PROCEEDINGS OF SCIENCE

The European Spallation Source neutrino Super Beam project: Status and Prospects

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Abstract

The ESSnuSB (European Spallation Source neutrino Super Beam) is a design study for a long-baseline neutrino experiment to precisely measure the CP violation in the lepton sector at the second neutrino oscillation maximum, using a beam driven by the uniquely powerful ESS linear accelerator. The ESSnuSBplus (ESSnuSB+) design study programme, which is an extension phase of the ESSnuSB project, aims in designing two new facilities, a Low Energy nuSTORM and a Low Energy Monitored Neutrino Beam to use them to precisely measure the neutrino-nucleus cross-section in the energy range of 0.2 –0.6 GeV, where the experimental data are very scarce. In addition, new target stations and a new water Cherenkov near-near detector will be designed to measure cross sections and serve to explore the sterile neutrino physics. An overall status of the project is presented together with the ESSnuSB+ additions.

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1. Introduction

The ESSnuSB project is the design of a novel Long Baseline (LBL) neutrino experiment intended to follow up after the successful completion of the currently under preparation LBL experiments [1]. ESSnuSB proposes to use the powerful proton beam (5MW, 2 GeV proton kinetic energy) of the European Spallation Source (ESS) in Lund, Sweden, to create a high intensity neutrino super beam. The proposed LBL setup includes a near detector complex at ESS and a far detector complex at the Zinkgruvan mine of Sweden [2]. The combination of the neutrino beam energy and the location of the far detector places the experiment on the second neutrino oscillation maximum, resulting in a dramatically improved matter-antimatter asymmetry largely immune to systematics and matter effects [2,3]. Fig. 1 shows the neutrino and antineutrino beam spectra in conjunction with the neutrino/antineutrino oscillation maxima for different values of the CP violating angle (δ_{CP}). There is sufficient neutrino/antineutrino flux, in both maxima, to allow for a high precision measurement of δ_{CP} as well as the measurement of the other neutrino oscillation parameters.

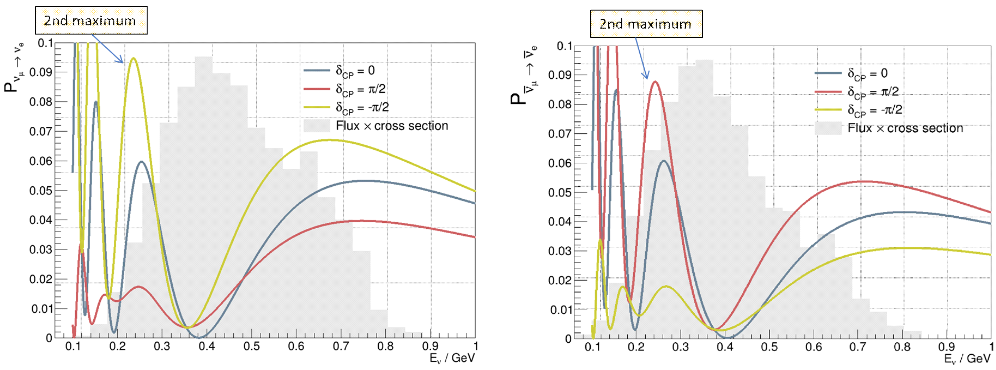

***Figure 1**: The neutrino(left) and antineutrino (right) beam spectra (grey histograms) of the ESSnuSB beam are shown with respect to the neutrino and antineutrino oscillation maxima for various δ_{CP} values.*

The conceptual design report (CDR) of the first phase of ESSnuSB (2018-2022) has been completed and published [4] in 2022. The CDR contains the details of the modifications required for the ESS linear accelerator, the design of the transfer lines, the accumulator, the specially designed target, the optimized horn structure as well as the design of the detector complexes. The near detector complex consists of a water Cherenkov detector, a super fine-grained scintillator detector [5] and a NINJA-like [6] emulsion detector, while the far detector complex consists of two large water Cherenkov detectors to be placed in two caverns, located 1000 m deep in the Zinkgruvan mine.

ESSnuSB has been optimized for the precision measurement of the CP violating angle δ_{CP}. The physics performance of ESSnuSB with respect to δ_{CP} is shown in Fig. 2. The results assume 5% normalization uncertainty, 5 years run with neutrino beam and 5 years with antineutrinos. The left plot shows the experiment's sensitivity for CP violation (CPV) discovery as a function of the δ_{CP} range of true values. It shows that at the maximal violation, i.e., $\delta_{CP} \sim \pm 90^{o}$, the CPV discovery sensitivity reaches about 12σ. The middle plot shows that ESSnuSB will cover about 72% of the range of the true δ_{CP} values with a confidence level of more than 5σ

to reject the no-CPV hypothesis, after 10 years of data taking. The right plot shows that the expected precision on the measured value of δ_{CP} will be better than 8^{o} for the whole δ_{CP} range.

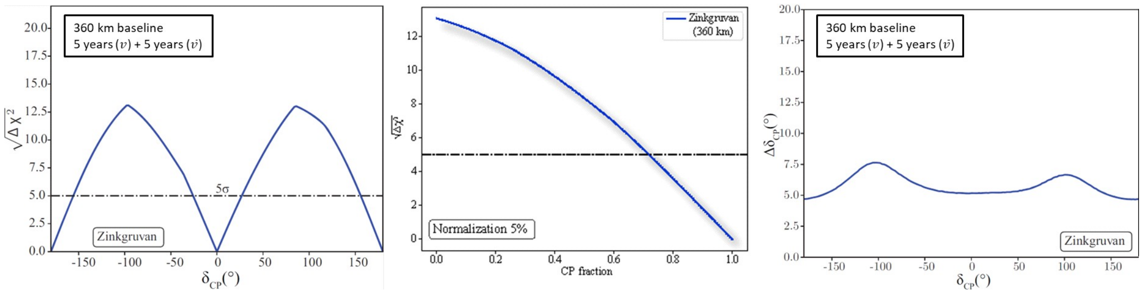

Figure 2: *(Left panel) Discovery sensitivity of the leptonic CP violation as a function of δ_{CP} range. (Middle) The fraction of the covered δ_{CP} range, for which CPV can be discovered, as a function of the significance. (Right) The precision of the δ_{CP} value as a function of the δ_{CP} range.*

2. The ESSnuSB+ project

The main source of systematics for the precision measurement of the CPV angle is the knowledge of the neutrino and antineutrino cross-sections. Indeed for the energy range of the ESSnuSB beam there are no or poor cross-section data [7]. The second phase of the design of ESSnuSB (ESSnuSB+, 2023-2026) is now in progress. This new project has the purpose to precisely measure the neutrino and antineutrino cross sections with water, as well as to further expand the physics potential of ESSnuSB. Fig. 3 shows the two new facilities being designed to provide well defined neutrino beams, a Low Energy Monitored Neutrino Beam (LENMB) facility and a Low Energy neutrino beam from Stored Muons (LEnuSTORM) facility.

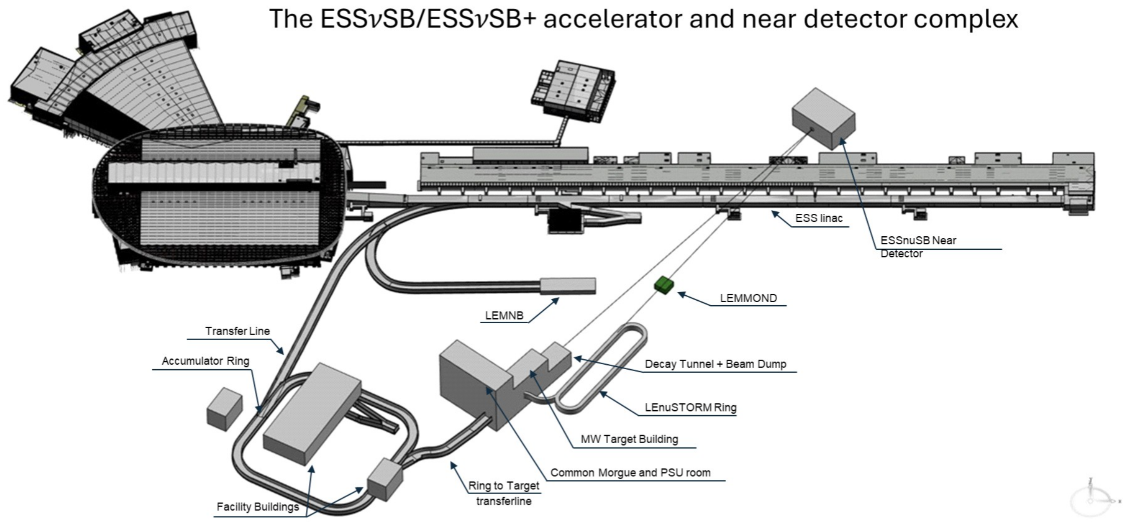

Figure 3: *The layout of ESSnuSB and the additions of ESSnuSB+ at ESS.*

The LEMNB facility follows the design ideas of the ENUBET project [8]. It is based on the instrumentation of the decay tunnel, where the muons from the pion decays are tagged, obtaining nearly monochromatic muon neutrino or antineutrino fluxes. The pions will be produced by extracting 10% of the ESS proton beam and using a dedicated target, while an optimized system of dipole and quadrupole magnets will direct and momentum-select them.

The LenuSTORM facility includes the design of a new target station to generate pions which will feed a muon racetrack storage ring, such as the nuSTORM facility planned for CERN [9]. The decay of negative (positive) polarity muons in the straight sections of LEnuSTORM will provide clean equal amounts of muon neutrinos (antineutrinos) and electron antineutrinos (neutrinos).

These well-defined quality neutrino beams, produced by LEMNB and LenuSTORM facilities, will be used with the LEMMOND detector, a dedicated water Cherenkov detector, to precisely measure the low energy neutrino and antineutrino cross sections with water. LEMMOND, the new near-near detector added to the ESSnuSB detector suite, is a cylindrical water Cherenkov with about 5 m diameter and 10 m length. It will be situated 50 m away from the new neutrino beam facilities LEnuSTORM and LEMNB. Additionally, LEnuSTORM and the combination of the LEMMOND detector with the near detector complex of ESSnuSB constitute an excellent Short Base Line (SBL) setup able to investigate the existence of sterile neutrinos of mass square differences of 1 eV^2 to 10 eV^2. Preliminary performance studies for the reconstruction of muons or electrons in the (anti)neutrino Charged Current (CC) interactions, using Graph Neural Networks (GNN) methodology show promising results. Fig 4 displays the errors for the vertex position, the time of the interaction and the θ, φ angles for muons in the range of 200-600 MeV, using GNN.

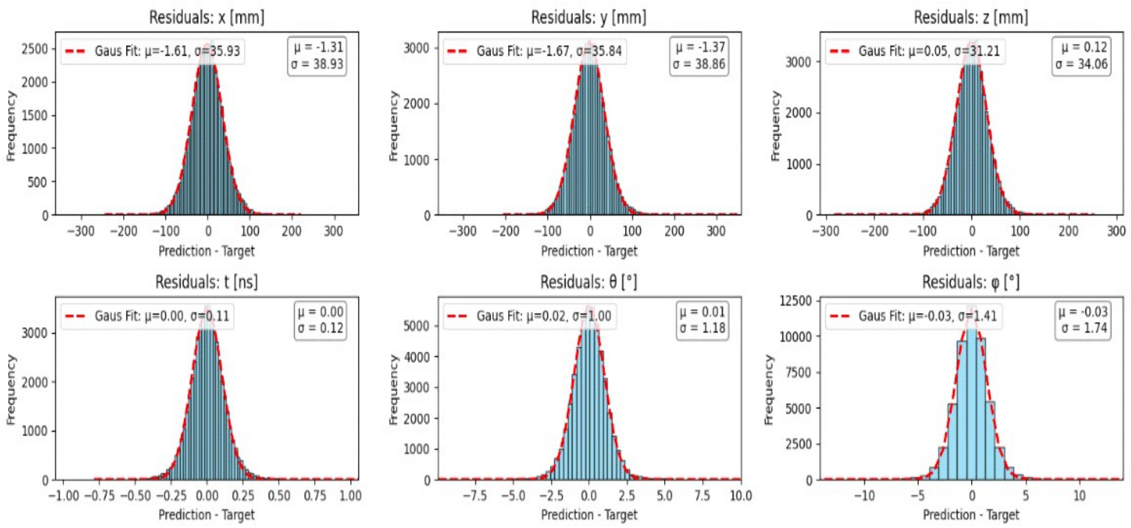

Figure 4: *Parameter prediction errors for muon tracks of 200-600 MeV using GNN.*

In addition to the use of the new infrastructure for neutrino cross section measurements and the added capability of the SBL setup for sterile neutrino investigations, further improvements for the detectors, the analysis techniques and more physics cases are being considered within the new project. The improvement of the detection capability of final state neutrons by the addition of Gadolinium in the water Cherenkov detectors is being evaluated. The use of Graphic Neural Networks to improve the event classification of the ESSnuSB near Water Cherenkov detector has been completed [10]. An example of the performance for electron neutrino and muon neutrino CC event selection is shown in Fig. 5. A Monte Carlo study of neutrino oscillations using atmospheric neutrinos in the far detector [11] showed encouraging results on the mass ordering, θ_{23} octant and Δm^2_{31} (see Fig. 6).

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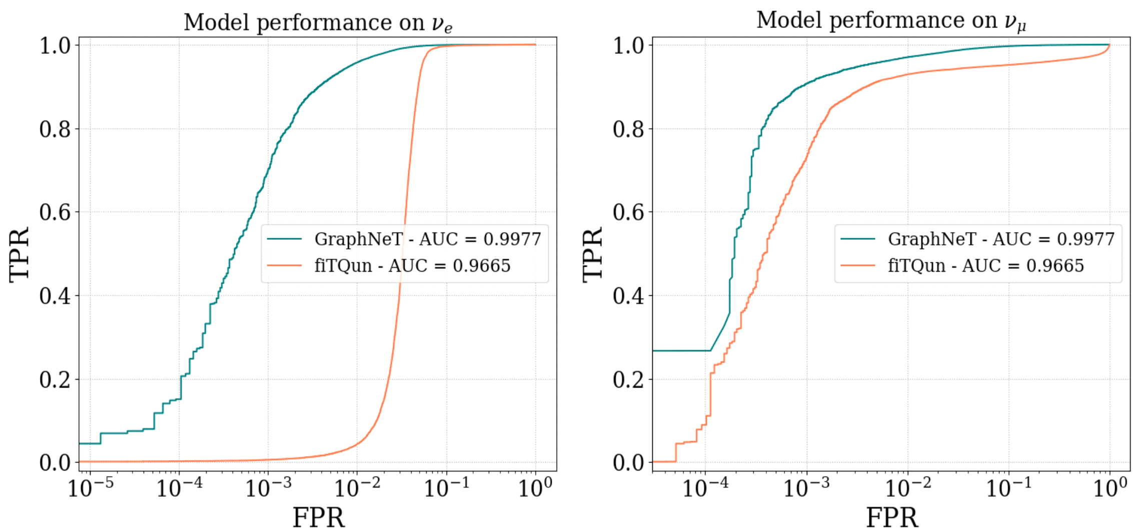

Figure 5: *TPR (True Positive Rate = efficiency) vs FPR (False Positive Rate = probability of labeling a background event as signal) for electron (left) and muon (right) neutrino CC events using the GraphNeT [12] GNN model as compared with the maximum likelihood based fiTQun [13].*

The sensitivity of ESSnuSB for Beyond the Standard Model (BSM) Physics is also being investigated within the new project. Results have been published for constraints on Scalar Non-Standard Interactions parameters [14], for constraints on Quantum Decoherence parameters [15] and for invisible neutrino decays [16]. The sensitivity for proton decay and cosmic neutrinos measurements is also being evaluated.

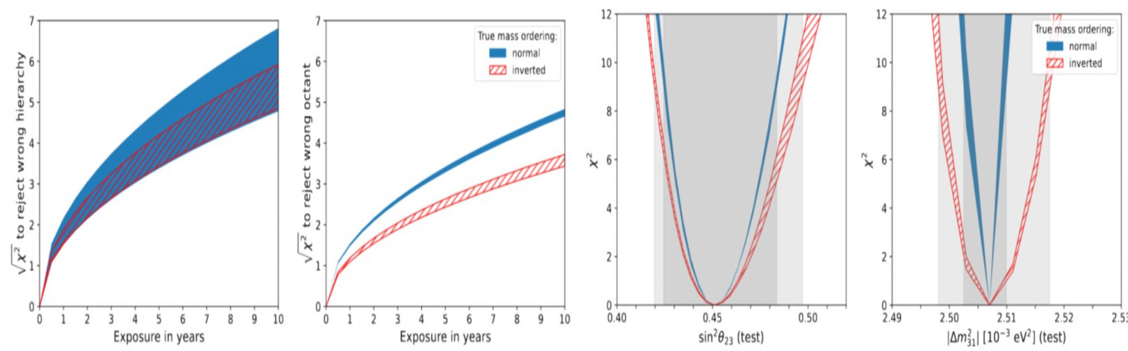

Figure 6: *Results on the hierarchy, θ_{23} octant, $\sin^2\theta_{23}$ and $\Delta m^2{}_{31}$ estimations using ESSnuSB far detector Monte Carlo data.*

3. Conclusions

ESSnuSB and ESSnuSB+ are the two phases of a next-to-next generation neutrino oscillation facility proposed which includes a) the precision measurement of the CP Violating phase with a long base-line neutrino setup including a near detector suite, made of a water Cherenkov detector, a super fine grained scintillator detector and an emulsion detector, and an underground far water Cherenkov detector at a distance of 360 Km, b) the design and construction of novel facilities, including a LEnuSTORM (Low Energy neutrinos from stored muons) ring, a LENMB (Low Energy neutrino monitored beam) instrumented neutrino tunnel and LEMMOND, a near-near water Cherenkov detector, to precisely measure low energy neutrino (200 MeV – 600 MeV) cross sections and c) investigate the existence of sterile neutrinos by employing a short base-line setup. More physics capabilities are also being evaluated during the second phase of the ESSnuSB project, such as, atmospheric neutrino oscillations, BSM physics, proton decay and cosmic neutrino physics.

Acknowledgments

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