Searches for new phenomena in final states involving leptons and jets using the ATLAS detector

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Investigated Topology

★ Reconstructed final states with both **leptons** and **jets** — probes for a wide variety of new physics predictions
  - Leptoquarks
  - See-saw mechanism
  - Lepton flavour violation
  - SUSY
  - Vector like quarks
  - Dark matter
  - …

★ In this talk I will concentrate on recently updated searches that cover full Run 2 dataset
  - Production of pairs of Scalar **Leptoquarks** (LQ)
  - **Lepton Flavour Violation** (LFV) in \( Z \rightarrow \ell \tau \)
  - **Type III See-saw** Heavy Leptons

(13TeV, 139 fb\(^{-1}\))
Leptoquarks (LQ)

★ Hypothetical particles that couple to leptons and quarks
  ★ Motivated by the symmetry in lepton and quark spectra
★ Predicted by many GUT models
★ Experimental motivation
  ★ Flavour anomalies in B decays
  ★ Anomalous magnetic moment of muon

★ Search of LQs in ATLAS
  ★ Focus on scalar LQ pair production
  ★ Different final states, including cross-generation

★ Will focus on searches extended to Run 2 dataset (139 fb⁻¹)
  ★ $LQ \rightarrow e/\mu + qq$ [arXiv:2006.05872]
  ★ $LQ \rightarrow \tau + t$ [ATLAS-CONF-2020-029]
  ★ $LQ \rightarrow e/\mu + t$ [ATLAS-CONF-2020-033]
**Event selection:**

- 2 oppositely charged, same-flavour leptons, $\geq 2$ jets (light jets, $c$ and $b$ jets), low $E_T^{miss}$
- All 6 LQ hypotheses (same and cross gen.) are tested independently — **no excess** observed
- LQ excluded up to $1.8 \ (1.7)$ TeV in **electron (muon)** channel for $\text{Br}(LQ \rightarrow lq) = 1$

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**Searches with Leptons and Jets @ ATLAS**
$LQ \rightarrow \tau + t$

- Pair production $LQ_3^d LQ_3^d \rightarrow t\bar{t}\tau\tau$
- Events categorised based on number of light leptons and $\tau$ decaying hadronically to cover the complex multi-lepton final states
  - NN-based technique for $\tau_{had}$ identification
- Simultaneous fit to 7 SRs and 15 CRs
- $t\bar{t}$ kinematic reweighing derived by binning in $N_{jet}$ and $m_{eff} = \sum_{e,\mu,\tau, jet} p_T + E_{miss}$
- Data-driven correction in the modelling of fake $\tau_{had}$
- Data-driven normalisation of fake $l$ and $ttW$ BGs
No sig. excess observed after profile-likelihood fit to $m_{\text{eff}}$

LQ masses excluded @ 95% CL up to $1.4 \text{ TeV} / 1.2 \text{ TeV}$ for $Br(LQ \rightarrow t\tau) = 1/0.5$
Cross-generation LQ decay

- Targeting high mass region, where both top quarks are **boosted**
  - Resulting in **large R (1.0) jets**

- Event selection
  - 2 oppositely charged, same-flavour leptons
  - \[ m(\ell\ell) > 120 \text{ GeV} \] (to reduce BG from SM production)

- Dominant background \( Z + \text{jets} \) and \( t\bar{t} \)

- XGBoost framework: BDT classifier used to distinguish signal from \( Z + \text{jets} \) and \( t\bar{t} \) background

- Simultaneous fit to 3 bins of BDT shape in SR and two CRs (for \( t\bar{t} \) and \( Z + \text{jets} \) backgrounds)
$LQ \rightarrow e/\mu + t$

- Data compatible with SM / no significant excess observed
- Lower limit on LQ masses @ 95% CL:
  - ★ 1.48 TeV / 1.47 TeV for electron / muon
Lepton flavour violation ($Z \rightarrow \ell \tau$)

★ From **neutrino mixing** — prediction: $\text{Br}(Z \rightarrow \ell \tau) \leq O(10^{-54})$

★ see e.g. arXiv:hep-ph/0001273

★ Analysis focuses on **hadronic** $\tau$ decays
  ★ Typically **one** or **three** charged tracks (1-prong, 3-prong)

★ Selection criteria:
  ★ At least **one hadronic** $\tau$ candidate and
    exactly **one light lepton** ($e$ or $\mu$) of opposite charge
  ★ $m_T(\tau_{\text{had-vis}}, E_T^{\text{miss}}) < 35 \text{ GeV}$
    to reject $Z \rightarrow \tau\tau$ and $W + jets$
  ★ $m_{\text{vis}}(\ell, \tau_{\text{had-vis}}) > 60 \text{ GeV}$
    to reject lepton pairs incompatible with $Z \rightarrow \tau\ell$
  ★ NN-based $\tau$ identification
Signal events — $Z \rightarrow \ell \tau$, main background events $Z \rightarrow \tau \tau$ and $W \rightarrow \ell \nu$ jet

Event topologies of signal and two main BGs show that the angular relations of the decay products is different between the three processes.

Consequently, transverse mass using $\mu$ vs $\tau$ candidate is a good discriminating distribution.
LFV ($Z \rightarrow \ell \tau$) — upper limit on $Br$

★ Main backgrounds:

★ **q or g-initiated jets** are misidentified as $\tau_{had-vis}$ ($W(\rightarrow l\nu)+$jets, QCD multijet, $Z+$jets, $t\bar{t}$)

★ Estimated using the data-driven fake factor method

★ $Z \rightarrow \tau\tau$

★ MC with data driven $p_T$-based corrections, derived in regions with negligible signal

★ Best-fit performed on NN score for $e\tau$ and $\mu\tau$

★ Constraints supersede the so-far most stringent limits by LEP experiments

<table>
<thead>
<tr>
<th>Experiment, polarisation assumption</th>
<th>Observed (expected) upper limit on $B(Z \rightarrow \ell\tau)$ [$\times 10^{-6}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS Run 2, unpolarised $\tau$</td>
<td>$8.1$ (8.1)</td>
</tr>
<tr>
<td>ATLAS Run 2, left-handed $\tau$</td>
<td>$8.2$ (8.6)</td>
</tr>
<tr>
<td>ATLAS Run 2, right-handed $\tau$</td>
<td>$7.8$ (7.6)</td>
</tr>
<tr>
<td>ATLAS Run 2, left-handed $\tau$</td>
<td>$9.9$ (6.3)</td>
</tr>
<tr>
<td>ATLAS Run 2, left-handed $\tau$</td>
<td>$9.5$ (6.7)</td>
</tr>
<tr>
<td>ATLAS Run 2, right-handed $\tau$</td>
<td>$10$ (5.8)</td>
</tr>
</tbody>
</table>
Type III Seesaw

- SM neutrinos are only **left-handed** — thus no standard mass term
- Neutrino oscillations observed → at least two neutrinos have \( m \neq 0 \)
- With **Seesaw mechanism** relative small neutrino mass can be explained by introducing new heavy right handed “neutrinos” (neutrino like particles)

- We focus on **Type III Seesaw** where a new fermion triplet is introduced \((N^0, L^+, L^-)\)
  - \( N^0 \rightarrow \nu h / \nu Z / \ell^\pm W^\mp \)
  - \( L^\pm \rightarrow \ell^\pm h / \ell^\pm Z / \nu W^\pm \)

- Search for pair production:
  - \( pp \rightarrow N^0 L^\pm \)
  - \( pp \rightarrow L^\pm L^\mp \)
Type III Seesaw — analysis

★ ATLAS analysis focuses on the following signature:

★ **2 lepton** final state:
  ★ opposite **sign** (OS) or same **sign** (SS)
  ★ same **flavour** ($ee, \mu\mu$) or opposite **flavour** ($e\mu$)

★ **2 jets** from quark hadronisation

★ Large **missing energy** ($E_T^{miss}$) due to neutrinos

★ Events split into 3 sets of 6 regions:
  ★ 6x signal (SR), 6x control (CR) and 6x validation (VR)

★ Backgrounds:

★ **Prompt leptons** (based on detailed MC)
  ★ $t\bar{t}$ pairs, diboson production

★ **Non-prompt or “fake” leptons** (data driven methods)
  ★ conversions, jets, semileptonic c/b, charge misID,…

Type III Seesaw — number of events

- Comparison of number of observed (data) and expected events in
- Background control and validation and signal regions

![Graph showing event comparison in control, validation, and signal regions.]
Type III Seesaw — limit

Lower limits on masses of Type III Seesaw heavy leptons at the 95 % CL

Heavy leptons are excluded below masses of 790 GeV using only final states with two light leptons.

$H_T$ — scalar sum of the transverse momenta of selected leptons and jets

Cut-based analysis
expected limit: $820^{+40}_{-60}$ GeV
observed limit: 790 GeV
Summary

★ Many different processes have signature with two leptons and jets in the final state

★ The presentation focuses on recently published results from ATLAS Experiment on the full data set of Run 2 (2015-2018, 13TeV, 139 fb$^{-1}$)

★ Leptoquarks
  ★ $LQ \rightarrow e/\mu + qq$ (c, b jets) — excluded up to 1.8 (1.7) TeV in electron (muon)
  ★ $LQ \rightarrow \tau + t$ — excluded up to 1.4 TeV
  ★ $LQ \rightarrow e/\mu + t$ — excluded up to 1.48 TeV / 1.47 TeV for electron / muon

★ Lepton Flavour Violation
  ★ $Br(Z \rightarrow e\tau) \leq 8.1 \times 10^{-6}$
  ★ $Br(Z \rightarrow \mu\tau) \leq 9.5 \times 10^{-6}$

★ Type III Seesaw
  ★ Heavy leptons ($N^0, L^+, L^-$) are excluded below masses of 790 GeV
Type III Seesaw — analysis

★ ATLAS analysis focuses on the following signature:
  ★ **2 lepton** final state:
    ★ opposite **sign** (OS) or same **sign** (SS)
    ★ same **flavour** ($ee, \mu\mu$) or opposite **flavour** ($e\mu$)
  ★ **2 jets** from quark hadronisation
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★ Events split into 3 sets of 6 regions:
  ★ 6x signal (SR), 6x control (CR) and 6x validation (VR)

★ Two different approaches:
  ★ **Cut-based** — presented here
  ★ Multivariate ML approach in preparation
Many different sources of background fit in two categories wrt to origin of reconstructed lepton

- **Prompt leptons** — estimated based on detailed MC (MadGraph/Sherpa/Pythia + Geant4)
  - Main sources: top quark pairs, diboson production (WW, WZ, ZZ)

- **Non-prompt or “fake” leptons** (data driven methods)
  - Photon conversions
  - Semileptonic decays of c/b
  - Jets
  - Punch trough particles
  - Charge misID