European Spallation Source Neutrino Superbeam Experiment

— Physics reach —

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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. 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 study 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. The first proton beam on target is scheduled in 2023.

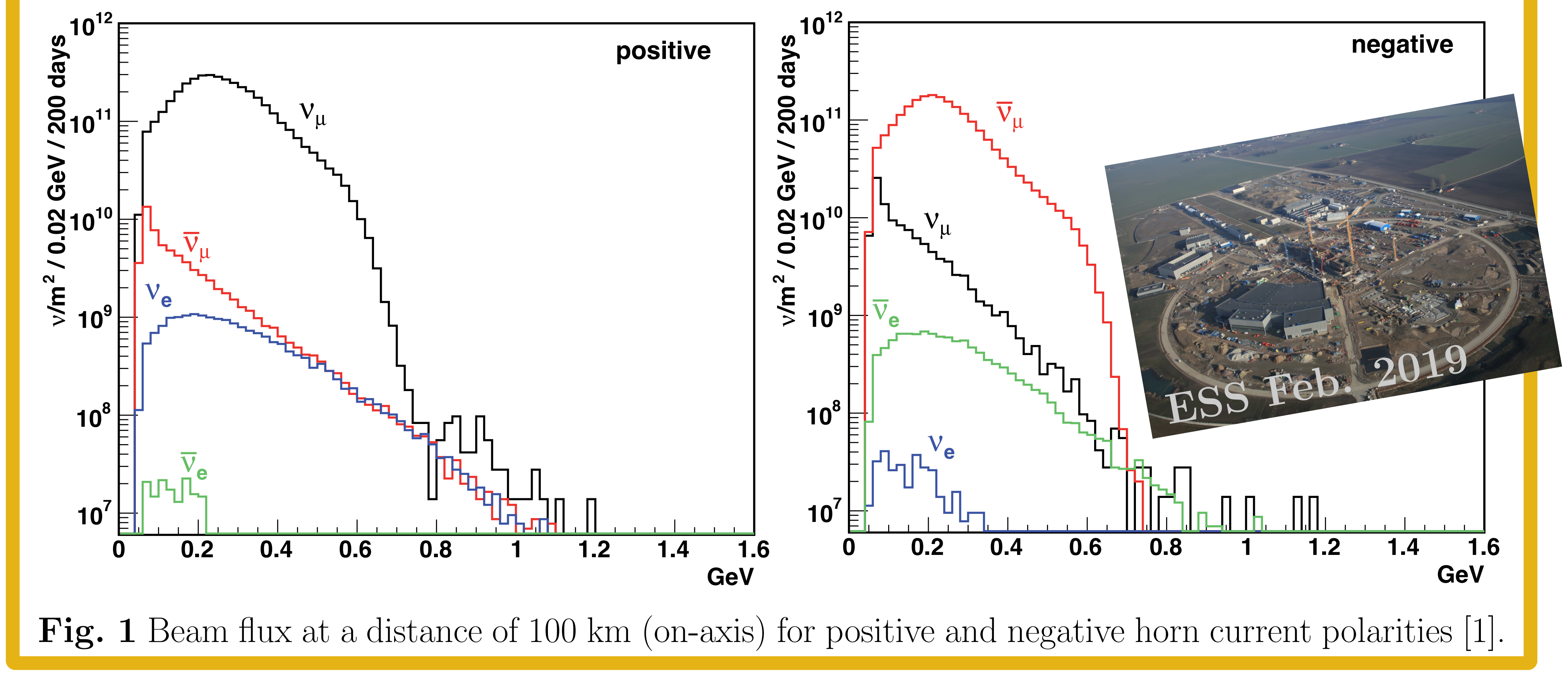

Fig. 1 Beam flux at a distance of 100 km (on-axis) for positive and negative horn current polarities [1].

Far detector for 2nd maximum

The interference term, which contains the information of the CP phase, accounts for a larger amount of the oscillation probability at the second maximum than at the first one [2]. To compensate the loss of the neutrino flux due to a long baseline for the second maximum, a megaton-class detector is required — the MEMPHYS proposal (Water Čerenkov) [3]

Fig. 2 Candidate sites

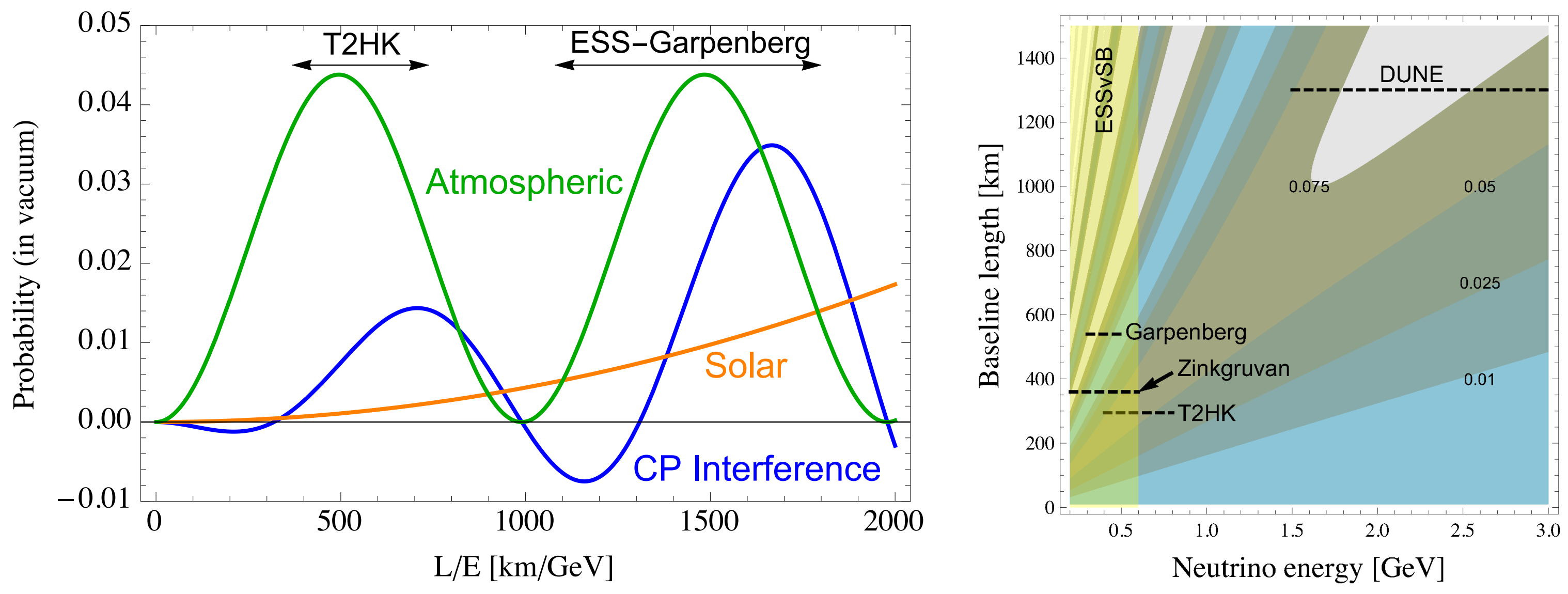

Fig. 3[Left] Components of $P^{\rm vac}_{\nu_\mu \to \nu_e}$. [Right] $P_{\nu_\mu \to \nu_e}$ on the E-L plane.

Physics performance of ESSνSB

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 [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".

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 ν_μ monitoring at the near detector, we take the 2 BGs, $B_{N,I=\{1,2\}}$: 1. ν_e misID and 2. ν_μ NC misID.

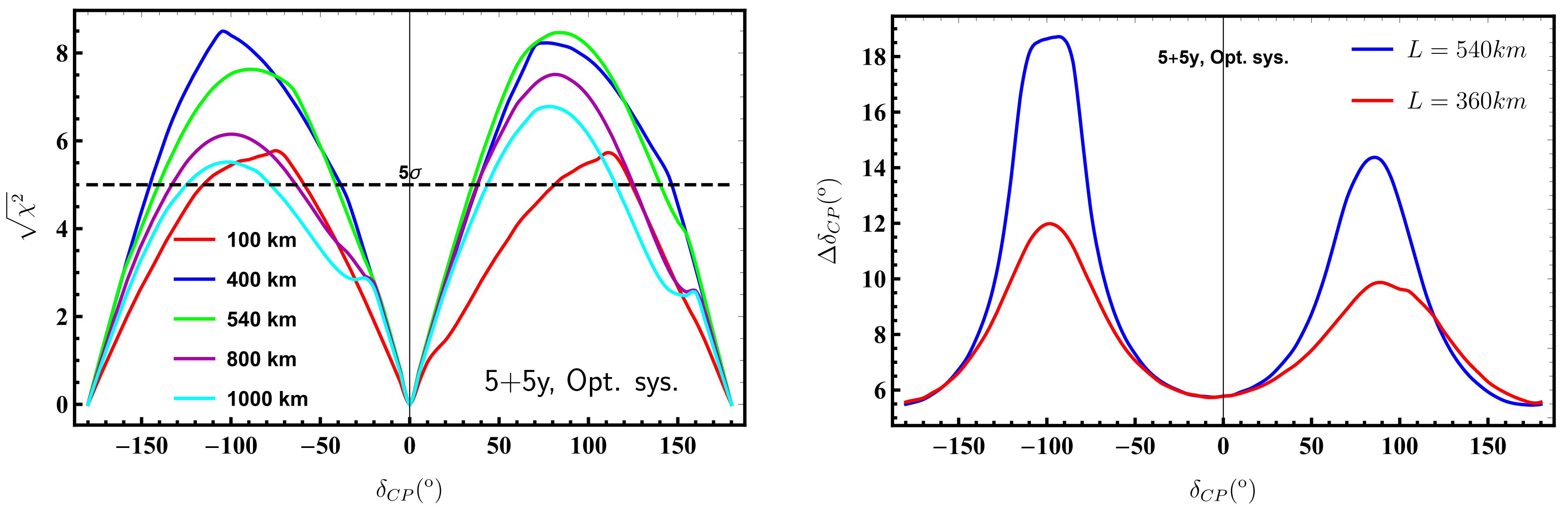

Fig. 4 [Left] Significance of the CP violation discovery. [Right] Precision in the measurement of $\delta_{\rm CP}$. Here "Optimistic" systematic errors in Tab. 1 are adopted.

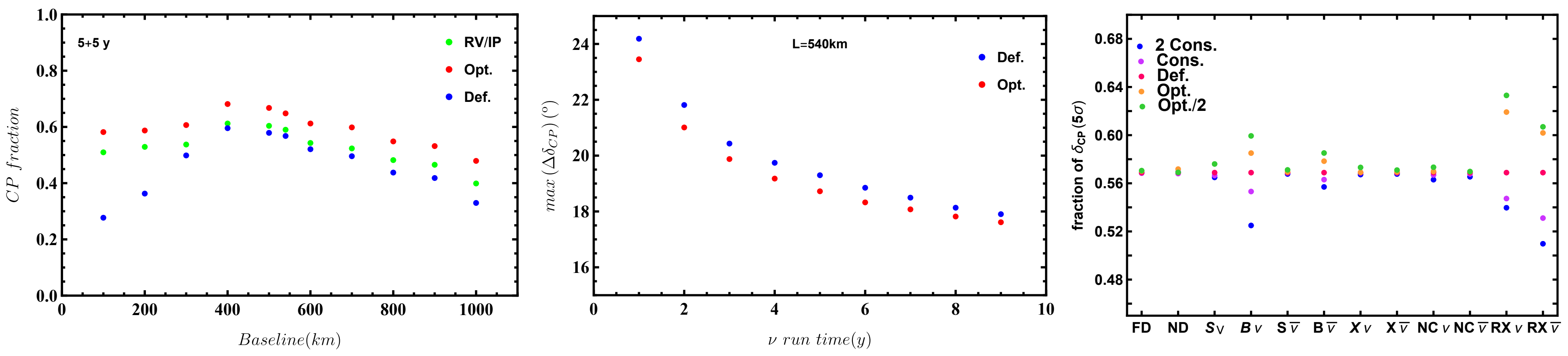

Fig. 5 [Left] Optimization in the baseline length [Middle] That in the distribution of the running time of $\nu/\bar\nu$, [Right] Impact of each systematic error.

Systematics (ξ)	Conservative	Default	**Optimistic**
Flux: ν_μ (Signal)	10%	7.5%	**5%**
Flux: $\bar\nu_\mu$ (Signal)	20%	15%	**10%**
Flux: ν Background	20%	15%	**10%**
Flux: $\bar\nu$ Background	40%	30%	**20%**
Fiducial volume: Near detector	1%	0.5%	**0.2%**
Fiducial volume: Far detector	5%	2.5%	**1%**
Cross section: QE	20%	15%	**10%**
Cross section: QE ν_e/ν_μ ratio	Free	11%	**3.5%**
Matter density	5%	2%	**1%**

Tab. 1 List of systematic errors. In the simulations in Fig. 4, we adopt the "Optimistic" setup.

The uncertainties of ξs are taken into account as the "pulls", which are given in Tab. 1.

We adopt the migration matrices described in [6] for the MEMPHYS-type detector, which contain the information of the cross section, the detection efficiency for the signals, and the misID rate etc for backgrounds.

The total running time is assumed to be 10 years, and the fiducial mass of the far detector is set to 0.5 mega tons. We explicitly simulate a near detector (WC) with the mass of 0.1 kton, which is placed at 0.5 km.

For the physics performance of ESSνSB, see also [7-9].

Work in progress

Combining the atmospheric neutrino observation at the far detector to improve the precision in the determination of the atmospheric parameters. Updating the QE cross sections provided by GENIE [10]. New physics searches: ν_s [11] and the trident process at the near detectors. Proton decay processes at the far detector.

References [1] E. Baussan et al., 1309.7022 [hep-ex]. [2] P. Coloma and E. Fernandez-Martinez, JHEP **1204** (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] MEMPHYS collaboration, 1206.6665 [hep-ex]. [7] S. K. Agarwalla, S. Choubey, S. Prakash, JHEP **1412** (2014) 020. [8] K. Chakraborty, K. N. Deepthi, S. Goswami, Nucl. Phys. **B937** (2018) 303. [9] K. Chakraborty et al., 1902.02963 [hep-ph]. [10] GENIE collaboration, http://www.genie-mc.org [11] M. Blennow, P. Coloma, E. Fernandez-Martinez, JHEP **1412** (2014) 120.

Acknowledgements: 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 (ESSnuSB).