

# Searches for Lepto-Quarks and Vectorlike-Quarks at the ATLAS Experiment



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**2024. Apr. 10 (Wed.)**

**Tomoya Iizawa**

University of Oxford

on behalf of the ATLAS Collaboration

**DIS2024 @ Maison MINATEC, Grenoble**

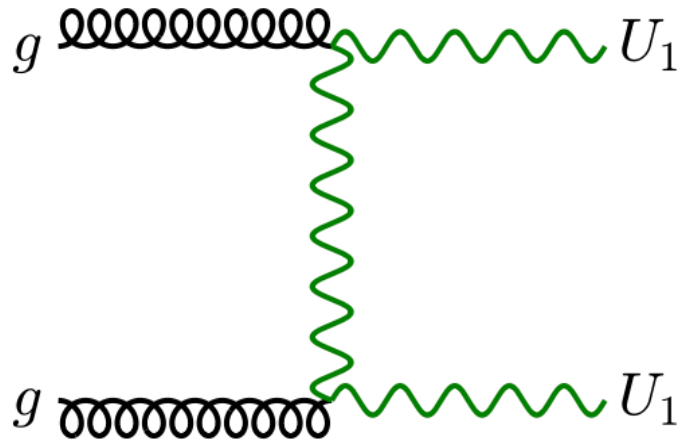


# Leptoquarks

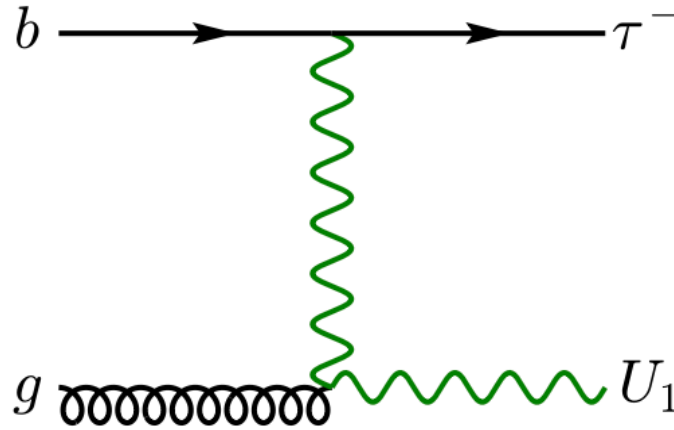


# Analysis Targets

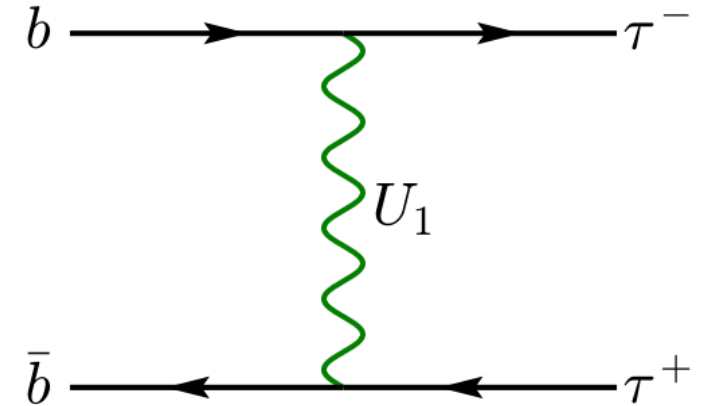
$U_1$ : Vector LQ in  $U_1$  model



Pair Production



Single Production



Non-resonant

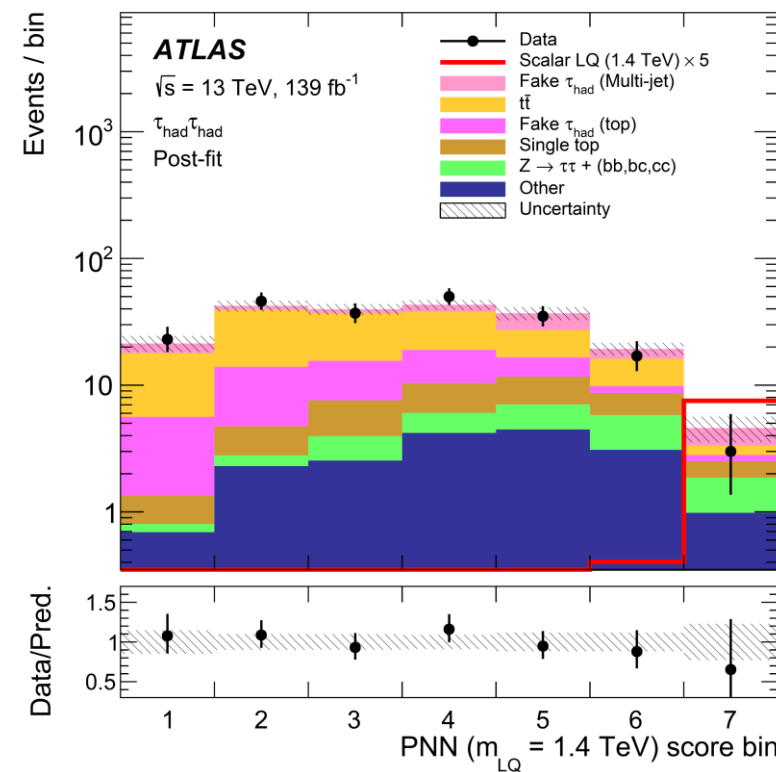
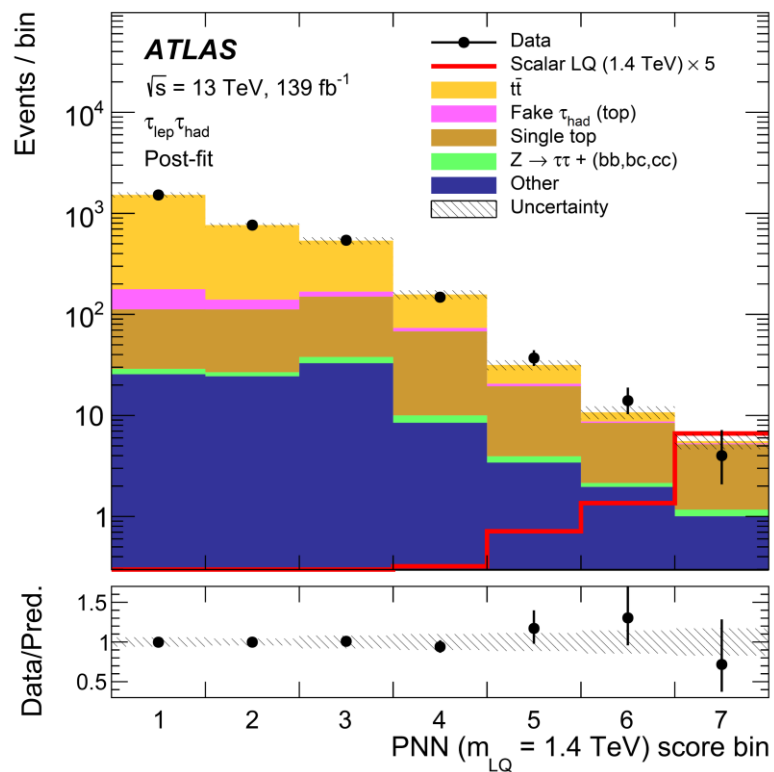
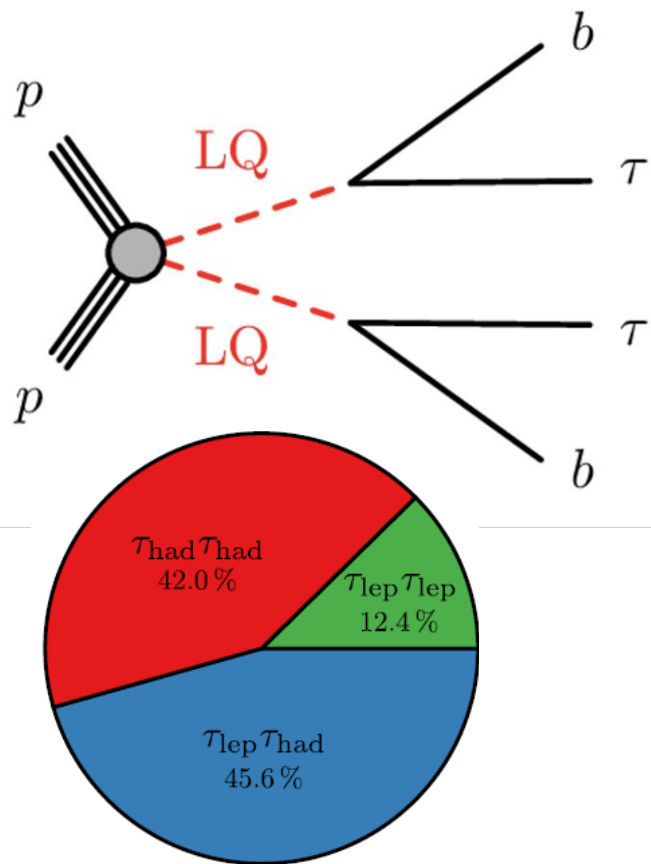
- ✓ LQs are hypothetical particles that **carry color and a fractional electric charge, decay into quark–lepton pairs.**
  - LQs appear in several BSM models, such as a part of GUT.
- ✓ **Scalar LQ** and **Vector LQ of minimal coupling scenario, Yang-Mills (YM) coupling scenario** are considered.
- ✓ LQ can be produced in pair, single, or non-resonant.
  - In this presentation, **searches targeting single- and pair- produced LQ resonant production with run-2 data.**
- ✓ Decay modes also have variations. As experimental signature,
  - **quark:** top, bottom, charm, light-jet
  - **lepton:**  $\tau$ ,  $\mu$ ,  $e$ ,  $\nu$

# Leptoquark Recent ( $\geq 2022$ ) Publications

- ✓ Pair-produced scalar and vector LQs decaying to 3rd-gen quarks and 1st/2nd-gen leptons ([Link](#))
- ✓ **Leptoquark pair production in  $b\tau b\tau$  final states** ([Link](#))
- ✓ Excited tau and leptoquark search (2taus+2jets) ([Link](#))
- ✓ **Search for single scalar leptoquark production in the  $b\tau b\tau$  final state** ([Link](#))
- ✓ Search for leptoquarks decaying to a top quark and a light lepton ([Link](#))
- ✓ **Combination of searches for pair-produced leptoquarks in final states with b-tagged jets** ([Link](#))
- ✓ Search for charged lepton flavour violation in top quark production and decay ([Link](#))
- ✓ Exotics Run 2 physics report ([Link](#))
  
- ✓ You can find all the ATLAS results in [ATLAS public results page](#)
- ✓ **The ones shown in red are introduced in the next pages, which are picked up by my bias!**

# Pair Production, Decaying to $b\tau b\tau$

[Link](#)

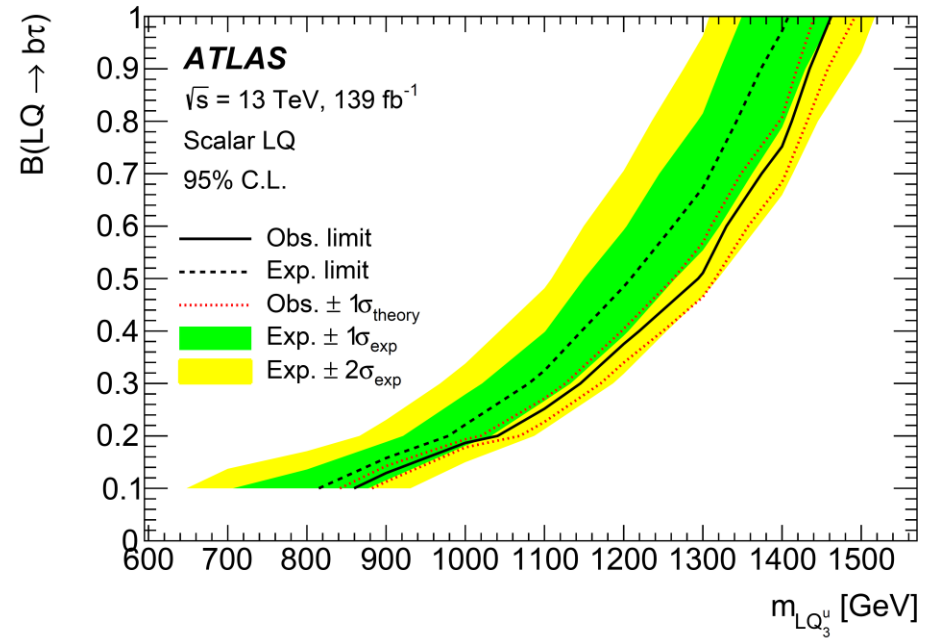
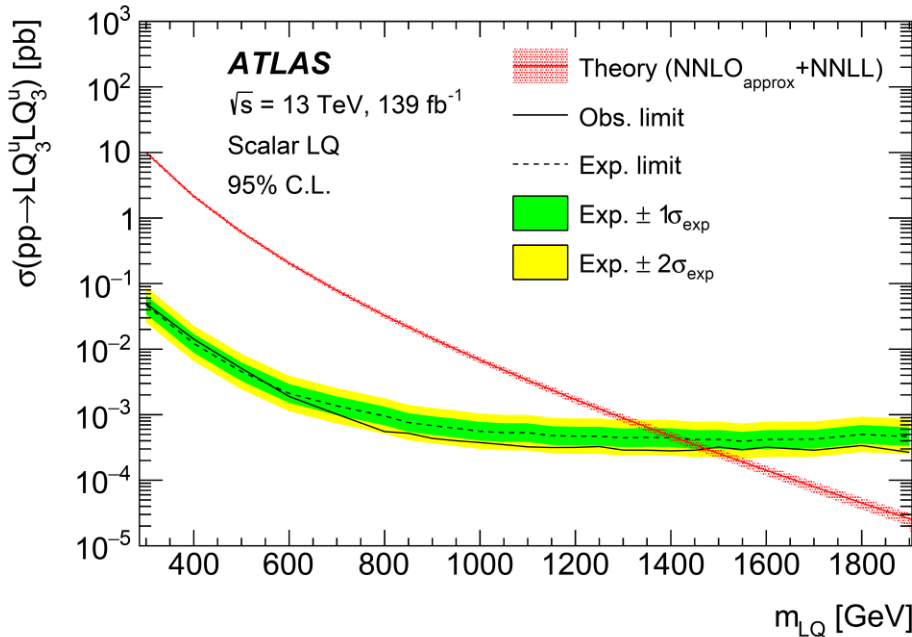


Variable	$\tau_{\text{lep}}\tau_{\text{had}}$ channel	$\tau_{\text{had}}\tau_{\text{had}}$ channel
$\tau_{\text{had-vis}} p_{\text{T}}^0$	✓	✓
$s_{\text{T}}$	✓	✓
$N_{b\text{-jets}}$	✓	✓
$m(\tau, \text{jet})_{0,1}$		✓
$m(\ell, \text{jet}), m(\tau_{\text{had}}, \text{jet})$	✓	
$\Delta R(\tau, \text{jet})$	✓	✓
$\Delta\phi(\ell, E_{\text{T}}^{\text{miss}})$	✓	
$E_{\text{T}}^{\text{miss}} \phi$ centrality	✓	✓

- ✓ Full hadronic  $\tau_{\text{had}}\tau_{\text{had}}$  and semi-leptonic  $\tau_{\text{lep}}\tau_{\text{had}}$  (lep = e,  $\mu$ ) channels.
- ✓ Higher energy phase space is selected by  $p_{\text{T}}, E_{\text{T}}^{\text{miss}}$ , scalar sum of  $p_{\text{T}}$  ( $s_{\text{T}}$ ).
- ✓ Top modeling is reweighted, fake  $\tau$  ID is corrected, multi-jet fakes are estimated by data-driven Fake Factor (FF) method.
- ✓ Parametric Neural Network (PNN) is used to separate signal and bkg.
  - PNN is used as final discriminant variable.

# Pair Production, Decaying to $b\tau b\tau$

[Link](#)



	Obs. limit [GeV]	Exp. limit [GeV]
Scalar LQ	1460	1410
Vector LQ (minimal-coupling)	1650	1590
Vector LQ (Yang–Mills)	1910	1820

- ✓ Binned Profile Likelihood fit is performed for PNN score distribution.
  - No significant excess over SM expectation is observed. 95% confidence-level upper limits are set.
- ✓ **Significantly improve the sensitivity mainly due to upgraded  $\tau$  and b-jet identification, improved MVA.**

# Pair Production, Combination

[Link](#)

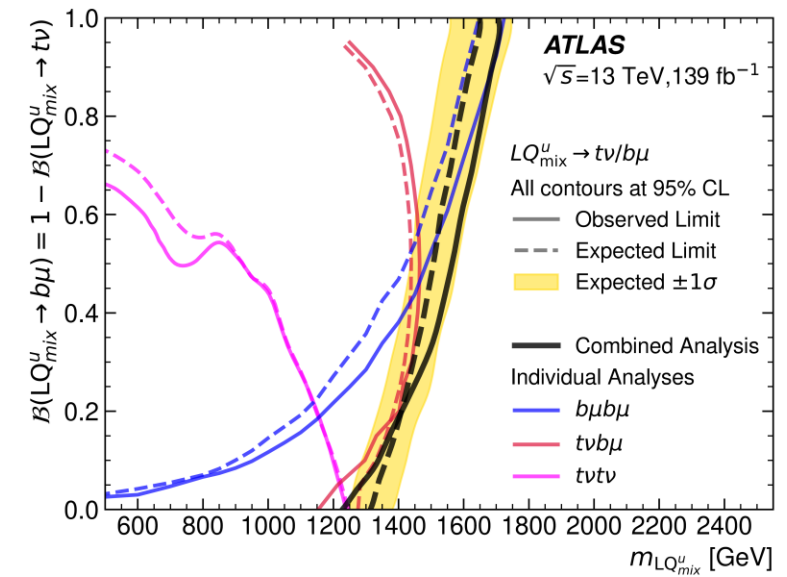
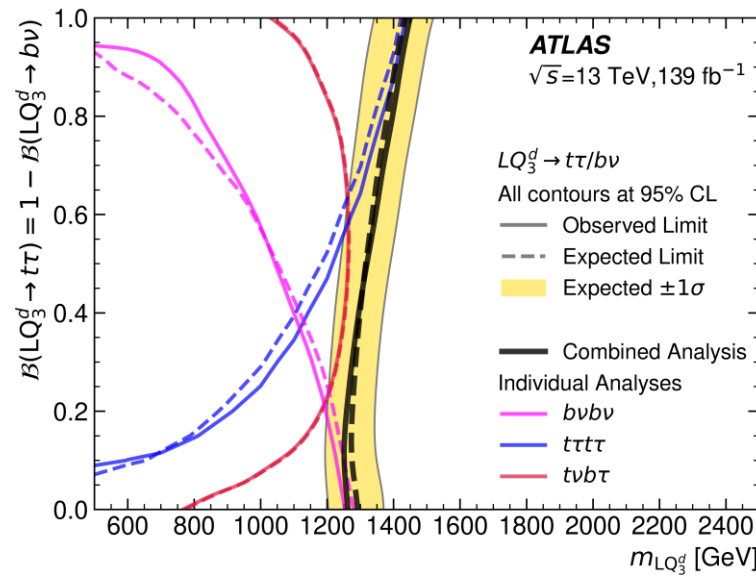
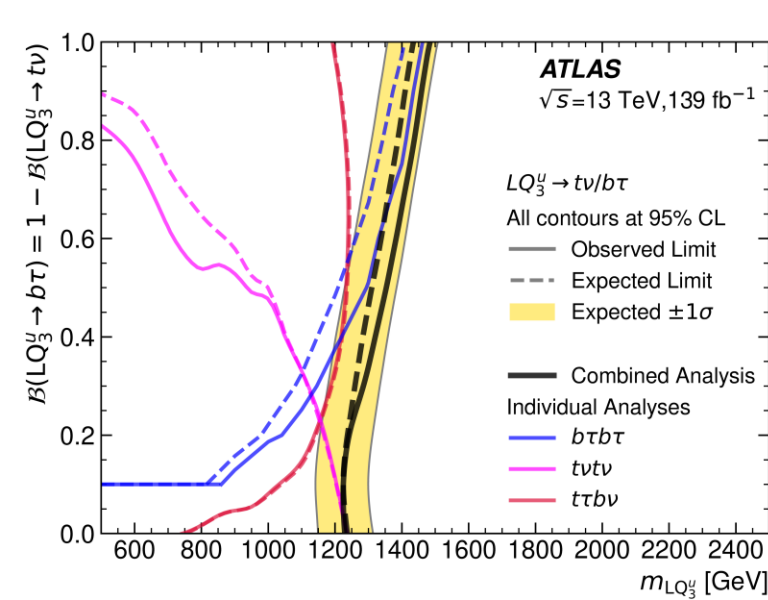
Search		Interpretation						Signal Region		
		Scalar		Vector						
Final State	Citation	$LQ_3^u$	$LQ_3^d$	$LQ_{\text{mix}}^u$	$LQ_{\text{mix}}^d$	$U_1^{\text{YM/MC}}$	$\tilde{U}_1^{\text{YM/MC}}$	$N_\ell$	$N_{\tau_{\text{had}}}$	$N_{b\text{jets}}$
$t\nu b\tau$		✓	✓	–	–	✓	–	0	1	$\geq 2$
$b\tau b\tau$		✓	–	–	–	✓	–	{0, 1}	{1, 2}	{1, 2}
$t\tau t\tau$		–	✓	–	–	–	✓	{1, 2, 3}	$\geq 1$	$\geq 1$
$t\nu b\ell$		–	–	✓	✓	–	–	1	–	$\geq 1$
$b\ell b\ell$		–	–	✓	–	–	–	2	–	{0, 1, 2}
$t\ell t\ell$ (2 $\ell$ )		–	–	–	✓	–	–	2	–	–
$t\ell t\ell$ ( $\geq 3\ell$ )		–	–	–	✓	–	–	{3, 4}	–	$\geq 2$
$t\nu t\nu$		✓	–	✓	–	✓	–	0	0	$\geq 2$
$b\nu b\nu$		–	✓	–	✓	–	–	0	–	$\geq 2$

- ✓ **A statistical combination** of various searches for pair-produced leptoquarks.
- ✓ All possible decays of the leptoquarks into **quarks of the third generation and charged or neutral leptons** of any generation are investigated.
- ✓ Overlap among regions, systematics effects are carefully checked.



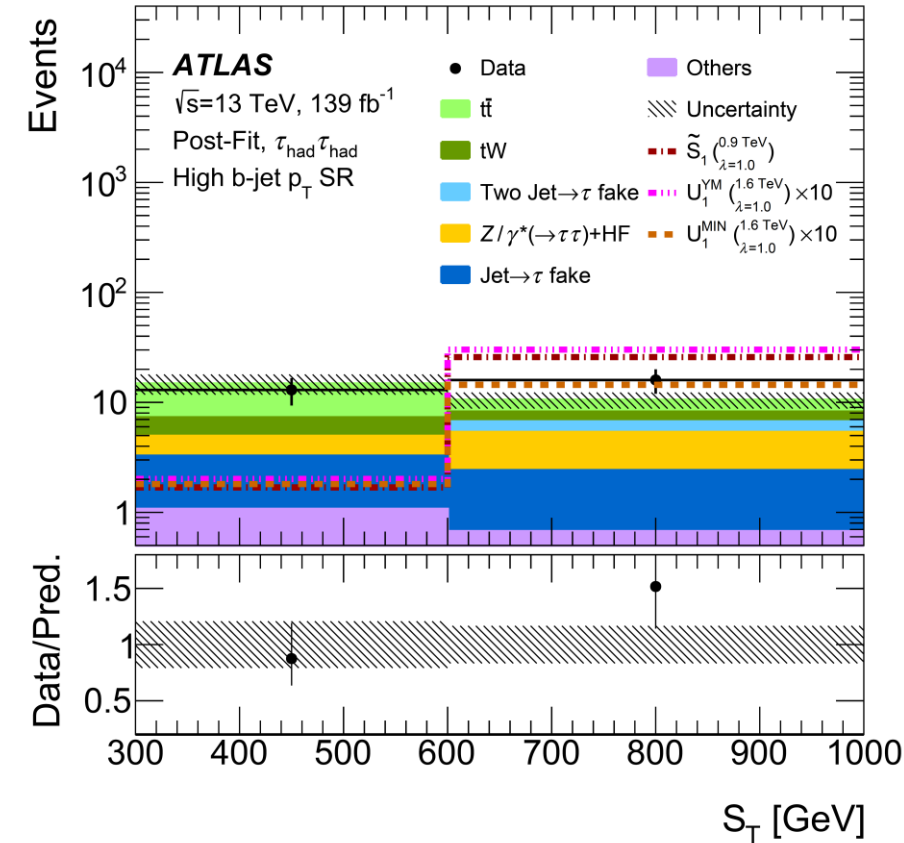
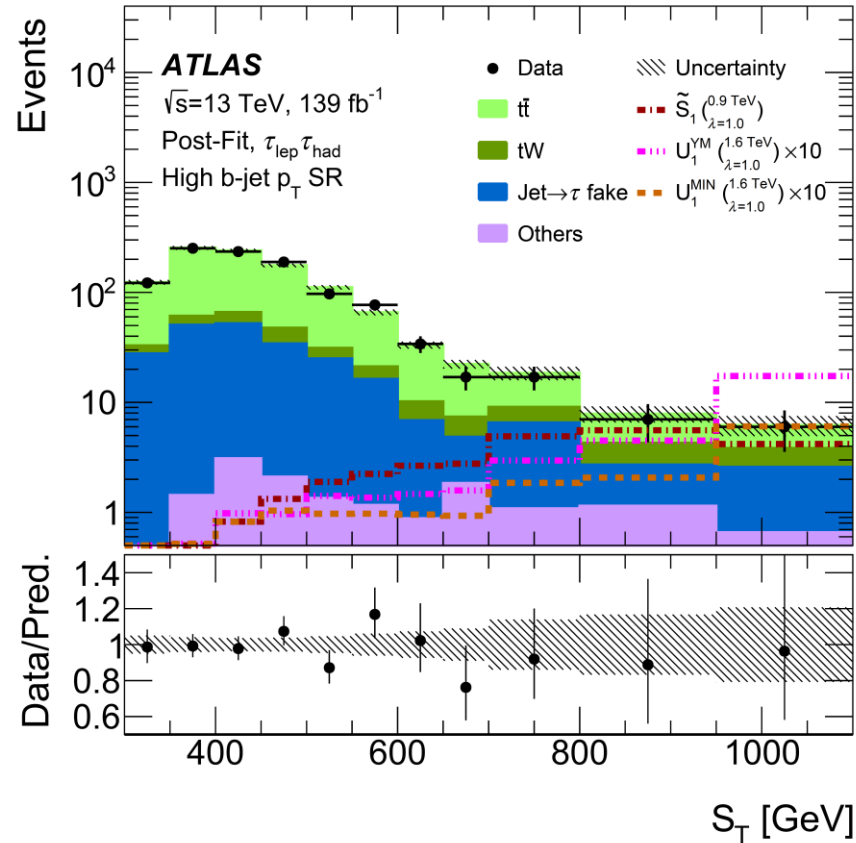
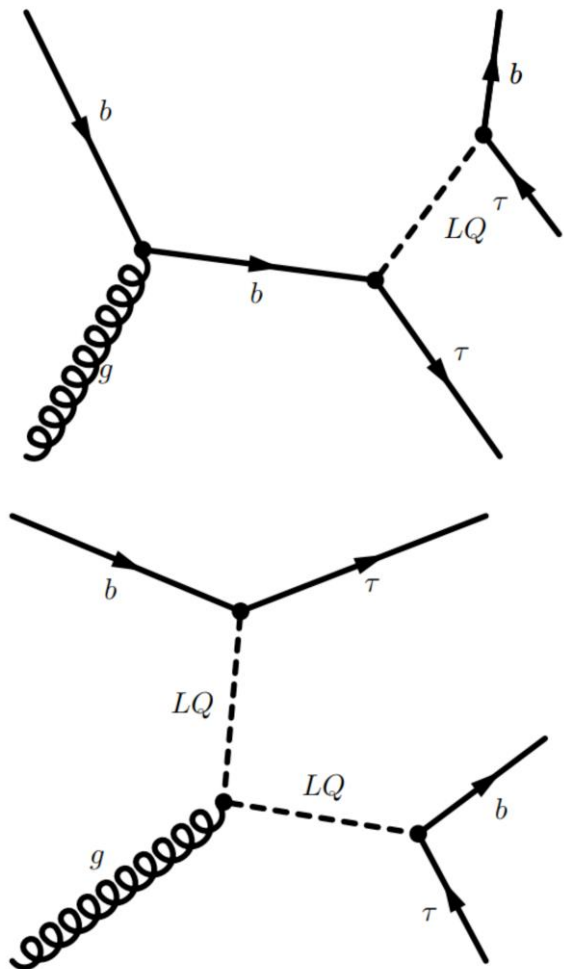
# Pair Production, Combination

[Link](#)



- ✓ Simultaneous binned profile-likelihood fits are performed to CRs and SRs.
- ✓ **The resulting lower bounds on leptoquark masses exceed those from the individual analyses by up to 100 GeV, depending on the signal hypothesis.**
- ✓ **For most combinations of the parameters, these are the best limits to date!**

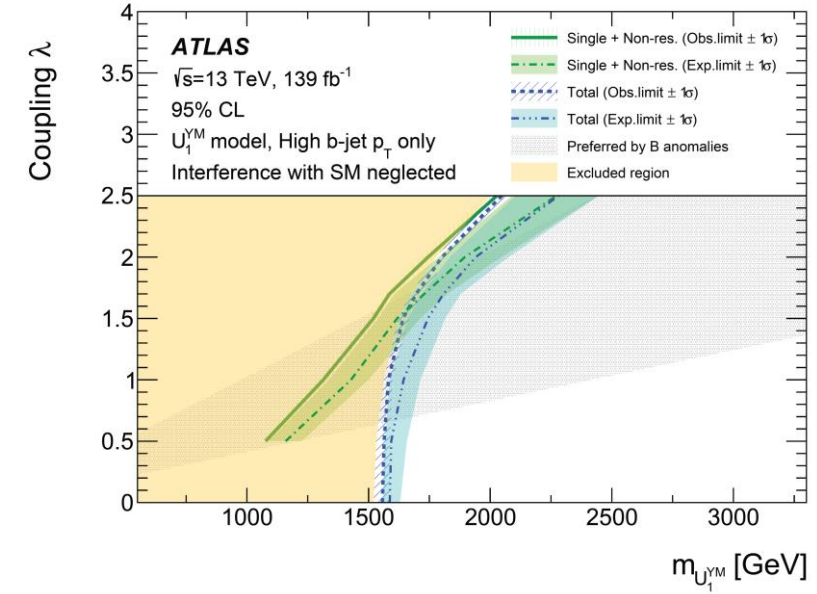
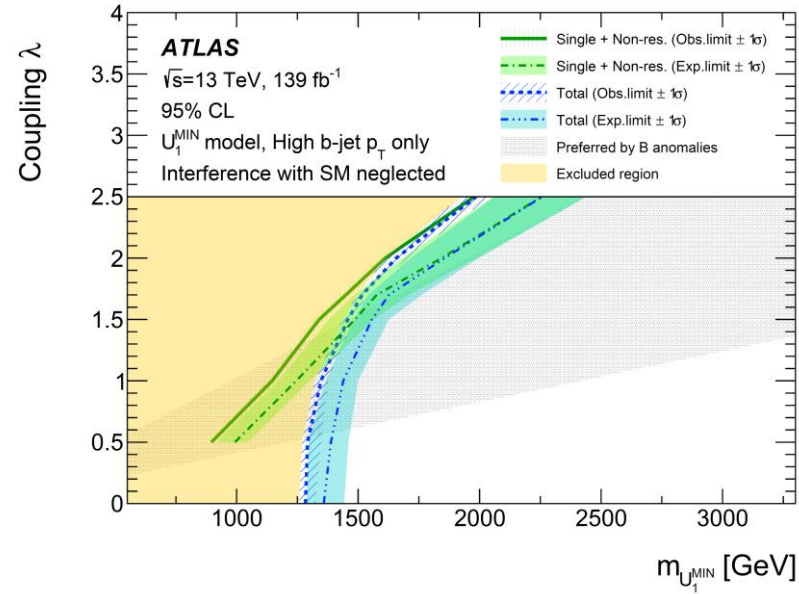
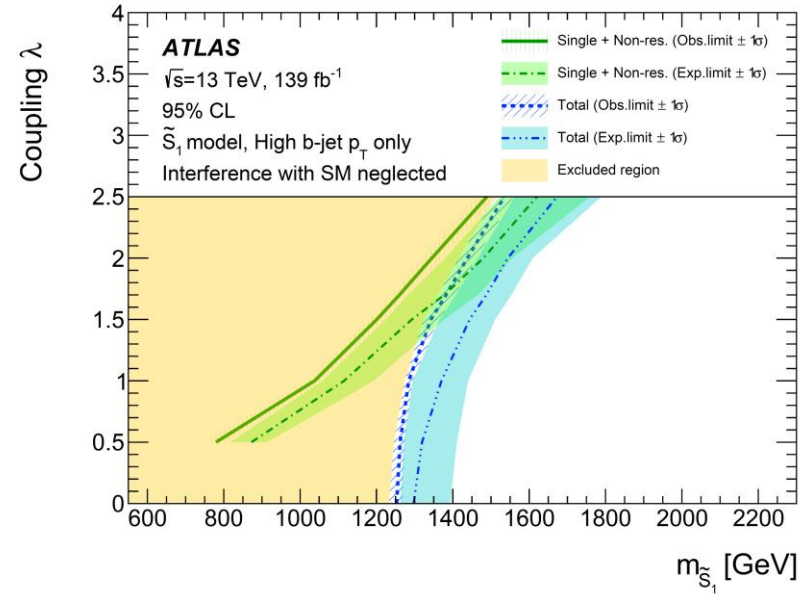
# Single Production, Decaying to $b\tau\tau$ [Link](#)



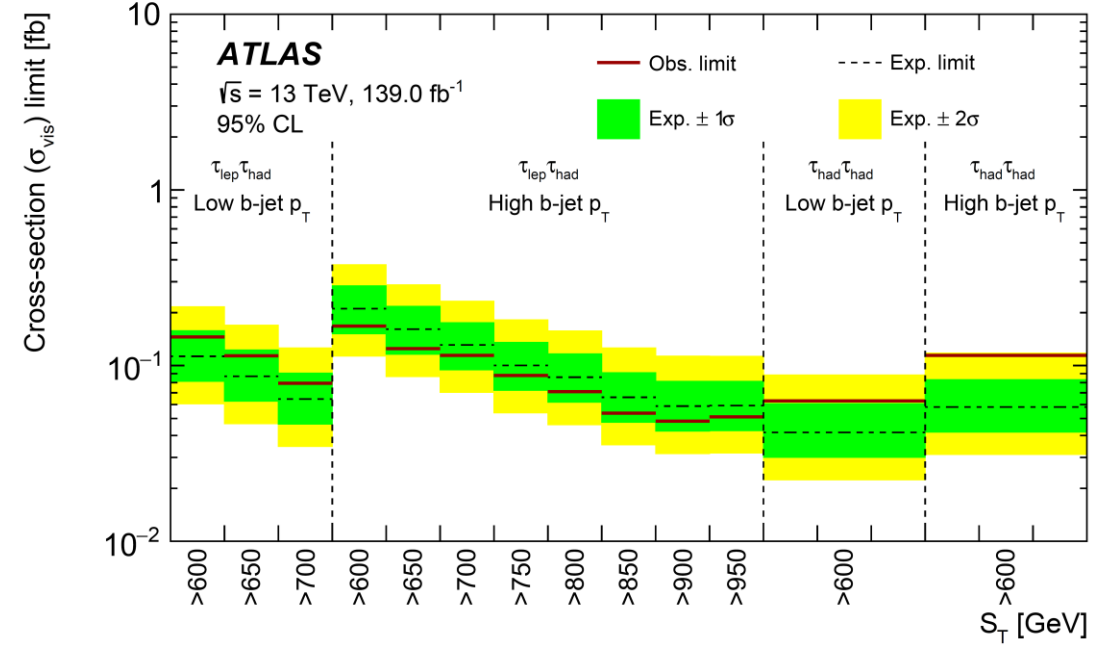
✓ The single production contribution becomes larger than that from pair production at high mass and coupling values.

- ✓ Higher energy phase space is selected by  $p_T$ ,  $E_T^{miss}$ , scalar sum of  $p_T$  of all the reconstructed objects ( $S_T$ ).
- ✓ Top modeling is reweighted, fake  $\tau$  ID is corrected, multi-jet fakes are estimated by data-driven FF method.
- ✓  $S_T$  is used as final discriminant variable.

# Single Production, Decaying to $b\tau\tau$ [Link](#)



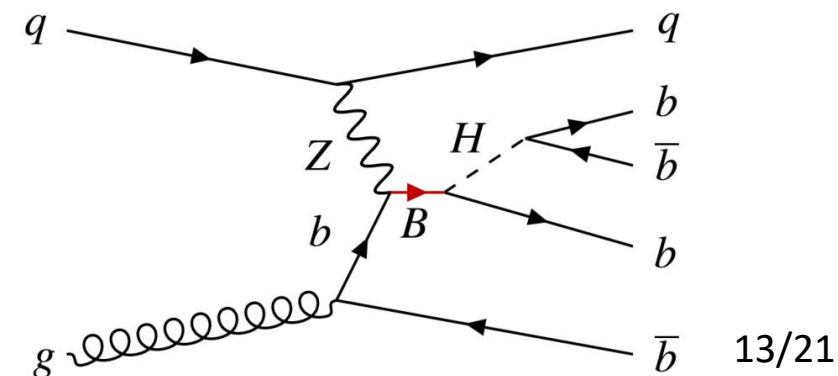
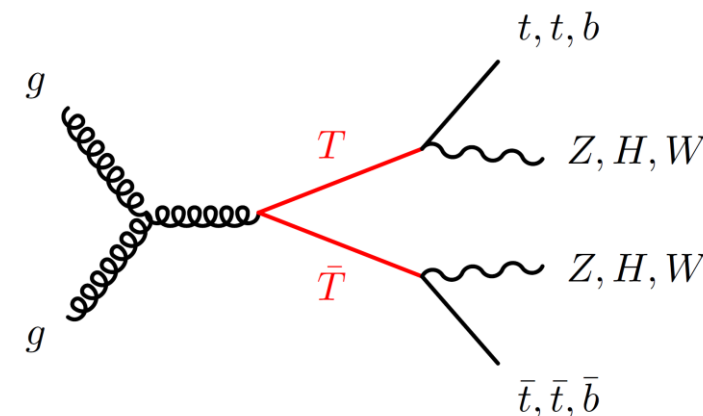
- ✓ Binned Profile Likelihood fit is performed for  $S_T$  distribution.
  - No significant excess over SM expectation is observed.
  - 95% confidence-level upper limits are set.
- ✓ The results are interpreted considering all LQ production modes in the  $U_1$  model.
- ✓ **This analysis is the first ATLAS result for the search of singly produced LQs in the  $b\tau\tau$  final state!**
- ✓ **An additional model-independent search considering both the high and low b-jet  $p_T$  signal regions is performed.**



# Vectorlike Quarks

# Vectorlike Quark Introduction

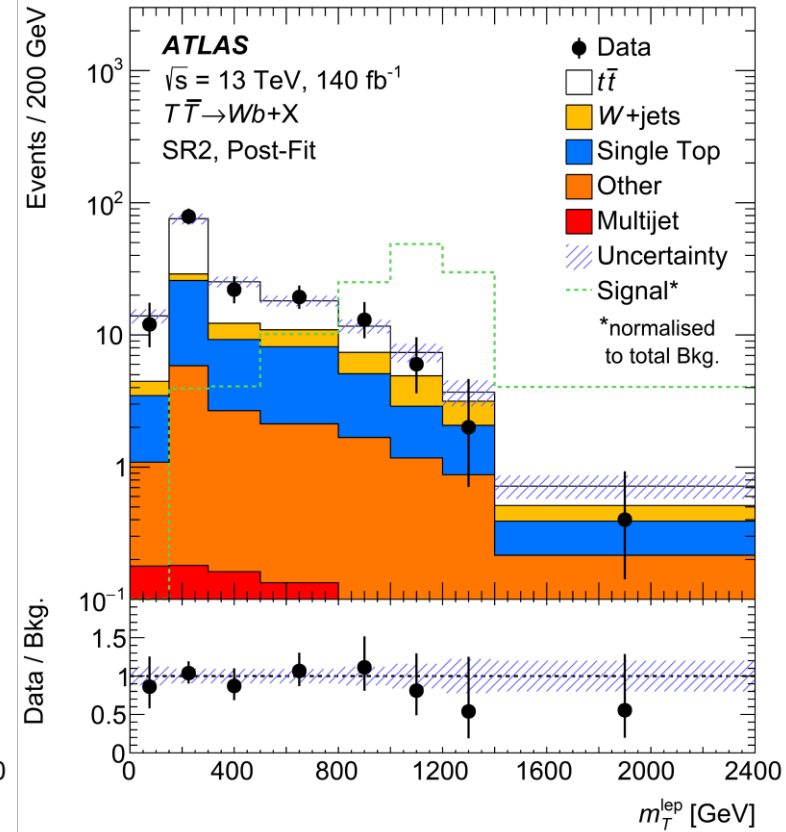
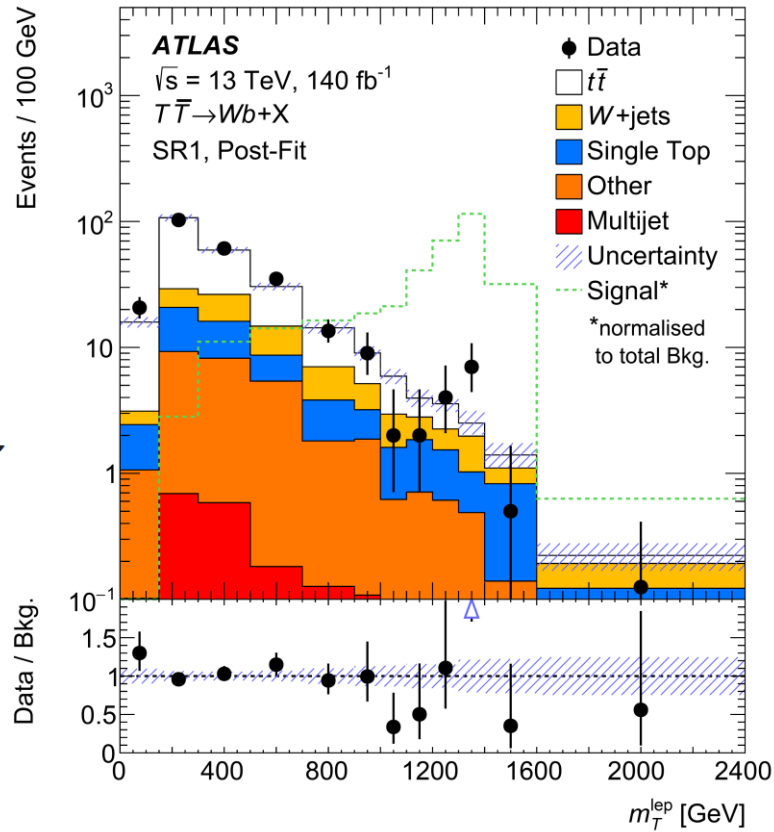
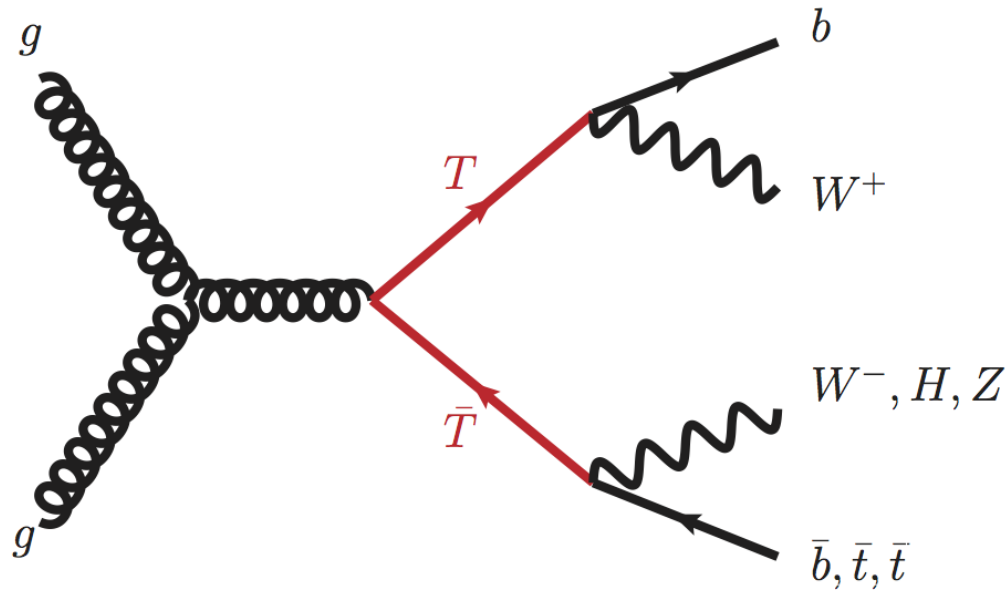
- ✓ **Vectorlike Quarks (VLQs)** are **color triplet, spin 1/2, fermionic partners of SM quarks** in many BSM models.
  - Composite Higgs, Little Higgs, Extra Dimensions, etc, to explain radiative divergences to the Higgs mass.
- ✓ VLQs could appear as different types of multiplets:
  - SU(2) **singlets, doublets, or triplets** of **T, B, X or Y**
    - $\xi_W=0.5, \xi_Z=\xi_H=0.25$  for singlet,  $\xi_W \sim 0, \xi_Z=\xi_H=0.5$  for doublet
- ✓ **T and B** have the same electric charge as the **SM t- and b-quarks**
- ✓ **X and Y** have electric charges **5/3 and -4/3**, respectively
- ✓ **Pair production** (dominates at low mass) and **single production** (dominates at high mass and high coupling)
- ✓ **Preferential coupling to third generation SM quarks** is assumed to cancel out the Higgs boson mass divergence from top-quark loops.
  - Possible decay channels:  **$T \rightarrow Wb, T \rightarrow Zt, T \rightarrow Ht, B \rightarrow Wt, B \rightarrow Zb, B \rightarrow Hb, X \rightarrow Wt, Y \rightarrow Wb$**
- ✓ Parameters of model:
  - $M_{T,B}$ : Mass of the T/B quark
  - $\kappa$ : Global electroweak coupling parameter
  - $\xi_W, \xi_Z, \xi_H$ : Relative couplings to W, Z, H bosons respectively
  - **Relative width**:  $\Gamma/M \sim \kappa^2 M^2$



# Vectorlike Quark Recent Publications

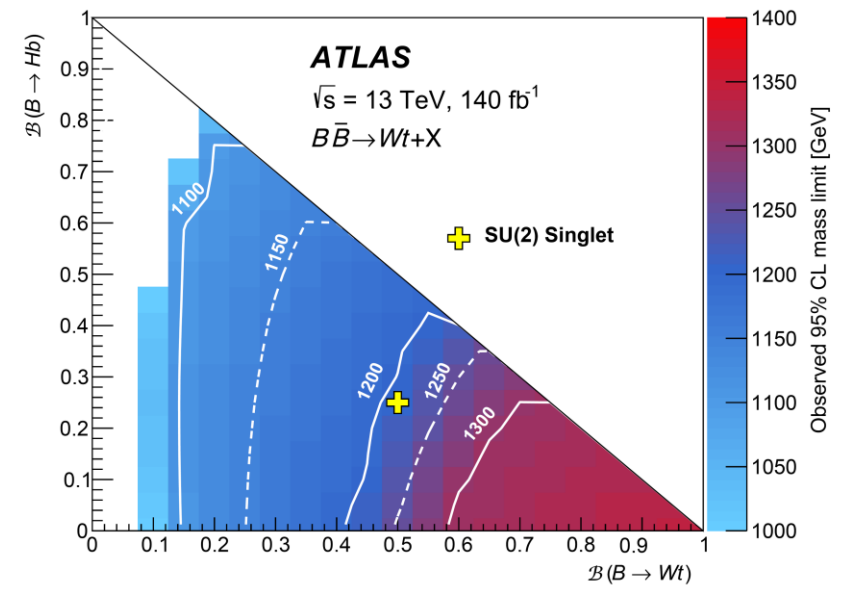
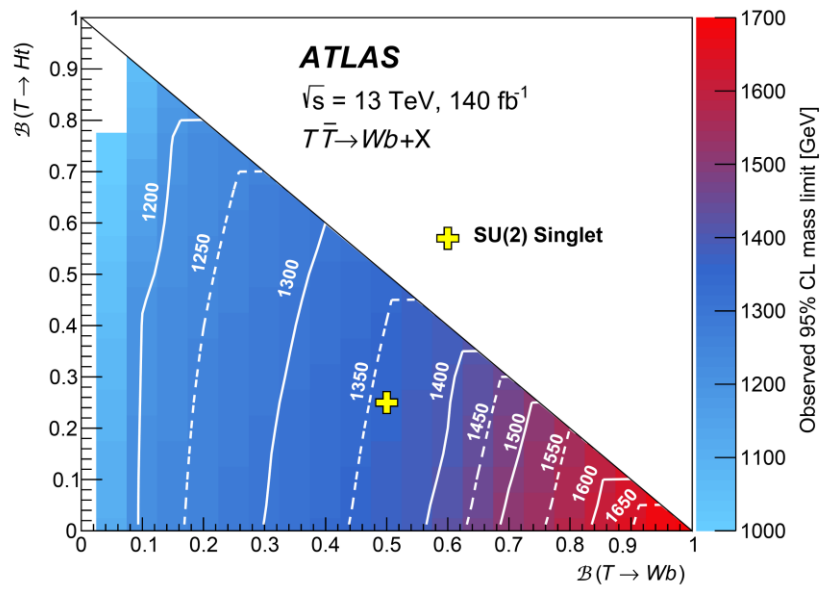
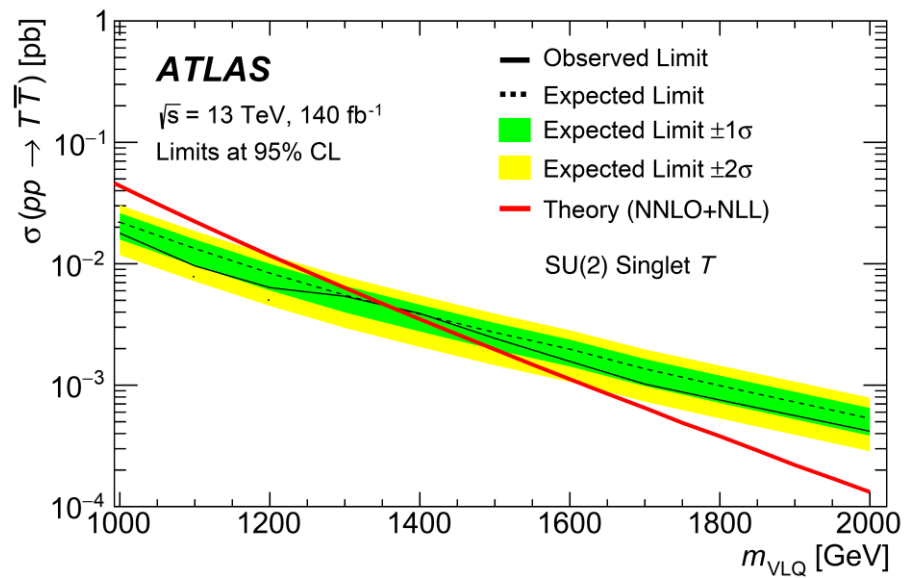
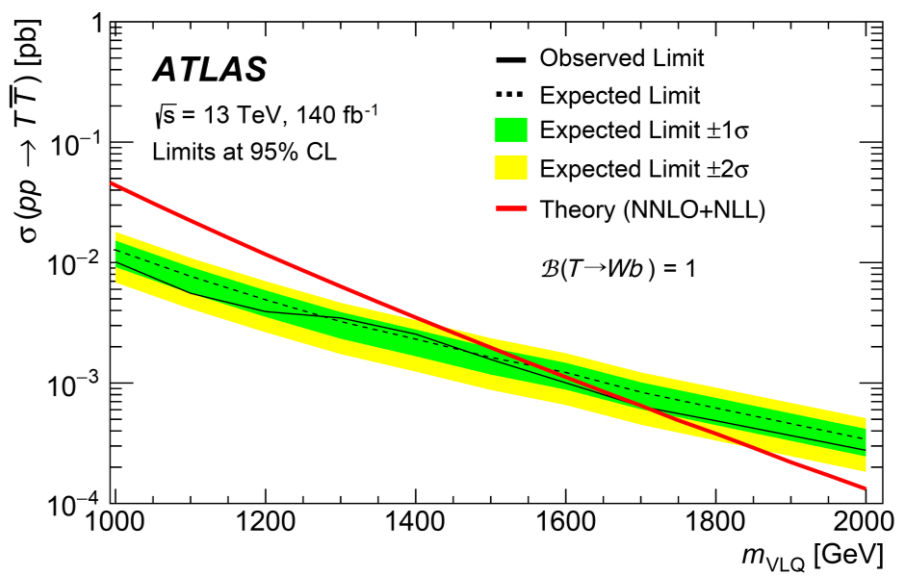
- ✓ Single VLQ production in all-hadronic final state ( $T \rightarrow Ht$ ,  $H \rightarrow bb$ ,  $t \rightarrow bqq$ ) ([Link](#))
- ✓ VLQ pair search with opposite sign multileptons ( $T/B$ ,  $T \rightarrow Zt/b$ ,  $B \rightarrow V(H)t/b$ ,  $Z \rightarrow ll$ ) ([Link](#))
- ✓ VLQ pair production search in the  $Zt+X$  decay with a 1 lepton plus MET plus jets final state ( $TT$ ,  $BB$ ) ([Link](#))
- ✓ Single VLQ via the  $Ht/Zt$  decay in the 1-lepton channel ( $T \rightarrow Ht$ ,  $Zt$ ) ([Link](#))
- ✓ VLQ single production search with opposite sign multileptons ( $T \rightarrow Zt$ ,  $Z \rightarrow ll$ ) ([Link](#))
- ✓ **Search for vector-like  $B \rightarrow bH$  with  $H \rightarrow bb$**  ([Link](#))
- ✓ **VLQ pair production search in the  $Wb+X$  final state ( $TT \rightarrow Wb$  and  $Wb$ ,  $Ht$ ,  $Zt$ ,  $BB \rightarrow Wt$  and  $Wt$ ,  $Hb$ ,  $Zb$ )** ([Link](#))
- ✓ **Search for MET plus a single-top-quark ( $T \rightarrow Zt$ ,  $Z \rightarrow \nu\nu$ ,  $t \rightarrow bqq$ )** ([Link](#))
- ✓ You can find all the ATLAS results in [ATLAS public results page](#)
- ✓ **The ones shown in red are introduced in the next pages which are picked up by my bias!**

# Pair Production, lepton+jets, $\geq 1b$ [Link](#)



- ✓ Optimised for the  $TT \rightarrow WbWb$  channel with one W boson decaying leptonically and the other hadronically.
- ✓ High- $p_T$  hadronically decaying W bosons are tagged as a single large-radius (large-R) jets. **New!**
- ✓ Top modelling is reweighted,  $t\bar{t}$  and W+jets are corrected from CR, multijets are estimated by Matrix-Method.
- ✓ T candidates are reconstructed such that the mass difference between the leptonically and hadronically decaying T candidates is minimised. The mass is the final discriminant variable.

# Pair Production, lepton+jets, $\geq 1b$ [Link](#)

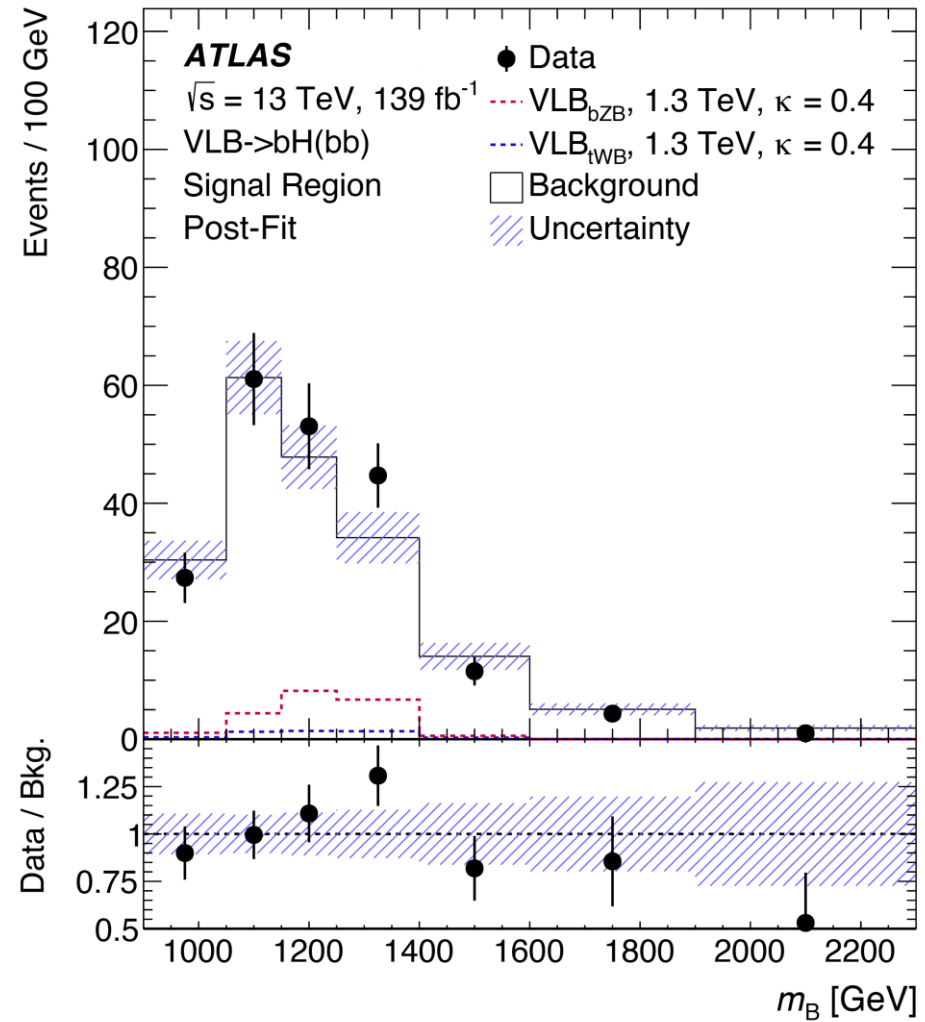
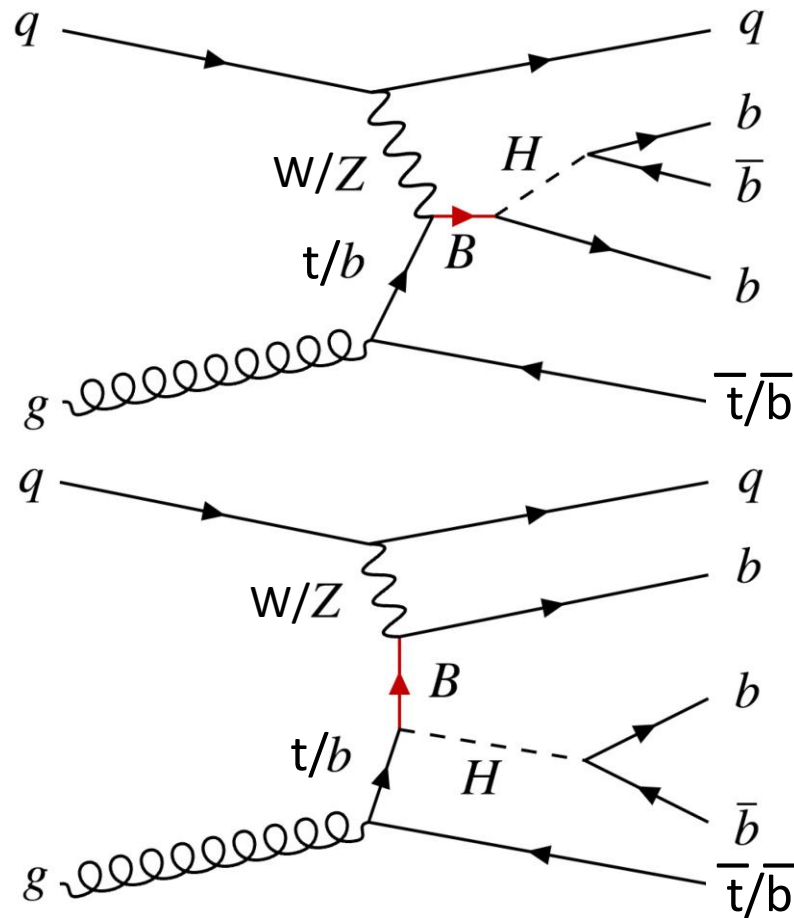


- ✓ Limits are set on
  - $B(T \rightarrow Wb) = 1$
  - SU(2) Singlet  $T$
- ✓ Limits between BRs are also checked.
- ✓ Though this analysis is optimized for  $T\bar{T} \rightarrow Wb+X$ ,  $B\bar{B} \rightarrow Wt+X$  is also considered.
- ✓ **The most stringent limits are set for the scenario  $B(T \rightarrow Wb) = 1$ .**



# Single Production, $B \rightarrow bH(bb)$

[Link](#)

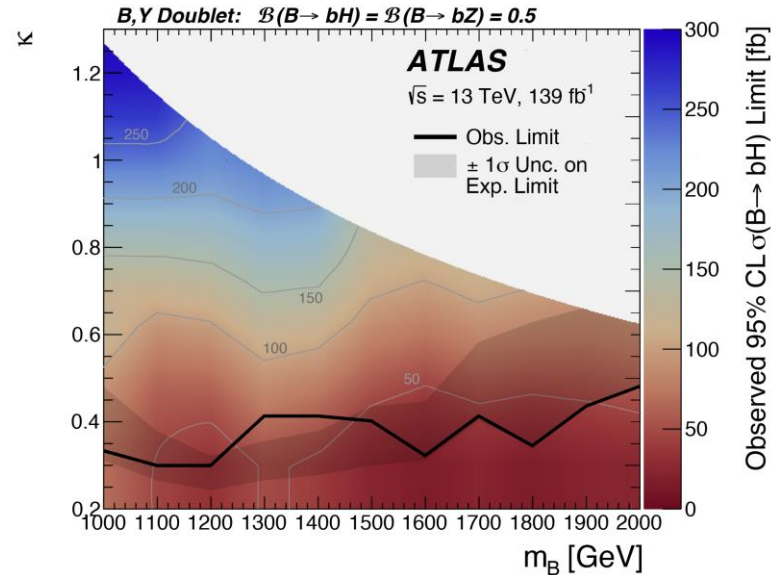
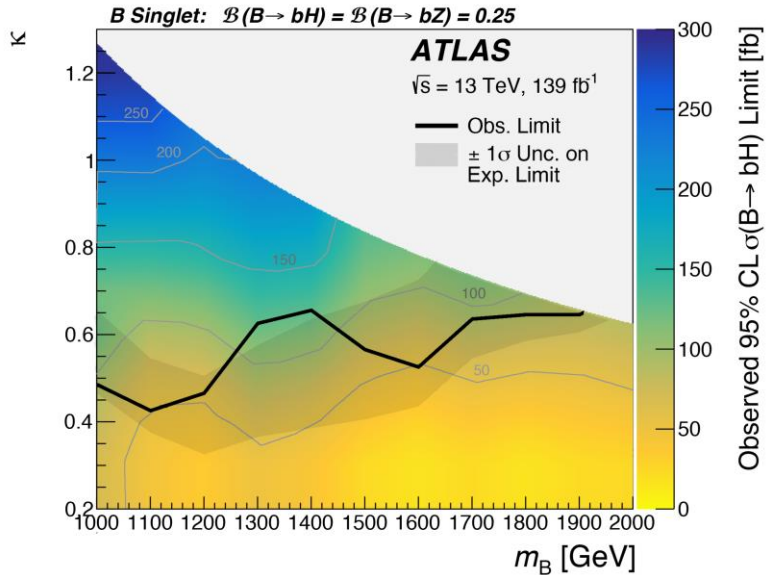


**New!**

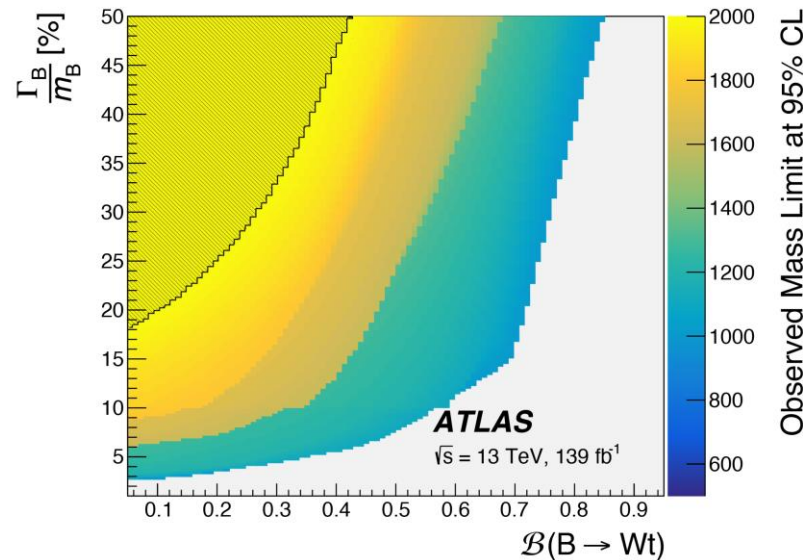
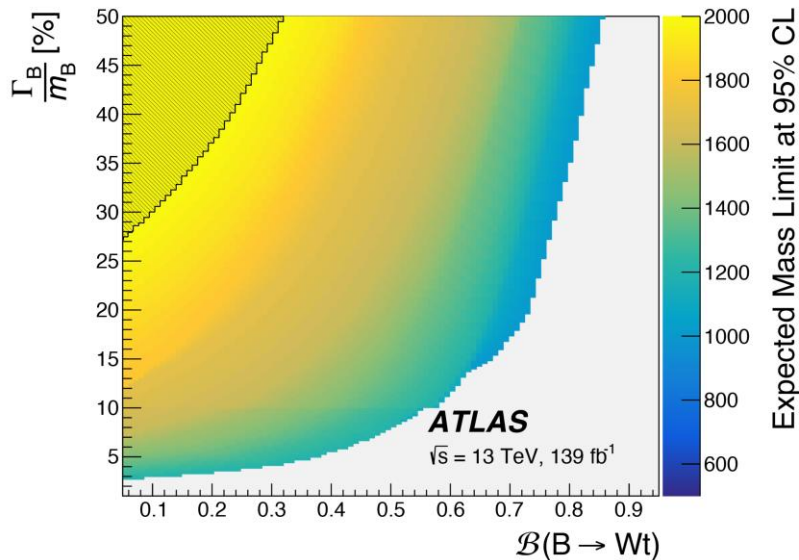
- ✓ This analysis focuses on  $B \rightarrow bH$  with  $H \rightarrow bb$ .
- ✓ **Large-R jet with variable-radius (VR) track-jets is exploited to explore presence of b-hadrons in large-R jets.**
  - Higgs Candidates (HC) are reconstructed as single large-R jets, classified by the b-tagged track-jet multiplicity.
- ✓ Multijets (> 90% in this analysis) are estimated by data-driven ABCD method.

# Single Production, $B \rightarrow bH(bb)$

[Link](#)

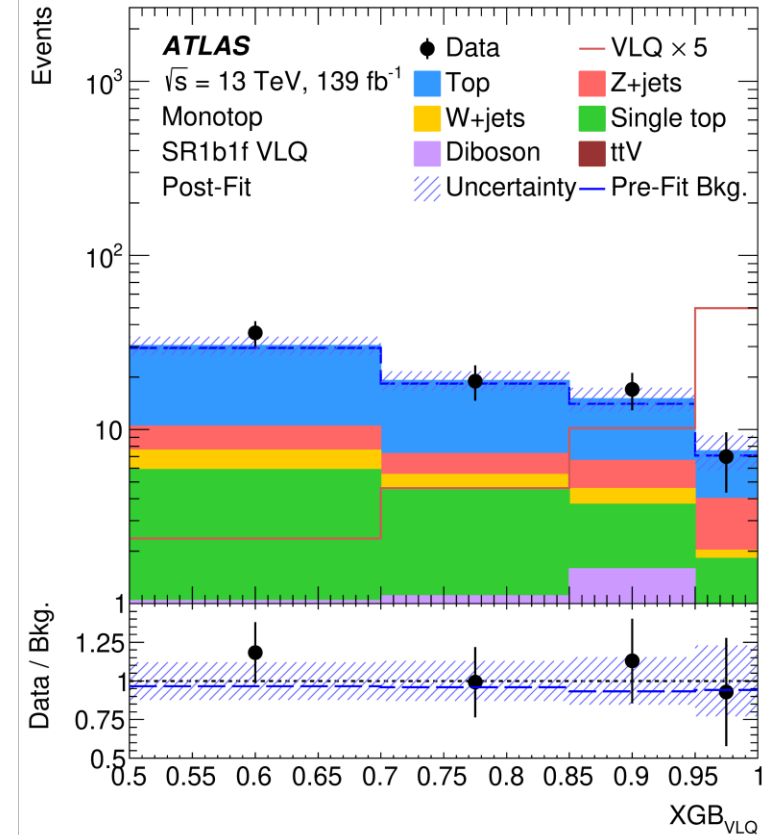
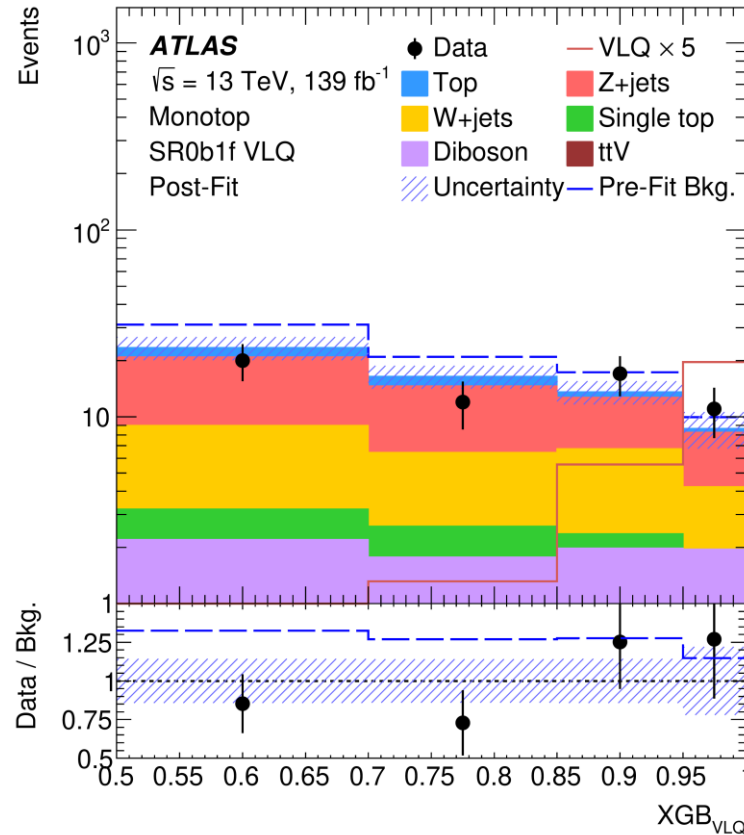
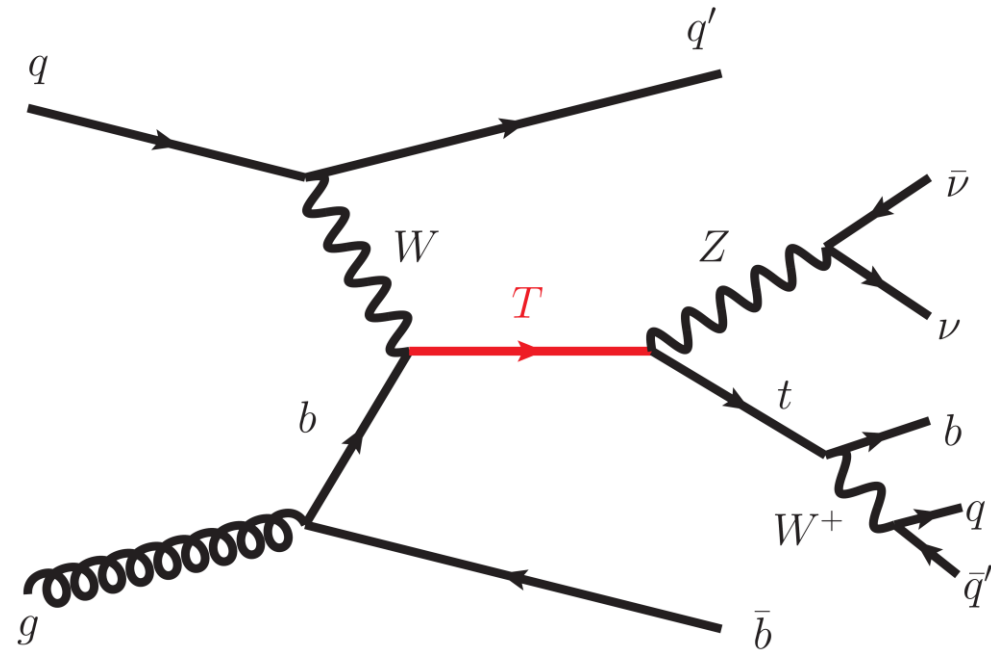


- ✓ Invariant mass of  $B$  candidate is used as discriminant variable.
- ✓ **The first search for a single vector-like  $B$  quark in the  $bH(bb)$  final state in ATLAS!**
- ✓ **This search improves on the previously published searches by CMS in the  $B \rightarrow bH$  channel!**



# Search for $E_T^{\text{miss}}$ + Single-top

[Link](#)

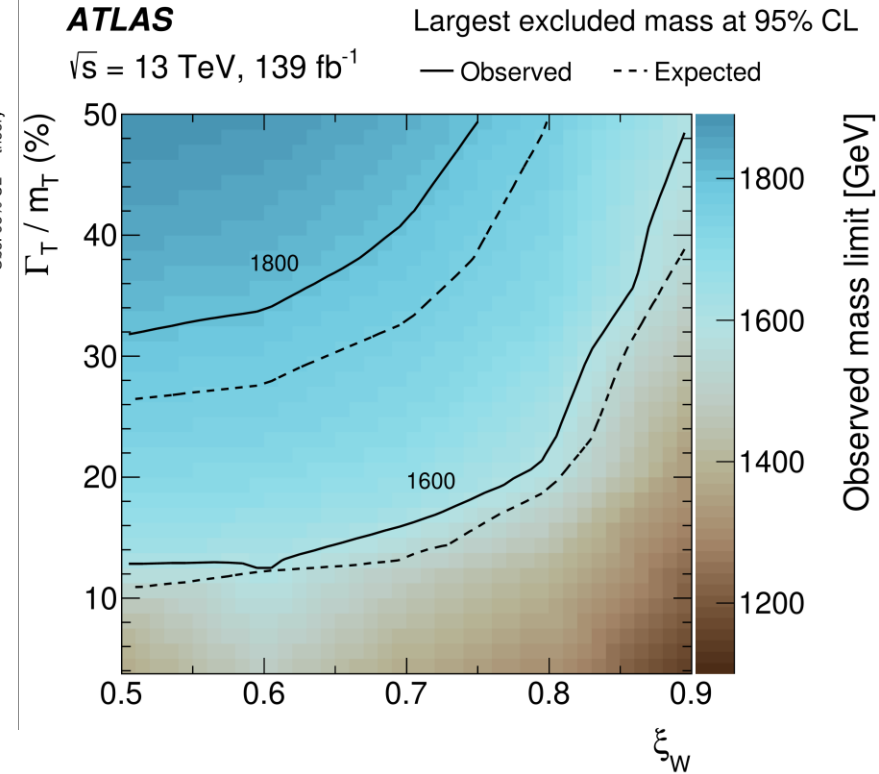
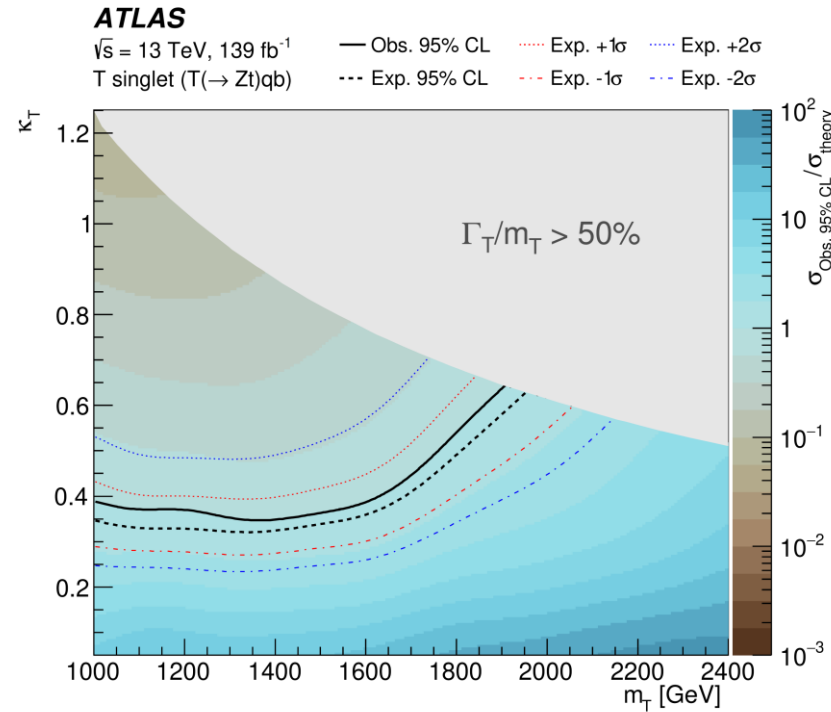
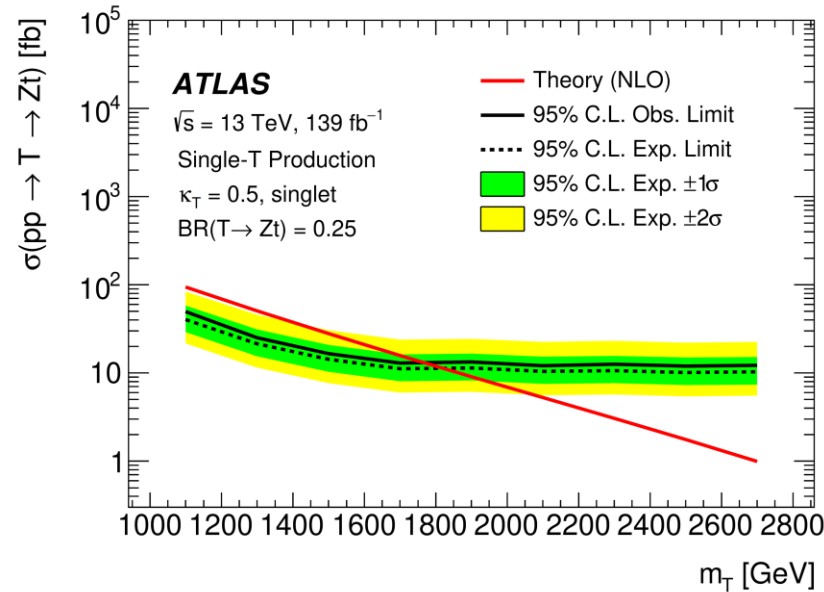


- ✓ A search for events with one top quark and missing transverse momentum in the final state is performed.
  - The results are interpreted in the context of simplified models for Dark Matter particle production and the **single production of a vector-like T quark.**
- ✓ **A Deep Neural Network (DNN) based identification of large-R jet originated from hadronically decaying top.**
- ✓ **Extreme gradient-boosted (XGBOOST) decision tree (BDT)** is used for signal and background separation.
  - It is used as final discriminant variable.

**New!**

# Search for $E_T^{\text{miss}}$ + Single-top

[Link](#)



- ✓ No significant excess above the SM expectation is found in any of the signal regions.
  - The results are therefore interpreted in terms of expected and observed upper limits on the signal cross-section as a function of the model parameters.
- ✓ This limit outperforms previous results by approximately **400 GeV**.
  - This improvement partially comes from the **refined object reconstruction** and a **XGBoost algorithm**.

# Summary

- ✓ The summary of ATLAS Run-2 Leptoquarks and Vectorlike Quarks searches are introduced.
  - No significant excess is found, thus the strongest limits are set.

## Leptoquarks

- ✓ Pair and single production searches are performed.
- ✓ Searches for LQ decaying to third generation particles as well as orthogonal generation are considered.
- ✓ Pair production to  $b\tau b\tau$ , orthogonal generation, combination and single production to  $\tau\tau$  are introduced.

## Vectorlike Quarks

- ✓ Pair and single production searches are performed.
- ✓ Limits are set on VLQ mass and couplings for singlet and doublet.
- ✓ Several combinations of parameter spaces are being searched.

The ATLAS results can be found and have been updated in [the ATLAS publication page](#), and...

**Stay tuned for the upcoming new channels and Run-3 results!**

# Backup

# Pair Production, Decaying to $b\tau b\tau$

[Link](#)

	$\tau_{\text{lep}}\tau_{\text{had}}$ channel	$\tau_{\text{had}}\tau_{\text{had}}$ channel
$e/\mu$ selection	= 1 'signal' $e$ or $\mu$ $p_{\text{T}}^e > 25, 27 \text{ GeV}$ $p_{\text{T}}^\mu > 21, 27 \text{ GeV}$	No 'veto' $e$ or $\mu$
$\tau_{\text{had-vis}}$ selection	= 1 $\tau_{\text{had-vis}}$ $p_{\text{T}}^\tau > 100 \text{ GeV}$	= 2 $\tau_{\text{had-vis}}$ $p_{\text{T}}^\tau > 100, 140, 180 \text{ (20) GeV}$
Jet selection		$\geq 2$ jets $p_{\text{T}}^{\text{jet}} > 45 \text{ (20) GeV}$ 1 or 2 $b$ -jets
Additional selection		Opposite charge $e, \mu, \tau_{\text{had}}$ and $\tau_{\text{had}}$ $m_{\tau\tau}^{\text{MMC}} \notin 40 - 150 \text{ GeV}$ $E_{\text{T}}^{\text{miss}} > 100 \text{ GeV}$ $s_{\text{T}} > 600 \text{ GeV}$
	Obs. limit [GeV ]	Exp. limit [GeV ]
Scalar LQ	1460	1410
Vector LQ (minimal-coupling)	1650	1590
Vector LQ (Yang–Mills)	1910	1820

# Pair Production, Orthogonal Generation

[Link](#)

Preselection				Variable	Description
$E_T^{\text{miss}}$ triggers exactly one signal lepton veto on additional baseline leptons $E_T^{\text{miss}} > 250 \text{ GeV}$ $\geq 4$ small- $R$ jets $m_T(\ell, E_T^{\text{miss}}) > 30 \text{ GeV}$ $\Delta\phi(E_T^{\text{miss}}, j_{1,2}) > 0.4$				$m_T(\ell, E_T^{\text{miss}})$	transverse mass of lepton and $E_T^{\text{miss}}$
				$m_{\text{eff}}$	scalar sum of the transverse momenta of leptons, jets, and $E_T^{\text{miss}}$
				Lepton flavour	flavour of the signal lepton
				$p_T(\ell)$	transverse momentum of the lepton
				$m_{\text{inv}}(b_1, \ell)$	invariant mass of the leading- $p_T$ $b$ -jet and the lepton
				$n_{\text{large}}$	reclustered large- $R$ jet multiplicity
				$am_{T2}$	asymmetric transverse mass
				$E_T^{\text{miss}}$ significance	measure for assessing the compatibility of the observed $E_T^{\text{miss}}$ with zero, taking resolutions into account
Top reweighting region	W+jets CR	Single-top CR	Training region	$m_T(b_1, E_T^{\text{miss}})$	transverse mass of leading- $p_T$ $b$ -jet and $E_T^{\text{miss}}$
$n_b \geq 1$	$n_b = 1$	$n_b = 2$	$n_b \geq 1$	$p_T(t_{\text{had}})$	transverse momentum of $t_{\text{had}}$
$m_T(\ell, E_T^{\text{miss}}) \geq 120 \text{ GeV}$	$50 \text{ GeV} \leq m_T(\ell, E_T^{\text{miss}}) < 120 \text{ GeV}$	$m_T(\ell, E_T^{\text{miss}}) < 120 \text{ GeV}$	$m_T(\ell, E_T^{\text{miss}}) \geq 120 \text{ GeV}$	$\Delta\phi(E_T^{\text{miss}}, b_2)$	azimuthal angle separation between $E_T^{\text{miss}}$ and subleading- $p_T$ $b$ -jet
$am_{T2} < 200 \text{ GeV}$	$am_{T2} > 200 \text{ GeV}$	$am_{T2} > 200 \text{ GeV}$	$am_{T2} > 200 \text{ GeV}$	$m_{\text{inv}}(b_2, \ell)$	invariant mass of subleading- $p_T$ $b$ -jet and lepton
-	$t_{\text{had}}$ candidate veto	large- $R$ jet veto	-	$\Delta\phi(E_T^{\text{miss}}, b_1)$	azimuthal angle separation between $E_T^{\text{miss}}$ and leading- $p_T$ $b$ -jet
-	lepton charge = $+1e$	-	-	$\Delta\phi(t_{\text{had}}, \ell)$	azimuthal angle separation between $t_{\text{had}}$ and lepton
-	-	$\Delta R(b_1, b_2) > 1.2$	-	$p_T(b_1)$	transverse momentum of leading- $p_T$ $b$ -jet



# Pair Production, Combination

[Link](#)

	$\mathcal{B} = 0.0$		$\mathcal{B} = 0.5$		$\mathcal{B} = 1.0$	
	95% CL Limit [GeV]		95% CL Limit [GeV]		95% CL Limit [GeV]	
	Observed	Expected	Observed	Expected	Observed	Expected
$LQ_3^u \rightarrow t\nu/b\tau$	1240	$1240^{+70}_{-90}$	1340	$1300^{+70}_{-80}$	1480	$1440^{+70}_{-80}$
$LQ_3^d \rightarrow t\tau/b\nu$	1260	$1260^{+80}_{-80}$	1360	$1340^{+60}_{-70}$	1520	$1470^{+70}_{-70}$
$LQ_{\text{mix}}^u \rightarrow t\nu/b\mu$	1230	$1310^{+70}_{-70}$	1570	$1510^{+70}_{-70}$	1710	$1650^{+90}_{-90}$
$LQ_{\text{mix}}^u \rightarrow t\nu/be$	1230	$1310^{+70}_{-70}$	1510	$1550^{+80}_{-80}$	1730	$1740^{+90}_{-100}$
$LQ_{\text{mix}}^d \rightarrow t\mu/b\nu$	1240	$1260^{+70}_{-80}$	1430	$1470^{+70}_{-70}$	1600	$1650^{+80}_{-80}$
$LQ_{\text{mix}}^d \rightarrow te/b\nu$	1230	$1250^{+70}_{-70}$	1450	$1500^{+70}_{-70}$	1650	$1660^{+90}_{-90}$
$U_1^{\text{YM}} \rightarrow t\nu/b\tau$	-	-	1840	$1810^{+80}_{-90}$	-	-
$U_1^{\text{MC}} \rightarrow t\nu/b\tau$	-	-	1580	$1560^{+70}_{-70}$	-	-
$U_1^{\text{YM}} \rightarrow t\nu/b\mu$	-	-	1980	$1930^{+50}_{-60}$	-	-
$U_1^{\text{MC}} \rightarrow t\nu/b\mu$	-	-	1710	$1660^{+50}_{-50}$	-	-
$U_1^{\text{YM}} \rightarrow t\nu/be$	-	-	1900	$1930^{+50}_{-70}$	-	-
$U_1^{\text{MC}} \rightarrow t\nu/be$	-	-	1620	$1650^{+50}_{-60}$	-	-
$\tilde{U}_1^{\text{YM}} \rightarrow t\tau$	-	-	-	-	1810	$1810^{+80}_{-70}$
$\tilde{U}_1^{\text{MC}} \rightarrow t\tau$	-	-	-	-	1540	$1530^{+90}_{-60}$

# Single Production, Decaying to $b\tau\tau$ [Link](#)

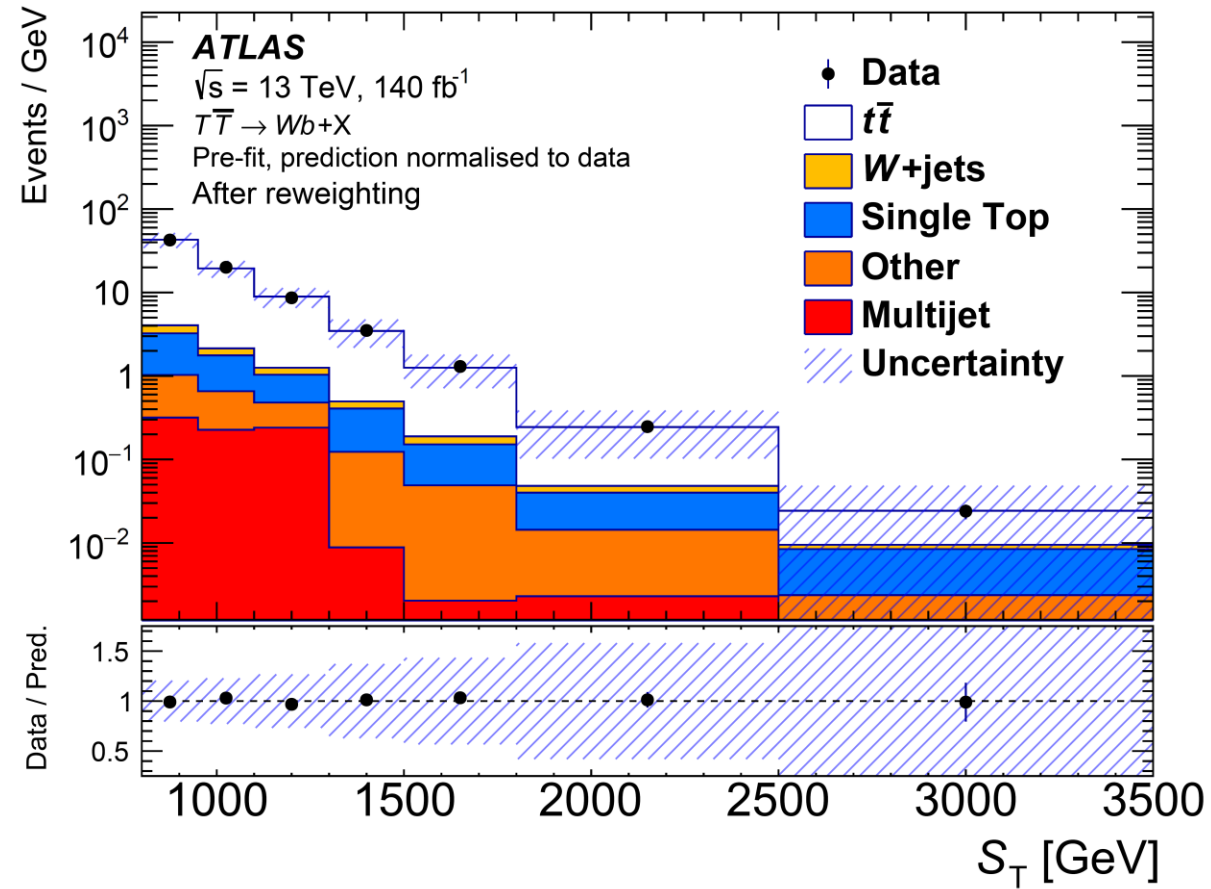
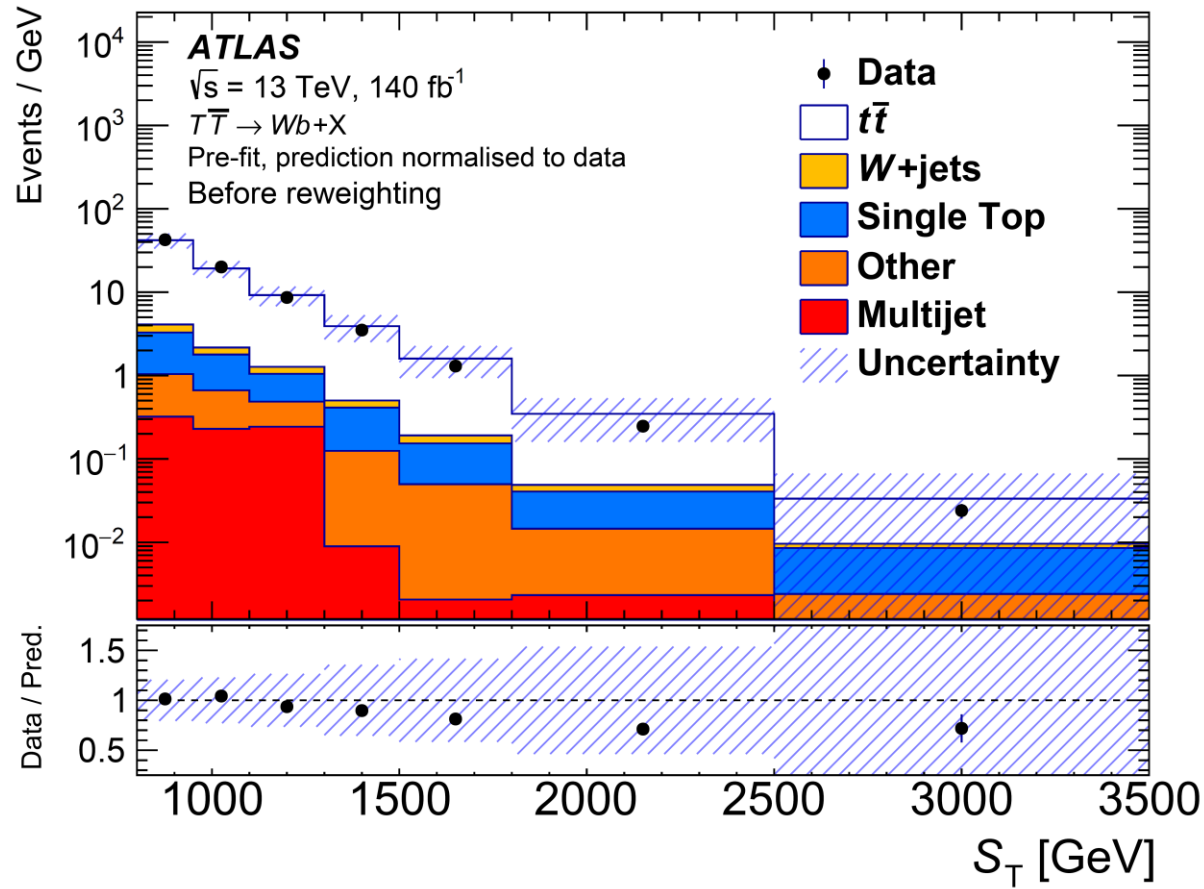
Signal Regions	Selection	
Preselection	$\ell$ (trigger, isolated), $\tau_{\text{had-vis}}$ (medium $\tau_{\text{had-ID}}$ ), $q(\ell) \times q(\tau_{\text{had-vis}}) < 0$ , $\Delta\phi(\ell, E_{\text{T}}^{\text{miss}}) < 1.5$ , $m_{\text{vis}}(\ell, \tau_{\text{had-vis}}) > 100$ GeV, $S_{\text{T}} > 300$ GeV, at least one $b$ -jet	
High $b$ -jet $p_{\text{T}}$ SR	Leading $b$ -jet $p_{\text{T}} > 200$ GeV	
Low $b$ -jet $p_{\text{T}}$ SR	Leading $b$ -jet $p_{\text{T}} < 200$ GeV	
Control/Validation Regions	Selection	Purpose
Multijet-CR	$\ell$ (trigger, pass/fail offline isolation), $m_{\text{T}}(\ell, E_{\text{T}}^{\text{miss}}) < 30$ GeV, one $b$ -jet, $\tau_{\text{had-ID}}$ score $< 0.01$ , $E_{\text{T}}^{\text{miss}} < 50$ GeV	Measure lepton fake-factor
Top-CR	Satisfy SR except: $\Delta\phi(\ell, E_{\text{T}}^{\text{miss}}) > 2.5$ , no $S_{\text{T}}$ and lead. $b$ -jet $p_{\text{T}}$ req.	Derive top correction
SS-CR	Satisfy SR except: $q(\ell) \times q(\tau_{\text{had-vis}}) > 0$ , no $\Delta\phi(\ell, E_{\text{T}}^{\text{miss}})$ , and $S_{\text{T}}$ req.	Measure jet $\rightarrow \tau$ background scale factor
High $b$ -jet $p_{\text{T}}$ VR	Satisfy high $b$ -jet $p_{\text{T}}$ SR except: $1.5 < \Delta\phi(\ell, E_{\text{T}}^{\text{miss}}) < 2.5$ , $300 \text{ GeV} < S_{\text{T}} < 600 \text{ GeV}$	Background modelling validation
Low $b$ -jet $p_{\text{T}}$ VR	Satisfy low $b$ -jet $p_{\text{T}}$ SR except: $1.5 < \Delta\phi(\ell, E_{\text{T}}^{\text{miss}}) < 2.5$ , $300 \text{ GeV} < S_{\text{T}} < 600 \text{ GeV}$	Background modelling validation
$b$ -tag Z-CR	Satisfy SR except: $45 \text{ GeV} < m_{\text{vis}}(\ell, \tau_{\text{had-vis}}) < 80 \text{ GeV}$ , $p_{\text{T}}(\ell)/p_{\text{T}}(b\text{-jet}) > 0.8$ , $ \Delta\phi(\ell, \tau_{\text{had-vis}})  > 2.4$ , no $S_{\text{T}}$ req.	Z+ heavy-flavour jets normalisation factor

Signal Regions	Selection	
Preselection	$\tau_{\text{had},1}$ (trigger, medium $\tau_{\text{had-ID}}$ ), $\tau_2$ (loose $\tau_{\text{had-ID}}$ ), $q(\tau_1) \times q(\tau_2) < 0$ , $m_{\text{vis}}(\tau_1, \tau_2) > 100$ GeV, $S_{\text{T}} > 300$ GeV, at least one $b$ -jet	
High $b$ -jet $p_{\text{T}}$ SR	Leading $b$ -jet $p_{\text{T}} > 200$ GeV	
Low $b$ -jet $p_{\text{T}}$ SR	Leading $b$ -jet $p_{\text{T}} < 200$ GeV	
Control/Validation Regions	Selection	Purpose
DJ-CR	$\tau_1$ and $\tau_2$ satisfy very loose $\tau_{\text{had-ID}}$ , $q(\tau_1) \times q(\tau_2) < 0$	Measure $\tau_{\text{had-vis}}$ fake-factor
CR-1	Satisfy SR except: $\tau_2$ fail loose $\tau_{\text{had-ID}}$	Apply $\tau_{\text{had-vis}}$ fake-factor
SS-VR	Satisfy SR except: $q(\tau_1) \times q(\tau_2) > 0$	Multijet modelling check
Z+light flavour jets VR	Satisfy SR except: 0 $b$ -jets, $\Delta\phi(\tau_1, \tau_2) > 0.25$ , $m_{\text{vis}}(\tau_1, \tau_2) < 100$ GeV, $E_{\text{T}}^{\text{miss}} > 60$ GeV	Z+light jets modelling

# Pair Production, lepton+jets, $\geq 1b$ [Link](#)

Selection	SR1 / SR2	$t\bar{t}$ CR	$S_T^{\text{Low}\Delta m\text{CR}} / S_T^{\text{High}\Delta m\text{CR}}$	W+jetsCR	$t\bar{t}$ RWR
Preselection	✓	✓	✓	✓	✓
$N_{\text{Large-}R \text{ Jet}}$	$\geq 1$	$\geq 1$	$\geq 1$	$\geq 1$	$\geq 1$
$S_T[\text{GeV}]$	$>1900$	1400–1900	1400–1900 / $>1900$	900–1900	$>800$
$N_{W\text{-tag}}$	$\geq 1$	$\geq 1$	$\geq 1$	$\geq 1$ partially inverted	$\geq 1$
$N_{b\text{-tag}}$	$\geq 1$	$\geq 1$	$\geq 1$	$\geq 1$	$\geq 2$
$\Delta R(W_{\text{had}}, b_{\text{had}})$	$> 1.0$	$> 1.0$	$> 1.0$	–	$< 1.0$
$\Delta R(\ell, \nu)$	$< 0.7$	$< 0.7$	$< 0.7$	$< 1.0$	$< 1.2$
$\Delta m_{\text{VLQ}}[\text{GeV}]$	$< 200 / 200\text{--}500$	$< 500$	$> 500$	–	–
$m_T^{\text{lep}}, m_T^{\text{had}}[\text{GeV}]$	–	–	–	–	$< 700$
Included in fit	yes / yes	yes	yes / yes	no	no
Goal	Optimise signal sensitivity	Constrain $t\bar{t}$ normalisation	Constrain single top uncertainties	Derive W+jets normalisation factor	Derive $t\bar{t}$ $S_T$ shape reweighting

# Pair Production, lepton+jets, $\geq 1b$ [Link](#)



✓ Top modelling is corrected by reweighting factor.

# Pair Production, Zt+X with 1 lepton + MET

[Link](#)

Preselection				
$E_T^{\text{miss}}$ triggers = 1 signal lepton no additional baseline lepton $\geq 4$ jets $\geq 1$ $b$ -jet $E_T^{\text{miss}} > 250$ GeV $m_T^W > 30$ GeV $ \Delta\phi(j_{1,2}, \vec{E}_T^{\text{miss}})  > 0.4$				
	Training region low- $NN_{\text{out}}$ CR/SR	Top reweighting region	W+jets CR	Single-top CR
$m_T^W$ [GeV]	$> 120$	$> 120$	$\in [30, 120]$	$\in [30, 120]$
$am_{T2}$ [GeV]	$> 200$	$< 180$	$> 200$	$> 200$
$b$ -jet multiplicity	$\geq 1$	$\geq 1$	$= 1$	$\geq 2$
Large- $R$ jet multiplicity	$\geq 1$	$\geq 1$	$\leq 1$	$\leq 1$
$m(\text{large-}R \text{ jet})$ [GeV]	–	–	$< 150$	$< 150$
Lepton charge	–	–	+1	–
$\Delta R(b_1, b_2)$	–	–	–	$> 1.4$
$NN_{\text{out}}$	$< 0.5 / \geq 0.5$	–	–	–

# Pair Production, $Zt+X$ with 1 lepton + MET

[Link](#)

Variable	Description
$m_{\text{eff}}$	scalar sum of the transverse momenta of leptons, jets, and $E_{\text{T}}^{\text{miss}}$
$N_{b\text{-jets}}$	$b$ -jet multiplicity
$m_{\text{T}}^{\text{W}}$	transverse mass of lepton and $E_{\text{T}}^{\text{miss}}$
$am_{\text{T}2}$	asymmetric transverse mass
$p_{\text{T}}(\text{large-}R \text{ jet}_2)$	transverse momentum of second-highest- $p_{\text{T}}$ large- $R$ jet
$ \Delta\phi(\text{jet}_1, E_{\text{T}}^{\text{miss}}) $	azimuthal angle between $E_{\text{T}}^{\text{miss}}$ and highest- $p_{\text{T}}$ jet
$E_{\text{T}}^{\text{miss}}$	missing transverse momentum
$\eta(\text{jet}_1)$	pseudorapidity of highest- $p_{\text{T}}$ jet
$m(\text{large-}R \text{ jet}_1)$	mass of highest- $p_{\text{T}}$ large- $R$ jet
$N_{\text{const}}(\text{large-}R \text{ jet}_1)$	number of small- $R$ jets reclustered to the highest- $p_{\text{T}}$ large- $R$ jet
$p_{\text{T}}(\ell)$	transverse momentum of lepton
$p_{\text{T}}(\text{jet}_3)$	transverse momentum of third-highest- $p_{\text{T}}$ jet
$p_{\text{T}}(\text{jet}_2)$	transverse momentum of second-highest- $p_{\text{T}}$ jet

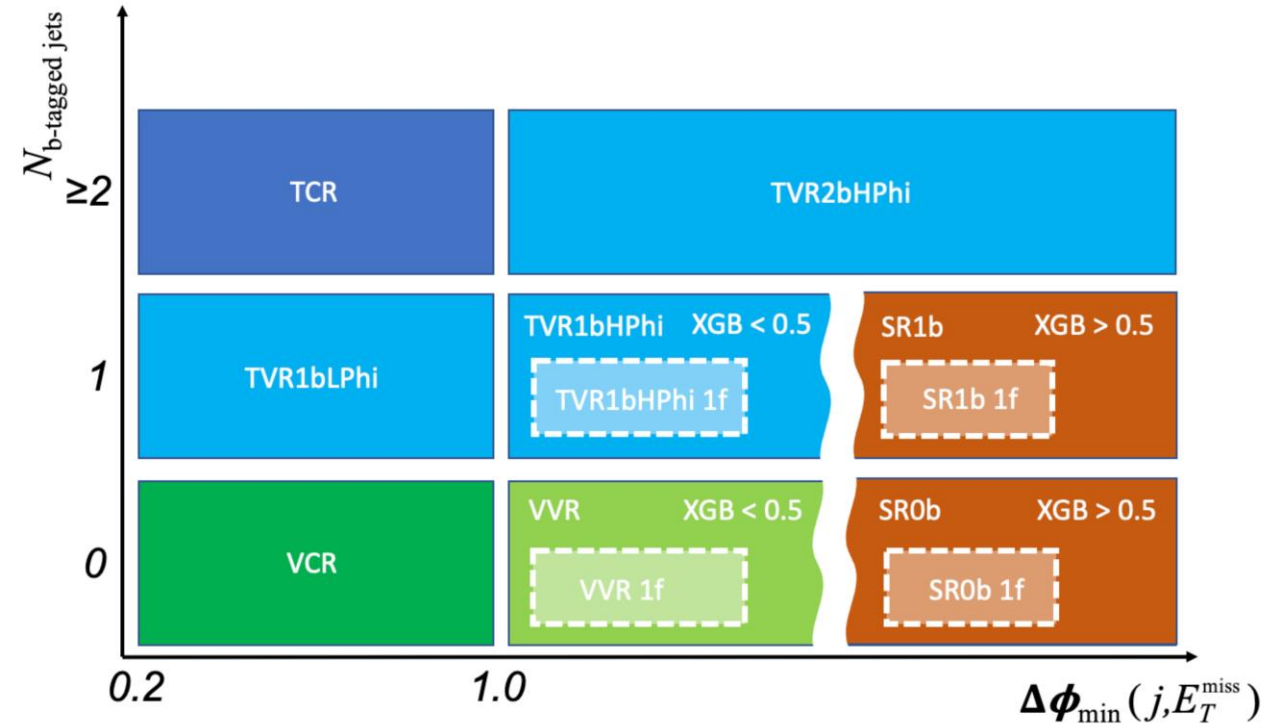
# Single Production, $B \rightarrow bH(bb)$

[Link](#)

Preselection							
$\geq 1$ large- $R$ jet, $p_T > 480$ GeV							
No leptons & no $\gamma\gamma$ pairs with $m_{\gamma\gamma} \in [105, 160]$ GeV							
$\geq 2$ track-jets associated with the large- $R$ jet, $\geq 1$ $b$ -tagged track-jet							
$\geq 1$ small- $R$ jet with $p_T > 300$ GeV							
$\Delta R(\text{small-}R \text{ jet, large-}R \text{ jet}) > 2.0$							
HC reconstruction							
Any large- $R$ jet with $p_T > 480$ GeV							
$\geq 2$ ghost-matched track-jets with $p_T > 50$ GeV							
Pass collinearity veto							
Highest $b$ -tag multiplicity: 2 track-jets				Highest $b$ -tag multiplicity: 1 track-jet			
Select candidate with largest $m_{HC}$							
VLB candidate reconstruction							
HC + small- $R$ jet, $p_T(\text{small-}R \text{ jet}) \geq 400$ GeV							
$\Delta R(\text{small-}R \text{ jet, large-}R \text{ jet}) \geq 2.5$							
Kinematic selection							
$\log \Delta R^* \geq 0.67$							
$p_T^{HC}/m_B \geq 0.4$							
$m_{HC} \in [105, 135]$ GeV							
$\geq 1$ forward jet							
$= 0$ forward jet		$\geq 1$ forward jet		$= 0$ forward jet			
Small- $R$ jet $b$ -tagging status							
Tag	No Tag	Tag	No Tag	Tag	No Tag	Tag	No Tag
SR	Control samples						

# Search for $E_T^{\text{miss}}$ + Single-top

[Link](#)



	$N_{b\text{-tagged jets}}$	$\Delta\phi_{\min}(j, E_T^{\text{miss}})$	XGBoost score	$N_{\text{forward jets}}$
TCR	$\geq 2$	$\in [0.2, 1]$	–	–
TVR1bLPhi	1	$\in [0.2, 1]$	–	–
TVR1bHPhi (1f)	1	$\geq 1$	$< 0.5$	– ( $\geq 1$ )
TVR2bHPhi	$\geq 2$	$\geq 1$	–	–
VCR	0	$\in [0.2, 1]$	–	–
VVR (1f)	0	$\geq 1$	$< 0.5$	– ( $\geq 1$ )
SR0b (1f)	0	$\geq 1$	$\geq 0.5$	– ( $\geq 1$ )
SR1b (1f)	1	$\geq 1$	$\geq 0.5$	– ( $\geq 1$ )



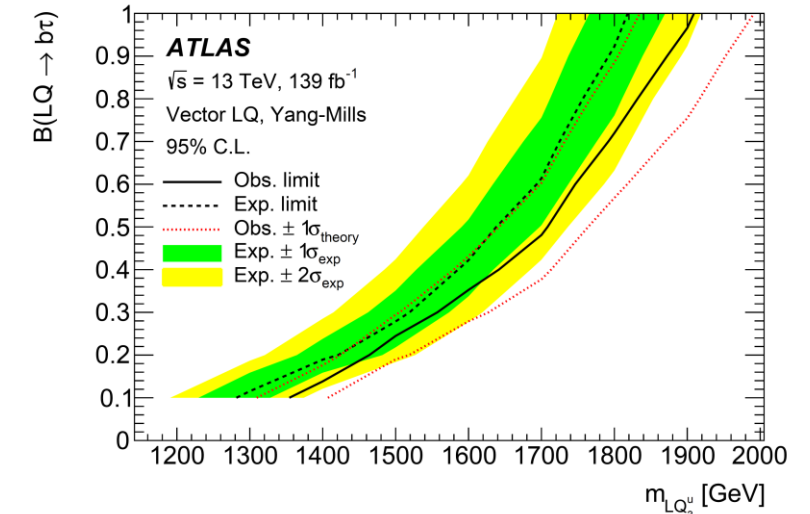
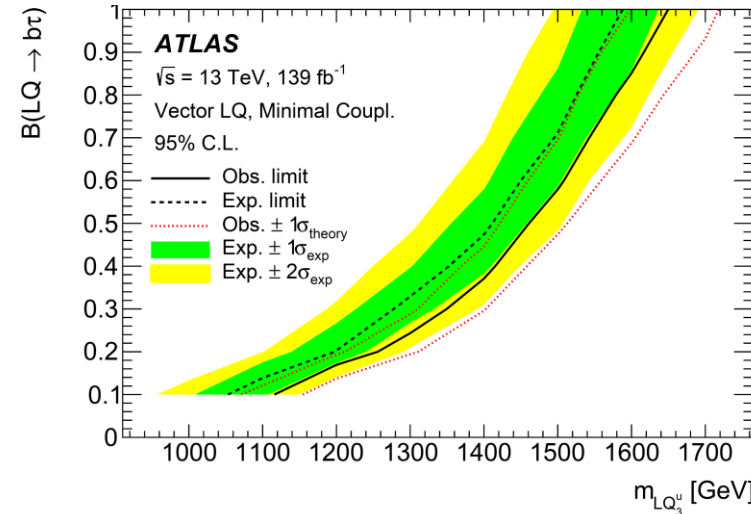
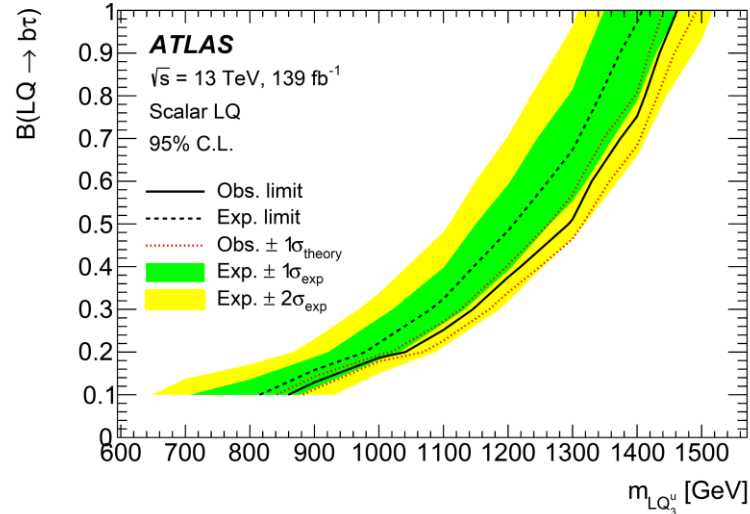
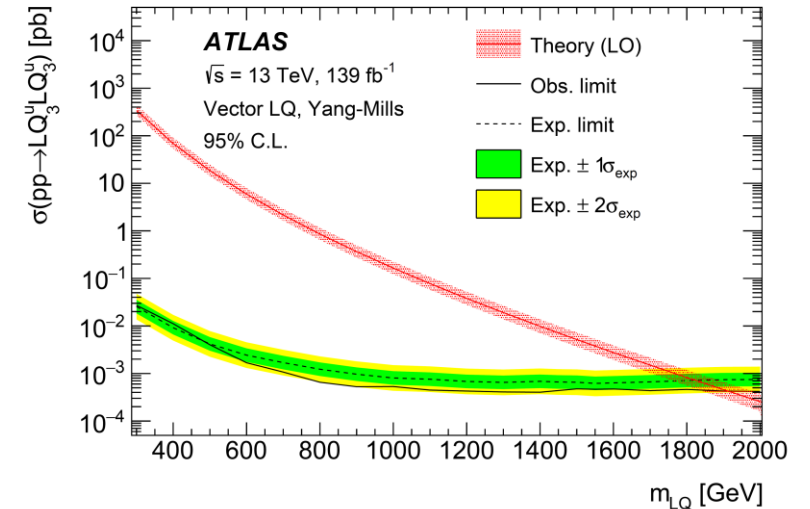
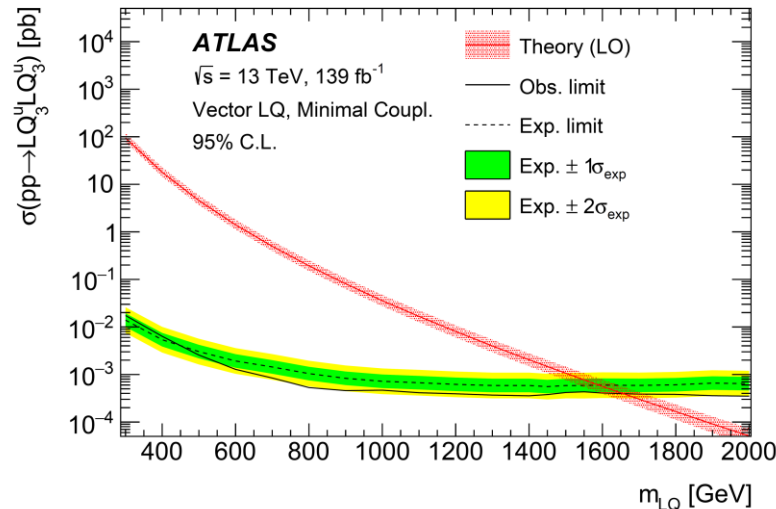
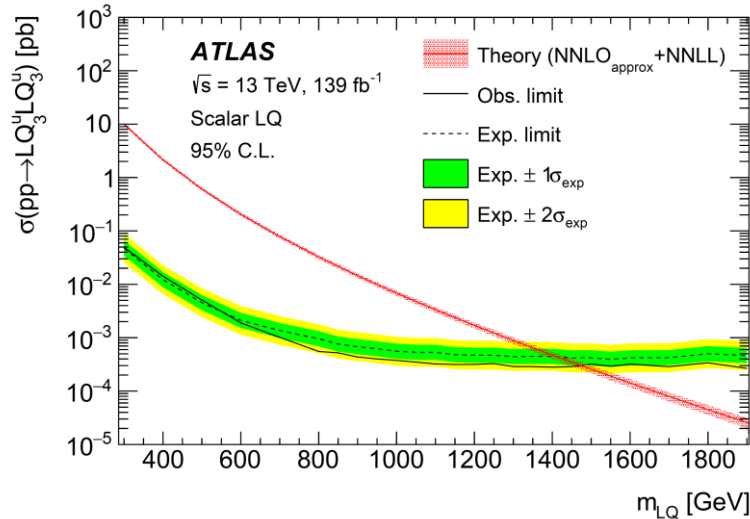
# Search for $E_T^{\text{miss}}$ + Single-top

[Link](#)

Variable	Description	Scalar DM mediator	Vector DM mediator	VLQ
$E_T^{\text{miss}}$	Missing transverse momentum	✓	✓	✓
$\Omega$	$E_T^{\text{miss}}$ and large- $R$ jet $p_T$ balance: $\frac{E_T^{\text{miss}} - p_T(J)}{E_T^{\text{miss}} + p_T(J)}$	✓	✓	✓
$N_{\text{jets}}$	Small- $R$ jet multiplicity	✓	✓	✓
$\Delta R_{\text{max}}$	Maximum $\Delta R$ between two small- $R$ jets	✓	✓	✓
$m_{T,\text{min}}(E_T^{\text{miss}}, b\text{-tagged jet})$	Transverse mass of $E_T^{\text{miss}}$ and the closest $b$ -tagged jet	✓	✓	✓
$m_{\text{top-tagged jet}}$	Mass of the large- $R$ top-tagged jet	✓		✓
$\Delta p_T(J, \text{jets})$	Scalar difference of large- $R$ jet $p_T$ and the sum of $p_T$ of all small- $R$ jets.	✓	✓	
$H_T$	Sum of all small- $R$ jet $p_T$		✓	✓
$H_T/E_T^{\text{miss}}$	Ratio of $H_T$ and $E_T^{\text{miss}}$		✓	✓
$\Delta E(E_T^{\text{miss}}, J)$	Energy difference between $E_T^{\text{miss}}$ and the large- $R$ jet		✓	✓
$\Delta\phi(E_T^{\text{miss}}, J)$	Angular distance in the transverse plane between $E_T^{\text{miss}}$ and large- $R$ jet		✓	✓
$p_T(J)$	Large- $R$ jet $p_T$			✓
$m_T(E_T^{\text{miss}}, J)$	Transverse mass of the $E_T^{\text{miss}}$ and large- $R$ jet			✓
$\Delta\phi(b\text{-tagged jet}, J)$	Angular distance in the transverse plane between the large- $R$ jet and the leading $b$ -tagged jet			✓

# Pair Production, Decaying to $b\tau b\tau$

[Link](#)

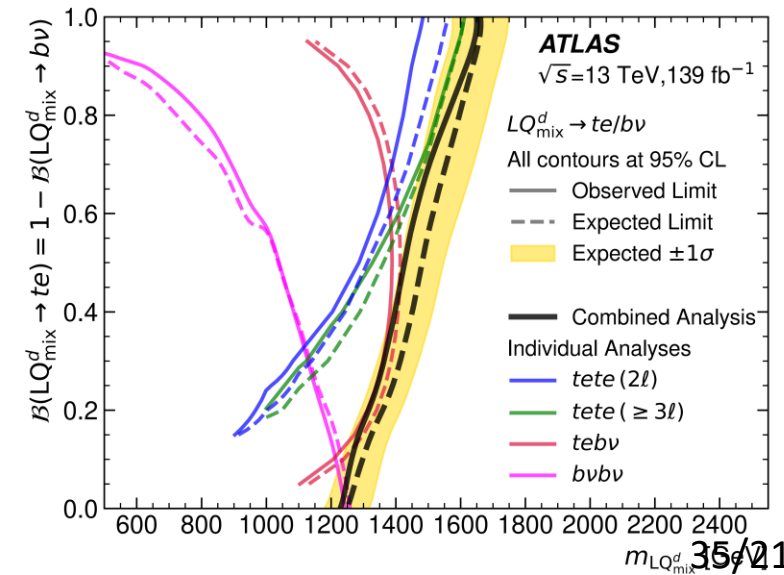
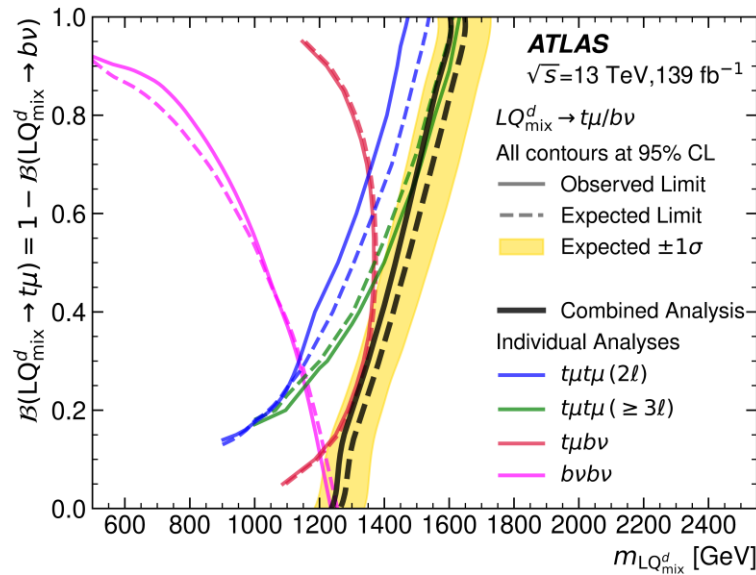
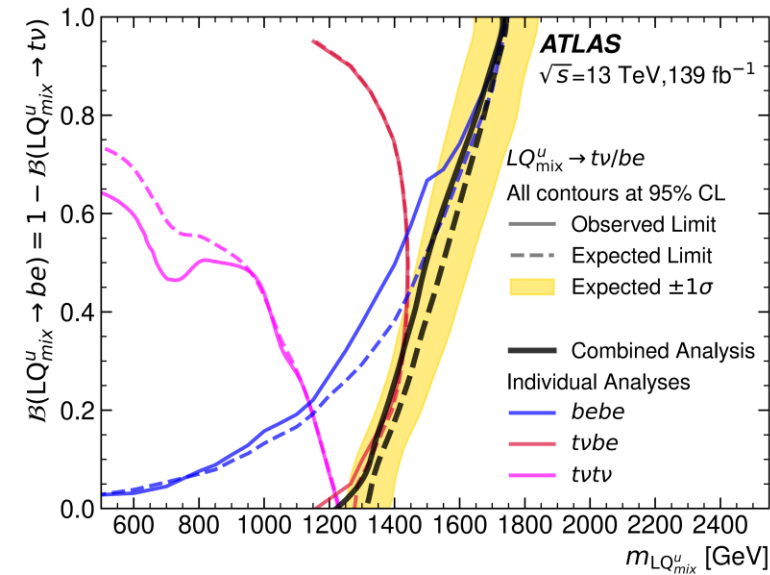
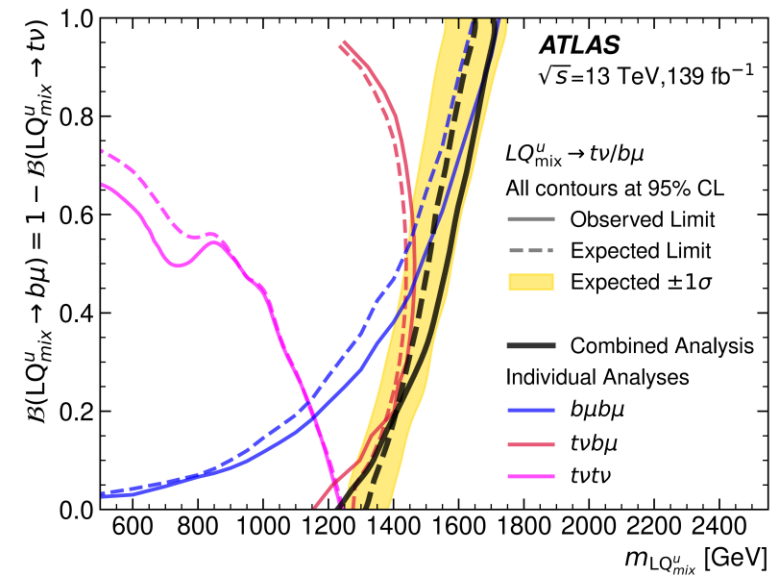
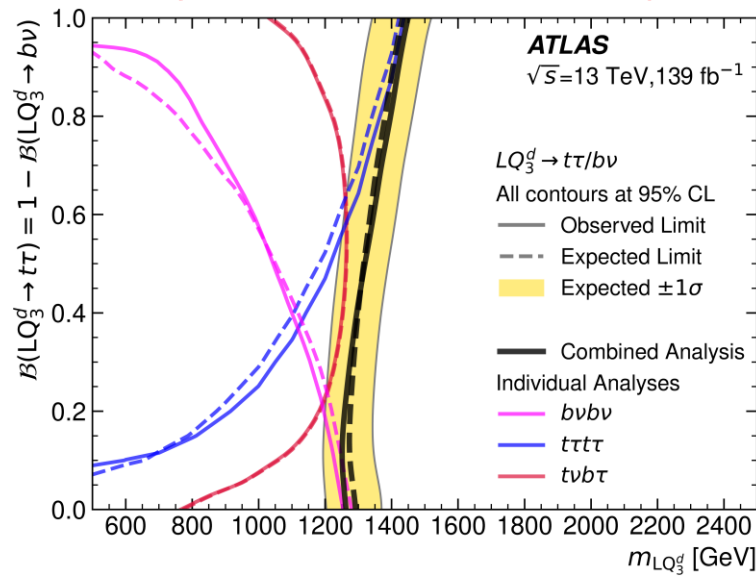
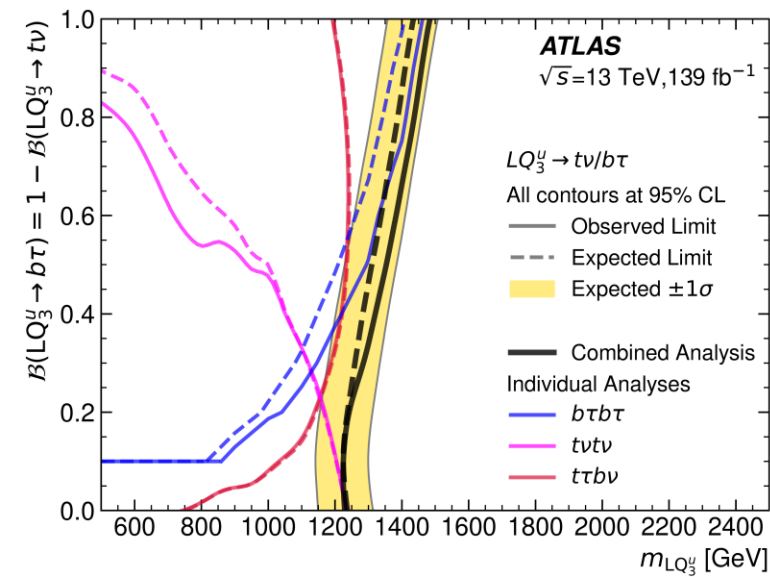


- ✓ Binned Profile Likelihood fit is performed for PNN score distribution.
  - No significant excess over SM expectation is observed. 95% confidence-level upper limits are set.
  - **Significantly improve the sensitivity mainly due to upgraded  $\tau$  and b-jet identification, improved MVA.**

# Pair Production, Combination

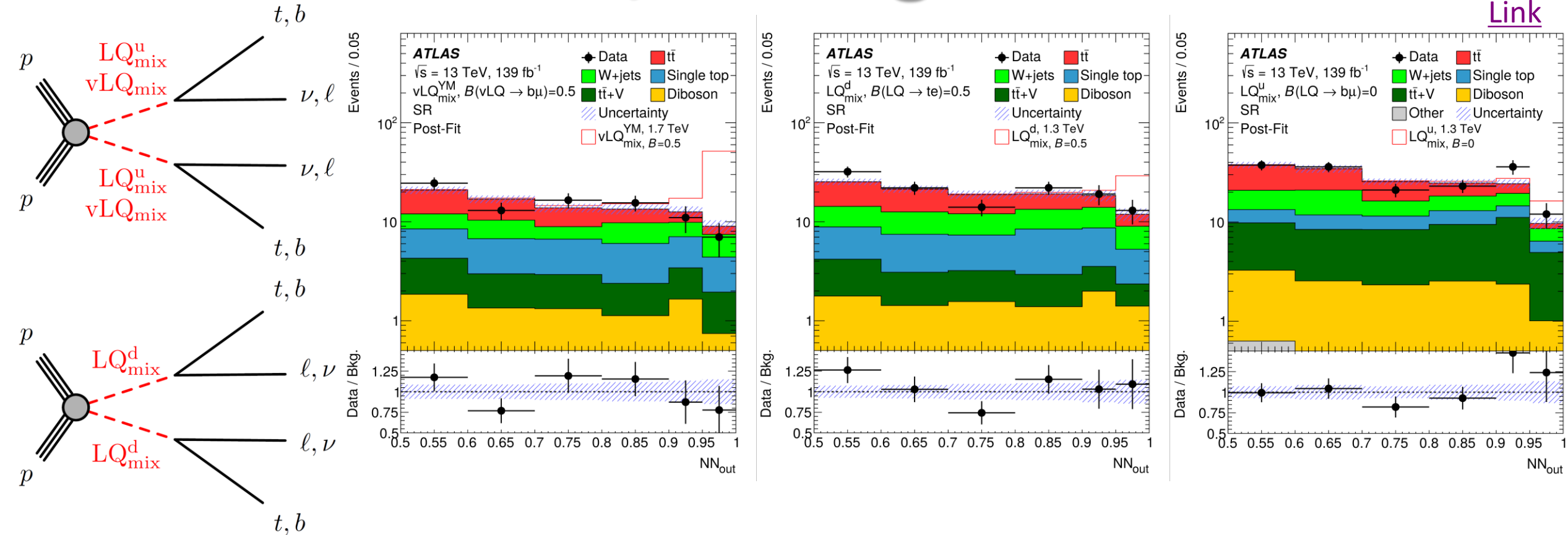
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For any combination of the parameters, these are the best limits to date!



# Pair Production, Orthogonal Generation

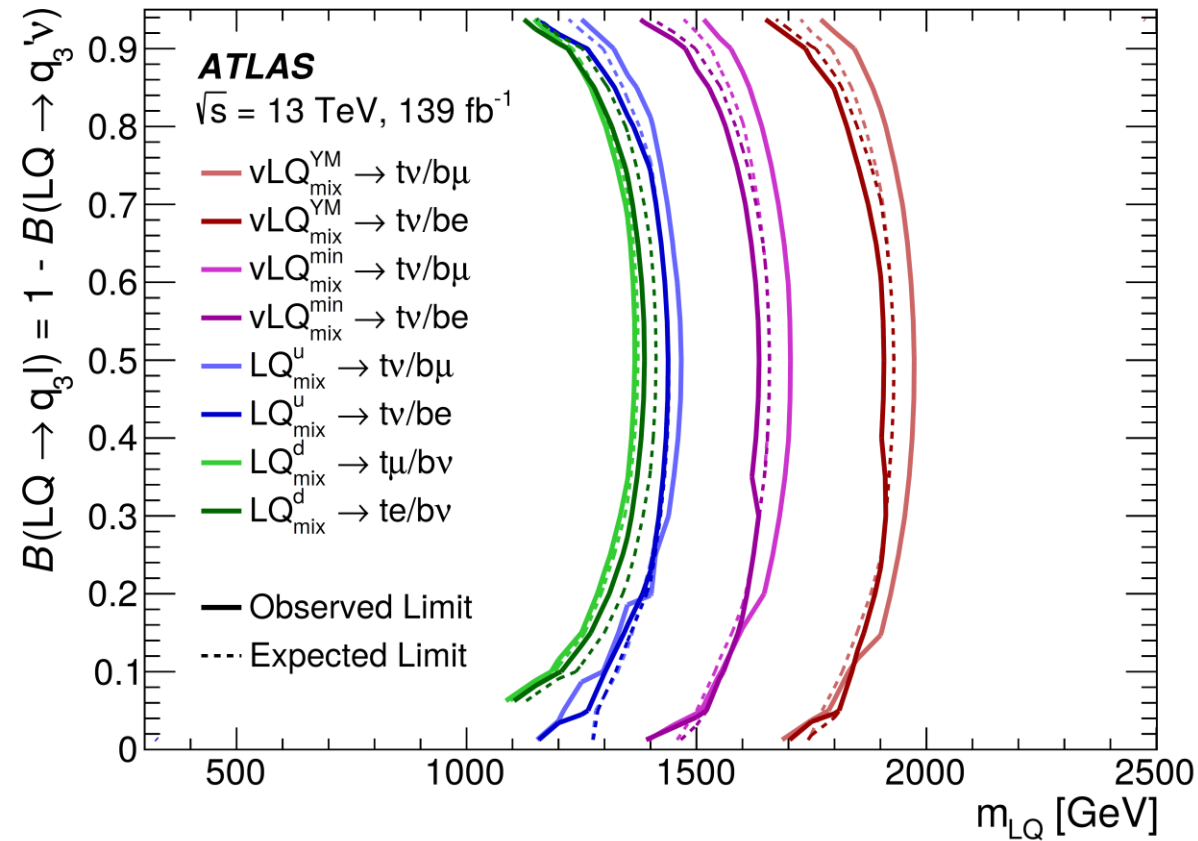
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- ✓ Searches for LQs decaying to **orthogonal generation quark (t, b) and lepton (e,  $\mu$ ,  $\nu$ )**.
  - Aroused interest to explain B-anomalies, muon g-2.
- ✓ Top modeling is reweighted, CRs are defined and fit simultaneously with SR to normalize top and W+jets.
- ✓ **NNs** are trained by mass and angular variables, and used to separate signal and background.
  - **NNs** are used as final discriminant variable.

# Pair Production, Orthogonal Generation

[Link](#)

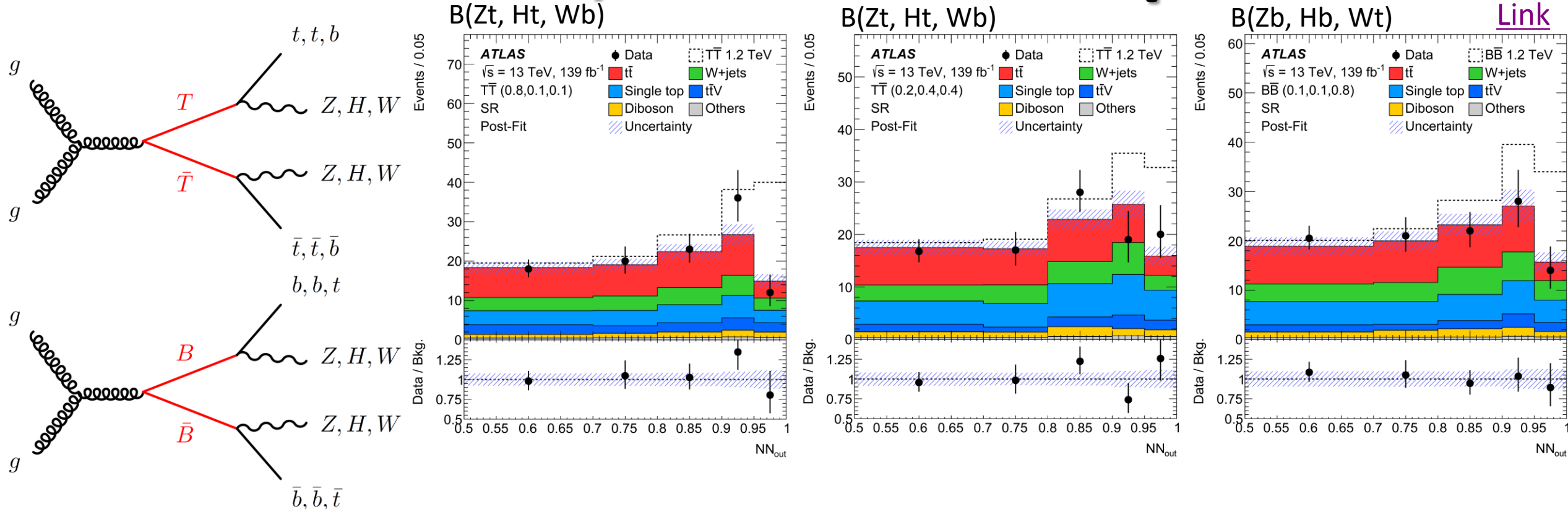


$B = 0.5$

	Exp. limit [GeV]	Obs. limit [GeV]
$LQ_{mix}^u \rightarrow tv/b\mu$	$1440^{+60}_{-60}$	1460
$LQ_{mix}^u \rightarrow tv/be$	$1440^{+60}_{-60}$	1440
$LQ_{mix}^d \rightarrow t\mu/b\nu$	$1380^{+50}_{-60}$	1370
$LQ_{mix}^d \rightarrow te/b\nu$	$1410^{+60}_{-60}$	1390
$vLQ_{mix}^{YM} \rightarrow tv/b\mu$	$1930^{+50}_{-60}$	1980
$vLQ_{mix}^{YM} \rightarrow tv/be$	$1930^{+50}_{-70}$	1900
$vLQ_{mix}^{min} \rightarrow tv/b\mu$	$1660^{+50}_{-50}$	1710
$vLQ_{mix}^{min} \rightarrow tv/be$	$1650^{+50}_{-60}$	1620

- ✓ Binned Profile Likelihood fit is performed for NN score distribution simultaneously for SR and CRs.
  - No significant excess over SM expectation is observed. 95% confidence-level upper limits are set.
- ✓ Upper limits on the production cross-section are derived for **eight models** as a function of leptoquark mass and branching ratio into the charged lepton.

# Pair Production, Zt+X with 1 lepton + MET



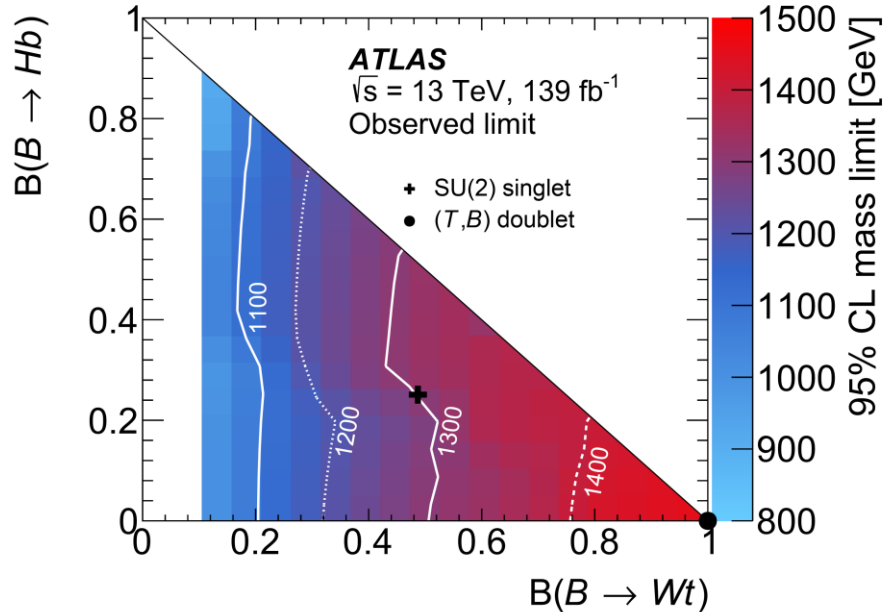
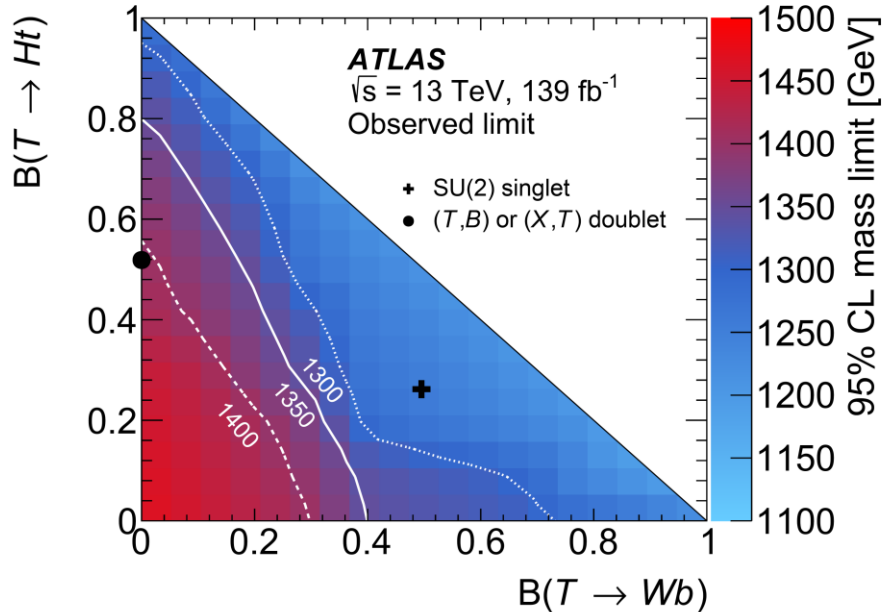
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- ✓ Investigates **all possible decay modes and combinations of branching ratios for the pair-produced T and B.**
- ✓ **Singlet and doublet T, B, as well as X are considered.**
- ✓ Top modelling is reweighted, single-top and W+jets are normalized from CR.
- ✓ **NNs** are trained for various signal hypotheses and branching ratio to better separate signal and background.
  - Used as final discriminant variables.

# Pair Production, $Zt+X$ with 1 lepton + MET

[Link](#)

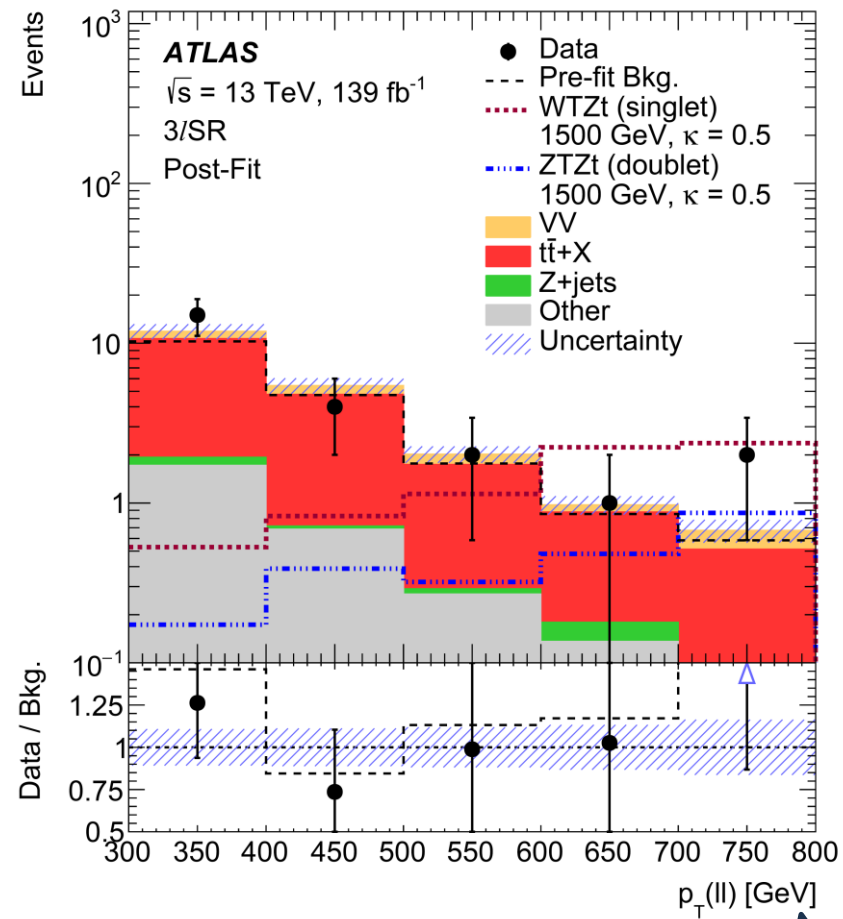
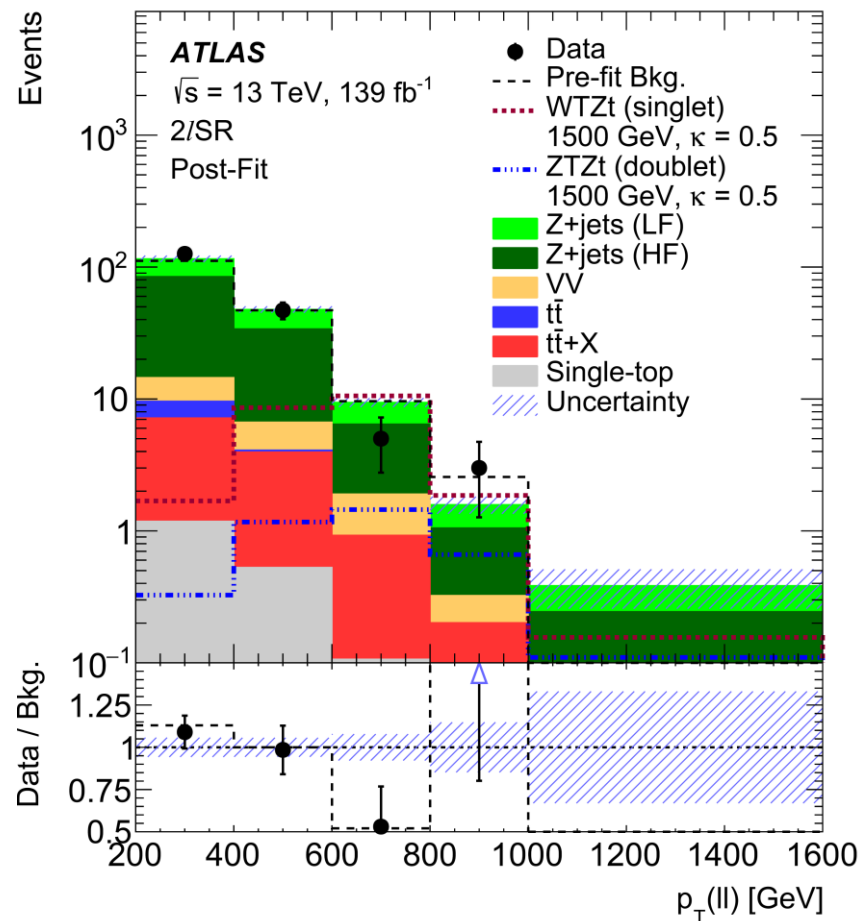
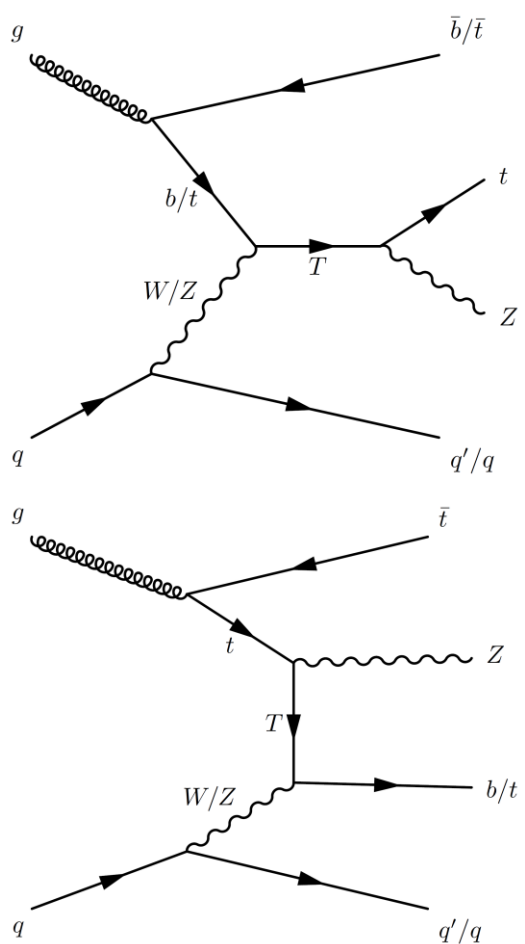
VLQ	Scenario	Exp. limit [TeV]	Obs. limit [TeV]
$T$	$\mathcal{B}(T \rightarrow Zt) = 100\%$	1.45	1.47
$T$	singlet	1.33	1.26
$T$	$(T, B)$ or $(X, T)$ doublet	1.41	1.41
$B$	singlet	1.30	1.33
$B/X$	$\mathcal{B}(B/X \rightarrow Wt) = 100\%$ or $(T, B)/(X, T)$ doublet	1.42	1.46
$T/B/X$	$(T, B)$ or $(X, T)$ doublet, mass degenerate	1.56	1.59



- ✓ The obtained mass limits are **300 to 400 GeV higher** than in the earlier ATLAS analysis in the same final state.
- ✓ **The strongest lower limits for  $T$ ,  $B$  and  $X$  are at 1.59 TeV for  $(T, B)$  and  $(X, T)$  weak-isospin doublets** where both VLQ are considered and assumed to be mass degenerate.

# Single Production, multi-lepton

[Link](#)



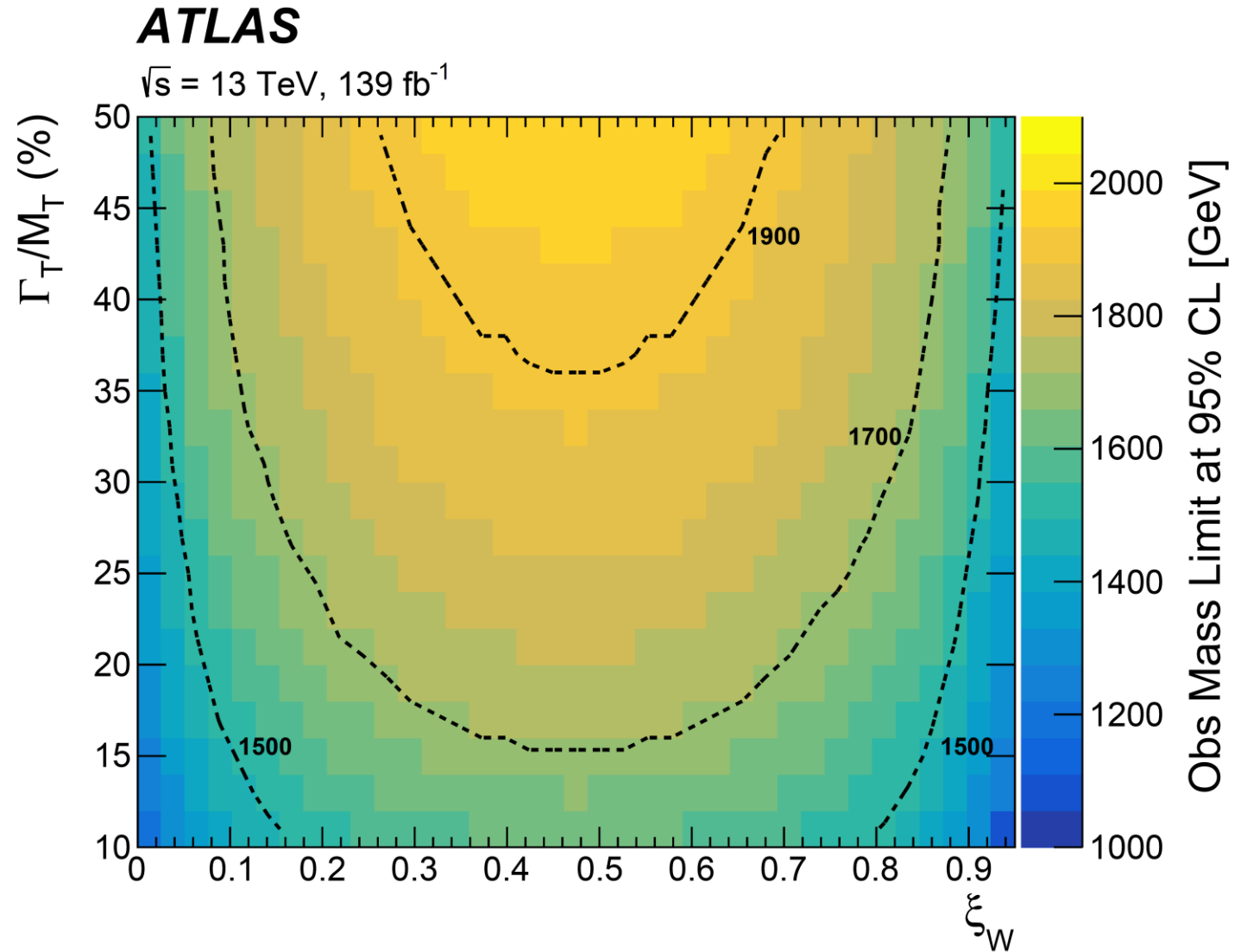
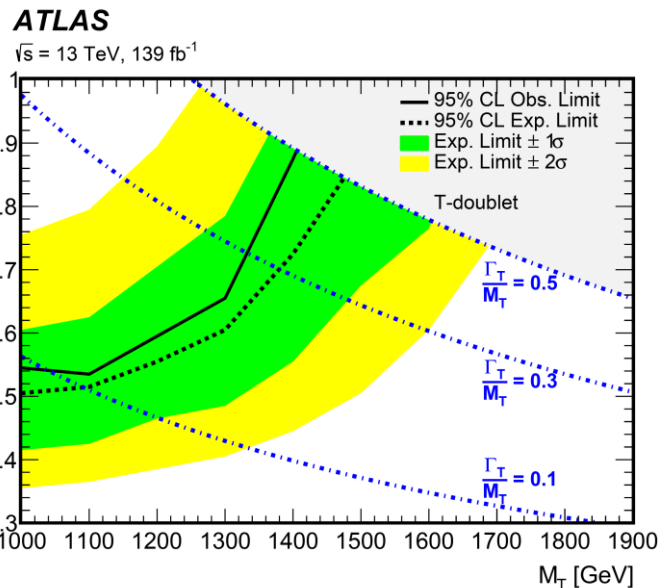
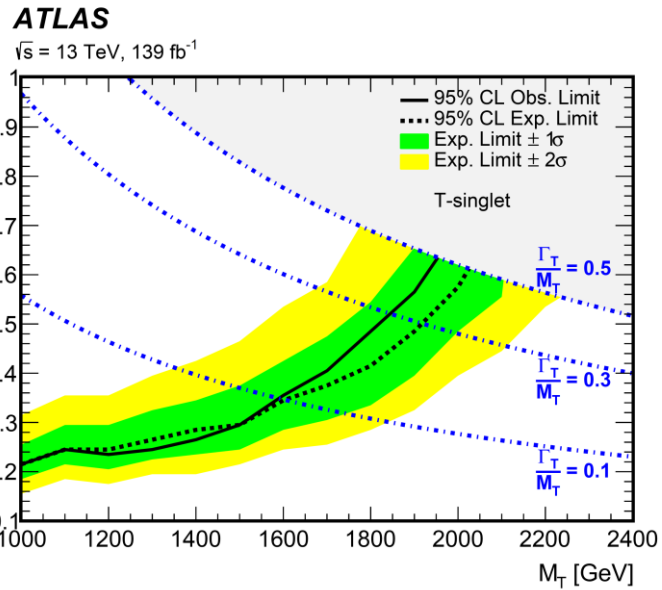
- ✓ Singly produced T and the final state has 2 leptons (e or  $\mu$ ) or 3 leptons (2l and 3l channels).
- ✓ **Variable radius reclustered jets (vRC jets) are used to identify hadronically decaying boosted top-quark jets.**
- ✓ Z+jets modelling is reweighted in 2l channel, VV and tt + X modellings are reweighted in 3l channel.
- ✓  $p_{T(II)}$  is final discriminant variable.





# Single Production, multi-lepton

[Link](#)



- ✓ 2l and 3l channels are statistically combined.
- ✓ Limits on the T mass and coupling are set for singlet and doublet.