Heavy Neutral Leptons – experimental perspective

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Still 3 missing pieces to the SM

SM

Spin-1/2 fermions

Quarks
Left: u, c, t
Right: d, s, b

Leptons
Left: ν₁, ν₂, ν₃
Right: e, μ, τ

Spin-1 bosons

g, γ, Z⁰, W⁺

νMSM

Spin-1/2 fermions

Quarks
Left: u, c, t
Right: d, s, b

Leptons
Left: ν₁, ν₂, ν₃
Right: e, μ, τ

Spin-0 bosons

H

Heavy neutral lepton (HNL)
Right-handed neutrino
Heavy neutrino
Majorana neutrino
Sterile neutrino, etc.

N₁ mass ~keV
→ dark matter

N₂,₃ mass ~GeV
→ neutrino masses
→ baryon asymmetry

Direct searches

Where to look?

Can’t be detected
In the lab

Can’t be produced
in the lab

Slow and stable

leptogenesis

seesaw

\[ eV \quad keV \quad MeV \quad GeV \quad TeV \quad 10^{14} \text{ GeV} \]
N production and detection in the lab

Very weak coupling

• High intensity
• Long lifetime

- Proton beam on target
- Charmed meson decays
- Pion and Kaon decays
- e^+e^- collider (LEP)
- Z decays
- LHC Prompt

HNL mass (GeV)

10^{-1}  1  10  10^2  10^3
N production and detection in the lab

**Very weak coupling**

- High intensity
- Long lifetime

The LHC is a W factory

- Proton beam on target
- Charmed meson decays
- Pion and Kaon decays

- e$^+$e$^-$ collider (LEP)
- Z decays

- Belle-II
- LHCb
- Codex-b
- Faser
- Mathusla
- ATLAS/CMS
- real Ws, displaced vertex
- HL-LHC

- SHiP
- NA62
- T2K

Coupling strength

HNL mass (GeV)
Pioneering signature at ATLAS and CMS: low-\(p_T\) lepton + DV

production

\[ \begin{array}{c}
W^\pm \\
\downarrow \quad \nu \\
N_{2,3} \\
\end{array} \quad \begin{array}{c}
I^\pm \\
\end{array} \]

Few cm displacement

- In Run-2: probe N in mass range 5-20 GeV beyond LEP constraints
- High-impact search

arXiv:1312.2900
arXiv:1504.02470
arXiv:1704.08635
Pioneering signature at ATLAS and CMS: low-$p_T$ lepton + DV

production

charged lepton essential for triggering

decay

Displaced vertex (DV) essential for background rejection

Main challenges:
- Trigger acceptance and $p_T$ thresholds
- Reconstruction of displaced tracks
Large-radius tracking in ATLAS

• Reprocessing with special tracking needed in ATLAS to access tracks with large impact parameters (CMS does not have this problem)

• HNL DV reconstruction efficiency gain: factor 2 up to 10 cm, factor 10 in range 10–30 cm

• However, this is computer-intensive, can be run only on a limited fraction of the RAW data → “filter” selection

• Example of filter for HNL search (dominant muon mixing):
  - Single-muon trigger and combined muon with $p_T > 28$ GeV
    - ~35% signal efficiency, from trigger acceptance and $p_T$ threshold
  - Second muon with $p_T > 5$ GeV either standalone, or, if combined, either large $d_0$ or large $\chi^2$
    - ~50% signal efficiency for events passing trigger
Backgrounds which can produce DVs

• **Cosmics producing back-to-back displaced muons** – efficiently rejected by vetoing back-to-back tracks

• **Hadronic interactions with detector material** – low mass

• **Metastable particle decays** – low mass or short distance. Example: boosted B decay into J/Psi or Psi(2S) → di-muon DV with $m_{DV} \sim 3$ GeV

• **Random crossings** of pile-up tracks – largely dominant for $m_{DV} > 4$ GeV

Most of these give hadrons: a “tight” lepton ID requirement significantly reduces fakes
Background estimates – lessons learned with first ATLAS analysis

• Low-pT processes with large cross sections and low combinatorial probabilities → impossible to estimate using MC

• Method to estimate random crossing backgrounds: combine different events to find crossing probabilities, as in arXiv:1504.05162

• Possible control regions for generic estimate
  – Lacks a prompt lepton – bias introduced by need for different trigger + some signal contamination
  – Prompt lepton is not tight – unbiased but low statistics
  – Same-sign tracks in DV – robust for random crossings and material interactions, but not metastable particle decay
  – No leptons in DV – independent from other control regions, can be used for ABCD method
  – Only one lepton in DV – signal contamination, but can be used as validation region in di-lepton search

• Study $m_{DV}$ and $r_{DV}$ distributions separately for same-charge and opposite-charge, and for low-density and high-density regions
About systematic uncertainties

- **Reconstruction efficiency of displaced tracks**
  - Dominant systematics in ATLAS search
  - Use sample of $K^0$s (select two-pion invariant mass around 500 MeV) – caveat: no high-mass DVs
  - From data/MC comparison, extract DV-level weights in bins of $r_{DV}$ and $\Sigma p_T$
  - Apply those weights to signal MC and check difference in efficiency (find 15% effect)

- **Displaced lepton ID efficiency**
  - No practical way to test this with data
  - The efficiency in MC for tight lepton ID criterion is relatively high (>80%) and thus this contribution is neglected
About signal MC samples

Example of process to generate:

- Can use Pythia, Madgraph... choice of generator does not matter much: simple kinematics, subdominant uncertainties
- Consider various HNL decay modes
  - $e, \mu, \tau$, leptonic, semi-leptonic...
  - Difficulty with semi-leptonic at low mass: make sure the hadron multiplicity is well modeled
- Can have lepton number violation or not
  - Design “agnostic” selection, then it does not matter
- Simulate mean proper decay distances of 1, 10, 100 mm
  - Cover decays in inner tracker
  - Can interpolate to intermediate lifetimes
About interpretation – relationship between coupling and lifetime

- It is a non-trivial task to list and compute all individual decay widths for various HNL masses
- Luckily this was done for us by theorists
  - See eg Gronau et al. PRD 29, 2539 (1984), whose results were used by the DELPHI search, eg,

\[
\tau_{N_e} = (4.15 \times 10^{-12} \text{ s})(M_N / 1 \text{ GeV})^{-5.17} |U|^{-2}
\]

\[
\tau_{N_{\mu}} = (4.49 \times 10^{-12} \text{ s})(M_N / 1 \text{ GeV})^{-5.19} |U|^{-2}
\]

\[
\tau_{N_{\tau}} = (1.08 \times 10^{-11} \text{ s})(M_N / 1 \text{ GeV})^{-5.44} |U|^{-2}
\]

- Use this parametrisation for HNL masses above 4 GeV
  - Model dependence?
  - Factor 2 discrepancy due to LFV decay modes??
  - The community should agree on a model
Planned improvements

- **Optimise vertexing algorithm for low-multiplicity dVs containing leptons**
- **Design and enable dedicated triggers**
  - Reduce $p_T$ thresholds for muon and electron channels
    (single-lepton have typically $p_T > \sim 28$ GeV)
  - Access the tau channel
  - **Examples:**
    - Combined $\mu$ + standalone $\mu$
    - $e + \gamma$
    - $\tau + \text{calo } \tau$
    + standalone $\mu$
    (more challenging)
Summary

- HNLs with masses below EW scale can be probed with displaced signatures in various complementary ways
  - Fixed target: NA62, SHiP
  - LHC and HL-LHC: ATLAS, CMS, LHCb, Codex-b, Faser, Mathusla

- The LHC is a W factory
  - In run-2, first look at signature of prompt lepton + DV with at least another lepton
  - Challenging but mostly background-free
  - Sensitivity scales directly with luminosity!
Outlook

Being probed already (UNOFFICIAL)