Searches for leptoquarks and heavy leptons with the ATLAS detector at the LHC

Sergio Grancagnolo

Humboldt-Universität zu Berlin

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Motivation

Vector-like leptons (VLL)
- explain mass hierarchy between lepton generations
- arise in composite Higgs and warped extra-dimensions

Type-III Seesaw leptons
- generate neutrino masses, couple to gauge bosons

Majorana neutrinos
- explain neutrino mixing, allow for lepton number violation

Scalar leptoquarks
- predicted by many extensions of SM
- explain similarities between quark and lepton sectors
No excess observed above the expected numbers of SM background events
No evidence of new heavy particles observed
Results are interpreted in the context of various models
95% CL exclusion limits are set for various masses and mixing parameters
Systematic uncertainties are assumed to be uncorrelated, and included in the test statistic as nuisance parameters
Heavy leptons

Vector-like leptons (VLL)
- only charged, colourless, spin 1/2 fermions, same L/R chiral properties

Type-III Seesaw leptons
- charged and neutral, degenerate in mass
- heavy SU(2) triplets with zero hypercharge

Previous searches
- L3: excl $m_{L^\pm} < 100$ GeV ($L^\pm \rightarrow W^\pm \nu$)
- CMS: excl $m_{L^\pm} < 180 - 210$ GeV (BR dep)
Results: vector like lepton – three leptons channel

VLL Limits \((Z + e)\):

- Observed:
  \[129 \leq m_{\text{VLL}} \leq 144 \text{ GeV} \text{ and} \]
  \[163 \leq m_{\text{VLL}} \leq 176 \text{ GeV} \]
- Expected:
  \[109 \leq m_{\text{VLL}} \leq 152 \text{ GeV} \]

VLL Limits \((Z + \mu)\):

- Observed:
  \[114 \leq m_{\text{VLL}} \leq 153 \text{ GeV} \text{ and} \]
  \[160 \leq m_{\text{VLL}} \leq 168 \text{ GeV} \]
- Expected:
  \[105 \leq m_{\text{VLL}} \leq 167 \text{ GeV} \]
Results: type-III seesaw – three leptons channel

Type-III seesaw limits (Z + e):

- Observed: $100 \leq m_{L}^{\pm} \leq 430$ GeV
- Expected: $100 \leq m_{L}^{\pm} \leq 436$ GeV

Type-III seesaw limits (Z + $\mu$):

- Observed: $100 \leq m_{L}^{\pm} \leq 401$ GeV and $419 \leq m_{L}^{\pm} \leq 468$ GeV
- Expected: $100 \leq m_{L}^{\pm} \leq 419$ GeV

arXiv:1506.01291 [hep-ex]
Results: type-III seesaw – dilepton + dijet + $E_T^{\text{miss}}$ channel

Obs lim ($b_T=0$): $m_{L/N} \leq 335$ GeV

Obs lim ($\mu$): $m_{L/N} \leq 400$ GeV

Obs lim ($N, L \rightarrow W\nu, \ell$): $m_{L/N} \leq 475$ GeV
Majorana neutrinos

\[ \bar{q}_a (W_R^{\mp})^* (W_R^{\pm}) \bar{q}_b \]

Left-right symmetric model – LRSM

- predict heavy gauge bosons $V_R = W_R, Z'$

- ATLAS: $m_{W_R} < 2.3$ TeV, $(m_{W_R} - m_N > 0.3$ TeV)
- CMS: $m_{W_R} < 3.0$ TeV, $(m_{W_R} - m_N > 0.05$ TeV)

Type-I seesaw – mTISM

- include right-handed neutrinos, type-I seesaw $\nu$ mass generation
- produced via off-shell W boson, decays on-shell to $W\ell$

Previous searches

- LEP: excl $m_N < m_Z$
- CMS: excl $90 < m_N < 200$ GeV ($ee$), $40 < m_N < 500$ GeV ($\mu\mu$)
Results: Majorana $\nu$ (mTISM), $\rightarrow$ 2 leptons + jet(s)

$\sigma \times \text{BR}$ production limits

Mixing parameter $|V_{\ell N}|^2$ limits

arXiv:1506.06020 [hep-ex]
Results: Majorana $\nu$ (LRSM), $\mu\mu$ + jet(s)

Full results for all mass points are in HepData
Leptoquarks

LQ1, LQ2, LQ3
- each coupling with corresponding SM families
- colour triplet bosons, fractional electric charge
- carry both baryon and lepton numbers
- can be scalar or vector, decay directly into $\ell q$ pair
- coupling strength $\lambda_{LQ \rightarrow \ell q}$ affecting lifetime and width

Previous searches
- ATLAS: excl $m_{LQ_1} < 660(607)$ GeV, $\beta = 1(0.5)$
- ATLAS: excl $m_{LQ_2} < 685(594)$ GeV, $\beta = 1(0.5)$
- ATLAS: excl $m_{LQ_3} < 534$ GeV, $LQ_3 \rightarrow b\tau$
- CMS: excl $m_{LQ_1} < 830(640)$ GeV, $\beta = 1(0.5)$
- CMS: excl $m_{LQ_2} < 840(650)$ GeV, $\beta = 1(0.5)$
- CMS: excl $m_{LQ_3} < 440$ GeV, $LQ_3 \rightarrow b\nu\tau$
- CMS: excl $m_{LQ_3} < 740$ GeV, $LQ_3 \rightarrow b\tau$
- CMS: excl $m_{LQ_3} < 685$ GeV, $LQ_3 \rightarrow t\tau$

- JHEP 06 (2013) 033
- CMS update (8TeV) LQ1: CMS-PAS-EXO-12-041
- JHEP 12 (2012) 055
Analysis method

- Selection
- Background estimate
- Systematic uncertainties

Will focus on most recent leptoquark (LQ$_1$, LQ$_2$) searches
Event selection – Leptoquarks

Good detector components working condition

**LQ1**
- not isolated dielectron trigger
  - allow for data-driven background estimate
  - thresholds: 35 GeV, 25 GeV
- $e^+e^-$, no charge request
  - $p_T^{e_1} > 40$ GeV, $p_T^{e_2} > 30$ GeV
- $\geq 2$ jets, $p_T > 30$ GeV

**LQ2**
- single muon trigger $p_T > 36$ GeV
- $\mu^+\mu^-$, $p_T > 40$ GeV, OS
- $\geq 2$ jets, $p_T > 30$ GeV

Acceptance:
- $eejj$: 65-80%
- $\mu\mu jj$: 50%

### Various signal regions, based on $m_{\ell\ell}$, $m_{LQ}^{min}$, $S_T$

<table>
<thead>
<tr>
<th></th>
<th>LQ masses [GeV]</th>
<th>$m_{\ell\ell}$ [GeV]</th>
<th>$m_{LQ}^{min}$ [GeV]</th>
<th>$S_T$ [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SR1</td>
<td>300</td>
<td>130</td>
<td>210</td>
<td>460</td>
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<tr>
<td>SR2</td>
<td>350</td>
<td>160</td>
<td>250</td>
<td>550</td>
</tr>
<tr>
<td>SR3</td>
<td>400</td>
<td>160</td>
<td>280</td>
<td>590</td>
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<tr>
<td>SR4</td>
<td>450</td>
<td>160</td>
<td>370</td>
<td>670</td>
</tr>
<tr>
<td>SR5</td>
<td>500-550</td>
<td>180</td>
<td>410</td>
<td>760</td>
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<tr>
<td>SR6</td>
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<td>850</td>
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<td>SR7</td>
<td>700-750</td>
<td>180</td>
<td>580</td>
<td>950</td>
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<tr>
<td>SR8</td>
<td>800-1300</td>
<td>180</td>
<td>610</td>
<td>1190</td>
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</tbody>
</table>

Various signal regions, based on $m_{\ell\ell}$, $m_{LQ}^{min}$, $S_T$...
**Background estimates**

**MC**
- normalisation factors applied to MC predictions
- derivation from background enriched control regions
  - $Z/\gamma + \text{jets}$: $eejj$ $1.1 \pm 0.2$
  - $\mu \mu jj$ $0.97 \pm 0.15$
  - $t\bar{t}$: $eejj$ $1.10 \pm 0.05$
  - $\mu \mu jj$ $1.01 \pm 0.05$

**Data-driven**
- mis-identified or non-prompt lepton contribution:
- multi-jets, $W + \text{jets}$, hadronic $t\bar{t}$, single $t$
- estimated with matrix method using a loose lepton selection
- $E_T, \eta$ dependent fake rate ($\sim 10\%$) measured in background enriched samples

**Main systematic uncertainties**
MC modelling, PDF, QCD, JES, ...
Results: Leptoquarks, 2 leptons + ≥ 2 jets

**Observed limits**

- $\beta = 1.0$
  - $m_{LQ1} < 1050$ GeV
  - $m_{LQ2} < 1000$ GeV

- $\beta = 0.5$
  - $m_{LQ1} < 900$ GeV
  - $m_{LQ2} < 850$ GeV

- $\beta = 0.2$
  - $m_{LQ1} < 650$ GeV
  - $m_{LQ2} < 650$ GeV
Results: Leptoquarks, reinterpreting SUSY searches

Search for SUSY $\tilde{b} \rightarrow b\tilde{\chi}^0$ and $\tilde{t} \rightarrow t\tilde{\chi}^0$ are reinterpreted in LQ model.

JHEP 10 (2013) 189

JHEP 11 (2014) 118

LQ3 pair production limits ($b\nu_\tau \bar{b}\bar{\nu}_\tau$):
- Observed: $m_{LQ3} < 625$ GeV
- Expected: $m_{LQ3} < 640$ GeV

LQ3 pair production limits ($t\nu_\tau \bar{t}\bar{\nu}_\tau$):
- Obs: $210 < m_{LQ3} < 640$ GeV
- Exp: $200 < m_{LQ3} < 685$ GeV
Summary

- Models predicting new heavy particles were tested
  - Vector-like leptons, type-III seesaw heavy leptons
  - Majorana neutrinos, leptoquarks
- No excess observed, using various final states
  - number of high momentum leptons, jets, $b$-tagged jets
  - highly specific signal and control region defined
  - good background understanding and prediction
- Potential of 8 TeV data exploited
- Looking forward for next updates at 13 TeV!

![Data-MC comparison for $Z \rightarrow ee$](image-url)
# Object selection

## Primary vertex and Tracks
- ≥ 3 tracks with $p_T > 0.4$ GeV
- Largest $|p_T|^2$ sum associated
- Compatible tracks impact parameters: $|d_0|$, $|z_0|$  

## Muons
- Consistent MS and ID good quality track match
- $|\eta| < 2.5$
- Separated from jets
- Track isolation  

## Electrons
- Track and calorimeter quality and match criteria
- Cluster energy deposit shape
- $|\eta| < 2.47$, exclude $1.37 < |\eta| < 1.52$
- Jet overlap removal
- Track and energy isolation  

## Jets
- anti-$k_t$ clustering algorithm with 0.4 radius
- Calibrated ($p_T, \eta$), in-situ correction
- Reject beam-halo, noise, overlap
- JVF $> 0.5$

## $E_T^{\text{miss}}$
- Vector sum of transverse momenta of all calibrated leptons and jets, and unassociated clusters with $|\eta| < 4.9$
Event selection – VLL, Type-III

Single e or $\mu$ trigger (iso or not) Lepton matching trigger

- at least three leptons (e or $\mu$)
- $p_T^{\ell_1} > 26$ GeV, $p_T^{\ell_2,3} > 15$ GeV
- $|m_{\ell\ell} - m_Z| < 10$ GeV
- $\Delta R(\ell, m_{\ell\ell}) \leq 3.0$
- if $\geq 4\ell$, no ZZ events
Event selection – Type-III

- ==2 leptons (e or \( \mu \))
- OS: \( p_T^\ell > 100 \text{ GeV}, p_T^\ell > 25 \text{ GeV}, m_{\ell\ell} > 130 \text{ GeV} \)
- SS: \( p_T^\ell > 70 \text{ GeV}, p_T^\ell > 40 \text{ GeV}, m_{\ell\ell} > 90 \text{ GeV} \)
- \( \geq 2 \) jets, no \( b \)-tagged jets
- OS: \( p_T^{j1} > 60 \text{ GeV}, p_T^{j2} > 30 \text{ GeV} \)
- SS: \( p_T^{j1} > 40 \text{ GeV}, p_T^{j2} > 25 \text{ GeV} \)
- \( 60 < m_{j1j2} < 100 \text{ GeV} \) (\( W \) boson hadronic decay)
- OS: \( \slashed{E}_T > 110 \text{ GeV}, \Delta R_{jj} < 2 \)
- SS: \( \slashed{E}_T > 100 \text{ GeV} \)
Event selection – Majorana

Common to Majorana analysis

- suite of single lepton (threshold 24GeV) and dimuon trigger (thresholds: 20GeV, 8GeV)
- \( \geq 2 \) same-sign leptons (e or \( \mu \)), veto any more loose lepton
- \( p_T^{\ell_1} > 25 \text{ GeV}, \ p_T^{\ell} > 20 \text{ GeV} \)

\( m_{\text{TISM}} \)

- \( \geq 2 \) jets, \( 60 < m_{j_1j_2} < 100 \text{ GeV} \) (\( W \) boson hadronic decay)
- \( m_{\ell\ell} > 40 \text{ GeV}, |m_{\ell\ell} - m_Z| > 20 \text{ GeV} \)
- \( E_T < 40 \text{ GeV} \)
- Total eff.: 0.5-24\% (ee), 3-30\% (\( \mu^+ \mu^- \))

\( m_{\ell\ell} \)

- \( \geq 1 \) jet
- \( m_{\ell\ell} > 110 \text{ GeV} \)
- \( W_R \) searches: \( m_{\ell\ell j(j)} > 400 \text{ GeV} \)
- \( Z' \) searches: \( m_{\ell\ell jj(jj)} > 200 \text{ GeV} \)
- Total eff.: 0.5-25\% (ee), 1.5-30\% (\( \mu^+ \mu^- \)), 15\% (\( m_{V_R} >> m_N \))
Event selection – Leptoquarks

LQ3 \( (b\nu_\tau \bar{b}\bar{\nu}_\tau) \)
- \( E_\text{miss} \) trigger
- \( \geq 2 \) b-tagged jets, \( p_T > 20 \) GeV, \( |\eta| < 2.5 \)
- other jets if \( p_T > 20 \) GeV, \( |\eta| < 4.9 \)
- no e (\( \mu \)) with \( p_T > 7 \) (6) GeV
- \( E_\text{miss} > 150 \) GeV, various signal regions

LQ3 \( (t\nu_\tau \bar{t}\bar{\nu}_\tau) \)
- \( \geq 1 \) \( \ell \), \( p_T > 25 \) GeV, \( |\eta| < 2.47 \) (2.4) for e (\( \mu \))
- veto on additional loose leptons with \( p_T > 10 \) GeV
- \( \geq 4 \) jets, \( p_T > 20 \) GeV, \( |\eta| < 2.5 \)
- \( \geq 1 \) b-tagged jet
- \( E_\text{miss} > 100 \) GeV, various signal regions
Control regions

Tight e with $E_T > 20$ GeV

- Validate MC modeling accuracy
- Derive normalization scale factors

**Z+jets control region**
- $60 < m_{ee} < 120$ GeV
- $70 < m_{\mu\mu} < 110$ GeV

**tt**
- $==1$ lepton, $p_T > 40$ GeV
- single electron trigger

- **Z/γ+jets:**
  - $eejj$: $1.1 \pm 0.2$
  - $\mu\mu jj$: $0.97 \pm 0.15$

- **tt:**
  - $eejj$: $1.10 \pm 0.05$
  - $\mu\mu jj$: $1.01 \pm 0.05$
Systematic uncertainties

- **MC modelling as a function of $S_T$**
  - $Z+\text{jets}$:
    - $eejj$: 8-25%
    - $\mu\mu jj$: 10-30%
  - $t\bar{t}$:
    - $eejj$: 6-24%
    - $\mu\mu jj$: 10-40%

- **NLO cross-section of diboson, single $t$, $W+\text{jets}$, $Z \rightarrow \tau\tau$**
- **PDF set**: 4-17% (low to high $m_{LQ}$)
- **Final PDF on signal**: 1-4%
- **QCD renormalisation and factorisation scales**: 14%
- **JES**: 8-26% (SR1-SR8), **JER**: 1%
- **$e, \mu$ scale, resolution**: $\sim$ 1%
MC Signal samples

Heavy lepton resonances:
- production MadGraph 4.52 (VLL), 5.2.2.1 (type-III)
- CTEQ6L1 PDF, AU2 tune, Pythia8 showering
- Decay: Bridge (VLL) and MadGraph (type-III)

Type-III seesaw heavy leptons:
- MadGraph5 (matrix elements), MadEvent (MSTW2008 PDF)

Majorana (mTISM):
- Alpgen 2.14 (LO in QCD) with CTEQ6L1 PDF set
- Neutrino masses: 100-500GeV
MC Signal samples

Majorana (LRSM):
- Pythia 8.170 (LO in QCD)
- Same coupling for heavy gauge bosons and neutrino than for SM
- $W_R$ masses between 0.6 and 4.5 TeV
- $Z'$ masses between 0.4 and 3.6 TeV
- Majorana neutrino 50-100 GeV below the heavy gauge boson mass
- No heavy neutrino mixing, same-flavor final state leptons

Leptoquarks:
- Pythia 8.160 event generator, with CTEQ6L1 PDF
- $\lambda_{LQ\rightarrow\ell q} = \sqrt{0.01 \times 4\pi\alpha}$
- $200 \leq m_{LQ} \leq 1300$ GeV in 50 GeV steps
- Normalised to NLO cross-section for scalar LQ pair prod

Detector response modelled using GEANT4, or fast detector simulation where calorimeter is parametrised