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ESSnuSB+ Project: Towards Precision Measurement of the CP Violation at the Second Neutrino Oscillation Maximum

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The ESSnuSB project aims to measure the leptonic CP violation at the second neutrino oscillation maximum using an intense neutrino beam, which will be produced by the powerful ESS proton linear accelerator. The first phase of the project was successfully concluded with the production of the Conceptual Design Report in which it was shown that this next-to-next generation neutrino oscillation experiment has a potential to start the precision era in the field of the leptonic CP violation measurement.

ESSnuSB+ is a continuation of this study which focuses on neutrino interaction cross-section measurement at the low enutrino energy region, exploring the sensitivity of the experimental set-up to additional physics scenarios and on the civil engineering of the near and far detectors sites. It foresees an intermediate step in the ESSnuSB construction phase in which a number of additional facilities will be built: a 1/4 power ESSnuSB neutrino production target system prototype, a low energy muon storage ring and a low energy monitored neutrino beam facility; a common near neutrino detector for the muon ring and monitored beam will be designed, and a study of the effect of Gd doping of ESSnuSB water Cherenkov detectors will be performed.

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1. Introduction

Neutrino oscillation is a widely studied phenomenon discovered 25 years ago by Super-Kamiokande [1]. A large number of neutrino oscillation experiments has been carried out since then and we have been able to determine most of the oscillation parameters with an uncertainty of few percents [2]. However, there is still an important feature of the neutrino oscillation which needs to be measured: the amount of CP violation. This is encoded in one of the parameters contained in the mixing matrix, namely the only phase $\delta_{\rm CP}$. Currently, only the two long baseline experiments T2K and NOνA could give some hints of the value of such a phase, pointing towards maximal CP violation ($\delta_{\rm CP} \sim -\pi/2$) [3, 4]. Nonetheless, the measurements are in slight tension and are not able to reach a 5σ sensitivity, which is required in order to claim the measurement. Next generation of long-baseline experiments aims to reach a good sensitivity to the mixing matrix phase, in particular if its value is maximal. However, their capabilities are not expected to be enough to perform a precise measurement of $\delta_{\rm CP}$. In this context, the next-to-next generation experiment long-baseline ESSnuSB will be focused on the precision measurement of the CP violating phase, looking at neutrino oscillation at the second oscillation maximum. In the following sections we will motivate this choice and we will explore the expected performances of the ESSnuSB experiment, describing finally the ESSnuSB+ project, namely a continuation of this study.

2. Neutrino oscillation at the second oscillation maximum

The main aim of the ESSnuSB experiment is to measure the CP-violating phase $\delta_{\rm CP}$. The most promising strategy for the determination of the CP violation is to look at both electron neutrino and antineutrino appearance using a muon neutrino beam from an accelerator facility. Since $\delta_{\rm CP}$ changes its sign when we consider neutrino or antineutrino oscillation probabilities, we can define the matter/antimatter asymmetry $\mathcal{A}_{\rm CP}^{\alpha\to\beta} = P_{\nu_\alpha\to\nu_\beta} - P_{\overline{\nu}_\alpha\to\overline{\nu}_\beta}$ which is directly related to the $\delta_{\rm CP}$ sensitivity. This, in the electron appearance channel can be shown to be equal to

$$\mathcal{A}_{\rm CP}^{\mu\to e} = P_{\nu_\mu\to\nu_e} - P_{\overline{\nu}_\mu\to\overline{\nu}_e} = -16J \sin\frac{\Delta m^2_{31}L}{4E} \sin\frac{\Delta m^2_{32}L}{4E} \sin\frac{\Delta m^2_{21}L}{4E} \ . \tag{1}$$

where $J \propto \sin\theta_{13}\sin\delta_{\rm CP}$ is the so-called Jarlskog invariant. It is clear that while $\mathcal{A}_{\rm CP}^{\mu\to e}$ strongly depends on $\delta_{\rm CP}$, its effect is suppressed by the smallness of the reactor mixing angle θ_{13}. We can now try to motivate the choice of the second atmospheric oscillation maximum for ESSnuSB. If we compute $\mathcal{A}_{\rm CP}^{\mu\to e}$ at the first and at the second maximum (when $\Delta m^2_{31}L/4E = \pi/2, 3\pi/2$), we obtain that [5]

$$\frac{\mathcal{A}_{\rm CP}^{\mu\to e}\ (\text{2nd max})}{\mathcal{A}_{\rm CP}^{\mu\to e}\ (\text{1st max})} \approx 2.7 \tag{2}$$

which clearly show that the effect of the CP violation is almost three times bigger at the second oscillation maximum than at the first.

The inclusion of matter effects in the probabilities can introduce fake CP violation effects since the matter potential changes its sign in antineutrino oscillation probabilities just like $\delta_{\rm CP}$. However, being matter effects proportional to the neutrino energy, at the second oscillation maximum they are always milder than at the first one. For this reason, the electron neutrino appearance at the second maximum is not only more sensitive to $\delta_{\rm CP}$, but also less affected by the fake CP violation effects induced by matter.

3. The ESSnuSB design

The main disadvantage of being at the second oscillation maximum is that we need the neutrino beam to travel more. Thus, in order to be able to collect the large number of events required to measure the feeble effect of $\delta_{\rm CP}$ a very intense neutrino beam is mandatory. For this reason, the future most powerful proton linear accelerator in the world, the ESS LINAC [6], has been chosen as accelerator facility for the experiment. The idea is to create a muon neutrino beam from pions in-flight decays. These mesons are produced shooting a proton beam onto a thin target. The relatively low energy (2.5 GeV) of such protons allows to have an almost pure muon neutrino beam, with only a very small electron neutrino contamination. Since the ESS accelerator main purpose is the production of spallation neutrons, several modifications are needed at the accelerator site in order to provide a neutrino beam suitable for a long-baseline experiment. Among them [7], an accumulator ring is required to reduce the proton pulse from 2.86 ms to 1.3 μs. This will allow to reduce the atmospheric neutrino interactions which could occur at the ESSnuSB far detector during a long pulse. Moreover, a target station that can withstand the very hight, 5 MW, power beam from the ESS linac is needed. Four identical horn/target systems, each of which will receive 1.25 MW beam, is planned to construct the main part of the target station. The magnetic horn will be used to select the charges of secondary mesons to let the ESSnuSB experiment run with a neutrino or antineutrino beam. This is crucial for the $\delta_{\rm CP}$ measurement since we need to observe both electron neutrino and antineutrino appearance. The final neutrino beam will be peaked at 0.35 GeV and will be relatively narrow in energy, having most of the neutrinos in the range between 0.15 GeV and 0.5 GeV.

3.1 Near detectors

The reduction of the uncertainties given by the poorely known neutrino interaction cross section and by the flux knowledge is crucial in order to perform a precise measurement of the CP violation. Thus, other than observing neutrinos travelling to the second oscillation maximum, a multi-purpose near detector complex is a very important feature for the ESSnuSB experiment. Located at roughly 250 meters from the neutrino production point, it will consist of 3 different detectors. The first one will be an emulsion detector with water target and will be mainly used to precisely measure the final state topology of neutrino-water interactions. Downstream of this detector, a SFGD-like magnetized scintillator detector will be installed. Such a detector will be able to discriminate between neutrinos and antineutrinos enabling a muon momentum measurements and calorimetric measurements of the particles produced in the neutrino interactions. The third component of the near detector will be a 0.75 kt target mass wass Cherenkov detector. This, a scaled copy of the far detector, is expected to collect a huge sample of neutrino interaction, precisely measuring the flux.

3.2 Far detectors

The ESSnuSB far detector will consist of two identical water Cherenkov detectors. Each of them will be a standing cylinder of 78 m high with a 78 m base diameter filled with pure water. The

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total fiducial mass of the two modules will be 540 kt. 20 inches PMTs will be placed in the inner side of the detector with a 30% coverage in order to detect Cherenkov light produced by neutrino interactions; moreover, outward facing 8 inches PMTs will be used as veto. The chosen location for these two detector is the Zinkgruvan mine, located in Sweden 360 km away from the neutrino beam source. Such a baseline has been proved to be optimized for the CP violation measurement, allowing ESSnuSB to explore not only the second oscillation maximum but also part of the first taking advantage of the larger number of events.

4. The physics reach

As pointed out, the main purpose of the ESSnuSB experiment is the precise measurement of the leptonic CP violation. Assuming 5 years running in neutrino mode and 5 years running in antineutrino mode, the expected sensitivity to CP violation reaches, in a realistic hypothesis of 5% total normalization systematics in the electron appearance channel (see Fig. 1, left panel) 17.5σ for the maximal values of $\delta_{\rm CP}$ ($\delta_{\rm CP} = \pm 90°$). The CPV sensitivity still remains competitive in a very pessimistic 25% systematics scenario. The fraction of the possible phase values for which at least 5σ sensitivity is expected to be higher than 70% for 10 years of data taking. Such a coverage is not expected to be reached by any of the next generation LBL experiments nor by their combination [7]. However, the astonishing performances of ESSnuSB in the measurement of the CP violating phase are not only related to the sensitivity, but also to the precision. Indeed, while the next generation of LBL experiments are expected to measure δ_{CP} with an error of about 10-20° in the case of a successfull CPV discovery [8, 9], ESSnuSB should be able to reduce this uncertainty below 7.5° for realistic values of systematic uncertainties (see [7] for a detailed study of the systematic uncertainties effect). The possibility to tune the neutrino and antineutrino running time if there will exist some rough estimations on the true δ_{CP} value at the time of the ESSnuSB data taking, may further improve the precision on the measurement up to 4.5°. The beam neutrino oscillation physics which could be probed at ESSnuSB, however, is not only related to the CPV. Indeed, apart from providing other oscillation parameters measurements [10], ESSnuSB should also be able to be a good environment where to search for new physics in the oscillation sector as already explored in several phenomenological studies [11].

5. Future developments: ESSnuSB+

The ESSnuSB design study is mainly focuesd on the CPV measurement. However, the construction of the experiment's facilities will require a large amount of time. The intermediate steps focused on the neutrino interaction cross section measurements, on the neutrino production target station R&D and on the further physics potential of the ESSnuSB far and near detectors will be studied within the ESSnuSB+ project [12]. In particular, the main proposals are:

- To build a new target station which will contain one of the four ESSnuSB targets/horns operating at 1/4 of the total ESSnuSB power.
- To construct a racetrack ring where muons from pions decays can be stored (low energy nuSTORM or LEnuSTORM); these muons could provide an electron and muon neutrino

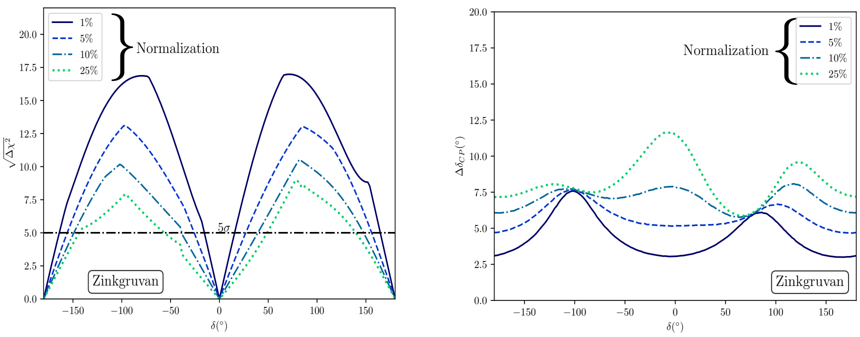

Figure 1: CPV sensitivity (left panel) and precision (right panel) for different choices of normalization systematic uncertainties. Figure taken from [7].

beam which could be used to measure the interaction cross section of both neutrino flavors in a newly built near detector and in the ESSnuSB near detector facility.

- Inspired by the ENUBET project, to develop an instrumented decay tunnel for pions where charged particles from pion decays can be directly measured in order to constrain the expected energy spectrum of neutrinos exiting the tunnel. Neutrinos from this low energy monitored beam (LEMNB) will be detected in a near detector shared with LEnuSTORM.
- To study the effect of the gadolinium doping of the ESSnuSB water Cherenkov detector. This could allow the ESSnuSB experiment to distinguish neutrinos from antineutrinos given the large Gadolinium cross section for neutron absorption.
- To perform simulation about the non-beam physics at the ESSnuSB detectors. In this context, the experiment might be used to measure interactions of atmospheric, solar or supernovae neutrinos.
- To explore the potentials of the LEnuSTORM and LEMNB near detector facilities to probe light sterile neutrino oscillations.

6. Conclusions

ESSnuSB is a design study for a next-to-next generation neutrino long baseline experiment which aims to the precise measurement of the CP violation in the leptonic sector looking at the second atmospheric oscillation maximum. Its unprecedent features will allow ESSnuSB to explore part of the parameter space which cannot be probed by the next-generation oscillation experiments. The new project ESSnuSB+ proposes to design intermediate facilities which could lead to the measurements of low energy neutrino cross section and to explore all the physics possibilities of the ESSnuSB detectors, which may not be limited to the study of the accelerator neutrino beam physics.

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