PROCEEDINGS OF SCIENCE

Neutrino CP Violation with the ESS neutrino Super Beam (ESSνSB)

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After measuring in 2012 a relatively large value of the neutrino mixing angle θ_{13}, it becomes now possible to observe for the first time a possible CP violation in the leptonic sector. The measured value of θ_{13} also 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 influence of 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 source, the European Spallation Source, will have a proton linac of 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 potential to discover a neutrino CP violation. The physics performance of that neutrino Super Beam in conjunction with a megaton underground Water Cherenkov neutrino detector installed at a distance of about 500 km from ESS has been evaluated. In addition, the choice of such detector will extent the physics program to proton decay, atmospheric neutrinos and astrophysics studies. The ESS proton linac upgrades, the accumulator ring needed for proton pulse compression, the target station optimization 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. This project is supported by the COST Action CA15139 "Combining forces for a novel European facility for neutrino-antineutrino symmetry-violation discovery" (EuroNuNet). It has also received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 777419.

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1. Introduction

After observing and well measuring CP violation in the hadronic sector and realising that the amount of this quantity wasn't enough to explain the matter-antimatter asymmetry in the Univers, it is now important to investigate onto other sources of CP violation. One of this possibility is the discovery of CP violation in the leptonic sector using neutrinos. Indeed, according to the already measured neutrino oscillation parameters, such a discovery, under some assumptions, could explain the matter-antimatter asymmetry.

For relatively high value of the last measured neutrino mixing parameter θ_{13}, as the one well measured now, the sensitivity of a CP violation observation and measurement of the violating parameter δ_{CP} is enhanced at the second oscillation maximum instead of performing observations at the first one [1, 2, 3]. The other advantage of placing the far detector at the second oscillation maximum is that the measurements are significantly less affected by systematic uncertainties compared to the first oscillation maximum. This is an important point since improvement of the present systematic errors is known to be very hard.

For this observation next generation very high intensity neutrino beams are needed. The European Spallation Source (ESS) facility under construction in Lund, Sweden, to produce spallation neutrons, will have a 5 MW, 2 GeV proton linac operated at a rate of 14 Hz (4% duty cycle). This linac, under construction, could also be used to produce an intense neutrino beam, which, combine with a megaton Water Cherenkov detector placed at a distance of about 500 km, could observe for the first time a CP violation by being operated at the second neutrino oscillation maximum. This is what is proposed by the ESS neutrino Super Beam (ESSνSB) project [4].

2. The Experimental Facility

In order to be used to produce a neutrino beam, the ESS proton linac needs few modifications. To compress the proton bunches from 2.86 ms used for neutron production to few μs needed for the neutrino beam, an accumulator is needed. The presence of an accumulator obliges to use H^- ions instead of protons to avoid space charge effects during the injection in the accumulator. As the linac duty cycle is very low, of the order of 4%, the pulse rate could be doubled in order to provide one pulse for neutron and one pulse for neutrino production. An evaluation of all required upgrades of the linac can be found in a CERN note [7]. In this note it is stated that no showstoppers have been identified or incompatibilities with the present design of the ESS neutron facility. On top of the accumulator a neutrino target station is necessary. This station could be placed just downstream of the accumulation ring and consists of the target, the magnetic horn, the hadron decay tunnel and the beam dump.

For the neutrino detection, a far megaton Water Cherenkov is needed. The MEMPHYS type detector has been adopted in order to evaluate the physics performance of the proposed facility. The neutrino detection performance of this detector is given in [5]. Compared to this performance, 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. The neutrino beam is directed towards the north in the direction of the Garpenberg mine, 540 km away, which could host the far detector. In this project it is also proposed to use a near detector, not only to monitor the unoscillated neutrino beam, but also to measure neutrino cross-sections at the energies relevant to this project and thus further reduce the systematic uncertainties.

3. Physics Performance

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 0.5% of electron neutrinos. Studying the $\nu_\mu \to \nu_e$ oscillation, this contribution polluting the primary muon neutrino beam, could be used to measure the electron neutrino cross-section using the near detector.

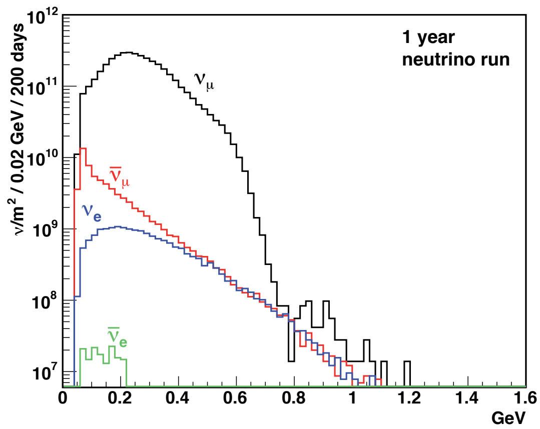

Figure 1: Neutrino energy distribution at a distance of 100 km from the target station, for 2.0 GeV protons.

The physics performance of all projects strongly depends on the considered systematic uncertainties. For this evaluation the systematic errors reported in publication [6] have been considered, with mainly 5% error on the signal. 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. It is also seen that the CP violation discovery potentiality is not affected by the unknown neutrino mass hierarchy.

After 10–years operation, it is expected that about 600 electron neutrinos and antineutrinos will be detected by the far detector. Studies are under way to increase the number of detected neutrinos by further optimising mainly the magnetic horn shape and the far detector performance.

Fig. 3 shows the CP violation discovery significance versus the covered δ_{CP} fraction. It is seen that for a confidence level corresponding to 5 σ, more than 60% of the δ_{CP} values are covered. This example is for a facility running with 5 years in “neutrino” mode and 5 years in “antineutrino” mode. After 10–years of operation the results are still dominated by the systematic errors.

Together with the neutrino production, a very high number of muons is also produced. It is estimated that more than 10^{21} muons could be collected at the level of the beam dump of the neutrino facility. These muons have a mean energy of about 0.5 GeV. They could be used by a

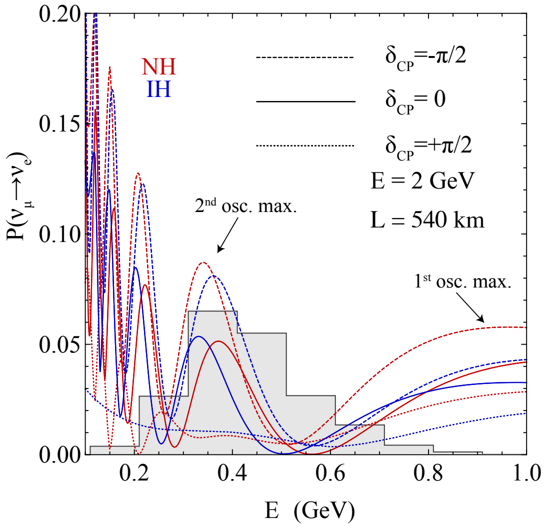

Figure 2: $\nu_\mu \to \nu_e$ oscillation probability as a function of the energy. The solid (dashed) lines are for normal hierarchy (inverted). The shaded histogram is the energy distribution of ν_e produced by the ν_μ oscillation and detected by the far detector.

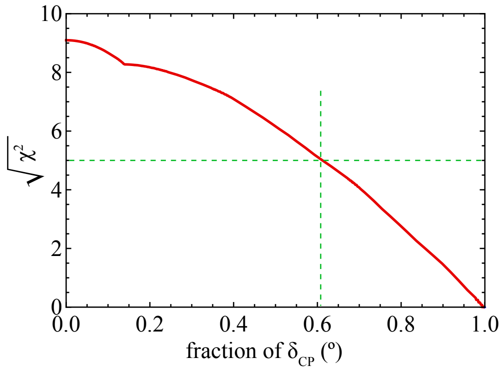

Figure 3: The significance with which CP violation can be discovered as function of the fraction of the full δ_{CP} range.

Neutrino Factory, according to the needs of the neutrino physics at that moment. These muons could also be used by muon cooling and re-acceleration R&D projects in view of the construction of a muon collider.

4. Acknowledgements

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