Searches for **leptoquarks**

with the ATLAS detector

Tamara Vázquez Schröder  
(CERN)  
on behalf of the ATLAS Collaboration

LeptonPhoton 2022 conference

Manchester/virtual - 12. January 2022
SM flavour structure

An extensive flavour puzzle...

Fermions: spin 1/2

- Why similar structure of quarks and leptons?
  - Underlying symmetry connecting both sectors?
  - Many grand unified theories (GUT SU(5), Pati-Salam SU(4), RPV SUSY) predict leptoquarks (LQ), carrying both lepton and baryon number
  - LQ are colour triplet bosons with a fractional electric charge
  - LQ can mediate flavour-changing-neutral-currents and enable violation of lepton flavour universality

- 6 quarks
- + 6 anti-quarks
- 6 leptons
- + 6 anti-leptons

+ mass
Anomalies in B-meson sector

- Hints for lepton flavour universality violation observed in **charged** and **neutral** current processes in B-physics

\[
R(D^{(*)}) \equiv \frac{\mathcal{B}(B^0 \to D^{(*)}+\tau \nu)}{\mathcal{B}(B^0 \to D^{(*)}+\ell \nu)}, \quad \ell = \mu, e
\]

3.1σ excess in \(R_D\) and \(R_{D^*}\) combination [1909.12524]

\[
R(K^{(*)}) = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}
\]

3.1σ excess in \(R_K\) [LHCb: 2103.11769] + tensions in angular observables and BRs

3.9σ global significance of NP in \(b \to s \mu \mu\) [2104.05631]

- The size of the anomalies suggest a tree-level mediator, such as **leptoquarks (LQ)**

- Two scalar or a single vector \(\text{LQ}(s)\) could explain the LFU anomalies
  - LQ decays into **flavour-diagonal** and **cross-generational** final states

Searches for LQ at ATLAS | LP 12-01-22 | Tamara Vazquez Schröder
Leptoquark production and decay

**Pair production**

- large QCD production
- cross section only depends on $m_{LQ}$
- resonant LQs

**Single production**

- cross section $\propto \lambda^2$
- sensitive to higher $m_{LQ}$
- for sufficiently high $\lambda$

**Off-shell production**

- cross section $\propto \lambda^4$
- non-resonant
- sensitive to very high $m_{LQ}$
- for sufficiently high $\lambda$

- Couplings determined by the parameter $\lambda$ via Yukawa interaction

- Also single LQ resonant production: although PDF for leptons inside the proton minuscule, compensated by resonant enhancement

- Simplified search strategy targeting certain final states from LQ decays at ATLAS
  - **up**- (Q=2/3e) or **down**- (Q=-1/3e) type LQs

- Thorough search for pair production of **scalar LQs**

- Re-interpretations based on **vector LQs** ongoing

<table>
<thead>
<tr>
<th>LQ decay</th>
<th>B=1</th>
<th>B=0</th>
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<tbody>
<tr>
<td>LQ$_{up}$</td>
<td>$b\tau$</td>
<td>$tv$</td>
</tr>
<tr>
<td>LQ$_{down}$</td>
<td>$t\tau$</td>
<td>$b\nu$</td>
</tr>
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</table>

ex.: 3rd generation flavour-diagonal scalar LQ

**Searches for LQ at ATLAS | LP 12-01-22 | Tamara Vazquez Schröder**
Scalar LQ state of the art

- Searches for leptoquarks cover a large variety of scenarios
- Here focusing on scalar leptoquark pair production

<table>
<thead>
<tr>
<th>Scenario</th>
<th>ATLAS</th>
<th>CMS</th>
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<tbody>
<tr>
<td>1st generation</td>
<td>1.4</td>
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<td>2nd generation</td>
<td>1.03</td>
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<tr>
<td>3rd gen. (LQ→bt)</td>
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<td>1.43</td>
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<td>3rd gen. (LQ→tv)</td>
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<td>3rd gen. (LQ→tt)</td>
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<td>1.25</td>
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<tr>
<td>3rd gen. (LQ→bν)</td>
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<td>1.25</td>
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<tr>
<td>2-3rd cross-gen. (LQ→te)</td>
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<td>1.48</td>
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<tr>
<td>2-3rd cross-gen. (LQ→tμ)</td>
<td>1.34</td>
<td>1.48</td>
</tr>
<tr>
<td>1-3rd cross-gen. (LQ→qe)</td>
<td>1.42</td>
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<tr>
<td>1-3rd cross-gen. (LQ→qμ)</td>
<td>1.7</td>
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</tr>
</tbody>
</table>

Observed lower limits on scalar LQ mass [TeV]

Searches for LQ at ATLAS | LP 12-01-22 | Tamara Vazquez Schröder
## Latest ATLAS LQ pair production results

- Dedicated and complementary searches targeting $B=0, 0.5$ or $1$
- LQ simulation at NLO QCD with MadGraph5_aMC@NLO + Pythia8
- LQ cross-section calculations equivalent to pair-produced top squarks
  - Approximate NNLO QCD + NNLL accuracy

<table>
<thead>
<tr>
<th>$B$</th>
<th>$u/d/s$</th>
<th>$c$</th>
<th>$b$</th>
<th>$t$</th>
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<td></td>
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<td>*not covered today</td>
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<td>$\mu$</td>
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<td>$t\tau\tau$</td>
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<td></td>
<td></td>
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<td>$b\nu b\nu$</td>
<td>*not covered today</td>
</tr>
</tbody>
</table>

Searches for LQ at ATLAS | LP 12-01-22 | Tamara Vazquez Schröder
Latest ATLAS LQ pair production results

<table>
<thead>
<tr>
<th>B=1</th>
<th>u/d/s</th>
<th>c</th>
<th>b</th>
<th>t</th>
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<tr>
<td></td>
<td>e</td>
<td></td>
<td></td>
<td>JHEP 10 (2020) 112</td>
</tr>
<tr>
<td></td>
<td>μ</td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>*not covered today</td>
</tr>
</tbody>
</table>

| B=0  | ν     |       |       | JHEP 05 (2021) 093 |
|      | -     |       |       | 2108.07665 [accepted by PRD] |

| B=0.5 | τ/ν  |       |       | tτbν |

*not covered today

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Cross-generational LQ searches

JHEP 06 (2019) 144 (36 fb⁻¹)

JHEP 06 (2021) 179


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Searches for LQ at ATLAS | LP 12-01-22 | Tamara Vazquez Schröder
LQLQ → tτtτ: analysis strategy

- First dedicated ATLAS search
- $1\ell+\geq 1\tau_{\text{had}}$ or $\geq 2\ell$
- $\geq 2$ jets; $\geq 1$ bjet
- Single and dilepton triggers

- Tighter light lepton isolation and identification in multilepton ($2\ell\text{SS}/3\ell$) regions to reduce contribution from non-prompt $\ell$ background
- Large variety of background contributions in each SR
- $M_{\text{eff}} (=\sum(\text{jet,e,}\mu,\tau)\ p_T + \text{MET})$ as discriminating variable in SRs

<table>
<thead>
<tr>
<th>CR</th>
<th>1$\ell+\geq 1\tau$</th>
<th>*eµOS+0$\tau$</th>
<th>**2$\ell$OS+≥1$\tau$</th>
<th>2$\ell$SS+0$\tau$</th>
<th>3$\ell$+0$\tau$</th>
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<tbody>
<tr>
<td>SR</td>
<td>1$\ell+\geq 1\tau$</td>
<td>2$\ell$OS+≥1$\tau$</td>
<td></td>
<td>2$\ell$SS/3$\ell$+≥1$\tau$</td>
<td></td>
</tr>
</tbody>
</table>

Number of e/µ

* used for $tt$ correction
** used for fake $\tau_{\text{had}}$ correction
LQLQ → tτtτ: results

- Simultaneous fit of 7 SRs and 15 CRs
- Main systematic uncertainties from:
  - τ identification and energy scale calibration, tt̄ modelling
- Sensitivity dominated by 1ℓ+≥1τ channel
- Statistically-limited search at high masses
- No significant excess over the SM background observed

\[ m_{LQ} < 1.43 \text{ TeV (1.22 TeV)} \text{ excluded for } B=1 \text{ (B=0.5)} \]
LQLQ → tτbν / tνbτ: analysis strategy

- MET trigger and offline MET > 280 GeV
- 1τ_{had}, no light leptons, ≥2 bjets
- Dedicated CRs and VRs for main backgrounds: t̅̅ (1 real τ) and single top
  - Large impact of single top vs t̅̅ interference modelling in measured single top normalisation correction
Strongest limits on pair-produced 3rd-generation scalar LQs for $B=0.5$ ($t\tau/b\nu$)

First interpretation for vector LQs in ATLAS!
• Reinterpretation from search for pair-produced $\tilde{b}\tilde{b}$ decaying into a b-quark and a stable neutralino ($0\ell$)

• SRA: optimised for large $\Delta m(\tilde{b}_1, \tilde{\chi}_1^0)$

• SRB: optimised for $50 < \Delta m(\tilde{b}_1, \tilde{\chi}_1^0) < 200$ GeV

• SRC: optimised for $\Delta m(\tilde{b}_1, \tilde{\chi}_1^0) < 50$ GeV

• Take best limits from SRA+SRB or SRC for leptoquark interpretation

$m_{LQ} < 1.26$ TeV ($0.4$ TeV) excluded for $B=0$ ($B=0.95$)
Towards combination

- Overlaying the $LQ_3^d$ limits from $\tau\tau\tau$, $\tau\tau\nu$ and $b\nu\nu$ results and $LQ_3^u$ limits from $b\tau\nu$ and $\tau\nu\tau$ results
  - $LQ_3^d$: covering the full phase space with 3 complementary analyses
  - Next step: **COMBINATION!**
Single LQ production

- First ATLAS single LQ production limits last Summer!
  - Assume LQ couples to $e_u$ and $\mu_c$
  - LQ couplings of $g^{e_u}_{1R} = g^{\mu_c}_{1R} > 0.46$ newly excluded
    for $m_{LQ} > 1420$ GeV up to $g^{e_u}_{1R} = g^{\mu_c}_{1R} = 1$ for
    $m_{LQ} = 1880$ GeV

$$H_P \equiv |\vec{p}_T^e| + |\vec{p}_T^\mu| + |\vec{p}_T^\tau|$$
Conclusions

- Latest findings from searches for leptoquarks with the ATLAS experiment
- Stringent limits set on scalar leptoquarks with flavour-diagonal and cross-generational couplings

- **Just the start!**
  - Many more scenarios to be covered (vector LQ, single LQ, s-channel and off-shell production)
  - Object improvements to be further exploited
  - All these searches are statistically limited → LHC expected to further improve sensitivity with increasing luminosity!

**Final goal:** explore the full phase-space
... and discover new physics!
LQLQ → μμj data event candidate

Thanks for your attention
If BSM... how to explain it?

- **EFT analysis**
  - Interpret data based on effective Lagrangian
    - Fermi theory \([E \ll m_W]\)
    - SMEFT \([E \ll m_{NP}]\)

- **Simplified model**
  - Which mediator could explain these tensions?
  - UV completion models including new mediator \(\rightarrow\) extra new particles
EFT analysis (I)

\[ \mathcal{L}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{cb} \sum_i C_i \Theta_i \]

\[ \sim \frac{1}{(3 \text{ TeV})^2} \]

\[ 3_q \rightarrow 2_q 3_\ell 3_\ell \]

\[ \mathcal{L}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{ts} V_{tb} \frac{\alpha}{4\pi} \sum_i C_i O_i \]

\[ \sim \frac{1}{(40 \text{ TeV})^2} \]

\[ 3_q \rightarrow 2_q 2_\ell 2_\ell \]

- Taken together, they point out to a well-defined structure of NP coupled mainly to 3rd generation, with a flavour structure connected to that appearing in the SM Yukawa couplings

\[ \sim \frac{1}{(1 \text{ TeV})^2} |V_q| \]

\[ \sim \frac{1}{(1 \text{ TeV})^2} |V_q| |V_\ell|^2 \]

[1909.02519]

Food-for-thought: connection to the hierarchy problem?
EFT analysis (II)

- EFT analysis

\[
\mathcal{L}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{cb} \sum_i C_i \mathcal{O}_i
\]

\[
\sim \frac{1}{(3 \text{ TeV})^2}
\]

\[
3_q \to 2_q 3_\ell 3_\ell
\]

\[
\mathcal{L}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{ts} V_{tb} \frac{\alpha}{4\pi} \sum_i C_i O_i
\]

\[
\sim \frac{1}{(40 \text{ TeV})^2}
\]

\[
3_q \to 2_q 2_\ell 2_\ell
\]

- Taken together, they point out to a well-defined structure of NP coupled mainly to the 3rd generation, with a flavour structure connected to that appearing in the SM Yukawa couplings.

Positive feedback between anomalies!
Improved fit to \(b \to s \ell \ell\)
Additionally... muon g-2

- Recent confirmation by Fermilab of the Brookhaven experimental result
  - Strong evidence of new physics: \(4.2\sigma\)
    (Fermilab + Brookhaven combo) *if using as benchmark the data-driven (R-ratio) SM calculation*

- If the \(S_1\) coupling to RH fermions is allowed, also a solution to \((g-2)_\mu\) is possible

[Muon g-2 collaboration, 2104.03281]

[SM prediction dominated by QED, but SM error dominated by QCD]

[Borsanyi et al., 2002.12347]
ATLAS LQ search strategy

- Simplified search strategy targeting certain final states from LQ decays
  - Extended Buchmüller, Rückl, Wyler (BRW) model \cite{PhysLettB1911987442}
  - \textbf{up}: (Q=2/3e) or \textbf{down}: (Q=-1/3e) type LQs
- Searches for pair production of \textbf{scalar LQs (LQ}_{up/down})
  - More model independent than vector LQ
  - Can be a pseudo-Nambu Goldstone boson (where the Higgs boson would also be included as a pNGB)
- Re-interpretations based on \textbf{vector LQs (LQ}_{V}) ongoing
  - Same charge and decay mode as LQ\textsubscript{up}
  - \textbf{Minimal-coupling (MC)}: LQ couples to SM gauge bosons through covariant derivative
  - \textbf{Yang-Mills (YM)}: LQ is massive gauge boson with additional couplings to SM gauge bosons
- Comparison of cross-sections (3rd generation):
  - \( \sigma_{YM}(LQ_{V}) \sim 5\sigma_{MC}(LQ_{V}) \sim 20\sigma(LQ_{up/down}) \) for \( m(LQ)=1.5 \text{ TeV} \)

![LQ decay table](image)

![Graph](image)

JHEP 10 (2017) 097
Other $b \rightarrow s \mu^+\mu^-$ probes

- Branching fractions of $b \rightarrow s \mu^+\mu^-$ decays
  - Multiple measurements are below SM predictions at low dilepton mass squared ($q^2$)
  - SM predictions suffer from large hadronic uncertainties

- Angular analyses: $B^+ \rightarrow K^{*+}\mu^+\mu^-$
  - Combined tension with SM at 3.1 sigma when floating $Re(C_9)$

- Angular analyses: $B^0 \rightarrow K^{*0}\mu^+\mu^-$
  - Large number of observables offering complementary information on NP
  - SM uncertainties smaller than for BFs
  - Combined tension between latest LHCb analysis and SM at 3.3 sigma when floating $Re(C_9)$
  - Extent of hadronic contributions still matter of debate

Harry Cliff, LHC seminar

Searches for LQ at ATLAS | LP 12-01-22 | Tamara Vazquez Schröder
Cross-sections LQ pair vs s-channel

**Table 1.** Inclusive cross sections in pb for the resonant leptoquark production from up-type quarks, $pp \rightarrow \text{LQ} + \text{charge-conjugated process}$, as a function of the leptoquark mass $m_{\text{LQ}}$ at $\sqrt{s} = 13$ TeV. The cross section $\sigma_{\text{S1/3}}$ ($\sigma_{\text{S2/3}}$) corresponds to the resonant production of scalar LQ with absolute electric charge $1/3$ ($5/3$) when the associated Yukawa coupling strength is set to one, $y_{\text{qL}} = 1$. The second column denotes which quark-lepton pair couples to the corresponding leptoquark. First (second) uncertainty is due to the renormalisation and factorisation scale variations (PDF replicas), and is given in per cent units. See Section 3 for details.
# Leptoquarks and quantum numbers

<table>
<thead>
<tr>
<th>Spin</th>
<th>$3B + L$</th>
<th>$SU(3)_c$</th>
<th>$SU(2)_W$</th>
<th>$U(1)_Y$</th>
<th>Allowed coupling</th>
<th>Types of LQs according to Buchmüller, Rückl, Wyler (BRW) model</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>−2</td>
<td>$\bar{3}$</td>
<td>1</td>
<td>1/3</td>
<td>$q^c_L\ell_L$ or $\bar{u}_R^c e_R$</td>
<td>$S_1$</td>
</tr>
<tr>
<td>0</td>
<td>−2</td>
<td>$\bar{3}$</td>
<td>1</td>
<td>4/3</td>
<td>$d_R^c e_R$</td>
<td>$S_1$</td>
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<tr>
<td>0</td>
<td>−2</td>
<td>$\bar{3}$</td>
<td>3</td>
<td>1/3</td>
<td>$q^c_L\ell_L$</td>
<td>$S_3$</td>
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<tr>
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<td>$\bar{3}$</td>
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<td>5/6</td>
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<td>$V_2$</td>
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<tr>
<td>1</td>
<td>−2</td>
<td>$\bar{3}$</td>
<td>2</td>
<td>−1/6</td>
<td>$\bar{u}_R^c \gamma^\mu \ell_L$</td>
<td>$\tilde{V}_2$</td>
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<td>2</td>
<td>1/6</td>
<td>$d_R \ell_L$</td>
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<td>$q_L^c \gamma^\mu \ell_L$ or $d_R \gamma^\mu e_R$</td>
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<td>5/3</td>
<td>$\bar{u}_R^c \gamma^\mu e_R$</td>
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<tr>
<td>1</td>
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<td>3</td>
<td>2/3</td>
<td>$q_L^c \gamma^\mu \ell_L$</td>
<td>$U_3$</td>
</tr>
</tbody>
</table>
LQ simulation & uncertainties

- Simulation at NLO QCD with MadGraph5_aMC@NLO + Pythia8
  - ME-PS matching done with CKKW-L prescription with matching scale = 1/4 * m_{LQ}
  - Narrow-decay-width approximation: 0.2% of m_{LQ} (on-shell production dominates)

- Samples with LQ mass between [400-2000] GeV
  - 50 GeV mass intervals within [800-1600] GeV, 100 GeV otherwise
  - additional dedicated β=1 samples

- **Signal cross-section calculations** equivalent to **pair-produced top squarks** (both massive, coloured, scalar particles with the same production modes)
  - Approximate NNLO QCD + NNLL accuracy
  - For LQ masses [400-2000] GeV, the cross-sections are [2.1 pb - 0.02 fb]
  - Renormalisation and factorisation scale uncertainties: 7-22% for LQ masses [400-2000] GeV

- **Acceptance and efficiency uncertainties**
  - Modelling of initial- and final-state radiation
  - Renormalisation and factorisation scale variations
  - PDF uncertainties
Vector LQs

Direct Searches - Vector LQ $U_1$

Limits and prospects from pair production of 3rd gen. LQ.

The coupling to gluons is model-dependent:

$$\mathcal{L}_{\text{kinetic}}^{U_1} = -\frac{1}{2} U_{\mu\nu} U_{\mu\nu} - ig_s \kappa \Gamma_{\mu\nu} U_{\mu} \Gamma_{\nu} U_{\mu} + M_{U_1}^2 U_{\mu} U_{\mu}.$$  

With Yang-Mills structure the limits are now $\sim 1.8$ TeV

$$\mathcal{L}_U = -\frac{1}{2} U_{\mu\nu} U_{\mu\nu} + M_U^2 U_{\mu} U_{\mu} + \mathcal{L}_{\text{an}} \quad (4.1)$$

where

$$U_{\mu\nu} = D_{\nu} U_{\mu} - D_{\mu} U_{\nu} \quad D_{\mu} \equiv \partial_{\mu} - ig_s \frac{\lambda^a}{2} G_{\mu}^a - ig_s \frac{2}{3} B_{\mu}, \quad (4.2)$$

and

$$\mathcal{L}_{\text{an}} = -ig_s k_a (U_{\mu} \frac{\lambda^a}{2} U_{\nu}) G_{\mu\nu}^a - ig_s \frac{2}{3} k_\gamma U_{\mu} U_{\nu} B_{\mu\nu} \quad (4.3)$$
LQ bounds and B-anomalies

$M_U$ [TeV]

\begin{align*}
pp \rightarrow U_1 U_1^* (13 \text{ TeV } 137 \text{ fb}^{-1}) \\
pp \rightarrow U_1 U_1^* (13 \text{ TeV } 3 \text{ ab}^{-1}) \\
pp \rightarrow \tau \tau (13 \text{ TeV } 139 \text{ fb}^{-1}) \\
pp \rightarrow \tau \tau (13 \text{ TeV } 3 \text{ ab}^{-1})
\end{align*}

with RH current
**LQLQ → bνbν**

<table>
<thead>
<tr>
<th>Variable</th>
<th>SRA</th>
<th>CRzA</th>
<th>VR\text{met}</th>
<th>VR\text{m_{01}}</th>
<th>VR\text{m_{02}}</th>
<th>VR\text{m_{03}}</th>
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</thead>
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<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Number of high-purity leptons</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
</tbody>
</table>

| \( p_T(\ell_1) \) [GeV] | > 27 | > 27 | > 27 | > 27 | > 27 | > 27 |
| \( p_T(\ell_2) \) [GeV] | > 20 | > 20 | > 20 | > 20 | > 20 | > 20 |
| \( m_T(\ell, \text{p}_{T}^{\text{miss}}) \) [GeV] | > 81 | > 81 | > 81 | > 81 | > 81 | > 81 |
| \( m_{\ell\ell} \) [GeV] | > 101 | > 101 | > 101 | > 101 | > 101 | > 101 |

| Number of jets | \( \epsilon \in [2, 4] \) | \( \epsilon \in [2, 4] \) | \( \epsilon \in [2, 4] \) | \( \epsilon \in [2, 4] \) | \( \epsilon \in [2, 4] \) | \( \epsilon \in [2, 4] \) |

| Number of b-tagged jets \( j_1 \) and \( j_2 \) | 2 | 2 | 2 | 2 | 2 | 2 |
| Number of \( \ell\ell \) b-tagged | ✔ | ✔ | ✔ | ✔ | ✔ | ✔ |

| \( p_T(j_1) \) [GeV] | > 150 | > 150 | > 150 | > 150 | > 150 | > 150 |
| \( p_T(j_2) \) [GeV] | > 50 | > 50 | > 50 | > 50 | > 50 | > 50 |
| \( p_T(j_3) \) [GeV] | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| \( \text{min}[\Delta\phi(j_1, 4, \text{p}_{T}^{\text{miss}})] \) [rad] | > 0.4 | > 0.4 | > 0.4 | > 0.4 | > 0.4 | > 0.4 |

| \( m_{\ell\ell} \) [GeV] | > 200 | < 200 | > 200 | < 200 | > 200 | < 200 |
| \( m_{\ell\ell} \) [GeV] | > 250 | > 250 | > 250 | > 250 | > 250 | > 250 |

| \( m_{\text{miss}} \) [GeV] | > 250 | < 250 | > 250 | < 250 | > 250 | < 250 |
| \( m_{\text{miss}} \) [GeV] | > 500 | > 500 | > 500 | > 500 | > 500 | > 500 |

| \( \text{w}_{XGB} \) | > 0.85 | > 0.3 | > 0.63 | > 0.63 | > 0.63 | > 0.63 |

<table>
<thead>
<tr>
<th>Variable</th>
<th>SRC-2b</th>
<th>SRC-1b1v</th>
<th>SRC-0b1v</th>
<th>VRC-2b</th>
<th>VRC-1b1v</th>
<th>VRC-0b1v</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of jets ( j_1 ) not b-tagged</td>
<td>( \epsilon \in [2, 5] )</td>
<td>( \epsilon \in [2, 5] )</td>
<td>( \epsilon \in [2, 5] )</td>
<td>( \epsilon \in [2, 5] )</td>
<td>( \epsilon \in [2, 5] )</td>
<td>( \epsilon \in [2, 5] )</td>
</tr>
<tr>
<td>Number of baseline leptons</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Number of b-tagged jets</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

| \( N_{\text{st}} \) | \( \geq 0 \) | \( \geq 1 \) | \( \geq 1 \) | \( \geq 0 \) | \( \geq 1 \) | \( \geq 1 \) |
| \( m_{\text{st}} \) [GeV] | > 0.6 | > 1.5 | > 1.5 | > 0.6 | > 1.5 | > 1.5 |
| \( \text{p}_{T}^{\text{st}} \) [GeV] | > 3 | > 5 | > 5 | > 3 | > 5 | > 5 |

| \( \text{H}_{T,3} \) [GeV] | < 80 | < 80 | < 80 | < 80 | < 80 | < 80 |
| \( \mathcal{A} \) | > 0.86 | > 0.86 | > 0.86 | > 0.86 | > 0.86 | > 0.86 |
| \( m_{jj} \) [GeV] | > 250 | > 250 | > 250 | > 250 | > 250 | > 250 |
| \( \Delta\phi(j_1, b_1) \) [rad] | > 2.2 | > 2.2 | > 2.2 | > 2.2 | > 2.2 | > 2.2 |
| \( \Delta\phi(j_1, \nu_{\text{TX}}) \) [rad] | < 1.2 | < 1.2 | < 1.2 | < 1.2 | < 1.2 | < 1.2 |
| \( |\eta_{\text{TX}}| \) | < 2 | < 2 | < 2 | < 2 | < 2 | < 2 |
Single LQ production

- $S$ is the so-called ‘object-based $p_T^{\text{miss}}$ significance’ defined in Eq. (15) of Ref. [46]. It is a dimensionless measure of the degree to which the apparent missing transverse momentum in the event is ‘real’ (i.e. attributable to momentum carried away by invisible particles) rather than due to object mismeasurement or pile-up.

- $M_{T2} \equiv \min_{\tilde{a} + \tilde{b} = \tilde{p}_T^{\text{miss}}} \max \left[ m_T(e, \tilde{a}), m_T(\mu, \tilde{b}) \right]$ was proposed in Ref. [45], where $\tilde{a}$ and $\tilde{b}$ represent the contributions to $p_T^{\text{miss}}$ from each semi-leptonic decay of a pair-produced particle, and all possible values that sum to the observed $p_T^{\text{miss}}$ are minimised over. It is evaluated using the algorithm of Ref. [47].

- $H_\rho \equiv |\tilde{p}_T^e| + |\tilde{p}_T^\mu| + |\tilde{p}_T^\tau|$ is a simple sum of the magnitudes of the transverse momenta of the two leptons and the most energetic jet in the event.
Search for
LQ LQ → tτtτ
Signal regions

- **1ℓ+≥1τ channel**
  - Split into: $1\ell+1\tau OS$, $1\ell+1\tau SS$, $1\ell+≥2\tau$
  - Signal regions with additional cuts on $p_T\tau$, $E_T^{miss}$, $m_{\ell\tau}$, $m_{eff}$, $m_T(\ell,E_T^{miss})$ and $m_{\tau\tau}$
  - Dominant background: $t\bar{t}$ with real ($1\ell+1\tau OS$) or fake ($1\ell+1\tau SS$, $1\ell+≥2\tau$) $\tau$ and/or $\ell$

- **2ℓOS+≥1τ channel**
  - Split into: $2\ell OS+1\tau$, $2\ell OS+≥2\tau$
  - Signal regions with additional cuts on $p_T\tau$, $m_{\tau\tau}^{min}$, $m_{\tau\tau}$, $m_{\ell\ell}$
  - Dominant background: $t\bar{t}$ with fake $\tau$ and/or $\ell$, $t\bar{t}W$, $t\bar{t}Z/\gamma^*$, $t\bar{t}H$

- **2ℓSS/3ℓ+≥1τ channel**
  - Split into: SR-H ($p_{T,1\tau} ≥ 225$ GeV), SR-L ($125 ≤ p_{T,1\tau} < 225$ GeV)
  - Dominant background: $t\bar{t}W$, $t\bar{t}Z/\gamma^*$, $t\bar{t}H$, $VV$

- **Acceptance x efficiency** = 10% in the combination of all SRs
Background estimation (I)

- Large variety of background contributions in each SR
- All backgrounds from MC simulation, data-driven corrections applied for some of them

- \( \bar{t}t \): background contributes with real or fake \( \ell/\tau \)
  - \( N_{\text{jets}} \) and \( m_{\text{eff}} \) correction: derived in OSe\( \mu \)+0\( \tau \) for \( \bar{t}t+Wt \)
  - Systematic variation: correction derived in 1\( \ell \)+1\( \tau \) channel

- Fake \( \tau \) correction: derived in OSe\( \mu \)+\( \geq 1 \tau \) with \( m_{\text{eff}} < 1000 \) GeV
  - Parametrised in \( p_{T}\tau \), and number of associated tracks (1 or 3 prongs)
  - Systematic variation: estimate from Z+jets CR OSe\( \mu \mu \)+\( \geq 1 \tau \)
Background estimation (II)

- Corrections derived **simultaneously** in final fit
  - 3 normalisation factors ($\lambda$) for **fake $\ell$ correction** (non-prompt HF electrons and muons, and material conversions + misidentified-charge electrons)
  - 2 $\lambda$ for $\bar{t}tW$ and internal conversions ($\gamma^* \rightarrow \ell\ell$ with $m_{\ell\ell} < 1$ GeV)

- Possible thanks to the **dedicated CRs in 2$\ell$SS+0$\tau$ and 3$\ell$+0$\tau$**
  - $H_T^{lep}$ fitted in non-prompt HF $\ell$ and $\bar{t}tW$, $t\bar{t}Z$, and VV CRs
  - Event yields used in material and internal conversions CRs
### $LQ \to t\tau t\tau$ (I)

| $e/\mu$ selection $N_{\text{had}}$ $\tau_{\text{had}}$ charge $p_{T,1}^{\tau}$ [GeV] $p_{T,2}^{\tau}$ [GeV] $N_{\text{jets}}$ $N_{\text{objects}}$ $E_{T}^{\text{miss}}$ [GeV] $m_{T}^{\ell T}$ [GeV] $m_{T}[e, E_{T}^{\text{miss}}]$ $m_{\tau}$ [GeV] | 1$\ell$+1$\tau$OS $1\ell$+1$\tau$SS $1\ell$+2$\tau$ | CR VR SR CR VR SR CR VR SR |
| --- | --- | --- | --- | --- | --- | --- | --- |
| $e/\mu$ selection | $t\bar{t}$ | $t\bar{t}$ | $t\bar{t}$ | $t\bar{t}$ | $t\bar{t}$ | $t\bar{t}$ | $t\bar{t}$ |
| $N_{\text{had}}$ | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| $\tau_{\text{had}}$ charge | Medium | Medium | SS | SS | SS | SS | SS |
| $p_{T,1}^{\tau}$ [GeV] | $\geq 50$ | $50-150$ | $\geq 150$ | $50-150$ | $\geq 150$ | $50-100$ | $\geq 100$ |
| $p_{T,2}^{\tau}$ [GeV] | — | — | — | — | — | — | — |
| $N_{\text{jets}}$ | $\geq 4$ | — | — | — | — | — | — |
| $N_{\text{objects}}$ | $\geq 2$ | $\geq 1$ | $\geq 2$ | $\geq 1$ | $\geq 2$ | $\geq 1$ | $\geq 2$ |
| $E_{T}^{\text{miss}}$ [GeV] | — | $\geq 80$ | — | — | $\geq 50$ | — | — |
| $m_{T}^{\ell T}$ [GeV] | — | $\geq 200$ | — | — | $\geq 200$ | — | — |
| $m_{T}[e, E_{T}^{\text{miss}}]$ [GeV] | — | $< 800$ | $\geq 800$ | $\geq 800$ | $< 800$ | $\geq 800$ | — |
| $m_{\tau}$ [GeV] | — | — | — | — | — | — | — |

<table>
<thead>
<tr>
<th>$2\ell$OS+1$\tau$</th>
<th>2$\ell$OS+2$\tau$</th>
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<td>$p_{T,1}^{\tau}$ [GeV]</td>
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<td>$m_{T}^{\ell T}$ [GeV]</td>
<td>—</td>
</tr>
<tr>
<td>$m_{T}[\ell T]$ [GeV]</td>
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</tr>
<tr>
<td>$Z$ veto</td>
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<td>$m_{\ell\ell}$ [GeV]</td>
<td>$&gt; 12$</td>
</tr>
</tbody>
</table>

| $2\ell$SS/3$\ell$+$\geq1\tau$ |
| --- | --- | --- |
| $e/\mu$ selection | $T^* (2\ell$SS) | $T^*/T (3\ell)$ |
| $N_{\text{had}}$ | $\geq 1$ | $\geq 1$ |
| $\tau_{\text{had}}$ ID | Loose | Loose |
| $p_{T,1}^{\tau}$ [GeV] | 25–125 | 125–225 |
| $Z$ veto | Yes | Yes |
| $m_{\ell\ell}$ [GeV] | $> 12$ | $> 12$ |
# LQ LQ → tttt (II)

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<tr>
<th>$e/\mu$ selection</th>
<th>$2\ell tt(e)\pm$</th>
<th>$2\ell tt(\mu)\pm$</th>
<th>$2\ell SS+0\tau$</th>
<th>$2\ell ttW\pm$</th>
<th>$2\ell IntC$</th>
<th>$2\ell MatC$</th>
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<td>$\mu\ell\ell\mu$</td>
<td>$ee\ell\mu\ell\ell\mu$</td>
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<td>Yes</td>
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<table>
<thead>
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<th>$e/\mu$ selection</th>
<th>$3\ell VV$</th>
<th>$3\ell ttZ$</th>
<th>$3\ell +0\tau$</th>
<th>$3\ell IntC$</th>
<th>$3\ell MatC$</th>
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<tbody>
<tr>
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<td>T</td>
<td>T</td>
<td>T($\ell_0$, $T^*(\ell_1$ and $\ell_2$))</td>
<td>T($\ell_0$, $T^*(\ell_1$ and $\ell_2$))</td>
<td>T($\ell_0$, $T^*(\ell_1$ and $\ell_2$))</td>
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<td>Yes</td>
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<td>Yes($\ell_1$ and $\ell_2$)</td>
<td>Inverted($\ell_1$ or $\ell_2$)</td>
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</tbody>
</table>

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**Searches for LQ at ATLAS**

*LP 12-01-22 | Tamara Vazquez Schröder*
- multivariate lepton isolation to reject non-prompt leptons based on:
  - lepton and overlapping track jets properties
  - lepton track/calorimeter isolation variables

- multivariate lepton identification to reject misidentified charge electrons

- The resulting electron candidates are further split into three classes: “Material Conversion,” “Internal Conversion,” and “Very Tight.”

<table>
<thead>
<tr>
<th>electron CO selection</th>
<th>CO radius</th>
<th>m\text{track-track}</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) material CO</td>
<td>&gt; 20 mm</td>
<td>&lt; 100 MeV (wrt. CV)</td>
</tr>
<tr>
<td>(2) internal CO</td>
<td>not (1)</td>
<td>&lt; 100 MeV (wrt. PV)</td>
</tr>
<tr>
<td>(3) very tight</td>
<td>not (1) and not (2)</td>
<td></td>
</tr>
</tbody>
</table>

(beam pipe @ 24 mm)
Systematic uncertainties $t\bar{t}t\bar{t}$

- $t\bar{t}$
  - Similar modelling uncertainties as in $t\ell\ell\ell$ analysis
  - $N_{jets}$ and $m_{eff}$ correction: slight difference in slope when derived in the $1\ell+1\tau$ channel

- Fake $\tau$ correction: alternative estimate from Z+jets CR $O\overline{S}ee/\mu\mu+\geq1\tau$ with $|m_{\ell\ell} - m_Z| < 10$ GeV

- Fake $\ell$ correction: relaxing lepton criteria to enrich samples in different types of fake

- Internal and material conversions: 25% extrapolation uncertainty derived in $Z\rightarrow\mu\mu\gamma^*(\rightarrow e\gamma)$ VR

- $t\bar{t}W$, $t\bar{t}Z/\gamma^*$, $t\bar{t}H$: modelling uncertainties from comparing to alternative generators

Nevertheless, the analysis is statistically-limited
Results (I)

- Simultaneous fit of 7 SRs and 15 CRs
- Main systematic uncertainties from:
  - $\tau$ identification and energy scale calibration, $t\bar{t}$ modelling
- Sensitivity dominated by $1\ell+\geq 1\tau$ channel
- Statistically-limited search at high masses
- No significant excess over the SM background observed
Results (II)

- Upper limits set on the LQ pair production cross-section at 95% CL
  
  - $m_{LQ} < 1.43$ TeV ($1.22$ TeV) excluded for $B=1$ ($B=0.5$)