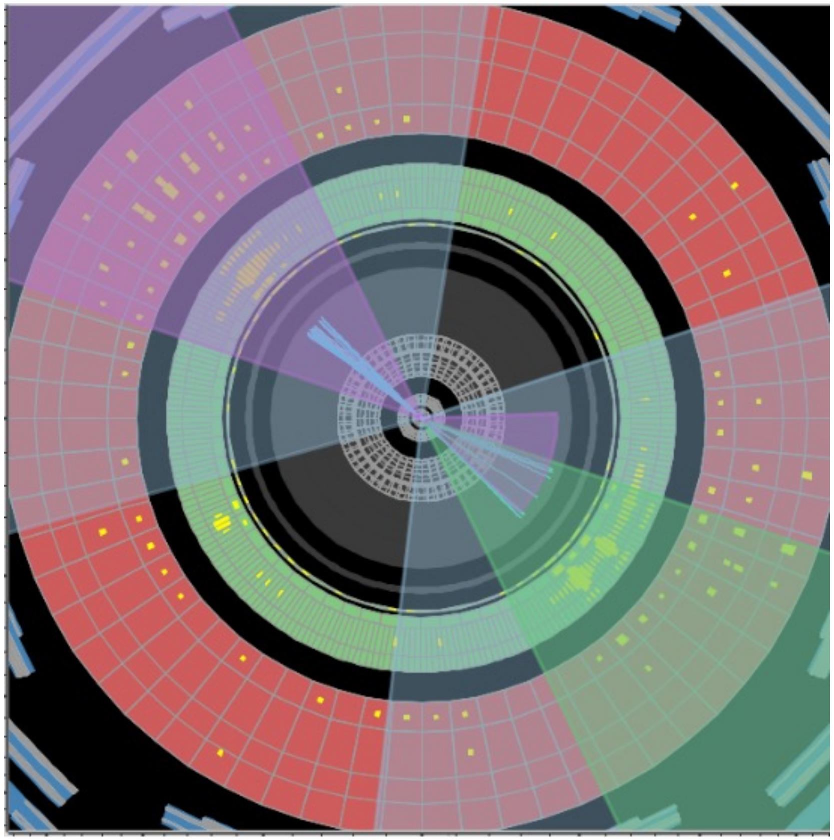
Physics
UNIVERSITY OF TORONTO

ATLAS EXPERIMENT



Vector-Like Quark Searches at ATLAS

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University of Toronto

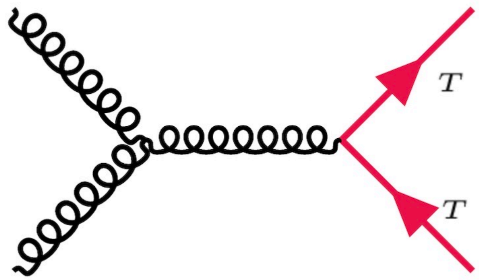
Representing the ATLAS Collaboration

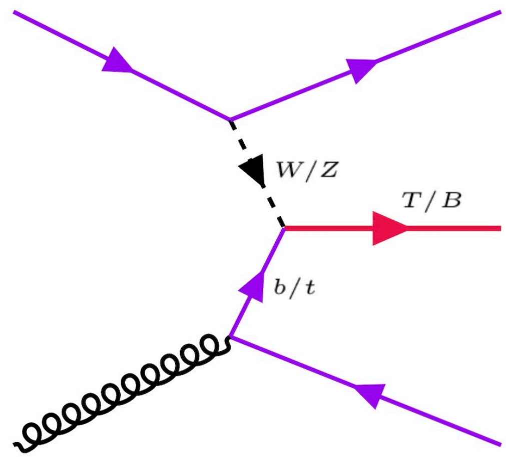
SUSY 2021, Beijing, China
23 August 2021

Introduction to VLQs

LHC has enabled numerous BSM searches

- We have the usual suspects, e.g. SUSY, new force carriers, substructure
- Many constraints, especially coming from the Higgs sector
- Vector-like quarks survive as a model for new fermion generations





Sketch of the theory:

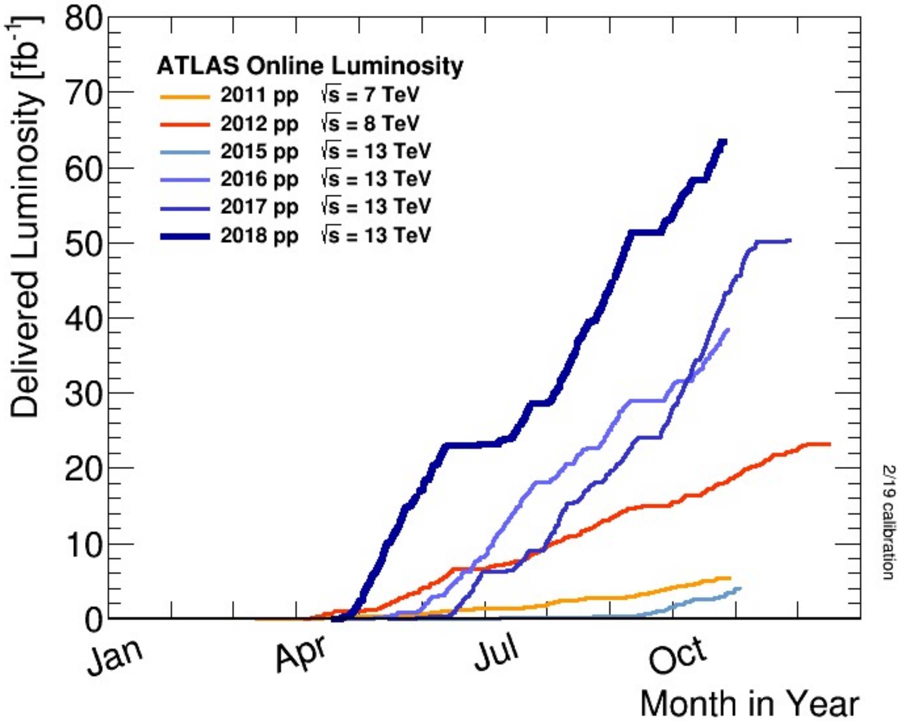
- VLQs are coloured spin-1/2 fermions
- L/R-handed components transform the same way under gauge transformations
- Mix with SM quarks to regulate Higgs mass
  - Expect to mix primarily with 3rd generation (t,b)

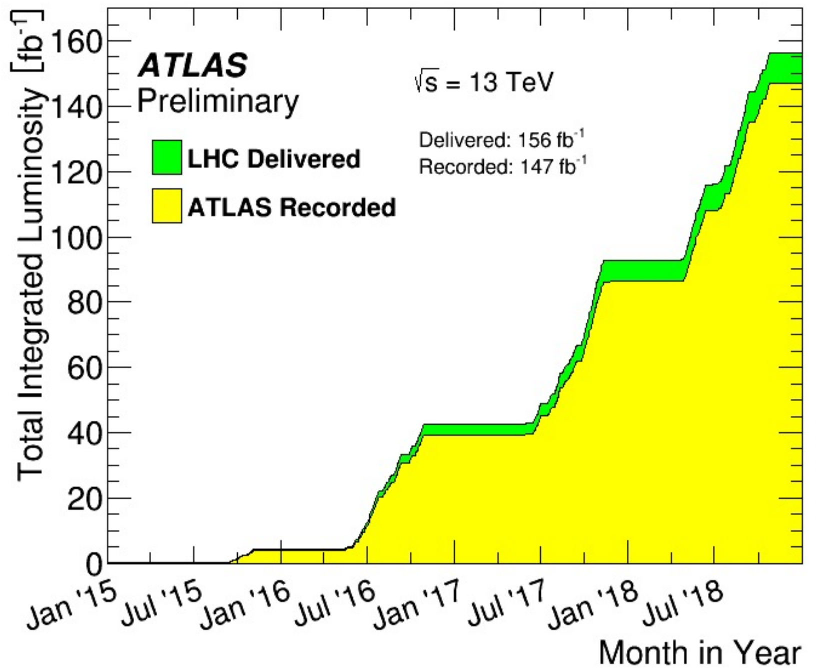
See, e.g., Buchkremer *et al.,* ArXiv: 1305.4172

LHC and ATLAS

Run 2: 139 fb^{-1} at $\sqrt{s}$ = 13 TeV

- Have sensitivity to fb-scale processes
- Sophisticated analyses have developed



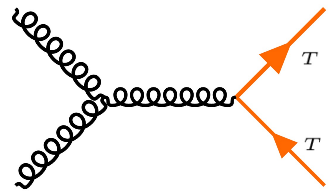


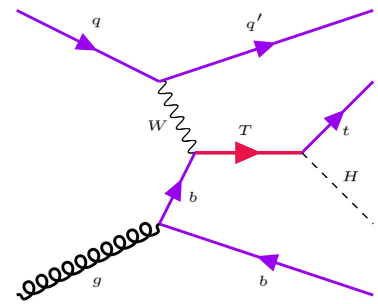
Full Run 2 dataset essential for VLQ searches

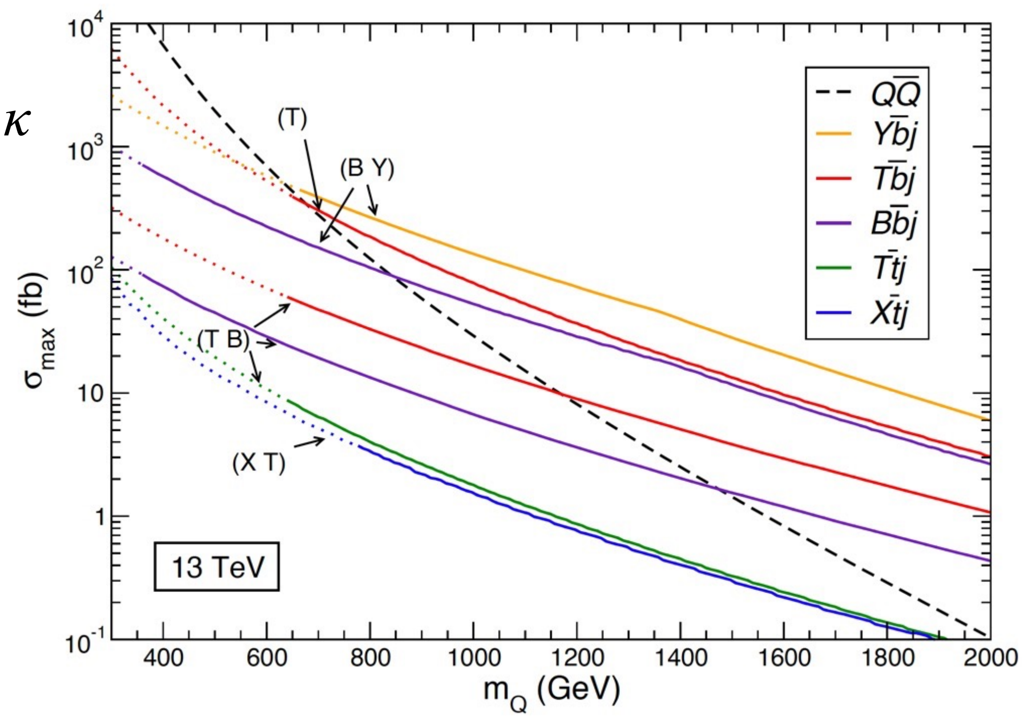
- VLQ production drops rapidly with mass
- Need to balance efficiency with background rejection

VLQ Production & Decay

- Both pair and single production possible
  - Single production is larger at masses $\gtrsim$ 1 TeV
  - Caveats abound
- Coupling to standard model particles free parameters, though constrained
  - Often characterized by overall coupling κ
  - Couplings to W, Z and H are related
- Multiplet structure also affects branching fractions as well
  - Singlet structure simplest (T,B)
    - Doublet and triplet multiplets allowed
    - Result in exotic q=+5/3 VLQs (X,Y)
- Focus of this talk will be ATLAS VLQ searches using full Run 2 statistics



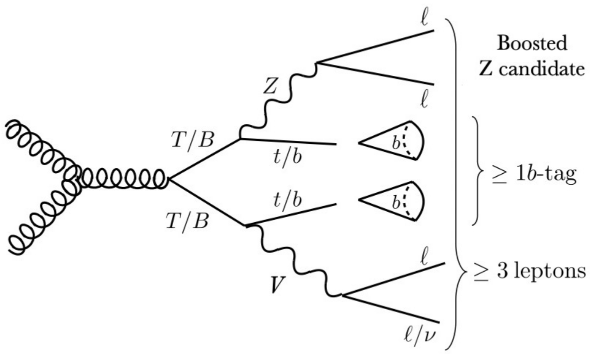


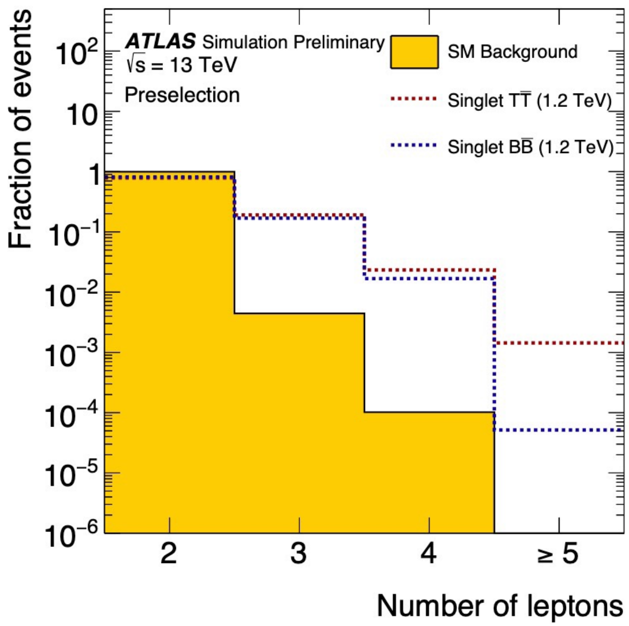


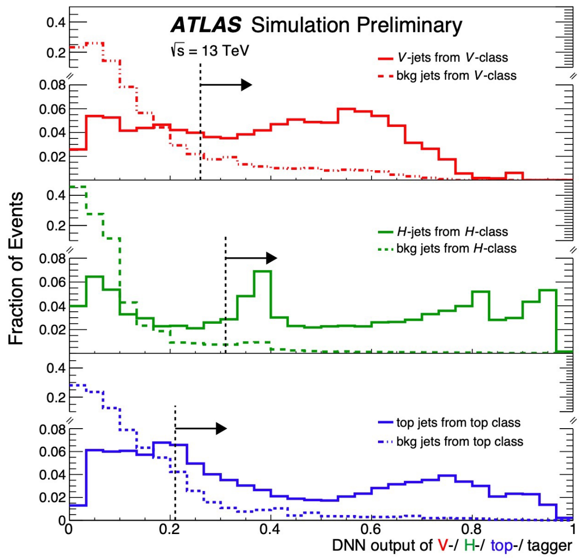
Aguilar-Saavedra *et al.*, ArXiv: 1306.0572

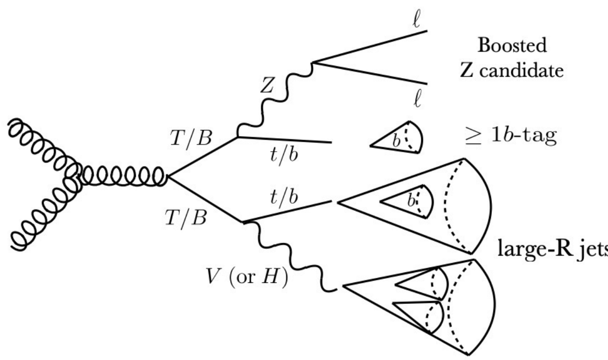
Search for pair-produced T and B

- Search for opposite sign, same flavour leptons
  - Tag $Z \rightarrow l^+l^-$ final state and *b*-jets
  - Two channels:
    1. V decays leptonically
    2. V & t/b hadronic decays boosted → large-R jets
       - Employ DNN "MCBOT" neural network
       - Identifies H, top-quark & W/Z-boson jets









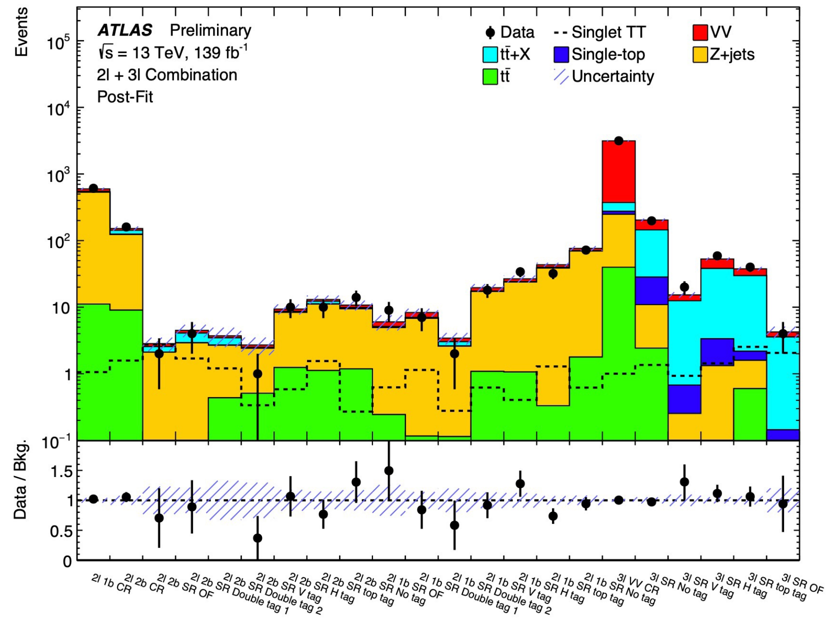
ATLAS-CONF-2021-024

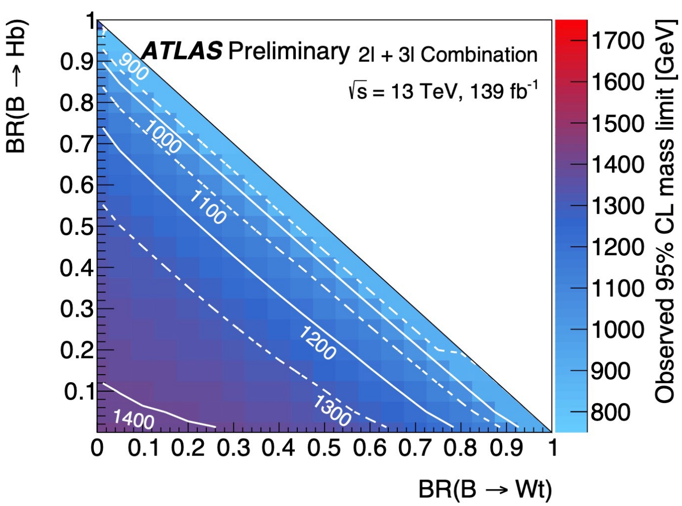
Search for pair-produced T and B

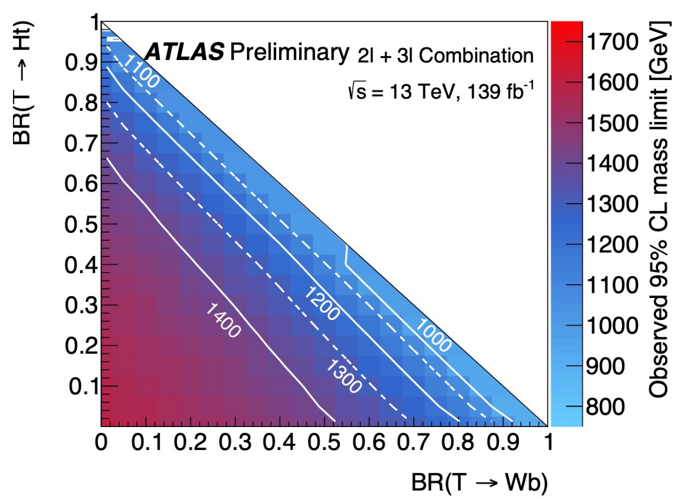
- Define 19 regions using $H/W/Z/t$ tags
  - Observables in two channels:
    1. Trileptons: $\sum P_T$ for jets+leptons
    2. Dileptons: $m(Zb)$
  - Yields in control regions well-modelled
  - No evidence of excess

    set cross-section and mass limits

    $m_T < 1.6$ TeV and $m_B < 1.42$ TeV excluded at 95% C.L. for 100% branching fraction







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% $T \rightarrow Zt$	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% $B \rightarrow Zb$	1.40 (1.47)	1.16 (1.18)	1.42 (1.49)

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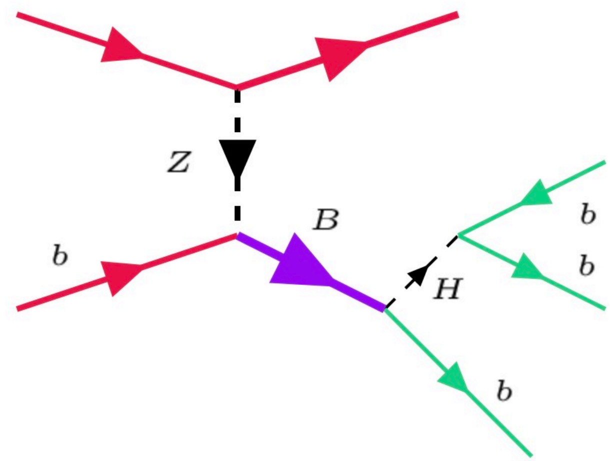
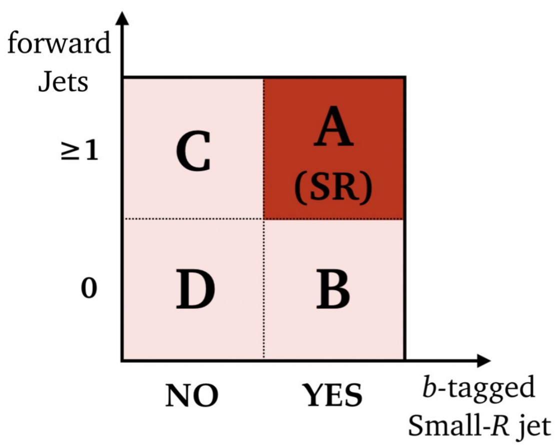
Search for single production of VL B

- Search for Z-mediated VL B production
  - Identify $H \rightarrow b\bar{b}$ with large-R jet & b-tagging
    - $p_T > 480$ GeV and $|\eta| < 2.0$
  - Require forward jet & *b*-tagged small-R jet
    - $p_T > 40$ GeV and $|\eta| > 2.5$
- Challenge is to estimate backgrounds
  - Dominated by multijet events

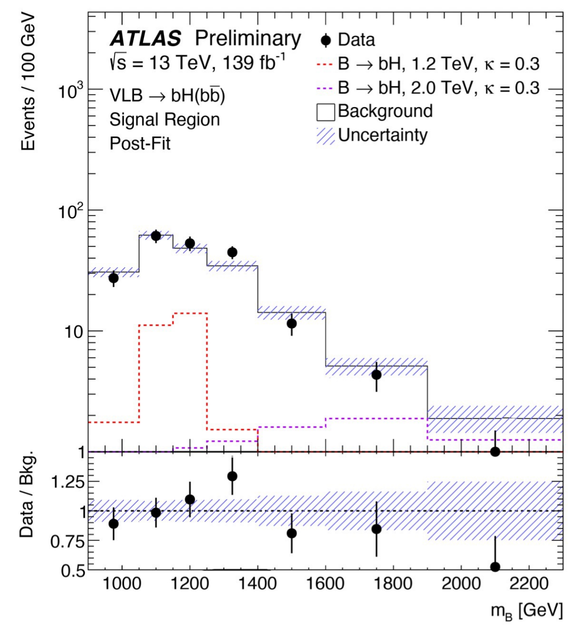


Estimate using data—driven technique

$N_A = N_B \times N_C / N_D$



- Require $\Delta R > 2.5$ for H and b
- Fit signal+bkgd model to $M(Hb)$ distribution
- Unfortunately, no evidence of excess
- Set 95% C.L. limits on cross-section & couplings



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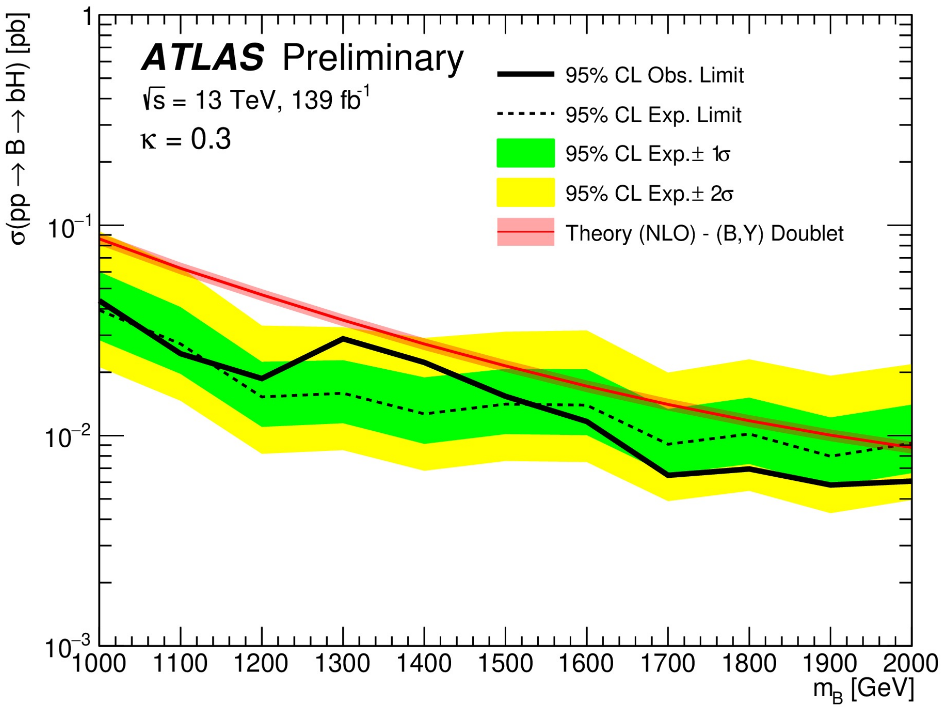
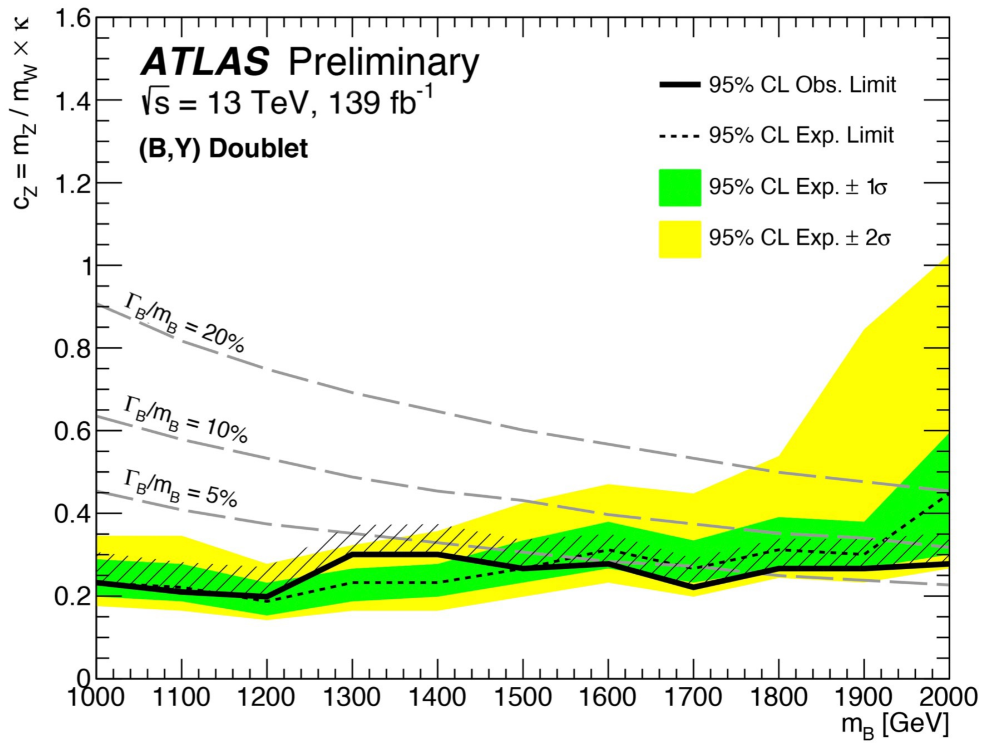
Search for single production of VL B

- Limits depend on coupling to SM particles and representation
- Exclude $1 < m_B < 2$ TeV for $\kappa = 0.3$

- Can express this in terms of width of *B*

$$\Gamma_B = \frac{g^2}{128\pi} \times \frac{m_B^3}{m_W^2} \times \kappa^2$$

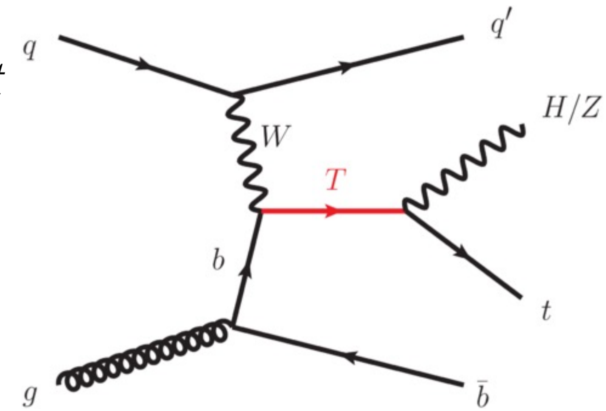




ATLAS-CONF-2021-018

Search for single production of T

- Most recent result is search for $T \rightarrow Ht$ & $T \rightarrow Zt$
  - Reconstruct H/Z decaying hadronically
    - Require large-R jet with $p_T > 350$ GeV for H/Z
      - $p_T > 400$ GeV for top-quark jet
  - Reconstruct lepton+jets top-quark candidate
    - Require top $p_T > 350$ GeV
  - Require forward jet $2.4 < |\eta| < 4.5$
- Define 24 regions based on:
  - B-jet multiplicity (1,2, 3,≥ 4)
  - Jet multiplicity (3-5 or ≥ 6) and forward jet (0 or ≥ 1)
  - Top, H or V (Z/W) candidates based on jet mass/substructure
- Signal-dominated region characterized by
  - Low jet multiplicity (3-5)
  - High b-jet multiplicity (2 b-jets for Zt; ≥ 4 for Ht)
  - H or Z candidate
  - ≥ 1 forward jet



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, $0(V+t_h)$	$t\bar{t}+\geq 1b$
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, $0(V+t_h)$	$t\bar{t}+\geq 1b$

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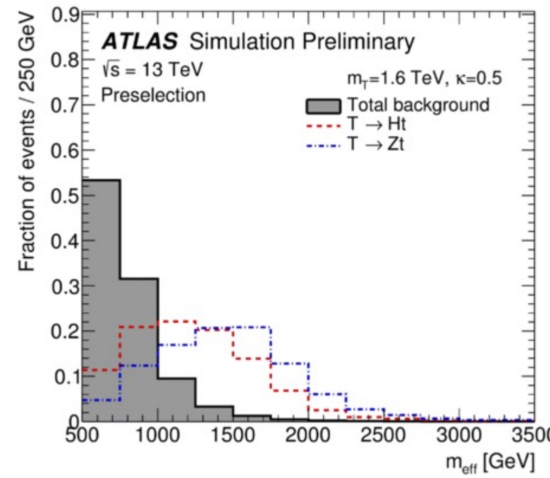
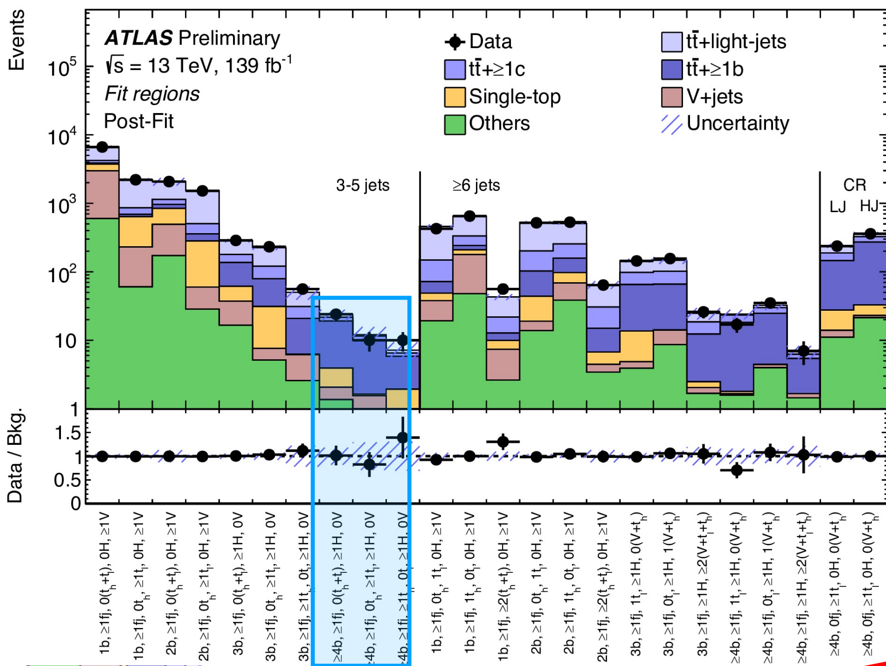
Search for single production of T

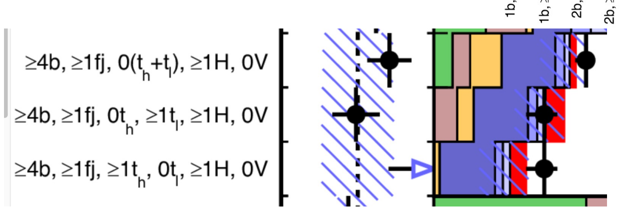
- Use "m_{eff}" variable
  - Scalar sum of pT for central jets ($|\eta| < 2.5$), lepton + MET
  - Good separation between background & T signal

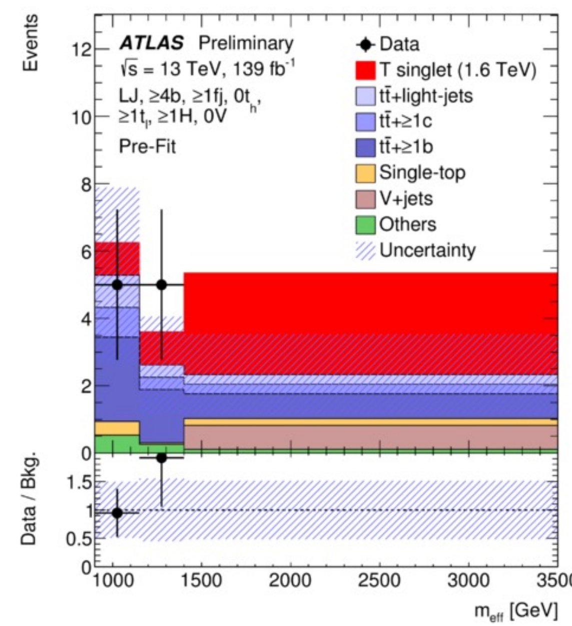


- Validation regions used to confirm background modelling (see backup)

- Resulting event yields consistent with bkgds







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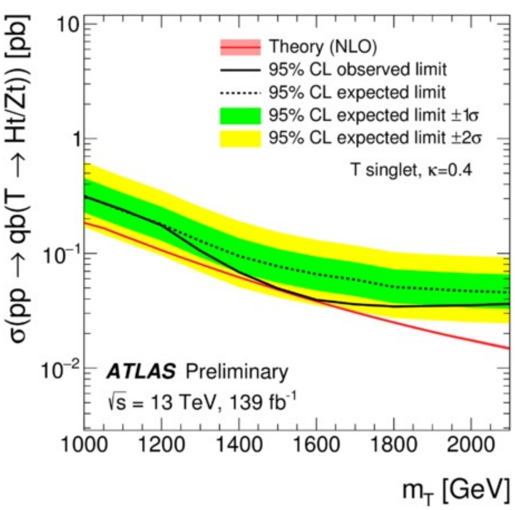
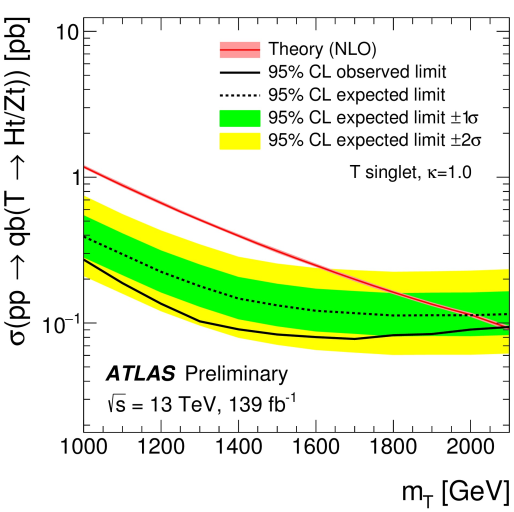
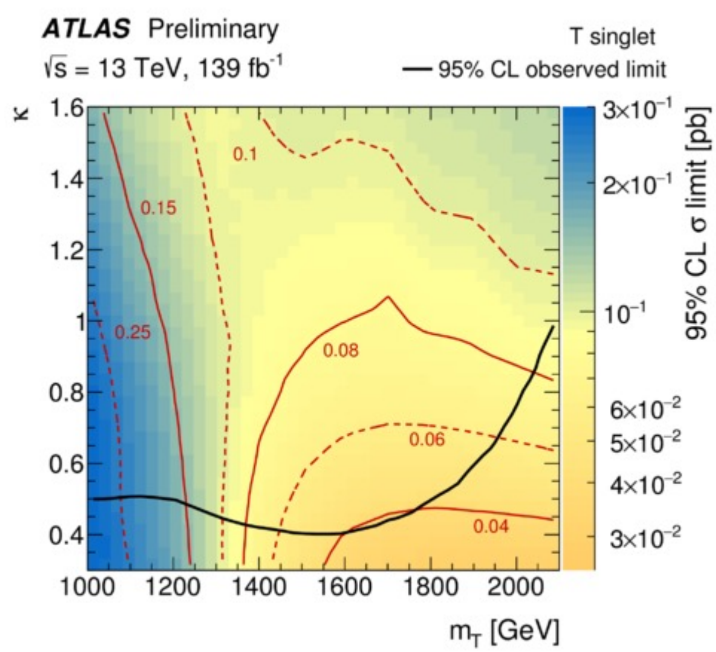
Search for single production of T

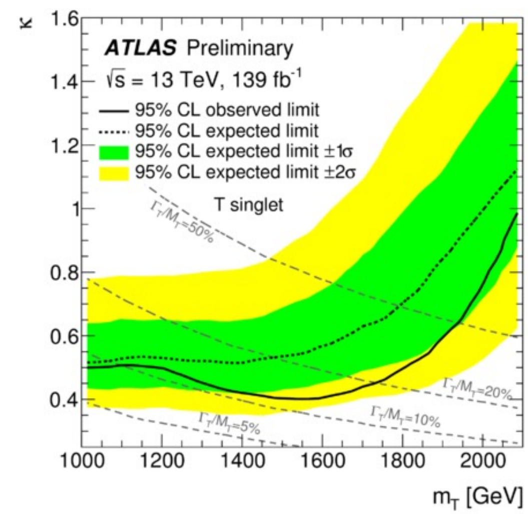
- Likelihood fit used to set limits on T cross-section
  - Interpret as limits on couplings to SM particles

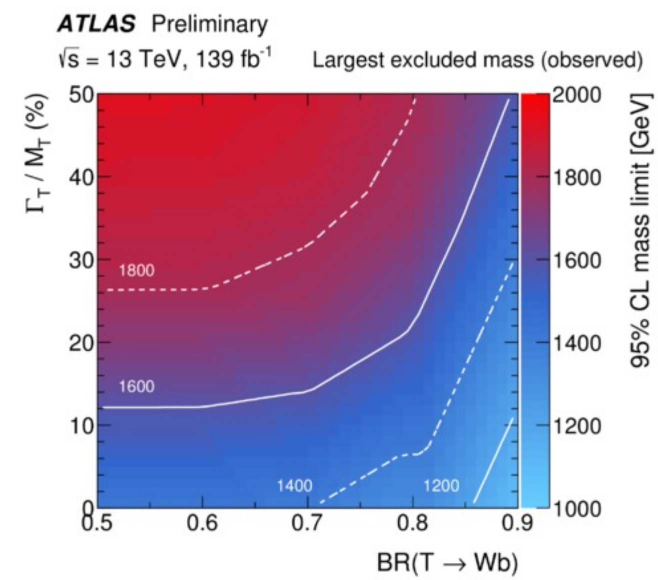




- Exclude $m_T < 2$ TeV for $\kappa \geq 1.0$
- Can also look at mass limits as function of T branching fractions and couplings







ATLAS-CONF-2021-040

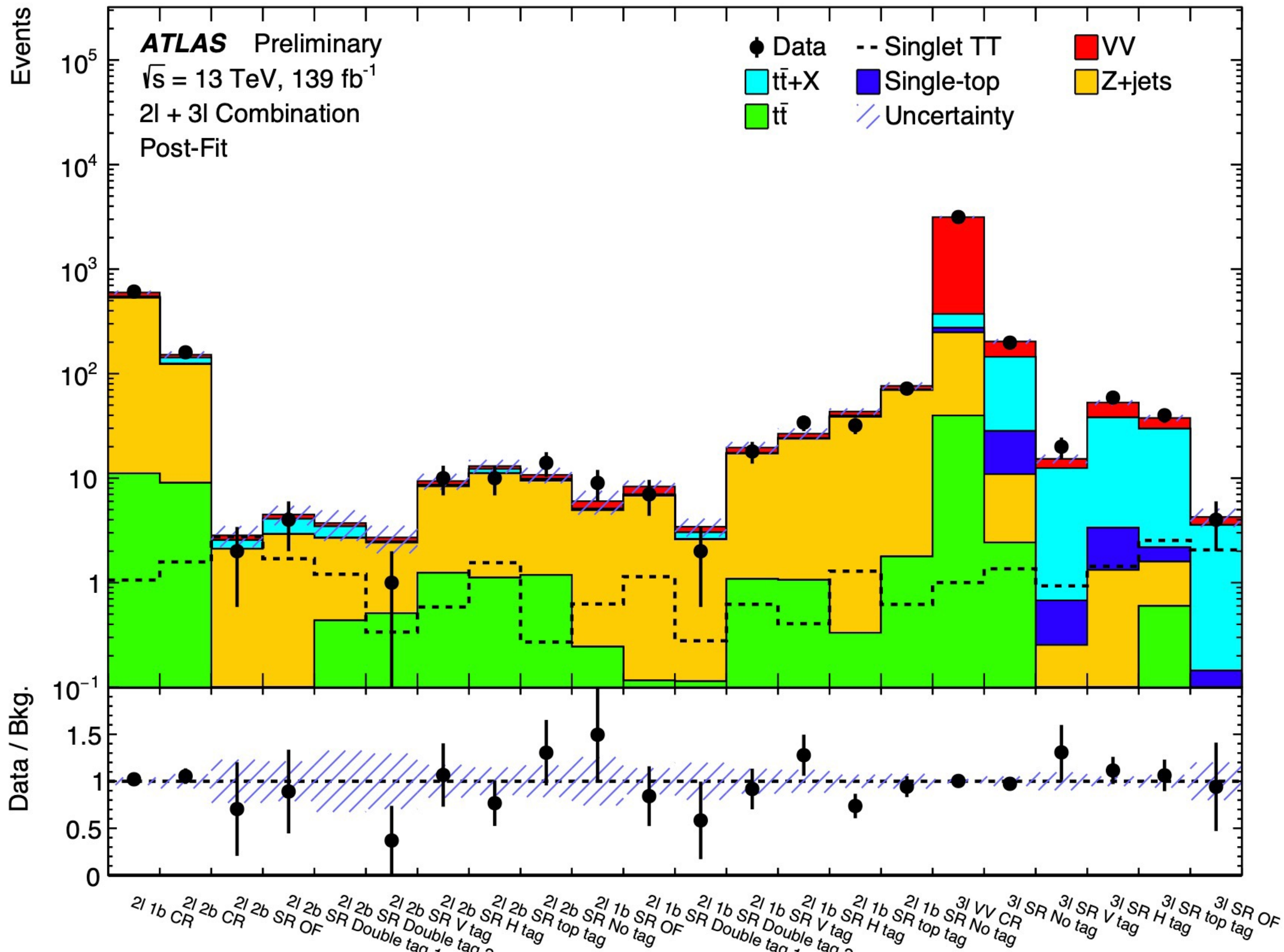
Conclusions

- Searches for vector-like quarks very active effort at ATLAS (and CMS though that is a separate talk*)
- Have started to constrain models with masses up to 2 TeV over large range of couplings
  - Developed techniques for efficient searches with good background rejection
- Much more work to be done to search for
  - Higher mass states
  - VLQs with smaller mixing with SM particles
- More results to come using Run 2 data and soon-to-collect Run 3 collisions

Mass Limits [TeV] (at 95% C.L.)	SM Couplings
$m_T < 1.60$ $m_B < 1.42$	$T \rightarrow Zt$ 100% $B \rightarrow Zb$ 100%
$1.0 < m_B < 2.0$	$\kappa > 0.3$
$m_T < 2.0$	$\kappa > 1.0$

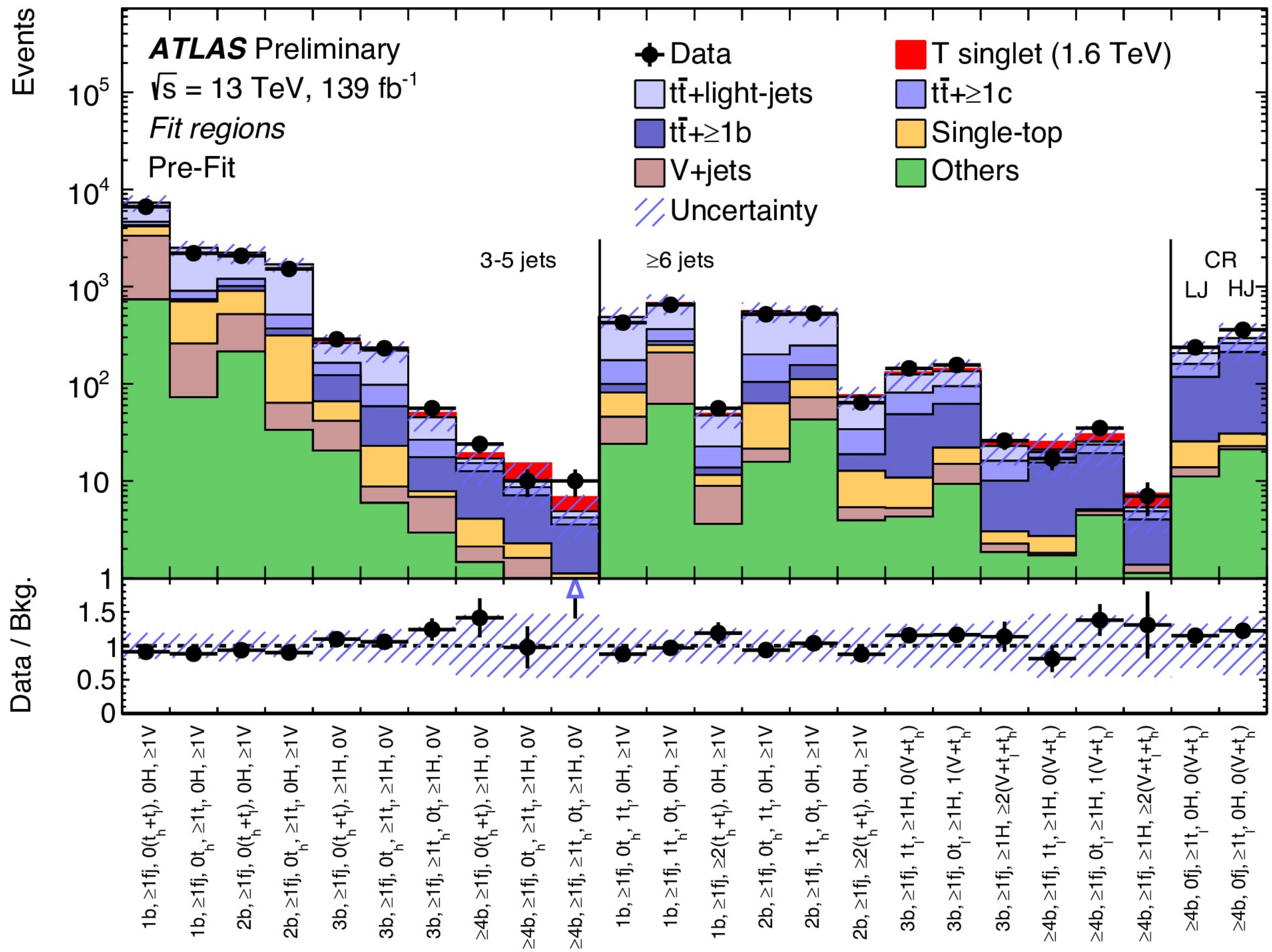
***Andrea Piccinelli's talk earlier this session**

Backup



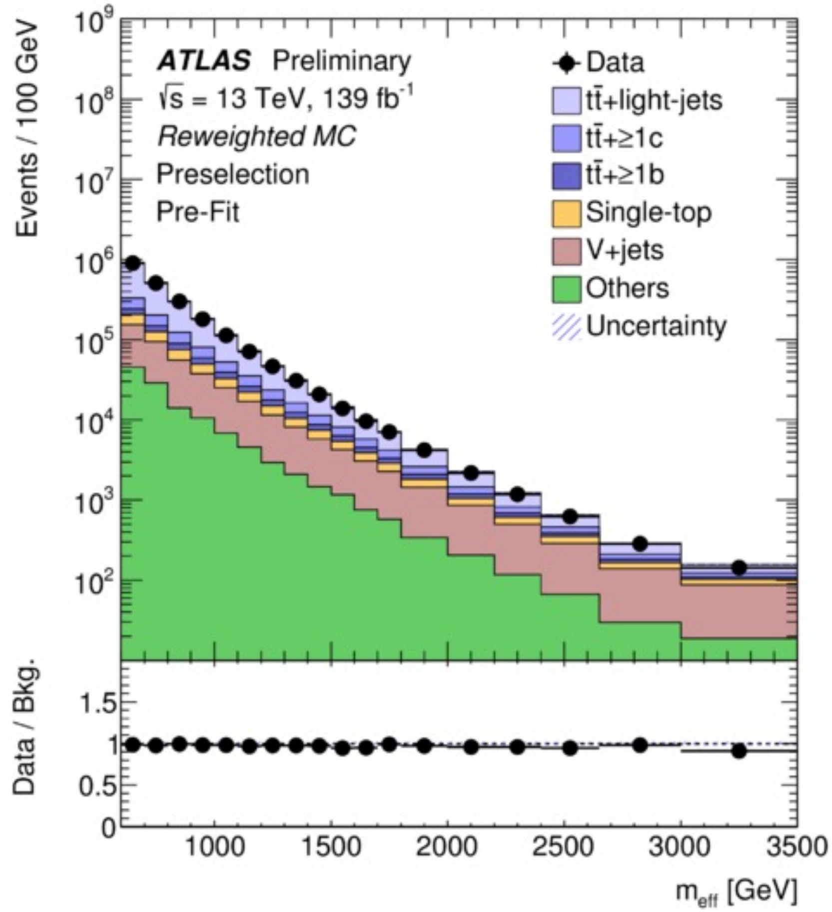
Validation regions yields for pair production of VL B and T Search

Backup



Validation regions yields for single production of VL T Search

Backup

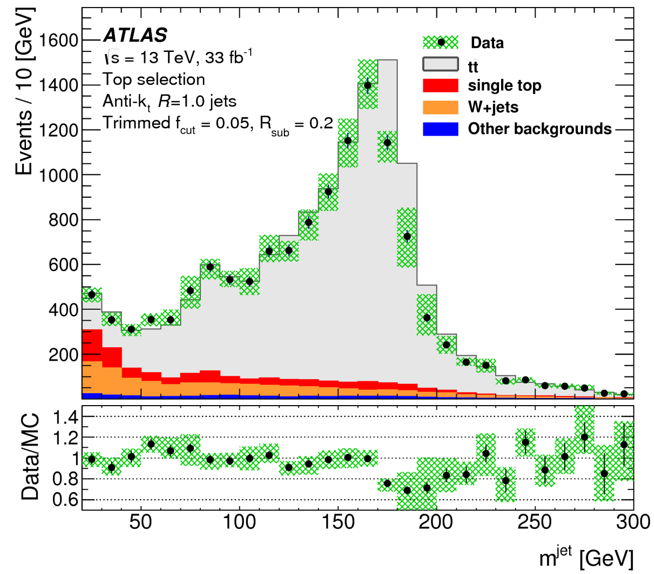


m_{eff} distribution for single production of VL T Search

Top Tagging in a Nutshell

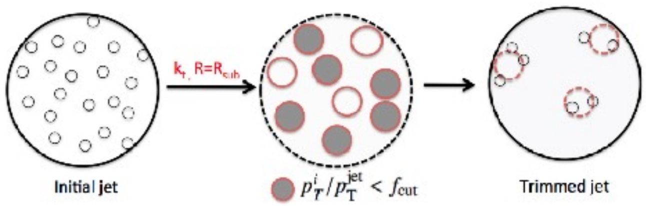
Apply **cut** on **substructure** variable(s) as a function of jet **kinematic** variables (p_T, *y*, *m*)

Boosted l+jets ($p_{T,1}$>350 GeV)



Key variables:

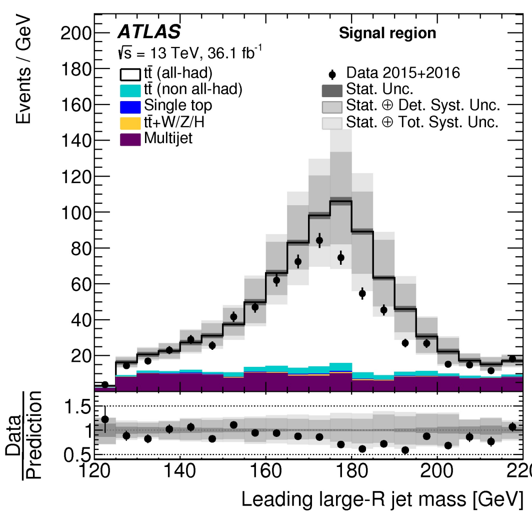
- Mass of the jet

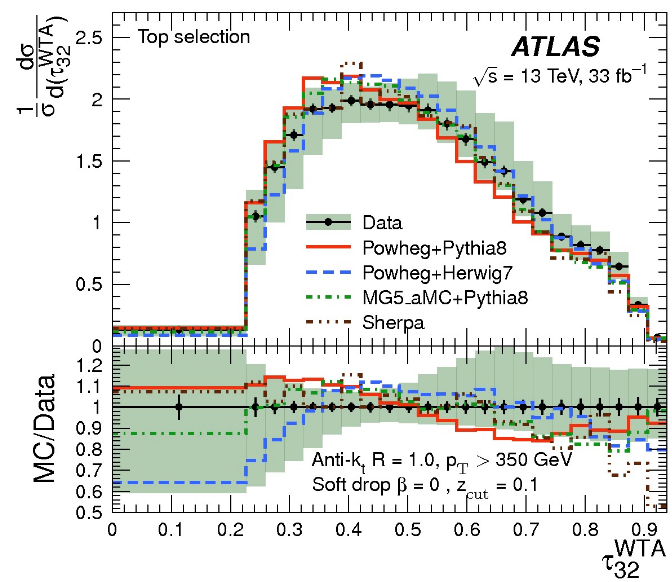


- Measures of internal substructure
- b-tagging of subjets

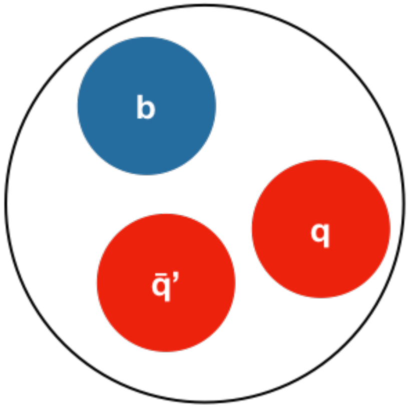
Results in clean tt̄ samples

All-hadronic ($p_{T,1}$>500 GeV, $p_{T,2}$>350 GeV)

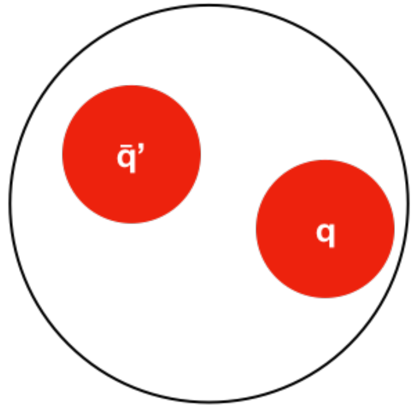




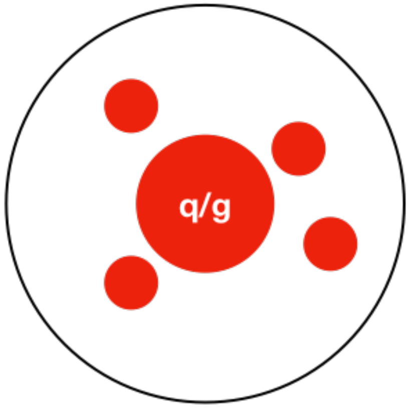
High-pT (Boosted) Tops



Top quark
Three-prong topology

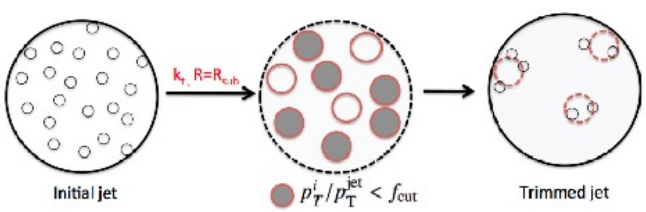


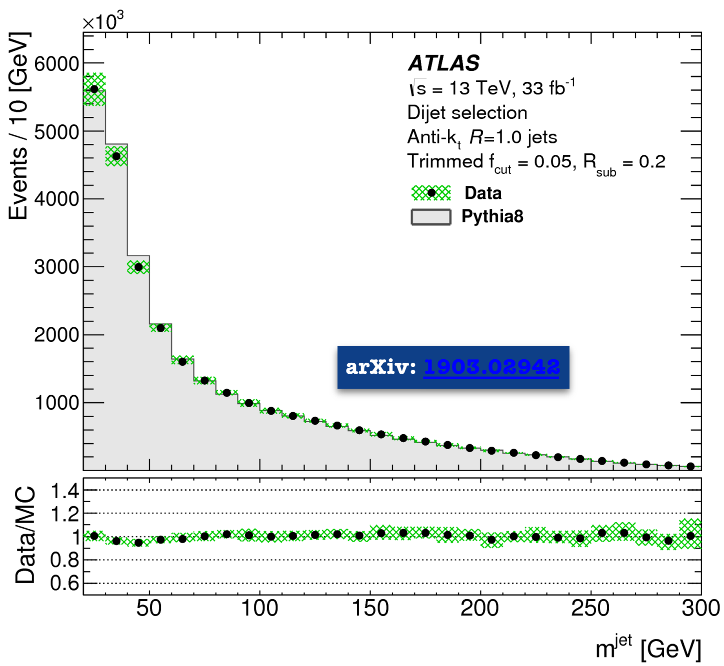
W boson
Two-prong topology



Quark/gluon
Axial topology

Trimming Thaler et al., JHEP 1002:084,2010
Removes pileup by discarding R=0.2 subjets with pT < 5% pT(J)





Substructure
Distribution in (η,ϕ,E) of calo clusters reflects underlying top quark decay

- *N*-subjettiness ratio τ_{32}
- Soft drop mass, n_{SD}
- ECF, $C_2^{(\beta)}$, $D_2^{(\beta)}$