PROCEEDINGS OF SCIENCE

NA62 sensitivity to heavy neutral leptons in the low scale seesaw model

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I present our study on heavy neutral leptons in the low scale type I seesaw model at the fixed target experiment NA62. First, I show the constraints on the heavy neutrino mixing parameter from the neutrino oscillation data. Afterwards, I present sensitivity estimates of the NA62 experiment in the beam dump mode for different benchmark scenarios.

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1. Introduction

I present a proposal to search for heavy neutrinos in the dump mode of NA62 [1, 2]. Neutrino oscillation experiments have established that at least two neutrinos have a mass, while one neutrino may still be massless $m_{\text{lightest}} = 0$. Between the three light neutrino masses m_1, m_2, m_3 there are two measured mass differences, which leads to two possible ordering patterns (cf. Figure 1).

2. Heavy Neutrinos

In type I seesaw models [3–6] three right handed neutrinos are added to the SM

$$\mathcal{L}_{\nu_R} = -\frac{1}{2}\overline{\nu^c_{Ri}} M_{ij} \nu_{Rj} - y_{ai} \overline{\ell}_a \varepsilon \phi \nu_{Ri} + \text{h.c.} \tag{2.1}$$

where y_{ai} is a Yukawa coupling and M_{ij} the Majorana mass. After electroweak symmetry breaking a Dirac mass $m_{ai} = v y_{ai}$ is generated. The seesaw mechanism

$$m_\nu = -m_{ai} M^{-1}_{ij} m^T_{bj} = -\theta_{ai} M_{ij} \theta^T_{bj} \ , \qquad \theta_{ai} = m_{aj} M^{-1}_{ij} \ , \tag{2.2}$$

produces tiny masses for the left handed neutrinos through mass diagonalization and leads to small mixing into mass eigenstates

$$\nu \simeq U^\dagger_\nu \left(\nu_L - \theta \nu^c_R\right) \ , \qquad N \simeq \nu_R + \theta^T \nu^c_L \ , \tag{2.3}$$

where the PNMS matrix U_ν diagonalises the m_ν. The N_i couple to the SM via

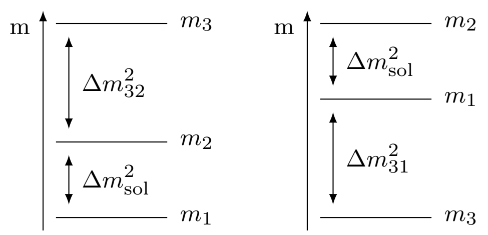
$$\mathcal{L} \supset -\frac{m_W}{v} \overline{N} \theta^*_a \gamma^\mu e_{La} W^+_\mu - \frac{m_Z}{\sqrt{2}v} \overline{N} \theta^*_a \gamma^\mu \nu_{La} Z_\mu - \frac{M}{v} \theta_a h \overline{\nu_{L\alpha}} N + \text{h.c.} \ . \tag{2.4}$$

The νMSM exploits that the SM is symmetric under $B-L$ [7, 8]. In the limit $M_{ij} \to 0$ this symmetry is restored. The Yukawa and Majorana matrices are now

$$y_{ai} = \begin{pmatrix} y_e + \epsilon_e & i(y_e - \epsilon_e) & \epsilon'_e \\ y_\mu + \epsilon_\mu & i(y_\mu - \epsilon_\mu) & \epsilon'_\mu \\ y_\tau + \epsilon_\tau & i(y_\tau - \epsilon_\tau) & \epsilon'_\tau \end{pmatrix} \ , \qquad M_{ij} = M \begin{pmatrix} 1-\mu & 0 & 0 \\ 0 & 1+\mu & 0 \\ 0 & 0 & \mu' \end{pmatrix} \ , \tag{2.5}$$

Variables	Normal Ordering	Inverted Ordering
m_1^2	m^2_{lightest}	$m^2_{\text{lightest}} - \Delta m^2_{32} - \Delta m^2_{\text{sol}}$
m_2^2	$m^2_{\text{lightest}} + \Delta m^2_{\text{sol}}$	$m^2_{\text{lightest}} - \Delta m^2_{32}$
m_3^2	$m^2_{\text{lightest}} + \Delta m^2_{31}$	m^2_{lightest}
larger Δm^2	$\Delta m^2_{31} = m^2_3 - m^2_1$	$\Delta m^2_{32} = m^2_3 - m^2_2$

(a) Neutrino mass parameter and their differences.



(b) Normal Ordering (c) Inverted Ordering

Figure 1: Neutrino mass parameter (Panel a) and an illustration of normal (Panel b) and inverted (Panel c) ordering. The smaller "solar" mass difference is given by $\Delta m^2_{\text{sol}} = m^2_2 - m^2_1$.

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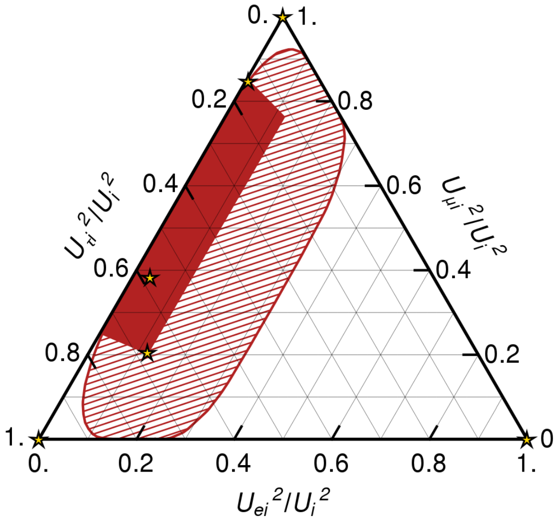
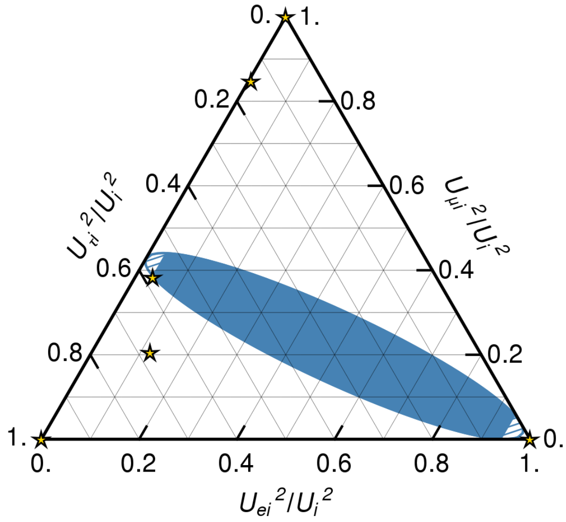
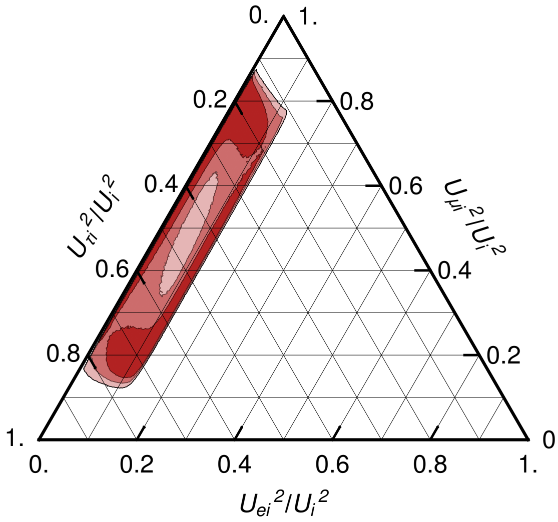


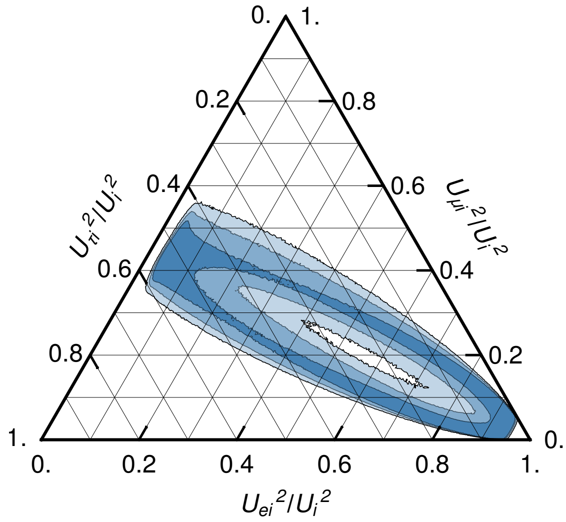
(a) Allowed values for normal ordering.



(b) Allowed values for inverted ordering.



(c) Preferred values for normal ordering.



(d) Preferred values for inverted ordering.

Figure 2: Allowed values for arbitrary parameter choices (hashed region) and in the symmetric limit (filled region) for normal (Panel a) and inverted (Panel b) ordering. The stars mark our benchmark scenarios (cf. Figure 4a). Probability contours for the heavy neutrino couplings for normal (Panel c) and inverted (Panel d) ordering. The coloured areas are consistent with neutrino oscillation data at 1σ, 2σ, 3σ. The Majorana phase is unknown and correspond to the circular structure in the plots.

where the $B-L$ violating parameter ϵ, ϵ', μ, μ' are small. The heavy neutrinos form an almost mass degenerate pseudo Dirac pair $\nu_{Ri} + \nu_{Rj}^c$ with coupling $\mathcal{O}(y)$ and a lighter Dark Matter candidate with coupling $\mathcal{O}(\epsilon')$. Besides the neutrino masses this model is able to explain oscillation data, baryogenesis via leptogenesis. In the following we use the

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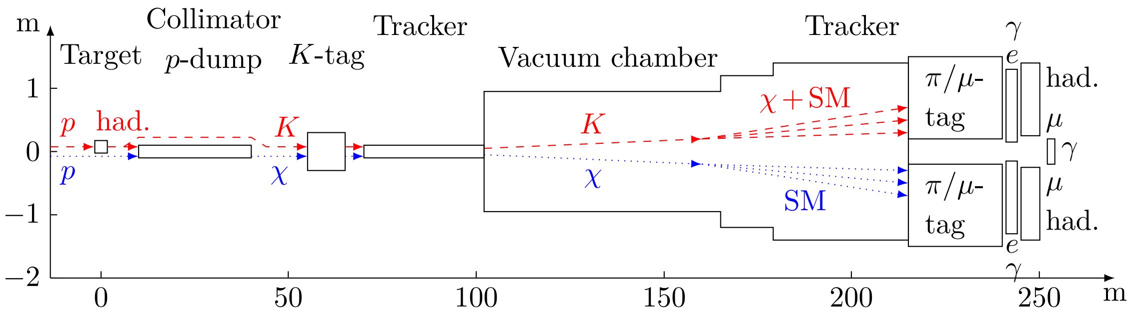


Figure 3: Hidden New Physics in the target (red) and dump (blue) mode of the NA62.

abbreviations

$$U^2 = \sum_a U_a^2 \,, \qquad U_a^2 = \sum_i U_{ai}^2 \,, \qquad U_{ai}^2 = |\theta_{ai}|^2 \tag{2.6}$$

The ratio U_a^2/U_2 becomes independent of other heavy neutrino parameter and the values preferred by neutrino oscillation data are shown in Figure 2.

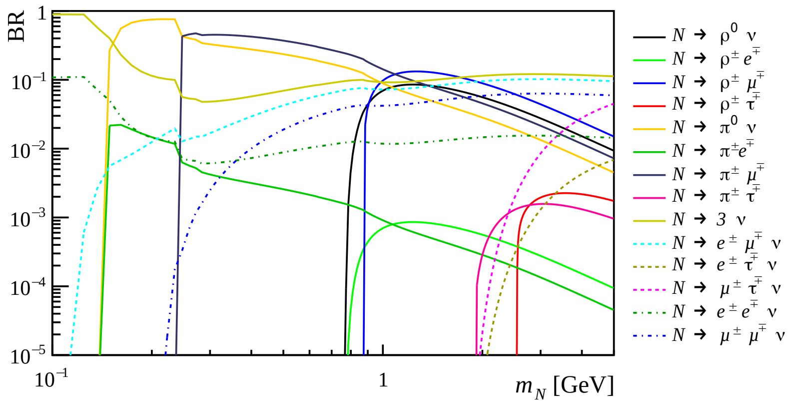
3. Heavy Neutrinos in the Dump mode of NA62

NA62 is a fixed target experiment at the North Area of CERN using the SPS with the goal to measure the very rare kaon decay $K^+ \to \pi^+ \nu \overline{\nu}$ and extract a 10 % measurement of the CKM parameter $|V_{td}|$. It can also be used to search for hidden new physics χ such as a heavy neutrinos, in either the target mode using K^+ induced processes or the dump mode using D- and B-meson induced processes (cf. Figure 3).

In Run 3 (2021–2023) the NA62 experiment plans to collect 10^{18} protons on target (POT) in the dump mode during about 80 days of data taking. We simulate the production

	U_{ei}^2	:	$U_{\mu i}^2$	:	$U_{\tau i}^2$
A	0.530	:	84.7	:	14.7
B	12.0	:	20.5	:	67.5
C	3.65	:	38.3	:	58.0
D	100	:	0	:	0
E	0	:	100	:	0
F	0	:	0	:	100

(a) Benchmark scenarios for U_a^2/U^2 in %.



(b) Branching fractions for scenario A [9]. The dominant modes are $N_i \to 3\nu$, $\pi^0\nu$, $\pi^\pm\ell^\mp$, $\rho^0\nu$, $\rho^\pm l$, $\ell^+\ell^-\nu$.

Figure 4: Heavy neutrino benchmark scenarios in Panel a and branching fractions of a heavy neutrino in scenario A in Panel b.

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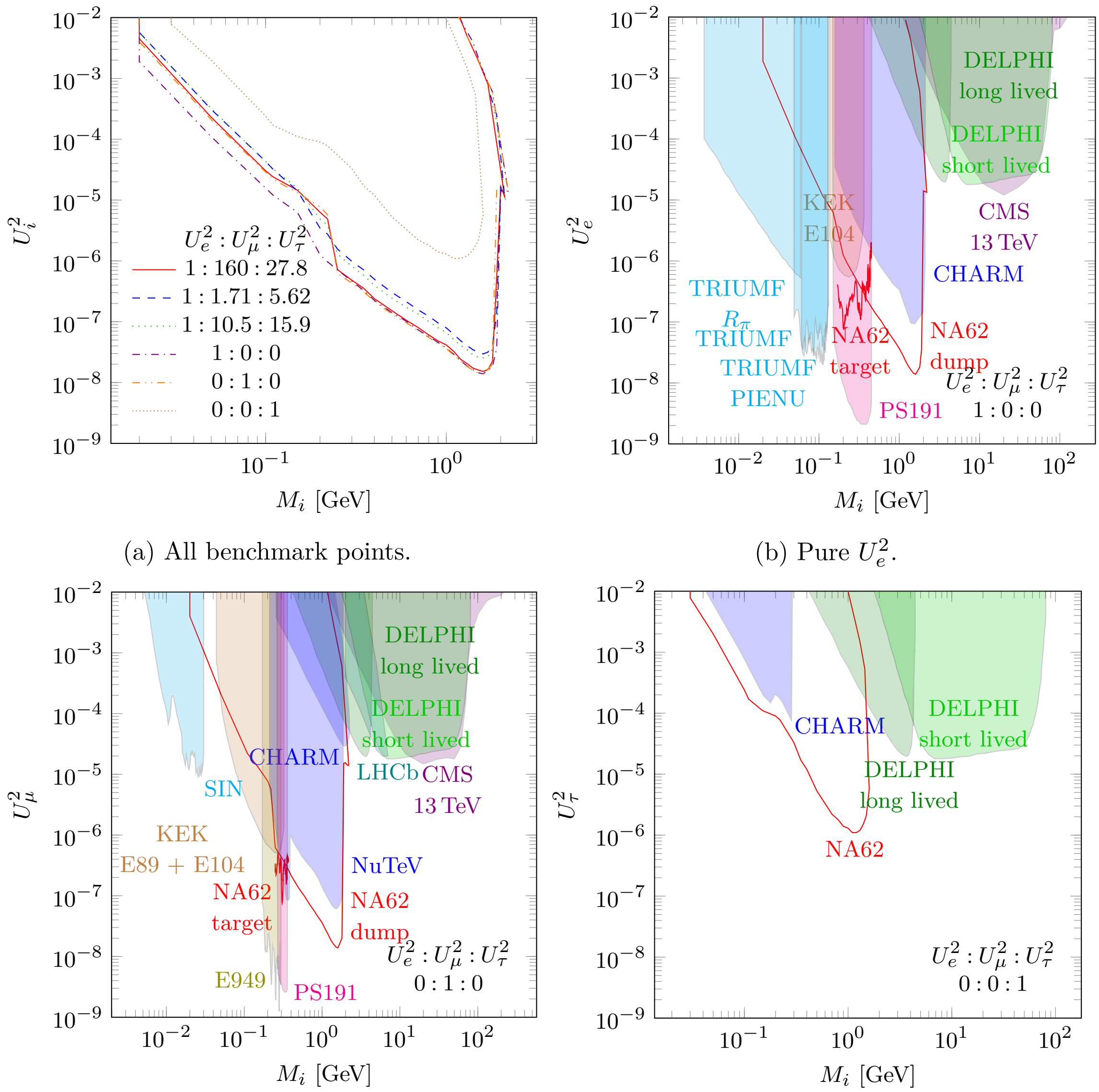

(a) All benchmark points.

(b) Pure U_e^2.

(c) Pure U_μ^2.

(d) Pure U_τ^2.

Figure 5: Exclusion reach of NA62 in the six benchmark points (cf. Figure 4a) in Panel a and comparison of the NA62 reach (red line) with previous experiments (coloured areas) in Panels b–d.

of heavy neutrinos via 2×10^{15} D- and 10^{11} B-mesons using a Toy Monte Carlo.

$$n_N \simeq 2N_{\text{POT}} \left(\chi_c \sum_{D_j = D^+, D^0, D_s} f_{D_j} \text{BR}(D_j \to X N_i) + \chi_b \sum_{B_k = B^+, B^0, B_s} f_{B_k} \text{BR}(B_K \to X N_i) \right) , \quad (3.1)$$

here χ is the production cross section normalization and f the production fractions of mesons. The Number of reconstructed events is given by

$$N_{\text{obs}} = n_N \sum_{f, f' = e, \mu, \tau, \pi, K} \text{BR}\left(N_i \to f^+ f'^- X\right) \mathcal{A}_i\left(f^+ f'^- X,\, M_i, U^2_{e,\mu,\tau}\right) \varepsilon\left(f^+ f'^- X,\, M_i\right) , \quad (3.2)$$

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where $\mathcal{A}_I$ is the geometrical acceptance and ε combines all efficiencies (trigger, reconstruction, selection). For simplicity we assumed all efficiencies to be 100 % and that all backgrounds can be sufficiently suppressed. One example of the heavy neutrino Branching Fraction is given in Figure 4b. Finally, we assume that the detector is able to reconstruct all final states with two charged tracks.

4. Results and Conclusion

Our results are presented in Figure 5. We show that the sensitivity varies within two orders of magnitude between the extreme benchmark points and that at the moment NA62 is the leading experiment for masses between the Kaon and the D-meson mass.

We have shown that heavy neutrinos constitute a minimal extension to the SM, which is able to explain neutrino oscillation data and easily can have properties detectable at current or future experiments.

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