Search for Leptonic CP Violation with the ESSnuSBplus Project

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Abstract

ESSνSB is a design study for a next-generation long-baseline neutrino experiment that aims at the precise measurement of the CP-violating phase, $\delta_{\rm CP}$, in the leptonic sector at the second oscillation maximum. The conceptual design report published from the first phase of the project showed that after 10 years of data taking, more than 70% of the possible $\delta_{\rm CP}$ range will be covered with 5σ C.L. to reject the no-CP-violation hypothesis. The expected value of $\delta_{\rm CP}$ precision is smaller than 8° for all $\delta_{\rm CP}$ values. The next phase of the project, the ESSνSB+, aims at using the intense muon flux produced together with neutrinos to measure the neutrino-nucleus cross-section, the dominant term of the systematic uncertainty, in the energy range of 0.2–0.6 GeV, using a Low Energy neutrinos from STORed Muons (LEnuSTORM) and a Low Energy Monitored Neutrino Beam (LEMNB) facilities.

Keywords: CP-violation, long-baseline, neutrino oscillations, ESS
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1. INTRODUCTION

Based on the tiny differences in how matter and antimatter behave at the scale of elementary particles, this soon after the Big Bang, after annihilation, led to a universe dominated by matter. In order for any theory to explain this observed baryon asymmetry of the universe, three conditions, known as Sakharov conditions [1], must be fulfilled: Baryon number violation, C and CP-violation (CPV) and interactions out of thermal equilibrium. The CPV has been already discovered in the hadron sector in 1964, in the neutral kaon decay [2]. However, the measured matter/antimatter asymmetry is ca. 9 orders of magnitude larger than what can be explained by the quark CPV. Several leptogenesis models predicts that the CPV necessary for the generation of the baryon asymmetry is driven exclusively by the CP-violating phase in the PMNS leptonic mixing matrix, δ_{CP}, and thus is directly related to the CPV at the electroweak scale in the leptonic sector (e.g., in neutrino (ν-)oscillations) [3, 4, 5, 6]. While, CPV has not been confirmed yet in the lepton sector [7], the value of δ_{CP} must be measured with the highest possible precision in order to verify or falsify the proposed leptogenesis models and the various lepton flavors models, whose predictions overall cover a rather broad range of δ_{CP} values. The current generation of ν-oscillation experiments [8, 9, 10] will determine the values of the three mixing-angle and the two mass-splitting parameters of the PMNS matrix with high precision. However, neither of these experiments can reach the confidence level required to claim the CPV discovery.

The measurement of the unexpectedly high value of the third neutrino mixing angle, θ_{13}, by the reactor neutrino experiments [11, 12] opened the possibility of discovering δ_{CP} with intense "super", i.e., with beam power larger than 1 MW, neutrino beam experiments. The next generation long-baseline experiments: the Deep Underground Neutrino Experiment (DUNE) in the USA [13], the Tokai to Hyper-Kamiokande (T2HK) in Japan [14], and the next-to-next generation: the European Spallation Source neutrino Super Beam (ESSνSB) in Europe [15], will use these intense neutrino beams at a Mega-Watt scale power for their measurements. While the design of the T2HK experiment aims for measurement at the first oscillation maximum and that of DUNE will allow it to explore a wide-band beam that fully covers the region of the first maxima and part of the second [16, 17], the ESSνSB will be measuring at the second oscillation maximum.

2. THE EUROPEAN SPALLATION SOURCE NEUTRINO SUPER BEAM

ESSνSB is a European scientific collaboration, gathering 21 institutes and universities, including CERN and ESS, from 11 EU countries. The first phase of the project was financed through the Horizon 2020 program for a design study and was concluded in March 2022. This phase demonstrated the ability of the use of the European Spallation Source (ESS) linac [18] to produce an intense neutrino beam. Several upgrades to the ESS facility will need to be applied in order to be able to host the neutrino facility. The pulse frequency of the ESS linac (the proton driver) will be increased from 14 Hz to 28 Hz to obtain additional acceleration cycles that will be used for neutrino production, without affecting the neutron program. An accumulator ring will be built to shorten the ESS pulse to about 1.2 μs. A neutrino production target station, composed of four identical targets enveloped by four magnetic focusing devices (horns), will be built. The horns will be used to charge select and focus the pions, and thus also the neutrinos resulting from their decay, toward the near and far detectors. A near detector will be used to monitor the neutrino beam and to measure neutrino interaction cross-sections, especially electron neutrino cross-sections, at a short baseline (250 m) from the neutrino source, while the far detector will be used to detect the oscillated neutrino beam at the long baseline 360 km. The results obtained from this design study were published in a comprehensive Conceptual Design Report (CDR) [19]. Two baselines were proposed for the location of the far detector: 360 km, which covers the second and part of the first oscillation maximum, and 540 km, which covers the second oscillation maximum only. The main physics results obtained from this study are shown in Figure 1 and concluded that the 360 km baseline offers better physics performance of the detector compared to that at 540 km. Therefore, the Zinkgruvan site at 360 km has been chosen to be the default baseline of the ESSνSB experiment, while the Garpenberg site, at 540 km, is chosen to be an alternative option. The left plot of Figure 1 shows the experiment's sensitivity for CP-violation discovery as a function of δ_{CP} range of true values. It shows that at the maximal violation, i.e., $\delta_{CP} \sim \pm 90^\circ$, the CPV discovery sensitivity reaches ca. 12σ for the default baseline of 360 km. The middle plot shows that ESSνSB will cover more than 70% of the range of the true δ_{CP} values with a confidence level of more than 5σ to reject the no-CPV hypothesis, after ca. 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° for the whole δ_{CP} range.

3. THE EUROPEAN SPALLATION SOURCE NEUTRINO SUPER BEAM PLUS

The ESSνSB experiment is foreseen to be implemented in a staged approach. The ESSνSB+ [20] is considered as the second phase design study of the ESSνSB program; however, it is supposed to be commissioned before the four-horn system target station. This phase is funded by the European commission Horizon-Europe programme for the period 2023–2026. The physics motivation of this phase comes from the fact that the data on neutrino interactions with matter at the low neutrino energy regime of the ESSνSB, i.e., with peak energies between 200 and 300 MeV and a flux dying of very quickly above 600 MeV, is scarce for neutrinos and almost nonexistent in the antineutrino case [21]. On the other hand, from the point of view of the nuclear response, this energy difference with other experiments is highly relevant and the influence of nuclear correlations on cross sections at these lower energies can be expected to be significantly different. The uncertainty on the neutrino-nucleus interaction cross-section in the water of the water-Cherenkov far detector of the ESSνSB will be limited foremost by systematic, rather than statistical, errors. There-

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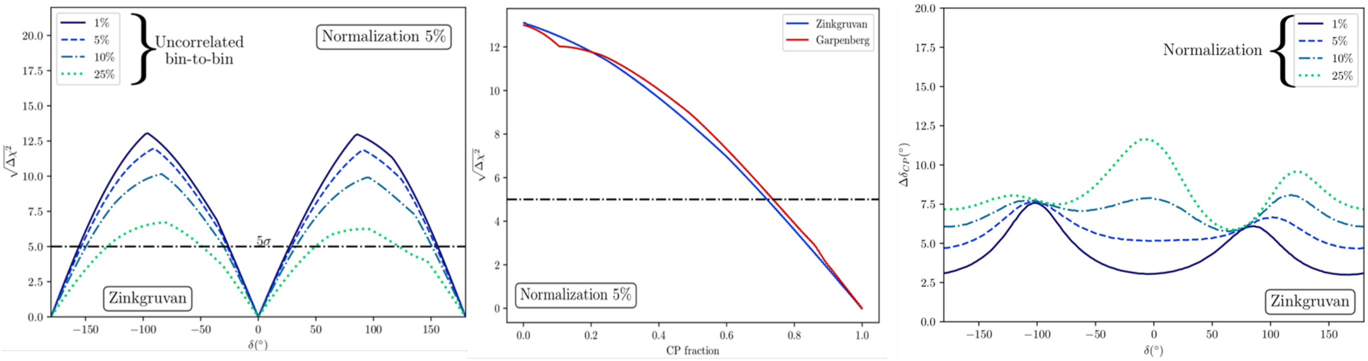

FIGURE 1: (Left) Discovery sensitivity of the leptonic CPV of the ESSνSB experiment as a function of $\delta_{\rm CP}$ range at the 360 km baseline, with different assumptions for the systematic uncertainty. (Middle) The fraction of the covered $\delta_{\rm CP}$ range for which CPV can be discovered as a function of the significance at the main baselines, the 360 km, and at the alternative baseline, the 540 km. (Right) The precision on $\delta_{\rm CP}$ value as a function of the $\delta_{\rm CP}$ range at the 360 km baseline option with different assumptions for the systematic uncertainty.

fore, it is crucial to measure the neutrino-nucleus cross section in the low energy range of the ESSνSB as precisely as possible for a precise determination of $\delta_{\rm CP}$ value. The ESSνSB+ aims at addressing the challenging task of measuring the neutrino-nucleus cross-section using a special target station, a Low Energy nuSTORM [22] (LEnuSTORM), and an ENUBET-like [23] Low Energy Monitored Neutrino Beam (LEMNB) facilities.

Figure 2 shows a layout of the ESS site with proposed positions of the LEnuSTORM racetrack ring, the LEMNB, the near detector complex and the dedicated target stations.

3.1. *The Target Station*

The ESSνSB+ target station will follow the design concept developed for the ESSνSB target station. While this latter consists of four target-horn assemblies with each assembly receiving 1.25 MW proton beam power, to make a total beam power on all targets equal to 5 MW, the ESSνSB+ target station will adopt a single target-horn system and will be designed for 1.25 MW proton beam power. The new target will adopt the packed bed concept composed of titanium spheres cooled by helium flow as the startup design of the ESSνSB+ target station. The pions produced in the secondary hadron beam will be extracted and directed toward the LEnuSTORM decay ring and/or the LEMNB decay tunnel.

To design the pion extraction, deflection, and focusing system, the target station will be equipped with magnetic systems, downstream of the target-horn assembly, which will rely on the use of conventional dipoles, which will bend the beam in horizontal and/or vertical planes. Moreover, sets of components for magnetic focusing, quadruples, placed upstream of- or downstream of- the extraction system will guide the extracted pion beam so that its transverse envelope is kept to a minimum as it propagates through the beam transport line. To obtain a well-focused dense flux of the pion beam, the horn geometry and/or structure will be optimized. The optimized horn geometry plays a crucial role in the design of the dipole which would then deflect the beam to the LEnuSTORM ring and the LEMNB tunnel.

3.2. *The Low Energy nuSTORM (LEnuSTORM)*

As discussed in the previous section, the secondary pion beam will be deflected toward the LEnuSTORM. The pions will then enter a "racetrack" muon storage ring via a transfer-line at the end of the extraction system, where they will decay, in the straight section of the LEnuSTORM ring, to muons. A bend at the end of the straight section will be designed to kinematically select muons to keep them in the ring, while the undecayed pions will be dumped into a beam dump. The muons circulating in the ring will then decay to neutrinos via $\mu^+ \to e^+ + \nu_e + \overline{\nu}_\mu$ (or its charged conjugate version for the π^-/μ^- mode). The LEnuSTORM ring will be designed to deliver a well-defined equal amount of muon- and electron-neutrino beams, which will be used for the cross-section measurements and for the sterile neutrino searches. It is worth noting that an additional source of muon-neutrinos will come from the pions that decay in the first straight section of the ring, through the process $\pi^+ \to \mu^+ + \nu_\mu$ (or its charged conjugate version for π^- mode of operation). These muon-neutrinos are of the opposite sign to those produced in the main LEnuSTORM beam. The preliminary physics simulations have shown that this contribution can be filtered out, if needed, in the analysis stage using timing information.

3.3. *The Low Energy Monitored Neutrino Beam (LEMNB)*

The LEMNB working principle depends on tagging (monitoring) the pions and muons associated with the neutrinos that have been produced in the decay of these mesons, in an instrumented decay tunnel. The decay tunnel walls will be instrumented by an iron-scintillator calorimeter, which will be used to reconstruct the energy and the direction of the charged muons from pion decays and electrons from the muon decays [15]. As the LEMNB technique favours long pulses to avoid pile-up, which is not accepted by the ESSνSB and LEnuSTORM, a bypass line between the accumulator ring and the LENMB tunnel will be added. This will require a static, rather than magnetic horn, focusing approach (since the horn will not be able to withstand long high-current pulses). The LEMNB and the LEnuSTORM will point their neutrino beam to the same near detector.

3.4. *The ESSνSB+ Detectors*

The ESSνSB near detector will be used as a far detector of LEnuSTORM. An additional detector, the Low Energy Neutrinos from Stored Muons and Monitored beam Detector (LEM-

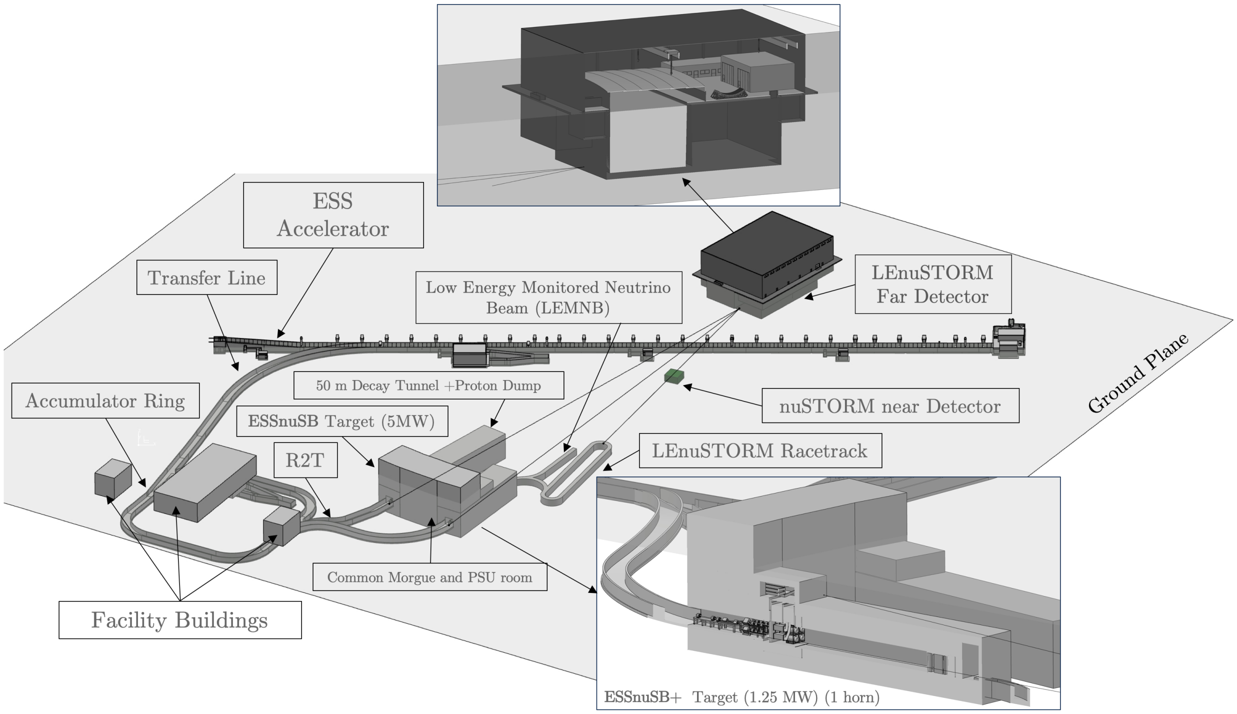

FIGURE 2: A CAD drawing of the conceptual layout of the ESS site with the proposed LEnuSTORM ring, the LEMNB, the near detector complex, and the target stations.

MOND), will be added to the experiment's detector complex. LEMMOND will be dedicated to obtaining a precise measurement of neutrino interaction cross sections on the water to be used in the ESSνSB experiment for the high-precision measurement of the CP violating phase. It will also serve as the near detector in the short baseline setup of the ESSνSB+ along with the near detectors complex of the ESSνSB long baseline project. It will be located downstream of the Low Energy Stored muons racetrack and the end of the decay tunnel of the Monitored Neutrino beam. It should be movable to be in the beam direction once each of the above facilities is operational.

4. CONCLUSION

The first phase of the ESSνSB design study has been successfully concluded, and a comprehensive conceptual design report has been published. The results reported in the CDR demonstrated the unprecedented physics potential of the experiment. The second phase of the ESSνSB program, ESSνSB+, has started and is focusing on including facilities for high precision neutrino cross-section measurements at low neutrino energy based on the build-up of a Low Energy Monitored Neutrino Beam and Low Energy nuSTORM as the first stages in the ESSnuSB programme. This phase will include a program dedicated to performing civil engineering conceptual studies and exploring the additional physics possibilities of the proposed infrastructure.

CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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