Vector-like quark coupling determination at the LHC and future hadron colliders

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Vector-like fermions

A fermion is **vector-like** under a gauge group
if its left-handed and right-handed chiralities transform in the **same way**

e.g. SM quarks are vector-like under $SU(3)_c$ but are chiral under $SU(2) \times U(1)_Y$

Why "vector-like"?

$$\mathcal{L}_W = g/\sqrt{2}\, j^{\mu\pm} W^{\pm}_{\mu}$$ Charged current Lagrangian

SM Chiral fermions

$$j^\mu_L = \bar{f}_L \gamma^\mu f'_L \qquad j^\mu_R = 0$$

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

V-A structure

Vector-like fermions

$$j^\mu_L = \bar{f}_L \gamma^\mu f'_L \qquad j^\mu_R = \bar{f}_R \gamma^\mu f'_R$$

$$j^\mu = j^\mu_L + j^\mu_R = \bar{f}\gamma^\mu f'$$

V structure

Peculiar Properties

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

No need to add both quarks and leptons: axial anomalies are automatically absent

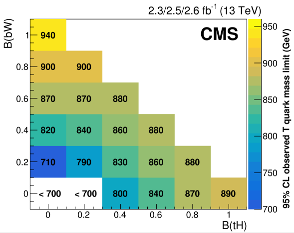
Vector-like quarks

Vector-like quarks in many models of New Physics

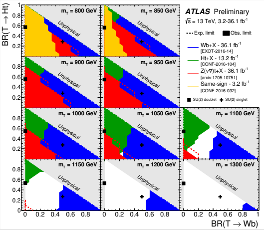
- Warped or universal **extra-dimensions**: KK excitations of bulk fields
- **Composite Higgs** models: excited resonances of the bound states which form SM particles
- **Little Higgs** models: partners of SM fermions in larger group representations which ensure the cancellation of divergent loops
- Non-minimal **SUSY extensions**: increase corrections to Higgs mass without affecting EWPT

Intense experimental effort

CMS-B2G-16-024 (t')



ATLAS twiki: summary plots (t')



Characterising VLQ properties if a discovery is made would be essential for embedding them into some scenarios (and exclude others!)

VLQ chirality

Minimal SM extensions with one VLQ representation interacting through Yukawa terms

	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
$\mathcal{L}_Y$	$-y_u^i \bar{q}_L^i H^c u_R^i$ $-y_d^i \bar{q}_L^i V_{CKM}^{i,j} H d_R^j$	$-\lambda_u^i \bar{q}_L^i H^c t'_R$ $-\lambda_d^i \bar{q}_L^i H b'_R$	$-\lambda_u^i \psi_L H^{(c)} u_R^i$ $-\lambda_d^i \psi_L H^{(c)} d_R^i$	$-\lambda_i \bar{q}_L^i \tau^a H^{(c)} \psi_R^a$

Mixing in left- and right-handed sectors behaves differently: $\mathcal{L} = \begin{pmatrix} \bar{q}_{SM} & \bar{Q}_{VLQ} \end{pmatrix}_L V_L^\dagger \mathcal{M} V_R \begin{pmatrix} q_{SM} \\ Q_{VLQ} \end{pmatrix}_R$

Singlets, triplets...

$$\frac{\tan\theta_R}{\tan\theta_L} = \frac{m_q^{SM}}{M_{VLQ}}$$

dominantly left-handed

$$M_{VLQ} \gg m_q^{SM}$$

Doublets, quadruplets...

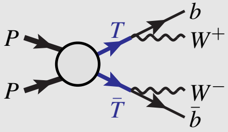
$$\frac{\tan\theta_L}{\tan\theta_R} = \frac{m_q^{SM}}{M_{VLQ}}$$

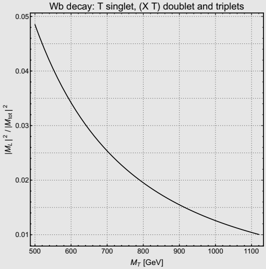
dominantly right-handed

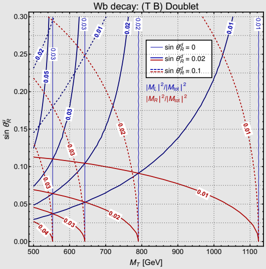
VLQ couplings always have a dominant chirality, which depends on their representation

Discriminating the chirality of a VLQ

Polarisation of the gauge boson







For a T singlet:

$$|M|_L^2 = \frac{g^2}{2} \sin^2 \theta_L^u (m_T^2 - m_W^2) \qquad |M|_0^2 = \frac{g^2}{4} \frac{m_T^2}{m_W^2} \sin^2 \theta_L^u \left(m_T^2 - m_W^2\right) \qquad |M|_R^2 = 0$$

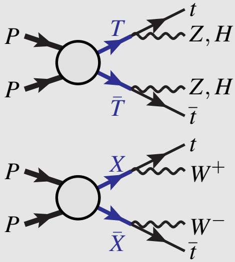
The W boson is always mainly longitudinally polarised for both L and R chiralities

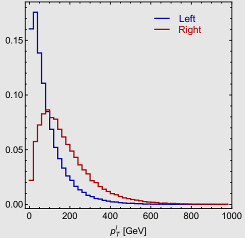
$\mathcal{O}(1)\%$ transverse component

- Same for Z polarisation in the $T \to tZ$ decay
- Higgs does not provide any information as it is a scalar

Discriminating the chirality of a VLQ

Polarisation of the top

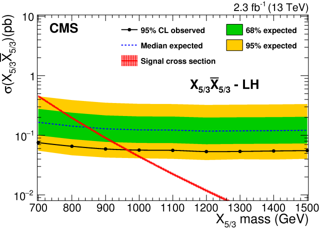


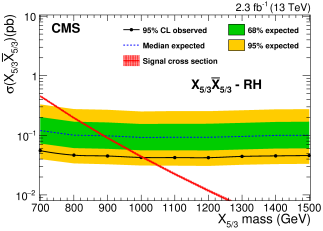


The polarisation of the top is transmitted to the leptons after W decay.

The **right-handed** p_T distribution of the leading lepton is harder than the **left-handed** one.

This information can be exploited to discriminate left from right chiralities!





Slightly higher reach for right-handed chirality

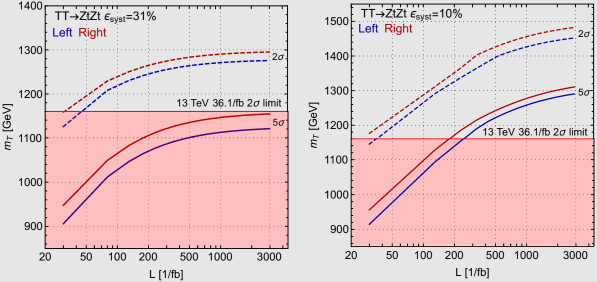
Recasting experimental data

Pair production of a VLQ with charge 2/3 decaying exclusively to Zt: $pp \to T\bar{T} \to ZtZ\bar{t}$

Exclusion and discovery reach of a single lepton ATLAS search

ATLAS CONF-2017-015

- 1 lepton
- $\geq$4 jets
- $\not{E}_T \geq$350GeV



High $\not{E}_T$ cut: the Z goes mostly invisible and the lepton comes from top decay

Depending on the uncertainty on the background, a discovery can be made in the HL phase
If it cannot be reduced, only exclusion bounds will be possible with this selection

Discrimination at higher luminosities

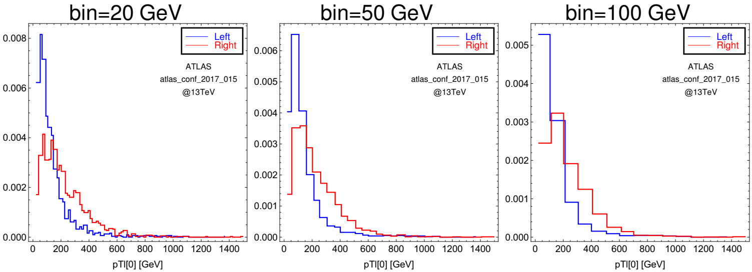
$pp \to T\bar{T} \to ZtZ\bar{t}$

Discrimination method on the leading lepton p_T distribution

$$\chi^2 = \sum_{\text{bins}} (L - R)^2 / \max(L, R)$$

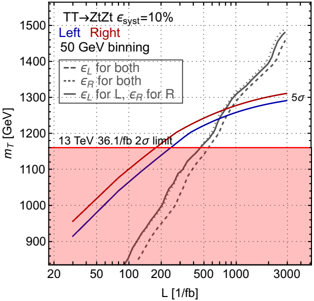
- We assume that the background can be neglected at discovery and only consider the poisson uncertainties on the signal for each bin
- The discrimination will depend on the number of bins (i.e. d.o.f. for the χ^2)

p_T of leading lepton after the cuts with different binning



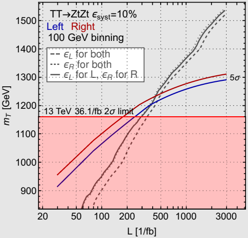
Discrimination at higher luminosities

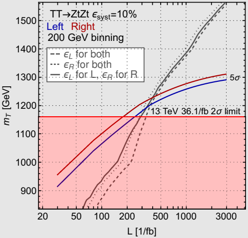
$pp \to T\bar{T} \to ZtZ\bar{t}$



Current exclusion limit @ 36.1 fb^{-1}: 1.16 TeV

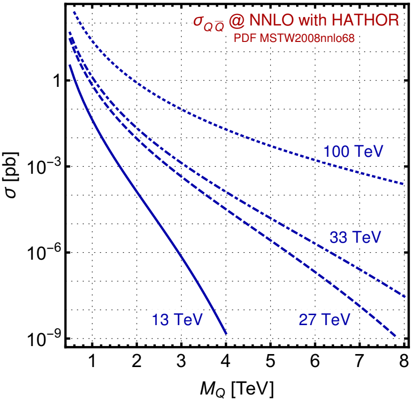
A discrimination can be done above $\sim$700 fb^{-1}





A larger binning of the distribution allows a discrimination for smaller values of masses and luminosities

Discrimination at higher energies

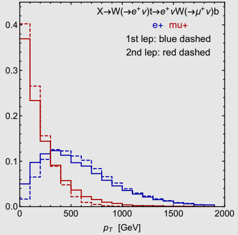


Higher energies mean (potentially) higher reach!

Discrimination at higher energies

Pair production of a VLQ with charge 5/3 decaying exclusively to Wt: $pp \to X\bar{X} \to WtW\bar{t}$

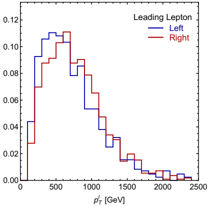
- Considering same-sign di-lepton final state
- For discrimination we must be able to identify the lepton from top decay

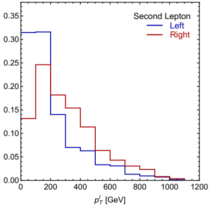


The leading lepton comes from W decay
The sub-leading lepton comes from top decay

Distributions after the cuts (SR defined in arXiv:1309.2234 for HE-LHC at 33 TeV)

Leading lepton
similar shapes



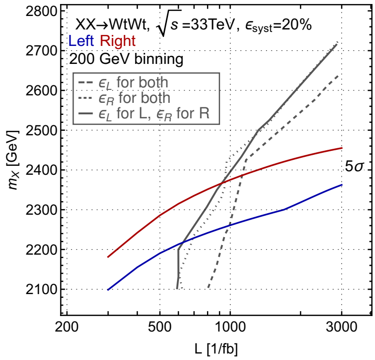


Sub-leading lepton
different shapes

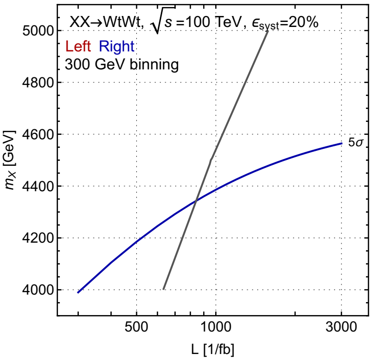
Discrimination at higher energies

$pp \to X\bar{X} \to WtW\bar{t}$

33 TeV



100 TeV



Promising perspectives for discrimination of coupling chiralities at high energy hadron collider prototypes!

Update for 27 TeV in progress

Conclusions and perspectives

- HL-LHC and future HE machines will **increase the reach** for discovering new physics
- It is paramount to be ready to **characterise new signals**, optimising strategies which depend on the observed final states
- For VLQs interacting with 3^{rd} SM generation, **top polarisation** can be used at HL-LHC and HE-LHC to test the **VLQ dominant chirality**

- Is chirality discrimination possible if VLQs interact with **light generations**?
- Would **single production** processes provide a better characterisation potential?
- How would results change if VLQs have a **large width**?