PROCEEDINGS OF SCIENCE

Sensitivity to Heavy Neutral Leptons with the SAND detector at the DUNE ND complex

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A study has been performed within the framework of the multi-instrument DUNE near detector complex, specifically regarding the on-Axis System, to assess the sensitivity to heavy neutral lepton within six years of exposure. By utilizing two MC generators, and charmed heavy meson decay channels, the sensitivity to heavy neutral lepton masses between 0.3 and 1.8 GeV/c^2 has been explored. A Mad-Graph/Mad-Dump model has been implemented based on the Neutrino Minimally extended Standard Model Lagrangian, and used to obtain accurate kinematics for the decay of mesons and heavy neutral lepton. The simulated final-state particles have been propagated through the detector; a track reconstruction algorithm, based on the Kalman Filter technique, along with a simple two-body decay selection, is implemented to estimate efficiency and background rejection. The heavy neutral lepton sensitivity has been estimated both from purely phenomenological as well as experimental point of view, reaching O(10^{-9}) for higher masses, with about a factor 3 deterioration between the phenomenological and the experimental case. In this paper, the results for direct and indirect decay channels of charmed meson D_s to heavy neutral lepton has been investigated and the potential for further improvements has been discussed.

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1. Introduction

Besides the numerous successes of the Standard Model (SM), no significant deviations in direct or indirect searches for new physics have been observed; yet, exploring and defining ranges and limits for new physics is still on-going. The νMSM (Neutrino Minimally extended Standard Model) is a renormalizable extended model of the SM [1]. It includes three neutral singlet right-handed fermions, or Heavy Neutral Leptons (HNLs), as the extended fields to the SM. This model with such choice of parameters also explains baryon asymmetry of the universe (BAU) as well as providing a dark matter candidate. System for on-Axis Neutrino Detection (SAND) is a permanently on-axis detector in DUNE near detector complex, with magnetized tracker [2]. The magnet is designed in conjunction with its iron yoke to produce 0.6 T over a 4.3×4.8 m volume, enveloping the multi-target tracker: Straw Tube Tracker (STT) and LAr meniscus at the upstream end [2].

2. Model Specifications, Simulation and Reconstruction

The νMSM Lagrangian includes three heavy, O($\sim$ GeV), right-handed neutrinos, $N_{1,2,3}$, where the lightest, N_1, represents the dark matter candidate, and the two others are responsible for baryogenesis and generation of lepton asymmetry through resonant production of N_1.

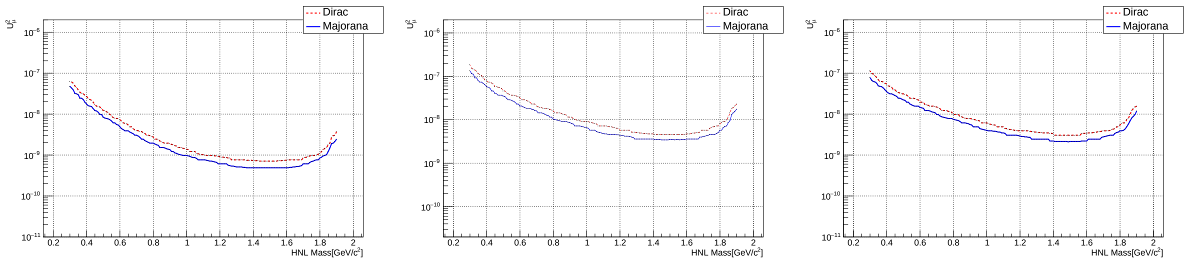
$$\mathcal{L}_{\nu MSM} = \mathcal{L}_{MSM} + \bar{N}_I i\partial_\mu \gamma^\mu N_I - F_{\alpha I}\bar{L}_\alpha N_I \Phi - \frac{M_{IJ}}{2}\bar{N}_I^c N_J + h.c. \tag{1}$$

This work is partly dedicated to phenomenological estimate on single event sensitivity, and partly to detector simulation and track reconstruction, by which the final sensitivity is estimated. The meson flux, D_s[1], has been generated by 10^7 p-p interaction with 120 GeV (in fixed target mode) using Pythia8. The main MC generator, Mad-Dump2.0, combines the model[2] built by FeynRules, and the D_s flux to process the generation and the decay of long-lived HNL[3] inside the detector[4]. The Pheno-Sensitivity has been estimated for three benchmark models within the νMSM context, for 6 years of exposure and 1.1×10^{21} number of protons on target (NPOT). Fig. 1 shows that the Pheno-Sensitivity is consistent with similar works in the D_s dominant mass region [3].

2.1 Selection, Acceptance and Efficiency, and Background

A customized Kalman Filter (KF) has been applied to the digitized (200 μm smearing) detector response. The customized KF runs under few assumptions: constant and uniform magnetic field of 0.6 T, discreteness (detector layers should be in exact z coordinate, and with no uncertainty on the z coordinate of the detector planes), external helical fit (optimizing the invariant mass and momentum resolution in $Q \ll 0$ limit), direction (independent Forward and Backward Kalman passes), and final reconstructed track merge, based on 50% shared hits (reconstruction optimization without losing the optimum resolution). Due to the geometry of the STT modules in SAND inner tracker, the hits coordinates (x and y) are extracted separately and then recombined referring to the z of the most upstream layer, resulting in each event presenting not only two reconstructed tracks, but

[1] Dominant source of HNL, in the range up 2 GeV in mass
[2] Including the effective vertices for meson decay
[3] HNL CC decay channels are usually preferred for reconstruction; $\pi\mu$ signal is chosen for this work
[4] Weight normalization is applied to compensate for forced decay assumption inside the detector



(a) **(b)** **(c)**

Figure 1: The U_μ^2 sensitivity to all direct and indirect channels of D_s for 6 years of exposure showing for three benchmark models. (a) $U_e : U_\mu : U_\tau \sim 52 : 1 : 1$, (b) $U_e : U_\mu : U_\tau \sim 1 : 16 : 3.8$, (c) $U_e : U_\mu : U_\tau \sim 0.061 : 1 : 4.3$ [7]

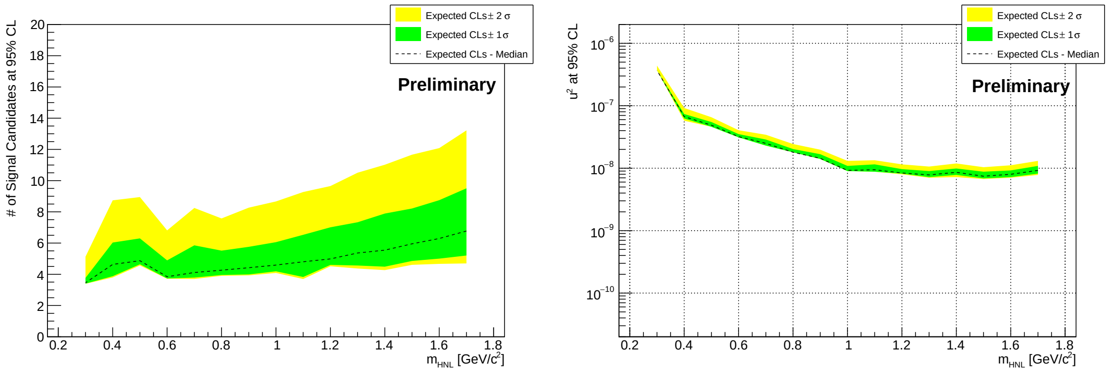
also two ghosts. An efficient event selection scheme can help rejecting the ghosts from the signal. The selection criteria are: tracks in opposite quadrants and with opposite charge, a 2D cut on angle separation for true tracks and the ghosts (in $\alpha - \theta$[5], there is a distinguished spread for ghosts that can be removed with a proper 2D cut), $\alpha > 2.9$ and $\theta < 0.02$, a cut on reconstructed vertex (the shortest distance between the two reconstructed tracks) at $1mm$. The long tracks, passing 6 planes or more, within the fiducial cut of the detector are accepted. The fraction of accepted events over the total number of generated ones in a cubic fiducial volume defines the efficiency. The efficiency estimate shows high sensitivity to the geometry of the event, and inversely proportional to the fraction of ghost contamination (for fully symmetric events). The efficiency of the KF in reconstructing the HNL events is $\sim$ 80% for single tracks and $\sim$ 60% for a track pair. The HNL signal candidate is defined as an accepted and selected track pair used to evaluate an invariant mass. The signal distribution is modeled with two sided Hypatia [6] p.d.f. To have an estimate on the background, few assumptions have been made at the generation stage: only neutrino interactions inside the STT have been taken into account, and the high statistics has been kept at the generation level, meaning that the most dangerous background, ν_μ CC interaction with single π at final state, have been cherry picked (30% of the total events). This pre-selected background is passed through the complete chain as the signal simulation. The resulting background invariant mass distribution is limited to 11 final background candidates for 6 years of exposure within the invariant mass squared region [0-9] GeV^2/c^4; both a uniform and an exponential p.d.f. is considered for background modeling.

2.2 Final Sensitivity

The final sensitivity is estimated by combining the methods and parameters from Phenomenology to the statistical analysis of the signal and background distributions after the selection. The statistical technique in calculating the confidence level follows a frequentist approach based on the likelihood ratio, using RooFit. Around 100 toy MC have been generated based on the signal and background models. Comparing the final sensitivity with the Pheno shows a factor $\approx$ 3 degradation, which is due to introducing the experimental setup against the simple assumption of full efficiency and zero background. Such downcast in final sensitivity is due to the combination of a slight

[5] α and θ are the angles between the tracks and with the z-axis, respectively

overestimate of the detector volume, using a cube in the Pheno-sensitivity, as well as the global reconstruction and selection efficiency.



(a) **(b)**

Figure 2: (a) Number of signal candidates corresponding to 95% CL for each HNL mass, (b) Final sensitivity to HNL searches in SAND at 95% CL for benchmark II (Majorana HNL assumption) [7]

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