PROCEEDINGS OF SCIENCE

Physics potential of the ESSnuSB

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The ESSnuSB project proposes to base a neutrino "Super Beam" of unprecedented luminosity at the European Spallation Source. The original proposal identified the second peak of the oscillation probability as the optimal to maximize the discovery potential to leptonic CP violation. However this choice reduces the statistics at the detector and penalizes other complementary searches such as the determination of the atmospheric oscillation parameters, particularly the octant of θ_{23} as well as the neutrino mass ordering. We find that including the atmospheric sample, the combination not only improves very significantly these drawbacks, but also enhances both the CP violation discovery potential and the precision in the measurement of the CP violating phase, for which the facility was originally optimized. We then reassess the optimization of the ESSnuSB setup when the atmospheric neutrino sample is considered, with an emphasis in performing a measurement of the CP violating phase as precise as possible. We find that for values of δ near to maximal CP violation, shorter baselines like that with the Zinkgruvan detector site (360km) would be optimal. In these conditions, a measurement better than 8° would be achievable for any value of the θ_{23} octant and the mass ordering. Conversely, if present and next generation facilities were not able to discover CP violation, longer baselines like that with the Garpenberg detector site (540 km) and more even splitting between neutrino and neutrino modes would be preferable.

**** The 22nd International Workshop on Neutrinos from Accelerators (NuFact2021) ****
**** 6–11 Sep 2021 ****
**** Cagliari, Italy ****

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PoS(NuFact2021)063

1. Introduction

After the discovery of a non-zero θ_{13} the emerging picture for the PMNS lepton matrix is strikingly different from its CKM counterpart. θ_{23} is compatible with maximal mixing as well as with a large but non-maximal value in either the first or the second octant, θ_{12} is around 33° and only $\theta_{13} \sim 8-9^\circ$ is relatively small but still comparable to the Cabibbo angle. Experiments such as T2K [1, 2] and NOνA [3] have started to provide the first hints on the CP-violating phase δ. Similarly, present oscillation experiments show some preference for normal ordering ($\Delta m^2_{31} > 0$).

The European Spallation Source (ESS) at Lund provides an opportunity to build a new-generation, long-baseline neutrino oscillation experiment with an unprecedented neutrino luminosity through an upgrade of the ESS Linac [4, 5]. Its 2.5 GeV protons would lead to a rather low energy neutrino flux, between 200 and 600 MeV. This energy range is very well suited for a water Cerenkov detector of the MEMPHYS type and the best baseline at which to study the neutrino beam from the ESS facility would be between $L \sim 400$ and $L \sim 600$ km. This choice makes the ESSnuSB design unique, as the observed neutrino flux observed mainly corresponds to the second maximum of the $\nu_\mu \to \nu_e$ oscillation probability [4–6], with a marginal contribution of events at the first oscillation peak. For the ESSnuSB the increased dependence on δ is well worth the loss of precious neutrino events at the second maximum. It could provide unprecedented discovery potential to leptonic CP-violation or the most precise measurement of the corresponding phase after discovery. Moreover, this choice also makes the physics reach much more resilient against unexpected sources of systematic errors [7], since the signal has a leading dependence on the unknown parameters.

In these proceedings, based on Refs. [5, 8], we will combine the observation of the ESSnuSB [5] flux tuned for the second maximum of the ν_e appearance probability with the complementary atmospheric neutrino data, more strongly dominated by the first maximum and ν_μ disappearance, and characterized by stronger matter effects. Finally, we will discuss which sources of systematic errors, including spectral uncertainties, impact the final sensitivity more significantly.

2. Physics potential

We use the GLoBES software [9, 10] to simulate the ESSnuSB experiment. The fluxes, cross sections and migration matrices are the same as from Ref. [5], while for the systematic uncertainties we include an overall 5% (10%) normalization uncertainty to signal (background). We will always assume a total 10 year running time, split in 5 (5) years in neutrino (antineutrino) mode. The simulation of the atmospheric neutrino sample in MEMPHYS is the one used in the analysis from Ref. [11] where the neutrino fluxes at Gran Sasso from Honda calculations [12] were used. This is a conservative estimate as fluxes become larger at higher geomagnetic latitudes such as Garpenberg ($L = 540$ km) or Zinkgruvan ($L = 360$ km). For further details on the atmospheric sample see [11].

In Fig. 1 the expected number of ν_e events are shown as a function of the energy. In the following, when discussing systematic uncertainties, we will include overall uncertainties which rescale the whole spectra as well as spectral uncertainties which can affect differently different energy bins, thus distorting the shape of the event rate. This second class of systematics could arise, for example, from cross section uncertainties at such low energies, and will be implemented by introducing an uncorrelated nuisance parameter in each energy bin.

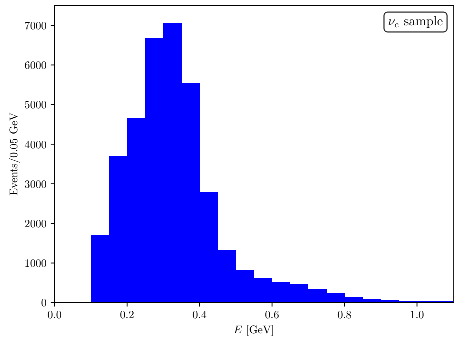

Figure 1: Number of signal ν_e events expected at the far detector of the ESSnuSB at Garpenberg ($L \sim$ 540 km), grouped in 50 MeV energy bins.

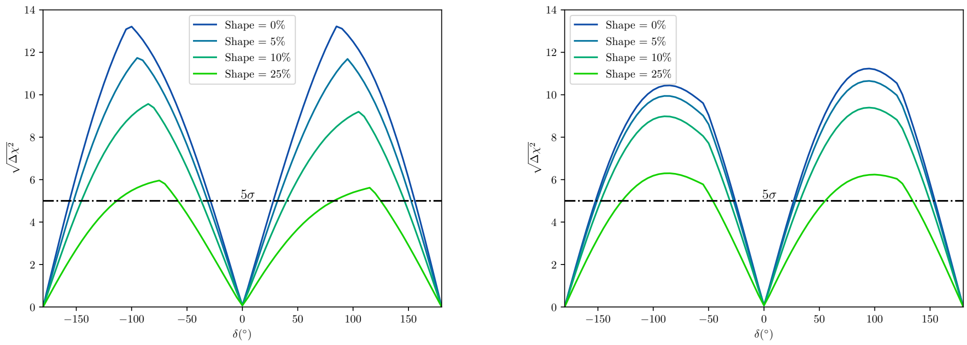

Figure 2: Sensitivity to CP violation for different assumptions on the size of the spectral uncertainties, both for L = 360 km (left panel) and L = 540 km (right panel). Although in the absence of spectral uncertainties the sensitivity is better at Zinkgruvan, it degrades much more as we increase the size of the shape systematic.

The sensitivity to CP violation for both baselines is shown in Fig. 2 for different assumptions of the spectral uncertainties, including the atmospheric neutrino sample. For spectral uncertainties below 5% we observe a discovery potential of leptonic CP violation for around 70% of the allowed values of δ, with a better performance at Zinkgruvan, while for larger uncertainties the better option would be to place the detector at Garpenberg, more centred at the second oscillation maximum and thus more resilient to systematic uncertainties. Next, we study the precision on the measurement of δ, for the same baselines and systematic uncertainties, in Fig. 3. Although the plots correspond to an equal time splitting between neutrino and antineutrino mode, the running times could be optimized by the time the experiment starts taking data to have the best precision possible according to the hints on the value of δ available [8]. In other words, if the value of δ is found near $\pm\pi/2$, the best option would be to run most of the time in neutrino mode to collect as many events as possible, while if δ is near 0 or π, it would be more convenient to run for similar periods in neutrino and antineutrino mode. In Fig. 3 we can see that $\Delta\delta$ could be below 8° (12°) for any value of δ at Zinkgruvan (Garpenberg) for small enough spectral uncertainties, while the precision is quickly degraded in Zinkgruvan as these systematics increase in size, in contrast to what happens at Garpenberg.

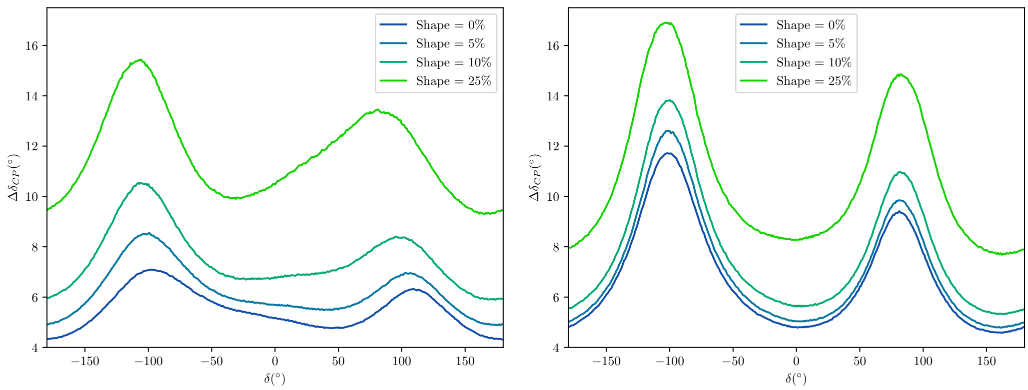

Figure 3: Precision on the measurement of δ for different assumptions on the size of the spectral uncertainties, both for $L = 360$ km (left panel) and $L = 540$ km (right panel).

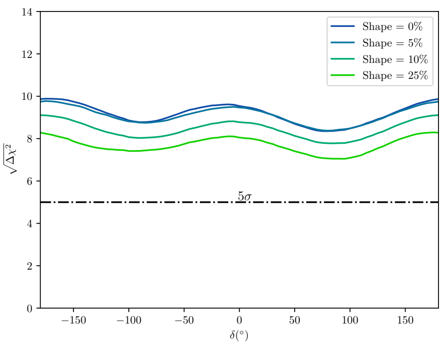

Figure 4: Sensitivity to the mass ordering for different spectral uncertainties as a function of the CP-violating function at Zinkgruvan ($L = 360$ km).

Finally, we show in Fig. 4 the sensitivity to the ordering at Zinkgruvan. The results at Garpenberg are very similar, although the sensitivity is slightly better at the shorter baseline due to the larger flux arriving at the detector. As can be seen, the ordering could be discovered for any value of δ and for any size of the shape systematics.

3. Conclusions

The ESSnuSB is a new-generation long-baseline neutrino oscillation experiment with an unprecedented luminosity which could study oscillations near the second maximum. This would translate into an unprecedented sensitivity to CP violation. In particular, given the two possible locations to place the far detector, it could discover CP violation for above 70% of the possible values of δ if spectral uncertainties are well under control. On the contrary, if spectral uncertainties are found to be large, the best option would be to place the detector at Garpenberg, well centred in the second oscillation maximum and thus more resilient to uncontrolled systematics. The precision on the measurement of δ could be well below 8° (12°) in Zinkgruvan (Garpenberg) if shape systematics are under control. Regarding the sensitivity to the mass ordering, in principle one could discover it for any values of δ and any size of the systematics, while the sensitivity to the octant is increased when including the atmospheric sample.

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