Recent lepton flavour results from ATLAS

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Lepton-flavour violation at ATLAS

What can ATLAS search for and why?

The Standard Model as we know it does not require lepton-flavour to be a conserved quantity or for lepton-flavour universality to be respected → an ***accidental symmetry***

Neutrino oscillations are proof of LFV in neutral leptons but LFV in charged leptons (cLFV) has not been observed

- In the SM cLFV is GIM suppressed by $G_F^2 m_\nu^2 \sim 10^{-50}$

Observation of cLFV would be evidence for BSM physics and there are a range of BSM models that ATLAS can directly probe:

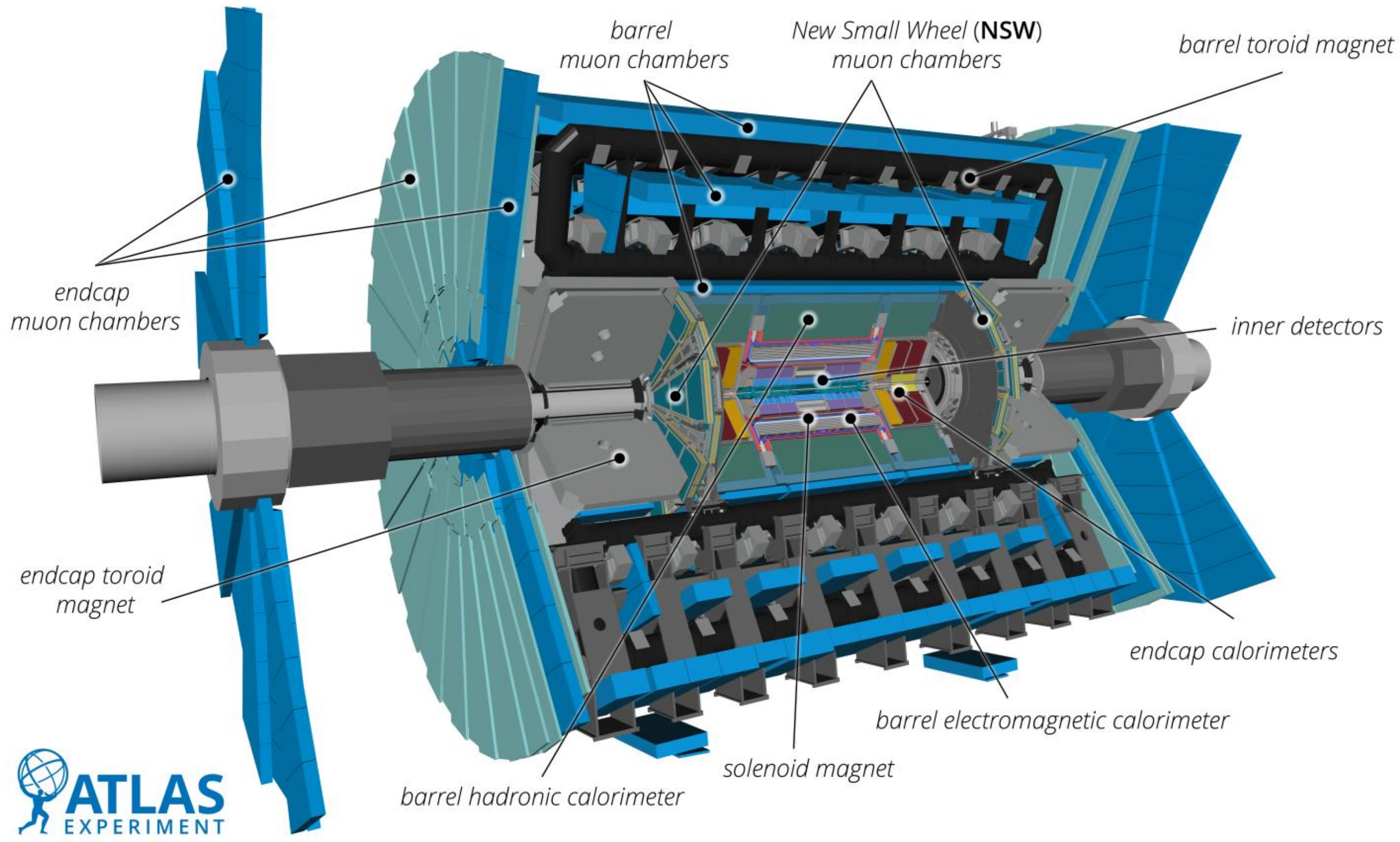
- Leptoquarks
- Heavy neutral leptons
- Effective field theories
- SUSY, Z' boson, Quantum black holes

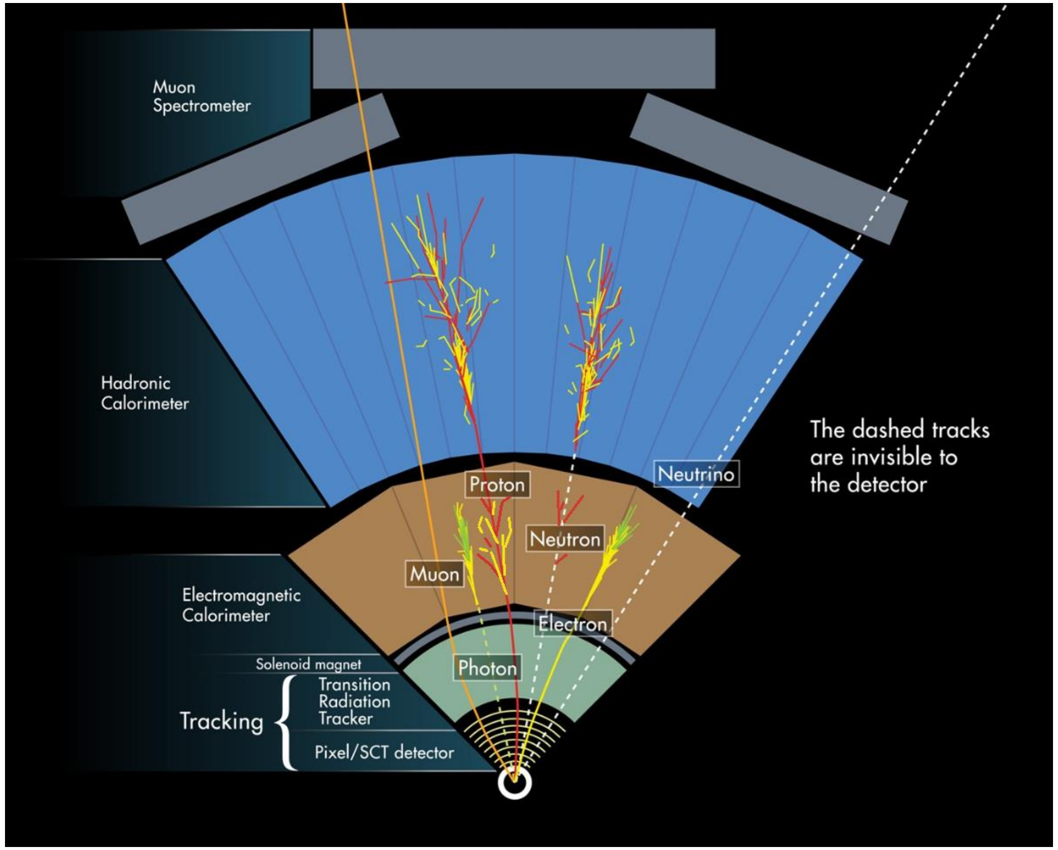
Can test lepton-flavour universality through precision measurements of branching ratios

[1] Introduction to Charged Lepton Flavour Violation, *Universe* 8 (2022)

The ATLAS detector

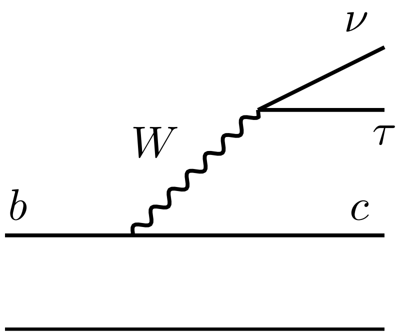
ATLAS sits 100m underground, is 44 m long and 25 m tall and weighs 7000 tonnes

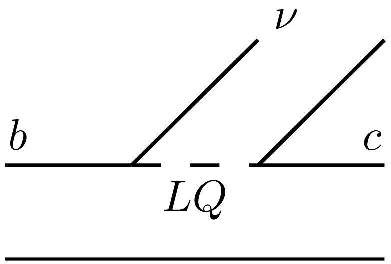




Leptoquark searches

Introduction to leptoquarks





They carry both **baryon** and **lepton** number and have **colour** charge and fractional **electric** charge

Come in up/down and scalar/vector types

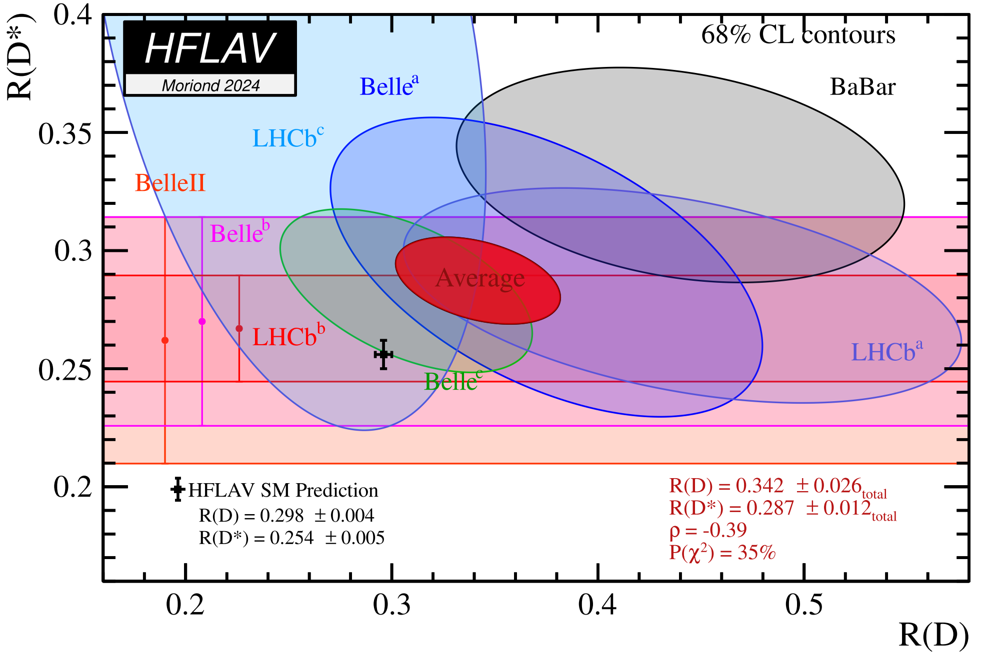
Focus on coupling to **3rd** generation of quarks and leptons

Motivated as an explanation of ***b*-meson anomalies**

- 3.3 σ deviation in R_D/R_{D^*}

Leptoquarks are a potential explanation for $\boldsymbol{g-2}$ **anomaly**

Many leptoquark models, requires a range of analysis and final states for comprehensive picture



Global limits by [heavy flavour averaging group]

$$R_D = \frac{\mathrm{Br}(B \rightarrow D\tau\bar{\upsilon}_\tau)}{\mathrm{Br}(B \rightarrow D\ell\bar{\upsilon}_\ell)}$$

Leptoquark searches

Single production: $b\tau\tau$

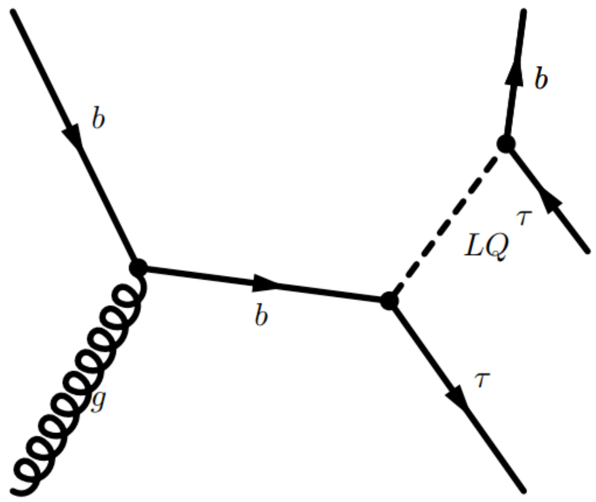
Select events containing a b-jet and $\tau_{\text{lep}}\tau_{\text{had}}$ or $\tau_{\text{had}}\tau_{had}$ pair

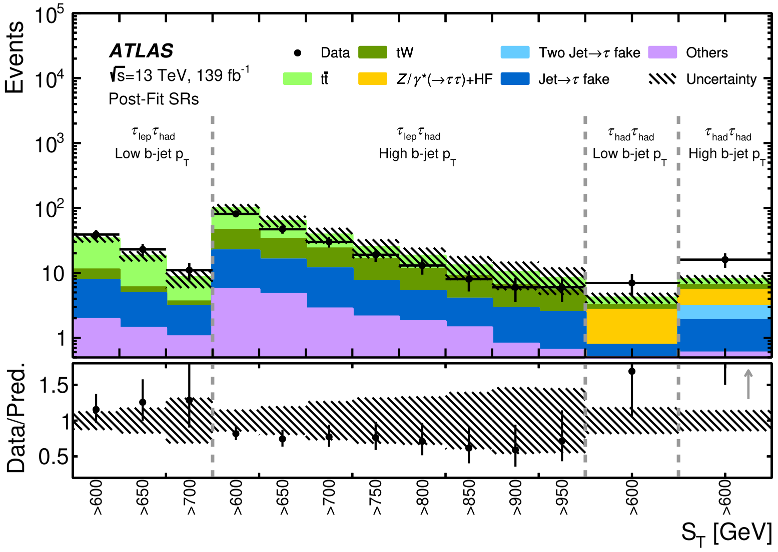
Non-resonant leptoquark interference with SM at low b-jet p_T

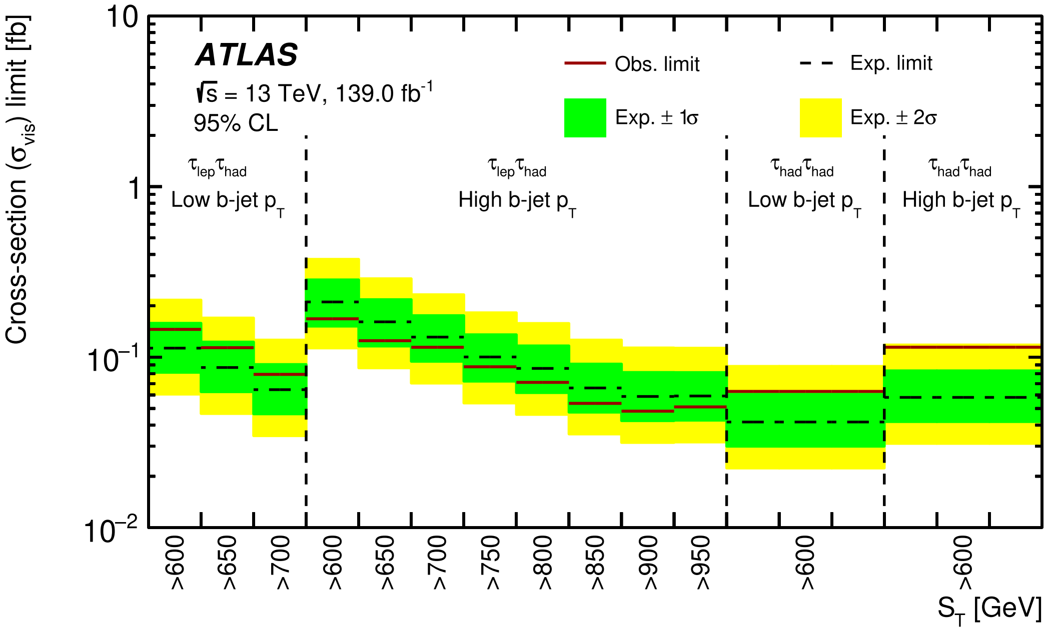
Unclear how to model and very model dependent

→ Perform search for leptoquarks in high b-jet p_T SR

→ Perform model-independent search in both high/low b-jet p_T SRs

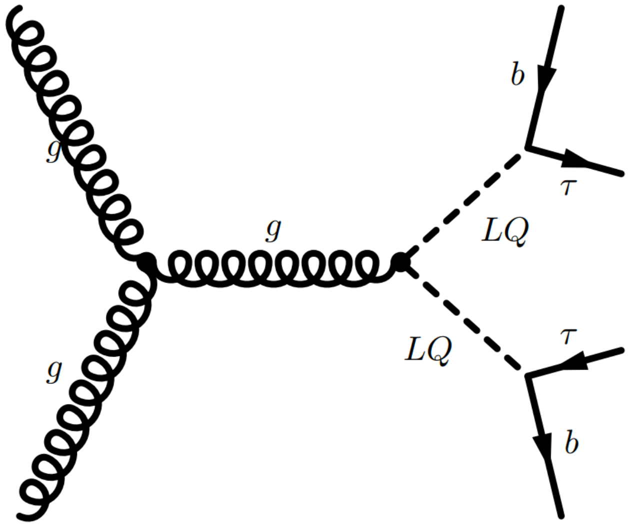






Leptoquark searches

Double production: $b\tau b\tau$



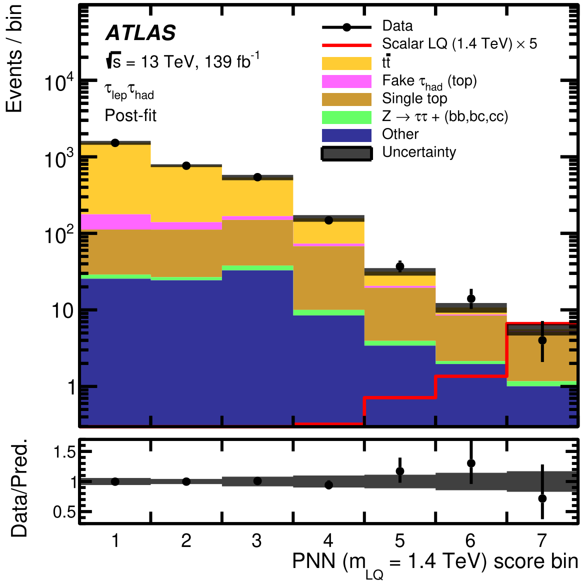
Select events containing **two b-jets** and $\boldsymbol{\tau_{lep}\tau_{had}}$ or $\boldsymbol{\tau_{had}\tau_{had}}$ pair

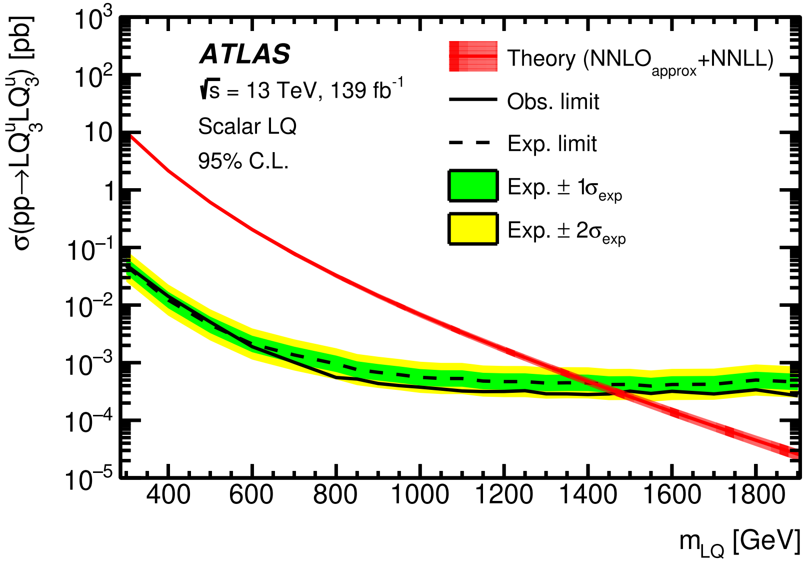
Train **parameterised neural network** (PNN) to separate LQ signal from backgrounds (mainly $t\bar{t}$ & single top)

Improvement on earlier analysis:

- More data ($36.1\ \mathrm{fb}^{-1} \rightarrow 139\ \mathrm{fb}^{-1}$)
- Improved tau ID and b-tagging
- PNN rather than BDT

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





Leptoquark searches

Double production: $t\ell t\ell$

Search targeting down-type scalar leptoquarks with 3rd generation couplings to quarks and 1st & 2nd generation couplings to leptons

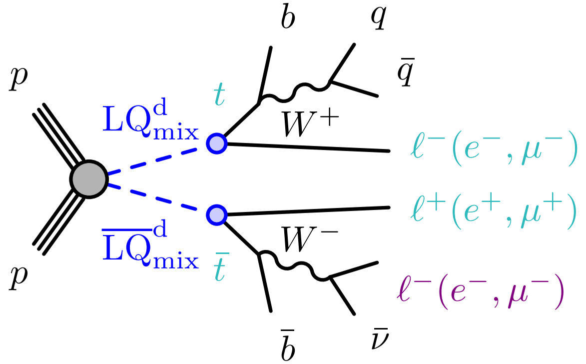
First time interpretation in context of iso-singlet LQ with charge +5/3e

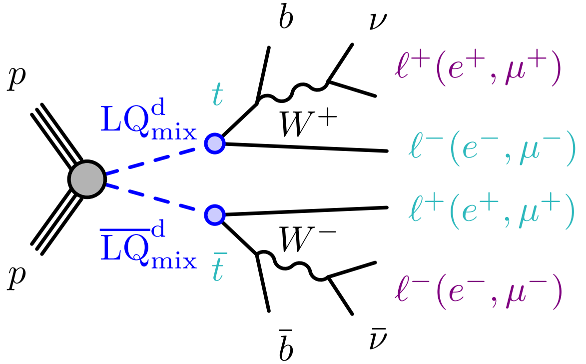
Signature is **at least three leptons** (e, μ) plus **at least one *b*-jets**.

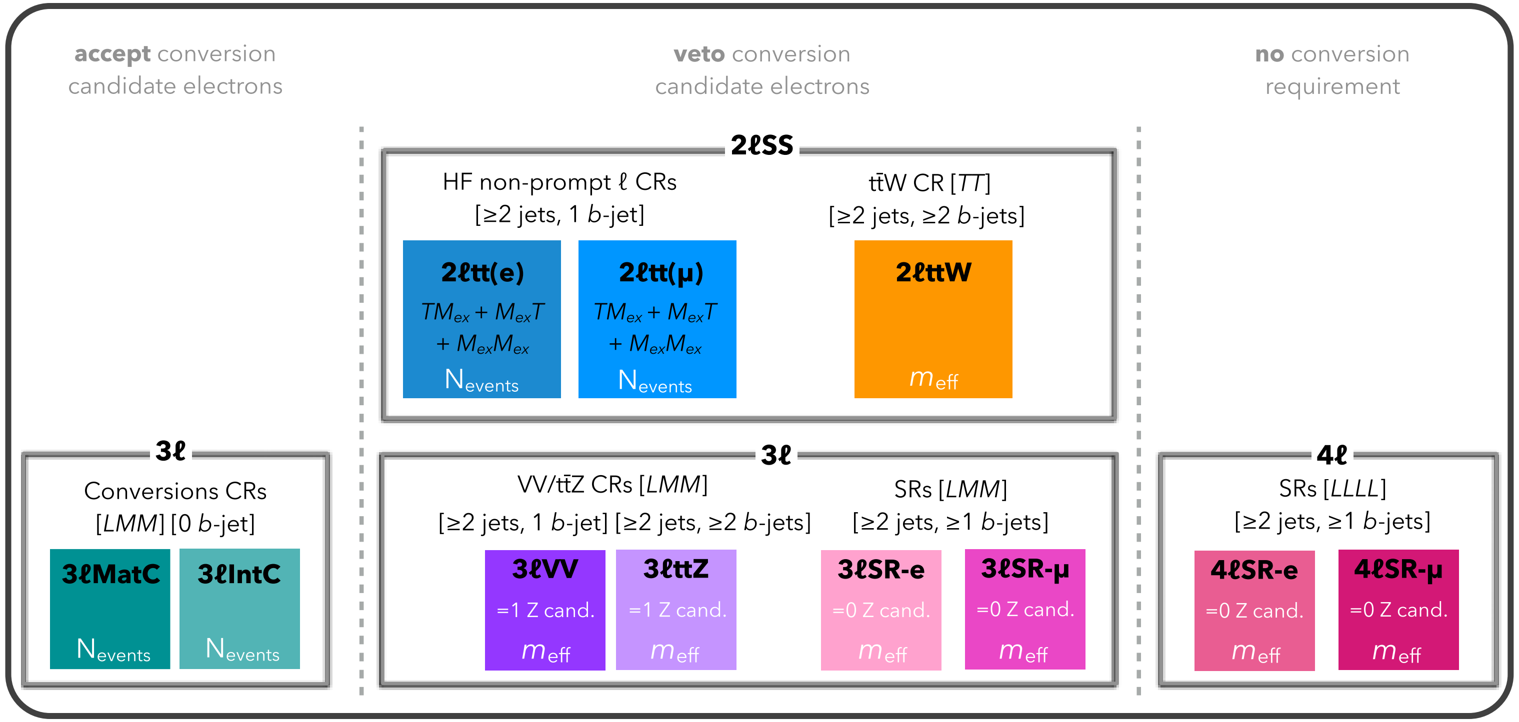
Main backgrounds:

- $t\bar{t}W$
- $t\bar{t}Z/\gamma^*$
- **Diboson** (WZ)
- **conversion electrons** (Internal/material)

Normalisations determined by final fit







Leptoquark searches

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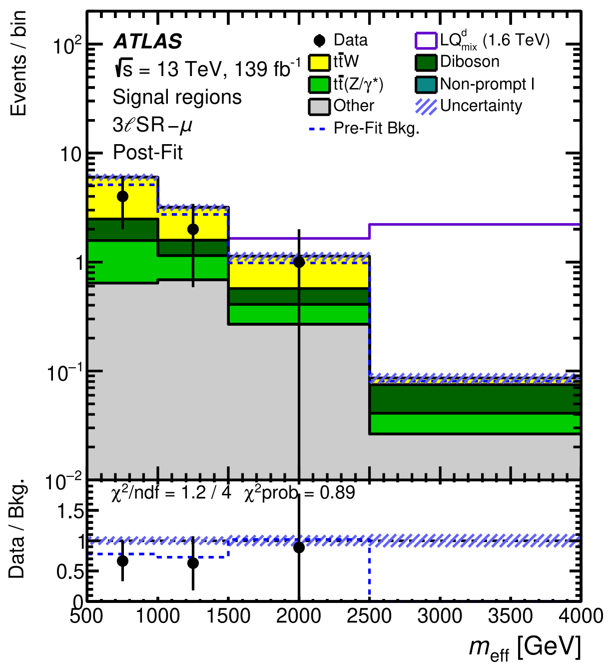
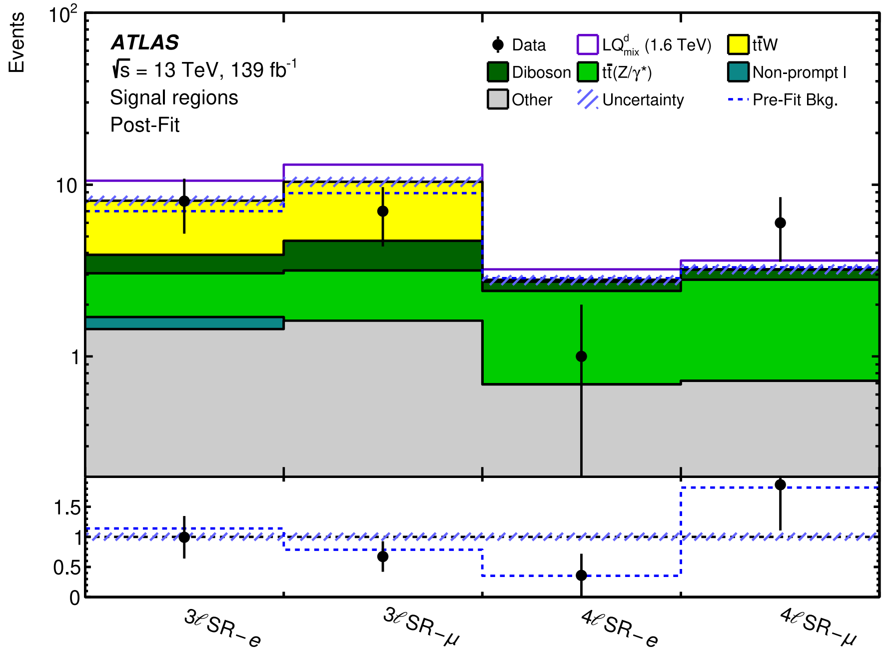
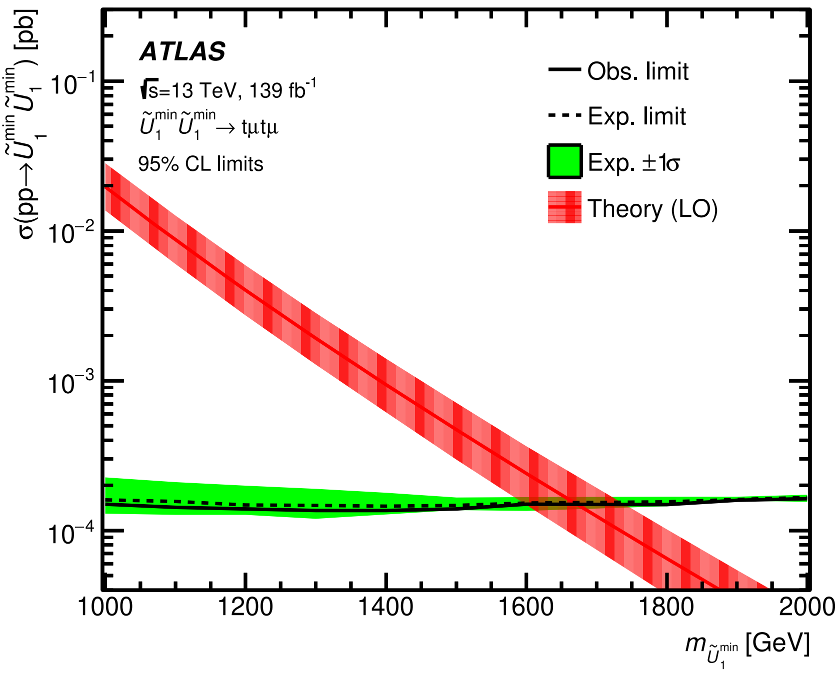






Binned fit in *effective mass*

$$\boldsymbol{m_{\text{eff}} = p_T^{\text{light leptons}} + p_T^{\text{jets}} + p_T^{\text{miss}}}$$

Charged-lepton-flavour violation in top decays

Leptoquark search and EFT interpretation in $\mu\tau q t$ interactions

Search for events with **two same-sign muons**, a **hadronic tau**, at least **one jet** and exactly **one *b*-jet**.

Limits set on six LFV EFT operator Wilson Coefficients and on scalar leptoquark

Main backgrounds:

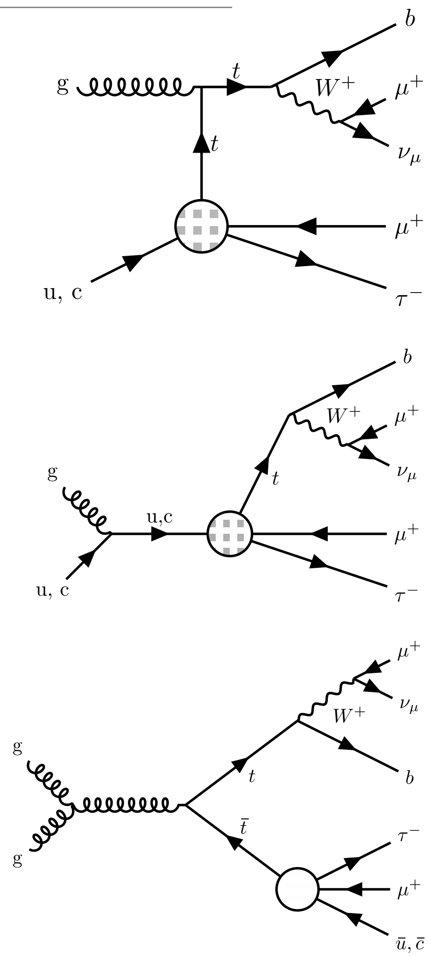
- $t\bar{t}$
- $t\bar{t}V$
- **Diboson** (WW, WZ)
- **non-prompt muons**
- **Mis-ID taus**

Enriched in signal

Used in data-driven estimate of jets misidentified as taus

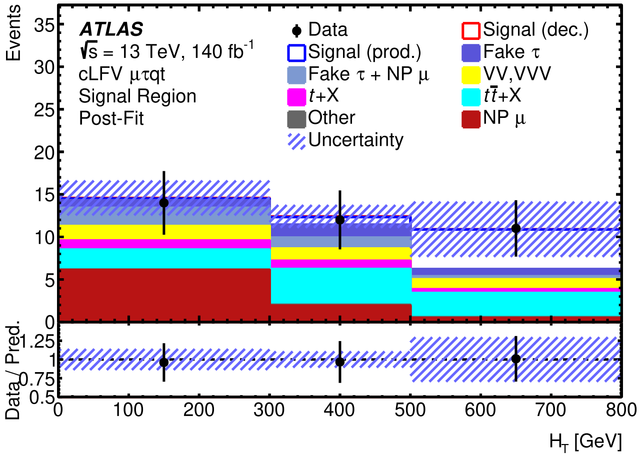
Included in fit to determine normalisation of non-prompt muons

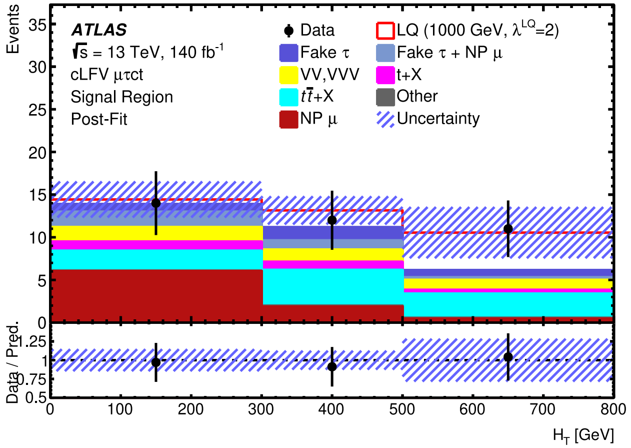
	SR	CRτ	CR$t\bar{t}\mu$
Lepton flavour	$2\mu 1\tau_{\text{had}}$		$2\mu 1e$ $(\ell_3 = \mu)$
N_{jets}	≥ 1	≥ 2	≥ 1
$N_{b\text{-tags}}$	1	1	≤ 2
τ_{had} p_{T}	> 20 GeV	> 20 GeV	–
Muon p_{T}	> 15 GeV	> 15 GeV	> 10 GeV
Higher p_{T} muon	Tight	Tight	Tight
Lower p_{T} muon	Tight	Tight	Loose
Muon charges	SS	OS	–
$m_{\mu\mu}^{\text{OS}}$	–	–	>15 GeV
$\lvert m_{\mu\mu}^{\text{OS}} - M_Z \rvert$	–	<10 GeV	>10 GeV
$3p_{\text{T}}^{\mu_1} + \sum m_{\ell\ell}^{\text{OS}}$	–	–	< 400 GeV

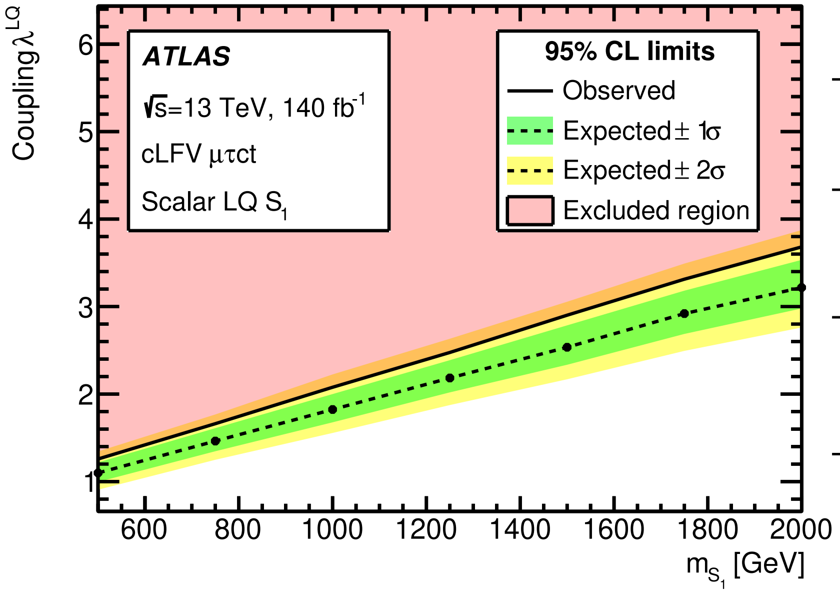


Charged-lepton-flavour violation in top decays

Leptoquark search and EFT interpretation in $\mu\tau qt$ interactions







SM prediction consistent within 1.6σ

	95% CL upper limits on $\|c\|/\Lambda^2$ [TeV^{-2}]					
	$c_{\mathrm{lq}}^{-(ijk3)}$	$c_{\mathrm{eq}}^{(ijk3)}$	$c_{\mathrm{lu}}^{(ijk3)}$	$c_{\mathrm{eu}}^{(ijk3)}$	$c_{\mathrm{lequ}}^{1(ijk3)}$	$c_{\mathrm{lequ}}^{3(ijk3)}$
Previous (u)*	12	12	12	12	18	2.4
Expected (u)	0.33	0.31	0.3	0.32	0.33	0.08
Observed (u)	0.43	0.41	0.4	0.42	0.44	0.10
Previous (u)*	14	14	14	14	21	2.6
Expected (c)	1.3	1.2	1.2	1.2	1.4	0.28
Observed (c)	1.6	1.6	1.6	1.6	1.8	0.36

Factor 7.2 – 41 improvement on previous limits!

*Previous limits: JHEP 04 (2019) 014

Phys. Rev. D 110 (2024) 012014

Leptoquark searches

Statistical Combination

Many of the ATLAS leptoquark searches are complementary, allowing for a statistical combination to produce more powerful overall limits

Separate combination for each leptoquark model

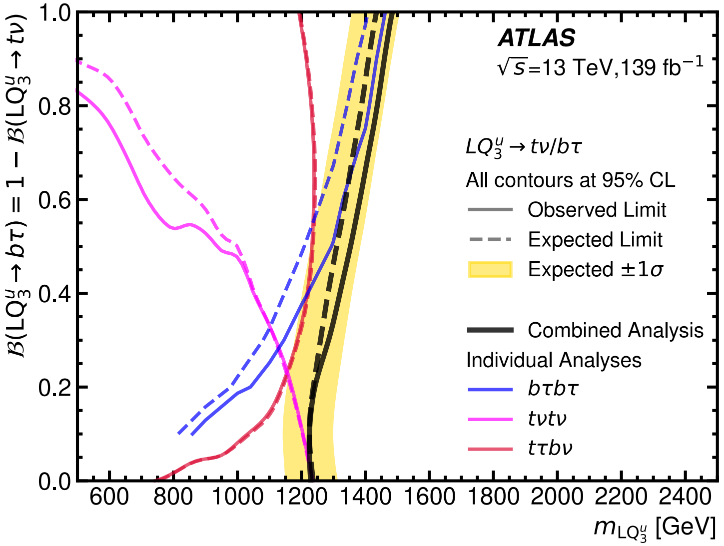
Search		Interpretation: Scalar				Vector		Signal Region		
Final State	Citation	LQ_3^u	LQ_3^d	$\mathrm{LQ}_{\mathrm{mix}}^u$	$\mathrm{LQ}_{\mathrm{mix}}^d$	$U_1^{\mathrm{YM/MC}}$	$\tilde{U}_1^{\mathrm{YM/MC}}$	N_ℓ	$N_{\tau_{\mathrm{had}}}$	$N_{b-\mathrm{jets}}$
$t\nu b\tau$	Phys.Rev.D 104 (2021) 11, 112005	✓	✓	–	–	✓	–	0	1	≥ 2
$b\tau b\tau$	Eur.Phys.J.C 83 (2023) 11, 1075	✓	–	–	–	✓	–	{0,1}	{1,2}	{1,2}
$\tau\tau t\tau$	JHEP 06 (2021) 179	-	✓	–	–	–	✓	{1,2,3}	≥ 1	≥ 1
$t\nu b\ell$	JHEP 2306 (2023) 188	-	–	✓	✓	–	–	1	–	≥ 1
$b\ell b\ell$	JHEP 10 (2020) 112	-	–	✓	–	–	–	2	–	{0,1,2}
$t\ell t\ell$ (2ℓ)	Eur.Phys.J.C 81 (2021) 4, 313	-	–	–	✓	–	–	2	–	–
$t\ell t\ell$ ($\geq 3\ell$)	Eur.Phys.J.C 84 (2024) 8, 818	-	–	–	✓	–	–	{3,4}	–	≥ 2
$t\nu t\nu$	Eur.Phys.J.C 80 (2020) 8, 737	✓	–	✓	–	✓	–	0	0	≥ 2
$b\nu b\nu$	JHEP 05 (2021) 093	–	✓	–	✓	–	–	0	–	≥ 2

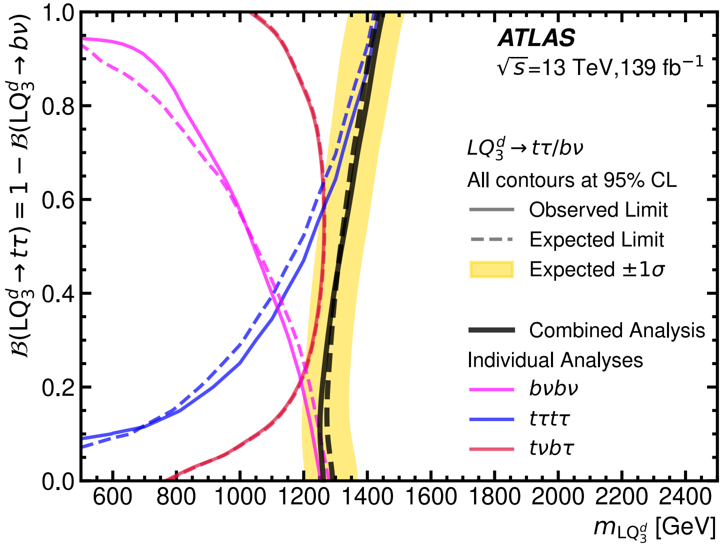
SRs and CRs treated as being statistically independent. Systematics correlated where possible

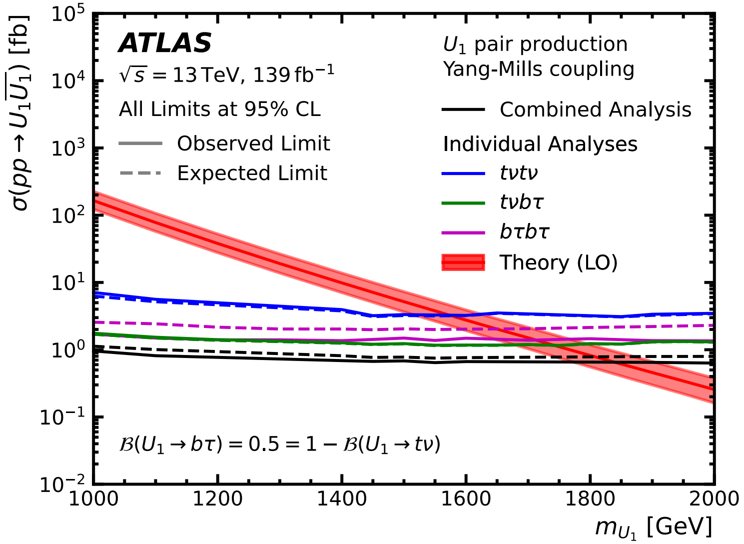
Phys. Lett. B 854 (2024) 138736

Leptoquark searches

Statistical Combination







Up to 100 GeV improvement in limits

Heavy neutral leptons

Search for TeV-scale heavy Majorana neutrinos

High-energy equivalent of ***neutrinoless double beta decay***

- Search for heavy neutrinos in type-I seesaw & Weinberg operator EFT

Two same-sign lepton plus two jet final state:

- VBS jet topology → **high m_{jj} & Δy_{jj}**
- High p_T back-to-back leptons

Dimuon channel published in 2023 (Eur. Phys. J. C 83 (2023) 824)

→ ***new for this year***, searches in ee & $e\mu$ channels

Main backgrounds:

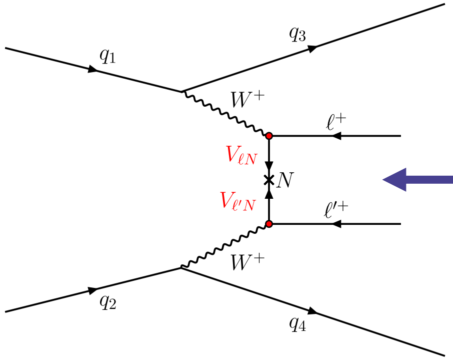
- Same-sign $W^{\pm}W^{\pm}jj$
- $W^{\pm}Zjj$

} Control regions defined

- Non-prompt/fake leptons
- Charge-flipped electrons

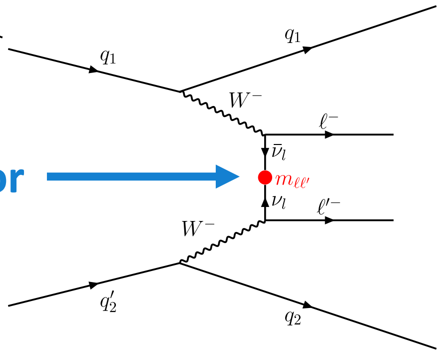
} Data-driven estimates

Binned fit in sub-leading lepton p_T in SR & CRs



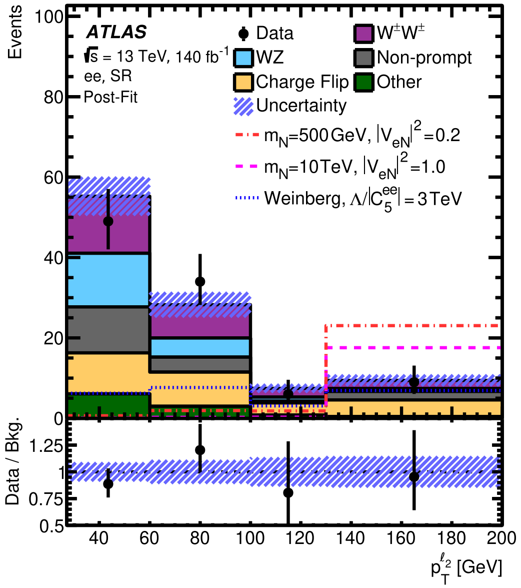
Type-I Seesaw

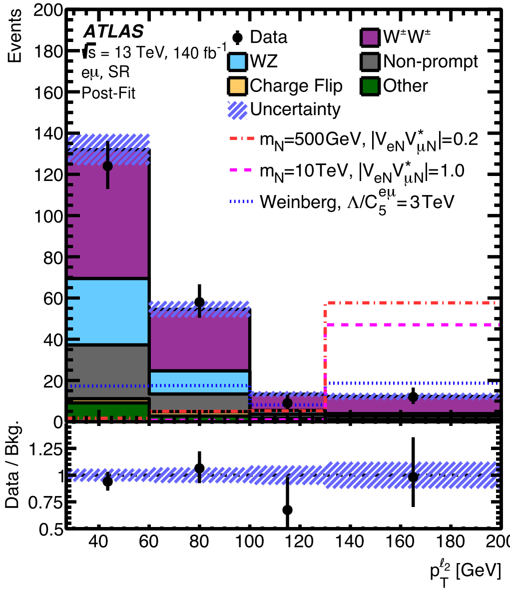
Two params: $|V_{\ell N}V^*_{\ell' N}|$, m_N



Weinberg Operator

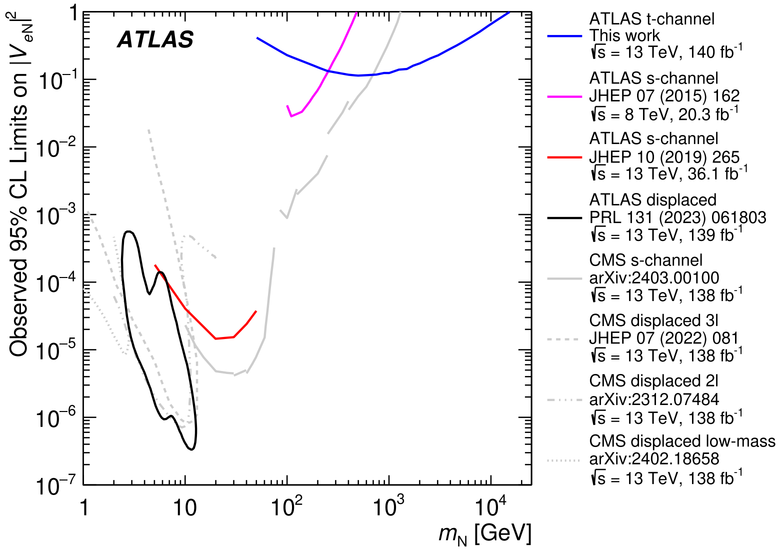
One param: $\Lambda/C_5^{\ell\ell'}$

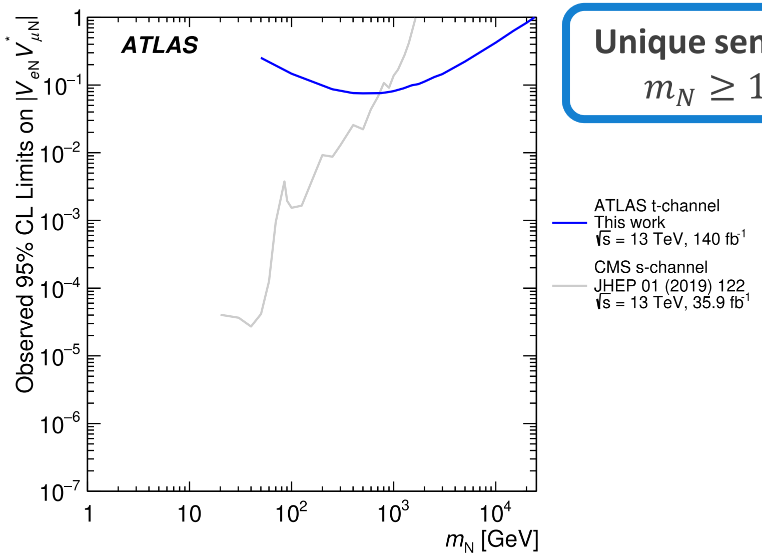




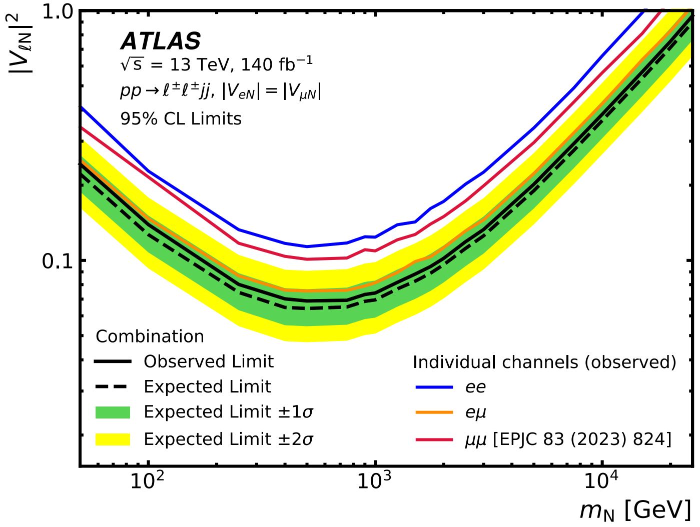
Heavy neutral leptons

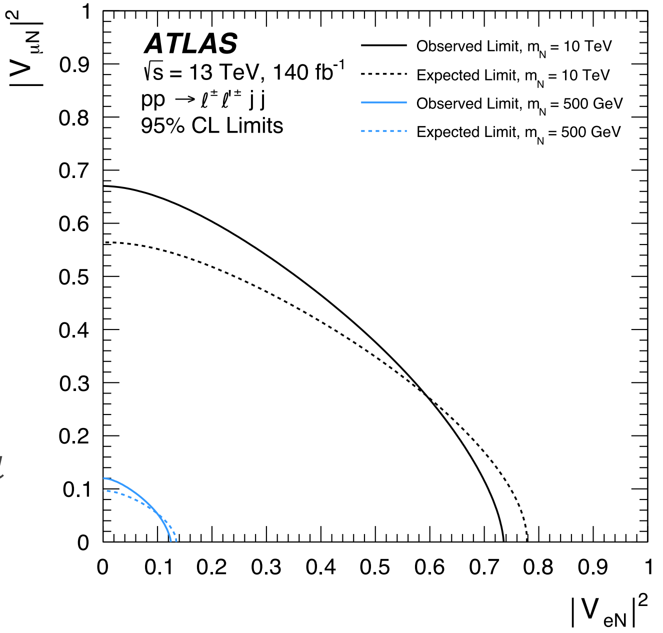
Search for TeV-scale heavy Majorana neutrinos





Unique sensitivity
$m_N \geq 1$TeV





Weinberg Operator 95% CL limits:
$\Lambda/C_5^{ee} > 2.47\ (2.47)$ TeV observed (expected)
$\Lambda/C_5^{e\mu} > 4.85\ (4.07)$ TeV observed (expected)

New combination of $\mu\mu, ee$ and $e\mu$ channels
Assuming $|V_{eN}| = |V_{\mu N}|$

High mass LFV dilepton resonances

Search for lepton $pp \rightarrow X \rightarrow \ell^{\pm}\ell'^{\mp}$

Search targeting **high-mass**, **back-to-back** $e\mu$, $e\tau$, $\mu\tau$ pairs

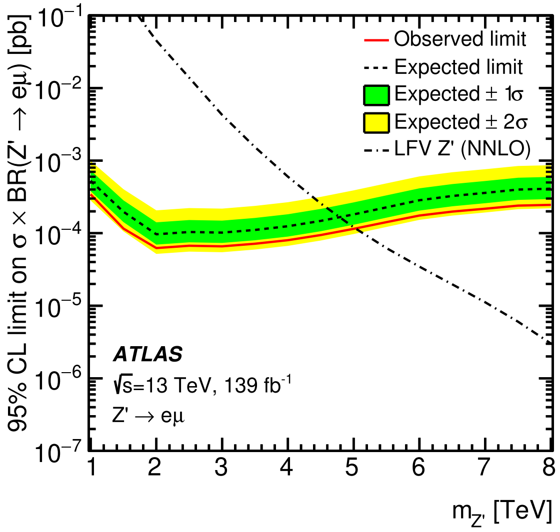
Broad range of interpretations:

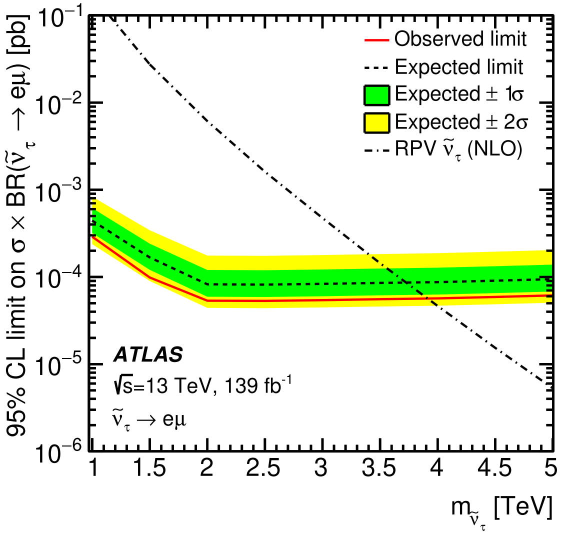
- $\boldsymbol{Z'}$ **boson**
- $\boldsymbol{\tau}$**-sneutrinos** in *R*-parity violating SUSY
- **Quantum black holes** (ADD & RS models)

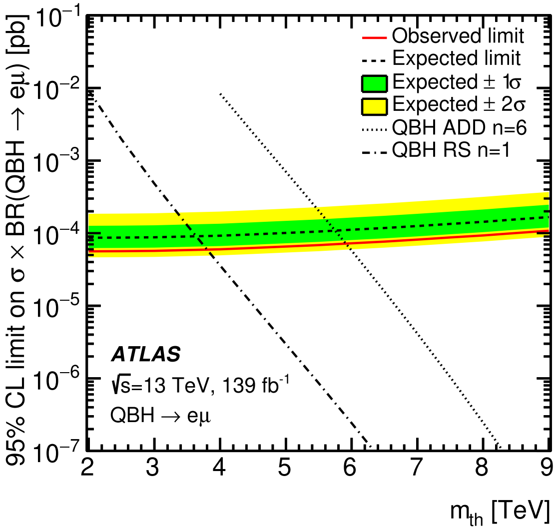
Improvements on earlier analysis (Phys.Rev.D 98 (2018) 9, 092008)

- 4x luminosity
- Improved object reconstruction
- Improved background estimation
- Simultaneous fit to SRs and CRs

Improvement of 0.6, 0.3 and 0.4 TeV in $e\mu, e\tau$ and $\mu\tau$ on previous Z' limits







Measurement of W-boson branching ratios

Precision test of lepton flavour universality in $W \to e\nu$ and $W \to \mu\nu$ deacys

Measurement of W-boson branching ratios through analysis of $\boldsymbol{t\bar{t}}$ **leptonic decays** ($ee, \mu\mu, e\mu$ plus one or two b-jets)

$$\boxed{R_W^{\mu/e} = \frac{\mathrm{Br}(W \to \mu\nu)}{\mathrm{Br}(W \to e\nu)}}$$

Systematic uncertainties in $t\bar{t}$ and background modelling cancel, but still limited by ID uncertainties on electrons & muons

Instead measure:

$$\boxed{R_{WZ}^{\mu/e} = \frac{R_W^{\mu/e}}{\sqrt{R_Z^{\mu\mu/ee}}}}$$

Then convert $R_{WZ}^{\mu/e}$ back to $R_W^{\mu/e}$ using precision measurement of $R_Z^{\mu\mu/ee}$ made by LEP

Ingredients for fit

- Number of $t\bar{t}$ events in $ee, \mu\mu$ and $e\mu$ channels
  - Separate counts for events with one b-jet and events with two b-jets
- Number of events in $Z \to ee$ and $Z \to \mu\mu$

$\rightarrow$ Fit to eight regions

The parameterisation used is somewhat complicated, see backup for detailed description

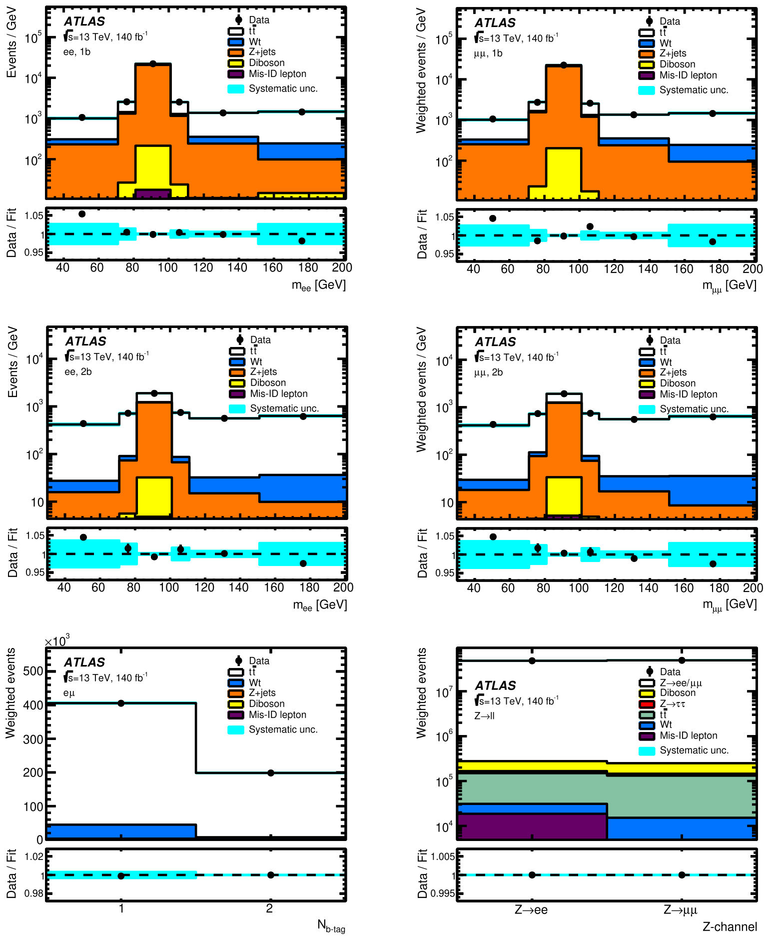
arXiv:2403.02133

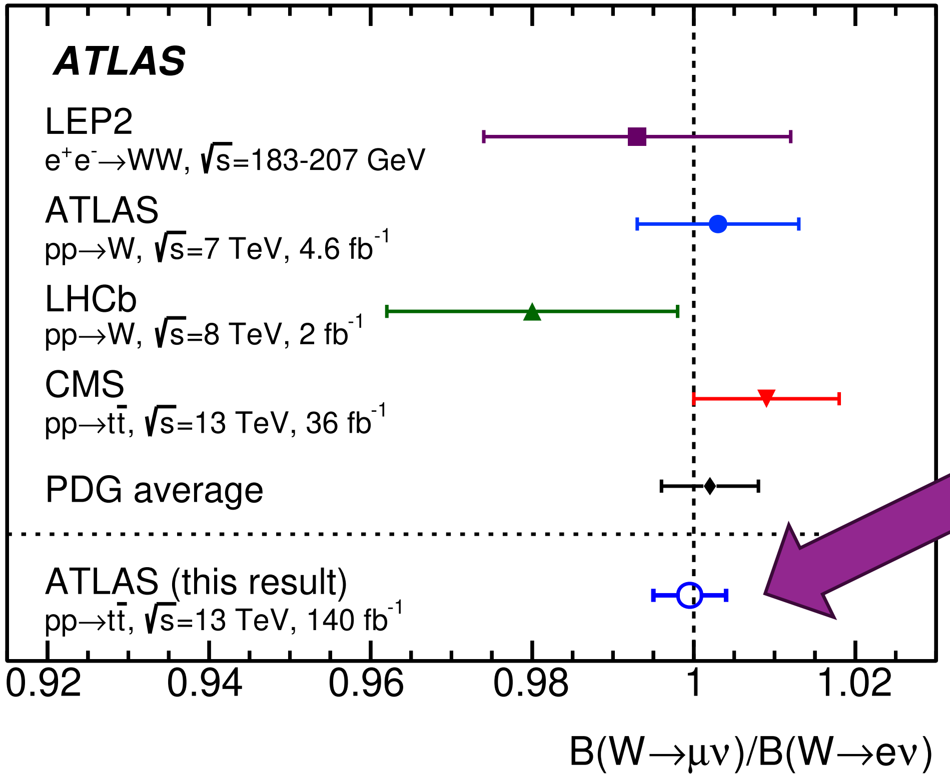
Measurement of W-boson branching ratios

Precision test of lepton flavour universality in $W \rightarrow e\nu$ and $W \rightarrow \mu\nu$ deacys

1 *b*-jet →

2 *b*-jet →





$$\mathrm{R}_{\mathrm{W}}^{\mu/e} = \mathbf{0.9995 \pm 0.0022\ (stat) \pm 0.0036\ (syst) \pm 0.0014\ (ext)}$$

arXiv:2403.02133

Summary

Comprehensive leptoquark program targeting a range of benchmark models and value is maximised through statistical combinations

Ability to probe a broad variety of searches exotic physics models with LFV signatures, from heavy neutrinos to quantum black holes

Delivered precision measurements of the W boson branching ratios to set world leading constraints on lepton flavour universality

Further reading:

- Review of ATLAS exotics searches: arXiv:2403.09292
- List of ATLAS publications: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/Publications

Backup

Leptoquarks and their properties

Can be either be **Scalar** (spin-0) or **Vector** (spin-1)

Vector leptoquarks can have an additional **Yang-Mills** (YM) coupling to gluons, those that don't are referred to as having **Minimal Coupling** (MC)

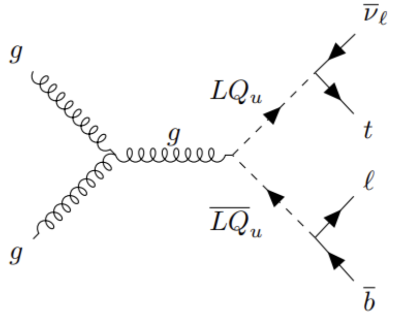
Scalar leptoquarks which have charge 2/3e are called LQ^{u} and those with charge 1/3 are labelled LQ^{d}

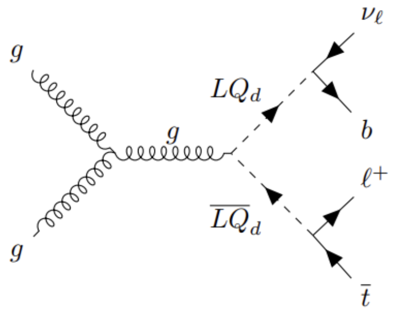
Scalar leptoquarks which exclusively couple to the third generation are called $LQ_{3}^{u,d}$. Those which can also couple to 2nd and 1st generations are called $LQ_{\mathrm{mix}}^{u,d}$

See review of LQs in arXiv:1603.04993

Leptoquark searches

Double production: $\ell\nu bt$





Search focusing pair-production where **one LQ decays to a neutrino**

- Up-type scalar and vector leptoquarks
- Down-type scalar leptoquarks

Signature is single **high-p_T lepton**, **high E_T^{miss}** & at least **one b-jet**

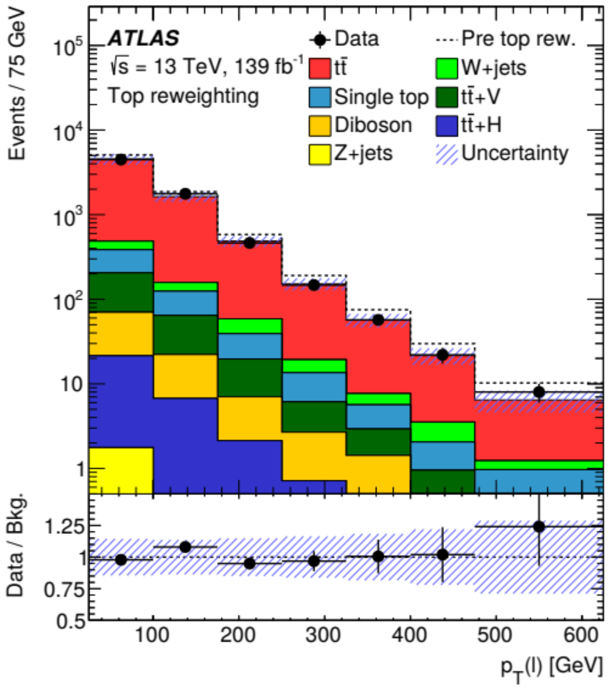
Signal-background separation done by **neural network** using NeuroBayes

→ Applies Bayesian regularisation to input features to improve generalisation and reduce overtraining

Main backgrounds:

- $t\bar{t}$ } Corrections applied from dedicated reweighting region
- **Single top**
- **W+jets**

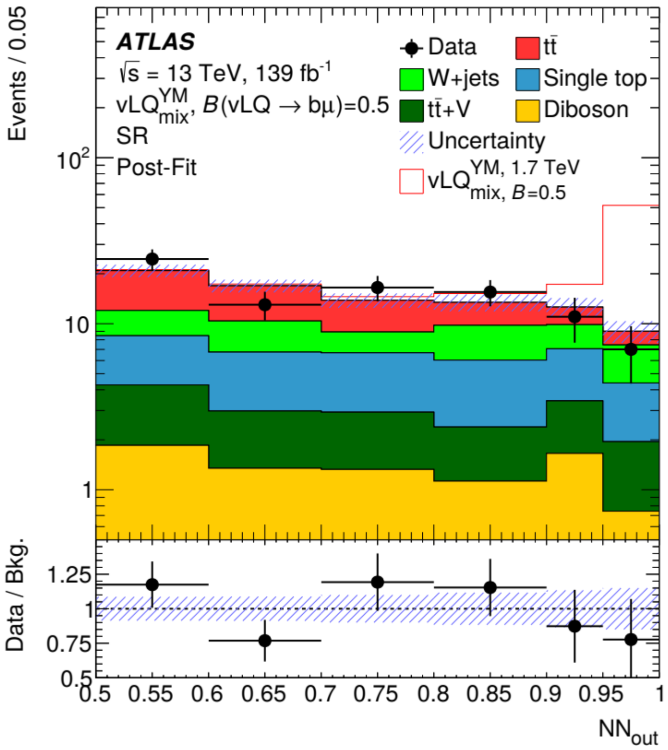
} Dedicated control regions

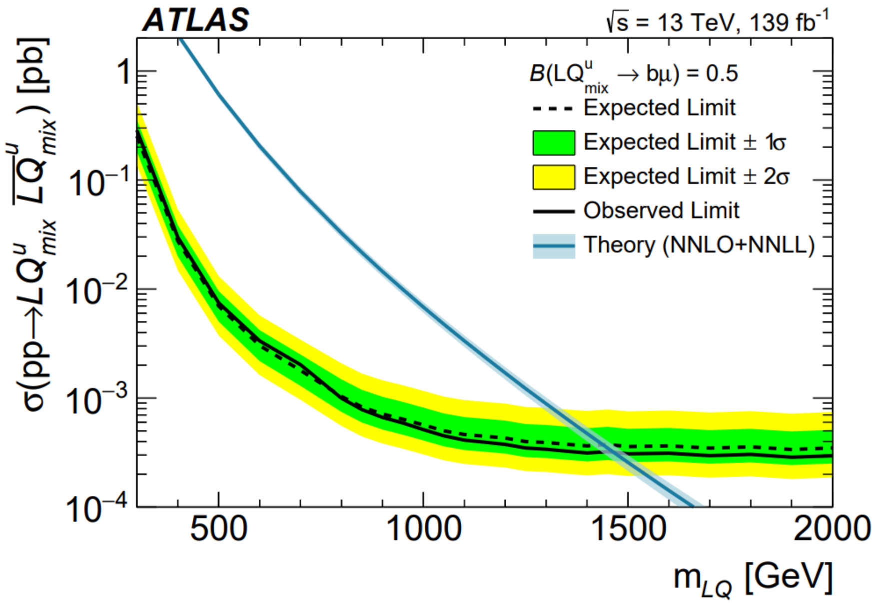


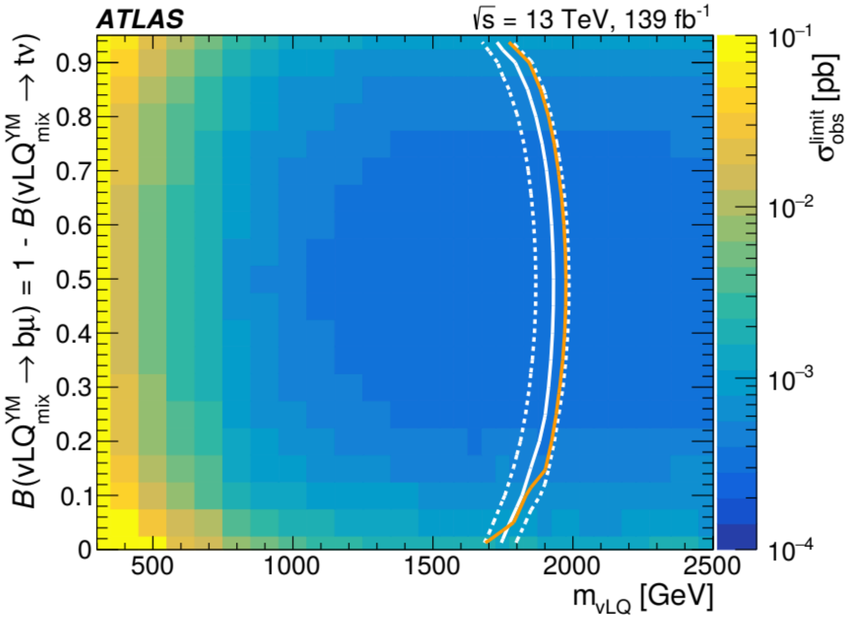
Normalisations of $t\bar{t}$, single top and W+jets obtained from fit

Leptoquark searches

Double production:$\ell\nu bt$







Leptoquark searches

Double production: $t\ell t\ell$ - Summary of cuts

	3ℓ						
	CR				VR	SR	
	3ℓVV	3ℓttZ	3ℓIntC	3ℓMatC	3ℓVR	3ℓSR-e	3ℓSR-μ
e/μ selection	M (SS pair), L other						
e/μ combination	$3e$ / $2e1\mu$ / $2\mu1e$ / 3μ					$3e$ / $2e1\mu$	3μ / $2\mu1e$
Total charge	±1		—		±1		
e internal conversion veto	Yes		Inverted (ℓ_1 or ℓ_2)	Yes (ℓ_1 and ℓ_2)	Yes		
e material conversion veto	Yes		Yes (ℓ_1 and ℓ_2)	Inverted (ℓ_1 or ℓ_2)	Yes		
Number of jets	≥ 2		≥ 0		≥ 2		
Number of b-jets	1	≥ 2	0		≥ 1		
p_T^ℓ [GeV]	> 20 (SS pair), > 10 other				> 20		
$m_{\ell^+\ell^-}^{OS-SF}$ [GeV]	> 12						
$\lvert m_{\ell^+\ell^-}^{OS-SF} - m_Z\rvert$ [GeV]	< 10		> 10		> 10		
$\lvert m_{\ell\ell\ell} - m_Z\rvert$ [GeV]	—		< 10		—		
$m_{\ell\ell}^{\min}$ [GeV]	—				< 200	≥ 200	
m_{eff} [GeV]	—				—	≥ 500	

	4ℓ		
	VR	SR	
	4ℓVR	4ℓSR-e	4ℓSR-μ
e/μ selection	L		
e/μ combination	$4e$ / $3e1\mu$ / $2e2\mu$ / $3\mu1e$ / 4μ	$4e$ / $3e1\mu$ / $2e2\mu$ (lead e)	4μ / $3\mu1e$ / $2\mu2e$ (lead μ)
Total charge	0		
Number of jets	≥ 2		
Number of b-jets	≥ 1		
p_T^ℓ [GeV]	> 10		
$m_{\ell^+\ell^-}^{OS-SF}$ [GeV]	> 12		
$\lvert m_{\ell^+\ell^-}^{OS-SF} - m_Z\rvert$ [GeV]	> 10		
$m_{\ell\ell}^{\min}$ [GeV]	< 100	≥ 100	
m_{eff} [GeV]	—	≥ 500	

Measurement of W-boson branching ratios

Precision test of lepton flavour universality in $W \rightarrow e\nu$ and $W \rightarrow \mu\nu$ deacys

$t\bar{t} \rightarrow e\mu$: Number of events given by

$N_1^{e\mu} = L\,\sigma_{t\bar{t}}\epsilon_{e\mu}g_{e\mu}^{t\bar{t}}2\epsilon_b^{e\mu}\left(1 - C_b^{e\mu}\epsilon_b^{e\mu}\right) + \sum_{k=\mathrm{bkg}} s_1^k g_{e\mu}^k N_1^{e\mu,k}$ ← 1 b-tagged jet

$N_2^{e\mu} = L\,\sigma_{t\bar{t}}\epsilon_{e\mu}g_{e\mu}^{t\bar{t}}C_b^{e\mu}\left(\epsilon_b^{e\mu}\right)^2 + \sum_{k=\mathrm{bkg}} s_2^k g_{e\mu}^k N_2^{e\mu,k}$ ← 2 b-tagged jets

$$C_b^{e\mu} = \frac{4N_{e\mu}^{t\bar{t}}N_2^{t\bar{t}}}{\left(N_1^{t\bar{t}}+2N_2^{t\bar{t}}\right)^2}$$

L: Integrated luminosity

$\sigma_{t\bar{t}}$: $t\bar{t}$ cross-section

$\epsilon_{e\mu}$: Opposite-sign $e\mu$ selection efficiency

$g_{e\mu}^{t\bar{t}}$: Term to account for possible deviations in simulated branching ratio

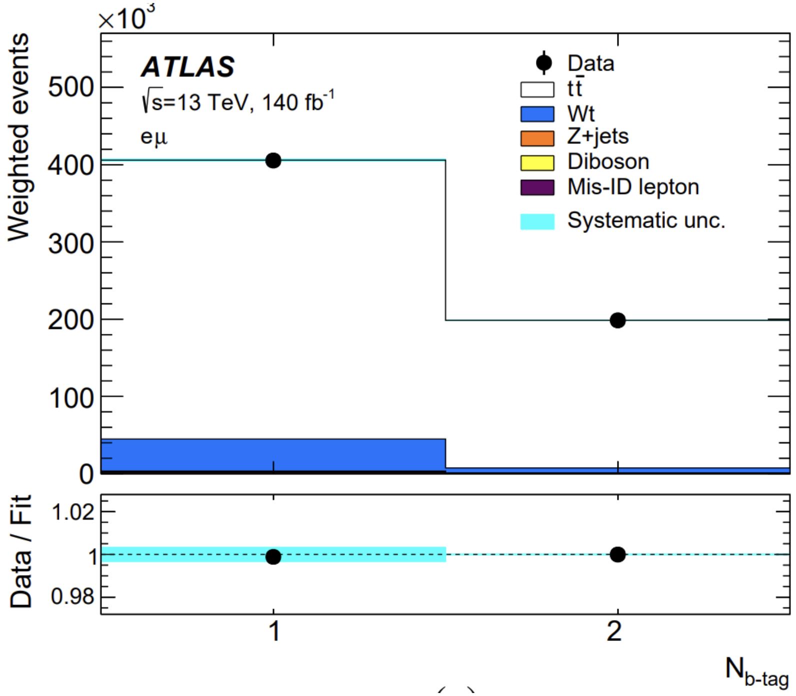
$C_b^{e\mu}$: Correlation coefficient to account for the tagging of two b-jets not being completely independent (≈ 1)

k: Indexes over the four background sources: Wt, Z+jets, diboson and lepton mis-ID

$s_{1,2}^k$: Scaling factors. Set to one for all backgrounds except $S_{1,2}^{Z\text{+jets}}$, which is a free parameter in the fit

$g_{e\mu}^k$: Scaling factor to allow for changes to W or Z leptonic branching ratios

$N_{1,2}^{e\mu,k}$: Number of background k events in channel



Measurement of W-boson branching ratios

Precision test of lepton flavour universality in $W \to e\nu$ and $W \to \mu\nu$ deacys

$t\bar{t} \to \ell\ell$: Fit in m bins of $m_{\ell\ell}$; number of events in each bin given by

$N^{\ell\ell}_{1,m} = L\,\sigma_{t\bar{t}}\epsilon_{\ell\ell}g^{t\bar{t}}_{\ell\ell}2\epsilon^{\ell\ell}_b\left(1 - C^{\ell}_b\epsilon^{\ell\ell}_b\right)f^{\ell\ell,t\bar{t}}_{1,m} + \sum_{k=\text{bkg}} s^k_1 g^k_{\ell\ell} f^{\ell\ell,k}_{1,m} N^{\ell\ell\,k}_1$ ← 1 b-tagged jet

$N^{\ell\ell}_{2,m} = L\,\sigma_{t\bar{t}}\epsilon_{\ell\ell}g^{t\bar{t}}_{\ell\ell}C^{e\mu}_b\left(\epsilon^{e\mu}_b\right)^2 f^{\ell\ell,t\bar{t}}_{2,m} + \sum_{k=\text{bkg}} s^k_2 g^k_{\ell\ell} f^{\ell\ell,k}_{1,m} N^{\ell\ell,k}_2$ ← 2 b-tagged jets

$\epsilon_{\ell\ell}$: Opposite-sign $e\mu$ selection efficiency

$g^{t\bar{t}}_{\ell\ell}$: Term to account for possible deviations in simulated branching ratio

$C^{\ell\ell}_b$: Correlation coefficient to account for the tagging of two b-jets not being completely independent (≈ 1)

k: Indexes over the four background sources: Wt, Z+jets, diboson and lepton mis-ID

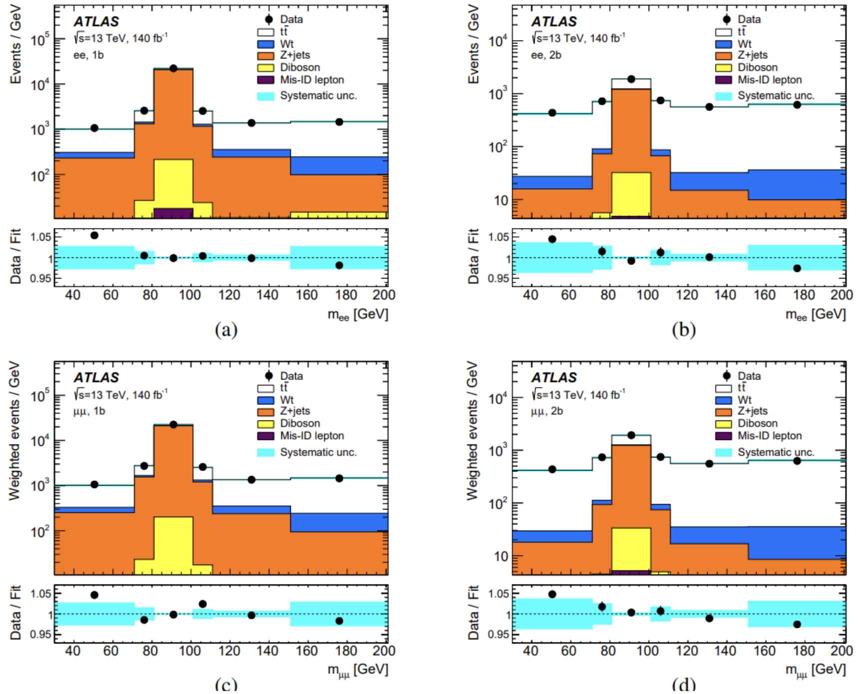
$s^k_{1,2}$: Scaling factors. Set to one for all backgrounds except $S^{Z\text{+jets}}_{1,2}$, which is a free parameter in the fit

$g^k_{\ell\ell}$: Scaling factor to allow for changes to W or Z leptonic branching ratios

$f^{\ell\ell,t\bar{t}}_{1,2,m}$: Fraction of events appearing in each m bin of $m_{\ell\ell}$ for $t\bar{t}$ signal

$f^{\ell\ell,k}_{1,2,m}$: Fraction of events appearing in each m bin of $m_{\ell\ell}$ for k background

$N^{e\mu,k}_{1,2}$: Number of background k events in channel



Measurement of $\boldsymbol{W}$-boson branching ratios

Precision test of lepton flavour universality in $W \to e\nu$ and $W \to \mu\nu$ deacys

Reparametrize $R_W^{\mu/e}$ in terms of the average branching ratio in SM $\overline{W}$ and deviation from SM Δ_W

$$R_W^{\mu/e} = \frac{\mathrm{Br}(W\to\mu\nu)}{\mathrm{Br}\ (W\to e\nu)} = \frac{\overline{W}(1+\Delta_W)}{\overline{W}(1-\Delta_W)}$$

$$\Delta_W = \frac{R_W^{\mu/e}-1}{R_W^{\mu/e}+1}$$

Also need to account for $W \to \tau \to e/\mu$. Assuming $\mathrm{Br}(W \to \tau\nu)$ is constant, then

$$g_{ee}^{t\bar{t}} = f_{0\tau}^{ee}(1\ - \Delta_W)^2 + f_{1\tau}^{ee}(1 - \Delta_W) + f_{2\tau}^{ee}$$

$$g_{e\mu}^{t\bar{t}} = f_{0\tau}^{e\mu}(1\ - \Delta_W)(1 + \Delta_W) + f_{1\tau}^{e\mu} + f_{2\tau}^{e\mu}$$

$$g_{\mu\mu}^{t\bar{t}} = f_{0\tau}^{\mu\mu}(1\ - \Delta_W)^2 + f_{1\tau}^{\mu\mu}(1 - \Delta_W) + f_{2\tau}^{\mu\mu}$$

Where $f_{n\tau}^{\ell\ell}$ are the fractions in selected dilepton events where n leptons were the result of $W \to \tau \to e/\mu$. These fractions are determined from simulation

Measurement of W-boson branching ratios

Precision test of lepton flavour universality in $W \to e\nu$ and $W \to \mu\nu$ deacys

Reparametrize $R_Z^{\mu\mu/ee}$ in terms of the average branching ratio in SM $\bar{Z}$ and deviation from SM Δ_Z

$$R_Z^{\mu\mu/ee} = \frac{\mathrm{Br}(Z\to\mu\mu)}{\mathrm{Br}(Z\to ee)} = \frac{\bar{Z}(1+\Delta_Z)}{\bar{Z}(1-\Delta_Z)}$$

$$\bar{Z} = (R_Z^{\mu\mu/ee} - 1)/(R_Z^{\mu\mu/ee} + 1)$$

Biases in lepton isolation efficiency in the busy hadronic environment of Z+b-jet events are accounted for by an additional ratio $R_{Z+b}^{\mu\mu/ee}$ and $\Delta_{Z+b} = (R_{Z+b}^{\mu\mu/ee} - 1)/(R_{Z+b}^{\mu\mu/ee} + 1)$

From this we can get the $g_{\ell\ell'}^{k}$ factors for Z+jets events:

$$g_{ee}^{Z\text{+jets}} = (1-\Delta_Z)(1-\Delta_{Z+b})$$

$$g_{e\mu}^{Z\text{+jets}} = 1$$

$$g_{\mu\mu}^{Z\text{+jets}} = (1+\Delta_Z)(1+\Delta_{Z+b})$$

Measurement of W-boson branching ratios

Precision test of lepton flavour universality in $W \rightarrow e\nu$ and $W \rightarrow \mu\nu$ deacys

To reduce sensitivity to electron and muon identification uncertainties, fit not performed to $R_W^{\mu/e}$ directly, but to $R_{WZ}^{\mu/e}$ and $R_Z^{\mu\mu/ee}$

$$R_{WZ}^{\mu/e} = \frac{R_W^{\mu/e}}{\sqrt{R_Z^{\mu\mu/ee}}} = \frac{\mathrm{Br}(W\to\mu\nu)}{\mathrm{Br}(W\to e\nu)} \cdot \sqrt{\frac{\mathrm{Br}(Z\to ee)}{\mathrm{Br}(Z\to\mu\mu)}}$$

By dividing by $\sqrt{R_Z^{\mu\mu/ee}}$ we get exactly one power of muon & electron ID efficiencies in both numerator and denominator

$R_Z^{\mu\mu/ee}$ is determined from counting events in inclusive $Z \rightarrow \ell\ell$ data. N_Z^{ee} and $N_Z^{\mu\mu}$ given by:

$$N_Z^{ee} = L\sigma_{Z\to\ell\ell}\epsilon_{Z\to ee}(1-\Delta_Z) + \sum_{k=\mathrm{bkg}} s_Z^k N_Z^{ee,k}$$

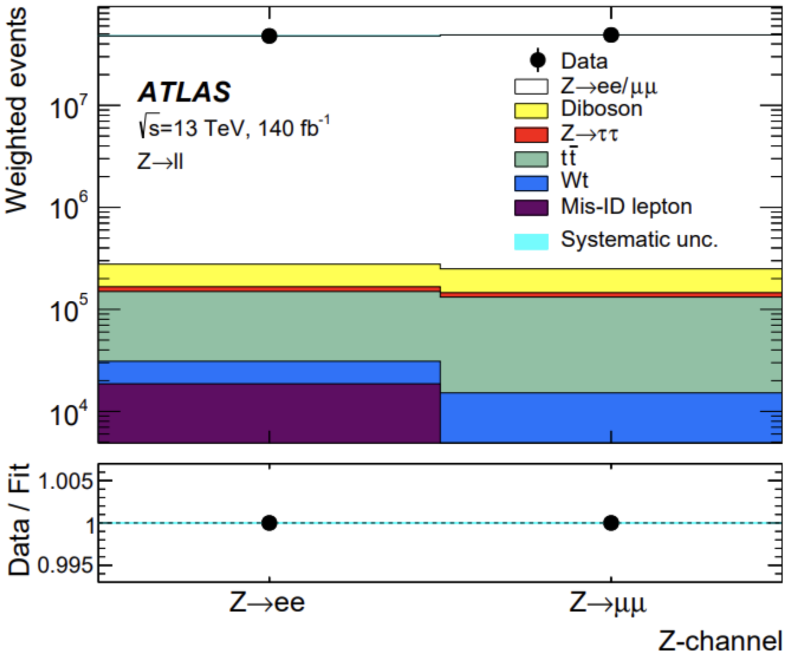
$$N_Z^{\mu\mu} = L\sigma_{Z\to\ell\ell}\epsilon_{Z\to\mu\mu}(1+\Delta_Z) + \sum_{k=\mathrm{bkg}} s_Z^k N_Z^{\mu\mu,k}$$

Where:

$\epsilon_{Z\to ee}$ & $\epsilon_Z \rightarrow \mu\mu$: Selection efficiencies

k: Indexes over backgrounds: diboson, $Z \rightarrow \tau\tau \rightarrow ee/\mu\mu$, $t\bar{t}$, Wt and mis-ID leptons. Backgrounds determined from simulation except for mis-ID leptons which were determined from a data driven estimate

$s_Z^{t\bar{t}}$: Scaled to fitted value of $\sigma_{t\bar{t}}$, all other s_Z^k values set to unity



Measurement of W-boson branching ratios

Precision test of lepton flavour universality in $W \rightarrow e\nu$ and $W \rightarrow \mu\nu$ deacys

The fit is done to the observed event counts $N_1^{e\mu}$ and $N_2^{e\mu}$ in the $t\bar{t} \rightarrow e\mu$ channel, observed event counts in bins of $m_{\ell\ell}$ in the $t\bar{t} \rightarrow ee/\mu\mu$ channels $N_{1,m}^{\ell\ell}$, $N_{2,m}^{\ell\ell}$ and the observed number of events in $Z \rightarrow \ell\ell$ channels N_Z^{ee}, $N_Z^{\mu\mu}$

There are 10 fitted parameters:

- $\sigma_{t\bar{t}}$
- $\sigma_{Z\rightarrow\ell\ell}$
- $R_{WZ}^{\mu/e}$
- $R_Z^{\mu\mu/ee}$
- The three b-tagging efficiencies $\epsilon_b^{\ell\ell'}$
- The scale factors $s_1^{Z\text{+jets}}$, $s_2^{Z\text{+jets}}$
- Z+jets isolation efficiency parameter $R_{Z+b}^{\mu\mu/ee}$

Apart from integrated luminosity and mis-ID lepton background all other parameters are determined from simulation

From the fit it was found that:

$R_{WZ}^{\mu/e} = 0.9990 \pm 0.0022 \pm 0.0036$

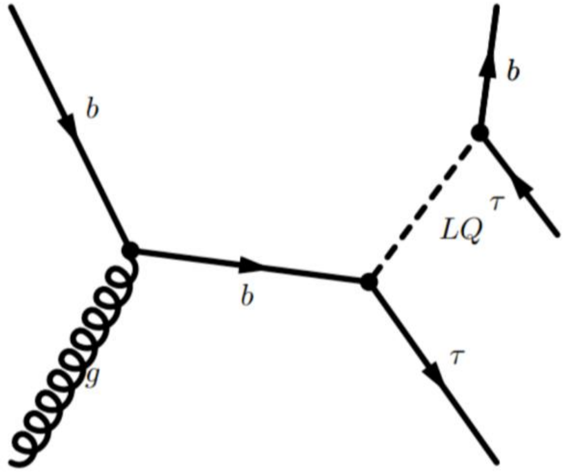
$R_Z^{\mu\mu/ee} = 0.9913 \pm 0.0002 \pm 0.0045$

Use more precise LEP & SLD measurement of $R_{Z-\text{ext}}^{\mu\mu/ee} = 1.0009 \pm 0.0028$ for final calculation of $R_W^{\mu/e}$

$R_W^{\mu/e} = R_{WZ}^{\mu/e}\sqrt{R_Z^{\mu\mu/ee}} = 0.9995 \pm 0.0022\ (\text{stat}) \pm 0.0036\ (\text{syst}) \pm 0.0014\ (\text{ext})$

Leptoquark searches

Single production: $b\tau\tau$



Select events containing a b-jet and $\tau_{\text{lep}}\tau_{\text{had}}$ or $\tau_{\text{had}}\tau_{\text{had}}$ pair

Consider vector leptoquarks with charge $2/3e$ and scalar leptoquarks with charge $4/3e$

Non-resonant leptoquark interference with SM at low b-jet p_T

Unclear how to model and very model dependent

→ Perform search for leptoquarks in high b-jet p_T SR

→ Perform model-independent search in both high/low b-jet p_T SRs

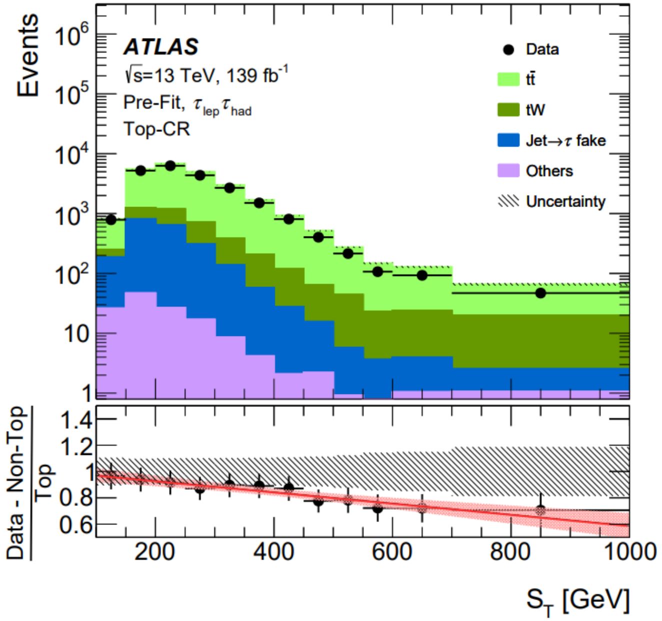
Main backgrounds:

- $t\bar{t}$ & single top
- $Z/\gamma^* \to \tau_{\text{had}}\tau_{\text{had}}$

Modelled by MC with corrections derived from dedicated CRs

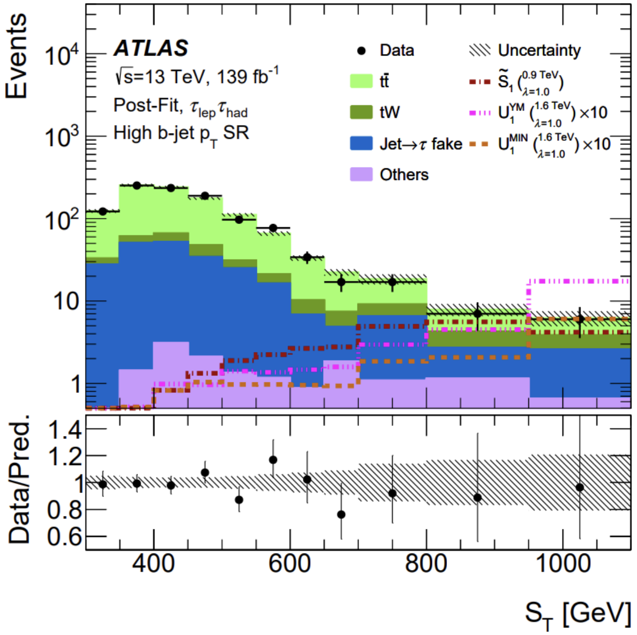
- Jets faking leptons

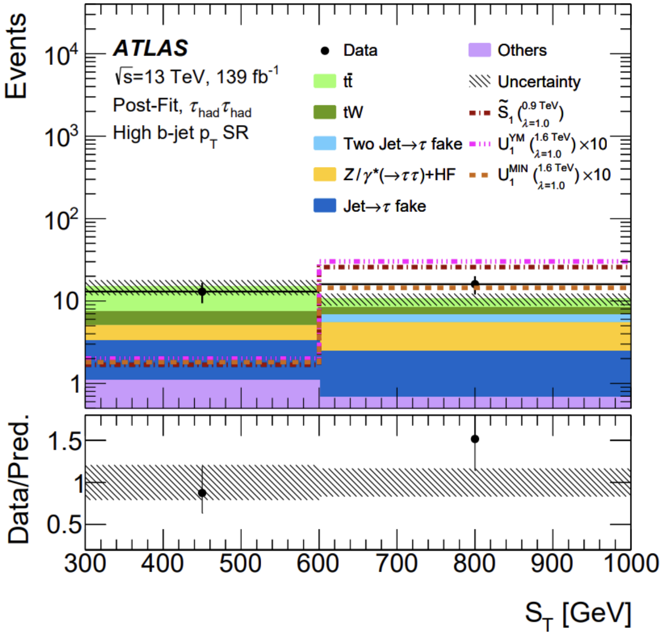
Data-driven estimates

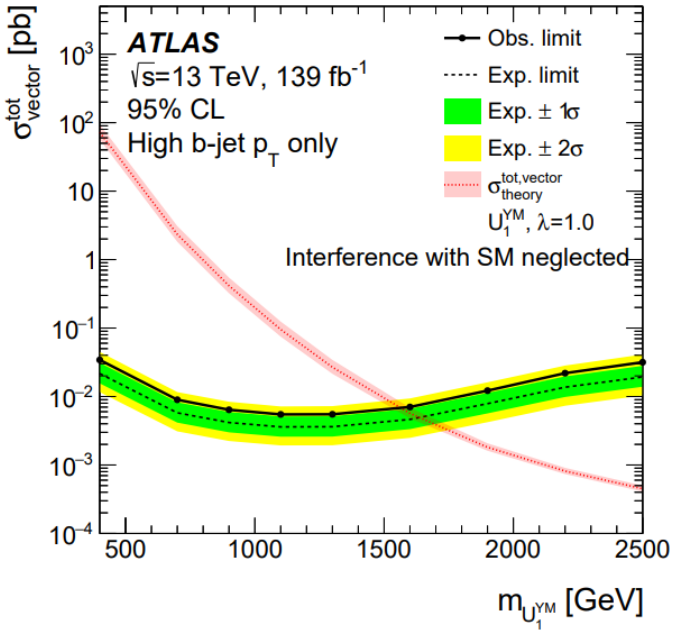


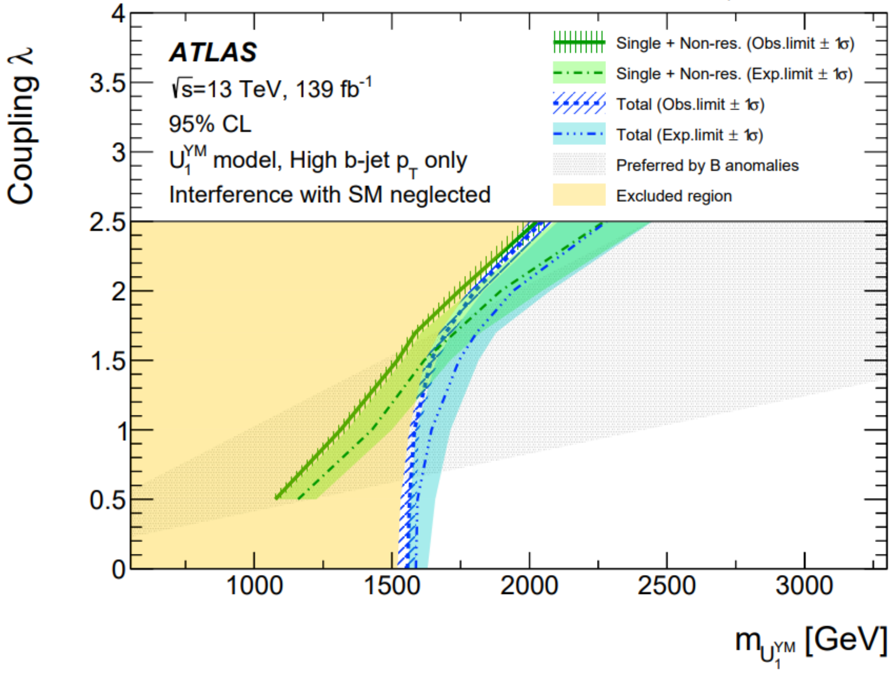
Leptoquark searches

Single production: $b\tau\tau$







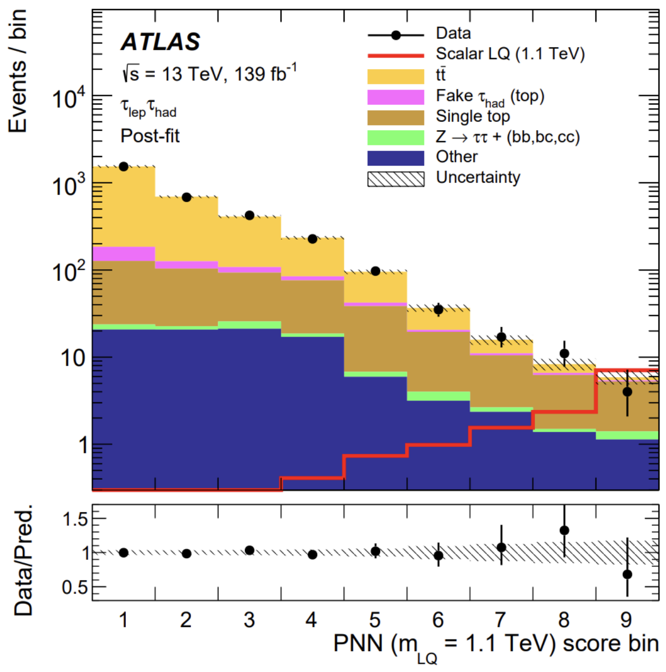


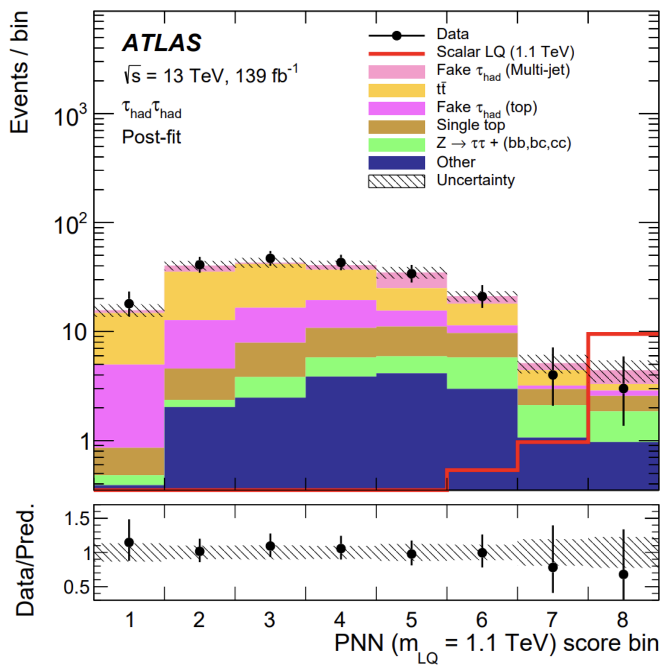
Signal regions binned in scalar sum of p_T

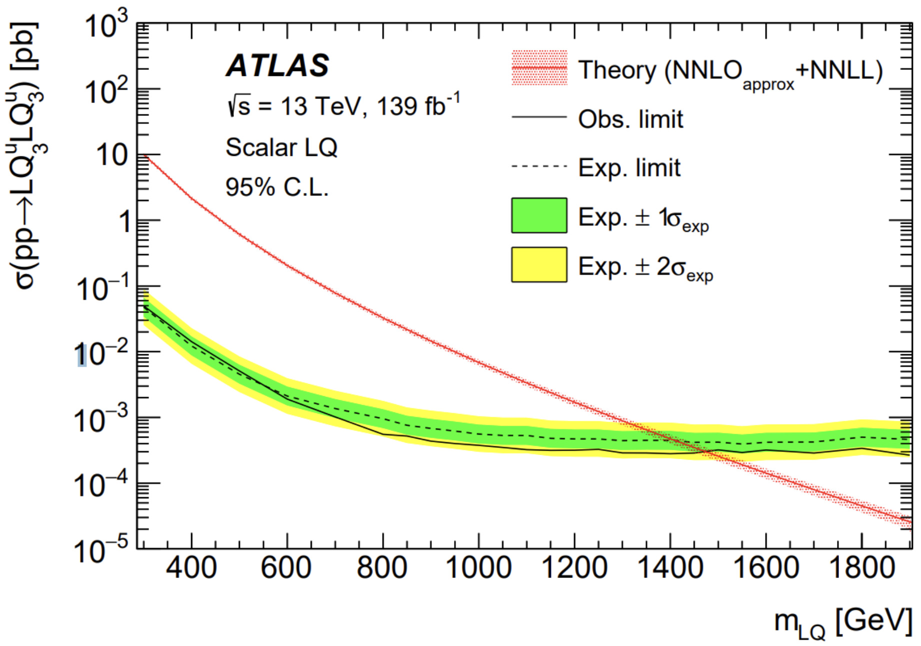
$$S_T = p_T^{\tau_1} + p_T^{\tau_2} + p_T^{b}$$

Leptoquark searches

Double production: $b\tau b\tau$







High mass LFV dilepton resonances

Search for lepton $pp \rightarrow X \rightarrow \ell^{\pm}\ell'^{\mp}$

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Search targeting high-mass $e\mu,\ e\tau,\ \mu\tau$ pairs

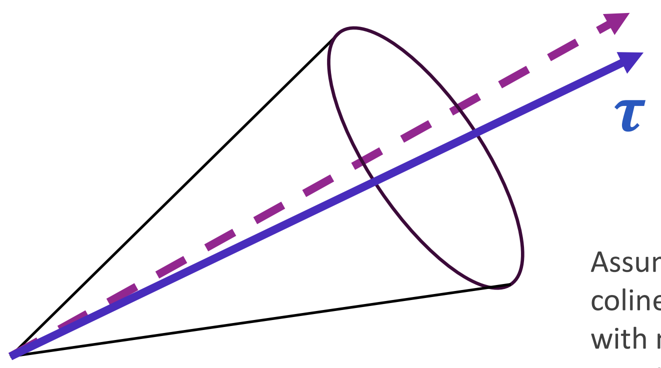
Three interpretations:
- **Z' boson**
- **τ-sneutrinos** in *R*-parity violating SUSY
- **Quantum black holes** (ADD & RS models)

Main Backgrounds:
- $t\bar{t}$
- WW

Control regions defined and normalisations obtained from fit

- **Fake/non-prompt leptons** } Data-driven estimate
- **W+jets** } Sizable in τ-channels where jet fakes a lepton. Dedicated CR to extrapolate yields to SR

How to reconstruct $m_{\ell\tau}$?

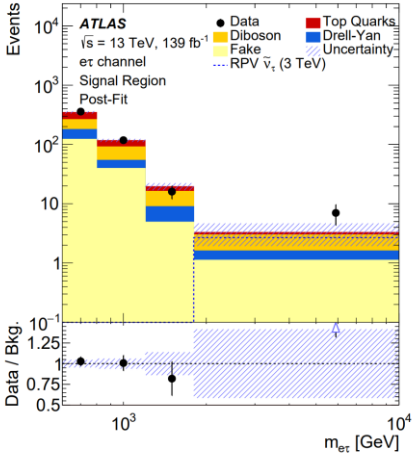


Region	Channels	Requirements
	Nominal $\Delta\phi_{\ell\ell'}$	
SR	$e\mu$, $e\tau$ and $\mu\tau$	$\Delta\phi_{\ell\ell'} > 2.7$, no b-jet, $m_{\ell\ell'} > 600$ GeV
$t\bar{t}$ CR	$e\mu$, $e\tau$ and $\mu\tau$	$\Delta\phi_{\ell\ell'} > 2.7$, at least one b-jet, $m_{\ell\ell'} > 600$ GeV
	Reversed $\Delta\phi_{\ell\ell'}$	
Low $\Delta\phi_{\ell\ell'}$ $t\bar{t}$ CR	$e\mu$	$\Delta\phi_{\ell\ell'} < 2.7$, at least one b-jet, $m_{\ell\ell'} > 600$ GeV
WW CR	$e\mu$	$\Delta\phi_{\ell\ell'} < 2.7$, no b-jet, $m_{\ell\ell'} > 600$ GeV

High mass LFV dilepton resonances

Search for lepton $pp \to X \to \ell^{\pm}\ell'^{\mp}$

Fit to $m_{\ell\ell'}$ spectrum



Improvements on early run 2 analysis (arXiv:1807.06573)

- 4x luminosity
- Improved object reconstruction
- Improved background estimation
- Simultaneous fit to SRs and CRs

Improvement of 0.6, 0.3 and 0.4 TeV in $e\mu$, $e\tau$ and $\mu\tau$ on previous Z' limits