



# Direct Searches at the LHC in the context of B-anomalies (ATLAS, CMS, LHCb)



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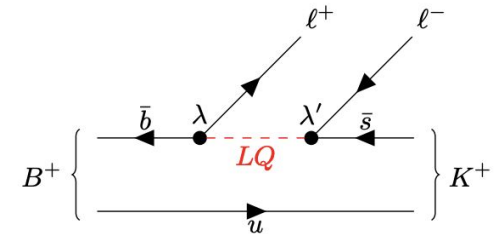
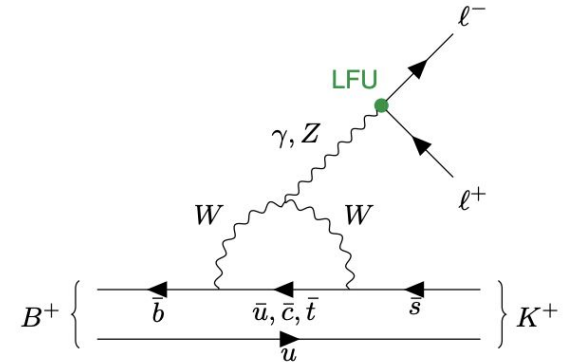
# Motivation

The recently measured B-anomalies may hint of Lepton Flavor Universality Violation in nature

- $R(K^{(*)})$  i. e.  $b \rightarrow sll$  (neutral current):  $\mu$  deficit vs.  $e$
- $R(D^{(*)})$  i. e.  $b \rightarrow clv$  (charged current):  $\tau$  enhanced

If true, these anomalies could be explained by the presence of new heavy particles with non-universal flavor couplings

- Candidates: leptoquarks, heavy vector bosons, . . .

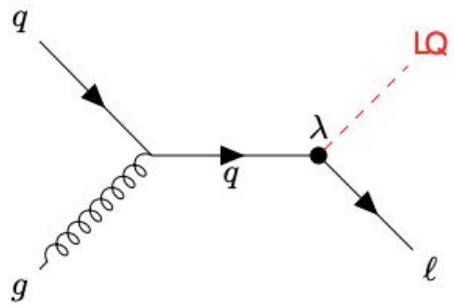
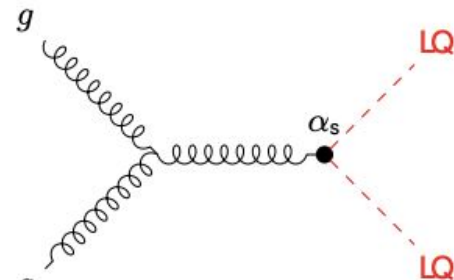


# This talk

- ATLAS, CMS and LHCb have rich programs in search resonant or non-resonant of phenomena from physics beyond the Standard Model
  - The talk covers direct searches for leptoquarks, heavy vector resonances, and long-lived lepton flavor violating decays
  - Due to the short time for the talk - I will only discuss recent results with very few details on the searches
- Interpretations of the results is as general/generic as possible: model-independent limits, or on specific simplified models (e. g. on allowed masses or coupling strengths)

# Lepto-quark models and production mechanisms

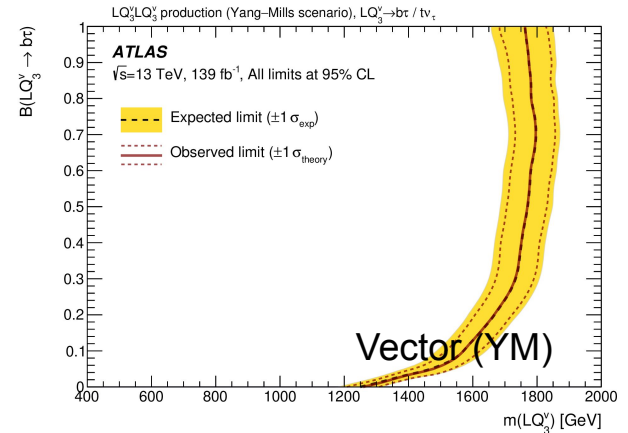
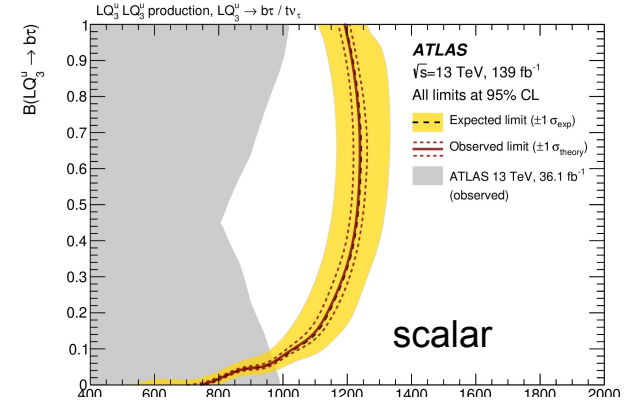
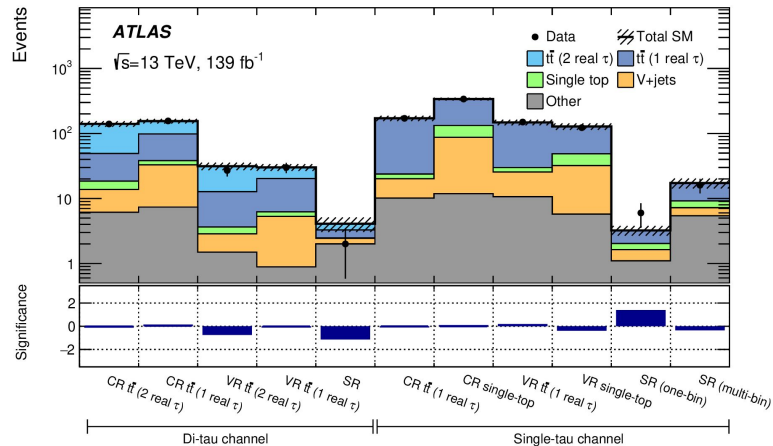
- LQs are hypothetical particles which mediate quark-lepton transitions
  - Color-triplet bosons (spin 0 or 1) with a fractional electric charge ( $+\frac{2}{3}$  (up-type),  $-\frac{1}{3}$  (down type))
  - Parameters:  $m(\text{LQ})$ ;  $\lambda$  - Yukawa coupling to the lepton-quark;  $B$  - relative coupling that control the branching fractions to  $\text{LQ} \rightarrow q\ell$  or  $\text{LQ} \rightarrow q\nu$
  - Models with third generation LQs and cross-generational mixing are favored by the anomalies
- Production
  - Pair production: At the LHC typically dominates, strong interaction  $\rightarrow$  it is largely independent of  $\lambda$
  - Scalar / Vector: Can have large difference in cross section (x5-20 in Vector models)
  - Single production could be important for large  $\lambda$  or large mass where pair production may be inaccessible
- Searches - in general: look for events with high- $p_T$  pairs of jets and pairs of leptons ( $ll/\nu\nu$ )



# LQ-Pair production decaying to third generation quarks and leptons

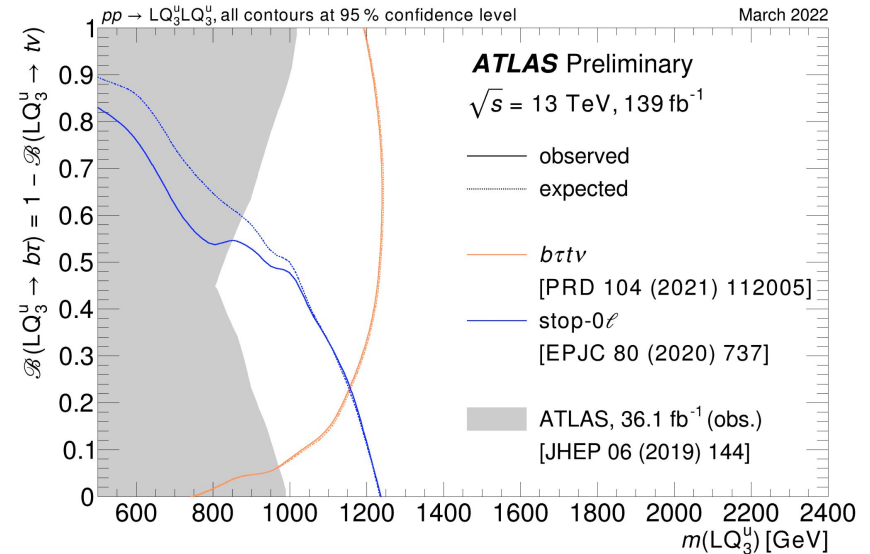
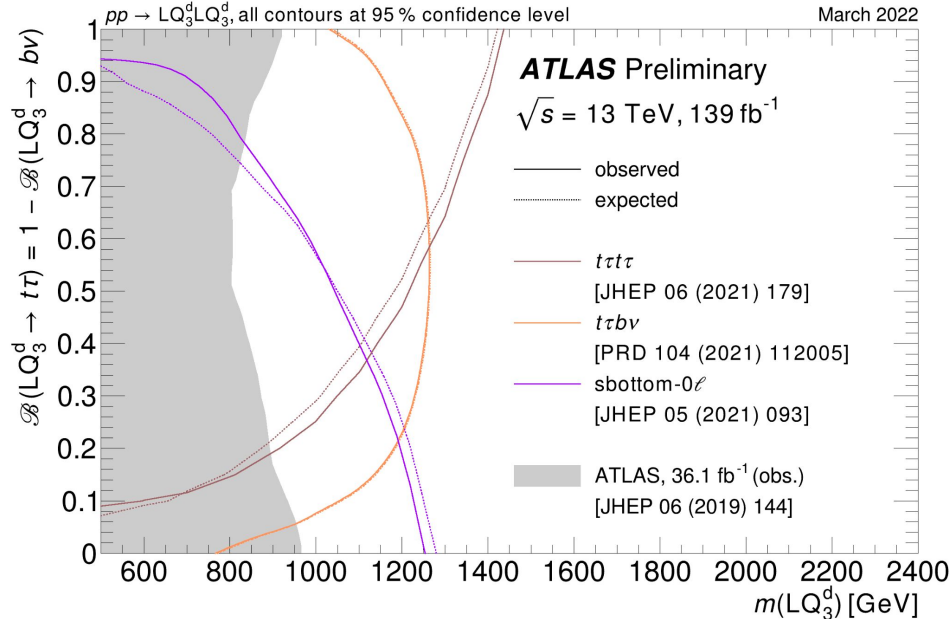
- Final state with  $\geq 2$  b-jets and 1  $\tau$ had
- **Scalar** (targets  $B = 0.5$ ): Exclusion up to 1.25 TeV for scalar LQLQ - for both  $LQ^{u/d}_3$
- **Vector**: Exclusion up to 1.5 / 1.8 TeV for vector LQLQ in minimal / Yang–Mills case

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[ATLAS material](#)



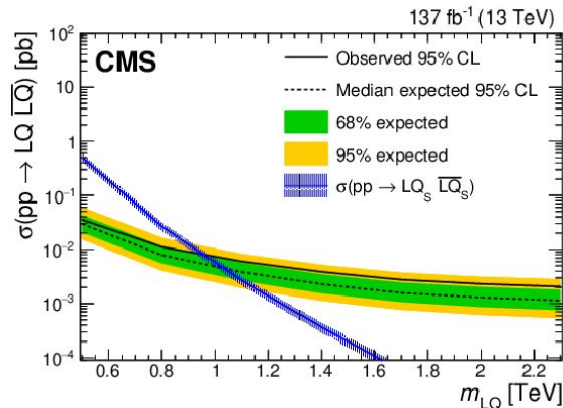
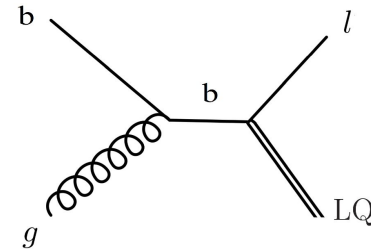
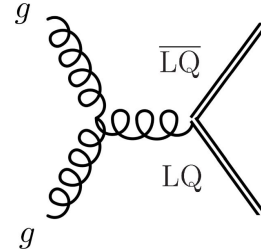
# Summaries - ATLAS third generation LQ searches

- Systematic coverage gives a strong mass reach over the whole range of branching fractions



# LQ single + pair production to third generation quarks and leptons

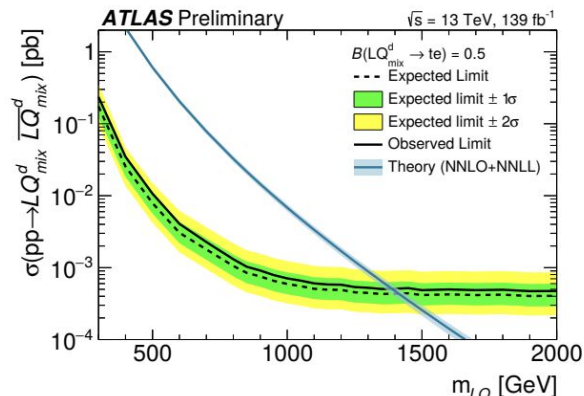
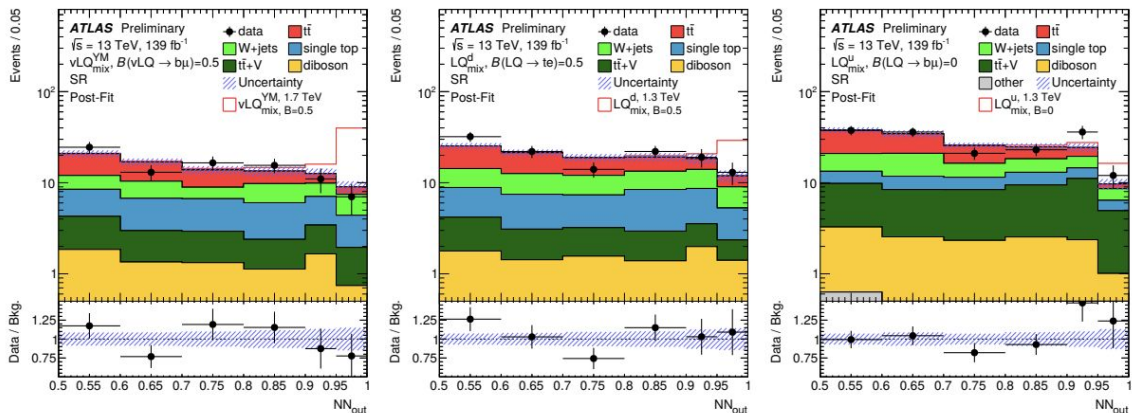
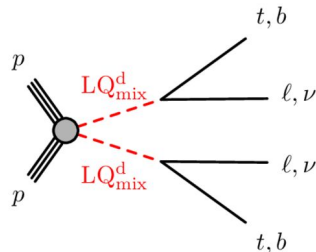
- Simultaneous search for single + pair production
- Select events with final states  $\tau\nu b$  or  $\tau\nu$
- Interpretation for scalar and vector LQ
- Assume equal  $\lambda$  for  $\tau\tau$ ,  $b\nu$ ,  $\tau\nu$ ,  $b\tau$  ( $B=0.5$ )



	LQ <sub>S</sub> (TeV)		LQ <sub>V</sub> $k=0$ (TeV)		LQ <sub>V</sub> $k=1$ (TeV)	
Pair	0.95 (1.03)		1.29 (1.39)		1.65 (1.77)	
	$\lambda = 1.5$	2.5	1.5	2.5	1.5	2.5
Single	0.55 (0.56)	0.75 (0.81)	1.03 (1.12)	1.25 (1.35)	1.20 (1.29)	1.41 (1.53)
Pair+Single	0.98 (1.06)	1.02 (1.10)	1.34 (1.46)	1.41 (1.54)	1.69 (1.81)	1.73 (1.87)

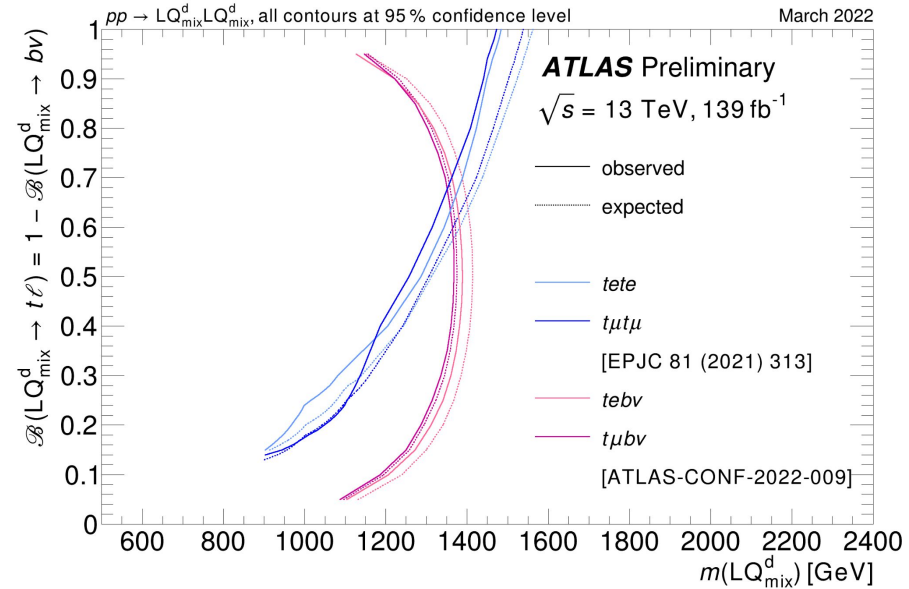
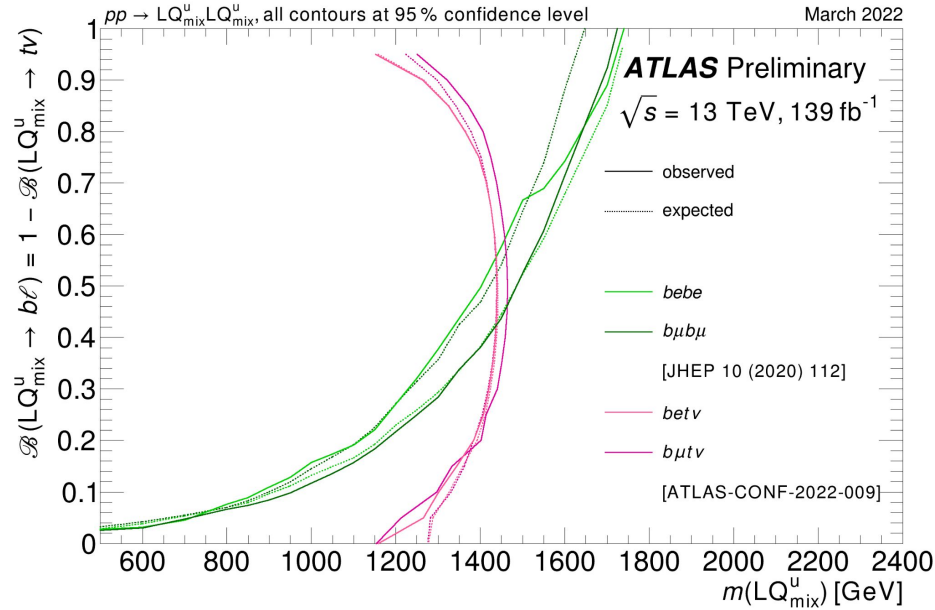
# LQ-Pair production with third generation quarks and first or second generation Leptons

- Final state with hadronically decaying top and a b-jet  $\geq 4$  jets (1-b jet), MET, and exactly one lepton
- Specialized neural networks (S and V case) for Signal and background classification
- Targets:  $B = 0.5$
- Vector and scalar interpretation



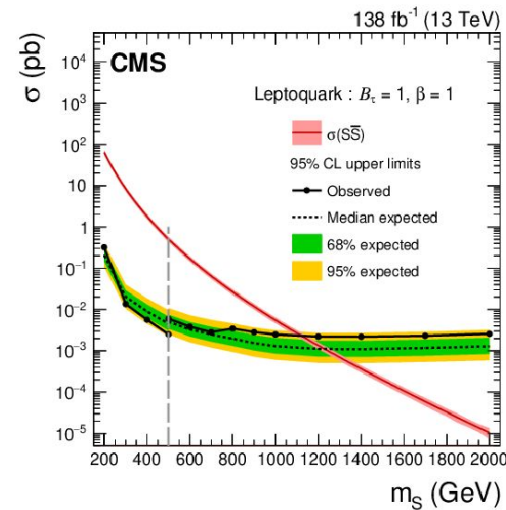
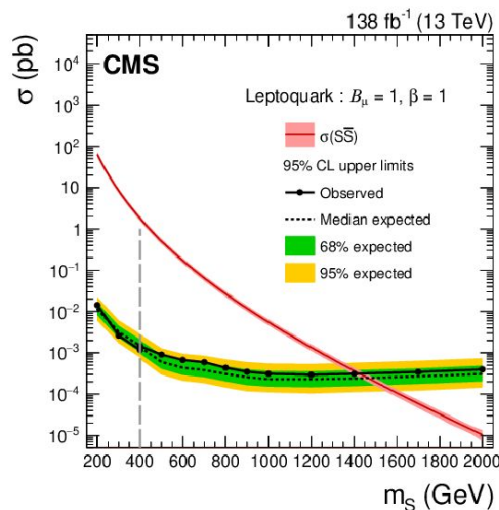
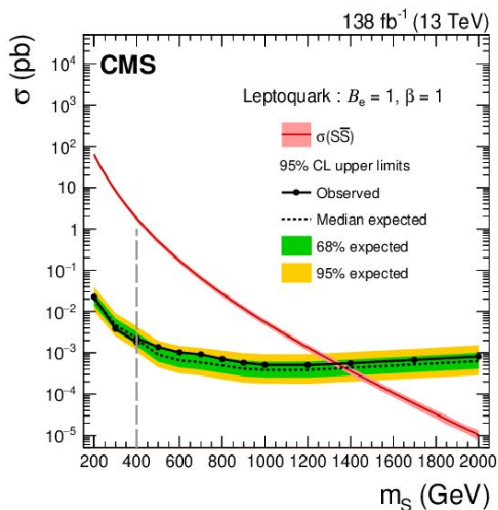
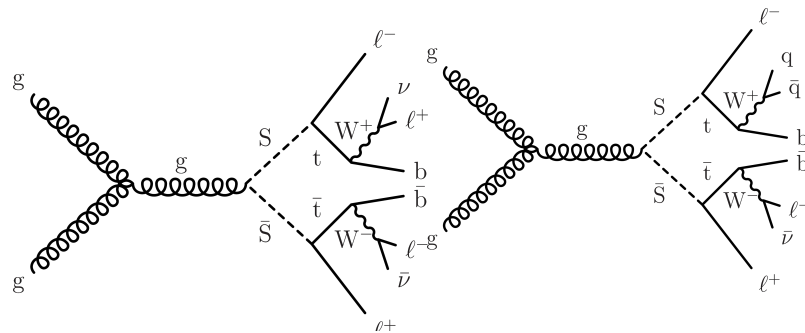


# Summaries - ATLAS LQ with third generation quarks and lower generation leptons

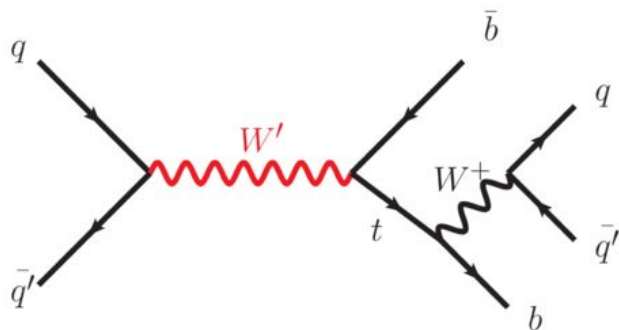


# Inclusive non-resonant multilepton search

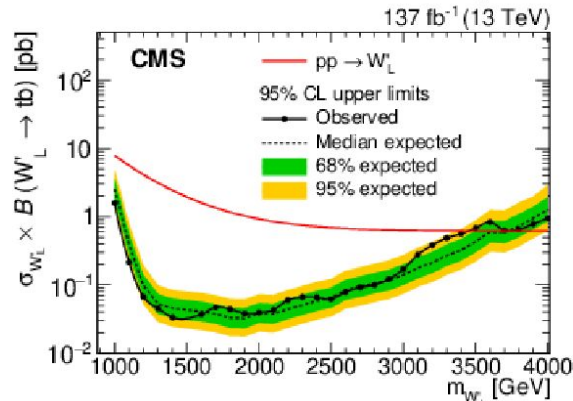
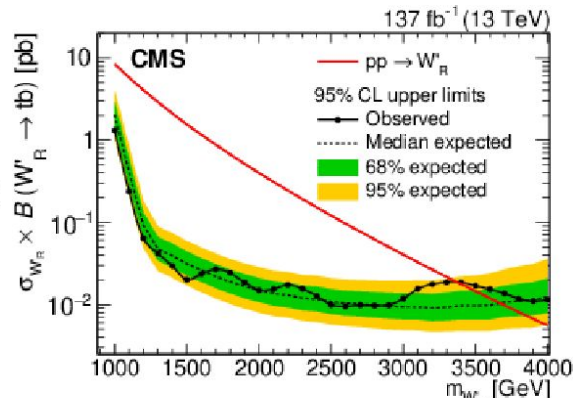
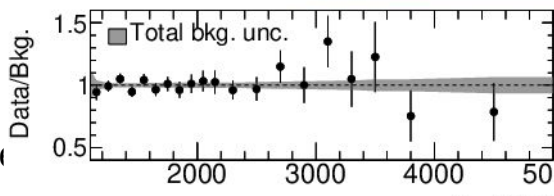
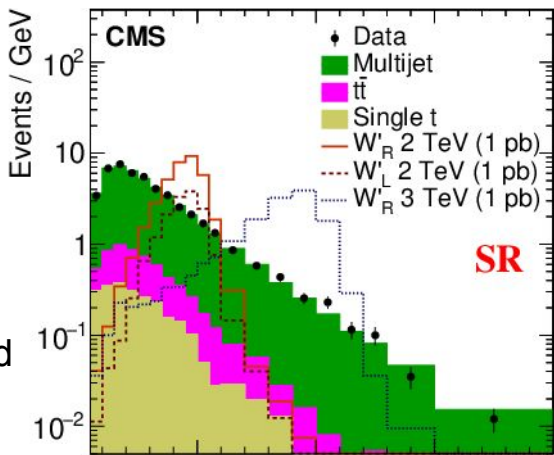
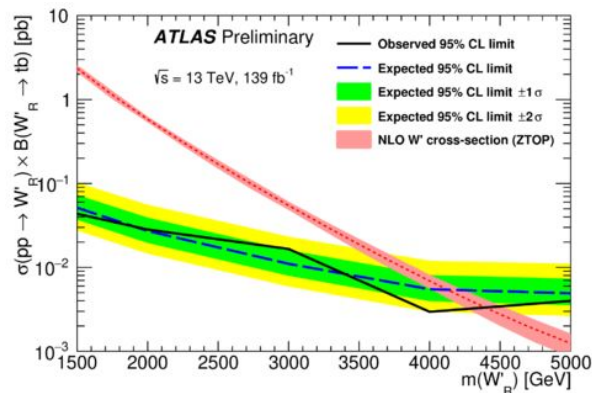
- Inclusive search for non-resonant signals with multi-leptons
  - LQLQ  $\rightarrow$  tt ( $l = e/\mu/\tau$ ), only scalar LQ,  $B = 1$
  - Model-independent SRs
  - SR in 7 channels: Leptons (1-3+) tops (0-2)



$$W' \rightarrow tb$$



- New heavy particles with flavor preferential couplings may be involved in the anomalies
- $W' \rightarrow tb$ : Final state reconstructed from top-tagged large-R jet + b-jet
- ATLAS considers  $W_R$  only

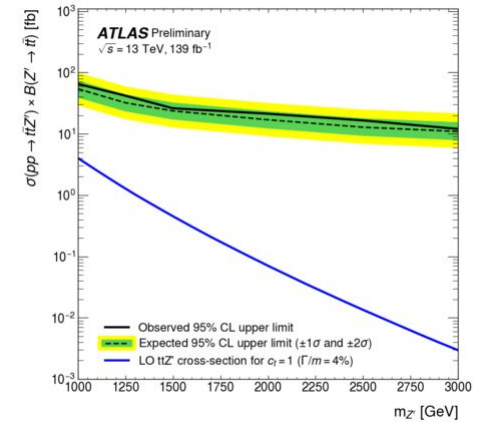
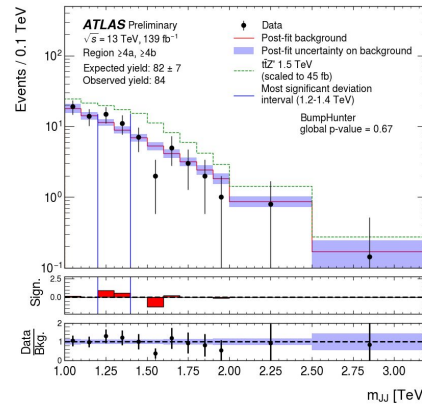
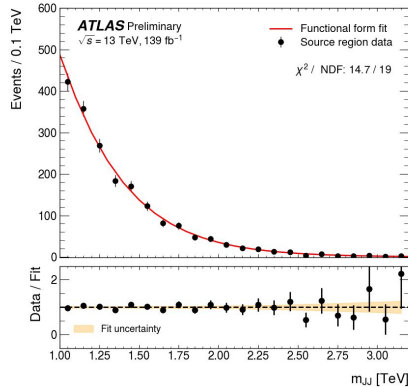
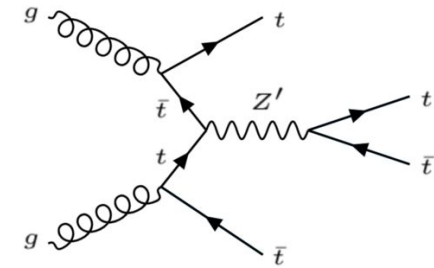


# Z' with top-philic couplings

Final state with four tops:

- Z' → 2 large-R jets
- 1 e/μ + >2 b-jets + 2 jets outside the large-R jets

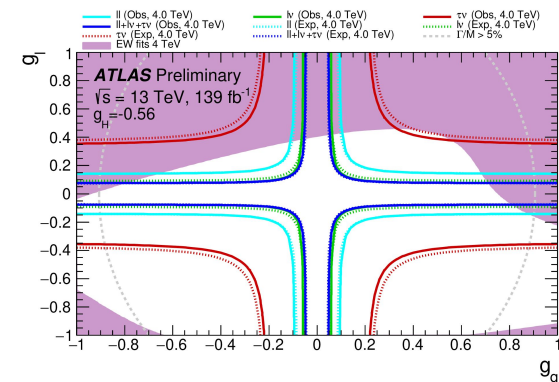
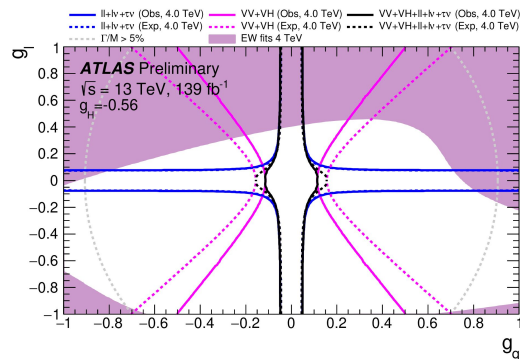
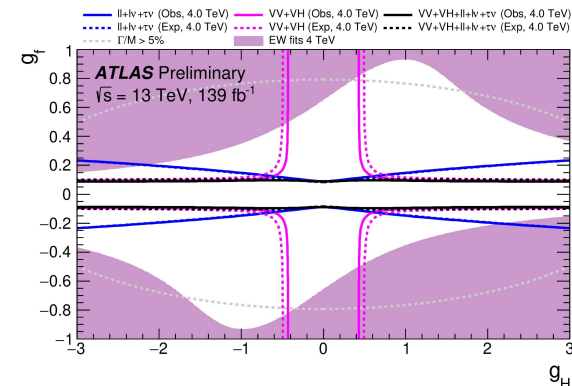
$N_{\text{add-jets}} \geq 4$	(≥4a,2b)	(≥4a,3b)	(≥4a,≥4b)
	(3a,2b)	(3a,3b)	(3a,≥4b)
	(2a,2b)	(2a,3b)	(2a,≥4b)
	2	3	≥ 4
			$N_{b\text{-jets}}$



# Heavy Boson Resonance Combination of searches

- Many different scenarios can be expressed within [HVT](#)
- This is powerful
  - Allows easily combining the results of different searches
  - Explore scenarios that we did not explicitly search for (from simple gauge group extensions, techni-color like theories, fermio-phobic scenarios, etc)
  - Statistical combination improves sensitivity; small real excesses add up, large independent fluctuations cancel out

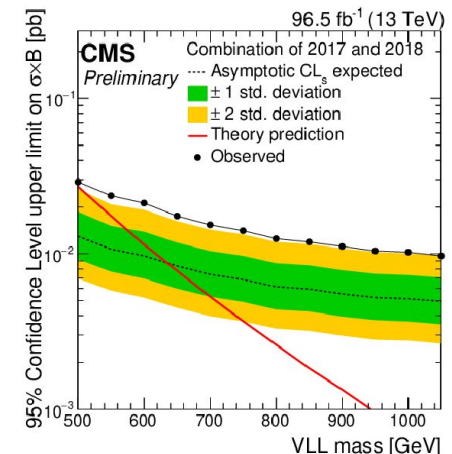
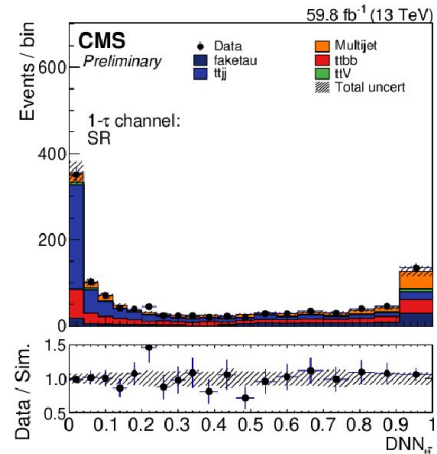
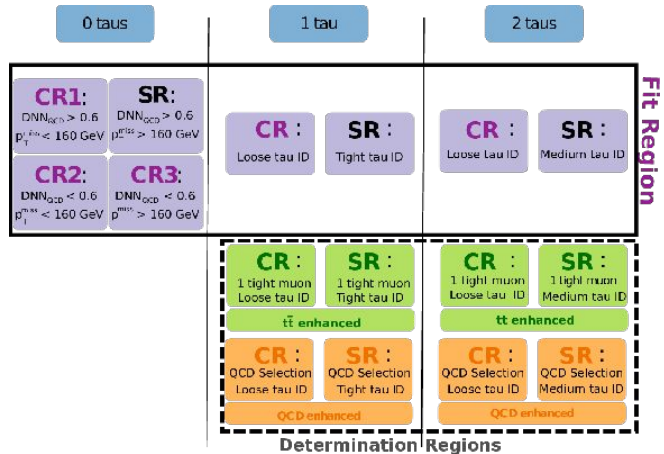
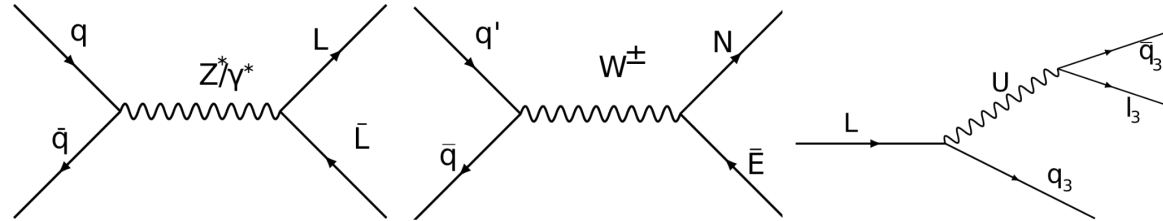
Analysis	leptons	$E_{T,miss}$	jets	b-tags	Discr.
$WW/WZ \rightarrow qqqq$	0	Veto	$\geq 2J$	-	$m_{VV}$
$WZ \rightarrow \nu\nu qq$	0	Yes	$\geq 1J$	0	$m_{VV}$
$WZ \rightarrow \ell\nu qq$	1e, 1 $\mu$	Yes	$\geq 2j, \geq 1J$	0, 1, 2	$m_{VV}$
$WZ \rightarrow \ell\ell qq$	2e, 2 $\mu$	-	$\geq 2j, \geq 1J$	0	$m_{VV}$
$WZ \rightarrow \ell\nu\ell\ell$	3 $\subset$ (e, $\mu$ )	Yes	-	0	$m_{VV}$
$WH \rightarrow qqbb$	0	Veto	$\geq 2J$	1, 2	$m_{VH}$
$ZH \rightarrow \nu\nu bb$	0	Yes	$\geq 2j, \geq 1J$	1, 2	$m_{VH}$
$WH \rightarrow \ell\nu bb$	1e, 1 $\mu$	Yes	$\geq 2j, \geq 1J$	1, 2	$m_{VH}$
$ZH \rightarrow \ell\ell bb$	2e, 2 $\mu$	Veto	$\geq 2j, \geq 1J$	1, 2	$m_{VH}$
$\ell\nu$	1e, 1 $\mu$	Yes	-	-	$m_T$
$\tau\nu$	1 $\tau$	Yes	-	-	$m_T$
$\ell\ell$	$\geq 2e, \geq 2\mu$	-	-	-	$m_{\ell\ell}$



# Pair produced Vector Like Leptons in 3b + 2( $\tau/\nu$ ) final states

The 4321 model: UV-complete model that can explain the anomalies

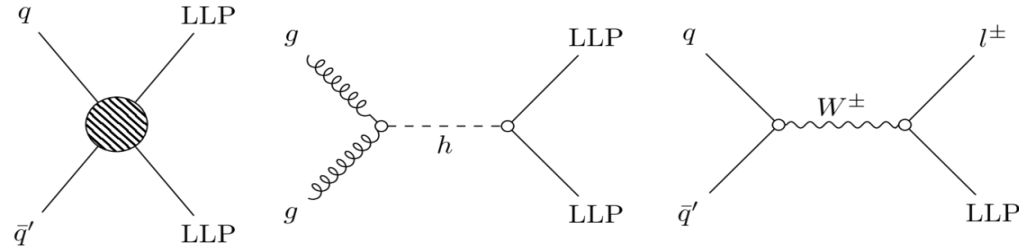
- Search uses final states with 3 b jets and two third generation leptons
- Graph neural networks to learn kinematics in large jet multiplicity environment



# Long Lived Particles with flavor violating decays

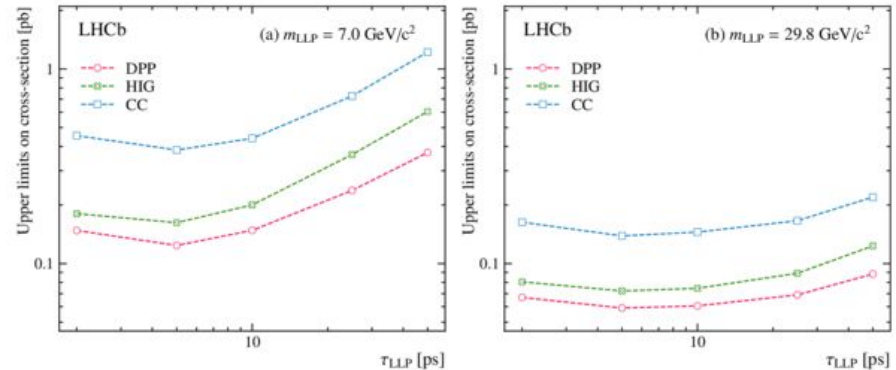
Search for a long-lived particle decaying to a  $e\mu\nu$

- Three Production mechanisms are considered (direct, H, W)



Selection:

- Isolated opposite charge  $e/\mu$
- High quality displaced vertex ( $d_{sig} > 15$ )
- BDT
- $M_{corr}$  (mass) from based on angle of  $e\mu$  and  $\nu$
- Simultaneous fit to  $M_{corr}$  and  $d_{e\mu}$



# Summary

B-anomalies → motivation for a broad range of searches at LHC

- Main suspects LQs: ATLAS and CMS have a systematic program exploring a whole range of scenarios: Pair, and single production, third gen and mixed, scalar and vector
  - No BSM found → Limits up to  $\sim 2$  TeV
- $W'/Z'$ 
  - ATLAS and CMS programs with boson, leptons, and quark decays (different production modes as well)
    - Third gen specific searches
    - Combination of  $VV, VH, II, IV$  searches