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 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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- SM chiral quarks: ONLY left-handed charged currents

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

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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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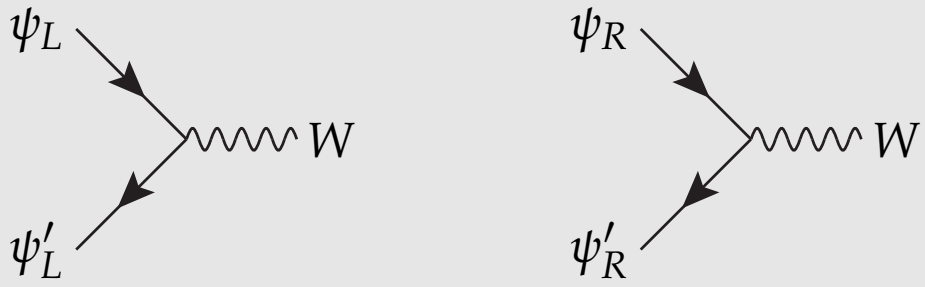
Charged currents both in the left and right sector



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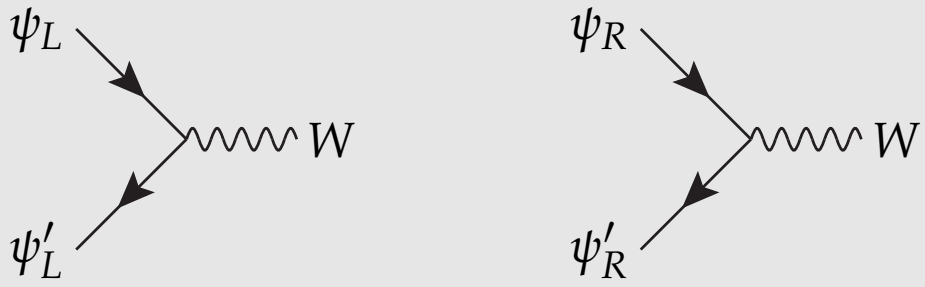

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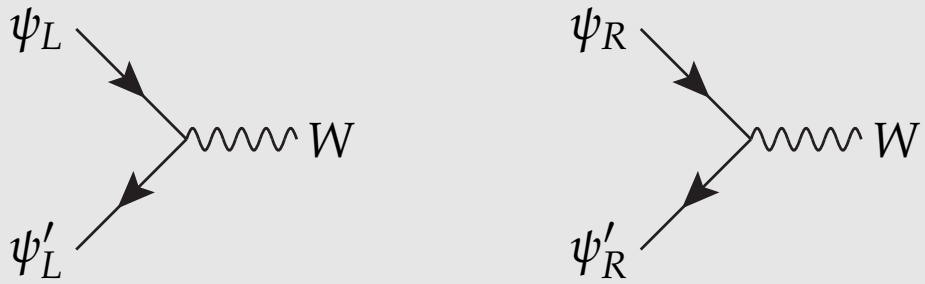
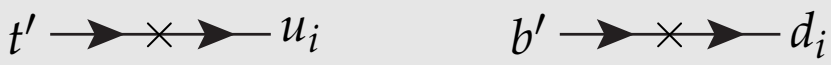


There can be **partners** of top and bottom or quarks with **exotic charges** (5/3,-4/3...)

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

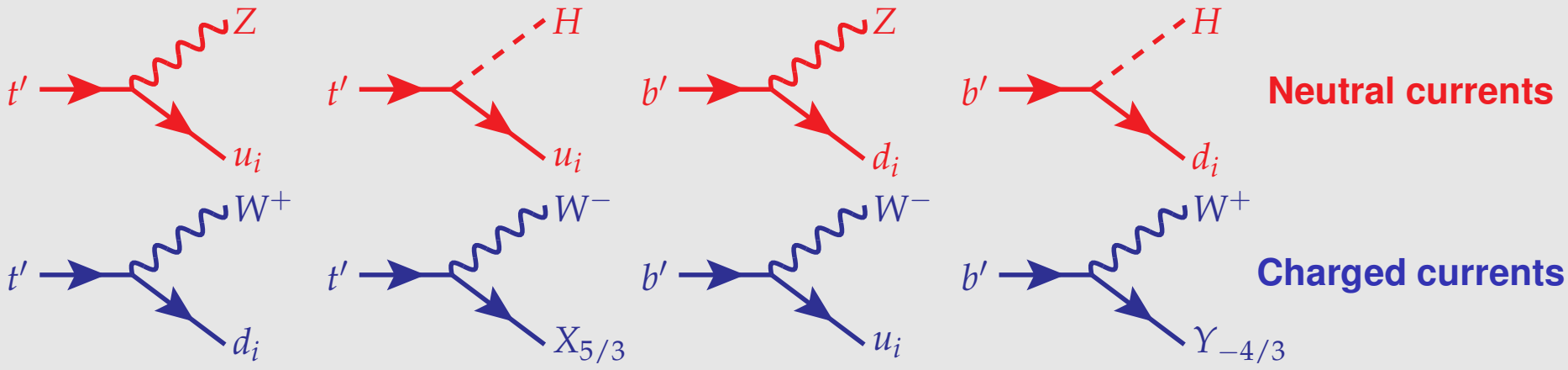
Production channels

Vector-like quarks can be produced
in the same way as SM quarks **plus** FCNCs channels

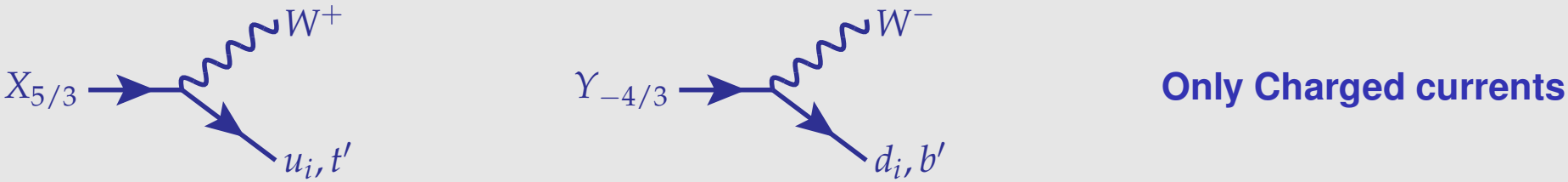
- **Pair production**, dominated by QCD and sentitive to the q' mass independently of the representation the q' belongs to
- **Single production**, only EW contributions and sensitive to both the q' mass and its mixing parameters

Decays

SM partners



Exotics

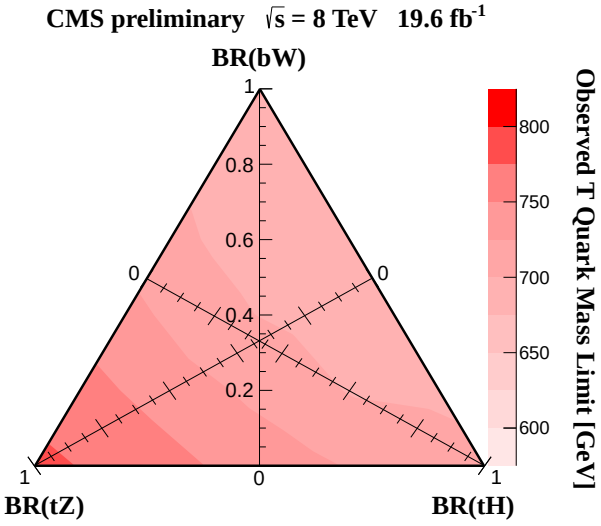


Not all decays may be kinematically allowed

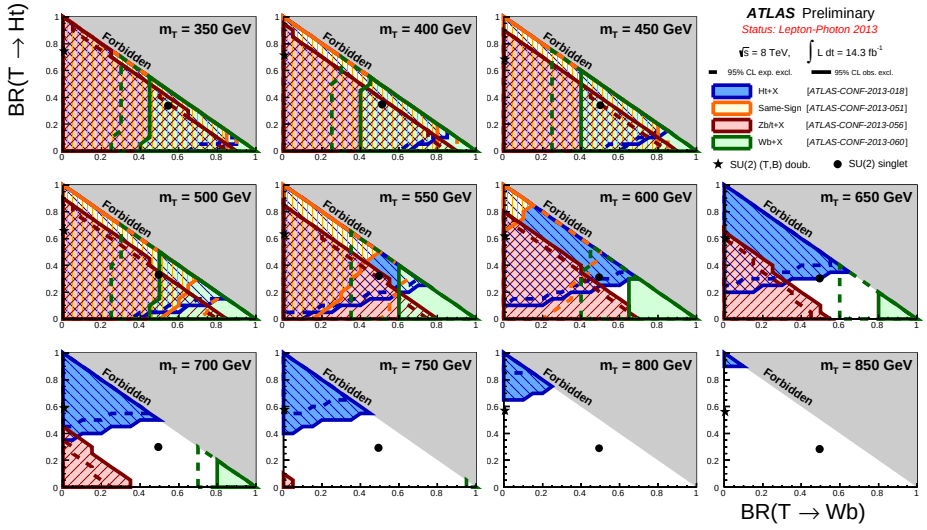
it depends on **representations** and **mass differences**

Searches at the LHC

CMS (t')



ATLAS (t')

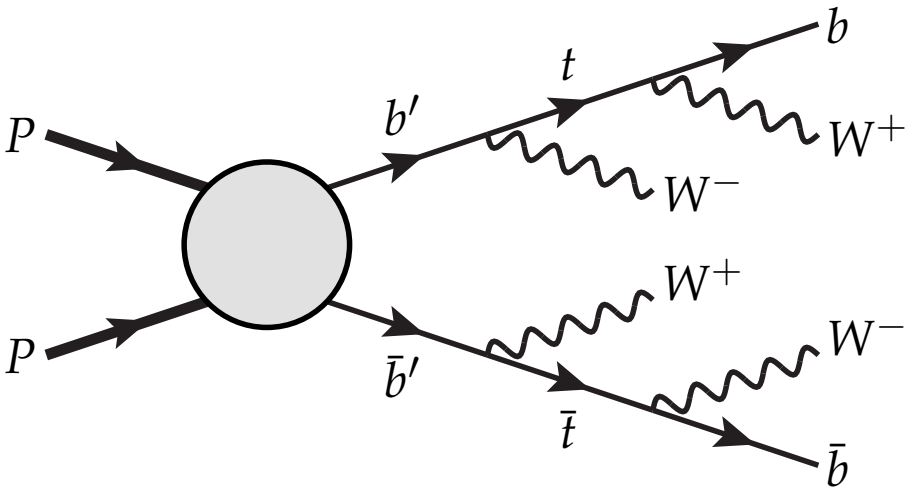


Bounds from pair production between 600 GeV and 800 GeV
depending on the decay channel

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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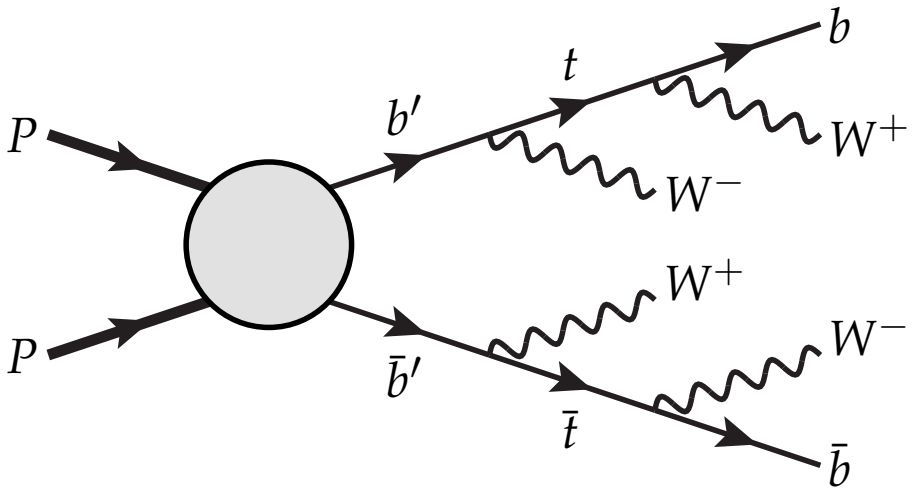

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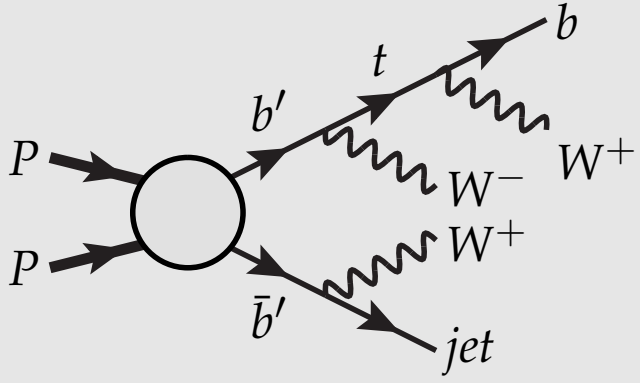
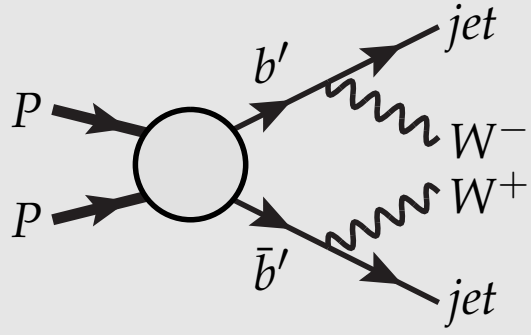
If the b' decays both into Wt and Wq

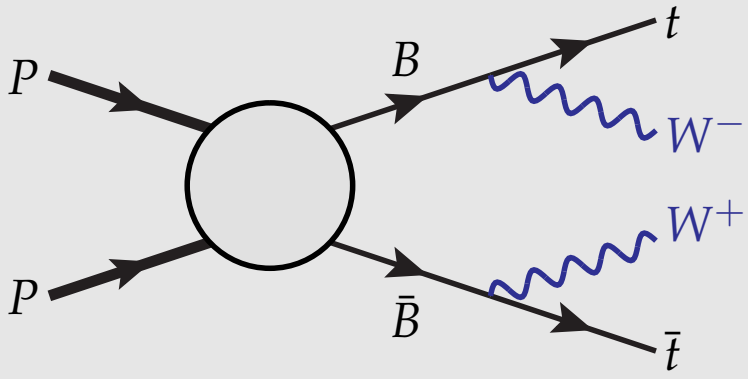


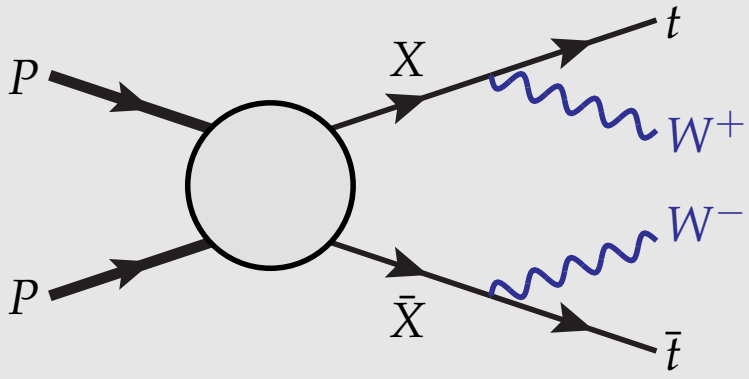


There can be less events in the same-sign dilepton channel!

Multiple vector-like quarks

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





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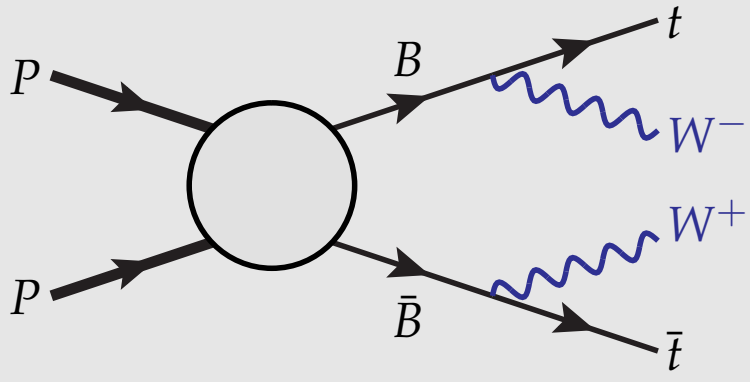
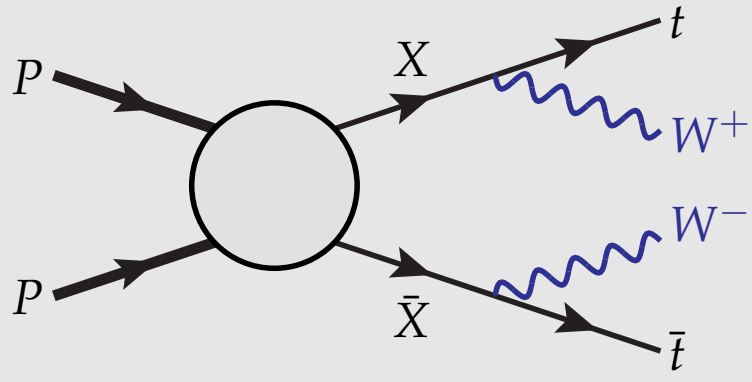
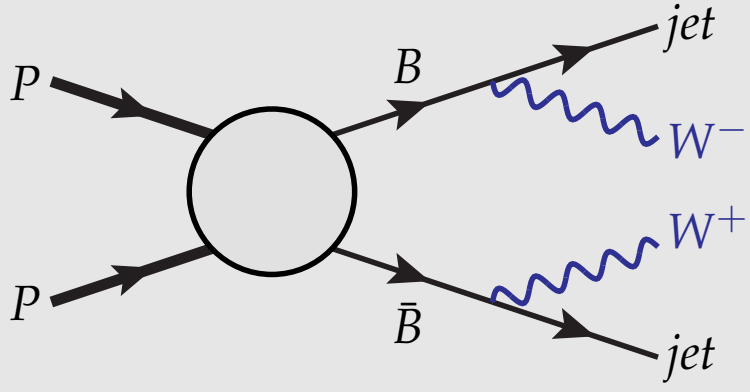
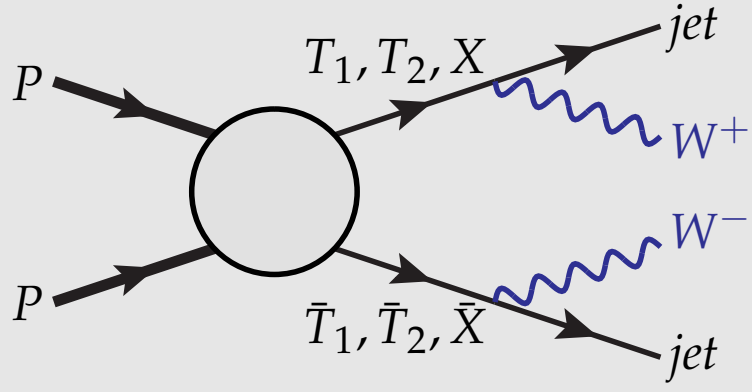




Scenario with a bidoublet $\begin{pmatrix} X & T_1 \\ T_2 & B \end{pmatrix}$ (general mixing)





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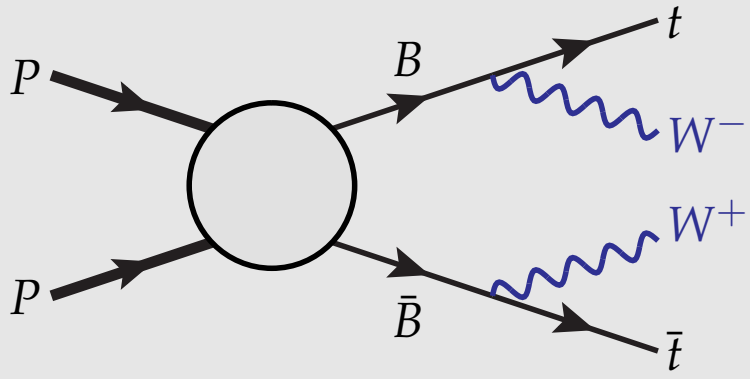

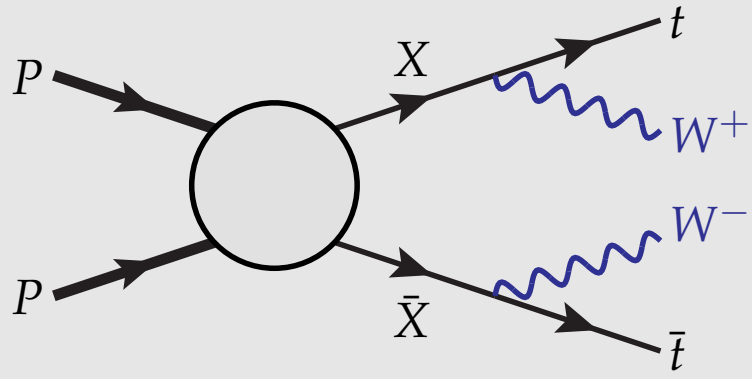

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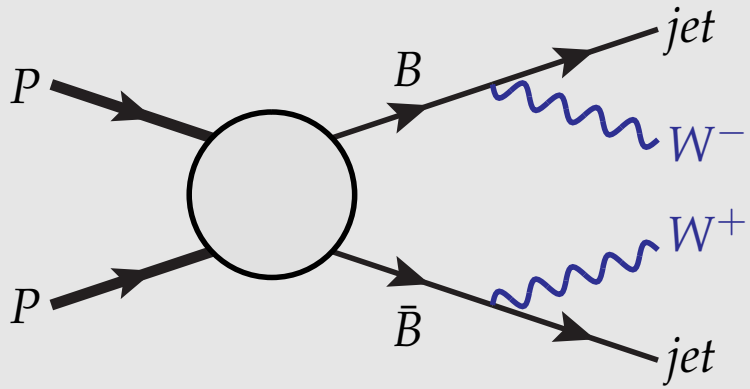

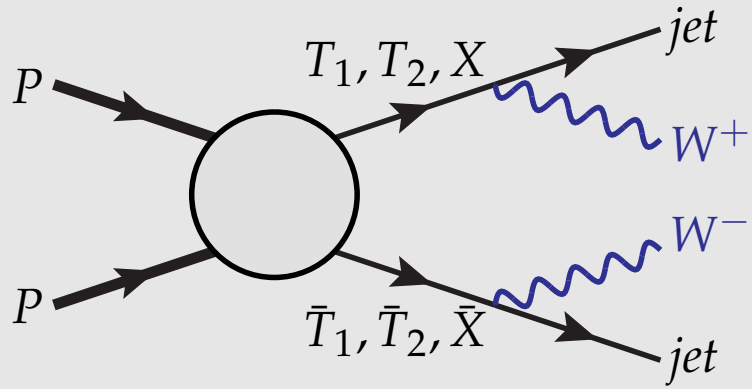

A given final state can be feeded by different channels!
(with different kinematics)

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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4 combinations

Y pair production $\longrightarrow$ W^-j W^-b

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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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Efficiencies

signal $\to$

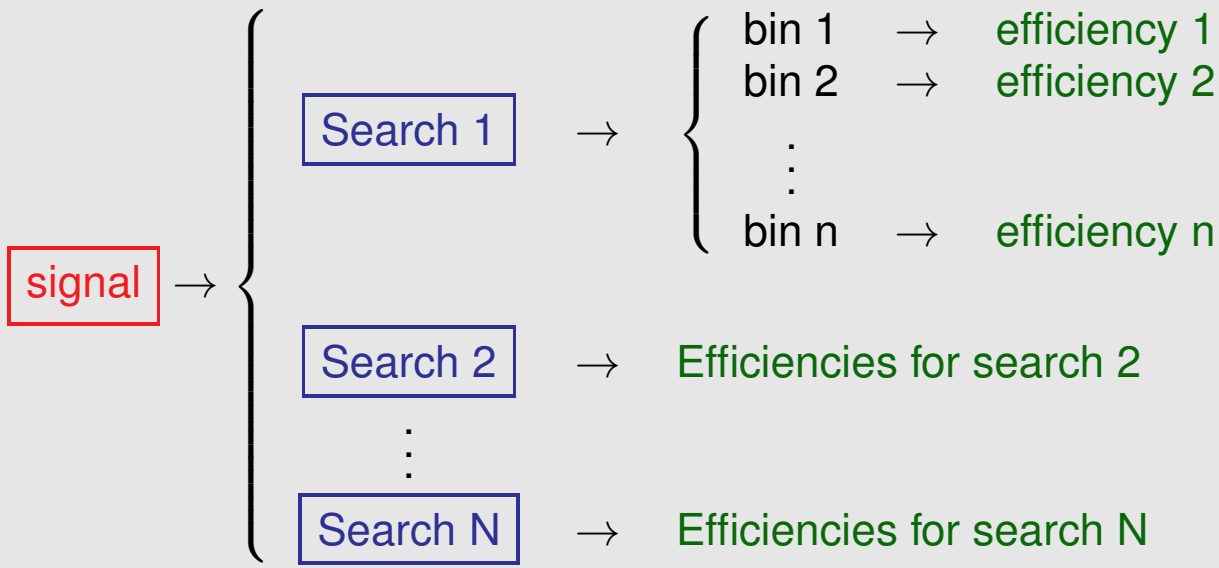
- Search 1 $\to$
  - bin 1 $\to$ efficiency 1
  - bin 2 $\to$ efficiency 2
  - $\vdots$
  - bin n $\to$ efficiency n
- Search 2 $\to$ Efficiencies for search 2
- $\vdots$
- Search N $\to$ Efficiencies for search N

Efficiencies of searches

Numerical Simulation

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

Efficiencies



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

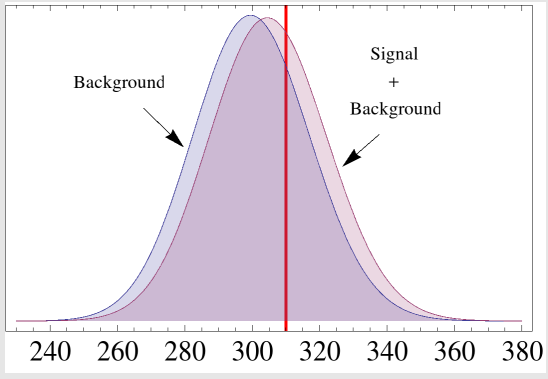
310 events

Background

300 events

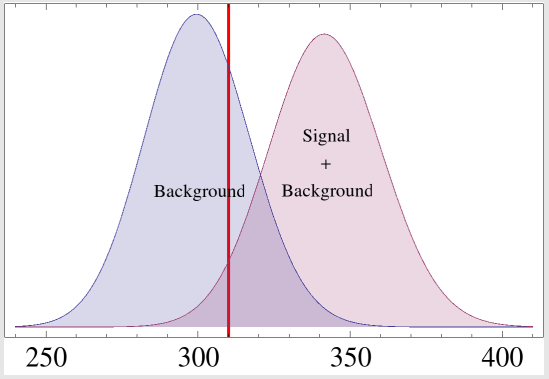
Signal

Case I: 5 events



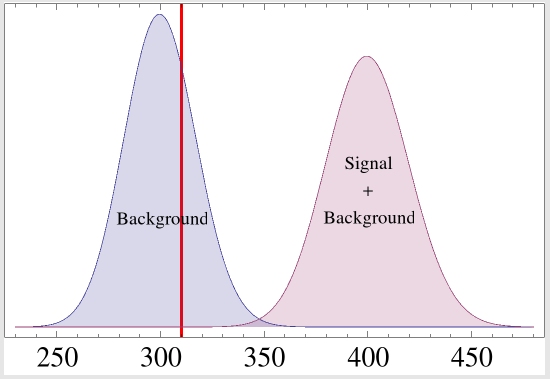
Exclusion CL $\simeq$ 14%

Case II: 42 events



Exclusion CL $\simeq$ 94%

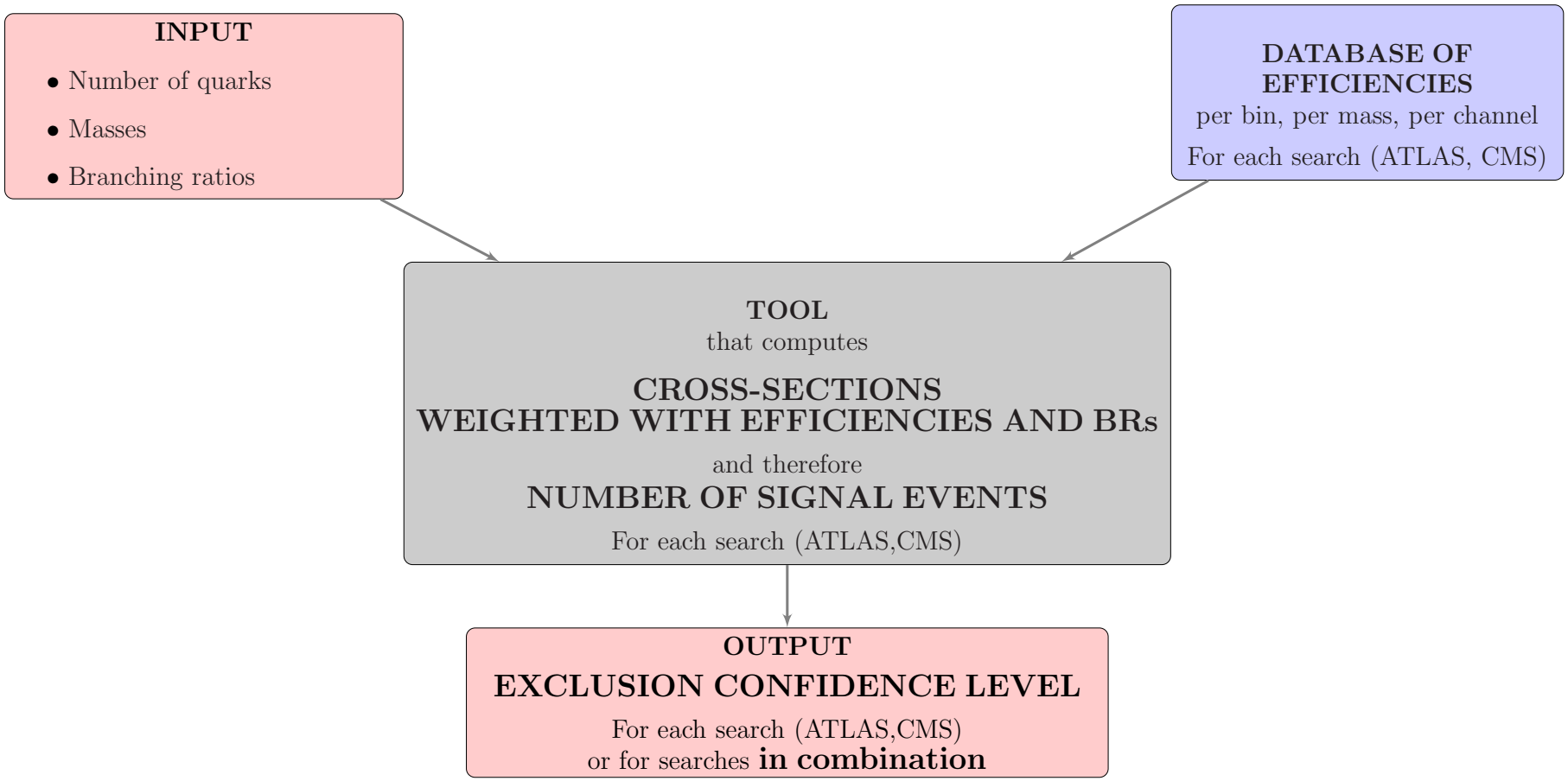
Case III: 100 events



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



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

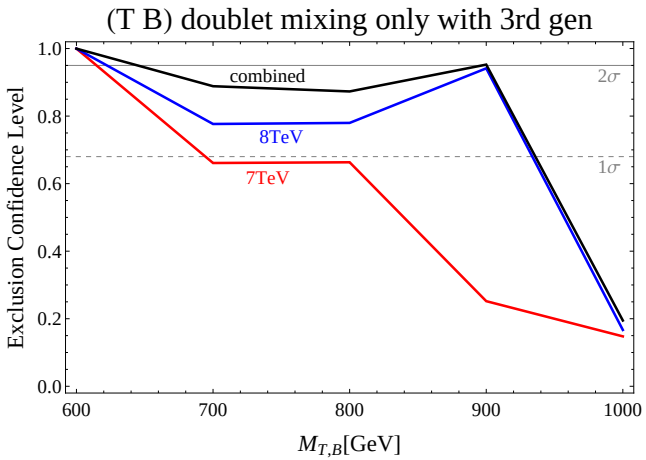
(Very) Preliminary results

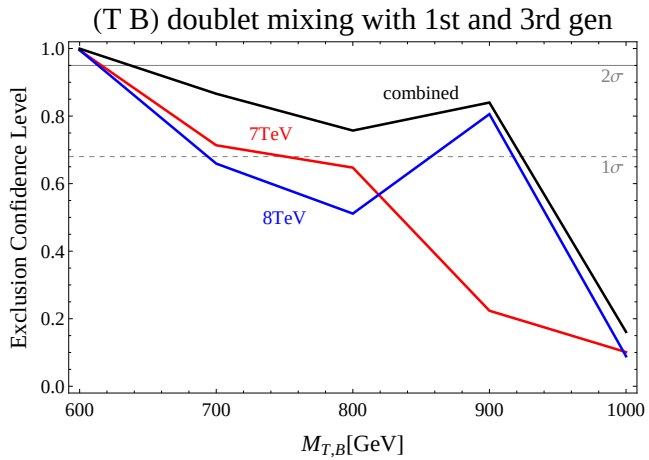
Degenerate $(T\ B)$ doublet

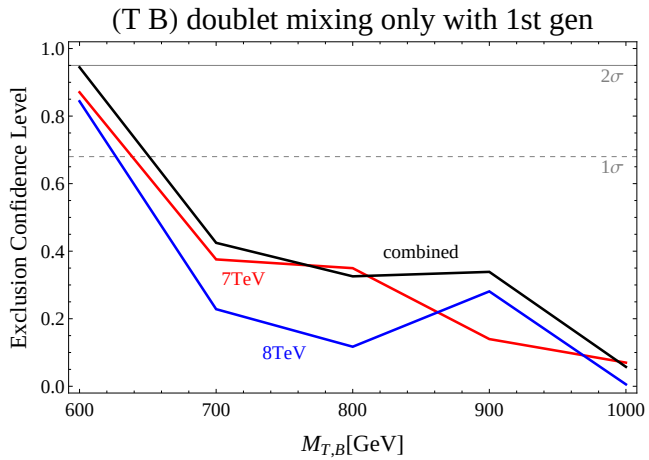
Implemented searches (only CMS temporarily)

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 since we only care about final states!







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

Remarks and subtleties

- **This is a conservative result**: a “non-exclusion” result does not mean that the benchmark is allowed. We are neglecting other potentially relevant decays!

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We only consider these topologies

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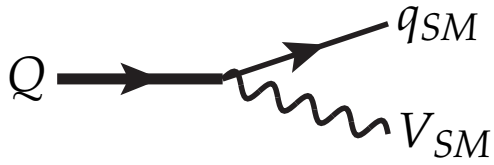
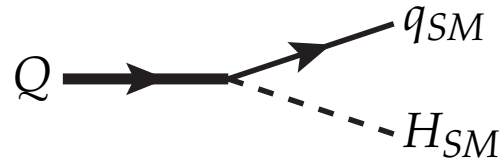
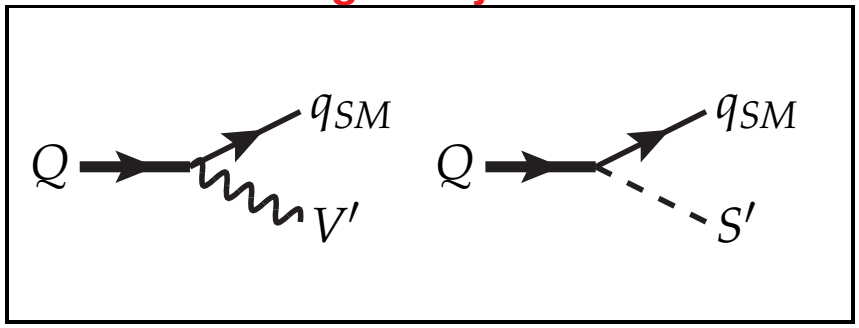
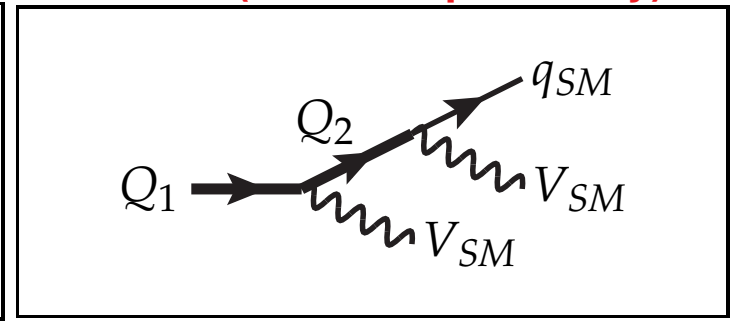




The following decays have not been considered (model-dependency)



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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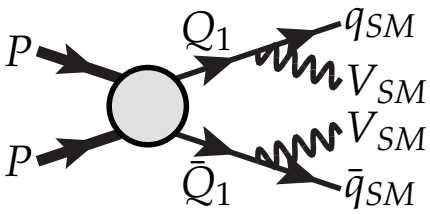
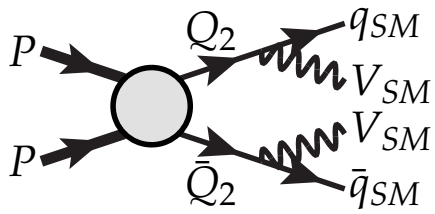
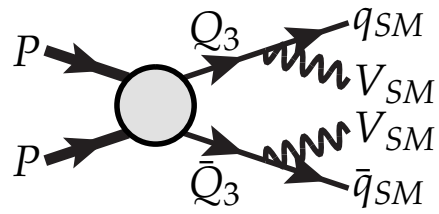
$\mathcal{A}_1 =$ 

$\mathcal{A}_2 =$ 

$\mathcal{A}_3 =$ 

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

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

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

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

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Diagonalisation of the matrix of the propagators

$$i\Delta_{ij} = \begin{pmatrix} Q_1 \to Q_1 & Q_1 \to Q_2 \\ Q_2 \to Q_1 & Q_2 \to Q_2 \end{pmatrix}$$

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
  - $\rightarrow$ Signatures of single and pair production of VL quarks are **accessible at current CM energy and luminosity** and have been explored to some extent
  - $\rightarrow$ 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**, and also to analyse scenarios with **multiple vector-like quarks** (work in progress, results very soon!)