Characterisation of vector-like fermions at the LHC

Luca Panizzi

University of Pisa, Italy

Beyond the Higgs boson
open problems

The Standard Model is complete
but are we happy with it?

Observations

Dark Matter	**Matter-antimatter asymmetry**	**Neutrino masses**

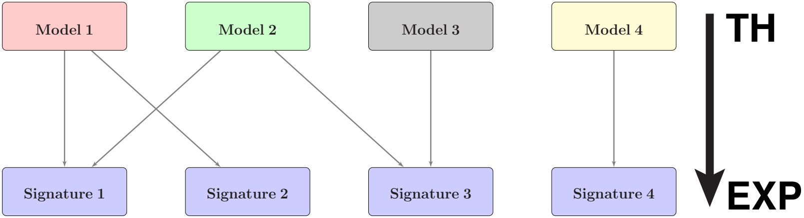
Theoretical issues

Fermion mass hyerarchies	Origin of flavour families	Gauge coupling unification	...

There must be new physics
and most probably it's already in our reach!

And if there's new physics we should be able to observe new particles (hopefully soon!)

Looking for new physics at the LHC



Designing searches or simulating signals to test specific models is a risky bet

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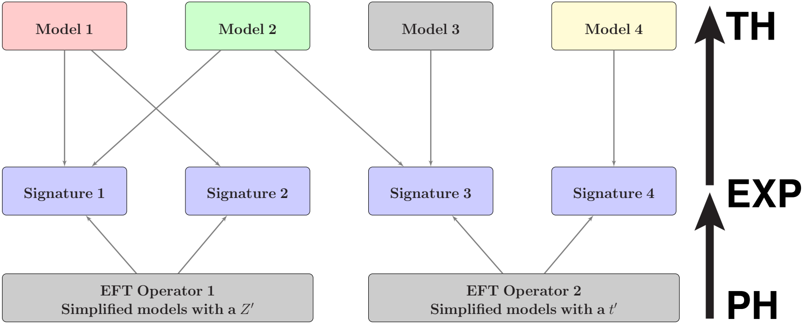
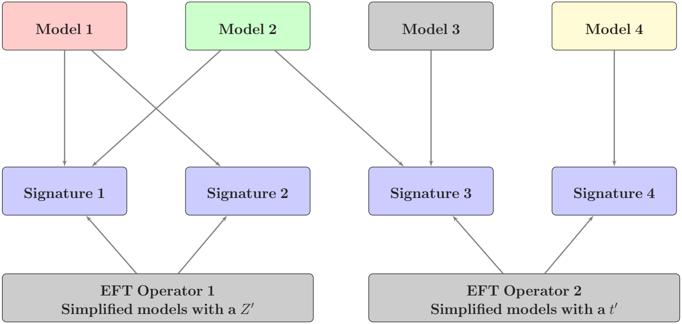


Designing searches or simulating signals to test specific models is a risky bet

Model-independent approach

EFTs: higher dimension operators where heavy d.o.f. are integrated out
Simplified models: minimal extensions of the SM with new states
Approximate description of classes of theoretical models

Characterisation of new physics



Suppose Signature 1 is discovered

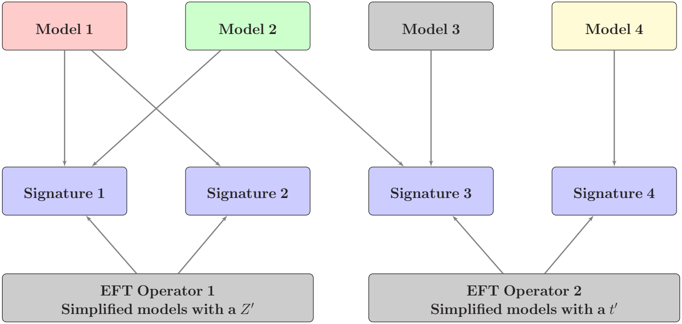
Is it possible to distinguish between Model 1 and Model 2?

Answer 1

Look for Signature 2 or Signature 3

Implies further experimental effort
and it takes an indefinite time

Characterisation of new physics



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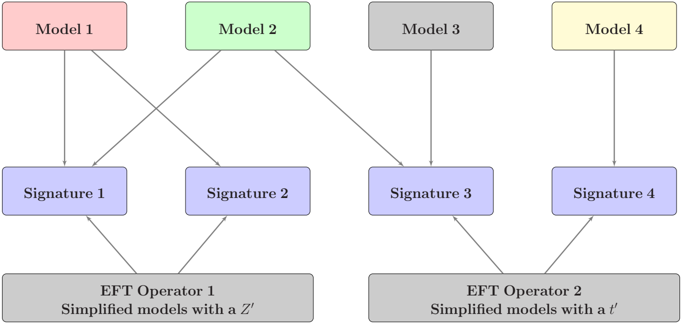
Implies a detailed analysis of available data
which can be done immediately
(though success is not always guaranteed)

Characterisation of new physics



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Let's focus on new fermions (quarks and leptons)!

Outline

1. Adding extra-fermions to the SM

2. Chirality of vector-like fermions
   - VL quarks interacting with SM — D.Barducci and **LP**, JHEP **1712** (2017) 057
   - VL leptons interacting with DM

   D.Barducci, A.Deandrea, S.Moretti, **LP**, H.Prager, Phys. Rev. D **97** (2018) no.7, 075006

3. Width of vector-like fermions
   - VLQs decaying to SM states — (1) S.Moretti, D.O'Brien, **LP**, H.Prager, Phys. Rev. D **96** (2017) no.7, 075035

     (2) A.Carvalho, S.Moretti, D.O'Brien, **LP** and H.Prager, arXiv:1805.06402
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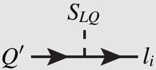
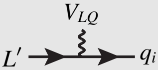
SM and new fermions

They can mix with SM fermions through Yukawa couplings

Dangerous FCNCs $\longrightarrow$ strong bounds on mixing parameters

They can couple without mixing





Non-minimal scenarios
e.g. with lepto-quarks

There can be **SM partners** (t', e') or fermions with **exotic charges** ($X_{5/3}$, $E^{--}\dots$)

SM and new fermions

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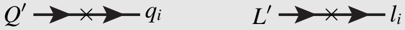

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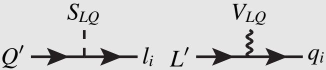

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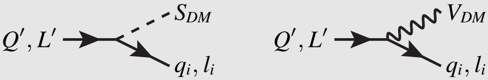
A special case

They can mediate dark matter production



Only **SM partners** are allowed (up to 4-dim operators)

They must be odd under the Z_2 parity of DM ⟶ they **cannot** mix with SM states

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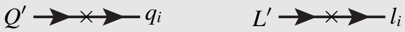

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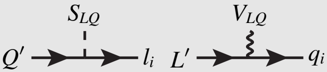

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If new fermions exist what can they be?

New fermions: the chiral hypothesis

aka adding a fourth chiral family to the SM

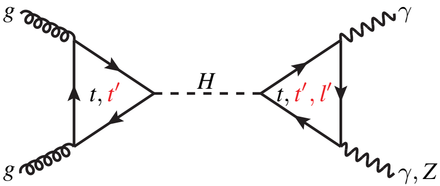
$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix} \quad \begin{pmatrix} t' \\ b' \end{pmatrix}$$

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix} \quad \begin{pmatrix} \nu' \\ l' \end{pmatrix}$$

both quarks and leptons for anomaly cancellation

$$Tr[Q] = 3(\tfrac{2}{3} - \tfrac{1}{3}) + (0 - 1) = 0$$

Modifications to observed processes



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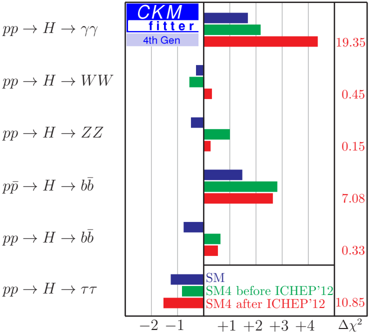

$(\mathcal{O}_{\text{exp}} - \mathcal{O}_{\text{fit}})/\Delta\mathcal{O}_{\text{exp}}$

O. Eberhardt, *et al.*
Impact of a Higgs boson at a mass of 126 GeV on the standard model with three and four fermion generations
Phys.Rev.Lett. 109 (2012) 241802, arXiv:1209.1101

400 GeV $< m_{t',b'} <$ 800 GeV
$m_{l'} >$ 100 GeV and $m_{\nu'} > M_Z/2$

A chiral 4th generation is excluded at 4.8σ
(or 5.3σ including $H \to b\bar{b}$ at Tevatron)
in the context of a simplified model where only the new family is added to the SM

Let's go for vector-like fermions

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 $SU(2) \times U(1)_Y$

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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

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

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V structure

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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

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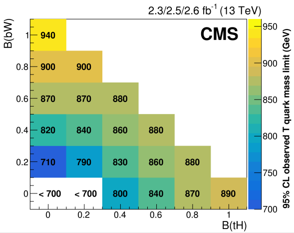
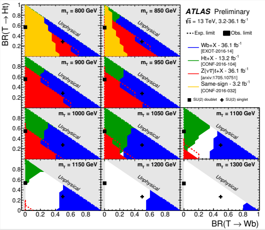
Intense experimental effort

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!)

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Outline

VLQ chirality

Minimal SM extensions with one VLQ representation interacting through Yukawa terms

	SM	Singlets		Doublets			Triplets	
	$\binom{u}{d}\binom{c}{s}\binom{t}{b}$	(t')	(b')	$\binom{X}{t'}$	$\binom{t'}{b'}$	$\binom{b'}{Y}$	$\begin{pmatrix}X\\t'\\b'\end{pmatrix}$	$\begin{pmatrix}t'\\b'\\Y\end{pmatrix}$
$SU(2)_L$	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: $\mathcal{L} = \left(\bar{q}_{SM}\ \bar{Q}_{VLQ}\right)_L V_L^\dagger \mathcal{M} V_R \binom{q_{SM}}{Q_{VLQ}}_R$

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...

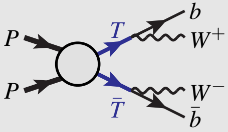
$$\frac{\tan\theta_L}{\tan\theta_R} = \frac{m_q^{SM}}{M_{VLQ}}$$

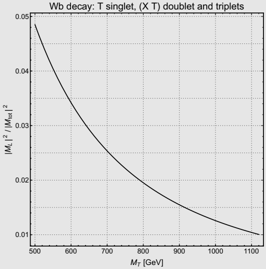
dominantly right-handed

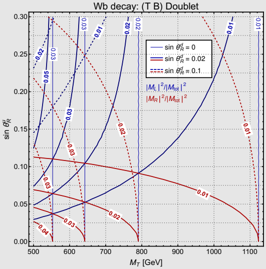
VLQ couplings always have a dominant chirality, which depends on their representation

Discriminating the chirality of a VLQ

Polarisation of the gauge boson







For a T singlet:

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

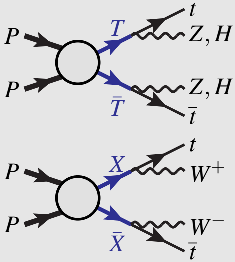
The W boson is always mainly longitudinally polarised for both L and R chiralities

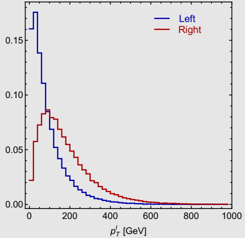
$\mathcal{O}(1)\%$ transverse component

- 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

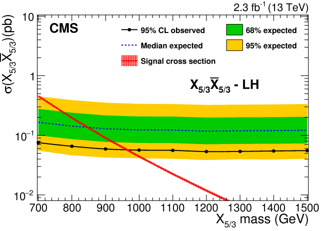


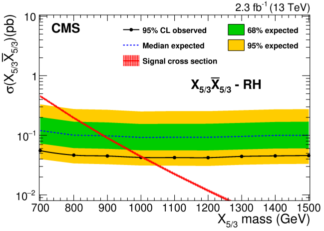


The polarisation of the top is transmitted to the leptons after W decay.

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

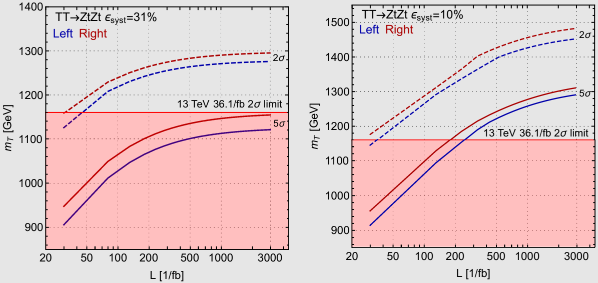
Recasting experimental data

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

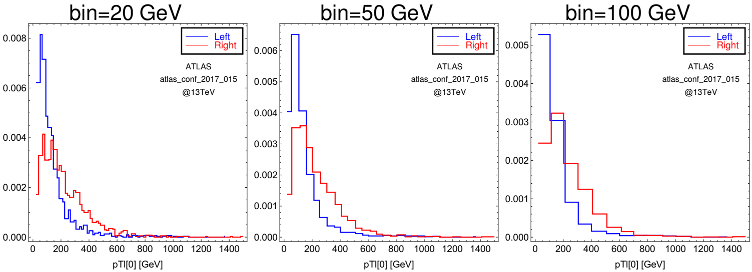
$pp \to T\bar{T} \to ZtZ\bar{t}$

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



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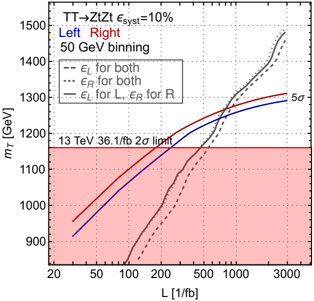
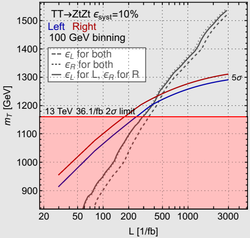
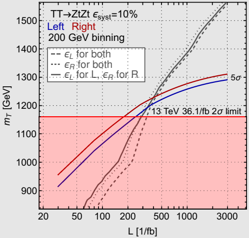


Current exclusion limit @ 36.1 fb^{-1}: 1.16 TeV

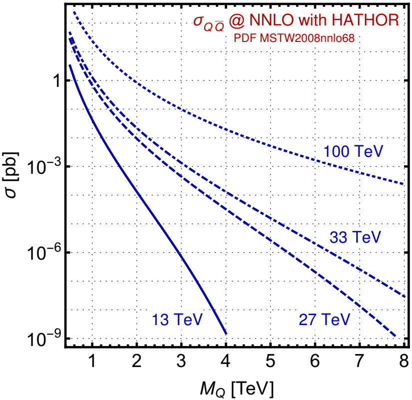
A discrimination can be done above ∼700 fb^{-1}





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

Discrimination at higher energies

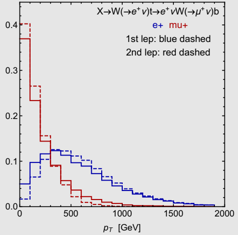


Higher energies mean (potentially) higher reach!

Discrimination at higher energies

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

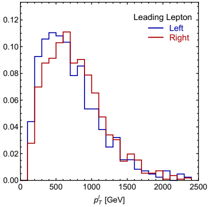
- Considering same-sign di-lepton final state
- For discrimination we must be able to identify the lepton from top decay

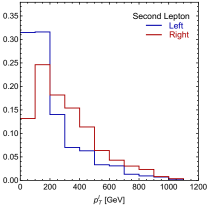


The leading lepton comes from W decay
The sub-leading lepton comes from top decay

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

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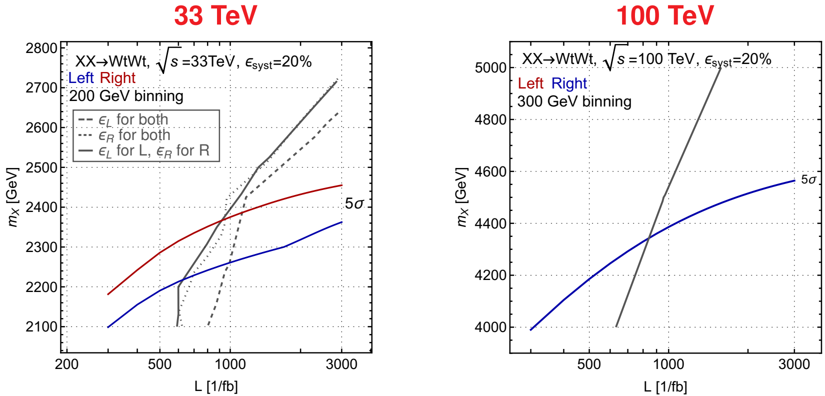

Promising perspectives for discrimination of coupling chiralities at high energy hadron collider prototypes!

Update for 27 TeV in progress

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- VLQs decaying to SM states — (1) S.Moretti, D.O'Brien, **LP**, H.Prager, Phys. Rev. D **96** (2017) no.7, 075035; (2) A.Carvalho, S.Moretti, D.O'Brien, **LP** and H.Prager, arXiv:1805.06402
- VLQs decaying to dark matter — S.Moretti, D.O'Brien, **LP**, H.Prager, Phys. Rev. D **96** (2017) no.3, 035033

Lagrangians

Interactions between the new lepton and a **singlet** dark matter

$$\mathcal{L}_1^S = \sum_{f=e,\mu,\tau} \left[\lambda_{11}^f \bar{E} P_R e_f + \lambda_{21}^f \left(\bar{N}\ \bar{E}\right) P_L \begin{pmatrix} \nu_f \\ e_f \end{pmatrix} \right] S_{DM}^0 + h.c.$$

$$\mathcal{L}_1^V = \sum_{f=e,\mu,\tau} \left[g_{11}^f \bar{E} \gamma_\mu P_R e_f + g_{21}^f \left(\bar{N}\ \bar{E}\right) \gamma_\mu P_L \begin{pmatrix} \nu_f \\ e_f \end{pmatrix} \right] V_{DM}^{0\mu} + h.c.$$

- The new lepton can be either **singlet** or **doublet**
- Since the lepton is **vector-like**, its couplings are either **purely left** or **purely right**

Interactions between the new lepton and the SM gauge bosons

$$\mathcal{L}_{AXL} = -eA^\mu \bar{E} \gamma_\mu E$$

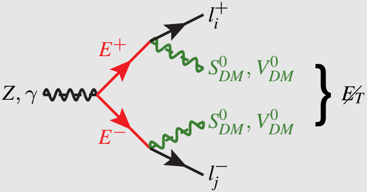
$$\mathcal{L}_{ZXL} = Z^\mu \bar{E} \gamma_\mu \left(g_L^{ZEE} P_L + g_R^{ZEE} P_R\right) E + Z^\mu \bar{N} \gamma_\mu \left(g_L^{ZNN} P_L + g_R^{ZNN} P_R\right) N$$

$$\mathcal{L}_{WXL} = W^{+\mu} \bar{N} \gamma_\mu \left(g_L^{WLN} P_L + g_R^{WLN} P_R\right) E + h.c$$

The couplings with the Z and W boson **depend on the VLL representation**
(in simplified scenarios)

focus on charged leptons

Tree-level



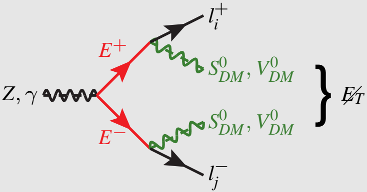
$$\{PP, e^+e^-\} \to Z, \gamma \to l_i^+ l_j^- + \not{E}_T$$

In the NWA, only the ZEE coupling affects the bounds: the E decay can be factorized by its BR

Collider signatures

LEP, LHC and future linear colliders

Tree-level



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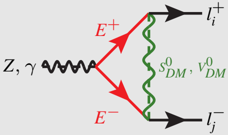
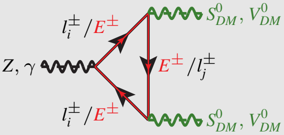
In the NWA, only the ZEE coupling affects the bounds: the E decay can be factorized by its BR

One-loop



$$\{PP, e^+e^-\} \to Z, \gamma \to l_i^+ l_j^-$$

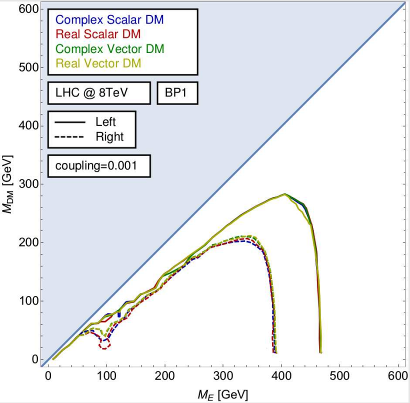


$\{PP, e^+e^-\} \to Z, \gamma \to$ invisible

Testing against data

Combination of ATLAS and CMS searches @ 8 TeV

VLL coupling to DM and SM electron



Bounds for the process of pair production of VL leptons via DY and decay into SM leptons and DM with different spin

Different gauge couplings between singlet and doublet VL leptons allow a potential discrimination between scenarios based on different cross-sections

and by the way, the spin of DM cannot be distinguished

Outline

1. Adding extra-fermions to the SM

2. Chirality of vector-like fermions
   - VL quarks interacting with SM — D.Barducci and **LP**, JHEP **1712** (2017) 057
   - VL leptons interacting with DM — D.Barducci, A.Deandrea, S.Moretti, **LP**, H.Prager, Phys. Rev. D **97** (2018) no.7, 075006

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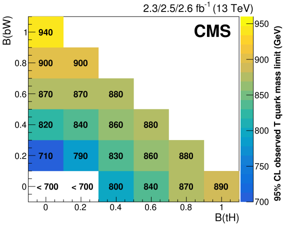
Searches at the LHC

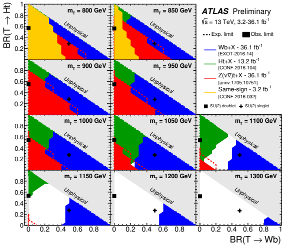
CMS (t')

CMS-B2G-16-024



ATLAS (t')

ATLAS twiki: summary plots



Common assumptions

- only one extra quark mixing with one generation only
- $\sigma \times BR$ assuming NWA . . . at least until recently!
- only interactions with the visible sector

Going beyond to find a signal

1 There can be **multiple** VLQs, with **general mixing** structure (third generation, light generations, universal couplings. . .)

Recasting tools (with different degrees of accuracy-vs-speed optimisations)

our one is **XQCAT**: JHEP **1412** (2014) 080, arXiv:1405.0737 and Comput. Phys. Commun. **197** (2015) 263, arXiv:1409.3116

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2 **Single production** can be the dominant channel in the region where experiments are setting current mass bounds

It is possible to describe single production channels in a model-independent way

M. Buchkremer, G. Cacciapaglia, A. Deandrea and **LP**, Nucl.Phys. B876 (2013) 376-417, arXiv:1305.4172

J.A. Aguilar-Saavedra, R. Benbrik and S. Heinemeyer, Phys.Rev. D88 (2013) no.9, 094010, arXiv:1306.0572

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3 VLQs may have **large width** so that the NWA is **not applicable**

4 VLQs may mediate **interactions with DM**

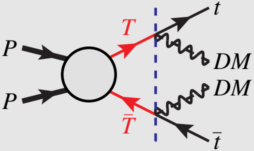
I will focus on points 3 and 4

Can we reinterpret current data? What are the bounds in these scenarios?
Can searches be sensitive to large widths (for visible and/or DM decays)?

Going to large width regime

example for DM decay

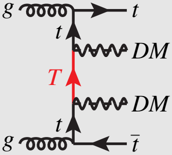
QCD pair production and decay of on-shell VLQs

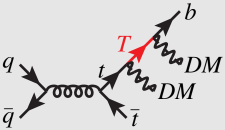


$$\sigma_X = \sigma_{2\to 2} \times BR(T)BR(\bar{T})$$

- Production and decays are factorized
- Basically no information on the spin of DM

Full signal





$\sigma_S = \sigma_{2\to 4}$ with any allowed topology

- Topologies with ≥ 1 VLQ propagator (generally subleading in the NWA)
- More sensitivity to the coupling structure between T and DM

If the width of the T mediator is large the kinematics will be different from NWA!

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How large the width can be

example with a T singlet

$$\mathcal{L}_{\text{Tsinglet}} = \kappa_W V^{4i}_{L/R} \frac{g}{\sqrt{2}} [\bar{T}_{L/R} W^+_\mu \gamma^\mu d^i_{L/R}] + \kappa_Z V^{4i}_{L/R} \frac{g}{2c_W} [\bar{T}_{L/R} Z_\mu \gamma^\mu u^i_{L/R}] - \kappa_H V^{4i}_{L/R} \frac{M}{v} [\bar{T}_{R/L} H u^i_{L/R}] + h.c.$$

Width expressions

$$\Gamma(T \to W d_i) = \kappa_W^2 |V^{4i}_{L/R}|^2 \frac{M^3 g^2}{64\pi m_W^2} \lambda^{\frac{1}{2}}(1, \frac{m_q^2}{M^2}, \frac{m_W^2}{M^2}) \left[\left(1 - \frac{m_q^2}{M^2}\right)^2 + \frac{m_W^2}{M^2} - 2\frac{m_W^4}{M^4} + \frac{m_W^2 m_q^2}{M^4} \right]$$

$$\Gamma(T \to Z u_i) = \kappa_Z^2 |V^{4i}_{L/R}|^2 \frac{M^3 g^2}{64\pi m_W^2} \frac{1}{2} \lambda^{\frac{1}{2}}(1, \frac{m_q^2}{M^2}, \frac{m_Z^2}{M^2}) \left[\left(1 - \frac{m_q^2}{M^2}\right)^2 + \frac{m_Z^2}{M^2} - 2\frac{m_Z^4}{M^4} + \frac{m_Z^2 m_q^2}{M^4} \right]$$

$$\Gamma(T \to H u_i) = \kappa_H^2 |V^{4i}_{L/R}|^2 \frac{M^3 g^2}{64\pi m_W^2} \frac{1}{2} \lambda^{\frac{1}{2}}(1, \frac{m_q^2}{M^2}, \frac{m_H^2}{M^2}) \left[1 + \frac{m_q^2}{M^2} - \frac{m_H^2}{M^2} \right]$$

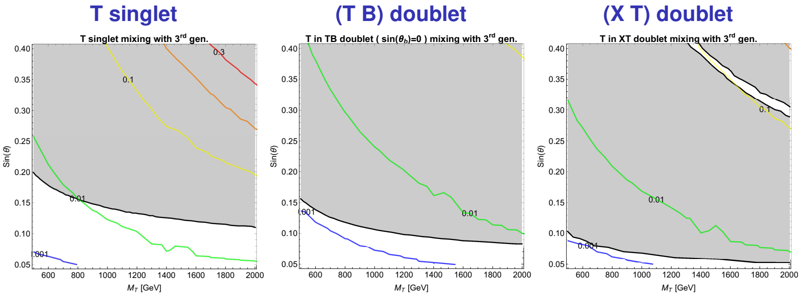
$$\Gamma_{T,\text{total}} = \Gamma(T \to W d_i) + \Gamma(T \to Z u_i) + \Gamma(T \to H u_i)$$

To obtain a large width:

- **Increase couplings**
  - ⟶ bounds from other observables (flavour, EWPT); perturbativity
  - ⟶ non-minimal extensions which allow to escape bounds while enlarging couplings
- **Increase number of decay channels** ⟶ new physics, non-minimal extension

How large the width can be

Increasing the couplings



Bounds from C.-Y. Chen, S. Dawson, and E. Furlan, *Vector-like Fermions and Higgs Effective Field Theory Revisited*, Phys. Rev. D **96** (2017) no.1, 015006.

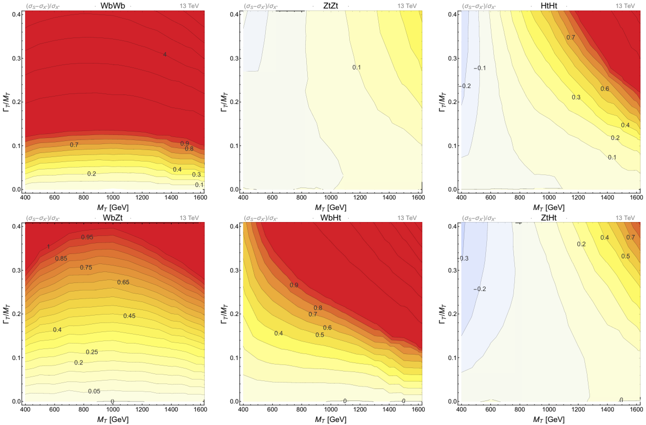
Simplified models with large couplings already excluded by other observables
New physics has to be invoked

Ratio of cross-sections

$$(\sigma_{LW} - \sigma_{NWA})/\sigma_{NWA}$$

"Diagonal" final states
WbWb ZtZt HtHt

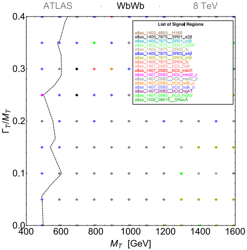
"Off-diagonal" final states
WbZt WbHt ZtHt

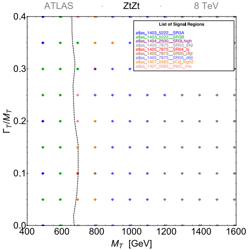


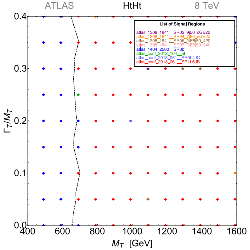
- Effects of "subleading" topologies is **very large**!
- How do **kinematical cuts** of current searches modify the picture?

LHC bounds

T mixing with third SM generation

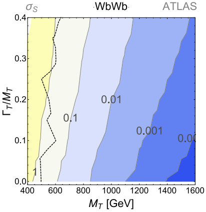


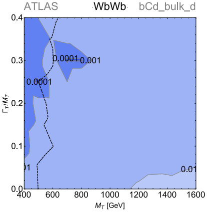




ATLAS @ 8 TeV combination of searches implemented in CheckMATE

Bounds weakly dependent on the width!

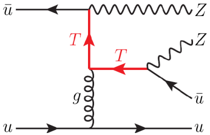


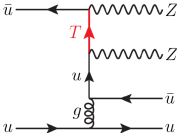


Increase of cross-section somehow compensated by decrease of search efficiencies in the region of the bound

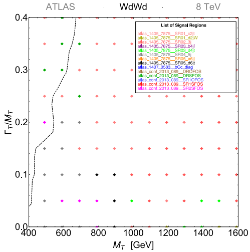
LHC bounds

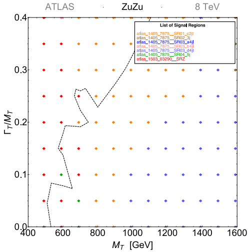
T mixing with first SM generation

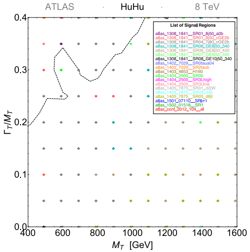




Topologies not present for mixing with third generation





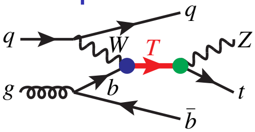


ATLAS @ 8 TeV combination of searches implemented in CheckMATE

Bounds strongly depend on the width!

For mixing with first generation current searches may be able to characterise the width of the T

A parametrisation for single production



also in collaboration with CMS

- Single T: Phys. Lett. B **781** (2018) 574 arXiv:1708.01062
- Single B: arXiv:1802.01486.

in the narrow-width approximation (NWA)

$$\sigma(C_1, C_2, m_Q, \Gamma_Q) = \sigma_P(C_1, m_Q) BR_{Q\to\text{decay channel}} = C_1^2 \hat{\sigma}_{NWA}(m_Q) BR_{Q\to\text{decay channel}}$$

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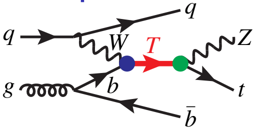

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in the finite width regime (FW) and assuming negligible interference contributions

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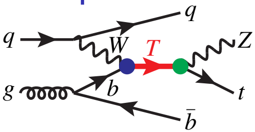

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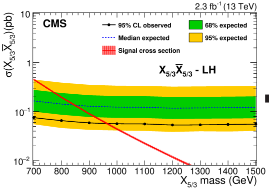
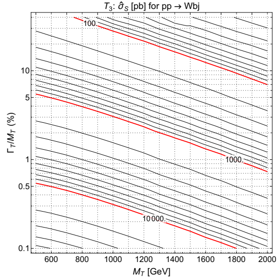
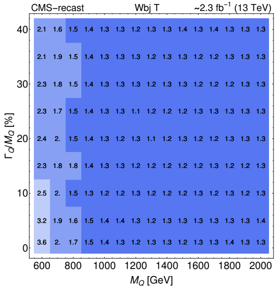


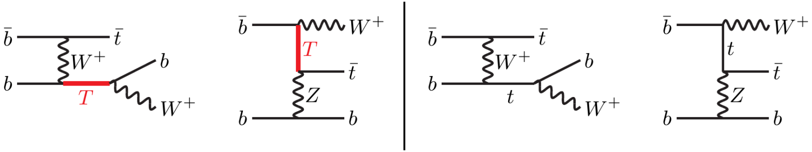




A parametrisation for single production

also in collaboration with CMS

If interference contributions are non negligible



signal with itself

$$\sigma_S = C_2^2\, \hat{\sigma}_S(C_1 \ldots, M_Q, \Gamma_Q, \chi_Q)$$

signal with background

$$\sigma_{SB}^{\text{int}} = C_2\, \hat{\sigma}_{SB}^{\text{int}}(C_1 \ldots, M_Q, \Gamma_Q, \chi_Q)$$

Model-dependency is unavoidable

Fiducial cross-section

$$S + B = L(\sigma_S \epsilon_S + \sigma_{SB_{\text{irr}}}^{\text{int}} \epsilon_{SB_{\text{irr}}}^{\text{int}}) + B_{\text{irr+red}} \equiv L\sigma_{\text{eff}} + B$$

Suppose the VLQ interacts only with one gauge boson:

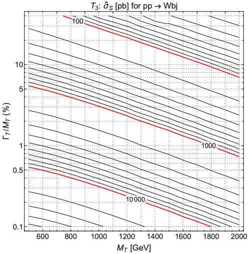
$$\sigma_{\text{eff}} = C_2^4\, \hat{\sigma}_S\, \epsilon_S + C_2^2\, \hat{\sigma}_{SB_{\text{irr}}}^{\text{int}}\, \epsilon_{SB_{\text{irr}}}^{\text{int}} \equiv C_2^4\, \hat{\sigma}_{S,\text{eff}} + C_2^2\, \hat{\sigma}_{SB_{\text{irr}},\text{eff}}^{\text{int}}$$

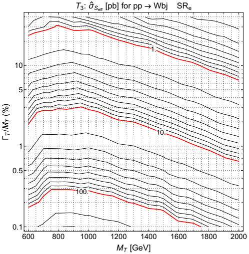
A parametrisation for single production

Recast of CMS-B2G-16-006

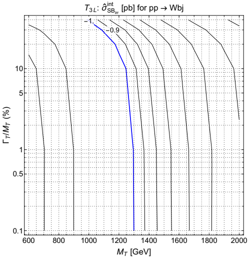
Folding search efficiencies into the reduced cross-section:

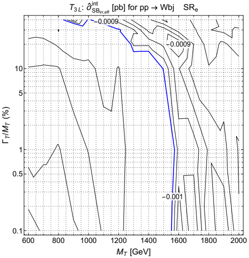
Signal





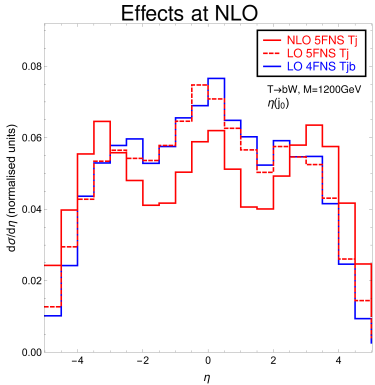
Interference with SM



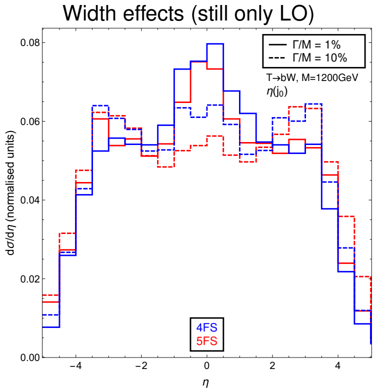


Development of new strategies

Preliminary results @NLO in LH proceedings arXiv:1803.10379



$pp \to Tj(+b)$ with $T \to Wb$



$pp \to Wbj(+b)$ via T

Outline

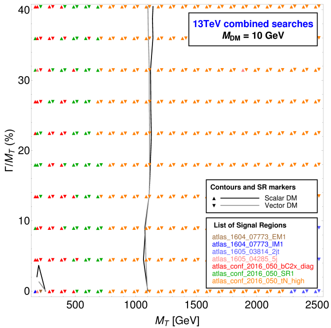
1. Adding extra-fermions to the SM

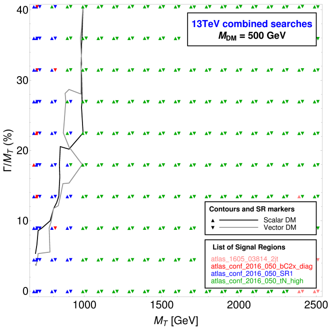
2. Chirality of vector-like fermions
   - VL quarks interacting with SM — D.Barducci and **LP**, JHEP **1712** (2017) 057
   - VL leptons interacting with DM — D.Barducci, A.Deandrea, S.Moretti, **LP**, H.Prager, Phys. Rev. D **97** (2018) no.7, 075006

3. Width of vector-like fermions
   - VLQs decaying to SM states — (1) S.Moretti, D.O'Brien, **LP**, H.Prager, Phys. Rev. D **96** (2017) no.7, 075035; (2) A.Carvalho, S.Moretti, D.O'Brien, **LP** and H.Prager, arXiv:1805.06402
   - VLQs decaying to dark matter — S.Moretti, D.O'Brien, **LP**, H.Prager, Phys. Rev. D **96** (2017) no.3, 035033

Width dependence of bounds

combination of ATLAS searches @ 13 TeV

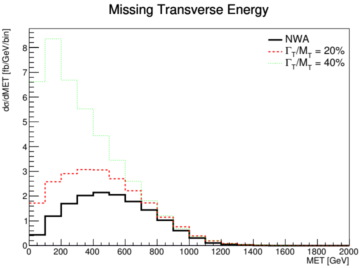




The **bounds weakly depend on the width** for light DM, somewhat more if the DM mass increases

Kinematics of the signal

Scalar DM: M_T=1100 GeV and M_{DM}=10 GeV

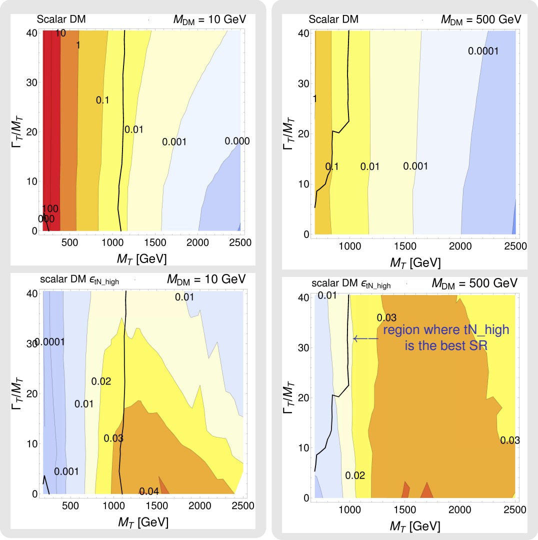


The distributions of $\not{E}_T$ and transverse momentum of the leading jet depend significantly on the width along the bound

Need to look at the performance of the searches

Cross-sections and efficiencies

SR tN_high of ATLAS CONF-2016-050 for scalar DM



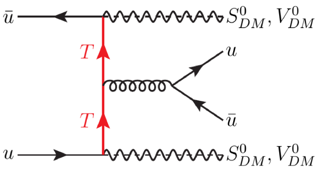
Cross-section weakly dependent on the width in the region of the bound

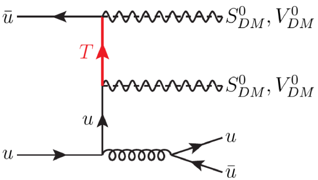
- Light DM: the efficiency of the best SR in the bound region depends in a complementary way, almost compensating the cross-section increase
- Heavier DM: the efficiency stays almost constant, as well as the cross-section

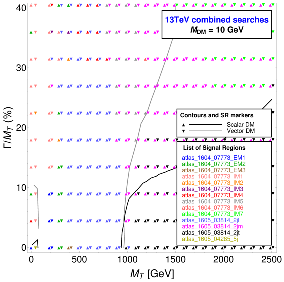
For vector DM results are qualitatively analogous

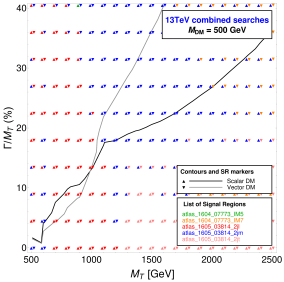
Interactions with light quarks

In this case the DM can interact directly with the initial state









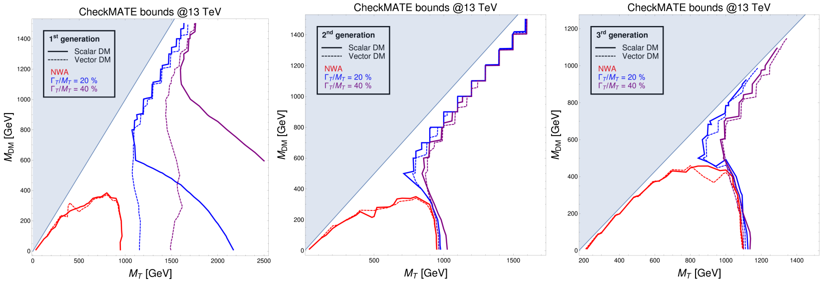
The bound strongly depends on the width

It is possible to distinguish scalar from vector DM

Different behaviour due to interplay between cross-sections and (shape-dependent) efficiencies

Exclusion limits

M_T vs M_{DM} plane



In the small splitting region, the width dependence is always large
For coupling with first generation, width effects are always sizable

considering pair production final states and with the selections of current searches

A shape analysis of the signal would provide information about different scenarios

Conclusions and perspectives

- Discovery of new physics may be (hopefully) **around the corner** and it is paramount to be ready to **characterise new signals**
- Characterisation of new fermions at the **LHC** and **future colliders** in **different channels** would be very useful to narrow down the theoretical possibilities

however

Any new signal may possibly be used to discriminate between classes of models if effective strategies are developed

Backup

Representations and lagrangian terms

Minimal extension of the SM with just one vector-like quark

	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
$\mathcal{L}_Y$	$-y_u^i \bar{q}_L^i H^c u_R^i$ $-y_d^i \bar{q}_L^i V_{CKM}^{i,j} H d_R^j$	$-\lambda_u^i \bar{q}_L^i H^c t_R'$ $-\lambda_d^i \bar{q}_L^i H b_R'$	$-\lambda_u^i \psi_L H^{(c)} u_R^i$ $-\lambda_d^i \psi_L H^{(c)} d_R^i$	$-\lambda_i \bar{q}_L^i \tau^a H^{(c)} \psi_R^a$
$\mathcal{L}_m$		$-M\bar{\psi}\psi$ (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 $M + 3 \times \lambda^i$

Mixing between VL and SM quarks

$$\mathcal{L}_{y+M} = \left(\bar{\tilde{u}}\ \bar{\tilde{c}}\ \bar{\tilde{t}}\ \bar{U}\right)_L \mathcal{M}_u \begin{pmatrix} \tilde{u} \\ \tilde{c} \\ \tilde{t} \\ U \end{pmatrix}_R + \left(\bar{\tilde{d}}\ \bar{\tilde{s}}\ \bar{\tilde{b}}\ \bar{D}\right)_L \mathcal{M}_d \begin{pmatrix} \tilde{d} \\ \tilde{s} \\ \tilde{b} \\ D \end{pmatrix}_R + h.c.$$

Mass matrices depend on representations

- Singlets and triplets:

$$\mathcal{M}_u = \begin{pmatrix} \tilde{m}_u & & & x_1 \\ & \tilde{m}_c & & x_2 \\ & & \tilde{m}_t & x_3 \\ & & & M \end{pmatrix} \qquad \mathcal{M}_d = \left(\begin{array}{c|c} \tilde{V}_L^{CKM} \begin{pmatrix} \tilde{m}_d & & \\ & \tilde{m}_s & \\ & & \tilde{m}_b \end{pmatrix} \tilde{V}_R^{CKM} & \begin{matrix} x_1 \\ x_2 \\ x_3 \end{matrix} \\ \hline & M \end{array}\right)$$

- Doublets: $\mathcal{M}^{4I}_{u,d} \leftrightarrow \mathcal{M}^{I4}_{u,d}$

Flavour and mass eigenstates

$$\begin{pmatrix} \tilde{u} \\ \tilde{c} \\ \tilde{t} \\ U \end{pmatrix}_{L,R} = V^u_{L,R} \begin{pmatrix} u \\ c \\ t \\ t' \end{pmatrix} \quad \text{and} \quad \begin{pmatrix} \tilde{d} \\ \tilde{s} \\ \tilde{b} \\ D \end{pmatrix}_{L,R} = V^d_{L,R} \begin{pmatrix} d \\ s \\ b \\ b' \end{pmatrix}$$

The exotics $X_{5/3}$ and $Y_{-4/3}$ do not mix $\rightarrow$ no distinction between flavour and mass eigenstates

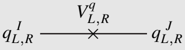
A key property of mixing matrices

$$\mathcal{L}_m = \left(\bar{u}\,\bar{c}\,\bar{t}\,\bar{t}'\right)_L (V_L^u)^\dagger \mathcal{M}_u (V_R^u) \begin{pmatrix} u \\ c \\ t \\ t' \end{pmatrix}_R + \left(\bar{d}\,\bar{s}\,\bar{b}\,\bar{b}'\right)_L (V_L^d)^\dagger \mathcal{M}_d (V_R^d) \begin{pmatrix} d \\ s \\ b \\ b' \end{pmatrix}_R + h.c.$$

$$(V_L^u)^\dagger \mathcal{M}_u (V_R^u) = diag\,(m_u, m_c, m_t, m_{t'}) \qquad (V_L^d)^\dagger \mathcal{M}_d (V_R^d) = diag\,(m_d, ms, m_b, m_{b'})$$

Mixing in left- and right-handed sectors behave differently

$$\begin{cases} (V_L^q)^\dagger (\mathcal{M}\mathcal{M}^\dagger)(V_L^q) = diag \\ (V_R^q)^\dagger (\mathcal{M}^\dagger\mathcal{M})(V_R^q) = diag \end{cases}$$



Singlets and triplets (case of up-type quarks)

$$V_L^u \implies \mathcal{M}_u \cdot \mathcal{M}_u^\dagger = \begin{pmatrix} \tilde{m}_u^2 + |x_1|^2 & x_1^* x_2 & x_1^* x_3 & x_1^* M \\ x_2^* x_1 & \tilde{m}_c^2 + |x_2|^2 & x_2^* x_3 & x_2^* M \\ x_3 x_1 & x_3 x_2 & \tilde{m}_t^2 + x_3^2 & x_3 M \\ x_1 M & x_2 M & x_3 M & M^2 \end{pmatrix}$$

mixing in the left sector present also for $\tilde{m}_q \to 0$

flavour constraints for q_L are relevant

$$V_R^u \implies \mathcal{M}_u^\dagger \cdot \mathcal{M}_u = \begin{pmatrix} \tilde{m}_u^2 & & & x_1^* \tilde{m}_u^2 \\ & \tilde{m}_c^2 & & x_2^* \tilde{m}_c^2 \\ & & \tilde{m}_t^2 & x_3 \tilde{m}_t^2 \\ x_1 \tilde{m}_u & x_2 \tilde{m}_c & x_3 \tilde{m}_t & \sum_{i=1}^3 |x_i|^2 + M^2 \end{pmatrix}$$

$m_q \propto \tilde{m}_q$

mixing is suppressed by quark masses

Doublets: other way round

Couplings

With Z

$$g_{ZL}^{IJ} = \frac{g}{c_W}\left(T_3^q - Q^q s_w^2\right)\delta^{IJ} + \frac{g}{c_W}(T_3^{q'} - T_3^q)(V_L^*)^{q'I} V_L^{q'J} \qquad g_{ZR}^{IJ} = \frac{g}{c_W}\left(-Q^q s_w^2\right)\delta^{IJ} + \frac{g}{c_W} T_3^{q'} (V_R^*)^{q'I} V_R^{q'J}$$

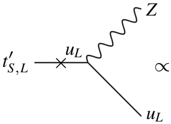
With $W^{\pm}$

$$g_{WL} = \frac{g}{\sqrt{2}}(V_L^u)^\dagger \left(\begin{array}{c|c} \tilde{V}_{CKM} & \\ \hline & 1 \end{array}\right) V_L^d \qquad g_{WR} = \frac{g}{\sqrt{2}}(V_R^u)^\dagger \left(\begin{array}{ccc|c} 0 & & & \\ & 0 & & \\ & & 0 & \\ \hline & & & 1 \end{array}\right) V_R^d$$

With Higgs

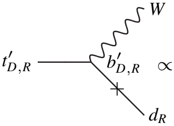
$$C^{IJ} = \frac{1}{v} m_I \delta^{IJ} - \frac{M}{v}(V_R^*)^{q'I} V_L^{q'J}$$

Singlet T



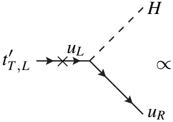
$\propto (V_L)^{t'u}$

Doublet (T B)



$\propto (V_R^d)^{b'J}$

Triplet (X T B)



$\propto V_L^{t'u}$

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