Searches for leptoquarks with the ATLAS detector

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Pheno 2021, Pittsburgh

24-26 May 2021
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Introduction Leptoquarks (LQ)

• Colour triplet bosons with fractional charge
• LQ decay flavour-diagonal and possibly cross-generations
• Yukawa interaction with coupling $\lambda$

**Pair-production**

| Large resonant cross-section |
|-----------------------------|

**single-production**

| Cross-section $\propto \lambda^2$ sensitive for large $m_{LQ}$ |

**off-shell production**

| Cross-section $\propto \lambda^4$ sensitive for larger $m_{LQ}$ |

| LQ decay | $B=1$ | $B=0$ |
|----------|-------|-------|
| $LQ_{\text{up}}$ | $b\tau$ | $t\nu$ |
| $LQ_{\text{down}}$ | $t\tau$ | $b\nu$ |
B-anomalies and dedicated search for bmédia

- Leptoquarks gain enhanced interest as a possible explanation of the B-anomaly (violation of lepton universality) LHCb, arXiv:2103.11769

- In ATLAS, a dedicated search was performed for bmédia.

\[
R_K = \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to J/\psi (\to \mu^+ \mu^-)K^+)} \bigg/ \frac{\mathcal{B}(B^+ \to K^+ e^+ e^-)}{\mathcal{B}(B^+ \to J/\psi (\to e^+ e^-)K^+)}
\]

- BaBar
  - $0.1 < q^2 < 8.12 \text{ GeV}^2/c^4$
- Belle
  - $1.0 < q^2 < 6.0 \text{ GeV}^2/c^4$
- LHCb 9 fb$^{-1}$
  - $1.1 < q^2 < 6.0 \text{ GeV}^2/c^4$

Pheno 2021, A.Sopczak
Search for new phenomena in final states with two leptons and one or no $b$-tagged jets, ATLAS-CONF-2021-012

- Benchmark signal model (inspired by the B-meson anomalies): four-fermion contact interaction between two quarks ($b,s$) and two leptons ($ee$ or $\mu\mu$).

Model is characterized by the energy scale and coupling, $\Lambda$ and $g_*$.
Summary of relative systematic uncertainties for signal regions with $m_{\ell\ell}^{\text{min}} = 2000$ (1500) GeV, \texttt{ATLAS-CONF-2021-012}

| Source                        | $e^+e^- + 0b$ (1b) [\%] | $\mu^+\mu^- + 0b$ (1b) [\%] |
|-------------------------------|-------------------------|--------------------------------|
|                               | Signal 0b (1b) | Background 0b (1b) | Signal 0b (1b) | Background 0b (1b) |
| Luminosity                    | 1.7 (1.7)       | 1.6 (1.5)          | 1.7 (1.7)       | 1.7 (1.7)          |
| Pile Up                       | <0.5 (<0.5)     | <0.5 (0.7)         | <0.5 (<0.5)     | <0.5 (<0.5)        |
| Leptons                       | 8.7 (8.6)       | 8.6 (6.3)          | 8.5 (6.5)       | 9.1 (4.2)          |
| Jets                          | <0.5 (1.8)      | <0.5 (3.4)         | <0.5 (1.6)      | <0.5 (1.9)         |
| b-tagging                     | <0.5 (1.4)      | <0.5 (2.0)         | <0.5 (1.4)      | <0.5 (2.2)         |
| Top Bkg. Extrapolation        | -               | 3.5 (32.0)         | -               | <0.5 (36.0)        |
| Multijet Extrapolation        | -               | 7.5 (15.0)         | -               | -                 |
| Top Quark Theory              | -               | <0.5 (<0.5)        | -               | <0.5 (<0.5)        |
| Z Theory                      | -               | 9.4 (4.3)          | -               | 10.0 (5.5)         |
| MC Statistics                 | 0.6 (0.8)       | 1.9 (3.5)          | 0.7 (1.0)       | 1.7 (2.4)          |
| Total                         | 8.9 (9.1)       | 15.0 (37.0)        | 8.7 (7.1)       | 14.0 (37.0)        |

- Contact interactions with $\Lambda/g_* < 2.0$ (2.4) TeV excluded for e ($\mu$) at 95% CL, still far from the value which is favored by the B-meson decay anomalies.
- Model-independent limits set as a function of di-lepton invariant mass, for the reinterpretation of the results in terms of other signal scenarios.
bb+MET, with taus search, pair production of third-generation leptoquarks, ATLAS-CONF-2021-008

- Search for Supersymmetry with scalar top (stop) has sensitivity for Leptoquark pair-production.
- Decay
  \[ tv\bar{v}, \ b\tau b\tau, \ b\nu b\nu, \ t\tau t\tau \]
- Charge $2/3e$ (left) and $-1/3e$ (right).
Third Generation Leptoquarks, 
ATLAS-CONF-2021-008

Di-tau preselection

$E_T^{\text{miss}}$-trigger fired and $E_T^{\text{miss}} > 250$ GeV
No light leptons ($e/\mu$)
At least two jets
At least one $b$-tagged jet

Single-tau preselection

At least two hadronic tau candidates
Exactly one hadronic tau candidate
At least two $b$-tagged jets

| Variable | CR $\ell\ell$ (2 real $\tau$) | CR $\ell\ell$ (1 real $\tau$) | VR $\ell\ell$ (2 real $\tau$) | VR $\ell\ell$ (1 real $\tau$) | SR |
|----------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|----|
| $E_T^{\text{miss}}$ | $-$                           | $-$                           | $-$                           | $-$                           | $-$ |
| $OS(\tau_1, \tau_2)$ | 1                             | 1                             | 1                             | $>$ 280 GeV                  |    |
| $m_{T2}(\tau_1, \tau_2)$ | $< 35$ GeV                    | $< 35$ GeV                    | [35, 70] GeV                  | [35, 70] GeV                 | $>$ 70 GeV          |
| $m(\tau_1, \tau_2)$ | $>$ 50 GeV                    | $>$ 50 GeV                    | $>$ 70 GeV                   | $>$ 70 GeV                   | $-$ |
| $m_T(\tau_1)$ | $>$ 50 GeV                    | $<$ 50 GeV                    | $>$ 70 GeV                   | $<$ 70 GeV                   | $-$ |

| Variable | CR $\ell\ell$ (1 real $\tau$) | CR single top | VR $\ell\ell$ (1 real $\tau$) | VR single top | SR |
|----------|-------------------------------|---------------|-------------------------------|---------------|----|
| $E_T^{\text{miss}}$ | $>$ 280 GeV                  | $>$ 280 GeV   | $>$ 280 GeV                  | $>$ 280 GeV   | $>$ 280 GeV      |
| $s_T$ | [500, 600] GeV                | $>$ 600 GeV   | $>$ 800 GeV                  | $>$ 800 GeV   | $>$ 800 GeV       |
| $m_T(b_{1,2})$ | [600, 700] GeV | [600, 700] GeV | [50, 150] GeV | [50, 150] GeV | $>$ 300 GeV   |
| $m_T(\tau)$ | $<$ 50 GeV                   | $<$ 50 GeV    | $<$ 50 GeV                   | $<$ 50 GeV    | $<$ 50 GeV       |
| $p_T(\tau)$ | $>$ 80 GeV                   | $>$ 80 GeV    | $>$ 80 GeV                   | $>$ 80 GeV    | $>$ 80 GeV       |

Pheno 2021, A.Sopczak
Expected and observed exclusion contours at 95% CL, as a function of $m(LQ)$ and the branching ratio $B(LQ_3^{u/d} \rightarrow q\ell)$ into charged leptons, ATLAS-CONF-2021-008

For $B(LQ^u \rightarrow b\tau)=0.5$ and $B(LQ^d \rightarrow t\tau)=0.5$, limits for LQs reach 1.25 TeV

Pheno 2021, A.Sopczak
bb+MET: pair production of third-generation down-type leptoquarks, arXiv:2101.12527

- Searches for bb+MET Supersymmetric prompt decays have sensitive to pair production of 3rd generation LQs
- Expected and observed mass limits, and cross-section upper limits at 95% CL.
tt+MET, all-hadronic search, pair production of third-generation down-type leptoquarks arXiv:2004.14060

• Searches for tt+MET all-hadronic
  Supersymmetric prompt decays have sensitive to pair production of 3rd generation LQs

• Z+jets (Z), t\bar{t}+Z (TTZ), ttbar (T), W+jets (W), and single-top (ST) backgrounds
tt+MET, all-hadronic search, arXiv:2004.14060

- Excluded $LQ^u_3$ (masses, branching ratios) and cross-section limits for $LQ^u_3$ pair-production
Summary: Up-type Third-Generation Model ($LQ^u_3$)

$b\tau b\nu$ ATLAS-CONF-2021-008, stop-0\ell\ EPJC 80 (2020) 737

Pheno 2021, A.Sopczak
Summary: Down-type Third-Generation Model ($LQ^d_3$) $b\tau bv$ ATLAS-CONF-2021-008, $\tau\tau\tau$ arXiv:2101.11582, sbottom-$0\ell$ arXiv:2101.12527
Summary: Up-type Mixed-Generation Model \((LQ_{\text{mix}}^u)\)

\(\text{bebe, } b\mu b\mu\) JHEP 10 (2020) 112, stop-0\(\ell\) be, \(b\mu\) EPJC 80 (2020) 737

stop-0\(\ell\) re-interpretation for mixed generation.
Published for \(B(LQ\rightarrow b\tau)\) limits.
Highest sensitivity for \(B(LQ\rightarrow t\nu) = 1\).
Summary: Down-type Mixed-Generation Model ($LQ^d_{\text{mix}}$)

tete, $t\mu t\mu$ EPJC 81 (2021) 313, sbottom-0$\ell$ te, $t\mu$
arXiv:2101.12527

sbottom-0$\ell$ reinterpretation for mix-generation limits. Published for $B(LQ\rightarrow t\tau)$ limits.

Highest sensitivity for $B(LQ\rightarrow b\nu) = 1$
Summary

ATLAS LQ lower limit (TeV) at 95%CL

| Category                        | Lower Limit |
|---------------------------------|-------------|
| 2nd-3rd cross.-gen. LQ→qμ       | 1.7         |
| 1st-3rd cross.-gen. LQ→qe       | 1.8         |
| 2nd-3rd cross.-gen. LQ→tμ       | 1.48        |
| 1st-3rd cross.-gen. LQ→te       | 1.48        |
| 3rd gen. LQ→t/bτB=0.5           | 1.22        |
| 3rd gen. LQ→ττ                  | 1.43        |
| 3rd gen. LQ→bτ                  | 1.03        |
| 2nd generation                  | 1.56        |
| 1st generation                  | 1.4         |

Reference

| Reference | L (fb) |
|-----------|--------|
| 1902.00377| 36     |
| 1902.08103| 36     |
| 2101.11582| 139    |
| 2010.02098| 139    |
| 2006.05872| 139    |

Pheno 2021, A.Sopczak
Same final states for Higgs boson production and Leptoquark production

• Example LQ pair-production and ttH \((H \rightarrow \tau \tau)\), 2lSS1tau(had).
• Potential for reinterpreting Higgs boson results for LQ searches.
Conclusions

• Growing interest in Leptoquarks as a possible explanation of the recently observed B-anomaly (hints for lepton flavour universality violation)

• Contact interaction limit $\Lambda/g^* > 2.0$ (2.4) TeV at 95% CL for ee ($\mu\mu$). Not sensitive yet to probe suggested range by B-anomaly (~30 TeV).

• Model-independent limits set as a function of di-lepton invariant mass.

• Current focus on 3rd generation, including cross-generational decays.

• Direct searches for Leptoquarks and re-interpretations of searches for Supersymmetry exclude phase-space of 1st, 2nd and 3rd generation Leptoquarks. Potential for reinterpretations of Higgs boson results.

• Search results statistically limited, expect more sensitivity with new data.

• Large potential in flavour physics for collaborations of phenomenologists and experimentalists.
References

• Motivated by B-anomalies
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