Searches for vector-like quarks with the ATLAS Detector

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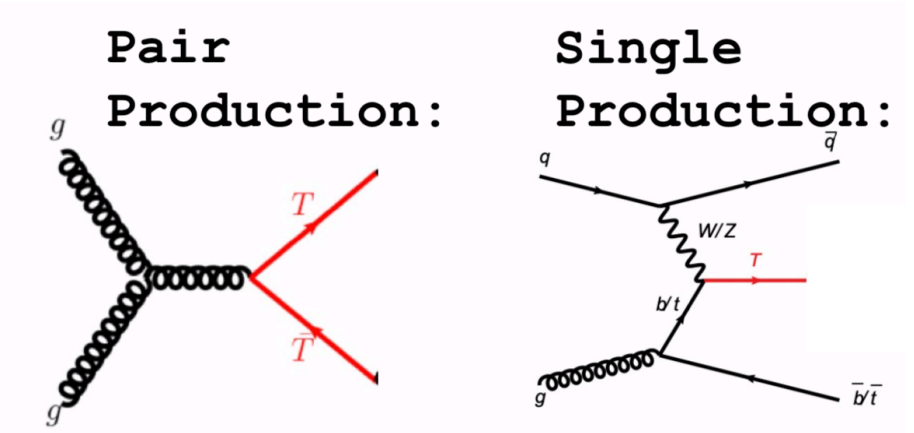
Vector-like quarks

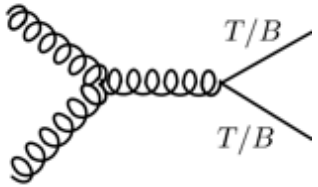
- Appear in several BSM models (e.g. Extra Dimensions, Composite Higgs, Little Higgs…)
- Colored spin ½ fermions
- L/R-handed chiralities transform the same under gauge transformations
- Can be “partners” to SM quarks with the same charges (e.g. $T_{2/3}$, $B_{-1/3}$) or can have more exotic charges ($X_{5/3}$, $Y_{-4/3}$…)
- In simplified models, VLQs mix predominantly with 3rd gen. SM partners to regulate Higgs boson mass



Q[e]	VLQs singlets	doublets	triplets
5/3		$\begin{pmatrix} X \\ T \end{pmatrix}$	$\begin{pmatrix} X \\ T \\ B \end{pmatrix}$
2/3	(T)	$\begin{pmatrix} T \\ B \end{pmatrix}$	$\begin{pmatrix} T \\ B \\ Y \end{pmatrix}$
−1/3	(B)	$\begin{pmatrix} B \\ Y \end{pmatrix}$	
−4/3			

Vector-like quarks

~800 GeV — *VLQ mass* — >1 TeV

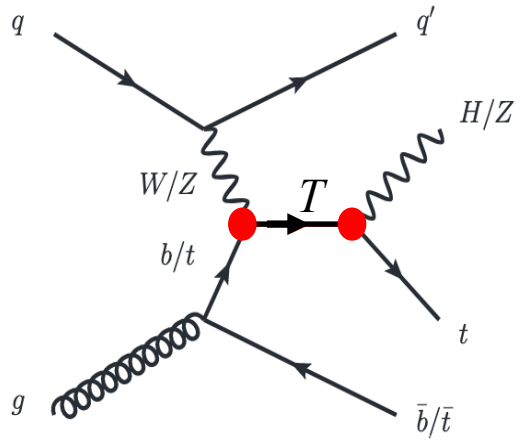


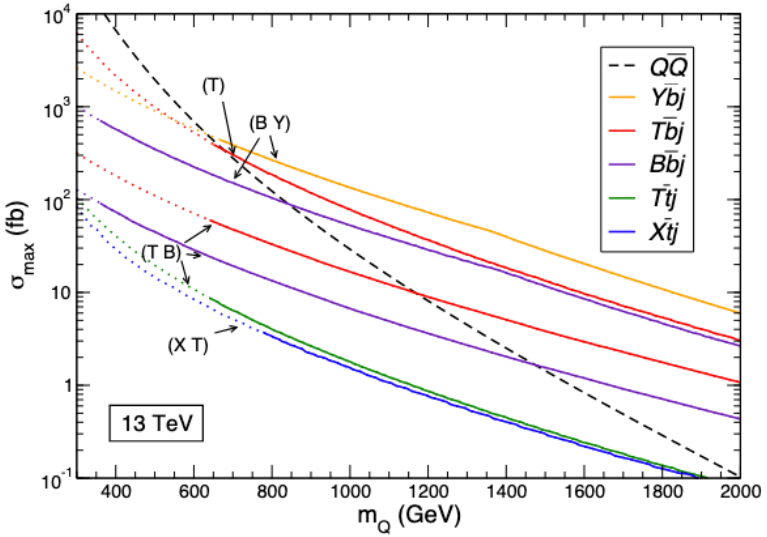
Pair Production Dominant

- Production independent on coupling to SM partners
  -> Model independent

Single Production Dominant

- Cross-section depends on coupling assumptions
- Both production and decay vertices have couplings
  -> Model dependent





arXiv:1306.0572 [hep-ph]

Possible decay channels:

BR(**T->Wb**) ~ 0.5
BR(**T->Ht**) ~ 0.25
BR(**T->Zt**) ~ 0.25

BR(**B->Wt**) ~ 0.5
BR(**B->Hb**) ~ 0.25
BR(**B->Zb**) ~ 0.25

BR(**X->Wt**) ~ 1.0
BR(**Y->Wb**) ~ 1.0

Search for Single Production VLQ -> Ht/Zt + X

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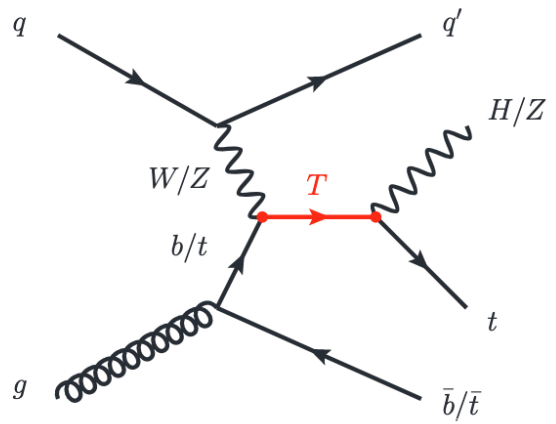
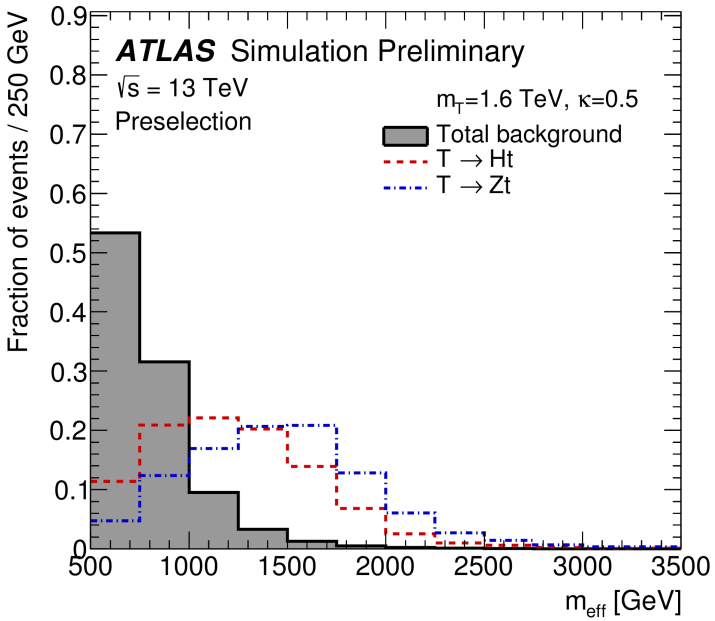
- [NEW] Focus on *b-associated* Single Production of VL *T*
  - *T(->Ht)qb with H->$b\bar{b}$*
  - *T(-> Zt)qb with Z->$q\bar{q}$*



*t-assoc. production is neglected due to small cross section

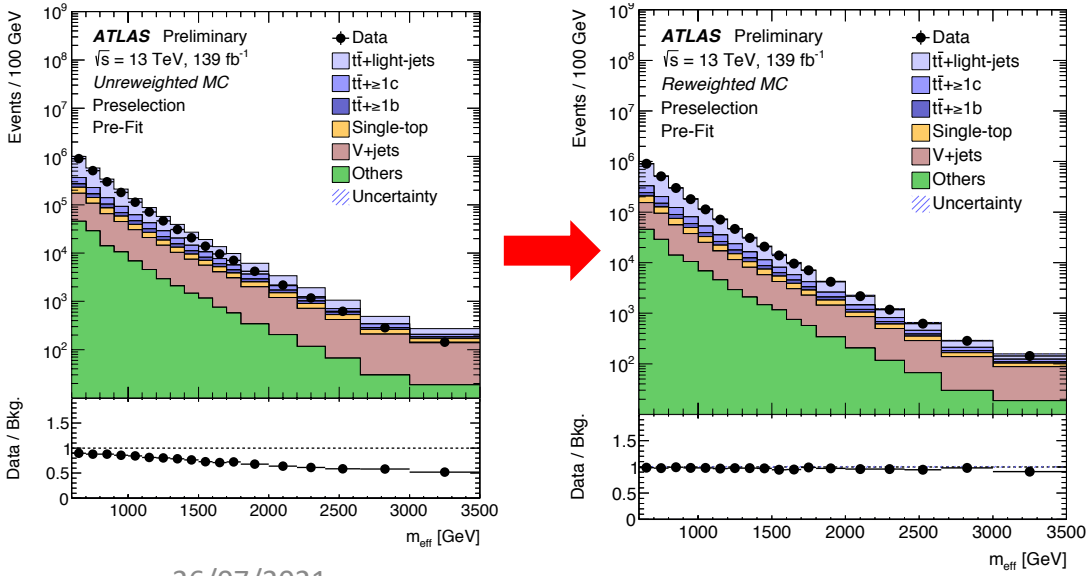
- Lepton(e/μ)+jets final state
- High b-tagged multiplicity particularly targets *H->$b\bar{b}$*
- $\geq$ 1 forward jet for signal purity
- Re-clustered large-R jets are used for top/H/W/Z tagging
- Discriminant variable: $\mathbf{m_{eff}} = \sum_{\text{central jets}} p_{\mathrm{T}}^{j} + \sum_{\text{leptons}} p_{\mathrm{T}}^{\ell} + E_{\mathrm{T}}^{\mathrm{miss}}$



Search for Single Production VLQ -> Ht/Zt + X

- Background reweighting is applied to improve modelling in tt+jets, single top and V+jets backgrounds
- To maximize search sensitivity, identify 4 baseline categories, which are split into 24 fit regions and 20 validation regions
- Low jet multiplicity (LJ) has most of the signal fraction whereas high jet multiplicity (HJ) maximizes signal acceptance

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



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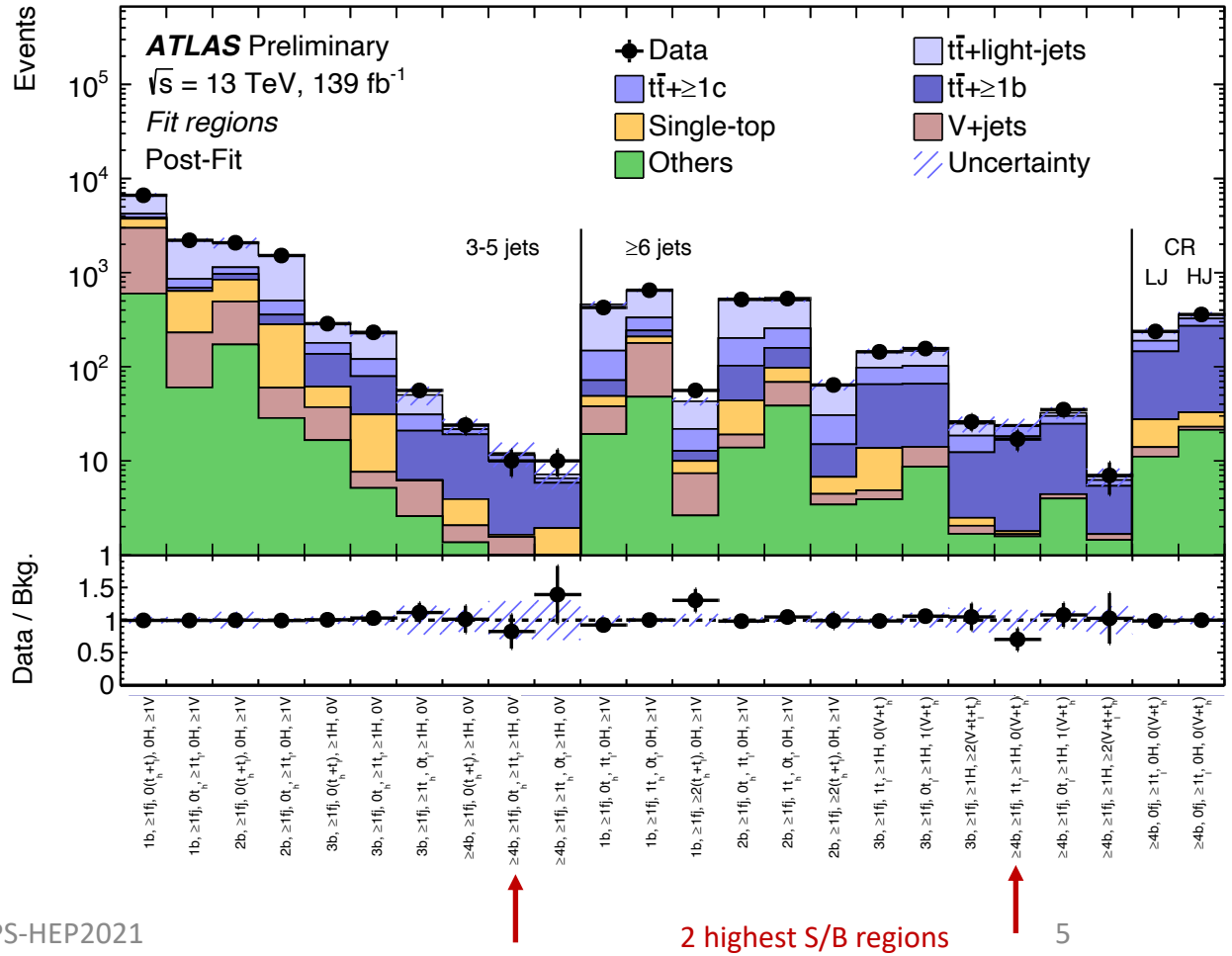
Baseline selections on jet and b-tag multiplicity

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



2 highest S/B regions

Search for Single Production VLQ -> Ht/Zt + X

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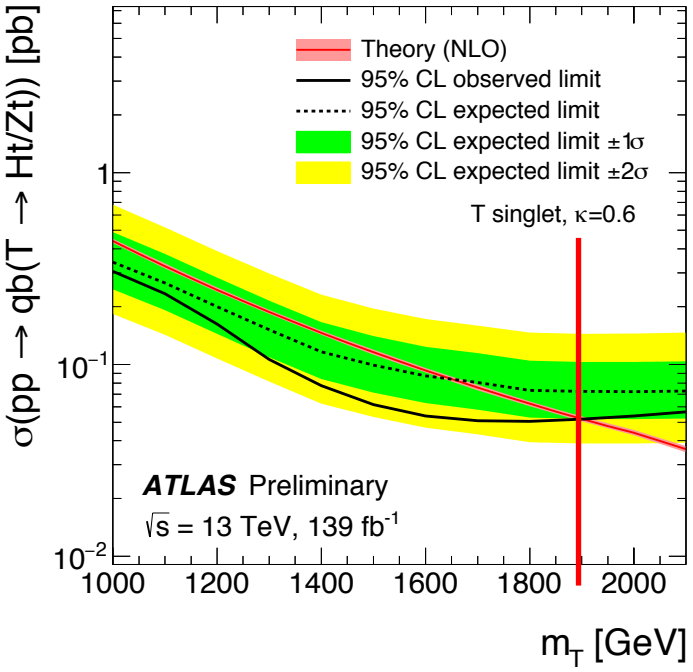
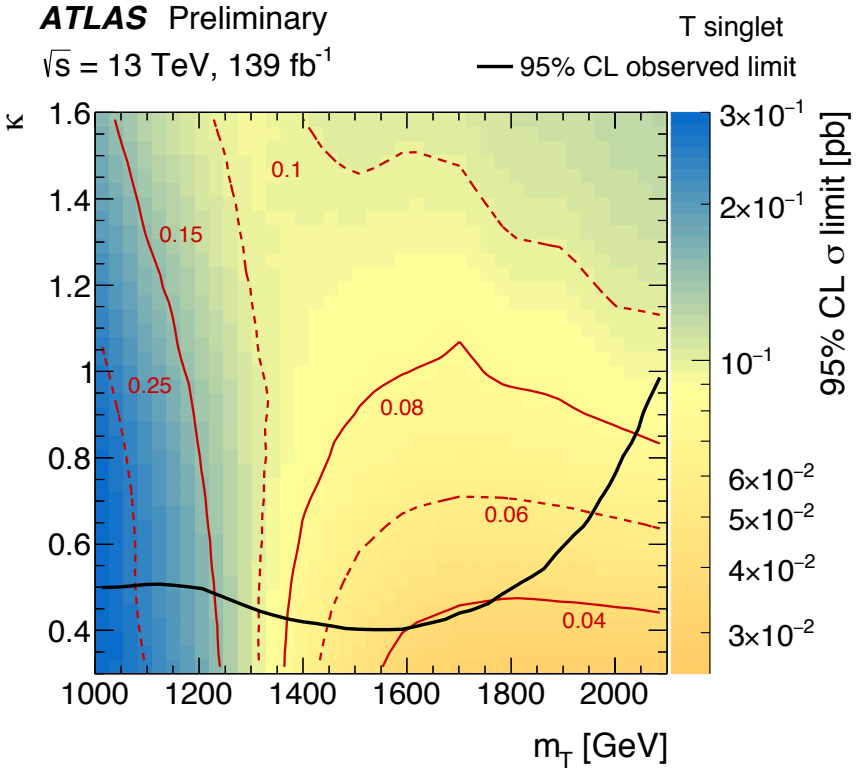
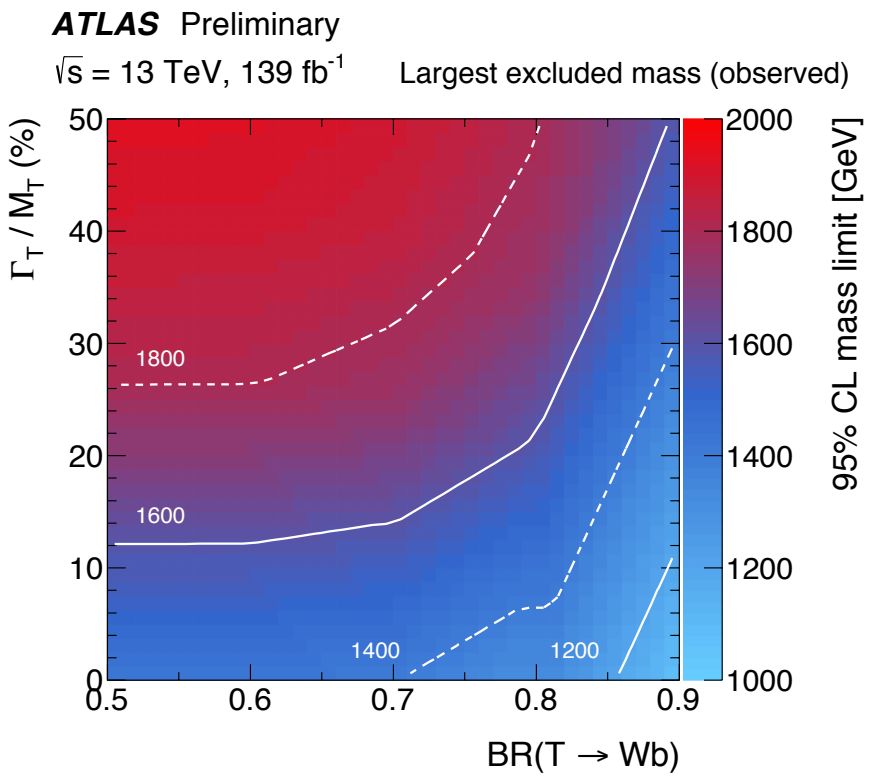


Masses above 1.9 TeV excluded for $\kappa > 0.6$

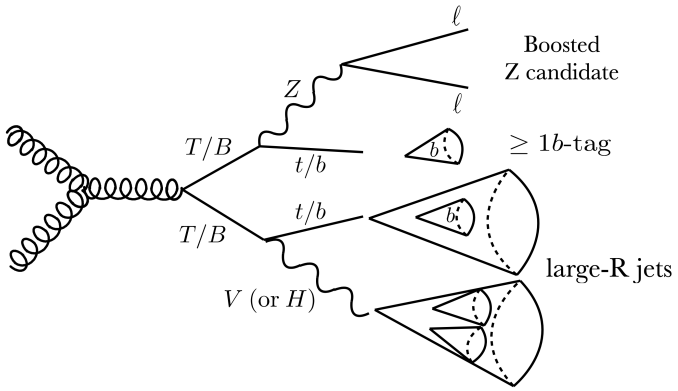


All values of κ above the black contour line are excluded at each mass point.

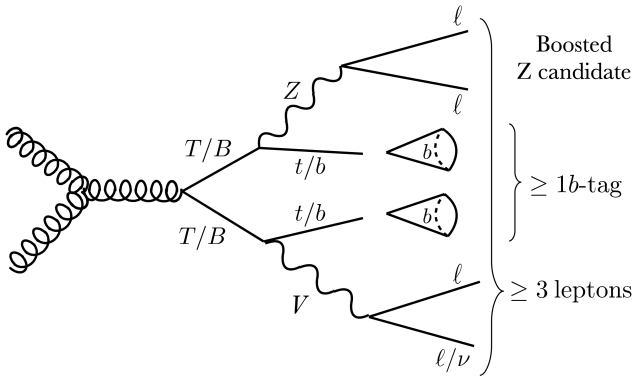


Largest excluded mass as a function of the relative T quark width and BR(T->Wb)

Search for Pair Production VL T/B with Opposite Sign Multilepton



- Same flavor, opposite sign multi-lepton final states
  - Leptonic *Z* boson tagged, significantly reduces SM backgrounds
  - 2 and >2 lepton channels



- DNN "*MCBOT*" identification of boosted objects
  - Small-R (0.4) jets, re-clustered with anti-k_t algorithm with R=1.0
  - Determine probability for hadronic *t/H/W/Z* simultaneously

*MCBOT: Multi-Class Boosted Object Tagger

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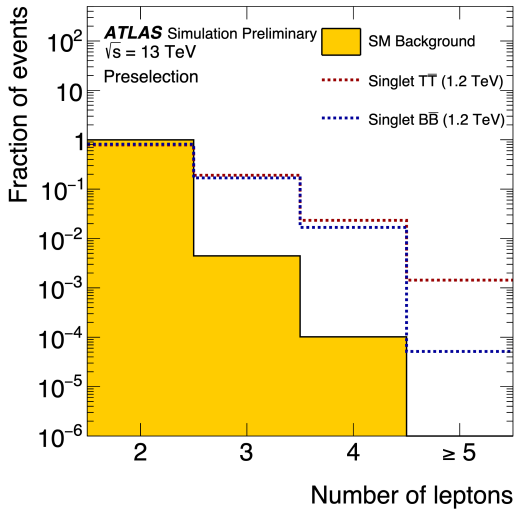
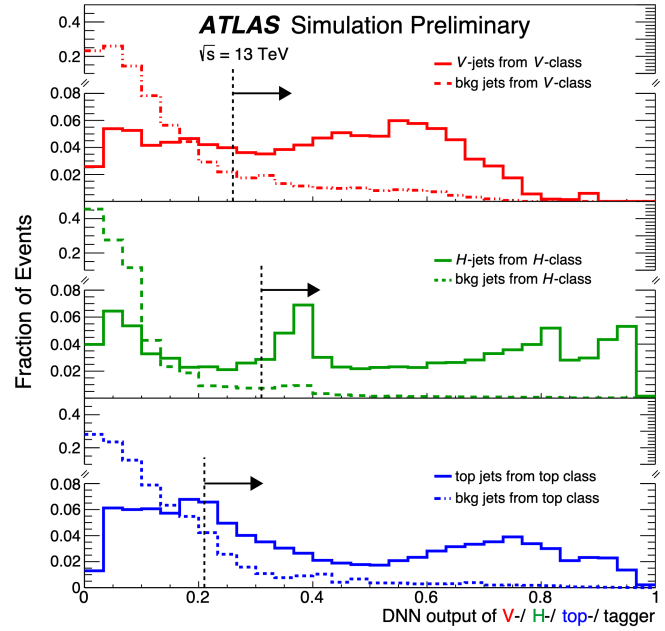
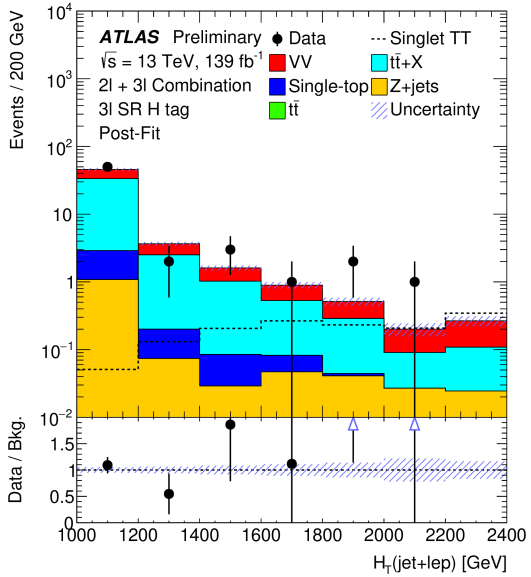
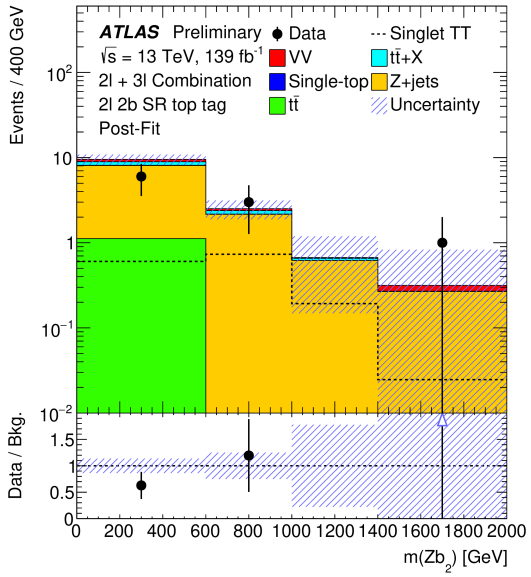




Search for Pair Production VL T/B with Opposite Sign Multilepton





- Trilepton channel:
  - Use scalar sum of jets and leptons p_T (H_T) as fit variable
- Dilepton channel:
  - Use m(Zb) as fit variable
  - 2 signal regions (1b and 2b)
  - Signal region requires H_T + MET > 1380 GeV
- 19 total separate regions based on hadronic t/H/W/Z tag multiplicity

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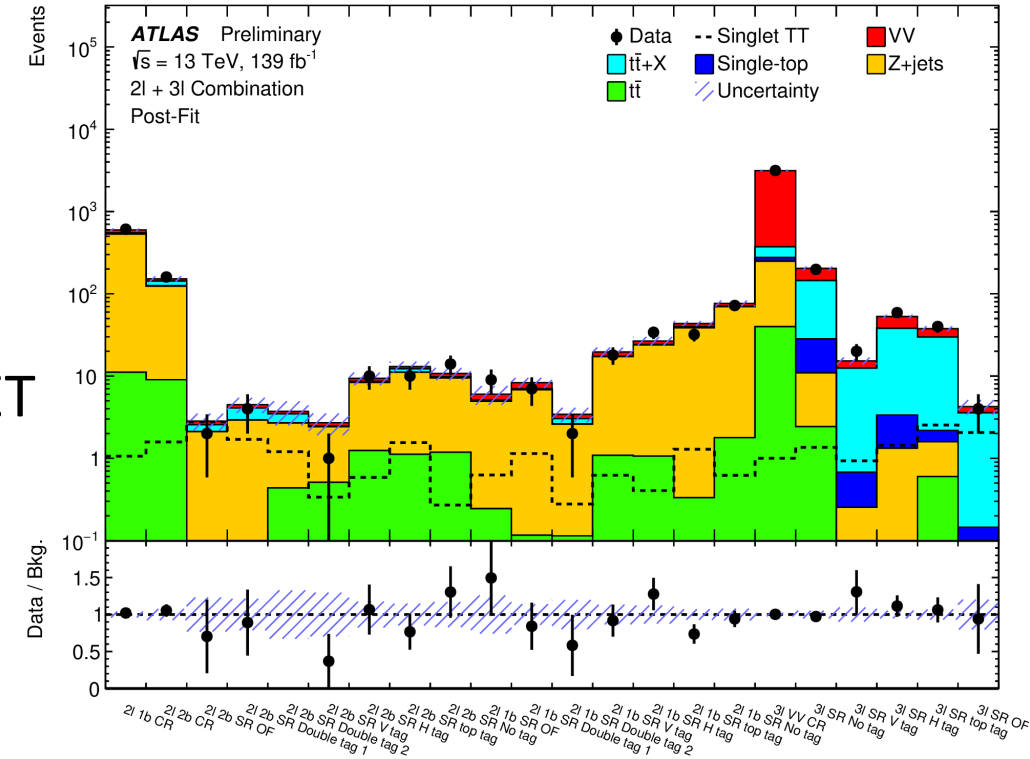

Search for Pair Production VL T/B with Opposite Sign Multilepton

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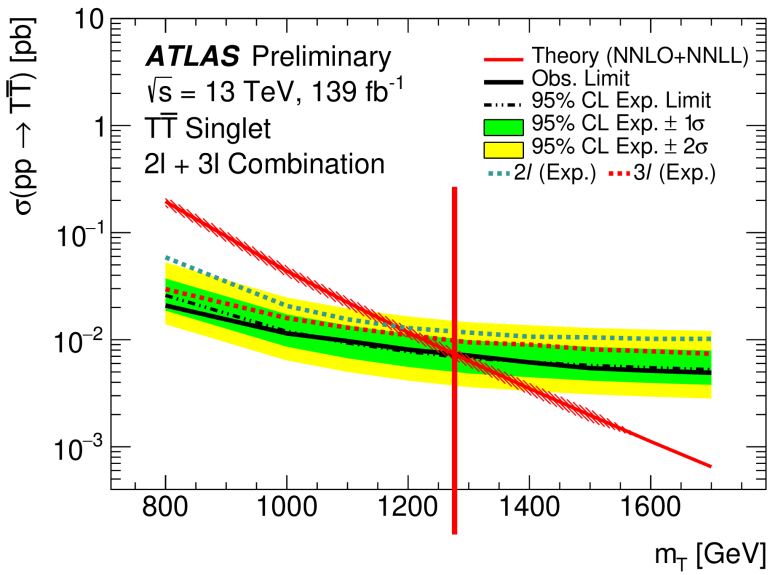
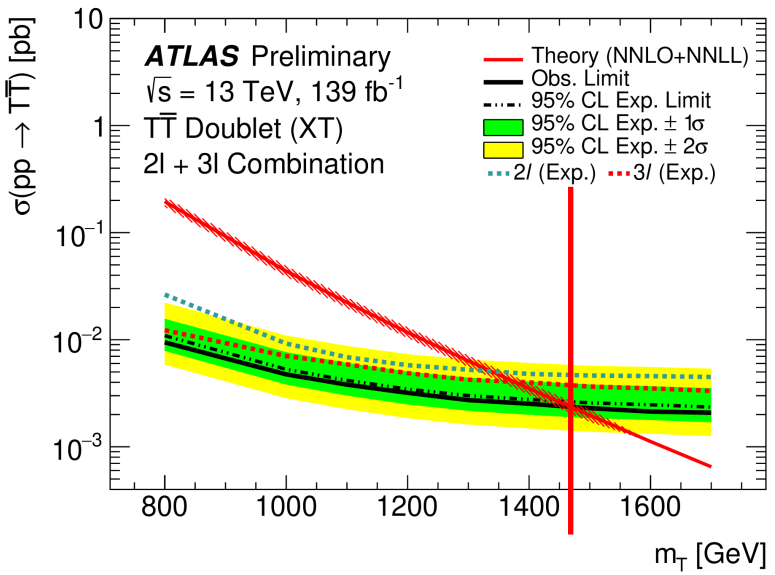
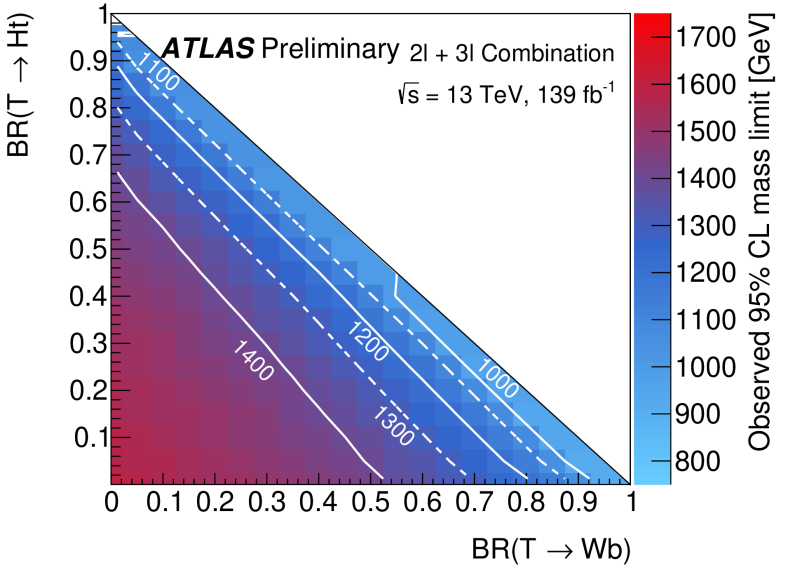
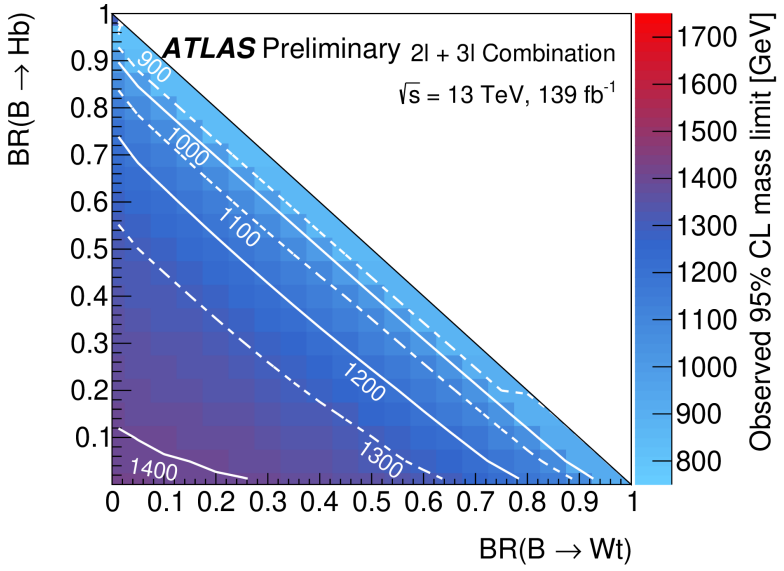




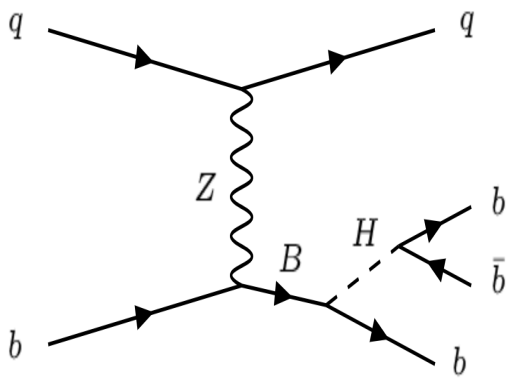




Model	Observed (Expected) Mass Limits [TeV] 2ℓ	3ℓ	Combination
$T\bar{T}$ Singlet	1.14 (1.16)	1.22 (1.21)	1.27 (1.29)
$T\bar{T}$ Doublet	1.34 (1.32)	1.38 (1.37)	1.46 (1.44)
100% $T \to Zt$	1.43 (1.43)	1.54 (1.50)	1.60 (1.57)
$B\bar{B}$ Singlet	1.14 (1.21)	1.11 (1.10)	1.20 (1.25)
$B\bar{B}$ Doublet	1.31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

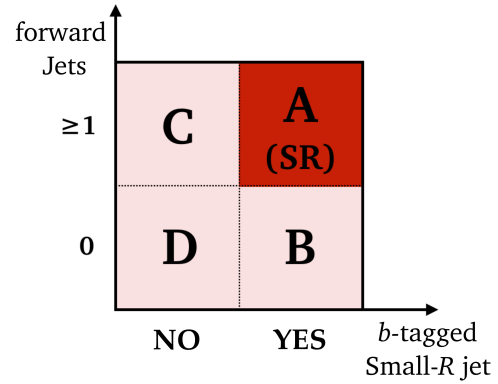
Search for Single Production VL B -> bH (bb)

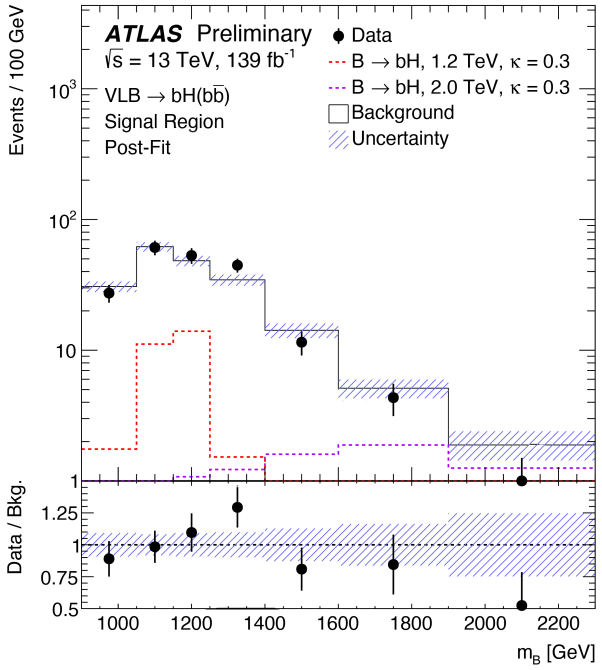
ATLAS-CONF-2021-018

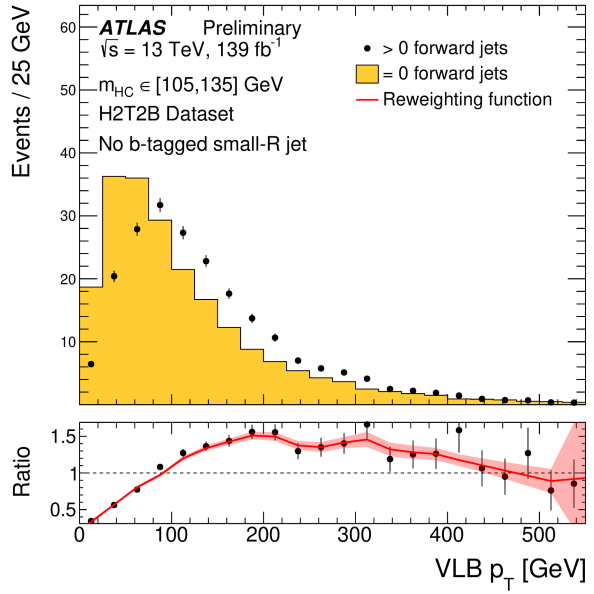


- Dedicated search for *VL B* of (B,Y) doublet with all hadronic event selection
- Reconstructed Higgs Candidate (HC) based on large radius jet p_T, m, and associated *b*-tagged track jets
- Data driven estimation for QCD multijet background using ABCD method
  - $N_A = N_B \times (N_C / N_D)$
- Fit using reconstructed *VL B* mass:

  M(B) = M(HC + jet) with ΔR*(jet, HC)* > 2.5







Search for Single Production VL B -> bH (bb)

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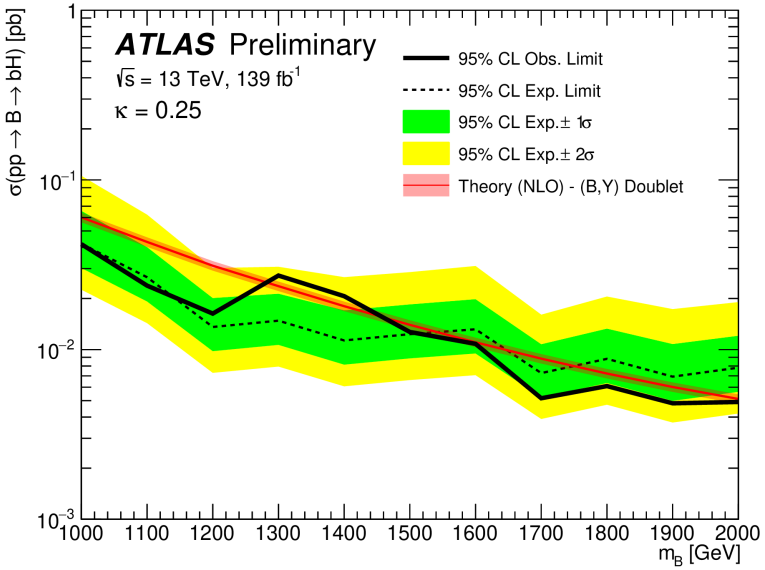
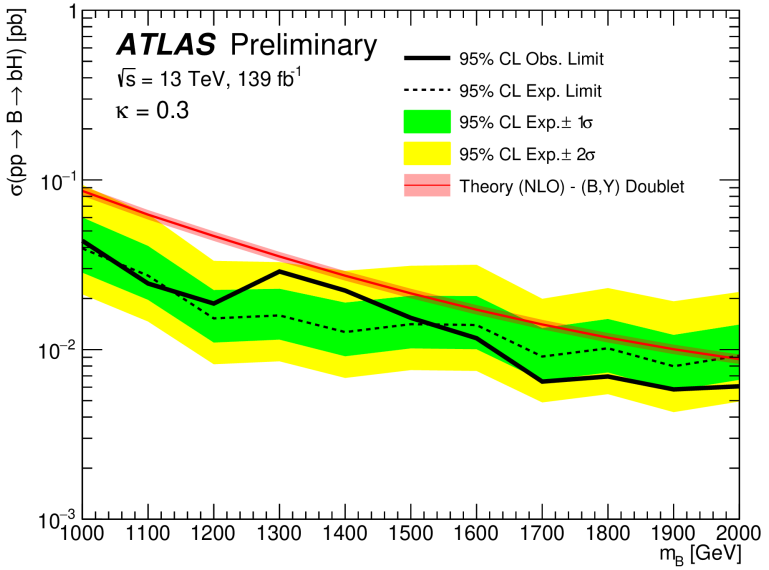
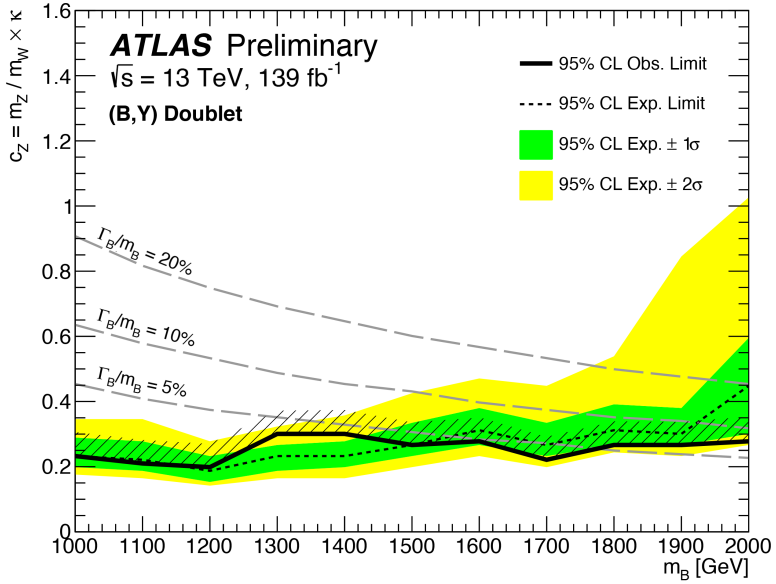


For κ=0.25, the exclusion is limited to the *1.0 TeV* < m_B< *1.28 TeV* and *1.46 TeV* < m_B< *2.0 TeV* resonance mass ranges



For κ=0.3, whole mass range is excluded



Limits on coupling as a function of VLB mass for doublet representation

VLB doublet resonance is excluded with relative width larger than 5% in the 1.0 TeV <m_B< 1.75 TeV mass range

Summary

- New results using full Run-2 dataset are shown
  - First debut of *Single Production VLQ -> Ht/Zt + X* analysis
  - Pair Production VL T/B with Opposite Sign Multilepton
  - Single Production VL B -> bH (bb)
- Many interesting searches for VLQ with masses in $\mathcal{O}$(TeV) range still possible
- An exciting time is before us!

Thank you!

Backup Slides

Search for Pair Production VL T/B with Opposite Sign Multilepton

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Category	2ℓ channel						3ℓ channel		
	1b SR			2b SR			–		
	V-tags	H-tags	top-tags	V-tags	H-tags	top-tags	V-tags	H-tags	top-tags
No tag	0	0	0	0	0	0	0	0	0
V tag	1	0	0	1	0	0	≥ 1	0	0
H tag	0	1	0	0	1	0	0	≥ 1	0
top tag	0	0	1	0	0	1	0	0	≥ 1
Double tag 1	2	0	0	2	0	0		–	
	0	2	0	0	2	0		–	
	1	0	1	1	1	0		–	
		–		0	0	2		–	
Double tag 2	0	1	1	0	1	1		–	
	0	0	2		–			–	
Overflow (OF)	1	1	0	1	0	1	0	≥ 1	≥ 1
		or > 2 tags			or > 2 tags		≥ 1	0	≥ 1
		–			–		≥ 1	≥ 1	0
		–			–		≥ 1	≥ 1	≥ 1

Search for Single Production VLQ -> Ht/Zt + X

T(→Ht)qb
T(→Zt)qb

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

Fit regions with ≥6 jets, ≥1 forward jet			
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	$T(\rightarrow Zt)qb$
1	$1t_h$, $0t_l$, 0H, ≥1V	HJ, 1b, ≥1fj, $1t_h$, $0t_l$, 0H, ≥1V	$T(\rightarrow Zt)qb$
1	≥2(t_h+t_l), 0H, ≥1V	HJ, 1b, ≥1fj, ≥2(t_h+t_l), 0H, ≥1V	$T(\rightarrow Zt)qb$
2	$0t_h$, $1t_l$, 0H, ≥1V	HJ, 2b, ≥1fj, $0t_h$, $1t_l$, 0H, ≥1V	$T(\rightarrow Zt)qb$
2	$1t_h$, $0t_l$, 0H, ≥1V	HJ, 2b, ≥1fj, $1t_h$, $0t_l$, 0H, ≥1V	$T(\rightarrow Zt)qb$
2	≥2(t_h+t_l), 0H, ≥1V	HJ, 2b, ≥1fj, ≥2(t_h+t_l), 0H, ≥1V	$T(\rightarrow Zt)qb$
3	1(V+t_h), $0t_l$, ≥1H	HJ, 3b, ≥1fj, 1(V+t_h), $0t_l$, ≥1H	$T(\rightarrow Ht)qb$
3	$0t_h$, $1t_l$, ≥1H, 0V	HJ, 3b, ≥1fj, $0t_h$, $1t_l$, ≥1H, 0V	$T(\rightarrow Ht)qb$
3	≥2(V+t_h+t_l), ≥1H	HJ, 3b, ≥1fj, ≥2(V+t_h+t_l), ≥1H	$T(\rightarrow Ht)qb$
≥4	1(V+t_h), $0t_l$, ≥1H	HJ, ≥4b, ≥1fj, 1(V+t_h), $0t_l$, ≥1H	$T(\rightarrow Ht)qb$
≥4	$0t_h$, $1t_l$, ≥1H, 0V	HJ, ≥4b, ≥1fj, $0t_h$, $1t_l$, ≥1H, 0V	$T(\rightarrow Ht)qb$
≥4	≥2(V+t_h+t_l), ≥1H	HJ, ≥4b, ≥1fj, ≥2(V+t_h+t_l), ≥1H	$T(\rightarrow Ht)qb$
≥4	$0t_h$, ≥$1t_l$, 0H, 0V	HJ, ≥4b, 0fj, $0t_h$, ≥t_l, 0H, 0V	$t\bar{t}$+≥1b