{cases} J^{\mu+}_L = \bar{u}_L \gamma^\mu d_L = \bar{u} \gamma^\mu (1 - \gamma^5) d = V - A \\ J^{\mu+}_R = 0 \end{cases}$$
Moreover, since a 4th generation of chiral quarks is excluded at 4.8\(\sigma\) by LHC Higgs data ([1209.1101]), searches for VLQs will acquire high priorities experimentally.
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### Quantum numbers

<table>
<thead>
<tr>
<th></th>
<th>SM quarks</th>
<th>Singlets</th>
<th>Doublets</th>
<th>Triplets</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q_L$</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>$q_R$</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Y_{q_L}$</td>
<td>1/6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Y_{u_R}$</td>
<td>2/3</td>
<td>7/6</td>
<td>2/3</td>
<td></td>
</tr>
<tr>
<td>$Y_{d_R}$</td>
<td>-1/3</td>
<td>1/6</td>
<td>-1/3</td>
<td></td>
</tr>
<tr>
<td>$L_m$</td>
<td>forbidden$^1$</td>
<td>$-M\bar{\psi}\psi$</td>
<td>$-M\bar{\psi}\psi$</td>
<td>$-M\bar{\psi}\psi$</td>
</tr>
</tbody>
</table>

$^1$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 $W^+ d_i$.

$$Q_{VL} \rightarrow q_{SM}^W W^\pm$$

- VLQ decaying to invisible particles (Dark Matter): the only possibility
  of decay for a VLQ
  $T$ is $\chi u_i$, where $\chi$ is a DM particle (scalar or vector) made stable by a
  $Z_2$ symmetry imposed to the Lagrangian.

$$Q_{VL} \rightarrow q_{SM}^Z Z$$

$$Q_{VL} \rightarrow q_{SM}^H H$$
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Introduction to vector-like quarks

Visible decay

Invisible decay (preliminary results)

The XQCAT program

Study of the interferences

Offshellness analysis

Presentation of the project

XQCAT in a nutshell

XQCAT = eXtra Quark Combined Analysis Tool

https://launchpad.net/xqcat


INPUT

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

For each heavy quark

CROSS-SECTIONS

WEIGHTED WITH EFFICIENCIES AND BRs

and therefore

NUMBER OF SIGNAL EVENTS

For each implemented search

OUTPUT

Exclusion confidence level

$$\epsilon CL \equiv 1 - CL_s$$

For each implemented search

or for searches in combination

Pre-simulated

DATABASE OF EFFICIENCIES

per bin, per mass, per channel

For each implemented search

(ATLAS, CMS)
First results of XQCAT: 1 T singlet
but with different mixing structure

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

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

- Model with two VLQs $T_1$ and $T_2$
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- We have $T_1 \bar{T}_1 \rightarrow W^+ b \ W^- \bar{b}$ but also $T_2 \bar{T}_2 \rightarrow W^+ b \ W^- \bar{b}$.
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- We have $T_1 \bar{T}_1 \rightarrow W^+ b \ W^- \bar{b}$ but also $T_2 \bar{T}_2 \rightarrow W^+ b \ W^- \bar{b}$.
- Cross section: $\sigma \propto (A_{T_1} + A_{T_2})^2 \propto A_{T_1}^2 + A_{T_2}^2 + 2 \text{Re}(A_{T_1} A_{T_2}^*)$

\[
\begin{align*}
\sigma & \propto (A_{T_1} + A_{T_2})^2 \\
& \propto A_{T_1}^2 + A_{T_2}^2 + 2 \text{Re}(A_{T_1} A_{T_2}^*) \\
& \propto \sigma_1 + \sigma_2 + \text{interference term}
\end{align*}
\]
Model with two VLQs $T_1$ and $T_2$

We have $T_1 \bar{T}_1 \rightarrow W^+ b \ W^- \bar{b}$ but also $T_2 \bar{T}_2 \rightarrow W^+ b \ W^- \bar{b}$.

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How to estimate the value of the interference term?
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- Cross section: $\sigma \propto (\mathcal{A}_{T_1} + \mathcal{A}_{T_2})^2 \propto \mathcal{A}^2_{T_1} + \mathcal{A}^2_{T_2} + 2 \text{Re}(\mathcal{A}_{T_1} \mathcal{A}^*_{T_2})$, i.e., the cross section is proportional to the squared couplings times the integral of the BW propagators.

How to estimate the value of the interference term?

- We can show using the narrow-width approximation (NWA) that $\sigma_i \propto g^2_{i+} g^2_{i-} \left( \int \frac{dq}{2\pi} \mathcal{P}_i^0 \mathcal{P}_i^{0*} \right)^2$, i.e., that the cross section is proportional to the squared couplings times the integral of the BW propagators.
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- How to estimate the value of the interference term?

- We can show using the narrow-width approximation (NWA) that
  
  \[ \sigma_i \propto g_i^2 g_{i-}^2 \left( \int \frac{dq^2}{2\pi} P_{i0} P_{i0}^* \right)^2, \]
  
  i.e. that the cross section is proportional to the squared couplings times the integral of the BW propagators.

  \[ \Rightarrow \text{Ansatz: } \sigma_{\text{int}} \propto 2g_1 + g_{2-} + g_2 - \text{Re} \left\{ \left( \int \frac{dq^2}{2\pi} P_{10}^* P_{20} \right)^2 \right\} \]
Interference plot

\[ F_{12} = \frac{\sigma_{\text{int}}}{\sigma_1 + \sigma_2} \approx \frac{2 \ g_1 g_{1-} g_2 + g_{2-} \ Re \left\{ \left( \int \frac{dq^2}{2\pi} \mathcal{P}_1^{0} \mathcal{P}_2^{0*} \right)^2 \right\}}{g_1^2 g_{1-} \left( \int \frac{dq^2}{2\pi} \mathcal{P}_1^{0} \mathcal{P}_1^{0*} \right)^2 + g_2^2 g_{2-} \left( \int \frac{dq^2}{2\pi} \mathcal{P}_2^{0} \mathcal{P}_2^{0*} \right)^2} = \kappa_{12} \]

\[ pp \rightarrow W^+ b \ Zt \ m_{t_1} = 300 \text{ GeV} \quad \text{NWF}=0.01 \]
Interference effects cannot be well-treated for large $\Gamma/M \rightarrow$ let’s explore in a quantitative way the deviations from NWA.
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Considering a general model featuring a $T$ singlet decaying into visible particles (BR = 100 % on the chosen channel).

<table>
<thead>
<tr>
<th>$\Gamma_T/\Gamma_T$ (%)</th>
<th>$(\sigma_{\text{off}} - \sigma_{\text{prod}})/\sigma_{\text{prod}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$T \rightarrow Wb$</td>
</tr>
<tr>
<td>-0.45</td>
<td>-0.4</td>
</tr>
<tr>
<td>-0.4</td>
<td>-0.35</td>
</tr>
<tr>
<td>-0.35</td>
<td>-0.3</td>
</tr>
<tr>
<td>-0.3</td>
<td>-0.25</td>
</tr>
<tr>
<td>-0.25</td>
<td>-0.2</td>
</tr>
<tr>
<td>-0.2</td>
<td>-0.15</td>
</tr>
<tr>
<td>-0.1</td>
<td>-0.1</td>
</tr>
<tr>
<td>-0.05</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.05</td>
<td>0</td>
</tr>
<tr>
<td>0.1</td>
<td>0</td>
</tr>
<tr>
<td>0.15</td>
<td>0</td>
</tr>
<tr>
<td>0.2</td>
<td>0</td>
</tr>
<tr>
<td>0.25</td>
<td>0</td>
</tr>
<tr>
<td>0.3</td>
<td>0</td>
</tr>
<tr>
<td>0.35</td>
<td>0</td>
</tr>
<tr>
<td>0.4</td>
<td>0</td>
</tr>
</tbody>
</table>

|                          | $T \rightarrow Ze$                              |
| -0.45                   | -0.4                                            |
| -0.4                    | -0.35                                           |
| -0.35                   | -0.3                                            |
| -0.3                    | -0.25                                           |
| -0.25                   | -0.2                                            |
| -0.2                    | -0.15                                           |
| -0.1                    | -0.1                                            |
| -0.05                   | 0                                               |
| 0                       | 0                                               |
| 0.05                    | 0                                               |
| 0.1                     | 0                                               |
| 0.15                    | 0                                               |
| 0.2                     | 0                                               |
| 0.25                    | 0                                               |
| 0.3                     | 0                                               |
| 0.35                    | 0                                               |
| 0.4                     | 0                                               |

|                          | $T \rightarrow Hb$                              |
| -0.45                   | -0.4                                            |
| -0.4                    | -0.35                                           |
| -0.35                   | -0.3                                            |
| -0.3                    | -0.25                                           |
| -0.25                   | -0.2                                            |
| -0.2                    | -0.15                                           |
| -0.1                    | -0.1                                            |
| -0.05                   | 0                                               |
| 0                       | 0                                               |
| 0.05                    | 0                                               |
| 0.1                     | 0                                               |
| 0.15                    | 0                                               |
| 0.2                     | 0                                               |
| 0.25                    | 0                                               |
| 0.3                     | 0                                               |
| 0.35                    | 0                                               |
| 0.4                     | 0                                               |

Wb and Ze channels: the offshell contribution is more important when $\Gamma_T/\Gamma_T$ 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.
Considering a general model featuring a $T$ singlet decaying into visible particles (BR = 100 % on the chosen channel).
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Global project

**Goal:** build a XQCATDM program to get exclusion confidence level for scenarios featuring VLQ decaying to DM.
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- same features than XQCAT for the LHC constraints,
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- same features than XQCAT for the LHC constraints,
- cosmological constraints coming from relic density calculation,
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- similar analysis to perform: interference and offshellness effects (ongoing work)
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- cosmological constraints coming from relic density calculation,
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**Interesting analogy with SUSY searches (same final state)**

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!
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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.
Conclusion

- We considered general models featuring VLQ in a model-independent way.
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- For VLQ decaying to **visible particles**.
Conclusion

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  For VLQ decaying to **visible particles**
  - We already have the *XQCAT* program which allows us to impose *LHC constraints* on a model.

- For VLQ decaying to **invisible particles**
  - We can build *XQCATDM* the same way than *XQCAT* to impose *LHC constraints* on a model, and we will have to consider carefully the **offshellness** and **interference** effects (especially for large widths). For this kind of models the **cosmological constraints** can put strong restrictions on the free parameters. It may be possible to distinguish the origin of a signal by studying the **kinematics** of the event.
We considered general models featuring VLQ in a *model-independent way*.

For VLQ decaying to **visible particles**
- We already have the *XQCAT* program which allows us to impose *LHC constraints* on a model.
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  - *XQCAT* results are only valid in the NWA so we have to take the *offshellness* effects into account when the width become large.

- For VLQ decaying to **invisible particles** (DM)
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Thank you for your attention.
Backup slides
Dimension of representation

- Minimal extension of the SM with only one VLQ $Q$
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- Yukawa coupling between a SM-quark $q$ and $Q$: $\mathcal{L}_Y = -y\bar{q}HQ + h.c$
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- The Lagrangian is a scalar and so a singlet of $G$
Dimension of representation

- Minimal extension of the SM with only one VLQ $Q$
- Yukawa coupling between a SM-quark $q$ and $Q$: $\mathcal{L}_Y = -y \bar{q}HQ + h.c$
- The Lagrangian is a scalar and so a singlet of $G$

\[ \Rightarrow \bar{q}HQ \text{ is a singlet} \]
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

2. $q_L \otimes H \otimes Q = 2 \otimes 2 \otimes n = 1 \oplus \ldots$
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$\Rightarrow Q$ can only be a singlet, a doublet or a triplet.
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$\Rightarrow$ **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.
We reproduce CMS 95 % CL bounds within 50-60 GeV in the whole BR range
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

\[ \mathcal{M} = \mathcal{M}_P \frac{1}{q^2 - M^2 - i\Gamma} \mathcal{M}_D \]
Proof of the NWA

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

\[ |\bar{\mathcal{M}}|^2 = |\mathcal{M}_P|^2 \frac{1}{(q^2 - M^2)^2 + (M \Gamma)^2} |\mathcal{M}_D|^2 \]
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With \( \sigma = \frac{1}{F} \int d\Phi |\bar{\mathcal{M}}|^2 \), \( d\Phi = d\Phi_P \frac{dq^2}{2\pi} d\Phi_D \) 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
Proof of the NWA

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

\[ |\bar{M}|^2 = |\mathcal{M}_P|^2 \frac{1}{(q^2 - M^2)^2 + (M\Gamma)^2} |\mathcal{M}_D|^2 \]

With \( \sigma = \frac{1}{F} \int d\Phi |\bar{M}|^2 \), \( d\Phi = d\Phi_P \frac{dq^2}{2\pi} d\Phi_D \) and our approximation

\[ \frac{1}{(q^2 - M^2)^2 + (M\Gamma)^2} \xrightarrow{\Gamma \ll M} \frac{\pi}{M\Gamma} \cdot \delta(q^2 - M^2), \text{ we find} \]

\[ \sigma \approx \sigma_P \cdot \frac{\Gamma_D}{\Gamma} \approx \sigma_P \cdot BR \]
Generalisation

2 to 4 processes with fermionic propagators.

\[ \sigma = \sigma_P \frac{\Gamma_{D+}}{\Gamma_+} \frac{\Gamma_{D-}}{\Gamma_-} = \sigma_P \cdot BR_+ \cdot BR_- \]
Simulation of the process $pp \rightarrow t \bar{t} + E_T$ 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

![Graph showing normalised leading lepton $p_T$](image)

$\frac{m_{t/t}}{m_{t/t}} = 600 GeV$

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

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

The preliminary results looks promising.