

# Searches for Leptoquarks with the ATLAS Detector

EPS-HEP Conference 2021

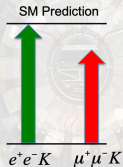
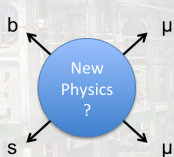
Yoav Afik (CERN)  
On behalf of the ATLAS collaboration

26.07.2021

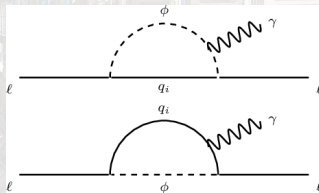
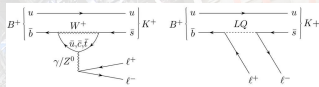


# Motivation

- Hints of Lepton Flavour Universality (LFU) violation in rare B-meson decays:
  - $b \rightarrow s \ell \ell$  ( $R_{K^{(*)}}$ );  $b \rightarrow c \ell \nu$  ( $R_{D^{(*)}}$ ).



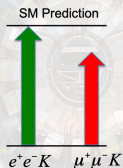
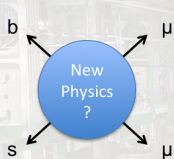
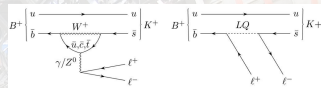
- Muon g-2 anomaly, possibly connected to the LFU anomaly.



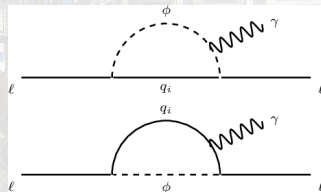
# Motivation

- Hints of Lepton Flavour Universality (LFU) violation in rare B-meson decays:

- $b \rightarrow s \ell \ell$  ( $R_{K^{(*)}}$ );  $b \rightarrow c \ell \nu$  ( $R_{D^{(*)}}$ ).



- Muon g-2 anomaly, possibly connected to the LFU anomaly.



- The existence of TeV-scale Leptoquarks (LQs) is a possible solution to the anomalies!
  - Cross-generational couplings are motivated.



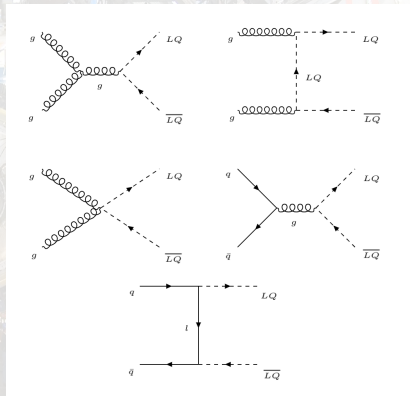
# LQ Searches at the LHC

- LQs are bosons which couple to a lepton and a quark.
- Dominant production  $gg \rightarrow LQ + \overline{LQ}$ .



- Analyses vary by the LQ type and decay mechanism:

- $LQ \rightarrow q/c/b + e/\mu$
- $LQ \rightarrow t + e/\mu$
- $LQ \rightarrow t + \tau$
- $LQ \rightarrow t + \nu$
- $LQ \rightarrow b + \nu$
- $LQ \rightarrow b + \tau$

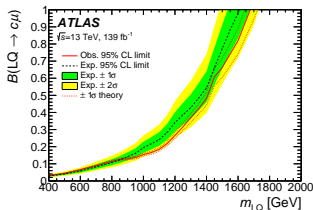
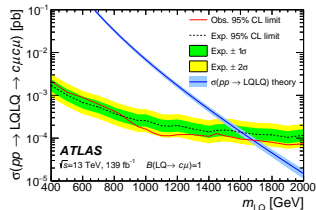
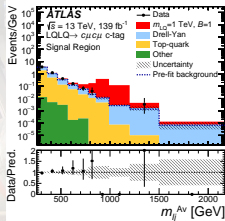


- Model parameters:
  - LQ mass ( $M_{LQ}$ ).
  - $\mathcal{B}(LQ \rightarrow XY)$ .



# Scalar $LQ \rightarrow q/c/b + e/\mu$

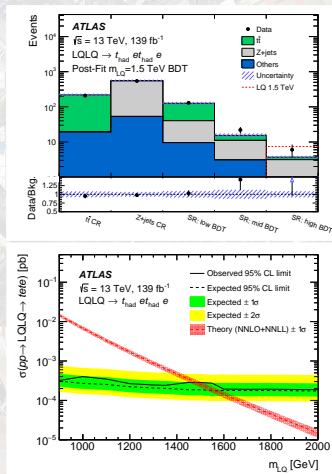
- First dedicated ATLAS search for cross-generational LQs.
- First use of  $c$ -tagging in LQ searches.
- Mass asymmetry:  $m_{asym} = \frac{M_{lj}^{max} - M_{lj}^{min}}{M_{lj}^{max} + M_{lj}^{min}}$ .
- Main backgrounds:  $Z + jets$ ,  $t\bar{t}$ , normalized from data.
- Further categorization by  $c$ - and  $b$ -tagging.



# Scalar $LQ \rightarrow t + e/\mu$

- First ATLAS search for top-philic cross-generational LQ couplings.
- Fully hadronic top-quark decay channel in the boosted regime.
- Boosted Decision Trees (BDT) are used.
- Main backgrounds:  $Z + jets$ , dileptonic  $t\bar{t}$ , normalized from data.

$t\bar{t}$ CR	$Z + jets$ CR	SR
	$N_\ell = 2$ ; opposite-sign $N_J \geq 2$	
$m_{\ell\ell} > 120 \text{ GeV}$ $e\mu$	$70 < m_{\ell\ell} < 110 \text{ GeV}$ $ee \text{ or } \mu\mu$	$m_{\ell\ell} > 120 \text{ GeV}$

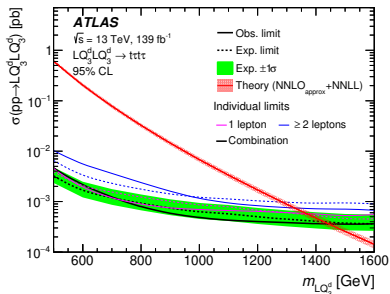
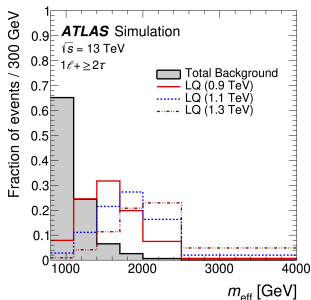


# Scalar $LQ_3^u \rightarrow t\tau$

- First dedicated ATLAS analysis for  $LQ \rightarrow t\tau$ .
- Main backgrounds:  $t\bar{t}$ ,  $t\bar{t} + V/H$ ,  $VV$ , Fake  $\tau_{had}$ .
- Main discriminating variable:

$$m_{eff} = \sum_{j,e,\mu,\tau} p_T + E_T^{miss}$$

Number of $\tau_{had}$	$1t + \geq 2\tau$ SR+CR+VR	$2tOS + \geq 2\tau$ SR+VR	$(2tSS \text{ or } 3t) + \geq 1\tau$ SR+VR	
	$1t + 1\tau_{OS}^{SS}$ SR+CR+VR	$2tOS + 1\tau$ SR+CR+VR		
		$2tOS + 0\tau$ CR*	$2tSS + 0\tau$ CR	$3t + 0\tau$ CR
Number of $e/\mu$				

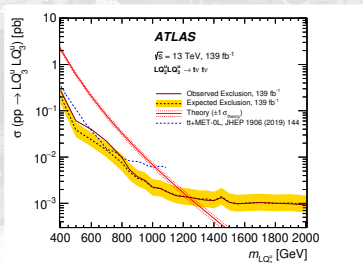
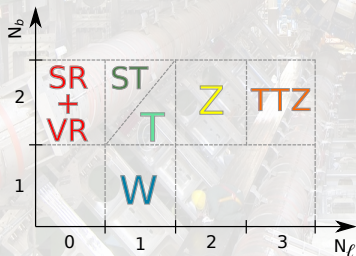


# Scalar $LQ_3^u \rightarrow t\nu/b\tau$

- Search for signature with  $t\bar{t} + E_T^{miss}$  in all-hadronic channel.
- Reclustered jets with  $R=1.2$  and  $R=0.8$  for top and W.

Variable/SR	SRA-TT	SRA-TW	SRA-T0	SRB-TT	SRB-TW	SRB-T0
$E_T^{miss}$	> 250 GeV					
$m_1^{R=1.2}$	> 120 GeV					
$m_2^{R=1.2}$	> 120 GeV	60–120 GeV	< 60 GeV	> 120 GeV	60–120 GeV	< 60 GeV
$m_1^{R=0.8}$	> 60 GeV			–		

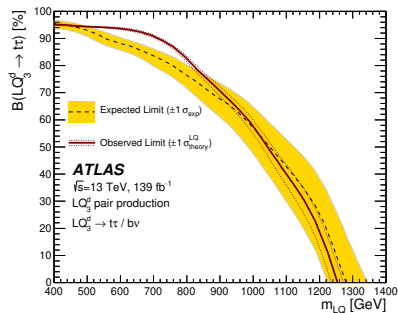
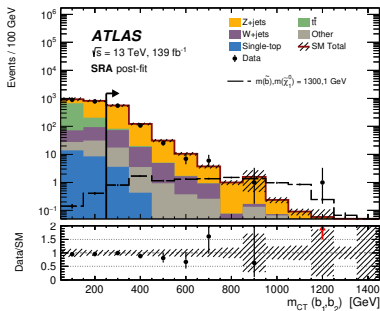
- Main backgrounds:  $Z + jets$ ,  $W + jets$ ,  $t\bar{t}$ ,  $t\bar{t} + Z$ , single top, all normalized from data.



\*\* Dedicated search in analysis targets also SUSY models. For more details, see talk by Jonathan Long in this [link](#).

# Scalar $LQ_3^d \rightarrow b\nu/t\tau$

- Search for signature with  $b\bar{b} + E_T^{miss}$ .
- Main discriminating variables:  $m_{eff} = \sum_j p_T + E_T^{miss}$ ;  
 $m_{CT}^2(v1, v2) = [E_T(v1) + E_T(v2)]^2 - [\mathbf{p}_T(v1) - \mathbf{p}_T(v2)]^2$ .
- Uses BDT output score as well.
- Main background:  $Z + jets$ , normalized from data.

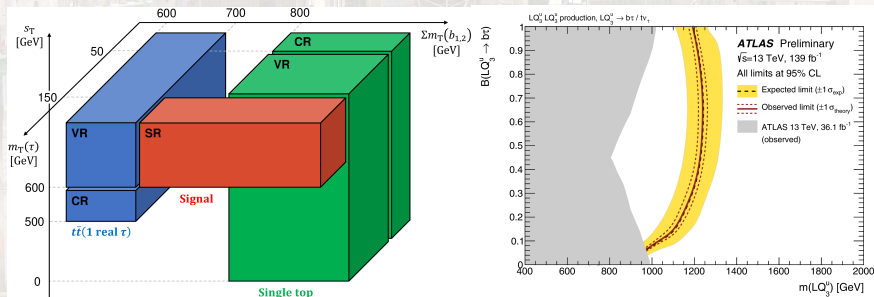


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# Scalar $LQ_3^u \rightarrow b\tau/t\nu$ and $LQ_3^d \rightarrow b\nu/t\tau$

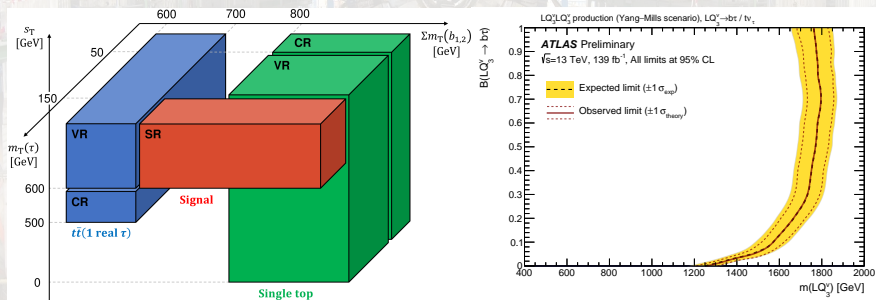
- Targeting  $\mathcal{B}(LQ \rightarrow q\ell) \sim 0.5$ .
- Most of the events:  $1\tau$ , 2  $b$ -jets, large  $E_T^{miss}$ .
- Main backgrounds:  $t\bar{t}$  (1 real  $\tau$ ) and single-top, normalized from data.
- Scalar LQs interpretation:  $LQ_3^u$  (right) and  $LQ_3^d$ .



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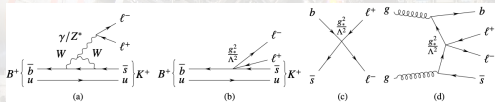
# Vector $LQ_3^u \rightarrow b\tau/t\nu$ and $LQ_3^d \rightarrow b\nu/t\tau$

- Targeting  $\mathcal{B}(LQ \rightarrow q\ell) \sim 0.5$ .
- Most events:  $1\tau$ , 2  $b$ -jets, large  $E_T^{miss}$ .
- Main backgrounds:  $t\bar{t}$  (1 real  $\tau$ ) and single-top, normalized from data.
- Vector-LQs (first time!): Yang-Mills (right) and minimal-coupling scenarios.



\*\* Dedicated search in analysis targets also SUSY models. For more details, see talk by Jonathan Long in this [link](#).

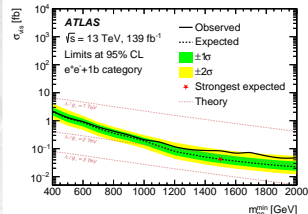
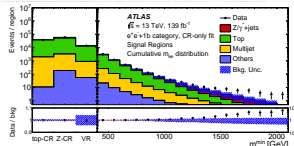
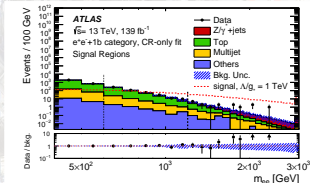
# *bsll* Contact Interaction



- Generalizing the *bsll* interactions.

Region	top-CRs	Z-CRs	VRs	SRs
$m_{\ell\ell}$ [GeV]	> 130	130-250	250-400	> 400 + $n \cdot 100$
$b$ -tagged jets	2		0/1	

- Enhanced sensitivity for other signal scenarios as well.
- Main backgrounds:  $Z + jets$ , dileptonic  $t\bar{t}$ , normalized from data.



# Summary

- A variety of searches for LQ pair production, differ by the decay mechanism of the LQ pair.
- A few dedicated searches were done for the first time in ATLAS.
- Still no sign of TeV-scale LQs. Limits were set:

Leptoquarks		
Decay Mechanism	Comments	$M_{LQ}$ Limits [TeV]
$LQ \rightarrow q/c/b + e/\mu$	electron	$> 1.8$
	muon	$> 1.7$
$LQ \rightarrow t + e/\mu$	electron	$> 1.5$
	muon	$> 1.5$
$LQ \rightarrow t + \tau$	-	$> 1.4$
$LQ \rightarrow t + \nu$	-	$> 1.2$
$LQ \rightarrow b + \nu$	-	$> 1.3$
$LQ \rightarrow b + \tau$	scalar	$> 1.3$
	vector, Yang-Mills	$> 1.8$
	vector, minimal-coupling	$> 1.5$
Contact Interaction		
$bs\ell\ell$ CI	electrons	$\Lambda/g_* > 2.0$ TeV
	muons	$\Lambda/g_* > 2.4$ TeV

# Thank You





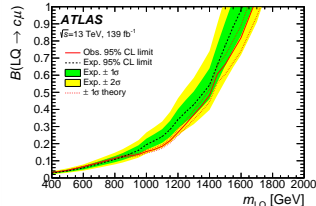
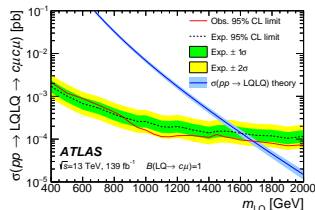
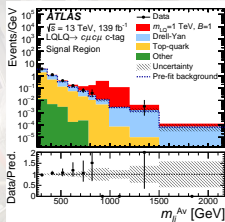
## Backup

# Scalar $LQ \rightarrow q/c/b + e/\mu$

- First dedicated ATLAS search for cross-generational LQs.
- First use of  $c$ -tagging in LQ searches.
- Mass asymmetry:  $m_{asym} = \frac{M_{lj}^{max} - M_{lj}^{min}}{M_{lj}^{max} + M_{lj}^{min}}$ .
- Main backgrounds:  $Z + jets$ ,  $t\bar{t}$ , normalized from data.

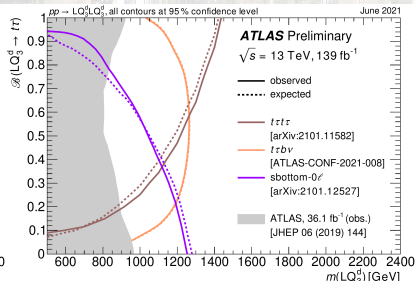
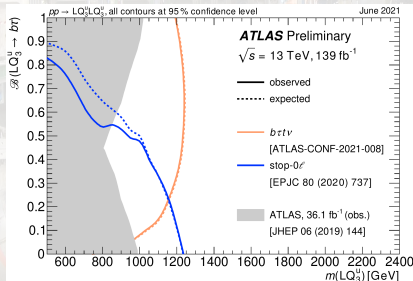
Preselection		
2 oppositely charged leptons ( $e, \mu$ )		
2 or more jets		
$p_T^{\ell\ell} > 75 \text{ GeV}$		
$E_T^{miss} / \sqrt{H_T} < 3.5 \text{ GeV}^{1/2}$		
$m_{\ell\ell} > 130 \text{ GeV}$		
SB	SR	Top CR
$ee \text{ or } \mu\mu$		$e\mu$
$0.2 < m^{asym} < 0.4$		$m^{asym} < 0.2$

- Further selections by  $c$ - and  $b$ -tagging.

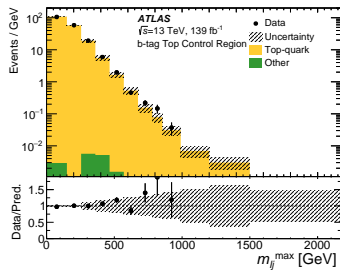
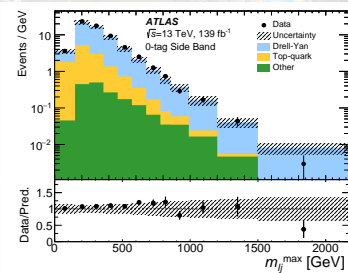


# Scalar $LQ_3^{u/d}$ Summary Plots

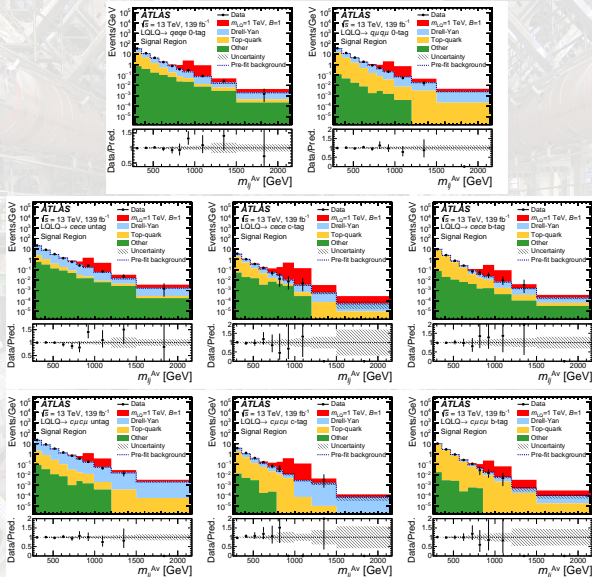
- Left:  $LQ_3^u \rightarrow b\tau$  as a function of  $M_{LQ}$  and  $\mathcal{B}(LQ_3^u \rightarrow b\tau)$ .
- Right:  $LQ_3^d \rightarrow t\tau$  as a function of  $M_{LQ}$  and  $\mathcal{B}(LQ_3^d \rightarrow t\tau)$ .
- Include reinterpretation of SUSY searches.



# Scalar $LQ \rightarrow q/c/b + e/\mu$

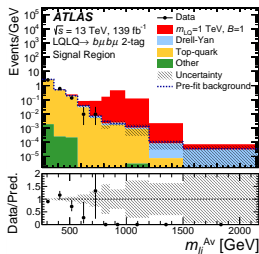
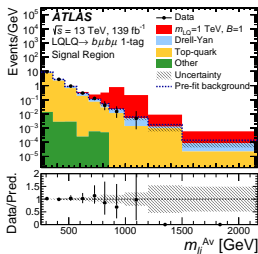
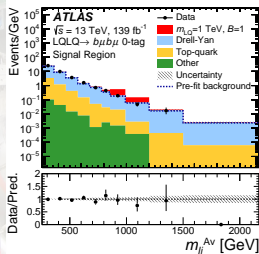
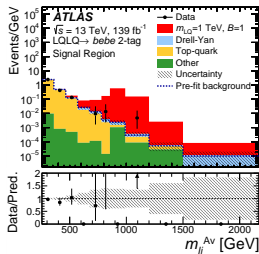
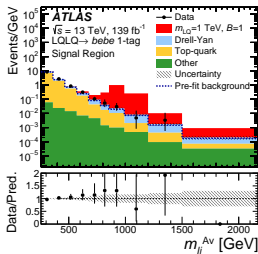
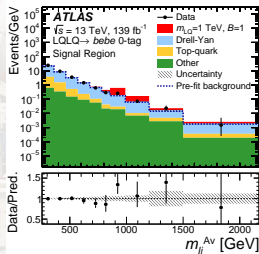


# Scalar LQ $\rightarrow q/c/b + e/\mu$

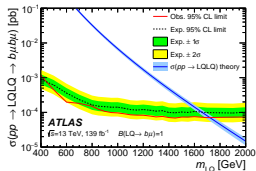
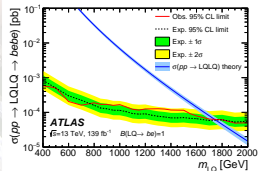
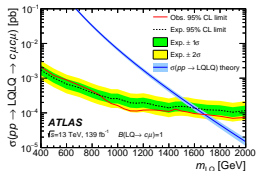
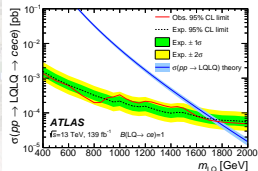
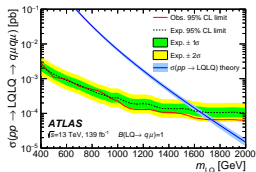
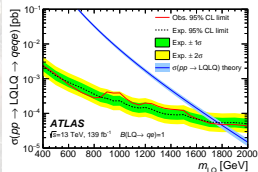




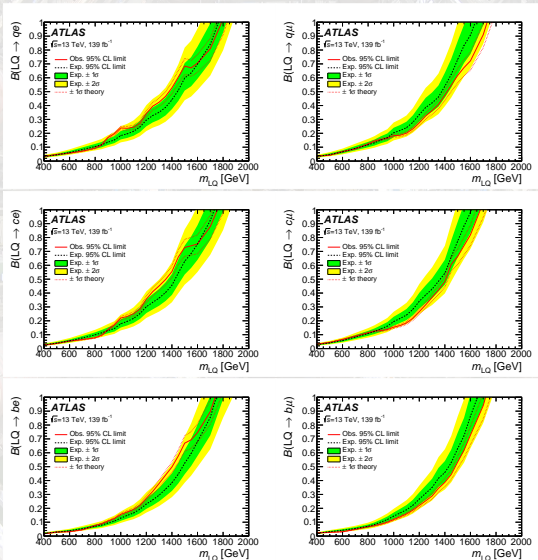
# Scalar $LQ \rightarrow q/c/b + e/\mu$



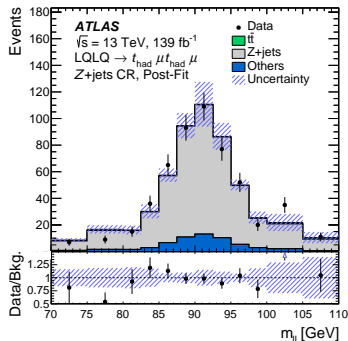
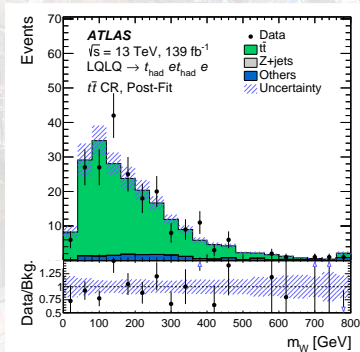
# Scalar LQ $\rightarrow q/c/b + e/\mu$



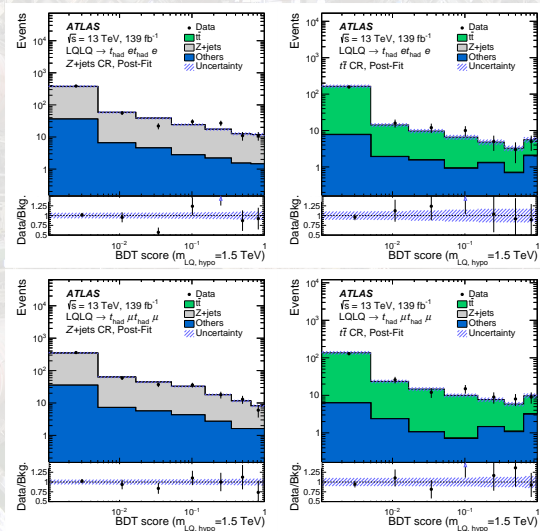
# Scalar $LQ \rightarrow q/c/b + e/\mu$



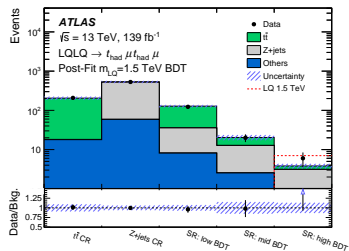
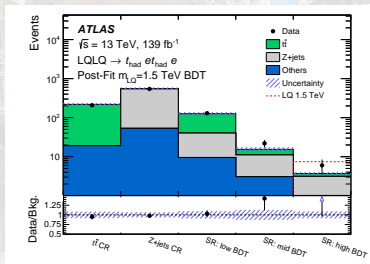
# Scalar $LQ \rightarrow t + e/\mu$



# Scalar $LQ \rightarrow t + e/\mu$

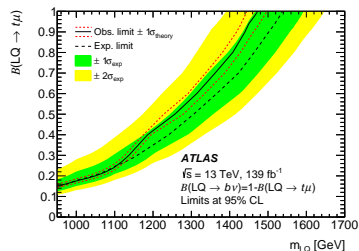
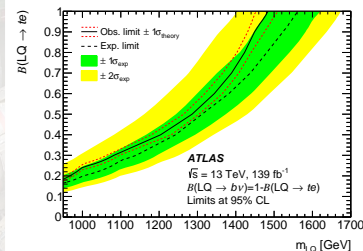
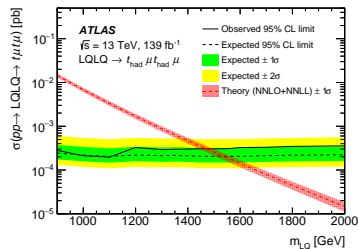
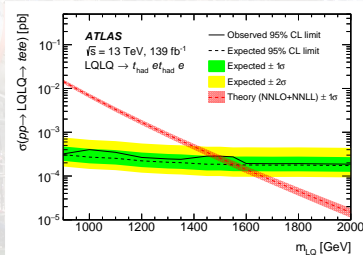


# Scalar $LQ \rightarrow t + e/\mu$

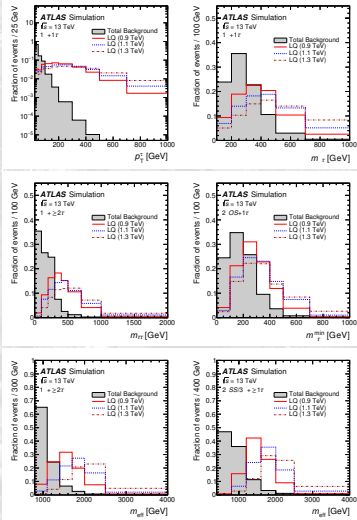




# Scalar $LQ \rightarrow t + e/\mu$



# Scalar $LQ_3^U \rightarrow t\tau$



# Scalar $LQ_3^u \rightarrow t\tau$

**ATLAS**

$\sqrt{s} = 13 \text{ TeV}$

Signal regions



1  $+1\tau\text{OS}$



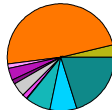
1  $+1\tau\text{SS}$



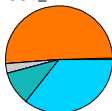
1  $+ \geq 2\tau$



2  $\text{OS}+1\tau$



2  $\text{OS}+\geq 2\tau$



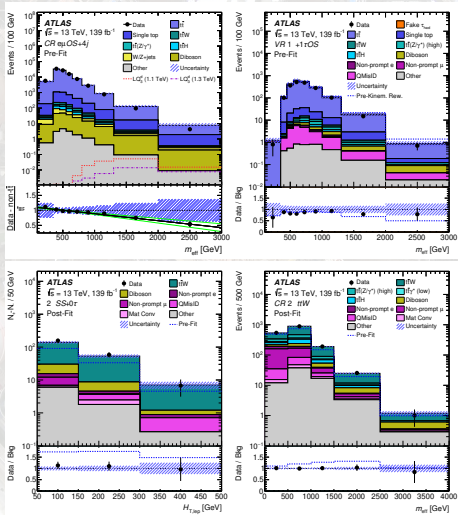
2  $\text{SS}/3 \ + \geq 1\tau\text{-L}$



2  $\text{SS}/3 \ + \geq 1\tau\text{-H}$



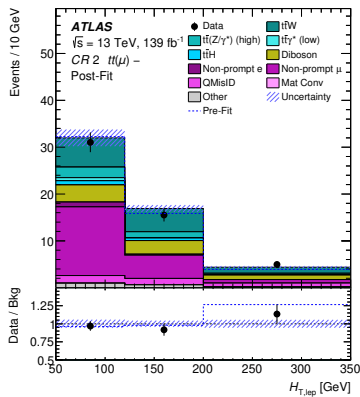
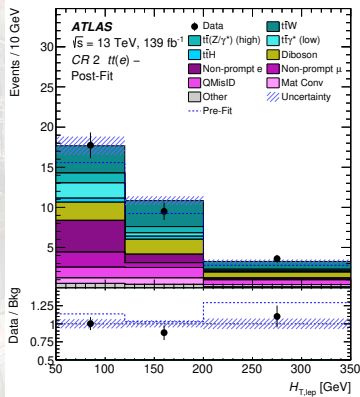
# Scalar $LQ_3^u \rightarrow t\tau$



The figure displays four ATLAS plots showing event distributions for different search channels. Each plot includes a main histogram showing the event distribution and a lower panel showing the ratio of Data to Background (Data/Bkg).

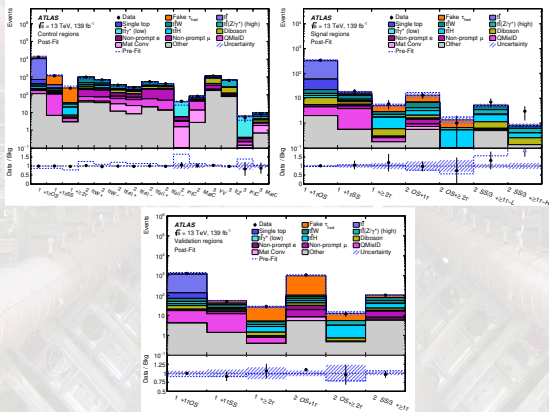
- Top Left Plot (CR 3 VV):** Shows the event distribution for the CR 3 VV channel. The x-axis is  $m_{ee}$  [GeV] (0 to 4000) and the y-axis is Events/500 GeV (log scale, 1 to 10<sup>4</sup>). The legend includes Data,  $t\bar{t}Z\gamma\gamma$  (high), Diboson, Non-prompt  $e$ , Non-prompt  $\mu$ , QMisID, Mat Conv, Other, Uncertainty, and Pre-Fit.
- Top Right Plot (CR 3 ttZ):** Shows the event distribution for the CR 3 ttZ channel. The x-axis is  $m_{ee}$  [GeV] (0 to 4000) and the y-axis is Events/500 GeV (log scale, 1 to 10<sup>4</sup>). The legend includes Data,  $t\bar{t}Z\gamma\gamma$  (high), Diboson, Non-prompt  $e$ , Non-prompt  $\mu$ , QMisID, Mat Conv, Other, Uncertainty, and Pre-Fit.
- Bottom Left Plot (CR 1 +1rSS):** Shows the event distribution for the CR 1 +1rSS channel. The x-axis is  $P_T^j$  [GeV] (50 to 400) and the y-axis is Events/25 GeV (log scale, 1 to 10<sup>4</sup>). The legend includes Data, Fake  $\tau_{had}$ ,  $t\bar{t}$ , Single top,  $t\bar{t}W$ ,  $t\bar{t}Z\gamma\gamma$  (high), Diboson, Non-prompt  $e$ , Non-prompt  $\mu$ , QMisID, Other, Uncertainty, and Pre-Fake  $\tau_{had}$  Corr.
- Bottom Right Plot (VR 2 OS+1r):** Shows the event distribution for the VR 2 OS+1r channel. The x-axis is Jet multiplicity (2 to 8) and the y-axis is Events (log scale, 1 to 10<sup>5</sup>). The legend includes Data, Fake  $\tau_{had}$ , Single top,  $t\bar{t}$ ,  $t\bar{t}W$ ,  $t\bar{t}Z\gamma\gamma$  (high), Diboson, Non-prompt  $e$ , Non-prompt  $\mu$ , QMisID, Mat Conv, Other, and Uncertainty.

# Scalar $LQ_3^u \rightarrow t\tau$

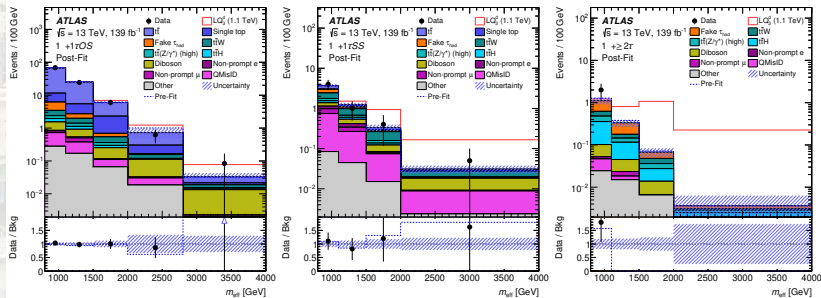




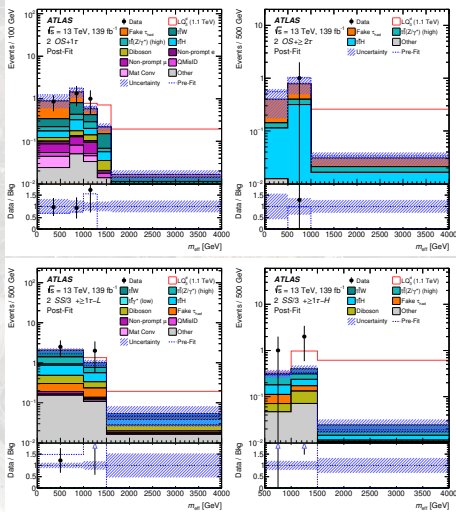
# Scalar $LQ_3^u \rightarrow t\tau$



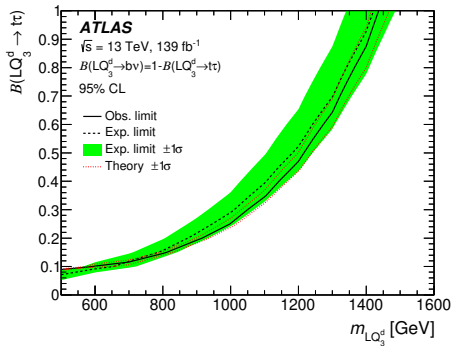
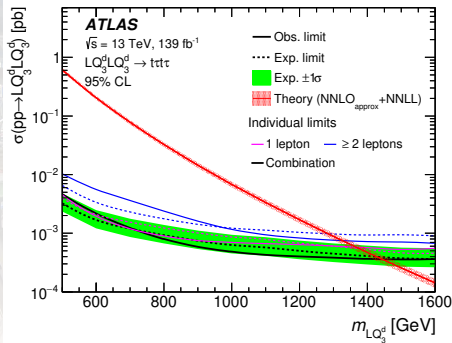
# Scalar $LQ_3^u \rightarrow t\tau$



# Scalar $LQ_3^u \rightarrow t\tau$



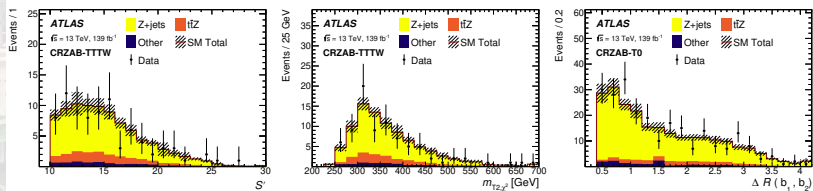
# Scalar $LQ_3^u \rightarrow t\tau$



# Scalar $LQ_3^u \rightarrow t\nu/b\tau$

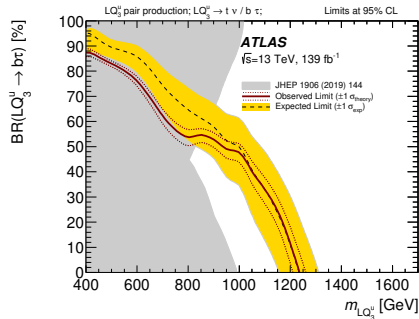
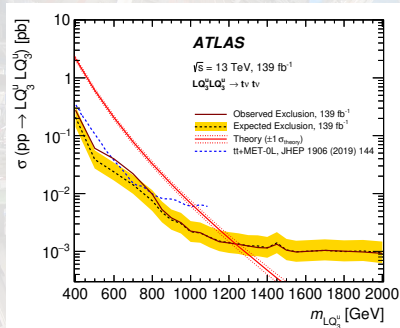
Variable/SR	SRA-TT	SRA-TW	SRA-T0	SRB-TT	SRB-TW	SRB-T0
Trigger				$E_T^{\text{miss}}$		
$E_T^{\text{miss}}$				> 250 GeV		
$N_\ell$				Exactly 0		
$N_j$				$\geq 4$		
$p_{T,2}$				> 80 GeV		
$p_{T,4}$				> 40 GeV		
$ \Delta\phi_{\min}(\mathbf{p}_{T,1-4}, \mathbf{p}_T^{\text{miss}}) $				> 0.4		
$N_b$				$\geq 2$		
$m_{T, \min}^{b, \min}$				> 200 GeV		
$\tau$ -veto				✓		
$m_1^{R=1.2}$				> 120 GeV		
$m_2^{R=1.2}$	> 120 GeV	60–120 GeV	< 60 GeV	> 120 GeV	60–120 GeV	< 60 GeV
$m_1^{R=0.8}$		> 60 GeV			–	
$j_1^{R=1.2}(b)$		✓			–	
$j_2^{R=1.2}(b)$	✓			–		
$\Delta R(b_1, b_2)$	> 1.0		–		> 1.4	
$m_{T, \max}^{b, \max}$		–			> 200 GeV	
$S$		> 25			> 14	
$m_{T2, \chi^2}$		> 450 GeV			< 450 GeV	

# Scalar $LQ_3^u \rightarrow t\nu/b\tau$





# Scalar $LQ_3^u \rightarrow t\nu/b\tau$



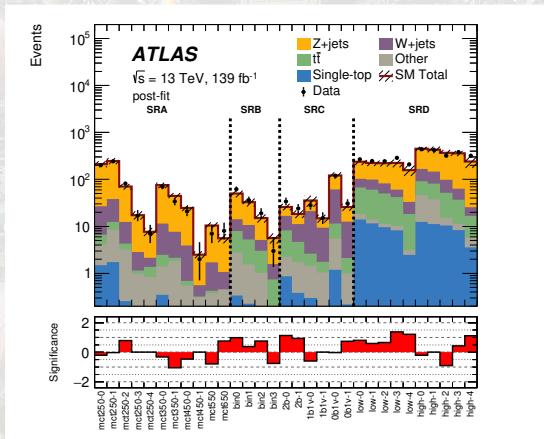
# Scalar $LQ_3^d \rightarrow b\nu/t\tau$

Variable		SRA	CRzA	$VR_{A1}^{m_{CT}}$	$VR_{A1}^{m_{bb}}$	$VR_{A2}^{m_{CT}}$	$VR_{A2}^{m_{bb}}$
Number of baseline leptons		0	2	0			
Number of high-purity leptons		—	2 SFOS	—			
$p_T(\ell_1)$	[GeV]	—	> 27	—			
$p_T(\ell_2)$	[GeV]	—	> 20	—			
$m_T(\mathbf{p}_T^\ell, \mathbf{p}_T^{\text{miss}})$	[GeV]	—	> 20	—			
$m_{\ell\ell}$	[GeV]	—	[81, 101]	—			
Number of jets		$\in [2, 4]$					
Number of $b$ -tagged jets		2					
$j_1$ and $j_2$ $b$ -tagged		✓					
$p_T(j_1)$	[GeV]	> 150					
$p_T(j_2)$	[GeV]	> 50					
$p_T(j_4)$	[GeV]	< 50					
$\min[\Delta\phi(\mathbf{p}_{1-4}^{\text{jet}}, \mathbf{p}_T^{\text{miss}})]$	[rad]	> 0.4					
$E_T^{\text{miss}}$	[GeV]	> 250	< 100	> 250			
$\hat{E}_T^{\text{miss}}$	[GeV]	—	> 250	—			
$E_T^{\text{miss}}/m_{\text{eff}}$		> 0.25	—	—			
$\hat{E}_T^{\text{miss}}/m_{\text{eff}}$		—	> 0.25	—			
$m_{bb}$	[GeV]	> 200		< 200	> 200	< 200	> 200
$m_{CT}$	[GeV]	> 250		> 250	[150, 250]	> 250	[150, 250]
$m_{\text{eff}}$	[GeV]	> 500		[500, 1500]		> 1500	

# Scalar $LQ_3^d \rightarrow b\nu/t\tau$

Variable		SRB	CRzB	VRzB
Number of baseline leptons		0	2	
Number of high-purity leptons		—	2 SFOS	
$p_{\text{T}}(\ell_1)$	[GeV]	—	$> 27$	
$p_{\text{T}}(\ell_2)$	[GeV]	—	$> 20$	
$m_{\ell\ell}$	[GeV]	—	$[76, 106]$	
$m_{\text{T}}(\mathbf{p}_{\text{T}}^{\ell}, \mathbf{p}_{\text{T}}^{\text{miss}})$	[GeV]	—	$> 20$	
Number of jets		$\in [2, 4]$		
Number of $b$ -tagged jets		2		
$p_{\text{T}}(j_1)$	[GeV]	$> 100$		
$p_{\text{T}}(j_2)$	[GeV]	$> 50$		
$\min[\Delta\phi(\mathbf{p}_{1-4}^{\text{jet}}, \mathbf{p}_{\text{T}}^{\text{miss}})]$	[rad]	$> 0.4$		
$j_1$ not $b$ -tagged		—	✓	—
$E_{\text{T}}^{\text{miss}}$	[GeV]	$> 250$	$< 100$	
$\tilde{E}_{\text{T}}^{\text{miss}}$	[GeV]	—	$> 250$	
$m_{\text{CT}}$	[GeV]	$< 250$		
$w_{\text{XGB}}$		$> 0.85$	$[0.3, 0.63]$	$> 0.63$

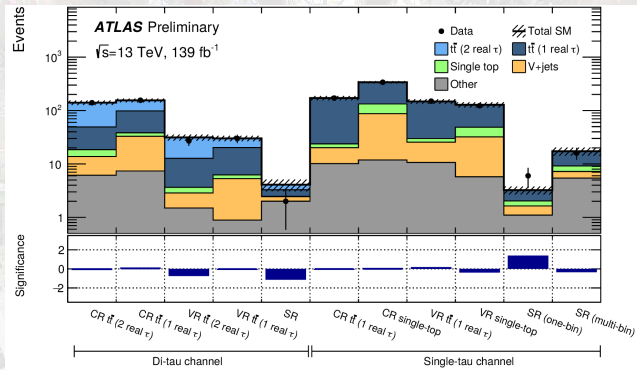
# Scalar $LQ_3^d \rightarrow b\nu/t\tau$



# Scalar $LQ_3^u \rightarrow b\tau/t\nu$ and $LQ_3^d \rightarrow b\nu/t\tau$

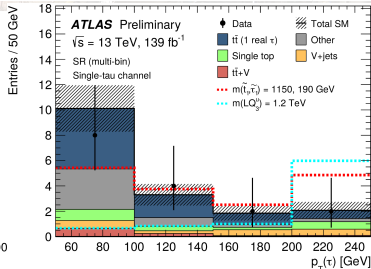
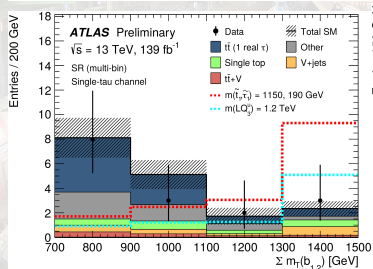
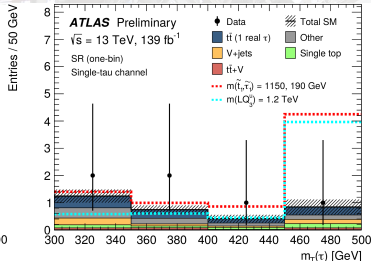
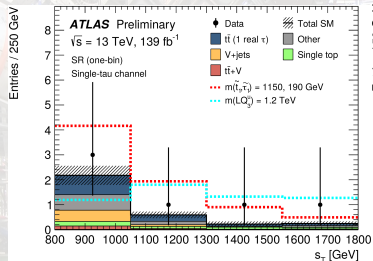
Variable	CR $t\bar{t}$ (1 real $\tau$ )	CR single top	VR $t\bar{t}$ (1 real $\tau$ )	VR single top	SR
$E_T^{miss}$ [GeV]	> 280	> 280	> 280	> 280	> 280
$S_T$ [GeV]	[500,600]	-	> 600	-	> 800(600)
$\sum m_T(b1, b2)$ [GeV]	[600,700]	> 800	[600, 700]	> 800	> 700
$m_T(\tau)$ [GeV]	-	< 50	-	[50, 150]	> 300(150)
$p_T(\tau)$ [GeV]	-	> 80	-	> 80	- (binned)

# Scalar $LQ_3^u \rightarrow b\tau/t\nu$ and $LQ_3^d \rightarrow b\nu/t\tau$

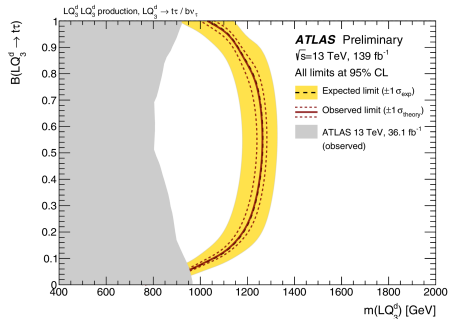
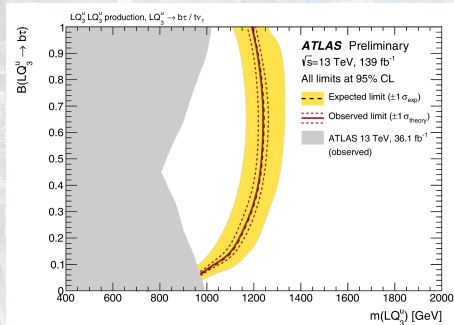




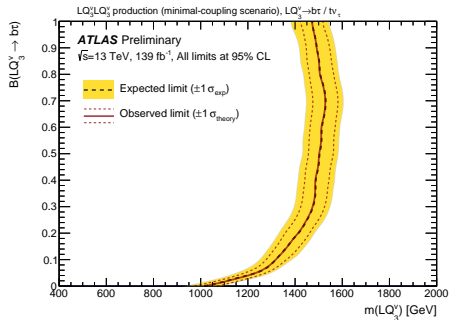
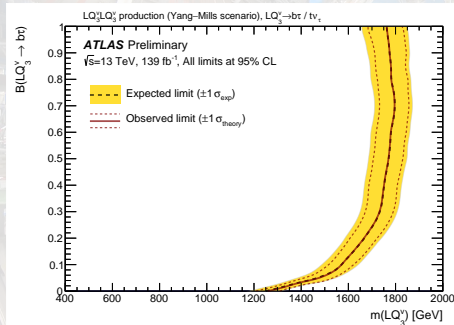
# Scalar $LQ_3^u \rightarrow b\tau/t\nu$ and $LQ_3^d \rightarrow b\nu/t\tau$



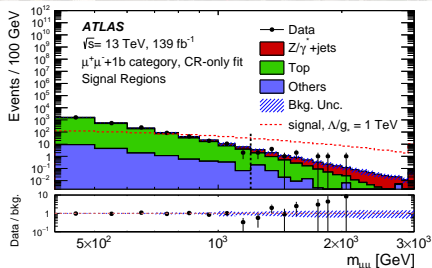
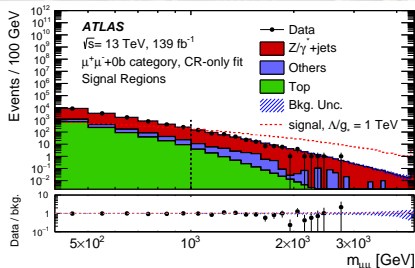
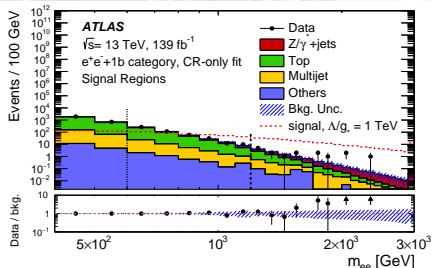
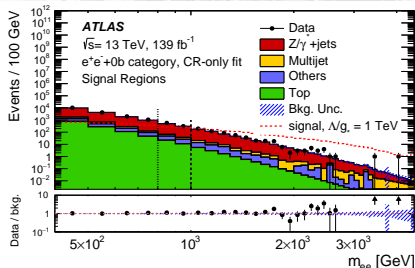
# Scalar $LQ_3^u \rightarrow b\tau/t\nu$ and $LQ_3^d \rightarrow b\nu/t\tau$



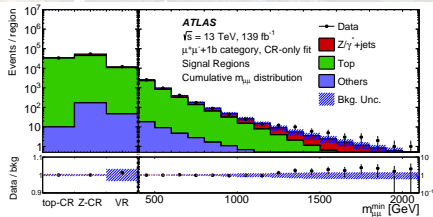
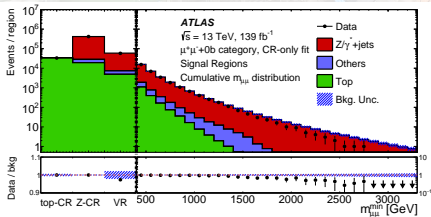
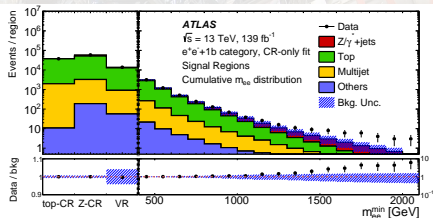
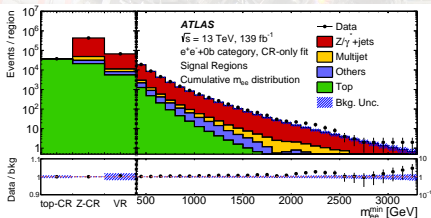
# Vector $LQ_3^u \rightarrow b\tau/t\nu$ and $LQ_3^d \rightarrow b\nu/t\tau$



# *bsll* Contact Interaction



# *bsll* Contact Interaction



# *bsll* Contact Interaction

