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# Production of HNL in 3-body decays of mesons. Comparison with PYTHIA approach

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The Standard Model (SM) is a particle physics theory that is consistent up to very high energy scales and verified in numerous experiments up to $\sim$ 14 TeV. However, it fails to explain some phenomena such as massiveness of neutrinos, dark matter, dark energy, baryon asymmetry of the Universe etc. Therefore SM is incomplete and requires an extension.

One possible approach is by adding new particles to the theory. There are two possible answers to the question "Why do we not observe particles of new physics in experiments?" The first answer is the following. The new particles are very heavy and can not be produced in modern accelerators like LHC. To detect them one has to build more powerful and more expensive accelerators. There is another possibility. The particles of new physics can be light particles that feebly interact with SM particles.
The last case is very interesting for the experimental search of the new physics in the intensity frontier experiments just now. There are different choices of new renormalized interaction Lagrangian of particles of new physics with SM particles. It's called portals.

In this paper, we consider a heavy neutral lepton (HNL) portal. The phenomenology of GeV-scale HNL was considered in details in [1]. We will compare the analytical results for HNL production in 3-body decays of mesons with PYTHIA approximation.

The simplest way of neutrino modification of the SM involves extension of the SM by neutrino singlets with right chirality (in the SM all right-handed fermions are singlets), which extremely faintly interact with SM particles. Such neutrinos are called sterile neutrinos or heavy neutral leptons. Renormalized and gauge-invariant interaction of new neutrinos with the SM particles is similar to the Yukawa interaction of left-handed quarks doublets with singlets of the right-handed quarks, namely:

$$\mathrm{L}_{int} = -\left(F_{\alpha I}\bar{L}_\alpha \tilde{H} N_I + h.c.\right),$$

where $\alpha = e, \mu, \tau$, index $I$ is from 1 to full number of the sterile neutrinos, $L_\alpha$ – doublet of leptons of $\alpha$-generation, $N_I$ – right-handed sterile neutrino, $F_{\alpha I}$ – new matrix of dimensionless Yukawa couplings, $\tilde{H} = i\sigma_2 H^\star$.

Taking the low energy limit and considering sterile neutrino as Majorana particles, we can write full Lagrangian of the modified neutrino sector of the SM

$$\mathrm{L}_{\nu,N} = i\bar{\nu_k}\ \partial\!\!\!/ \nu_k + i\bar{N}_I\ \partial\!\!\!/ N_I - \left(F_{\alpha I}\bar{\nu}_\alpha N_I + \tfrac{M_I}{2}\bar{N}_I{}^c N_I + h.c.\right),$$

where $M_I$ – Majorana mass terms. As a result of the neutrino states mixture, the active neutrino states become superposition of the mass states of the active and the sterile neutrinos. It means that sterile neutrinos interact with SM particles similarly to active neutrinos:

$$\mathrm{L}_{int} = -\left(\tfrac{g}{2\sqrt{2}} W^+_\mu \textstyle\sum_{I,\alpha} \overline{N^c}_I U_{I\alpha}\gamma^\mu(1-\gamma_5)\ell^-_\alpha + \tfrac{g}{4\cos\theta_W} Z_\mu \textstyle\sum_{I,\alpha} \overline{N^c}_I U_{I\alpha}\gamma^\mu(1-\gamma_5)\nu_\alpha + h.c.\right),$$

where $U_{I\alpha} = F_{I\alpha}/M_I$ is so called mixing angle.

For intensity frontier experiment it is very important to built sensitivity region. It is a region in space of parameters of new particle (mass and coupling), when particle can be detected in the experiment. To build it one has to solve inequality $N^{reg}_{HNL} > N_0$, where $N_0$ is minimal expected number of new particle for successful of experiment, $N^{reg}_{HNL}$ is number of HNL that can be detected:

$$\mathrm{N}^{reg}_{HNL} \simeq N^{produced}_{HNL} P_{geom} P_{decay}.$$

Here $N^{produced}_{HNL}$ is number of the produced *HNL*-particles, $P_{geom}$ is a probability of the produced HNL-particles to move towards the detector, $P_{decay}$ is a probability of the produced HNL-particles to decay in the volume of the vacuum tank before the detectors.

For approximate calculations of the sensitivity region, PYTHIA is often used. It is a widely used program for the generation of high-energy physics events. PYTHIA is good for generation of 2-body mesons' decay, but for HNL production it is important to take into account 3-body decay too. PYTHIA uses predefined matrix element to generate 3-body semileptonic decays of $B$ and $D$ mesons correspondingly

$$\overline{|M_{fi}|^2_B} = (p_h\, p_\nu)(p_{h'}\, p_\ell), \quad \overline{|M_{fi}|^2_D} = (p_h\, p_\ell)(p_{h'}\, p_\nu).$$

It does not contain mesons' form-factors and its matrix elements obviously differs from correct matrix elements for HNL production in 3-body mesons' decay. The goal of the project is to estimate the importance of this uncertainty for construction of sensitivity region to HNL.

We considered in details probability density function for the energy of the HNL-particles $pdf(E_N)$, $P_{geom}$ and $P_{decay}$ and make following conclusions.

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<li>Computations of 3-body decay of $\tau$-lepton with HNL production in Pythia coincide with correct computations.</li>

<li>For description of reactions of pseudoscalar meson 3-body decay into another pseudoscalar meson ($B^- \to D^0 + \ell^- + N$ and $D^- \to K^0 + \ell^- + N$) the matrix elements of type $B$ in Pythia is better to use</li>

<li>For description of reactions of pseudoscalar meson 3-body decay into another vector meson ($B^- \to D^\star(2007)^0 + \ell^- + N$ and $D^- \to K^\star(892) + \ell^- + N$) the matrix elements of type $D$ in Pythia is better to use.</li>

<li>Among the considered 3-body reactions, due to a suitable choice of PYTHIA matrix elements (type of $B$ and $D$), one can get the smallest difference with correct matrix element for reaction $B^- \to D^0 + e^- + N$ (difference $\sim 1\%$), while the largest unremovable difference is for reaction $D^- \to K^\star(892) + e^- + N$ (difference $\sim 5\%$).</li>

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[1] Kyrylo Bondarenko, Alexey Boyarsky, Dmitry Gorbunov, and Oleg Ruchayskiy. Phenomenology of GeV-scale Heavy Neutral Leptons. *JHEP*, 11:032, 2018.

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