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Neutrino Physics at ESS and the upgrades needed for the ESSnuSB

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The European Spallation Source (ESS) in Lund, Sweden, will provide, by 2023, the world's most powerful neutron source. The 2 GeV ESS linac will provide 5 MW protons. The total power of the linac can be raised to 10 MW by increasing its pulse frequency, thus making possible the production of, in addition, a very intense, 0.4 GeV neutrino Super Beam, ESSnuSB. Search for leptonic CP violation at the second oscillation maximum, where the sensitivity is about 3 times higher than at the first, would be possible at 5σ significance level in 56% (65% for an upgrade to 2.5 GeV beam energy) of the leptonic CP-violating phase range after 10 years of data taking. 5% systematic error in the neutrino flux and 10% in the neutrino cross section are assumed. The outstanding physics reach possible with ESSnuSB and the upgrade of the ESS accelerator complex needed for ESSnuSB will be discussed in the paper.

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1. The Opportunity: The ESS Linac

The European Spallation Source (ESS) [1] in Lund, Sweden, will provide users with high-flux spallation neutrons for a large variety of experiments where neutrons are needed as a probe. It will deliver 2.86 ms long proton pulses, using a 2 GeV superconducting proton linac delivering a 5 MW beam to a rotating, helium gas cooled tungsten target (Table 1, column Protons). ESS is a partnership between 11 European nations. The ESS linac is planned to deliver beam in 2019 and the neutron facility to start operating as a user facility in 2023.

Parameter	Protons	Protons and H^-
Average Beam Power	5 MW	10 MW
Ion kinetic energy	2 GeV	2 GeV
Average linac pulse current	62.5 mA	62.5 mA
Average linac pulse length	2.86 ms	2.86 ms
Pulse repetition rate	14 Hz	28 Hz
Reliability	95 %	95 %
Number of protons per linac pulse	$1.1\ 10^{15}$	$1.1\ 10^{15}$
Beam Duty Cycle	4%	8%

Table 1: Selected parameters of the ESS linac, in the column "Protons" are shown the characteristics when the linac produces only neutrons, in the column "Protons and H^-" when the linac is used for production of neutrons and neutrinos.

This impressively powerful proton driver has been proposed for use also for particle physics: the ESS neutrino Super Beam (ESSnuSB) project plans to use a 5 MW beam from the ESS linac to produce an intense neutrino beam with a dedicated target station [2, 3]. The 4% duty factor of the ESS linac can be doubled, by increasing the linac pulse repetition rate, making it possible to produce a 5MW beam for neutrino production in addition to the 5 MW beam already planned for neutron spallation.

The uniquely high intensity of the ESS linac allows for sufficient event statistics to be collected with a Megaton neutrino detector positioned at the second neutrino oscillation maximum, where the relative CP violation sensitivity is about three times higher than at the first maximum. For the proton energy of 2.5 GeV, the second oscillation maximum is situated at about 540 km from the neutrino source. The Garpenberg mine in Sweden situated at this distance has been selcted as the location for the neutrino detector.

The ESSnuSB Design Study takes advantage of many results obtained in the FP7 Design Study EUROnu [4] on future neutrino facilities. The EUROnu study of the 4.5 GeV / 5 MW neutrino Super Beam from the CERN Superconducting Proton Linac SPL [5, 6, 7], and several studies of the MEMPHYS large Water Cherenkov detector in the Fréjus tunnel [8, 9], have served as very useful references in particular for the target station and the far detector.

2. Upgrades of the ESS Accelerator Facility needed for neutrino production

The 10 MW operation of the linac will require additional RF power and RF stations, more cryogenic capacity and extra electric power and infrastructure for electric and cryogenic distribution. The target station and the near detector will be built on the ESS site. In addition an accumulator ring is needed to shorten the linac beam pulse from 2.86 ms to a few micro-seconds due to too important ohmic heating of the current sheets of the target focusing horn when the pulses are longer than a few microseconds. Multiturn injection of protons into the ring can not be made efficiently, therefore acceleration of H^- in the linac is proposed to be able to use H^- stripping to get protons into the accumulator ring. This means that the linac has to accelerate both protons and H^- ions. An additional H^- source would be needed, and doubling of the low and medium energy beam transport systems. The transport of the beam through the linac is more challenging for H^- due to Lorentz stripping, which may make it necessary to have different focusing of the H^- linac beam. Studies show that the upgrade, also considering the possibility to increase the beam energy to 2.5 GeV, is feasible [10]. The preliminary simulations of the ring, accumulating so far only 1/4 of the intensity, assuming 4 accumulators or a more frequent pulsing of the linac, show that the beam and the injection process can be handled with present technology.

3. The Physics

As the relative variation of the signal at the second oscillation maximum is 3 times higher as compared to the first maximum, the measurement of the signal at the second maximum is 3 times less sensitive to systematic errors. Measuring at the 3 times more distant second maximum will require 9 times more statistics to have the same statistical error as at the first maximum. The exceptionally high power of the ESS linac provides enough neutrino beam intensity to have approximately the same relative statistical error in the signal as other proposed experiments will have measuring at the first maximum and at the same time a 3 times lower relative systematic error as these other experiments.

Figure 1(a) shows the 1σ error in the determination of δ_{cp} horizontal axis) as a function of the covered fraction of of δ_{cp} (vertical axis). Among the shown accelerator based projects, the resolution possible to attain with ESSnuSB is surpassed only by the Neutrino Factory project (IDS-NF). Figure 1(b) shows with which level of significance, in terms of number of standard deviations σ, CP violation can be discovered (vertical axis) versus the fraction of the total range of possible values for δ_{cp} for which CP violation (horizontal axis) can be discovered. These plots show that ESSnuSB has the widest discovery coverage of the δ_{cp} range among the Super Beam experiments investigated. The systematic errors chosen for these studies made in 2013 are quite conservative; for example, the error for the ν_e signal is 7.5%, but this is to our knowledge the only comparison made under the assumption of equal systematic errors for all experiments. There is in principle no reason why there should be a significant difference in the systematic errors between the future Hyper-K and ESSnuSB which are planned to have similar neutrino beam energies and neutrino detectors. The about three times higher CP signal in ESSnuSB does however represent a significant difference.

4. Future work and Conclusion

The collaboration will apply for funding from the European programme H2020 for a Design Study grant starting in the autumn of 2017 and lasting 4 years. In conclusion the ESS proton linac

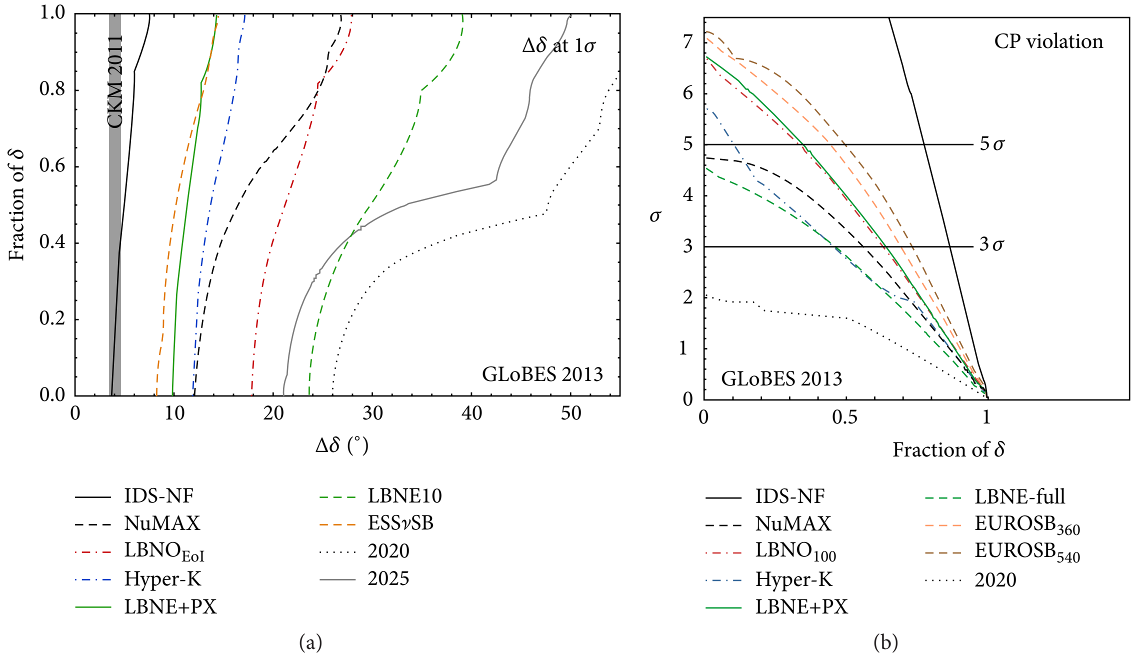

Figure 1: Left: The 1σ error in the determination of δ_{cp} is shown as a function of the δ_{CP} fraction for which this accuracy can be reached [11]. The right panel shows with what level of significance that leptonic CP violation can be discovered versus the fraction of the total range of possible values for δ_{cp} [2]. The systematic errors are taken from [12].

gives an excellent opportunity to design a neutrino facility with a detector at the second oscillation maximum.

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