Prospect to search Heavy Neutral Leptons

Nico Serra (Universität Zürich)

CERN Council Open Symposium on the Update of European Particle Physics Strategy 2019
13\textsuperscript{th}-16\textsuperscript{th} May - Granada (Spain)
HNLs are in general introduced to naturally explain neutrino masses and oscillations.

It is common to add to this Lagrangian a Majorana mass term:
- Helps to explain smallness of neutrino masses
- Matter anti-matter asymmetry in the Universe (Leptogenesis)
- Dark Matter HNLs (discussed in the talk by Christoph Weniger)

There are many models (e.g. nuMSM, Left-Right symmetric model, SUSY, …)
HNLS

Talk by
Silvia Pascoli

Neutrino masses and mixing
This Talk

TeV see-saw I
see-saw II, see-saw III
extended-type seesaws
radiative models
R-parity V SUSY...

GUT see-saw I

Low energy
See-saw

Bonnie Fleming’s Talk

sub-eV eV keV MeV GeV TeV

Intermediate scale GUT scale

Neutrino masses and mixing

Talk by Silvia Pascoli
- HNLs in the GeV region can explain the BAU (Akhmedov, Rubakov, Smirnov 9803255, Shaposhnikov et al. 050513/0804.4542 nuMSM) and simultaneously neutrino oscillations
- A generalised L symmetry explains a range of couplings making them observable experimentally (Shaposhnikov 0605047, Kersten/Smirnov 0705.3221)
- Signatures such as 0ν2β decay (see talk by Susanne Mertens) can be induced by HNLs (Hernandez 1606.06719), in other models such as nuMSM are suppressed
HNL Production

1. The production of sterile neutrinos happens via mixing of sterile neutrinos with active neutrinos, i.e. it is suppressed by a factor $U^2$.
2. If the mass is small enough they can be produced in semileptonic meson decays (pions, kaons, D-mesons, B-mesons).
3. The decay is also mediated by the mixing with active neutrinos.

$D_s^- \rightarrow N\mu^-$

$N \rightarrow e^-\pi^+$

Gorbunov, Shaposhnikov, arXiv:0705.1729

- These processes can violate Lepton Number and Lepton Flavour.
- Direct searches for these decays proportional to $U^4$. 

Nico Serra - EPPSU
Low mass HNLs

Production for \( U_e^2 : U_\mu^2 : U_\tau^2 = 1 : 1 : 1 \)

- If \( U_\tau^2 \) coupling dominates neutral current decays most important

Decays

\[ N \rightarrow \ell h \]
\[ N \rightarrow \nu \ell^+ \ell^- \]
High mass HNLs

- At high masses you have that the lifetime becomes short and the sterile neutrino decays immediately
- Can be searched for at colliders, e.g. ATLAS/CMS and FCCee

\[ L \sim \frac{3[\text{cm}]}{|U|^2 \times (m_N[\text{GeV}])^6} \]

Blondel et al., arXiv:1411.5230

- For boosted displaced leptons see Izaguirre/Shuve [1504.02470]
- For Higgs decays mediated by HNLs see Dev et al. [1207.2756]; Das et al. [1704.00880]
Higher Masses

- For masses larger than the mass of the Z, HNL can be produced by decays of virtual W and/or Z (limits from e.g. ATLAS/CMS) with loss in sensitivity.

- At high mass the same-sign dilepton and 2 jets has better acceptance.
- At low mass the tri-lepton and missing $E_T$ has better sensitivity due to bkg.
The capability to probe massive neutrino mechanisms for generating the matter-antimatter asymmetry in the Universe should be a central consideration in the selection and design of future colliders. (from the neutrino town meeting report to the ESPP)
Displaced Vertexes

- Main signatures are two (displaced) charged leptons or one charged lepton and two jets or two displaced jets
- These searches are complementary with other planned/proposed experiments
- FCCee has a large potential for HNL searches because of clean environment and clean signatures

Blondel et al., arXiv:1411.5230
Updated plot from Drewes et al., 1609.09069
Antusch et al., 1710.03744
c.f. also Cai et al., 1711.02180
Similarly HNLs can be produced as virtual particles in heavy flavour decays, resulting in LNV decays, analogous to neutrinoless double beta decays (limits from e.g. LHCb)

\[ \mathcal{B}(B^- \rightarrow D^0 \pi^+ \mu^- \mu^-) < 1.6 \times 10^{-6} \text{ at } 95\% \text{ C.L.} \]

\[ \mathcal{B}(B^- \rightarrow \pi^+ \mu^- \mu^-) < 4.0 \times 10^{-9} \text{ at } 95\% \text{ C.L.} \]

\[ \mathcal{B}(D_s^+ \rightarrow \pi^- \mu^+ \mu^+) < 1.2 \times 10^{-7} \text{ at } 90\% \text{ C.L.} \]


LHC interaction points

- The LHC produces a large number of Beauty and Charm which can decay into HNLs (with long lifetime)
- The idea is to have a (large) fiducial volume relatively with vetoes, timing and tracking capabilities
- The experimental signature of HNLs (as well as of any Hidden Sector Particles) is an excess of vertexes (aiming to have zero bkg)
- The physics sensitivity is given by the interplay between:
  - Size of the fiducial volume
  - Distance from pp interaction point
  - Momentum measurement/particle identification
- Located 480 m downstream of ATLAS in service tunnel (R=10 cm, L=1.5m)
- FASER II (HL-LHC era) R=1m. L=5m (need civil engineering work)
- FLUKA demonstrated low radiation levels and background
- Further background studies and detector optimisation ongoing
• Location of detector to be finalised (probably smaller detector)
• Tracking with RPC or Extruded Scintillators \( \sigma(T) \sim 1ns, \sigma(X) \sim 1cm \)
• Layer of detector in the floor considered for additional veto capabilities
• Preliminary background studies with toy simulation (indicate zero bkg)
• Ongoing studies with full simulation for comics (\(10^{15}\) interactions in total)
• MATHEUSLA-like test stand (3x3x5 m\(^3\)) taking data
• Full scale detector in the HL-LHC era
• CODEX-b consisting of tracking detector and vetos
• CODEX-b located in the LHCb cavern, behind 3m concrete from IP8
• Location available from Run3 of LHCb (2021), can be interfaced to LHCb trigger and reconstruction stream
• Fiducial volume of 10x10x10 m$^3$
• Data-driven background estimate ongoing
Sensitivity to HNLs

- Estimates assume zero background (to be demonstrated)
- All estimates assume full LH-LHC integrated luminosity
- MATHUSLA and CODEX-b signature are displaced vertex
- FASER in addition can perform measurements to characterise the signal

Sensitivity curves from Physics Beyond Colliders WG, arXiv:1901.09966
Proton Beam Dump

- To test small values of $U^2$ the best way is to use c-/b-hadrons (apart for the phase space that can be tested by FCCee)
- If we are optimistic and assume we can discover these decays we certainly want to make measurements on these particles to answer questions such as:
  - What is the mass of these particles
  - How many of these particles do we have
  - Are the parameters the right one to explain $\nu$-oscillation/leptogenesis
- In general proton beam dump experiment allow large fiducial volume and many sub-detectors allowing to measure mass and decay channels
• Experiment at SPS of CERN
• Main goal of NA62 is to measure ultra-rare K-decays such as $K^+ \rightarrow \pi^+\nu\bar{\nu}$
• Possible to operate NA62 in beam-dump mode, acquiring about $10^{18}$ PoT
• NA62 Collaboration preparing a plan for Run3 (2021-2023)
• Already collected about $10^{16}$ PoT in dump mode, demonstrated that background is under control for fully reconstructed mode
• Possibility to add veto detector to extend the sensitivity to partially reconstructed mode
HNL at NA62


\[ K^+ \rightarrow \mu^+ N \]

\[ m_N^2 = (p_{K^+} - p_{\mu^+})^2 = m_{miss}^2 \]


- NA62 is searching for HNLs coming from K with missing mass techniques
- Results with 1% of the nominal beam intensity arXiv:1712.00297
- Possibility to probe the region below the K with full data
- NA62 running in beam dump mode has potential to improve present constraints for HNL coming from heavy mesons

Sensitivity curve from Physics Beyond Colliders WG, arXiv:1901.09966

Sensitivity curve from

\[ U^2 \]

\[ M_N \]

14th May 2019

Nico Serra - EPPSU
Proposal for Beam Dump Facility in the North area of CERN compatible with present and planned activities

Consolidation and upgrade of SPS would allow data taking in Run4 (2026)
• Heavy target followed by Hadron Absorber
• Muon shield to reduce the muon rate to less than 100KHz
• Pyramidal Frustum fiducial volume
• Decay Spectrometer consisting of Tracking System, Timing Detector, Calorimeter System and Muon Detector
• Experiment optimised for acceptance while minimising background
SHiP Experiment

<table>
<thead>
<tr>
<th>Cut</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Track momentum</td>
<td>$&gt; 1.0$ GeV/$c$</td>
</tr>
<tr>
<td>Dimuon distance of closest approach</td>
<td>$&lt; 1$ cm</td>
</tr>
<tr>
<td>Dimuon vertex position</td>
<td>($&gt; 5$ cm from inner wall)</td>
</tr>
<tr>
<td>IP w.r.t. target (fully reconstructed)</td>
<td>$&lt; 10$ cm</td>
</tr>
<tr>
<td>IP w.r.t. target (partially reconstructed)</td>
<td>$&lt; 250$ cm</td>
</tr>
</tbody>
</table>

Timing cut around 350 ps
Various veto cuts considered

- All backgrounds simulated with full Monte Carlo (Pythia6,8/GEANT4/Genie)
- Demonstrated capability of having less than 0.1 bkg events
- Possible to measure the background data driven in the experiment itself

Nico Serra - EPPSU

SHiP Coll., CERN-SPSC-2019-010
• NA62++ equivalent beam dump sample collected every few days
• One signal event corresponds to $3\sigma$ (also for partially reconstructed)
• In case of discovery momentum, invariant mass and particle identification allow to measure branching ratios and flavour structure
• Very similar sensitivity for $U_\mu^2$
• For $U_\tau^2$ sensitivity to partially reconstructed decays is crucial
Conclusions

- HNLs in the multi-GeV region well justified from theory point of view
  - Can provide explanation to neutrino masses and oscillations
  - Mechanism for leptogenesis
  - Test LFV and LNV

- HL-LHC, DUNE ND, FCCee and Beam Dump Experiments have the possibility to constraint very interesting region:
  - About 2-3 orders of magnitude in mass
  - About 2-3 orders of magnitudes in couplings

- In case of discovery important to measure mass and branching ratios to check compatibility with neutrino oscillation and leptogenesis
Incomplete Reference List

• This talk was based on the contribution to the EPPSU: 1, 12, 42, 45
  
  [https://indico.cern.ch/event/765096/contributions/](https://indico.cern.ch/event/765096/contributions/)

  **Disclaimer: all relevant papers written on this subject do not fit in many pages, the following is just a list of papers I have used while preparing this talk**

• vMSM


• RH neutrinos at low mass, seesaw, 0nu2beta decays


• HNL and Leptogenesis


• HNL Production, decays and sensitivity:


• Experiment Proposals:

  Physics Beyond Colliders WG arXiv:1901.09966 and references therein
Backup Slides
- Naturalness as a guiding principle of Nature is nowadays put into question
- We should therefore not forget that we have a 2D problem (Mass VS Coupling)
Majorana Mass

- 0.05 eV
- 1 TeV
- $10^{16}$ GeV

- strong coupling
- no see-saw
- neutrino masses are too small

- LSND
- $\nu$ MSM
- LHC
- GUT
- see-saw
$0^v2\text{beta VS DM/M}$
Boosted Leptons

\[ |V_{\mu N}|^2 \]

\[ M_N \text{ (GeV)} \]

- K $\rightarrow \mu \nu$
- BBN
- PS191
- BEBC
- NuTeV
- CHARM
- Belle
- DELPHI
- L3
- CMS
- ATLAS

Displaced Lepton Jet

Prompt Trilepton

Nico Serra - EPPSU

14th May 2019
HNLs @ CMS

Same-sign di-leptons + 2 jets
- Fully reconstructed N mass peak
- N has to be heavy (jet $P_T > 30$ GeV)
- Sensitive to LNV N-decays

Tri-leptons + missing $E_T$
- No clear mass peak
- Sensitive to light N (lepton $P_T > 5$ GeV)
- Sensitive to LN-conserving N-decays

Prompt same-sign dilepton search: coupling to muons
HNLs @ CMS

Search variables: low mass N ($< m_W$)

Key differences wrt previous searches:

- softer leptons (from 5 GeV)
- low $E_T^{\text{miss}} < 75$ GeV
- low $M_{3\ell} < 80$ GeV
- $M_{2\ell\text{OS}}^{\min}$ as a proxy for $M_N$

$m_N = 10$ GeV

$m_N = 60$ GeV

$m_N = 200$ GeV

L. Shchutska ALPS 2019
Search variables: high mass N ( > m_W )
Phase-space is more similar to previous searches, e.g. electroweak SUSY:

- higher lepton $p_T$ thresholds ($p_T > 55, 15, 10$ GeV)
- veto a Z boson
- use $M_{2\ell\ell OS}$ and $M_T$ shapes to differentiate signal and background
- but do not make any selection on $E_T^{\text{miss}}$
Search for DV

- a displacement kills SM bkg, signal acceptance estimated with gen-level info:
  - $DV_S$: a displaced vertex search in a tracker at ATLAS or CMS
  - $DV_L$: a search with muon system at CMS (3 m decay volume)
  - LHCb reach: an inclusive HNL search in B decays

Boiarska et al. arXiv:1902.04535
NA62 Detector

- Large angle electromagnetic calorimeters
- Lead glass blocks surround (VETO)
- Silicon pixel stations
- Guard ring detector
- Straw tubes
- RICH counter filled with Neon separates $\pi$, $\mu$ and $e$ up to 40 GeV/c
- HCAL: iron-scintillator sandwiches
- Fast scintillator arrays
- Shashlik calo
- Scintillator hodoscopes
- ECAL filled with liquid krypton
Figure 2: Tentative timescale for PBC projects exploring the MeV-GeV mass range compared to other similar initiatives in the world that could compete on the same physics cases.
PBC Sensitivity

Electron coupling dominance: $U_\nu^2; U_e^2; U_\tau^2 = 1:0:0$

- FASER, 150 fb$^{-1}$
- FASER2, 3 ab$^{-1}$
- CHARM
- CODEx-b, 300 fb$^{-1}$
- NA62, $10^{18}$ pot
- SHiP, $2 \times 10^{20}$ pot
  - solid: without $B_e$
  - dotted: with $B_e$ (upper limit)
- MATHUSLA200, 3 ab$^{-1}$
  - solid: $B,D$ mesons
  - dotted: $W,Z$
- BBN
- See Saw
- FCC-ee
PBC Sensitivity
- Collecting $5 \times 10^{11}$ proton to validate the muons flux simulations
- Analysis of data in progress
**Figure 10:** View of the magnetised section of the target shielding with the yoke configuration and the coil. The coil is embedded in specially designed shielding blocks which restrains the coil during operation and which provides crane lifting points should an intervention be necessary.
**Magnet**

**Figure 14:** 3D view of the optimised muon magnetic shield.

**Figure 16:** Preliminary mechanical design of magnets. GO steel sheets are packed into sections about 50 mm thick (left). Packs are bolted together into rectangular block about 50 cm thick (left, central). Blocks of different dimensions are installed on the support beams (right).

**Figure 31:** Position of muons leaving the magnetized hadron absorber.

**Figure 30:** Momentum distributions of muons leaving the hadron absorber, total momentum (left) and transverse momentum (right). Different contributions are shown. The rates are normalized to $5 \times 10^{13}$ protons on target.
Muon Shield

- Global optimisation of the magnetic field (with Machine Learning) still ongoing

Challenging Aspects:
- Narrow separation between field directions
- Aiming to 1.8T to minimize length (with grain oriented steel sheets)
- Have reliable muon sample to optimise with

Running the simulation with material
- ~3x10^9 muons/spill with magnets off
- With the magnet on 3x10^5 muons/spill
- ~6.5x10^4 muons/spill with p>3GeV
**Figure 27:** Reconstruction of $1 \text{ GeV}/c^2$ HNL $\rightarrow \mu^- \pi^+$. 

**Figure 28:** Reconstruction of $1 \text{ GeV}/c^2$ HNL $\rightarrow \mu^+ \rho^0 (\rightarrow \pi^+ \pi^0 (\rightarrow \gamma \gamma))$. 

**Figure 29:** Reconstruction of $1 \text{ GeV}/c^2$ HNL $\rightarrow \nu \rho^0 (\rightarrow \pi^+ \pi^-)$. 
Figure 83: Global project schedule for the Beam Dump Facility and the SHiP detector. CDS, TDR, PRR mark the submission of the Comprehensive Design Study report, submission of Technical Design Reports, and Production Readiness Reviews for the SHiP detector, and CwB marks commissioning with beam.
Backup
Backup