# VLQ searches and hadronic final states in the ATLAS experiment

**11th Large Hadron Collider Physics Conference**

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# Introduction

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- Introduction to vector-like quarks and minimal Composite Higgs Models
- Pair-produced vector-like top and bottom partners in events with large $E_T^{miss}$ arxiv:2212.05263
- Pair-production of vector-like quarks with at least one leptonically decaying $Z$ boson and a $3^{rd}$ generation quark ATLAS-CONF-2021-024
- Search for singly produced vector-like top partners in multilepton final states ATLAS-CONF-2023-020

This list is not exhaustive. A complete list of analyses with the full Run-2 data collected by ATLAS can be found here.

# What are VLQs?

Vector-like fermions, $\psi$, have left- and right-handed chiralities that transform in the same way under the SM gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y$

- Only left-handed charged currents for SM quarks:

$$J^{\mu+} = J_L^{\mu+} = \bar{u}_L \gamma^\mu d_L = \bar{u}_L \gamma^\mu \left(1 - \gamma^5\right) d \rightarrow V - A$$

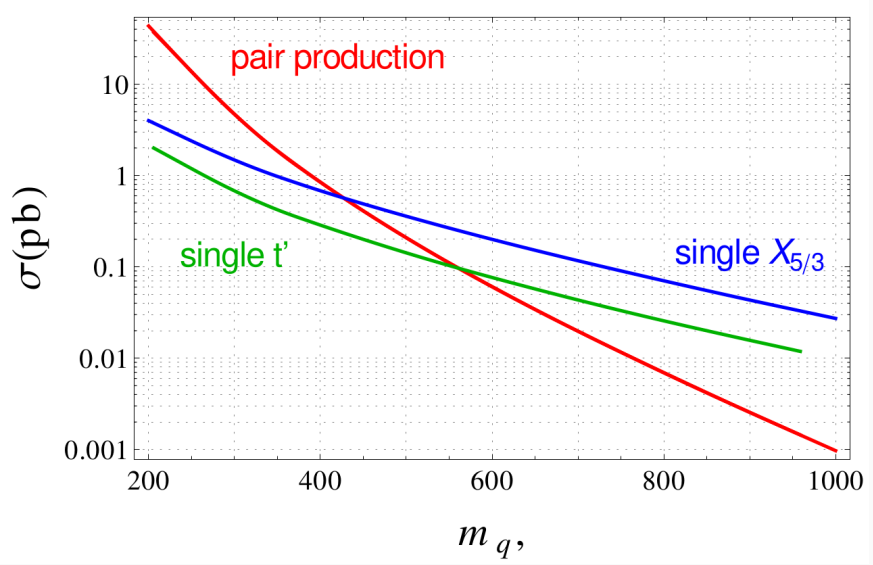
- BOTH left- and right-handed charged currents for VLQs:

$$J^{\mu+} = J_L^{\mu+} + J_R^{\mu+} = \bar{u}_L \gamma^\mu d_L + \bar{u}_R \gamma^\mu d_R = \bar{u} \gamma^\mu d \rightarrow V$$

Additionally, gauge-invariant mass terms, $-M\bar{\psi}\psi$, allowed without the need of Higgs.

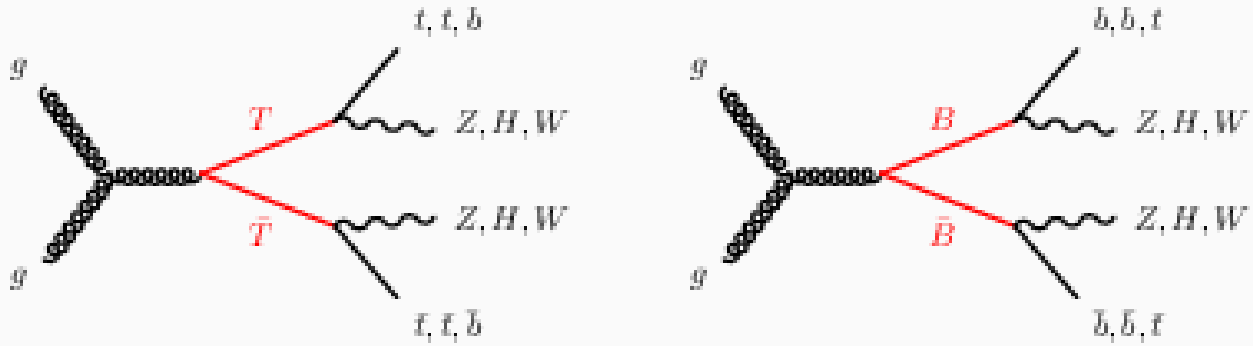
# Composite-Higgs models and vector-like quarks

- The Higgs boson is a composite pseudo-Nambu-Goldstone boson (pNGB) from spontaneous breaking of a global symmetry in a new strongly coupled sector
  $\rightarrow$ This protects the Higgs mass.
- Models with partial compositeness predict **new vector-like fermions**.
- Simplest extensions with VLQ ($T$ and $B$)
- VLQs assumed to decay via **charged and neutral currents** to 3rd generation quarks.




- **QCD pair-production:** Mass-independent, dominant at low mass
- **Single-production:** Scales with coupling, model dependent, significant at high mass.

# Pair-produced vector-like top and bottom partners in events with large $E_T^{miss}$ arxiv:2212.05263




| Preselection |
|---|
| $E_T^{miss}$ triggers |
| = 1 signal lepton |
| no additional baseline lepton |
| $\geq 4$ jets |
| $\geq 1$ $b$-jet |
| $E_T^{miss} > 250\,GeV$ |
| $m_T^W > 30\,GeV$ |
| $\lvert\Delta\phi(j_{1,2}, \vec{E}_T^{miss})\rvert > 0.4$ |

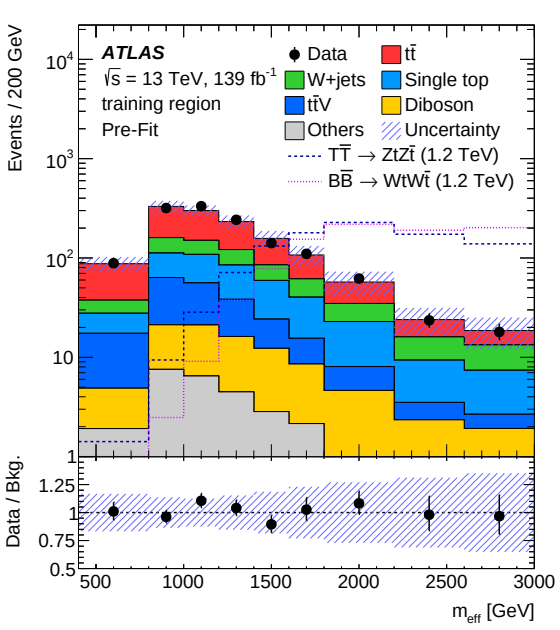
- Vector-like $T^{2/3}$, $B^{-1/3}$, and $X^{5/3}$ considered
- Events characterized by low lepton-multiplicity, high jet-multiplicity, and large $E_T^{miss}$
- Contributions of mis-measured jets to $E_T^{miss}$ reduced using the $\Delta\phi$ cut
- Signal regions defined using Neural Network

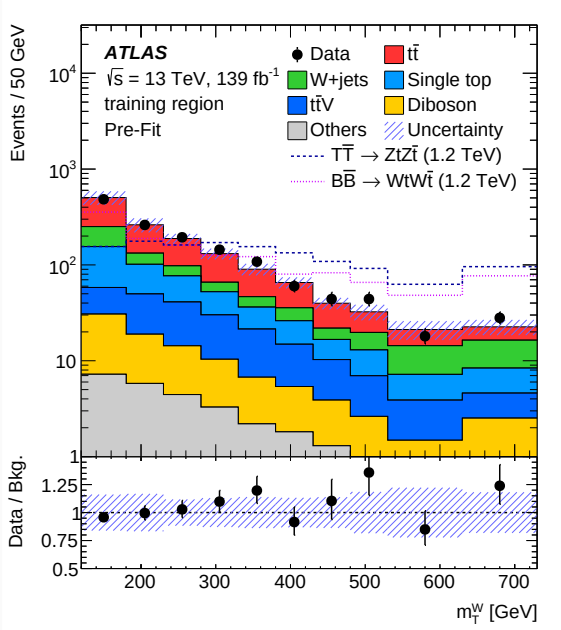
# Event selection

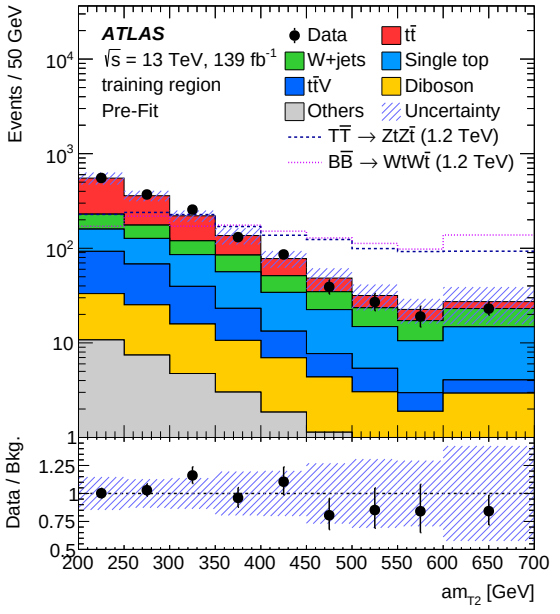
| | Training region low-$NN_{\text{out}}$ CR / SR | Top reweighting region | $W$+jets CR | Single-top CR |
|---|---|---|---|---|
| $m_{\text{T}}^{W}$ [GeV] | $> 120$ | $> 120$ | $\in [30, 120]$ | $\in [30, 120]$ |
| $am_{\text{T2}}$ [GeV] | $> 200$ | $< 180$ | $> 200$ | $> 200$ |
| $b$-jet multiplicity | $\geq 1$ | $\geq 1$ | $= 1$ | $\geq 2$ |
| Large-$R$ jet multiplicity | $\geq 1$ | $\geq 1$ | $\leq 1$ | $\leq 1$ |
| $m$(large-$R$ jet) [GeV] | – | – | $< 150$ | $< 150$ |
| Lepton charge | – | – | $+1$ | – |
| $\Delta R(b_1, b_2)$ | – | – | – | $> 1.4$ |
| $NN_{\text{out}}$ | $< 0.5 / \geq 0.5$ | – | – | – |

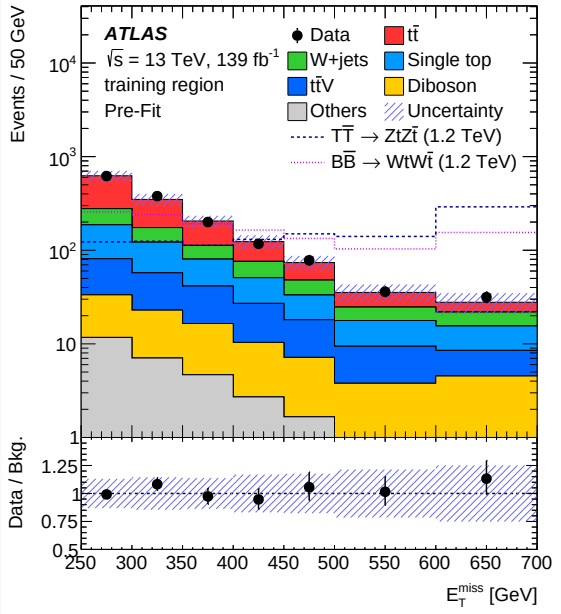
- Dominant backgrounds after pre-selection cuts are $t\bar{t}$ and $W$+jets
  - Cut on $m_T^W$ used to reduce semi-leptonic $t\bar{t}$ and $W$+jets
  - Di-leptonic $t\bar{t}$ events where one lepton is not detected reduced using requirements on the asymmetric transverse mass
- At least one top quark from the signal expected to have high-$p_T$
  - Requirement on number of large-R jets
- Neural networks used to distinguish between signal and background
  - Trained for different signal hypotheses (depending of branching ratios of $T$ and $B$) using events in the training region
  - Input variables such as high $m_{eff}$ for VLQ mass, properties of large-R jets, $b$-jet multiplicity, transverse mass etc. used

# Examples of discriminating variables



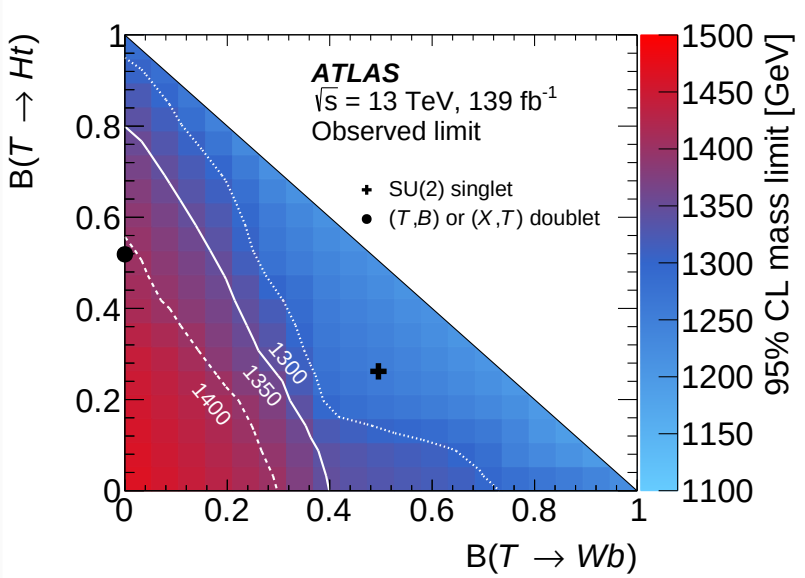



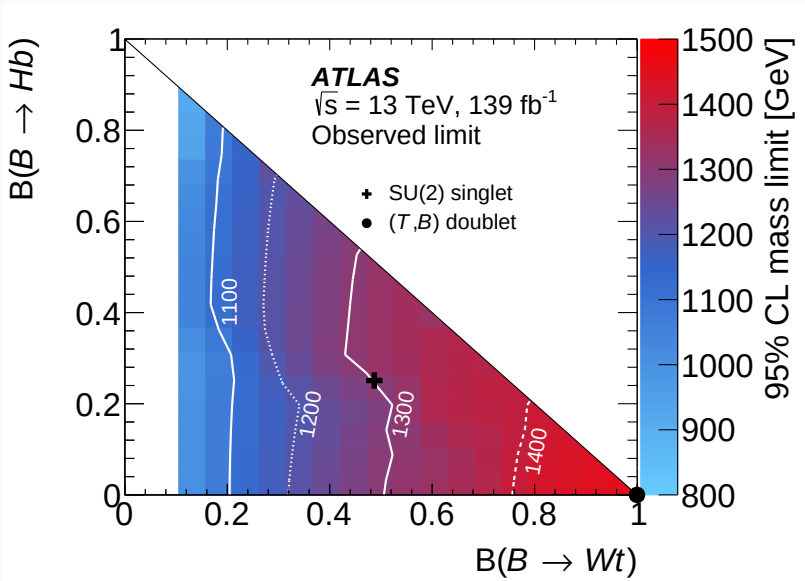



# Results

| VLQ | Scenario | Exp. limit [TeV] | Obs. limit [TeV] |
|---|---|---|---|
| $T$ | $\mathcal{B}(T \to Zt) = 100\%$ | 1.45 | 1.47 |
| $T$ | singlet | 1.33 | 1.26 |
| $T$ | $(T,B)$ or $(X,T)$ doublet | 1.41 | 1.41 |
| $B$ | singlet | 1.30 | 1.33 |
| $B/X$ | $\mathcal{B}(B/X \to Wt) = 100\%$ or $(T,B)/(X,T)$ doublet | 1.42 | 1.46 |
| $T/B/X$ | $(T,B)$ or $(X,T)$ doublet, mass degenerate | 1.56 | 1.59 |

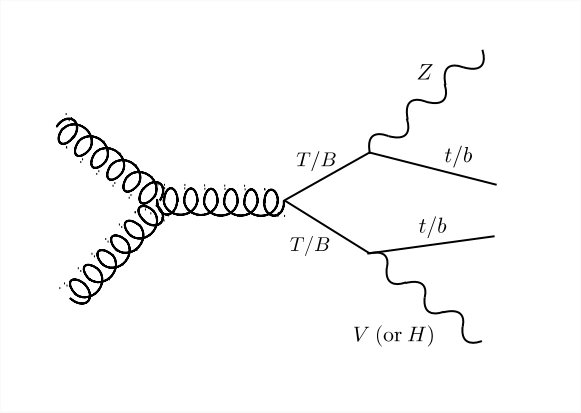
- No significant excesses
- Analysis most sensitive to the $T \to Zt$ and $B \to Wt$ decay modes
- Strongest limits for the $(T,B)$ and $(X,T)$ when $m_X = m_T = m_B$ are at 1.59 TeV
- Limits also shown for all possible branching ratios where the VLQs can decay only to SM particles



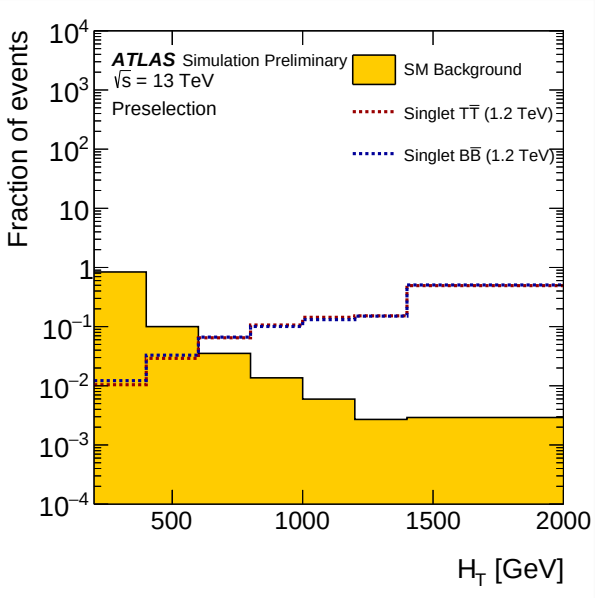
# Pair-production of vector-like quarks with at least one leptonically decaying $Z$ boson and a $3^{rd}$ generation quark

ATLAS-CONF-2021-024



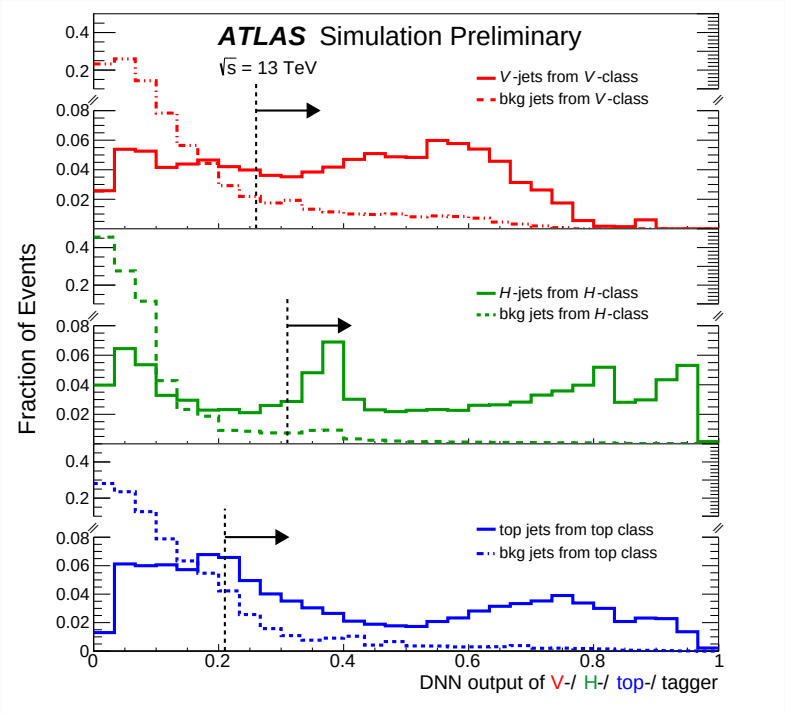

- Optimized for decays to a leptonically-decaying Z boson and a third generation SM quark.
- Events characterized by high-$p_T$ Z boson, $b-$tagged jets, high-$p_T$ large-R jets, exactly $2\ell$ or $\geq 3\ell$, boosted $W, Z, H$, and $t$.
- Categorization done using a **neural-network based boosted object tagger.**

# Multi-Class Boosted Object Tagger (MCBOT)




- Based on multi-class DNN trained using RC jets from $Z' \to t\bar{t}$ and $W' \to WZ$ simulations, with multijet as background.
- Three signal labels ($V$, $H$, top) are obtained by matching the RC jet to the corresponding boson or top quark at generator-level within $\Delta R < 0.75$.

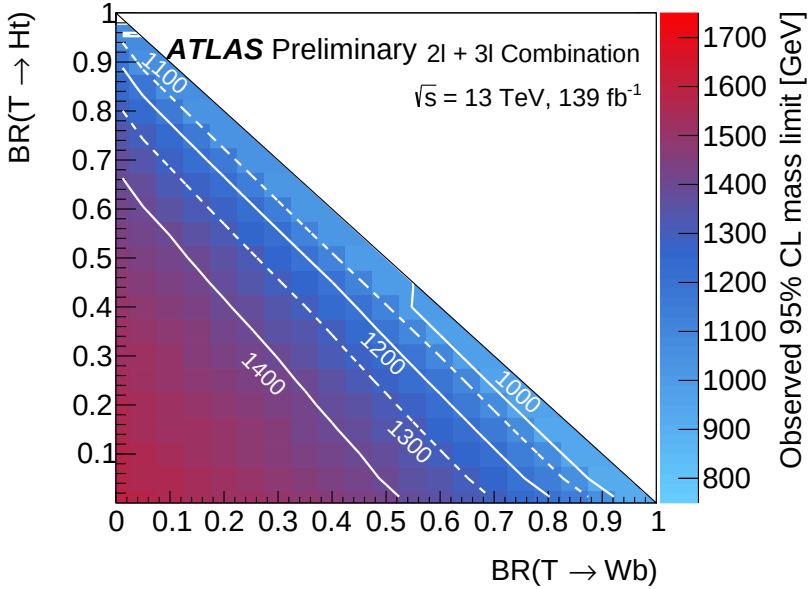
- Analysis exploits the high multiplicities of jets, large-R jets, and $b-$jets in addition to requirements on $p_T^Z$ and $H_T$ to suppress backgrounds.
- Large-R jets reclustered from calibrated R=0.4 jets used as input to MCBOT to identify hadronically decaying $V$, $H$, and top quark.

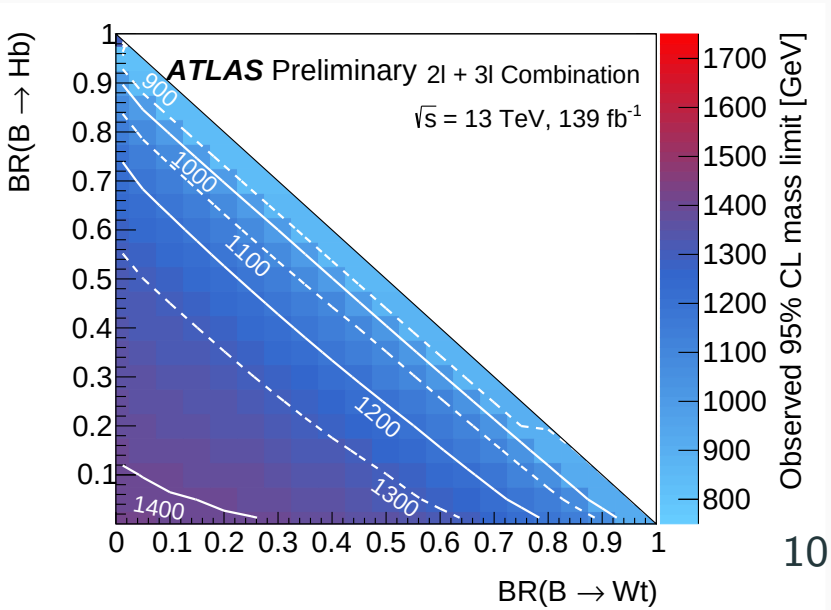


# Results

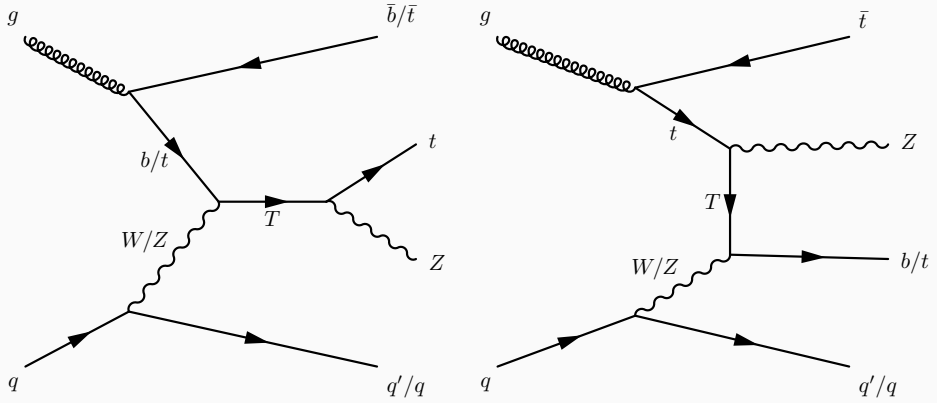
| Model | Observed (Expected) Mass Limits [TeV] | | |
|---|---|---|---|
| | $2\ell$ | $3\ell$ | Combination |
| $T\bar{T}$ Singlet | 1.14 (1.16) | 1.22 (1.21) | 1.27 (1.29) |
| $T\bar{T}$ Doublet | 1.34 (1.32) | 1.38 (1.37) | 1.46 (1.44) |
| 100% $T \to Zt$ | 1.43 (1.43) | 1.54 (1.50) | 1.60 (1.57) |
| $B\bar{B}$ Singlet | 1.14 (1.21) | 1.11 (1.10) | 1.20 (1.25) |
| $B\bar{B}$ Doublet | 1.31 (1.37) | 1.07 (1.04) | 1.32 (1.38) |
| 100% $B \to Zb$ | 1.40 (1.47) | 1.16 (1.18) | 1.42 (1.49) |

- No significant excesses
- Combined results **exclude T masses upto 1.27 and 1.46 TeV** for singlet and doublet configurations
- Combined results **exclude B masses upto 1.20 and 1.32 TeV** for singlet and doublet configurations
- These limits are better than the previous searches by more than 200 GeV.



# Search for singly produced vector-like top partners in multi-lepton final states ATLAS-CONF-2023-020



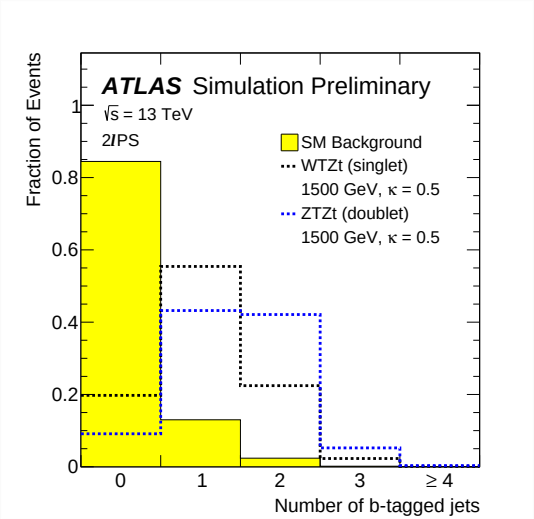

- Optimized for vector-like quarks decaying to Z bosons which further decays to a pair of electron or muons
- Characterized by the presence of a pair of opposite-sign dileptons, *b*-jets, and forward jets
- Two final states ($2\ell$ and $3\ell$) optimized independently
- Improvement compared to previous iteration of this search are mainly from more data, better kinematic selections, and more efficient top-tagging

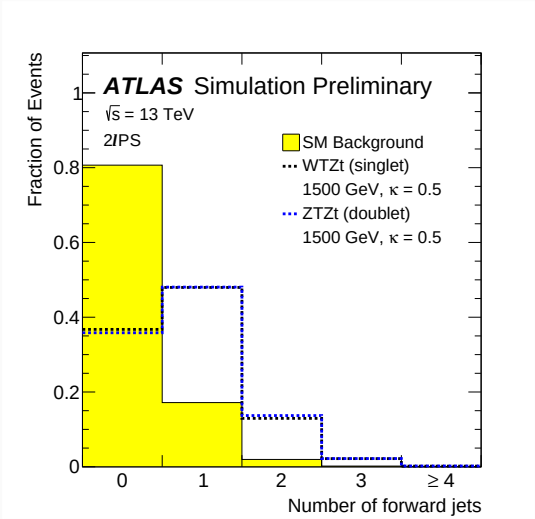
# Dilepton channel

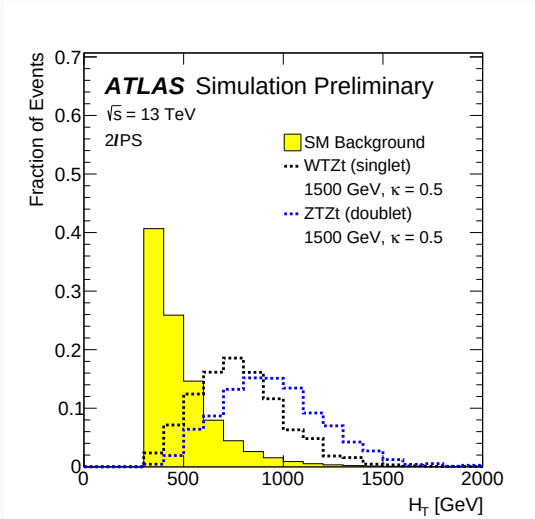
| | 2$\ell$CR1 | 2$\ell$CR2 | 2$\ell$CR3 | 2$\ell$VR1 | 2$\ell$VR2 | 2$\ell$SR |
|---|---|---|---|---|---|---|
| Preselection | 1 pair of OS-SF leptons with $\lvert m(\ell\ell) - m_Z \rvert < 10$ GeV<br>$p_{\mathrm{T}}(\ell\ell) > 200$ GeV, $H_{\mathrm{T}} > 300$ GeV<br>$\geq 1$ vRC jet<br>$H_{\mathrm{T}} + E_{\mathrm{T}}^{\mathrm{miss}} < m_{\ell\ell J}$ | | | | | |
| forward jets | $\geq 1$ | 0 | 0 | $\geq 1$ | 0 | $\geq 1$ |
| $b$-tagged jets | 0 | $\geq 1$ | 0 | 0 | $\geq 1$ | $\geq 1$ |
| top-tagged jets | - | - | $\geq 1$ | $\geq 1$ | $\geq 1$ | $\geq 1$ |
| top-vetoed jets | $\geq 1$ | $\geq 1$ | - | - | - | - |

- Dominant backgrounds from $Z$+jets, and smaller contribution from $VV$ and $t\bar{t}$
- Signal expected to have high energy objects, including $Z$ boson and top quark
  - Requirements on $p_T(\ell\ell)$ and $H_T$
  - Require atleast one variable radius reclustered (vRC) jet originating from the boosted top quark
- Mass of the VLQ reconstructed using the $Z$ boson candidate, and the leading vRC jet
- Forward jets scattering off of a heavy, off-shell vector boson from one of the incoming partons also expected

# Dilepton channel



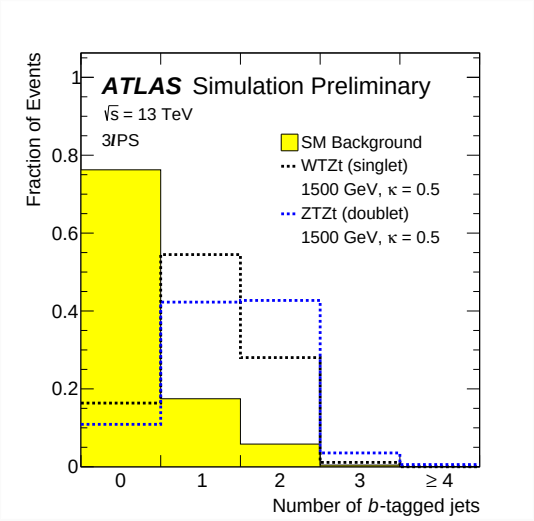

- Signal expected to have high energy objects, including $Z$ boson and top quark
  - Requirements on $p_T(\ell\ell)$ and $H_T$
  - Require atleast one variable radius reclustered (vRC) jet originating from the boosted top quark
- Mass of the VLQ reconstructed using the $Z$ boson candidate, and the leading vRC jet
- Forward jets scattering off of a heavy, off-shell vector boson from one of the incoming partons also expected

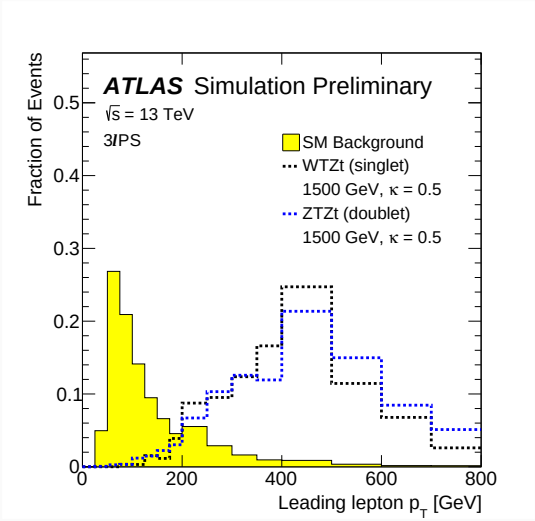
# Trilepton channel

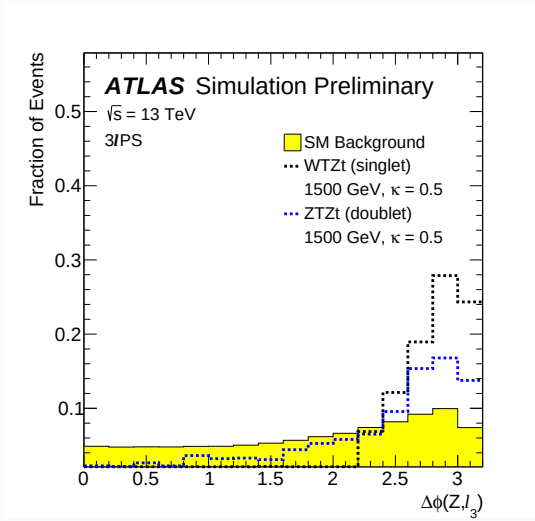
| | $3\ell$VV | $3\ell$Mixed | $3\ell$ttX | $3\ell$VR | $3\ell$SR |
|---|---|---|---|---|---|
| Preselection | $\geq 3$ leptons<br>$\geq 1$ pair of OS-SF leptons with $\lvert m(\ell\ell) - m_Z \rvert < 10$ GeV | | | | |
| $b$-tagged jets | 0 | 1 | $\geq 2$ | $\geq 1$ | $\geq 1$ |
| forward jets | - | 0 | 0 | $\geq 1$ | $\geq 1$ |
| $\Delta\phi$ selections | - | $\Delta\phi(Z, \ell_3) < 2.6$ | $\Delta\phi(Z, \ell_3) < 2.6$ | $\Delta\phi(Z, \ell_3) < \frac{\pi}{2}$ **OR**<br>$\Delta\phi(Z, b_{\text{lead}}) < \frac{\pi}{2}$ | $\Delta\phi(Z, \ell_3) > \frac{\pi}{2}$ **AND**<br>$\Delta\phi(Z, b_{\text{lead}}) > \frac{\pi}{2}$ |
| other selections | - | - | - | - | $\max(p_{\text{T}}(\ell)) > 200$ GeV<br>$p_{\text{T}}(\ell\ell) > 300$ GeV<br>$H_{\text{T}} \cdot n(\text{jets}) < 6$ TeV |

- Dominant background sources are $VV$, $ttV$, $ttH$
- Similar to the $2\ell$ channel, $b-$jets and forward jets are expected, in addition to high $p_T$ objects such as the $Z$ boson and top quark
- Angular separation between $Z$ and top quark expected to be high
  - Additional requirements on $\Delta\phi(Z, \ell_3)$ and $\Delta\phi(Z, b_{lead})$

# Trilepton channel

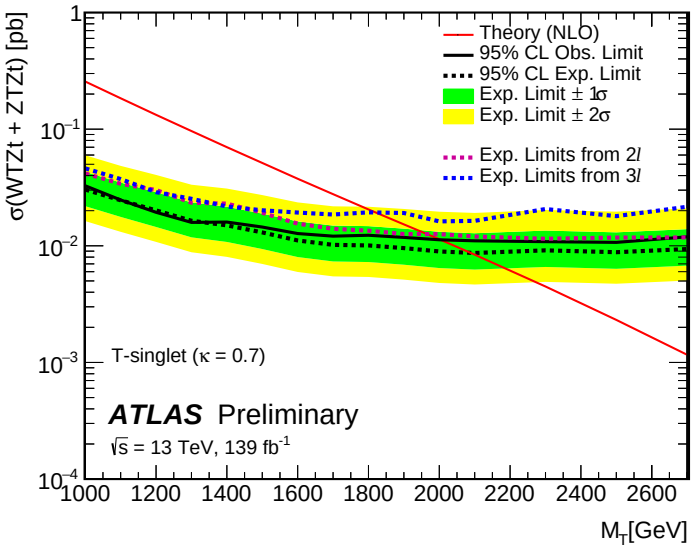


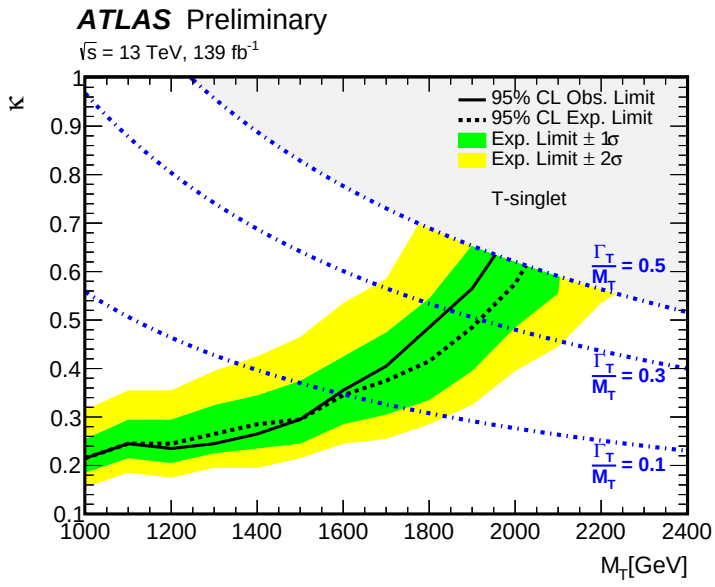



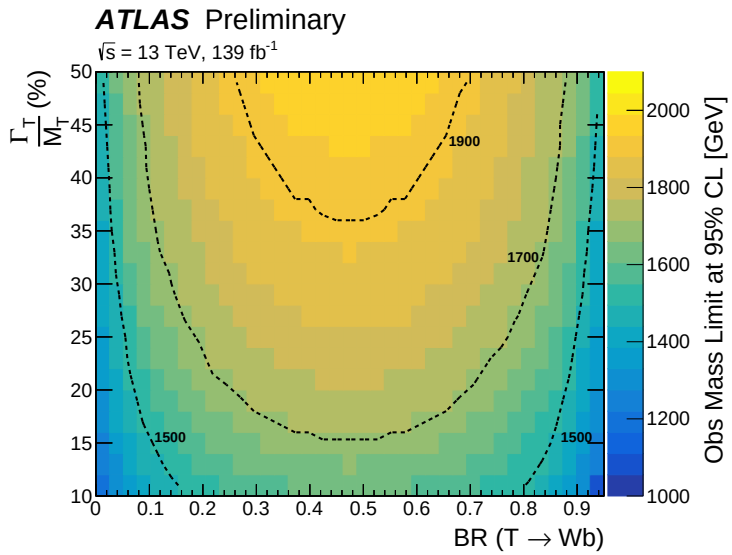




- Dominant background sources are $VV$, $ttV$, $ttH$
- Similar to the $2\ell$ channel, $b-$jets and forward jets are expected, in addition to high $p_T$ objects such as the $Z$ boson and top quark
- Angular separation between $Z$ and top quark expected to be high
  - Additional requirements on $\Delta\phi(Z, \ell_3)$ and $\Delta\phi(Z, b_{lead})$

# Results




- No significant excesses
- Limits on cross-sections reinterpreted in the coupling-mass, and width-BR planes
- Only singlet case shown here
- Coupling, $\kappa$, between 0.22 and 0.64 excluded for masses between 1000 and 1975 GeV
- Doublet exclusions slightly weaker

# Summary

- Vector-like quarks predicted by several models including CHMs
- Searches presented in this talk consider the minimal CHMs with three types of VLQs, $T^{2/3}, B^{-1/3}$, and $X^{5/3}$ decaying to SM
- Searches for third generation vector-like quarks produced singly and in pairs presented here
- No significant excesses seen but several new and innovative methods were developed
- Limits on the masses with more data and newer methods stronger than before.