Search for Heavy Neutral Lepton Production and Decay with the IceCube DeepCore

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Colophon
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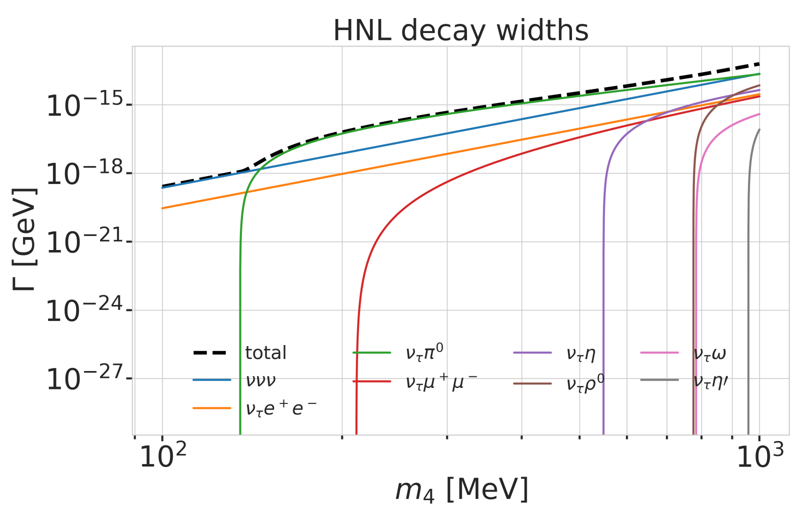

Figure 3.1: Decay widths of the HNL within the mass range considered, calculated based on the results from [2]. Given the existing constraints on $|U_{e4}|^2$ and $|U_{\mu4}|^2$, we consider that the corresponding decay modes are negligible.

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Re-write/re-formulate this section (copied from HNL technote).

5.2.1 Custom LeptonInjector

Signal events are simulated using a custom LeptonInjector (LI) tool [3], modified from its standard version to include the HNL particle and the description of the HNL decays needed to produce the double cascade signature (currently only ν_τ related). In its SM work mode, LI injects a lepton and a cascade (under the general name *Hadrons*) at the interaction vertex of the neutrino. Both objects have the same (x,y,z,t) coordinates. In the modified version, the lepton at the interaction vertex is replaced by the HNL. After a chosen distance the HNL is forced to decay. The decay is sampled from the kinematically accessible decay modes shown in Figure 5.2.

[3]: Abbasi et al. (2021), *LeptonInjector and LeptonWeighter: A neutrino event generator and weighter for neutrino observatories*

A big addition to the standard LI is that the decay products of the HNL are added to the list of particles in the I3MCTree with a displaced position and delayed time from the interaction vertex. These daughter particles form a second cascade, not in the form of a *Hadrons* object, but as the explicit particles forming the shower. The kinematics of the two-body decays are computed analytically, while the three-body decays are dealt with using MadGraph5. To do so, we randomly pick an event from a list that we generated for each three-body decay mode. Independent of the number of particles in the final state of the HNL decay, the kinematics are calculated/simulated at rest and then boosted along the HNL momentum. The decay mode is randomly chosen based on the mass dependent branching ratios shown in Figure 5.2.

Each file is produced by running the generation level processing script using the filenumber as random seed and the above settings for the sampling distributions. The main part is calling the *MultiLeptonInjector* module in *volume mode* adding two generators (for ν_τ and $\bar{\nu}_\tau$) with 50% of the events. The generators are provided with the custom double-differential/total cross section splines described in Section 5.2.1 and the parameters defining the sampling distributions. For each frame *OneWeight* and a reference weight are also calculated and stored using the weighting functions and a baseline atmospheric ν_τ flux + oscillation spline. The weight will later be calculated inside of the analysis framework

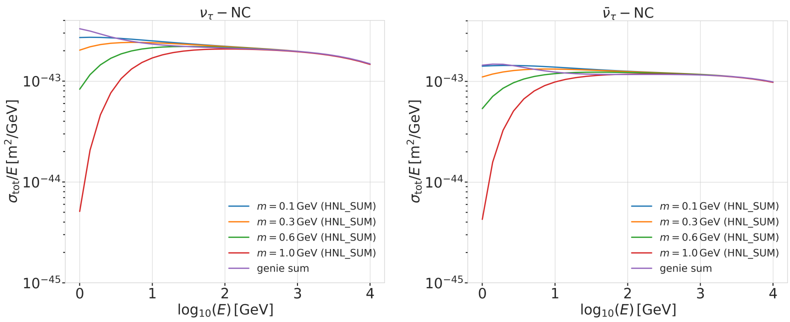

Figure 5.1: Custom HNL total cross sections for the four target masses compared to the total ($\nu_\tau/\bar{\nu}_\tau$ neutral current) cross section used for SM neutrino simulation production with GENIE.

PISA, based on the input OneWeight. In addition to the i3 file itself, a LeptonInjector configuration file is written which stores the needed information to produce event weights using LeptonWeighter. Optionally the script can also produce an hdf5 file with the same name in the same location. This will store a fixed set of keys, extracted from the i3 file.

We are using *volume mode*, for the injection of the primary particle on a cylindrical volume. The main generation/sampling happens in `VolumeLeptonInjector::DAQ` inside `LeptonInjector.cxx`. After writing the config (s) frame (currently not kept), the energy is sampled from a power law distribution, then the cosine(zenith) and azimuth angles are sampled from uniform distributions. The (x,y) position is sampled uniform in r, ϕ (for position on disk) and the z position is sampled from a uniform distribution. After the primary properties have been sampled the *EventProperties* is created and handed over to the `FillTree` functions which is where the custom HNL simulation happens:

Cross Sections

The cross sections are calculated using a modified version of Carlos Argüelles' NuXSSplMkr, which is a tool to calculate neutrino cross sections from parton distribution functions (PDFs) and then produce splines that can be read and used with IceCube software. The main modification to calculate the cross sections for the ν_τ neutral current interaction into the new heavy mass state is the addition of a kinematic condition to ensure that there is sufficent energy to produce the heavy mass state. It is the same confition that needs to be fulfilled for the charged current case, where the outgoing lepton mass is non-zero. Following [4] (equation 7), the condition

[4]: Levy (2009), *Cross-section and polarization of neutrino-produced tau's made simple*

$$(1 + x\delta_N)h^2 - (x + \delta_4)h + x\delta_4 \leq 0, \tag{5.1}$$

is implemented for the neutral current case. Here $\delta_4 = \frac{m_4^2}{s-M^2}$, $\delta_N = \frac{M^2}{s-M^2}$, and $h \overset{def}{=} xy + \delta_4$, with x, y being the Bjorken variables, m_4 and M the mass of the heavy state and the target nucleon, respectively, and s the center of mass energy squared. Since the (SM) neutrino background simulation used for this analysis was created using GENIE (version 2.12.8), interfaced through the IceCube software package *genie-icetray*, with the GRV98LO PDFs, those were added as *GRV98lo_patched* to the cross section spline maker, to ensure the best possibe agreement. Double-differential ($dsdxdy$) and total (σ) cross sections were produced for the

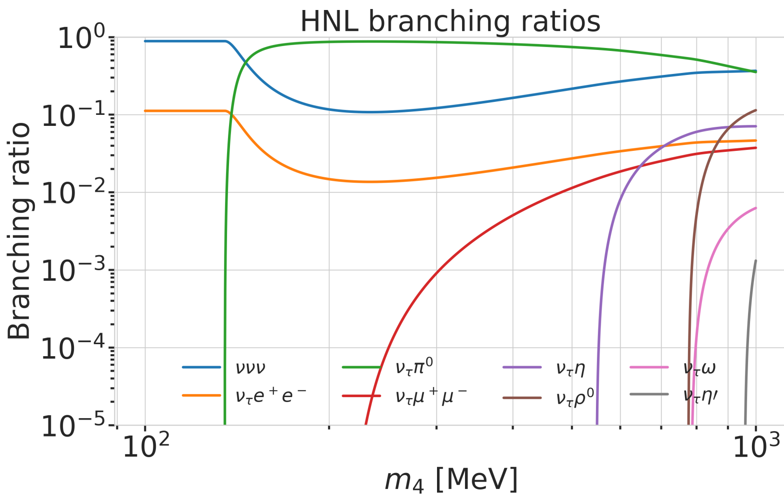

Figure 5.2: Branching ratios of the HNL within the mass range considered, calculated based on the results from [2]. Given the existing constraints on $|U_{e4}|^2$ and $|U_{\mu 4}|^2$, we consider that the corresponding decay modes are negligible.

Table 5.1: xx

Channel	Opens [MeV]	Max BR [%]
$\nu_4 \longrightarrow \nu_\tau \nu_\alpha \bar{\nu_\alpha}$	0	100.0
$\nu_4 \longrightarrow \nu_\tau e^+ e^-$	1	?
$\nu_4 \longrightarrow \nu_\tau \pi^0$	135	?
$\nu_4 \longrightarrow \nu_\tau \mu^+ \mu^-$	211	?
$\nu_4 \longrightarrow \nu_\tau \eta$	548	?
$\nu_4 \longrightarrow \nu_\tau \rho^0$	770	?
$\nu_4 \longrightarrow \nu_\tau \omega$	783	?
$\nu_4 \longrightarrow \nu_\tau \eta'$	958	?

four target HNL masses and then splined. The produced cross section splines are stored in the resources of the custom LeptonInjector module. Figure 5.1 shows the total cross sections that were produced compared to the cross section used for the production of the SM $\nu_\tau/\bar{\nu}_\tau$ neutral current background simulation .

Add comparions of SM cross sections between NuXSS-plMkr and genie

Decay Channels

The accessible decay channels are dependent on the mass of the HNL and the allowed mixing. For this analysis, where only $|U_{\tau 4}|^2 \neq 0$, the considered decay channels are listed in Table 5.1 and the corresponding branching ratios are shown in Figure 5.2. The indiviudal branching ratio for a specific mass is calculated as $\mathrm{BR}_i(m_4) = \Gamma_i(m_4)/\Gamma_{\mathrm{total}}(m_4)$, where $\Gamma_{\mathrm{total}}(m_4) = \sum \Gamma_i(m_4)$. The formulas to calculate the decay width show up in multiple references, but we chose to match them to [2], which also discusses the discrepencies in previous literature.

[2]: Coloma et al. (2021), *GeV-scale neutrinos: interactions with mesons and DUNE sensitivity*

2-Body Decay Widths The decay to a neutral pseudoscalar mesons is

$$\Gamma_{\nu_4 \to \nu_\tau P} = |U_{\tau 4}|^2 \frac{G_F^2 m_4^3}{32\pi} f_P^2 (1 - x_p^2)^2, \tag{5.2}$$

with $x_P = m_P/m_4$ and

$$f_{\pi^0} = 0.130\,\mathrm{GeV}, \qquad f_\eta = 0.0816\,\mathrm{GeV}, \qquad C_2 = f_{\eta'} = -0.0946\,\mathrm{GeV}, \tag{5.3}$$

while the decay to a neutral vector meson is given by

$$\Gamma_{\nu_4\to\nu_\tau V} = |U_{\tau 4}|^2 \frac{G_F^2 m_4^3}{32\pi}\left(\frac{f_V}{m_V}\right)^2 g_V^2 (1+2x_V^2)(1-x_V^2)^2, \qquad (5.4)$$

with $x_V = m_V/m_4$,

$$f_{\rho^0} = 0.171\,\mathrm{GeV}^2, \qquad f_\omega = 0.155\,\mathrm{GeV}^2, \qquad (5.5)$$

and

$$g_{\rho^0} = 1 - 2\sin^2\theta_w, \qquad g_\omega = \frac{-2\sin^2\theta_w}{3}, \qquad \sin^2\theta_w = 0.2229 \qquad (5.6)$$

[5].

[5]: Tiesinga et al. (2021), *CODATA recommended values of the fundamental physical constants: 2018*

3-Body Decay Widths The (invisible) decay to three neutrinos is

$$\Gamma_{\nu_4\to\nu_\tau\nu_\alpha\bar{\nu_\alpha}} = |U_{\tau 4}|^2 \frac{G_F^2 m_4^5}{192\pi^3}, \qquad (5.7)$$

while the decay to two charged leptons (using $x_\alpha = (m_\alpha/m_4)^2$) of the same flavor reads

$$\Gamma_{\nu_4\to\nu_\tau l_\alpha^+ l_\alpha^-} = |U_{\tau 4}|^2 \frac{G_F^2 m_4^5}{192\pi^3}\left[C_1 f_1(x_\alpha) + C_2 f_2(x_\alpha)\right], \qquad (5.8)$$

with the constants defined as

$$C_1 = \frac{1}{4}(1 - 4s_w^2 + 8s_w^4), \qquad C_2 = \frac{1}{2}(-s_w^2 + 2s_w^4), \qquad (5.9)$$

the functions as

$$f_1(x_\alpha) = (1 - 14x_\alpha - 2x_\alpha^2 - 12x_\alpha^3)\sqrt{1-4x_\alpha} + 12x_\alpha^2(x_\alpha^2 - 1)L(x_\alpha), \qquad (5.10)$$

$$f_2(x_\alpha) = 4[x_\alpha(2+10x_\alpha-12x_\alpha^2)\sqrt{1-4x_\alpha}+6x_\alpha^2(1-2x_\alpha+2x_\alpha^2)L(x_\alpha)], \qquad (5.11)$$

and

$$L(x) = \ln\left(\frac{1-3x_\alpha-(1-x_\alpha)\sqrt{1-4x_\alpha}}{x_\alpha(1+\sqrt{1-4x_\alpha})}\right). \qquad (5.12)$$

Madgraph 3-body Decay Kinematics

Add description of MadGraph5 decay files (Harvard needs to provide this)

5.2.2 Sampling Distributions

This is the description of the signal simulation generator used to (re-)start simulation production in December 2023. The underlying sampling distributions are listed in Table 5.2. Judging from how the generation/processing efficiency was for the 190607 set, we target $1e04$ files per set with $5e05$ events per file at generation, resulting in a maximum of $5e09$ events per set at generation level. Note here that the actual number of events

variable	distribution	range
energy	E^{-2}	$[2, 10^4]$ GeV
zenith	uniform (in $\cos(\theta)$)	[180 °, 80 °]
azimuth	uniform	[0 °, 360 °]
vertex (x, y)	uniform	$r = 600$ m
vertex z	uniform	[-600, 0] m
m_{HNL}	fixed	[0.3, 0.6, 1.0] GeV
L_{decay}	L^{-1}	[0.0004, 1000.0] m / [1.0, 1000.0] m

Table 5.2: Sampling distributions of HNL simulation generation.

per set at generation might be a little lower since some events won't be allowed if they don't have enough energy to produce the HNL.

5.2.3 Weighting Scheme

The weighting for the HNL signal simulation happens in a custom stage of PISA. The only input is the stored OneWeight and the variable physics parameter $|U_{\tau 4}|^2$, which is the mixing strength of the new heavy mass state and the tau sector. The custom re-weighting is needed to go from the used sampling PDF (1/L with fixed range in lab frame decay length) to the target PDF (exponential defined by proper lifetime of the HNL). For each event the re-weighting factor is calculated using the gamma factor

$$\gamma = \frac{\sqrt{E_{\mathrm{kin}}^2 + m_{\mathrm{HNL}}^2}}{m_{\mathrm{HNL}}}, \tag{5.13}$$

with the HNL mass m_{HNL} and it's kinetic energy E_{kin}. The speed of the HNL is calculated as

$$v = c \cdot \sqrt{1 - \frac{1}{\gamma^2}}, \tag{5.14}$$

where c is the speed of light. With these the lab frame decay length range can be converted into the rest frame lifetime range for each event

$$\tau_{\mathrm{min/max}} = \frac{s_{\mathrm{min/max}}}{v \cdot \gamma}. \tag{5.15}$$

The proper lifetime of each HNL event can be calculated using the total decay width Γ_{total} shown in Figure 3.1 and the chosen mixing strength $|U_{\tau 4}|^2$ as

$$\tau_{\mathrm{proper}} = \frac{\hbar}{\Gamma_{\mathrm{total}}(m_{\mathrm{HNL}}) \cdot |U_{\tau 4}|^2}, \tag{5.16}$$

where $\hbar$ is the reduced Planck constant. Since the decay length/lifetime of the events is sampled from an inverse distribution instead of an exponential as it would be expected from a particle decay we have to re-weight accordingly to achieve the correct decay length/lifetime distribution. This is done by using the wanted exponential distribution

$$\mathrm{PDF}_{\mathrm{exp}} = \frac{1}{\tau_{\mathrm{proper}}} \cdot e^{\frac{-\tau}{\tau_{\mathrm{proper}}}}, \tag{5.17}$$

and the inverse distribution that was sampled from

$$\mathrm{PDF}_{\mathrm{inv}} = \frac{1}{\tau \cdot (\ln(\tau_{\mathrm{max}}) - \ln(\tau_{\mathrm{min}}))}. \tag{5.18}$$

The lifetime re-weighting factor is calculated as

$$w_{\text{lifetime}} = \frac{\text{PDF}_{\text{exp}}}{\text{PDF}_{\text{inv}}} = \frac{\Gamma_{\text{total}}(m_{\text{HNL}}) \cdot |U_{\tau 4}|^2}{\hbar} \cdot \tau \cdot (\ln(\tau_{\max}) - \ln(\tau_{\min})) \cdot e^{\frac{-\tau}{\tau_{\text{proper}}}} . \tag{5.19}$$

Adding another factor of $|U_{\tau 4}|^2$ to account for the mixing at the interaction vertex the total re-weighting factor becomes

$$w_{\text{total}} = |U_{\tau 4}|^2 \cdot w_{\text{lifetime}}, \tag{5.20}$$

which can be applied on top of flux and oscillation weight to get the final HNL weight for a given mixing (and mass).

6 Search for an Excess of Heavy Neutral Lepton Events

APPENDIX

A

First Appendix

Bibliography

Here are the references in citation order.

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[2] Pilar Coloma et al. "GeV-scale neutrinos: interactions with mesons and DUNE sensitivity". In: *Eur. Phys. J. C* 81.1 (2021), p. 78. DOI: 10.1140/epjc/s10052-021-08861-y (cited on pages 5, 11).

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[4] Jean-Michel Levy. "Cross-section and polarization of neutrino-produced tau's made simple". In: *J. Phys. G* 36 (2009), p. 055002. DOI: 10.1088/0954-3899/36/5/055002 (cited on page 10).

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