European Spallation Source Neutrino Superbeam Experiment (ESSνSB)

— Physics potential

Eur.Phys.J. C80 (2020) 190, arXiv:1912.04309 [hep-ph]

Mattias Blennow[a,b], **Enrique Fernandez-Martinez**[a], **Toshihiko Ota**[a], **and Salvador Rosauro-Alcaraz**[a]

[a]IFT-UAM/CSIC Madrid, [b]KTH AlbaNova Stockholm

Abstract

The high-intensity and low-energy neutrino beam provided by the European Spallation Source (ESS) gives a unique opportunity to access the second maximum in the neutrino oscillation probability driven by the atmospheric mass-squared difference. The superbeam experiment based on the ESS neutrino source (ESSνSB) is complementary with the next generation long-baseline experiments, DUNE and T2HK, which focus on the first maximum. A megaton-class far detector assumed in the ESSνSB allows us to collect a large amount of atmospheric neutrino data. We present the expected sensitivity reach of the ESSνSB experiment to the CP-violating phase in the lepton mixing matrix. We reveal the optimal experimental setup and investigate the robustness of the results and the impact of improvements of the systematic errors with realistic numerical simulations.

ESS: Accelerator

The accelerator is now under construction in Lund, Sweden. The power of the proton driver with the energy of 2.5 GeV is expected to reach 5 MW [1]. The average energy of the neutrino beam is $\langle E \rangle \simeq 0.3$ GeV. The high-intensity low-energy beam provided by ESS gives an opportunity to observe the second maximum in the $\nu_\mu \to \nu_e$ oscillation probability: $L \sim$400-600 km for $E \sim$0.2-0.4 GeV, cf. Fig. 3. The first proton beam on target is scheduled in 2023.

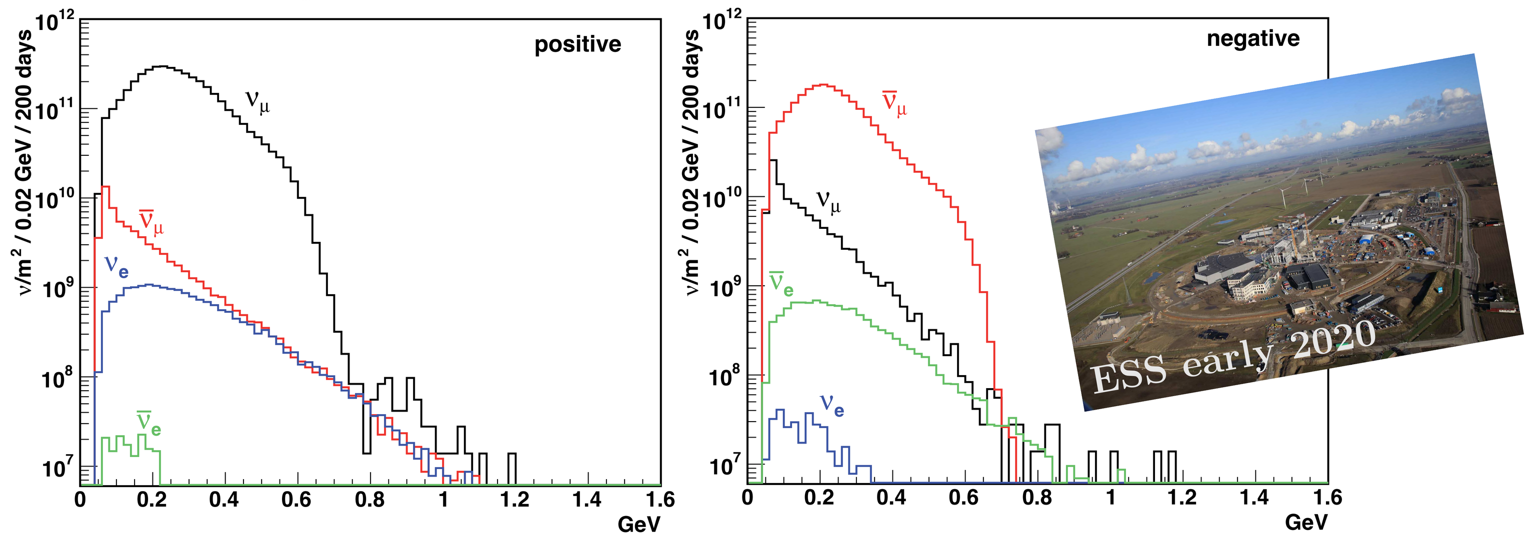

Fig. 1 Beam fluxes at a distance of 100 km (on-axis) for positive and negative horn current polarities [1].

Far detector for 2[nd] maximum

The interference term, which contains the information of the CP phase, takes a larger part of the oscillation probability at the second maximum $\Delta m^2_{31} L/(4E) \sim 3\pi/2$ than at the first maximum $\Delta m^2_{31} L/(4E) \sim \pi/2$ [2]. To compensate the loss of the neutrino flux due to a long baseline for the second maximum, a megaton-class detector is required, e.g., the MEMPHYS proposal (Water Čerenkov) [3]. There are several good candidates for the sites (mines) around Lund, which are capable of accommodating a large detector. In this study, we focus on the two options: Zinkgruvan ($L = 360$ km) and Garpenberg ($L = 540$ km), which are qualitatively different. As shown in Fig. 3, Garpenberg focuses on the second maximum. Zinkgruvan can trace the oscillation probability from the fist maximum to the second maximum via a minimum. In our simulation, a WC detector with the size of 1 Mton (fiducial 0.5 Mton) is adopted as a far detector.

Fig. 2 Candidate sites.

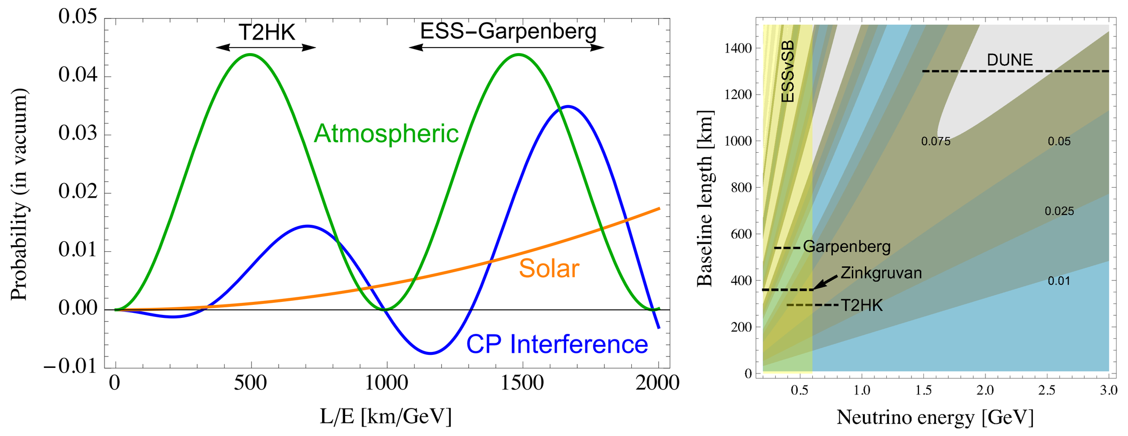

Fig. 3 [Left] Components of $P^{\rm vac}_{\nu_\mu \to \nu_e}$. [Right] $P_{\nu_\mu \to \nu_e}$ on the E-L plane.

Atmospheric neutrinos at the far detector

A megaton-class WC detector will provide an unprecedented size of atmospheric neutrino data: A typical rate of atmospheric neutrino events is $\sim 10^5$/(Mton·yrs). This can compensate for disadvantages of the beam experiment focusing on the second oscillation maximum, one of which is the θ_{23} determination.

Physics performance of ESSνSB+atmos

We carry out numerical simulations to evaluate the physics potential of the ESSνSB with the public code GLoBES [4]. In the treatment of the systematic errors, we follow the method developed in Ref. [5]. The test statistics is defined by comparing a test value T with the *observed* (true) value O as

$$\chi^2_{\rm Far/Near} = \sum_i^{\rm bins} \frac{|T_{{\rm F/N},i} - O_{{\rm F/N},i}|^2}{O_{{\rm F/N},i}}, \quad T_{{\rm F/N},i} = S_{{\rm F/N},i} + \sum_I^{\rm BGs} B_{{\rm F/N},I,i},$$

$$S_{{\rm F/N},i} = \left[1 + \sum_A^{\rm errors} \xi_{{\rm F/N,Sig.},A}\right] N_{{\rm F/N,Sig.},i}, \quad B_{{\rm F/N},I,i} = \left[1 + \sum_A^{\rm errors} \xi_{{\rm F/N},I,A}\right] N_{{\rm F/N},I,i}$$

where the signal S and the background B consist of the event numbers Ns and the systematic errors parameterized with ξs. Ns are calculated as "Flux×Probability×Cross section×Energy smearing". We use the QE cross section calculated with GENIE (G18_10a_00_000) [6]. For the detection efficiency and the energy smearing, we adopt Ref. [7]. The uncertainties ξs are taken into account as the "pulls", which are given in Tab. 1. For the $\nu_\mu \to \nu_e$ appearance signal at the far detector, we count in the following 5 BGs, $B_{F,I=\{1\cdots5\}}$: 1. ν_μ misID, 2. ν_e contami., 3. $\bar{\nu}_e$ contami., 4. ν_μ NC misID, and 5. $\bar{\nu}_\mu \to \bar{\nu}_e$ app. For the ν_μ flux monitored at the near detector, we take the 2 BGs into account, $B_{N,I=\{1,2\}}$: 1. ν_e misID and 2. ν_μ NC misID. Finally, we add the χ^2 for atmospheric neutrino data, following Refs. [8,9].

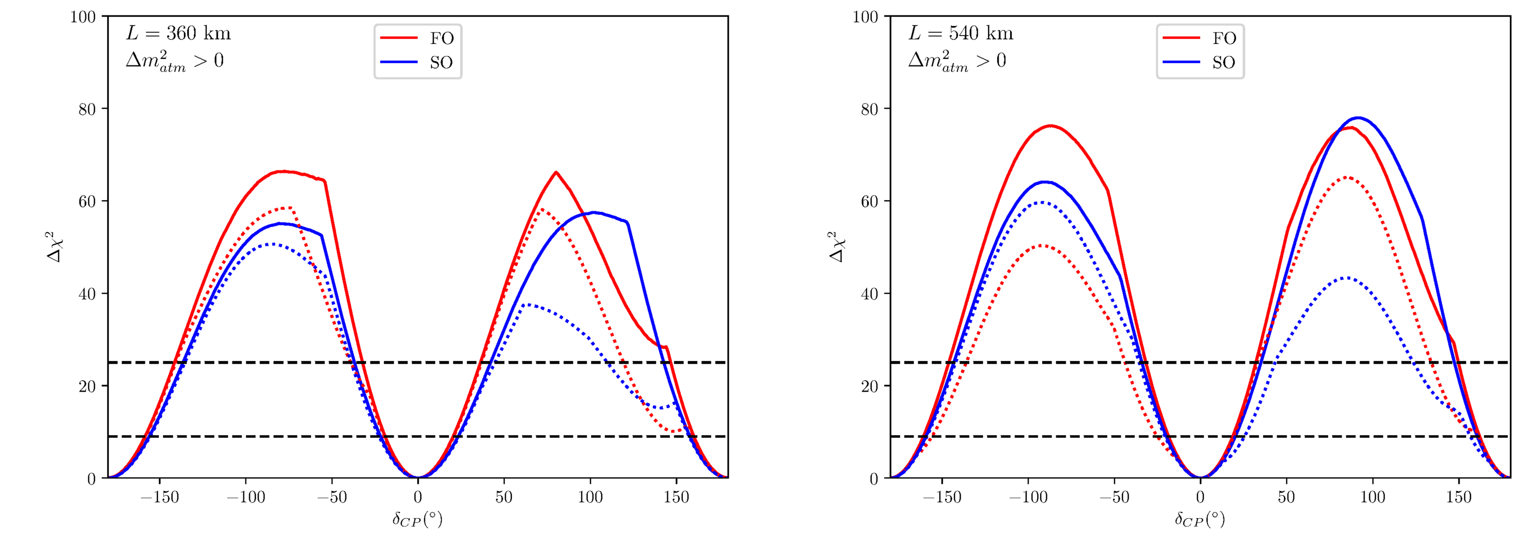

Fig. 4 Significance of the rejection of the CP conserving cases $\delta_{\rm CP}^{\rm true} = \{0, \pi\}$.

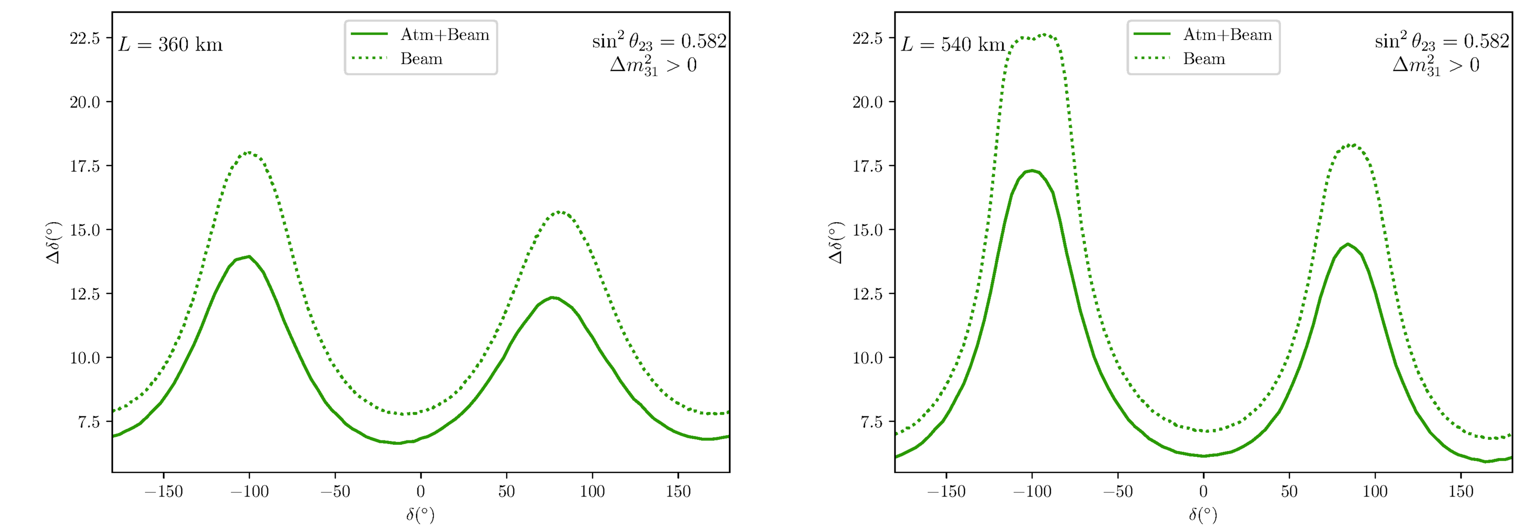

Fig. 5 Precision in the determination of the CP violating phase δ.

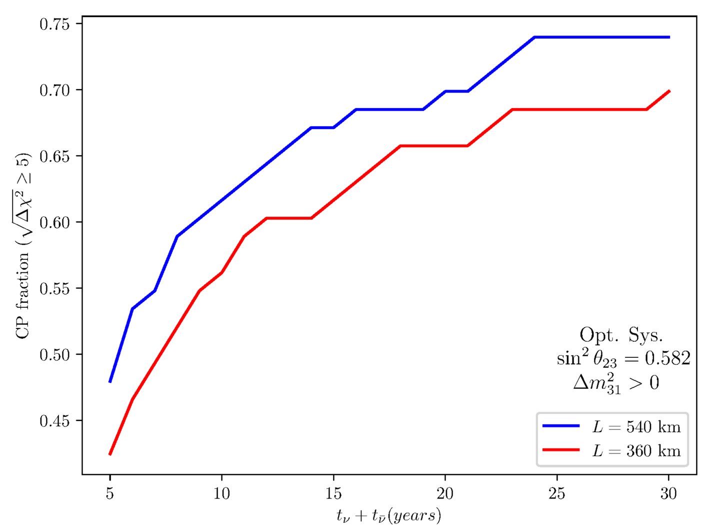

Fig. 6 CP fraction as a function of the running time.

The results show that the beam experiment suffers from the θ_{23} octant and mass hierarchy degeneracies (kinks in Fig. 4), and they are lifted by including the atmospheric neutrino data, cf., dotted (beam only) vs solid (beam+atmos) curves in Figs. 4 and 5. As shown in Fig. 6, the improvement of the CP fraction is saturated only after the total running time reaches $\sim$25 years, where the systematic uncertainties start dominating the error.

For studies on the physics performance of ESSνSB, see also Refs. [10-13].

To improve the performance...

Our simulation also reveals that it is important to control the uncertainties of 1. the ν flux for the BG events ($\delta\phi_{B\nu}$), 2. the number of NC backgrounds (δNC_B), and 3. the ratio between the CC cross section of ν_e and that of ν_μ ($\delta\sigma_e/\sigma_\mu$) to keep a good CP sensitivity. An optimization study in terms of the baseline length shows that both Zinkgruvan ($L = 360$ km) and Garpenberg ($L = 540$ km) are the favourable options. The systematics have a greater impact in the case with a shorter baseline $L < 400$ km, i.e., Zinkgruvan suffers more from the effect of the systematics, where a large part of the CP information comes from the measurement of the first oscillation maximum. Since the CP term is subleading at the first oscillation maximum (cf. Fig. 3), an experiment with a shorter baseline, which mainly observes the first maximum, is more easily affected by systematic uncertainties, in general.

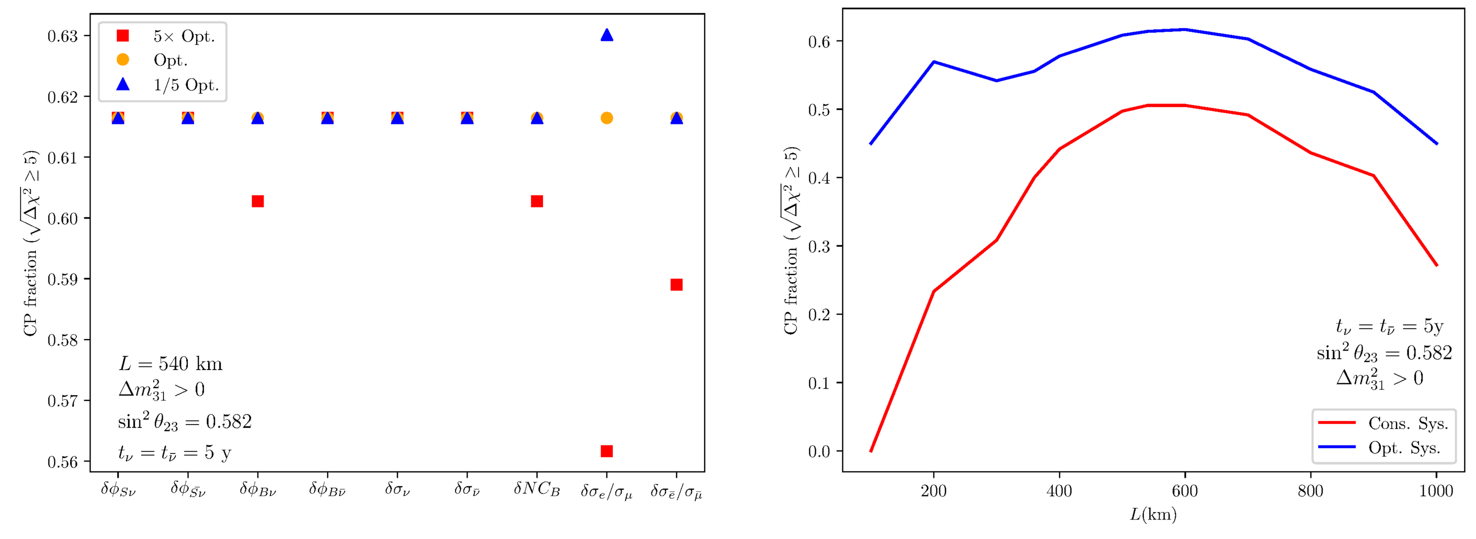

Fig. 7 Impact of the systematic errors and the choice of the baseline length on the CP fraction.

Systematics	Optimistic (%)	Conservative (%)
Fiducial volume ND	0.2	0.5
Fiducial volume FD	1.0	2.5
Flux error ν	5.0	7.5
Flux error $\bar{\nu}$	10	15
NC BG	5.0	7.5
$\sigma\times$ eff. QE	10	15
Ratio ν_e/ν_μ QE	3.5	11

Tab. 1 Systematic uncertainties for a typical superbeam experiment, taken from Ref. [5].

Related studies and Work in progress

Searches for ν_s [14,15] and neutrino portal DMs [16] at the ESSνSB have been discussed. A test of flavour symmetries with ESSνSB is studied in Ref. [17]. We are planning to #1 update the simulations with new cross sections/energy smearing matrices. #2 study on the sensitivity to new physics, in particular, the trident process at the near detectors and proton decays at the far detector.

References: [1] E. Baussan et al., 1309.7022 [hep-ex]. [2] P. Coloma and E. Fernandez-Martinez, JHEP **04** (2012) 089. [3] A. de Bellefon et al., hep-ex/0607026. [4] GLoBES collaboration, Comput. Phys. Commun. **167** (2005) 195, **177** (2007) 432. [5] P. Coloma et al., Phys. Rev. **D87** (2013) 033004. [6] GENIE collaboration, http://www.genie-mc.org [7] MEMPHYS collaboration, arXiv:1206.6665. [8] P. Huber, M. Maltoni, and T. Schwetz, Phys. Rev. **D71** (2005) 053006. [9] J.-E. Campagne, JHEP **04** (2007) 003. [10] S. K. Agarwalla, S. Choubey, and S. Prakash, JHEP **12** (2014) 020. [11] K. Chakraborty, K. N. Deepthi, and S. Goswami, Nucl. Phys. **B937** (2018) 303. [12] K. Chakraborty et al., JHEP **05** (2019) 137. [13] M. Ghosh and T. Ohlsson, Mod. Phys. Lett. **A35** (2020) 2050058. [14] M. Blennow, P. Coloma, and E. Fernandez-Martinez, JHEP **12** (2014) 120. [15] M. Ghosh, T. Ohlsson, and S. Rosauro-Alcaraz, JHEP **03** (2020) 026. [16] M. Blennow et al., Eur.Phys.J. **C79** (2019) 7. [17] M. Blennow et al., arXiv:2005.12277.

Acknowledgements: We are extremely grateful to Michele Maltoni for providing us with the simulations of atmospheric neutrino dataset. We are also indebted to Budimir Klicek and Marco Roda for suggestions and help with the GENIE tunes most appropriate for the ESSνSB energy range. We also want to thank WP6 of the ESSνSB design study, in particular Monojit Ghosh. This work is supported in part by the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreements 674896-Elusives, 690575-InvisiblesPlus, and 777419-ESSnuSB, as well as by the COST Action CA15139 EuroNuNet. MB, EFM, and SR acknowledge support from the "Spanish Agencia Estatal de Investigación" (AEI) and the EU "Fondo Europeo de Desarrollo Regional" (FEDER) through the project FPA2016-78645-P; and the Spanish MINECO through the "Ramón y Cajal" programme and through the Centro de Excelencia Severo Ochoa Program under grant SEV-2016-0597. MB also acknowledges support from the Göran Gustafsson foundation.