

HNLs in PYTHIA

[HNLs in Pythia]

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Searching for long-lived particles at the LHC and beyond
Eighth workshop of the LHC LLP Community

Particle data of right handed neutrinos are already present

```
<particle id="9900012" name="nu_Re" spinType="2" chargeType="0" colType="0"
      m0="500.00000" mWidth="0.00098" mMin="50.00000" mMax="0.00000">
<channel onMode="1" bRatio="0.1987400" products="11 -1 2"/>
<channel onMode="1" bRatio="0.0102040" products="11 -1 4"/>
```

Implementation as heavy resonances

```
// A left-right-symmetric scenario with new righthanded neutrinos,
// righthanded gauge bosons and doubly charged Higgses.
resonancePtr = new ResonanceNuRight(9900012);
setResonancePtr( 9900012, resonancePtr);
resonancePtr = new ResonanceNuRight(9900014);
setResonancePtr( 9900014, resonancePtr);
resonancePtr = new ResonanceNuRight(9900016);
setResonancePtr( 9900016, resonancePtr);
```

Missing

Decays from and to SM mesons



Phenomenology of GeV-scale heavy neutral leptons

Kyrylo Bondarenko,^a Alexey Boyarsky,^a Dmitry Gorbunov^{b,c} and Oleg Ruchayskiy^d

Production in leptonic meson decays

$$\Gamma(h \rightarrow \ell_\alpha N) = \frac{G_F^2 f_h^2 m_h^3}{8\pi} |V_{UD}|^2 |U_\alpha|^2 \left[y_N^2 + y_\ell^2 - (y_N^2 - y_\ell^2)^2 \right] \sqrt{\lambda(1, y_N^2, y_\ell^2)},$$

Production in semi-leptonic meson decays in association with pseudo-scalar mesons

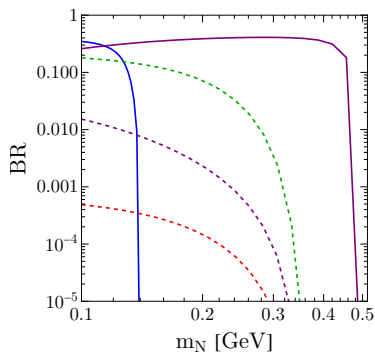
$$\Gamma(h \rightarrow h'_P \ell_\alpha N) = \frac{G_F^2 m_h^5}{64\pi^3} C_K^2 |V_{UD}|^2 |U_\alpha|^2 (I_{P,1} + I_{P,2} + I_{P,3} + I_{P,4}),$$

Production in semi-leptonic meson decays in association with vector mesons

$$\Gamma(h \rightarrow h'_V \ell_\alpha N) = \frac{G_F^2 m_h^7}{64\pi^3 m_{h'}^2} C_K^2 |V_{UD}|^2 |U_\alpha|^2 \left(I_{V,g^2} + I_{V,f^2} + I_{V,a_+^2} + I_{V,a_-^2} \right. \\ \left. + I_{V,gf} + I_{V,ga_+} + I_{V,ga_-} + I_{V,fa_+} + I_{V,fa_-} + I_{V,a_+a_-} \right),$$

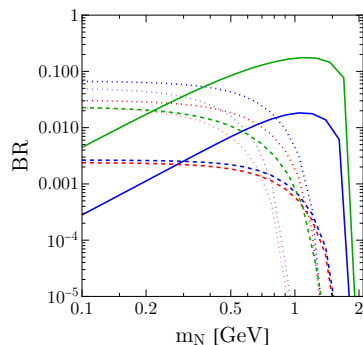
Production of HNLs using PYTHIA

Light mesons



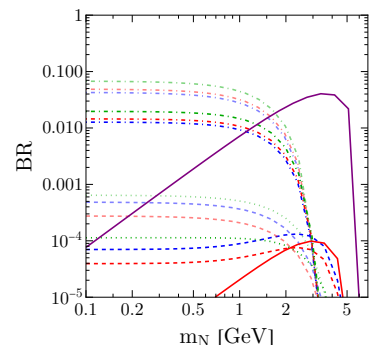
- $\pi^+ \rightarrow N_e e^+$
- - - $K_S \rightarrow N_e e^+ \pi^-$
- - - $K_L \rightarrow N_e e^+ \pi^-$
- $K^+ \rightarrow N_e e^+$
- - - $K^+ \rightarrow N_e e^+ \pi^0$

D-mesons



- - - $D^+ \rightarrow N_e e^+ K^0$
- $D^+ \rightarrow N_e e^+$
- - - $D^+ \rightarrow N_e e^+ K^{0*}$
- - - $D^+ \rightarrow N_e e^+ \pi^0$
- - - $D^0 \rightarrow N_e e^+ K^{*-}$
- - - $D^0 \rightarrow N_e e^+ \pi^-$
- - - $D^0 \rightarrow N_e e^+ K^-$
- $D_s^+ \rightarrow N_e e^+$
- - - $D_s^+ \rightarrow N_e e^+ \eta$

B-mesons



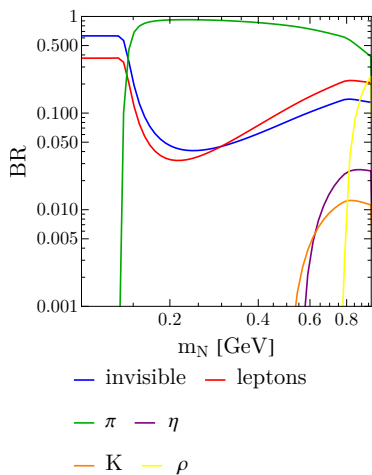
- - - $B^0 \rightarrow N_e e^+ D^{*-}$
- - - $B^0 \rightarrow N_e e^+ D^-$
- - - $B^0 \rightarrow N_e e^+ \rho^-$
- - - $B^0 \rightarrow N_e e^+ \pi^-$
- - - $B^+ \rightarrow N_e e^+ D^{0*}$
- - - $B^+ \rightarrow N_e e^+ D^0$
- - - $B^+ \rightarrow N_e e^+ \rho^0$
- $B^+ \rightarrow N_e e^+$
- - - $B_s^0 \rightarrow N_e e^+ D_s^{*-}$
- - - $B_s^0 \rightarrow N_e e^+ D_s^-$
- - - $B_s^0 \rightarrow N_e e^+ K^{*-}$
- - - $B_s^0 \rightarrow N_e e^+ K^-$
- $B_c^+ \rightarrow N_e e^+$

Preliminary implementation on GitHub: [janhajer/hnl](https://github.com/janhajer/hnl)

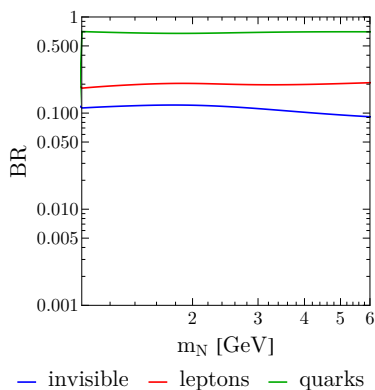
Problems in $B \rightarrow N_e e \pi$

Decay of HNLs using PYTHIA

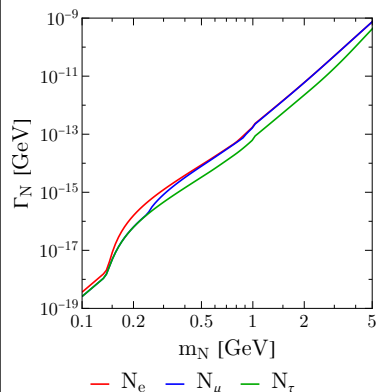
Masses below 1 GeV



Masses above 1 GeV



Decay width



Scale for the transition from mesons to quarks estimated using τ measurements

Underlying equations

[1805.08567]

$$\Gamma(N \rightarrow \ell_\alpha h_P) = \frac{G_F^2 f_h^2 M_N^3}{16\pi} |V_{UD}|^2 |U_\alpha|^2 \left[(1 - x_\ell^2)^2 - x_h^2 (1 + x_\ell^2) \right] \sqrt{\lambda(1, x_h^2, x_\ell^2)},$$

$$\Gamma(N \rightarrow \ell_\alpha^- h_V^+) = \frac{G_F^2 g_h^2 |V_{UD}|^2 |U_\alpha|^2 M_N^3}{16\pi m_h^2} \left((1 - x_\ell^2)^2 + x_h^2 (1 + x_\ell^2) - 2x_h^4 \right) \sqrt{\lambda(1, x_h^2, x_\ell^2)}.$$

The good Code simulates HNL production from and decay into mesons within PYTHIA

The bad Code is preliminary and has small discrepancy with the literature

The ugly At the moment the Code missuses the `Resonance` class from PYTHIA

- J. Hajer (2020). 'Heavy Neutral Leptons in Pythia'. GitHub: [janhajer/hnl](#)
- T. Sjöstrand et al. (2015). 'An introduction to PYTHIA 8.2'. In: *Comput. Phys. Commun.* 191, pp. 159–177. DOI: [10.1016/j.cpc.2015.01.024](#). arXiv: [1410.3012 \[hep-ph\]](#). №: LU-TP-14-36, MCNET-14-22, CERN-PH-TH-2014-190, FERMILAB-PUB-14-316-CD, DESY-14-178, SLAC-PUB-16122
- K. Bondarenko, A. Boyarsky, D. Gorbunov and O. Ruchayskiy (2018). 'Phenomenology of GeV-scale Heavy Neutral Leptons'. In: *JHEP* 11, p. 032. DOI: [10.1007/JHEP11\(2018\)032](#). arXiv: [1805.08567 \[hep-ph\]](#)