Heavy vector-like quarks

Constraints and phenomenology at the LHC

Luca Panizzi

Outline

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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

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

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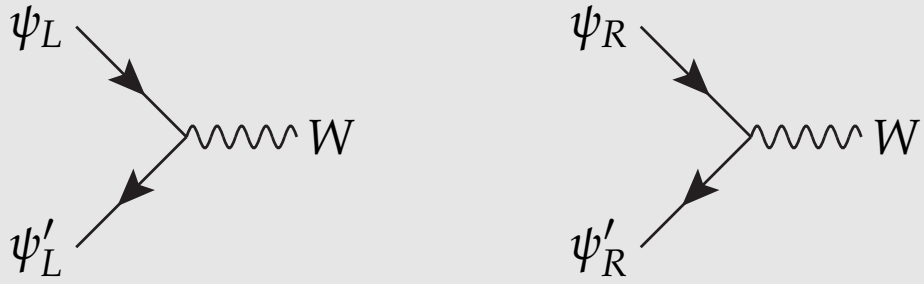
Vector-like quarks in many models of New Physics

- Warped or universal **extra-dimensions**
- **Composite Higgs** models
- **Little Higgs** models
- **Gauged flavour group** with low scale gauge flavour bosons
- Non-minimal **SUSY extensions**

SM and a vector-like quark

Charged currents both in the left and right sector



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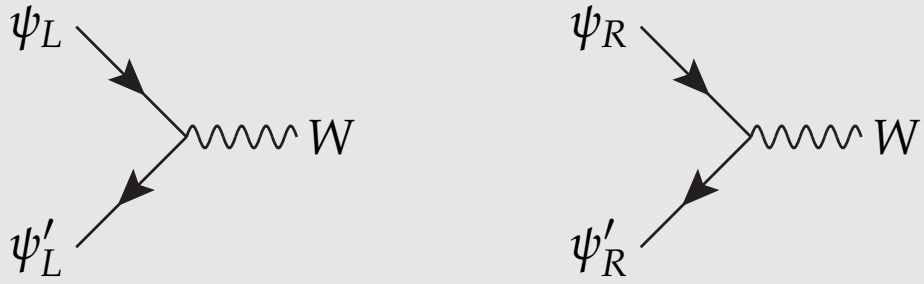
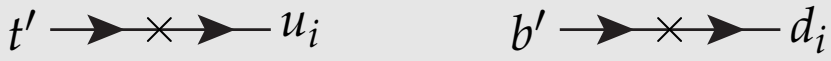


They can mix with SM quarks



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

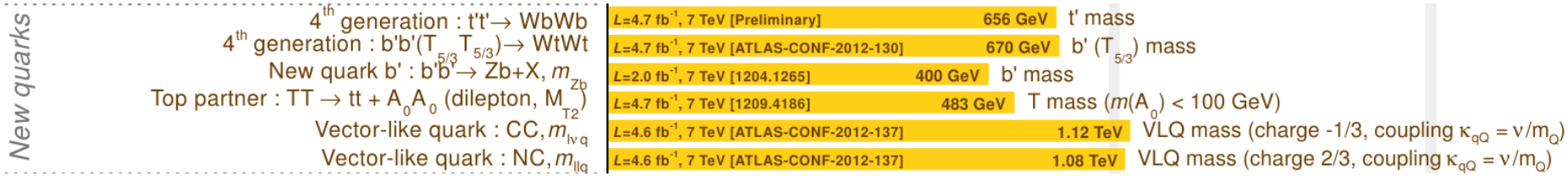
Searches of new quarks at the LHC

not necessarily vector-like

Overview of ATLAS searches

from ATLAS Twiki page

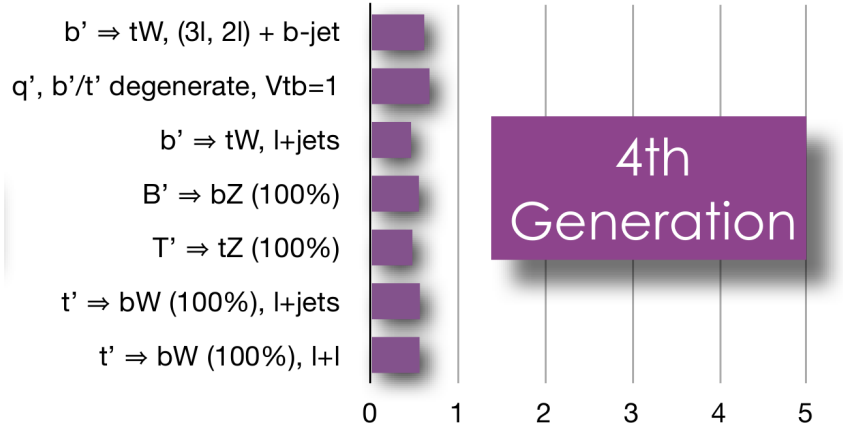
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/CombinedSummaryPlots



Overview of CMS searches

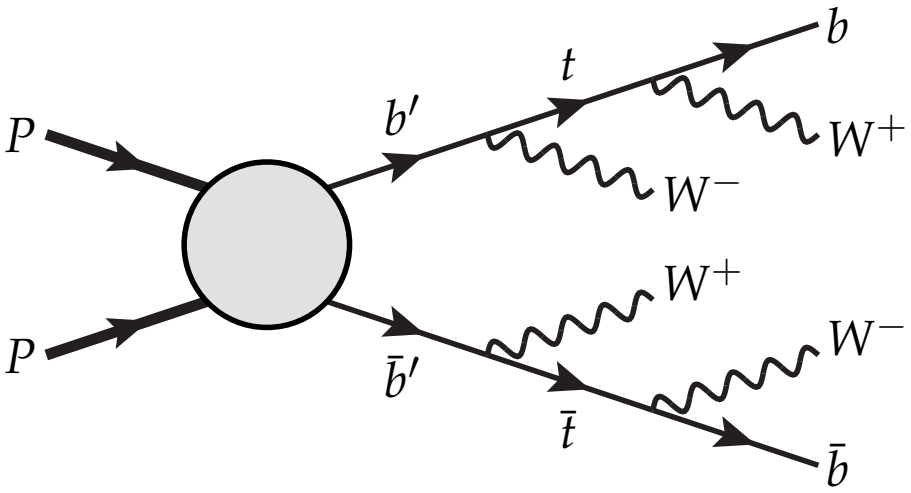
from CMS Twiki page

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO



But look at the hypotheses . . .

Example: b' pair production



Common assumption
$BR(b' \to tW) = 100\%$

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

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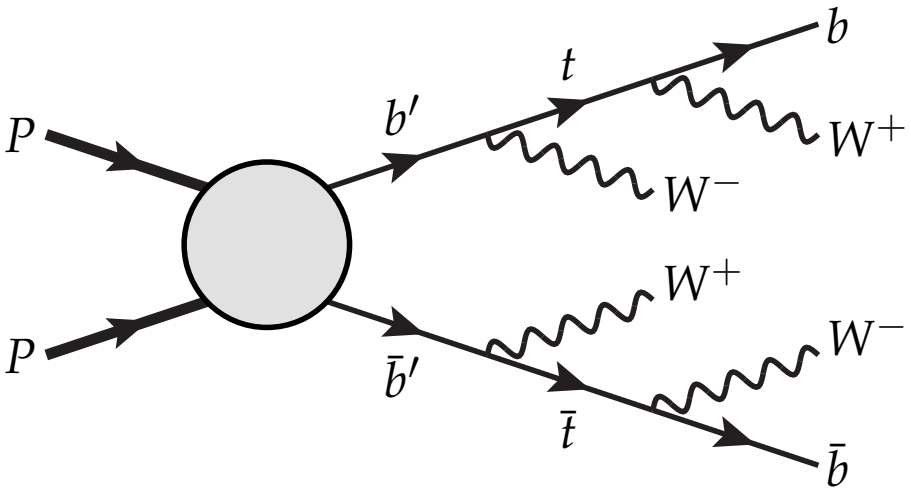

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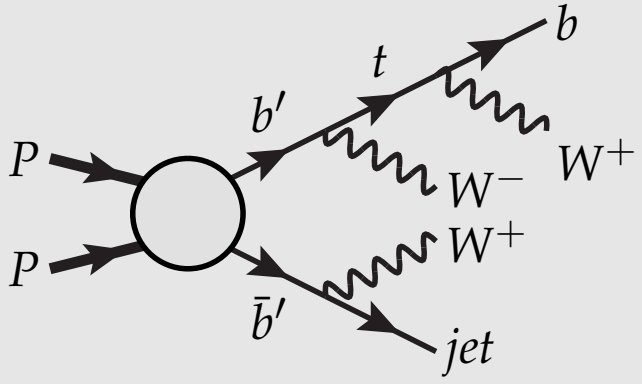
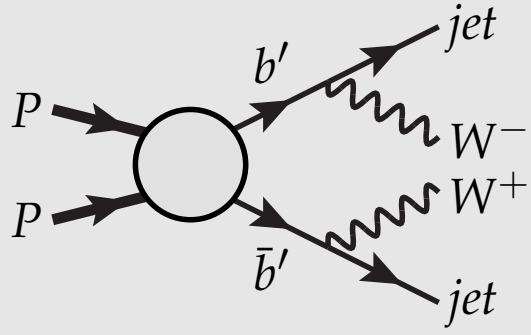
If the b' decays both into Wt and Wq





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

Representations and lagrangian terms

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

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	SM	Singlets	Doublets	Triplets
	$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$	(U) (D)	$\begin{pmatrix} X \\ U \end{pmatrix}$ $\begin{pmatrix} U \\ D \end{pmatrix}$ $\begin{pmatrix} D \\ Y \end{pmatrix}$	$\begin{pmatrix} X \\ U \\ D \end{pmatrix}$ $\begin{pmatrix} U \\ D \\ Y \end{pmatrix}$
$SU(2)_L$	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
$\mathcal{L}_Y$	$-y_u^i \bar{q}_L^i H^c u_R^i$ $-y_d^i \bar{q}_L^i V_{CKM}^{i,j} H d_R^j$	$-\lambda_u^i \bar{q}_L^i H^c U_R$ $-\lambda_d^i \bar{q}_L^i H D_R$	$-\lambda_u^i \psi_L H^{(c)} u_R^i$ $-\lambda_d^i \psi_L H^{(c)} d_R^i$	$-\lambda_i \bar{q}_L^i \tau^a H^{(c)} \psi_R^a$

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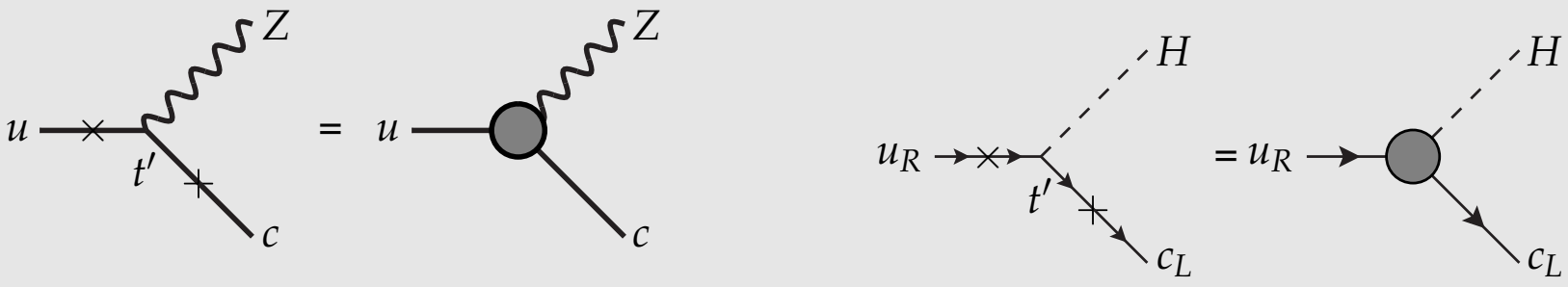
$\mathcal{L}_m$		$-M\bar{\psi}\psi$ (gauge invariant since vector-like)		
Free parameters		4 $M + 3 \times \lambda^i$	4 or 7 $M + 3\lambda_u^i + 3\lambda_d^i$	4 $M + 3 \times \lambda^i$

Outline

Couplings

Major consequences

Flavour changing neutral currents



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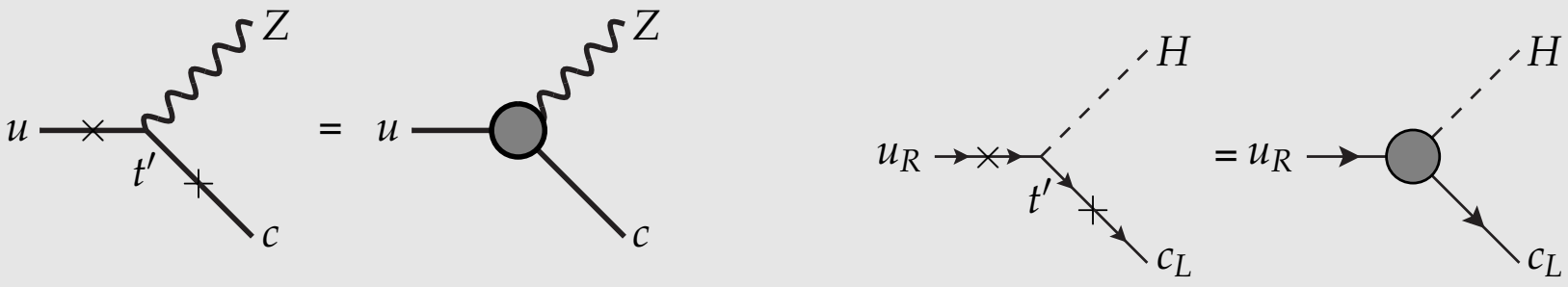

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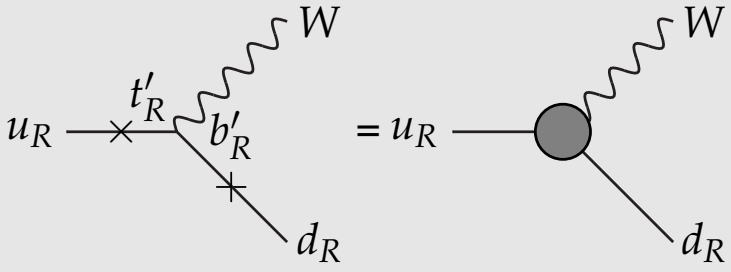
Charged currents between right-handed SM quarks



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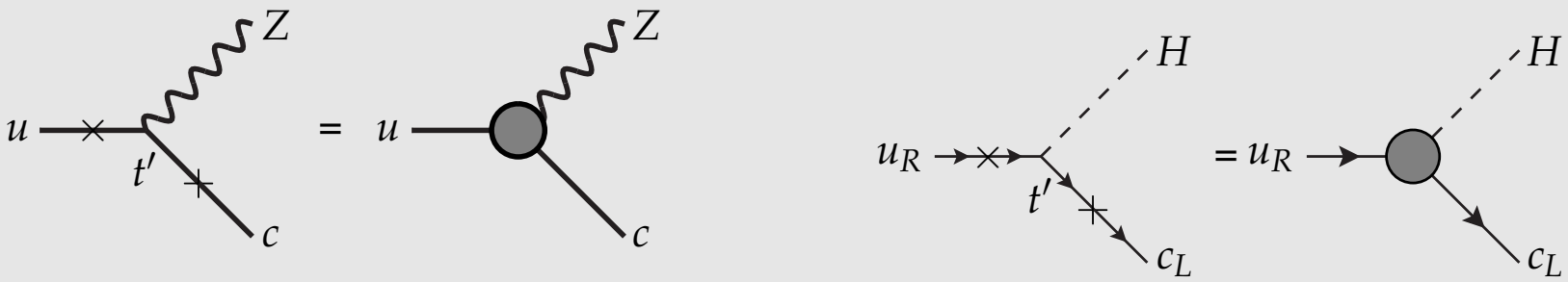

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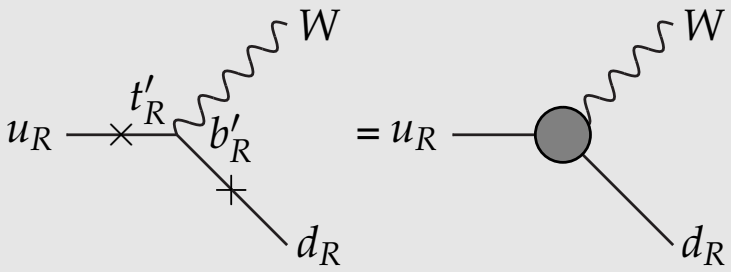
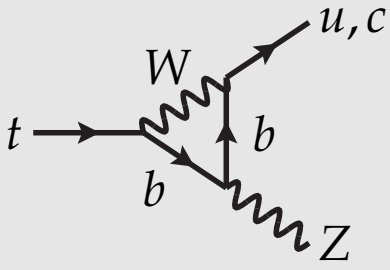


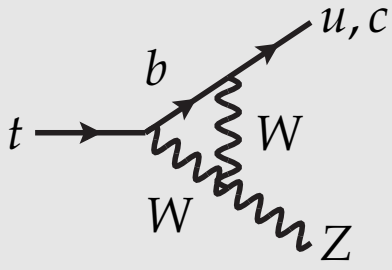
and charged currents between left-handed SM quarks receive a contribution

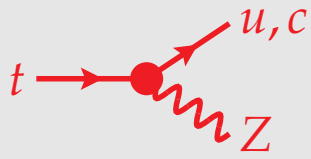
All proportional to combinations of mixing parameters

FCNC constraints

Rare top decays







$BR(t \to Zq) = \mathcal{O}(10^{-14})$
SM prediction

$BR(t \to Zq) < 0.24\%$
measured at CMS @ $5\ fb^{-1}$

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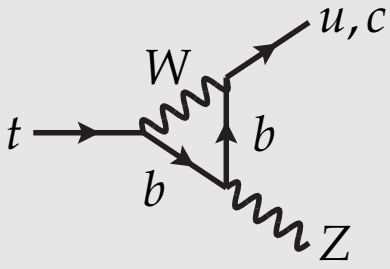

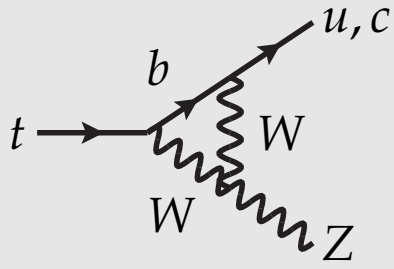

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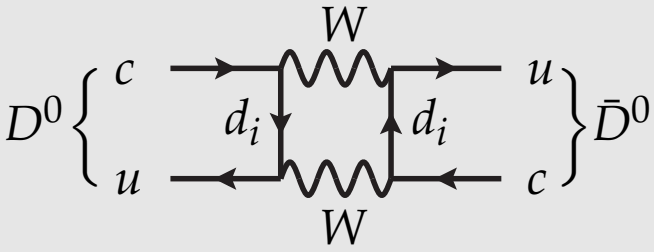
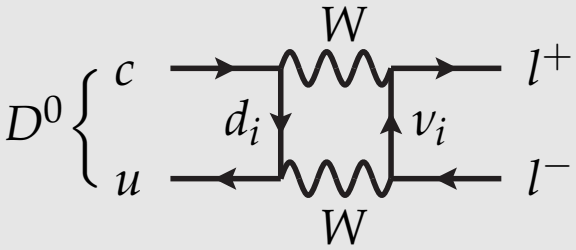
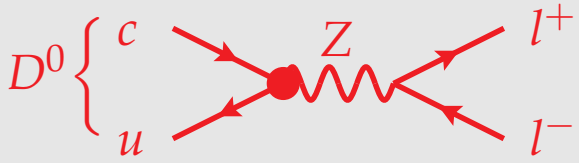
Meson mixing and decay

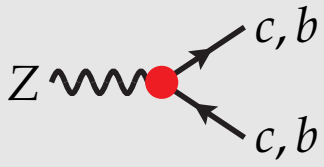






Flavour conserving NC constraints

$Zc\bar{c}$ and $Zb\bar{b}$ couplings



- Direct coupling measurements: $g^q_{ZL,ZR} = (g^q_{ZL,ZR})^{SM}(1 + \delta g^q_{ZL,ZR})$
- Asymmetry parameters: $A_q = \frac{(g^q_{ZL})^2 - (g^q_{ZR})^2}{(g^q_{ZL})^2 + (g^q_{ZR})^2} = A_q^{SM}(1 + \delta A_q)$
- Decay ratios: $R_q = \frac{\Gamma(Z \to q\bar{q})}{\Gamma(Z \to hadrons)} = R_q^{SM}(1 + \delta R_q)$

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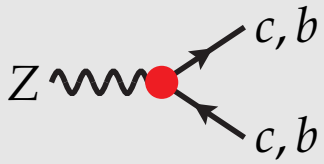

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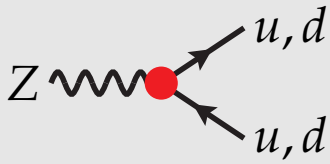
Atomic parity violation



Weak charge of the nucleus

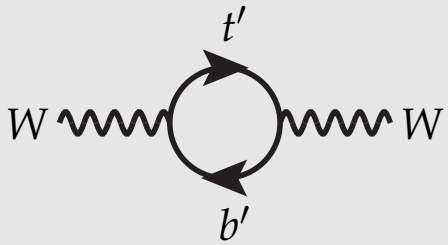
$$Q_W = \frac{2c_W}{g}\left[(2Z+N)(g^u_{ZL} + g^u_{ZR}) + (Z+2N)(g^d_{ZL} + g^d_{ZR})\right] = Q_W^{SM} + \delta Q_W^{VL}$$

Most precise test in Cesium ^{133}Cs:

$$Q_W(^{133}\text{Cs})|_{exp} = -73.20 \pm 0.35 \qquad Q_W(^{133}\text{Cs})|_{SM} = -73.15 \pm 0.02$$

Constraints from EWPT and CKM

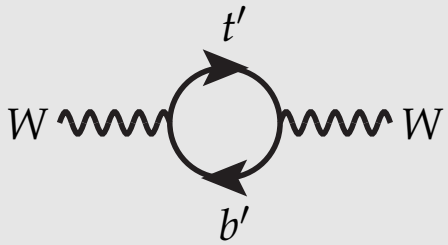
EW precision tests



Contributions of new fermions
to S,T,U parameters

Constraints from EWPT and CKM

EW precision tests



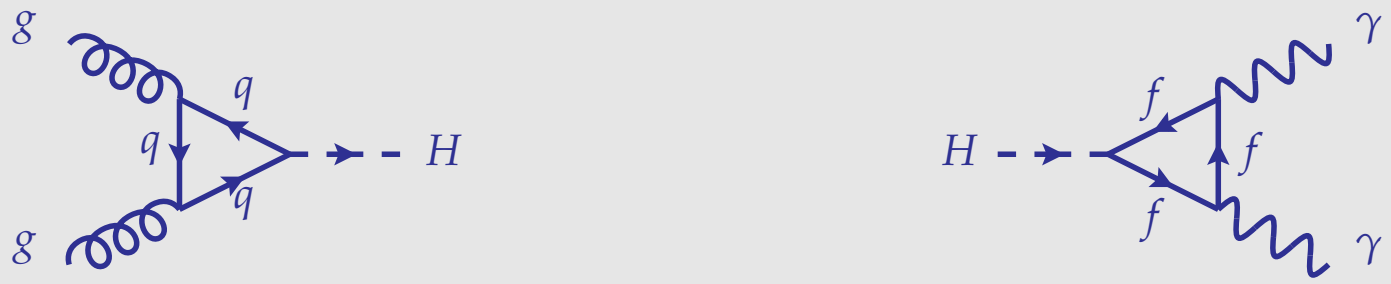
Contributions of new fermions
to S,T,U parameters

CKM measurements

- Modifications to CKM relevant for singlets and triplets because mixing in the left sector is NOT suppressed
- The CKM matrix is not unitary anymore
- If BOTH t' and b' are present, a CKM for the right sector emerges

Higgs coupling with gluons/photons

Production and decay of Higgs at the LHC



New physics contributions mostly affect loops of heavy quarks t and q':

$$\kappa_{gg} = \kappa_{\gamma\gamma} = \frac{v}{m_t} g_{ht\bar{t}} + \frac{v}{m_{q'}} g_{hq'\bar{q}'} - 1$$

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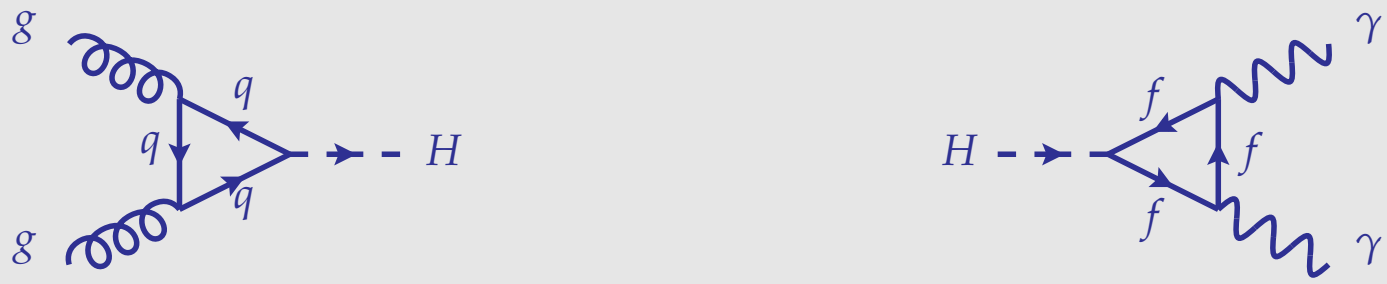

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The couplings of t and q' to the higgs boson are:

$$g_{ht\bar{t}} = \frac{m_t}{v} + \delta g_{ht\bar{t}} \qquad g_{hq'\bar{q}'} = \frac{m_{q'}}{v} + \delta g_{hq'\bar{q}'}$$

In the SM: $\kappa_{gg} = \kappa_{\gamma\gamma} = 0$

The contribution of just one VL quark to the loops turns out to be negligibly small
Result confirmed by studies at NNLO

Outline

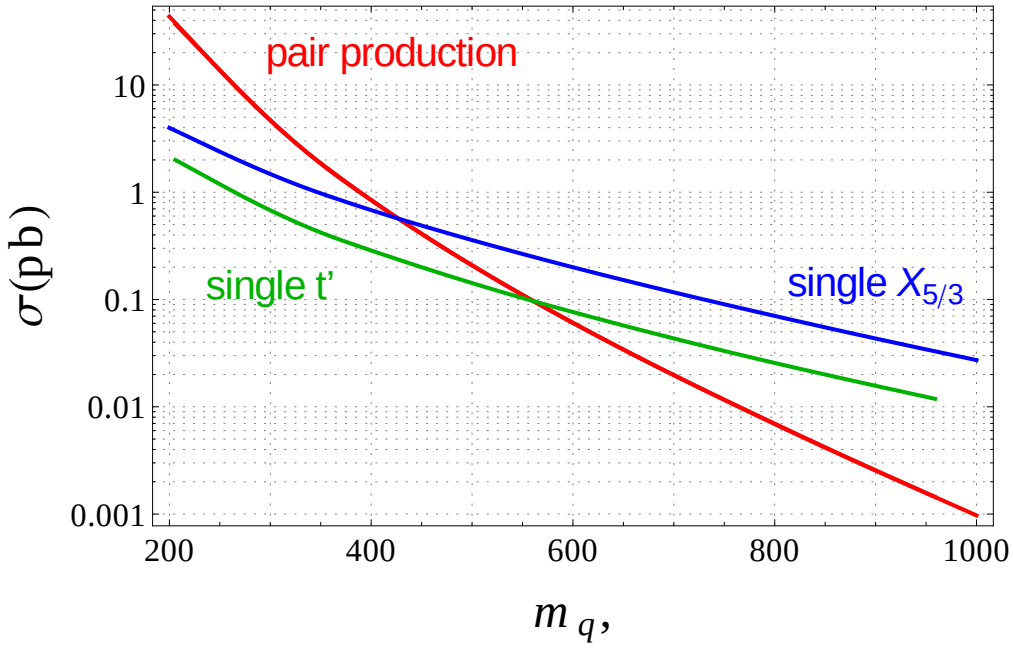
Production channels

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 $(X_{5/3}\ t')$

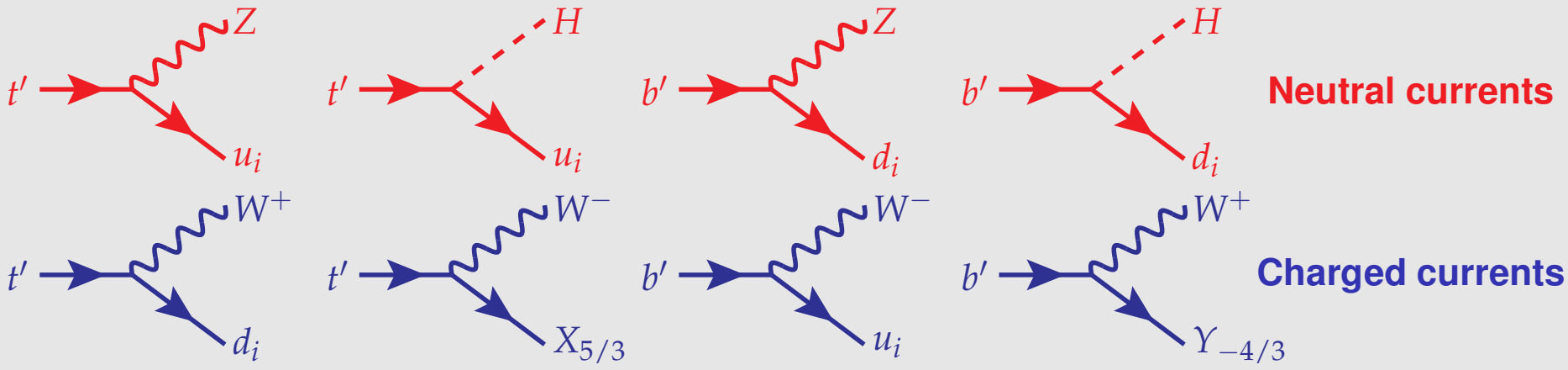


pair production depends only on the mass of the new particle and **decreases faster** than single production due to different **PDF scaling**

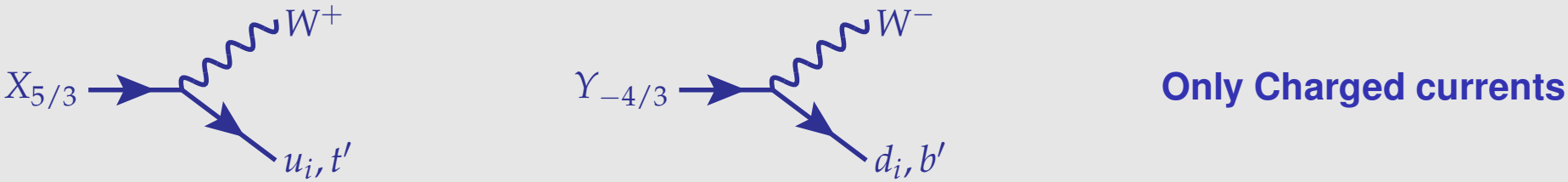
current **bounds from LHC** are around the region where (model dependent) **single production dominates**

Decays

SM partners



Exotics

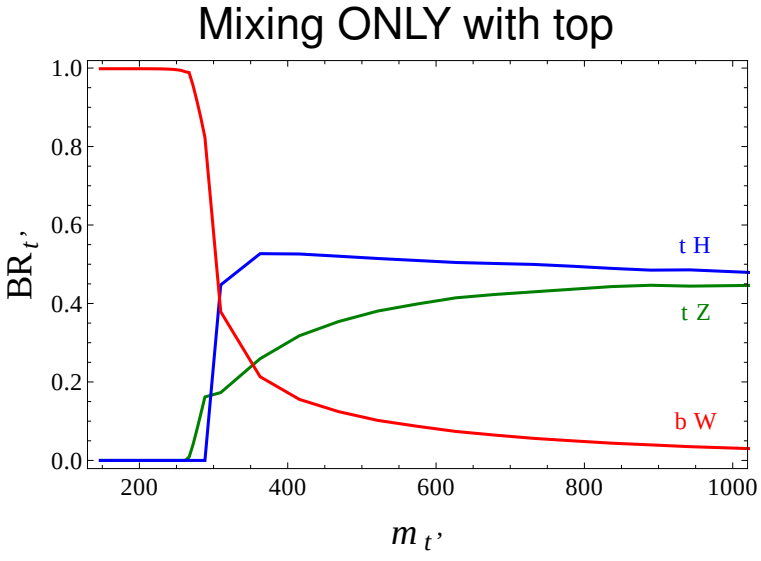


Not all decays may be kinematically allowed

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

Decays of t'

Examples with non-SM doublet $(X_{5/3}\ t')$



Bounds at $\sim$600 GeV assuming

$$BR(t' \to bW) = 100\%$$

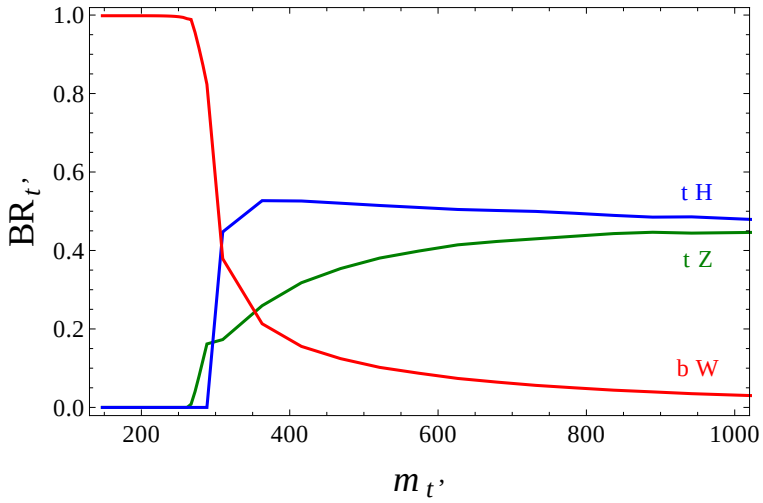
or

$$BR(t' \to tZ) = 100\%$$

Decays of t'

Examples with non-SM doublet $(X_{5/3}\ t')$

Mixing ONLY with top



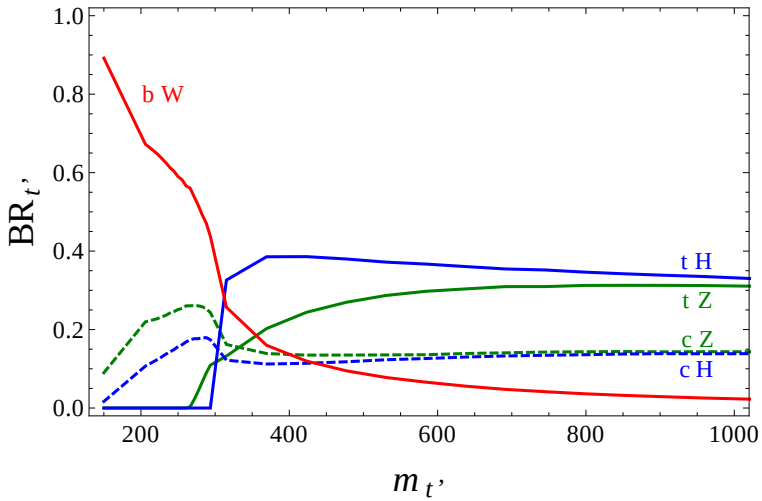
Bounds at ∼600 GeV assuming

$$BR(t' \to bW) = 100\%$$

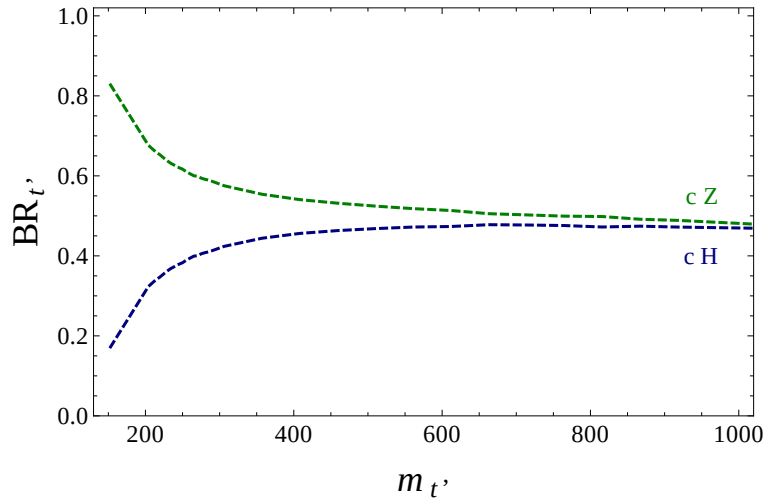
or

$$BR(t' \to tZ) = 100\%$$

Mixing ALSO with charm



Mixing ONLY with charm



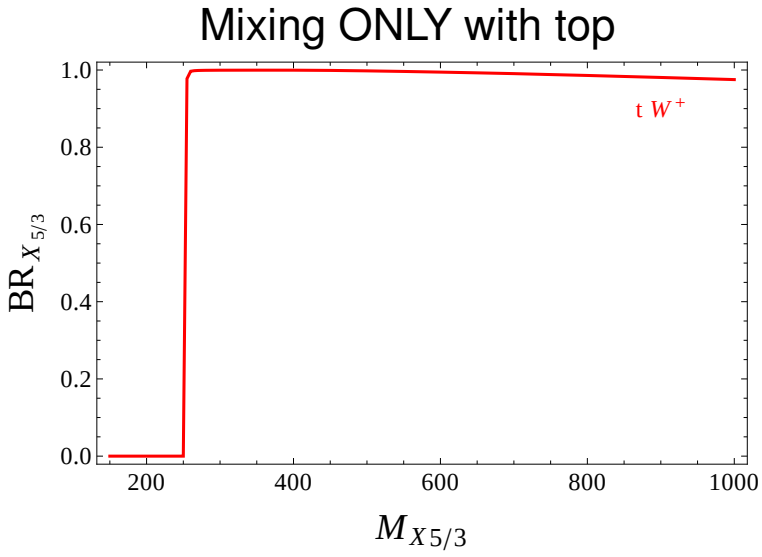
Charge	Resonant state	After t' decay
0	$t'\bar{t}'$	$t\bar{t}+\{ZZ, ZH, HH\}$ $tj+\{ZZ, ZH, HH\}$ $jj+\{ZZ, ZH, HH\}$ $tW^-+\{b, j\}+\{Z, H\}$ $W^+W^-+\{bb, bj, jj\}$
	$t'\bar{u}_i \quad t'\bar{t}$	$t\bar{t}+\{Z, H\}$ $tj+\{Z, H\}$ $jj+\{Z, H\}$ $tW^-+\{b, j\}$ $W^\pm+\{bj, jj\}$
1/3	$t'd_i \quad t'b$	$t+\{b, j\}+\{Z, H\}$ $\{bj, jj\}+\{Z, H\}$ $W^\pm+\{bb, bj, jj\}$
	$W^+\bar{t}'$	$tW^-+\{Z, H\}$ $jW^-+\{Z, H\}$ $W^+W^-+\{b, j\}$
2/3	$t'Z \quad t'H$	$t+\{ZZ, ZH, HH\}$ $W^\pm+\{b, j\}+\{Z, H\}$
1	$t'\bar{d}_i \quad t'\bar{b}$	$t+\{b, j\}+\{Z, H\}$ $\{bj, jj\}+\{Z, H\}$ $W^\pm+\{bb, bj, jj\}$
4/3	$t't'$	$tt+\{ZZ, ZH, HH\}$ $tj+\{ZZ, ZH, HH\}$ $jj+\{ZZ, ZH, HH\}$ $tW^++\{b, j\}+\{Z, H\}$ $W^\pm W^\pm+\{bb, bj, jj\}$
	$t'u_i \quad t't$	$tt+\{Z, H\}$ $tW^++\{b, j\}$ $tj+\{Z, H\}$ $W^\pm+\{bj, jj\}$

Possible final states from pair and single production of t' in general mixing scenario

only 2 effectively tested since now

Decays of $X_{5/3}$

Examples with non-SM doublet $(X_{5/3}\ t')$



ATLAS search with 4.64fb^{-1}

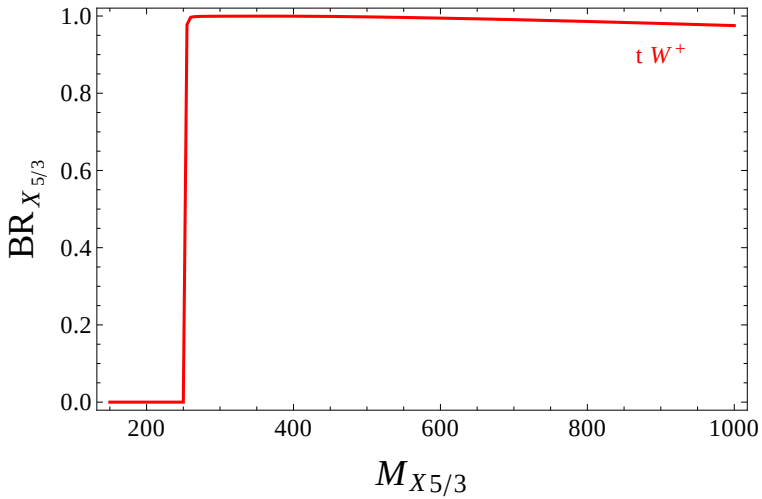
same-sign dilepton + 4 jets

$$m_{X_{5/3}} \geq 670 GeV$$

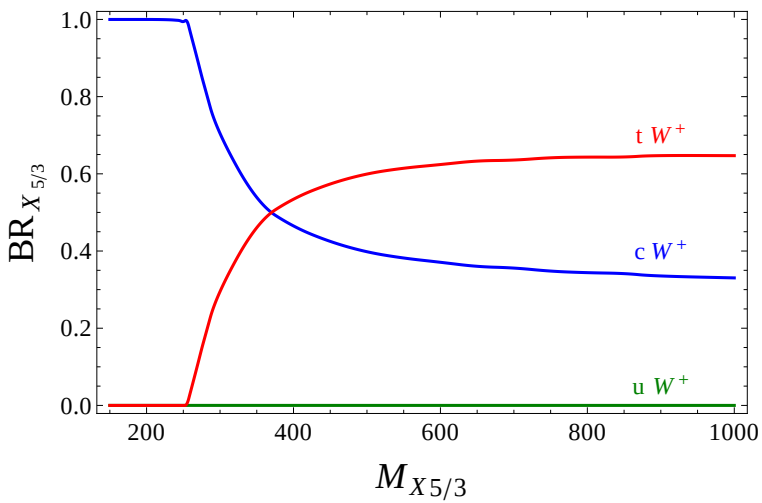
Decays of $X_{5/3}$

Examples with non-SM doublet $(X_{5/3}\ t')$

Mixing ONLY with top



Mixing ALSO with charm



ATLAS search with $4.64 fb^{-1}$

same-sign dilepton + 4 jets

$m_{X_{5/3}} \geq 670 GeV$

Bounds estimated using an optimized set of cuts in arXiv:1211.4034

same-sign dilepton + 2 jets

Evidence: $m_{X_{5/3}} \geq 609 GeV$

Observation: $m_{X_{5/3}} \geq 561 GeV$

Conclusions and Outlook

- **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 GeV**, but searches are not fully optimized for **general scenarios**.