PHYSICS WITH NEXT GENERATION NEUTRINO EXPERIMENTS: ESSnuSB*

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In this contribution, we explore the physics potential of the ESSnuSBplus setup to study beam- and non-beam-based physics scenarios in both standard and New Physics cases. The ESSnuSBplus setup consists of three neutrino sources: the main ESS linac, a low-energy monitored neutrino beam, and a low-energy nuSTORM facility and three detectors: the main far detector and two near detectors. The goal of this facility is to measure the leptonic CP phase with extremely high precision and the neutrino–nucleus cross section in the few-hundred-MeV region.

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1. Introduction

While the aim of the current generation of long-baseline experiments [1] T2K and NOνA is to find the hint of the correct neutrino mass ordering, the true octant of the atmospheric mixing angle θ_{23}, and the true value of the leptonic CP phase δ_{CP}, the goal of the future generation experiments T2HK [2], DUNE [3], and ESSnuSB [4] is to confirm these hints in a firm footing. Apart from measuring the parameters in the standard three-flavour oscillation scenario, these experiments are also capable of probing various New Physics scenarios. In this contribution, we will study the capability of the ESSnuSBplus setup [5] to probe a wide variety of physics scenarios in both standard and New Physics cases.

The text is organized as follows. In the next section, we will describe the ESSnuSBplus setup in detail, and then, in the following sections, we demonstrate its sensitivity to various physics cases. Finally, we will summarize the results and conclude.

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2. The ESSnuSBplus facility

The ESSnuSBplus facility in Sweden will consist of three neutrino sources and three detectors. A preliminary layout of the facility has been shown in Fig. 1. The main ESS linac in Lund will deliver a 5 MW proton beam with 2.5 GeV proton energy and a 2.8 ms pulse. Then the accumulator ring will reduce the pulse length to 1.2 μs in order to minimize the atmospheric background. These protons will collide with a target to produce an intense beam of muon neutrinos via pion decay. These neutrinos will pass through a near detector located at 250 m (END), and then finally reach the far detector (FD) consisting of 540 kt of ultra-pure water, located 360 km away at Zingruvan. In addition, this facility will also have a low-energy monitored neutrino beam (LEMNB) which is inspired by the original ENUBET[1] idea [7]. This will be an instrumented decay pipe to measure neutrino flux to 1% uncertainty. These neutrinos will be detected at another near detector called LEMMOND. Moreover, for the measurement of cross section, this facility will also have a low-energy neutrino source from muon decay (LEnuSTORM) inspired by the original nuSTORM idea [8]. These neutrinos will be detected in LEMMOND and END detectors.

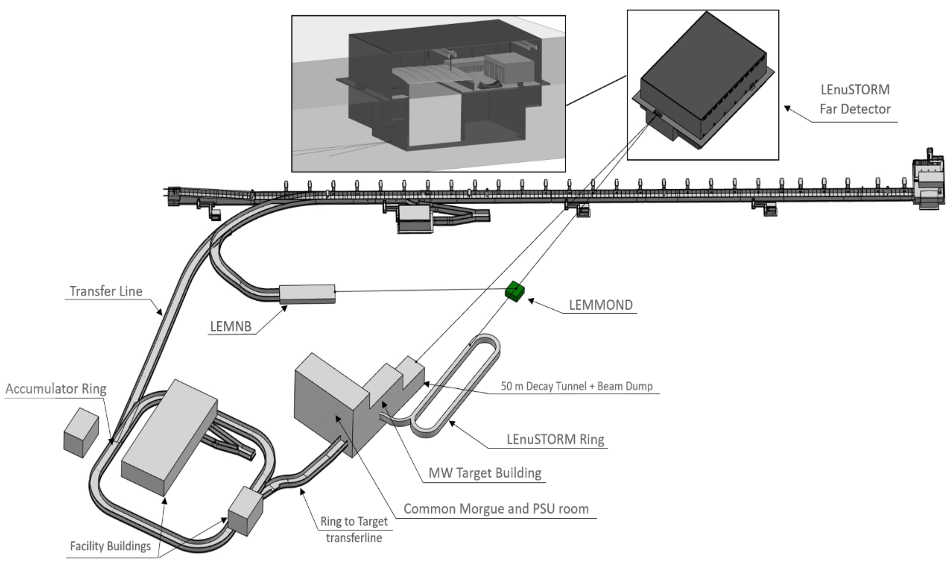

Fig. 1. The ESSnuSBplus facility.

[1] To be implemented in nuSCOPE [6].

3. Results

3.1. Sensitivity to δ_{CP}

Figure 2 shows the CP sensitivity of the ESSnuSB facility using the main ESS beam, the END, and the FD. The left panel shows the CP violation sensitivity, whereas the right panel shows the CP precision sensitivity. The different curves in each panel show the different values of systematic errors. From the plot, we see that ESSnuSB will have world leading sensitivity for the δ_{CP}. The CP sensitivity of ESSnuSB is better than T2HK and DUNE because ESSnuSB probes the second oscillation maximum in the probability spectrum, whereas the other experiments probe the first oscillation maxima. As the CP sensitivity at the second oscillation maximum is three times higher as compared to the first maximum, ESSnuSB provides a better sensitivity.

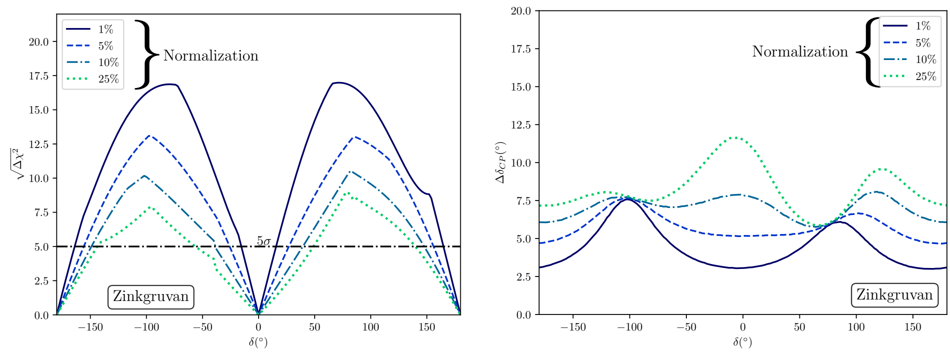

Fig. 2. CP sensitivity of the ESSnuSB experiment.

3.2. Sensitivity to sterile neutrinos

Figure 3 shows the sensitivity of the ESSnuSB facility to the eV scale sterile neutrinos using the main ESS beam and the FD [9]. In this figure, we have compared the sensitivity of the ESSnuSB experiment to constrain the sterile mixing parameters θ_{14} and θ_{24} with T2HK and DUNE. The different curves for ESSnuSB refer to different run-times in the neutrino and antineutrino modes. These results were generated using an older version of the flux files and an older version of the detector responses. We plan to update these results with our latest flux and detector responses. This plot shows results only for the far detector, whereas we expect a significant change in sensitivity once we include the near detectors in the analysis.

3.3. Sensitivity to neutrino decay

Figure 4 shows the sensitivity of the ESSnuSB facility to invisible neutrino decay using the main ESS beam and the FD [10]. This plot shows

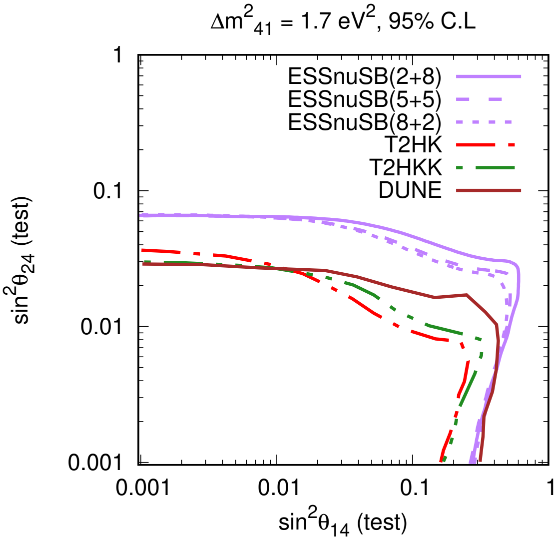

Fig. 3. Sensitivity of the ESSnuSB experiment to sterile neutrinos.

the capability of the ESSnuSB FD to constrain the lifetime of the heavier neutrino mass state m_3 in the normal mass ordering of the neutrinos. The red curve is for the baseline of 360 km, whereas the blue curve is for the baseline of 540 km which was one of the earlier baseline options of this experiment. While comparing our sensitivity with the other experiments, we find our sensitivity to be better than DUNE.

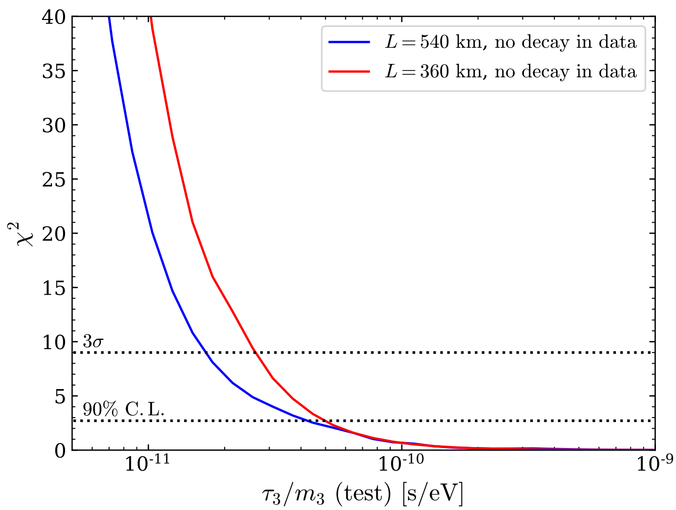

Fig. 4. Sensitivity of the ESSnuSB experiment to invisible neutrino decay.

3.4. Sensitivity to scalar NSI

Figure 5 shows the sensitivity of the ESSnuSB facility to non-standard interaction mediated by a scalar field (SNSI) using the main ESS beam and the FD [11]. This figure shows the CP violation discovery χ^2 as a function of SNSI parameter η for $\delta_{\rm CP} = -90°$. In this figure, the different curves show sensitivity for three diagonal SNSI parameters. The point $\eta = 0$ refers to the standard three-flavour case where all the curves coincide. From this figure, we can see an interesting phenomenon that for $\eta_{ee} = -1.8$, the CP violation sensitivity of the ESSnuSB experiment vanishes. Therefore, if SNSI exists in nature, then this can be a clear signal of this theory.

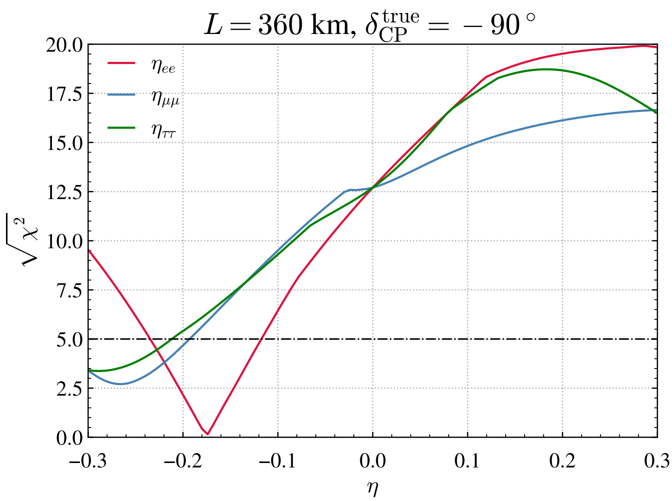

Fig. 5. Sensitivity of the ESSnuSB experiment to scalar NSI.

3.5. Sensitivity to quantum decoherence

Figure 6 shows the sensitivity of the ESSnuSB facility to quantum decoherence using the main ESS beam and the FD [12]. This figure shows the capability of the ESSnuSB FD to constrain the decoherence parameter Γ. In this panel, different curves represent different values of the systematic error. In this analysis, we have considered an open quantum system formalism where neutrino as a subsystem interacts with the environment giving rise to decoherence. While comparing our sensitivity with the other experiments, we find that our sensitivity is comparable with DUNE.

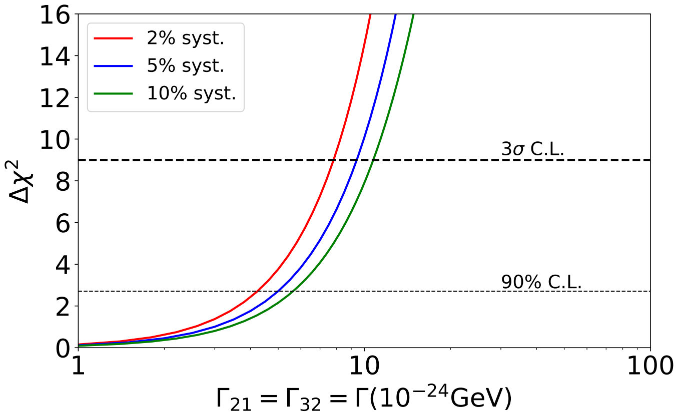

Fig. 6. Sensitivity of the ESSnuSB experiment to quantum decoherence.

3.6. Sensitivity to atmospheric neutrinos

Figure 7 shows the sensitivity of the ESSnuSB facility to atmospheric neutrinos that are produced in Earth's atmosphere via interaction with the cosmic rays, using the FD [13]. The left panel shows the capability of the ESSnuSB FD to reject the wrong neutrino mass ordering and the right panel shows the capability to reject the wrong octant of θ_{23} as a function of the exposure. In each panel, the blue band is for normal mass ordering and the red band is for inverted mass ordering. In ESSnuSB FD, we have excellent sensitivity as compared to other experiments due to the strong flux near the pole and the larger detector volume.

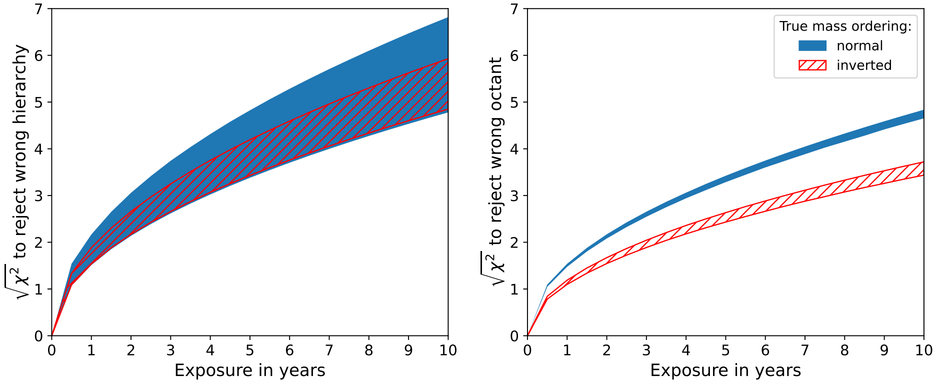

Fig. 7. Sensitivity of the ESSnuSB experiment to atmospheric neutrinos.

3.7. Other sensitivities

Apart from the results shown above, we are currently studying the sensitivity of the ESSnuSB FD to solar neutrinos and supernova neutrinos. Additionally, study of sterile neutrinos involving the near detectors, LEMNB and LEnuSTORM, is also in progress. The results are expected to be published soon.

4. Summary and conclusion

In this contribution, we have shown the capability of the ESSnuSBplus setup to probe various physics scenarios in both standard three-flavour and New Physics cases. First, we have outlined the experimental configuration of the ESSnuSBplus setup and then demonstrated the sensitivity of the ESSnuSB far detector to CP violation and CP precision in the standard three-flavour framework, sensitivity to sterile neutrinos, sensitivity to invisible neutrino decay, sensitivity to non-standard interaction mediated by scalar NSI, sensitivity to quantum decoherence, and sensitivity to the atmospheric neutrinos. Estimation of the sensitivity of the far detector for solar neutrinos and supernova neutrinos and estimation of the sensitivity to sterile neutrinos using the near detectors END and LEMMOND and the neutrino sources LEMNB and LEnuSRTORM are in progress. In conclusion, we would like to stress that ESSnuSB will be an extremely powerful neutrino facility in Europe with excellent sensitivities to a variety of physics cases.

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