Search for scalar leptoquarks in the b$\tau\tau$ final state with the ATLAS detector

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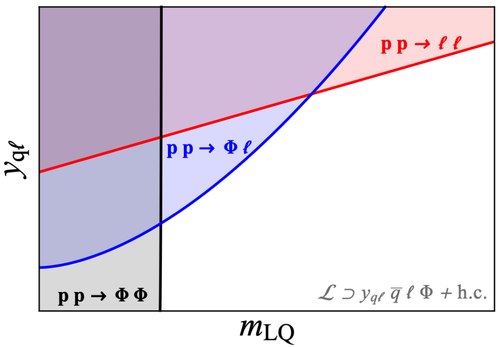
Introduction to Leptoquark (LQ)

- LQs can explain deviations from lepton flavor universality from the SM in B-physics
  - Predicted in many BSM scenarios and decay to lepton-quark pairs
  - Carry color charge, fractional electric charge and non-zero baryon and lepton number

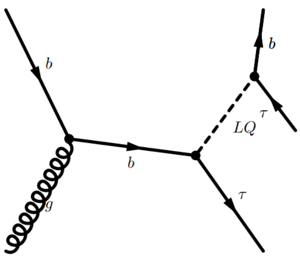
- The cross section of singly-produced LQ not only depends on the mass of LQ but also depends on the Yukawa coupling(λ) of LQ-lepton-quark



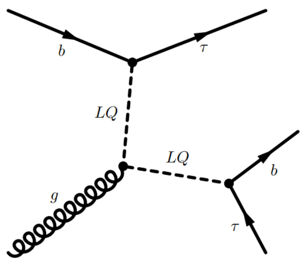
Spin	$3B+L$	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$	Allowed coupling
0	-2	$\bar{3}$	1	1/3	$\bar{q}^c_L \ell_L$ or $\bar{u}^c_R e_R$
0	-2	$\bar{3}$	1	4/3	$\bar{d}^c_R e_R$
0	-2	$\bar{3}$	3	1/3	$\bar{q}^c_L \ell_L$
1	-2	$\bar{3}$	2	5/6	$\bar{q}^c_L \gamma^\mu e_R$ or $\bar{d}^c_R \gamma^\mu \ell_L$
1	-2	$\bar{3}$	2	$-1/6$	$\bar{u}^c_R \gamma^\mu \ell_L$
0	0	3	2	7/6	$\bar{q}_L e_R$ or $\bar{u}_R \ell_L$
0	0	3	2	1/6	$\bar{d}_R \ell_L$
1	0	3	1	2/3	$\bar{q}_L \gamma^\mu \ell_L$ or $\bar{d}_R \gamma^\mu e_R$
1	0	3	1	5/3	$\bar{u}_R \gamma^\mu e_R$
1	0	3	3	2/3	$\bar{q}_L \gamma^\mu \ell_L$

LQ search in b$\tau\tau$ final state (CONF)

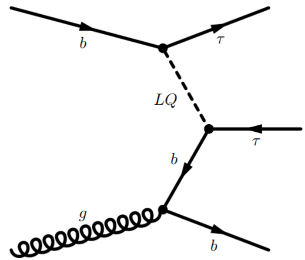
- Main focus on singly produced scalar LQ:
  - considering $\tilde{S}_1$ model with LQ having $4/3e$ and $3B + L = -2$
  - LQ production mostly through quark-gluon fusion and scattering
- Include also pair production of scalar LQs since similar final state
- Assuming LQ exclusive decay in $b\tau$
- Scan over several mass and coupling points



quark-gluon fusion



quark-gluon scattering



quark-gluon scattering

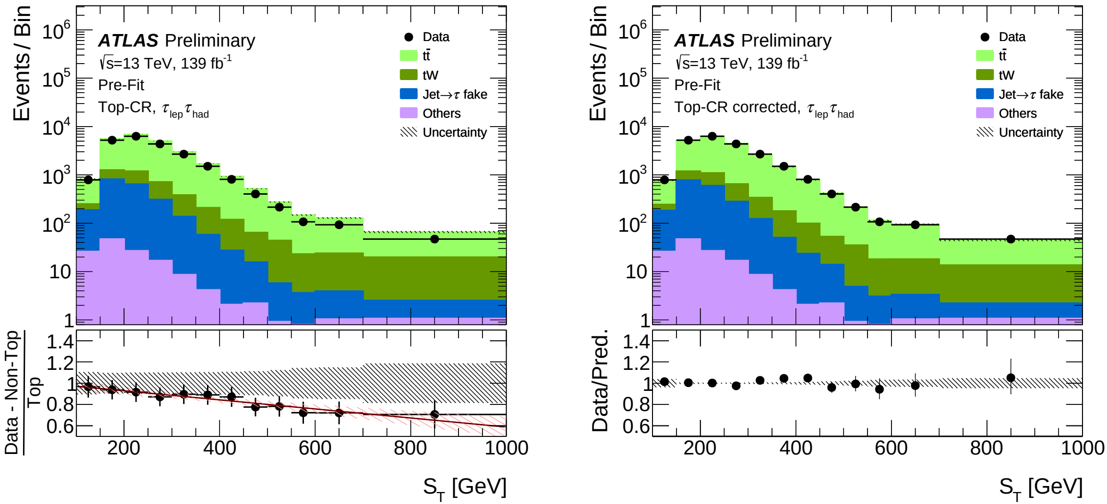
- Considered two final states depending on τ decay mode : $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$

$\tau_{lep}\tau_{had}$ event selection

	Selection	
Signal Region	ℓ (trigger, isolated), τ_{had} (medium), $q(\ell) \times q(\tau_{\text{had}}) < 0$, $\Delta\phi(\ell, E_{\text{T}}^{\text{miss}}) < 1.5$, $m_{\text{vis}}(\ell, \tau_{\text{had}}) > 100$ GeV, $S_{\text{T}} > 300$ GeV, at least one b-jet, lead. b-jet $p_{\text{T}} > 200$ GeV	
Control/Validation Region	**Selection**	**Notes**
Multijet-CR	ℓ (trigger, pass or fail offline isolation), $m_{\text{T}}(\ell, E_{\text{T}}^{\text{miss}}) < 30$ GeV, one b-jet, RNN τ ID score < 0.01, $E_{\text{T}}^{\text{miss}} < 50$ GeV	Measure lepton fake factor
Top-CR	Pass 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	Pass SR except: $q(\ell) \times q(\tau_{\text{had}}) > 0$, no $\Delta\phi(\ell, E_{\text{T}}^{\text{miss}})$ and S_{T} req.	Correct fake modelling
VR	Pass SR except: $1.5 < \Delta\phi(\ell, E_{\text{T}}^{\text{miss}}) < 2.5$, 300 GeV $< S_{\text{T}} <$ 600 GeV	Background modeling
b-tag Z-CR	Pass SR except: 45 GeV $< m_{\text{vis}}(\ell, \tau_{\text{had}}) <$ 80 GeV, $p_T(\ell)/p_T(b\text{-jet}) > 0.8$, and $\lvert\Delta\phi(\ell, \tau_{\text{had}})\rvert > 2.4$, no S_{T} req.	Z+HF normalisation factor

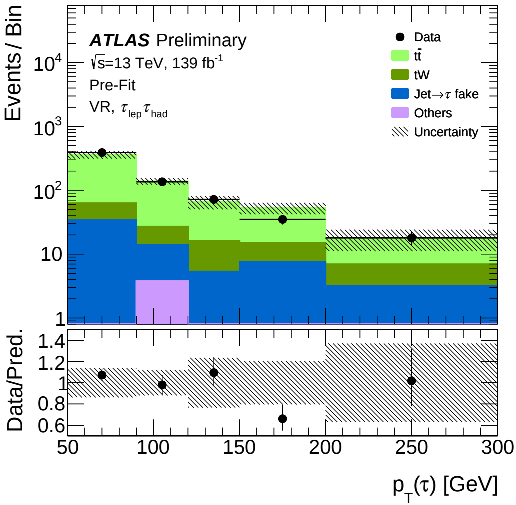
- Events triggered by single-electron/muon trigger
- Main backgrounds:
  - Top ($t\bar{t}$ + single top) : estimated through simulation + correction derived in *TopCR*
  - Mis-identified τ : estimated through simulation + correction
- Minor backgrounds:
  - Multi-jet : estimated through data-driven method using dedicated *Multijet-CR*
  - V+jets, Diboson : estimated through simulation

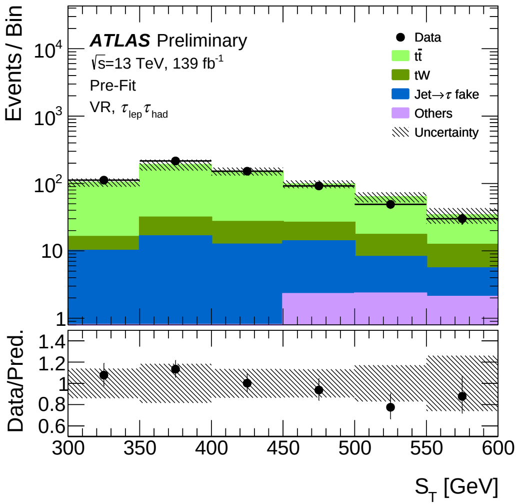
Top background correction



- Found large mis-modelling for Top background in *TopCR*
- Derive correction as function of S_T ($= p_T^{\tau} + p_T^{\tau} + p_T^{b-jet}$) fitting with linear function

Background modelling validation





- Modelling cross-checked in a dedicated VR; good modelling within pre-fit uncertainties

$\tau_{had}\tau_{had}$ event selection

	Selection	
Signal Region	$\tau_{\text{had},1}$ (trigger, med.), $\tau_{\text{had},2}$ (loose), $q(\tau_{\text{had},1}) \times q(\tau_{\text{had},2}) < 0$, $m_{\text{vis}}(\tau_{\text{had},1}, \tau_{\text{had},2}) > 100$ GeV, $S_{\text{T}} > 300$ GeV, at least one b-jet, lead. b-jet $p_{\text{T}} > 200$ GeV	
Control/Validation Region	**Selection**	**Notes**
DJ-FR	Jet trigger, $\tau_{\text{had},1}$ and $\tau_{\text{had},2}$ pass very loose ID, $q(\tau_{\text{had},1}) \times q(\tau_{\text{had},2}) < 0$	Measure τ_{had} fake factor
CR-1	Pass SR except: $\tau_{\text{had},2}$ (fail loose)	Apply τ_{had} fake factor
SS-VR	Pass SR except: $q(\tau_{\text{had},1}) \times q(\tau_{\text{had},2}) == 1$	Multijet modelling check
Z+LF VR	Pass SR except: 0 b-jets, $\Delta\phi(\tau_{\text{had},1}, \tau_{\text{had},2}) > 0.25$, $m_{\text{vis}} < 100$ GeV, $E_{\text{T}}^{\text{miss}} > 60$ GeV	Z+light jets modelling

- Events triggered by single-τ trigger
- Main backgrounds:
  - Top ($t\bar{t}$ + single top) : estimated through simulation + correction from $\tau_{lep}\tau_{had}$ *TopCR*
  - Multi-jet : estimated through data-driven method using dedicated CR
  - Z+jets : estimated through simulation + normalisation correction
- Minor backgrounds:
  - W+jets, Diboson : estimated through simulation

Statistical model and fit strategy

- Results extracted from binned likelihood fit on S_T distribution
  - Tested other discriminant variables but less performant

$$\mathcal{L}(\mu, \vec{\theta}) = \prod_{i=1} e^{-(\mu s_i + b_i)} \frac{(\mu s_i + b_i)^{n_i}}{n_i!} \cdot \prod_{j=1} G(\theta_j)$$

- Binning optimised to ensure $N_{bkg} > 10$ events in the last S_T bin
- Simultaneous fit combining $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$ signal regions
- Performing two types of fit:
  - Background-only fit on data to get post-fit plots
  - Signal+Background fit to extract upper limits

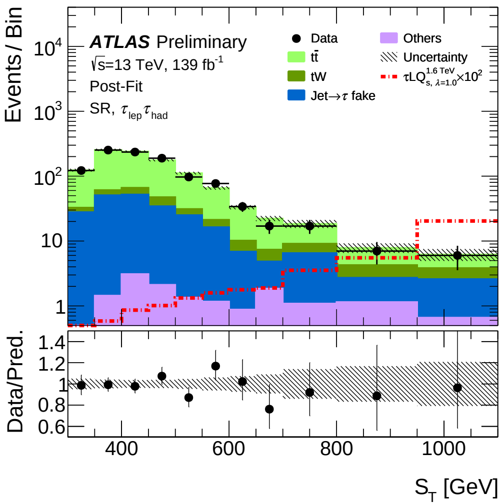
Systematic uncertainty impact

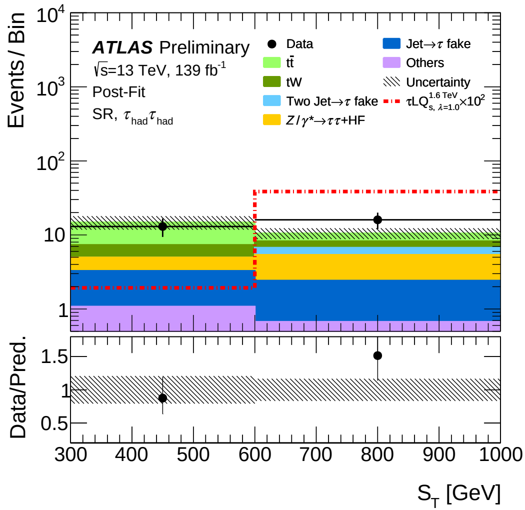
Source / m_{LQ}	$\lambda = 1.0$		$\lambda = 1.7$		$\lambda = 2.5$	
	0.9 TeV	1.6 TeV	0.9 TeV	1.6 TeV	0.9 TeV	1.6 TeV
Top background modelling	0.11	0.05	0.12	0.08	0.13	0.12
Tau reconstruction/identification	0.06	0.05	0.06	0.05	0.06	0.06
Tau energy scale	0.05	0.02	0.05	0.05	0.06	0.05
Flavor tagging	0.02	0.03	0.02	0.03	0.02	0.03
Signal acceptance	0.01	0.03	0.01	0.03	0.04	0.04
Others	0.03	0.02	0.03	0.03	0.04	0.04
Total	0.16	0.11	0.17	0.15	0.22	0.21

- Impact by several syst. sources evaluated as relative increase on expected limits relative to stat-only expected limits
  - Correlation between nuisance parameter neglected

- Most impacting uncertainty sources:
  - Top bkg model: initial/final state radiation, parton shower and matrix element uncertainties
  - Tau related systematics: reconstruction, identification and energy scale uncertainties

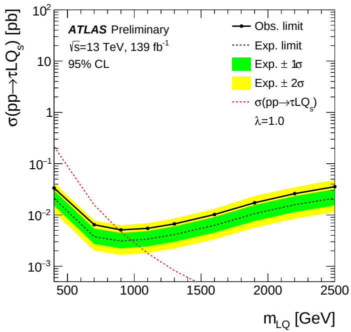
Post-fit plots from Background-only fit



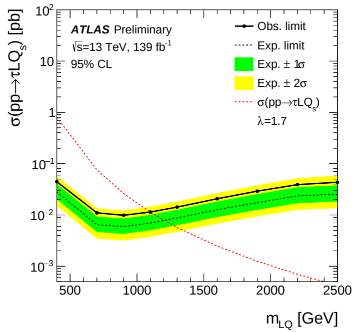


- Signal mainly at higher S_T values
- Good agreement with the background prediction; no significant excess observed in data

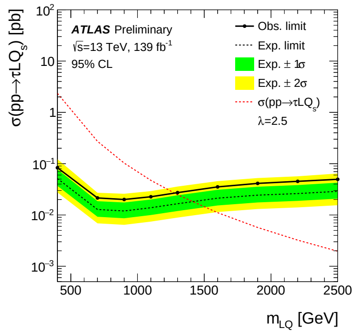
Upper limits on singly-produced LQ



$\lambda = 1$



$\lambda = 1.7$

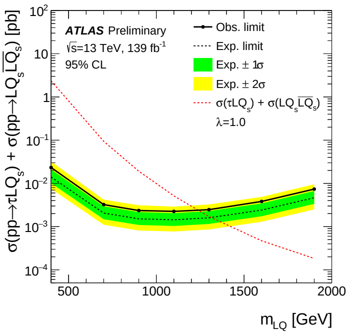


$\lambda = 2.5$

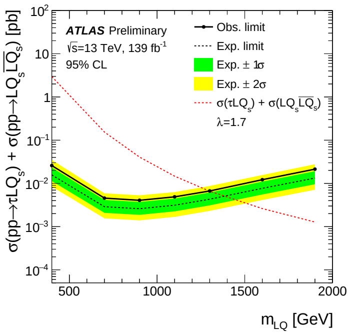
- The observed limits obtained are lower than the expected limit; mostly driven by the high S_T in $\tau_{had}\tau_{had}$ channel
- First ATLAS result for the search of singly-produced LQ in $b\tau\tau$ final state

	m_{LQ} Obs (Exp) lim at 95% CL
$\lambda = 1$	0.89 (1.0) TeV
$\lambda = 1.7$	1.01 (1.22) TeV
$\lambda = 2.5$	1.28 (1.43) TeV

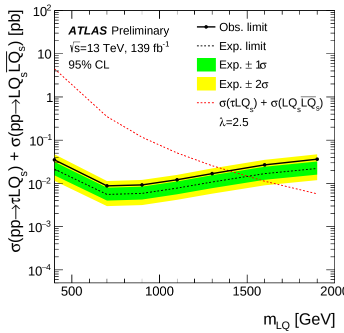
Upper limits on singly+pair produced LQ



$\lambda = 1$



$\lambda = 1.7$

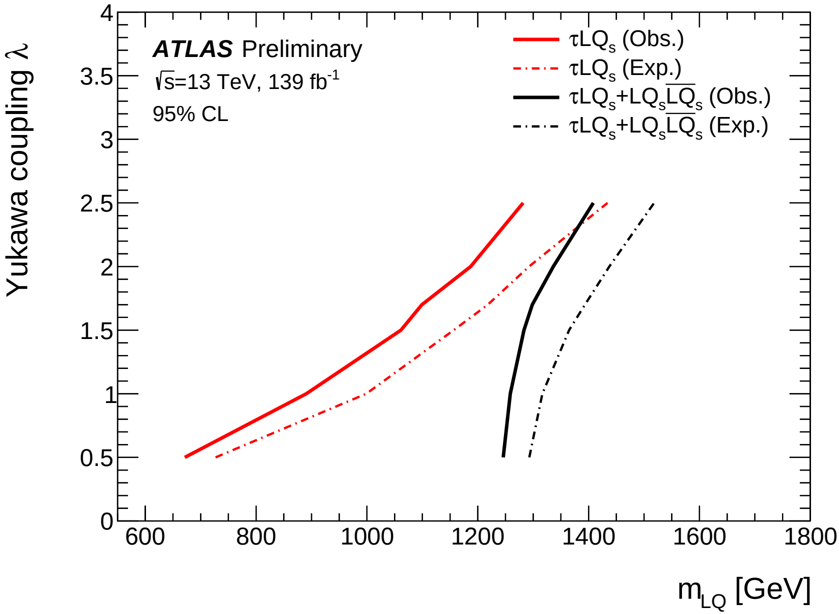


$\lambda = 2.5$

- More stringent limit compared to standalone singly produced LQ limits
- Masses below 1.25 TeV are excluded for all λ values above 0.5

	m_{LQ} Obs (Exp) lim at 95% CL
$\lambda = 1$	1.26 (1.32) TeV
$\lambda = 1.7$	1.30 (1.40) TeV
$\lambda = 2.5$	1.41 (1.52) TeV

Exclusion limits in the λ-m_{LQ} plane



- All values on the left side-band with respect to the lines are excluded

Summary

- A search for scalar leptoquarks in the b$\tau\tau$ final state have been presented
  - considering both singly and pair scalar leptoquark production
  - scan over several mass and coupling (λ) points
  - considering $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$ final states

- No significant excess observed in data $\rightarrow$ setting limits for singly (first results in ATLAS) and singly+pair LQ production
  - for singly-produced LQ, masses below 1 TeV are excluded for all λ values $>$1.0
  - for singly+pair LQ production, masses below 1.25 TeV are excluded for all λ values > 0.5

Thanks For Your Attention

Backup

MC sample generator summary

Process	Generator		PDF set		Tune	Normalisation
	ME	PS	ME	PS		
LQ→ $b\tau$	MadGraph5_aMC@NLO	Pythia 8.244	NNPDF3.0nnlo	NNPDF2.3lo	A14	LO
LQLQ→ $b\tau b\tau$	MadGraph5_aMC@NLO	Pythia 8.244	NNPDF3.0nnlo	NNPDF2.3lo	A14	NNLO + NNLL
$t\bar{t}$	Powheg Box v2	Pythia 8	NNPDF3.0nnlo	NNPDF2.3lo	A14	NNLO + NNLL
Single top	Powheg Box v2	Pythia 8	NNPDF3.0nnlo	NNPDF2.3lo	A14	NLO
$Z/\gamma^* \rightarrow \tau\tau$	Powheg Box v1	Pythia 8	CT10nlo	CTEQ6L1	AZNLO	NLO
W+jets	Sherpa 2.2.1		NNPDF3.0nnlo		Sherpa	NNLO
Diboson	Sherpa 2.2.1/Sherpa 2.2.2		NNPDF3.0nnlo		Sherpa	NLO

Post-fit yields in $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$ ch.

Process	$\tau_{\text{lep}}\tau_{\text{had}}$	$\tau_{\text{had}}\tau_{\text{had}}$
Background	Yields (with post-fit uncertainties)	
$t\bar{t}$	765±82	9.9±2.6
Single top	65±35	3.9±1.0
Single Jet$\rightarrow\tau$ fake	214±79	3.9±1.0
Two Jet$\rightarrow\tau$ fake	-	1.3±0.3
$Z(\tau\tau)$+HF	5.5±1.4	4.7±1.1
$Z(\tau\tau)$+LF	1.6±0.3	0.4±0.1
$Z(ee,\mu\mu)$+jets	1.0±0.3	-
Others	7.1 ±0.8	1.4±0.3
Total background	1059±51	25.4±4.8
Data	1053	29
Signal	Yields (with pre-fit uncertainties)	
LQ, m_{LQ}=0.9 TeV, $\lambda = 1$	13±1	14±1
LQ, m_{LQ}=1.6 TeV, $\lambda = 1$	0.40±0.05	0.40±0.06
LQ, m_{LQ}=0.9 TeV, $\lambda = 1.7$	42±4	42±4
LQ, m_{LQ}=1.6 TeV, $\lambda = 1.7$	1.7±0.2	1.7±0.2
LQ, m_{LQ}=0.9 TeV, $\lambda = 2.5$	92±11	87±14
LQ, m_{LQ}=1.6 TeV, $\lambda = 2.5$	5.5±1.0	5.1± 0.8
LQLQ, m_{LQ}=0.9 TeV	74±5	93±14
LQLQ, m_{LQ}=1.6 TeV	0.6±0.1	1.0±0.1
	(a)	(b)