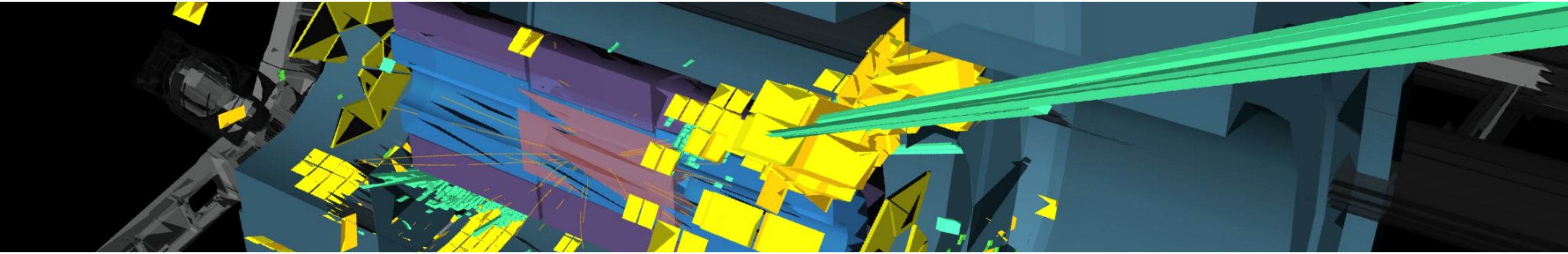
Leptoquark searches with 3rd generation final states

Large Hadron Collider Physics Conference

Northeastern University, Boston
June 4th 2024



Patrick Rieck
New York University

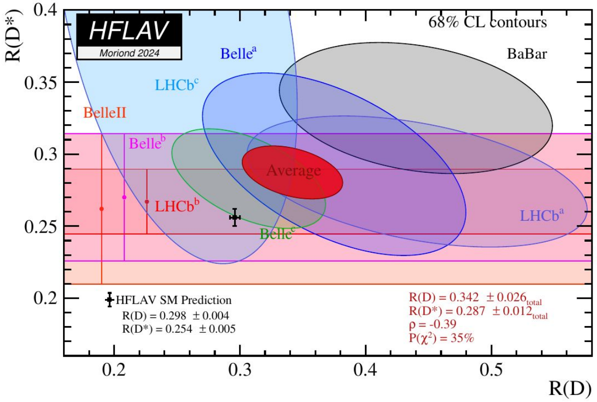
on behalf of the ATLAS collaboration

ATLAS EXPERIMENT

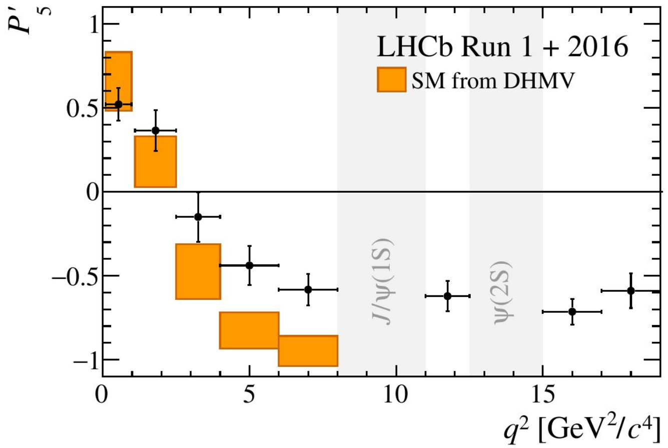
NYU

Tensions in the Flavour Sector

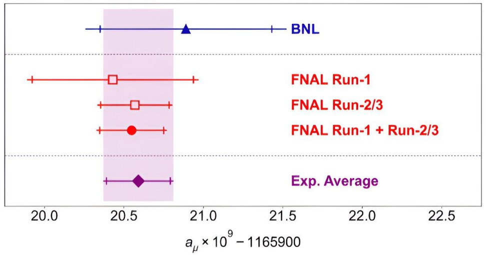
HFLAV

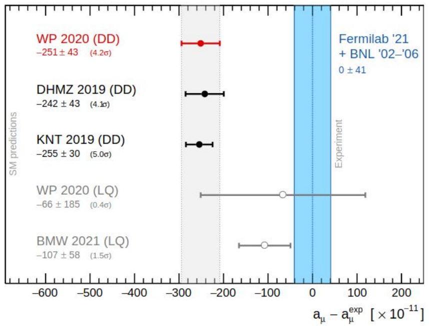


LHCb



FNAL





- Flavour puzzle: why three generations of fermions?
- Still tension between theory and experiment in the flavour section for several observables

Leptoquarks

- Several extensions of the Standard Model addressing the flavour puzzle include particles carrying both baryon and lepton number: Leptoquarks
  - Mediators of quark / lepton interaction
  - Color and electroweak quantum numbers
    ⇒ strong and electroweak production
- Many possible types of leptoquarks
  - Some preference for 3rd generation couplings

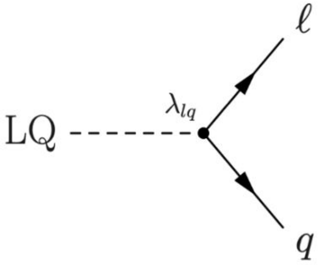


Table 1
Quantum numbers of scalar and vector leptoquarks with $SU(3)\times SU(2)\times U(1)$ invariant couplings to quark–lepton pairs ($Y=Q_{em}-T_3$).

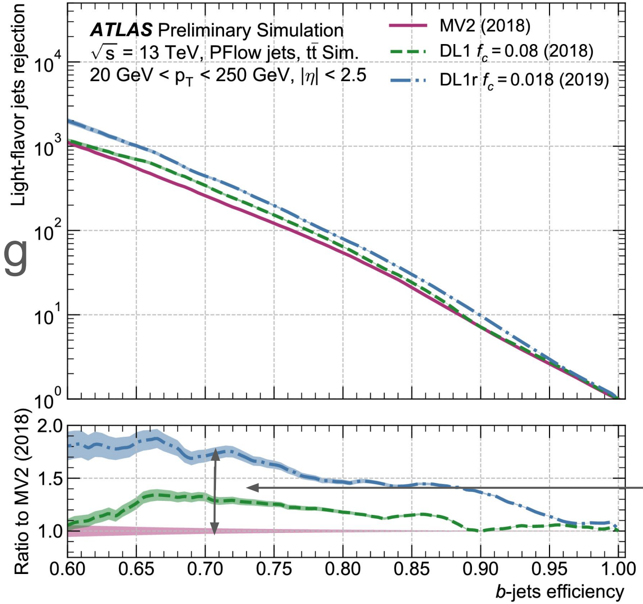
	Spin	$F=3B+L$	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$
S_1	0	−2	3^*	1	$\frac{1}{3}$
$\tilde{S}_1$	0	−2	3^*	1	$\frac{4}{3}$
S_3	0	−2	3^*	3	$\frac{1}{3}$
V_2	1	−2	3^*	2	$\frac{5}{6}$
$\tilde{V}_2$	1	−2	3^*	2	$-\frac{1}{6}$
R_2	0	0	3	2	$\frac{7}{6}$
$\tilde{R}_2$	0	0	3	2	$\frac{1}{6}$
U_1	1	0	3	1	$\frac{2}{3}$
$\tilde{U}_1$	1	0	3	1	$\frac{5}{3}$
U_3	1	0	3	3	$\frac{2}{3}$

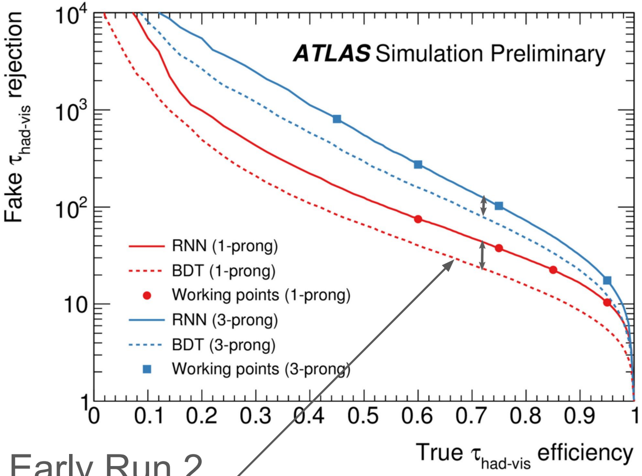
PLB 191, 1987

Identification of 3rd generation fermions

ATLAS-FTAG-2019-005
ATL-PHYS-PUB-2019-033

b-tagging





τ-tagging

Early Run 2
vs. end of Run 2

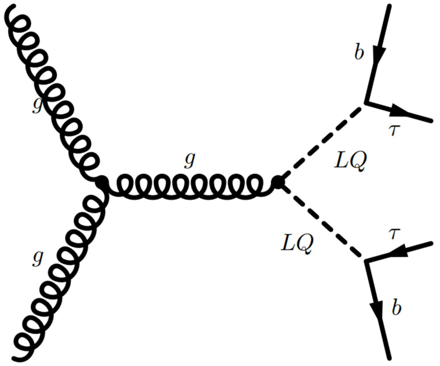
- 3rd generation charged fermions: short-lived with complex decays
  ⇒ sophisticated event reconstruction and detailed detector understanding required
- Improvements of b-jet and hadronic tau-decay identification via deep learning, more improvements in preparation for Run 3 (Graph Neural Networks)

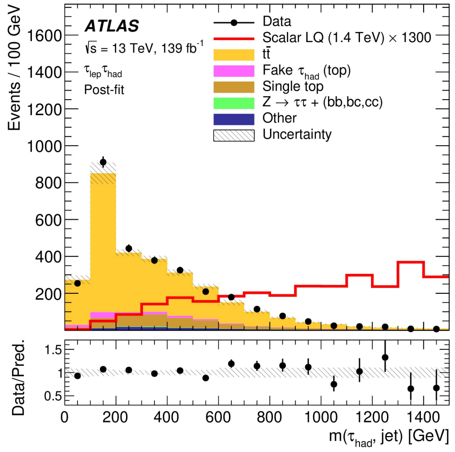
Leptoquark Pair Production

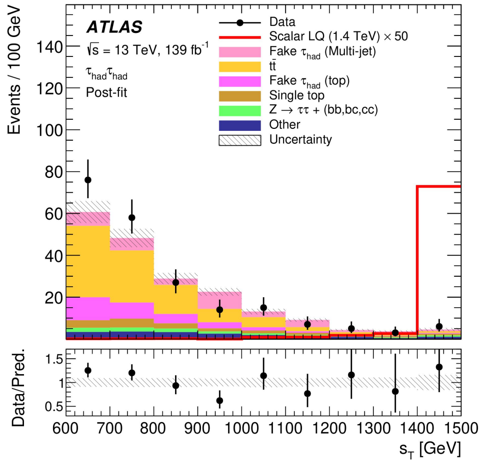
2303.01294

$bb\tau\tau$ Final State

- Signal region: $\tau_{had}\tau_{had}$ or $\tau_{had}\tau_{lep}$ decays, $\sum p_T > 600$ GeV
- Background: mostly top-quark events
  - Inaccuracies of top-quark simulation at high $\sum p_T$ data-driven background reweighting, using events with 2 light leptons
- Neural Network to discriminate signals
  - Leptoquark mass as an input parameter
  - 8 input variables, including in particular $\sum p_T$







Leptoquark Pair Production

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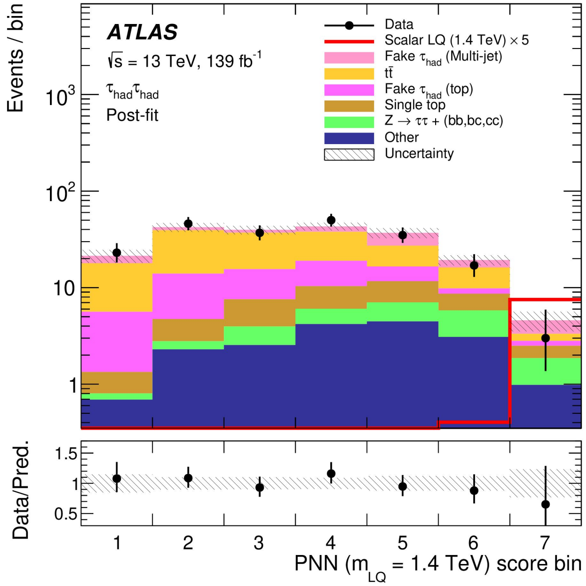
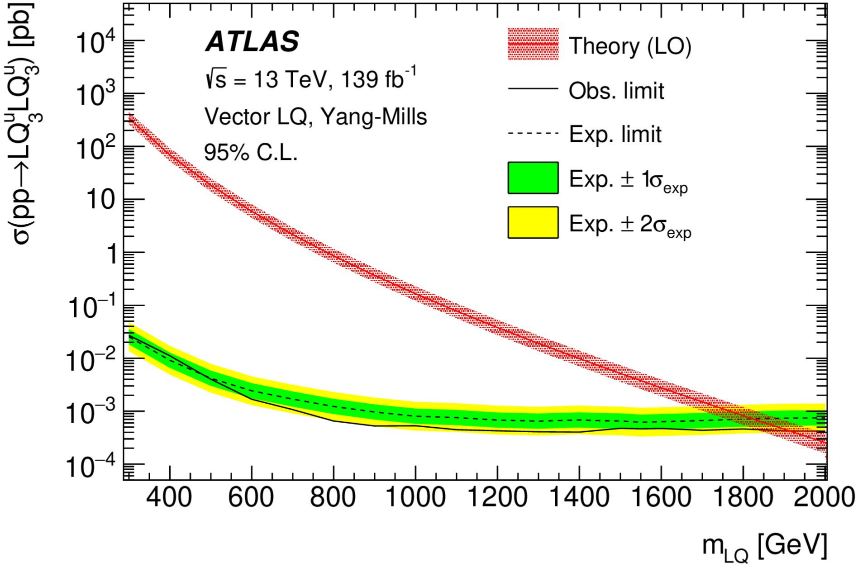
$bb\tau\tau$ Final State





Fits to the Neural Network distribution

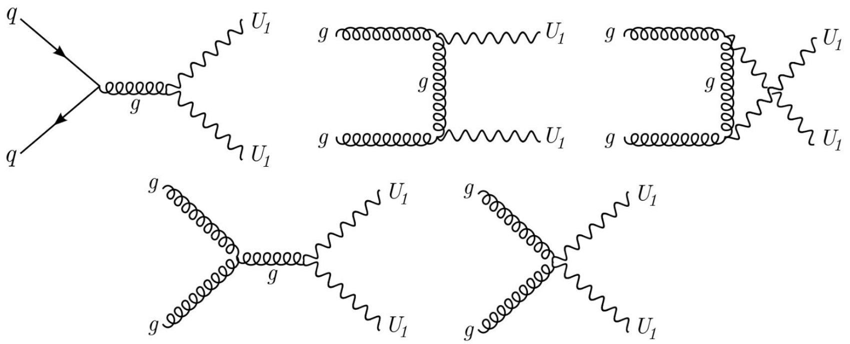
⇒ Limits on masses of various leptoquarks, depending on spin and coupling to gluons

Pair Production: Combination

2401.11928

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

- Statistical combination of LQ searches
  - Strong pair production
  - Multiple LQ decays ⇒ 9 analyses
- Spin-0 and spin-1 LQs



Pair Production: Combination

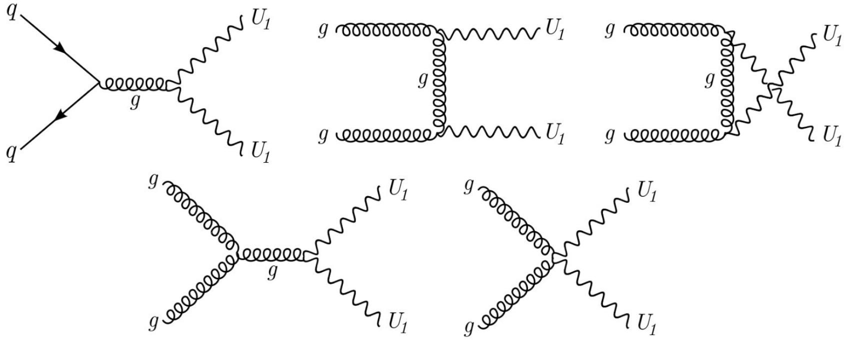
2401.11928

This Talk

Search		Interpretation						Signal Region		
		Scalar				Vector				
Final State	Citation	$\mathrm{LQ}_3^{\mathrm{u}}$	$\mathrm{LQ}_3^{\mathrm{d}}$	$\mathrm{LQ}_{\mathrm{mix}}^{\mathrm{u}}$	$\mathrm{LQ}_{\mathrm{mix}}^{\mathrm{d}}$	$U_1^{\mathrm{YM/MC}}$	$\tilde{U}_1^{\mathrm{YM/MC}}$	N_ℓ	$N_{\tau_{\mathrm{had}}}$	$N_{b\mathrm{jets}}$
$t\nu b\tau$		✓	✓	–	–	✓	–	0	1	≥ 2
$b\tau b\tau$		✓	–	–	–	✓	–	$\{0,1\}$	$\{1,2\}$	$\{1,2\}$
$t\tau t\tau$		–	✓	–	–	–	✓	$\{1,2,3\}$	≥ 1	≥ 1
$t\nu b\ell$		–	–	✓	✓	–	–	1	–	≥ 1
$b\ell b\ell$		–	–	✓	–	–	–	2	–	$\{0,1,2\}$
$t\ell t\ell$ (2ℓ))		–	–	–	✓	–	–	2	–	–
$t\ell t\ell$ ($\geq 3\ell$)		–	–	–	✓	–	–	$\{3,4\}$	–	≥ 2
$t\nu t\nu$		✓	–	✓	–	✓	–	0	0	≥ 2
$b\nu b\nu$		–	✓	–	✓	–	–	0	–	≥ 2

Margherita's talk

- Statistical combination of LQ searches
    - Strong pair production
    - Multiple LQ decays ⇒ 9 analyses
- Spin-0 and spin-1 LQs



Pair Production: Combination

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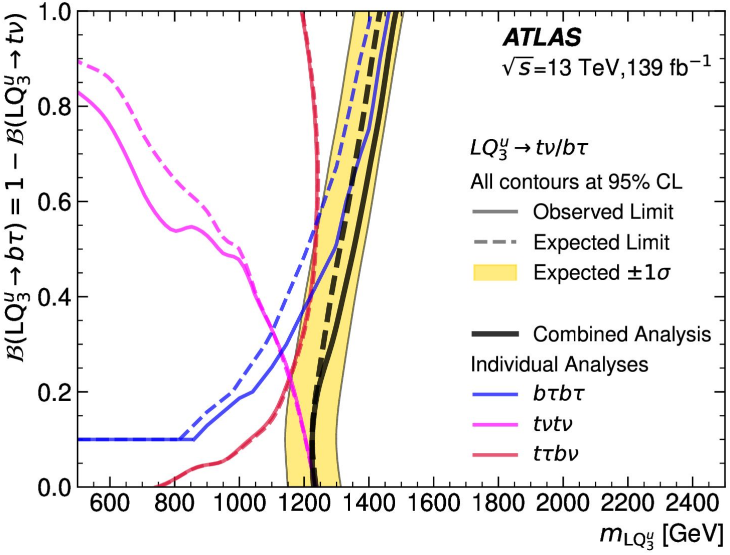
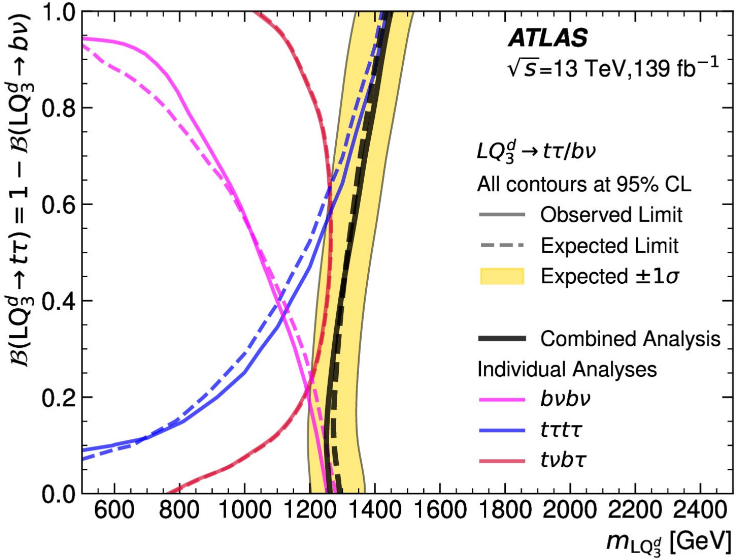


LQ electric charge 2/3



LQ electric charge -1/3

Pair Production: Combination

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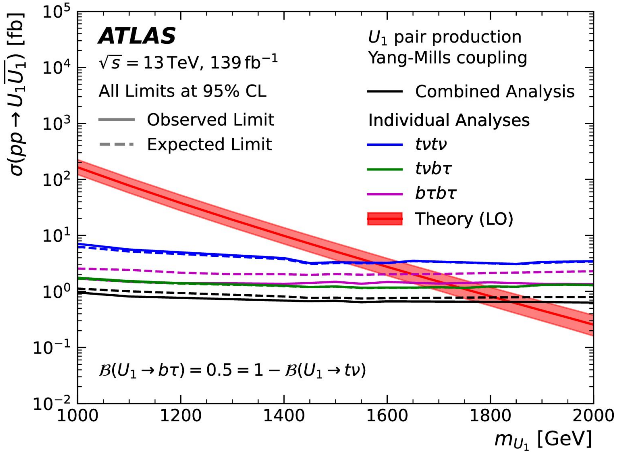
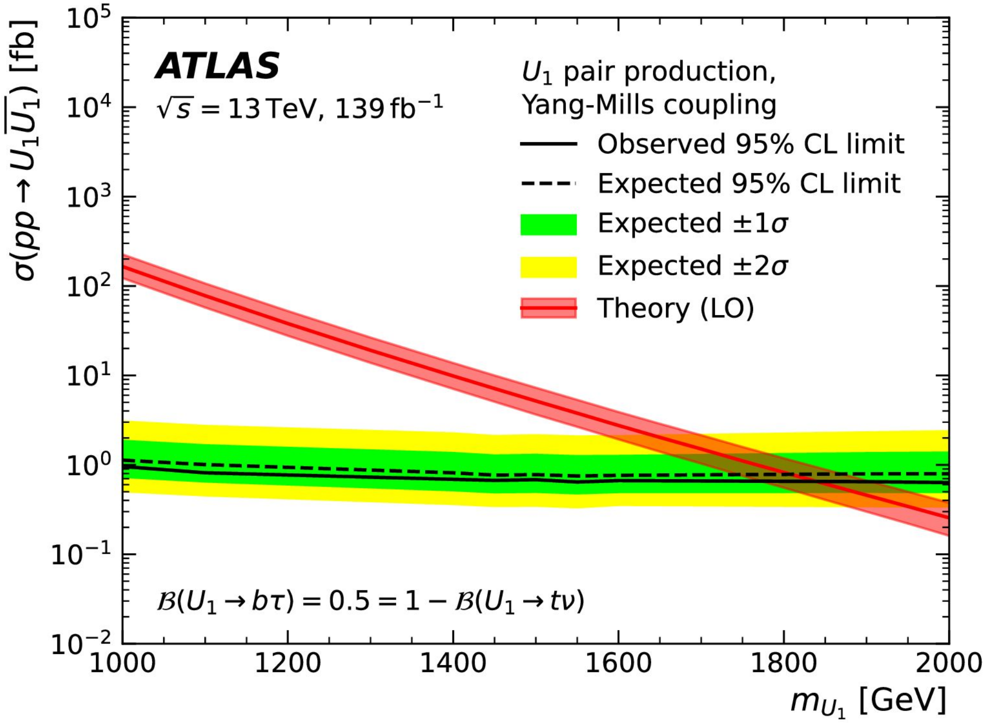
Spin-1 leptoquark



- Most distinguished final state: $b\nu b\tau \Rightarrow$ highest sensitivity
- Yang-Mills coupling scenario: M_{LQ} < 1,84 TeV @ 95 % CL(s)



Single Leptoquark Production

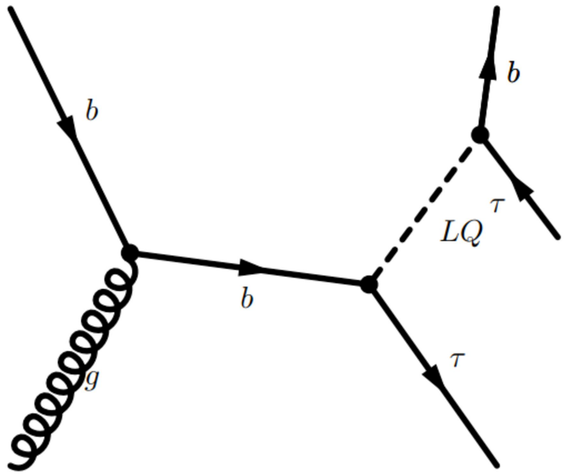
$b\tau\tau$ Final State

2305.15962

- Comparison to pair production:
  - Higher cross-section for large leptoquark mass
  - Production cross-section depending on the LQ-b-τ coupling strength

⇒ Dedicated search, similar to the pair production search in the $bb\tau\tau$ channel

  - Relaxed cut $\sum p_T > 300$ GeV
  - Dedicated Z+jets control region
  - Distinguish two regions by b-jet p_T, threshold 200 GeV



Single Leptoquark Production

$b\tau\tau$ Final State

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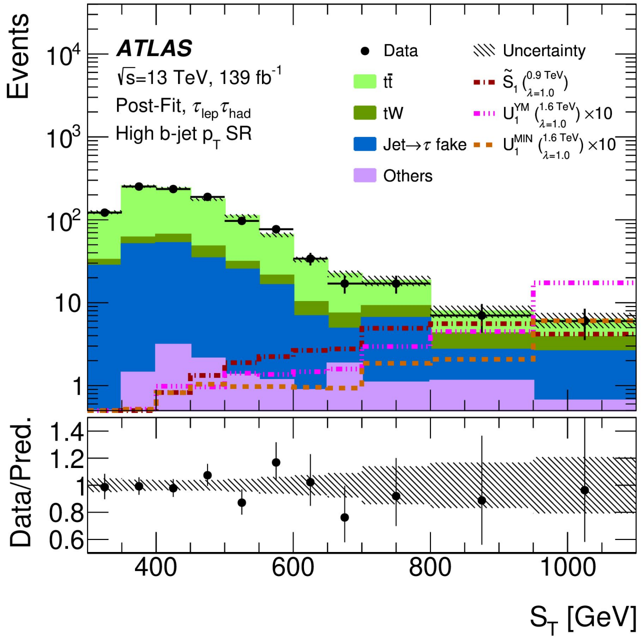

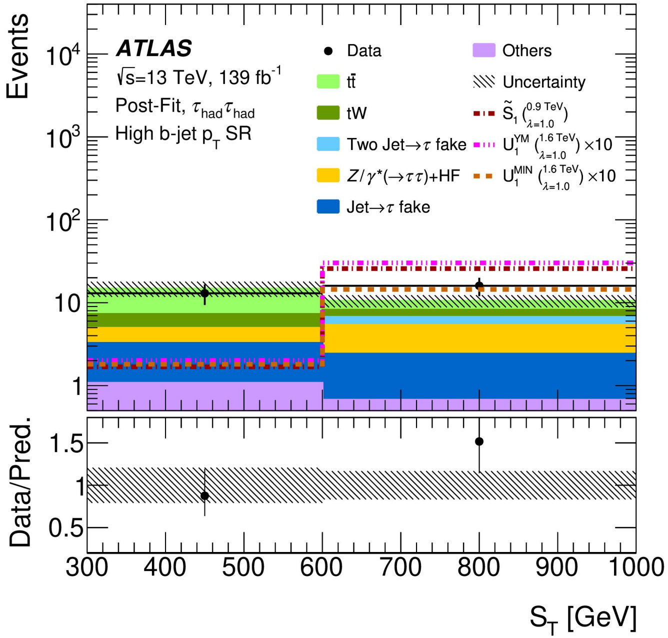

Signal strengths constrained by $\sum p_T$ distributions

Single Leptoquark Production

$b\tau\tau$ Final State

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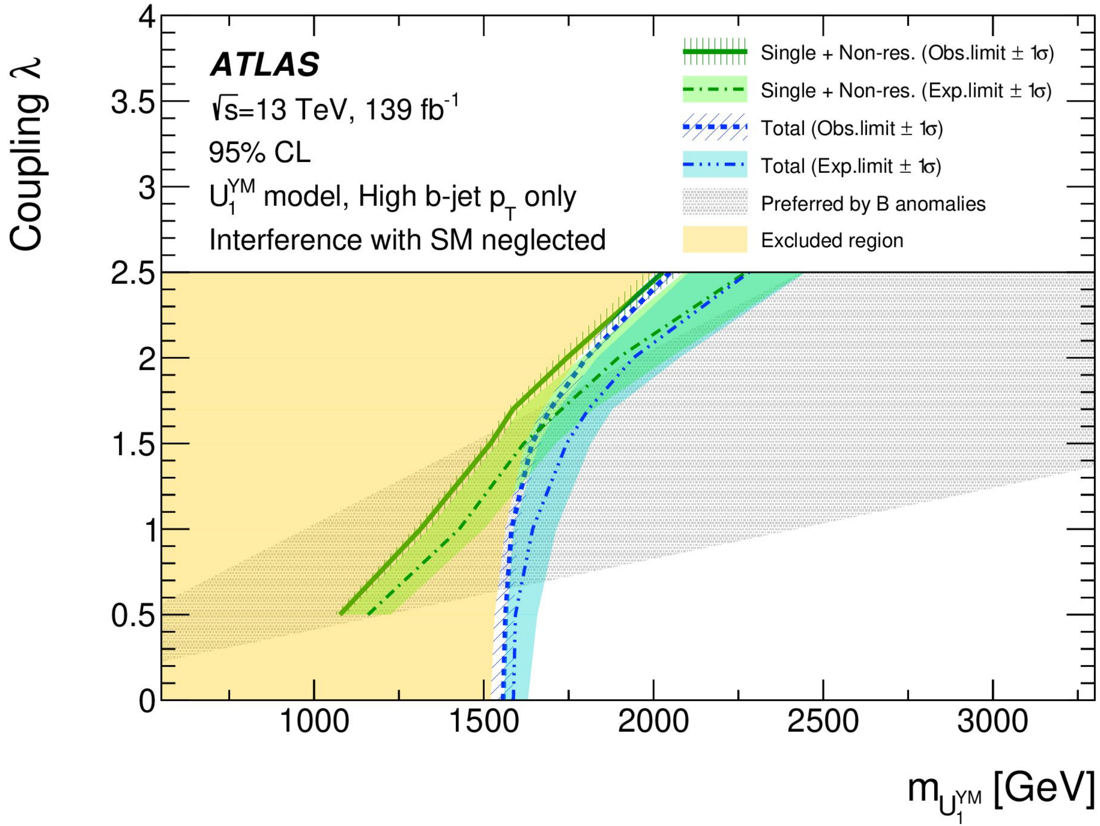

Single Leptoquark Production

$b\tau\tau$ Final State

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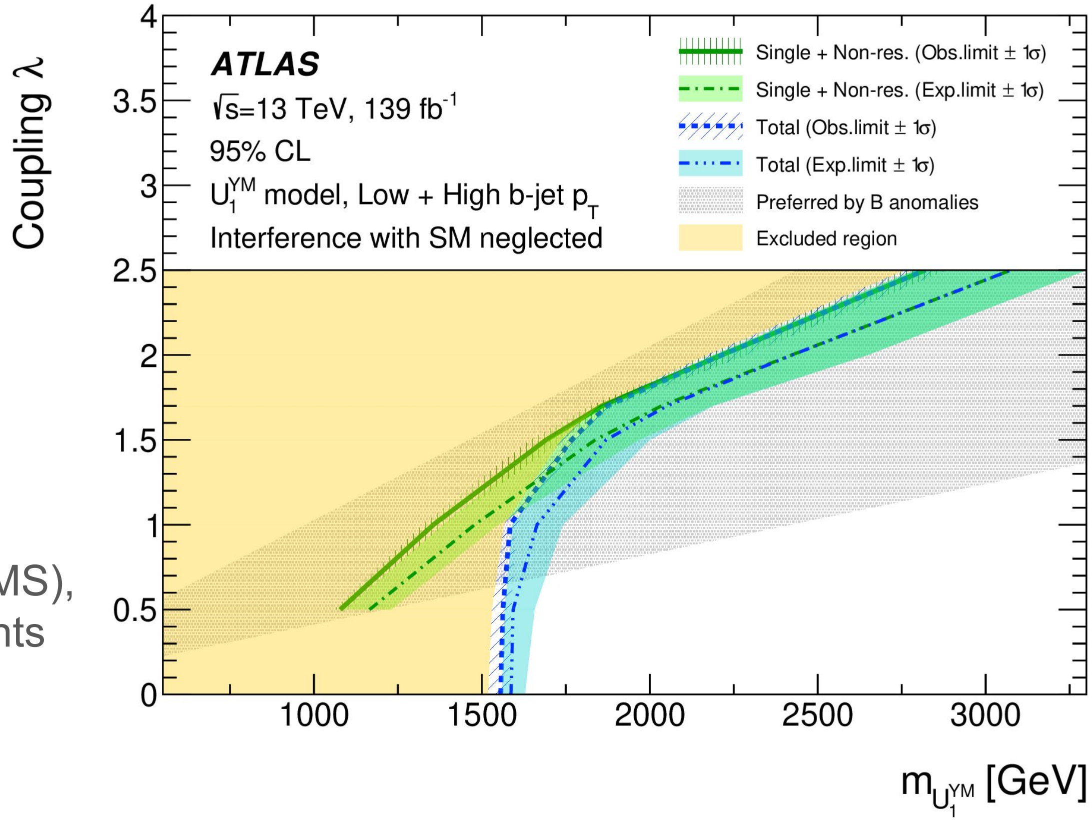


Interference term still to be included by ATLAS (and CMS), weakens constraints slightly

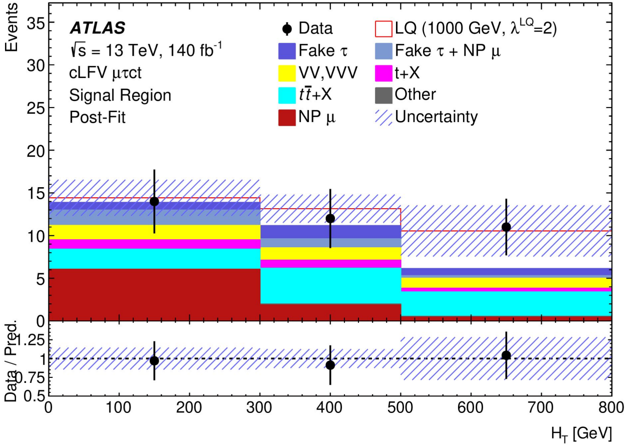
Lepton Flavour Violation in Top-Quark Interactions

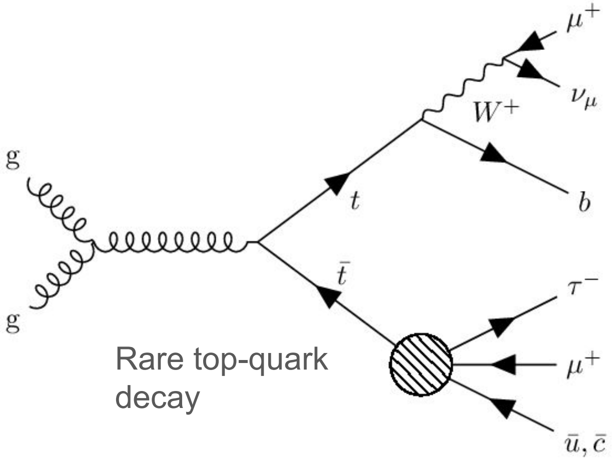
2403.06742

- Single-top events with same-sign muon pairs:

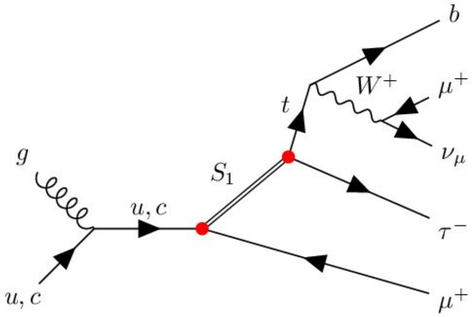
  take advantage of huge top-quark production cross-sections, searching for rare interactions

- Signal strengths constrained by $\sum p_T$ + Missing E_T distribution





Rare top-quark decay



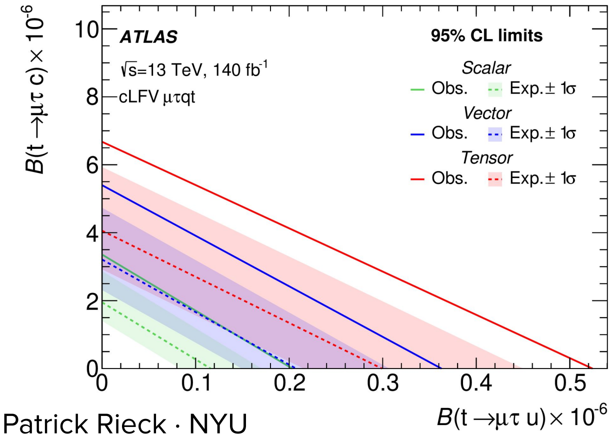
Lepton Flavour Violation in Top-Quark Interactions

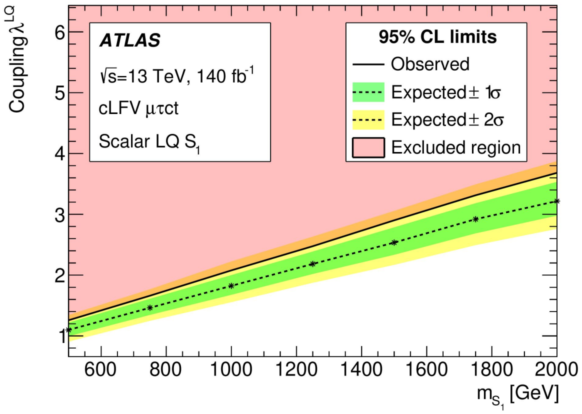
2403.06742

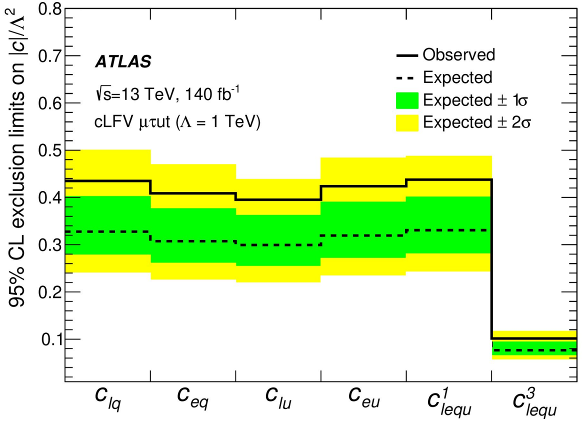
$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{eff}} = \mathcal{L}_{\mathrm{SM}} + \sum_{\mathrm{X}} \frac{c_{\mathrm{X}}}{\Lambda^2} O_{\mathrm{X}} + \cdots$$

Operator	Interaction	Lorentz Structure
$O_{\mathrm{lq}}^{1(ijkl)}$	$(\bar{\mathrm{l}}_i\gamma^\mu \mathrm{l}_j)(\bar{\mathrm{q}}_k\gamma_\mu \mathrm{q}_l)$	Vector
$O_{\mathrm{lq}}^{3(ijkl)}$	$(\bar{\mathrm{l}}_i\gamma^\mu\sigma^I \mathrm{l}_j)(\bar{\mathrm{q}}_k\gamma_\mu\sigma_I \mathrm{q}_l)$	Vector
$O_{\mathrm{eq}}^{(ijkl)}$	$(\bar{\mathrm{e}}_i\gamma^\mu \mathrm{e}_j)(\bar{\mathrm{q}}_k\gamma_\mu \mathrm{q}_l)$	Vector
$O_{\mathrm{lu}}^{(ijkl)}$	$(\bar{\mathrm{l}}_i\gamma^\mu \mathrm{l}_j)(\bar{\mathrm{u}}_k\gamma_\mu \mathrm{u}_l)$	Vector
$O_{\mathrm{eu}}^{(ijkl)}$	$(\bar{\mathrm{e}}_i\gamma^\mu \mathrm{e}_j)(\bar{\mathrm{u}}_k\gamma_\mu \mathrm{u}_l)$	Vector
$O_{\mathrm{lequ}}^{1(ijkl)}$	$(\bar{\mathrm{l}}_i \mathrm{e}_j)\varepsilon(\bar{\mathrm{q}}_k \mathrm{u}_l)$	Scalar
$O_{\mathrm{lequ}}^{3(ijkl)}$	$(\bar{\mathrm{l}}_i\sigma^{\mu\nu} \mathrm{e}_j)\varepsilon(\bar{\mathrm{q}}_k\sigma_{\mu\nu} \mathrm{u}_l)$	Tensor

- General approach, several interpretations
  - Effective Field Theory
  - Top-quark decay branching ratios
  - Leptoquark







Conclusion

- Leptoquarks as one approach to the flavour puzzle
- ATLAS Run 2 data analysed in view of single and pair production of leptoquarks, focus on decays into 3rd generation fermions
- Sensitivity driven by *b* and τ-tagging performances, with further improvements to come for Run 3
- Started probing parameter space suggested by *B*-physics results