Search for Vector-Like Quarks

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Why Vector-Like Quarks?

- VLQ are colored, fractionally-charged fermions that are non-chiral under SU(2)
  - why search for these particular particles?

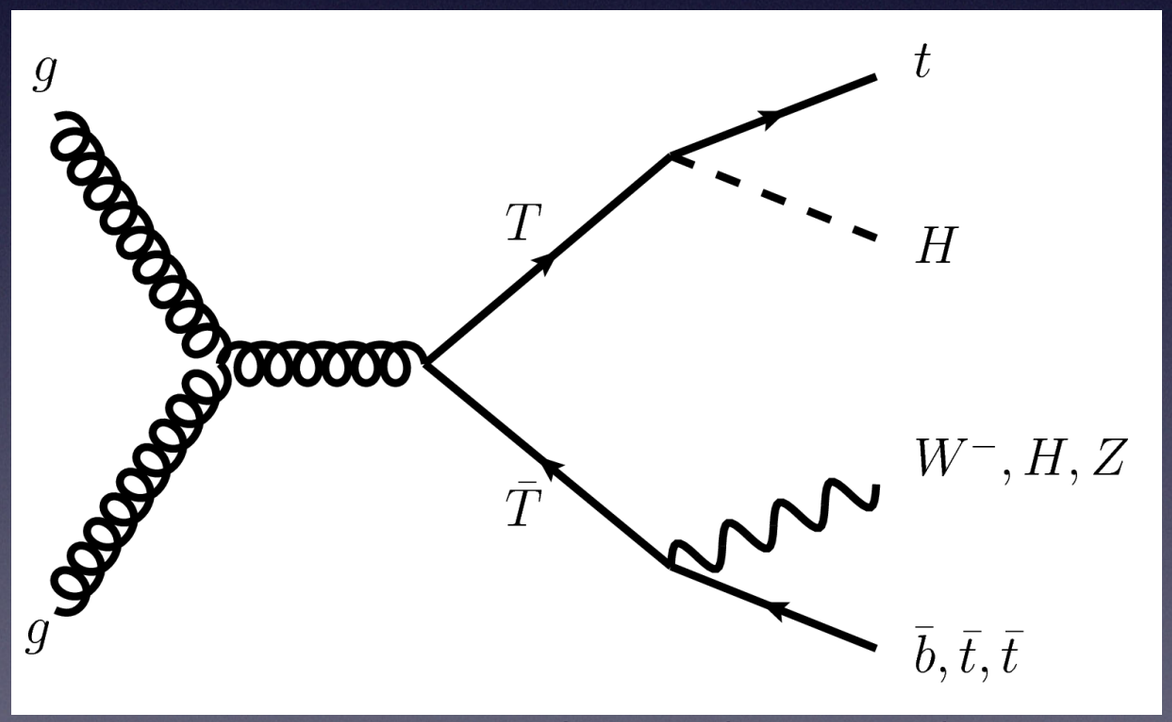
- Well-motivated:
  - appear in many BSM models that address the naturalness issue (Little Higgs, extra dimensions, etc)
  - (maybe) explain fermion mass hierarchy

- Allowed
  - not constrained by Higgs measurements

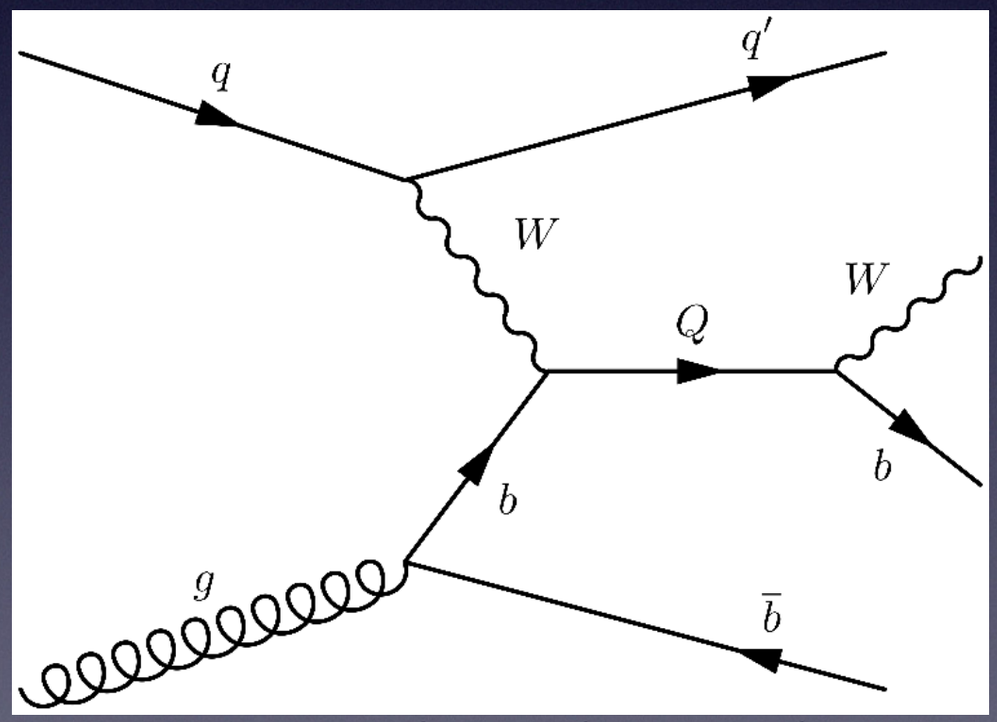
- Accessible at the LHC
  - mass < ~ 2TeV to preserve naturalness

VLQ Phenomenology

- Both "normal" (-1/3, 2/3) and "exotic" (-4/3, 5/3) charges possible B T $B^{-4/3}, Y$ $T^{5/3}, X$
- Can appear as SU(2) singlets, doublets, or triplets
- Natural models tend to favor coupling to 3rd-gen SM quarks
- Pair (single) production via QCD (EW) interactions



Cross section depends mainly on mass

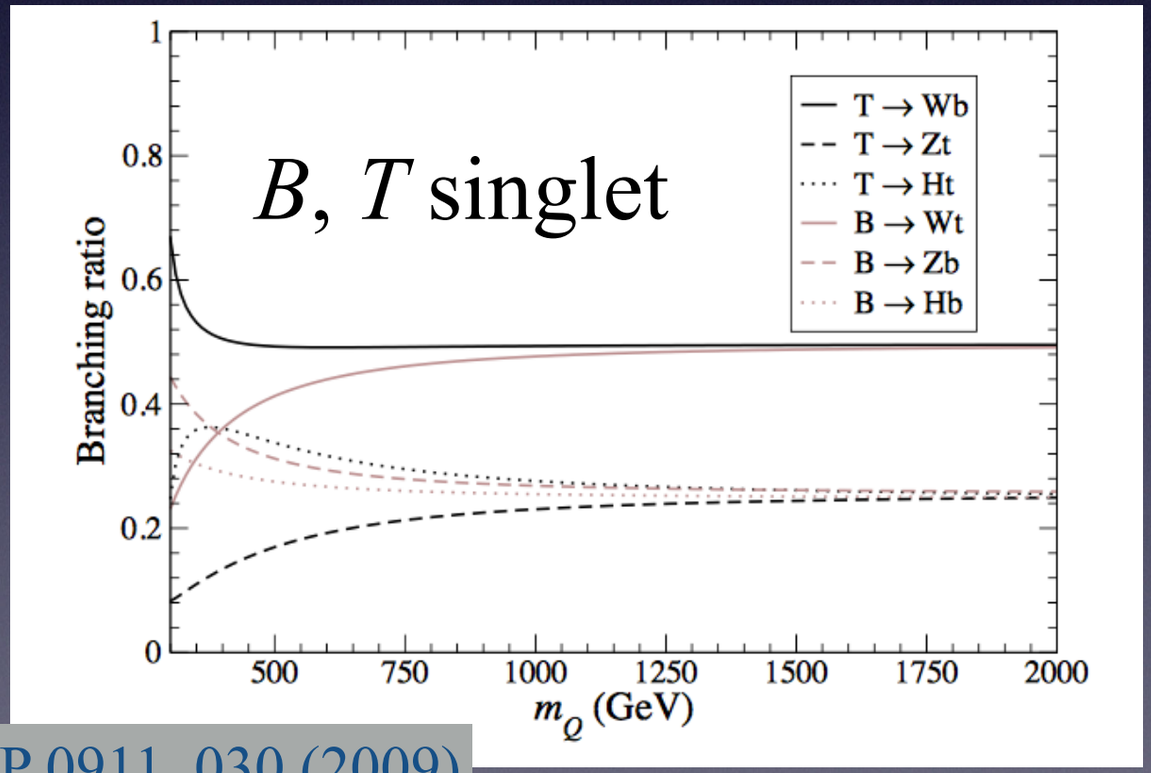


Cross section depends on mass and EW coupling

VLQ Phenomenology

- Both charged- and neutral-current decays are possible for *B* and *T*:
  - $B \rightarrow Zb, Hb, Wt$
  - $T \rightarrow Zt, Ht, Wb$
- BRs are constrained in some models

Wide variety of potential signatures



JHEP 0911, 030 (2009)

But the general case should be considered as well

General Strategy

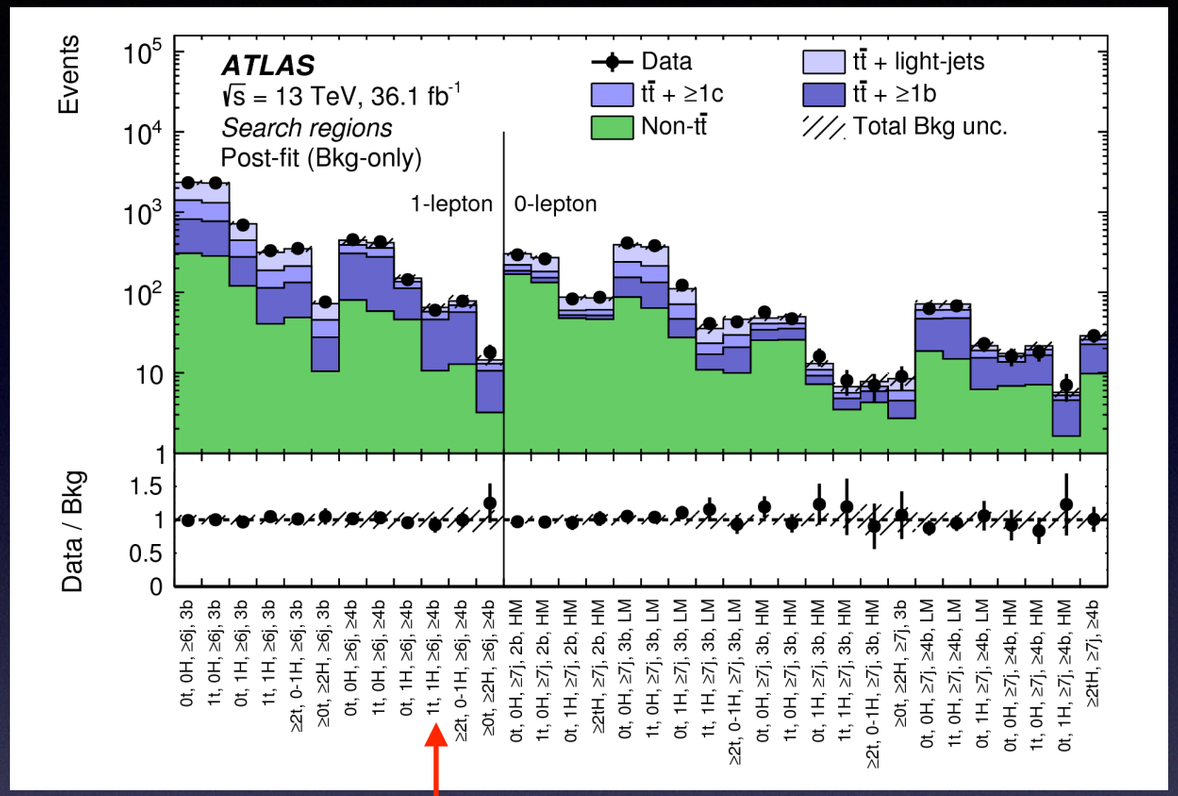
- Searches are typically targeted toward a particular VLQ in a particular decay mode
  - often substantial cross-sensitivity exists
- Backgrounds estimated using:
  - MC for irreducible sources (e.g. Pythia, Sherpa, POWHEG, MC@NLO…)
  - data-driven methods for reducible sources (i.e. fake/non-prompt leptons and electron charge misID)
- Data assessed for evidence of VLQ by either counting number of events passing selection or from the distribution of a sensitive variable
- Limits are set at 95% CL using the CL_S method

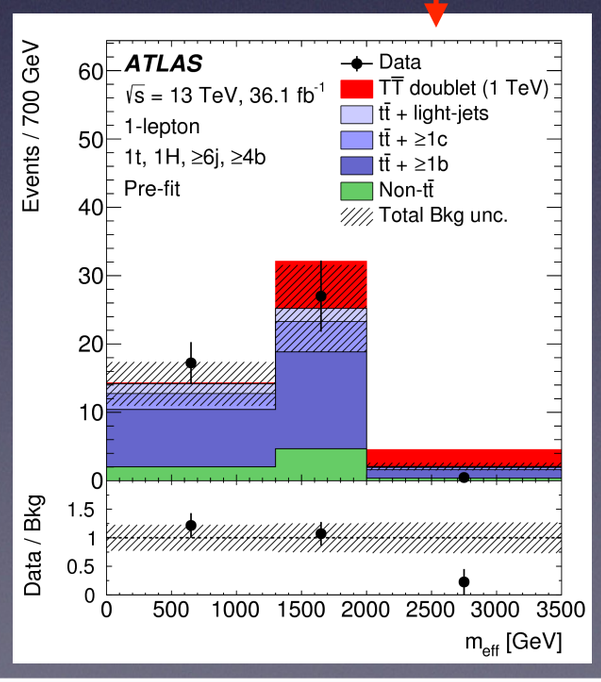
Searches for VLQ Pair Produciton

JHEP 07 (2018) 089

Search for $T \rightarrow Ht + X$

- Two separate topologies considered: 0-lepton and 1-lepton
  - $E_{T}^{\text{miss}} > 200$ GeV if 0-leptons
  - Ht signature: ≥ 2 b-tagged jets
- Several signal regions defined, based on:
  - number of b-tagged jets
  - number of $R = 1.0$ jets consistent with Higgs or top decay
  - kinematic variables
    - these provide sensitivity to both low- and high-mass signals





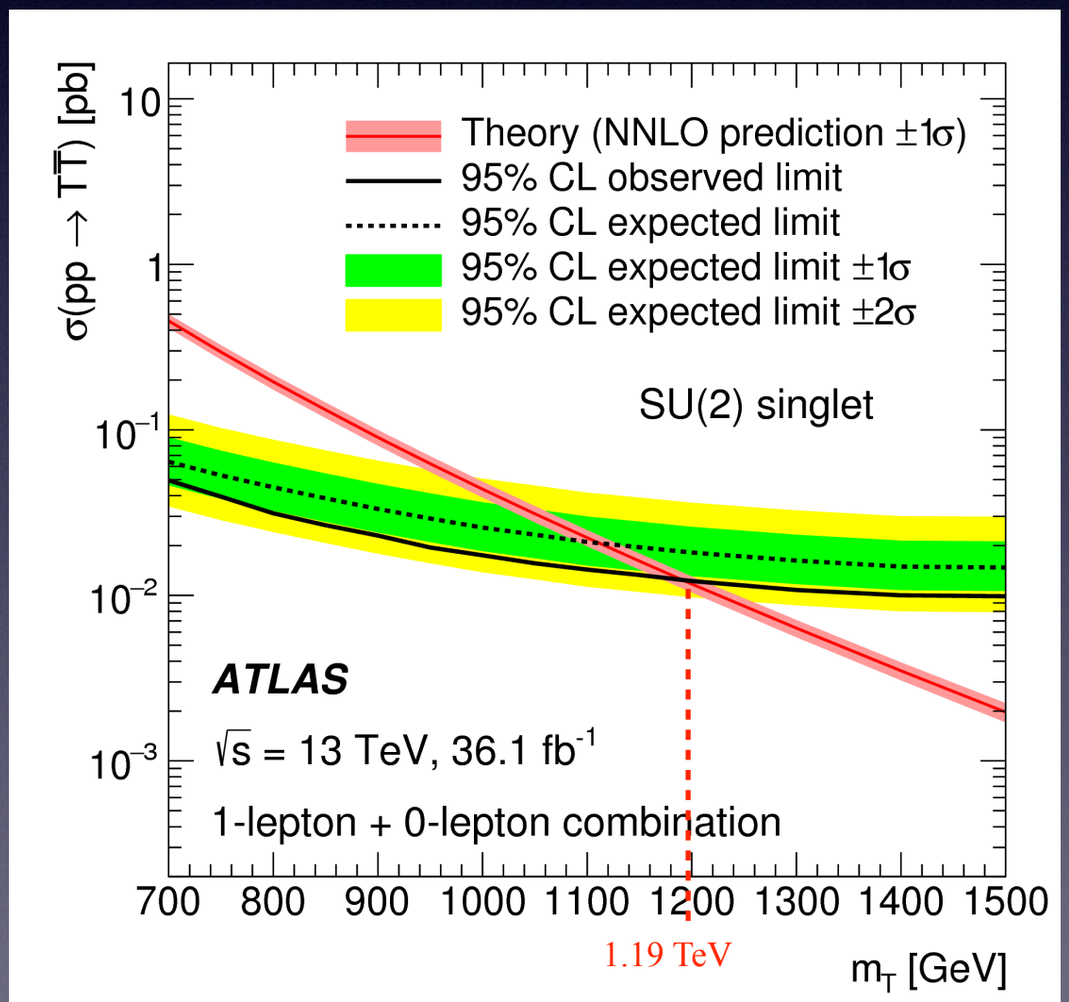
Distribution of m_{eff} (=sum of object p_Ts) in each region used to search for VLQ

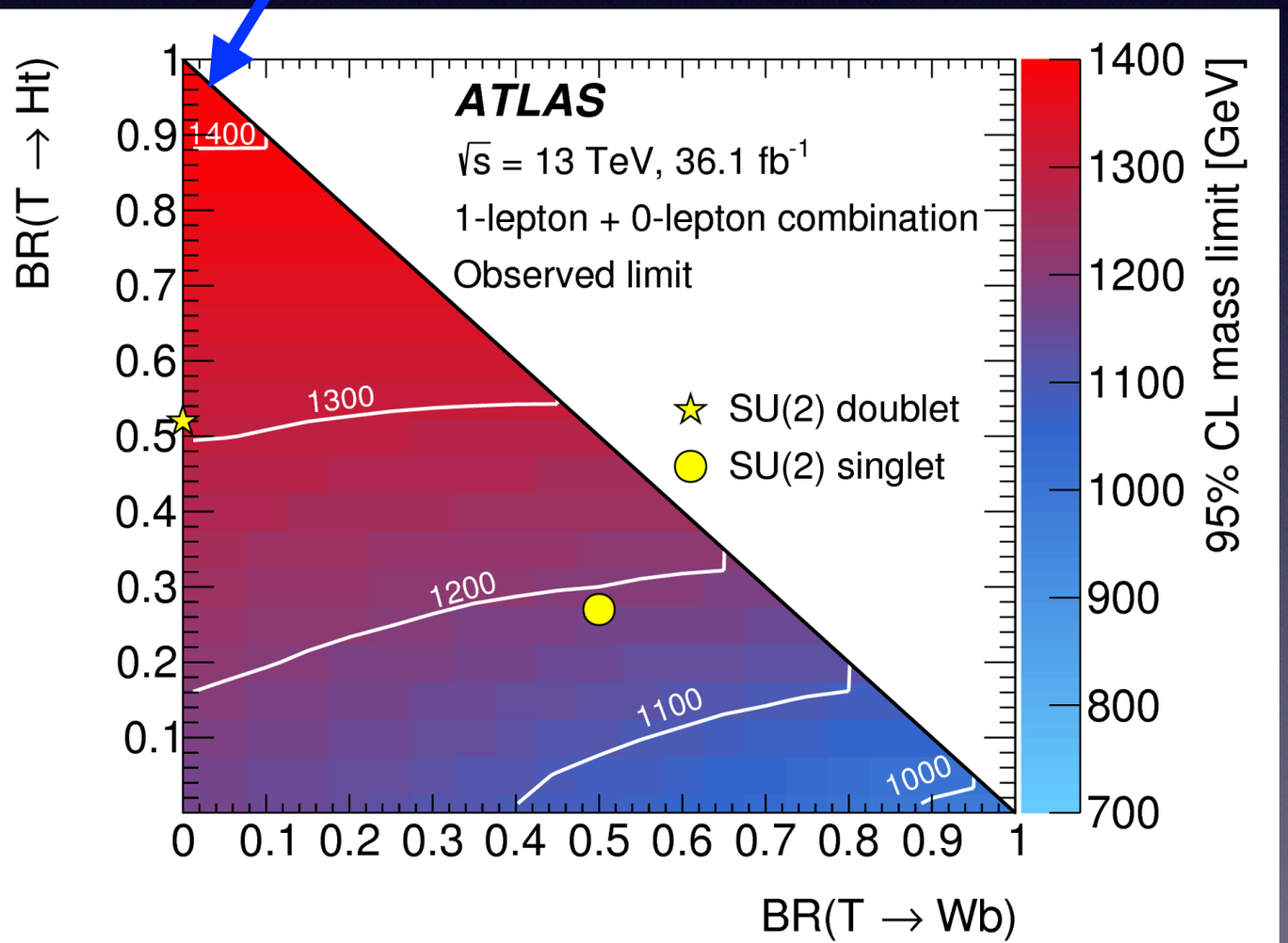
[JHEP 07 (2018) 089]

Search for $T \rightarrow Ht + X$

- Good agreement between observed and expected background in all regions
  - i.e. no sign of VLQ
- Resulting limits:

Most sensitive to $T \rightarrow Ht$ (as expected)

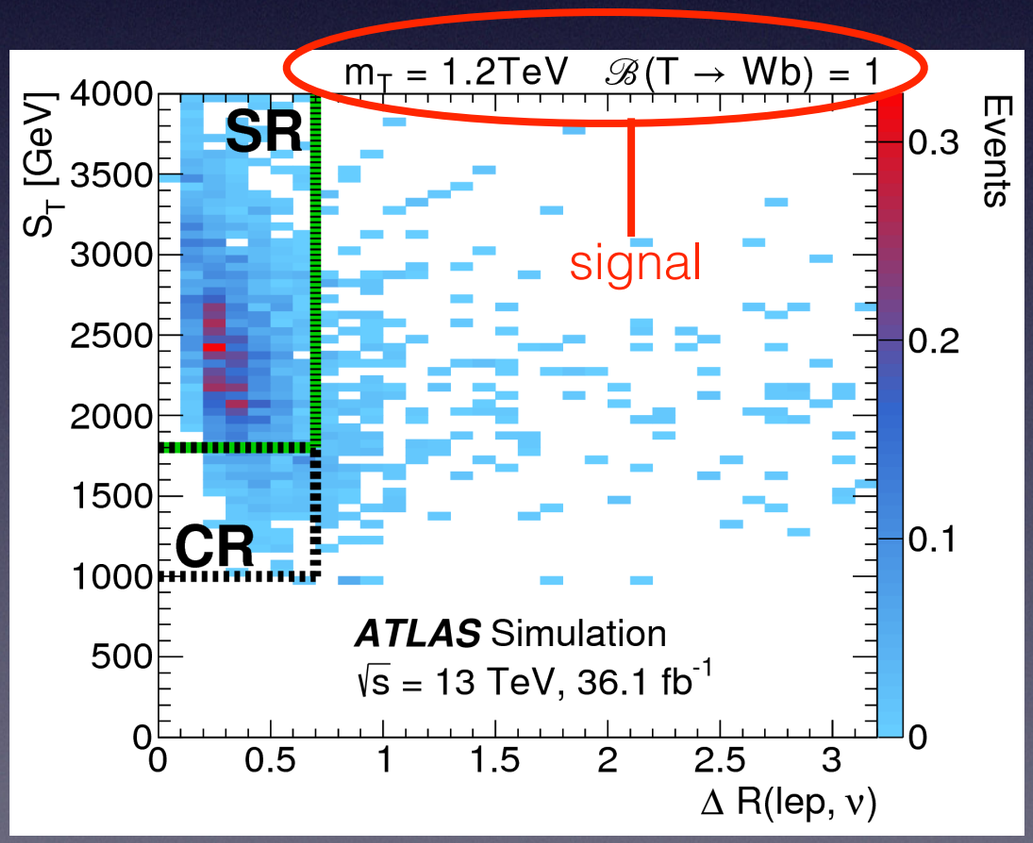


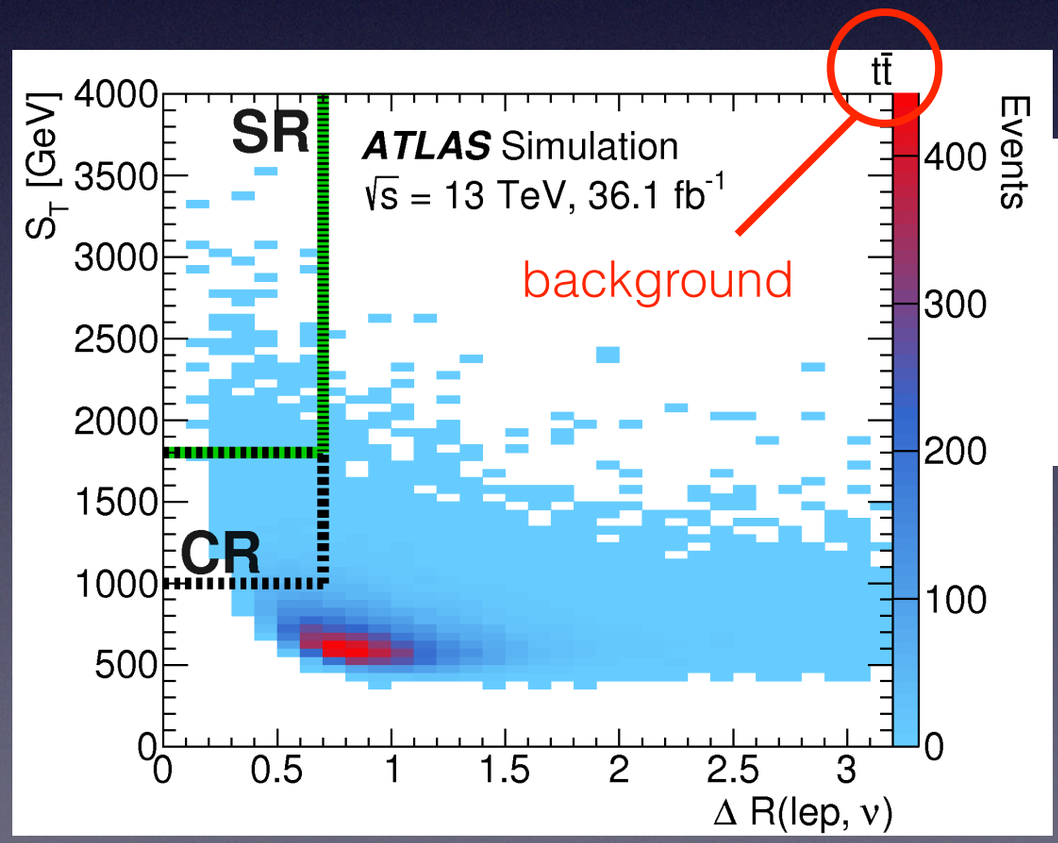


JHEP 10 (2017) 141

Search for $T \rightarrow Wb + X$

- Final-state objects are similar to $T \rightarrow Zt$ search
  - one lepton, ≥ 3 jets (≥ 1 b-tagged), ≥ 1 W-candidate jet, $E_{T\text{miss}}$
- Optimized for Wb by:
  - reconstructing ν momentum, and requiring $\Delta R(l, \nu) < 0.7$ and $S_T > 1800$ GeV



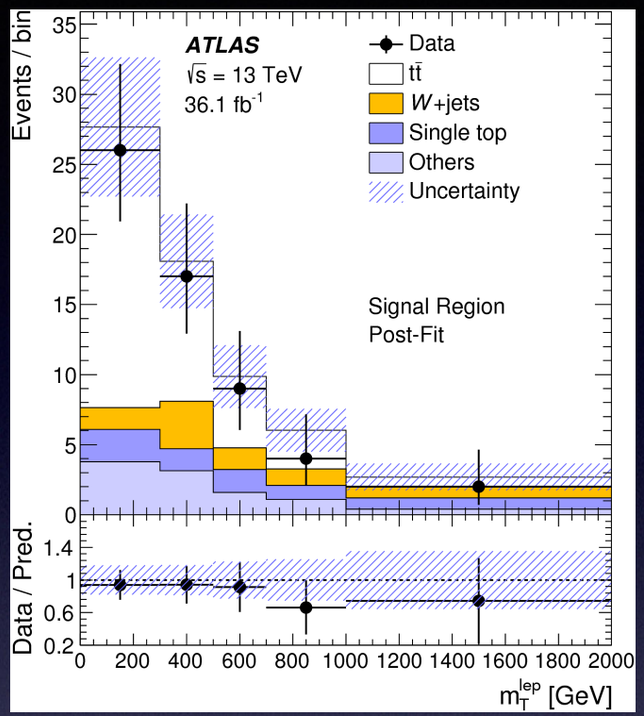


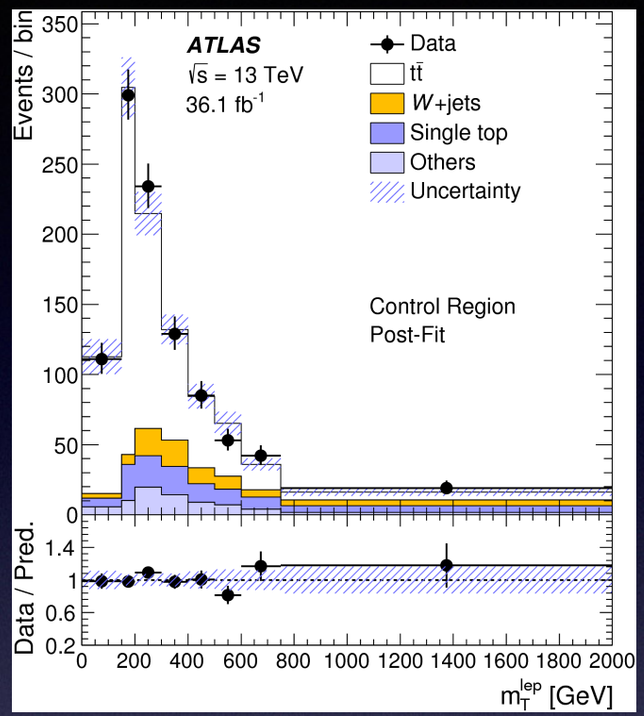
$$S_T \equiv \sum_{\text{jets},l,E_{T\text{miss}}} |p_T|$$

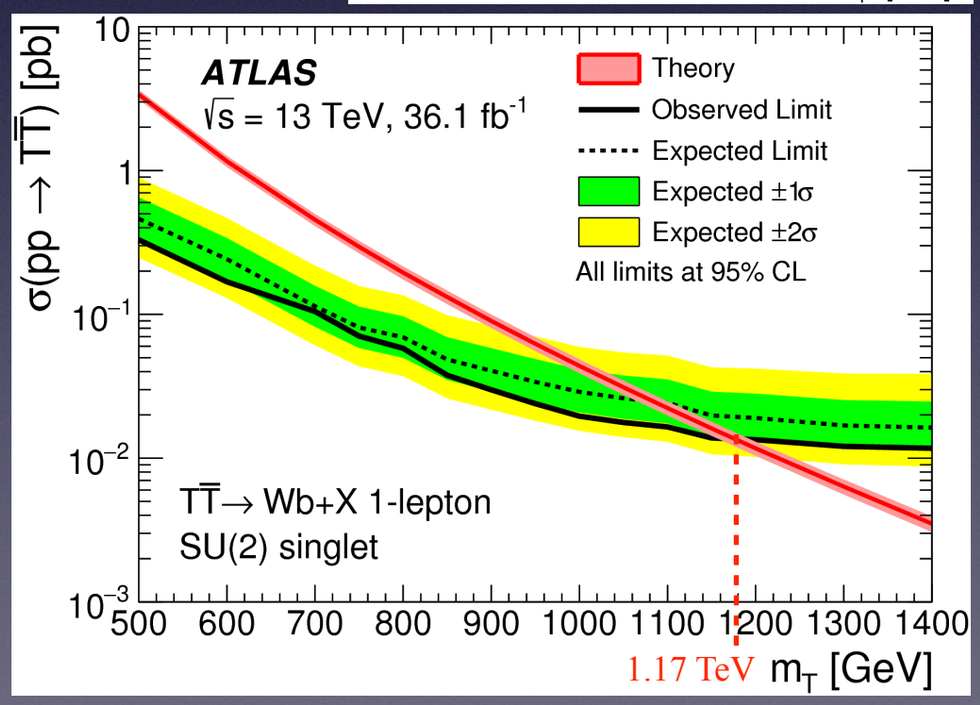
JHEP 10 (2017) 141

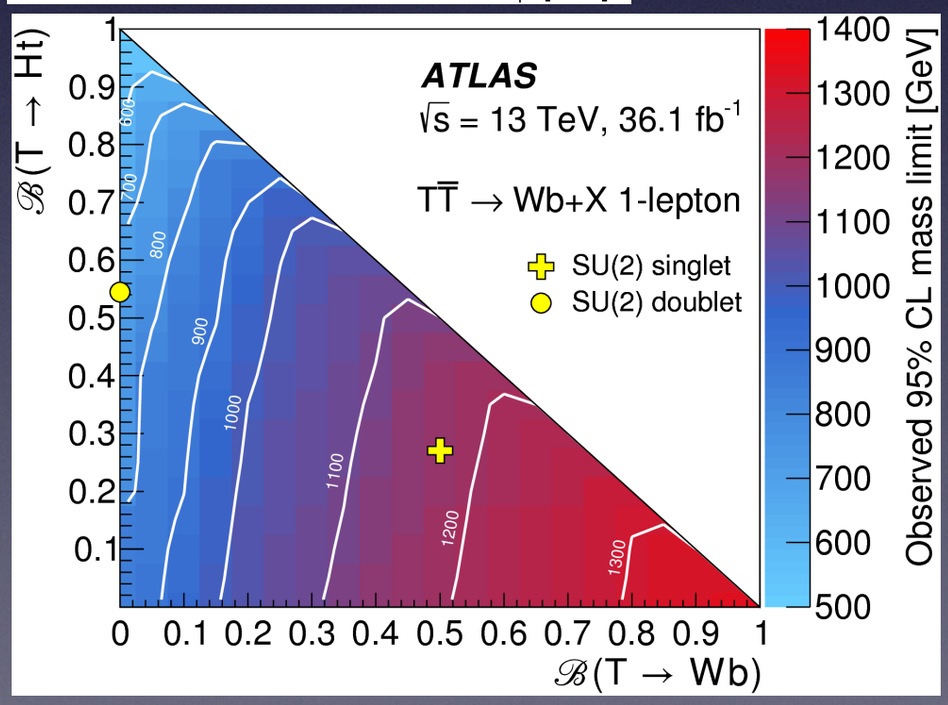
Search for $T \rightarrow Wb + X$

- Leptonically-decaying T candidate mass used to test for signal







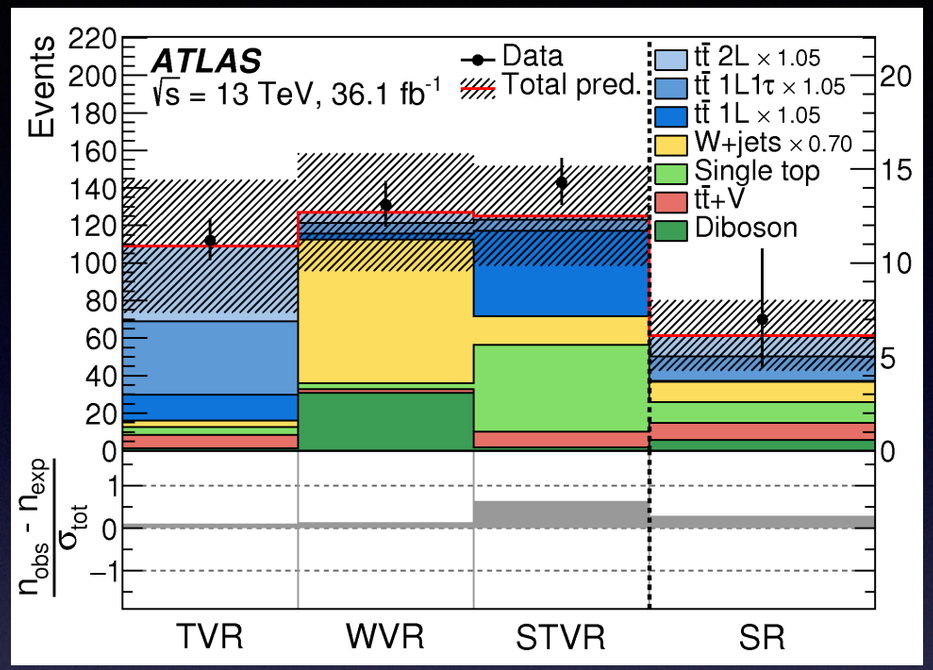


JHEP 08 (2017) 052

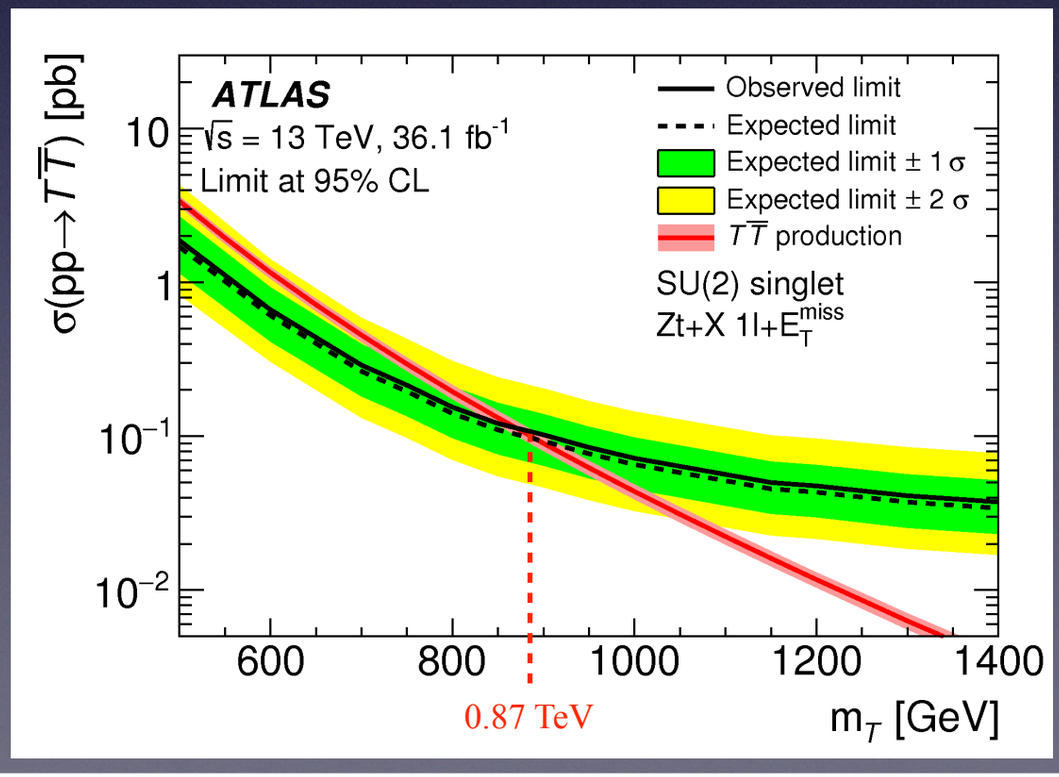
Search for $T \to Z(\to \nu\nu)t$

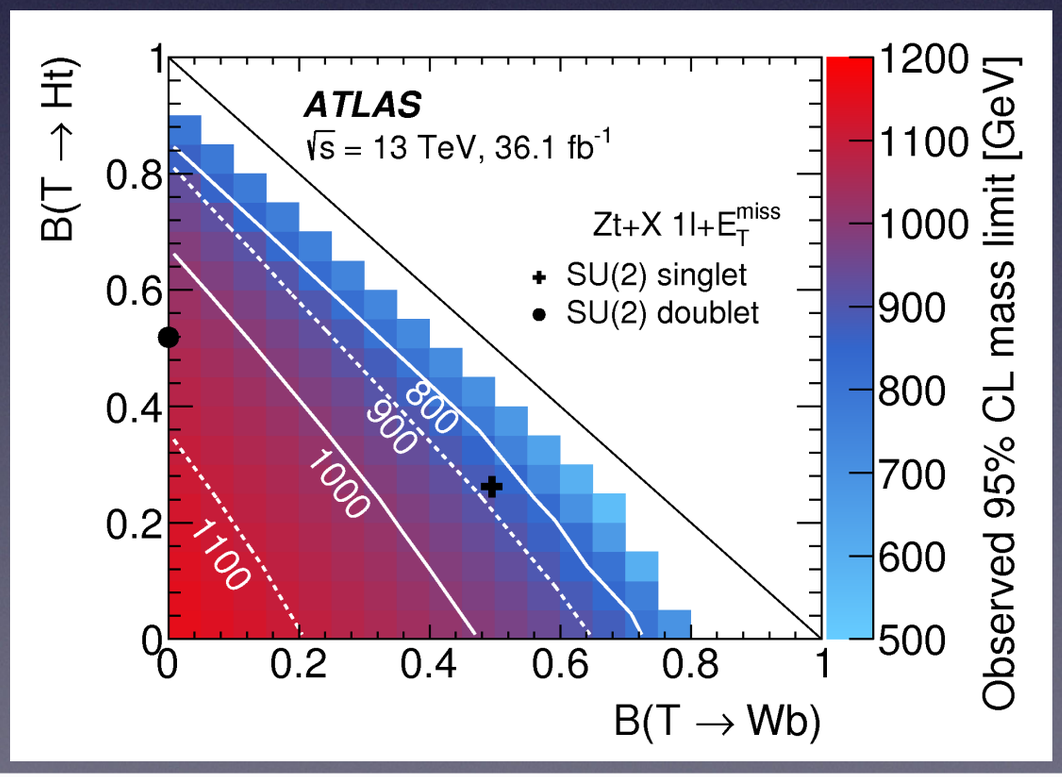
- One lepton, ≥ 4 jets (≥ 1 *b*-tagged), E_{T}^{miss} > 300 GeV

Validation regions require ==1 large-R jet
Kinematic selections favor a particular bkg



Signal region requires >1 large-R jet

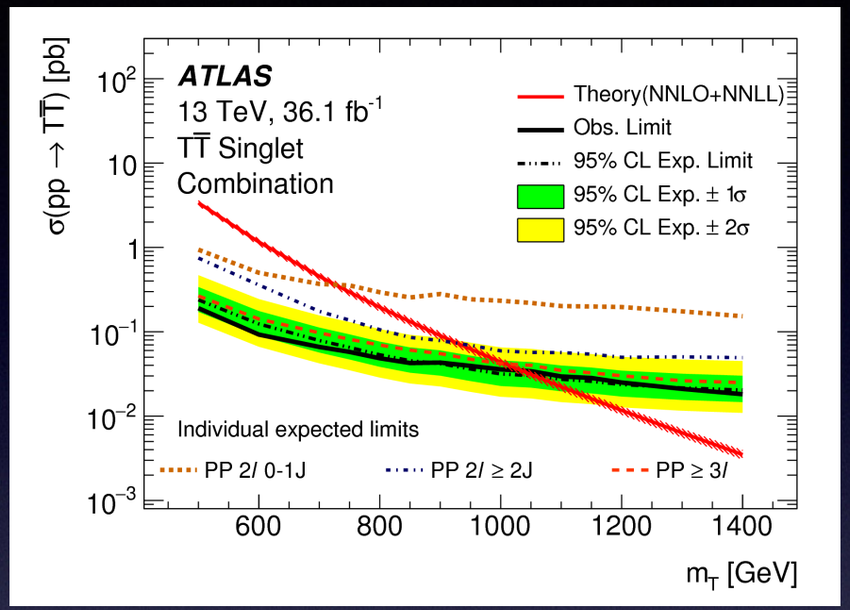


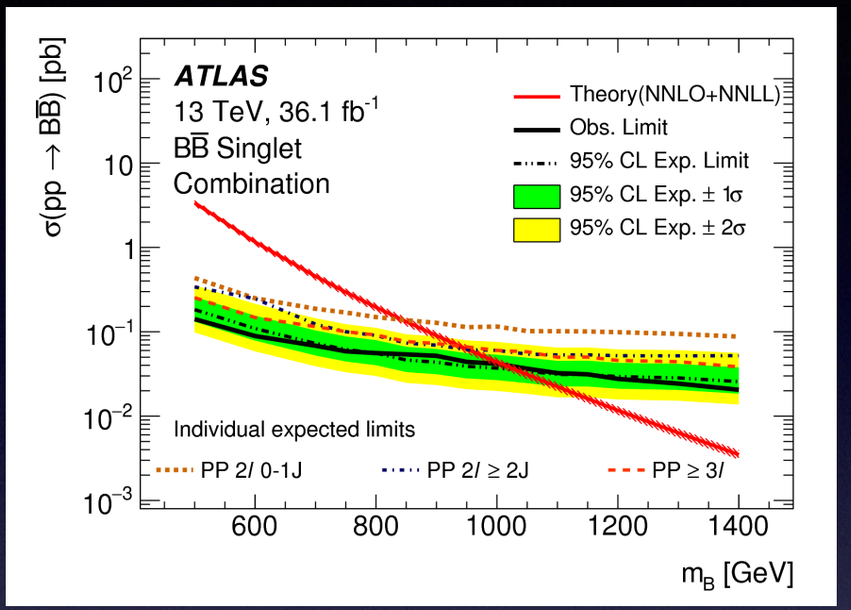


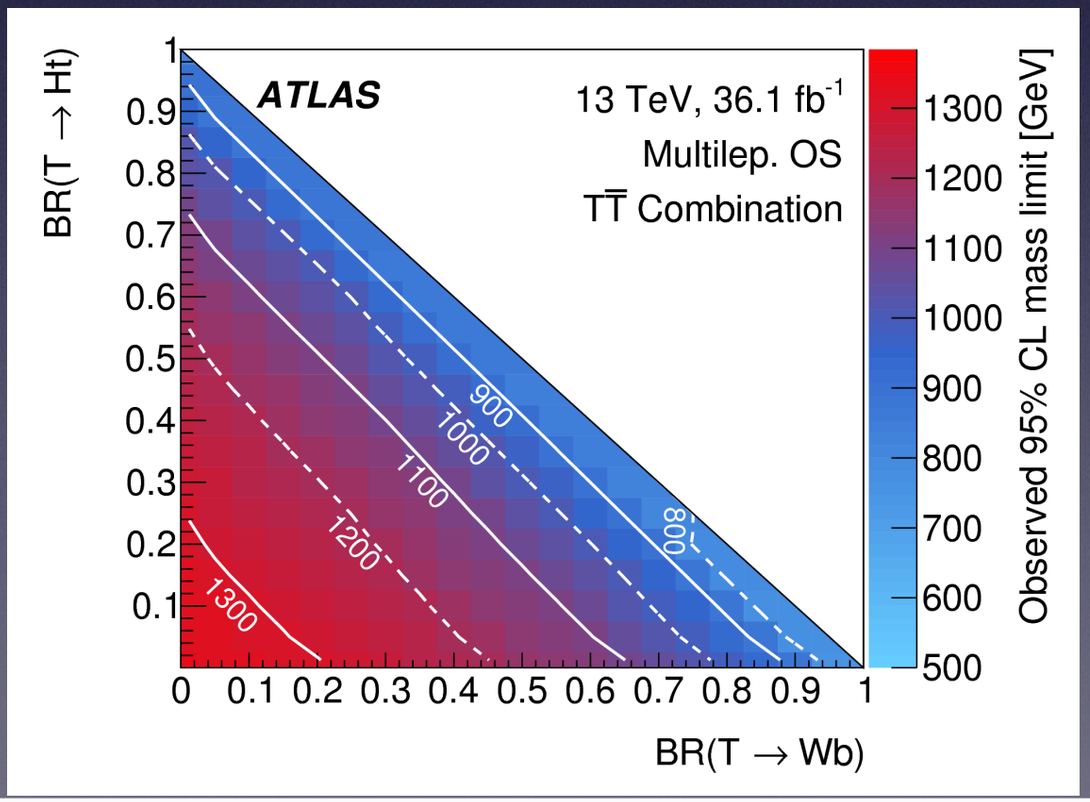
ATLAS-EXOT-2016-35

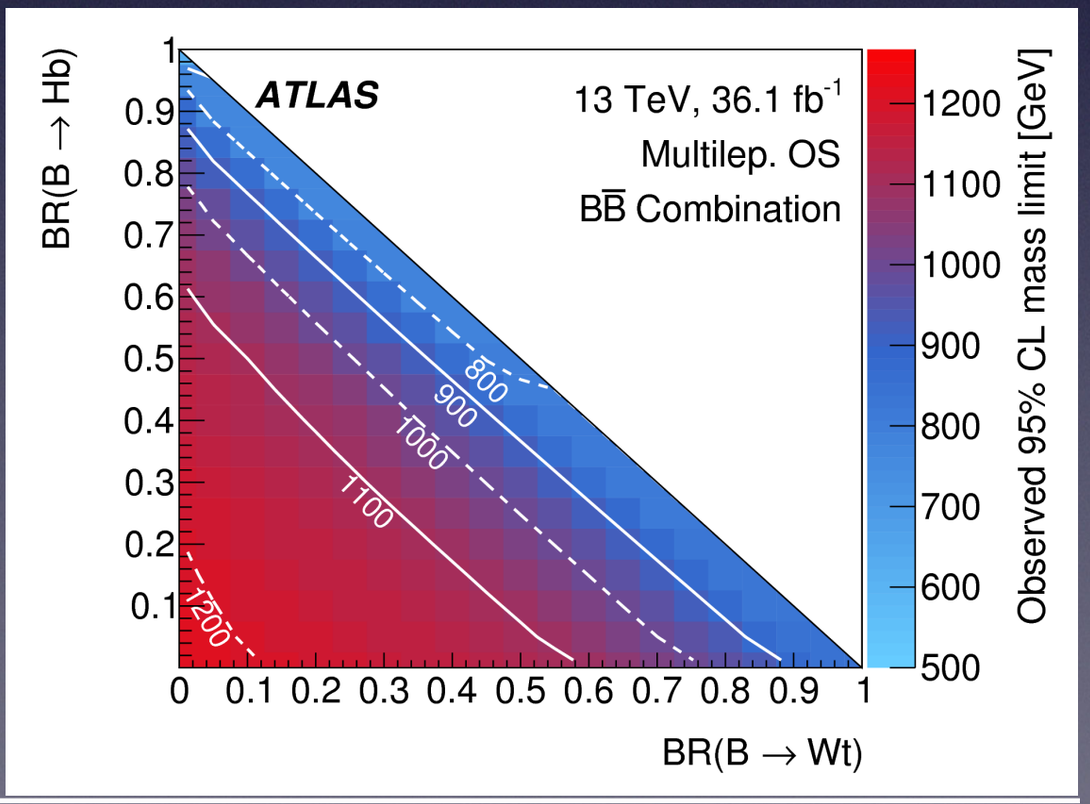
Search for $Z \to \ell\ell$ final states

- Select events with $Z \to \ell\ell$ candidate, ≥ 2 b-tagged jets, large-R jets









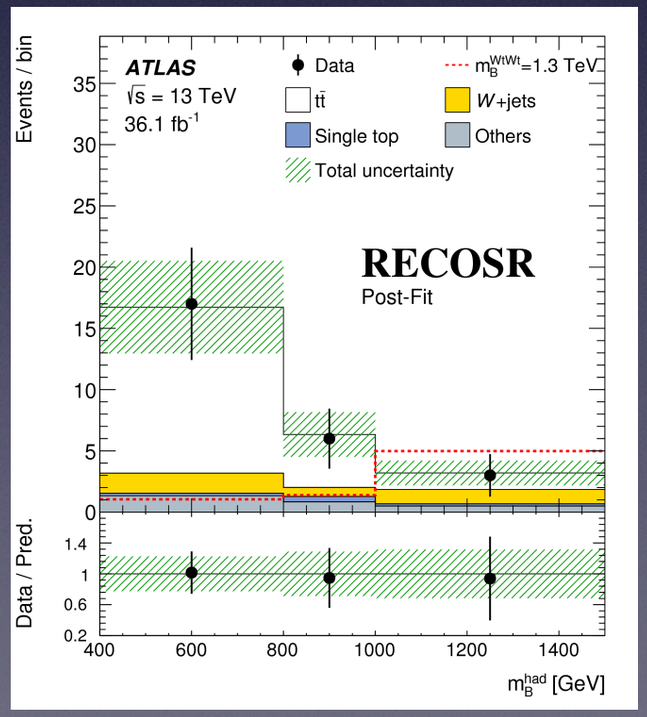
ATLAS-EXOT-2017-34 Search for $B \rightarrow Wt + X$

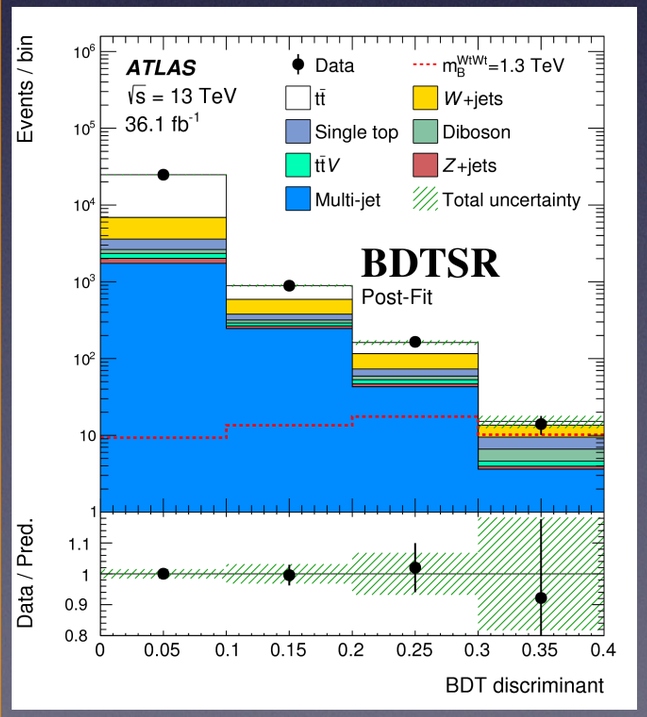
- Search optimized for high-mass B
  - 1 lepton, ≥ 4 jets (≥ 1 b-tagged), ≥ 1 large-R jet, $S_T > 1.2$ TeV

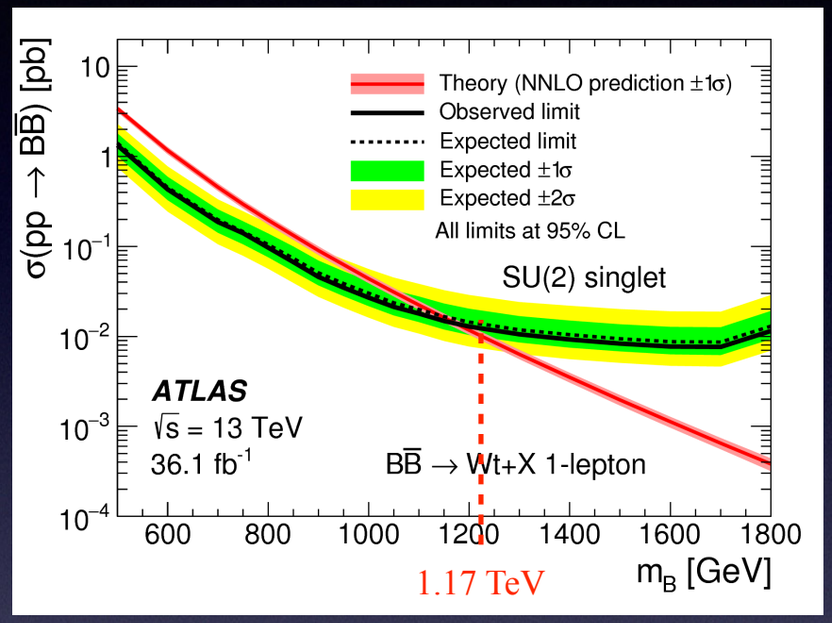
$$N_{\text{jets}}^{\text{large}} \geq 3$$
$$N_{W_{\text{had}}} \geq 1$$
$$\Delta R(\text{lep, leading } b\text{-jet}) \geq 1$$
$$S_{\text{T}} \geq 1500 \text{ GeV}$$

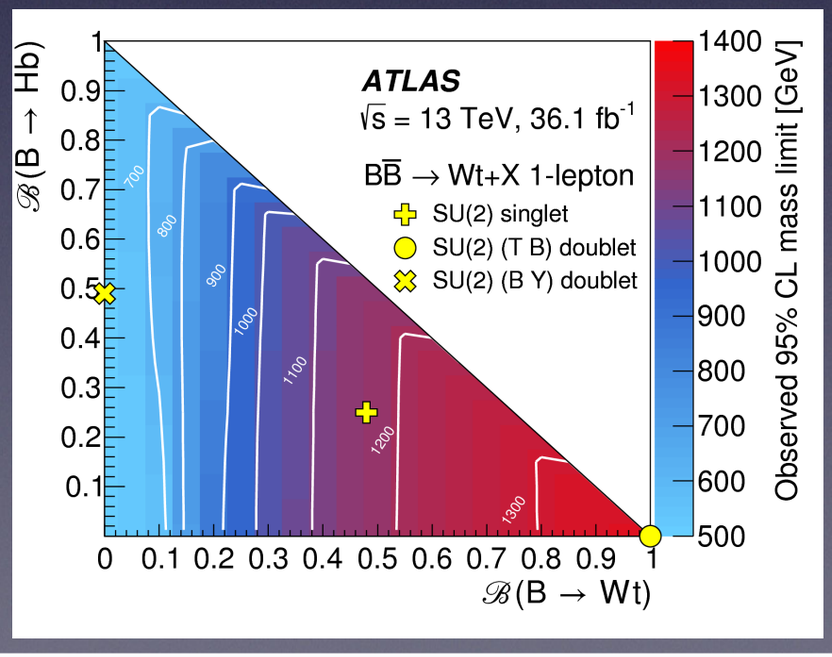
B mass reconstructed

All remaining events BDT used to discriminate against background





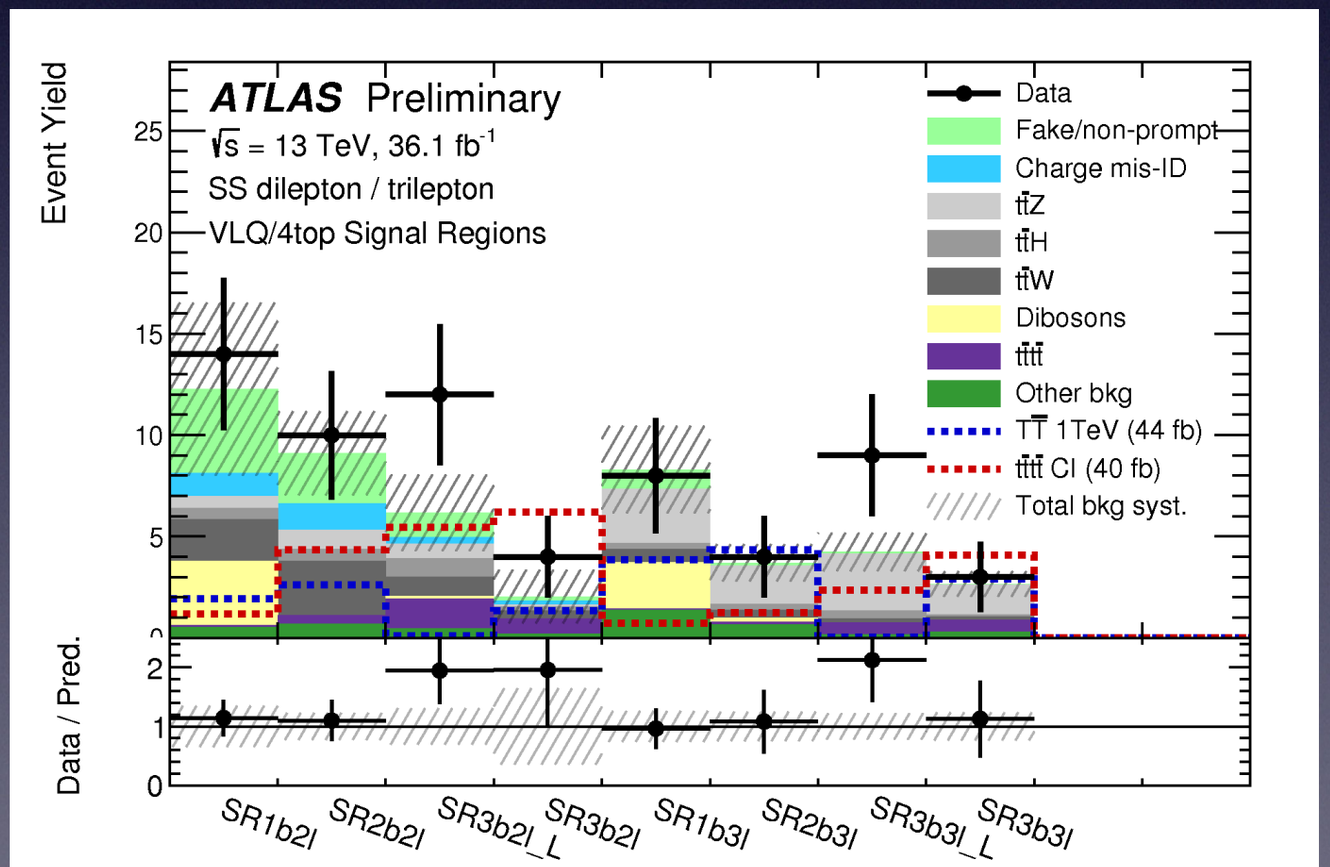




ATLAS-EXOT-2016-16 Search using same-sign leptons

- Events with 2 like-charge leptons are rare in SM
  - low background ↦ sensitive to many BSM effects, incl. VLQ
- Challenge: understanding of rare backgrounds: *e* charge mis-ID, fake/non-prompt leptons
- Multiple SRs defined
  - provides sensitivity to *B*, *T*, and $T^{5/3}$ VLQ

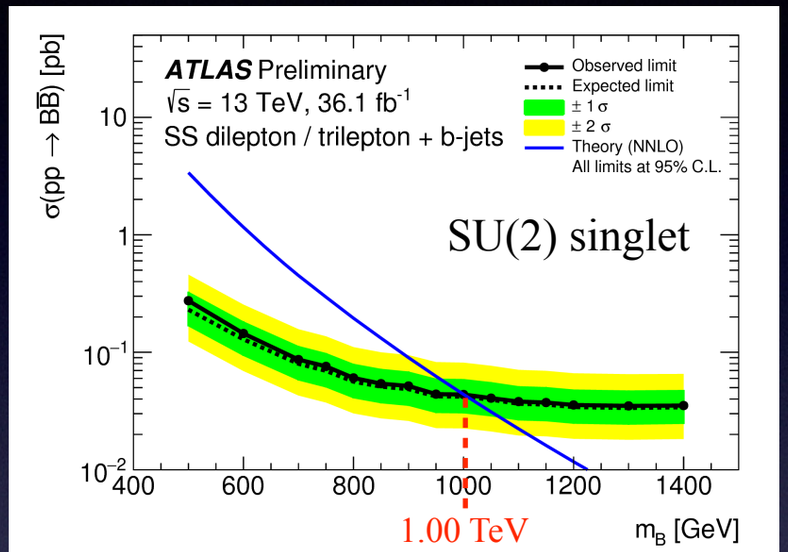
Region name	N_j	N_b	N_ℓ	Lepton charges	Kinematic criteria
VR1$b2\ell$	≥ 1	1	2	++ or −−	400 < H_T < 2400 GeV or E_T^{miss} < 40 GeV
SR1$b2\ell$	≥ 1	1	2	++ or −−	H_T > 1000 GeV and E_T^{miss} > 180 GeV
VR2$b2\ell$	≥ 2	2	2	++ or −−	H_T > 400 GeV
SR2$b2\ell$	≥ 2	2	2	++ or −−	H_T > 1200 GeV and E_T^{miss} > 40 GeV
VR3$b2\ell$	≥ 3	≥ 3	2	++ or −−	400 < H_T < 1400 GeV or E_T^{miss} < 40 GeV
SR3$b2\ell$_L	≥ 7	≥ 3	2	++ or −−	500 < H_T < 1200 GeV and E_T^{miss} > 40 GeV
SR3$b2\ell$	≥ 3	≥ 3	2	++ or −−	H_T > 1200 GeV and E_T^{miss} > 100 GeV
VR1$b3\ell$	≥ 1	1	3	any	400 < H_T < 2000 GeV or E_T^{miss} < 40 GeV
SR1$b3\ell$	≥ 1	1	3	any	H_T > 1000 GeV and E_T^{miss} > 140 GeV
VR2$b3\ell$	≥ 2	2	3	any	400 < H_T < 2400 GeV or E_T^{miss} < 40 GeV
SR2$b3\ell$	≥ 2	2	3	any	H_T > 1200 GeV and E_T^{miss} > 100 GeV
VR3$b3\ell$	≥ 3	≥ 3	3	any	H_T > 400 GeV
SR3$b3\ell$_L	≥ 5	≥ 3	3	any	500 < H_T < 1000 GeV and E_T^{miss} > 40 GeV
SR3$b3\ell$	≥ 3	≥ 3	3	any	H_T > 1000 GeV and E_T^{miss} > 40 GeV



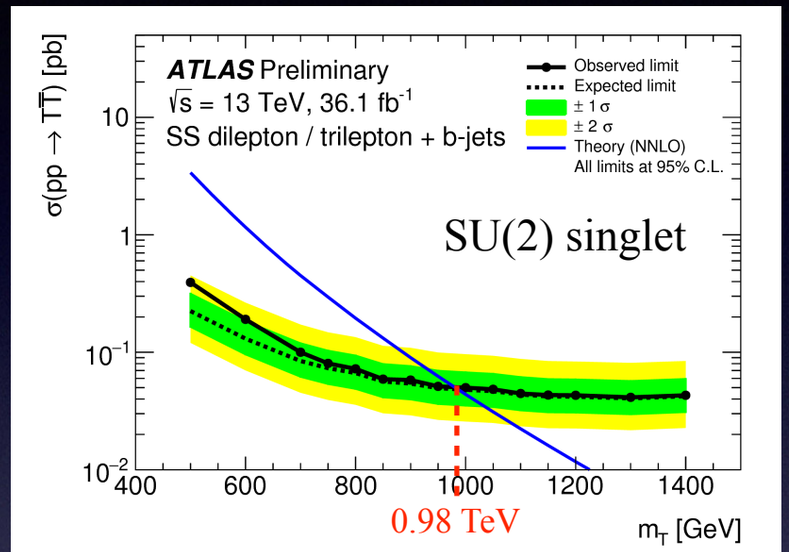
ATLAS-EXOT-2016-16 Search using same-sign leptons

- No significant excess seen. Resulting limits:

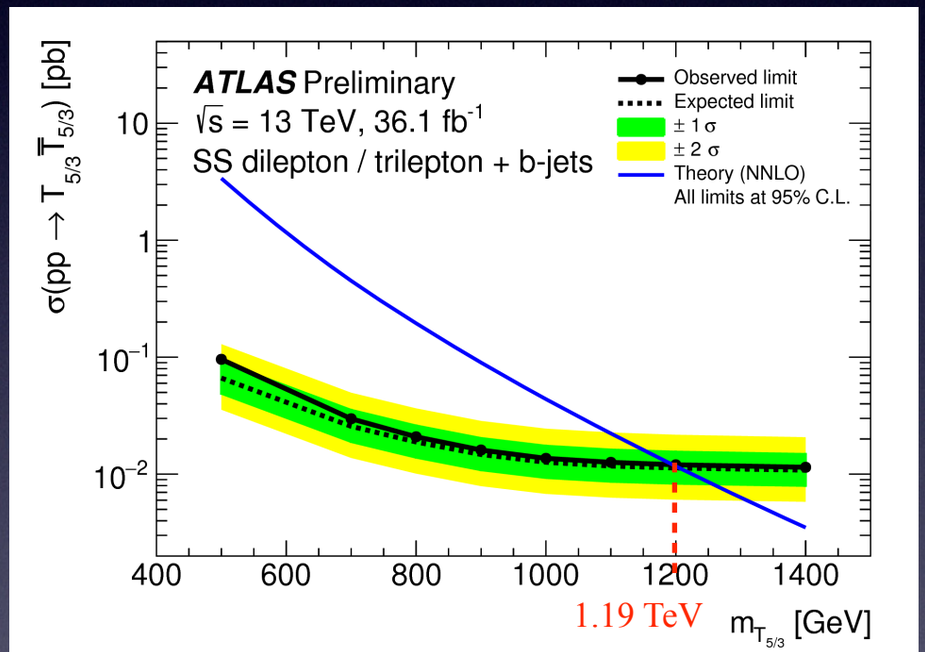
B

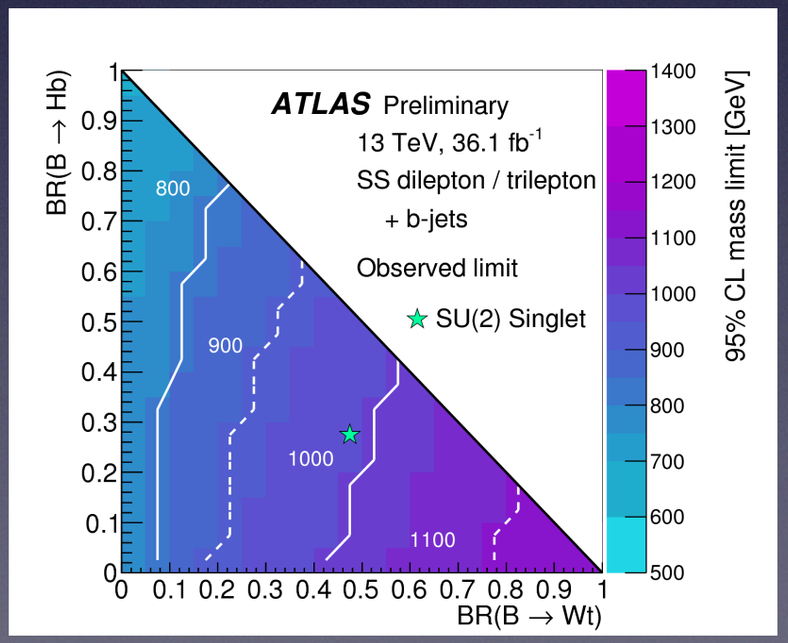


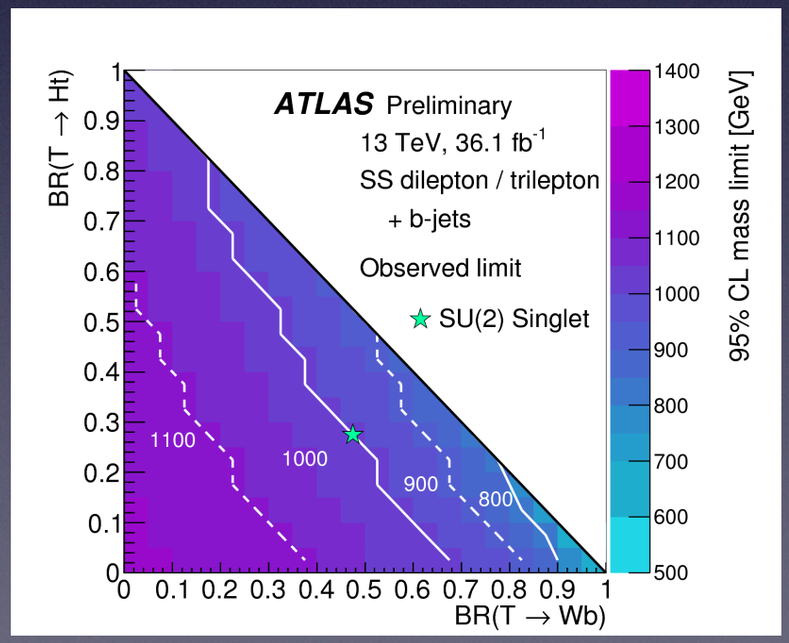
T



$T_{5/3}$

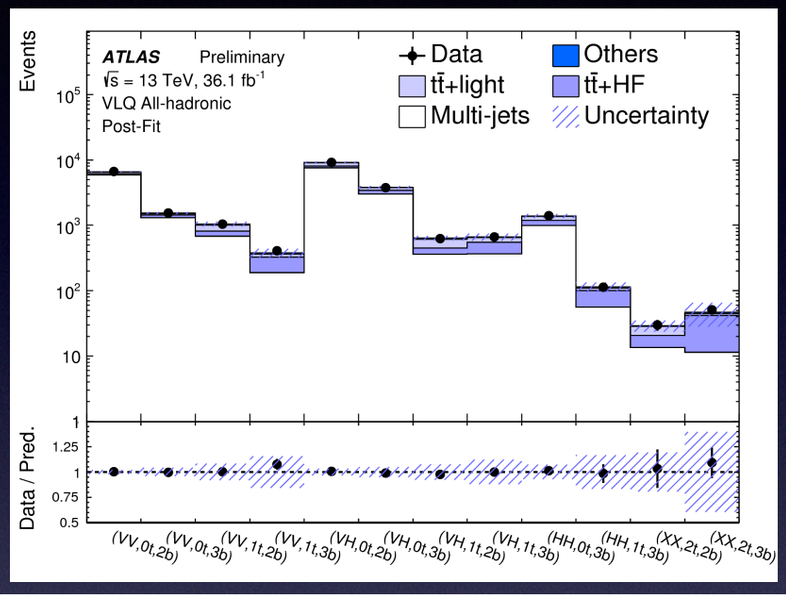


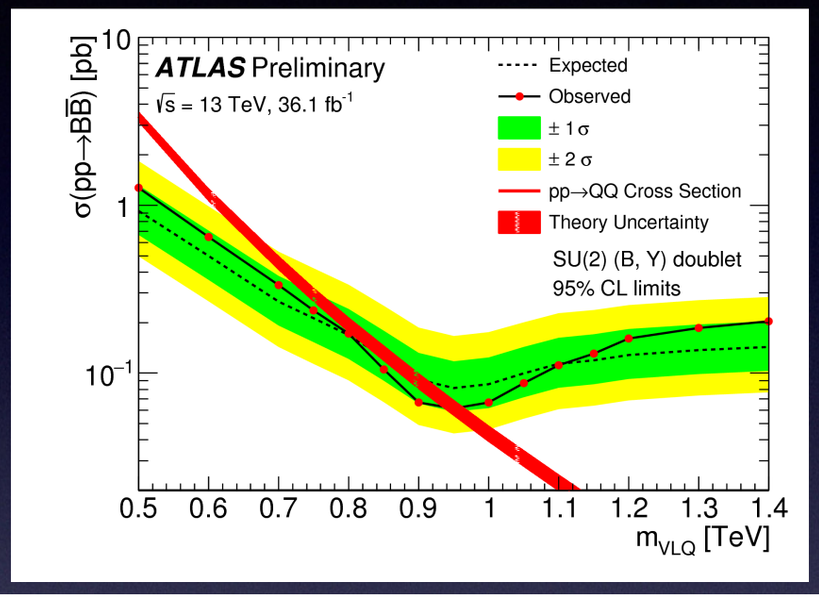


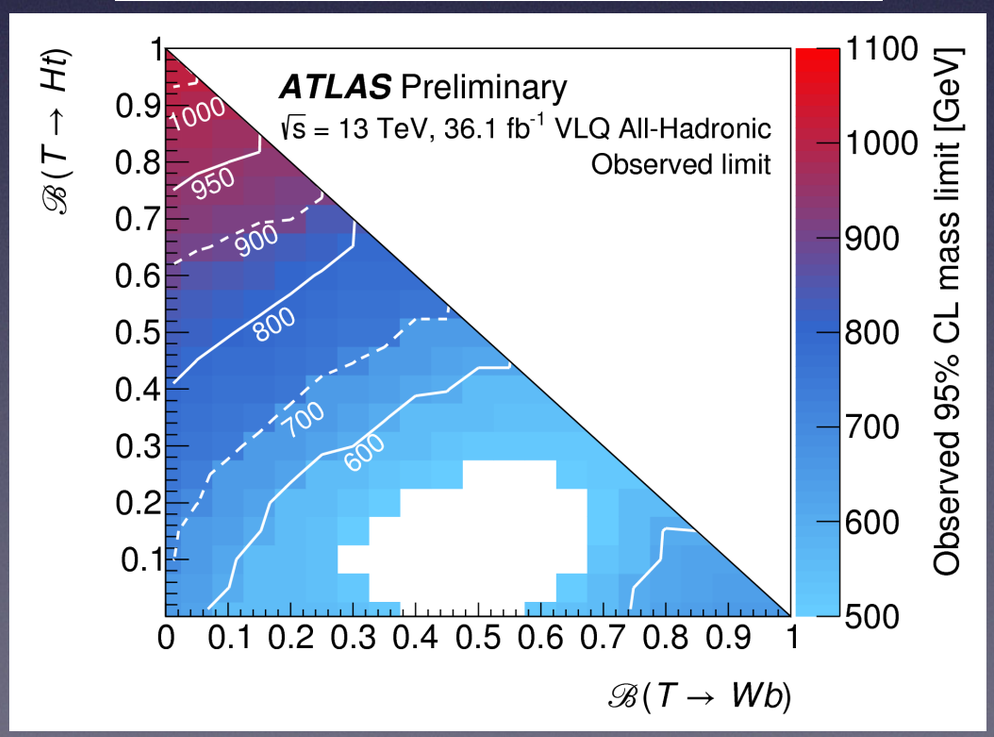


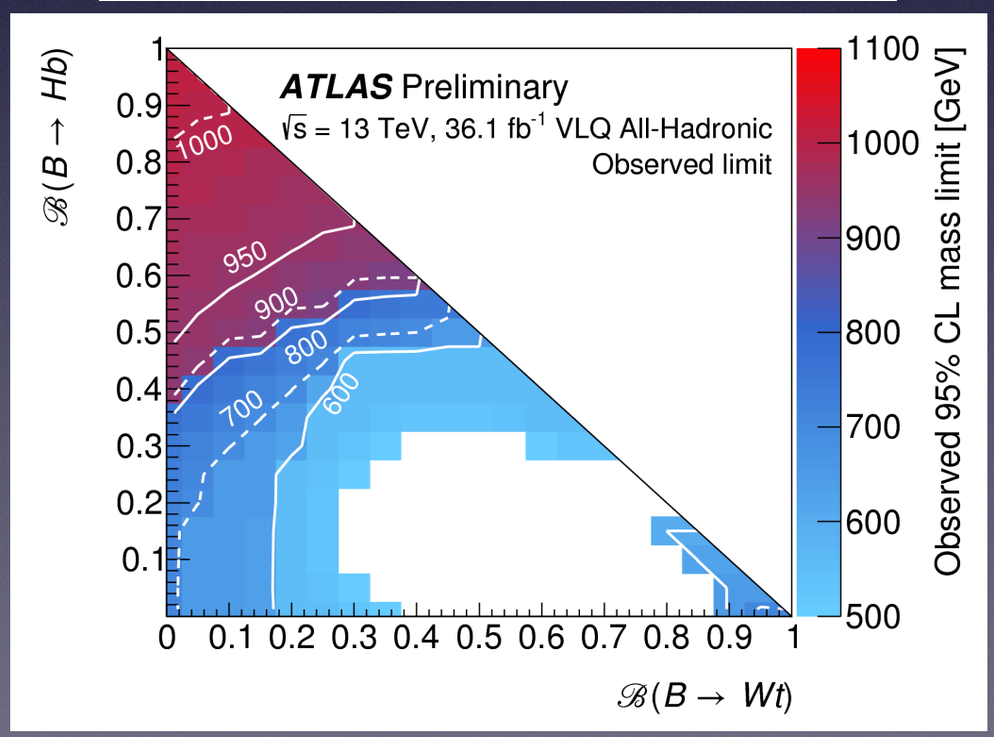
ATLAS-EXOT-2017-14 All-Hadronic Search

- Small-R jets combined into variable-size large-R jets
  - NN used to identify *W,Z,H,t,* and bkg jets





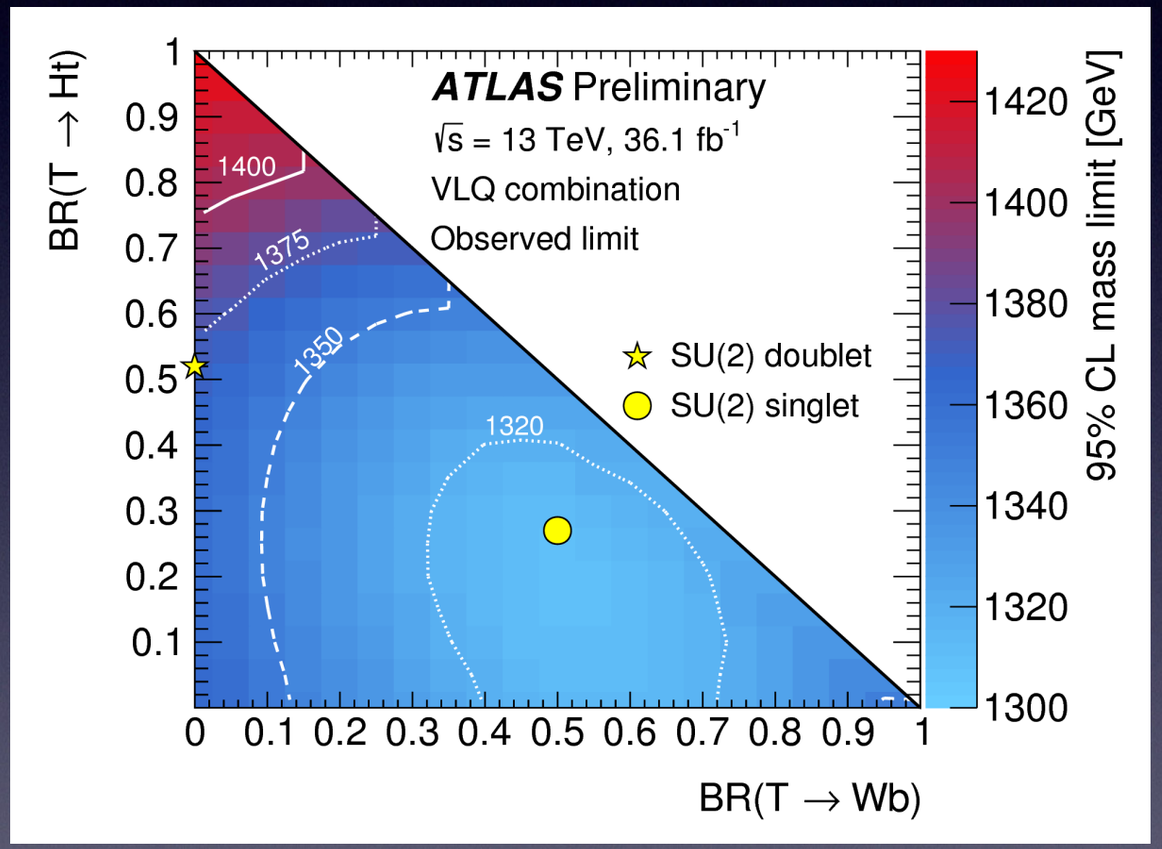




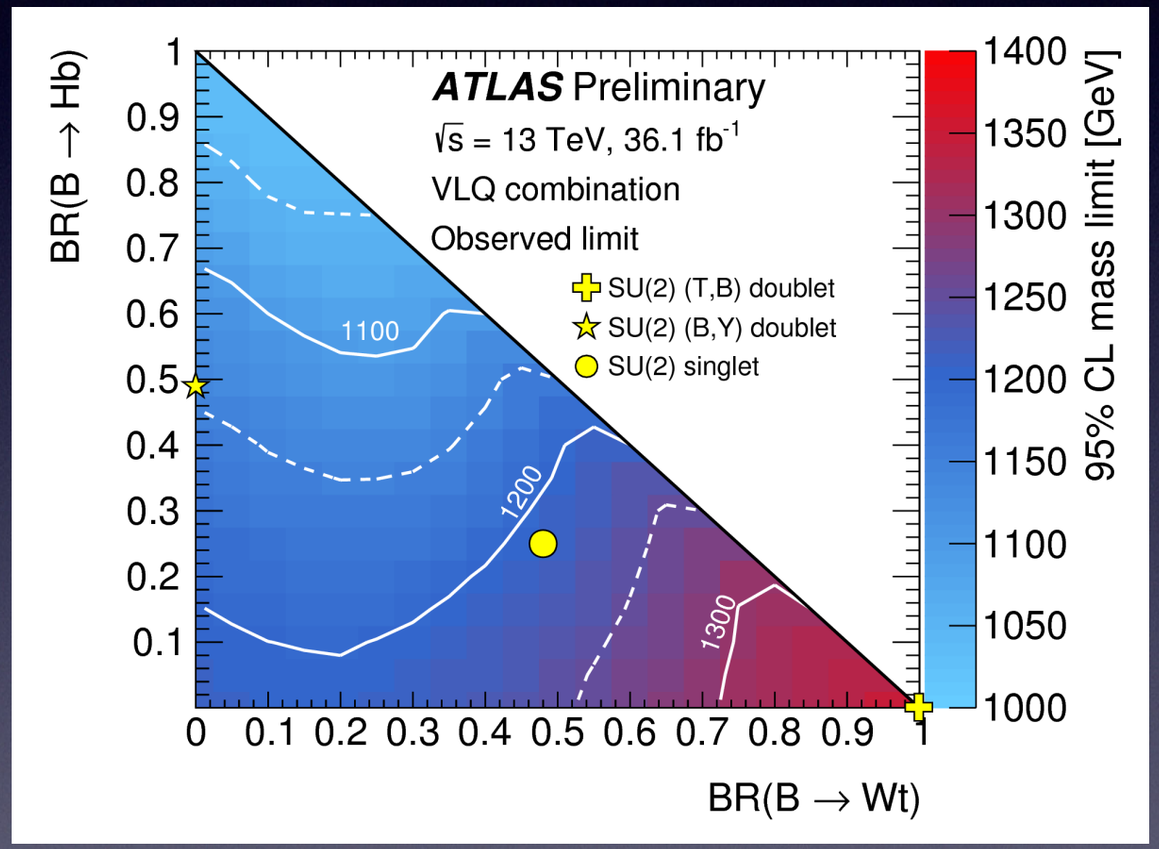
ATLAS-CONF-2018-032

$B\bar{B}$ and $T\bar{T}$ Search Combination

- Statistical combination of all the pair-production searches maximizes the sensitivity
  - selections modified in some cases to avoid overlaps



$m_T > 1.31$ TeV (singlet)
> 1.31 TeV (any BR)



$m_B > 1.22$ TeV (singlet)
> 1.03 TeV (any BR)

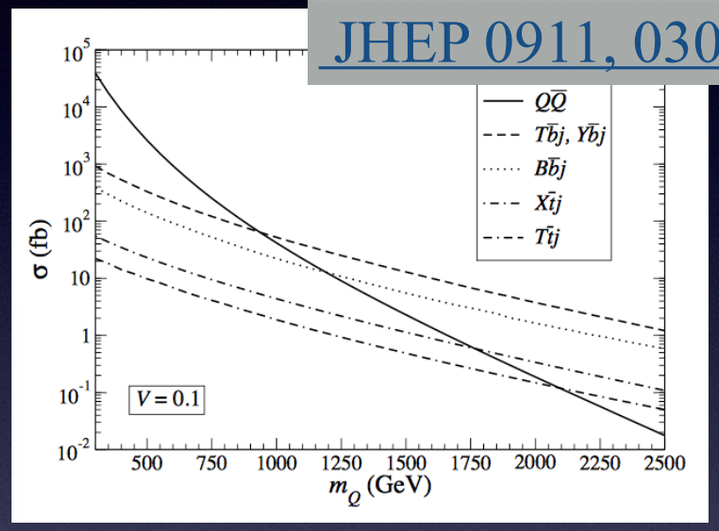
Searches for single VLQ production

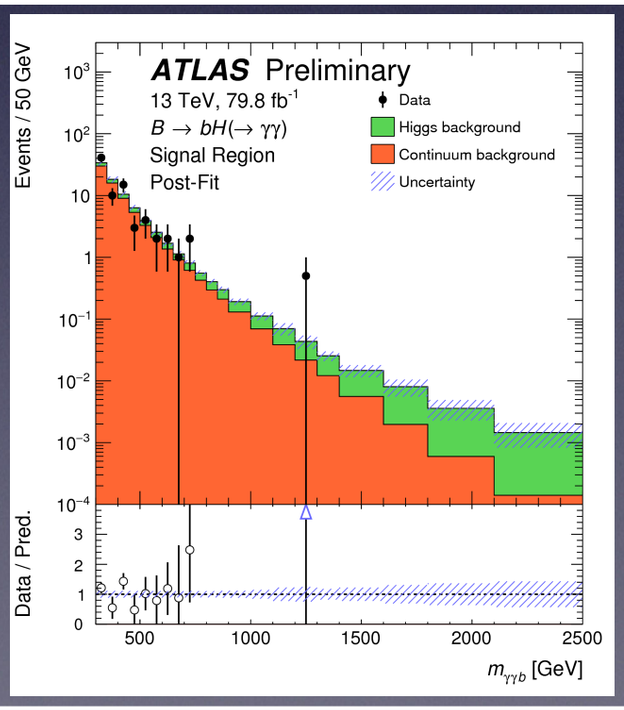
Search for single VLB production

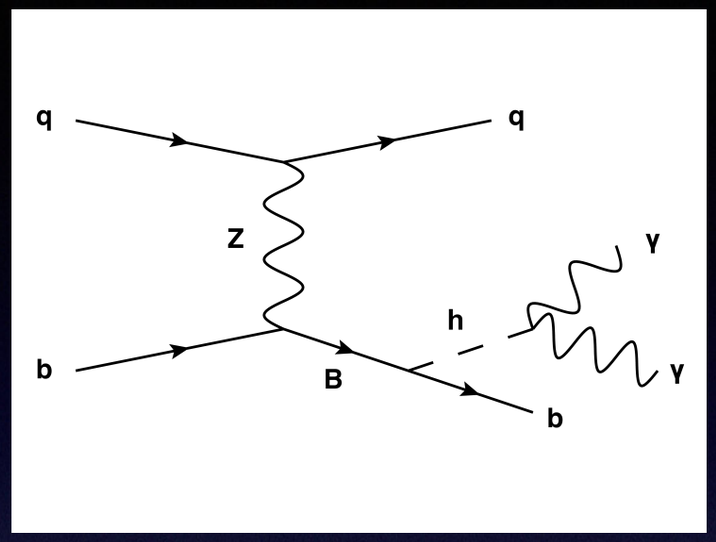
ATLAS-CONF-2018-024

- Cross section depends on VQq coupling
- Can become dominant mechanism at high VLQ mass:

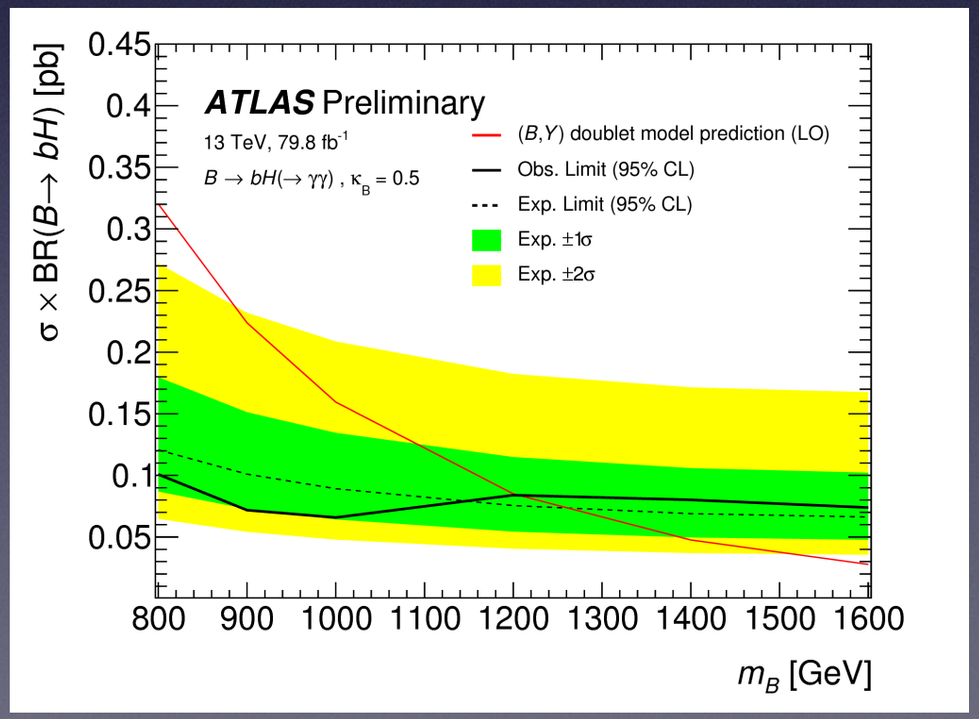
JHEP 0911, 030 (2009)







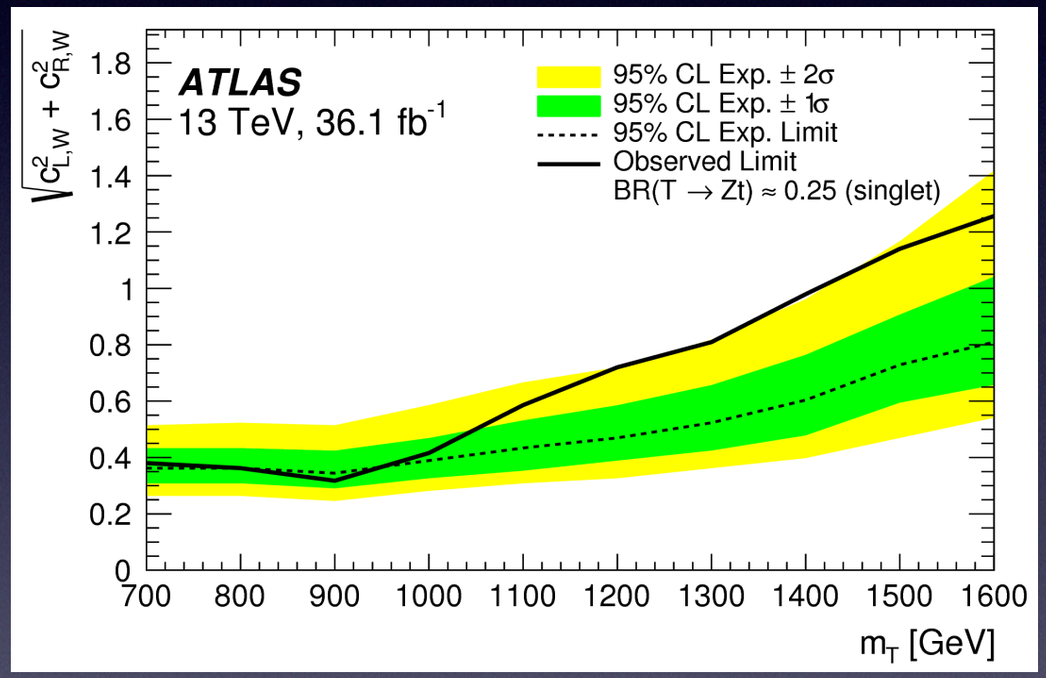
- Search focussed on $B \to H(\to \gamma\gamma)b+X$



Other single VLQ searches

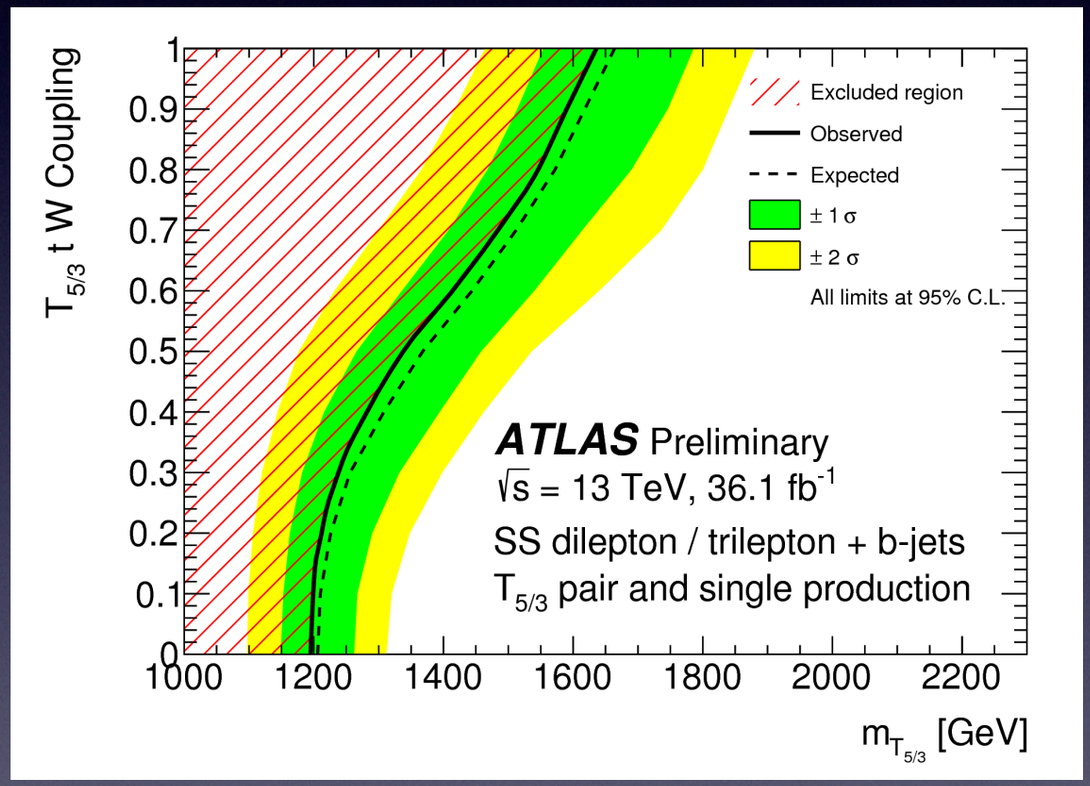
- Some of the searches already discussed can be interpreted in the context of single VLQ

T in $Z \to \ell\ell$ candidate search



ATLAS-EXOT-2016-35

$T_{5/3}$ in same-sign lepton search:



ATLAS-EXOT-2016-16

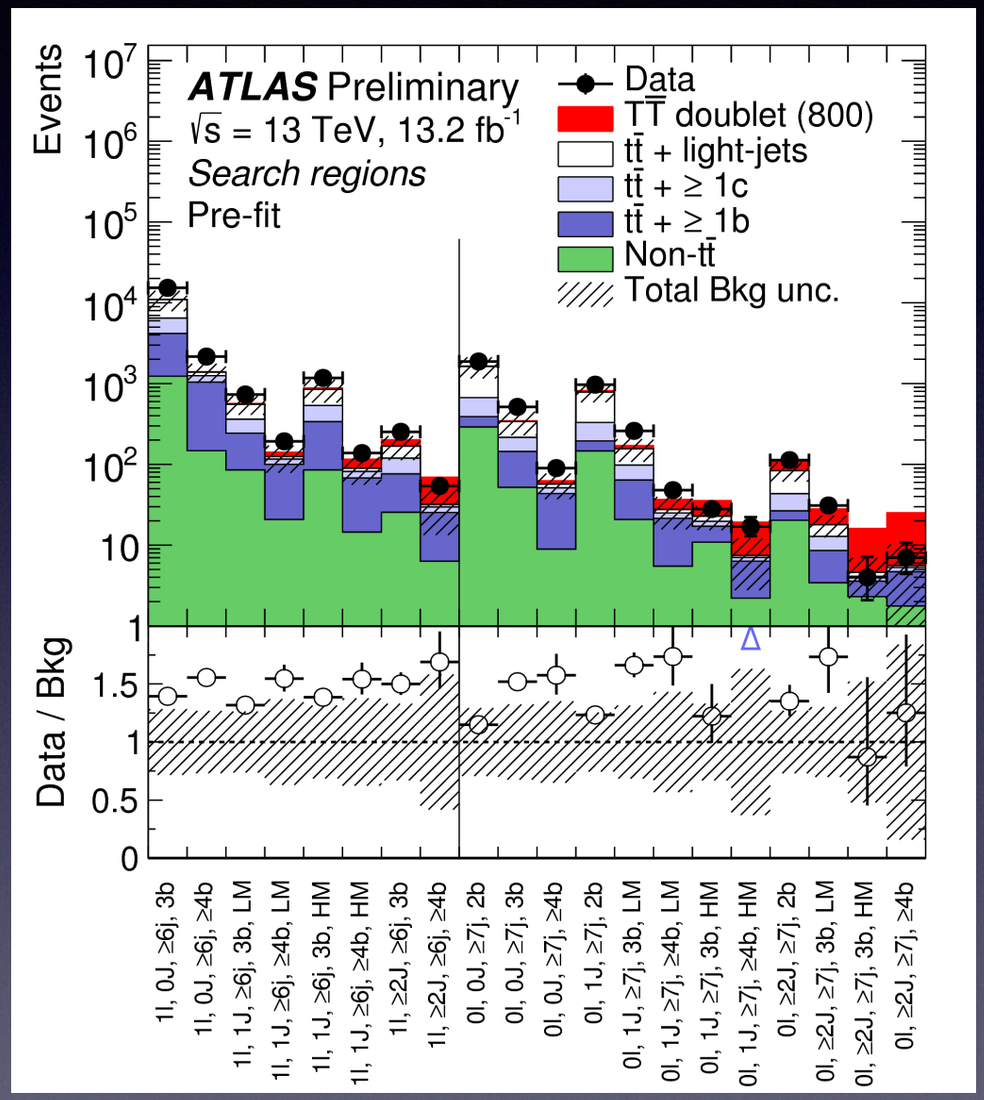
Summary

- ATLAS is pursuing a broad search for vector-like quarks
  - using multiple channels to cover all possible decay modes
- No evidence for their existence uncovered so far
  - masses below 1 TeV excluded in the most common models
- Still to come:
  - further updates using the 2017/18 data samples
    - including channels not presented here

Backup

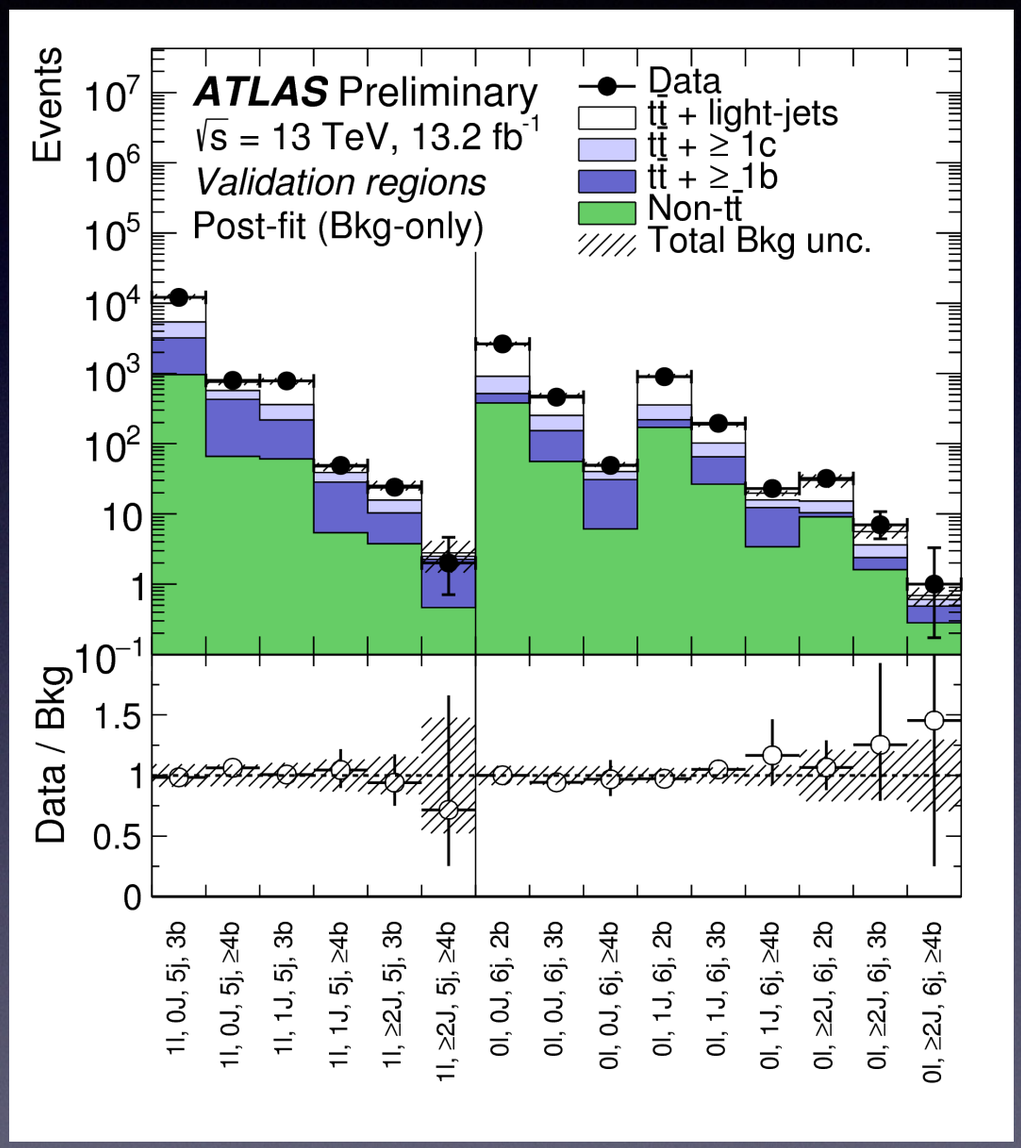
ATLAS-CONF-2016-104 Search for $T \rightarrow Ht + X$

- This analysis includes an example of the power of fitting multiple regions simultaneously



Let $t\bar{t} + \geq 1b$ normalization float

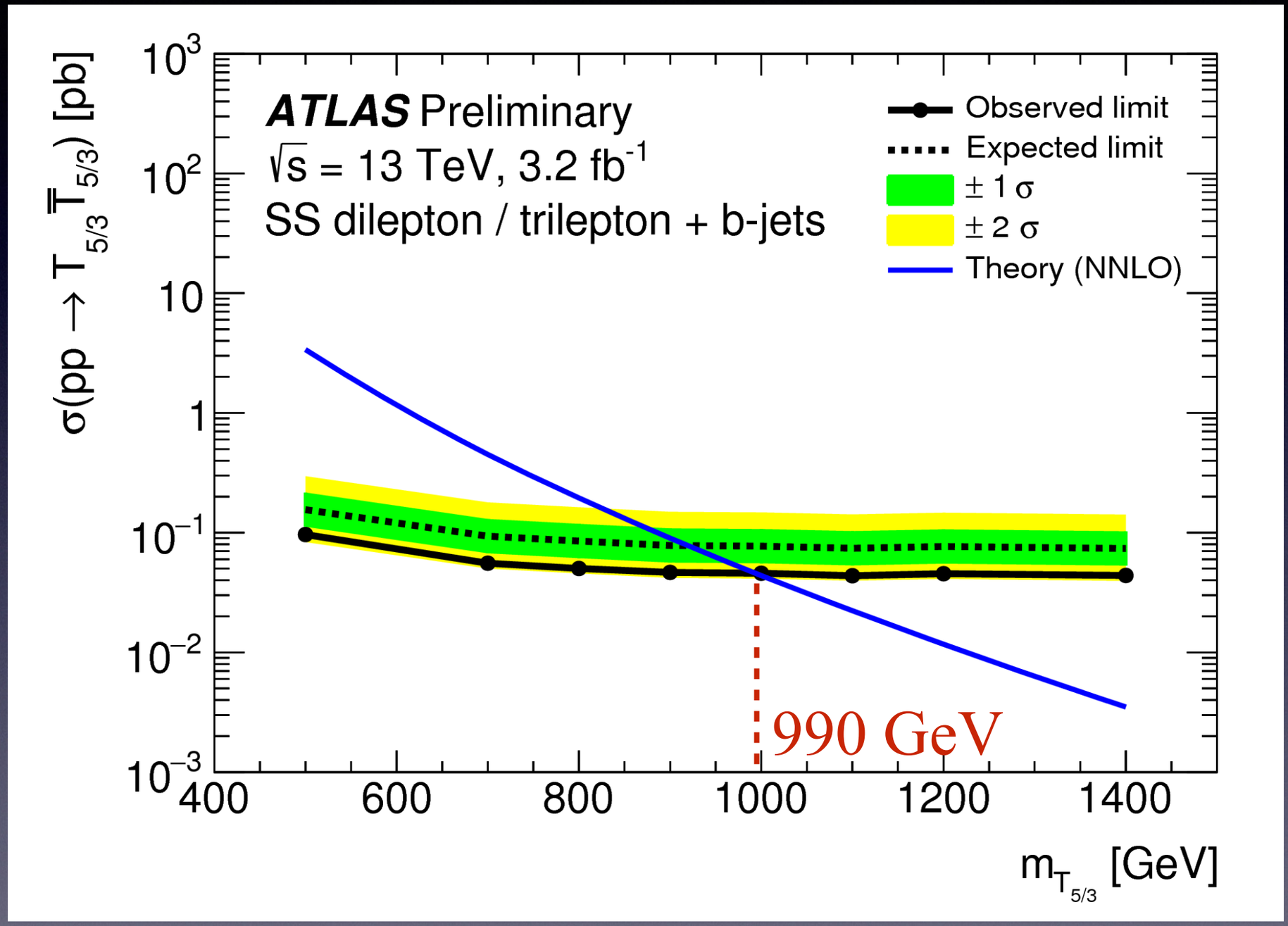
→



Fitted normalization is within initial uncertainties

ATLAS-CONF-2016-032 Search using same-sign leptons

- Limits on $T^{5/3}$ pair production:



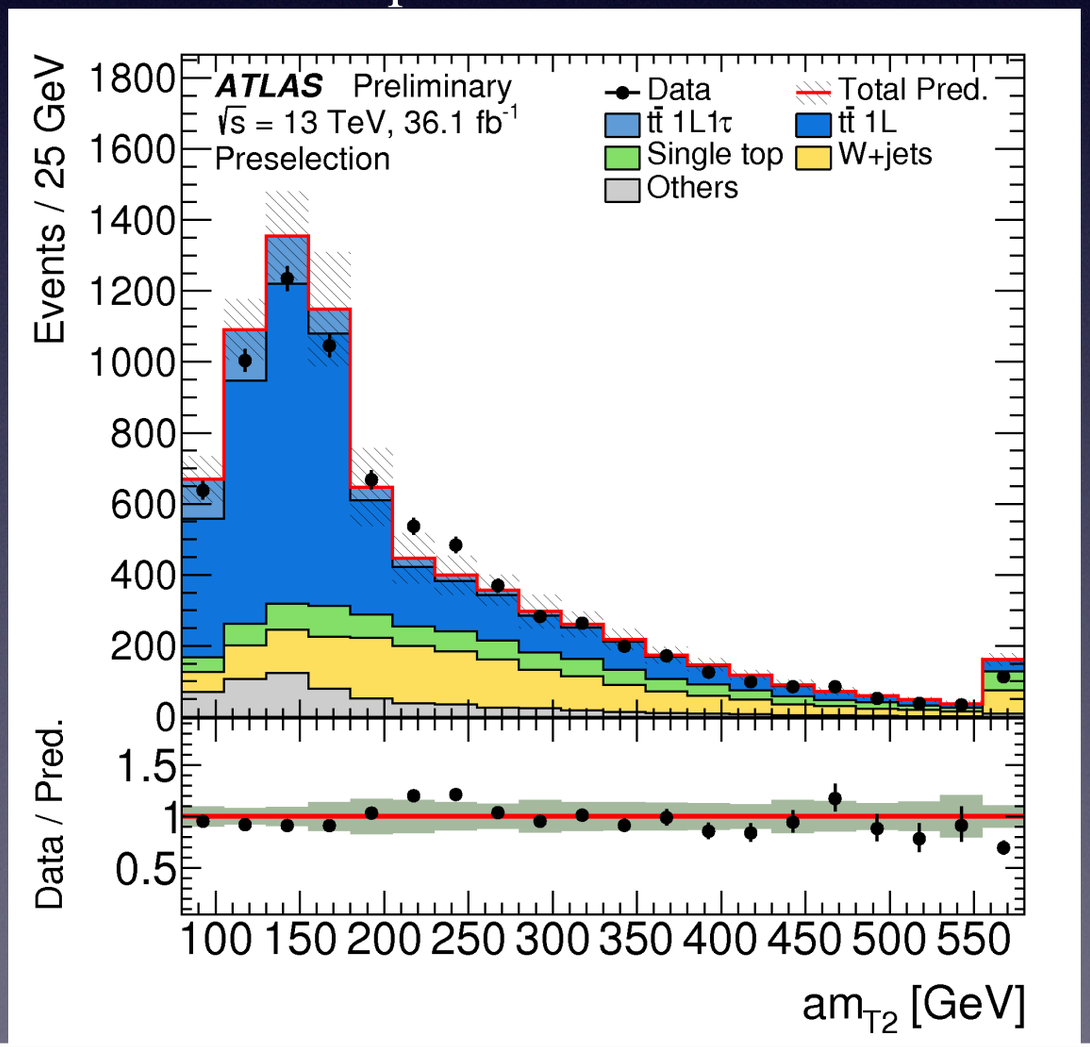
ATLAS-CONF-2017-015

Definition of m_{T2}

$$m_{T2} \equiv \min_{\vec{q}_{Ta}+\vec{q}_{Tb}=\vec{p}_T^{\,\mathrm{miss}}} \left\{ \max\left(m_{Ta}, m_{Tb} \right) \right\}$$

- Two versions used in the analysis:

For ttbar to dileptons, one lepton undetected



For W bosons decaying to hadronic tau