Searches for new physics with leptons using the ATLAS detector

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On behalf of the ATLAS Collaboration

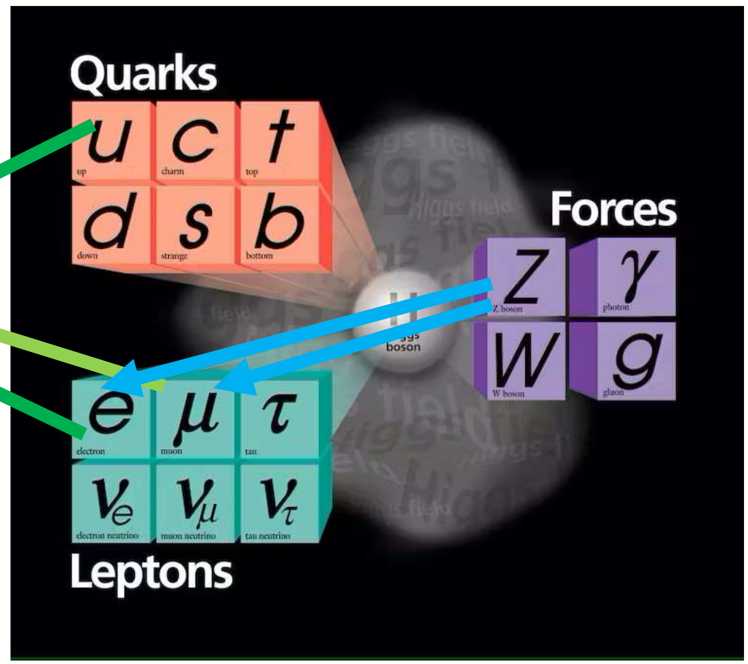
SUSY2023, Southampton

Beyond the Standard Model

Many different theories beyond the Standard Model (SM) predict

new physics → XYZ? + leptons

Leptoquarks



Lepton-Flavour Violation

New Gauge Bosons

same and cross-generational final states

Heavy-Neutrinos

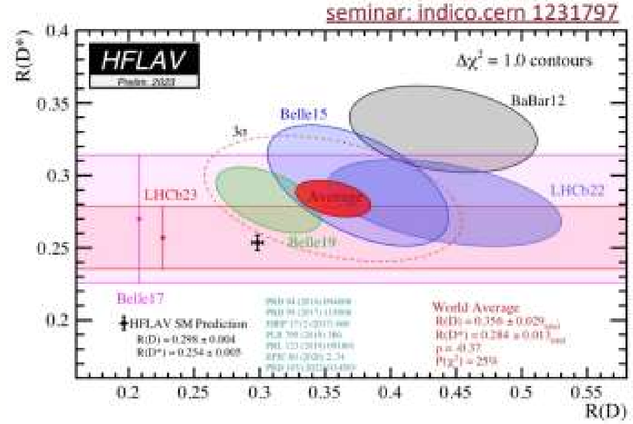
Present 13 TeV results on the searches using the ATLAS detector

Beyond the Standard Model

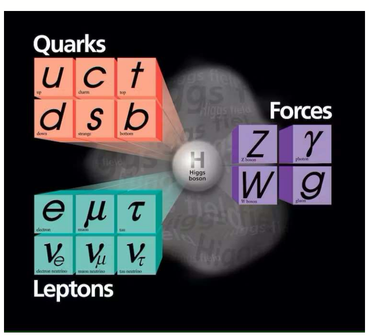
Anomalies in the flavour sector recently observed

- R_o/R_D, 3.2 sigma anomaly in global average
- R_K/R_{K*}, anomalies by LHCb in 2019, gone 2022
- ΔC_9 anomaly, 3.4 s deviation measured by LHCb
- g-2 anomaly measured at Fermilab

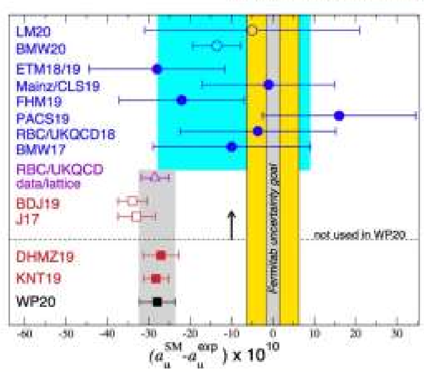
seminar: indico.cern 1231797



ATLAS searching for new physics to explain these in leptonic final state



arXiv:2106.06723



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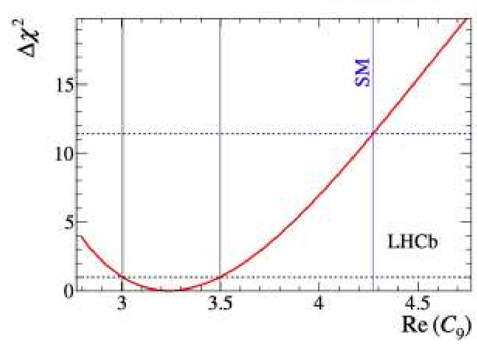
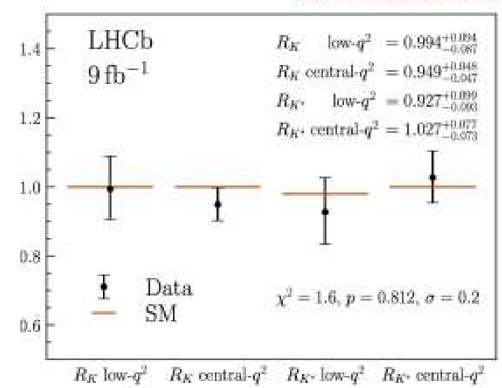
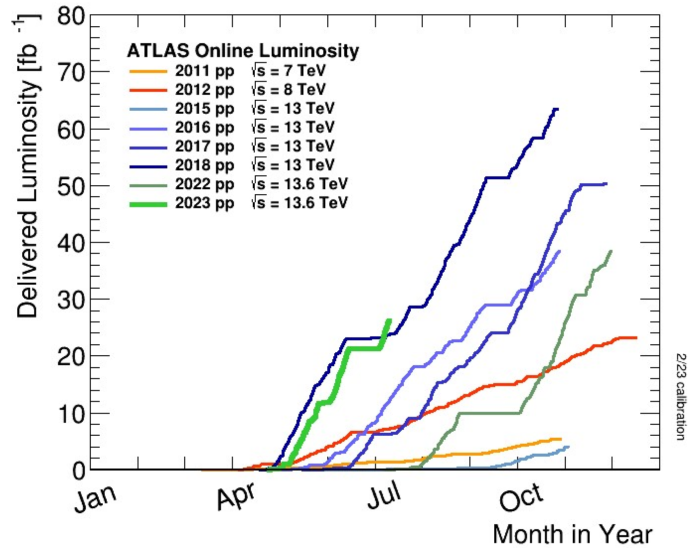


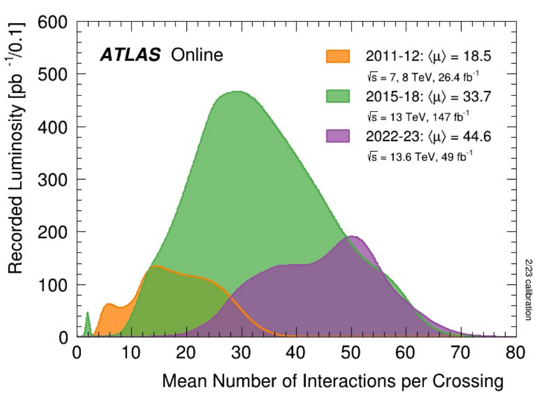
arxiv:2212.09152



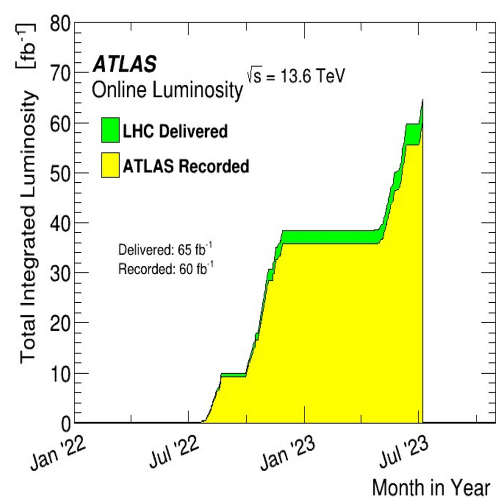
ATLAS Data – Run 2 & 3

LHC / HL-LHC Plan updated in February 2022



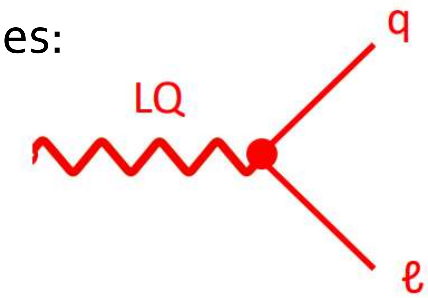


- Results presented for Run 2 @ 13 TeV, 139 fb^{-1}
- Excellent data taking Run 3



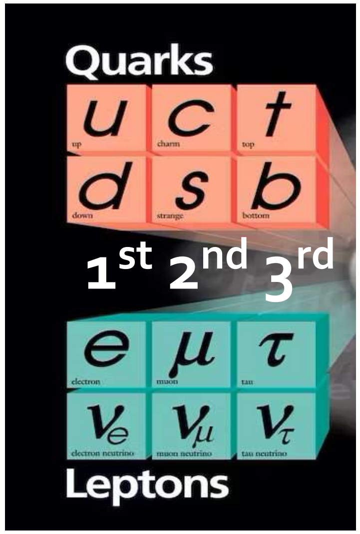
Leptoquarks

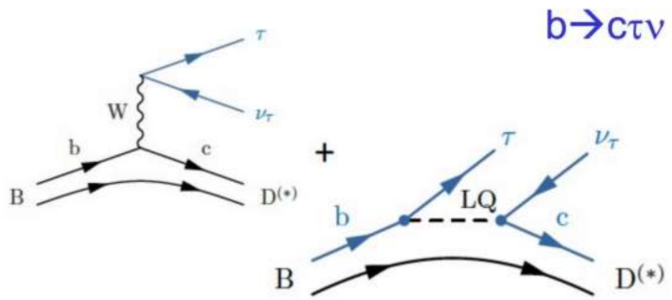
- Leptoquarks: possible explanation for many flavour anomalies:
  flavour-diagonal and cross-generational final states

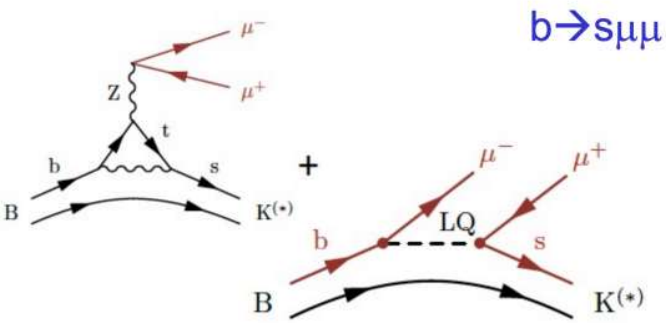


- ➢ interact with both leptons and quarks
- ➢ scalar or vector, fractional electric charge
- ➢ two coupling scenarios: minimal coupling or Yang-Mills

- First introduced in the 70s by Pati & Salam







Leptoquarks : production modes

- Three classes of production processes:

1) pair-production ⇒ 2 ℓ + 2 jet final states

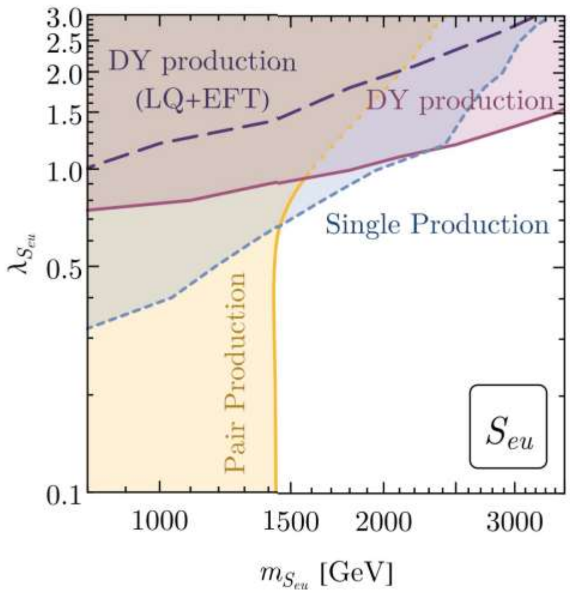
2) single production ⇒ 2 ℓ + 1 jet final states

3) Drell-Yan with exchange in t-channel ⇒ 2 ℓ final states

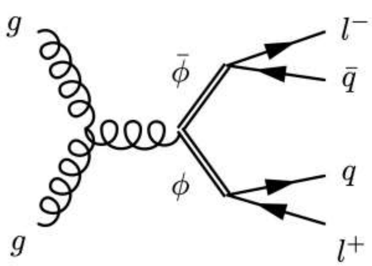
- Production process determines the exclusion area:

➢ pair-production good for low masses at any coupling

➢ single production and Drell-Yan good for high masses



1)



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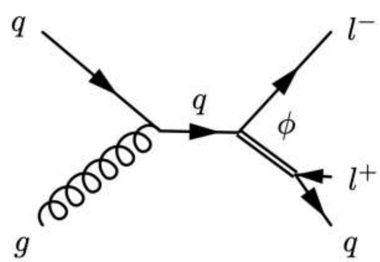

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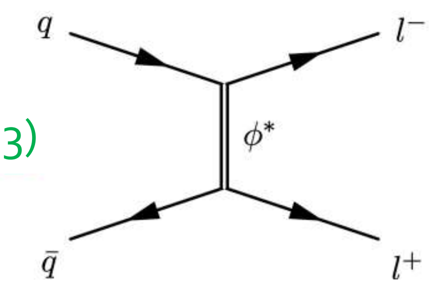
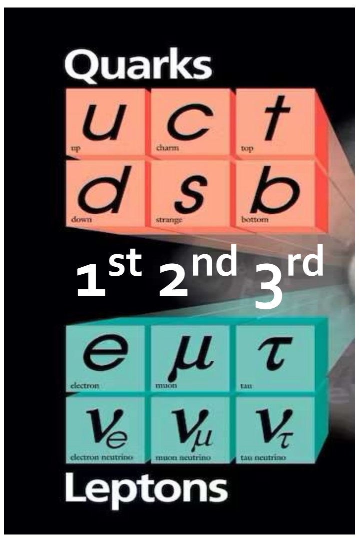


arxiv 1810.10017

Leptoquark Results Summary

LQ						
Scalar LQ 1st gen	2 e	≥2 j	Yes	139	LQ mass 1.8 TeV	✓
Scalar LQ 2nd gen	2 μ	≥2 j	Yes	139	LQ mass 1.7 TeV	✓
Scalar LQ 3rd gen	1 τ	2 b	Yes	139	LQ_3^u mass 1.49 TeV	✓
Scalar LQ 3rd gen	0 e, μ	≥2 j, ≥2 b	Yes	139	LQ_3^u mass 1.24 TeV	
Scalar LQ 3rd gen	≥2 e, μ, ≥1 τ	≥1 j, ≥1 b	–	139	LQ_3^d mass 1.43 TeV	✓
Scalar LQ 3rd gen	0 e, μ, ≥1 τ	0 – 2 j, 2 b	Yes	139	LQ_3^d mass 1.26 TeV	
Vector LQ mix gen	multi-channel	≥1 j, ≥1 b	Yes	139	LQ_3^V mass 2.0 TeV	
Vector LQ 3rd gen	2 e, μ, τ	≥1 b	Yes	139	LQ_3^V mass 1.96 TeV	✓



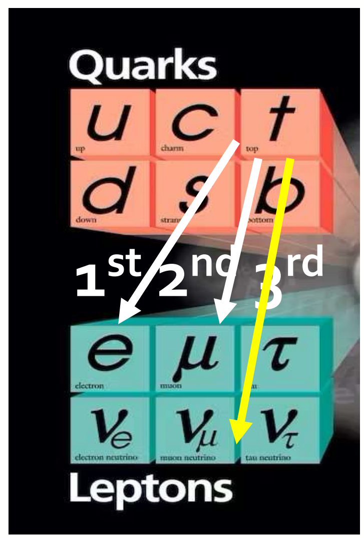
$\beta = 1$	2006.05872 ✓
$\beta = 1$	2006.05872 ✓
$\mathcal{B}(\mathrm{LQ}_3^u \to b\tau) = 1$	2303.01294 ✓
$\mathcal{B}(\mathrm{LQ}_3^u \to t\nu) = 1$	2004.14060
$\mathcal{B}(\mathrm{LQ}_3^d \to t\tau) = 1$	2101.11582 ✓
$\mathcal{B}(\mathrm{LQ}_3^d \to b\nu) = 1$	2101.12527
$\mathcal{B}(\tilde{U}_1 \to t\mu) = 1$, Y-M coupl.	ATLAS-CONF-2022-052
$\mathcal{B}(\mathrm{LQ}_3^V \to b\tau) = 1$, Y-M coupl.	2303.01294 ✓

2306.17642 ✓

2305.15962 ✓

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2023-008/fig_01.png

Searches for leptoquarks
coupling across different & mixed flavour families



Pair production of leptoquarks → t+ light lepton(l) ttbar $\ell^+\ell^-$: in 3l or 4l final states

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arXiv:2306.17642

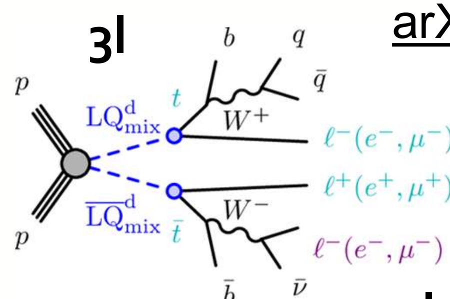
- Events selection: ≥ 2 light lep, ≥ 2 jets, ≥ 1 b-jet
- Analysis regions:

➢ Signal: (3l, 4l), for tete tμtμ, min(m_{ll})>100 GeV

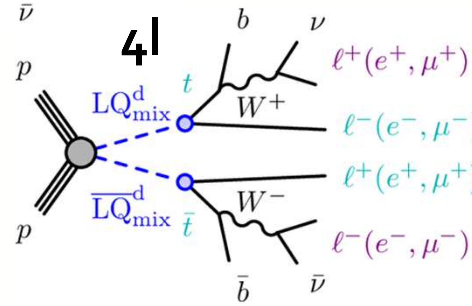
➢ Control Regions, Main backgrounds ttW, ttZ/γ*

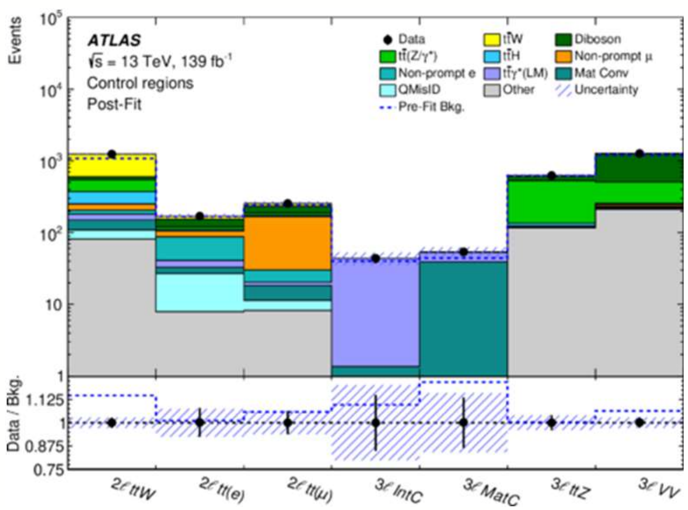
➢ 4 Signal Regions

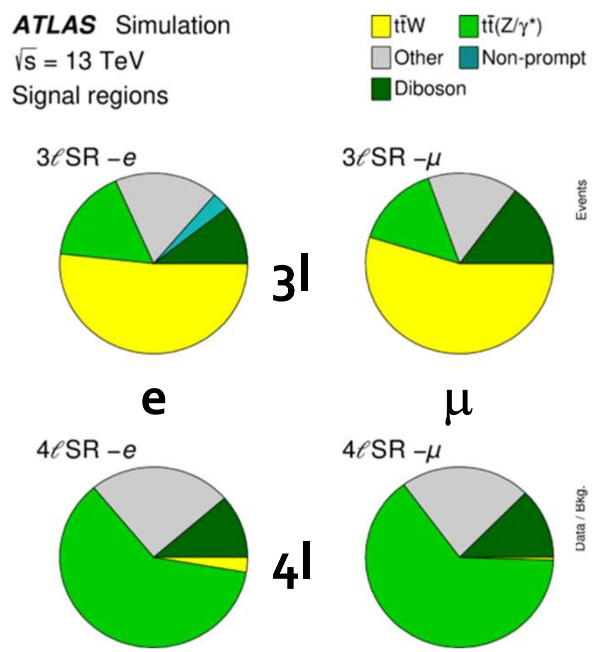
3l

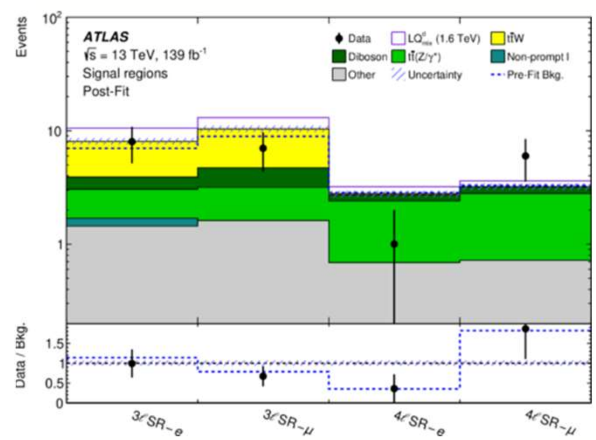


4l





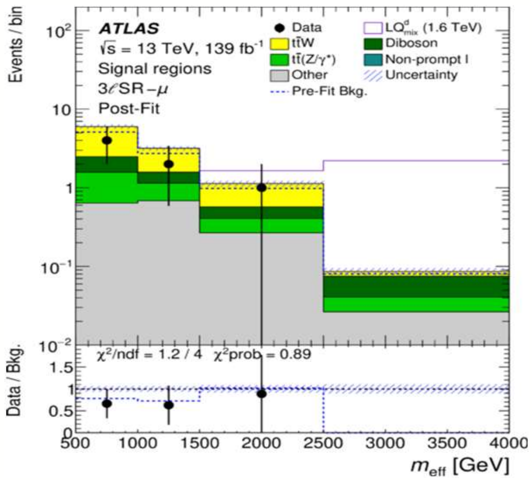




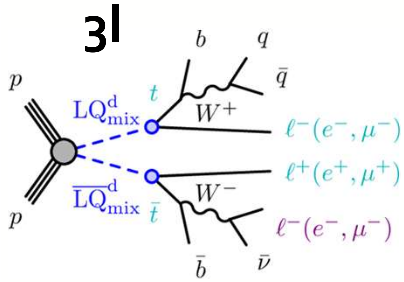
Pair production of leptoquarks → t+ light lepton(l) ttbar $\ell^+\ell^-$: in 3l or 4l final states

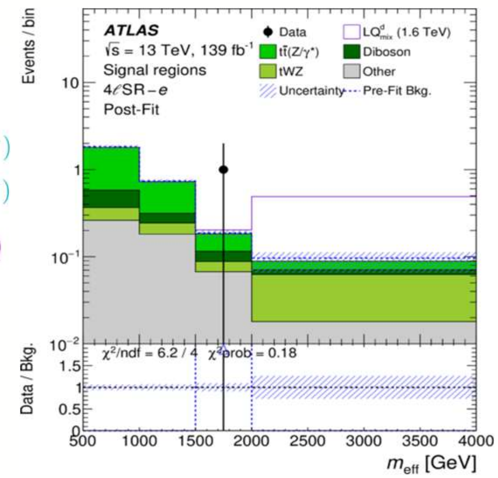
- Fit done on effective mass $m_{eff} = \sum_{l,jet} p_T + p_T^{miss}$

arXiv:2306.17642

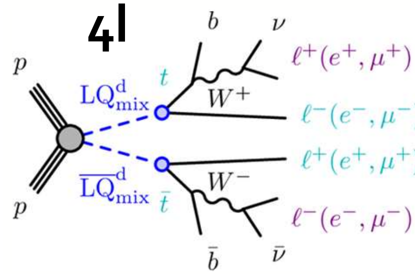


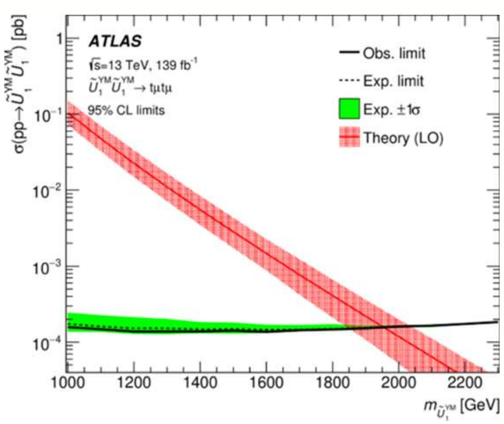
3l





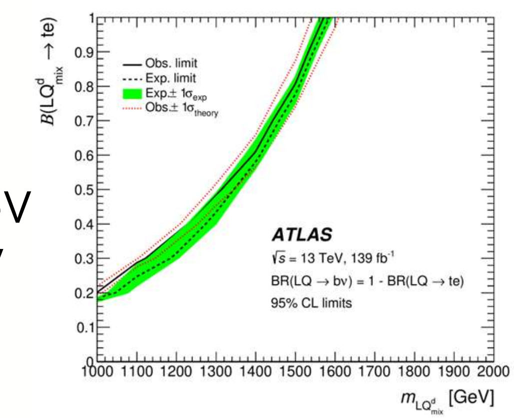
4l





Limit results, separately in te (tμ):

- ➢ scalar LQ: 1.58 (1.59) TeV
- ➢ vector LQ minimal coupl: 1.67 (1.67) TeV
- ➢ vector LQ Y-M couple. : 1.95 (1.95) TeV



Yang-Mills scenario and $\tilde{U}_1^{YM}$ exclusive decay into tμ

Pair-produced scalar and vector LQs decaying to 3rd-gen quarks and 1st/2nd-gen leptons – mixed

Scalar leptoquarks with charge -(1/3)e as well as scalar and vector leptoquarks with charge +(2/3)e

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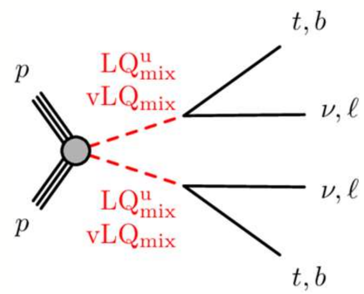
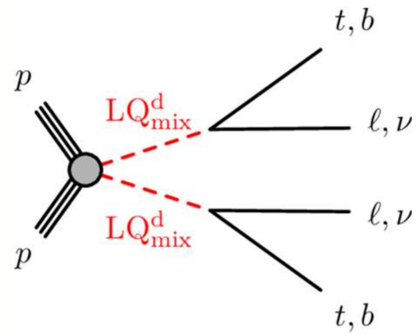
2210.04517

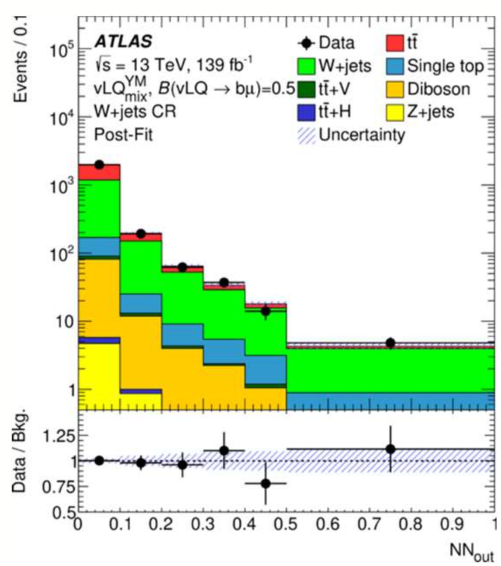


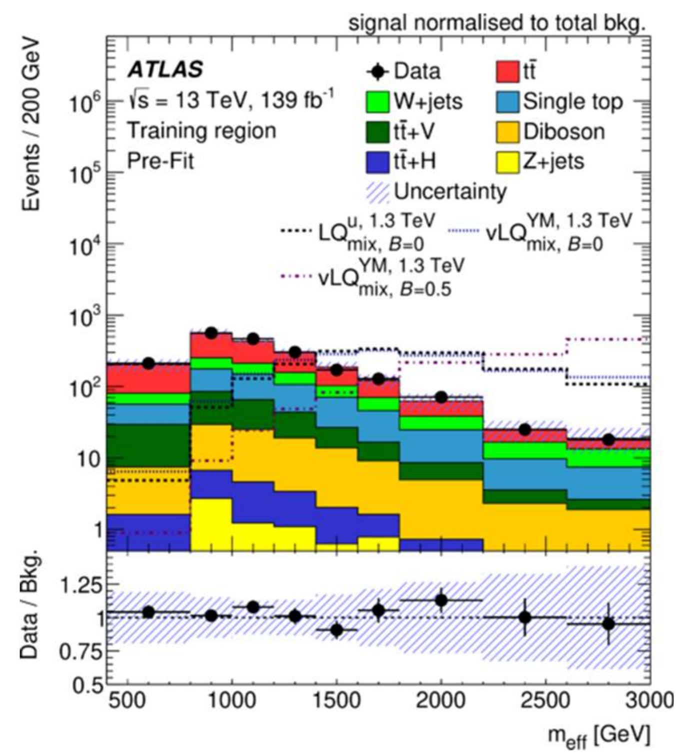
up-type scalar (LQ_{mix}^u) vector (vLQ_{mix}) LQs



down-type scalar (LQ_{mix}^d) LQs with l = e, μ

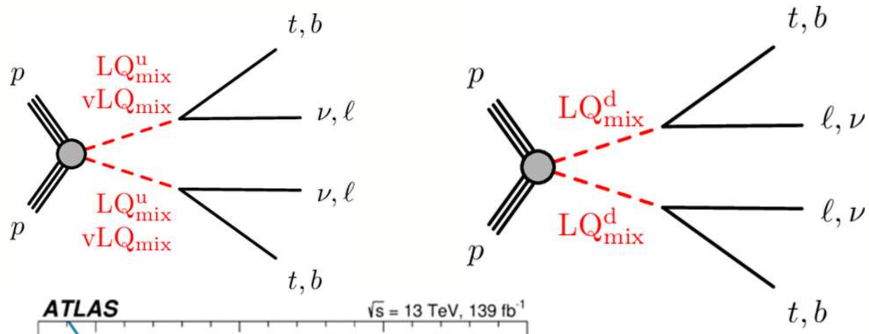
Two of these models have the goal of providing an explanation for the recent B-anomalies

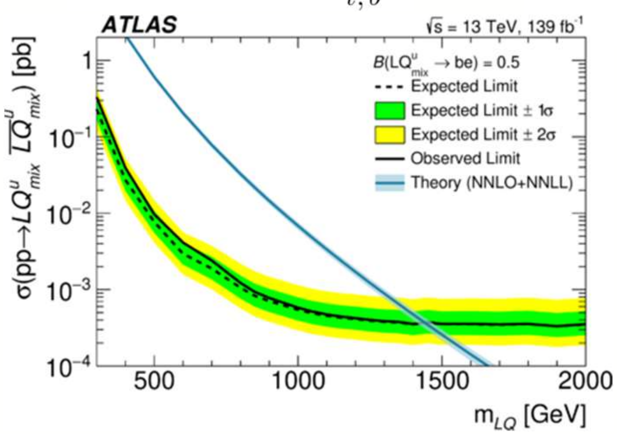


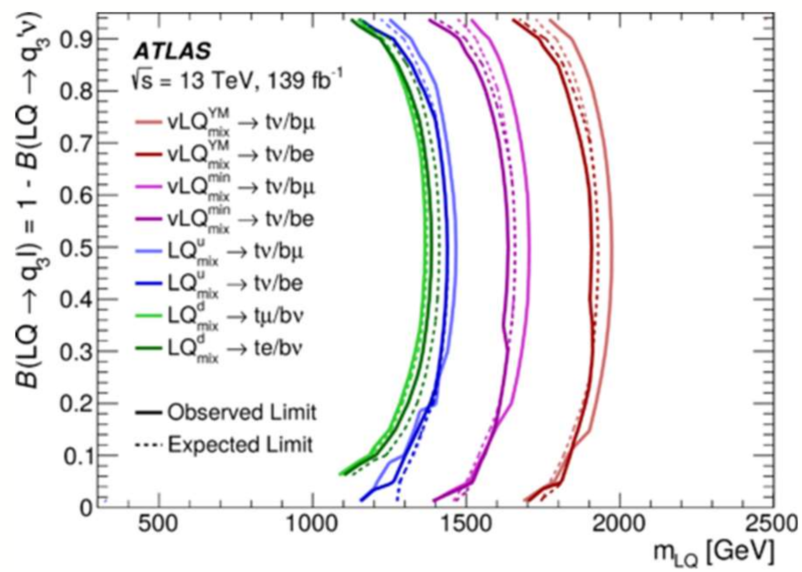


Pair-produced scalar and vector LQs decaying to 3rd-gen quarks and 1st/2nd-gen leptons – mixed

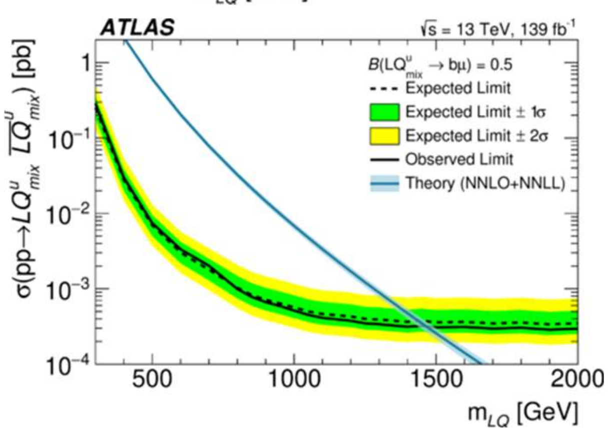
2210.04517







- ➢ up-type LQs the range in B is 0--0.95
- ➢ down-type it is 0.05--0.95.



Lower limits

- ➢ Scalar leptoquark = 1.98 TeV
- ➢ Vector leptoquark = 1.71 GeV

Leptoquark pairs with 1st/2nd generation leptons (e/μ) and light, c or b quarks

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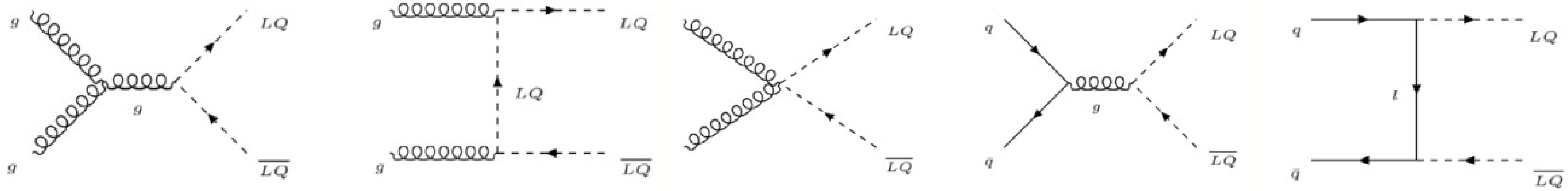
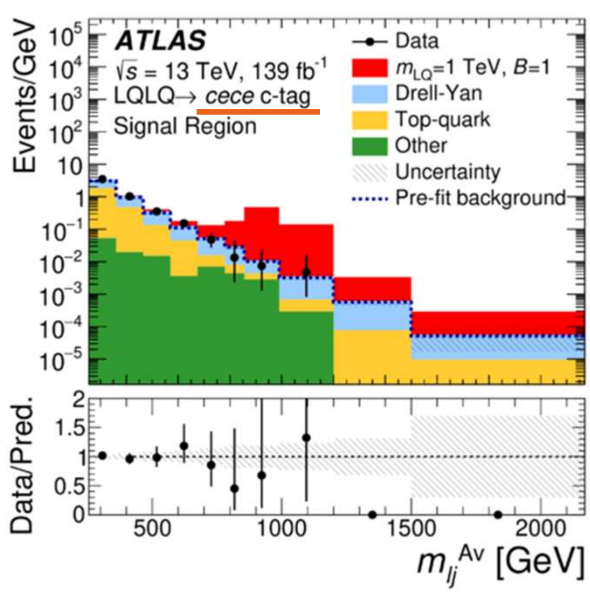
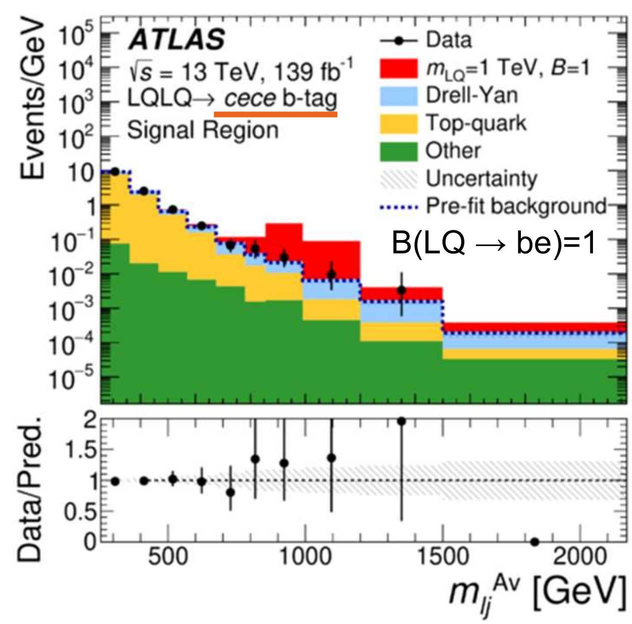
2006.05872

Event Selection

- 2e or 2μ & => 2 jets
- including jets from c- or b-quarks







Leptoquark pairs with 1st/2nd generation leptons (e/μ) and light, c or b quarks

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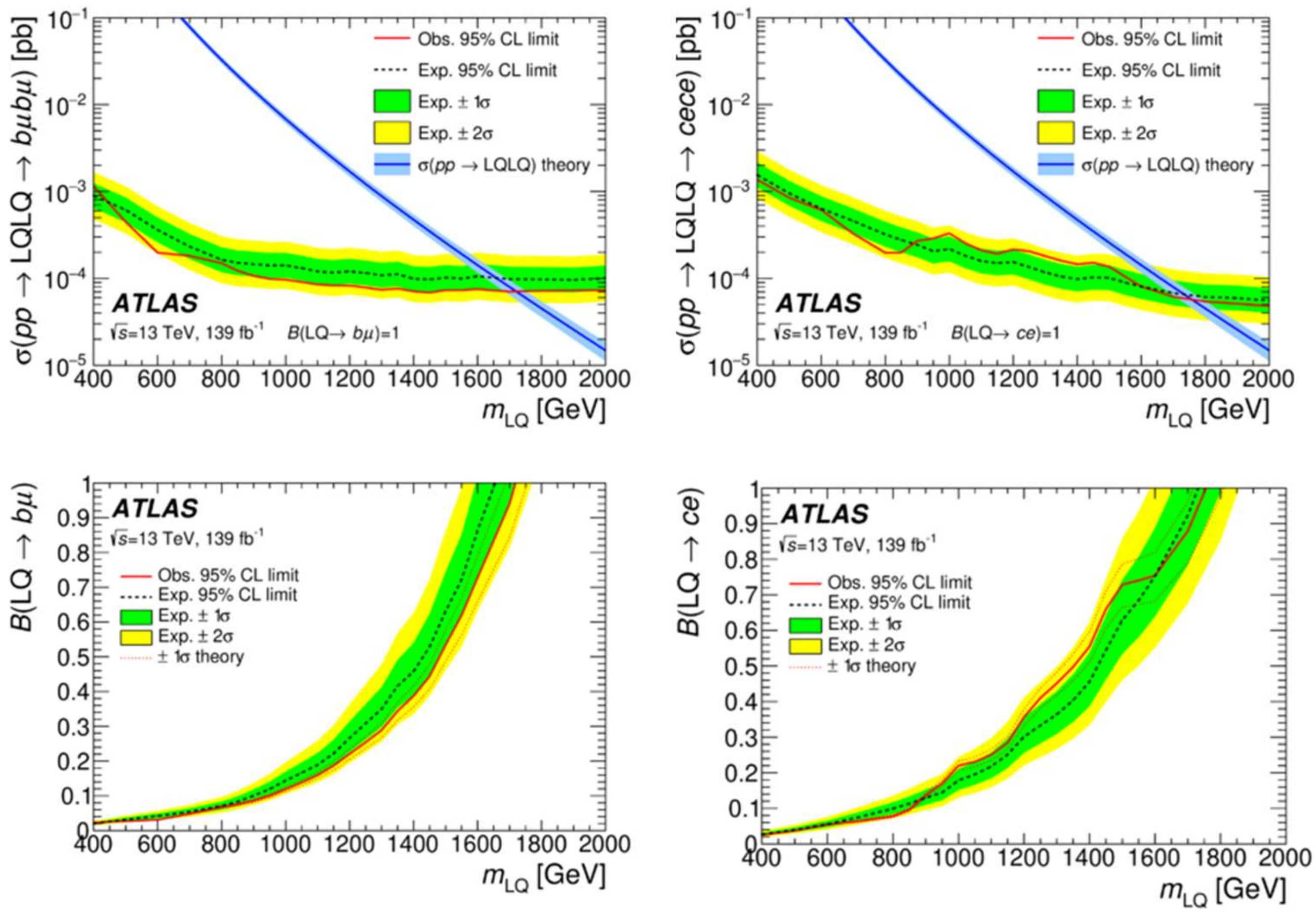
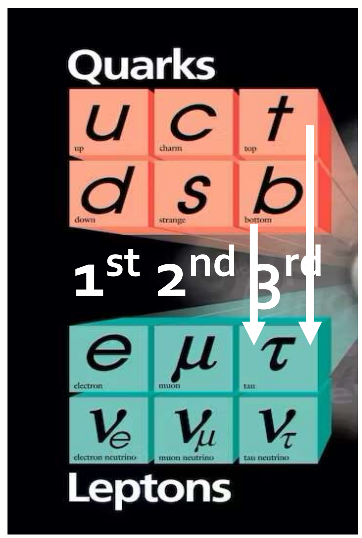


Leptoquarks with masses below

- Electron channel = 1.8 TeV
- Muon channel = 1.7 TeV

Searches for leptoquarks coupling across same flavour families

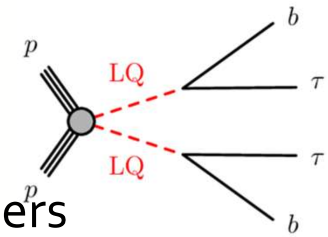


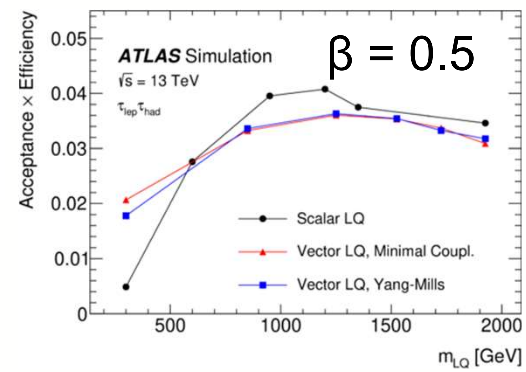
Pair Production leptoquarks decaying to $bb\tau\tau$

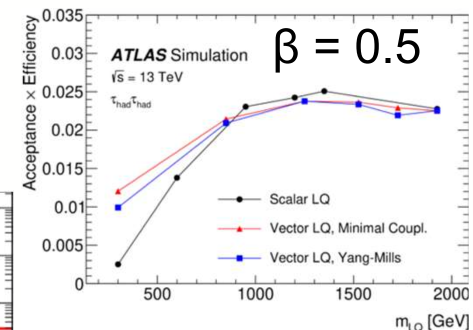
third-generation

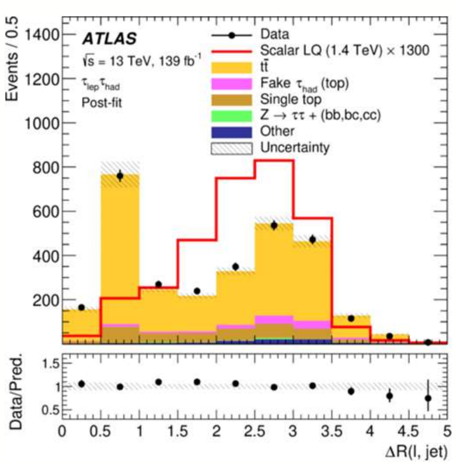
arXiv:2303.01294

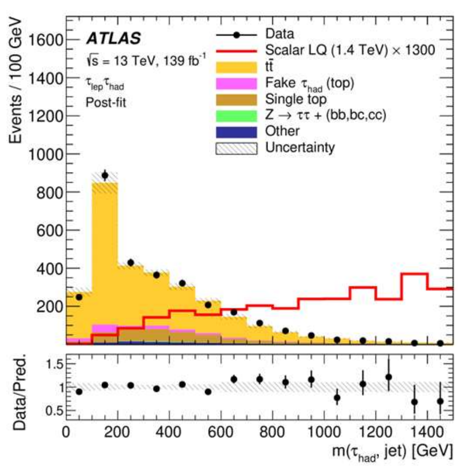
- Events selection:
  - $\tau_{lep}\tau_{had}$, $\tau_{had}\tau_{had}$ (lep=e, μ) channels
  - single-tau triggers and single lepton triggers
- Scalar sum variable: $S_T = \sum_{\tau,j} p_T + p_T^{miss} > 600$ GeV
- Major backgrounds: top, Z+jets, fake-τ_{had}
- Final fit done on **Parametric Neural Network** score
  input variables in $\tau_{lep}\tau_{had}$ SR: Δ R(ℓ, jet), m(τ_{had}, jet), s_T

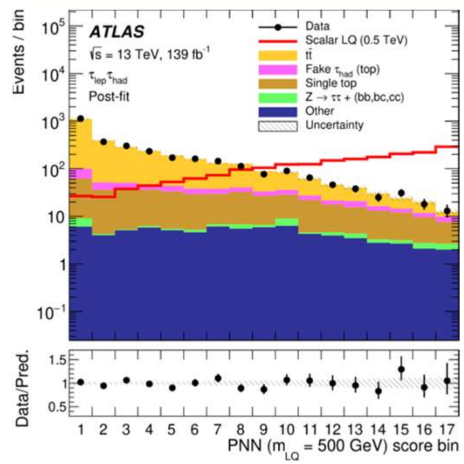












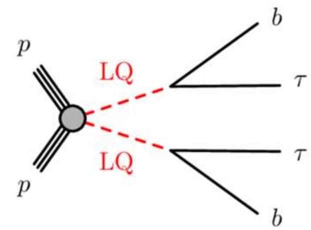
PNN score distributions in $\tau_{lep}\tau_{had}$ SR for m_{LQ} = 500 GeV

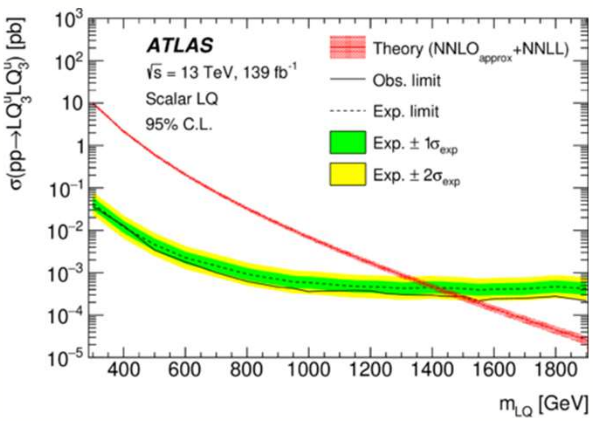
Pair Production leptoquarks decaying to bbττ

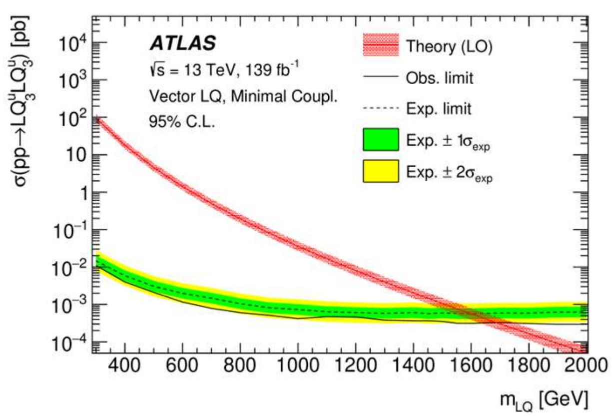
third-generation

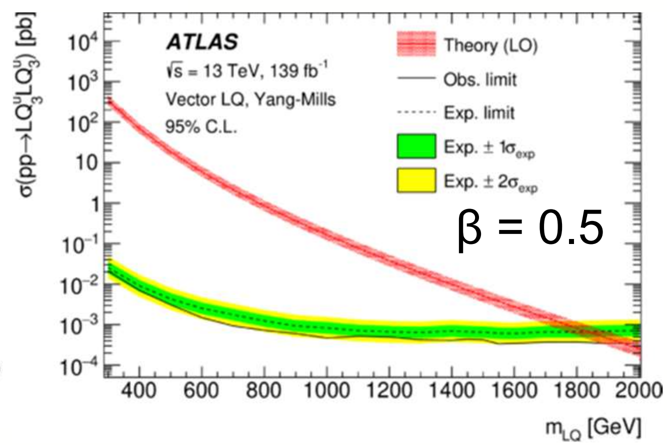
arXiv:2303.01294

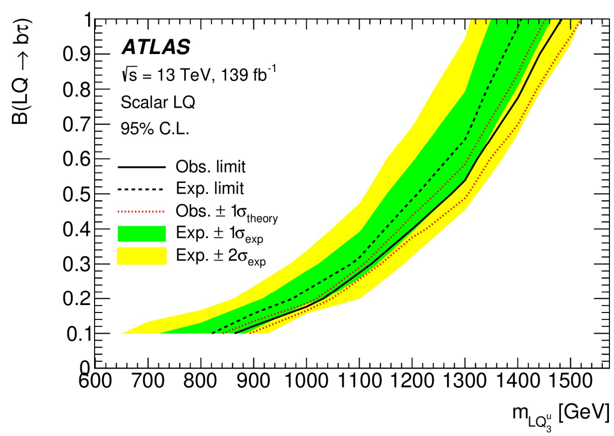
➢ $\tau_{lep}\,\tau_{had}$, $\tau_{had}\,\tau_{had}$ (lep=e, μ) channels











- Limit results

➢ scalar LQ : 1.49 TeV 100 % B.R.

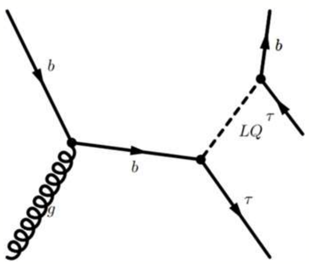
➢ vector LQ min.: 1.69TeV

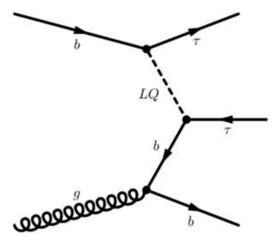
➢ vector LQ YM : 1.96 2 TeV

Leptoquark decaying to bτ final states

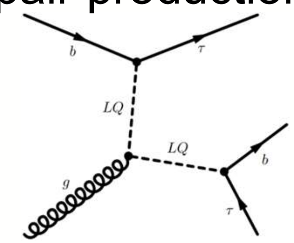
arXiv:2305.15962

single LQ production

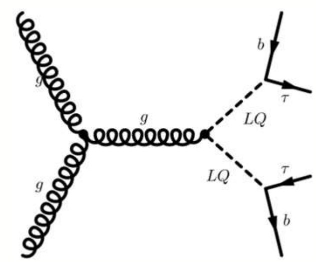




non-resonant pair production

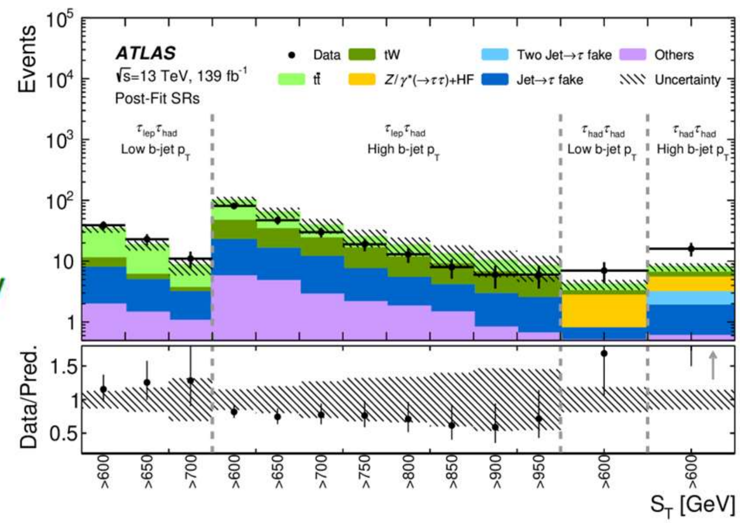


LQ pair production



vector leptoquarks: electric charge of 2/3e
scalar leptoquarks with an electric charge of 4/3e.

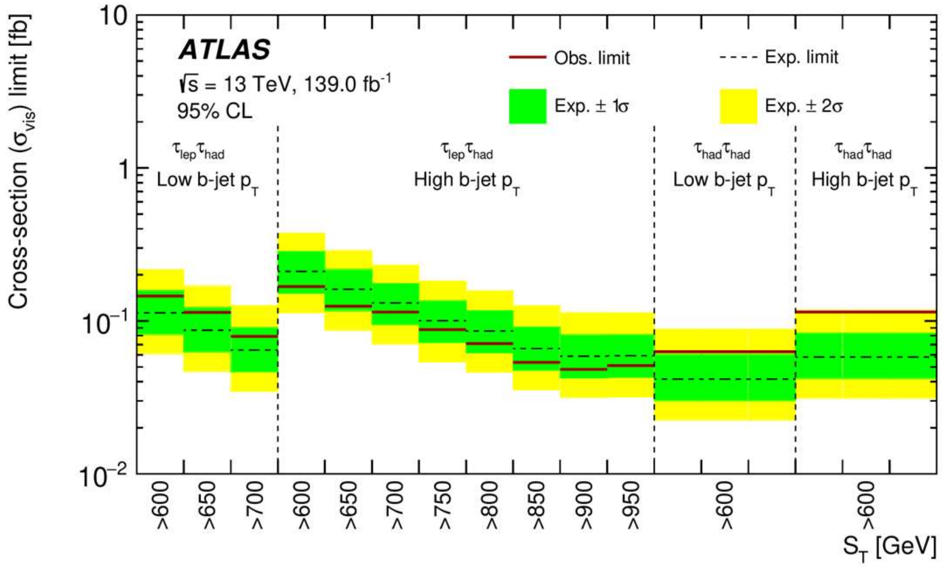
- Events selection:
  - $\tau_{lep}\tau_{had}$, $\tau_{had}\tau_{had}$ (lep=e, μ) channels
  - single-tau triggers and single lepton triggers
- Scalar sum variable: $S_T = \sum_{\tau,j} p_T + p_T^{miss}$ > 600 GeV
- Major backgrounds: top, Z+jets, fake-τ_{had}

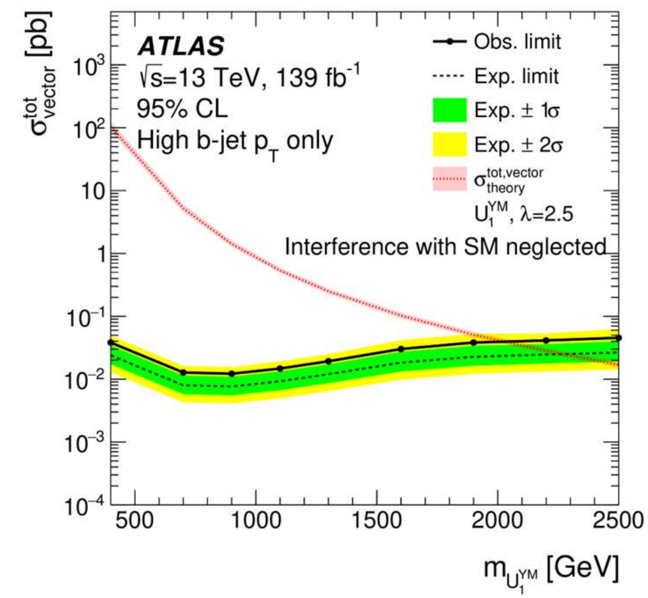


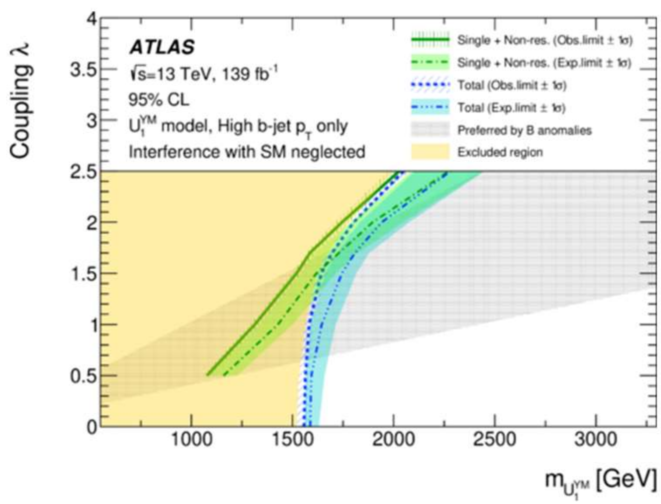
Leptoquark decaying to bτ final states

third-generation

arXiv:2305.15962







- Limit results

for min/YM & gauge coupling 1.0 2.5

- ➢ scalar LQ YM. : 1.28 TeV 1.53TeV
- ➢ vector LQ min.: 1.35 TeV 1.99 TeV
- ➢ vector LQ YM : 1.58 TeV 2.05 TeV

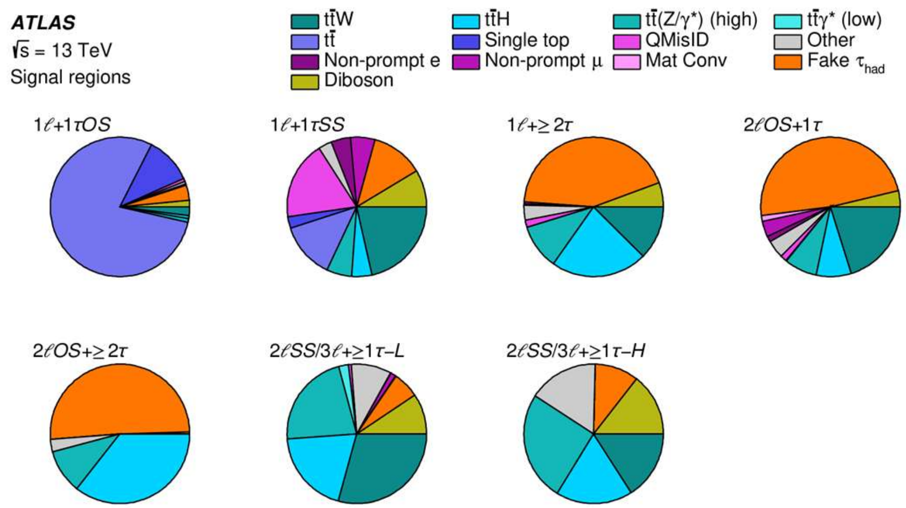
Scalar pair production of 3rd-generation leptoquarks : decaying to t quark & τ

2101.11582

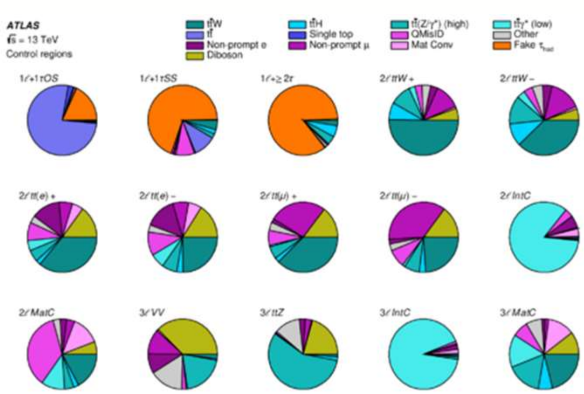
Event Selection

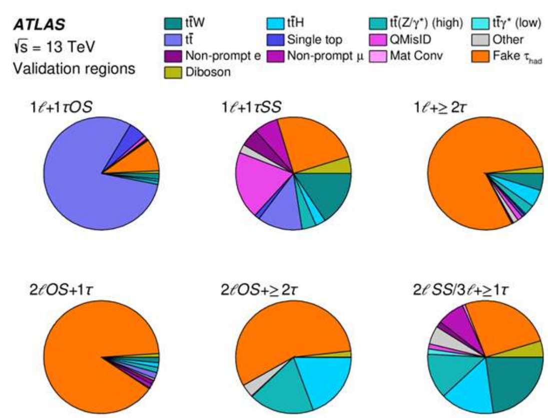
- one light lepton (l) (e or μ)
- >= one τ_{had}-lepton, or >= 2 l
- >= 2 jets, one or more b-tag

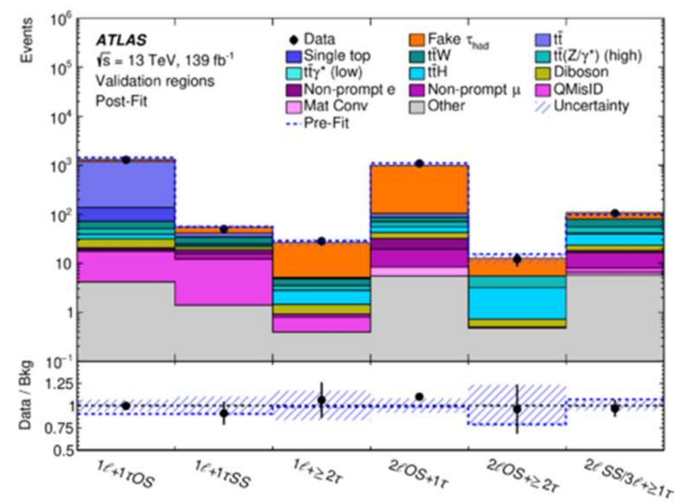
Final states, defined by the multiplicity and flavour of lepton candidates



- ➢ Total predicted background in each of
- ➢ 15 control region categories
- ➢ 6 validation region categories







Scalar pair production of 3rd-generation leptoquarks: decaying to t quark & τ

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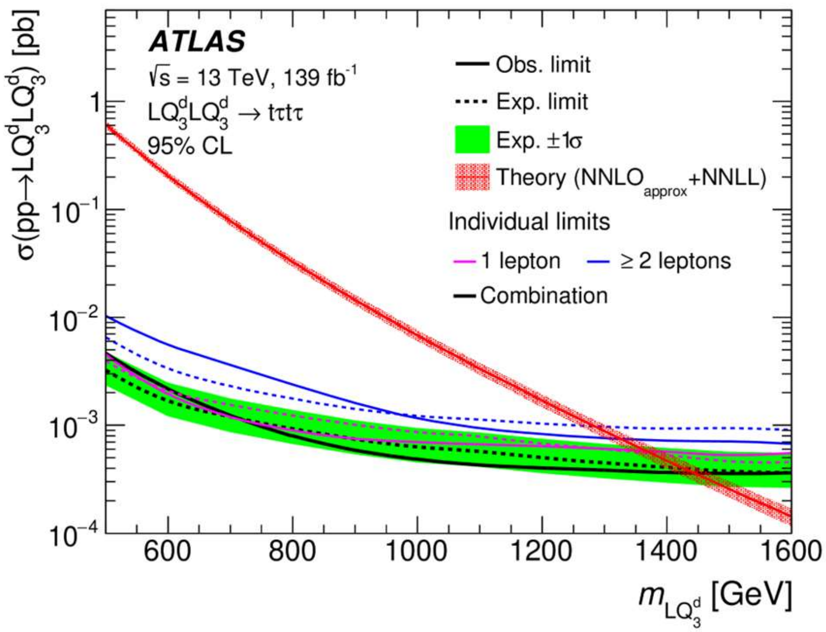
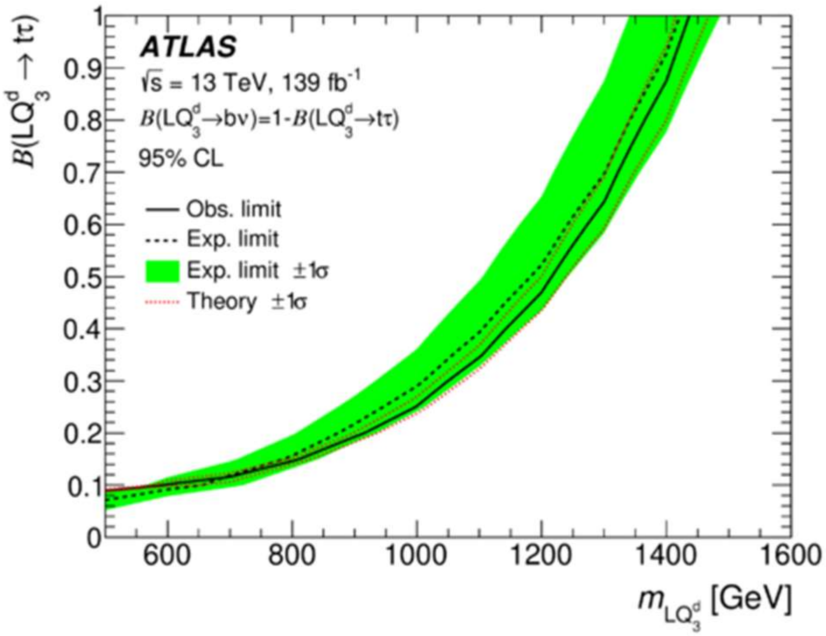
2101.11582





Scalar leptoquarks decaying exclusively to tτ are excluded up to

- masses of 1.43 TeV
- for BF 50% into tτ, lower mass limit is 1.22 TeV.

Majorana neutrinos in same-sign WW

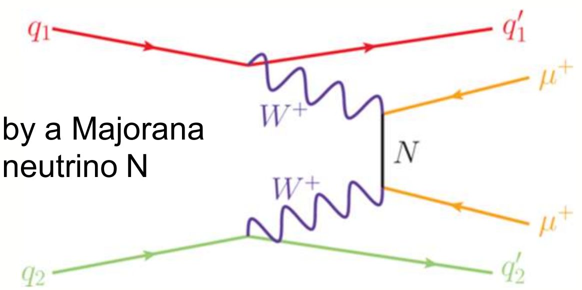
arXiv:2305.14931

Final states include
- ➢ exactly two same-sign muons
- ➢ & ≥ hadronic jets well separated in rapidity

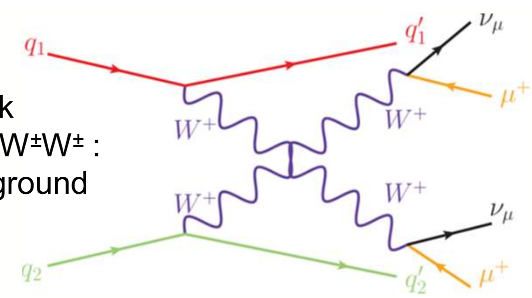
Main backgrounds:
SM same-sign WW scattering and WZ production modelled and constrained with data in dedicated signal-depleted Control Regions

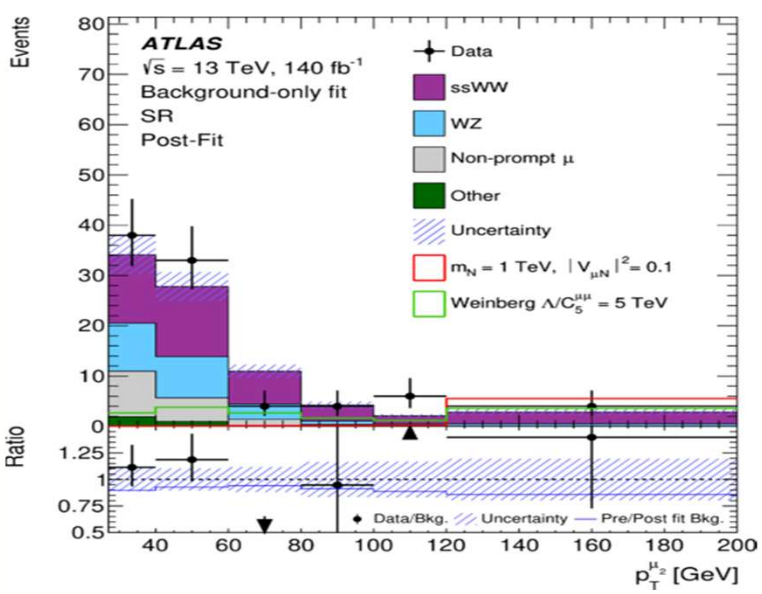
same-sign $\mu^\pm\mu^\pm$ production in $W^\pm W^\pm$ scattering mediated

by a Majorana neutrino N



electroweak same-sign $W^\pm W^\pm$: main background



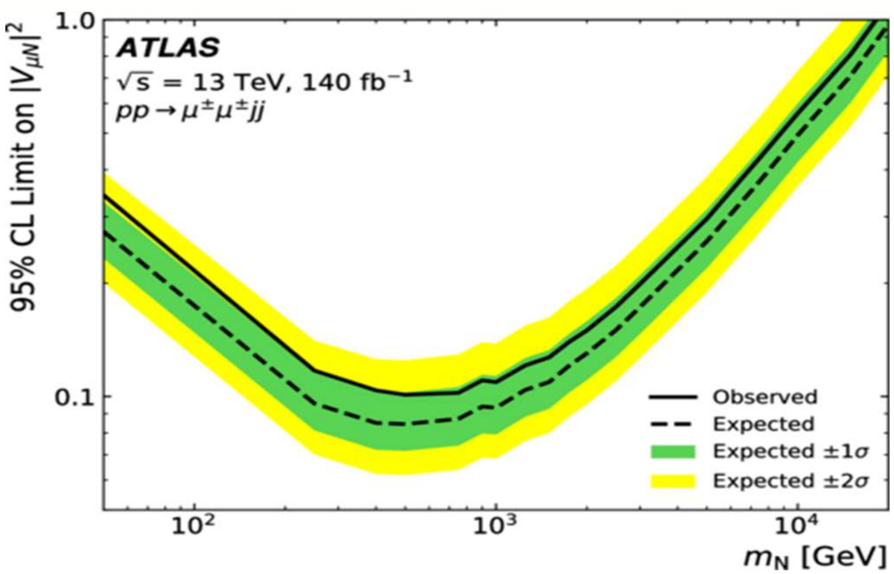


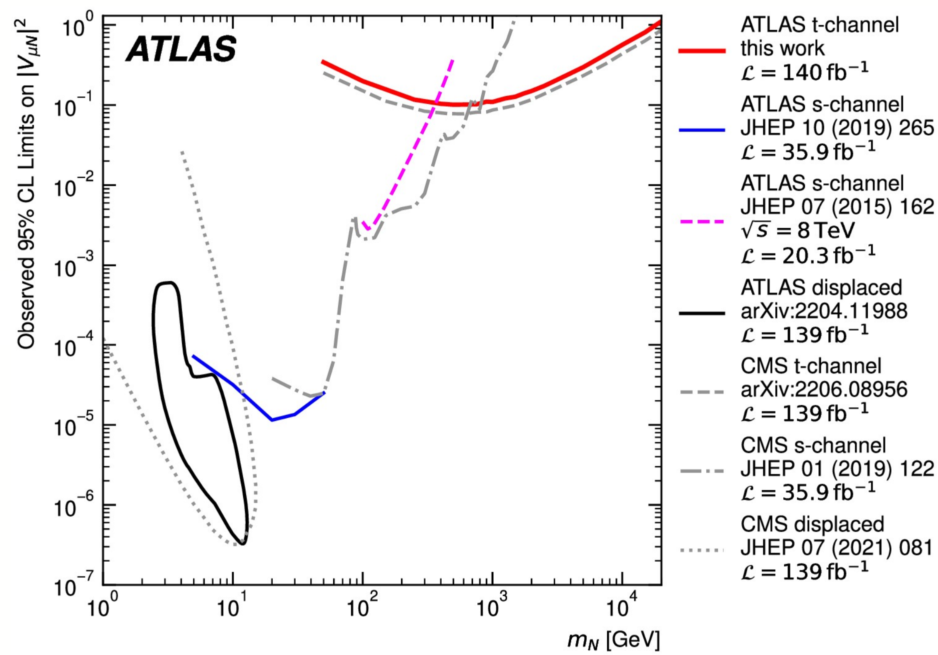
Search region: 50 GeV and 20 TeV

Majorana neutrinos in same-sign WW

arXiv:2305.14931

Benchmark:
PType-I Seesaw model



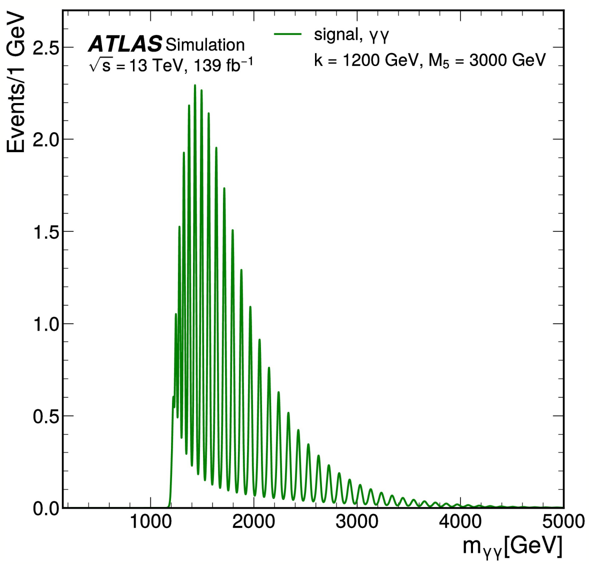


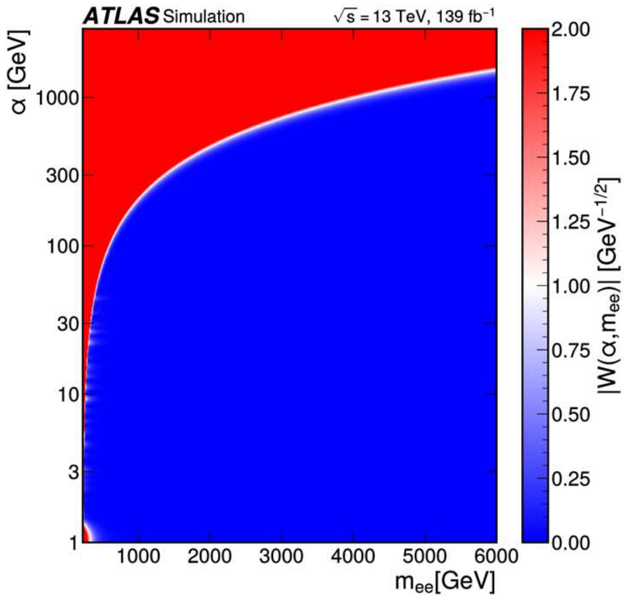
Search for periodic signals in dielectron and diphoton masses

2305.10894

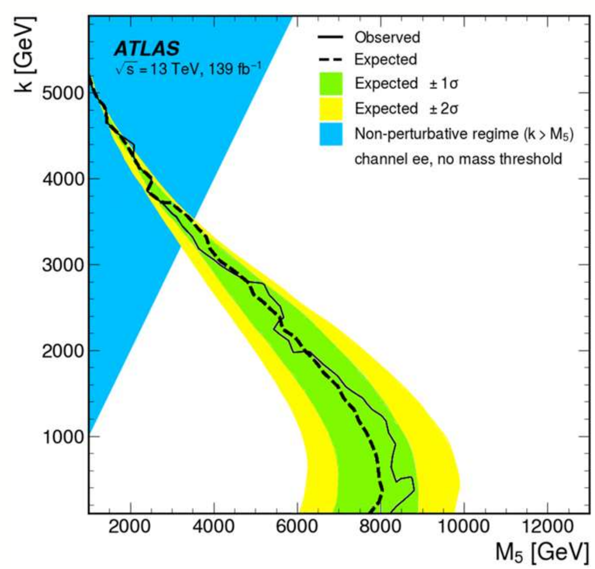
- Novel search techniques based on continuous wavelet transforms
- used to infer the frequency of periodic signals from the invariant mass spectra
- neural network classifiers used to enhance sensitivity to periodic resonances

Signal invariant mass shape





Scalogram output of the CWT of dielectron background-only toy exper.
α = CWT scale parameter
W(α,β) = wavelet coefficients,
invariant mass → β.



Summary

ROYAL HOLLOWAY UNIVERSITY OF LONDON

- ATLAS have an active search program searching for
- New physics to explain anomalies
- Leptoquarks – cross and same generation
- Novel search for gravitons
- New gauge bosons, Lepton Flavour Violation

- We are looking forward to analysing the Run 3 data!

Thanks for listening!

ATLAS EXPERIMENT

Thanks for listening!