Search for pair production of vector-like top quarks in the Zt+X channel

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BMBF-Forschungsschwerpunkt
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Physik bei höchsten Energien mit dem ATLAS-Experiment am LHC
FSP 103
ATLAS

Introduction

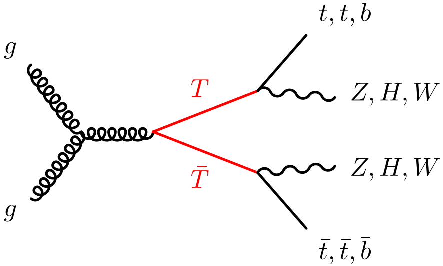
Search for pair production of vector-like top quarks in the Zt+X channel

1. Introduction and motivation
2. Event selection
3. Background estimate
4. Results

Based on publication: [JHEP 1708 (2017) 052] [Figures]

Vector-like quarks

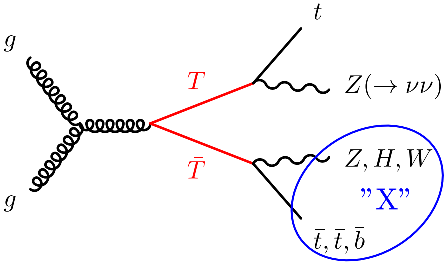
- Vector-like quarks are a potential extension of the Standard Model
  - left- and right-handed components transform identically under weak force



- Mass terms in Lagrangian possible – independent of Higgs mechanism
  - Coupling to Higgs boson allows to solve „naturalness problem“
- Here: focus on „top partner“ – T with $q = {}^2\!/_3\,|e|$
  - Assume mixing only with third generation of quarks
  - Possible decays $T \to Zt$, $T \to Ht$ and $T \to Wb$
  - SU(2) Singlet, or SU(2) Doublet $(T\ B)$, $(X\ T)$ possible models for branching ratios

The $Zt + X$ channel

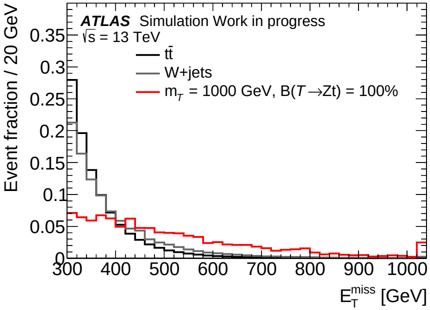
- Select $T\bar{T} \to Zt + X$ decay with $Z \to \nu\bar{\nu}$
  - Higher branching ratio compared to $Z \to \ell\ell$
  - High $E_{\mathrm{T}}^{\mathrm{miss}}$ for trigger selection and background supression
  - Require one lepton (e/μ) from top quark decay
    - QCD multijet suppression

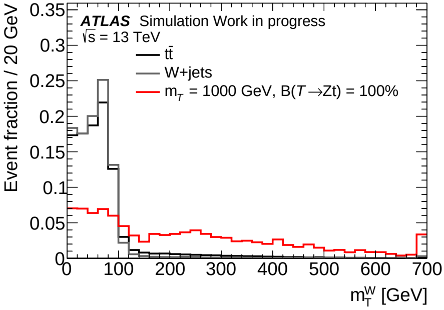


- Target hadronic boson decay in „second leg“
  - High branching ratios and boosted, massive object for selection
  - Less dependent on exact branching ratios – no specific Z, W or H selection
- Overall signature: 1ℓ, ≥ 4 jets, b-jets, high $E_{\mathrm{T}}^{\mathrm{miss}}$ and boosted objects

Signal characteristics

- Standard Model processes with similar signature: $t\bar{t}$, W+jets, single-top (Wt) and $t\bar{t} + Z(\rightarrow \nu\nu)$





- Boosted $Z \rightarrow \nu\nu$ decay
- Trigger selection and signal discrimination

- Main backgrounds: $m_{\mathrm{T}}^{W} \leq m_W$

$$m_{\mathrm{T}}^{W} = \sqrt{2\, p_{\mathrm{T}}^{\ell}\, E_{\mathrm{T}}^{\mathrm{miss}} \cdot \left(1 - \cos \Delta\phi \left(\vec{\ell}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}}\right)\right)}$$

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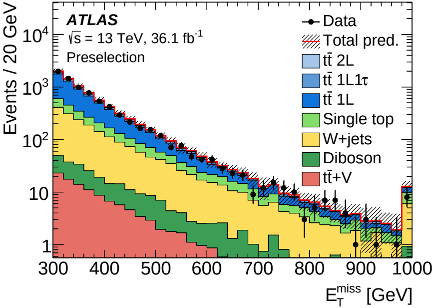

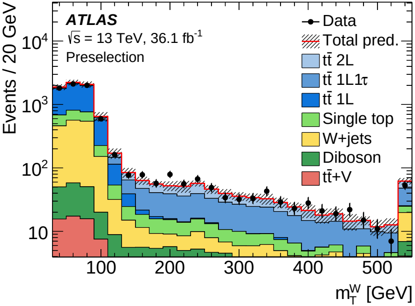

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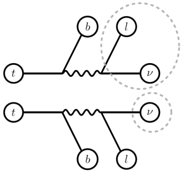
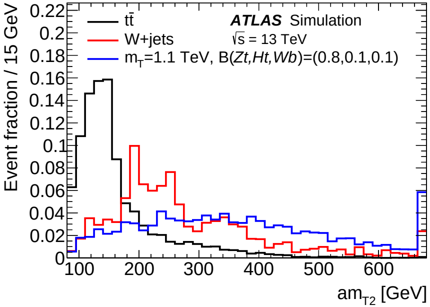
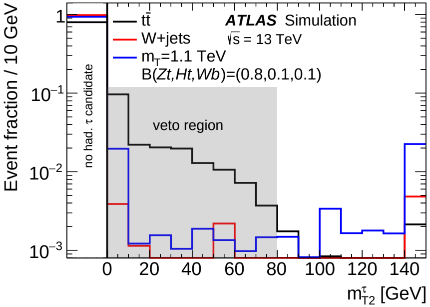
Signal characteristics

- Dominated by dileptonic $t\bar{t}$ after m_{T} requirement
- Use m_{T2} based variables for suppression



$$m_{\mathrm{T2}} = \min_{\vec{q}_a + \vec{q}_b = \vec{E}_{\mathrm{T}}^{\mathrm{miss}}} \max\left(m_{\mathrm{T},a}, m_{\mathrm{T},b}\right)$$





- Built from $E_{\mathrm{T}}^{\mathrm{miss}}$, lepton and b-jets
- Veto on hadronic τ decay
- τ candidate and selected lepton

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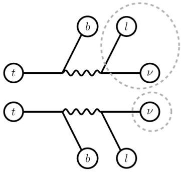

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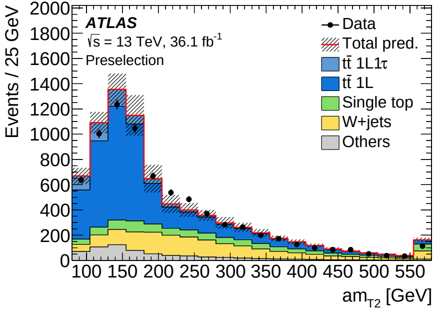

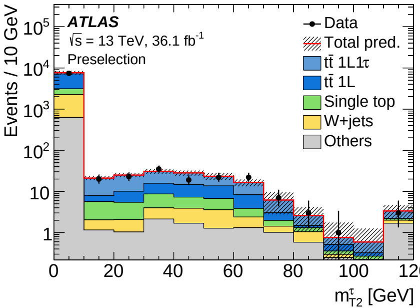

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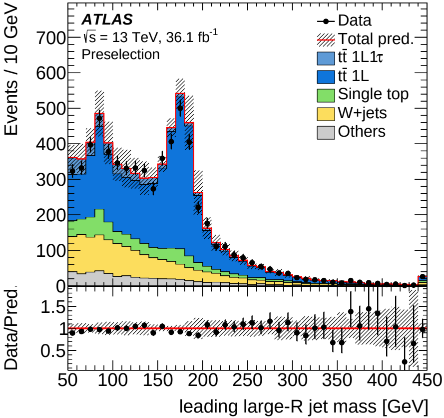
Signal characteristics



- Signal has two massive T particles
  - $\Rightarrow$ Decay products aquire high boost
- Fully hadronically decaying objects may overlap in the detector
  - Top quark decay
  - $W/Z/H \to jj$

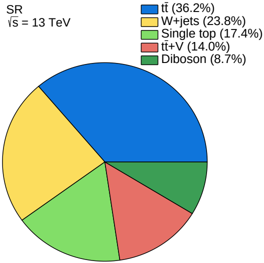
- Large-radius jets used to reconstruct such objects
  - $R = 1.0$ jets reclustered from $R = 0.4$ jets
  - Calibration and uncertainties derived from constituents

Signal selection

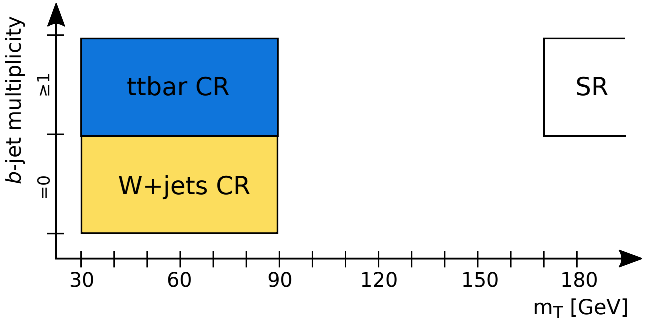
- Signal region selection based on discriminating variables
- Single-bin signal region
- Optimised for $\mathcal{B}(T \to Zt) = 80\%$
- Two large-R jets intended to capture had. top quark and boson decays
- SM backgrounds dominated by dileptonic $t\bar{t}$, W+jets and single-top events

SM background:	6.1 ± 1.9 events
Signal ($m = 1$ TeV) for $\mathcal{B}(T \to Zt) = 80\%$	13.4 ± 0.5 events

Variable	Signal Region
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 350 GeV
m_{T}^{W}	> 170 GeV
am_{T2}	> 175 GeV
m_{T2}^{τ}	> 80 GeV
$H_{\mathrm{T,sig}}^{\mathrm{miss}}$	> 12
Jet p_{T}	$> 120, 80, 50, 25$ GeV
$\lvert\Delta\phi(j_{1,2}, E_{\mathrm{T}}^{\mathrm{miss}})\rvert$	> 0.4
# b-tagged jets	≥ 1
# large-R jets	≥ 2
Large-R jet mass	$> 80, 60$ GeV
Large-R jet p_{T}	> 290 GeV (> 200 GeV)



Background estimate



- Dominant backgrounds normalised in control regions
  - Similar selection as in SR, inverted m_{T}^{W} requirement
  - For W+jets background require $= 0$ b-jets
- Background normalisation determined in simultaneous fit

$$\mu_{t\bar{t}} = 1.05 \pm 0.17 \qquad \mu_{W+\text{jets}} = 0.70 \pm 0.10$$

Background estimate

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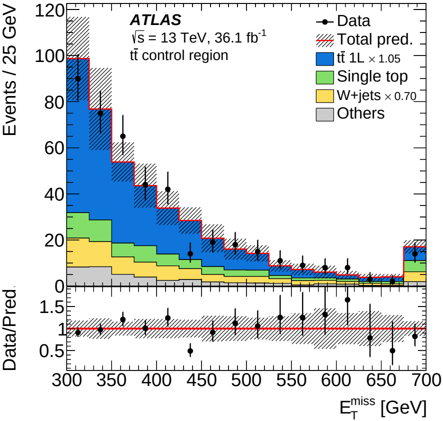

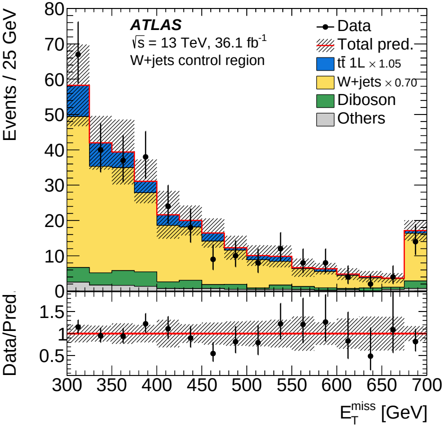

- Good agreement of data and simulation in control regions
  - Using background normalisation from fit
- Checked distributions of all relevant observables

Systematic uncertainties

Uncertainty	SR
Total background prediction	6.1
Total statistical ($\sqrt{n_{\mathrm{exp}}}$)	± 2.5
Total background uncertainty	± 1.9 [31%]
$t\bar{t}$ MC generator	± 1.1 [17%]
$t\bar{t}$ fragmentation	± 0.8 [14%]
$t\bar{t}$ radiation	± 0.7 [11%]
MC stat. (nominal samples)	± 0.7 [11%]
$t\bar{t}$ Single-top interference	± 0.6 [11%]
Single-top radiation	± 0.4 [6.6%]
$\mu_{t\bar{t}}$	± 0.4 [6.6%]
Diboson fact. scale	± 0.4 [6.5%]
Diboson renorm. scale	± 0.4 [6.1%]
W+jets heavy flavour fraction	± 0.3 [5.3%]
Jet mass resolution	± 0.3 [5.0%]
Diboson resum. scale	± 0.3 [4.7%]
Flavour-tagging light-jet mistag rate	± 0.3 [4.5%]
Single-top fragmentation	± 0.2 [3.5%]
Flavour-tagging c-jet mistag rate	± 0.2 [3.4%]
W+jets MC generator	± 0.2 [3.1%]
$t\bar{t}$PDF	± 0.2 [2.8%]
$\mu_{W+\mathrm{jets}}$	± 0.2 [2.4%]
W+jets merging scale	± 0.1 [2.4%]
W+jets renorm. scale	± 0.1 [2.3%]
W+jets resum. scale	± 0.1 [2.3%]
W+jets fact. scale	± 0.1 [2.3%]
Jet energy scale (1st component)	± 0.1 [2.0%]

- Systematic uncertainties as nuisance parameters in profile likelihood fits
- Overall dominated by statistical uncertainty: 40% (syst.: 31%)
- Dominant systematic unc.: $t\bar{t}$ modelling ($\leq$ 17%)
  - Reduced influence by CR→SR approach, normalization effects cancel
- Dominant experimental uncertainty: jet mass resolution (5%)

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Background validation

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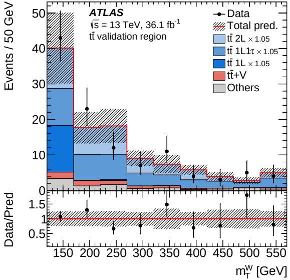
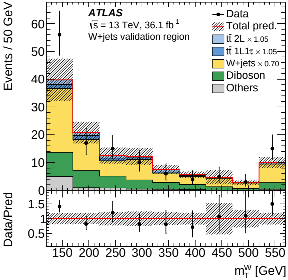
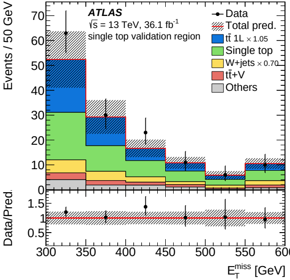
- Validation of background estimate in dedicated regions
  - Defined disjunct to CR and SR: require exactly 1 large-R jet
  - Allows to test m_{T}^{W} extrapolation ($1\ell \to 2\ell\ t\bar{t}$)
  - Additional validation region for single-top background

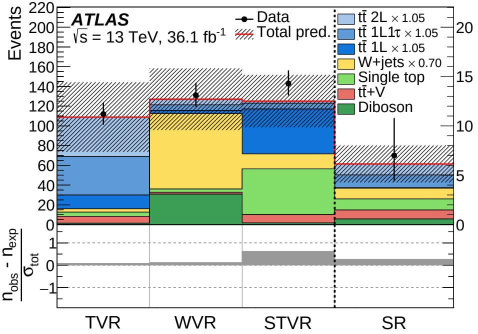






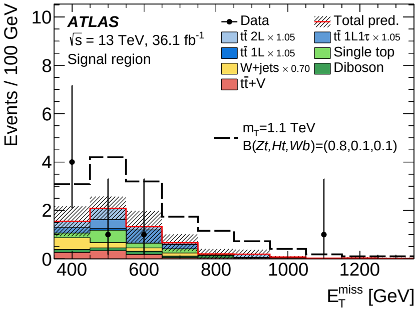
- Checked overall counts and distributions of all relevant observables
  - Largest discrepancy: 0.5σ in the single-top VR normalisation
  - $\Rightarrow$ Good agreement of data and simulation in validation regions

Results



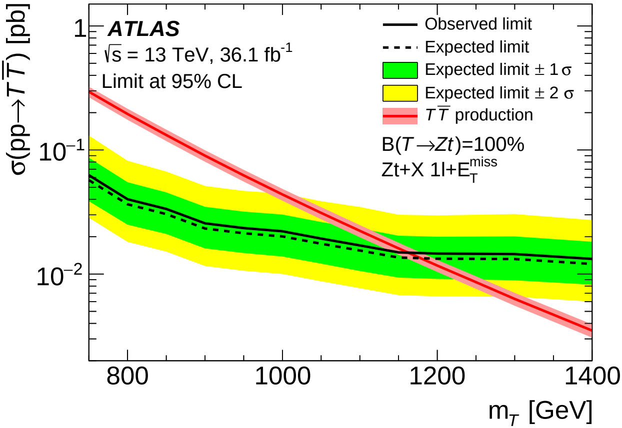
- Good agreement of data and background estimate in SR
  - No significant deviation
- Good agreement in shapes

Observed events	7
Expected events	6.1 ± 1.9
Deviation	$< 0.5\sigma$



Limits on VLQs

- No excess → 95% CL limits on cross section

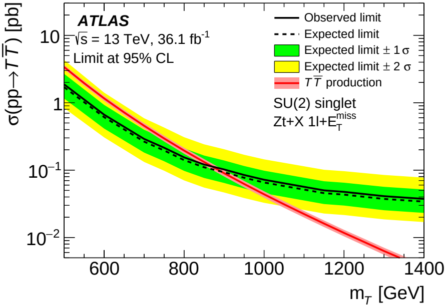


- For $\mathcal{B}(T \to Zt) = 100\%$ exclude $m_T < 1.16$ TeV (exp. 1.17 TeV)

Limits on VLQs

$SU(2)$ singlet model

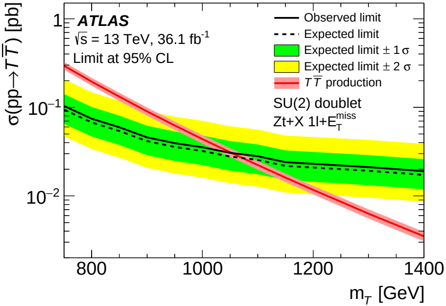
$T \to$	Zt	Ht	Wb
$\mathcal{B} =$	25%	25%	50%



- Weaker limits because of low $\mathcal{B}(T \to Zt)$

$SU(2)$ doublet model

$T \to$	Zt	Ht	Wb
$\mathcal{B} =$	50%	50%	0%

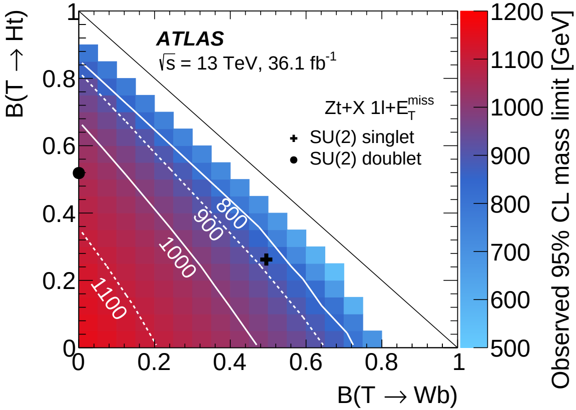


- Contributions of second VLQ in doublet ignored (B or $X^{4/3}$)

$\rightarrow$ $+\mathcal{O}(50\%)$ signal for same mass

Limits on VLQs

- Mass limits for arbitrary decay branching ratios
  - assuming $\mathcal{B}(Zt) + \mathcal{B}(Ht) + \mathcal{B}(Wb) = 100\%$



Summary and outlook

- Search for vector-like T quarks in $T \to Zt$ decays
  - Require high $E_{\mathrm{T}}^{\mathrm{miss}}$ from $Z \to \nu\nu$ decay
  - Require 2 large-R jets for hadronic top quark and boson decays
- Dominant backgrounds normalised in control regions
  - Data well modelled in control and validation regions
- No excess $\to$ limits on VLQ T production

Signal	Obs. 95% CL lower mass limit	Exp. 95% CL lower mass limit
$T \to Zt$	1.16 TeV	1.17 TeV
Singlet	0.87 TeV	0.89 TeV
Doublet	1.05 TeV	1.06 TeV

Backup

Preselection, SR and CRs

<table>
<tr><th>Variable</th><th>Preselection</th><th>SR</th><th>TCR</th><th>WCR</th></tr>
<tr><td>$E_{\mathrm{T}}^{\mathrm{miss}}$</td><td>$> 300$ GeV</td><td>> 350 GeV</td><td colspan="2">> 300 GeV</td></tr>
<tr><td>m_{T}^{W}</td><td>> 30 GeV</td><td>> 170 GeV</td><td colspan="2">$\in [30, 90]$ GeV</td></tr>
<tr><td>am_{T2}</td><td>–</td><td>> 175 GeV</td><td colspan="2">> 100 GeV</td></tr>
<tr><td>m_{T2}^{τ}</td><td>–</td><td>> 80 GeV</td><td colspan="2">> 80 GeV</td></tr>
<tr><td>$H_{\mathrm{T,sig}}^{\mathrm{miss}}$</td><td>–</td><td>$> 12$</td><td colspan="2">–</td></tr>
<tr><td>Jet p_{T}</td><td>> 25 GeV</td><td>$> 120, 80, 50, 25$ GeV</td><td colspan="2">$> 120, 80, 50, 25$ GeV</td></tr>
<tr><td>$|\Delta\phi(j_i, E_{\mathrm{T}}^{\mathrm{miss}})|$, $i = 1, 2$</td><td>> 0.4</td><td>> 0.4</td><td colspan="2">> 0.4</td></tr>
<tr><td># b-tagged jets</td><td>≥ 1</td><td>≥ 1</td><td>≥ 1</td><td>$= 0$</td></tr>
<tr><td># large-radius jets</td><td>–</td><td>≥ 2</td><td colspan="2">≥ 2</td></tr>
<tr><td>Large-radius jet mass</td><td>–</td><td>$> 80, 60$ GeV</td><td colspan="2">$> 80, 60$ GeV</td></tr>
<tr><td>Large-radius jet p_{T}</td><td>–</td><td>> 290 GeV if $E_{\mathrm{T}}^{\mathrm{miss}} < 450$ GeV
> 200 GeV if $E_{\mathrm{T}}^{\mathrm{miss}} > 450$ GeV</td><td colspan="2">> 200 GeV</td></tr>
</table>

- SR: signal region
- TCR: $t\bar{t}$ control region
- WCR: W+jets control region

SR and VRs

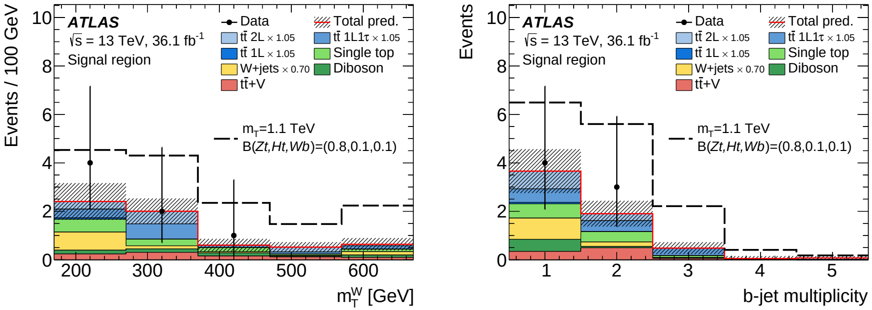
Variable	Signal Region	TVR	WVR	STVR
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 350 GeV	> 300 GeV		
m_{T}^{W}	> 170 GeV	> 120 GeV		> 60 GeV
am_{T2}	> 175 GeV	$\in [100, 200]$ GeV	> 100 GeV	> 200 GeV
m_{T2}^{τ}	> 80 GeV	> 80 GeV		
$H_{\mathrm{T,sig}}^{\mathrm{miss}}$	> 12	–		
Jet p_{T}	$> 120, 80, 50, 25$ GeV	$> 120, 80, 50, 25$ GeV		
$\lvert\Delta\phi(j_i, E_{\mathrm{T}}^{\mathrm{miss}})\rvert$, $i = 1, 2$	> 0.4	> 0.4		
# b-tagged jets	≥ 1	≥ 1	$= 0$	≥ 2
# large-radius jets	≥ 2	$= 1$		
Large-radius jet mass	$> 80, 60$ GeV	> 80 GeV		
Large-radius jet p_{T}	> 290 GeV if $E_{\mathrm{T}}^{\mathrm{miss}} < 450$ GeV > 200 GeV if $E_{\mathrm{T}}^{\mathrm{miss}} > 450$ GeV	> 200 GeV		

- TVR: $t\bar{t}$ validation region
- WVR: W+jets validation region
- STVR: single-top validation region

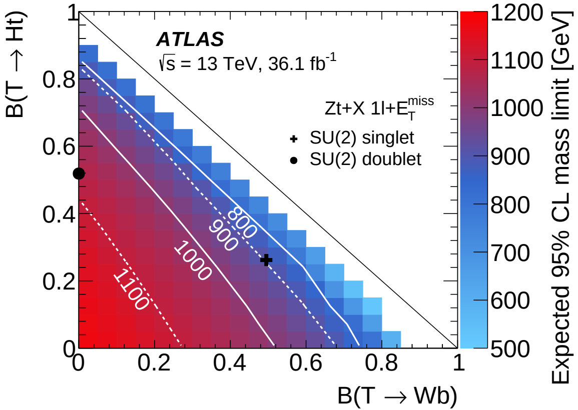
Observed and expected events

Region	SR	TCR	WCR	TVR	WVR	STVR
Observed events	7	437	303	112	131	143
Fitted bkg events	6.1 ± 1.9	437 ± 21	303 ± 17	109 ± 35	127 ± 31	125 ± 27
Fitted $t\bar{t}$ events	2.5 ± 1.7	280 ± 40	38 ± 15	90 ± 40	15 ± 8	53 ± 23
Fitted W + jets events	1.1 ± 0.7	70 ± 28	224 ± 27	3.5 ± 2.0	77 ± 30	15 ± 7
Fitted singletop events	1.1 ± 0.7	63 ± 24	10 ± 5	4.2 ± 2.6	$3.3^{+3.5}_{-3.3}$	46 ± 17
Fitted $t\bar{t} + V$ events	0.91 ± 0.20	9.7 ± 1.6	1.03 ± 0.30	7.0 ± 1.4	1.9 ± 0.7	8.3 ± 1.4
Fitted diboson events	0.6 ± 0.6	11 ± 5	30 ± 12	1.3 ± 1.3	31 ± 9	1.7 ± 1.1
MC exp. bkg events	6.5	450	398	106	160	129

Signal region distributions



Expected mass limit



$\mathcal{B}(Zt) + \mathcal{B}(Ht) + \mathcal{B}(Wb) < 100\%$?

What if there are more decay modes for the vector-like top?

→ See for example:

J.A. Aguilar-Saavedra, D.E. López-Fogliani, C. Muñoz
Novel signatures for vector-like quarks
[JHEP 1706 (2017) 095] [arXiv:1705.02526]

Mikael Chala
Direct Bounds on Heavy Top-Like Quarks With Standard and Exotic Decays
[Phys. Rev. D96, 015028 (2017)] [arXiv:1705.03013]