PROCEEDINGS OF SCIENCE

A long baseline neutrino project in Europe: the ESSnuSB project

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Abstract

ESSnuSB (the European Spallation neutrino Super Beam) is a design study for a long-baseline neutrino experiment to precisely measure the CP violation in the leptonic sector, at the second neutrino oscillation maximum, using a beam driven by the uniquely powerful ESS linear accelerator. The ESSnuSB CDR showed that after 10 years, about 72% of the possible CP-violating phase, δ_{CP}, range will be covered with 5σ C.L. to reject the no-CP-violation hypothesis. The expected precision for δ_{CP} is better than 8° for all δ_{CP} values, making it the most precise proposed experiment in the field. The extension project, ESSnuSB+, 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. A new water Cherenkov detector will also be designed to measure cross sections and serve to explore the sterile neutrino case.

The 43rd International Symposium on Physics in Collision (PIC2024)
22–25 October 2024
Athens, Greece

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ISSN 1824-8039 . Published by SISSA Medialab.

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1. Introduction

The next generation long base line (LBL) neutrino experiments [1], currently in preparation, are mainly designed to resolve the question of neutrino mass ordering, to determine the quadrant of the atmospheric mixing angle θ_{23} via precision measurements and to prove the existence of CP violation (CPV). However, their precision in measuring the CP violating phase angle is not sufficient to resolve the theoretical models proposed to explain the lack of antimatter in the Universe [2,3]. ESSnuSB is a next-to-next generation experiment under design, with the main purpose of measuring the CPV phase angle to such high precision as to enable the selection of the correct theory.

The probability of neutrino oscillations in vacuum is given by [4]:

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{I<j} Re(U_{\alpha i}U^*_{\beta i}U^*_{\alpha j}U_{\beta j})X_{ij} \pm 2\sum_{I<j} Im(U_{\alpha i}U^*_{\beta i}U^*_{\alpha j}U_{\beta j})X'_{ij} \qquad (1)$$

where $X_{ij}=\sin^2\Delta(m^2_{ij}L/4E)$, $X'_{ij}=\sin\Delta(m^2_{ij}L/2E)$, U_{aj} are the elements of the PMNS [5] matrix, the plus sign is for neutrino oscillations while the minus sign is for antineutrino oscillations, E is the energy of the neutrino or antineutrino, L is the distance between the near and far detectors and $\Delta m^2_{ij}=m^2_i-m^2_j$ is the splitting between the square masses of ν_i and ν_j.

The determination of the CP violating phase angle relies on the measurement of the neutrino-antineutrino (matter-antimatter) asymmetry A, which in the case of ESSnuSB is:

$$A_{CPV}=\frac{P(\nu_\mu\to\nu_e)-P(\bar{\nu}_\mu\to\bar{\nu}_e)}{P(\nu_\mu\to\nu_e)+P(\bar{\nu}_\mu\to\bar{\nu}_e)} \qquad (2)$$

The equation (1) is modified by matter effects, in the case of neutrinos traveling through matter (the case in all LBL neutrino experiments). The matter effects are not important for ESSnuSB because the neutrino energy spectrum is partly on the second oscillation maximum (see next section).

2. The ESSnuSB project

ESSnuSB proposes modifications to the European Spallation Source (ESS) proton linear accelerator (linac), designed for 2 GeV proton kinetic energy and 5 MW power, aiming to create an intense neutrino beam, of energies from 200 MeV/v to 600 MeV/c, and to design a long baseline neutrino experiment tuned to measure the CPV angle to high precision. The Conceptual Design Report (CDR) of this study has been completed and published in 2022 [6]. The study intends to establish a parallel experimental facility at ESS, without interfering with ESS's main mission. The proton linac power is proposed to be doubled so to provide equal power for the neutron and neutrino programs. The neutrino program needs the proton pulses to be shortened from 2.86 ms to 1.2 μs. This is accomplished by an accumulator which also requires that the linac accelerates H^- instead of protons. A target station is designed with four targets and four horns to handle the high-power proton beam. A long baseline setup is proposed for the neutrino oscillation studies: A far water Cherenkov detector consisting of two tanks of 270 ktons each,

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placed in Sweden's Zinkgruvan mine, 360 km away, at a depth of about 1 Km, and a Near Detector complex, at ESS, consisting of a water Cherenkov, a super fine-grained scintillator detector [7] and a NINJA-like [8] emulsion detector (see Fig. 1).

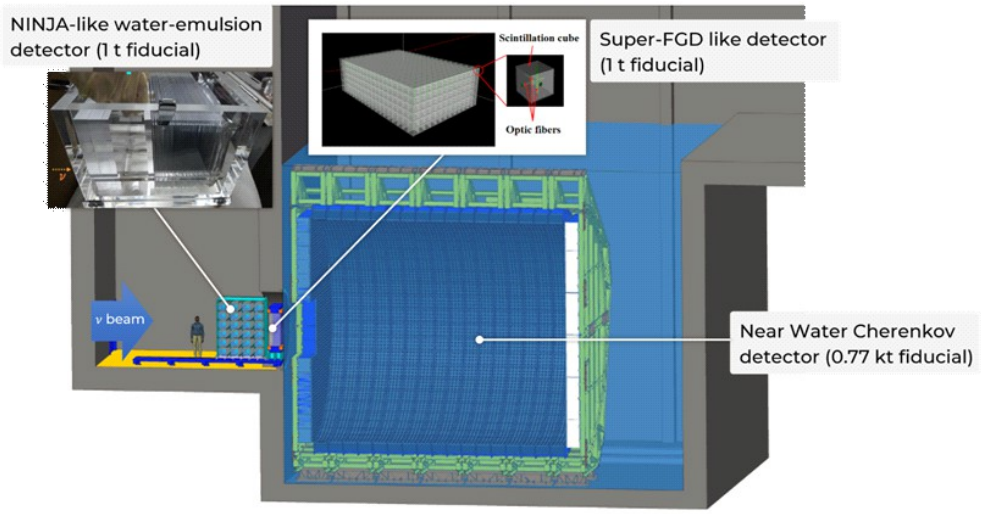

Figure 1: The Near Detector complex of ESSnuSB.

The Physics reach of ESSnuSB covers the measurement of the neutrino oscillation parameters, especially focusing on the precision measurement of the CPV phase. Its ability to obtain a high precision is because a large part of the ESSnuSB neutrino spectrum is sitting at the second oscillation maximum and as a consequence: a) It makes the matter-antimatter asymmetry A_{CPV} about 2.5 times larger than for the case of spectra at the first maximum [9] due to a larger interference term, a fact which also makes the measurement of the CPV more stable against systematical errors, and b) the matter effects of neutrino interactions on their way to the far detector are much smaller at the second maximum, diminishing the danger of faking CPV as when working in the first maximum [10].

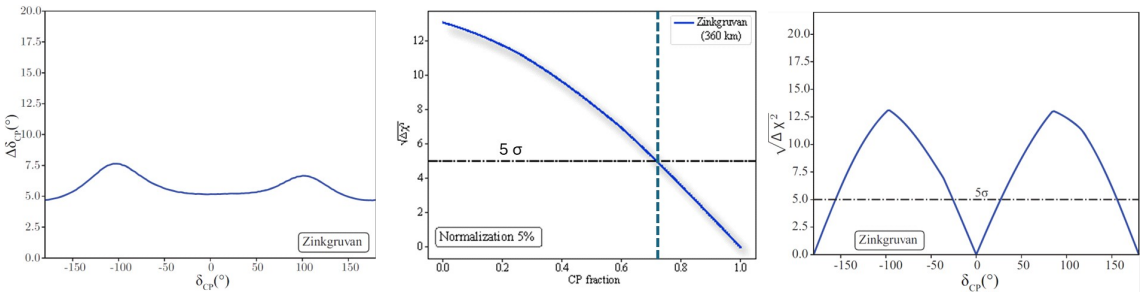

Figure 2: (Left panel) Discovery sensitivity of the leptonic CPV as a function of δCP range. (Middle) The fraction of the covered δCP range for which CPV can be discovered as a function of the significance. (Right) The precision on δCP value as a function of the δCP range.

The main physics results obtained from this study are 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 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

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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.

3. The ESSnuSB+ project

After the successful completion of the ESSnuSB design study, we have proposed the ESSnuSB+ project [11]. Its purpose is to extend the Instrumentation of ESSnuSB, by adding two more neutrino beam devices and a near-near detector for precise low energy neutrino cross section measurements, as well as to expand and improve the Physics potential of ESSnuSB. The precise knowledge of the neutrino cross sections for the ESSnuSB neutrino beam spectrum is necessary to reduce the systematics of the measurements of the neutrino oscillation parameters. The new project is funded by the European commission Horizon-Europe program for the period 2023–2026. The layout of the ESSnuSB/ESSnuSB+ project is seen in Fig. 3.

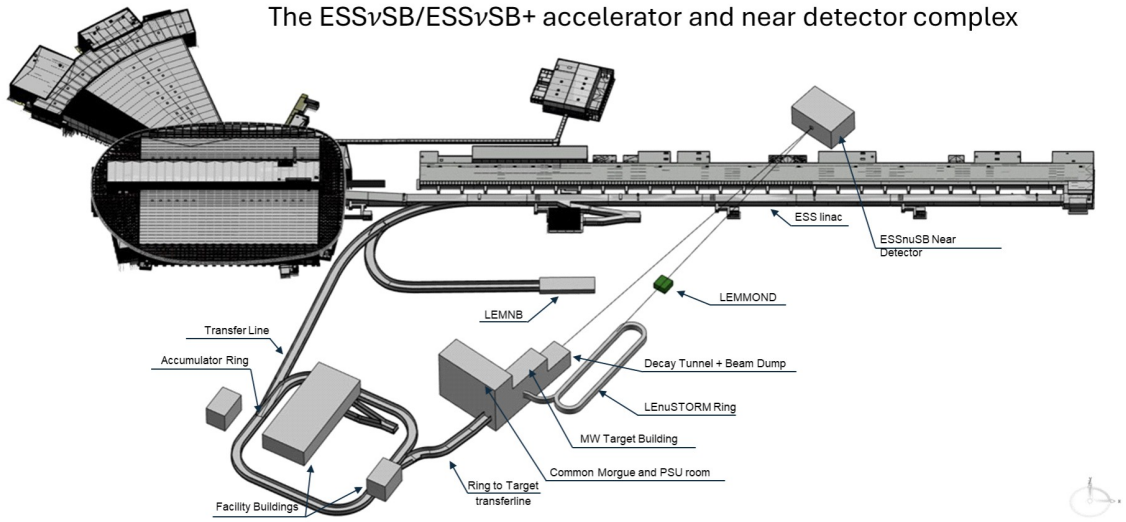

Figure 3: The layout of ESSnuSB and the additions of ESSnuSB+ at ESS.

The design of a new target station is foreseen, for the new project, to generate pions which will feed a Low Energy nuSTORM (LEnuSTORM), i.e. a muon racetrack storage ring, like the nuSTORM facility planned for CERN [12], and a Low Energy Monitored neutrino beam (LEMNB) decay tunnel inspired by the ENUBET project [13]. Both facilities will constitute the first phase of staging ESSnuSB, the main long baseline experiment, a phase which will involve the precision neutrino cross section measurements with a new under design near-near detector, the Low Energy neutrino from stored Muons and Monitored beam Near Detector (LEMMOND). 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). LEMNB will also provide clean neutrino and antineutrino beams by tagging the muons from pion decays. These well-defined quality neutrino beams will be used with the LEMMOND detector, to precisely measure low energy neutrino 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

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away from the new neutrino 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.

In addition to the use of the new infrastructure for neutrino cross section measurements and the added capability 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 for the event classification the the Cherenkov detectors is being investigated. A Monte Carlo study of neutrino oscillations using atmospheric neutrinos in the far detector [14] showed interesting results on the mass ordering, θ_{23} and Δm^2_{31}.

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 [15], for constraints on Quantum Decoherence parameters [16] and for invisible neutrino decays [17]. The sensitivity for proton decay and cosmic neutrinos measurements is also being evaluated.

4. 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, 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 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 with a short base-line setup. More Physics capabilities are being evaluated during the second phase of the ESSnuSB project, such as BSM physics, proton decay and cosmic neutrino physics.

Acknowledgements

This work is funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them. We acknowledge further support provided by the following research funding agencies: Centre National de la Recherche Scientifique, France; Deutsche Forschungsgemeinschaft, Projektnummer 423761110 and the Excellence Strategy of the Federal Government and the Länder, Germany; Ministry of Science and Education of Republic of Croatia grant No. KK.01.1.1.01.0001; the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska -Curie grant agreement No 860881-HIDDeN; the European Union NextGenerationEU, through the National Recovery and Resilience Plan of the Republic of Bulgaria, project No. BG-RRP-2.004-0008-C01.

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