VLQ searches and hadronic final states in the ATLAS experiment

11th Large Hadron Collider Physics Conference

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On behalf of the ATLAS collaboration

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Contents

- Introduction to vector-like quarks and minimal Composite Higgs Models
- **Pair-production**:
  - 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 arxiv:2210.15413
- **Single-production**:
  - Search for singly produced vector-like top partners in multilepton final states ATLAS-CONF-2023-020
  - Search for single production of vector-like T quarks decaying into Ht or Zt arXiv:2305.03401

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, ψ, 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:

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

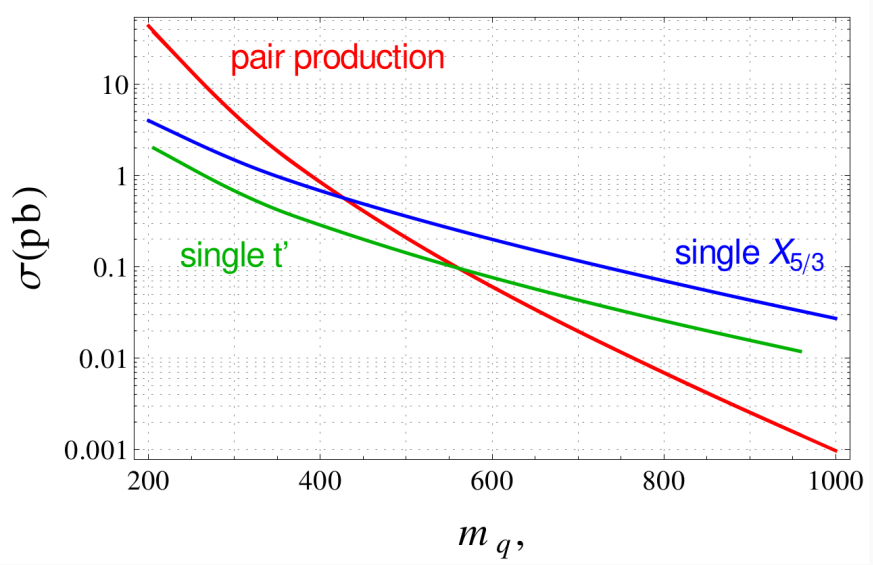
- BOTH left- and right-handed charged currents for VLQs:

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

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

Composite-Higgs models and vector-like quarks

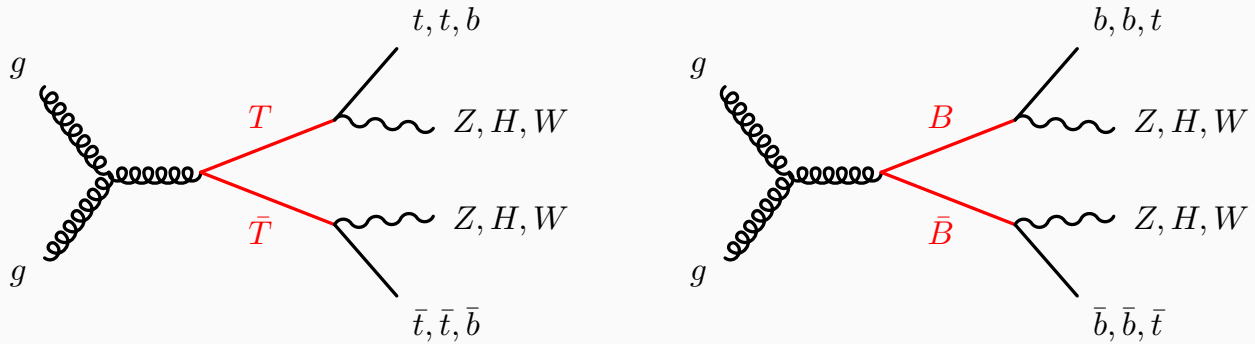
- The Higgs boson is a composite pseudo-Nambu-Goldstone boson (pNGB) from spontaneous breaking of a global symmetry in a new strongly coupled sector
  $\rightarrow$ This protects the Higgs mass.
- Models with partial compositeness predict **new vector-like fermions**.
- Simplest extensions with VLQ ($T^{2/3}$, $B^{-1/3}$ and $X^{5/3}$) singlets, doublets, and triplets.
- 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.

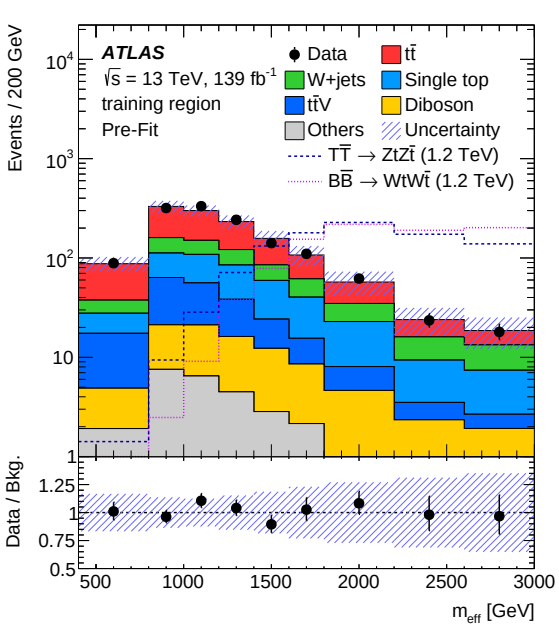
Pair-Production

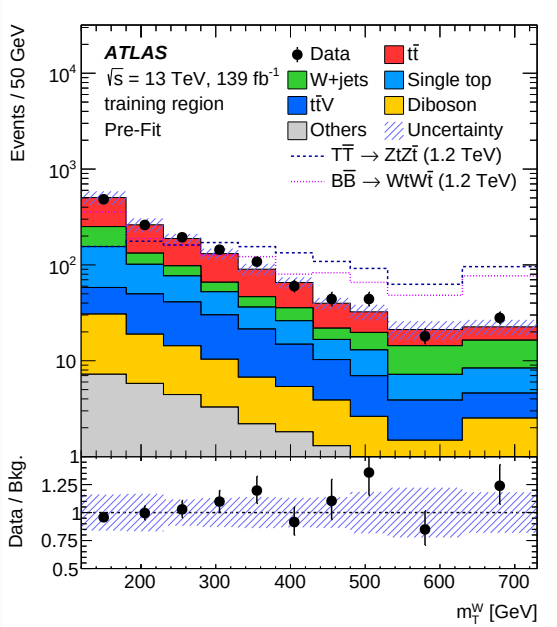
Pair-produced vector-like top and bottom partners in events with large E_T^{miss} arxiv:2212.05263

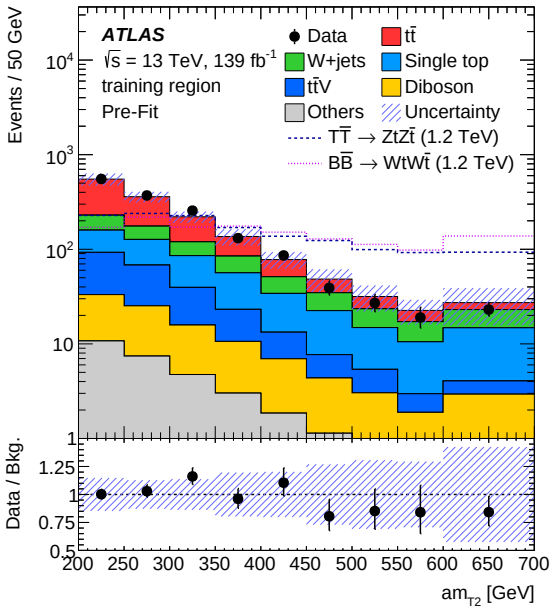


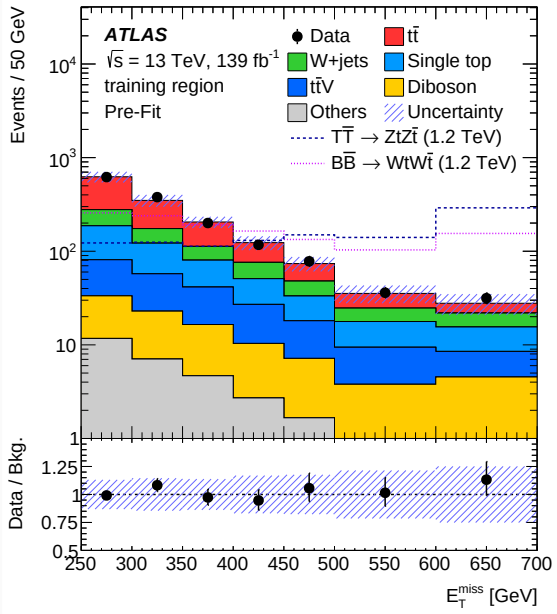
- Vector-like $T^{2/3}$, $B^{-1/3}$, and $X^{5/3}$ considered
- Events characterized by **low lepton-multiplicity, high jet-multiplicity, and large E_T^{miss}**
- Dominant backgrounds: $t\bar{t}$ and W+jets
  $\Rightarrow$ reduced using **cuts on transverse mass**
- At least one top quark from the signal expected to have a high p_T
  $\Rightarrow$ **requirement on large-R jets**
- **Neural networks** used to discriminate between signal and background
  $\Rightarrow$ Input variables such as high m_{eff} for VLQ mass, properties of large-R jets, b-jet multiplicity, transverse mass etc. used
- The search uses 139 fb^{-1} data collected with the ATLAS detector

Examples of discriminating variables





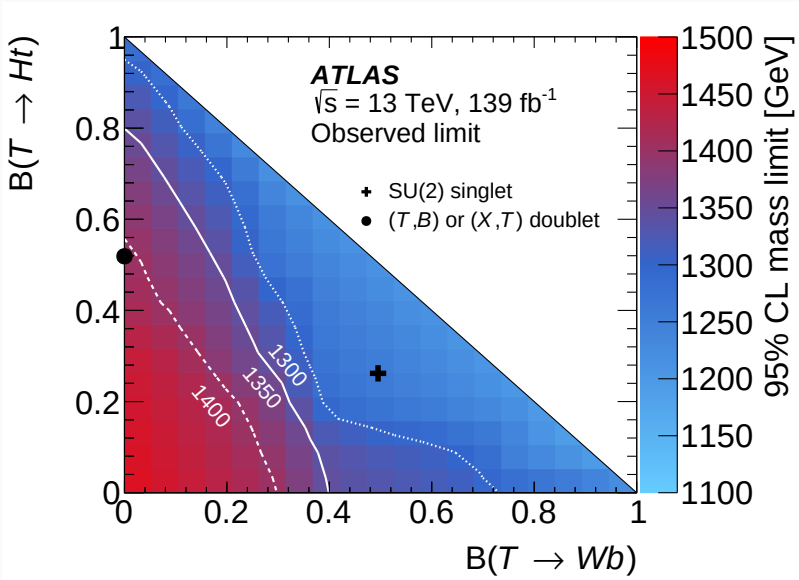


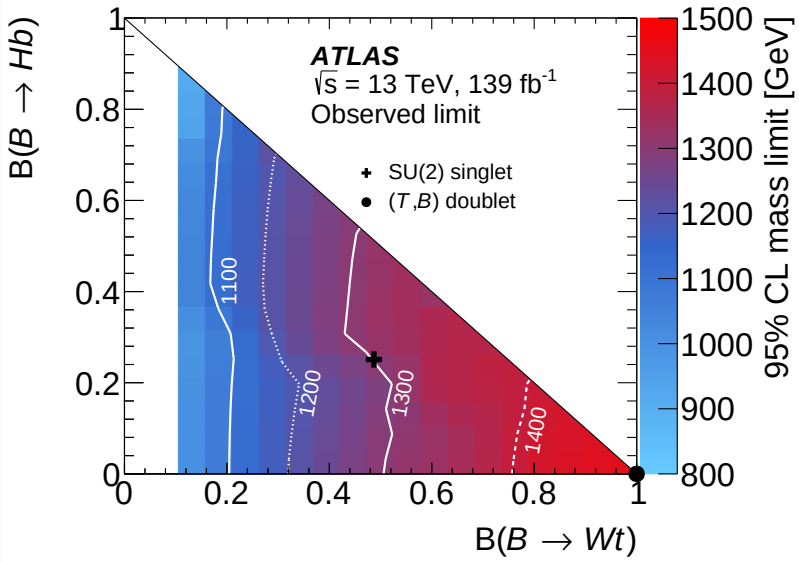


Results

VLQ	Scenario	Obs. limit (TeV)
$T(B)$	Singlet	1.26 (1.33)
T	(T,B) or (X,T) doublet	1.41
B/X	(T,B) or (X,T) doublet or $\mathcal{B}(B/X) \to Wt = 100$	1.46
$T/B/X$	(T,B) or (X,T) doublet mass-degenerate	1.59

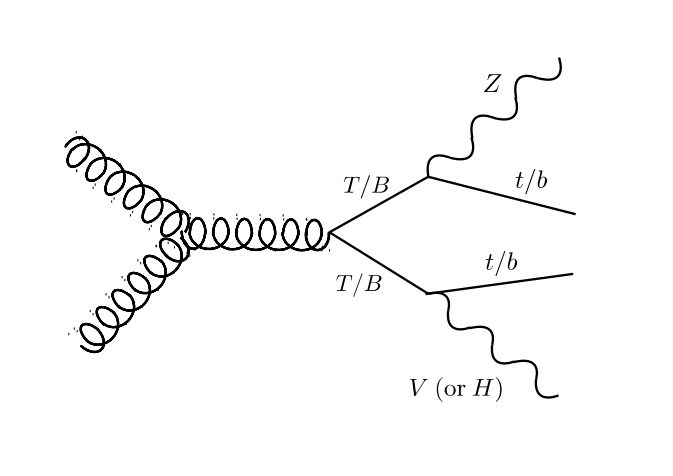
- No significant excesses
- Analysis most sensitive to the $T \to Zt$ and $B \to Wt$ decay modes
- **Strongest limits for the (T,B) and (X,T) when $m_X = m_T = m_B$ are at 1.59 TeV**





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

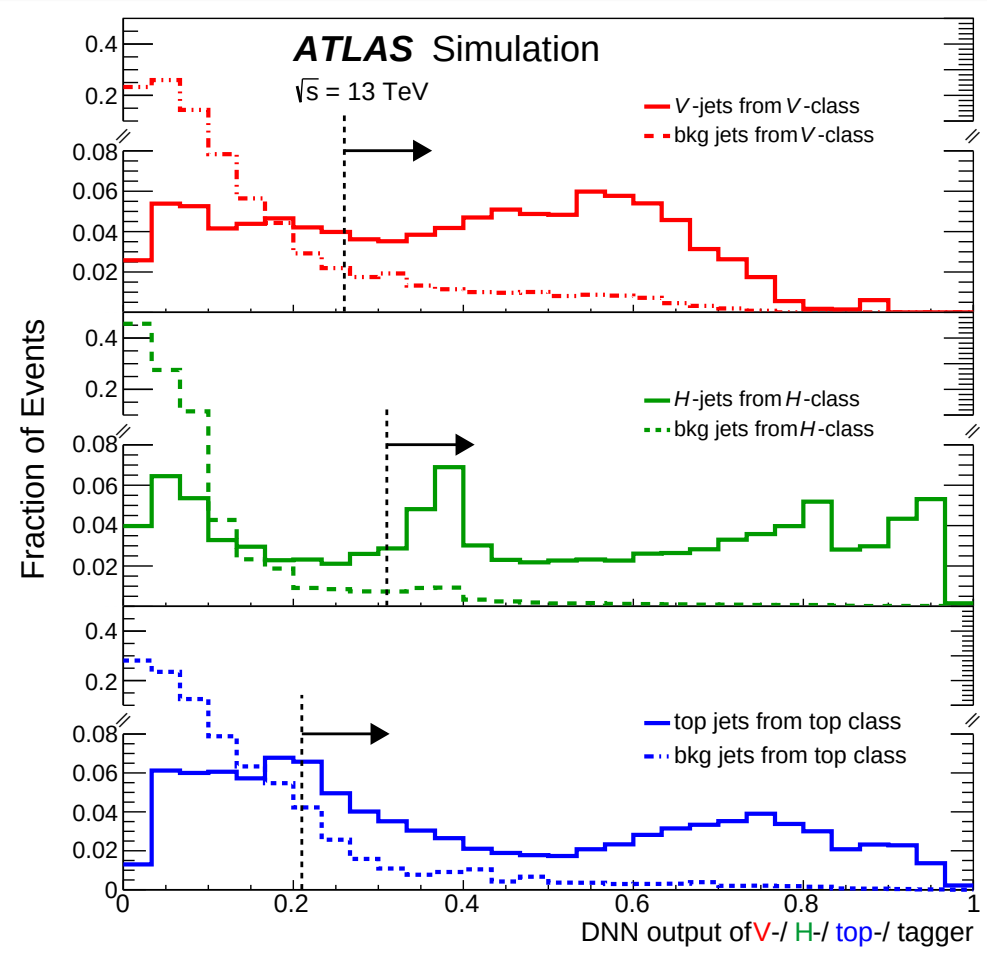
arxiv:2210.15413



- 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 2ℓ 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)

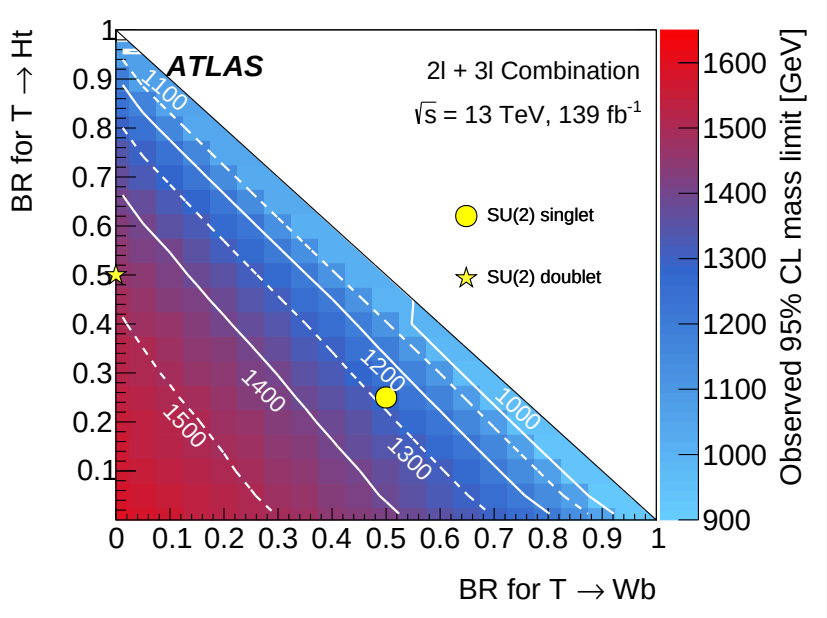
- Large-R jets reclustered from calibrated R=0.4 jets used as input to MCBOT to identify hadronically decaying V, H, and top quark.
- Based on **multi-class DNN trained using RC jets** from $Z' \to t\bar{t}$, $W' \to WZ$, and KK-graviton$\to hh$ simulations, with multijet as background.
- Three signal labels (V, H, top) are obtained by matching the RC jet to the corresponding boson or top quark at generator-level within $\Delta R < 0.75$.

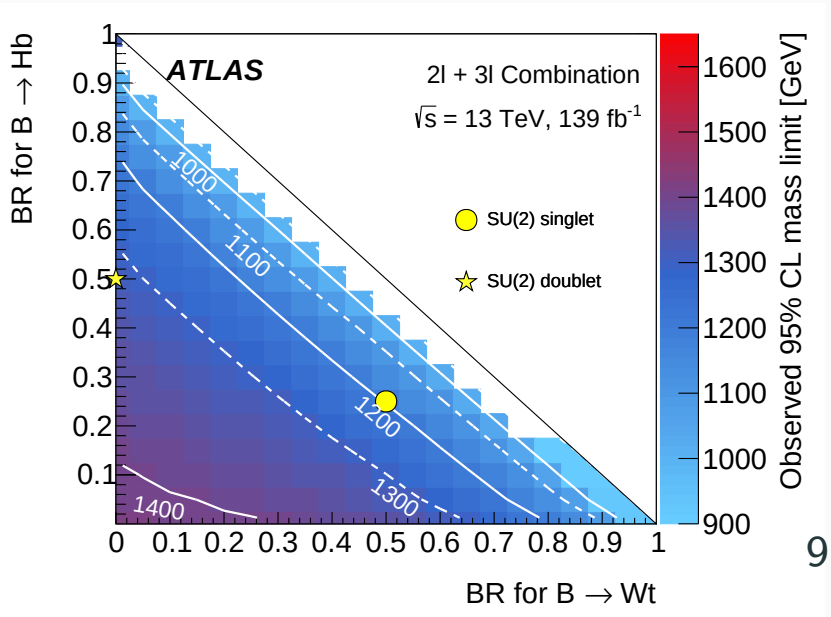


Results

Model	Observed (Expected) Mass Limits [TeV] 2ℓ	3ℓ	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)

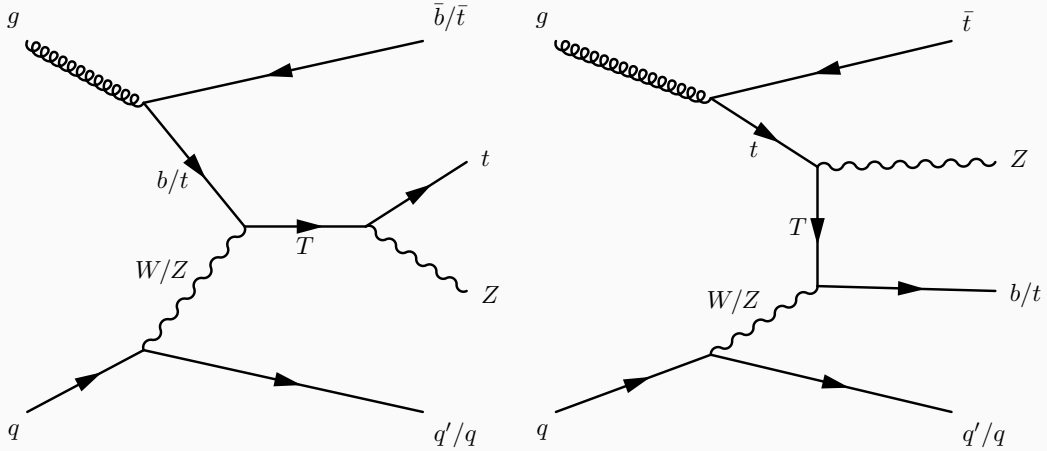
- No significant excesses
- Combined results **exclude T masses upto 1.27 and 1.46 TeV** for singlet and doublet configurations
- Combined results **exclude B masses upto 1.20 and 1.32 TeV** for singlet and doublet configurations
- These limits are better than the previous searches by more than 200 GeV.





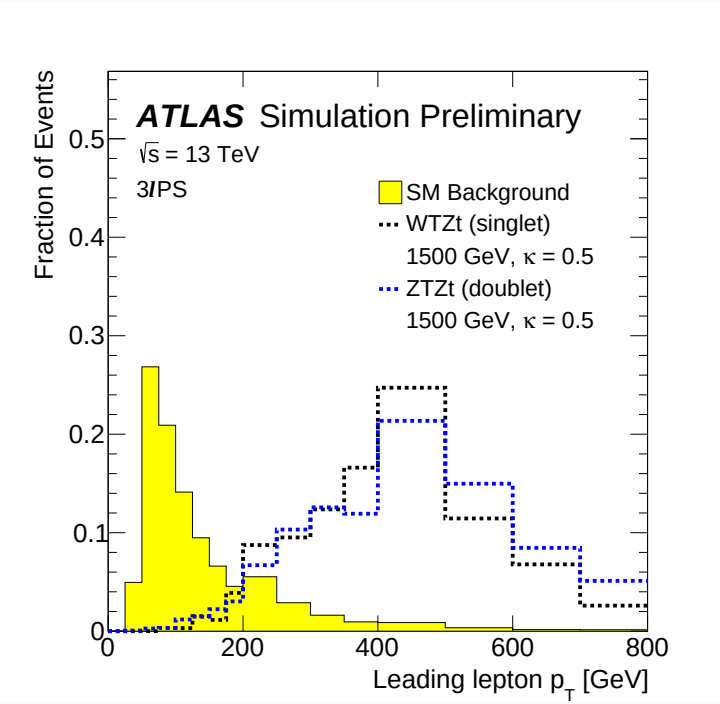
Single-production

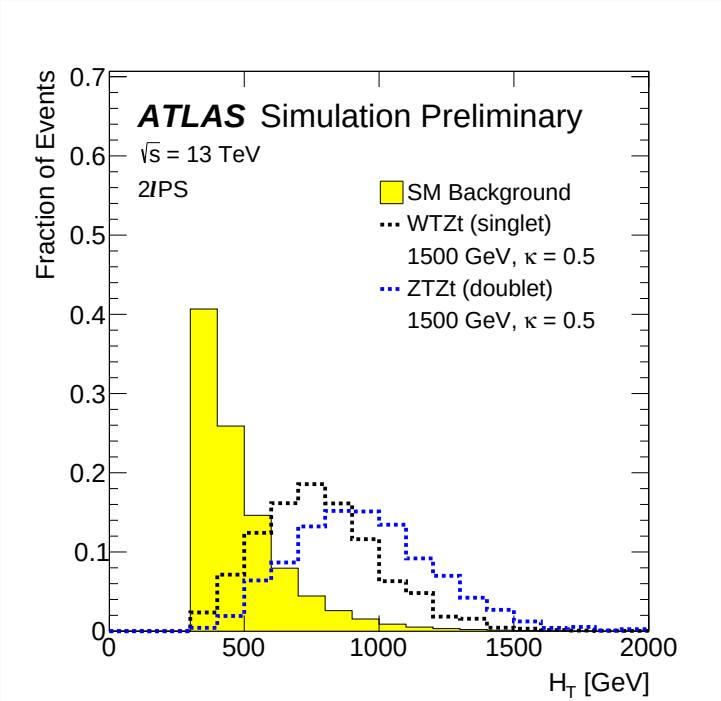
Search for singly produced vector-like top partners in multi-lepton final states ATLAS-CONF-2023-020



- 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 (2ℓ and 3ℓ)** optimized independently
- Analysis uses 139 fb^{-1} data collected with the ATLAS detector
- Improvements compared to previous iteration of this search are mainly from **more data, better kinematic selections, and more efficient top-tagging**

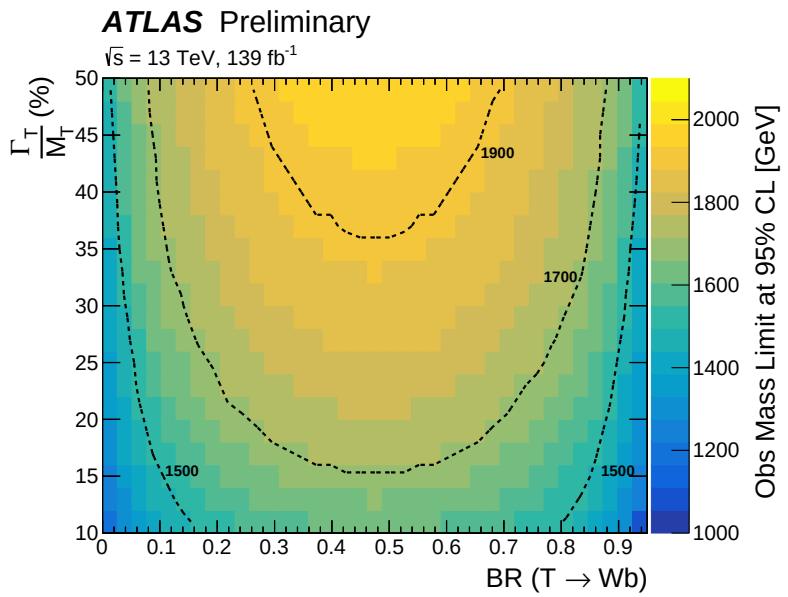
Signal topology

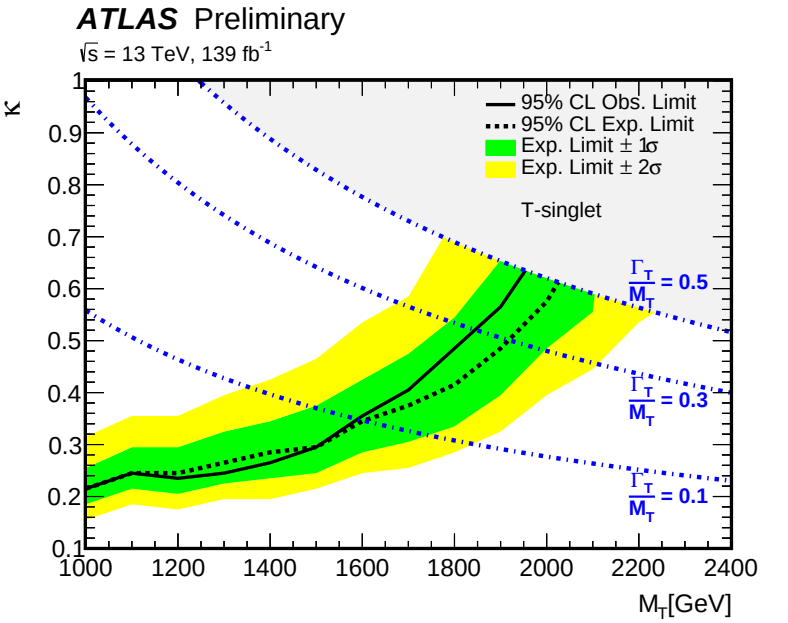




- Signal expected to have high energy objects, including Z boson and boosted top quark
- Forward jets scattering off of a heavy, off-shell vector boson from one of the incoming partons
- Angular separation between Z and top quark expected to be high

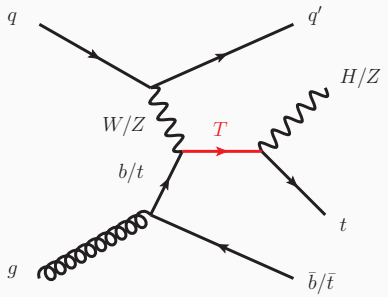
Results

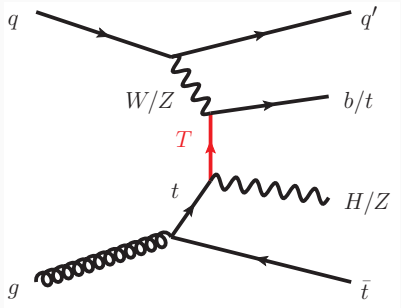




- No significant excesses
- Limits on cross-sections reinterpreted in the coupling-mass, and width-BR planes
- Only singlet case shown here
- **Coupling, κ, between 0.22 and 0.64 excluded for masses between 1000 and 1975 GeV**
- Doublet exclusions slightly weaker

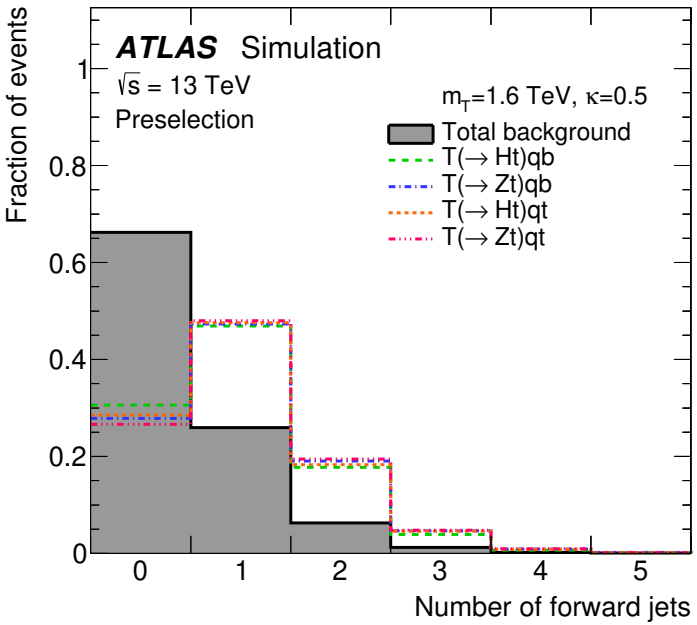
Search for single production of vector-like T quarks decaying into Ht or Zt arXiv:2305.03401

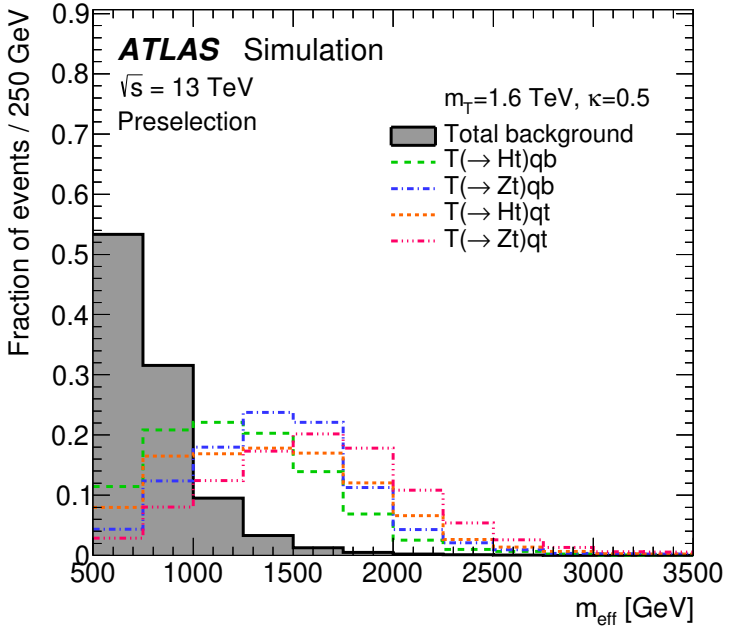




- Analysis targets final states with **1ℓ, multiple jets and b−jets** using 139 fb^{-1} data collected with the ATLAS detector
- Presence of **boosted resonance** used to discriminate between signal and background
- **Wide range of couplings** of the VLQ to W, Z and h bosons probed
- Improvements of ∼1.6x in the exclusion limits of the coupling compared to previous search thanks to **more data, better kinematic selections, improved top-tagging**

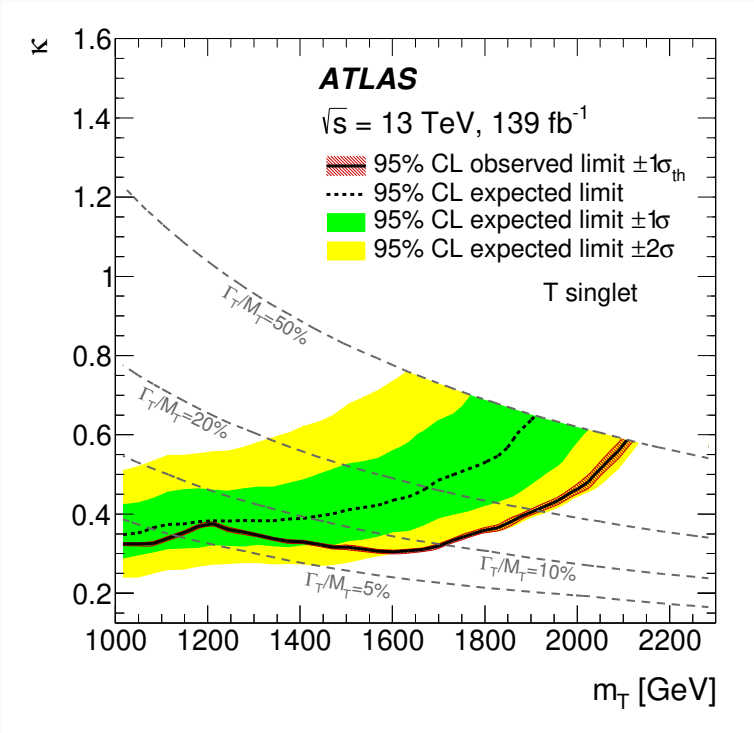
Signal topology

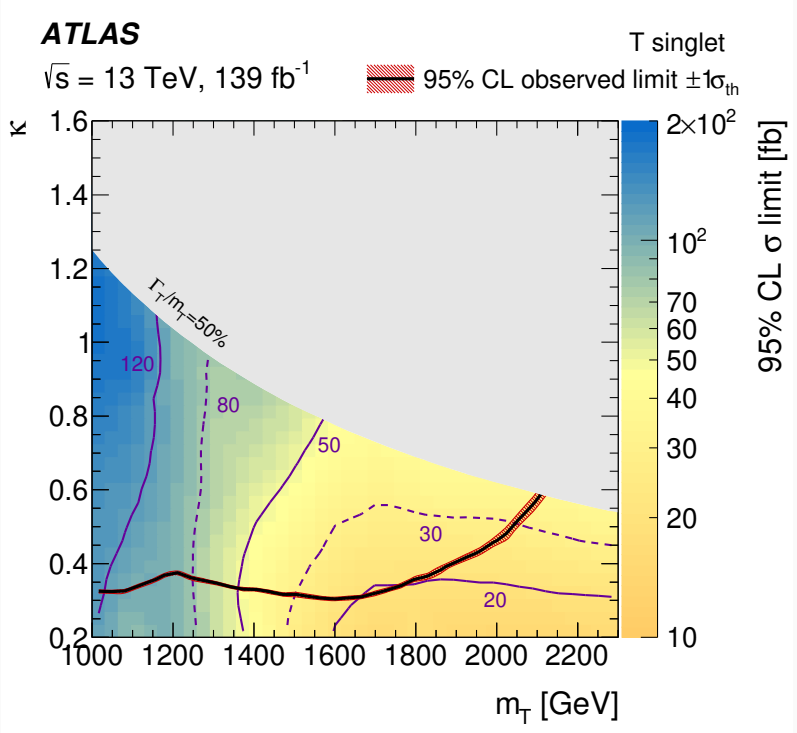




- Major backgrounds: $t\bar{t}$, single top, V+jets
- Several high energy objects from decay of VLQ
  $\Rightarrow$ high m_{eff} + boosted jets from top quark, W/Z/Higgs bosons
- Presence of forward jets
- Target signal categories: $T(\rightarrow Zt)qb$, $T(\rightarrow Ht)qb$, $T(\rightarrow Zt)qt$, $T(\rightarrow Zt)qt$
  $\Rightarrow$ Requirements on object multiplicities for different SRs

Results





- No significant excess
- Upper limits on cross-section, universal coupling (κ), and relative couplings to W, Z, Higgs
- **Singlet case**: $m_T < 2.1$ TeV excluded for $\kappa > 0.6$
- **Doublet case**: $m_T < 1.68$ TeV excluded for $\kappa > 0.75$

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.

Backup

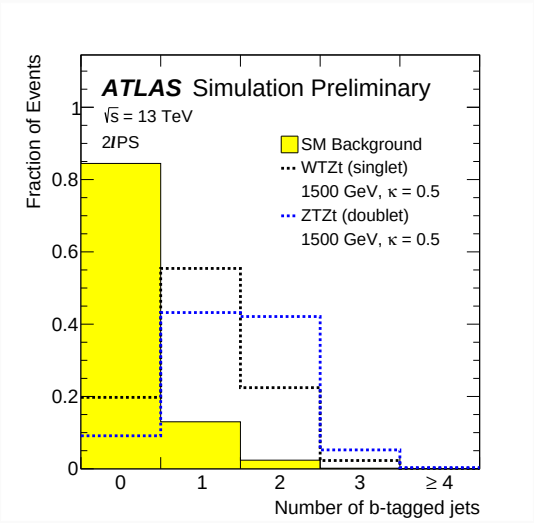
Search for singly produced vector-like top partners in multi-lepton final states ATLAS-CONF-2023-020

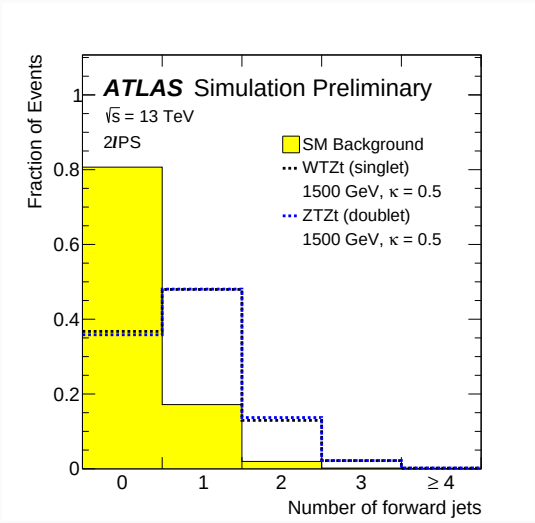
Dilepton channel

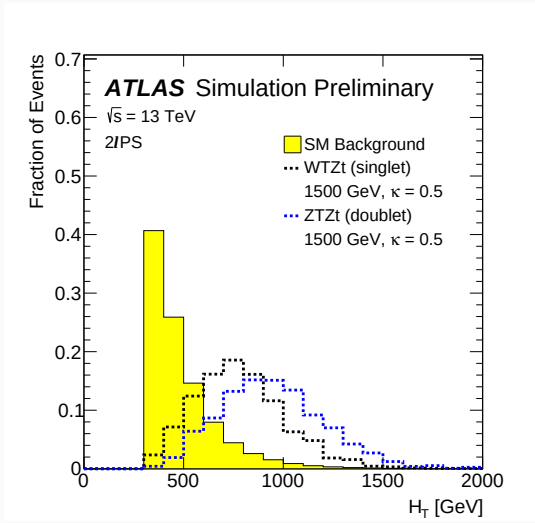
	2ℓCR1	2ℓCR2	2ℓCR3	2ℓVR1	2ℓVR2	2ℓSR
Preselection	1 pair of OS-SF leptons with $\lvert m(\ell\ell) - m_Z \rvert < 10$ GeV $p_{\mathrm{T}}(\ell\ell) > 200$ GeV, $H_{\mathrm{T}} > 300$ GeV ≥ 1 vRC jet $H_{\mathrm{T}} + E_{\mathrm{T}}^{\mathrm{miss}} < m_{\ell\ell J}$					
forward jets	≥ 1	0	0	≥ 1	0	≥ 1
b-tagged jets	0	≥ 1	0	0	≥ 1	≥ 1
top-tagged jets	-	-	≥ 1	≥ 1	≥ 1	≥ 1
top-vetoed jets	≥ 1	≥ 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







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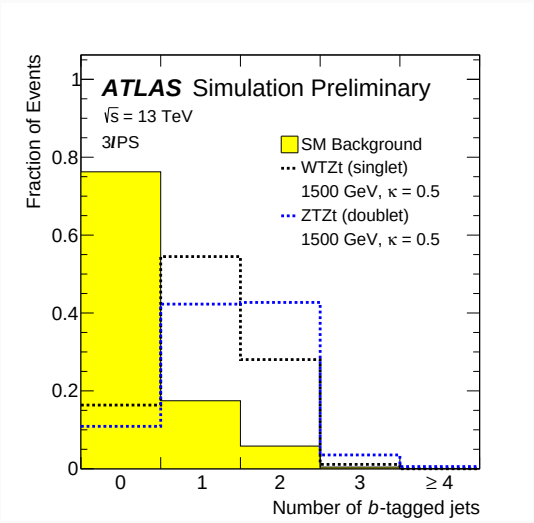
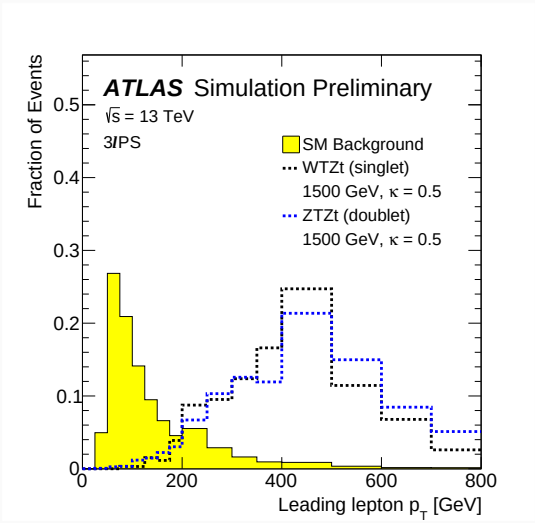
Trilepton channel

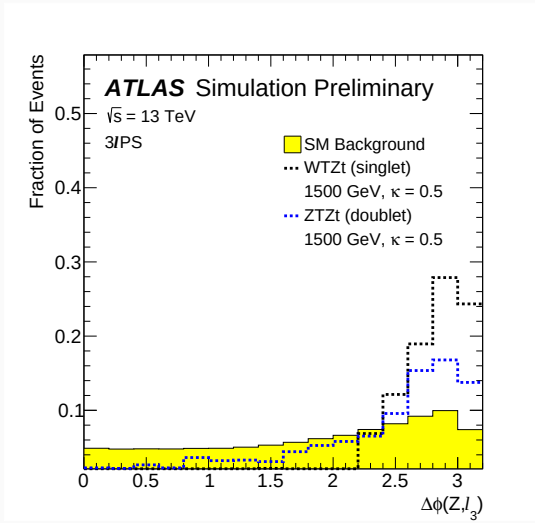
	3ℓVV	3ℓMixed	3ℓttX	3ℓVR	3ℓSR
Preselection	≥ 3 leptons ≥ 1 pair of OS-SF leptons with $\lvert m(\ell\ell) - m_Z \rvert < 10$ GeV				
b-tagged jets	0	1	≥ 2	≥ 1	≥ 1
forward jets	-	0	0	≥ 1	≥ 1
$\Delta\phi$ selections	-	$\Delta\phi(Z, \ell_3) < 2.6$	$\Delta\phi(Z, \ell_3) < 2.6$	$\Delta\phi(Z, \ell_3) < \frac{\pi}{2}$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

- Dominant background sources are VV, ttV, ttH
- Similar to the 2ℓ 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







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