# Searches for leptoquarks with the ATLAS detector


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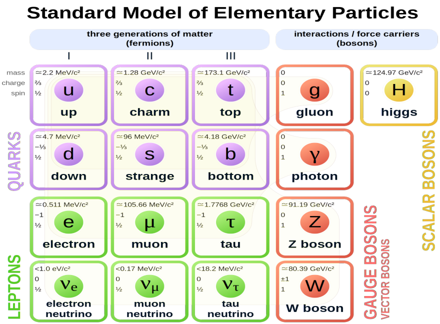
26th October 2021

# Why leptoquarks ?




- 3 gen. mirrored lepton $\leftrightarrow$ quark
- Charge: $q_{lep} \leftrightarrow$ n$_{color}$ x $q_{quark}$
- leptoquarks (LQ) show up in many possible GUT scenarios.

## LQ models:

| | Model | $R_{K^{(*)}}$ | $R_{D^{(*)}}$ | $R_{K^{(*)}}$ & $R_{D^{(*)}}$ |
|---|---|---|---|---|
| Scalars | $S_1 = (\bar{\mathbf{3}}, \mathbf{1})_{1/3}$ | ✗ | ✓ | ✗ |
| Scalars | $R_2 = (\mathbf{3}, \mathbf{2})_{7/6}$ | ✗ | ✓ | ✗ |
| Scalars | $\widetilde{R}_2 = (\mathbf{3}, \mathbf{2})_{1/6}$ | ✗ | ✗ | ✗ |
| Scalars | $S_3 = (\bar{\mathbf{3}}, \mathbf{3})_{1/3}$ | ✓ | ✗ | ✗ |
| Vector | $U_1 = (\mathbf{3}, \mathbf{1})_{2/3}$ | ✓ | ✓ | ✓ |
| Vector | $U_3 = (\mathbf{3}, \mathbf{3})_{2/3}$ | ✓ | ✗ | ✗ |

Angelescu, Becirevic, DAF, Sumensari [1808.08179]

- LQ have color+lepton number
- scalar and vector particles

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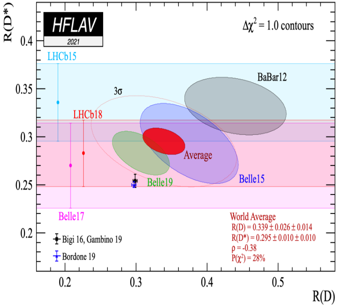
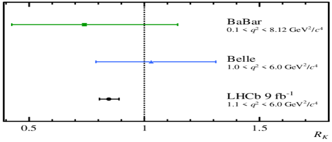
# Observed anomalies

## $R_{D^{(*)}}$ - $3\sigma$ discrepancy to SM




Heavy Flavor Averaging Group [1]

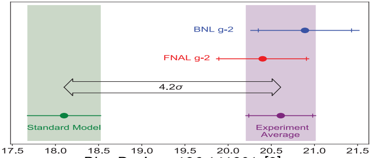
## $R_K$ - $3.1\sigma$ discrepancy to SM



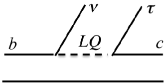

arXiv: 2103.11769 [2]

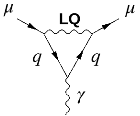
- $$R_{K^{(*)}} = \frac{BR(\mathrm{B}\to\mathrm{K}^{(*)}\mu^-\mu^+)}{BR(\mathrm{B}\to\mathrm{K}e^-e^+)}$$
- $$R_{D^{(*)}} = \frac{BR(\mathrm{B}\to\mathrm{D}^{(*)}\tau^-\nu_\tau)}{BR(\mathrm{B}\to\mathrm{D}^{(*)}\ell\nu)}$$

## $\mu$ magnetic Moment



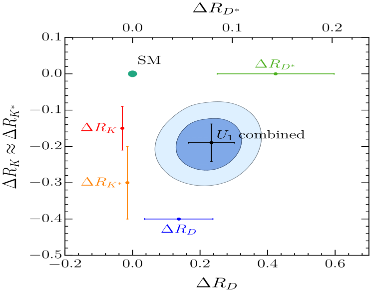

PhysRevLett.126.141801 [3]




→ Results show significant deviation from SM prediction.
Contributions from LQs could explain this nicely!

# U1 vector LQ




JHEP07(2019)168 [4]

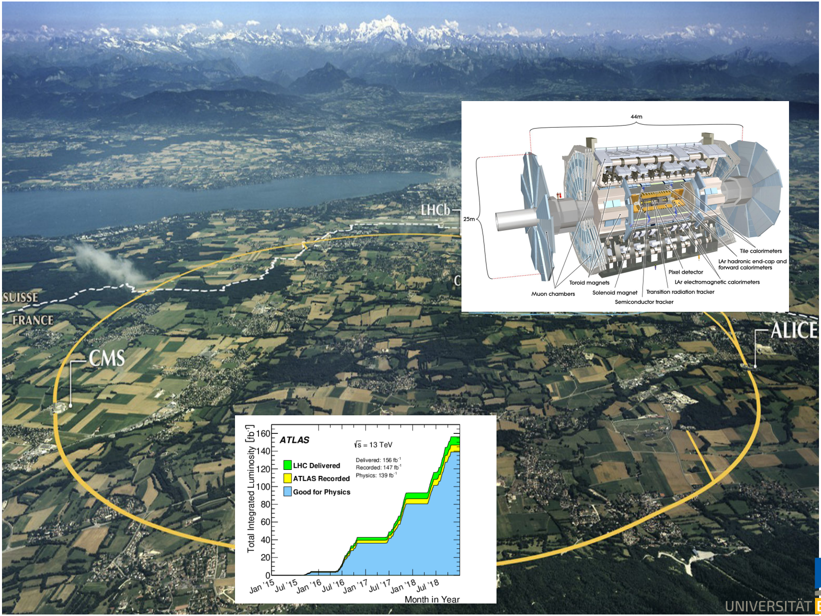
- $U_1$ LQ explains $D^{(*)}+ K^{(*)}$ simultaneously
- Much larger x-section compared to kin. suppressed scalar LQs

$$\mathcal{L}_{U_1} \supset -ig_s\,(1-\kappa)\,U_{1\mu}^{\dagger}\,T^a\,U_{1\nu}\,G^{a\mu\nu}$$

For the $U_1$ coupling to color can be suppressed $(\kappa)$ $\Rightarrow$ 2 scenarios :

- Nominal coupling to color $(\kappa = 0)$ Yang Mills (YM)
- Minimal coupling $(\kappa = 1)$: coupling to gluon only via covariant derivative

# Search for LQ's at ATLAS

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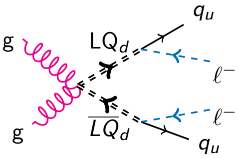
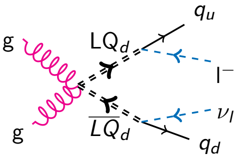
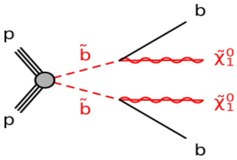
# ATLAS search strategy




flavour-diagonal LQ




cross-generational




SUSY

- Investigation of pair produced (PP) leptoquarks
- Process analogous to other PP BSM particles (e.g. SUSY)
  $\Rightarrow$ Allows reinterpretation of existing analyses complementary to dedicated searches
- $LQ_d$: q $=-\frac{1}{3}$e, $LQ_u$: q $=+\frac{2}{3}$e
- Exclusion contours : Leptoquarkmass (m(LQ)) against branching fraction to final state ($\mathcal{B}$)

# LQLQ$\rightarrow$ jet lepton + jet lepton

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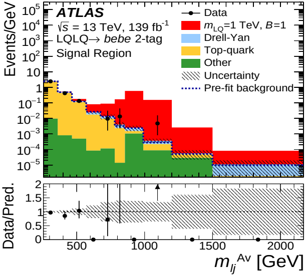
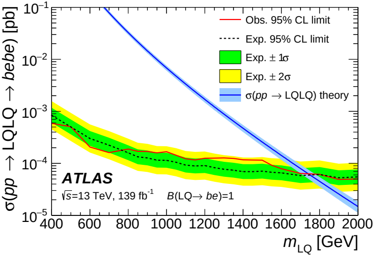
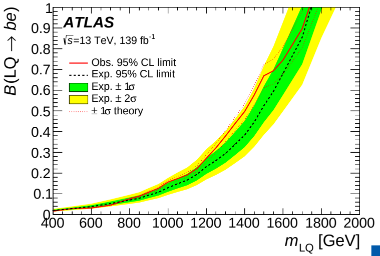
## Strategy

- Select $e^+e^-$ $e$ / $\mu^+\mu^+$ + $\geq$ 2 jets
- 7 event categories based on # of $b$-/$c$-tagged jets
- LQ candidates: $\ell$-j closest in $m_{\ell j}$
- Main bkg. DY and $t\bar{t}$ taken from MC + CR

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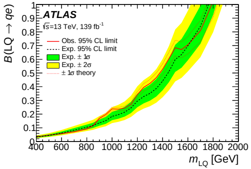
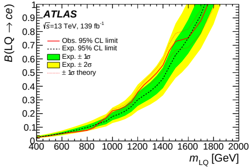
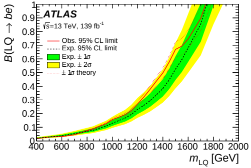
LQLQ $\rightarrow qeqe$



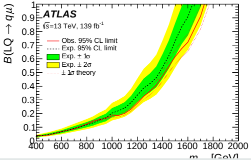

LQLQ $\rightarrow cece$



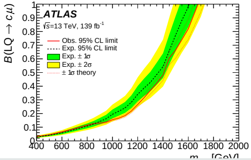

LQLQ $\rightarrow bebe$



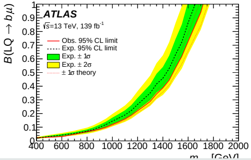

LQLQ $\rightarrow q\mu q\mu$




LQLQ $\rightarrow c\mu c\mu$




LQLQ $\rightarrow b\mu b\mu$




- Analysis explored 6s cases: 3 quark (light/charm/bottom) and 2 lepton flavor ($e$,$\mu$)
- Exclusion limits
  - for $\mathcal{B}(\mathrm{LQ} \rightarrow \ell^{\pm}\ q) = 1$: m(LQ) > 1.8 TeV (el.) m(LQ) > 1.7 TeV ($\mu$ )
  - for $\mathcal{B}(\mathrm{LQ} \rightarrow \ell^{\pm}\ q) \geq 0.1$ : m(LQ) > 0.8 TeV (el. and $\mu$ )
- First limits on mixed decays employing dedicated $c$- and $b$-jet id. algorithms
- Improves (95 % CL.) exlusion limit on $m_{LQ}$ by 400 GeV over earlier results

# LQLQ $\to t\ell\, t\ell$

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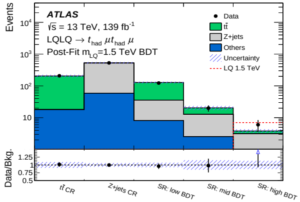
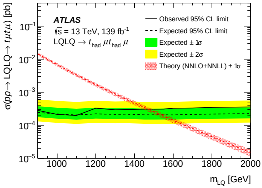
## Strategy

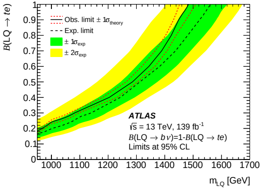
- Select $e^+ e^-$ / $\mu^+ \mu^+$ + large-R jets [1]
- BDT based on 29/32 (e/$\mu$) kinetic observables
- Obs. in rest-frames of intermediate particles ($LQ$, $t$, $Z$) using jigsaw technique



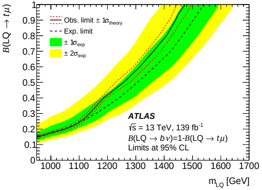

$\sigma$(pp $\to$ LQLQ $\to t\mu t\mu$)




LQLQ $\to tete$




LQLQ $\to t\mu t\mu$




## Observed limits at 95 % CL

- m(LQ) $>$ 1.48 TeV for $tete$ (CMS : 1.34 TeV EXO-21-002 [5] )
- m(LQ) $>$ 1.47 TeV for $t\mu t\mu$ (CMS : 1.42 TeV EXO-21-002 [5] )

[1] large-R jet : anti$_{kt}$ with $\Delta$ R = 1

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# LQLQ $\rightarrow t\tau t\tau$

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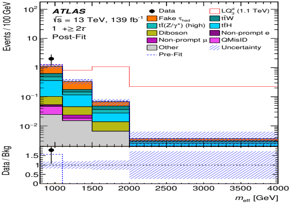
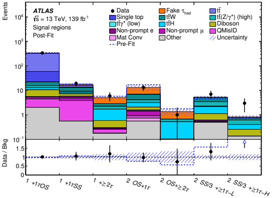
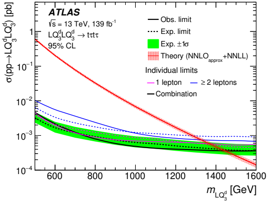
## Strategy

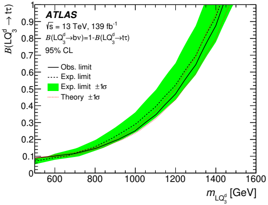
- Events w. at least $1\ell$, 1 $b$-jet and 2 jets
- 7 SR: ($1\ell/2\ell$ OS/$2\ell/2\ell$ SS/$3\ell$ ) split into $1\tau/2\tau$ regions
- 15 CR for $t\bar{t}W$ & fake lepton normalization




$$m_{eff} = \sum_{jet,l,\tau_{had}} p_{\mathrm{T}} + MET$$




## Observed limits at 95 % CL

- m(LQ) $> 1.43$ TeV for $\mathcal{B}(\mathrm{LQ} \rightarrow t\tau) = 1.0$ (CMS : 1.12 TeV EXO-21-002 [5] )
- m(LQ) $> 1.22$ TeV for $\mathcal{B}(\mathrm{LQ} \rightarrow t\tau) = 0.5$

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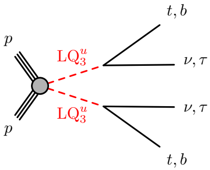
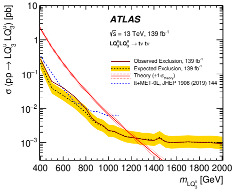
# LQLQ $\rightarrow t\nu\ t\nu$

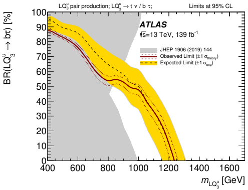
Eur.Phys.J. C 80, 737 (2020)

## Strategy

- Optimized for pair produced top squarks decaying to $t\bar{t}$ + MET
- Events w. MET >250 GeV at least 4 jets & 2 $b$-jets
- 2 SRs defined via MET-significance ($\mathcal{S}$)> 25 and 14 + $m_T^{b,min}$ >200 GeV
- Main bkg. $Z \rightarrow \nu\nu$ + jets from CR




## Observed limits at 95 % CL

- m(LQ) > 1.24 TeV for $\mathcal{B}$(LQ $\rightarrow$ t $\nu$) = 1.0

$$m_T^{b,min} = \sqrt{2 p_\mathrm{T}^b E_\mathrm{T}^{miss} \left[1 - cos\Delta\phi(\vec{p}_\mathrm{T}^{\,b} \vec{p}_\mathrm{T}^{\,miss})\right]}$$

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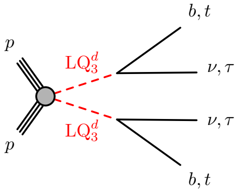
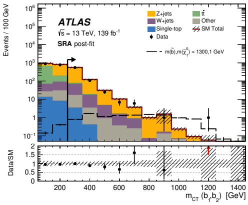
# LQLQ $\rightarrow b\nu\ b\nu$

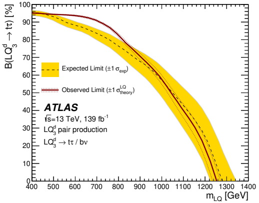
JHEP 05 (2021) 093

## Strategy

- Analysis optimized for PP of bottom squarks decaying to b-quarks + MET
- Events w. MET >250 GeV at least 2 to 4 jets incl. 2 b-jets
- reject main bg. $t\bar{t}$ by $m_{CT}$ [1] $> 250$ GeV ($m_{CT}(t\bar{t}) \leq 135$ GeV)
- Z bg. normalization taken from CR




## Observed limits at 95 % CL

- m(LQ) > 1.26 TeV for $\mathcal{B}(LQ \rightarrow b\ \nu) = 1.0$

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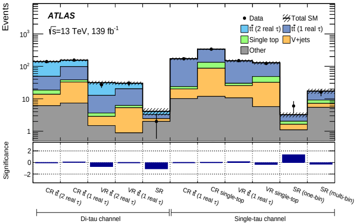
[1] $m_{CT}^2(b_1, b_2) = [E_T(b_1) + E_T(b_2)]^2 - [\vec{p}_T(b_1) - \vec{p}_T(b_2)]^2$

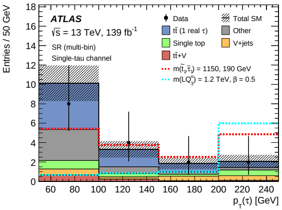
# LQLQ $\rightarrow b\nu\ t\tau\ /\ b\tau\ t\nu$

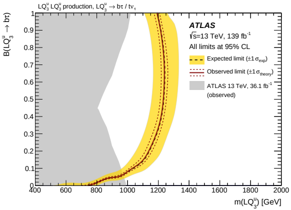
arXiv:2108.07665

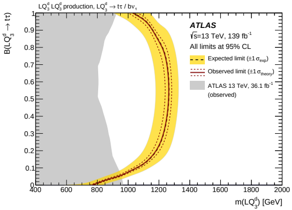
## Strategy

- Analysis optimized for stop pair decaying to staus and scalar LQ
- Events with at least 1 $\tau_{had}$, 2b-jet and MET
- SR based on cuts on MET, $p_T(\tau)$, $m_T(\tau)$, $m_T(b_1)$, $m_T(b_2)$
- BG norm. for $t\bar{t}$ & single top from CR




## Max. Observed limits at 95 % CL.

- $m(LQ) < 1.25\,\text{TeV}$

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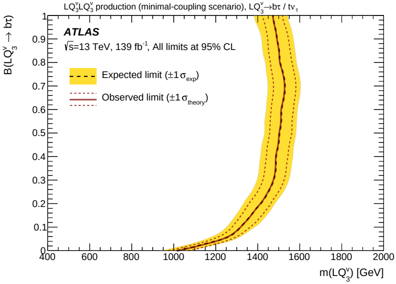
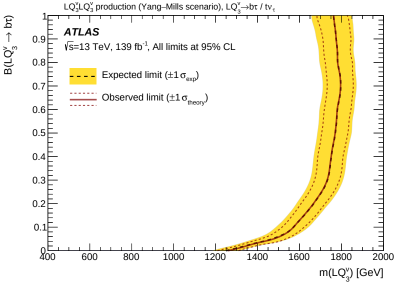
# $LQ_3^V LQ_3^V \rightarrow b\tau\ t\nu$: vector LQ

arXiv:2108.07665

Minimal coupling:



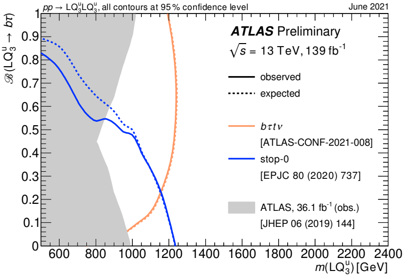

Yang-Mills-coupling:

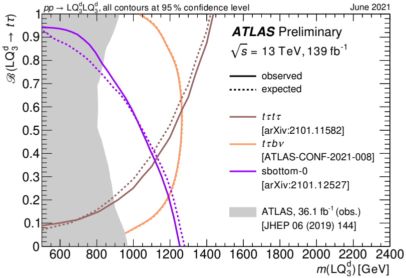


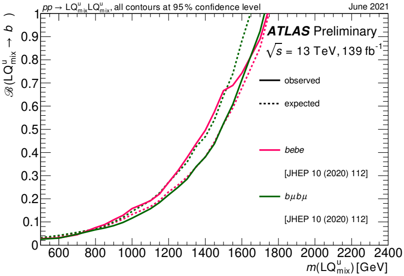

- First result of ATLAS for vector LQ
- Exclusion up to:
  - $m(LQ_3^V) > 1.5$ TeV Min. coupling
  - $m(LQ_3^V) > 1.8$ TeV Yang-Mills coupling
  - CMS result Phys.Lett.B 819 (2021) 136446:
    - 1.34 TeV-1.41 TeV Min. coupling (SP+PP)
    - 1.69 TeV-1.73 TeV Yang-Mills (SP+PP)

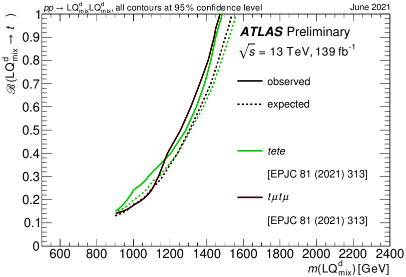
# Summary plots:

ATL-PHYS-PUB-2021-017



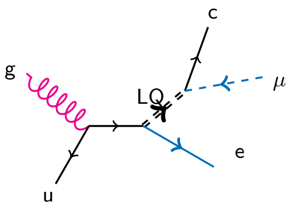



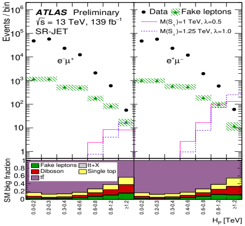
# LQ single production

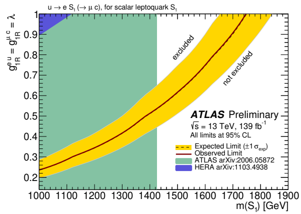
ATLAS-CONF-2021-045

## Strategy

- Data driven analysis of $\rho = \frac{N(e^+\mu^-)}{N(e^-\mu^+)}$ e/$\mu$ asymmetry measurement
- Events with exactly 1 $\mu$ and 1 e (oposite charge)
- Main discriminating variable: $H_P = |\vec{p_T}^e| + |\vec{p_T}^\mu| + |\vec{p_T}^{jet_{lead}}|$
- MET significance $< 6$




## Observed limits at 95 % CL

- m(LQ) $> 1.5$ TeV for $\mathcal{B}(\text{LQ} \to c\ \mu) = \mathcal{B}(\text{LQ} \to ue) = 0.5$ with coupling strength $g_{eu} = g_{\mu c} > 0.6$

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# Summary

- ATLAS published wide range of searches for LQ pair production using $140\,\mathrm{fb}^{-1}$ recorded during Run 2 at LHC
- Further full Run 2 results are expected
- LHC Run 3 will start next year and HL LHC will follow: ATLAS is looking forward to significantly more data to be analyzed ($\approx$ 20 times more data expected)

Y. S. Amhis et al. “Averages of $b$-hadron, $c$-hadron, and $\tau$-lepton properties as of 2018”. In: *Eur. Phys. J.* C81 (2021). updated results and plots available at https://hflav.web.cern.ch/, p. 226. DOI: 10.1140/epjc/s10052-020-8156-7. arXiv: 1909.12524 [hep-ex].

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