PROCEEDINGS OF SCIENCE

Neutrino CP Violation with the European Spallation Source neutrino Super Beam project

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After measuring in 2012 a relatively large value of the neutrino mixing angle θ_{13}, the door is now open to observe for the first time a possible CP violation in the leptonic sector. The measured value of θ_{13} privileges the 2nd oscillation maximum for the discovery of CP violation instead of the usually used 1st oscillation maximum. The sensitivity at this 2nd oscillation maximum is about three times higher than for the 1st oscillation maximum inducing a lower sensitivity to systematic errors. Going to the 2nd oscillation maximum necessitates a very intense neutrino beam with the appropriate energy. The world's most intense pulsed spallation neutron facility, the European Spallation Source, will have a proton linac with 5 MW power and 2 GeV energy. This linac, under construction, also has the potential to become the proton driver of the world's most intense neutrino beam with very high probability to discover a neutrino CP violation. The physics performance of this neutrino Super Beam in conjunction with a megaton underground Water Cherenkov detector installed at a distance of about 500 km from ESS, has been evaluated. In addition, the choice of such detector will extend the physics program to proton–decay, atmospheric neutrinos and astrophysics searches. The ESS proton linac upgrades, the accumulator ring needed for proton pulse compression, the target station and the physics potential are described. In addition to neutrinos, this facility will also produce at the same time a copious number of muons which could be used by a muon collider. The ESS neutron facility will be fully ready by 2025 at which moment the upgrades for the neutrino facility could start.

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1. Introduction

The last measured neutrino mixing parameter θ_{13} has been found to be relatively high compared to expectations. In this landscape the sensitivity to CP violation observation and measurement of the violating parameter δ_{CP}, is enhanced at the second oscillation maximum compared to observations at the first one [1, 2, 3]. Moreover, by placing the far detector at the second oscillation maximum, the experiment is significantly less affected by systematic uncertainties. This is an important point since improvement of the present systematic errors is known to be very hard.

The drawback by placing the far detector at the 2nd oscillation maximum comes from the fact that very high intensity neutrino beams are needed to compensate for the longer baseline. The European Spallation Source (ESS) neutron facility under construction in Lund, Sweden, will have a 5 MW, 2 GeV proton linac operated at a rate of 14 Hz (4% duty cycle). This linac could also be used to produce an intense neutrino beam, which, combined with a megaton Water Cherenkov detector placed at a distance of about 500 km (second oscillation maximum), could observe for the first time CP violation in the leptonic sector. This could help to understand the matter-antimatter asymmetry in the Universe. This project, called ESS neutrino Super Beam (ESSνSB) [4], has been proposed after measuring the last mixing angle θ_{13} and it is under optimisation for an exclusive operation on the 2nd oscillation maximum.

2. The ESSνSB project

Taking into account the low duty cycle of the ESS proton linac, the ESSνSB project proposes to double the proton pulse frequency from 14 Hz to 28 Hz. In this way, the facility will send one pulse for neutron production and one pulse to the neutrino facility. To produce a neutrino beam, the ESS proton linac needs some modifications on top of the cooling power upgrades. Due to limitations at the level of the hadron collector of the neutrino facility, the proton bunches have to be compressed from 2.86 ms, used for neutron production, to few μs for the neutrino beam. For this, an accumulation ring is needed to be placed after the linac and before the neutrino target station. The presence of an accumulator obliges to use H^- ions instead of protons to avoid space charge effects during the injection in the accumulator.

An evaluation of all required upgrades of the linac can be found in a CERN note [7]. This report also makes the recommendation to increase the proton energy from 2 GeV to 2.5 GeV in order to reduce space charge effects. This proton energy is now considered as the baseline of the ESSνSB project.

A neutrino target station including a hadron decay tunnel has to be placed just downstream of the accumulation ring. The adopted design is the one proposed by the EU Design Study EUROν [5]. It consists of four targets and magnetic horns hit alternatively by the proton pulses. The four target/horn scheme has been adopted in order to mitigate the effect of the 5 MW proton beam. The length of the decay tunnel, 25 m, has been optimised to increase the number of decaying pions, producing muon neutrinos, and keeping the number of decaying muons, producing electron neutrinos, to a limited level.

The MEMPHYS type detector (Water Cherenkov) has been adopted as far detector in order to evaluate the physics performance of the proposed facility. The neutrino detection performance of this detector can be found in [6]. Compared to this performance evaluated several years ago, the MEMPHYS detection capability could now be significantly improved for the same cost, by increasing the number of photomultipliers with furthermore higher Quantum Efficiency, profiting from recent developments on this subject. This will significantly improve the electron neutrino detection efficiency and thus increase the physics performance of the facility.

The neutrino beam is directed towards the north of Sweden in the direction of the Garpenberg mine, 540 km away, which could host the far detector. Another alternative location is the Zinkgruvan mine at 360 km from Lund.

3. Physics Performance

The neutrino oscillation to be studied here is $\nu_\mu \to \nu_e$. Fig. 1 presents the unoscillated neutrino energy distribution which could be obtained by the proposed facility at an arbitrary on-axis distance of 100 km from the neutrino target. This distribution corresponds to one year neutrino run (200 days). An almost pure muon neutrino beam is produced with a main contamination of about 0.5% of electron neutrinos. This contribution polluting the primary muon neutrino beam, could be used to measure the electron neutrino cross-section using a perfomant near detector.

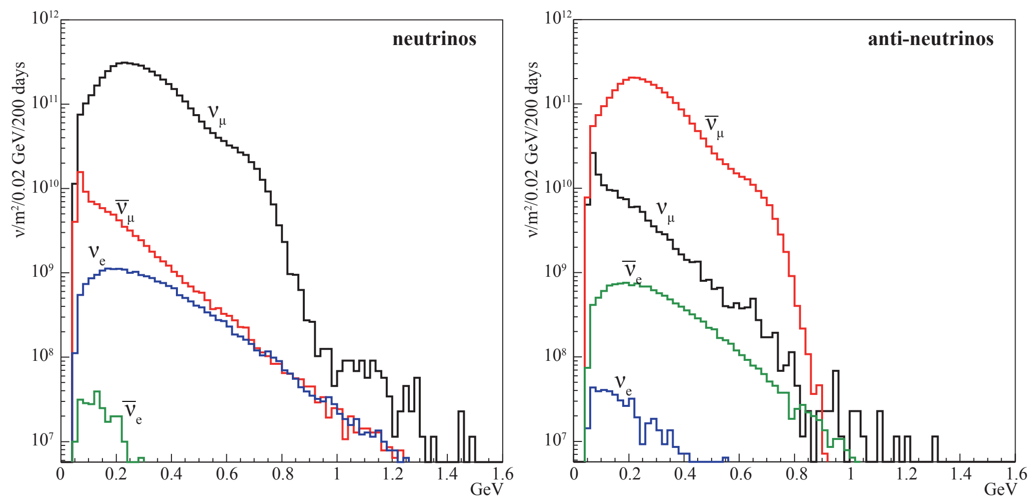

Figure 1: Neutrino energy distribution for neutrino (left) and anti-neutrino (right) runs at an arbitrary distance of 100 km from the target station, for 2.5 GeV protons.

Fig. 2 presents the $\nu_\mu \to \nu_e$ oscillation probability at a distance of 540 km for several values of δ_{CP} and for normal and inverted neutrino mass hierarchies. The overlapping grey distribution is the ν_e energy distribution coming from the ν_μ oscillation. It is well seen that the 2nd oscillation maximum is fully covered. From this figure it is also seen that the CP violation discovery potentiality is not affected by the unknown neutrino mass hierarchy. It has to be mentioned that this project is exclusively devoted to CP violation discovery and not to the masse hierarchy determination which is believed to be solved by then by experiments supposed to start taking data during the next decade.

The physics performance of all projects strongly depends on the considered systematic uncertainties. As said before, systematic uncertainties play less a role on the 2nd oscillation maximum, thanks to the interference term in the oscillation probability dominating the solar and atmospheric

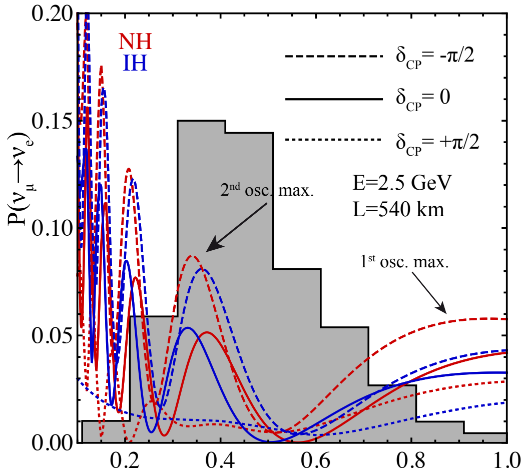

Figure 2: $\nu_\mu \to \nu_e$ oscillation probability as a function of the neutrino energy. The red (blue) lines are for normal hierarchy (inverted). The shaded histogram is the energy distribution of ν_e produced by the ν_μ oscillation and detected by the far detector.

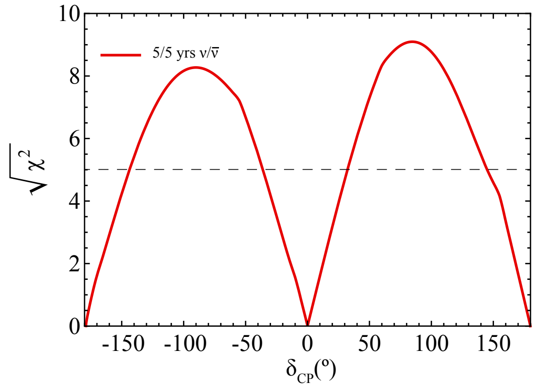

Figure 3: The significance with which CP violation can be discovered as function δ_{CP}.

terms [2]. For this evaluation the systematic errors reported in publication [8] have been considered, with mainly 5% error on the signal. After 10–years operation, it is expected that about 600 electron neutrinos and antineutrinos will be detected by the far detector. Fig. 3 slows the CP violation discovery significance versus δ_{CP}. Up to 60% of the δ_{CP} values can be covered with a significance of 5 σ. Studies are under way to increase the number of detected neutrinos by further optimising mainly the magnetic horn shape and the far detector performance.

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