Leptoquarks and other leptonic final states with the ATLAS experiment

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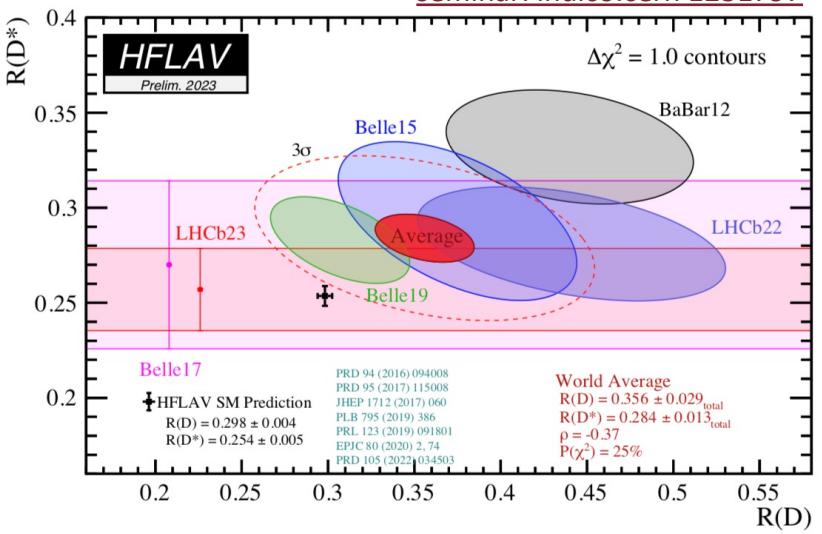
Introduction : anomalies in the flavour sector

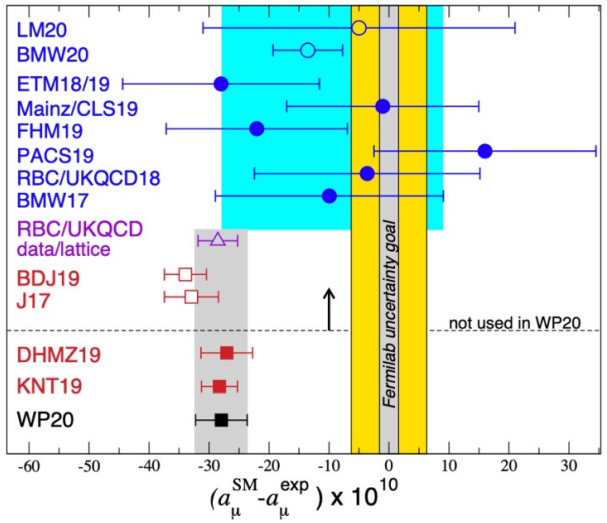
- Several **anomalies** in the **flavour** sector have been recently measured:
  - R_D / R_{D^*} , 3.2σ anomaly in global average
  - R_K / R_{K^*} , anomalies measured by LHCb in 2019, gone away in 2022
  - ΔC_9 anomaly, 3.4σ deviation measured by LHCb
  - g-2 anomaly measured at Fermilab ...

- **ATLAS** is looking for new physics to explain this, **in leptonic final states**

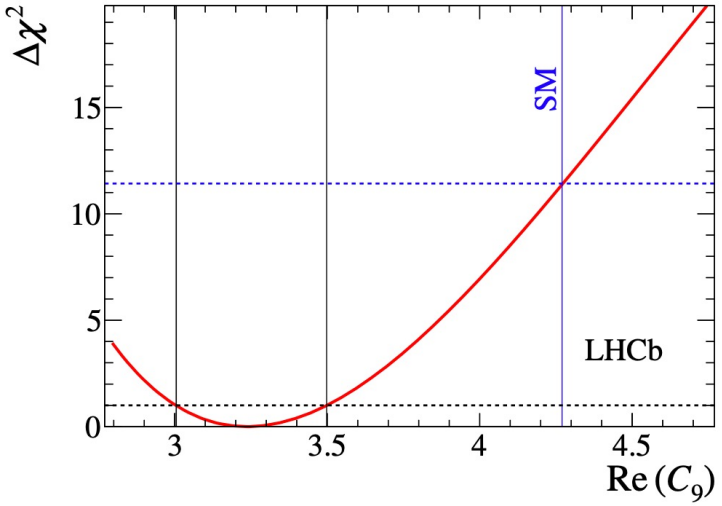
seminar: indico.cern 1231797



arXiv:2106.06723



JHEP 02 (2016) 104



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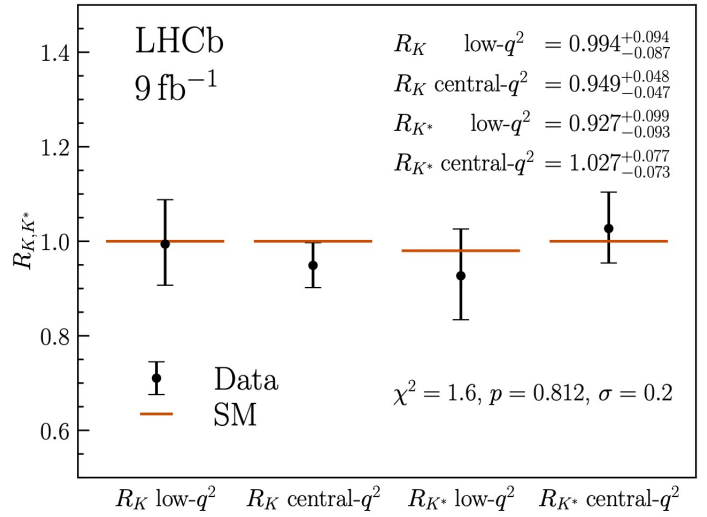
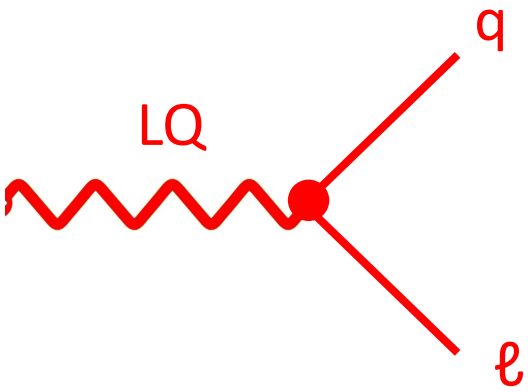


Leptoquarks : a possible solution to anomalies

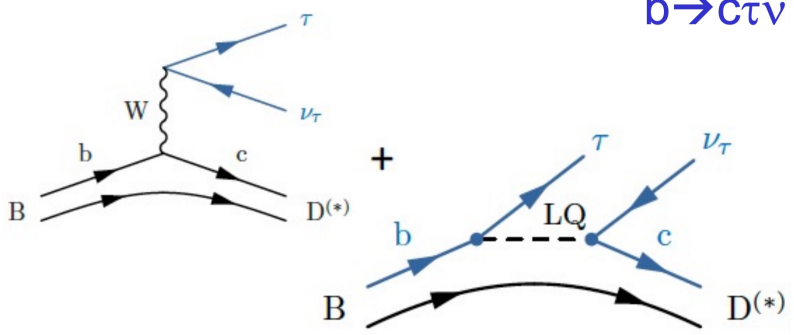
- **Leptoquarks**: possible explanation for many flavour anomalies:
  - interact with both leptons and quarks (lep. number as 4th colour)
  - **scalar** or **vector**, fractional electric charge
  - two coupling scenarios: **minimal** coupling or **Yang-Mills**



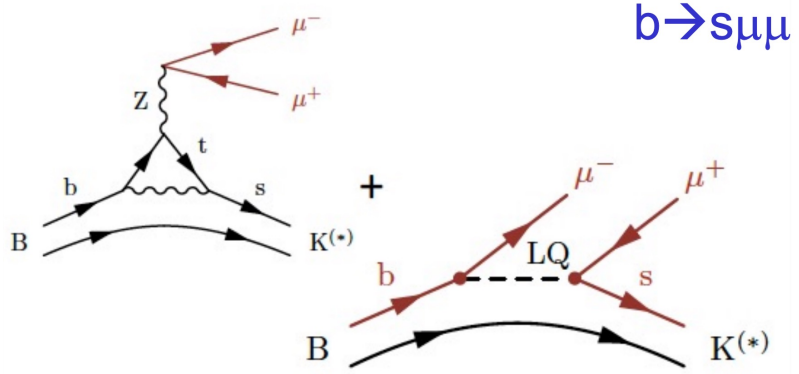
- First introduced in the 70s by **Pati & Salam**, based on the **SU(4)** symmetry

- Today improved and extended theory, e.g. “4321” model, U_1 LQ model

b→cτν



b→sμμ

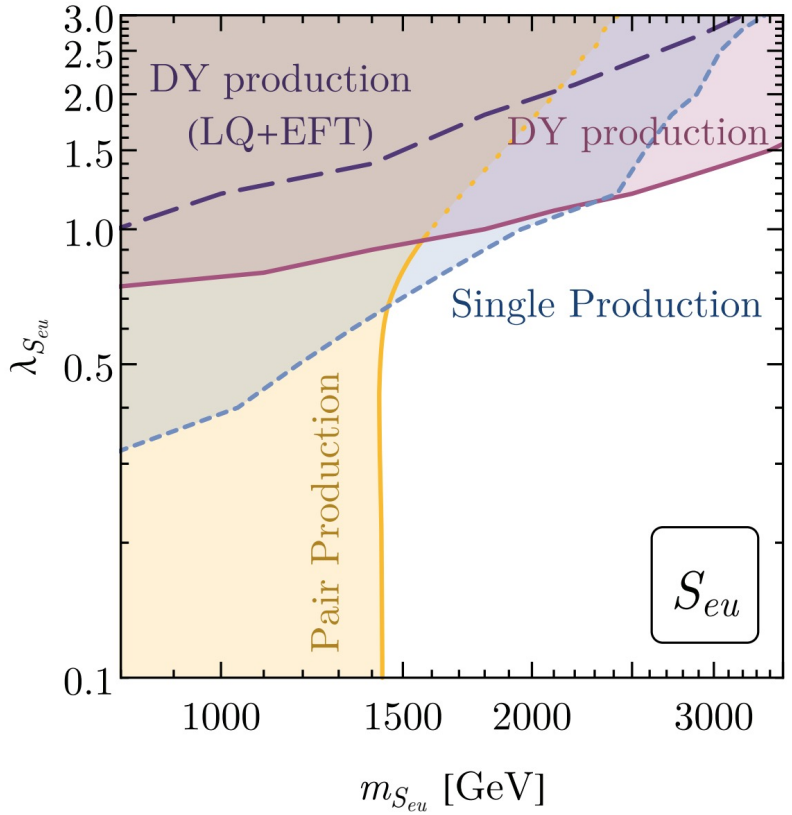


LQ type	$R_{K^{(*)}}$	$R_{D^{(*)}}$	$(g-2)_\ell$ at 1L
S_1	✗*	✓	✓
$\tilde{S}_1$	(✗)	(✗)	✗
$\vec{S}_3$	✓	✗	✗
R_2	✗*	✓	✓
$\tilde{R}_2$	✗	✗	✗
U_1	✓	✓	✗
$\tilde{U}_1$	✓	✗	(✗)
$\vec{U}_3$	✓	✗	(✗)

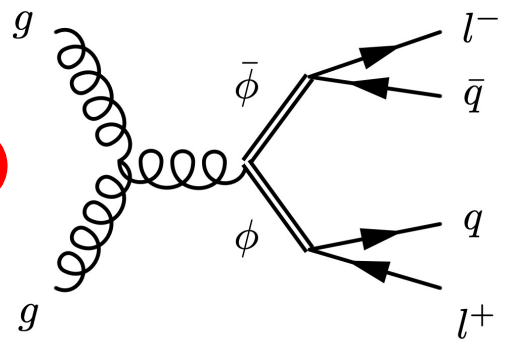
Leptoquarks : production modes

- Three classes of production processes:
  - **pair-production** ⇒ 2 ℓ + 2 jet final states. (A)
  - **single production** ⇒ 2 ℓ + 1 jet final states (B)
  - **Drell-Yan** with exchange in t-channel ⇒ 2 ℓ final states. (C)

- Production process determines the **exclusion area**:
  - pair-production good for low masses at any coupling
  - single production and Drell-Yan good for high masses



A



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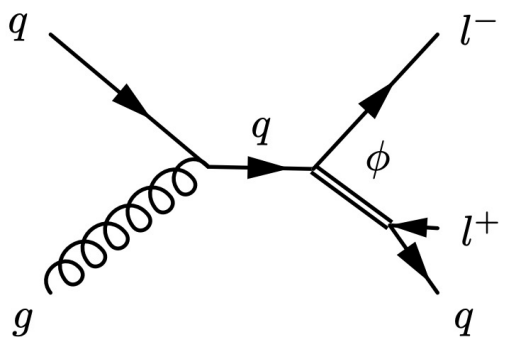
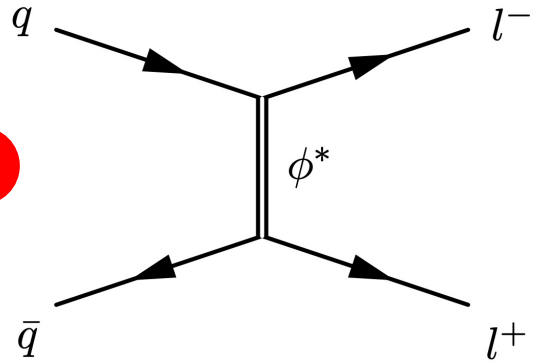


C



arxiv 1810.10017

Looking for new physics : leptoquarks and leptonic final states

- Leptoquark decay is ruled by the β tensor encoding the flavour structure:
  - **cross-generational decay** $\Longrightarrow$ off-diagonal terms
  - **same-generation decay** $\Longrightarrow$ in-diagonal terms

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$$\mathcal{L}_U \supset \frac{g_U}{\sqrt{2}} \left(U^\mu J_\mu^U + \text{h.c.}\right)$$

$$J_\mu^U = \beta_L^{i\alpha} \left(\bar{q}_L^i \gamma_\mu \ell_L^\alpha\right) + \beta_R^{i\alpha} \left(\bar{d}_R^i \gamma_\mu e_R^\alpha\right)$$

- **Not only leptoquarks**: other exotic hypotheses addressing flavour anomalies, with multilepton final state:
  - **vector-like** fermions
  - new heavy **resonances** at the TeV scale
  - **clockworks**

$$\beta_L = \begin{pmatrix} 0 & 0 & \beta_L^{d\tau} \\ 0 & \beta_L^{s\mu} & \beta_L^{s\tau} \\ 0 & \beta_L^{b\mu} & 1 \end{pmatrix}$$

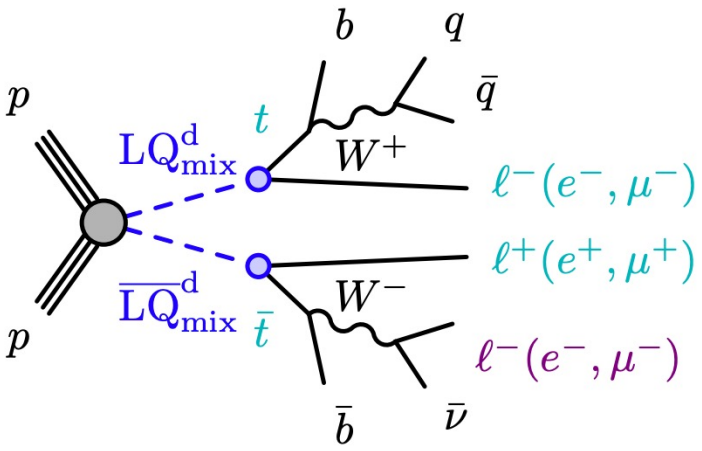
$$\beta_L \sim$$ 

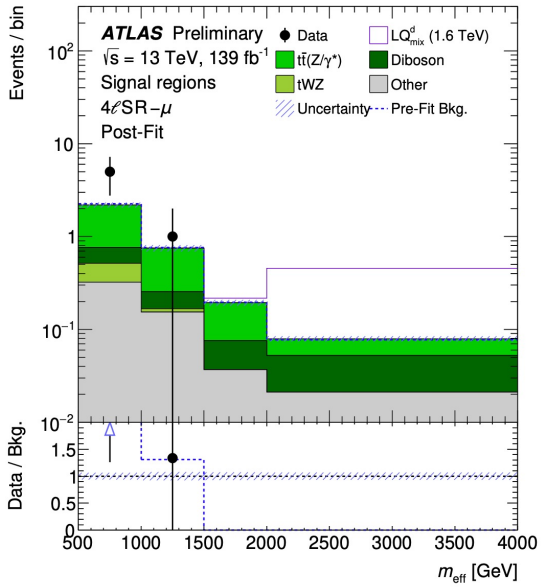
This talk: overview of all first ATLAS searches looking for New Physics exploiting leptonic final states

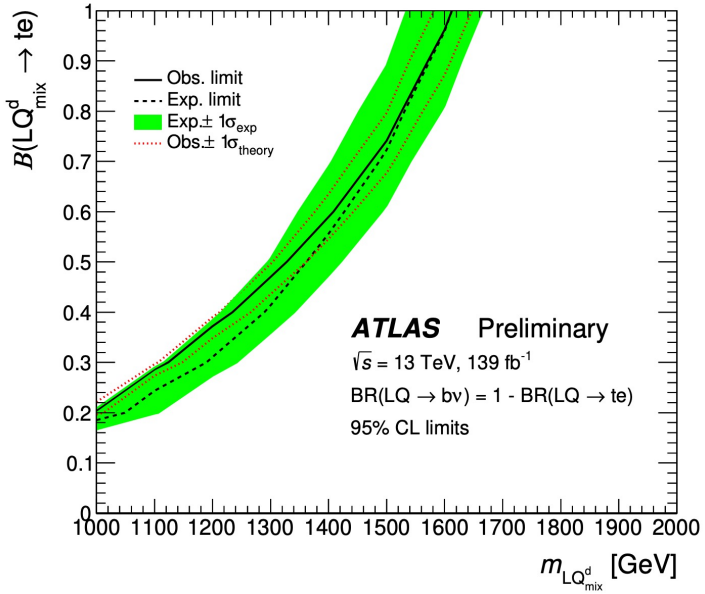
Searches for leptoquarks coupling across different flavour families

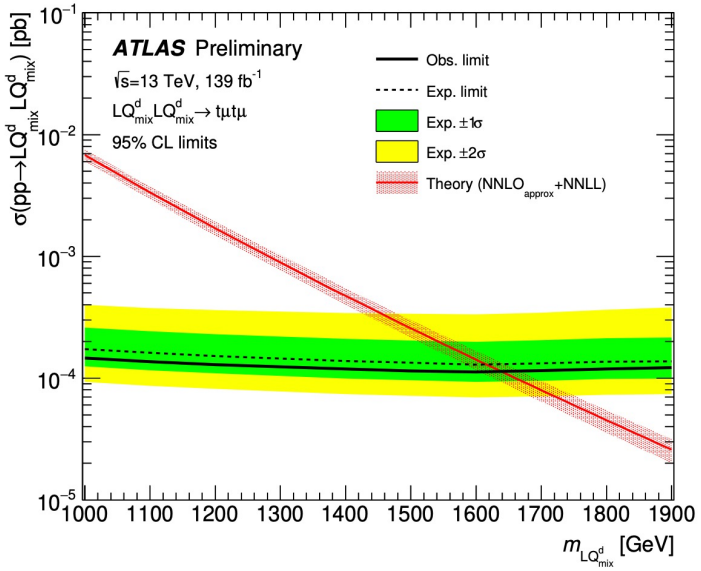
ttbar $\ell^+\ell^-$: pair production in multilepton final states

- Events selection: ≥ 2 light lep, ≥ 2 jets, ≥ 1 b-jet
- **Analysis regions**:
  - signal: (3l, 4l), for tete tμtμ, min(m_{ll})>100 GeV
  - control: backgrounds ttW, ttZ/γ*
- Fit done on **effective mass**: $m_{eff} = \sum_{l,jet} p_T + p_T^{miss}$









ATLAS-CONF-2022-052

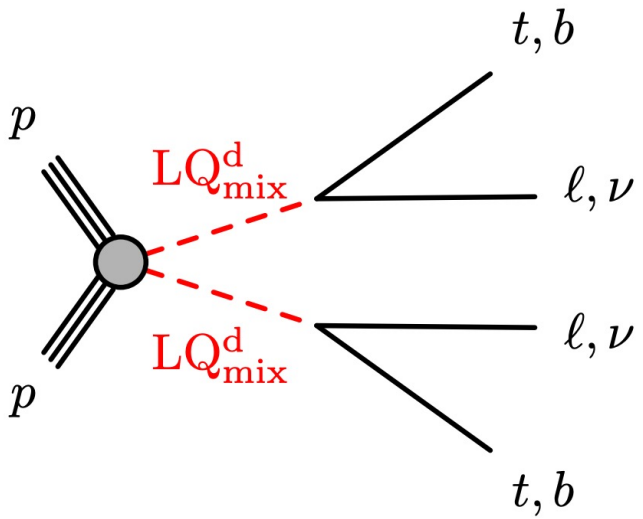
- **Limit results**, separately in te (tμ):
  - scalar LQ: 1.61 (1.64) TeV
  - vector LQ minimal coupl. : 1.71 (1.73) TeV
  - vector LQ Y-M coupl. : 2.0 (2.0) TeV

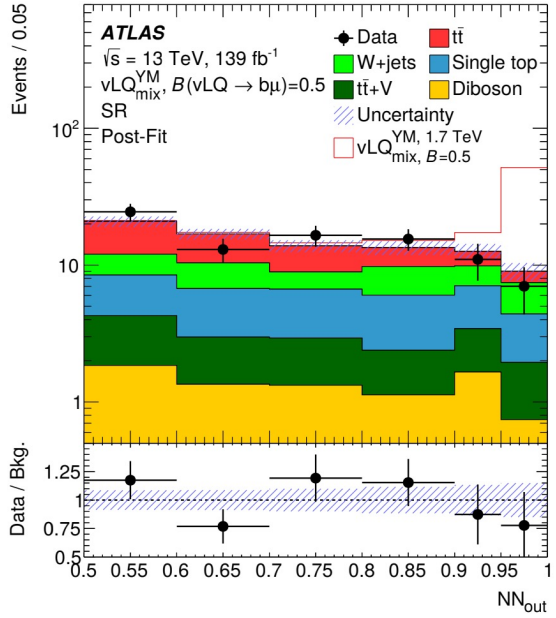
t,b ℓ,ν: pair production in single lepton final state

- Events selection:
  - **exactly one lepton** (e,μ) form LQ or t_{lep} decay
  - missing transverse momentum (from ν)
  - ≥ 4 hadronic jets

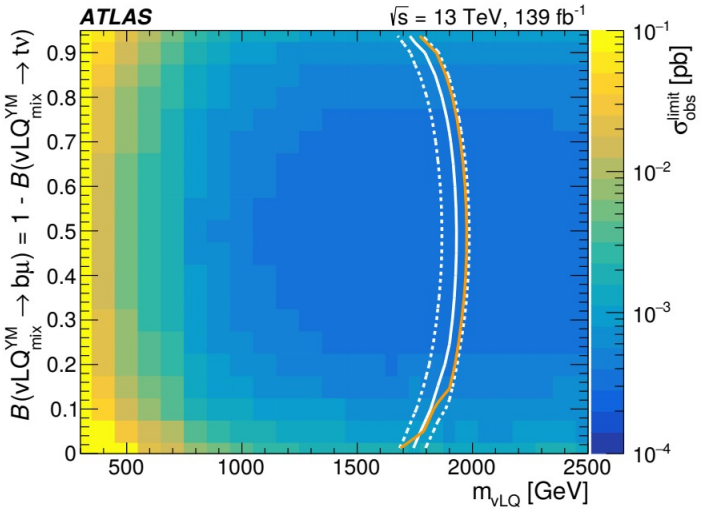
- **Top reweighting** region for data-driven rescaling of ttbar and single-top backgrounds

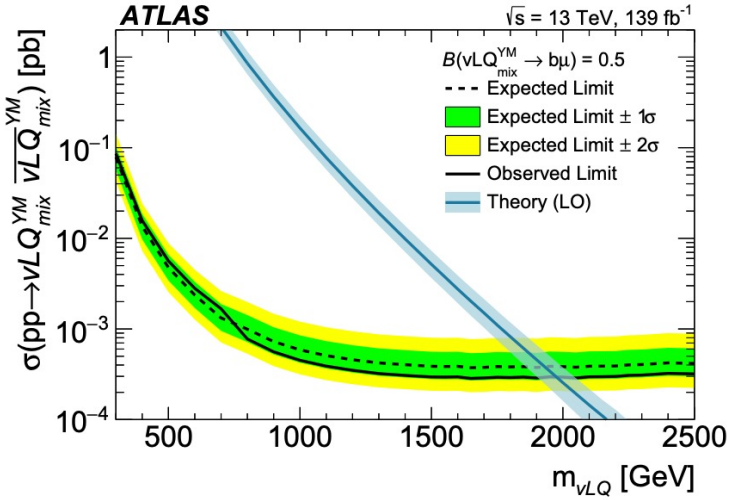
- Fit done on **NN_{out} score** after training in a separate region





arxiv:2210.04517

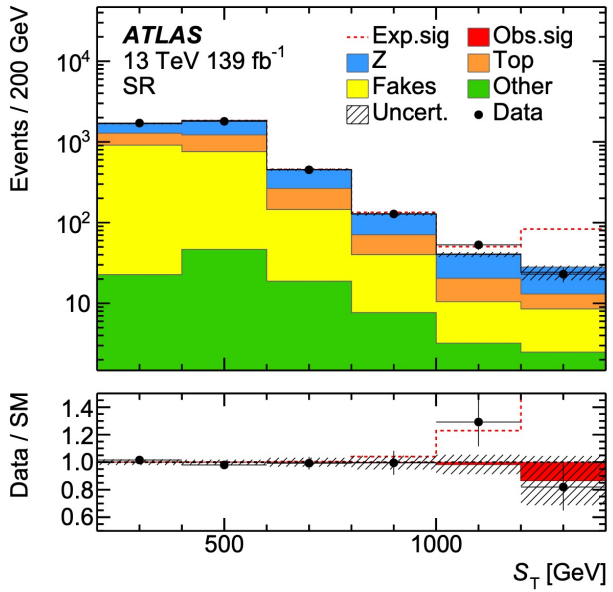


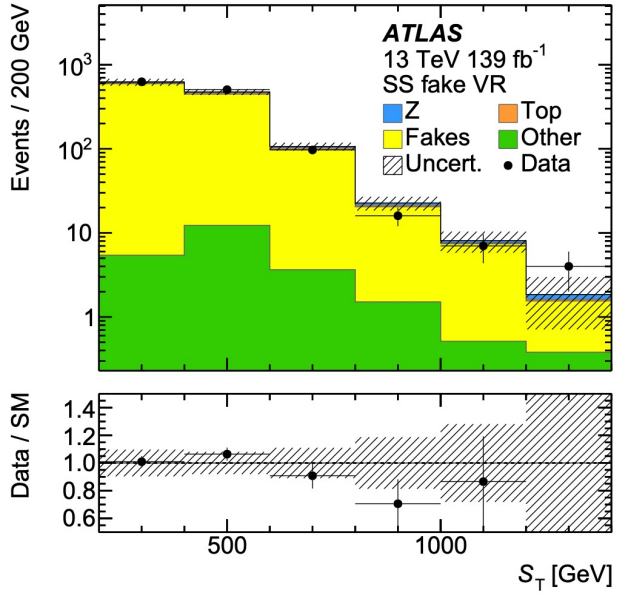


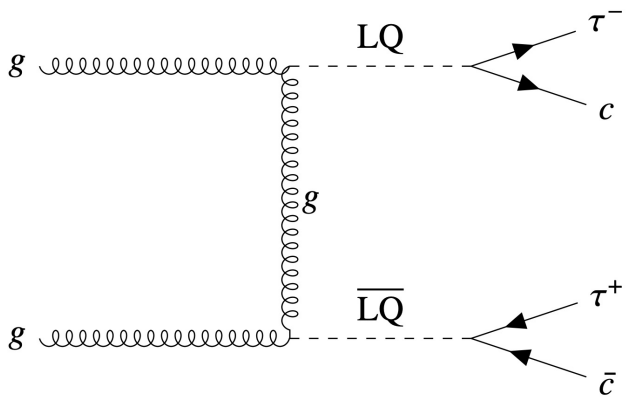
- **Limit results**, in μ(e) final states:
  - up sc. LQ: 1.47 (1.44) TeV
  - down sc. LQ: 1.37 (1.39) TeV
  - vector LQ min. coupling: 1.71 (1.62) TeV
  - vector LQ Y-M coupling: 1.98 (1.90) TeV

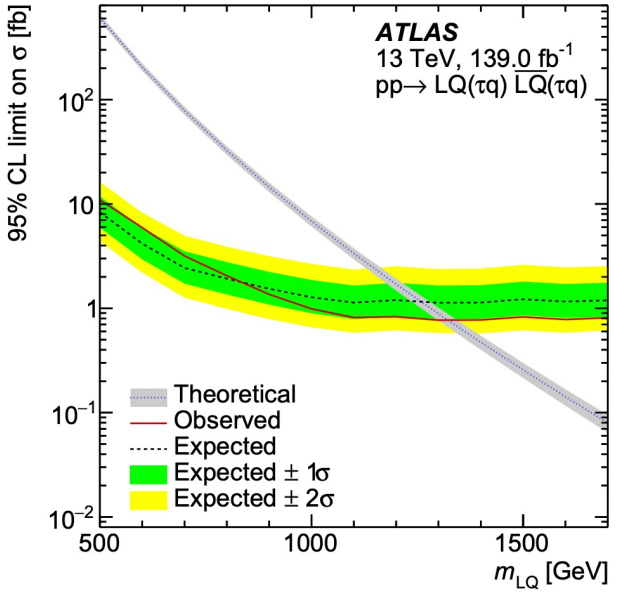
$cc\tau\tau$: pair production in di-tau final states

- Events selection: 2 τ_{had} + $\geq$ 2 jets, di-tau triggers
- Main backgrounds: Z+jets, multijet, ttbar, single top.
- Multijet background due to **jet** $\rightarrow$ τ_{fakes} , estimated with the **FakeFactors method**:
  - ➢ same-sign validation region to cross-check the estimate









arxiv:2303.09444

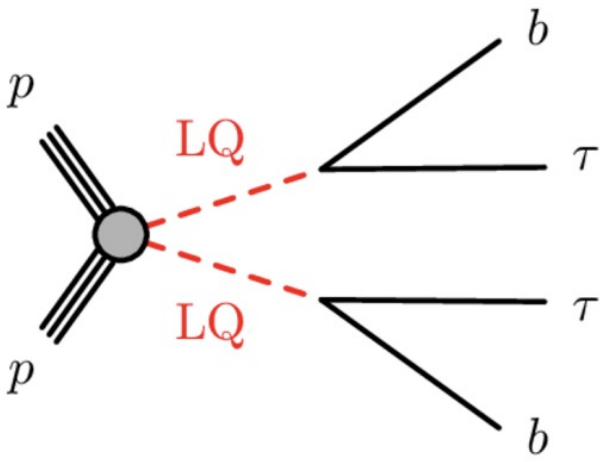
- Limit result for scalar LQ only: m_{LQ} > 1.3 TeV

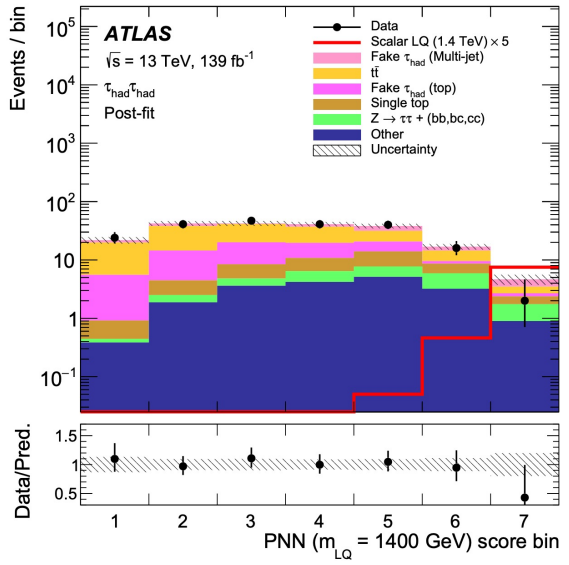
Note: no flavour tagging algorithm is used in the analysis, hence limit results hold also for lighter quarks u, d, s

Searches for leptoquarks coupling in the same flavour family

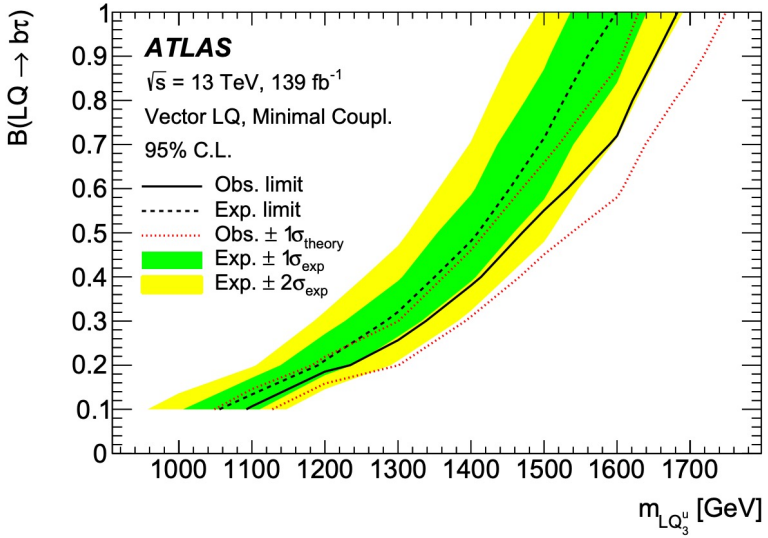
$bb\tau\tau$: pair production in di-tau final states

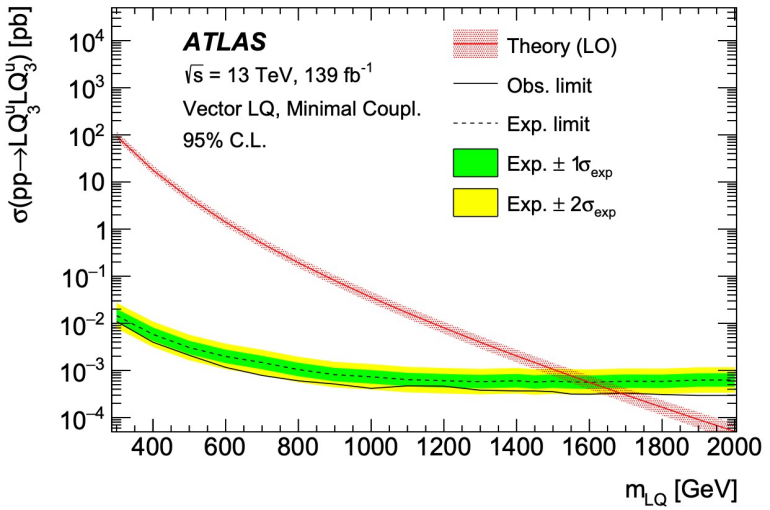
- Events selection:
  - $\tau_{lep}\tau_{had}$, $\tau_{had}\tau_{had}$ (lep=e, μ) channels
  - single-tau triggers and single lepton triggers
- Scalar sum variable: $S_T = \sum_{\tau,j} p_T + p_T^{miss} > 600$ GeV
- Major backgrounds: top, Z+jets, fake-τ_{had}
- Final fit done on parametric **neural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





arxiv:2303.01294





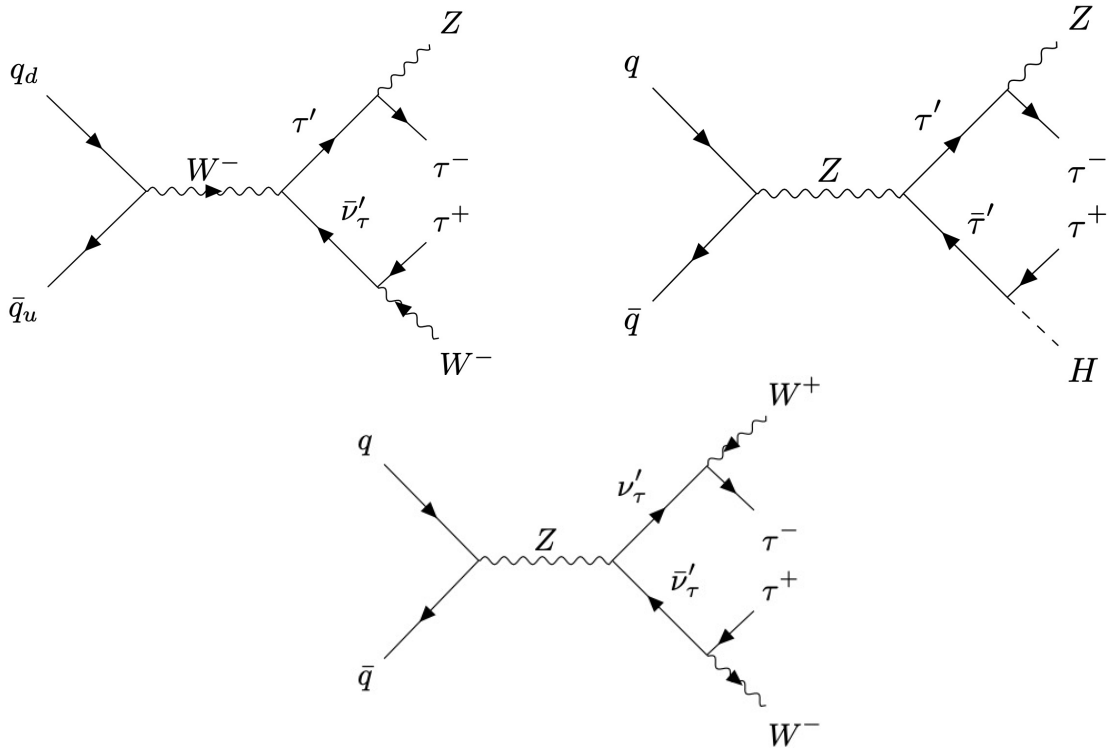
- Limit results:
  - scalar LQ: 1.49 TeV
  - vector LQ min. coupling: 1.69 TeV
  - vector LQ YM coupling: 1.96 TeV

Searches for other exotic leptonic final states

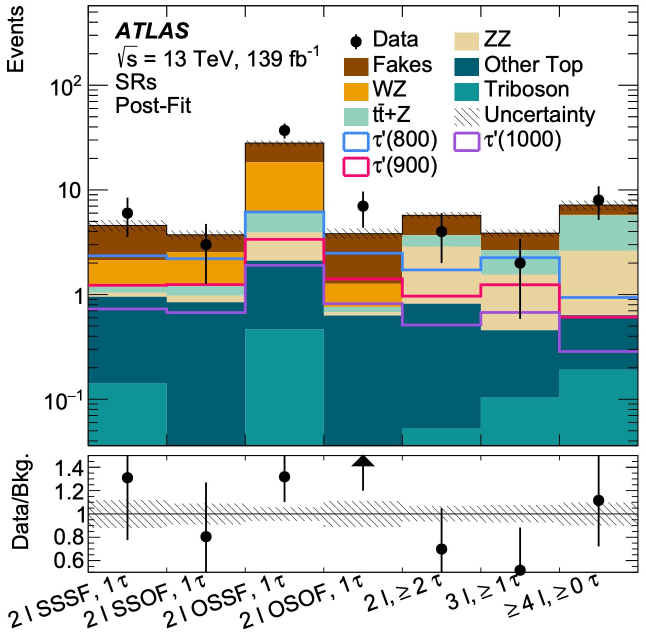
Vector-like leptons : multi-lepton final states

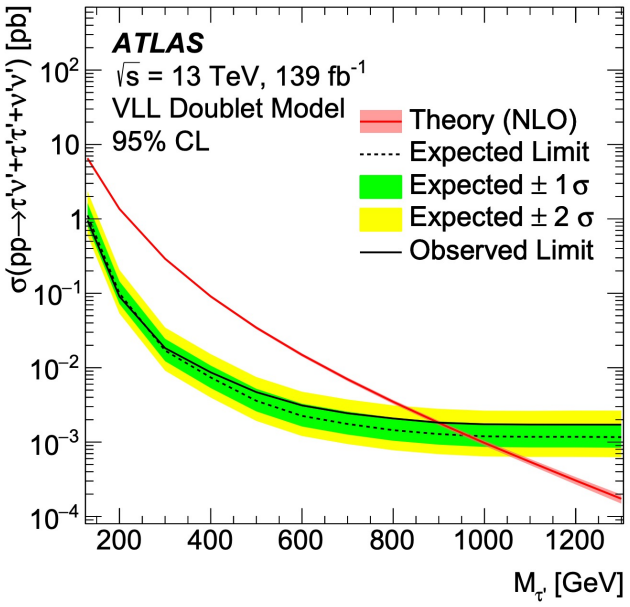
- VLL are **doublets L' = (τ' ν_τ')**, coupling to third generation fermions and decaying into W/Z/H bosons:
  - ➢ $\nu_\tau' \rightarrow W\,\tau$, $\tau' \rightarrow Z\,\tau$, $\tau' \rightarrow H\,\tau$

- Signal signature: ≥ 2 light leptons (e, μ), ≥ 0 τ_{had}



arxiv:2303.05441



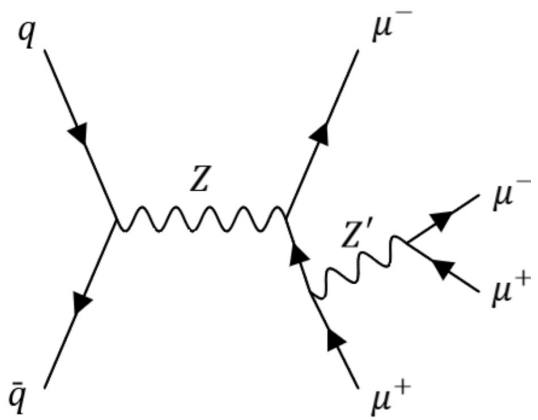


- Analysis performed training a **BDT** across **7 training/signal** regions (charge/flavour sign, ..)

- Exclusion **limit** on $m_{\tau'}$ in the range 130 - 900 GeV

Z'→ μμ + 2 μ : exotics gauge boson coupling to muons

- Exotic gauge boson addressing g-2 and R_K/R_{K*} anomalies
- Events selection:
  - ≥ 4 μ with p_T > 20/15/8/3 GeV
  - min($m_{\mu\mu}$) > 4 GeV, min$\Delta R_{\mu\mu}$ > 0.2, 80 < $m_{4\mu}$ < 180 GeV
- Di-muon **mass pairing**:
  - Z_1: $\mu^+\mu^-$ pair with smallest $|m_{Z1} - m_Z|$
  - Z_2: remaining $\mu^+\mu^-$ pair with largest m_{Z2}



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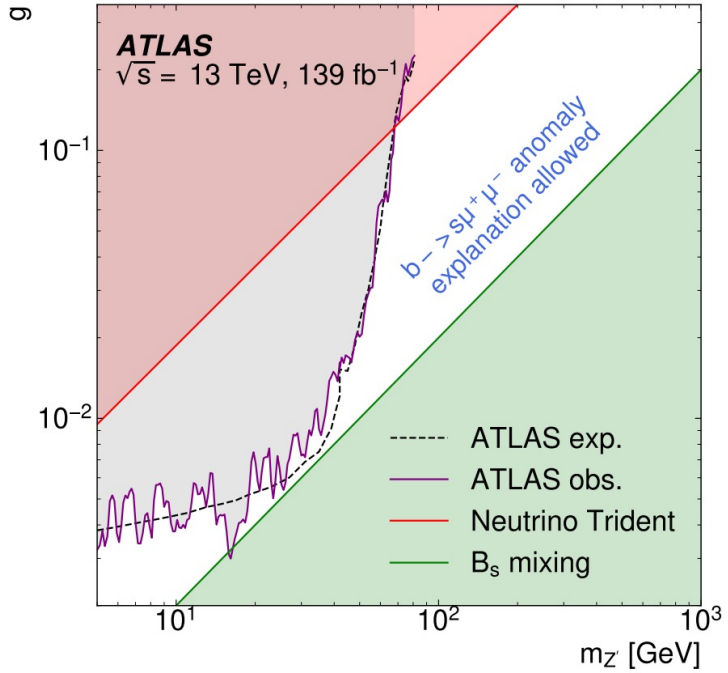
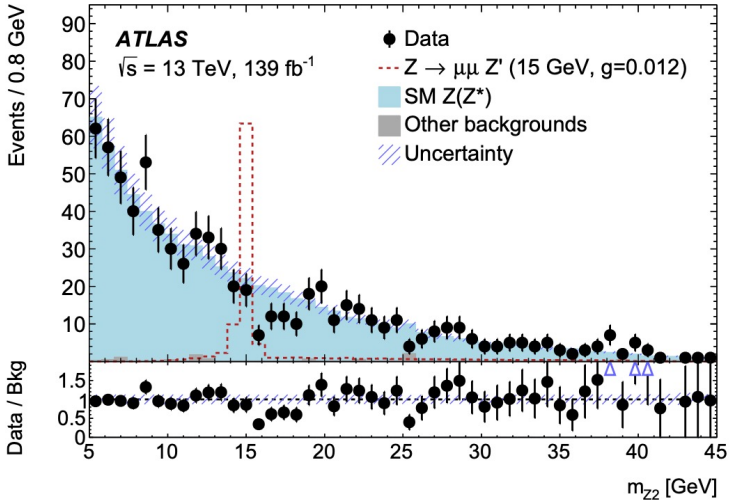
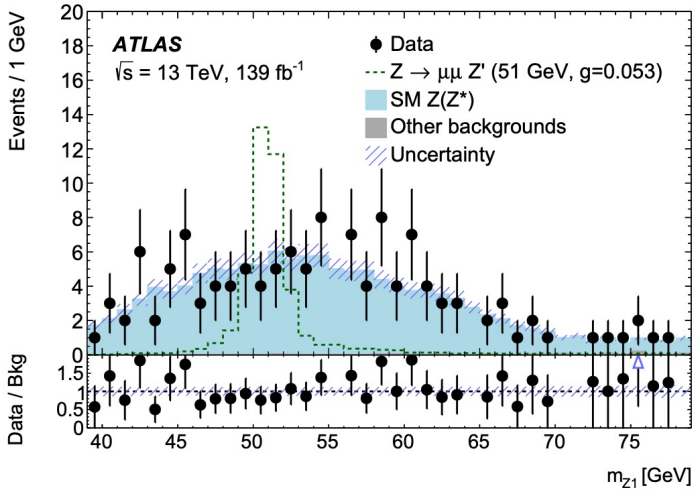




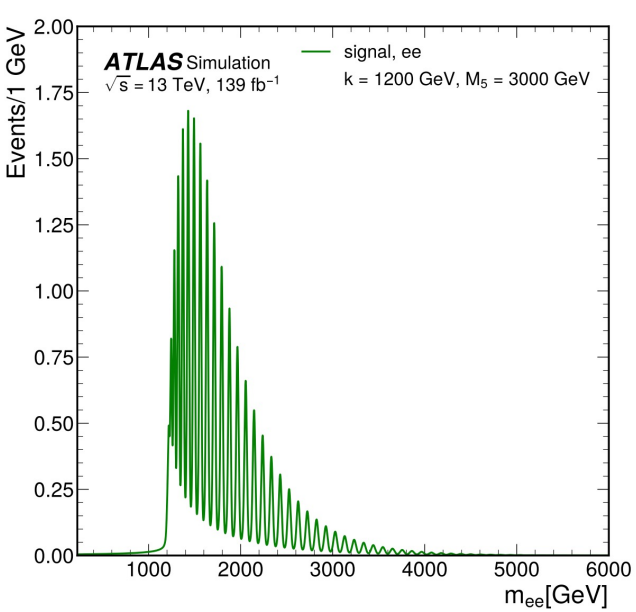


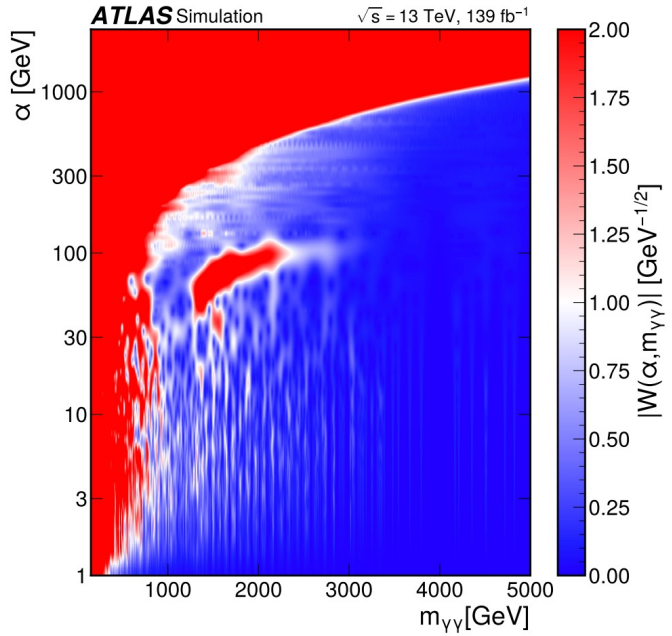
- **Parametric-DNN** to achieve further discrimination, then fit
- Exclusion limit: 5 < $m_{Z'}$ < 81 GeV and 0.003 < $g_{Z'}$ < 0.2

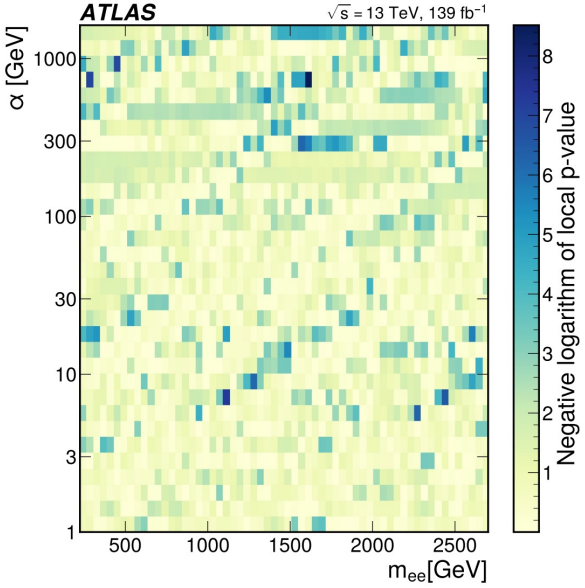
Clockworks : periodic signals in ee γγ mass spectrum

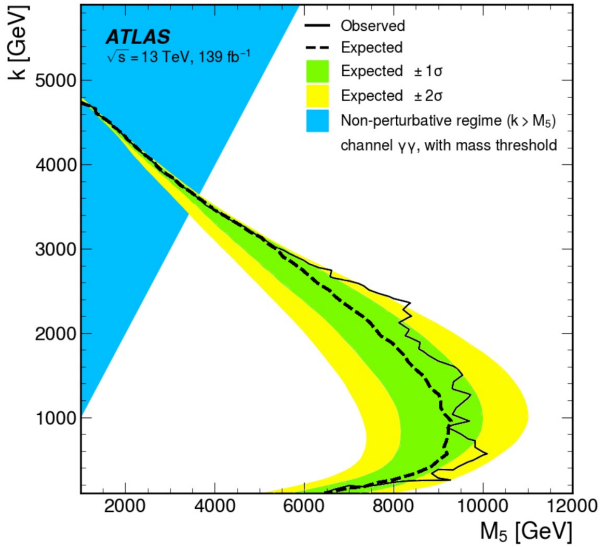
- Exotic periodic signals addressing Higgs naturalness and hierarchy problem
- Look for excess in ee / γγ channels
- Spot in the scalogram, i.e. diagram of **Wavalet transform** amplitude in mass (β) vs scale (α ≈ 1/freq) space

$$W(\alpha,\beta) = \frac{1}{\sqrt{\alpha}} \int_{-\infty}^{+\infty} f(m)\, \psi^* \left(\frac{m-\beta}{\alpha} \right) dm$$









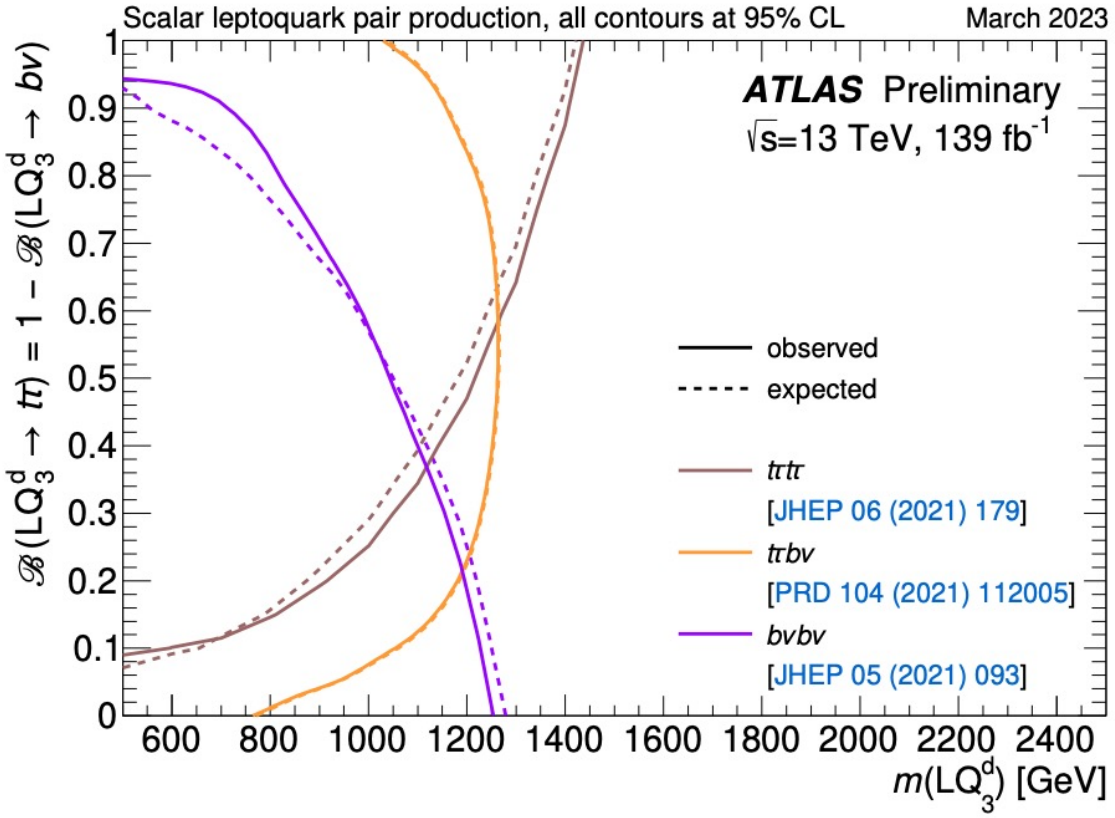
arxiv:2305.10894

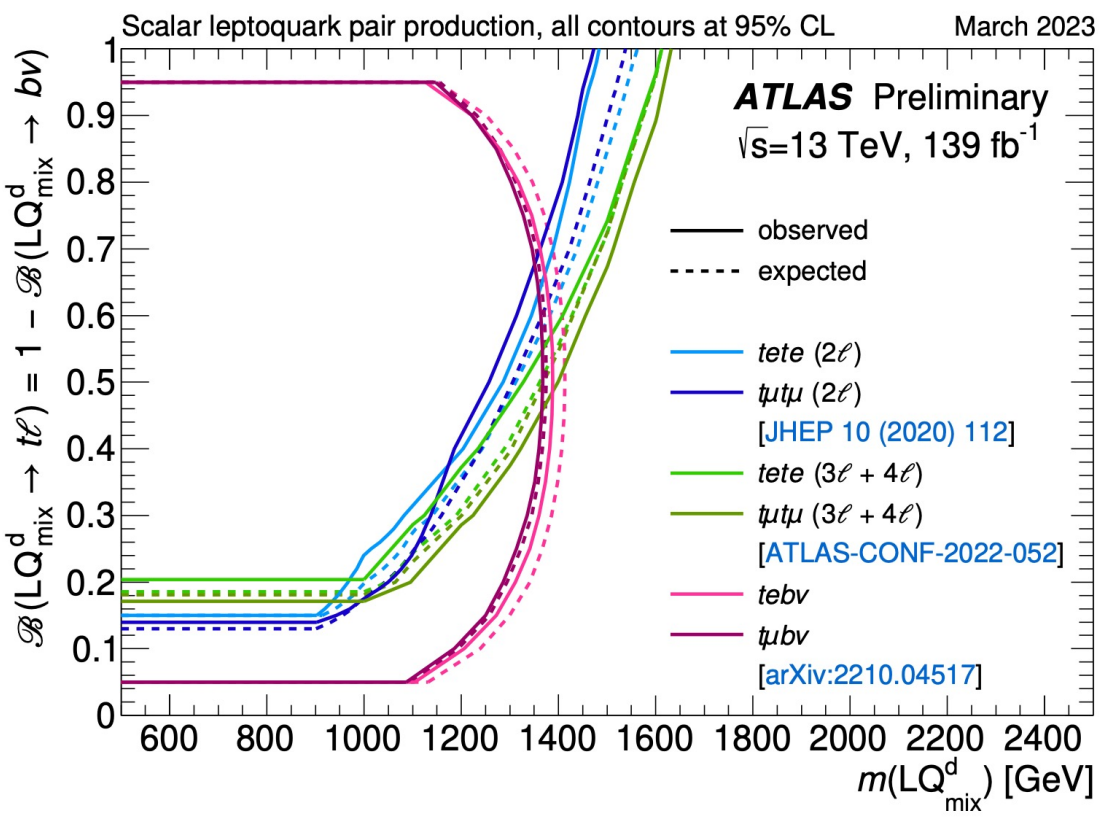
- **Scalograms** processed with NN techniques:
  - **autoencoder** ⟹ model indep. anomaly detection
  - **binary classifier** ⟹ model dep. discriminator
- In the CW/LD model scenario exclusion for theory parameters: $1 < M_5 < 11$ TeV and $0.1 < k < 5$ TeV

Summary plots : leptoquark searches

- Broad program of leptoquark searches with cross-generational couplings, **growing program** for **3rd generation** couplings
- Pair production and single production have been exploited, now **ongoing searches** are targeting **Drell-Yan** production to probe the high mass range

ATL-PHYS-PUB-2023-006



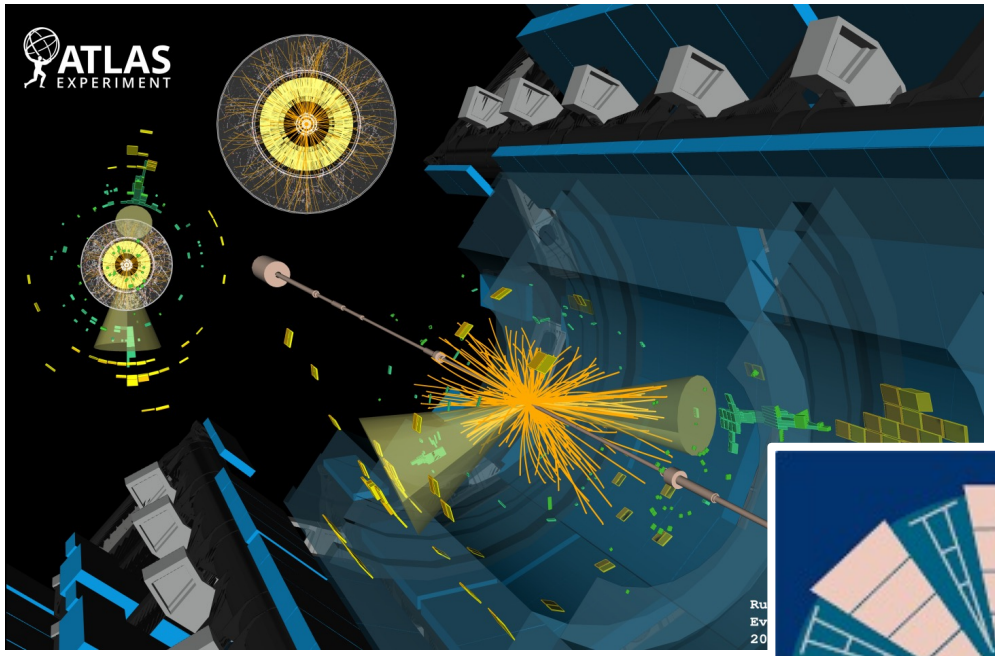


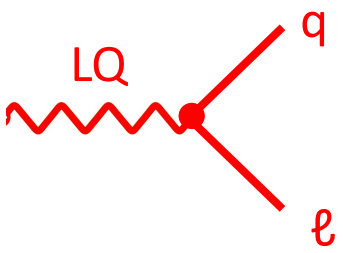
Conclusions

- The picture painted by flavour anomalies is exciting, many results, others coming

- **No** clear **new physics** evidence in Run 2 dataset in searches for:
  - leptoquarks (both vector and scalar)
  - vector-like fermions
  - exotic vector bosons
  - clockworks

- New **Run 3** dataset and **improvements** in complex **object reconstruction** (e.g. taus, c-jets)





Thanks for your attention !

Backup

Summary plots : leptoquark searches

- Other summary plots (complementary to those already shown in sl. 15)
- Scalar LQ of up-type, pair-produced, exclusion limits for same-generation and cross-generational searches

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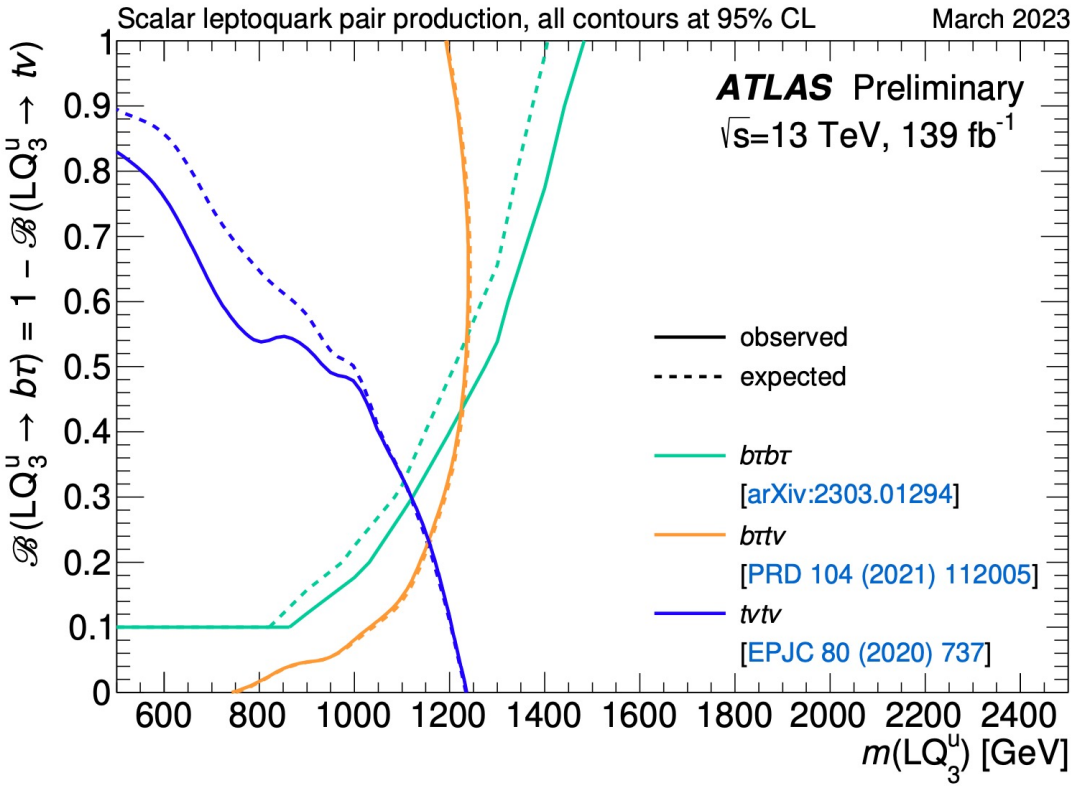
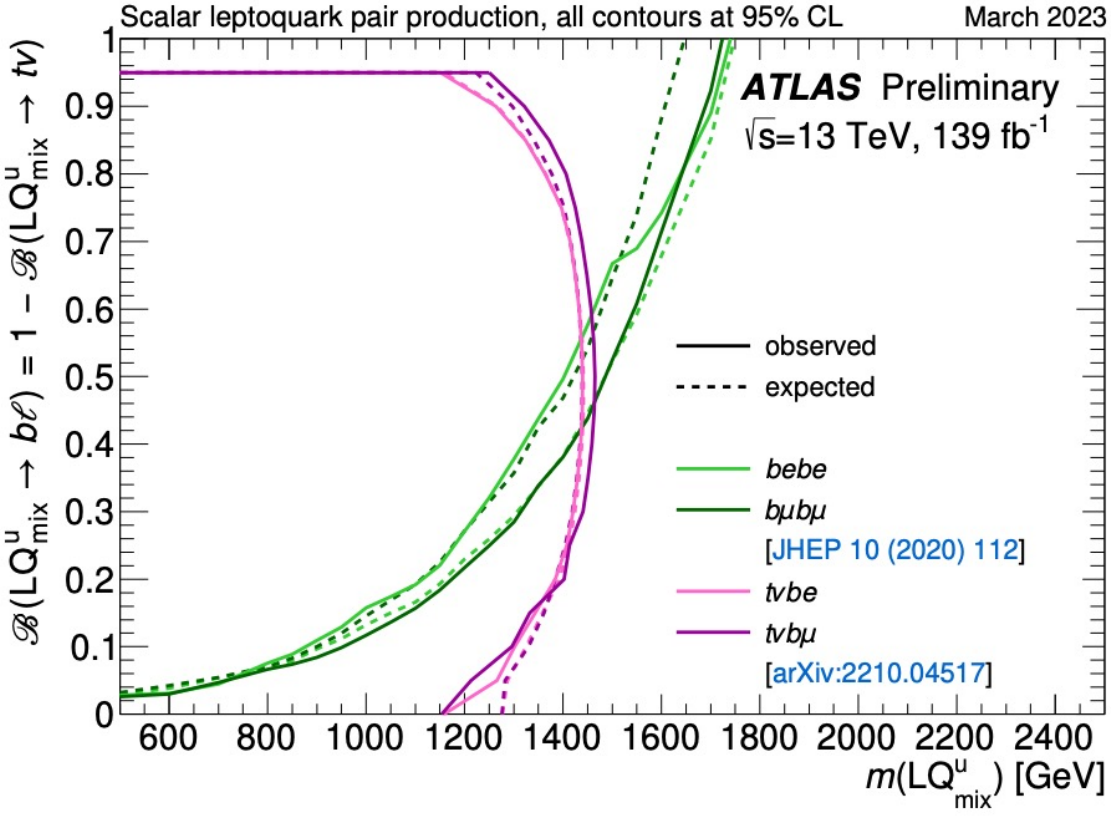
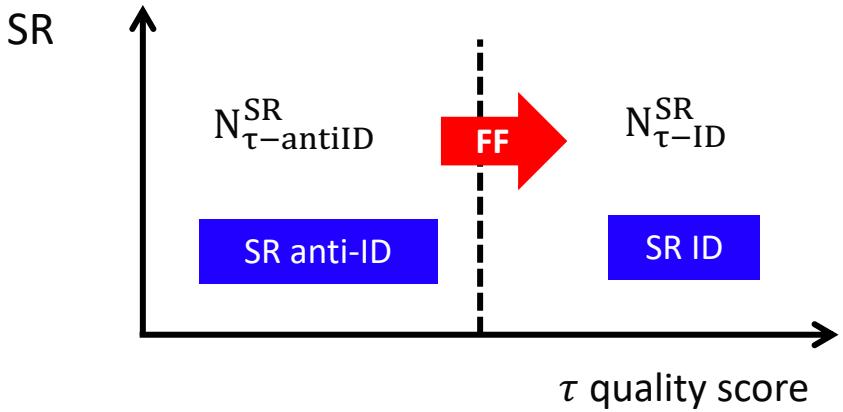




Example for tau fakes estimate : fake factors method

- **Definitions**:
  - SR anti-ID: same as SR but with reversed cut on RNN score
  - FF: transfer factor anti-ID → ID

$$FF = \frac{N^{CR}_{\tau-ID}}{N^{CR}_{\tau-antiID}} \qquad N^{SR}_{\tau-ID} = FF \times N^{SR}_{\tau-antiID}$$



- **Method (FakeFactors)**:

1) template **fit** in the SR anti-ID on the tau-width to extract the fractions of quark / gluon / plie-up jets:

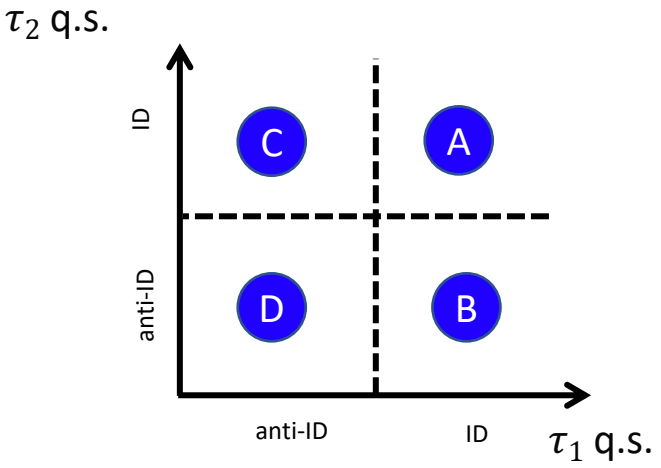
$$histo_{comb} = n_Z \; histo_{Zmm} + (1- n_Z) * [n_{lJVT} \; histo_{ljVT} + (1-n_{lJVT}) \; histo_{hJVT}]$$

2) build **combined FF** from fitted fractions:

$$FF_{comb} = n_Z \; FF_{Zmm} + (1- n_Z) * [n_{lJVT} \; FF_{lJVT} + (1-n_{lJVT}) \; FF_{hJVT}]$$

3) use FF_{comb} to **extrapolate** the di-tau fakes bkg. in the SR ID:

$$bkg. = N(\tau_{ID}\tau_{anti\text{-}ID}) \; FF_2 + N(\tau_{anti\text{-}ID}\tau_{ID}) \; FF_1 - N(\tau_{anti\text{-}ID}\tau_{anti\text{-}ID}) \; FF_1 \, FF_2 = B + C - D$$



Note: here just a paradigmatic example, every analysis has its **own** specific strategy for implement this