Framework for Model Independent Analyses of Multiple Extra Quark Scenarios

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Why Extra Quarks?

A coloured new fermion is a common new particle in BSM theories

- A fourth generation of SM fermions is (almost) ruled out ✗
- Extra Quarks can appear in other ways
  - Model of Composite Higgs ✓
  - Extra Dimensions ✓
  - Little Higgs ✓
  - Non minimal SUSY theories ✓
  - and more...

Usually Extra Quarks appear as Vector Like Quarks

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Vector Like Quarks

Many BSM models predict the existence of Vector Like Quarks

- Colored Dirac fermions with 1/2 spin
- Their right and left handed components transform in the same way under the SM gauge group $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$

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Why are they called vector-like?

$$\mathcal{L} \supset \frac{g}{\sqrt{2}}(j^{\mu+} W_\mu^+ + j^{\mu-} W_\mu^-) \qquad j^{\mu\pm} = j_L^{\mu\pm} + j_R^{\mu\pm}$$

SM chiral quarks

$$j_L^\mu = \bar{f}_L \gamma^\mu f'_L \qquad j_R^\mu = 0$$

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

$V-A$

VLQs

$$j_L^\mu = \bar{f}_L \gamma^\mu f'_L \qquad j_R^\mu = \bar{f}_R \gamma^\mu f'_R$$

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V

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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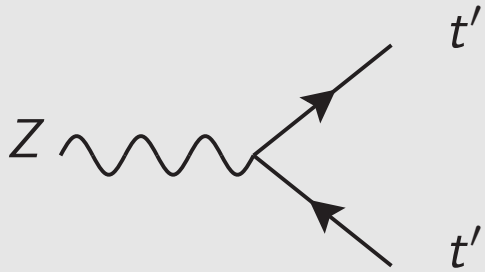
They interact with SM gauge bosons



Properties of VLQs

Assumption: VLQs interact with SM through Yukawa type couplings

	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
$\mathcal{L}_Y$	$\bar{q}_L^i H^c u_R^i$ $\bar{q}_L^i V_{CKM}^{i,j} H d_R^j$	$\bar{q}_L^i H^c t_R'$ $\bar{q}_L^i H b_R'$	$\psi_L H^{(c)} u_R^i$ $\psi_L H^{(c)} d_R^i$	$\bar{q}_L^i \tau^a H^{(c)} \psi_R^a$
$\mathcal{L}_m$		$-M\bar{\psi}\psi$ (gauge invariant since vector-like)		

Limited number of $SU(2)_L$ representations that can be used

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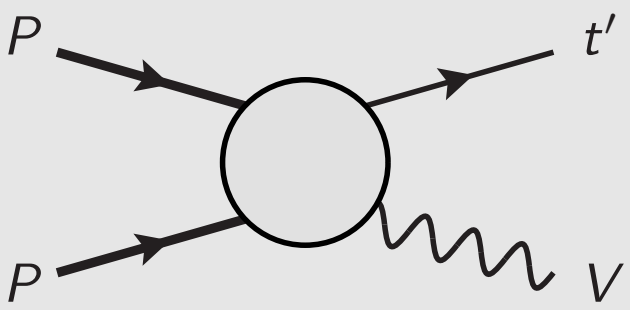
Production modes

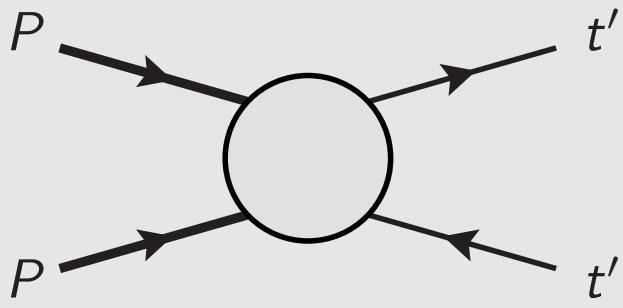
At the LHC VLQs can mainly be produced via

Single production



Also with a SM quark or Higgs

Pair production



Sensitive to

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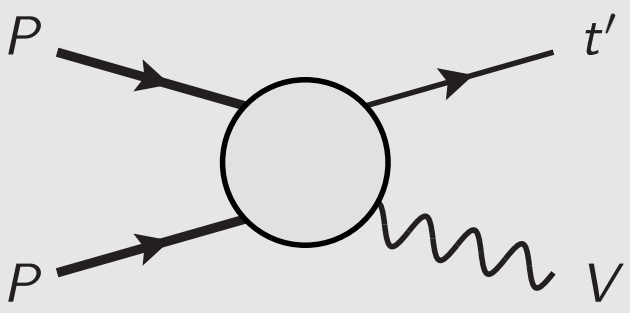

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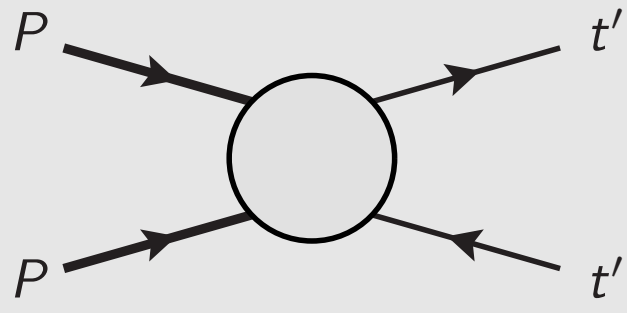

Sensitive to

VLQ mass
Mixing parameters/couplings

Model dependent

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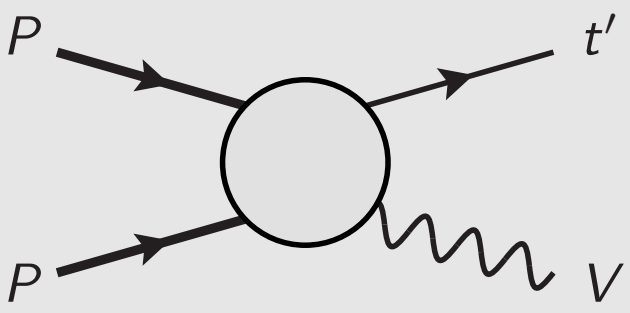

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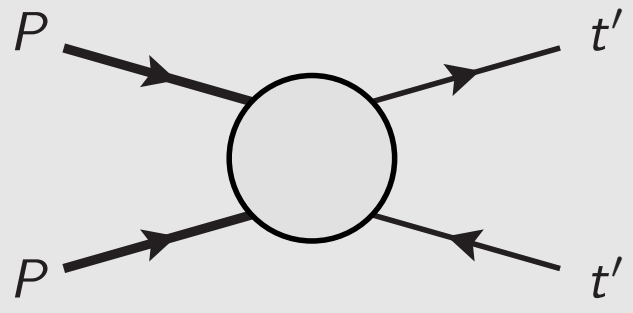
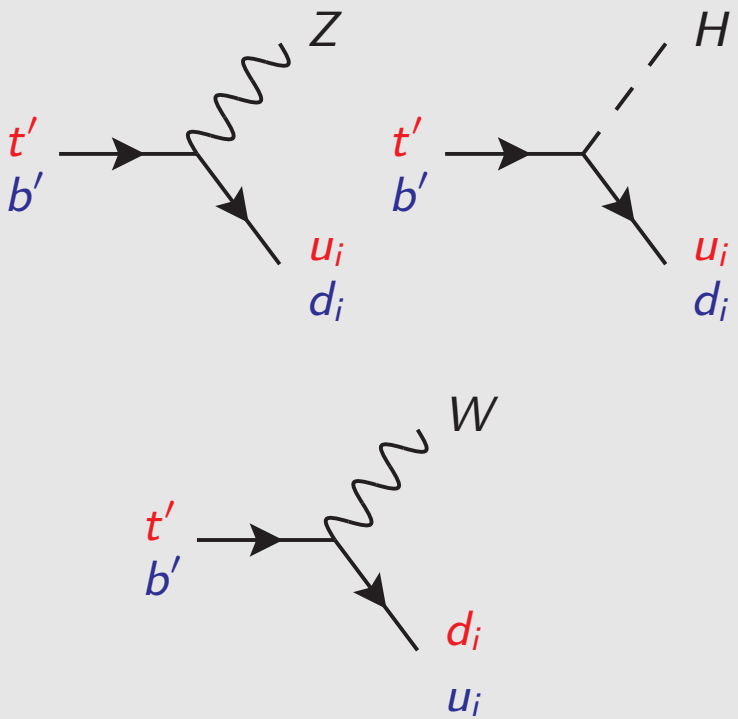


Sensitive to

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

Decay modes

SM partner



- Both Neutral and Charged Currents

Decay modes

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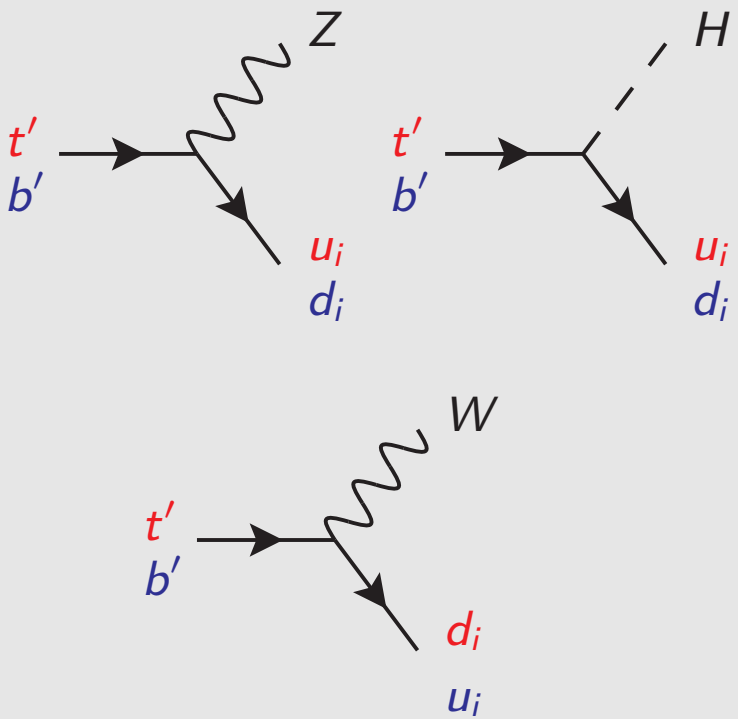

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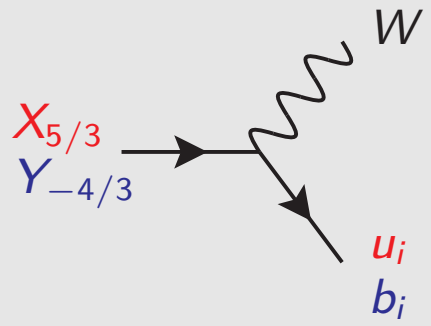

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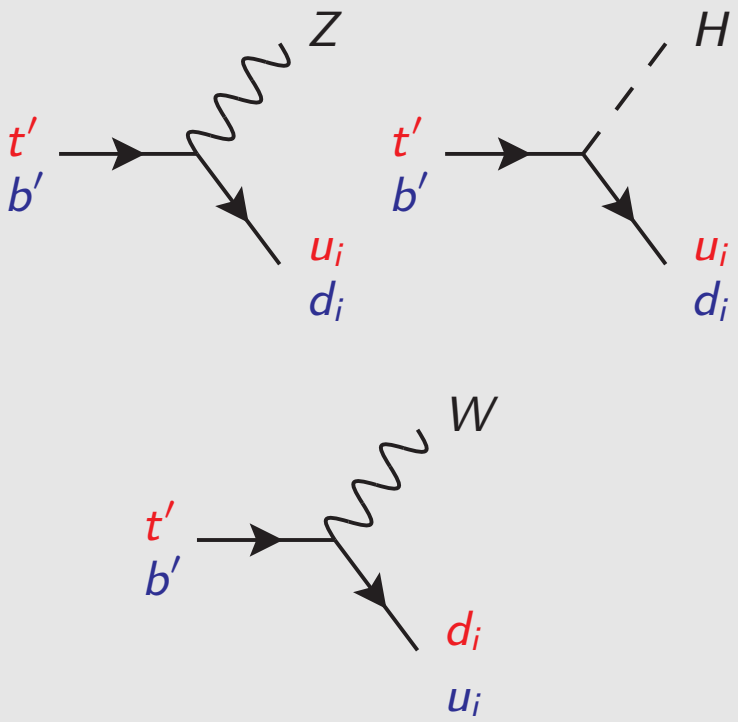

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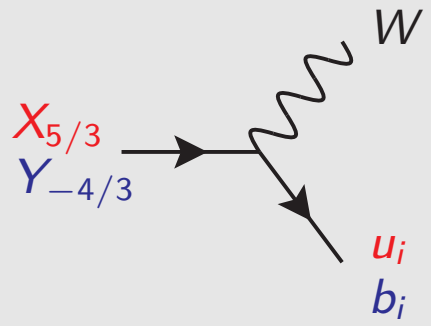

- Only Charged Currents

- No decay into extra quarks
- No extra gauge boson
- No DM candidate

Decay modes

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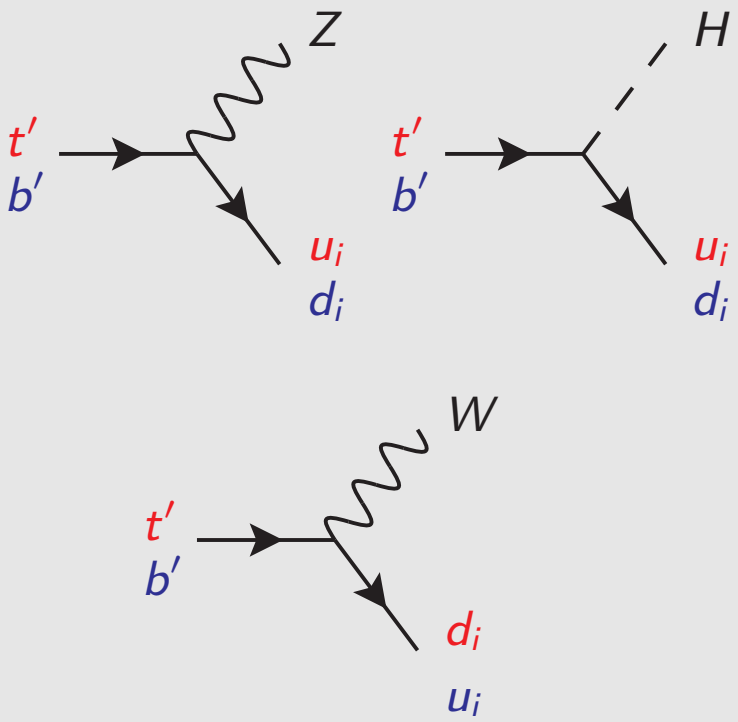

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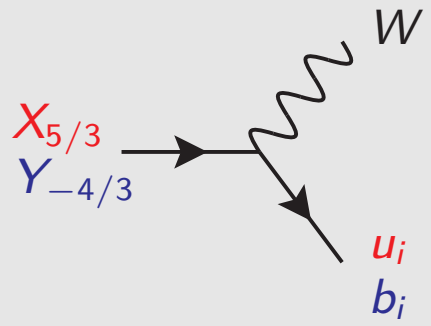

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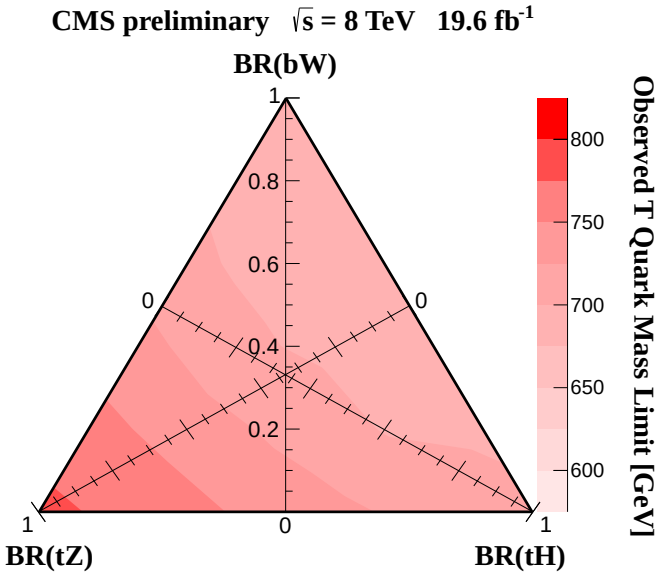
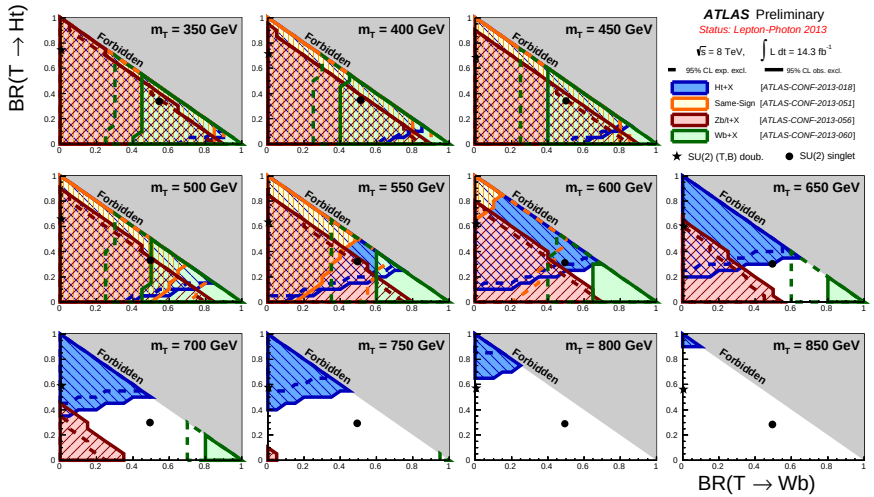
Rich phenomenology to explore at the LHC!!

Experimental status

ATLAS and CMS bounds on VLQs, assuming QCD pair production cross section, are between 600 and 800 GeV





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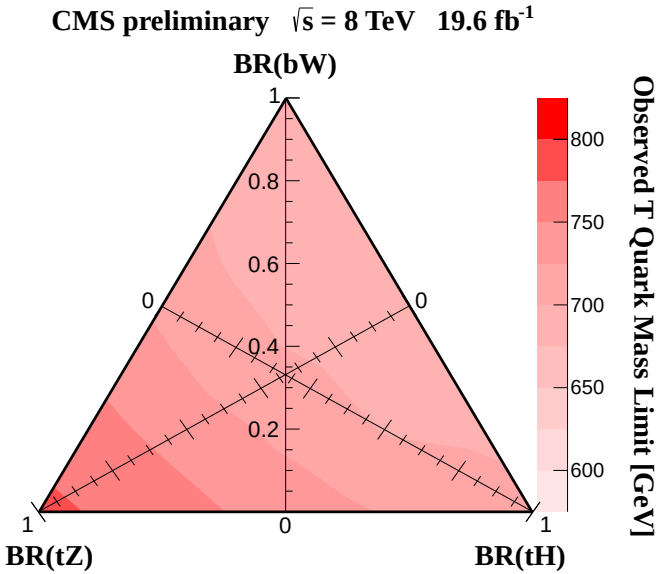

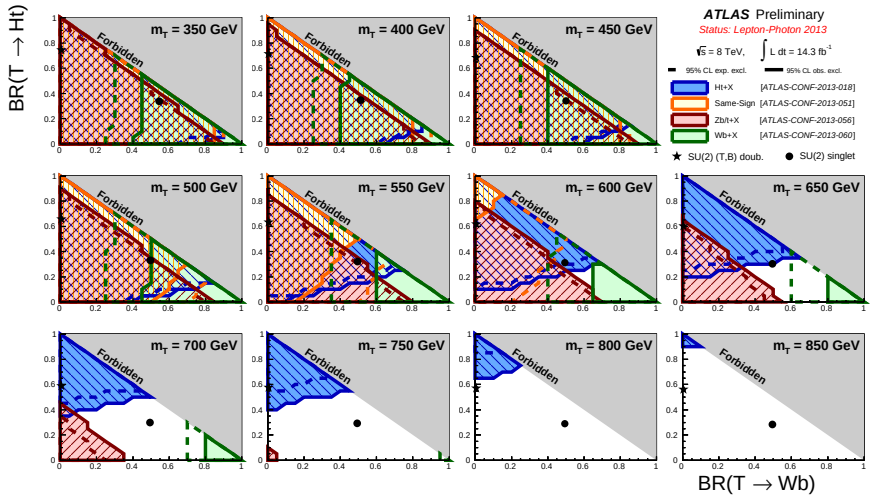

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Just one VLQ in the spectrum

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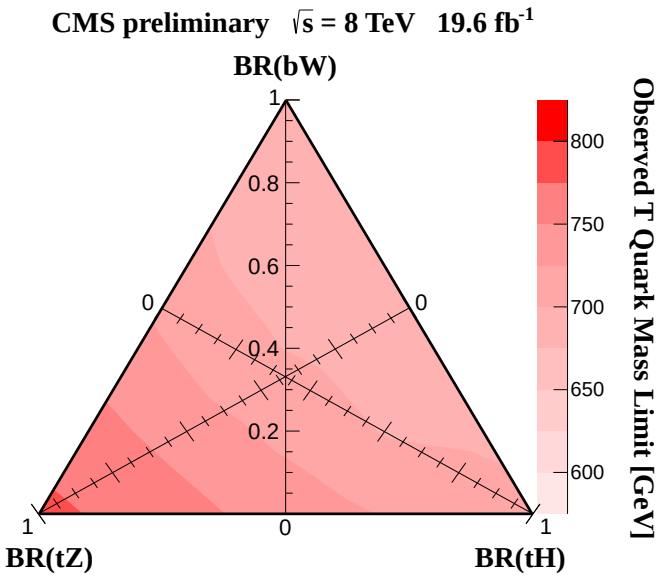

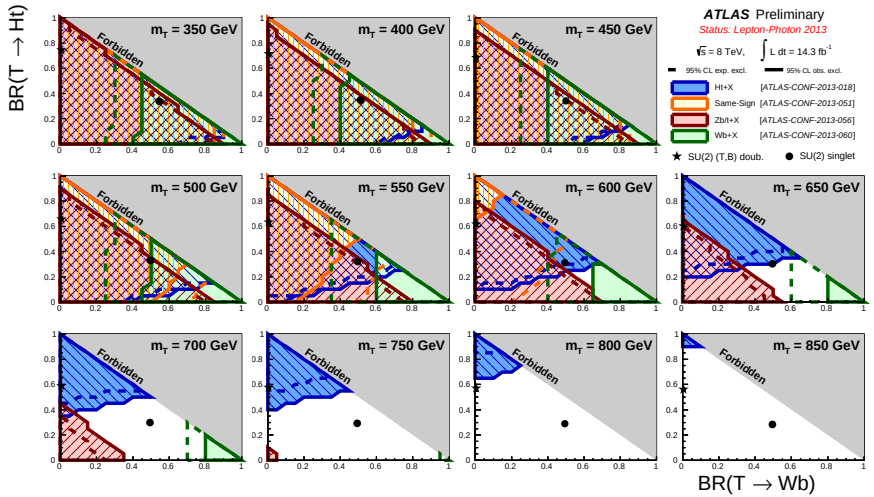

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Theoretical "reality"

Realistic model present a VLQ sector

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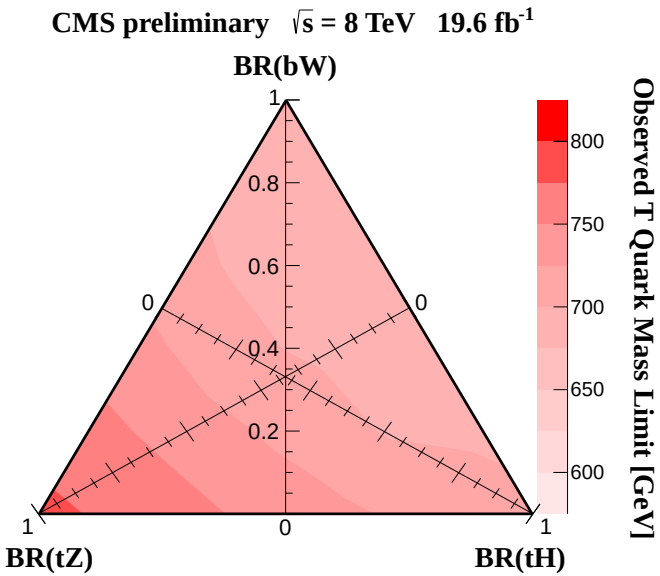

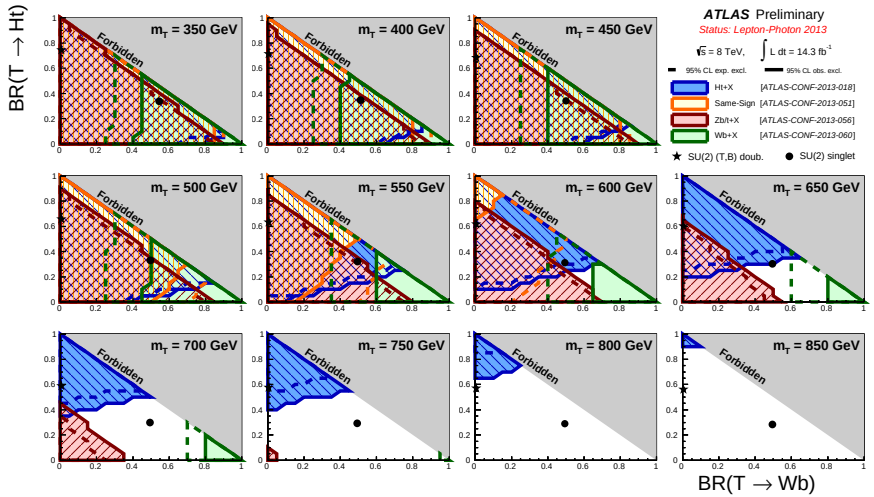

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Decay just in 3rd generation

$t' \to Zt$ $t' \to Ht$ $t' \to W^- t$

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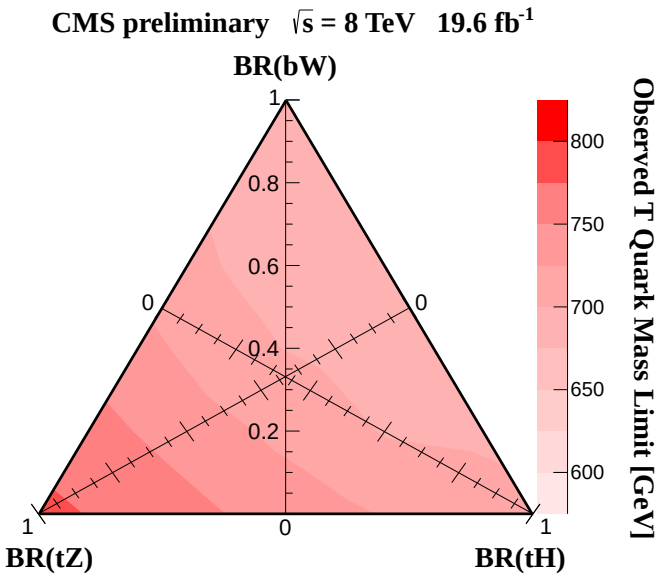

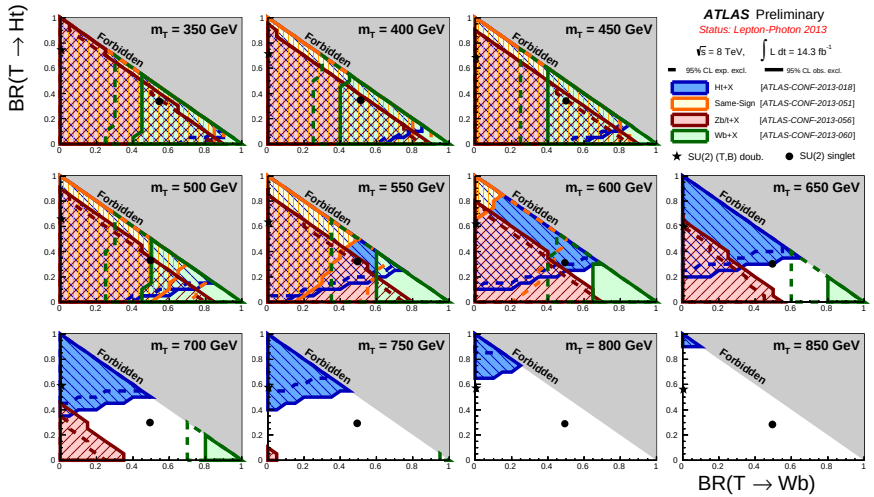

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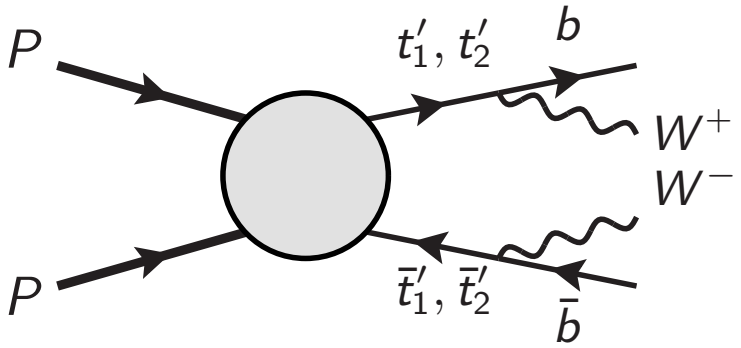
Theoretical "reality"

Realistic model present a VLQ sector

Decay in light quarks cannot be excluded a priori

More than one VLQ in the spectrum

Case 1: two VLQs of the same specie



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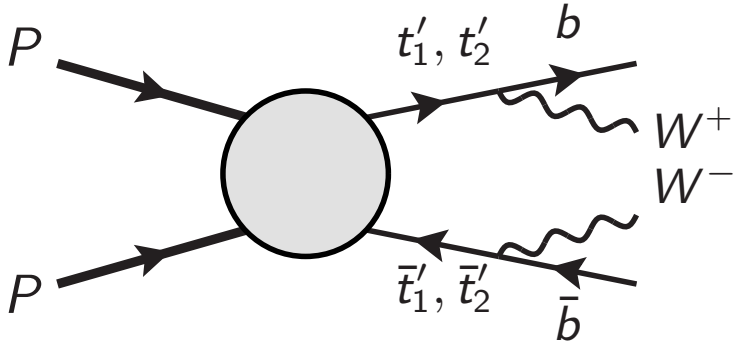
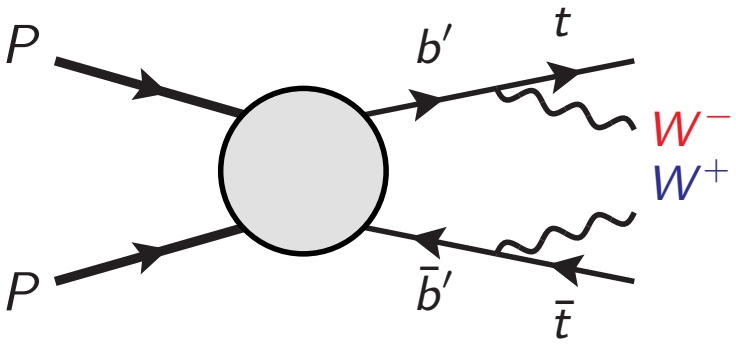
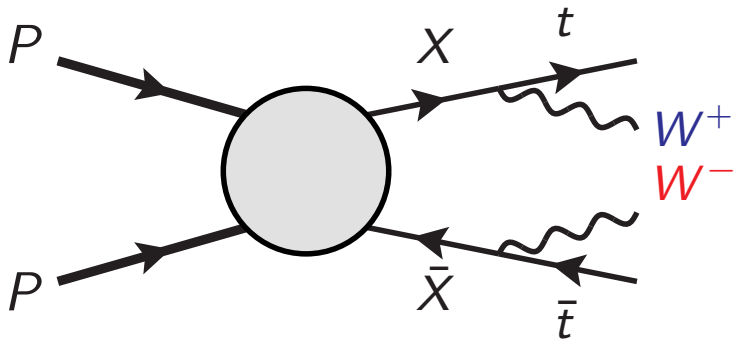


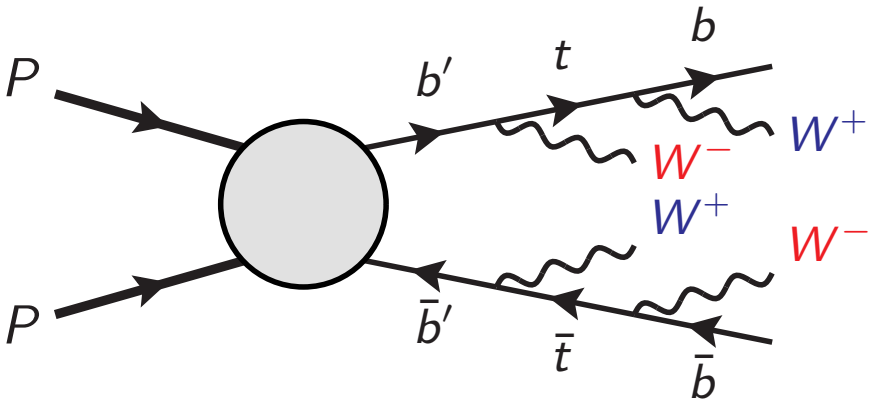
Case 2: two VLQs of different specie





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

Decay also in 1st generation



Decay channel: $b' \to Wt$

- Same Sign dilepton channel
- Eventual b-tagging

Relaxing the third generation exclusive decay hypothesis

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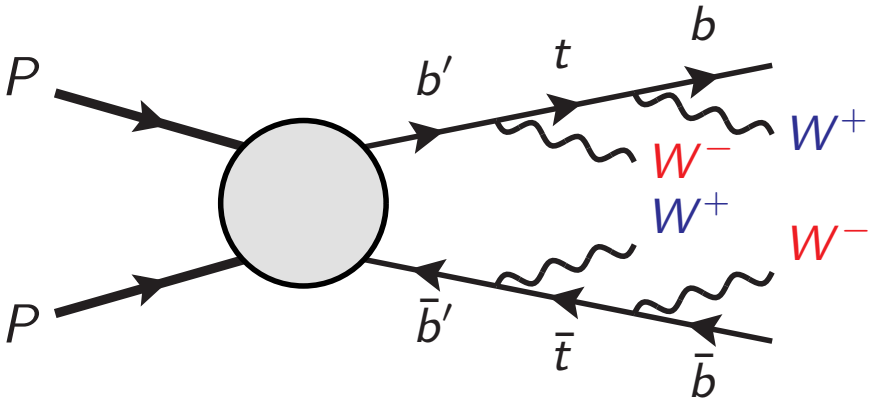
Decay also in 1st generation



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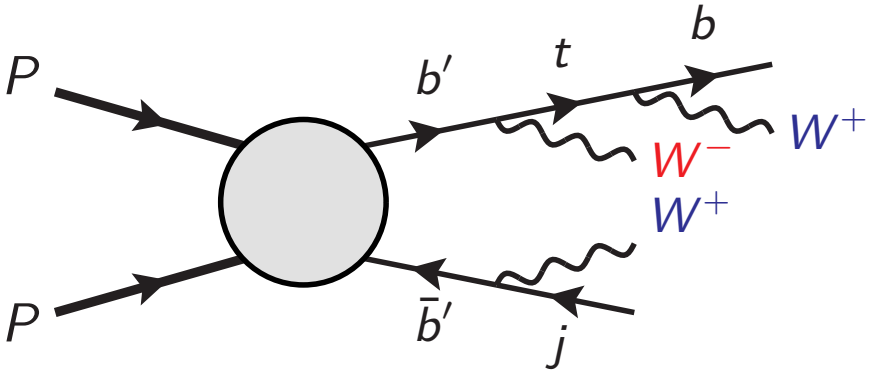

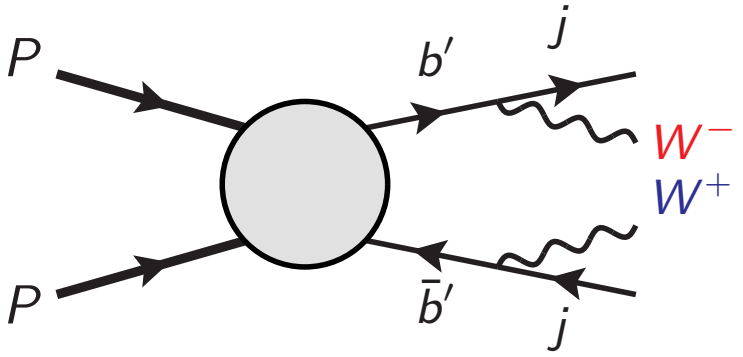

Less events in the Same Sign dilepton channel and less b-jets

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How to constrain VLQs models with generic couplings and spectrum?

1th Approach

- Simulate events for a given model's parameter points
- Apply experimental analysis to generated events

2th Approach

- Rely on a database of pre-simulated efficiencies for selected signal topologies
- No need to simulated events

Tools on the market

- MadAnalysis
- CheckMate

Tools on the market

- XQCAT
- FastLim, SModels (SUSY)

XQCAT: `https://launchpad.net/xqcat`

The database include a direct search for VLQs and SUSY searches

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Reconstructing the signal

Knowing the efficiencies for given VLQ mass and decay channel is it possible to reconstruct any signal arising from a general VLQ spectrum

$$N_{ev} = \mathcal{L} \sum_{n=1}^{N_{VLQ}} \sigma(m_{T_n}) \sum_{i,j} Br(T_n \to i)\, Br(\bar{T}_n \to j)\, \epsilon(m_{T_n}, i, j)$$

The total number of events allows to compute an exclusion confidence level for the, given SM Background and experimental data

Just need to know

- Mass of the VLQs
- Decay channels (BRs) of the VLQs

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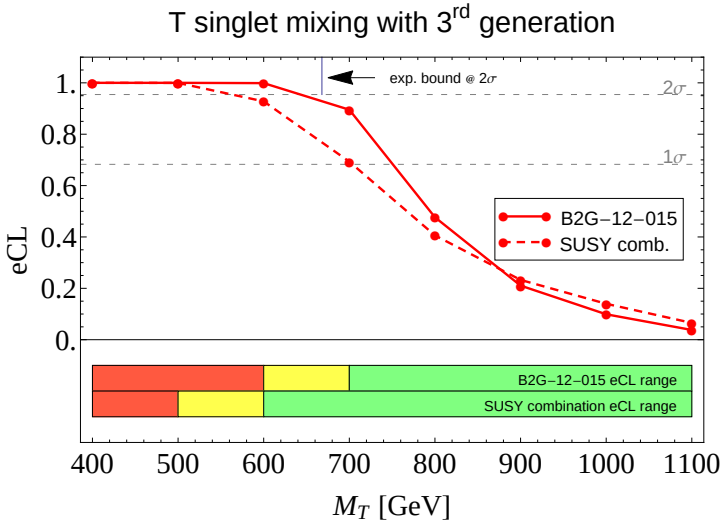
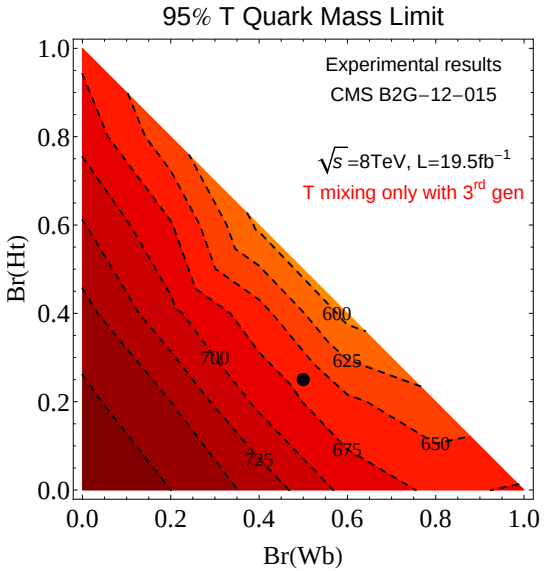
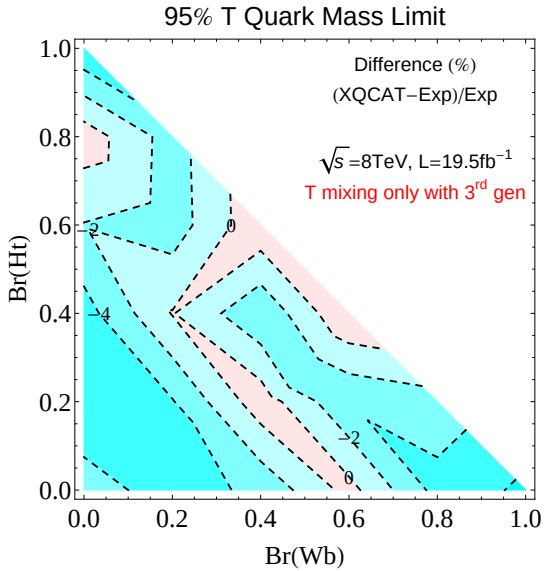
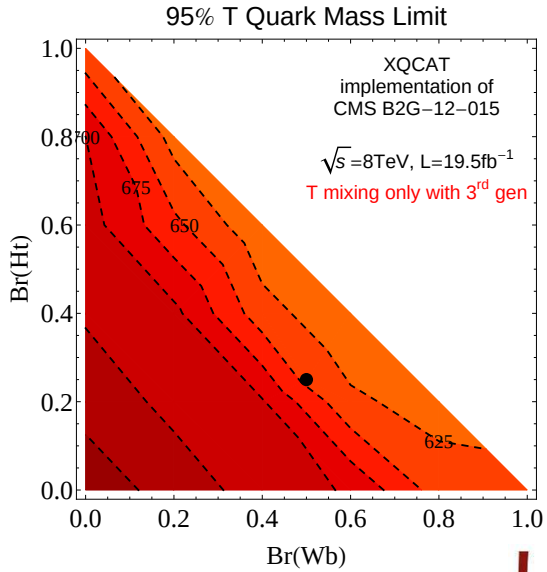
Single top partner



- Exclusion within 5% discrepancy from CMS results
- SUSY reach not too far from the direct analysis



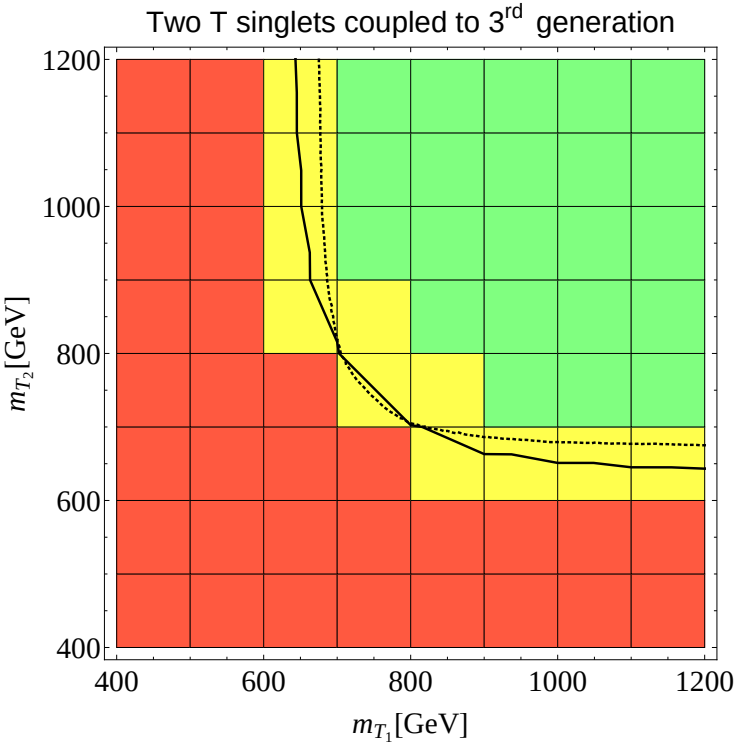




Multiple VLQs

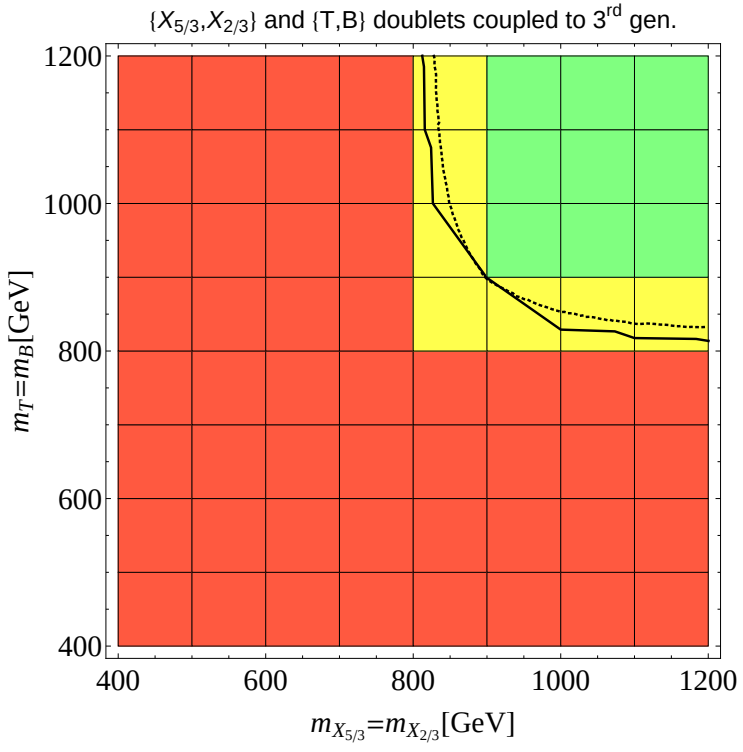
Simplified model: Two T type quarks

$Br(t' \to Zt) = Br(t' \to Ht) = 25\%$
$Br(t' \to Wb) = 50\%$



Composite Higgs model:
De Simone et al, arXiv:1211.5663 [hep-ph]

$Br(X_{5/3} \to Wb) = Br(B \to Wt) = 100\%$
$Br(X_{2/3} \to Zt) = Br(X_{2/3} \to Ht) = 50\%$
$Br(t' \to Zt) = Br(t' \to Ht) = 50\%$



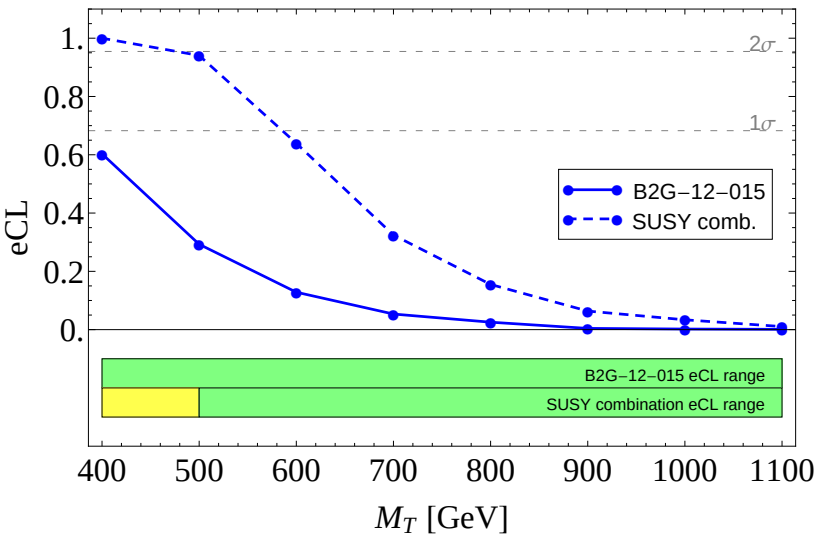
Strong increase of the mass limit in the (quasi) degenerate regime

Complementarity with other searches

One T type quark:

mixing with light generations

T singlet mixing with 1st gen.

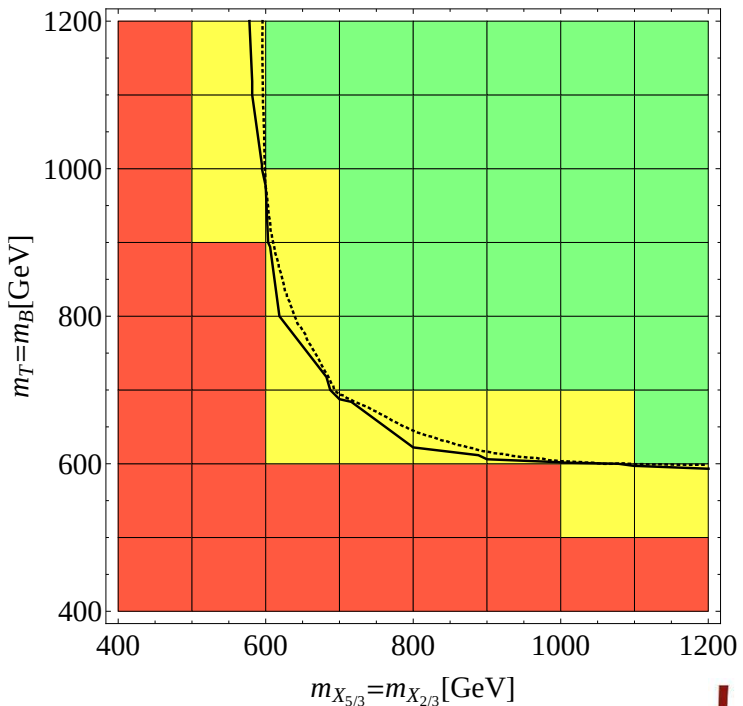


- SUSY search can give a bound when mixing is only with light generations

Modified CHM model:
exclusive mixing with light generations

$Br(X_{5/3} \to Wj) = Br(B \to Wj) = 100\%$
$Br(X_{2/3} \to Zj) = Br(X_{2/3} \to Hj) = 50\%$
$Br(t' \to Zj) = Br(t' \to Hj) = 50\%$

($X_{5/3}$ $X_{2/3}$) and (T B) doublets coupling to light generation
(combination of SUSY searches)



Conclusions

- VLQs have a rich phenomenology to be explored at the LHC
- Reinterpret ATLAS and CMS results on VLQs is crucial to set bounds on generic models
- The reinterpretation can be done in a model independent way using a pre simulated database of efficiencies
- Models with a rich VLQ spectrum can be severely constrained already with the 8 TeV LHC data
- The Reinterpretation of SUSY inspired searches can be used to put constraints on scenarios not (yet) explored by the experimental collaborations

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Thank you!!!

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!

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Example

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

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

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

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

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

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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

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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

b' quark decays: W^-j W^-t Zj Zb Hj Hb
$PP \to b'\bar{b}'$: 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

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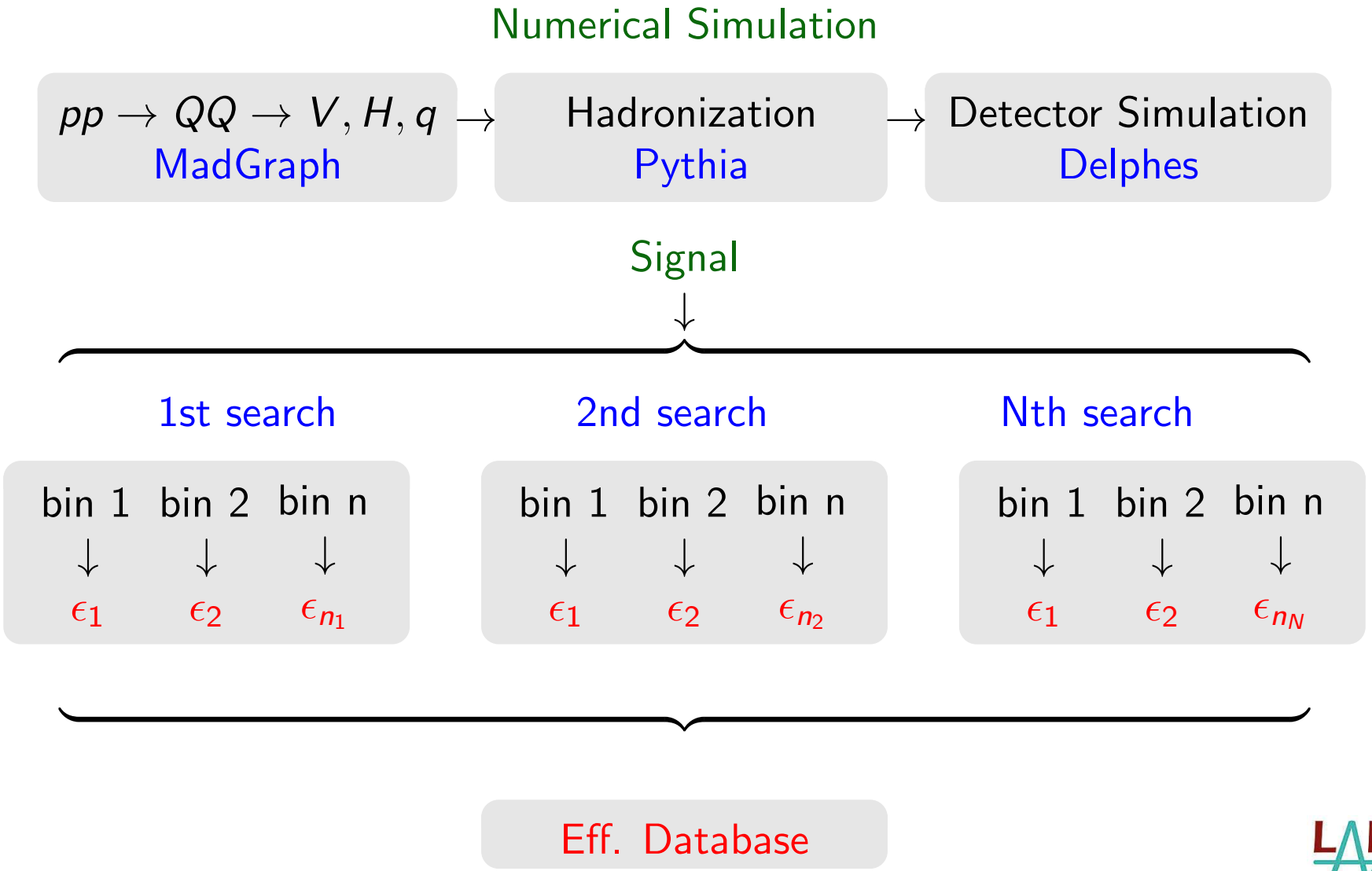
Generation of the efficiency database



Generation of the efficiencies database

Database of efficiencies

- Per VLQs pair: $t'\bar{t}', b'\bar{b}', X\bar{X}, Y\bar{Y}$
- Per decay channel: $t'\bar{t}' \to ZtZ\bar{t}, ZtZ\bar{u}, ..., b'\bar{b}' \to ZbZ\bar{b}, ZtZ\bar{d}, ...$
- Per search: CMS and ATLAS search
- Per mass: simulation at 100 GeV step in the 400-2000 GeV range
- Per chirality: L and R, VLQs couplings are mainly chiral

80 channels · 2 chirality · 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!!!

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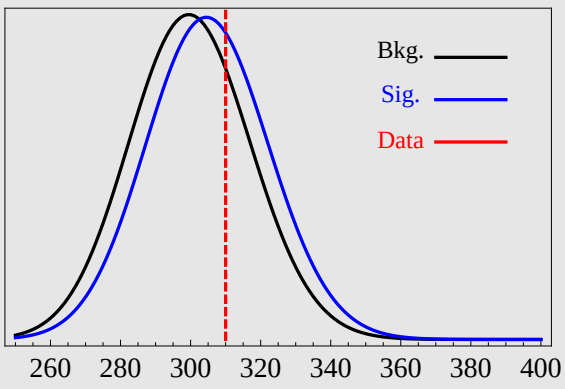
Computing the exclusion confidence level

Suppose to have just one bin

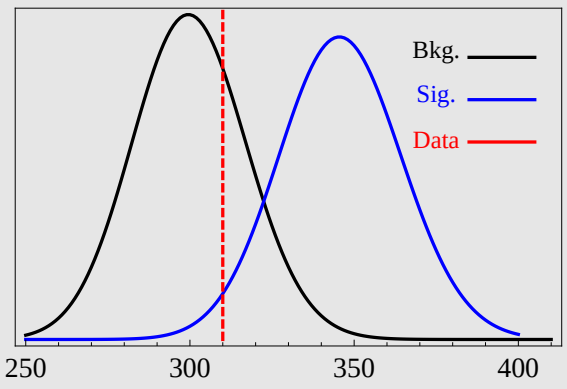
Background: 300 events

Observation: 310 events

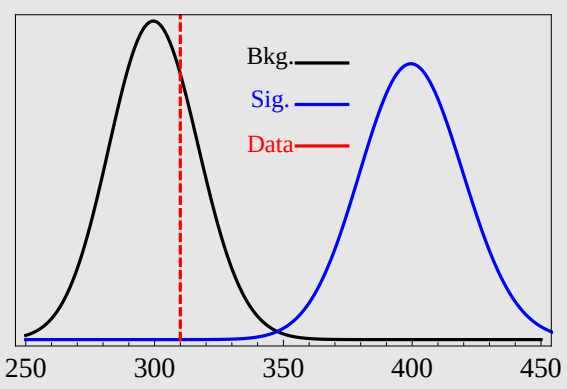
$$eCL = 1 - \frac{CL(s+b)}{CL(b)}$$



Signal: 5
eCL=14%



Signal: 46
eCL=96%



Signal: 100
eCL=99.9997%

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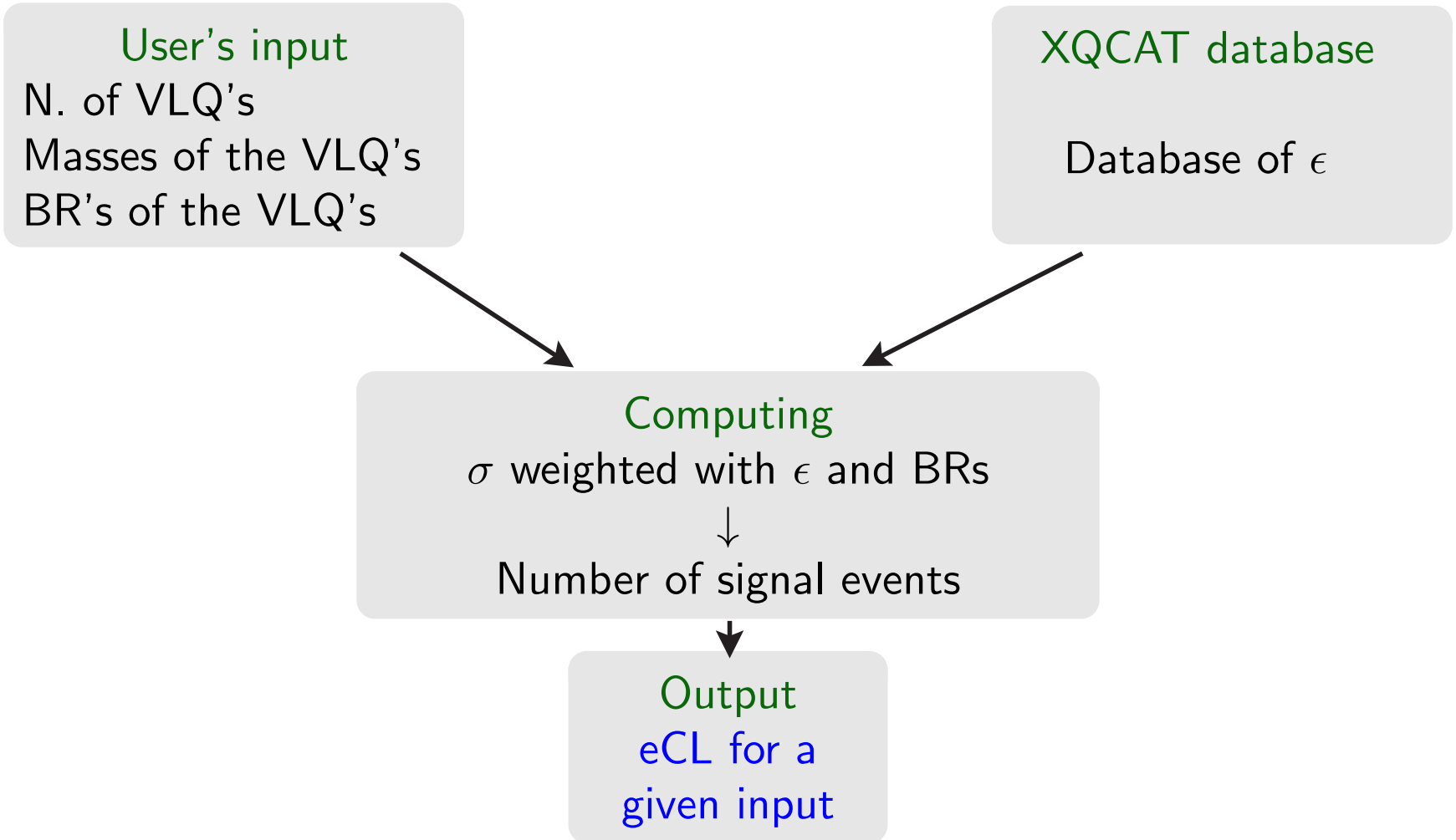
Flowchart of the project



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!

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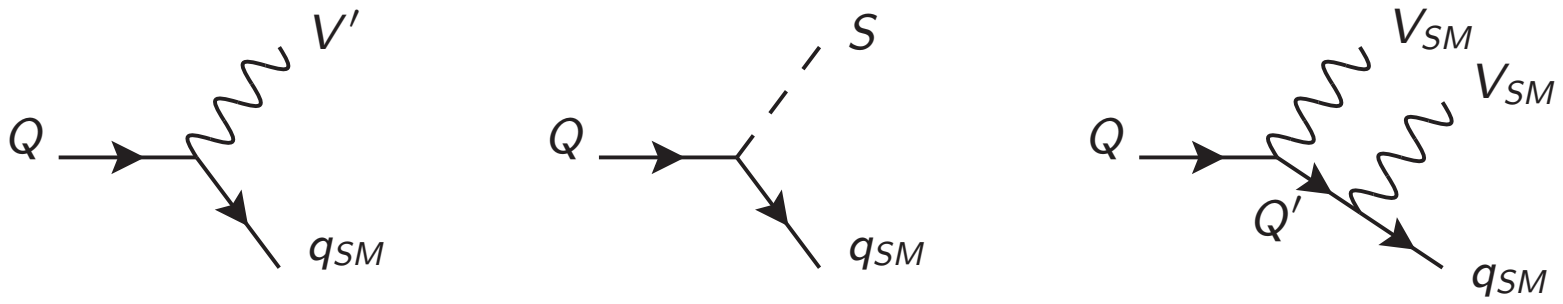
Other decay modes

We want to a conservative bound

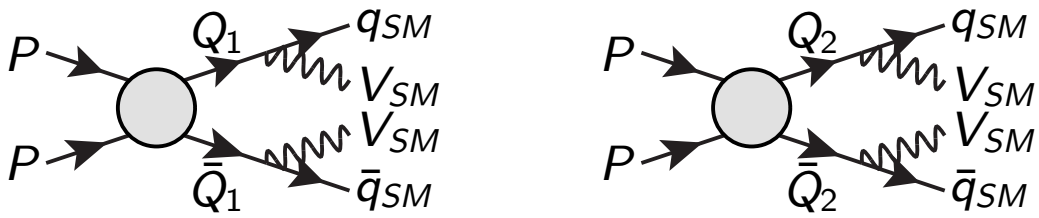
- A non exclusion doesn't mean that the scenario is allowed
- Possible other effect can increase the signal

Other decay modes



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

Interference effects



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

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]

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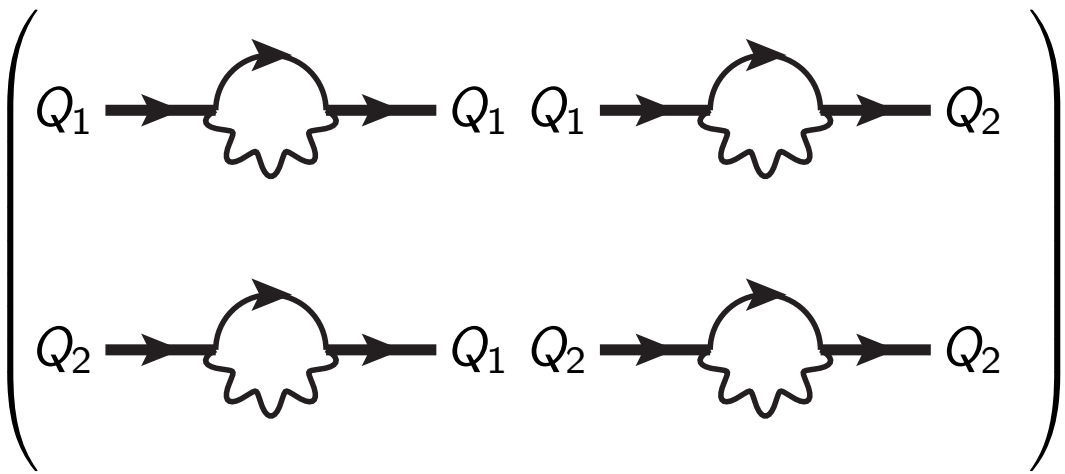
Quantum mixing between states

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

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



These effects are strongly model dependent

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