Search for the Single Production of Vector-Like Top Quarks in the Decay T→Ht or T→Zt with the ATLAS Detector

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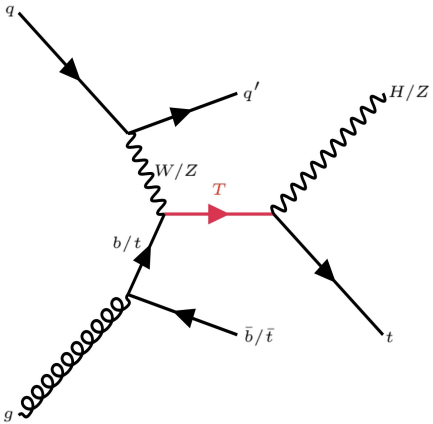
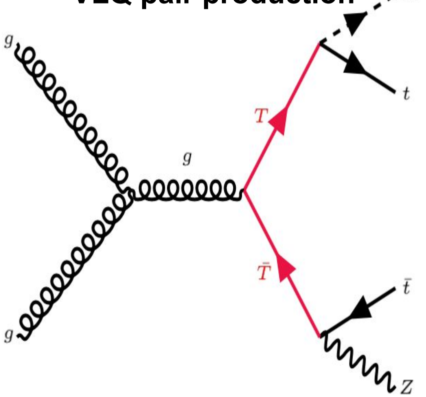
Vector-Like Quarks Overview

- **Hierarchy problem**: Fine tuning required to explain observable Higgs boson mass from quantum loop corrections from the top quark
- Vector-Like Quarks (VLQs) predicted by some beyond the Standard Model (BSM) theories aiming to solve the hierarchy problem
  - Composite Higgs, RS extra dimension models: **cancel quadratic divergences from top quark**
  - Spin 1/2 color triplets (quarks) whose left and right chiral components transform equally under the weak-isospin SU(2) group (vector-like)
- Single production expected to be the **dominant production mechanism at higher masses** with the cross section being proportional to κ^2
- κ is the common coupling strength between VLQs and SM bosons

VLQ single production

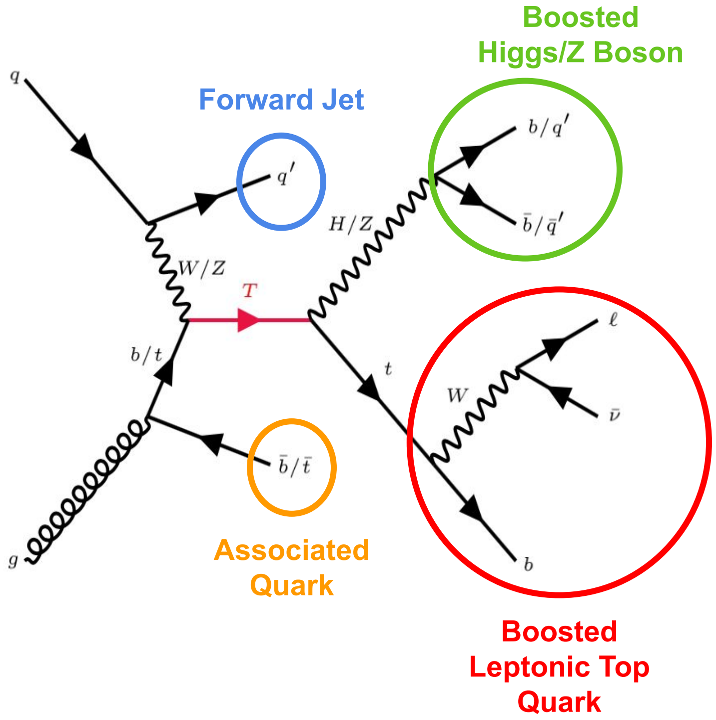


VLQ pair production



T→Ht/Zt+X Search

- **First result** in singly produced T→Ht/Zt searches using the ATLAS full Run-2 dataset [ATLAS-CONF-2021-040]
- SU(2) T singlet configuration in 1-lepton final states used as a benchmark
  - **SU(2) T singlet**: BR(T→Ht)=BR(T→Zt)=0.25, BR(T→Wb)=0.5
- Initial quark recoiling off the vector boson often results in a **high pseudorapidity jet**
- Optimized for T decaying into boosted **leptonically decaying top quark** and **hadronically decaying Higgs/Z boson**



Analysis Search Regions

[ATLAS-CONF-2021-040]

- Four base regions defined to individually target the Ht and Zt decay topologies

Baseline selections on jet and b-tag multiplicity

Jet multiplicity	b-tag multiplicity	Channel name	Targeted signal
3–5	1–2	LJ, 1-2b	$T \to Zt$
3–5	≥3	LJ, ≥3b	$T \to Ht$
≥6	1–2	HJ, 1-2b	$T \to Zt$
≥6	≥3	HJ, ≥3b	$T \to Ht$

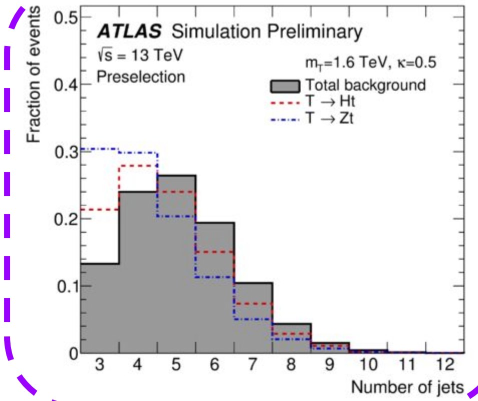
- Additional requirements on **number of boosted objects** tailored to targeted signal results in 24 search regions (SRs)

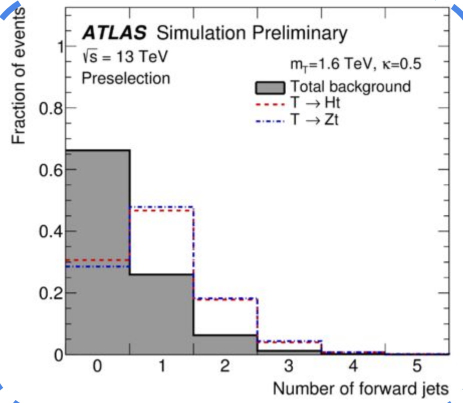
Targeted signal

T→Ht

Example search region

LJ, 3b, ≥1fj, 0t_h, ≥1t_l, ≥1H, 0V





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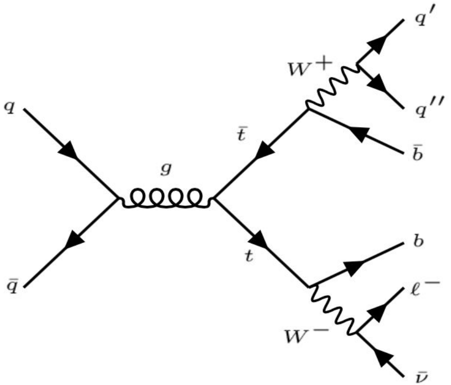
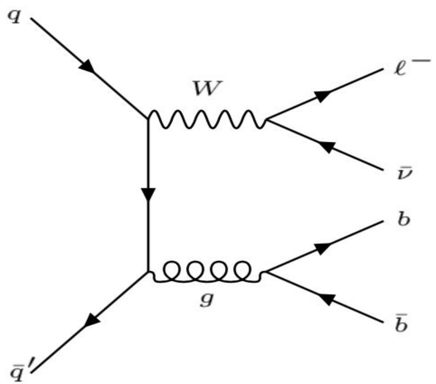
Main Background Processes

ttbar production



- Dominant across all b-tag multiplicity regions
- Process is split into components according to flavor composition of additional jets originating outside the decay of the ttbar system

W+jets production



- Subdominant process with significant contribution in regions with low b-tag multiplicity

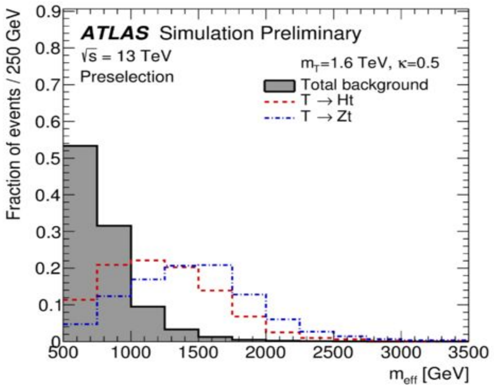
Signal Discriminant

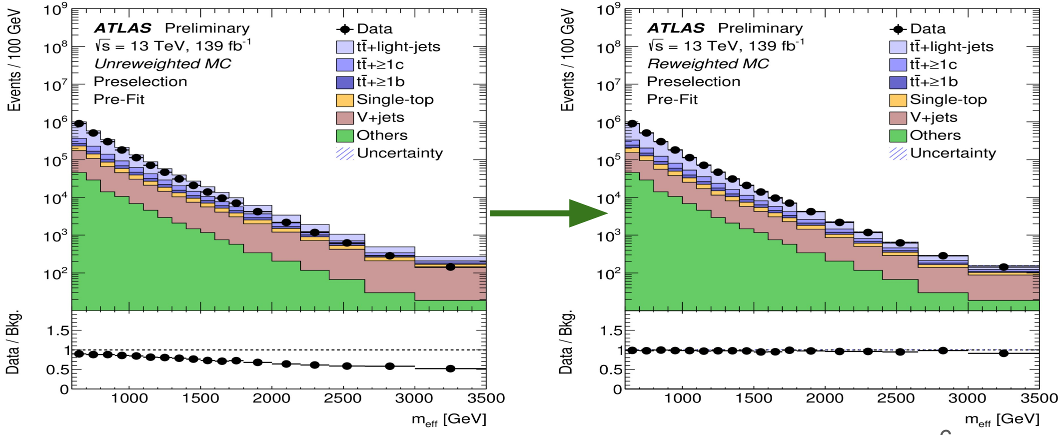
[ATLAS-CONF-2021-040]

- The **effective mass (m_{eff})** has good separation power between signal and background due to the **large T mass resulting in high p_T decay products**

$$m_{\text{eff}} = \sum_{\text{central jets}} p_{\text{T}}^{j} + \sum_{\text{leptons}} p_{\text{T}}^{\ell} + E_{\text{T}}^{\text{miss}}$$

- MC generators for ttbar[1,2] and W/Z+jets[3] processes **mismodel the high p_T and high-jet multiplicity** spectra
- Data-driven correction factors are derived in signal depleted regions to correct the mismodeling





[1] EPJC 79 (2019) 1028, [2] EPJC 80 (2020) 528, [3] ATL-PHYS_PUB-2017-006

T→Ht/Zt+X Results

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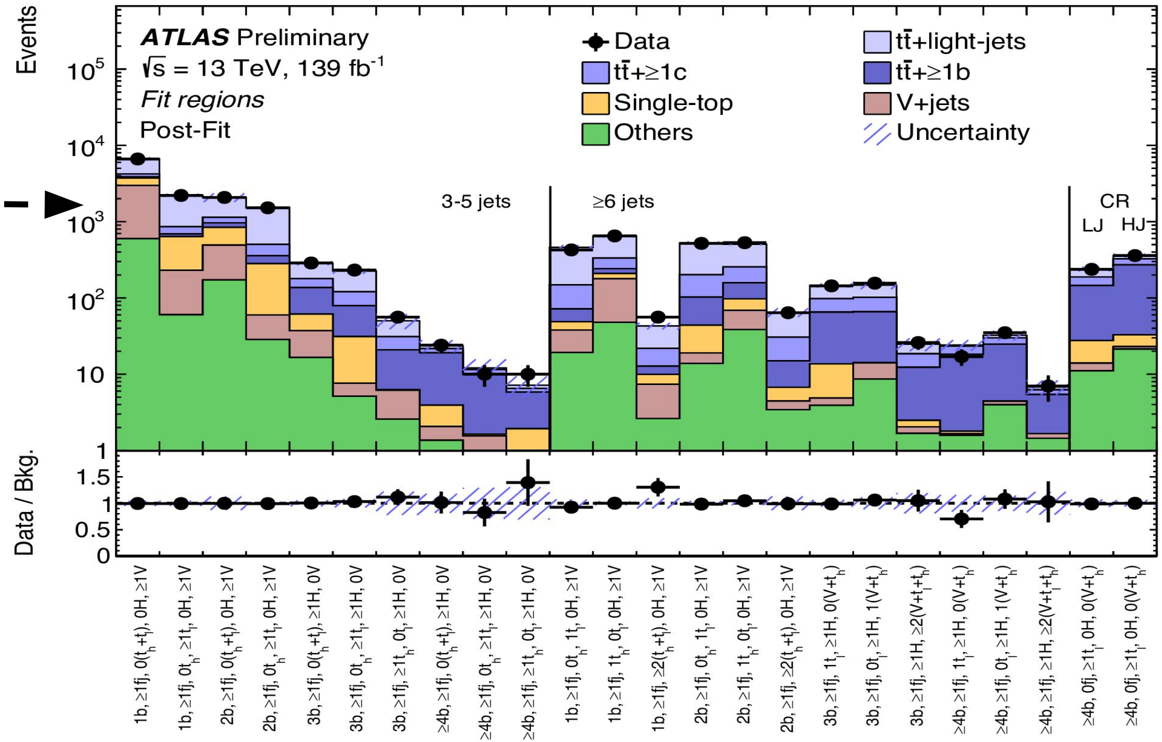
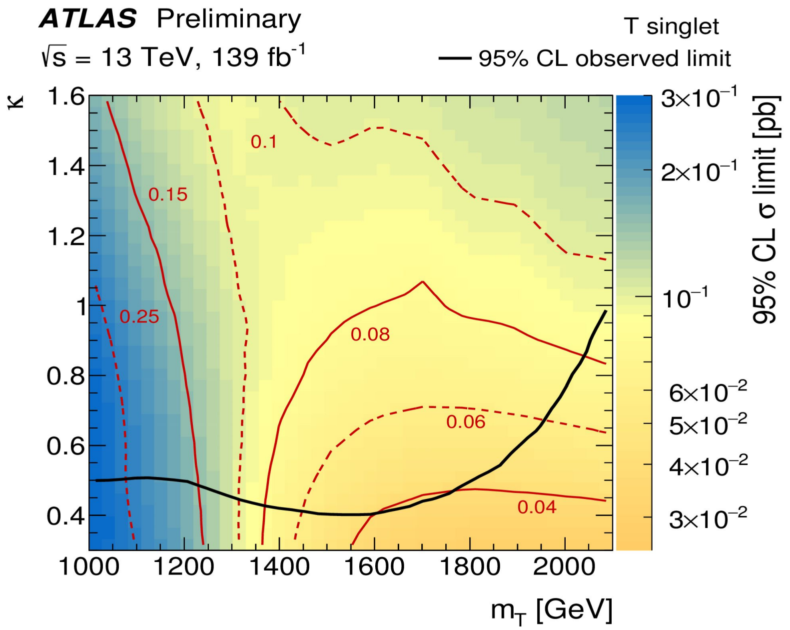
- Binned likelihood fit to data on m_{eff} across all SRs
- **No significant deviation from the SM is observed**



T→Ht/Zt+X Results

[ATLAS-CONF-2021-040]

- Upper limits on the single production of the SU(2) singlet T are derived and interpreted in the search parameter space
  - coupling strength - T mass plane
  - T decay width - BR(T→Wb) plane
- **Coupling strength values (κ) above black line are excluded**
- Red contour lines indicate points on the parameter space of equal cross section that are excluded



Summary

- First set of results for the search of singly produced T decaying to Ht or Zt in the 1-lepton channel using the ATLAS full Run-2 dataset is presented
  - Most recent public CMS result with the same final state set production cross section exclusion limits up to a T mass of 1.8 TeV but only considered the T→Ht decay channel [PLB 771 (2017) 80]
- Search is sensitive across a large range of T masses and coupling strength values
- Upper limits on the production cross section of T in the SU(2) singlet scenario exclude coupling strength values of $\kappa \geq 0.5$ for T masses below 1.8 TeV

Backup

Vector-Like Quarks SU(2) Multiplets

- There are 7 possible SU(2) multiplets
- VLQs couple preferentially to the third generation SM quarks

Electric charge	Singlets		Doublets			Triplets		Allowed decays
5/3			X			X		X→ Wt
2/3	T		T	T		T	T	T→ Ht, Zt, Wb
-1/3		B		B	B	B	B	B→ Hb, Zb, Wt
-4/3					Y		Y	Y→ Wb

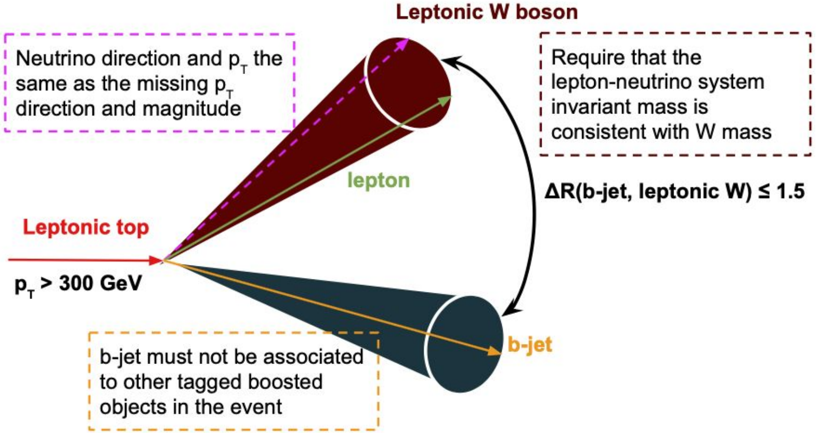
[ATLAS-CONF-2021-040]

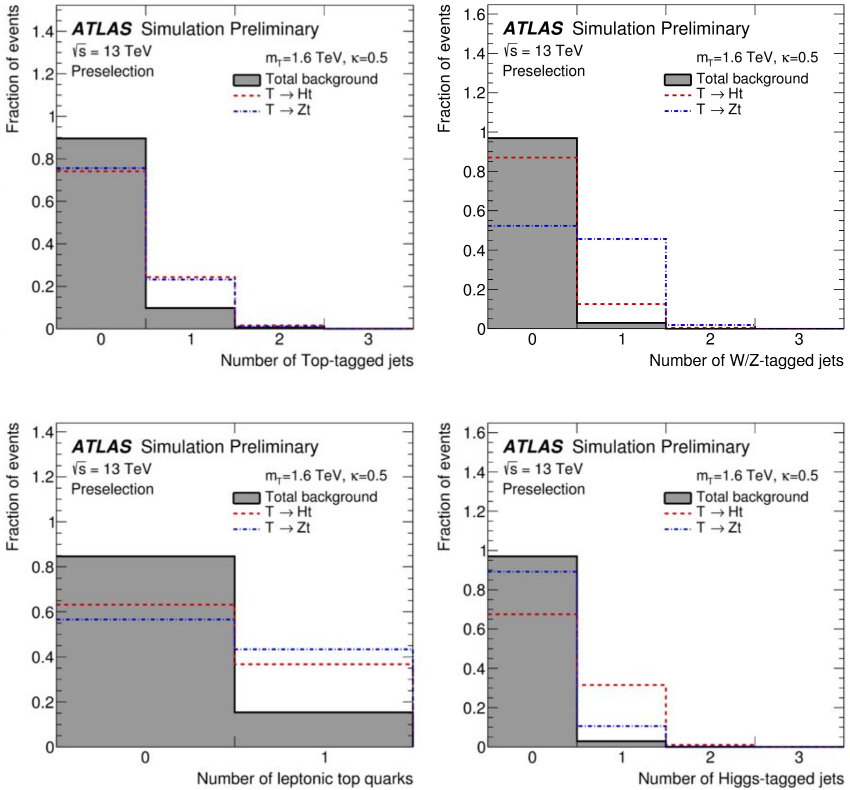
Boosted Objects

- Simple boosted object tagger designed to identify hadronically decaying objects using variable-radius jets

Observable	t-tag	H-tag	V-tag
p_{T} (GeV)	>400	>350	>350
Mass (GeV)	>140	[105, 140]	[70, 105]
N_{const}	≥ 2 if $p_{\mathrm{T}} < 700$ GeV ≥ 1 if $p_{\mathrm{T}} > 700$ GeV	$=2$ if $p_{\mathrm{T}} < 600$ GeV ≤ 2 if $p_{\mathrm{T}} > 600$ GeV	$=2$ if $p_{\mathrm{T}} < 450$ GeV ≤ 2 if $p_{\mathrm{T}} > 450$ GeV

- Leptonic top reconstruction





Kinematic Reweighting of Background

[ATLAS-CONF-2021-040]

- Multistep procedure that fixes the mismodeling on the number of jets (N_{jets}) and m_{eff} that are introduced by the ttbar and W/Z+jets MC generators
- Correction factors for N_{jets} and m_{eff} are derived in reweighting source regions that are designed to be enriched in the background to be reweighted and that are signal depleted

Correction factor for process 'a'

$$R_a(x) = \frac{Data(x) - MC^{non-a}(x)}{MC^{a}(x)}$$

Reweighting source regions				
Lepton multiplicity	Jet multiplicity	b-tag multiplicity	Additional cuts	Targeted background
1	≥3	2	–	$t\bar{t} + tW$
2	≥3	1	$\lvert m_{\ell\ell} - M_Z \rvert \leq 10$ GeV, $E_T^{miss} < 100$ GeV	Z+jets

- For each background process an initial $R(N_{jets})$ is derived and applied to the simulation. Subsequently $R(m_{eff})$ is derived, smoothed to reduce statistical fluctuations and then applied to the simulation
- The procedure is first applied to the W/Z+jets background with the correction factors derived for Z+jets
- The procedure is then applied to the ttbar and single top tW channel jointly using the corrected W/Z+jets background
    - Due to interferences arising from the same final state of the ttbar and tW processes, these are reweighted jointly

T→Ht/Zt+X Search Regions

[ATLAS-CONF-2021-040]

Fit regions with 3–5 jets			
b-tag mult.	Boosted-object mult.	Region name	Targeted signal / bkg
1	$0(t_h+t_l)$, 0H, ≥1V	LJ, 1b, ≥1fj, $0(t_h+t_l)$, 0H, ≥1V	$T \rightarrow Zt$
1	$0t_h$, $\geq 1t_l$, 0H, ≥1V	LJ, 1b, ≥1fj, $0t_h$, $\geq 1t_l$, 0H, ≥1V	$T \rightarrow Zt$
2	$0(t_h+t_l)$, 0H, ≥1V	LJ, 2b, ≥1fj, $0(t_h+t_l)$, 0H, ≥1V	$T \rightarrow Zt$
2	$0t_h$, $\geq 1t_l$, 0H, ≥1V	LJ, 2b, ≥1fj, $0t_h$, $\geq 1t_l$, 0H, ≥1V	$T \rightarrow Zt$
3	$0(t_h+t_l)$, ≥1H, 0V	LJ, 3b, ≥1fj, $0(t_h+t_l)$, ≥1H, 0V	$T \rightarrow Ht$
3	$0t_h$, $\geq 1t_l$, ≥1H, 0V	LJ, 3b, ≥1fj, $0t_h$, $\geq 1t_l$, ≥1H, 0V	$T \rightarrow Ht$
3	$\geq 1t_h$, $0t_l$, ≥1H, 0V	LJ, 3b, ≥1fj, $\geq 1t_h$, $0t_l$, ≥1H, 0V	$T \rightarrow Ht$
≥4	$0(t_h+t_l)$, ≥1H, 0V	LJ, ≥4b, ≥1fj, $0(t_h+t_l)$, ≥1H, 0V	$T \rightarrow Ht$
≥4	$0t_h$, $\geq 1t_l$, ≥1H, 0V	LJ, ≥4b, ≥1fj, $0t_h$, $\geq 1t_l$, ≥1H, 0V	$T \rightarrow Ht$
≥4	$\geq 1t_h$, $0t_l$, ≥1H, 0V	LJ, ≥4b, ≥1fj, $\geq 1t_h$, $0t_l$, ≥1H, 0V	$T \rightarrow Ht$
≥4	$\geq 1t_l$, 0H, $0(V+t_h)$	LJ, ≥4b, 0fj, $\geq 1t_l$, 0H, $0(V+t_h)$	$t\bar{t}$+≥1*b*
Fit regions with ≥6 jets			
b-tag mult.	Boosted-object mult.	Region name	Targeted signal / bkg
1	$0t_h$, $1t_l$, 0H, ≥1V	HJ, 1b, ≥1fj, $0t_h$, $1t_l$, 0H, ≥1V	$T \rightarrow Zt$
1	$1t_h$, $0t_l$, 0H, ≥1V	HJ, 1b, ≥1fj, $1t_h$, $0t_l$, 0H, ≥1V	$T \rightarrow Zt$
1	$\geq 2(t_h+t_l)$, 0H, ≥1V	HJ, 1b, ≥1fj, $\geq 2(t_h+t_l)$, 0H, ≥1V	$T \rightarrow Zt$
2	$0t_h$, $1t_l$, 0H, ≥1V	HJ, 2b, ≥1fj, $0t_h$, $1t_l$, 0H, ≥1V	$T \rightarrow Zt$
2	$1t_h$, $0t_l$, 0H, ≥1V	HJ, 2b, ≥1fj, $1t_h$, $0t_l$, 0H, ≥1V	$T \rightarrow Zt$
2	$\geq 2(t_h+t_l)$, 0H, ≥1V	HJ, 2b, ≥1fj, $\geq 2(t_h+t_l)$, 0H, ≥1V	$T \rightarrow Zt$
3	$1t_l$, ≥1H, $0(V+t_h)$	HJ, 3b, ≥1fj, $1t_l$, ≥1H, $0(V+t_h)$	$T \rightarrow Ht$
3	$0t_l$, ≥1H, $1(V+t_h)$	HJ, 3b, ≥1fj, $0t_l$, ≥1H, $1(V+t_h)$	$T \rightarrow Ht$
3	≥1H, $\geq 2(V+t_l+t_h)$	HJ, 3b, ≥1fj, ≥1H, $\geq 2(V+t_l+t_h)$	$T \rightarrow Ht$
≥4	$1t_l$, ≥1H, $0(V+t_h)$	HJ, ≥4b, ≥1fj, $1t_l$, ≥1H, $0(V+t_h)$	$T \rightarrow Ht$
≥4	$0t_l$, ≥1H, $1(V+t_h)$	HJ, ≥4b, ≥1fj, $0t_l$, ≥1H, $1(V+t_h)$	$T \rightarrow Ht$
≥4	≥1H, $\geq 2(V+t_l+t_h)$	HJ, ≥4b, ≥1fj, ≥1H, $\geq 2(V+t_l+t_h)$	$T \rightarrow Ht$
≥4	$\geq 1t_l$, 0H, $0(V+t_h)$	HJ, ≥4b, 0fj, $\geq 1t_l$, 0H, $0(V+t_h)$	$t\bar{t}$+≥1*b*

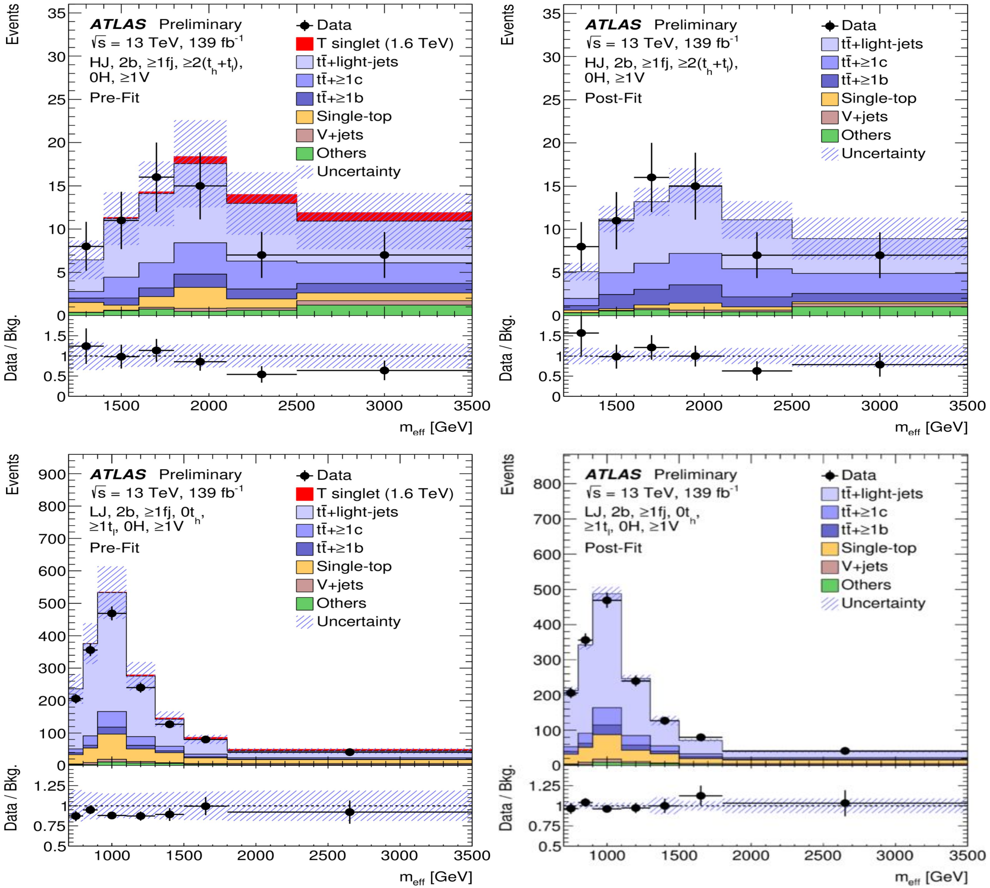
Validation regions with 3–5 jets			
b-tag mult.	Fwd-jet mult.	Boosted-object mult.	Region name
1	0	$0t_h$, $0t_l$, 0H, ≥1V	LJ, 1b, 0fj, $0t_h$, $0t_l$, 0H, ≥1V
1	0	$0t_h$, $\geq 1t_l$, 0H, ≥1V	LJ, 1b, 0fj, $0t_h$, $\geq 1t_l$, 0H, ≥1V
1	≥1	$\geq 1(t_h+t_l)$, 0H, 0V	LJ, 1b, ≥1fj, $\geq 1(t_h+t_l)$, 0H, 0V
1	≥1	$\geq 1t_h$, $0t_l$, 0H, ≥1V	LJ, 1b, ≥1fj, $\geq 1t_h$, $0t_l$, 0H, ≥1V
2	0	$0t_h$, $0t_l$, 0H, ≥1V	LJ, 2b, 0fj, $0t_h$, $0t_l$, 0H, ≥1V
2	0	$0t_h$, $\geq 1t_l$, 0H, ≥1V	LJ, 2b, 0fj, $0t_h$, $\geq 1t_l$, 0H, ≥1V
2	≥1	$\geq 1(t_h+t_l)$, 0H, 0V	LJ, 2b, ≥1fj, $\geq 1(t_h+t_l)$, 0H, 0V
2	≥1	$\geq 1t_h$, $0t_l$, 0H, ≥1V	LJ, 2b, ≥1fj, $\geq 1t_h$, $0t_l$, 0H, ≥1V
≥3	0	$0(t_h+t_l)$, ≥1H, 0V	LJ, ≥3b, 0fj, $0(t_h+t_l)$, ≥1H, 0V
≥3	≥1	0H, $\geq 1(V+t_l+t_h)$	LJ, ≥3b, ≥1fj, 0H, $\geq 1(V+t_l+t_h)$
Validation regions with ≥6 jets			
b-tag mult.	Fwd-jet mult.	Boosted-object mult.	Region name
1	0	$1(t_h+t_l)$, 0H, ≥1V	HJ, 1b, 0fj, $1(t_h+t_l)$, 0H, ≥1V
1	0	$\geq 2(t_h+t_l)$, 0H, ≥1V	HJ, 1b, 0fj, $\geq 2(t_h+t_l)$, 0H, ≥1V
1	≥1	$0t_h$, $0t_l$, ≥1H, ≥1V	HJ, 1b, ≥1fj, $0t_h$, $0t_l$, ≥1H, ≥1V
1	≥1	$\geq 2(t_h+t_l)$, ≥1H, 0V	HJ, 1b, ≥1fj, $\geq 2(t_h+t_l)$, ≥1H, 0V
2	0	$1(t_h+t_l)$, 0H, ≥1V	HJ, 2b, 0fj, $1(t_h+t_l)$, 0H, ≥1V
2	0	$\geq 2(t_h+t_l)$, 0H, ≥1V	HJ, 2b, 0fj, $\geq 2(t_h+t_l)$, 0H, ≥1V
2	≥1	$0t_h$, $0t_l$, ≥1H, ≥1V	HJ, 2b, ≥1fj, $0t_h$, $0t_l$, ≥1H, ≥1V
2	≥1	$\geq 2(t_h+t_l)$, ≥1H, 0V	HJ, 2b, ≥1fj, $\geq 2(t_h+t_l)$, ≥1H, 0V
≥3	0	≥1H, $\geq 1(V+t_l+t_h)$	HJ, ≥3b, 0fj, ≥1H, $\geq 1(V+t_l+t_h)$
≥3	≥1	0H, $\geq 1(V+t_l+t_h)$	HJ, ≥3b, ≥1fj, 0H, $\geq 1(V+t_l+t_h)$

- All signal search regions require the presence of a forward jet to suppress background
- Validation regions are constructed by inverting the forward jet requirement or most relevant boosted object requirement of a search region
- The validation regions are kinematically similar to the search regions

[ATLAS-CONF-2021-040]

Pre-Fit/Post-Fit m_{eff} Distributions

- Post-fit agreement between data and SM prediction is good overall including the most sensitive signal search regions



[ATLAS-CONF-2021-040]

Decay Width - Branching Ratio Limit Interpretation

- Limits derived under the assumption that BR(T→Ht)=BR(T→Zt) and BR(T→Ht)+BR(T→Zt)+BR(T→Wb) = 1
- White contour lines indicate exclusion limits of equal mass
- Values above contour lines are excluded for that particular mass