# Model-independent analysis of scenarios with vector-like quarks

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# What are vector-like fermions?

## and where do they appear?

The left-handed and right-handed chiralities of a vector-like fermion $\psi$ 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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- SM chiral quarks: ONLY left-handed charged currents

$$J^{\mu +} = J^{\mu +}_L + J^{\mu +}_R \qquad \text{with} \qquad \left\{ \begin{array}{l} J^{\mu +}_L = \bar{u}_L \gamma^\mu d_L = \bar{u} \gamma^\mu (1 - \gamma^5) d = V - A \\ J^{\mu +}_R = 0 \end{array} \right.$$

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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 a vector-like quark

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

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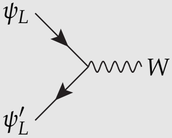
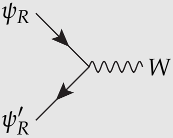
Charged currents both in the left and right sector





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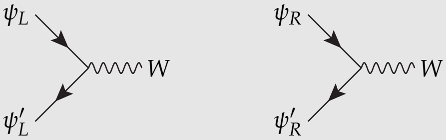

There can be **partners** of top and bottom or quarks with **exotic charges** (5/3,-4/3. . . )

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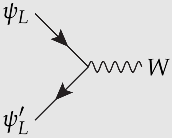

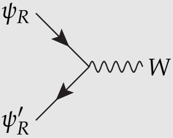

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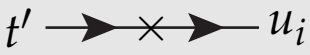
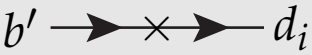
## They can mix with SM quarks





Dangerous FCNCs $\longrightarrow$ strong bounds on mixing parameters
BUT
Many open channels for **production** and **decay** of heavy fermions

## Rich phenomenology to explore at LHC

# Representations and lagrangian terms

**Assumption:** vector-like quarks couple with SM quarks through Yukawa interactions

# Representations and lagrangian terms

Assumption: vector-like quarks couple with SM quarks through Yukawa interactions

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

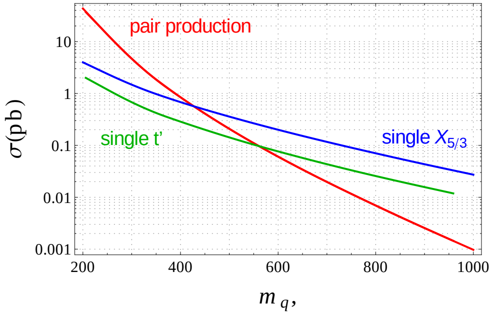
# Production channels

Vector-like quarks can be produced
in the same way as SM quarks **plus** FCNCs 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 and sensitive to both the $q'$ mass and its mixing parameters

# Production channels

Pair vs single production, example with non-SM doublet $(X_{5/3}\ t')$

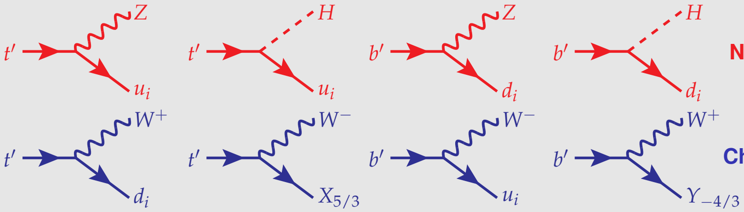


**pair production** depends only on the mass of the new particle and **decreases faster** than single production due to different **PDF scaling**

current **bounds from LHC** are around the region where (model dependent) **single production dominates**

# Decays

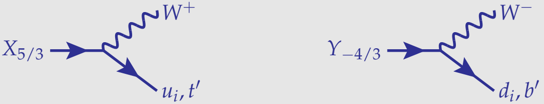
## SM partners



**Neutral currents**

**Charged currents**

## Exotics



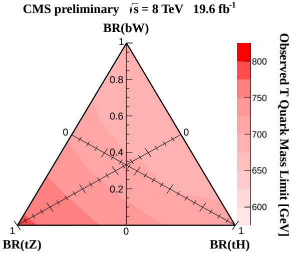
**Only Charged currents**

**Not all decays may be kinematically allowed**

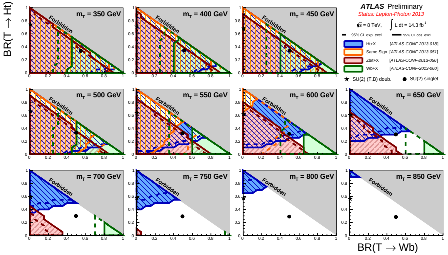
it depends on **representations** and **mass differences**

# Searches at the LHC

## CMS ($t'$)



## ATLAS ($t'$)



Bounds from pair production between 600 GeV and 800 GeV

depending on the decay channel

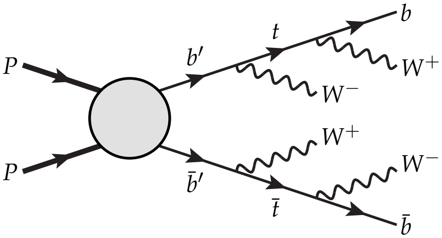
Common assumption

only one vector-like quark mixing only with third generation

While most theoretical models predict a new **quark sector**

and, in principle, mixing can be with all families

# General mixing: $b'$ pair production



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CC: $b' \to tW$

Searches in the
same-sign dilepton channel
(possibly with b-tagging)

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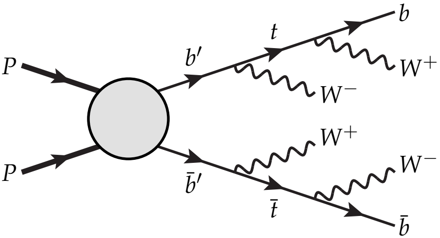

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Searches in the
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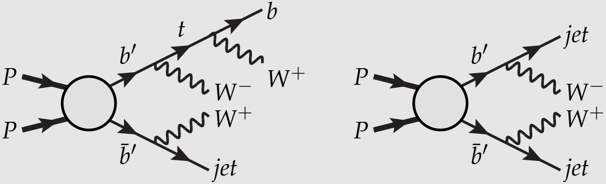
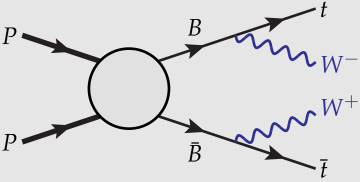
If the $b'$ decays both into $Wt$ and $Wq$

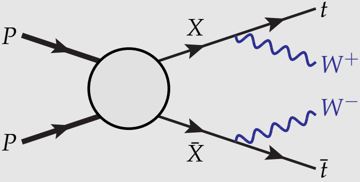


There can be less events in the same-sign dilepton channel!

# Multiple vector-like quarks

Scenario with $X$ and $B$ (decaying to third generation only)





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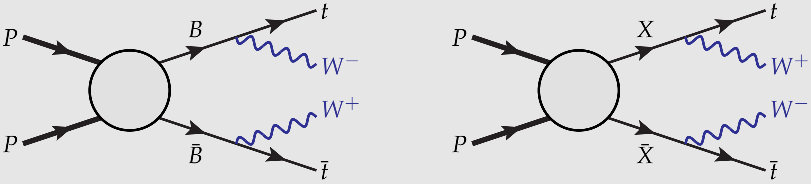
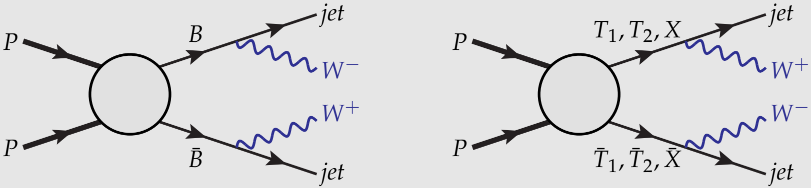


## Scenario with a bidoublet $\begin{pmatrix} X & T_1 \\ T_2 & B \end{pmatrix}$ (general mixing)



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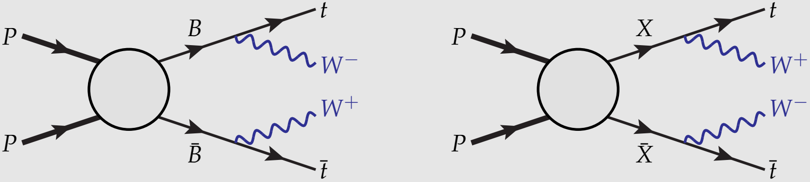

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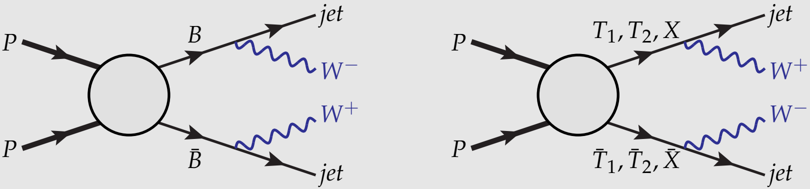

A given final state can be feeded by different channels!
(with different kinematics)

# Counting the final states

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

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

each one with its peculiar kinematics

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$B$ pair production $\longrightarrow$ 6 possible decays: $W^-j \quad W^-t \quad Zj \quad Zb \quad Hj \quad Hb$

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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

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36 possible combinations of decays into SM particles

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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!

# Efficiencies of searches

## Numerical Simulation

| MadGraph, CalcHEP, . . . | | Pythia | | Delphes | | |
|---|---|---|---|---|---|---|
| $PP \to Q\bar{Q} \to$ final state | $\to$ | hadronization | $\to$ | detector simulation | $\to$ | signal |

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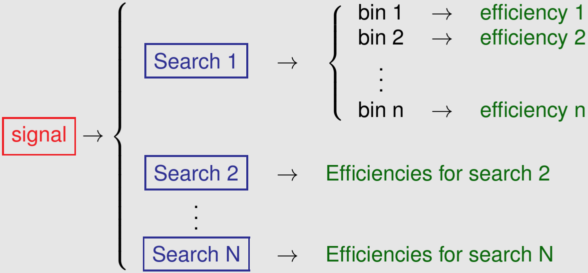

signal →

Search 1 →
- bin 1 → efficiency 1
- bin 2 → efficiency 2
- ⋮
- bin n → efficiency n

Search 2 → Efficiencies for search 2

⋮

Search N → Efficiencies for search N

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## Numerical Simulation

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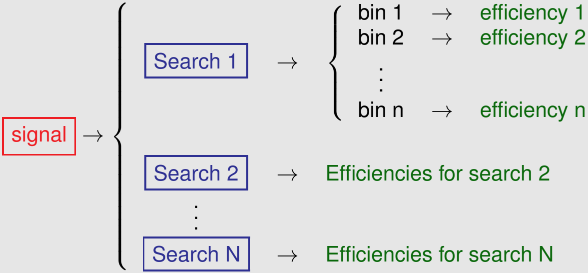

signal →

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  - bin 1 → efficiency 1
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  - ⋮
  - bin n → efficiency n
- Search 2 → Efficiencies for search 2
- ⋮
- Search N → Efficiencies for search N

Knowing the efficiencies for all combinations of final states it is possible to reconstruct any signal

Any model containing any number of VLQs can be analysed in a single framework!

# The exclusion confidence level

## Example with a fictional search

**Observation**

310 events

**Background**

300 events

# The exclusion confidence level

## Example with a fictional search

### Observation

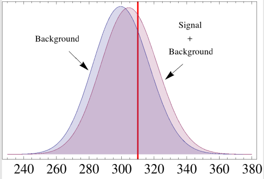
310 events

### Background

300 events

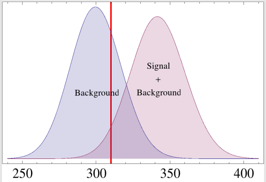
### Signal

### Case I: 5 events



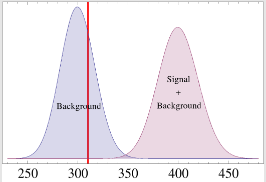
Exclusion CL $\simeq$ 14%

### Case II: 42 events



Exclusion CL $\simeq$ 94%

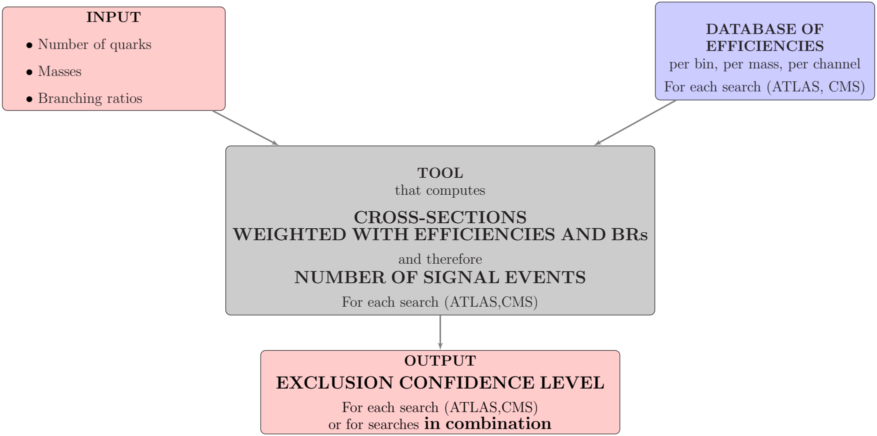
### Case III: 100 events



Exclusion CL $\simeq$ 99.99%

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

# Flowchart of the project



**INPUT**

- Number of quarks
- Masses
- Branching ratios

**DATABASE OF EFFICIENCIES**
per bin, per mass, per channel
For each search (ATLAS, CMS)

**TOOL**
that computes
**CROSS-SECTIONS WEIGHTED WITH EFFICIENCIES AND BRs**
and therefore
**NUMBER OF SIGNAL EVENTS**
For each search (ATLAS,CMS)

**OUTPUT**
**EXCLUSION CONFIDENCE LEVEL**
For each search (ATLAS,CMS)
or for searches **in combination**

Select a benchmark, i.e. number of VLQs of each charge, masses and BRs
Exclusion confidence level of the benchmark
against data from searches (any search!) using only one simulation

# (Very) Preliminary results

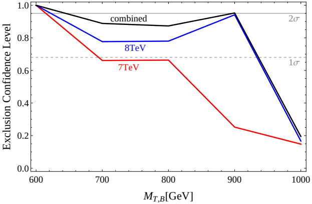
## Degenerate $(T\ B)$ doublet

### Implemented searches (only CMS temporarily)

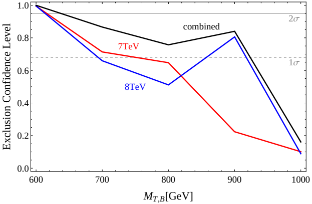
| $\alpha_T$ | $L_P$ (monolepton) | SS dileptons | OS dileptons |
|---|---|---|---|
| 7 and 8 TeV | 7 TeV | 7 and 8 TeV | 7 TeV |

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

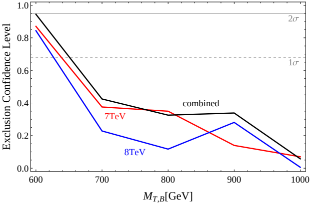
(T B) doublet mixing only with 3rd gen



(T B) doublet mixing with 1st and 3rd gen



(T B) doublet mixing only with 1st gen



1. **Stronger bounds** when mixing with 3rd generation
2. Bounds in the ballpark of those obtained with **direct searches** of VLQs
3. Potential to **improve direct searches** and to exploit **other BSM-inspired searches** to test scenarios with VLQ

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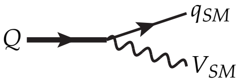
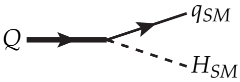
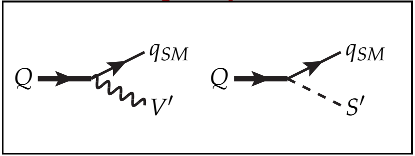
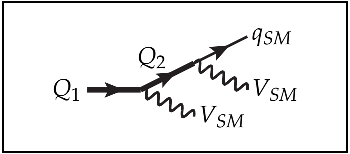




**The following decays have not been considered (model-dependency)**



Other new sectors besides the VLQs



Chain decays between VLQs

**A dedicated simulation is required for these channels**

But if a benchmark is already excluded by this analysis, adding new channels would only increase the exclusion confidence level. The signal of new physics is, at worst, underestimated, therefore an “exclusion” result is **robust**!

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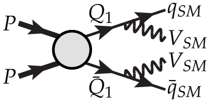
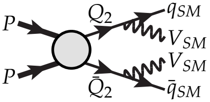
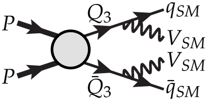
$\mathcal{A}_1 =$



$\mathcal{A}_2 =$



$\mathcal{A}_3 =$



$$\sigma \propto |\mathcal{A}_1|^2 + |\mathcal{A}_2|^2 + |\mathcal{A}_3|^2 + 2Re\left[\mathcal{A}_1\mathcal{A}_2^* + \mathcal{A}_1\mathcal{A}_3^* + \mathcal{A}_2\mathcal{A}_3^*\right]$$

It is possible to estimate the interference effect knowing the total widths and couplings to SM particles!

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

This expression describes with remarkable accuracy the interference effects in the NWA approximation

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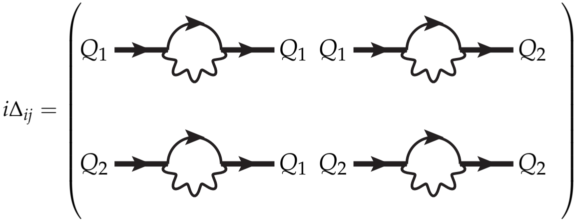
**Diagonalisation of the matrix of the propagators**



**The matrix is model-dependent:**
**any particle (also new ones) can enter the loops!!**

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**It’s crucial to take into account these issues in order not to overestimate the signal!**

# 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 **accessible at current CM energy and luminosity** and have been explored to some extent
  - → Current bounds on masses around **600-800 GeV**, but searches are not fully optimized for **general scenarios**.
- **Model-independent studies** can be performed for **pair** and **single production** to analyse scenarios with **multiple vector-like quarks** (work in progress, results very soon!)