Search for leptoquarks decaying into $b\tau$ final state in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

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on behalf of the ATLAS Collaboration

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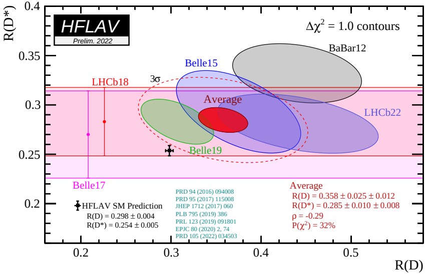
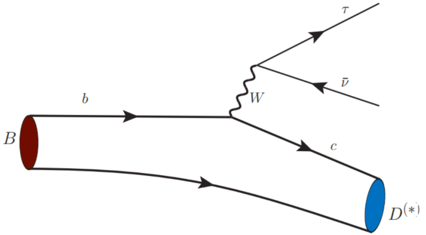
- Many experiments show hints deviations of $R(D^{(*)})$ measurement.
- Existence of Leptoquarks (LQs) could be one of explanations to such deviations.

$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\overline{\nu})}{\mathcal{B}(B \to D^{(*)}\ell\overline{\nu})}$$



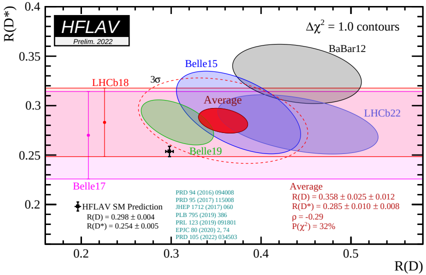
Heavy Flavor Averaging Group



Motivation

- Many experiments show hints deviations of $R(D^{(*)})$ measurement.
- Existence of Leptoquarks (LQs) could be one of explanations to such deviations.

$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\overline{\nu})}{\mathcal{B}(B \to D^{(*)}\ell\overline{\nu})}$$



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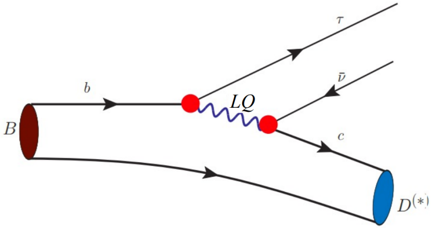
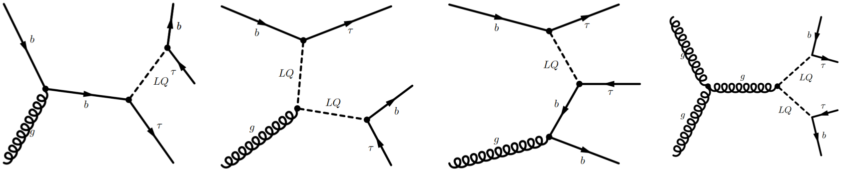


Signal model

- Leptoquarks
  - Predicted by many BSM theories
  - Carry color charge, fractional electric charge and non-zero baryon and lepton number
  - Couple to both quarks and leptons
- Search for LQ in $b\tau\tau$ final states
  - Optimized for single production of $\widetilde{S}_1$ (scalar) LQ and U_1 (vector) LQ
    - Vector LQ: $U_1^{MIN}(\kappa = 1)$ and $U_1^{YM}(\kappa = 0)$
  - Consider also LQ pair production since have similar final states
  - Consider two channels: $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$



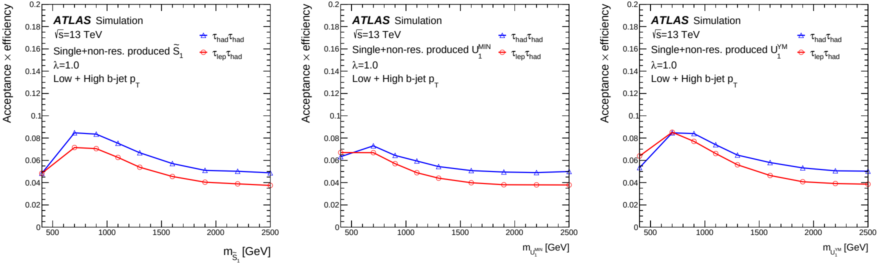
Event selections

- $\tau_{lep}\tau_{had}$
- Single lepton trigger
- Isolated and trigger-matched lepton + τ passing medium RNN τ ID
- $p_T(l) > 30$ GeV, $p_T(\tau) > 50$ GeV
- Opposite-sign charge between l and τ
- At least one b-jet, 70% b-tagging WP of DL1r
- $m_{vis}(l, \tau) > 100$ GeV
- $\Delta\phi(l, E_T^{miss}) < 1.5$
- $S_T > 300$ GeV

- $\tau_{had}\tau_{had}$
- Single τ trigger (80, 125, 160 GeV)
- Leading τ: trigger-matched, $p_T >$ (trigger threshold + 5 GeV), pass medium RNN τ ID
- Sub-leading τ: $p_T > 65$ GeV, pass loose RNN τ ID
- Opposite-sign charge between τ and τ
- Veto electrons or muons
- At least one b-jet, 70% b-tagging WP of DL1r
- $m_{vis}(\tau, \tau) > 100$ GeV
- $S_T > 300$ GeV

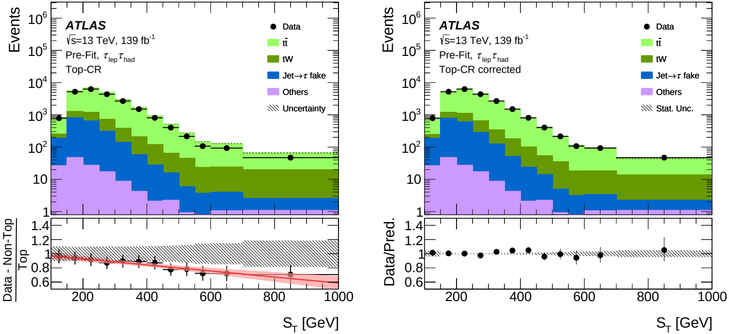
- Low bjet pT category: 25 GeV $< p_T(bjet) <$ 200 GeV
- High bjet pT category: $p_T(bjet) > 200$ GeV
- The discriminant variable: $S_T = p_T^{\tau} + p_T^{\tau(\ell)} + p_T^{bjet}$

Signal acceptance times efficiency



- Low acceptance times efficiency due to:
  - $S_T > 300$ GeV $\Rightarrow$ have to suppress top-quark backgrounds

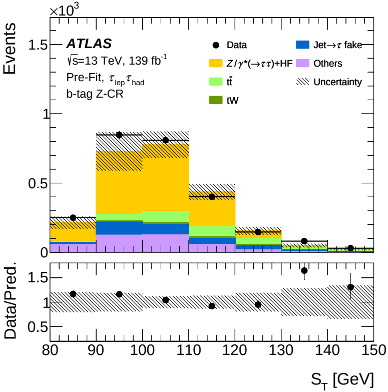
Top background correction in $\tau_{lep}\tau_{had}$



- Large mis-modelling for Top backgrounds in Top-CR
- S_T parameterization. SFs fitted by linear function after considering statistical uncertainty and MC variations ($\sim$10%)
- Uncertainty from alternative choice of fit functions considered
- Uncertainty from difference in fraction of single top between Top-CR and SR

$$SF_{Top}(S_T) = \frac{(N_{data} - N_{non-top})(S_T)}{N_{top}(S_T)}$$

Z+HF normalization in $\tau_{had}\tau_{had}$



- Check Z+HF in b-tag Z-CR ⇒ 63% Z+HF purity
- Derive scale factor for normalization by subtracting non-ZHF MC:

$$SF_{ZHF} = \frac{N_{data} - N_{non-ZHF}}{N_{ZHF}} = 1.13 \pm 0.23$$

- Uncertainty: statistical uncertainty, modeling variation on MC samples, extrapolation to SR

Systematic uncertainties

- Experimental uncertainty:
  - Luminosity, pile-up
  - Electrons, muons, taus, jets, b-tagging, MET
- Background modeling uncertainty:
  - Top correction
  - Acceptance variation on top backgrounds (ttbar and single top modeling uncertainty)
    - By comparing nominal and alternative MC samples with dedicated corrections in phase space of Top-CR and SR.
  - Fake tau correction, multi-jets estimation, Z+jets
- Signal modeling uncertainty:
  - Acceptance uncertainty

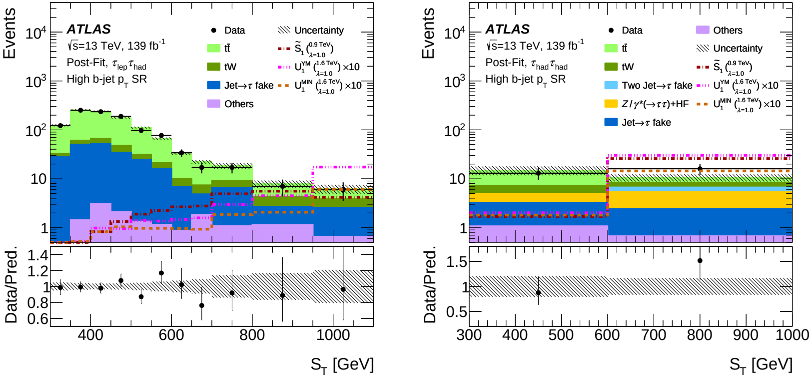
Statistical model and fit strategy

- Binned likelihood function in bins of S_T:

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

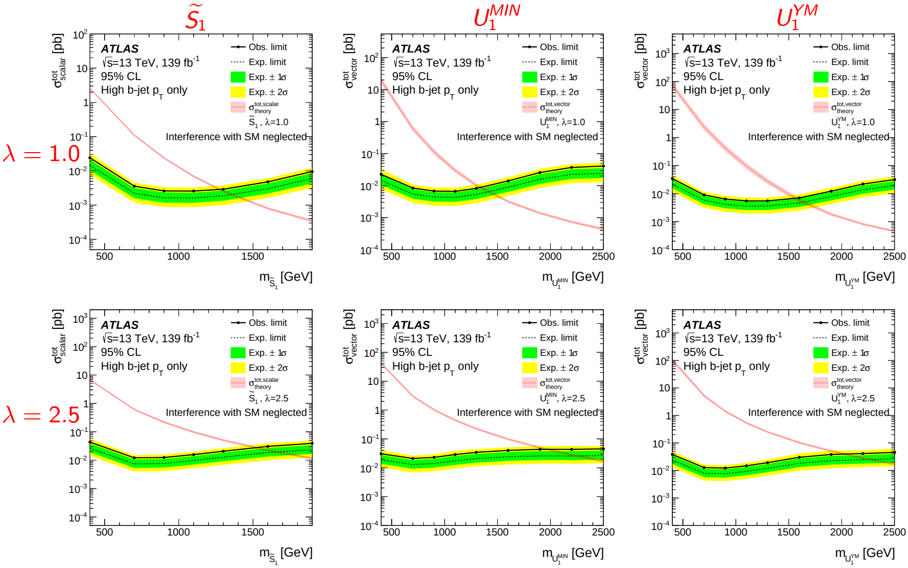
- Simultaneous fit by combining:
  - $(\tau_{lep}\tau_{had},\ \tau_{had}\tau_{had}) \times$ high b-jet $p_T = 2$ SRs
- Two kinds of fit performed:
  - B-only fit on real data in SRs to get post-fit plots
  - S+B fit on real data in SRs to get upper limits

Post-fit plots

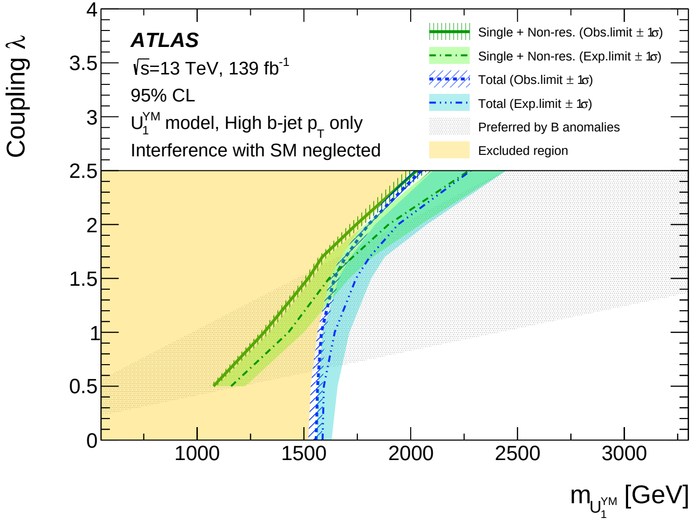


- No significant excess observed in data

Upper limits for single+pair LQs

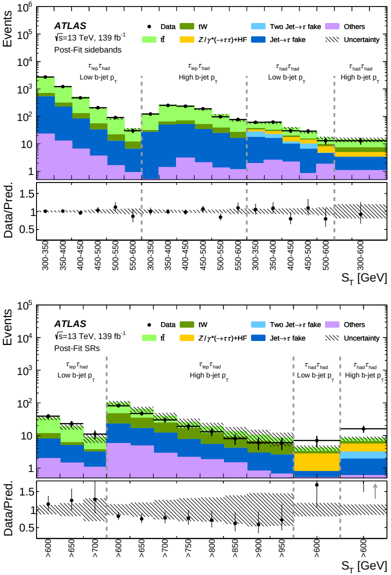


2D exclusion limits in mass-λ plane



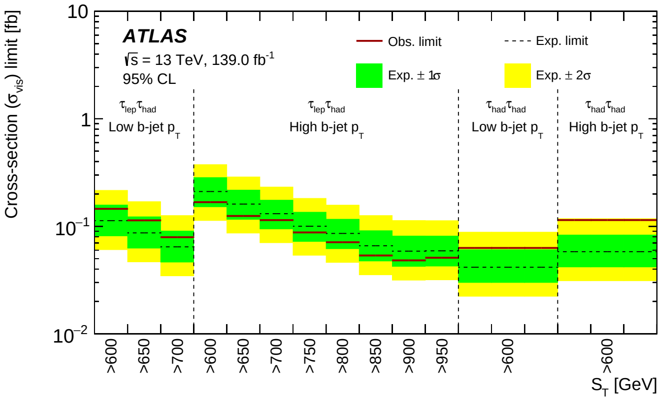
Model-independent interpretation

- Interference between non-res. signals and SM neglected
- Model-independent interpretation
  - Low + high b-jet pT categories
  - Same likelihood function with POI = μ
- Events with $S_T < 600$ GeV in SRs
  - $\Rightarrow$ 4 sidebands
- Events with S_T above a threshold
  - $\Rightarrow$ a new SR with generic signal injected
- B-only fit performed in 4 sidebands



Model-independent interpretation

- Simultaneous S+B fit repeated:
  - 4 sidebands x 1 SR with S_T above a threshold $\sigma_{vis}^{95} = \frac{N_s^{95}}{L} = \frac{N_s \times \mu^{95}}{L} = \sigma_0 \times \mu^{95}$
- Upper limits on visible cross sections:



Summary

- Search for leptoquarks decaying into $b\tau$ final state in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector
- No significant excess observed in data
- Upper limits on the cross section at 95% CL for scalar and vector LQ provided as well as 2D exclusion limits in mass-lambda plane
- Finally, a model-independent interpretation is provided with respect to upper limits on visible cross sections
- Paper link: JHEP10(2023)001

Thank You!

Backup

MC samples

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
Scalar LQLQ→ $b\tau b\tau$	MadGraph5_aMC@NLO	Pythia 8.230	NNPDF3.0nnlo	NNPDF2.3lo	A14	NNLO + NNLL
Vector LQLQ→ $b\tau b\tau$	MadGraph5_aMC@NLO	Pythia 8.244	NNPDF3.0nnlo	NNPDF2.3lo	A14	LO
$t\bar{t}$	Powheg Box v2	Pythia 8.230	NNPDF3.0nnlo	NNPDF2.3lo	A14	NNLO + NNLL
Single top	Powheg Box v2	Pythia 8.230	NNPDF3.0nnlo	NNPDF2.3lo	A14	NLO
Z/γ^*	Powheg Box v1	Pythia 8.186	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

Event selection

$\tau_{\text{lep}}\tau_{\text{had}}$ Signal Regions	Selection
SR	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	SR selection, leading b-jet $p_{\text{T}} > 200$ GeV
Low b-jet p_{T} SR	SR selection, leading b-jet $p_{\text{T}} < 200$ GeV

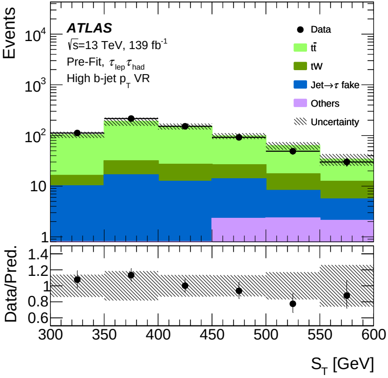
$\tau_{\text{had}}\tau_{\text{had}}$ Signal Regions	Selection
SR	τ_1 (trigger, medium τ_{had}-ID), τ_2 (loose τ_{had}-ID), $q(\tau_1) \times q(\tau_2) < 0$, $m_{\text{vis}}(\tau_1, \tau_2) > 100$ GeV, $S_{\text{T}} > 300$ GeV, at least one b-jet
High b-jet p_{T} SR	SR selection, leading b-jet $p_{\text{T}} > 200$ GeV
Low b-jet p_{T} SR	SR selection, leading b-jet $p_{\text{T}} < 200$ GeV

CR/VR

$\tau_{lep}\tau_{had}$ Control/Validation Regions	Selection	Purpose
Multijet-CR	ℓ (trigger, pass/fail offline isolation), $m_T(\ell, E_T^{miss}) < 30$ GeV, one b-jet, τ_{had}-ID score < 0.01, $E_T^{miss} < 50$ GeV	Measure lepton fake-factor
Top-CR	Satisfy SR except: $\Delta\phi(\ell, E_T^{miss}) > 2.5$, no S_T and lead. b-jet p_T req.	Derive top correction
SS-CR	Satisfy SR except: $q(\ell) \times q(\tau_{had\text{-}vis}) > 0$, no $\Delta\phi(\ell, E_T^{miss})$, and S_T req.	Measure jet $\to \tau$ background scale factor
High b-jet p_T VR	Satisfy high b-jet p_T SR except: $1.5 < \Delta\phi(\ell, E_T^{miss}) < 2.5$, 300 GeV $< S_T <$ 600 GeV	Background modelling validation
Low b-jet p_T VR	Satisfy low b-jet p_T SR except: $1.5 < \Delta\phi(\ell, E_T^{miss}) < 2.5$, 300 GeV $< S_T <$ 600 GeV	Background modelling validation
b-jet Z-CR	Satisfy SR except: 45 GeV $< m_{vis}(\ell, \tau_{had\text{-}vis}) < 80$ GeV, $p_T(\ell)/p_T(b\text{-jet}) > 0.8$, $\lvert\Delta\phi(\ell, \tau_{had\text{-}vis})\rvert > 2.4$, no S_T req.	Z+heavy-flavour jets normalisation factor

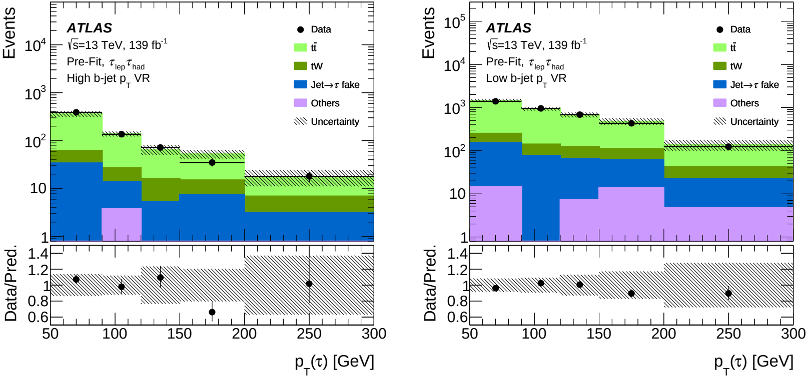
$\tau_{had}\tau_{had}$ Control/Validation Regions	Selection	Purpose
Dijet-CR	Satisfy SR except: τ_1 and τ_2 satisfy very loose τ_{had}-ID, τ_1 fail medium τ_{had}-ID	Measure $\tau_{had\text{-}vis}$ fake-factor
CR-1	Satisfy SR except: τ_2 fail loose τ_{had}-ID	Apply $\tau_{had\text{-}vis}$ fake-factor
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, $\Delta\phi(\tau_1, \tau_2) > 0.25$, $m_{vis}(\tau_1, \tau_2) < 100$ GeV, $E_T^{miss} > 60$ GeV	Z+light jets modelling

Background modelling validation in $\tau_{lep}\tau_{had}$



- VR: $1.5 < \Delta\phi(l, E_T^{miss}) < 2.5$
- Top correction applied, pre-fit plots
- Modeling looks good within pre-fit uncertainties, no additional uncertainty assigned.

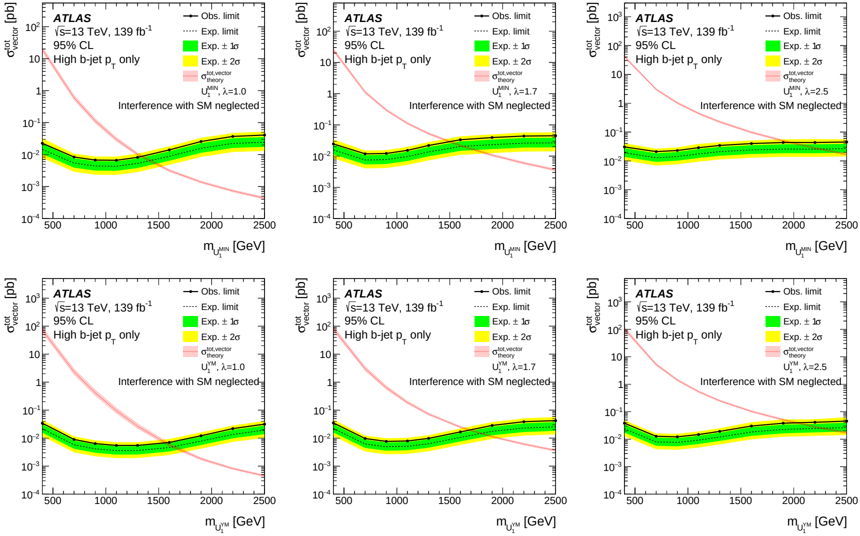
Background modelling validation in $\tau_{lep}\tau_{had}$



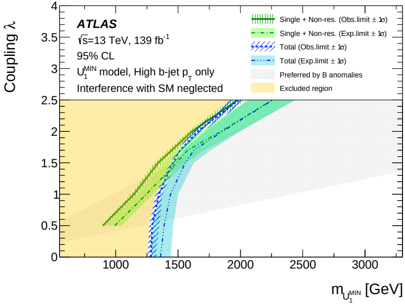
Background post-fit yields (high b-jet p_T)

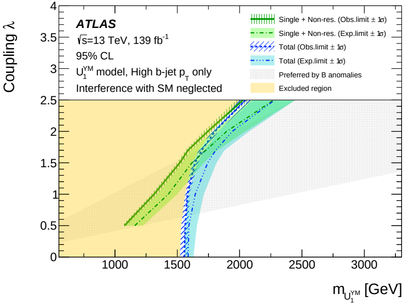
Process	$\tau_{lep}\tau_{had}$	$\tau_{had}\tau_{had}$
$t\bar{t}$	764 ± 82	9.9 ± 2.6
Single top	65 ± 35	3.9 ± 1.0
Jet$\rightarrow \tau$ *fake*	215 ± 79	3.9 ± 1.0
Two jet$\rightarrow \tau$ *fake*	—	1.34 ± 0.27
$Z(\rightarrow \tau\tau)$+HF jets	5.5 ± 0.4	4.6 ± 1.1
Others	9.7 ± 1.0	1.75 ± 0.30
Total	1059 ± 51	25.4 ± 4.9
Data	1053	29

Upper limits for single+pair U_1 LQs

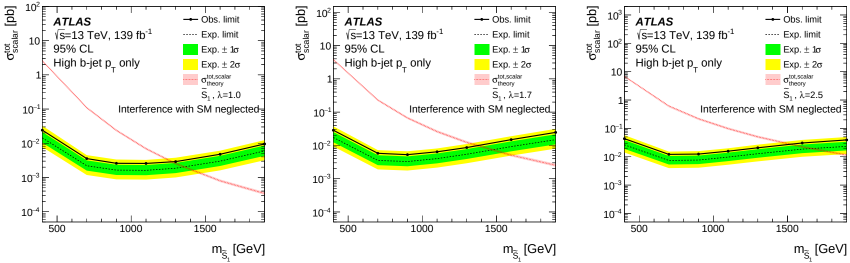


2D exclusion limits in mass-λ plane

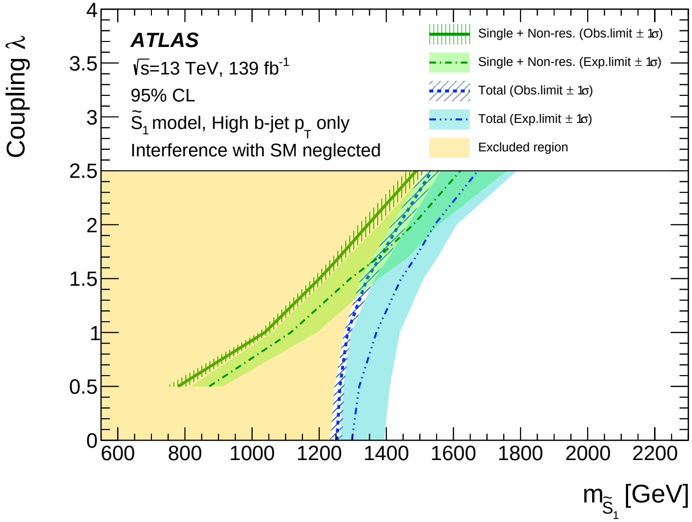




Upper limits for single+pair $\widetilde{S}_1$ LQs



2D exclusion limits in mass-λ plane



2D exclusion limits table

Model	$\lambda = 1.0$	$\lambda = 1.7$	$\lambda = 2.5$
Single+non-resonant U_1^{YM} production	1.31 (1.43)	1.59 (1.73)	2.03 (2.27)
Single+non-resonant U_1^{MIN} production	1.15 (1.24)	1.45 (1.58)	1.98 (2.26)
Single+non-resonant+pair U_1^{YM} production	1.58 (1.64)	1.70 (1.81)	2.05 (2.28)
Single+non-resonant+pair U_1^{MIN} production	1.35 (1.44)	1.52 (1.63)	1.99 (2.26)
Single+non-resonant $\widetilde{S}_1$ production	1.04 (1.11)	1.26 (1.38)	1.49 (1.62)
Single+non-resonant+pair $\widetilde{S}_1$ production	1.28 (1.37)	1.38 (1.49)	1.53 (1.67)