Heavy Neutrino Searches at ATLAS

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The ATLAS experiment @ the LHC

The dashed tracks are invisible to the detector.
The ATLAS experiment @ the LHC

Obviously, not the focus of this talk!
Heavy Neutrino theoretical models

- Experimental signature of neutrino oscillation concludes neutrinos have very small masses
  - Several searches at ATLAS try to explain it and why they are so small

- Left Right Symmetric Models — LRSM
  - Restores parity by introducing heavy right-handed $W_R/Z_R$ bosons and Heavy Neutral Leptons (HNLs)
    —> postulates heavy new $SU(2)_R$ for SM $SU(2)_L$
  - Models naturally embed the Seesaw Mechanism which couples light $\nu_L$ to HNLs through a mass mixing matrix
    —> allows HNLs at GeV/TeV scale (good for ATLAS!)
  - Models consider SeeSaw type I, II, and III

- Neutrino Minimal Standard Model ($\nu$MSM)
  - Incorporates SeeSaw type I mechanism
  - Small $\nu_L$ masses result from large mass of HNLs
  - Includes HNLs without additional vector bosons

image credit symmetry-magazine
Analysis Overview:

- Search for HNLs & WR in LRSM
- Search for HNLs in type III SeeSaw models ($L^\pm, N^0$)
- Search for HNLs in $\nu$MSM
Analysis Overview:

- **Search for HNLs & $W_R$ in LRSM**
- Search for HNLs in type III SeeSaw models ($L^\pm, N^0$)
- Search for HNLs in $\nu$MSM
Search for HNLs and $W_R$ in LRSM

- Search in the 2D plane of $N_R$ and $W_R$
- Assume perfect symmetry at high scales: $g_L = g_R$
- Using dilepton events ($ee/\mu\mu$) with jets
Search for HNLs and $W_R$ in LRSM — boosted

- Search in the 2D plane of $N_R$ and $W_R$
- Assume perfect symmetry at high scales: $g_L = g_R$
- Boosted topology when $m_{WR} >> m_{NR}$
- Using events ($e/\mu\mu$) with large-radius jet
Analysis Overview:

- Search for HNLs & $W_R$ in LRSM
- *Search for HNLs in type III SeeSaw models ($L^\pm, N^0$)
- Search for HNLs in $\nu$MSM
Search for type III Fermionic Triplet

- Search for mass-degenerate fermionic triplet \((L^\pm, N^0)\)
- Assume equal branching \(B_e = B_\mu = B_\tau = 1/3\)
- Three main topologies considered:
  - 2 leptons + jets
  - 3 leptons + jets
  - 4 leptons + jets

Main backgrounds in this search:
- Rare top events (3t, 4t, tt+W/H/Z) & Diboson events (irreducible)
- Fake non-prompt leptons (reducible)
Search for type III Fermionic Triplet

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Brand new result this week!
Analysis Overview:

• Search for HNLs & $W_R$ in LRSM
• Search for HNLs in type III SeeSaw models ($L^\pm$, $N^0$)
• \textit{Search for HNLs in vMSM}
Indirect Searches for long-lived particles

- Introduce right-handed sterile neutrino states or **heavy neutral leptons (HNL)**

- HNLs with GeV masses could help explain Standard Model neutrino oscillations, baryon asymmetry of the universe and dark matter

**Lepton Number Conserving (LNC)**

**Lepton Number Violating (LNV)**
probing heavy neutral leptons (HNLs) at various experiments

- below Kaon mass can use decays $K^\pm \to \ell^\pm N$, $K^\pm \to \mu\mu\pi$ (e.g. NA62)
- below B or D meson masses $B^\pm, D_s^\pm, \tau^\pm \to \ell^\pm N$, $D^0 \to \ell^\pm \pi^\mp N$ (e.g. Belle, LHCb)
- below W, Z boson masses results from LEP ($Z \to N\nu$), actively explored also at ATLAS, CMS
- above W, Z boson masses decay to onshell bosons $W^\pm \to \ell^\pm N$, $N \to \ell^\pm W^\mp, \nu Z, \nu H$
ATLAS HNL searches — prompt and long-lived

prompt HNL Signal:
- Prompt tri-lepton event
- Sensitive to higher masses

long-lived HNL Signal:
- Prompt lepton
- Displaced vertex (DV) with 2 leptons with opposite charge
- $m_{HNL} < m_W$ HNL becomes long-lived

$$
\sigma(pp \rightarrow W) \cdot B(W \rightarrow \ell N) = \sigma(pp \rightarrow W) \cdot B(W \rightarrow \ell \nu) \cdot |U|^2 \left(1 - \frac{m_N^2}{m_W^2}\right) \left(1 + \frac{m_N^2}{2m_W^2}\right)
$$

image credit D. Trischuk
Why LLP searches use non-standard reconstructions?

If you want to reconstruct a charged particle with Impact Parameters \((d_0, z_0)\) outside the \textit{prompt phase-space} \(\rightarrow\) you need special reconstruction
Why LLP searches use non-standard reconstructions?

If you want to reconstruct a charged particle with Impact Parameters \((d_0, z_0)\) outside the prompt phase-space —> you need special reconstruction
Long-lived special reconstructions

• Default tracking on ATLAS turns off at $d_0 > 10$mm
• Computationally expensive; only available for 10% of data
• We use these tracks (and standard tracks) to form displaced vertices
Challenges to remove non-standard backgrounds

Cosmic muon
+ prompt lepton

Material interaction
+ prompt lepton

Metastable particle decay
(e.g. J/ψ)
+ prompt lepton

Random track crossing
+ prompt lepton
ATLAS HNL searches — prompt and long-lived

**ATLAS Simulation**
\[ \sqrt{s} = 13 \text{ TeV}, \ W \rightarrow \mu N \rightarrow \mu \mu e \nu_e \]

- \( m_N = 10 \text{ GeV}, \) prompt
- \( m_N = 5 \text{ GeV}, \) displaced
- \( m_N = 7.5 \text{ GeV}, \) displaced
- \( m_N = 10 \text{ GeV}, \) displaced
- \( m_N = 12.5 \text{ GeV}, \) displaced

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**ATLAS**
\[ \sqrt{s} = 13 \text{ TeV}, \ 32.9\text{-}36.1 \text{ fb}^{-1} \]

- 95% CL exclusion, dominant \( \nu_L \) mixing
- Observed (prompt, LNV)
- Observed (displaced, LNV)
- Expected

Too few decays in decay volume

Decay too fast

max. mass \( \rightarrow \) kinematic limitations
• Unique sensitivity to HNL coupling —> strength in relatively low-mass region
• Future ATLAS searches will push down to lower couplings and additional couplings
Global constraints on Sterile Neutrinos

- Complementarity of searches is enormous for HNLs

EWPO, 0νββ, cLFV, CKM unitarity, BBN, direct searches, ν-osc.
Conclusions

• Heavy Neutrino searches are an exciting challenge in ATLAS

• HNL searches still have huge potential to grow in ATLAS
  → full LHC Run2 data still being analyzed; stay tuned!
  → especially long-lived signatures exciting!

• Exciting prospects for next LHC data taking run
  • We benefit from technical advances
  • New opportunities for discovery

• Complementarity to other experiments makes this an exciting and rich field!
Backup