Input from
ESSnuSB (European Spallation Source neutrino Super Beam)
to the 2026 update of the European Strategy for Particle Physics

Corresponding authors: Marcos Dracos[1], Tord Ekelöf[2], George Fanourakis[3]
on behalf of the ESSnuSB Collaboration

Abstract

ESSnuSB (the European Spallation Source neutrino Super Beam) is a design study for a Long Baseline (LBL) 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 proton linear accelerator in Lund, Sweden, a near detector suite and two large underground water Cherenkov detectors of a total fiducial volume 540,000 m^3, located 360 Km north of Lund. The ESSnuSB Conceptual Design Report showed that after 10 years of running, 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 ESSnuSB collaboration is currently working on the extension project, the ESSnuSB+, which aims in designing two new facilities, a Low Energy nuSTORM and a Low Energy Monitored Neutrino Beam to be used 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 also serve to explore the sterile neutrino case in a Short Baseline (SBL) experiment. An overall status of the project is presented together with the ESSnuSB+ additions.

[1] IPHC, Université de Strasbourg, CNRS/IN2P3, Strasbourg, France. email: marcos.dracos@in2p3.fr
[2] Department of Physics and Astronomy, FREIA Division, Uppsala University, P.O. Box 516, 751 20 Uppsala, 33 Sweden. email: Tord.Ekelof@physics.uu.se
[3] Institute of Nuclear and Particle Physics, NCSR Demokritos, Neapoleos 27, 15341 Agia Paraskevi, Greece. email: gfan@inp.demokritos.gr

1 Context

1.1 The new possibility to discover and measure with high precision CP violation in the lepton sector.

The discovery in 1998 of neutrino flavour oscillations opened the possibility that there be CP violation in the lepton sector and that this CP violation could be discovered and measured through precision measurements of the oscillations' parameters. At low energies, the potentially most sensitive to CP violation oscillation is that between ν_μ and ν_e. The oscillation probability is approximately equal to the sum of three terms, the atmospheric, the solar and the interference term, see Fig. 1[4]. The observation of a CP violating signal requires the interference term to be of measurable magnitude.

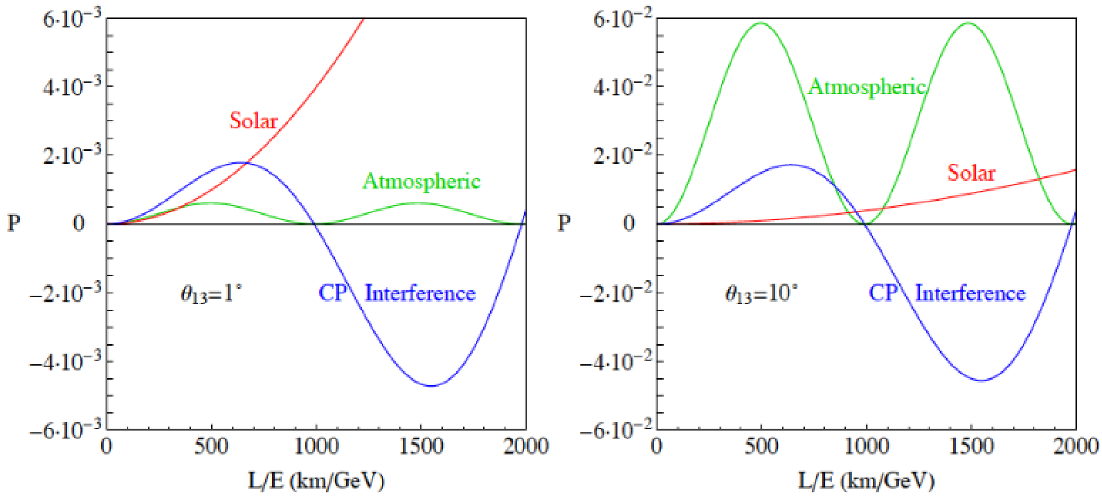

Figure 1: *Solar, atmospheric and interference terms of the $\nu_\mu \rightarrow \nu_e$ in vacuum as function of L/E for a small (left) and a large (right) ϑ_{13} value.*

The atmospheric term increases with the angle θ_{13} while the solar term increases with L/E, where L is the distance between the creation point of neutrinos and the detector and E the neutrino energy. In order to maximize the interference term, and thus the CP violation signal, these two terms should be of similar magnitude. Before 2012 the value of θ_{13} had not been measured but it was thought to be very small, implying that to have the two terms of similar magnitude, the L/E ratio should be approximately 500 km/GeV, corresponding to the position of the first oscillation maximum, as illustrated in the left plot of Fig. 1.

An optimization, under the new paradigm of a large θ_{13} value, is crucial in order to obtain the interference term as high as possible, thereby reducing the effect of the systematic uncertainties of the other two terms. The ESSνSB (or ESSnuSB) design study setup for a Long Baseline (LBL) experiment already incorporates this novel feature: the 360 km baseline and the 200-600 MeV neutrino energy range of the ESSnuSB neutrino flux implies L/E values in the range of 1800-600 km/GeV covering both the first and the second oscillation maxima, with considerable flux in the second oscillation maximum. Moreover, the asymmetry between the neutrino and anti-neutrino appearance probability at the second oscillation maximum is of the order of $0.75\sin\delta_{CP}$[5] while on the first oscillation maximum is only $0.30\sin\delta_{CP}$. For these reasons and considering the limitations imposed by systematic errors, the ESSnuSB setup provides, as confirmed by Monte Carlo simulations, a better sensitivity to CP violation by a factor of at least 2.5 than similar setups which were designed before 2012 to have their neutrino detector placed at the first oscillation maximum and which have not been able to re-optimize their experimental design subsequent to the discovery of the large value of θ_{13}.

The future experiments Hyper-K and DUNE, proposed already before 2012, were designed under the assumption of a very small value of θ_{13}, for which case there would not be enough statistics at the second oscillation maximum. For the

[4]Optimization of neutrino oscillation facilities for large θ_{13}, P. Coloma, E. Fernandez-Martinez, JHEP 1204 (2012) 089, DOI: 10.1007/JHEP04(2012)089, e-Print: arXiv:1110.4583 [hep-ph]

[5] Neutrinos: Theory and Phenomenology, S. Parke, Phys.Scripta T158 (2013) 014013, FERMILAB-CONF-13-453-T, DOI: 10.1088/0031-8949/2013/T158/014013

now known larger value of θ_{13}, the situation has changed and additionally there is a relative CP violation signal 2.5 times larger at the second maximum as compared to that at the first maximum (see above). This now implies, for equal performance at the first and the second oscillation maximum, the requirement for the systematic errors is reduced by a factor of 2.5 when measuring at the first maximum as compared to the second. It also implies that, in order to keep the statistical errors on a level comparable to the systematic errors, a very intense neutrino beam is needed for the measurement at the three times more distant second oscillation maximum. With ESSνSB this requirement is satisfied using what is to become the world's most powerful proton accelerator, the European Spallation Source linac[6].

1.2 The precision of the CP violation angle measurement of the three proposed future Long Baseline experiments

The ESSnuSB study (2018-2022) for the design of a Research Infrastructure within the ESS ERIC, capable of measuring the δ_{CP} angle with very high precision, produced a Conceptual Design Report (CDR) [7], where the creation of the neutrino super-beam and the physics capabilities of the detector suite proposed are described in detail.

Fig. 2 shows the physics performance of the three different proposed Long Baseline neutrino experiments **assuming the same level of systematic errors of about 5% and 10 years of data taking for all three in order to make a comparison on an equal footing**. The plots show the resolution in the measurement of δ_{CP} versus the true value of δ_{CP}. They clearly demonstrate that ESSνSB has a much better resolution in the measurement of the CP violating angle δ_{CP} than the other two experiments.

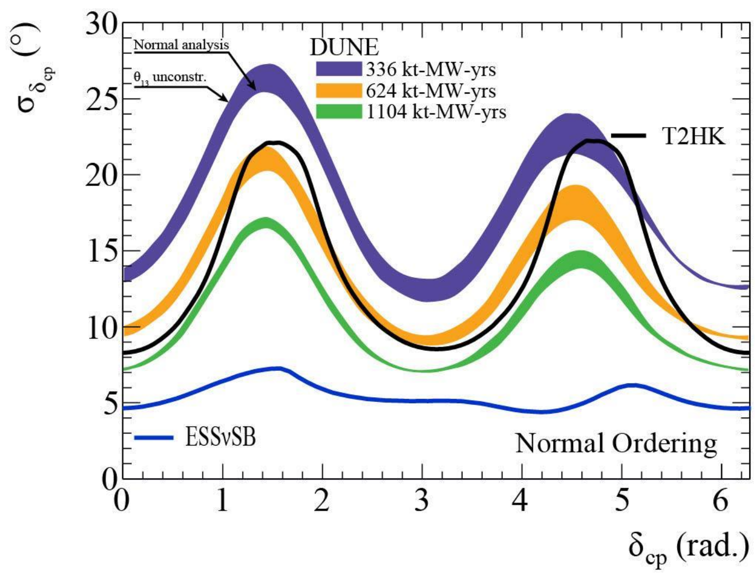

***Figure 2**. Resolution of the CP violating angle, $\Delta\delta_{CP}$, vs δ_{CP} for the ESSnuSB design as compared to the two under construction experiments DUNE in the United States (https://arxiv.org/abs/2002.03005 p. 174) and HyperK in Japan (https://arxiv.org/abs/1611.06118 p. 60).*

For the determination of the mass hierarchy, a 3 σ significance is reached by ESSνSB for nearly all δ_{CP} values. This performance can be brought to the level of more than 5 σ for all δ_{CP} values by including in the results of the detection of atmospheric neutrinos[8], which will also be copiously recorded by a Far detector of the MEMPHYS-type[9] (this possibility was studied by the LAGUNA collaboration). However, it is very likely that this measurement will be done during the coming 10 years by other experiments , e.g., JUNO and PINGU/ORCA[10], before the next generation of long baseline neutrino experiments, including ESSνSB, will start taking data.

1.3 The ESSnuSB Research Infrastructure program (2018-2022)

The ESSnuSB project proposes modifications to the 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 60 MeV to 600 MeV, and to design a long baseline neutrino experiment tuned to measure the CPV angle to high precision. The Conceptual Design Report of this study has been completed and published in 2022. The study intends to establish a parallel experimental facility at ESS, without interfering with ESS's original mission to produce the world's largest pulsed flux of spallation

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[6] The European Spallation Source, http://europeanspallationsource.se/, *ESS Technical Design Report*, Release 1.0, Nov. 2012.

[7] A. Alekou et al., *The European Spallation Source neutrino super-beam conceptual design report.* Eur. Phys. *J. ST 2022,* **231**, 3779–3955, [arXiv:hep-ex/2206.01208]. https://doi.org/10.1140/epjs/s11734-022-00664-w.

[8] Physics potential of the ESSνSB, Eur. Phys. J. C (2020) 80:190, https://doi.org/10.1140/epjc/s10052-020-7761-9.

[9] "MEMPHYS: A Large scale water Cerenkov detector at Frejus", hep-ex/0607026.

[10] *Quantifying the sensitivity of oscillation experiments to the neutrino mass ordering*, M. Blennow, P. Coloma, P. Huber, T. Schwetz, Nov 7, 2013, JHEP 1403 (2014) 028, e-Print: arXiv:1311.1822 [hep-ph].

neutrons. The proton linac power is proposed to be doubled and so 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 the use of an accumulator ring which also requires that the linac accelerates H^- together with protons. A target station is designed to produce the neutrino intense beam 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 placed in Sweden's Zinkgruvan mine, 360 km away, at ~ 1 km depth, and a Near Detector complex, at ESS, consisting of a water Cherenkov, a super fine-grained scintillator detector and an emulsion detector.

1.4 The continuation of the ESSnuSB studies within the ESSnuSB+ program (2023-2026)

After the successful completion of the ESSnuSB design study, we proposed the ESSnuSB+ project[11]. Its purpose is to extend the Instrumentation of ESSnuSB, by adding two more neutrino beam facilities 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 Horizon-Europe program for the period 2023–2026. The layout of the ESSnuSB/ESSnuSB+ project is seen in Fig. 3.

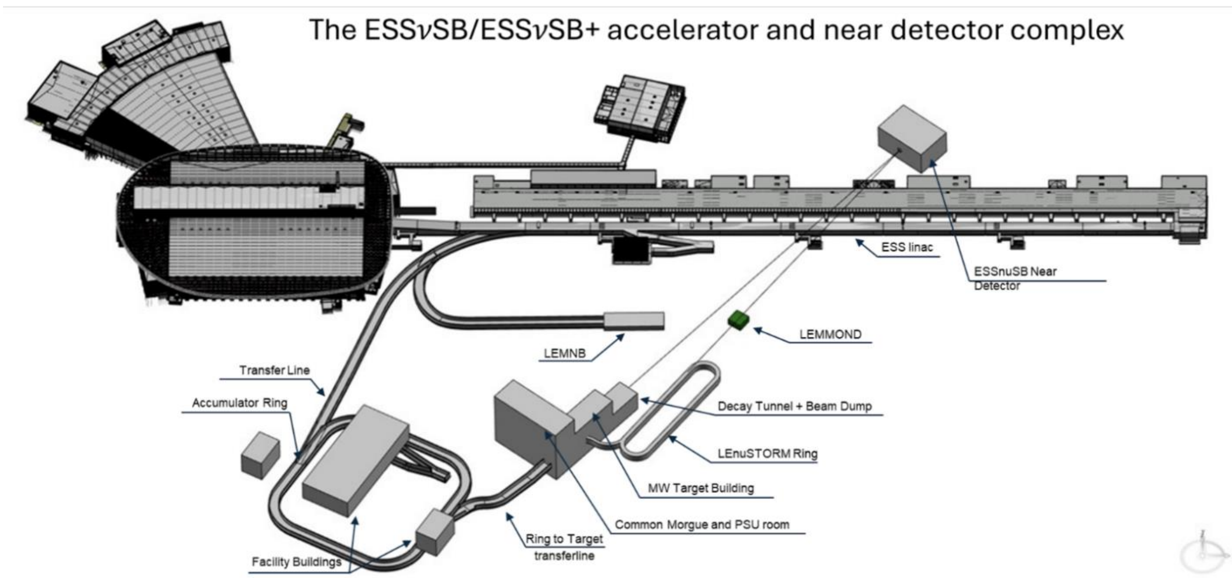

Figure 3: *The layout of the ESS linac and the ESSnuSB complex with the additions of ESSnuSB+ at ESS.*

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, similar to 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 near-near detector, currently under design, 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 200-ton cylindrical water Cherenkov. It will be situated 50 m away from the new neutrino facilities LEnuSTORM and LEMNB.

[11] Search for Leptonic CP Violation with the ESSnuSBplus Project. *LHEP*-**517**, 202.

[12] Neutrinos from Stored Muons (nuSTORM). arXiv:2203.07545, in Proc. of the Snowmass 2021 (2022).

[13] Enhanced NeUtrino BEams from kaon Tagging (ENUBET). arXiv:2203.08319, in Proc. of the Snowmass 2021.

1.5 The ongoing construction of the ESS linac which is to become the world's most powerful proton accelerator

The ESS linac will have an average beam power of 5 MW, which is nearly an order of magnitude higher than any other currently operating proton accelerator in the world. It will deliver a beam of 2 GeV kinetic energy protons to a Tungsten target to produce neutron beams from spallation. ESS is currently well into its construction phase and expected to deliver first beams in 2025. It is a major European user facility where researchers from universities, national laboratories and industry from all over the world will investigate scientific questions relating to material science, molecular biology and other sciences and a broad spectrum of applications.

2 Objectives

2.1 The precision measurement of the CP violating angle δ_{CP} and its importance

The implications of the discovery and precise measurement of δ_{CP} are far reaching, leading to the inference that neutrino CP violation may in fact be the reason that a small residual fraction of matter survived the massive annihilation of the matter and antimatter created in the Big Bang, a residual that is what presently makes up the matter of the Universe. The neutrino may also have played a crucial role in the birth and evolution of the Universe itself, in view of its enormous abundance. An understanding of the contribution of neutrinos in these areas requires precise measurements of the parameters governing neutrino oscillations, in particular δ_{CP}.

A measurement of δ_{CP} could also imply the discovery of a completely new source of CP violation. The quark mixing matrix provides a consistent description of the quark CP violation amount observed so far, which can be encoded in the reduced Jarlskog invariant $J = (3.0 \pm 0.2)\cdot 10^{-5}$. This value has been shown to be far too small to account for the observed Baryon Asymmetry of the Universe (BAU). The recent measurement of θ_{13} indicates that the corresponding quantity in the neutrino sector J=0.3·sinδ_{CP} is potentially four orders of magnitude larger. A measurement of δ_{CP} could thus provide very illuminating information on the origin of the baryon asymmetry of the Universe.

2.2 The measurement of supernova neutrinos

The far detectors can also be used, simultaneously with neutrino beam operation, for astroparticle physics. In 1987, 12 neutrinos emitted from a supernova explosion in the Large Magellanic Cloud near our galaxy were detected by the Kamiokande detector. Such detection of the neutrinos emitted in supernova explosions help to understand the supernova explosion mechanism. With its over 500 kt large fiducial mass, the far detector complex will record about $5\text{x}10^4$ neutrinos from a supernova explosion at 10 kiloparsec distance in our galaxy which would provide very detailed and highly interesting information on the mechanism of the explosion.

There is a diffuse flux of neutrinos emitted from all the supernova explosions that have occurred in the universe. The measurement of this flux is important for the understanding of stellar birth and death, the production of chemical elements, neutron stars and black holes. Their diffuse neutrino energy spectrum is below 20 MeV and therefore difficult to detect. Adding Gadolinium to the water in the far detectors will increase the sensitivity to low energy electron anti-neutrinos by detecting the neutron from the inverse beta decays (anti_ν_e+p→n+e^+).

2.3 Search for proton decay

The far detectors can also be used, simultaneously with the neutrino detection, for proton lifetime measurements. Proton decay is not allowed by the SM. On the other hand, Grand Unified Theories (GUT) predict proton decay. Its discovery would once again reveal the existence of a more fundamental theory beyond the SM. The present lower limit of the half-life for the decay $p\rightarrow\pi^0e^+$ is $1.6\text{x}10^{34}$ years set by Super-Kamiokande[14] employing the same Water Cherenkov detector technique as ESSνSB is planning to use, but with a detector volume 20 times smaller than the ESSnuSB far detector complex. If the proton lifetime is below 10^{35} years, then proton decays would be observed after 10 years of data taking. If, on the other hand, no proton decays would be observed, this would impose a stringent limit on the GUT.

[14] *Search for nucleon decay into charged antilepton plus meson in Super-K*, H. Nishino et al., Phys. Rev. D 85, 112001 (2012).

2.4 Sterile neutrinos

The sensitivity to sterile neutrinos have been investigated for the ESSnuSB setup[15] assuming both a far detector (FD) and a near detector (ND) and the capability of ESSnuSB to constrain the sterile mixing parameters as well as the effect of light sterile neutrinos on the CP violation sensitivity.

Additionally, LEnuSTORM and the combination of the LEMMOND detector with the near detector complex of ESSnuSB constitute an excellent Short Baseline (SBL) setup able to investigate the existence of sterile neutrinos of mass square differences of 1 eV^2 to 10 eV^2.

2.5 Exploring the atmospheric neutrinos

A Monte Carlo study of neutrino oscillations using atmospheric neutrinos in the far detector[16] showed results on the mass ordering, θ_{23} and Δm^2_{31}. It is found that ESSnuSB is able to determine the correct neutrino mass ordering with 3σ CL after 4 years and with 5σ CL after 10 years of data taking when the value of δ_{CP} is not known, regardless of the mass ordering. It is also shown that ESSnuSB would be able to determine the θ_{23} octant at 3σ CL after 4 years if the neutrino mass ordering is normal ordering and 7 years if it is inverted ordering. The atmospheric neutrino data collected by the ESSnuSB far detectors could also provide individual constraints on the values of θ_{23} and Δm^2_{31}. The sensitivities derived are complementary to the beam-based Long Baseline neutrino oscillation program for ESSnuSB.

2.6 Physics beyond the Standard Model

The sensitivity of ESSnuSB for Beyond the Standard Model (BSM) Physics is also being investigated. Results have been published for constraints on scalar Non-Standard Interactions parameters[17], for constraints on Quantum Decoherence parameters[18] and for invisible neutrino decays[19].

3 Methodology

3.1 The ESS linac upgrade required to deliver a 10 MW beam

In order to achieve a sufficiently intense neutrino beam for measuring the appearance of a large enough number of electron neutrinos and antineutrinos at the second maximum, a proton beam of about 5 MW average power will be required. The ESS linac currently under construction will be used to accelerate protons to the energy of 2 GeV (to be later upgraded to 2.5 GeV) in 2.86 ms long 62.5 mA pulses at 14 Hz pulse frequency to be used for spallation neutron production. The low duty cycle of 4% of the ESS linac makes it possible to accelerate 14 additional pulses per second of H^- ions, interleaved with the proton pulses, to be used for the proposed production of a uniquely high-intensity neutrino beam. The necessary modifications to the linac have been studied in detail and included in the published CDR.

3.2 The development of an accumulator ring capable of compressing the ESS linac H^- pulses to about 1.3 microseconds

The very high current (350 kA) pulse needed in the hadron collector (magnetic horn) that focuses the produced pions in the forward direction causes a high heat dissipation in the thin walls of the hadron collector. The flat top of the current pulse can for this reason not be longer than of the order of a few microseconds. The 2.86 ms length of the pulses from the ESS linac will therefore be compressed by about three orders of magnitude to about 1.2 µs using a ca. 400 m circumference accumulator ring. The shortening of the pulses is also a main requirement of the detectors to minimize the effect of cosmic ray interactions in the water volumes. The accumulator has been designed considering similar rings such as the SNS[20]

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[15] Ghosh et al., *Sensitivity to light sterile neutrinos at ESSnuSB,* JHEP03 (2020) 026, ArXiv:1912.10010v2.

[16] J. Aguilar et al. *Exploring atmospheric neutrino oscillations at ESSnuSB.* http://arxiv.org/abs/2407.21663, accepted for publication in *JHEP*.

[17] J. Aguilar et al. *Study of nonstandard interactions mediated by a scalar field at the ESSnuSB experiment. Phys. Rev. D* **109**, (2024) 115010.

[18] M. Ghosh et al. *Quantum Decoherence at ESSnuSB Experiment.* arXiv:2404.17559, *JHEP* V2024, No **63**, (2024).

[19] S. Choubey et al., *Exploring invisible neutrino decay at ESSnuSB.* arXiv:2010.16334, *JHEP* V2021 No **133**, (2021).

[20] J. Wei et al., Low-loss design for the high-intensity accumulator ring of the spallation neutron source. Phys. Rev. ST Accel. Beams **3**, 080101 (2000). https://doi.org/10.1103/PhysRevSTAB.3.080101

accumulator ring. The details of the design are included in the published CDR. The accumulator technique to produce very short and intense pulses of neutrons for the neutron's community is being investigated.

3.3. The development of a target station for a 5 MW proton beam for neutrino production

The neutrino beam Target Station includes the proton target itself, the hadron collector, the decay tunnel and the beam dump. The design of a target for neutrino production capable of withstanding the heat load of a 5 MW beam seems not feasible. In order to reduce the heat-load there will be four targets, which will be hit in sequence by the proton pulses, thereby reducing the beam power hitting each target to 1.25 MW. Following the EUROv studies[21], a packed bed of titanium spheres cooled with helium gas has become the baseline design for the ESSnuSB with a power of up to 1.3 MW per target. Detailed in the CDR, the target station has been designed to provide an intense neutrino beam from a 5 MW proton beam at **2.5 GeV**, delivered by the ESS linac. Using genetic algorithm optimization, an optimized horn shape as well as an optimized geometry of the entire target station was accomplished. A cooling method for the packed-bed target has been developed, making use of transverse flow of gaseous helium through the target pores. The calculated high temperatures of the helium cooling gas and the titanium spheres making up the target appear to fall within acceptable limits.

Target integration is more challenging than for most comparable experiments, mainly due to the high level of power deposited in the target, which is concentrated into a very limited space within a magnetic horn. An integration concept has been proposed, which prevents heat from being transferred from the target to the horn conductor. Mechanical deformations and the stress in the target container caused by the temperature gradient appear to be manageable. Experimental verification is still required to confirm the simulation results. This applies in particular to the flow of helium gas through a porous medium, the determination of the heat transfer coefficient between the water spray and the horn skin, as well as the behavior of the spheres inside the target container. Material issues pertaining to high-temperature and radiation exposure require further study. These studies are being conducted in the current design work.

A separate Special Target Station is under design in the on-going program, starting from the parameter of the design of the ESSvSB Target Station, to feed the two new instruments (LEnuSTORM and LEMNB) proposed and described in sections 3.6 and 3.7. As discussed above, an optimized design of the hadron collector for neutrino production has been produced during the ESSvSB studies. An evaluation of whether this design is well suited also for pion collection for LEnuSTORM and LEMNB usage will be done initially. At the end final reports will be produced on the target/hadron collector station, the pion extraction system, the shielding and the beam dump, with an estimation of the total cost to be included in the final CDR.

3.4 The development of a near detector for the high intensity, low energy ESSvSB neutrino beam

The near detector suite of the ESSnuSB project will consist of three different detectors, in upstream to downstream order: the emulsion detector with water as a target, the Super Fine Grained Detector (SFGD-like) granulated scintillator detector and the water Cherenkov detector. The emulsion near detector (named *v*iking) will have a 1 t water target mass and will be used to precisely measure the final state topology of the neutrino–water interactions. Immediately downstream of the emulsion detector, a SFGD-like magnetized granulated scintillator detector will be installed. It will feature a fiducial target mass of 1 t and a dipole magnetic field of up to 1 T perpendicular to the beam direction. Having a magnetic field, it will be able to discriminate between positively and negatively charged leptons and therefore between neutrinos and antineutrinos. Its granular design will enable both muon momentum measurement and calorimetric measurement of the final state particles in neutrino interactions. Downstream of the scintillator detector, a 0.75 kt target mass (~0.42 kt fiducial) water Cherenkov detector will be situated. Due to its large mass, it is expected to record the bulk of the neutrino interactions among the three detectors. It will be used to collect a high statistics sample of v_{μ} interactions and a significant sample of v_e interactions. A sample of neutrino–orbital electron scattering events $v+e^- \rightarrow v+e^-$ will be additionally identified. The interaction cross-section for this process is precisely known, so it can be used to directly measure the neutrino flux. It should be noted that having the same target material and detection technology as the far

[21] *A High Intensity Neutrino Oscillation Facility in Europe*, European Commission Framework Program 7 Design Study: EUROnu, Project No. 212372

detector, it will be possible to correlate systematic uncertainties to some extent between the two detectors using a dedicated analysis.

3.5 The design of an underground megaton water Cherenkov far detector

The far detector shall detect and identify the ν_μ and the ν_e interactions and provide a measurement of their energy with as large as possible fiducial target mass and identify background events caused by cosmic rays by the use of an outer detector layer. The far detector site will consist of two identical large water Cherenkov detectors. Each detector will be placed in a cavern in the shape of a standing cylinder with a height of 78 m and a base diameter of 78 m, having an extra room on top for access and housing of the required infrastructure. The design with two caverns was chosen due to the extreme technical challenge of excavating a single one large enough to contain the required water volume. A cylindrical structure 76 m high and having a 76 m base diameter will be constructed in the cavern to house the photomultipliers (PMT). The entire cavern will be filled with ultra-pure water. The addition of gadolinium to aid in the detection of neutrons is investigated in the current project. Assuming a 2 m fiducial cut inward from the walls of the PMT structure, each detector will contain a 270 kt fiducial mass of water, for a total of 540 kt fiducial mass.

The Zinkgruvan mine, located at 360 km from ESS, is the option for the location of the Far Detector. Zinkgruvan is located near the second neutrino oscillation maximum. At Zinkgruvan there is only one main transport shaft, which is fully used by the mining activities for ore hoisting, so a new transport shaft for the hoisting of the ESSνSB excavation debris may have to be made. The underground mine surroundings will be studied in detail collecting geological and rock mechanics information by making core drillings, core logging, rock strength testing and rock stress measurements of the bedrock at 1000 m depth. The technical part of this task will be the responsibility of the Mining and Rock Engineering Division of Luleå Technical University being assisted by specialised rock engineering companies.

As to the selection of the far detector photo-detectors, more efficient and less costly designs, like that of the MCP photomultipliers produced for JUNO, have appeared on the market, replacing the classical Venetian-blind-dynode-amplified photomultiplier and making a higher photo-detection efficiency and larger photodetector coverage possible with no increase in detector cost. Any further progress in this field will be followed closely.

3.6 The design of a Low Energy Neutrinos from Stored Muons (LEnuSTORM) muon racetrack storage ring

The dominant source of systematic uncertainty in the determination of the CPV phase δ_{CP} from neutrino oscillations is the uncertainty in the neutrino-nucleus cross-sections. ESSνSB will be measuring at the second oscillation maximum where the CPV sensitivity is close to three times larger than that at the first oscillation maximum (where the other future neutrino Long Baseline experiments plan to measure), whereby the influence on δ_{CP} of the systematic errors will be close to three times smaller as compared to these other experiments. Even so, it is of vital importance to measure the neutrino cross-sections in this energy range as precisely as possible, especially since data on neutrino cross-sections in the neutrino energy range of ESSνSB 60-600MeV is currently very scarce. For this purpose, two new instruments are being designed in the current program, one of them being the Low Energy nuSTORM.

A detailed design of a nuSTORM facility was developed in 2015 for the Fermilab[22] and later for CERN[23]. In this project, we are specifically designing a LEnuSTORM (Low Energy nuSTORM) facility for the energy range of interest to the ESSnuSB Long Baseline experiment, i.e. 200–600MeV. This would require muons of at least 600MeV/c. LEnuSTORM relies on much of the same infrastructure as the ESSnuSB Long Baseline experiment, e.g. the same transfer lines, and target building and facilities. It will use one out of four sub-pulses per linac pulse, compressed in the accumulator. That means an average beam power of 1.25MW, which will be directed towards a single target station equipped with a horn. Pions will be collected from the horn and transported to a racetrack-shaped storage ring where they will be injected. In the first straight section of the ring, which is oriented towards the near detector LEMMOND, most of the pions will decay and emit muons

[22] Ao Liu. "Design and simulation of the nuSTORM facility". In: (Apr. 2015). doi: 10.2172/1209538. url: https://www.osti.gov/biblio/1209538.

[23] C.C. Ahdida et al. nuSTORM at CERN: Feasibility Study. Tech. rep. Geneva: CERN, 2020. doi: 10.17181/CERN.FQTB.O8QN. url: https://cds.cern.ch/record/2654649.

that will be stored in the ring for a number of turns. When the muons decay, they will emit neutrinos that will be utilized for measuring the cross section.

The momentum of the collected pions will lie within the range 600-900MeV whereas the momentum of the muons will be somewhere between 400MeV and 800MeV. The pion transfer line will be ≤20m and the length of the straight section between 75m and 100m. The ring arc is expected to be between 20m and 35m. The design work is in progress within the current program.

3.7 The design of Low Energy Monitored Neutrino Beam (LEMNB)

The second instrument, under design in the on-going program for the low energy neutrino cross section measurements, is a Low Energy Monitored Neutrino Beam (LEMNB). The ENUBET[24]-like LEMNB measures neutrino cross-sections in the energy region mentioned above using a neutrino tagged technique to improve the normalization of the measurements. The advantage of this technique is that there is no need to have short proton pulses, so the measurements could be made before the accumulator ring is constructed using the proton extraction line and the ESSvSB Target Station.

The aim of the tunnel instrumentation of the low energy Monitored Neutrino Beam of ESSnuSB+ is to identify the muons produced by pions in the decay pipe at the single particle level. This will allow to constrain the neutrino flux at the neutrino detector and to make precise cross-section measurements in the energy range of interest for ESSnuSB and HyperKamiokande. Current results show that a detector configuration, implementing a high granularity fast tracker device (Micromegas or picosecond Micromegas), has a better performance than the sampling calorimetric technology foreseen in ENUBET at CERN. A 5 cm iron shielding placed in front of the first detector layer allows to reduce the muon peak rate per channel by a factor of 20 compared to the benchmark scenario without shielding. These detectors can be operated at a few MHz/cm^2 and the 10^{15} protons per pulse of the ESS LINAC may be too high for proper detector operation. Envisaging the operation of LINAC with this number reduced by about one order of magnitude with respect to the nominal value, the muon peak rate decreases to 2 MHz/channel, well within the specifications of 1 cm^2 Micromegas channels. A good discrimination power between signal muons and background pions is expected from the differences in the topology of the particle tracks, as expected in ENUBET at CERN, which will allow it to reject a good fraction of the background events and to obtain a high signal-to-noise ratio.

3.8 The design of a near-near water Cherenkov detector for cross section measurements and sterile neutrinos investigations

At the relatively low neutrino energy of the ESSvSB neutrino beam (200-600 MeV) there are very few measurements of the neutrino and antineutrino interaction cross-sections published, making the precise measurement of these quantities an important requirement. The fact that the ESSvSB neutrino energy is lower compared to other proposed experiments implies lower contributions from resonant and deep inelastic neutrino scattering, decreasing the uncertainty in the neutrino energy determination for each event. Considering that the active medium of this detector should be the same as for the near and far detectors of ESSnuSB a cylindrical water Cherenkov detector was selected with a 200-ton water volume, called LEMMOND (Low Energy neutrinos from stored Muons and low energy MOnitored Neutrino beam Detector). This near-near detector will also form a Short Baseline (SBL) experiment together with the ESSnuSB near detector for the investigation of sterile neutrinos.

4 Readiness

4.1 The ESSvSB consortium within two EU supported Design Studies – Timeline - Cost

The concept of using the ESS linac to generate a uniquely intense neutrino beam to enable measurements at the second oscillation maximum was first presented in a 2012 seminar at CERN. In 2015 the ESSvSB consortium received a ca 0.3 MEUR allocation from the EU COST Association for the period 2016-2019 to set up a European network, EuroNuNet[25], with the purpose of "Combining forces for a novel European facility for neutrino-antineutrino symmetry-violation

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[24] Enhanced NeUtrino BEams from kaon Tagging (ENUBET), ENUBET Collaboration (Mar 15, 2022) e-Print: 2203.08319 [hep-ex].

[25] https://www.cost.eu/actions/CA15139#tabs|Name:overview

discovery". The COST grant was used for financing travel and scientific missions of neutrino scientists between the 13 participating countries.

In 2017 the ESSνSB consortium (15 Institutes, 11 countries) received 3 MEUR funding from the H2020 program to finance a Design Study of the ESSνSB project of a total cost of 4.7 M€, during the period 2018-2021[26]. **In 2022** the ESSνSB consortium (20 Institutes, 11 counties) received 3 MEUR funding from the Horizon program to further the Design Study of the ESSνSB project of a total cost of 5.0 M€, during the period 2023-2026 [see footnote #26]. ESSnuSB now numbers more than 90 colleagues, 28 Institutes, 14 countries. The ESSνSB and ESSnuSB+ Design Studies are coordinated by CNRS.

The plan is that the ESSνSB INFRADEV-1 Design Studies 2018-2021 and 2023-2026 will be followed by an INFRADEV-2 Preparatory Phase 2027-2030 resulting in a preliminary Technical Design Report (TDR). From 2030, the TDR will be used as a basis to obtain permits and for seeking financial support from European governments to enable the start of ESSνSB construction work around 2033. By that time the ESS baseline infrastructure with the proton linac, the neutron spallation target and 15 neutron instruments will already have been built up and started operation. It is foreseen that the build-up of the neutrino production infrastructure at ESS and the neutrino detector will be going on for about7 years leading up to the start of data taking some time around 2040. A first task for ESSνSB, after the neutrino cross section measurement campaigns will be to discover leptonic CP violation and measure δ_{CP} with high precision. In subsequent updates and according to the physics needs, this neutrino Super Beam could be transformed to a muon facility to serve a Neutrino Factory or/and a muon collider.

The expected cost of the LBL part of the ESSnuSB RI is estimated to be about 1400 M€ (detailed in the "Standardized set of technical data" and the CDR[27]). The detailed cost of the ESSnuSB+ additions will be published in the final CDR.

5 Expected challenges

5.1 The handling of the very high-power H^- beam in the linac and the proton beam in the accumulator ring and in the target station

The particles to be accelerated in the ESS linac and injected into the accumulator will be H^- ions. If the two electrons of the H^- are lost due to different kinds of perturbations in the accelerator and beam transfer line from the H^- ion source to the accumulator injection point, the resulting proton will hit the beam pipe walls of the linac and transfer line and induce radioactivity in the surrounding equipment. Currently, a proton beam loss of 0.1 W/m is foreseen for proton acceleration in the linac. An increase in the loss of up to 1 W/m due to increased beam loss with H^- acceleration and transfer could probably be tolerated. The conditions to minimize losses are being carefully studied.

5.2 The design of the large far detector caverns in the Nordic granite bedrock

There have already been detailed engineering design studies of the required very large volume to be excavated at ca. 1000 m depth in the bedrock within the previous LAGUNA project in Finland and the Hyper-Kamiokande project in Japan. The bedrock of the Zinkgruvan site is similar to that in Finland, however verification will be needed. The ESSνSB collaboration has access to sufficient technical expertise to work out a conceptual design of the required excavation of two caverns of the order of a half million m^3 each, after the required bedrock pressure and strength measurements have been made employing core drillings.

5.3 ESSνSB will need continued EU funding to enable the preparation of a Technical Design Report

In its Strategy Session in 2013 the CERN Strategy Council recommended that "CERN should develop a neutrino program to pave the way for a substantial European role in future Long Baseline experiments", which CERN has since then in part done with the development of the CERN Neutrino Platform. This Platform has predominantly been used to support the US DUNE Liquid Argon detector project and the T2K and Hyper-Kamiokande near detector projects. The Council also recommended that "Europe should explore the possibility of major participation in leading Long Baseline neutrino projects

[26] http://essnusb.eu/

[27] A. Alekou et al., *The European Spallation Source neutrino super-beam conceptual design report*. [arXiv:hep-ex/2206.01208].

in the US and Japan". After this recommendation was made in 2013 the construction of the ESS began in 2014 and a Design Study of the use of the ESS linac to create a uniquely intense neutrino beam enabling measurements at the second oscillation maximum started.

To demonstrate, in the form of a Technical Design Report, the feasibility and performance of ESSvSB as a precision experiment, the ESSvSB consortium will need continued support from EU as from 2027 in the form of Preparatory Phase funding. A formal requirement for ESSvSB to be in a position to apply for EU Preparatory Phase funding at the end of the ESSvSB Design Study is that ESSvSB be included in the ESFRI Roadmap 2026. The European Strategy for Particle Physics will represent one of the significant inputs for the ESFRI committee when it will decide in 2026 on the ESFRI list update. In view of this we propose that the CERN Strategy Council should include, in its upcoming 'European Strategy for Particle Physics', the opportunity, new since 2013, of the ESSvSB Collaboration producing a thorough Technical Design Study of the proposal to use the European Spallation Source linac to drive a uniquely intense Long Baseline neutrino beam.

5.4 The unique scientific potential of the ESSνSB project will make possible a further successive build-up of a forceful scientific collaboration around the ESSνSB project

The mission of the ESSvSB project is to demonstrate experimentally the existence of leptonic CP violation and to make precision measurement of the leptonic CP violating angle at the second oscillation maximum where sensitivity is greater than at the first oscillation maximum, making the project complementary to DUNE and HyperK. The present ESSvSB consortium is confident that the high potential of the ESSvSB project, unique both by its ca 3 times smaller dependency on systematic errors for the CP violation measurement and by its future potential, in a longer perspective for high intensity muon physics, will lead to a further successive build-up of a strong and productive scientific collaboration around the ESSvSB project.

6 Summary: *The ESSνSB consortium is in the process of completing the Conceptual Design of a unique Long Baseline (LBL) infrastructure at ESS*

The European Spallation Source (ESS), at its final phase of construction, in Lund (Sweden), uses a linac proton driver to deliver a **5 MW, 2 GeV** proton beam to produce neutrons for neutron scattering science and applications. A first European Design Study, in the framework of Horizon 2020, called ESSνSB, took place between 2018 and 2022. ESSnuSB investigated the possibility to add to the neutron facility, a neutrino Super Beam devoted to the discovery and precise measurement of CP violation in the lepton sector, which could help to explain the matter dominance in the Universe. As detailed in the published CDR, it is proposed to double the proton linac power in order to have 5 MW for neutron production and 5 MW for neutrino production. To shorten the proton linac pulses from 2.86 ms to less than 1.5 μs, necessary for the neutrino program, it is proposed to use an accumulator ring, which obliges to accelerate H^- in addition to protons in the linac. A target station with four targets/horns, pulsed alternatively, is designed to share the very powerful proton pulses. A near detector suite and a far water Cherenkov detector placed at a distance 360 km is foreseen for these neutrino oscillation studies. The impressive results on the physics reach, due to the measurements being made at the second oscillation maximum, can be found in the CDR.

After the first successful ESSvSB Design Study, the next one - ESSνSB+ has been undertaken, proposing to use the ca. 8 years of construction of the equipment required for the LBL measurements to build up and use two intermediate instruments designed to precisely measure the relevant neutrino cross–sections, in order to further decrease the systematic errors. The first instrument is a low energy ENUBET-like monitored neutrino beam (LEMNB) to measure ν_μ cross–sections and the second one is a low energy nuSTORM race-track ring (LEnuSTORM) to measure ν_μ and ν_e cross–sections. These instruments are capable of producing well-defined neutrino beams, increasing the precision of cross-section measurements and enriching our knowledge of neutrino interactions at low energies. Additionally, with the LEnuSTORM and a combination of a near-near detector (LEMMOND) with the near detector of the Long Baseline setup, ESSνSB will also perform a Short Baseline experiment to search for sterile neutrinos. At the end of the ESSnuSB+ a new Conceptual Design Report will be produced also including the physics performance and the cost of all stages of the proposed neutrino facility.