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

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on behalf of the ATLAS Collaboration

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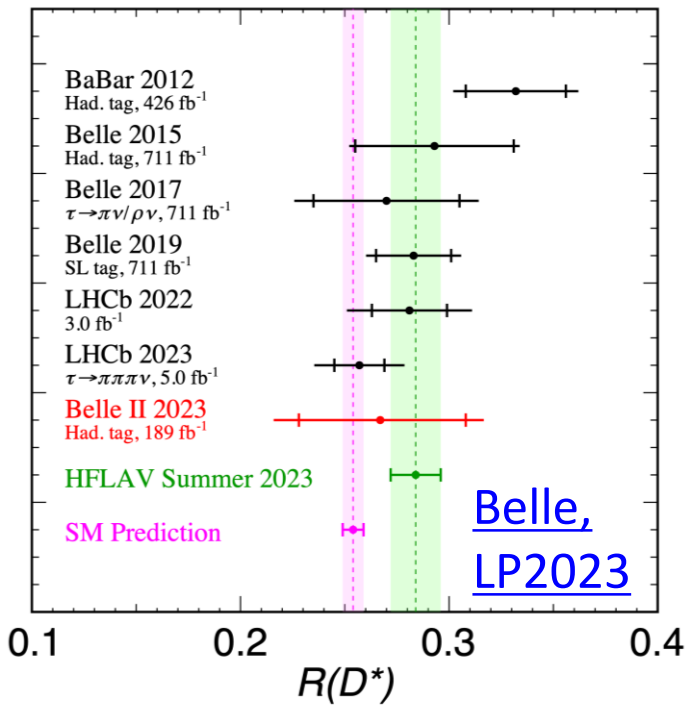
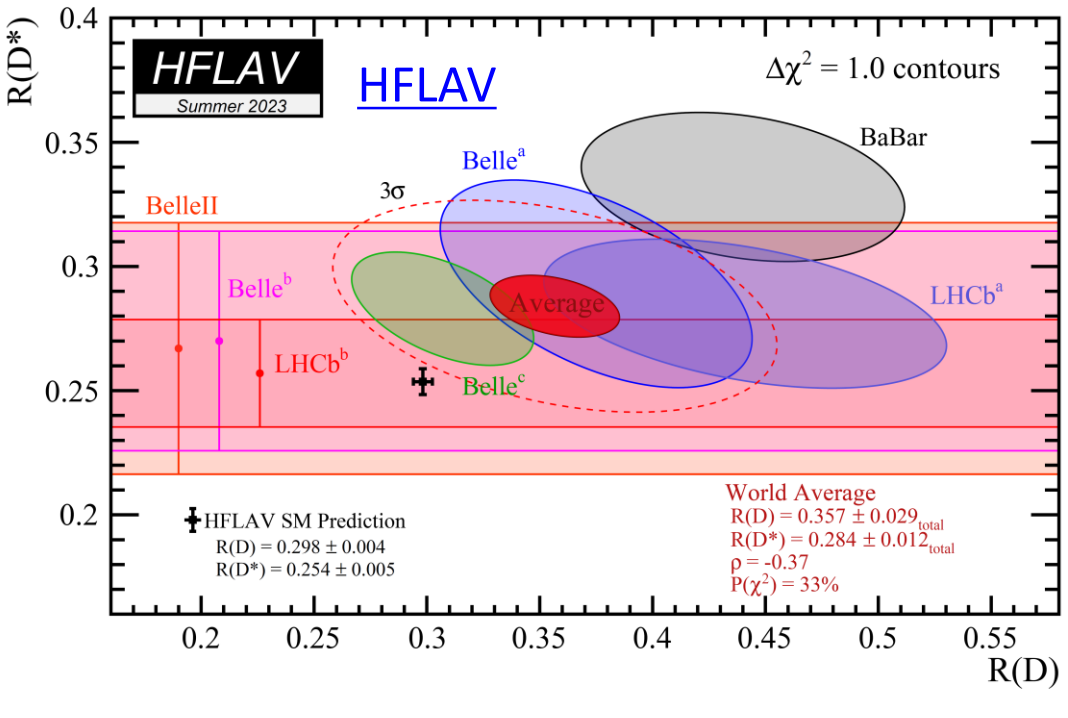
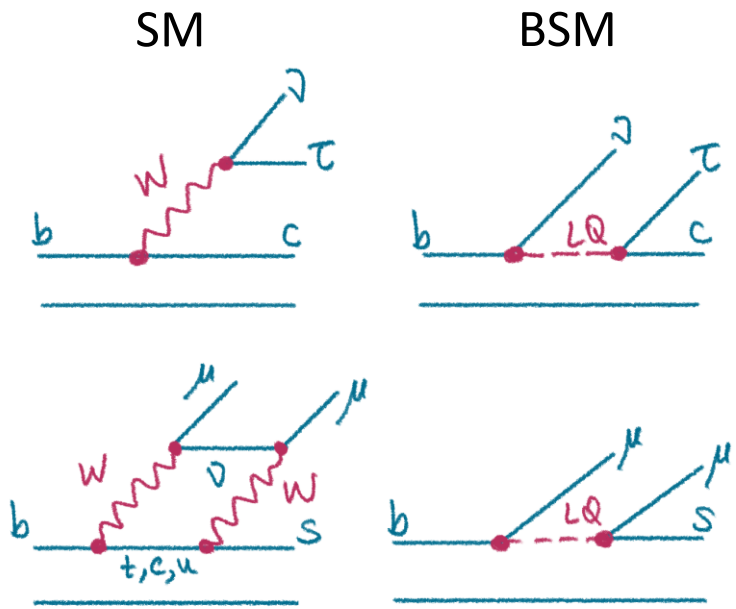
Leptoquarks

Motivations







✓ **Hints for lepton flavour universality violation** is observed in charged and neutral current processes in B-physics.

- R_D/R_{D^*}: 3.2 σ deviation in global average
- R_K/R_{K^*}: Now SM consistent?
- B→Kμμ angular variable discrepancies, muon g-2
- and more…

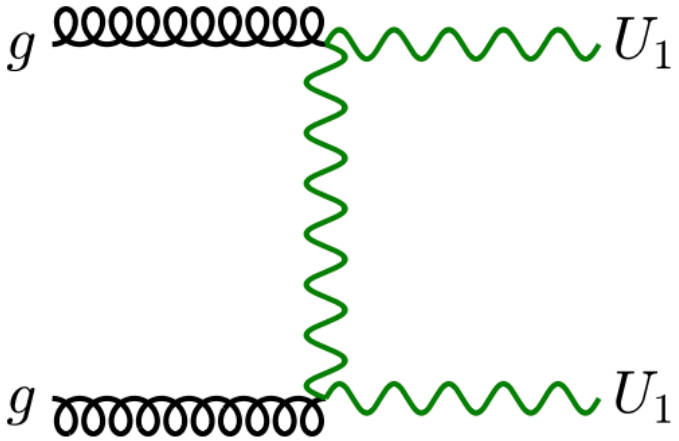
$$R\left(D^{(*)}\right) = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell)}, (\ell = e \text{ or } \mu)$$

✓ The size of the anomalies suggests a tree-level mediator, such as **leptoquarks (LQs)**.

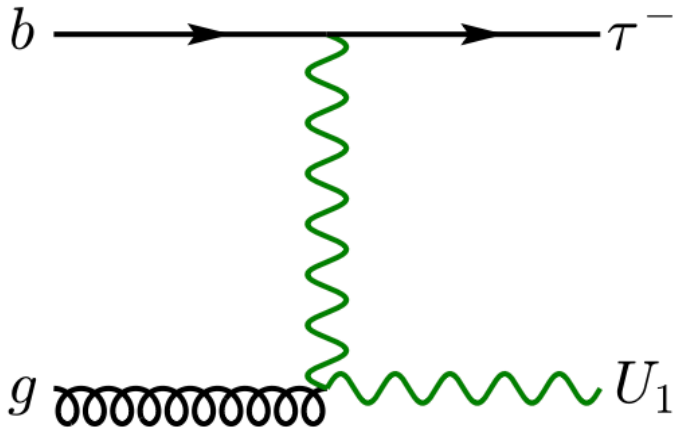
- LQs appear in several BSM models, such as a part of GUT.

Analysis Targets

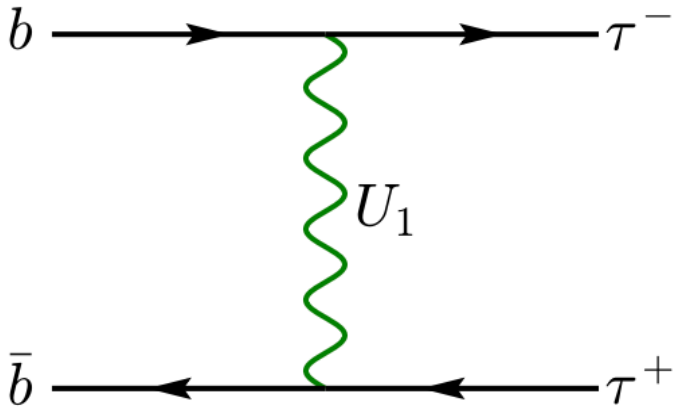
U_1: Vector LQ in U_1 model



Pair Production



Single Production



Non-resonant

- ✓ LQs are hypothetical particles that **carry color and a fractional electric charge, decay into quark–lepton pairs**.
- ✓ **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**: τ, μ, e, ν

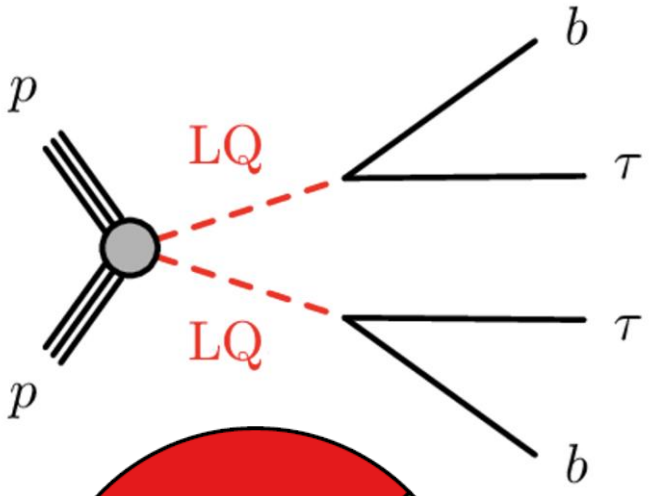
Leptoquark Recent (>= 2022) Publications

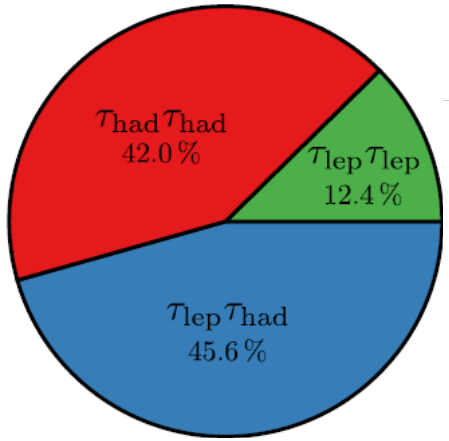
- ✓ Pair-produced scalar and vector LQs decaying to 3rd-gen quarks and 1st/2nd-gen leptons (Link)
- ✓ **Leptoquark pair production in bτbτ final states** (Link)
- ✓ Excited tau and leptoquark search (2taus+2jets) (Link)
- ✓ **Search for single scalar leptoquark production in the btautau final state** (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)

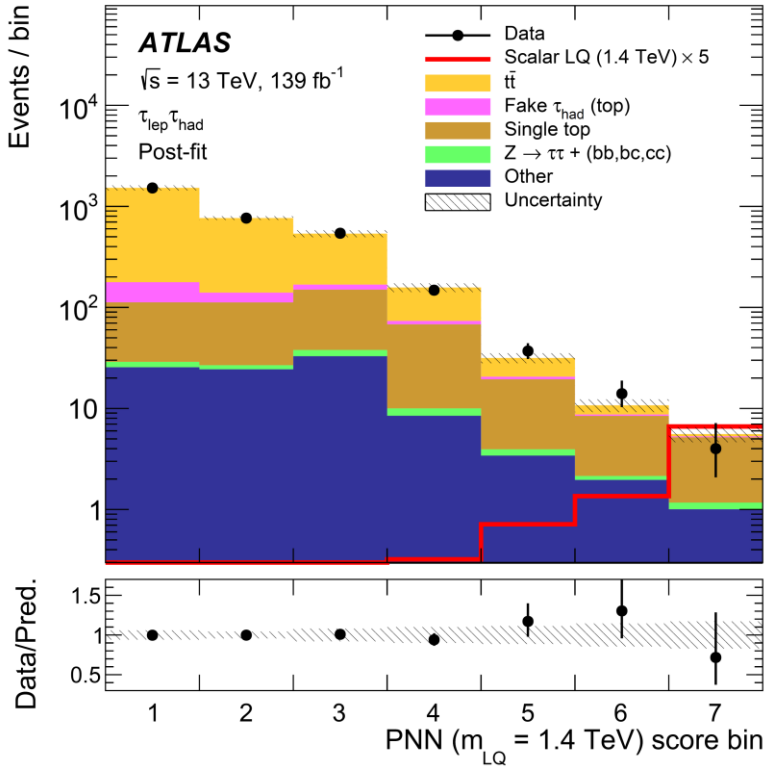
- ✓ You can find all the ATLAS results in ATLAS public results page
- ✓ **The ones shown in red are introduced in the next pages, which are picked up by my bias!**

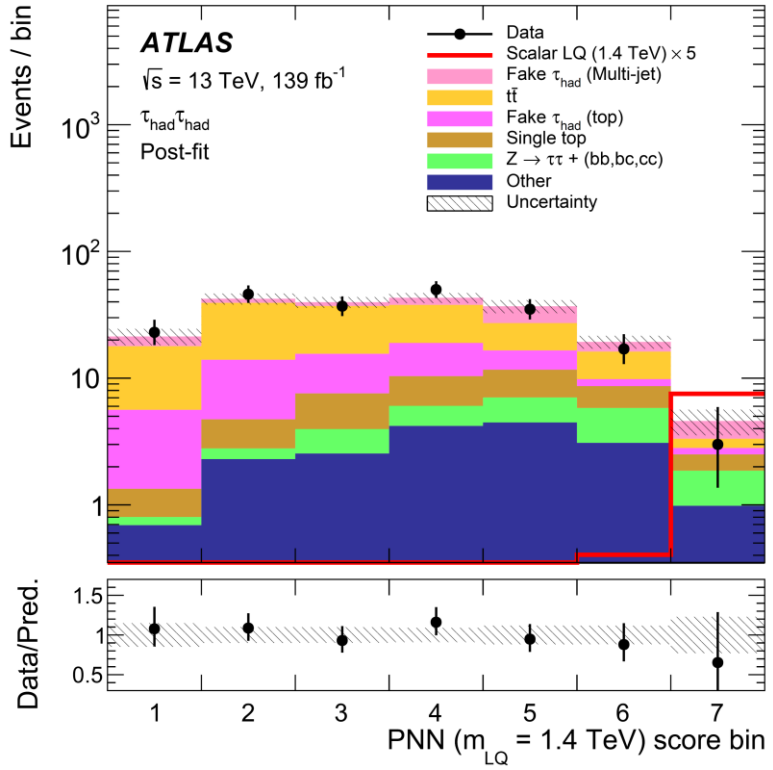
Pair Production, Decaying to bτbτ

Link







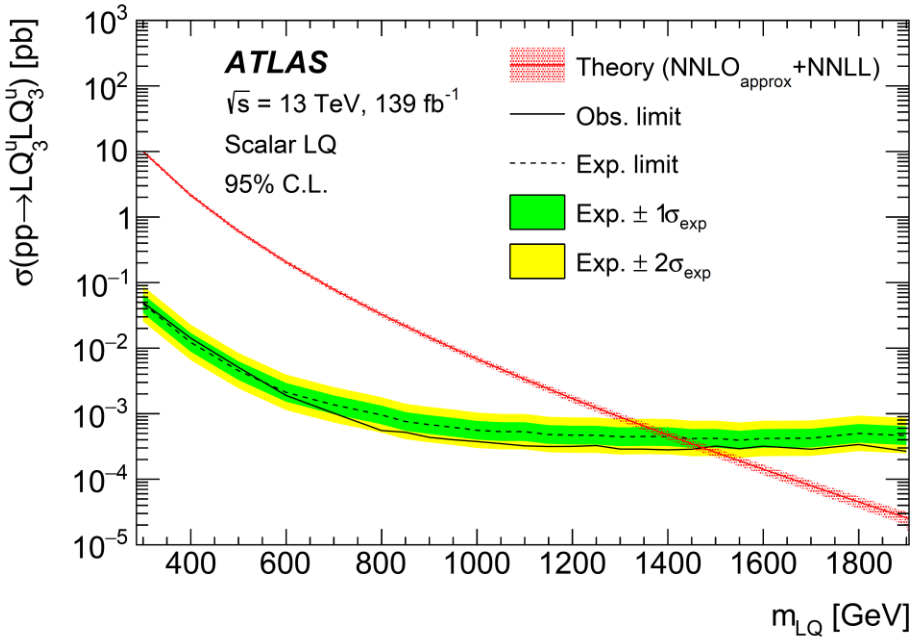


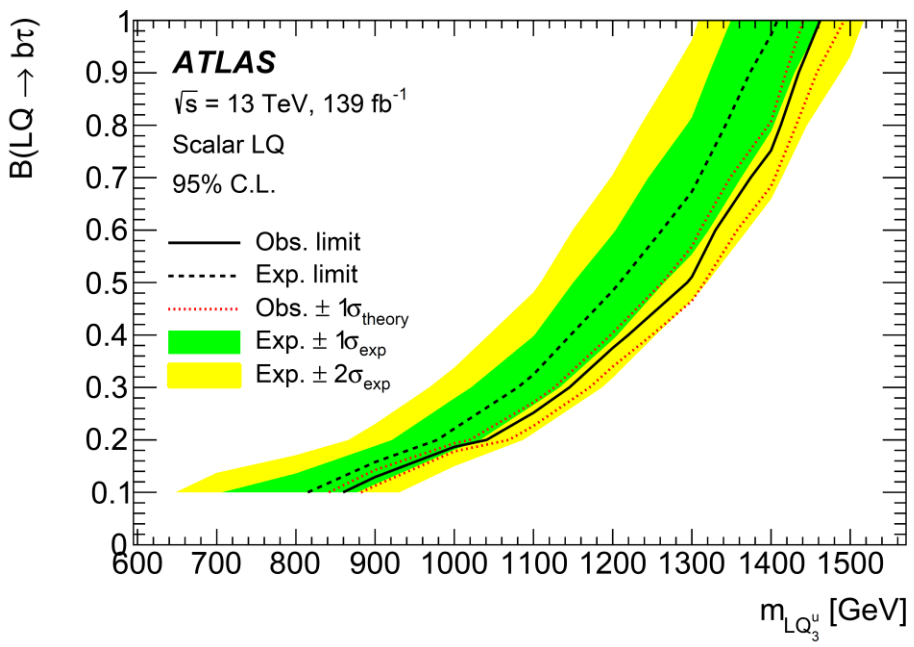
- ✓ **Full hadronic $\tau_{had}\tau_{had}$ and semi-leptonic $\tau_{lep}\tau_{had}$** (lep = e, μ) channels.
- ✓ Higher energy phase space is selected by p_T, E_T^{miss}, scalar sum of p_T (s_T).
- ✓ Top modeling is reweighted, fake τ ID is corrected, multi-jet fakes are estimated by data-driven Fake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

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

Pair Production, Decaying to bτbτ

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 τ and b-jet identification, improved MVA.**

Pair Production, Combination

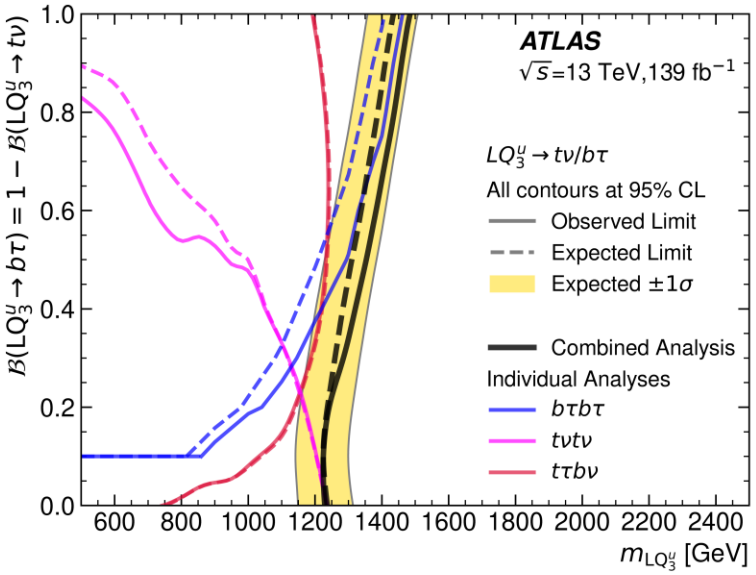
Link

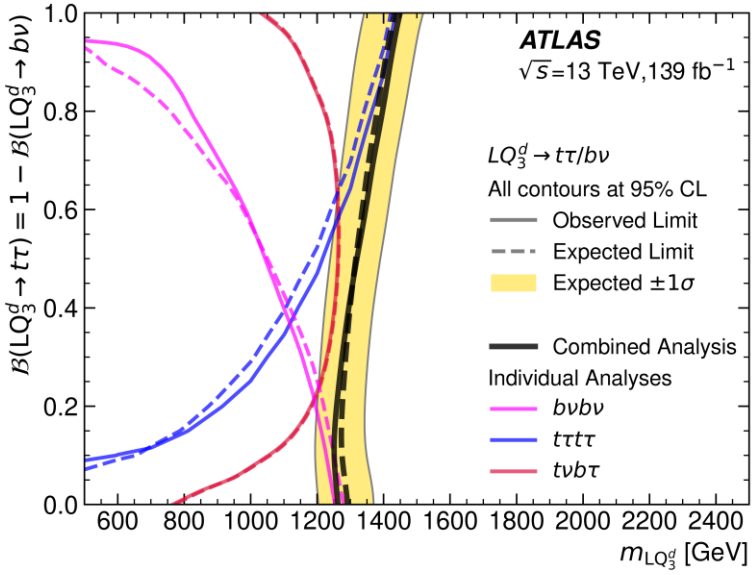
Search		Interpretation								
		Scalar				Vector		Signal Region		
Final State	Citation	LQ_3^u	LQ_3^d	LQ_{mix}^u	LQ_{mix}^d	$U_1^{YM/MC}$	$\tilde{U}_1^{YM/MC}$	N_ℓ	$N_{\tau_{had}}$	$N_{b\text{jets}}$
$t\nu b\tau$		✓	✓	–	–	✓	–	0	1	≥ 2
$b\tau b\tau$		✓	–	–	–	✓	–	$\{0, 1\}$	$\{1, 2\}$	$\{1, 2\}$
$t\tau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

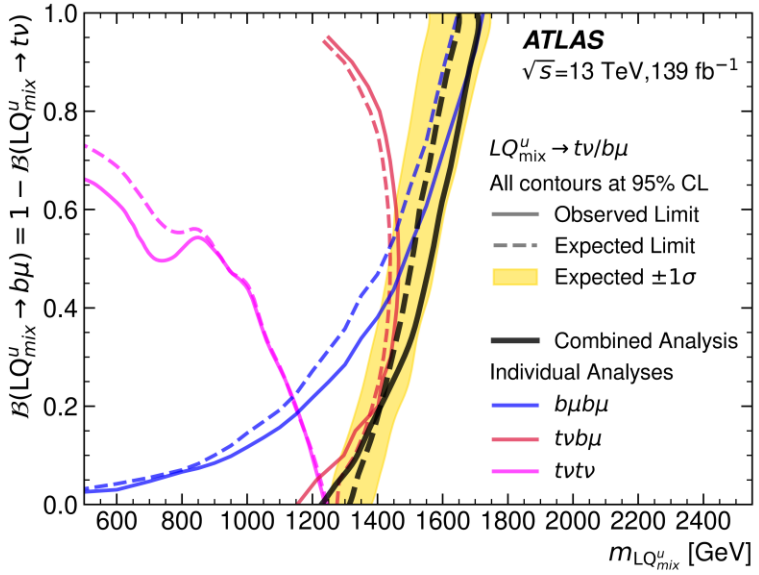
- ✓ **A statistical combination** of various searches for pair-produced leptoquarks.
- ✓ All possible decays of the leptoquarks into **quarks of the third generation and charged or neutral leptons** of any generation are investigated.
- ✓ Overlap among regions, systematics effects are carefully checked.

Pair Production, Combination

Link

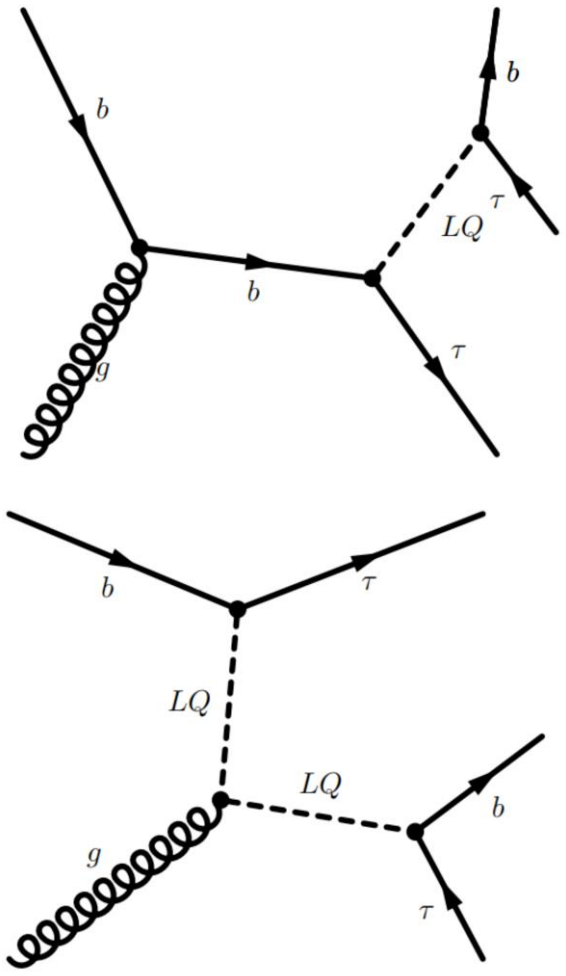


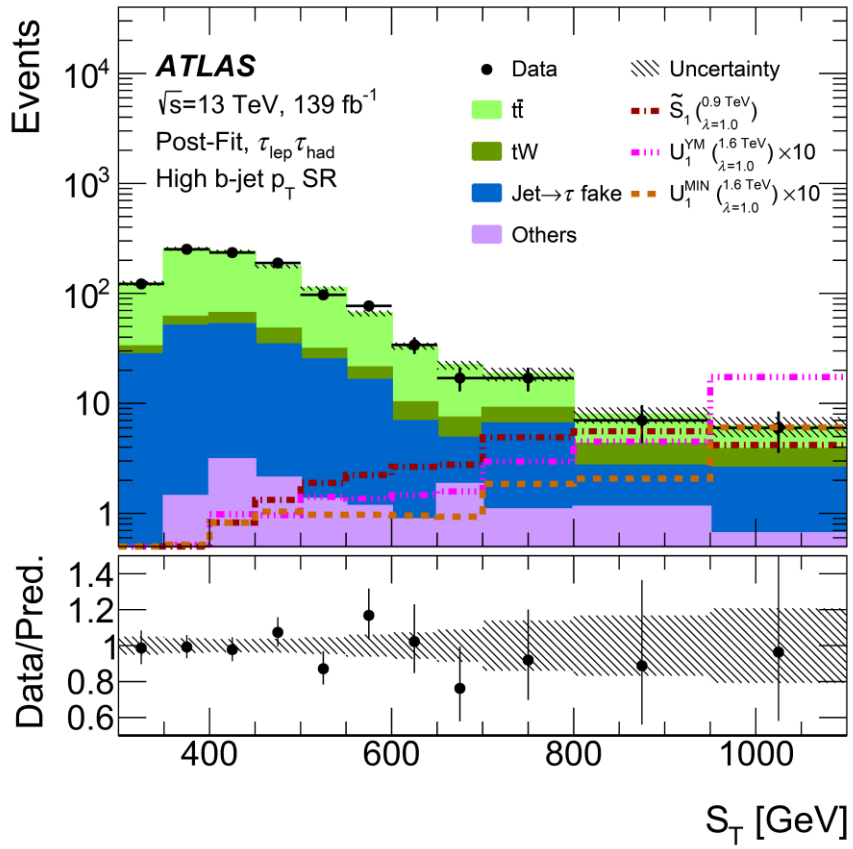


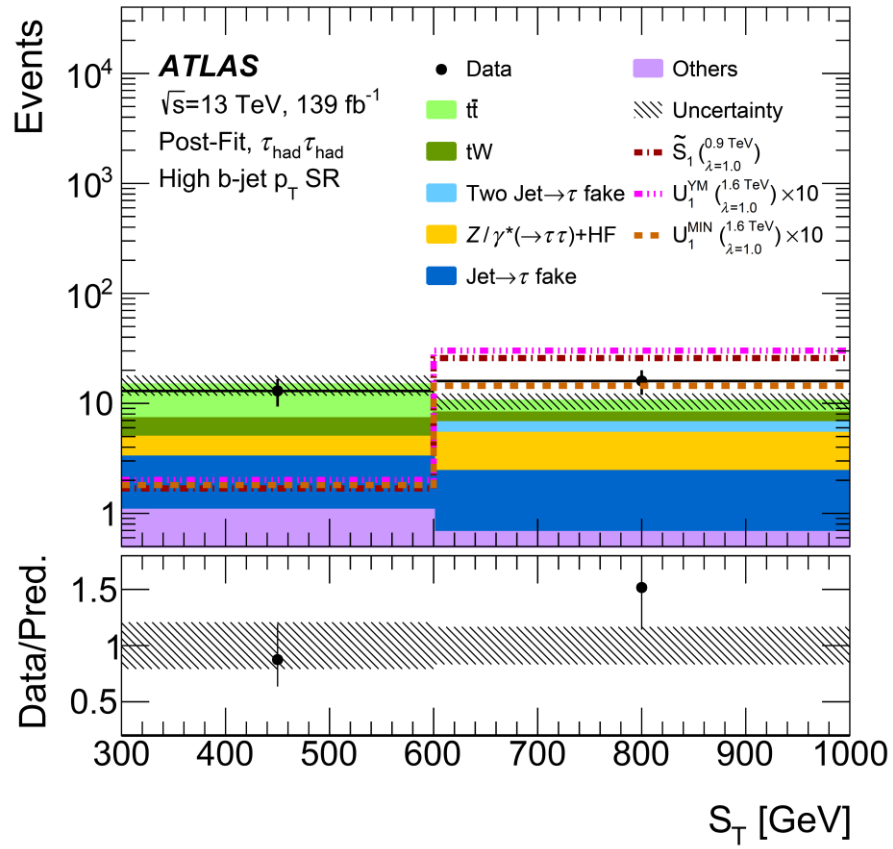


- ✓ Simultaneous binned profile-likelihood fits are performed to CRs and SRs.
- ✓ **The resulting lower bounds on leptoquark masses exceed those from the individual analyses by up to 100 GeV, depending on the signal hypothesis.**
- ✓ **For most combinations of the parameters, these are the best limits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

Single Production, Decaying to bττ [Link]







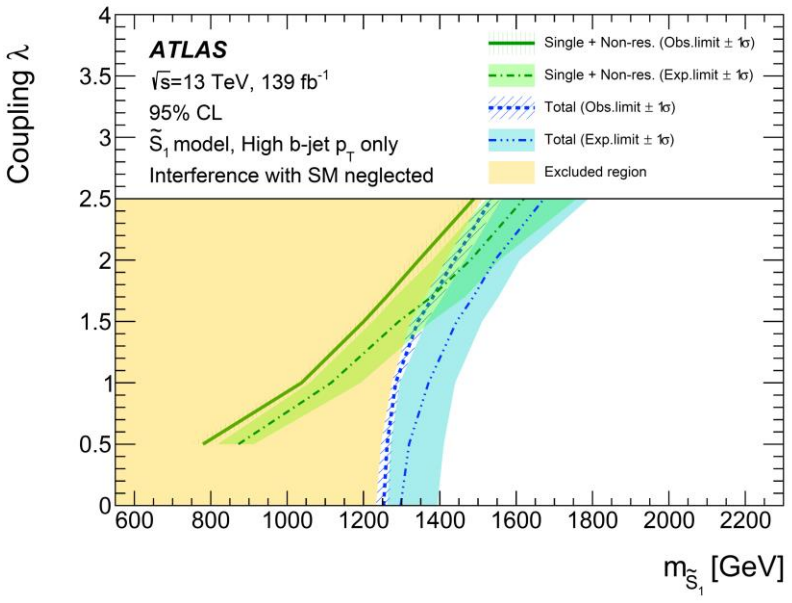
✓ The single production contribution becomes larger than that from pair production **at high mass and coupling values**.

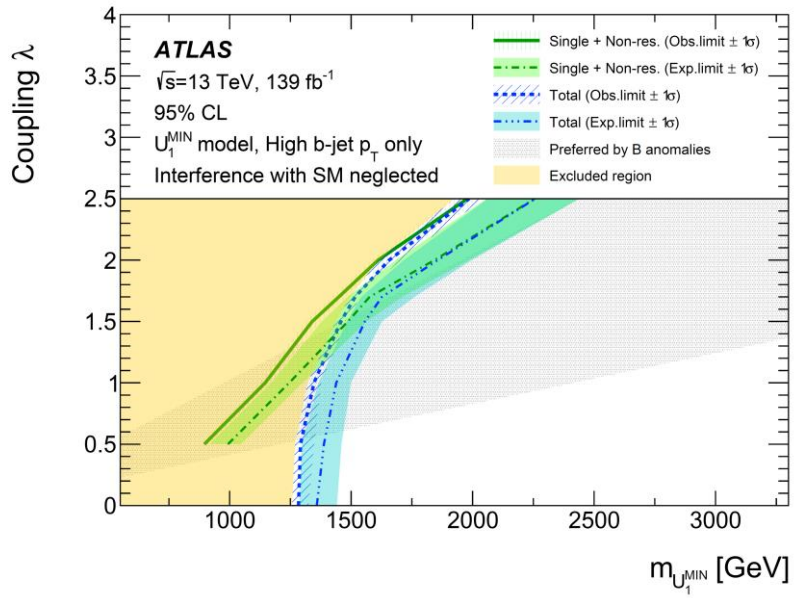
✓ Higher energy phase space is selected by p_T, E_T^{miss}, scalar sum of p_T of all the reconstructed objects (S_T).

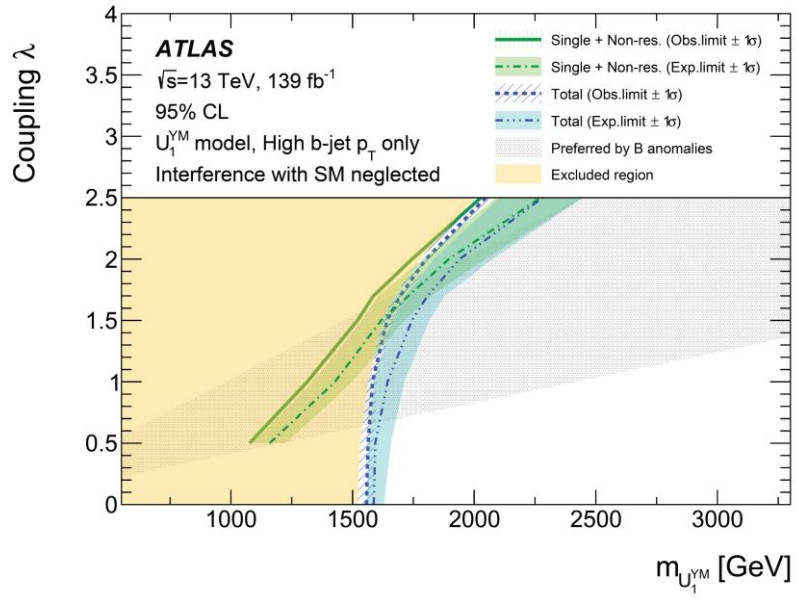
✓ Top modeling is reweighted, fake τ ID is corrected, multi-jet fakes are estimated by data-driven FF method.

✓ **S_T** is used as final discriminant variable.

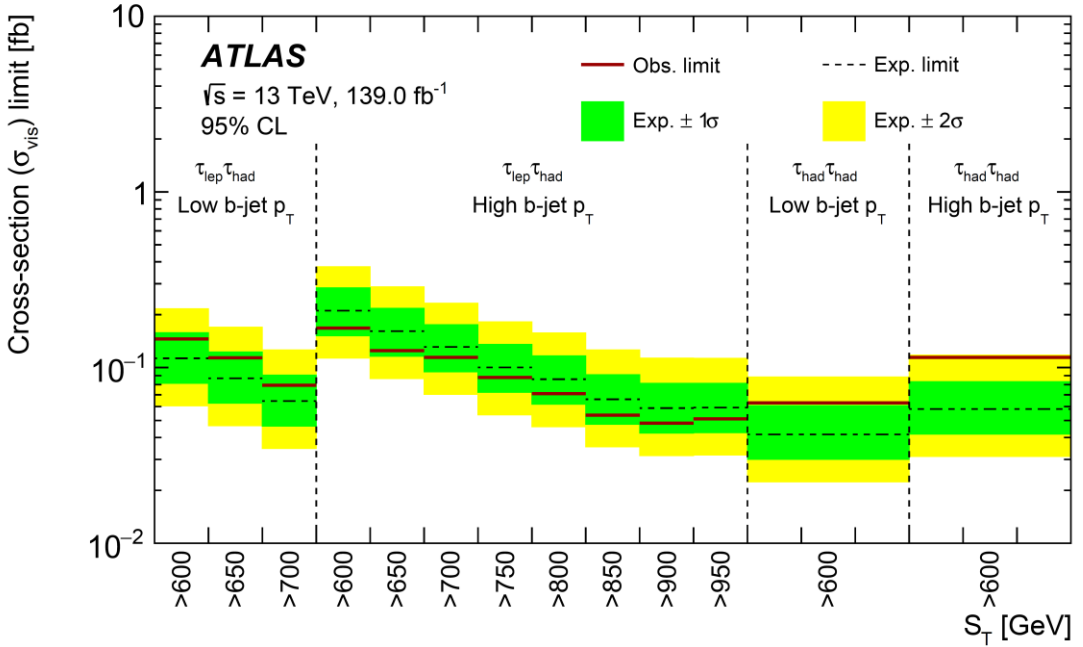
Single Production, Decaying to bττ [Link]







- ✓ 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 bττ final state!**
- ✓ **An additional model-independent search considering both the high and low b-jet p_T signal regions is performed.**

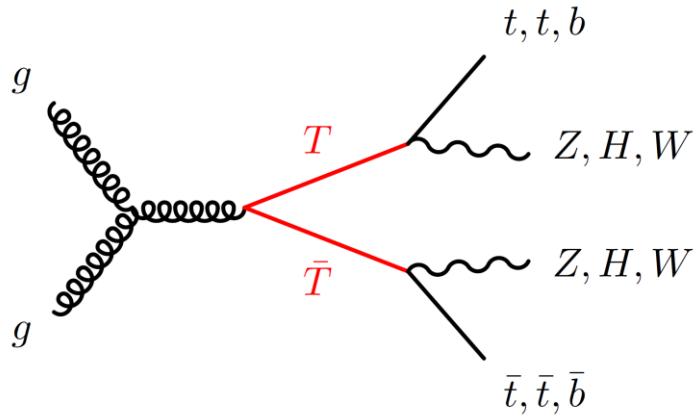


Vectorlike Quarks

Vectorlike Quark Introduction

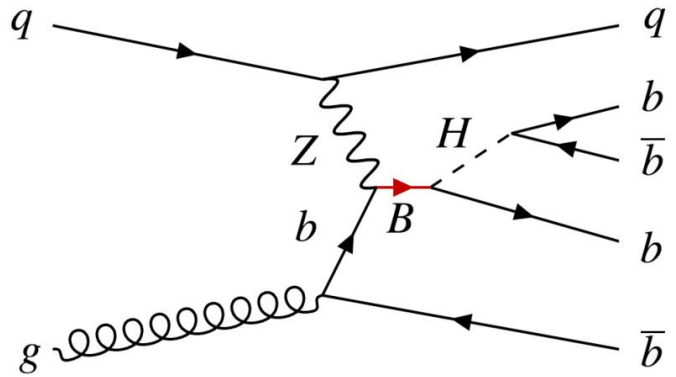
- ✓ **Vectorlike Quarks (VLQs)** are **color triplet, spin 1/2, fermionic partners of SM quarks** in many BSM models.
  - Composite Higgs, Little Higgs, Extra Dimensions, etc, to explain radiative divergences to the Higgs mass.

- ✓ VLQs could appear as different types of multiplets:
  - SU(2) **singlets, doublets** (or triplets of T, B, X or Y)
    - **ξW=0.5, ξZ=ξH=0.25** for singlet, **ξW~0, ξZ=ξH=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→Wb, T→Zt, T→Ht, B→Wt, B→Zb, B→Hb, X→Wt, Y→Wb**

- ✓ Parameters of model:
  - **$M_{T,B}$**: Mass of the T/B quark
  - **κ**: Global electroweak coupling parameter
  - **ξW, ξZ, ξH**: Relative couplings to W, Z, H bosons respectively
  - **Relative width**: $\Gamma/M \sim \kappa^2 M^2$

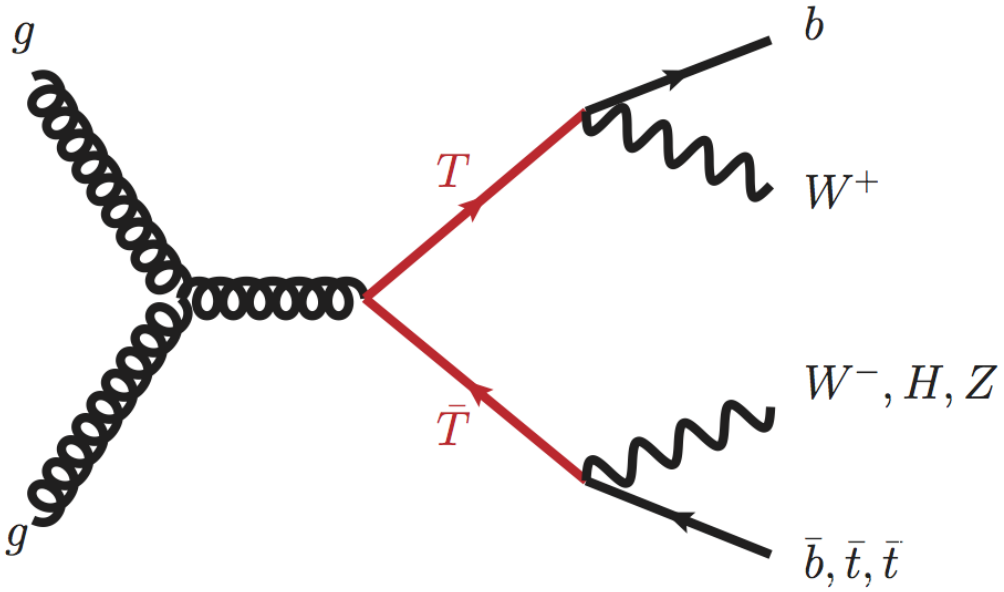


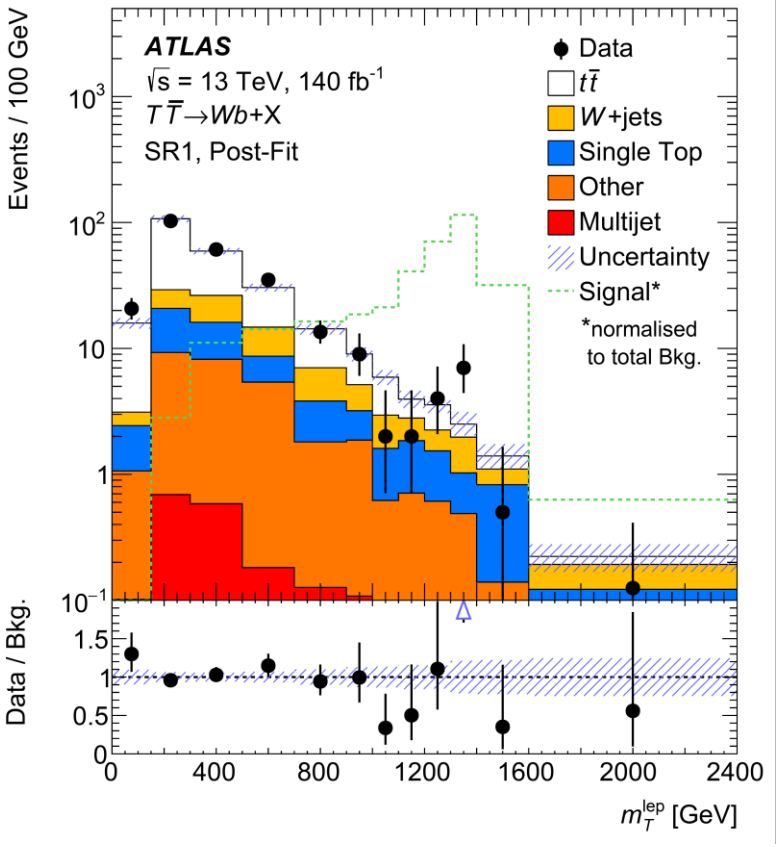
Vectorlike Quark Recent Publications

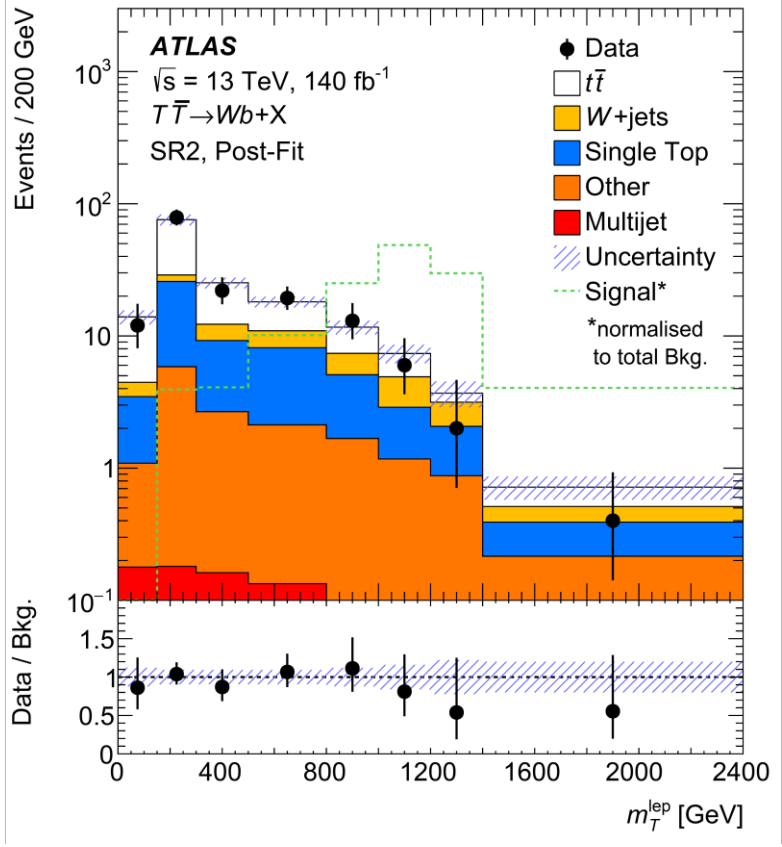
- ✓ Single VLQ production in all-hadronic final state (T→Ht, H→bb, t→bqq) (Link)
- ✓ VLQ pair search with opposite sign multileptons (T/B, T→Zt/b, B→V(H)t/b, Z→ll) (Link)
- ✓ VLQ pair production search in the Zt+X decay with a 1 lepton plus MET plus jets final state (TT, BB) (Link)
- ✓ Single VLQ via the Ht/Zt decay in the 1-lepton channel (T→Ht, Zt) (Link)
- ✓ VLQ single production search with opposite sign multileptons (T→Zt, Z→ll) (Link)
- ✓ **Search for vector-like B → bH with H → bb** (Link)
- ✓ **VLQ pair production search in the Wb+X final state (TT→Wb and Wb, Ht, Zt, BB→Wt and Wt, Hb, Zb)** (Link)
- ✓ **Search for MET plus a single-top-quark (T→Zt, Z→νν, t→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, >= 1b [Link]

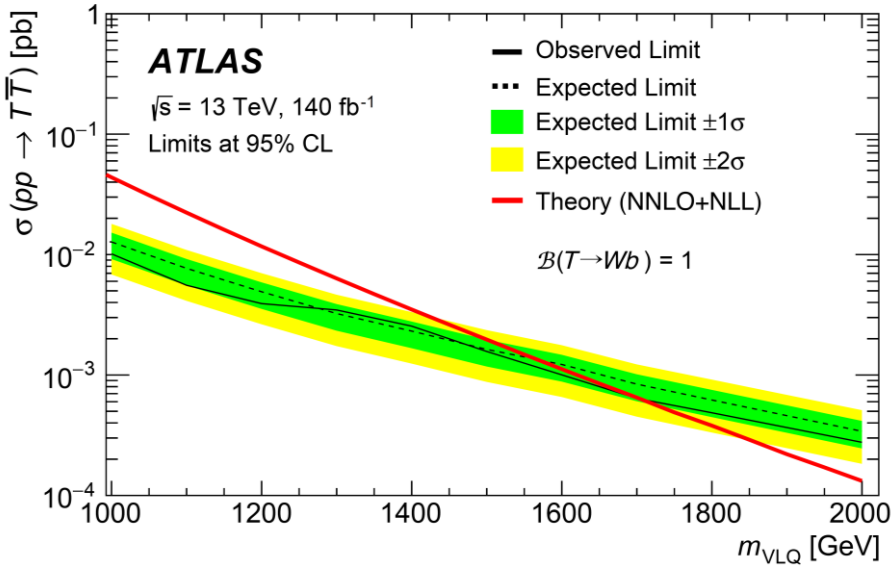


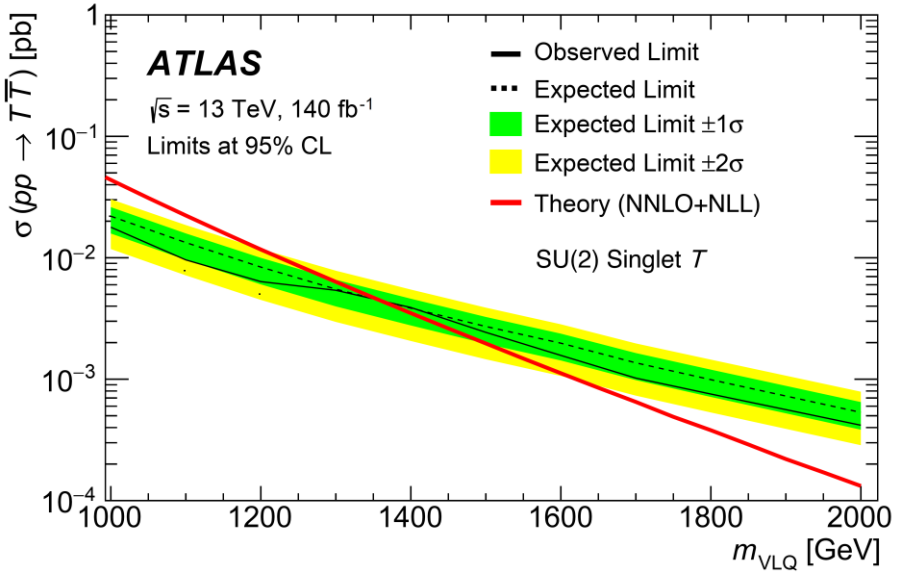


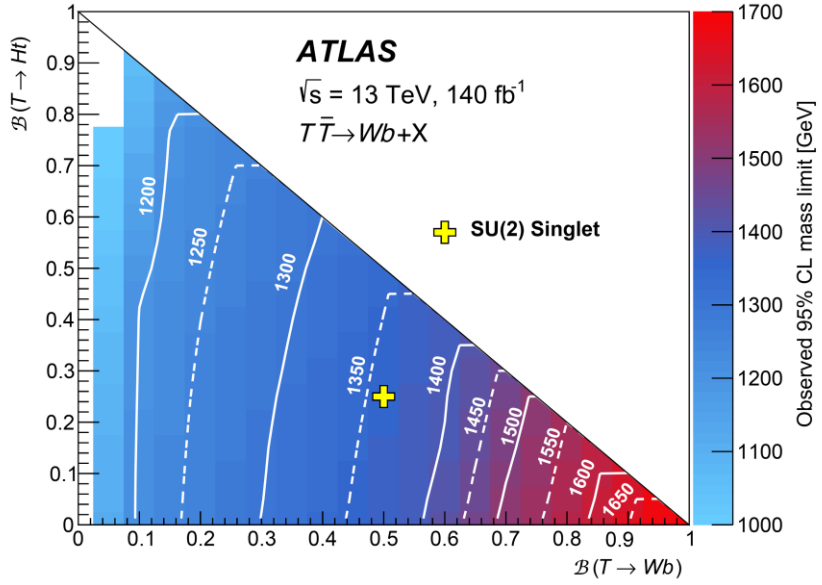


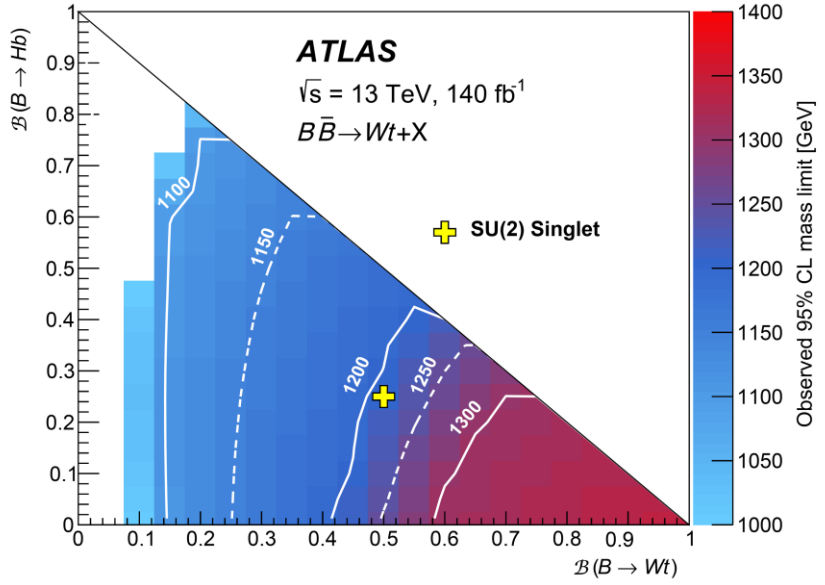
- ✓ **Optimised for the TT→WbWb** channel with one W boson decaying leptonically and the other hadronically.
- ✓ **High-pT hadronically decaying W bosons are tagged as a single large-radius (large-R) jets.** New!
- ✓ Top modelling is reweighted, tt and W+jets are corrected from CR, multijets are estimated 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, >= 1b [Link]





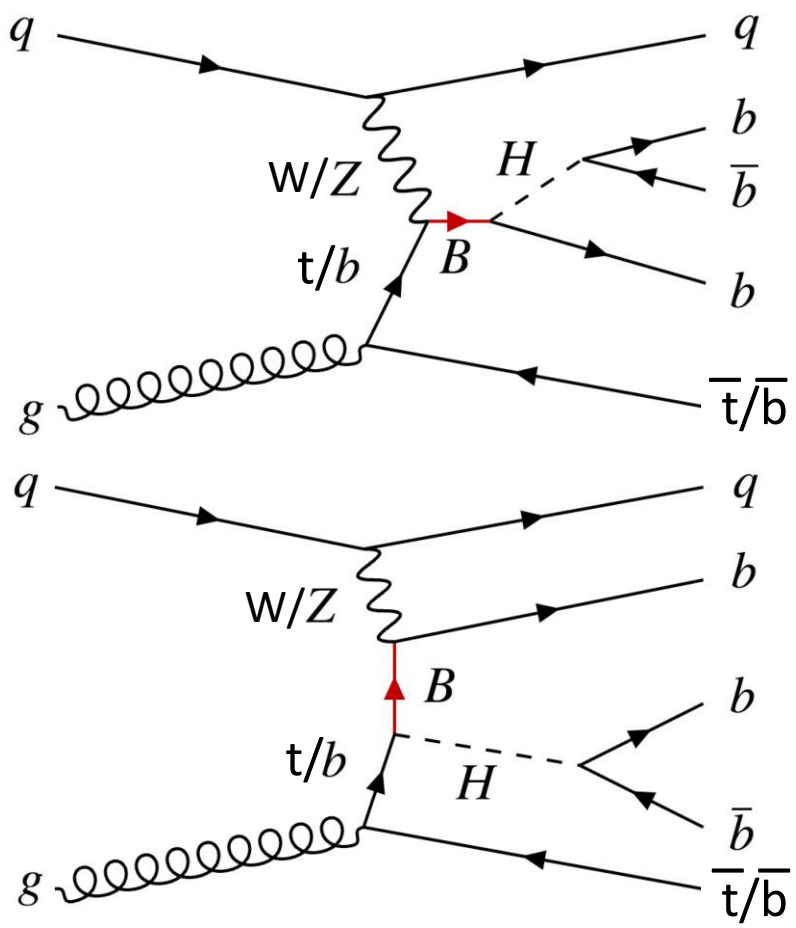


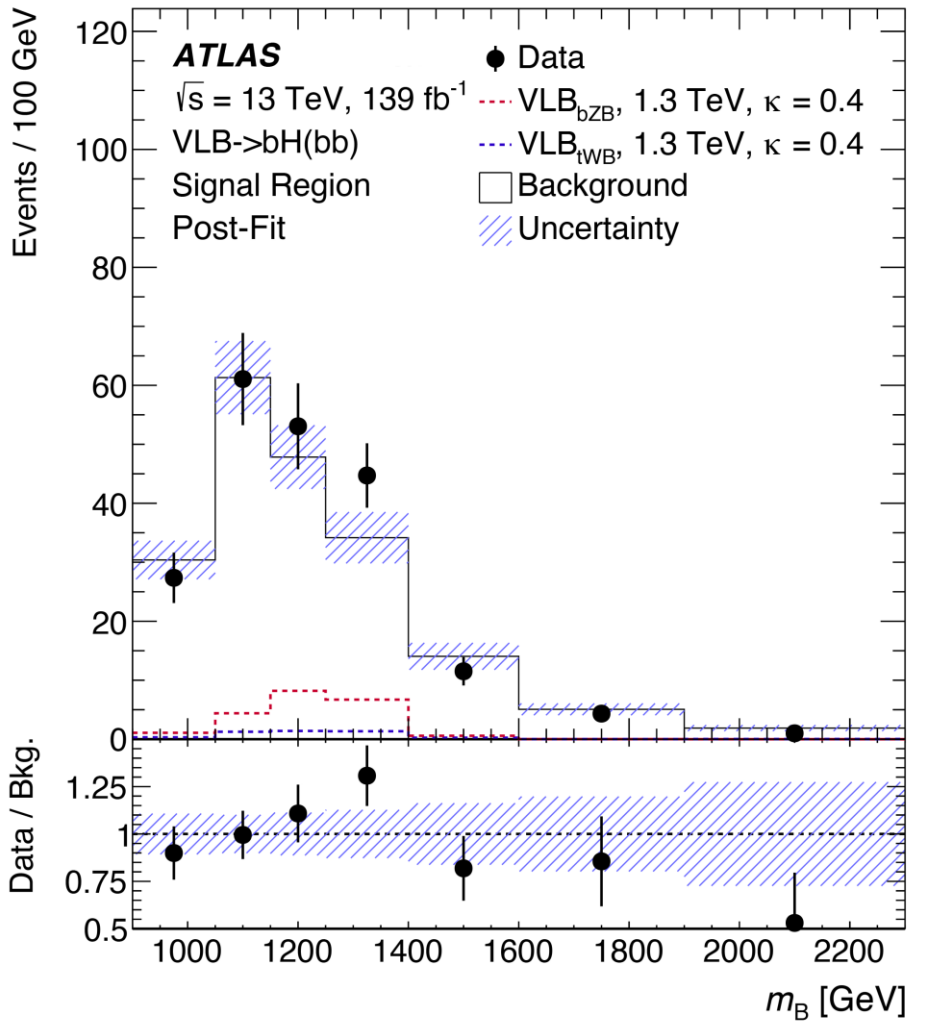


- ✓ Limits are set on
  - B(T→Wb) = 1
  - SU(2) Singlet T
- ✓ Limits between BRs are also checked.
- ✓ Though this analysis is optimized for TT→Wb+X, BB→Wt+X is also considered.
- ✓ **The most stringent limits are set for the scenario B(T→Wb) = 1.**

Single Production, B → bH(bb)

Link



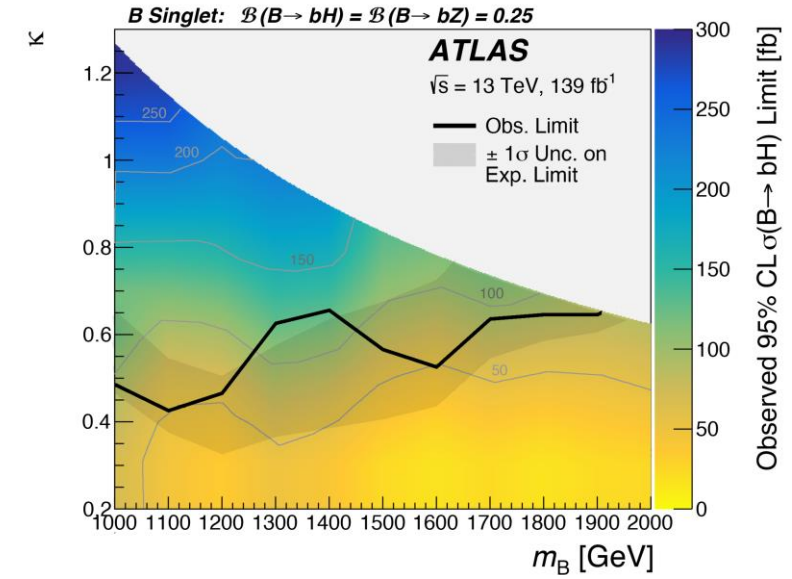


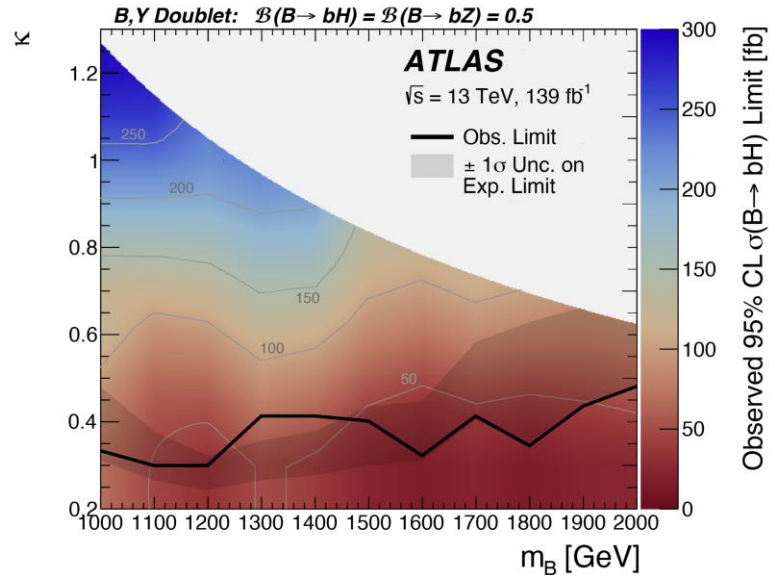
New!

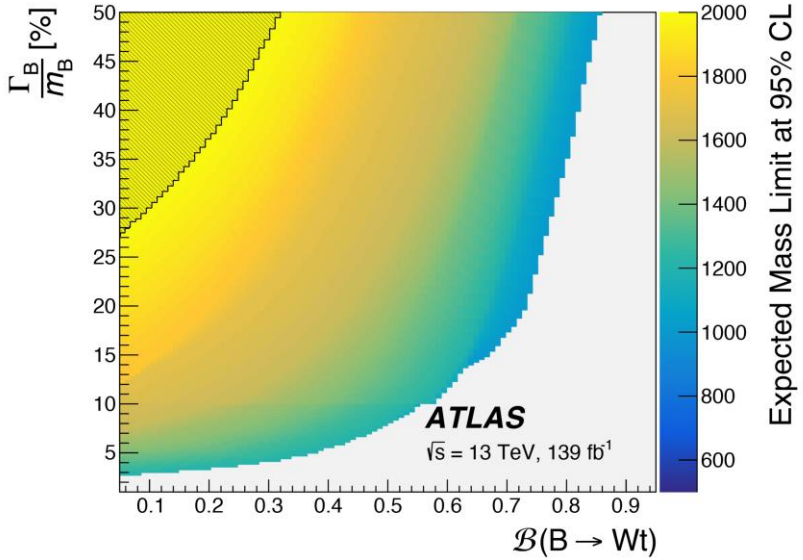
- ✓ This analysis focuses on B → bH with H → bb.
- ✓ **Large-R jet with variable-radius (VR) track-jets is exploited to explore presence of b-hadrons in large-R jets.**
  - Higgs Candidates (HC) are reconstructed as single large-R jets, classified by the b-tagged track-jet multiplicity.
- ✓ Multijets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

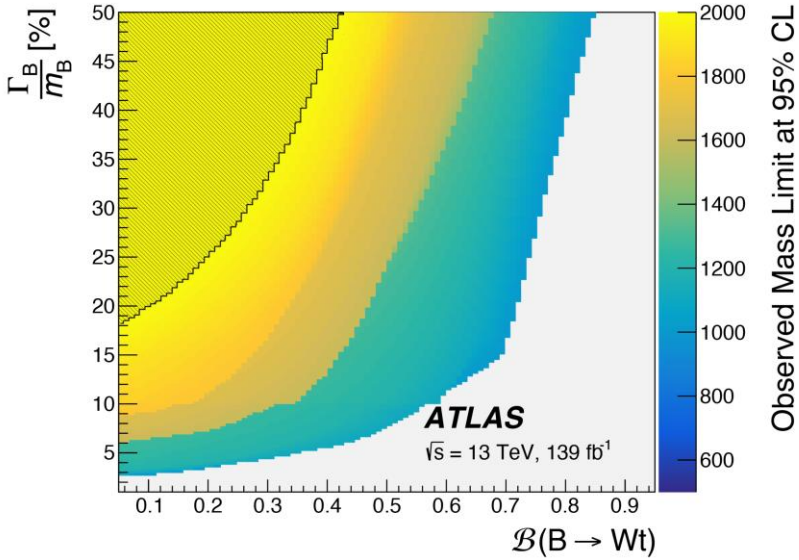
Single Production, B → bH(bb)

Link





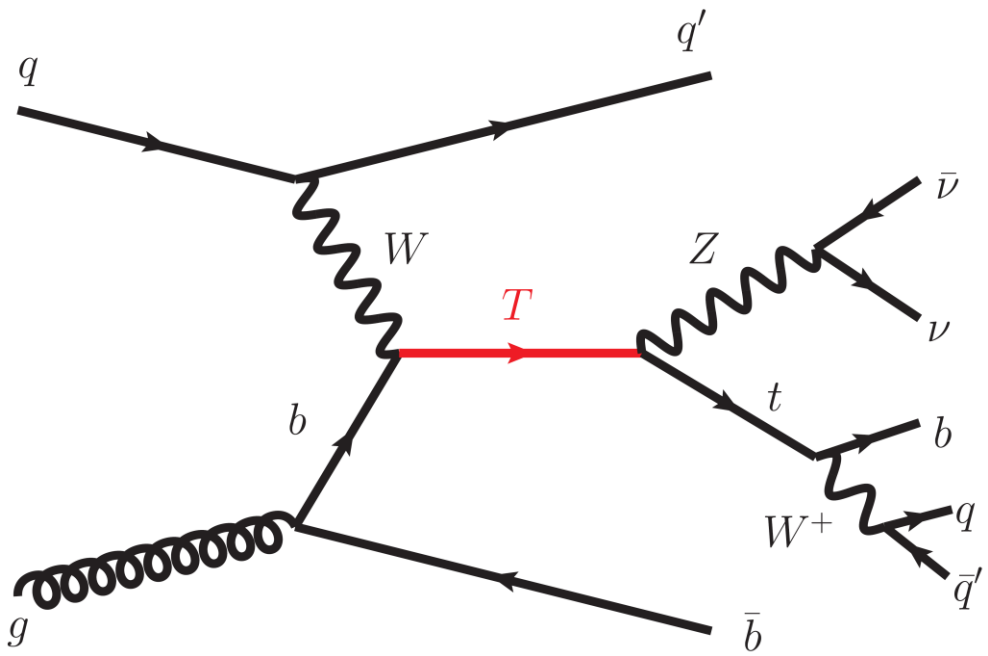


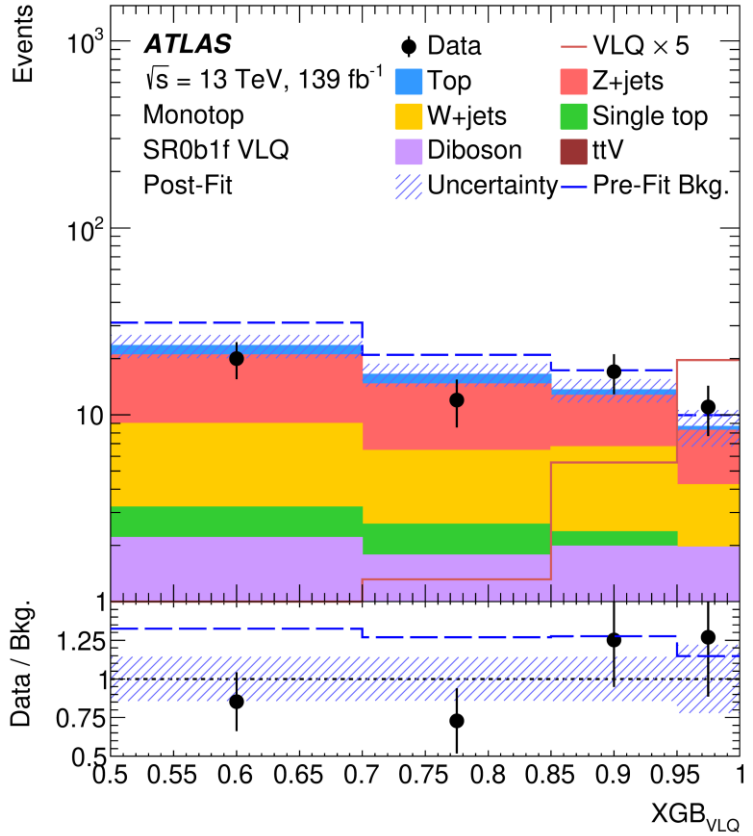


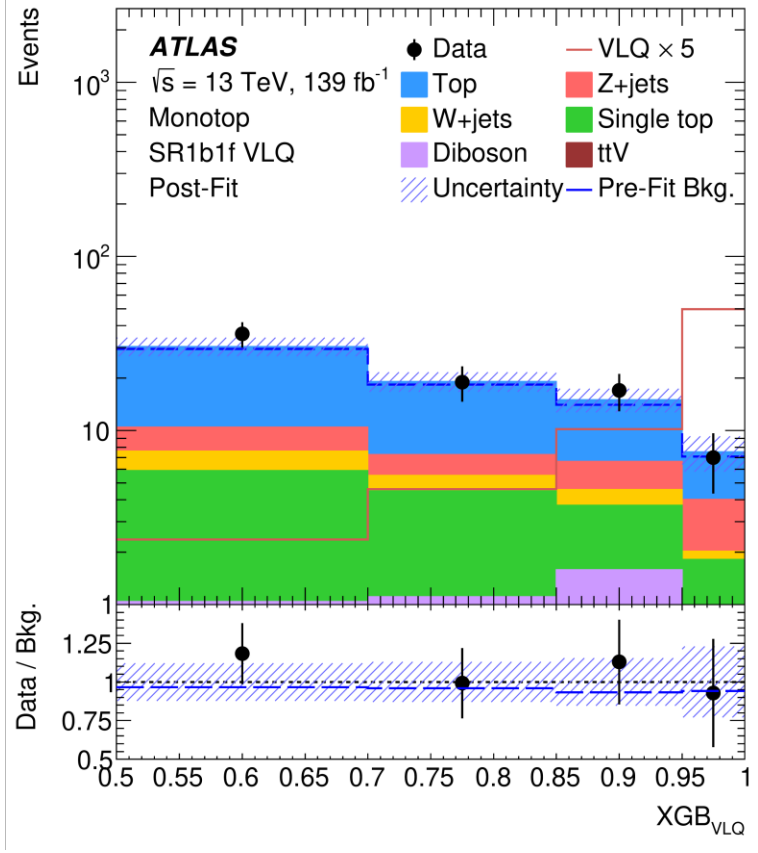
- ✓ **Invariant mass of B candidate** is used as discriminant variable.
- ✓ **The first search for a single vector-like B quark in the bH(bb) final state in ATLAS!**
- ✓ **This search improves on the previously published searches by CMS in the B → bH channel!**

Search for E_T^{miss} + Single-top

Link



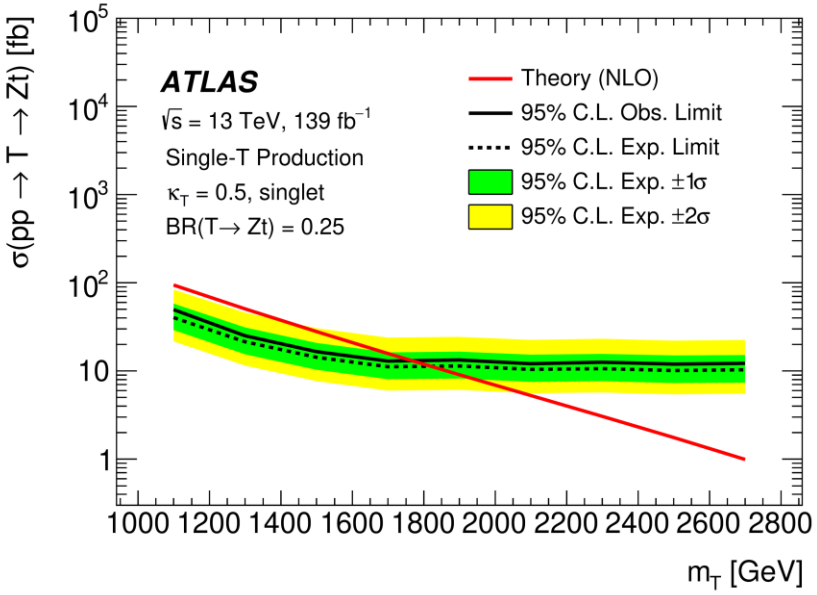


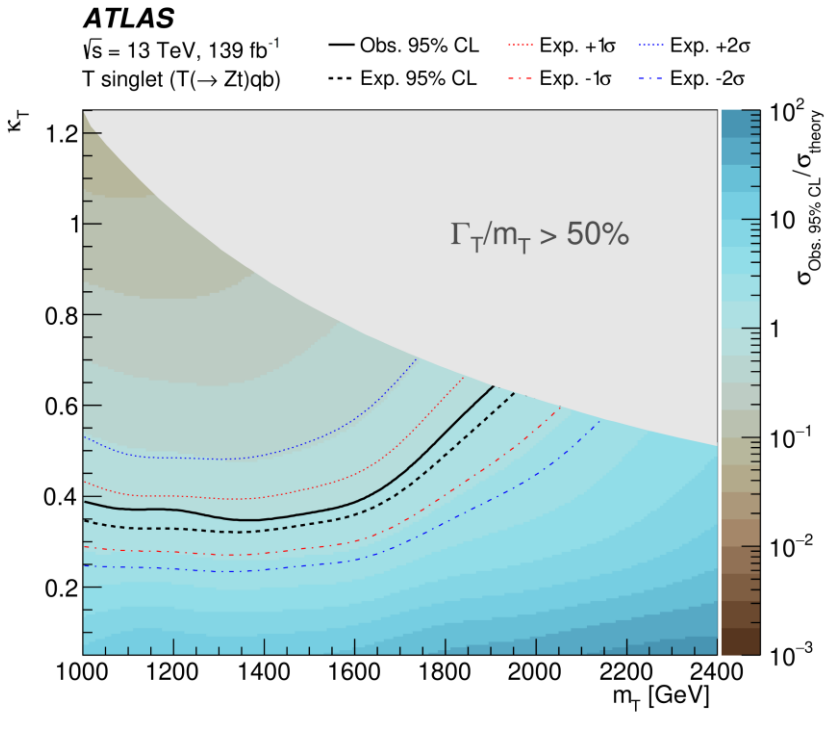


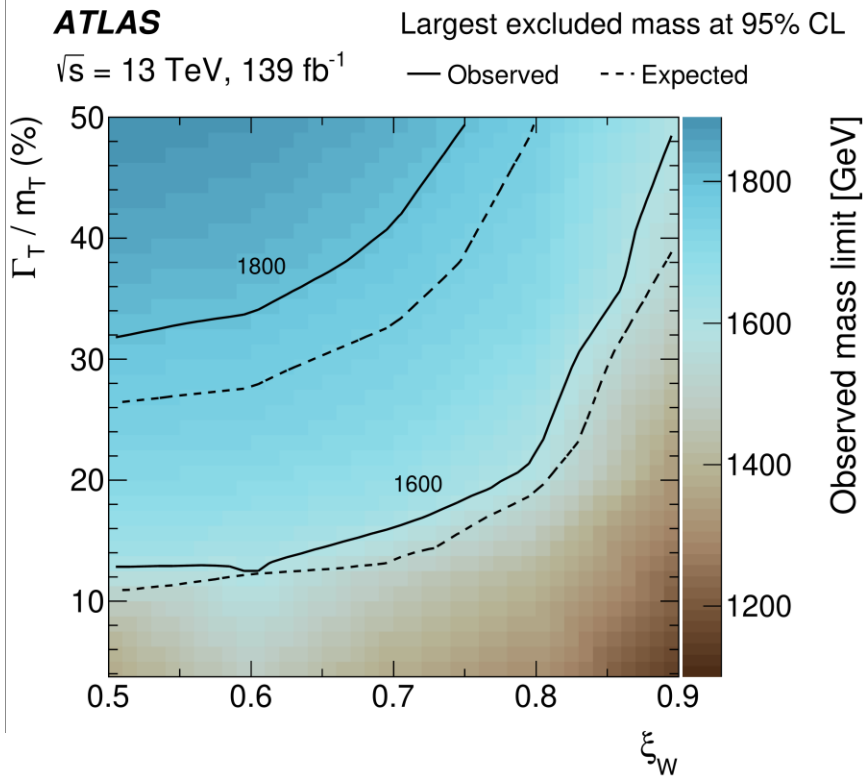
- ✓ A search for events with one top quark and missing transverse momentum in the final state is performed.
  - The results are interpreted in the context of simplified models for Dark Matter particle production and the **single production of a vector-like T quark.**
- ✓ **A Deep Neural Network (DNN)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

Search for E_T^{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 bτbτ

Link

	$\tau_{\text{lep}}\tau_{\text{had}}$ channel	$\tau_{\text{had}}\tau_{\text{had}}$ channel
e/μ selection	$= 1$ 'signal' e or μ $p_{\text{T}}^{e} > 25, 27$ GeV $p_{\text{T}}^{\mu} > 21, 27$ GeV	No 'veto' e or μ
$\tau_{\text{had-vis}}$ selection	$= 1$ $\tau_{\text{had-vis}}$ $p_{\text{T}}^{\tau} > 100$ GeV	$= 2$ $\tau_{\text{had-vis}}$ $p_{\text{T}}^{\tau} > 100, 140, 180$ (20) GeV
Jet selection	≥ 2 jets $p_{\text{T}}^{\text{jet}} > 45$ (20) GeV 1 or 2 b-jets	
Additional selection	Opposite charge $e, \mu, \tau_{\text{had}}$ and τ_{had} $m_{\tau\tau}^{\text{MMC}} \notin 40 - 150$ GeV $E_{\text{T}}^{\text{miss}} > 100$ GeV $s_{\text{T}} > 600$ 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			
$E_{\mathrm{T}}^{\mathrm{miss}}$ triggers exactly one signal lepton veto on additional baseline leptons $E_{\mathrm{T}}^{\mathrm{miss}} > 250\,\mathrm{GeV}$ ≥ 4 small-R jets $m_{\mathrm{T}}(\ell, E_{\mathrm{T}}^{\mathrm{miss}}) > 30\,\mathrm{GeV}$ $\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, j_{1,2}) > 0.4$			
Top reweighting region	W+jets CR	Single-top CR	Training region
$n_b \geq 1$	$n_b = 1$	$n_b = 2$	$n_b \geq 1$
$m_{\mathrm{T}}(\ell, E_{\mathrm{T}}^{\mathrm{miss}}) \geq 120\,\mathrm{GeV}$	$50\,\mathrm{GeV} \leq m_{\mathrm{T}}(\ell, E_{\mathrm{T}}^{\mathrm{miss}}) < 120\,\mathrm{GeV}$	$m_{\mathrm{T}}(\ell, E_{\mathrm{T}}^{\mathrm{miss}}) < 120\,\mathrm{GeV}$	$m_{\mathrm{T}}(\ell, E_{\mathrm{T}}^{\mathrm{miss}}) \geq 120\,\mathrm{GeV}$
$am_{\mathrm{T2}} < 200\,\mathrm{GeV}$	$am_{\mathrm{T2}} > 200\,\mathrm{GeV}$	$am_{\mathrm{T2}} > 200\,\mathrm{GeV}$	$am_{\mathrm{T2}} > 200\,\mathrm{GeV}$
-	t_{had} candidate veto	large-R jet veto	-
-	lepton charge $= +1e$	-	-
-	-	$\Delta R(b_1, b_2) > 1.2$	-

Variable	Description
$m_{\mathrm{T}}(\ell, E_{\mathrm{T}}^{\mathrm{miss}})$	transverse mass of lepton and $E_{\mathrm{T}}^{\mathrm{miss}}$
m_{eff}	scalar sum of the transverse momenta of leptons, jets, and $E_{\mathrm{T}}^{\mathrm{miss}}$
Lepton flavour	flavour of the signal lepton
$p_{\mathrm{T}}(\ell)$	transverse momentum of the lepton
$m_{\mathrm{inv}}(b_1, \ell)$	invariant mass of the leading-p_{T} b-jet and the lepton
n_{large}	reclustered large-R jet multiplicity
am_{T2}	asymmetric transverse mass
$E_{\mathrm{T}}^{\mathrm{miss}}$ significance	measure for assessing the compatibility of the observed $E_{\mathrm{T}}^{\mathrm{miss}}$ with zero, taking resolutions into account
$m_{\mathrm{T}}(b_1, E_{\mathrm{T}}^{\mathrm{miss}})$	transverse mass of leading-p_{T} b-jet and $E_{\mathrm{T}}^{\mathrm{miss}}$
$p_{\mathrm{T}}(t_{\mathrm{had}})$	transverse momentum of t_{had}
$\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, b_2)$	azimuthal angle separation between $E_{\mathrm{T}}^{\mathrm{miss}}$ and subleading-p_{T} b-jet
$m_{\mathrm{inv}}(b_2, \ell)$	invariant mass of subleading-p_{T} b-jet and lepton
$\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, b_1)$	azimuthal angle separation between $E_{\mathrm{T}}^{\mathrm{miss}}$ and leading-p_{T} b-jet
$\Delta\phi(t_{\mathrm{had}}, \ell)$	azimuthal angle separation between t_{had} and lepton
$p_{\mathrm{T}}(b_1)$	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
$LQ^{u}_{3} \to t\nu/b\tau$	1240	1240^{+70}_{-90}	1340	1300^{+70}_{-80}	1480	1440^{+70}_{-80}
$LQ^{d}_{3} \to t\tau/b\nu$	1260	1260^{+80}_{-80}	1360	1340^{+60}_{-70}	1520	1470^{+70}_{-70}
$LQ^{u}_{mix} \to t\nu/b\mu$	1230	1310^{+70}_{-70}	1570	1510^{+70}_{-70}	1710	1650^{+90}_{-90}
$LQ^{u}_{mix} \to t\nu/be$	1230	1310^{+70}_{-70}	1510	1550^{+80}_{-80}	1730	1740^{+90}_{-100}
$LQ^{d}_{mix} \to t\mu/b\nu$	1240	1260^{+70}_{-80}	1430	1470^{+70}_{-70}	1600	1650^{+80}_{-80}
$LQ^{d}_{mix} \to te/b\nu$	1230	1250^{+70}_{-70}	1450	1500^{+70}_{-70}	1650	1660^{+90}_{-90}
$U_1^{YM} \to t\nu/b\tau$	-	-	1840	1810^{+80}_{-90}	-	-
$U_1^{MC} \to t\nu/b\tau$	-	-	1580	1560^{+70}_{-70}	-	-
$U_1^{YM} \to t\nu/b\mu$	-	-	1980	1930^{+50}_{-60}	-	-
$U_1^{MC} \to t\nu/b\mu$	-	-	1710	1660^{+50}_{-50}	-	-
$U_1^{YM} \to t\nu/be$	-	-	1900	1930^{+50}_{-70}	-	-
$U_1^{MC} \to t\nu/be$	-	-	1620	1650^{+50}_{-60}	-	-
$\tilde{U}_1^{YM} \to t\tau$	-	-	-	-	1810	1810^{+80}_{-70}
$\tilde{U}_1^{MC} \to t\tau$	-	-	-	-	1540	1530^{+90}_{-60}

Single Production, Decaying to bττ [Link]

Signal Regions	Selection
Preselection	ℓ (trigger, isolated), $\tau_{\text{had-vis}}$ (medium τ_{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_{T} SR	Leading b-jet $p_{\text{T}} > 200$ GeV
Low b-jet p_{T} SR	Leading b-jet $p_{\text{T}} < 200$ GeV

Control/Validation Regions	Selection	Purpose
Multijet-CR	ℓ (trigger, pass/fail offline isolation), $m_{\text{T}}(\ell, E_{\text{T}}^{\text{miss}}) < 30$ GeV, one b-jet, τ_{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_{T} and lead. b-jet p_{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_{T} req.	Measure jet$\rightarrow\tau$ background scale factor
High b-jet p_{T} VR	Satisfy high b-jet p_{T} SR except: $1.5 < \Delta\phi(\ell, E_{\text{T}}^{\text{miss}}) < 2.5$, 300 GeV $< S_{\text{T}} <$ 600 GeV	Background modelling validation
Low b-jet p_{T} VR	Satisfy low b-jet p_{T} SR except: $1.5 < \Delta\phi(\ell, E_{\text{T}}^{\text{miss}}) < 2.5$, 300 GeV $< S_{\text{T}} <$ 600 GeV	Background modelling validation
b-tag Z-CR	Satisfy SR except: 45 GeV $< m_{\text{vis}}(\ell, \tau_{\text{had-vis}}) <$ 80 GeV, $p_{\text{T}}(\ell)/p_{\text{T}}(b\text{-jet}) > 0.8$, $\lvert\Delta\phi(\ell, \tau_{\text{had-vis}})\rvert > 2.4$, no S_{T} req.	Z+ heavy-flavour jets normalisation factor

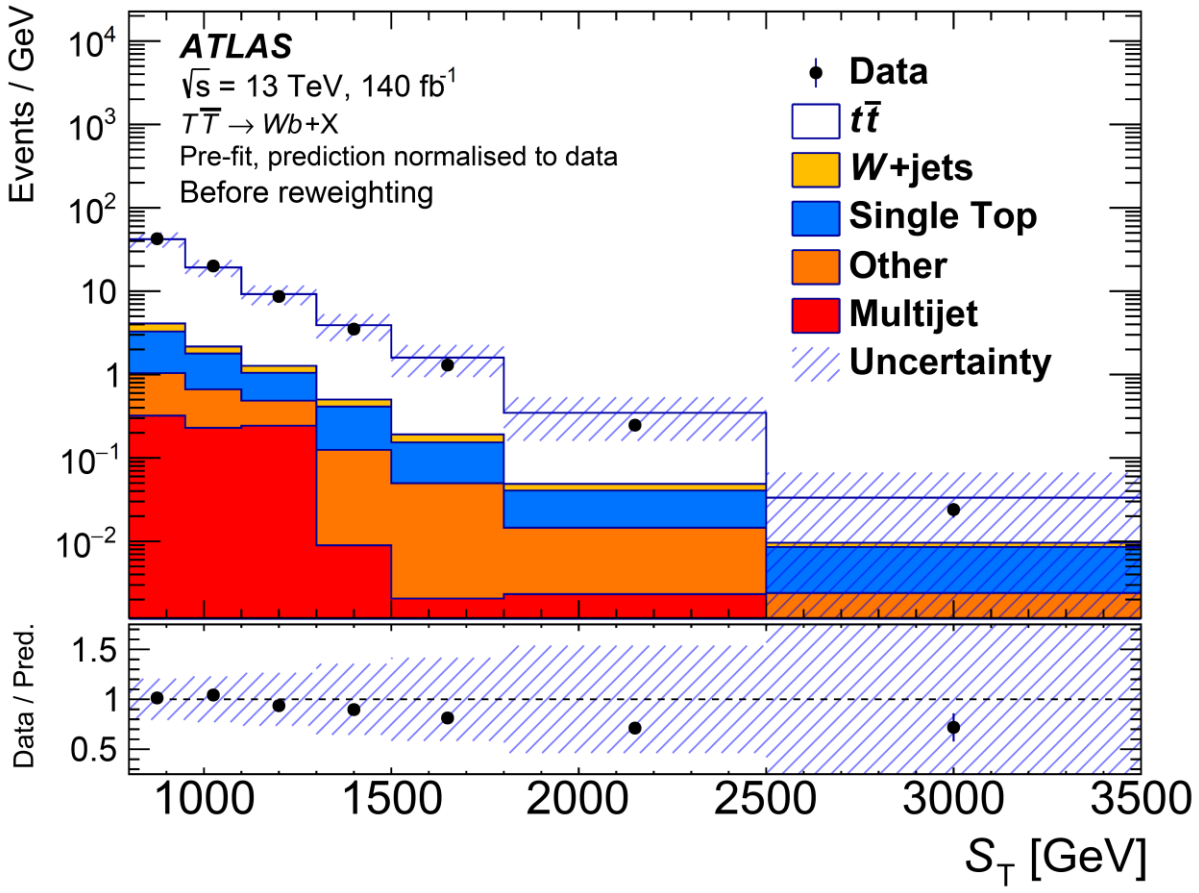
Signal Regions	Selection
Preselection	$\tau_{\text{had},1}$ (trigger, medium τ_{had}-ID), τ_2 (loose τ_{had}-ID), $q(\tau_1) \times q(\tau_2) < 0$, $m_{\text{vis}}(\tau_1, \tau_2) > 100$ GeV, $S_{\text{T}} > 300$ GeV, at least one b-jet
High b-jet p_{T} SR	Leading b-jet $p_{\text{T}} > 200$ GeV
Low b-jet p_{T} SR	Leading b-jet $p_{\text{T}} < 200$ GeV

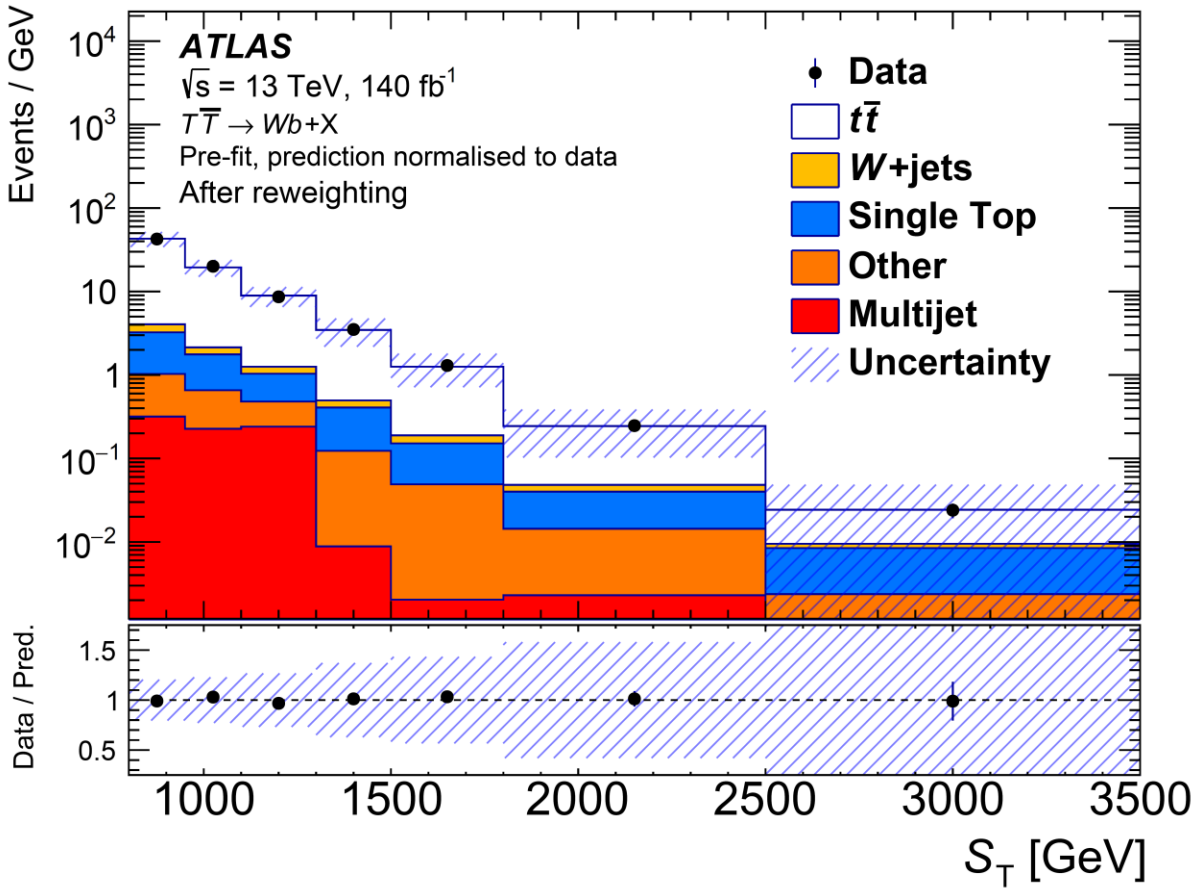
Control/Validation Regions	Selection	Purpose
DJ-CR	τ_1 and τ_2 satisfy very loose τ_{had}-ID, $q(\tau_1) \times q(\tau_2) < 0$	Measure $\tau_{\text{had-vis}}$ fake-factor
CR-1	Satisfy SR except: τ_2 fail loose τ_{had}-ID	Apply $\tau_{\text{had-vis}}$ fake-factor
SS-VR	Satisfy SR except: $q(\tau_1) \times q(\tau_2) > 0$	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, >= 1b [Link]

Selection	SR1 / SR2	$t\bar{t}$CR	$S_{\mathrm{T}}^{\mathrm{Low}}\Delta m$CR / $S_{\mathrm{T}}^{\mathrm{High}}\Delta m$CR	W+jetsCR	$t\bar{t}$RWR
Preselection	✓	✓	✓	✓	✓
$N_{\text{Large-}R\text{ Jet}}$	≥ 1	≥ 1	≥ 1	≥ 1	≥ 1
S_{T} [GeV]	>1900	1400–1900	1400–1900 / >1900	900–1900	>800
$N_{W\text{-tag}}$	≥ 1	≥ 1	≥ 1	≥ 1 partially inverted	≥ 1
$N_{b\text{-tag}}$	≥ 1	≥ 1	≥ 1	≥ 1	≥ 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
Δm_{VLQ} [GeV]	< 200 / 200–500	< 500	> 500	–	–
$m_T^{\text{lep}}, m_T^{\text{had}}$ [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, >= 1b [Link]





✓ Top modelling is corrected by reweighting factor.

Pair Production, Zt+X with 1 lepton + MET

Link

Preselection				
$E_{\mathrm{T}}^{\mathrm{miss}}$ triggers = 1 signal lepton no additional baseline lepton ≥ 4 jets ≥ 1 b-jet $E_{\mathrm{T}}^{\mathrm{miss}} > 250\,\mathrm{GeV}$ $m_{\mathrm{T}}^{W} > 30\,\mathrm{GeV}$ $\lvert\Delta\phi(j_{1,2}, \vec{E}_{\mathrm{T}}^{\mathrm{miss}})\rvert > 0.4$				
	Training region low-NN_{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	≥ 1	≥ 1	$= 1$	≥ 2
Large-R jet multiplicity	≥ 1	≥ 1	≤ 1	≤ 1
m(large-R jet) [GeV]	–	–	< 150	< 150
Lepton charge	–	–	+1	–
$\Delta R(b_1, b_2)$	–	–	–	> 1.4
NN_{out}	$< 0.5 / \geq 0.5$	–	–	–

Pair Production, Zt+X with 1 lepton + MET

Link

Variable	Description
m_{eff}	scalar sum of the transverse momenta of leptons, jets, and $E_{\text{T}}^{\text{miss}}$
$N_{b\text{-jets}}$	b-jet multiplicity
m_{T}^{W}	transverse mass of lepton and $E_{\text{T}}^{\text{miss}}$
am_{T2}	asymmetric transverse mass
$p_{\text{T}}(\text{large-}R\ \text{jet}_2)$	transverse momentum of second-highest-p_{T} large-R jet
$\lvert\Delta\phi(\text{jet}_1, E_{\text{T}}^{\text{miss}})\rvert$	azimuthal angle between $E_{\text{T}}^{\text{miss}}$ and highest-p_{T} jet
$E_{\text{T}}^{\text{miss}}$	missing transverse momentum
$\eta(\text{jet}_1)$	pseudorapidity of highest-p_{T} jet
$m(\text{large-}R\ \text{jet}_1)$	mass of highest-p_{T} large-R jet
$N_{\text{const}}(\text{large-}R\ \text{jet}_1)$	number of small-R jets reclustered to the highest-p_{T} large-R jet
$p_{\text{T}}(\ell)$	transverse momentum of lepton
$p_{\text{T}}(\text{jet}_3)$	transverse momentum of third-highest-p_{T} jet
$p_{\text{T}}(\text{jet}_2)$	transverse momentum of second-highest-p_{T} jet

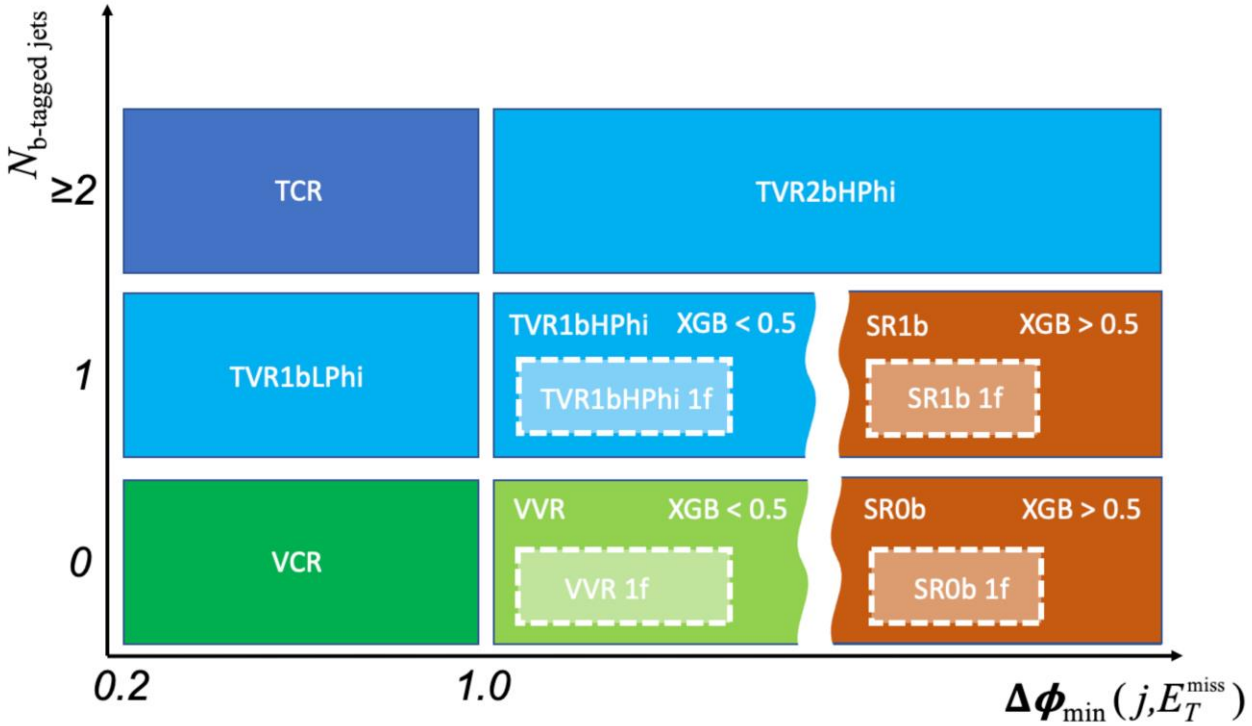
Single Production, B → bH(bb)

Link

Preselection							
$\geqslant 1$ large-R jet, $p_{\mathrm{T}} > 480$ GeV							
No leptons & no $\gamma\gamma$ pairs with $m_{\gamma\gamma} \in [105, 160]$ GeV							
$\geqslant 2$ track-jets associated with the large-R jet, $\geqslant 1$ b-tagged track-jet							
$\geqslant 1$ small-R jet with $p_{\mathrm{T}} > 300$ GeV							
ΔR(small-R jet, large-R jet) > 2.0							
HC reconstruction							
Any large-R jet with $p_{\mathrm{T}} > 480$ GeV							
$\geqslant 2$ ghost-matched track-jets with $p_{\mathrm{T}} > 50$ 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}(small-R jet) ¿ 400 GeV							
ΔR(small-R jet, large-R jet) ¿ 2.5							
Kinematic selection							
$\log \Delta R^{*}$ ¿ 0.67							
$p_{\mathrm{T}}^{\mathrm{HC}}/m_B$ ¿ 0.4							
$m_{\mathrm{HC}} \in [105, 135]$ GeV							
$\geqslant 1$ forward jet							
$=$ 0 forward jet	$\geqslant 1$ 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^{miss} + Single-top

Link



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

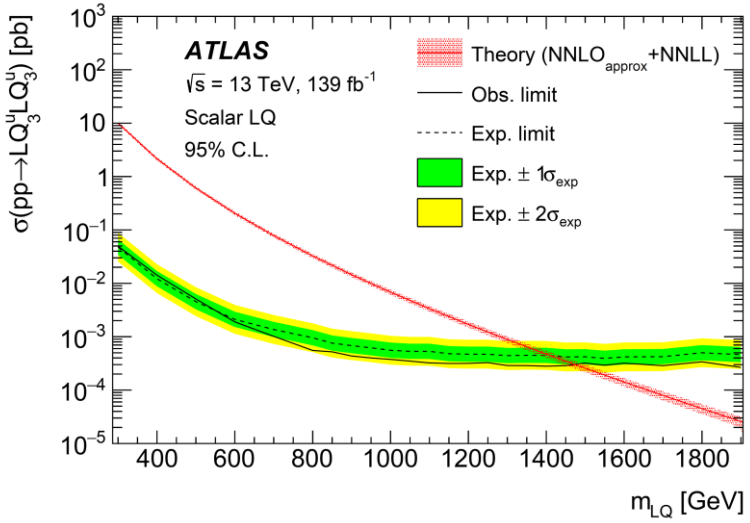
Search for E_T^{miss} + Single-top

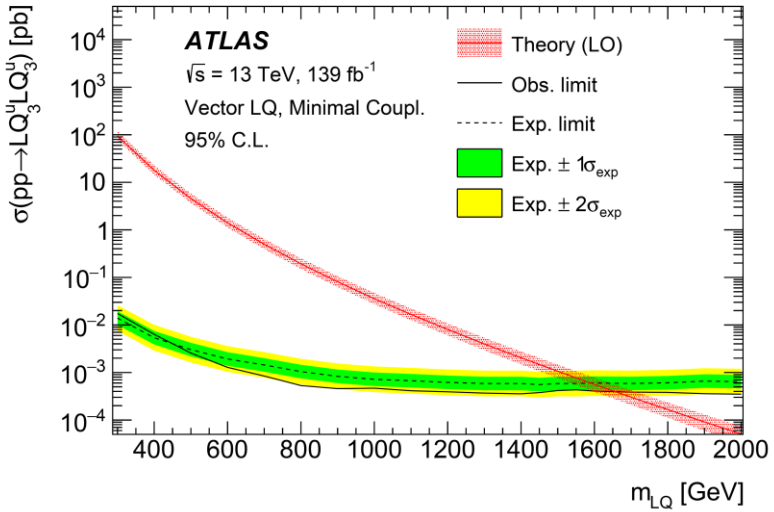
Link

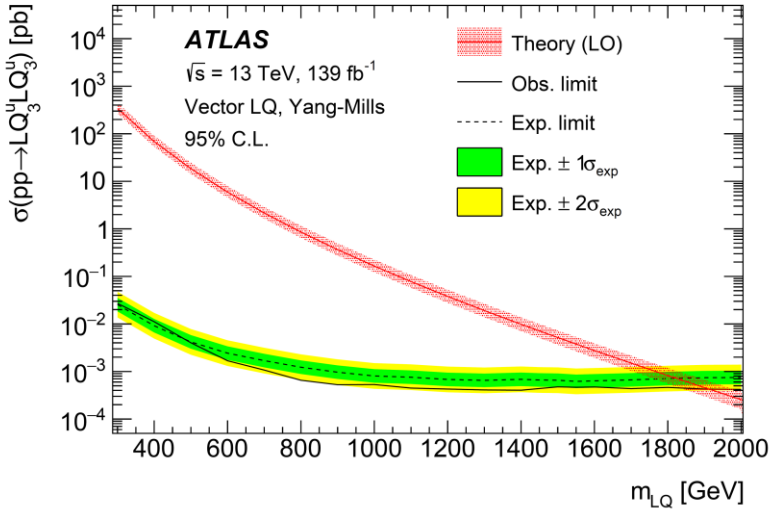
Variable	Description	Scalar DM mediator	Vector DM mediator	VLQ
$E_{\mathrm{T}}^{\mathrm{miss}}$	Missing transverse momentum	✓	✓	✓
Ω	$E_{\mathrm{T}}^{\mathrm{miss}}$ and large-R jet p_{T} balance: $\frac{E_{\mathrm{T}}^{\mathrm{miss}}-p_{\mathrm{T}}(J)}{E_{\mathrm{T}}^{\mathrm{miss}}+p_{\mathrm{T}}(J)}$	✓	✓	✓
$\mathrm{N}_{\mathrm{jets}}$	Small-R jet multiplicity	✓	✓	✓
ΔR_{max}	Maximum ΔR between two small-R jets	✓	✓	✓
$m_{\mathrm{T,min}}(E_{\mathrm{T}}^{\mathrm{miss}}, b\text{-tagged jet})$	Transverse mass of $E_{\mathrm{T}}^{\mathrm{miss}}$ and the closest b-tagged jet	✓	✓	✓
$m_{\text{top-tagged jet}}$	Mass of the large-R top-tagged jet	✓		✓
$\Delta p_{\mathrm{T}}\ (J, \text{jets})$	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}		✓	✓
$H_{\mathrm{T}}/E_{\mathrm{T}}^{\mathrm{miss}}$	Ratio of H_{T} and $E_{\mathrm{T}}^{\mathrm{miss}}$		✓	✓
$\Delta E(E_{\mathrm{T}}^{\mathrm{miss}}, J)$	Energy difference between $E_{\mathrm{T}}^{\mathrm{miss}}$ and the large-R jet		✓	✓
$\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, J)$	Angular distance in the transverse plane between $E_{\mathrm{T}}^{\mathrm{miss}}$ and large-R jet		✓	✓
$p_{\mathrm{T}}(\mathrm{J})$	Large-R jet p_{T}			✓
$m_{\mathrm{T}}(E_{\mathrm{T}}^{\mathrm{miss}}, J)$	Transverse mass of the $E_{\mathrm{T}}^{\mathrm{miss}}$ 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			✓

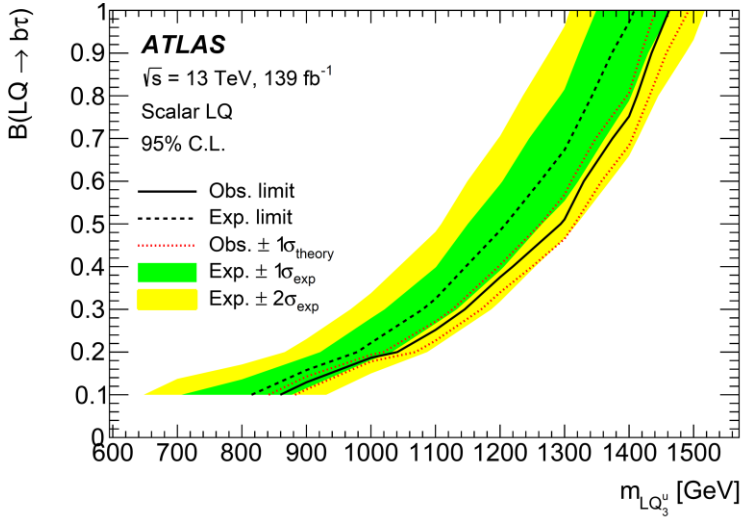
Pair Production, Decaying to bτbτ

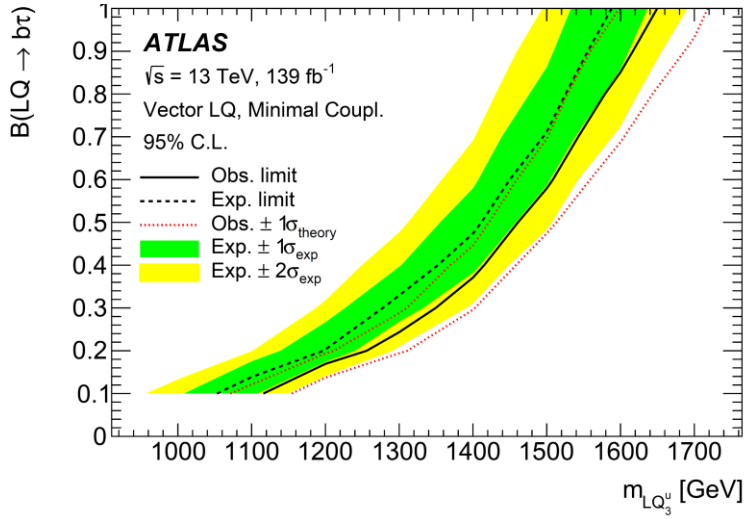
Link

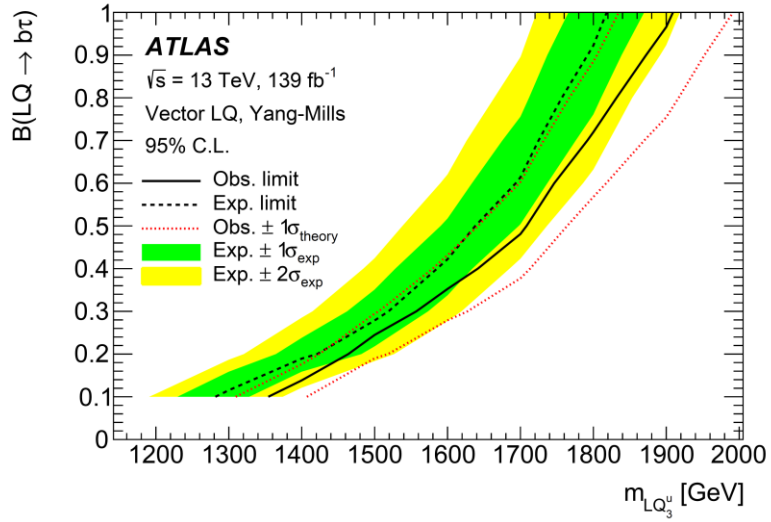










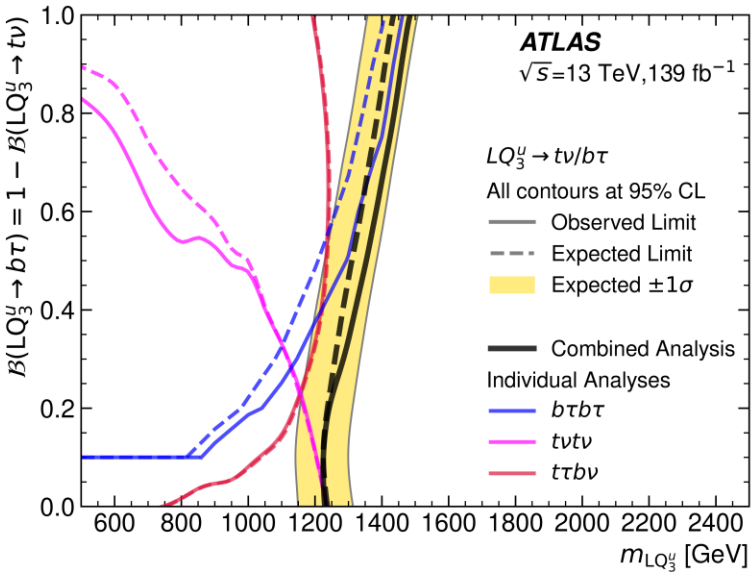


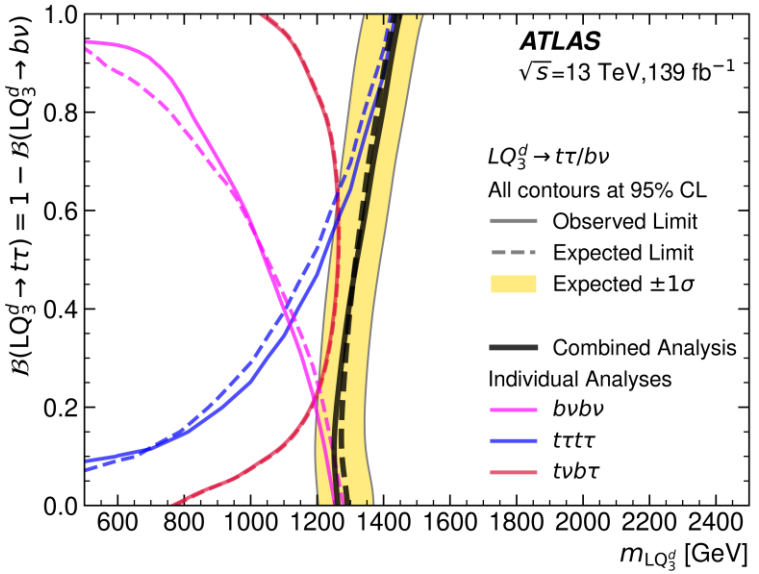
- ✓ Binned Profile Likelihood fit is performed for PNN score distribution.
  - No significant excess over SM expectation is observed. 95% confidence-level upper limits are set.
  - **Significantly improve the sensitivity mainly due to upgraded τ and b-jet identification, improved MVA.**

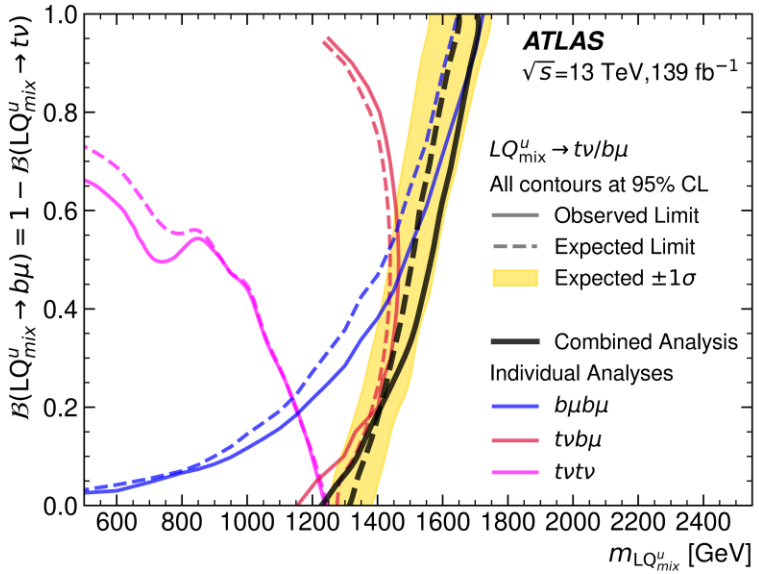
Pair Production, Combination

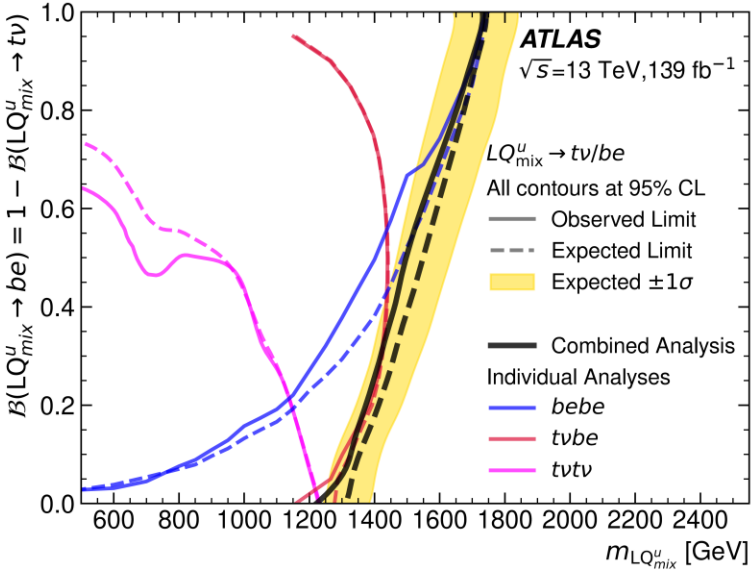
Link

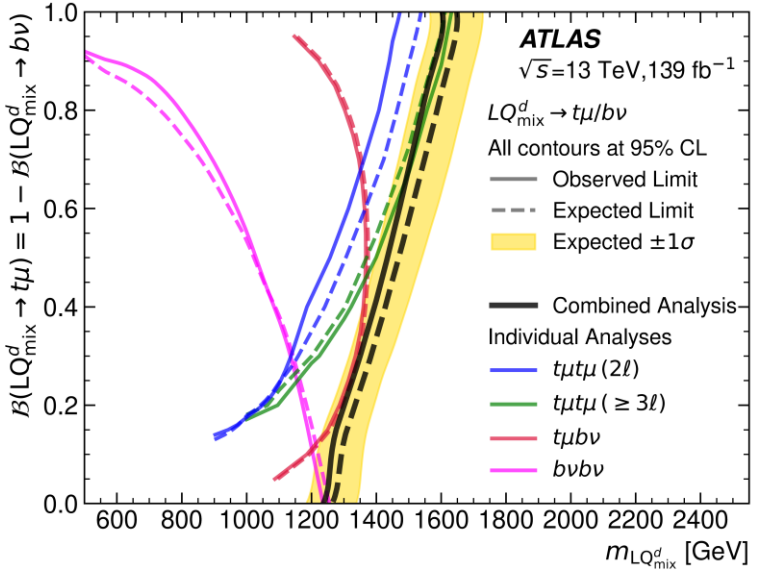
For any combination of the parameters, these are the best limits to date!

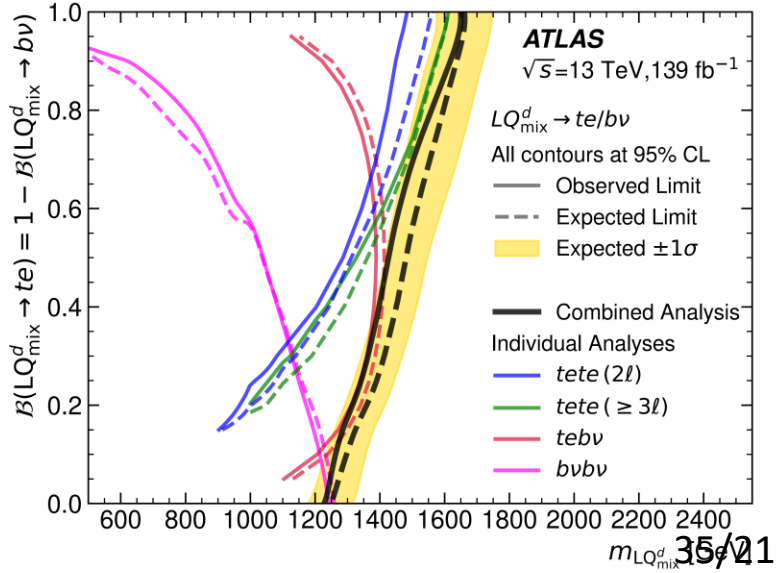




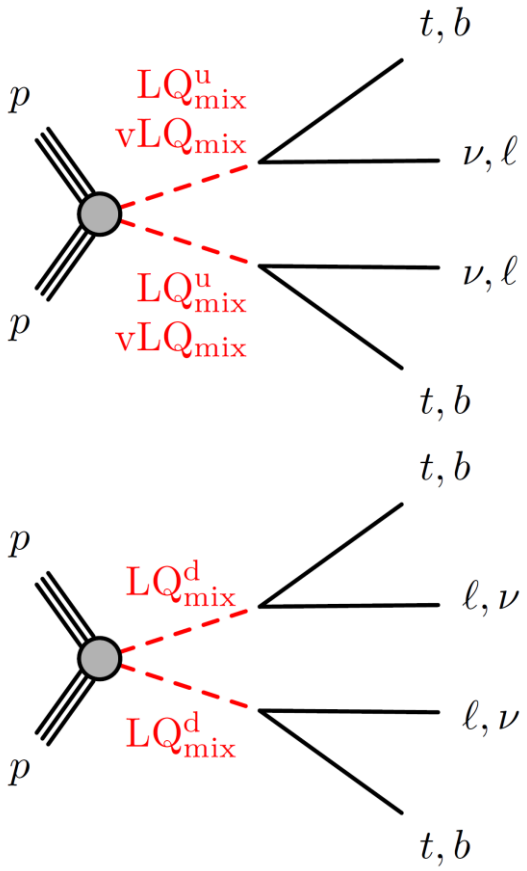








Pair Production, Orthogonal Generation



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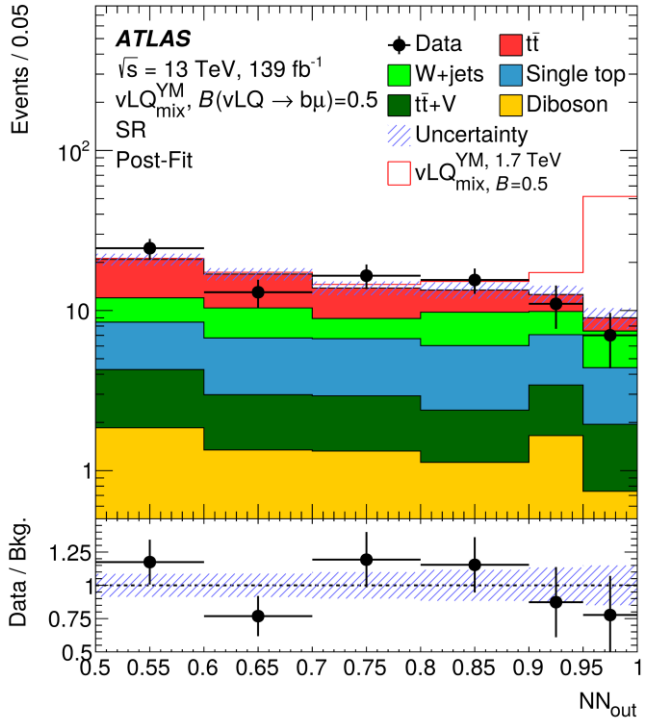
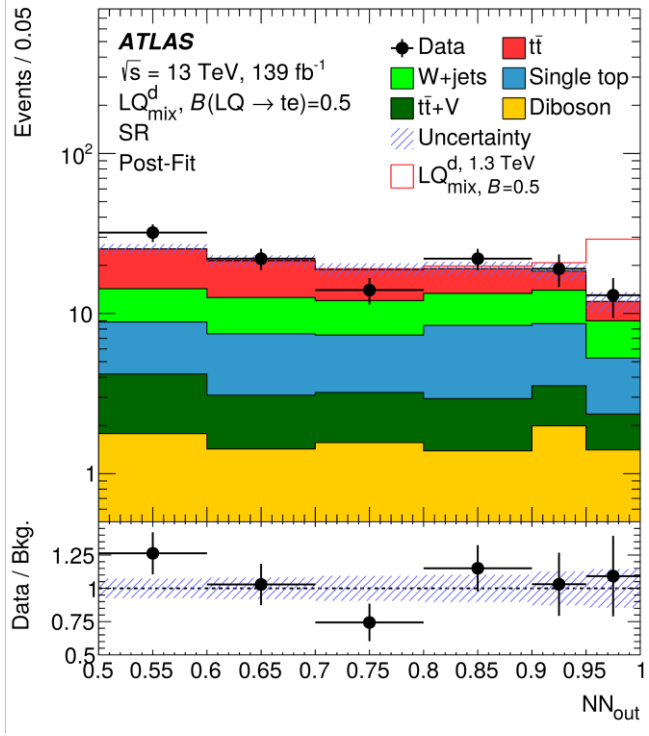
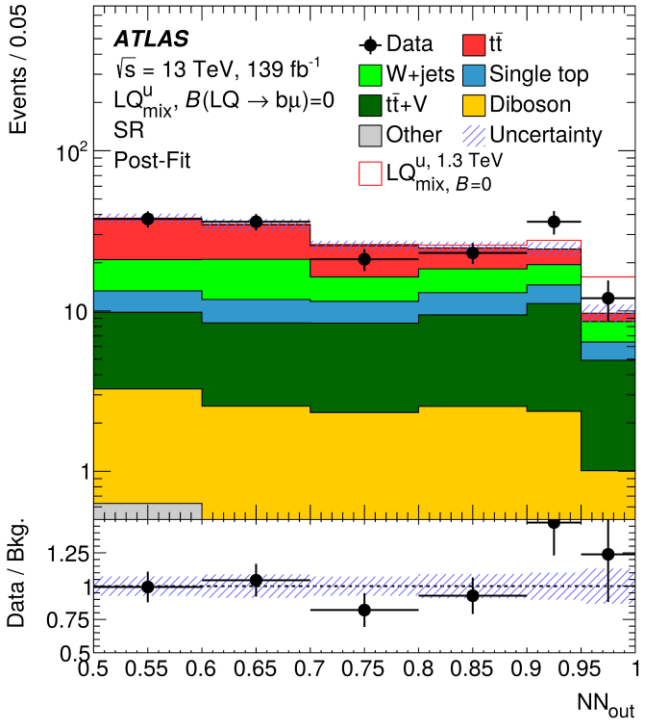
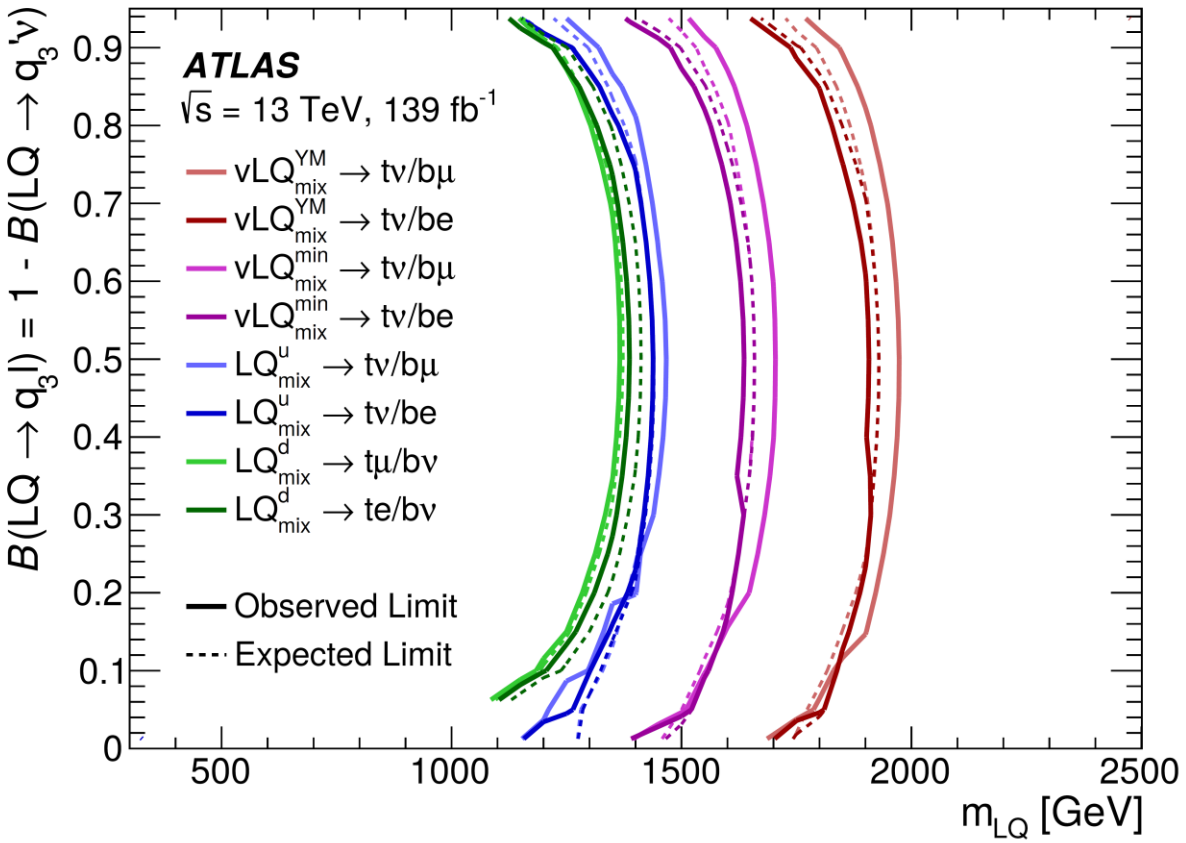






- ✓ Searches for LQs decaying to **orthogonal generation quark (t, b) and lepton (e, μ, ν)**.
  - Aroused interest to explain B-anomalies, muon g-2.
- ✓ Top modeling is reweighted, CRs are defined and fit simultaneously with SR to normalize top and W+jets.
- ✓ **NNs** are trained by mass and angular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

Pair Production, Orthogonal Generation



B = 0.5

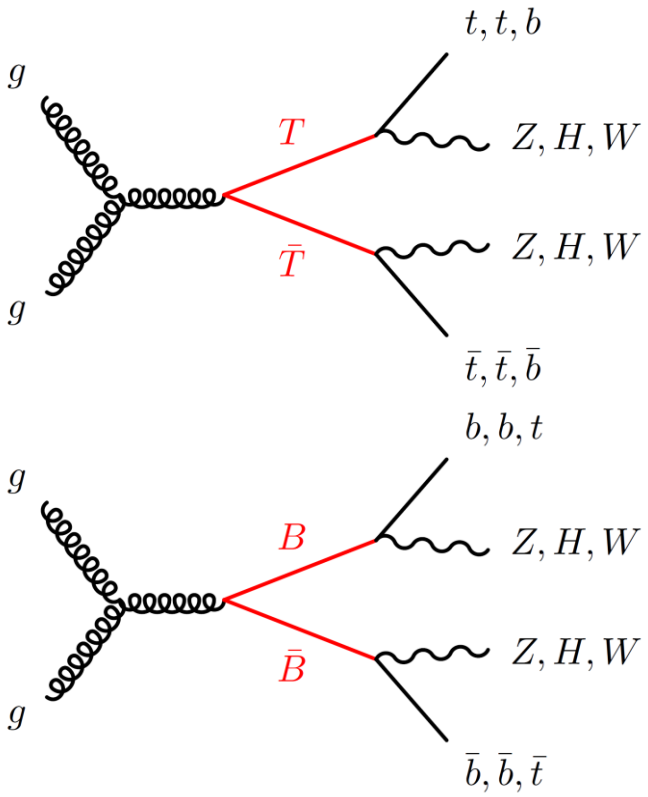
Link

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

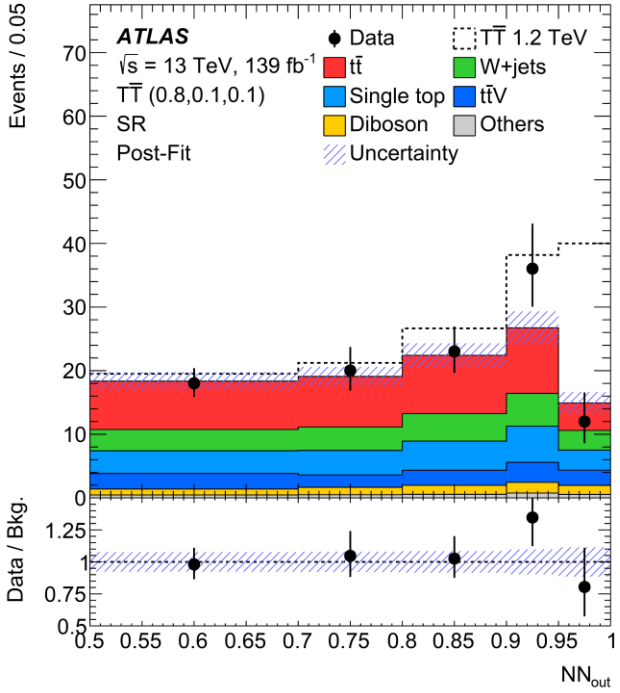
✓ Binned Profile Likelihood fit is performed for NN score distribution simultaneously for SR and CRs.
- No significant excess over SM expectation is observed. 95% confidence-level upper limits are set.

✓ 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



B(Zt, Ht, Wb)



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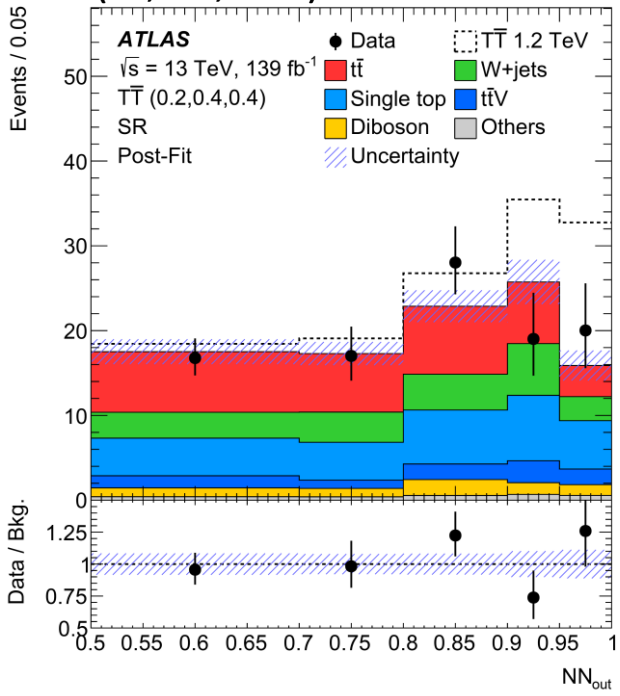
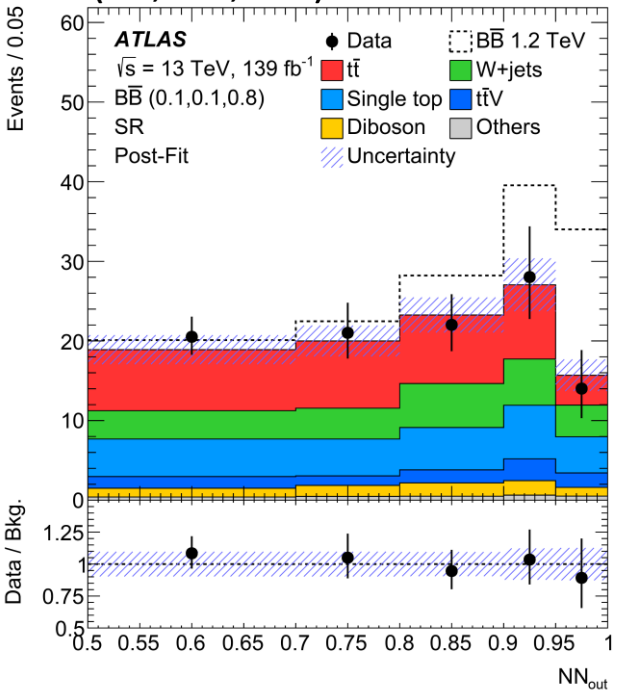


B(Zb, Hb, Wt) Link

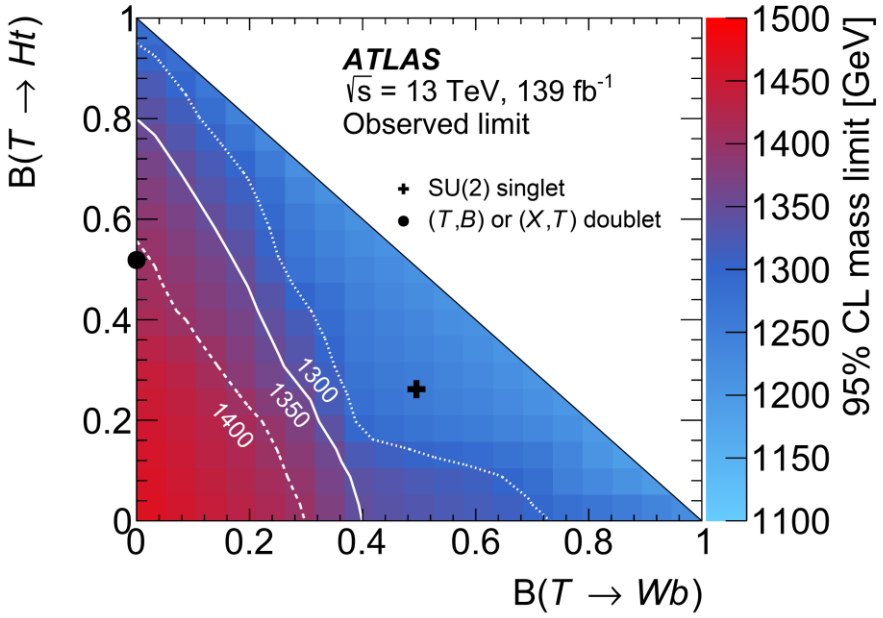


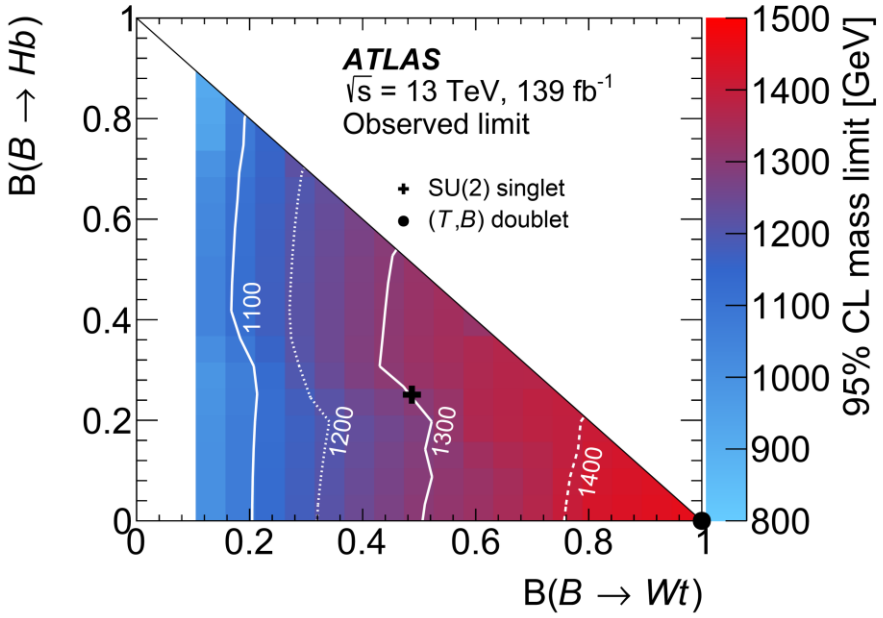
- ✓ Investigates **all possible decay modes and combinations of branching ratios for the pair-produced T and B**.
- ✓ **Singlet and doublet T, B, as well as X** are considered.
- ✓ Top modelling is reweighted, single-top and W+jets are normalized from CR.
- ✓ **NNs** are trained for various signal hypotheses 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	$\mathcal{B}(T \to Zt) = 100\%$	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	$\mathcal{B}(B/X \to Wt) = 100\%$ 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

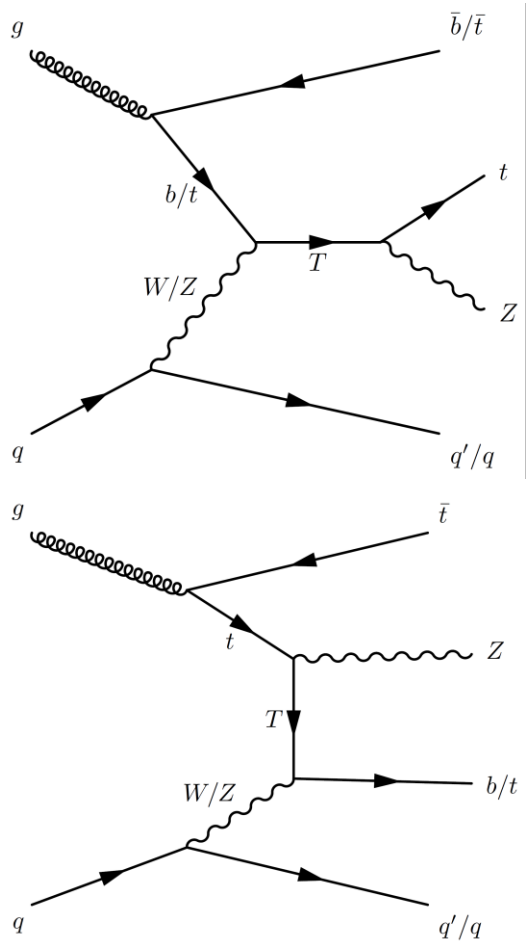


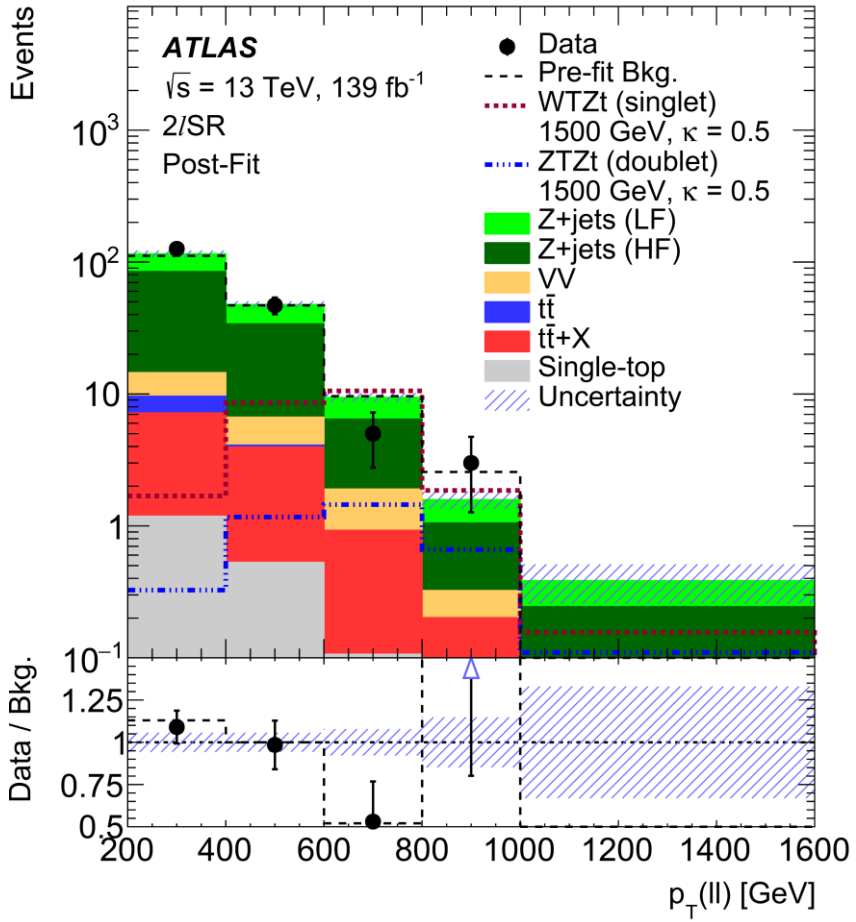


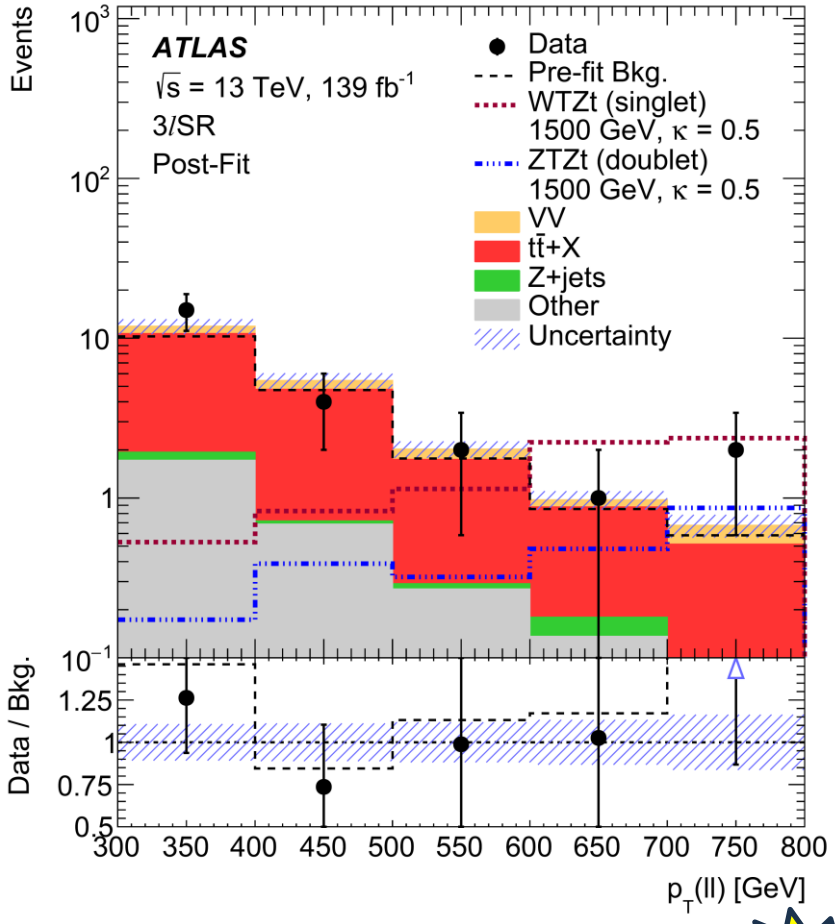
- ✓ The obtained mass limits are **300 to 400 GeV higher** than in the earlier ATLAS analysis in the same final state.
- ✓ **The strongest lower limits for T , B and X are at 1.59 TeV for (T, B) and (X, T) weak-isospin** doublets where both VLQ are considered and assumed to be mass degenerate.

Single Production, multi-lepton

Link





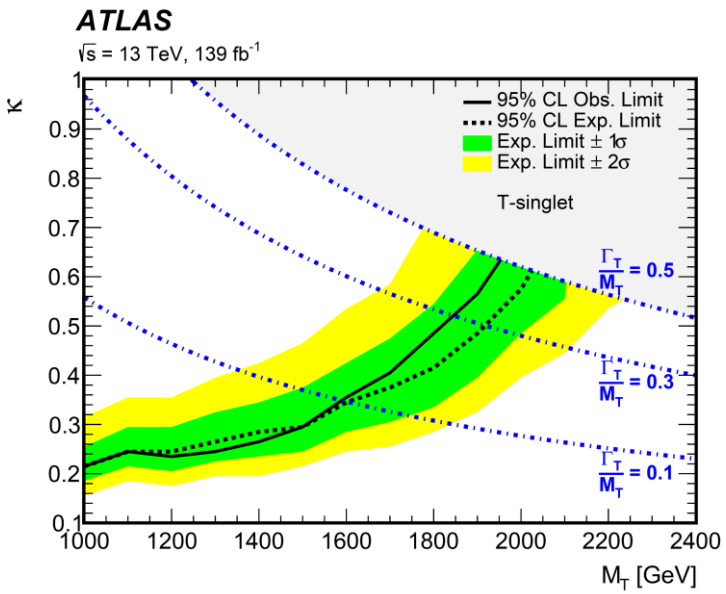


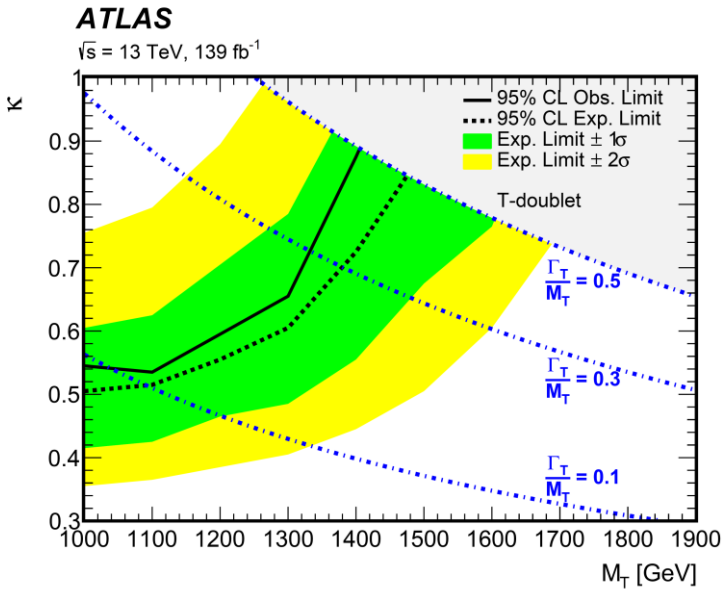
- ✓ Singly produced T and the final state has 2 leptons (e or μ) or 3 leptons (2l and 3l channels).
- ✓ **Variable radius reclustered jets (vRC jets) are used to identify hadronically decaying boosted top-quark jets.**
- ✓ Z+jets modelling is reweighted in 2l channel, VV and tt + X modellings are reweighted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

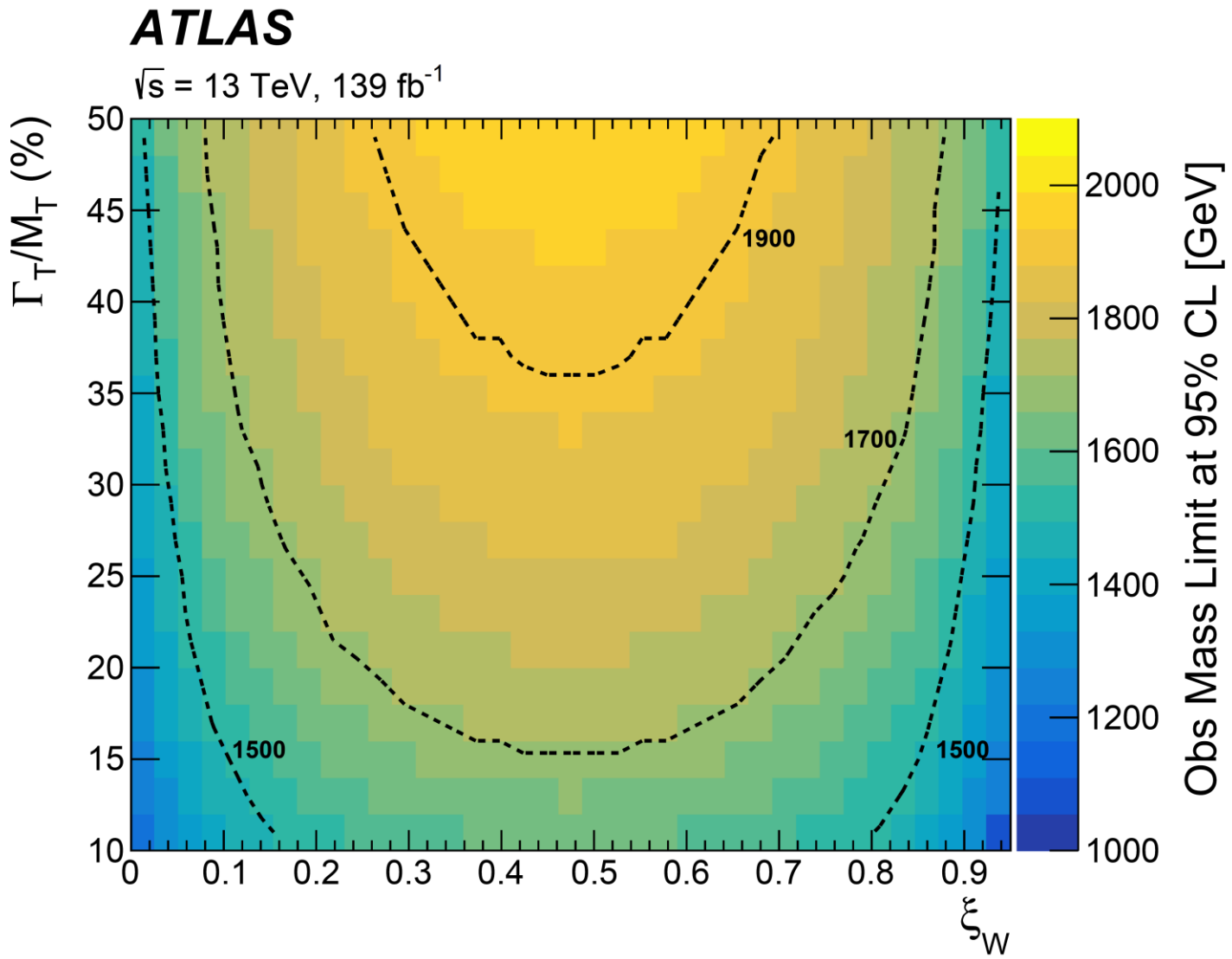
New!

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.