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ESS NEUTRINO SUPER BEAM

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Abstract

We compute the expected physics performance according to the initial parameters as defined in D.2.1. We also perform studies optimizing the physics performance as a function of the running time of the experiment in each polarity and the distance between the beam and the detector. Finally we study the relative impact on the physics performance of each of the individual sources of systematic errors studied, which are expected to be bottlenecks of the physics reach, to identify the most relevant ones so that the work of other WPs can focus on reducing them.

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1. INTRODUCTION

In this document we will present the first estimates of the physics reach of the ESSnuSB experiment according to the initial parameters defined in D.2.1. We also go beyond these initial parameters so as to identify both possible bottlenecks to the physics reach that could potentially be tackled by other WPs as well as possible optimizations to the design or measurement strategy. This first computation of the physics reach also served to ready and calibrate the setup that will be used to update the expected performance of the facility from input from the different WPs as they provided more updated and optimized descriptions of the different parts of the experiment.

The simulation of the physics performance of the facility is done via the GLoBES software [1,2]. The file used to describe the ESSnuSB experiment in GLoBES has been prepared according to the initial set of parameters defined in D.2.1 as summarized in Table 1.1:

1. Equipment	Parameter	Nominal value	Minimal value	Maximal value	Units	Comments
Detector	Fiducial mass	507			kton	Updated with latest assumptions from WP5
Beam	Proton energy	2.5	2	3.0	GeV	FFlux from Ref. [3]
Location	Baseline	540	100	1000	Km	To optimize
Beam	Total running time	10			yrs	$1.7\cdot10^7$ s per year assumed
Beam	Neutrino/Antineutrino runs	2/8	1/9	9/1	yrs	To optimize
Detector	Expected performance for signal and background components					Migration matrices and efficiencies from Ref. [4]
Detector	Systematic uncertainty on near detector fiducial volume	0.5%	0.2%	1%		See Ref [5]
Detector	Systematic uncertainty on far detector fiducial volume	2.5%	1%	5%		See Ref [5]
Beam	Systematic uncertainty signal neutrino component	7.5%	5%	10%		See Ref [5]
Beam	Systematic uncertainty background neutrino component	15%	10%	20%		See Ref [5]
Detector	Systematic uncertainty on QE cross section	15%	10%	20%		See Ref [5]
Detector	Systematic uncertainty on electron to muon neutrino ratio of QE cross	11%	3.5%	Free		See Ref [5]
Location	Systematic uncertainty on matter density along neutrino beam	2%	1%	5%		See Ref [5]

Table 1.1 Initial set of parameters for the simulation performance.

The fiducial mass of 507 kton corresponds to the latest estimations from WP5 and agrees with is expected for a MEMPHYS-type water Cerenkov detector with a total mass of 1 Mton [4].

The neutrino fluxes expected at the detector for the different neutrino beam focusing as computed in Ref. [3] have been used. In what follows we will assume the beams from 2.5 GeV protons as this represents the nominal working value for the other WPs. These fluxes will be updated when input from the other WPs becomes available. a total running time of the experiment of 10 years (with $1.7 \cdot 10^7$ s per year) will be assumed, however the relative time spent running with positive focusing (neutrino mode) and negative focusing (antineutrino mode) will be varied to explore the optimal strategy to maximize the physics reach.

The baseline between the beam production and the detector corresponds to the distance to the Garpenberg mine at 540 km. However, other options will be considered to study what configuration optimizes the physics reach of the facility. Particular attention will be devoted to a 360 km baseline which would correspond to the distance to Zinkgruvan, another potentially interesting mine to host the ESSnuSB detector.

The expected detector response in terms of energy reconstruction as well as signal efficiency and background suppression factors after selection cuts are performed has been taken from the study of Ref. [4]. These assumptions will be updated as soon as new results from WP5 become available.

Finally, different sources of systematic errors are expected to affect the physics reach of the facility. We have followed Ref. [5] which discussed the most likely sources of systematic that this type of neutrino oscillation facilities would face as well as a set of "optimistic" (listed as minimal value in Table 1.1), "default" (listed as nominal) and "conservative" (listed as maximal) values for them. We will mainly show results for the "default" and "optimistic" scenarios since the present consensus among most new generation neutrino oscillation facilities is that systematic errors on the ballpark of the "optimistic" values will be achievable with the information available by the time these facilities are built. These values will also be updated as new information from WP5 becomes available.

2. RESULTS

In the upper panels of Fig. 2.1, we study the optimal baseline between the beam and the detector to maximize the physics reach of the experiment. In particular we use as performance indicator the fraction of all possible values that the unknown CP violating phase δ_{CP} could have for which the facility would be able to claim a 5σ discovery of CP violation. That is, we simulate the number of events expected at the detector for values of δ_{CP} between -180 and 180 and for each set of events we compare them, via the $\Delta\chi^2$ function, with the expectation in absence of leptonic CP violation (i.e. values of δ_{CP} equal to 0^o or 180^o). In the upper-left panel of Fig.2.1 we show the computed values of the $\Delta\chi^2$ as a function of δ_{CP} for different values of the baseline between beam and detector in the case that "default" systematics are assumed. The horizontal dashed line at $\Delta\chi^2 = 25$ represents the 5σ significance under the assumption of a Gaussian distribution. The upper-right panel of Fig. 2.1 shows the fraction of values of δ_{CP} for which $\Delta\chi^2 > 25$ as a function of the baseline. The red and blue dots are computed under the assumption of "optimistic" and "default" systematics respectively, while the green dots represent an assumption more similar to the latest T2HK estimations of their physics reach which assume a detector with a smaller fiducial mass (374 ktons) but better photodetector coverage where only an overall systematic error of around 3% is assumed (after combining the information from the near and far detectors). The lower panels of Fig. 2.1 show the same results but as a function of the time running in neutrino mode (with the rest of the 10 years running in antineutrino mode) instead of the baseline.

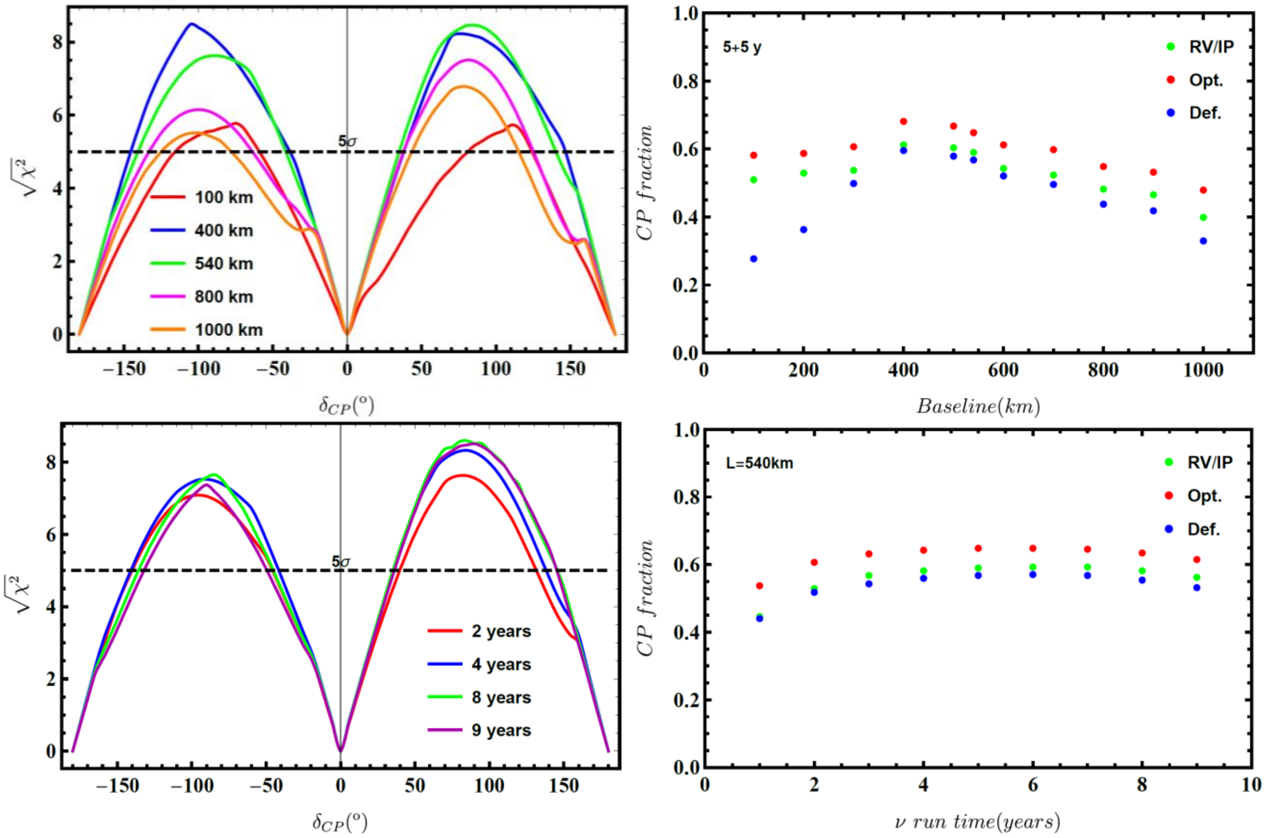

Figure 2.1. Significance for the discovery of CP violation as a function the baseline between the beam and detector (upper panels) and of the running time in neutrino mode (lower panels). The right panels show the achievable significance as a function of the possible values of δ_{CP}, while the left panels show the fraction of values of δ_{CP} for which a 5σ discovery would be possible as a function of the baseline and running time in neutrino mode respectively.

As can be seen from the upper-right panel of Fig. 2.1, the ESSnuSB performance is not very sensitive to the level of systematic errors as long as relatively long baselines above 300 km are considered. Indeed, these baselines are close to the second oscillation maximum where it has been shown that the effect of δ_{CP} is maximized and the impact of systematic errors minimized [6]. Conversely, at shorter baselines closer to the first oscillation maximum the distance between the red and blue dots is much more significant and a better control of the systematic errors becomes mandatory to improve the physics reach. The optimal baseline in terms of physics reach would be around 400 km, close to both the Garpenberg (540 km) and Zinkgruvan (360 km) options. Regarding the running time in neutrino versus antineutrino mode, the lower-right panel shows that the fraction of values of δ_{CP} for which a 5σ discovery would be possible, does not depend significantly on this parameter. Nevertheless, the optimal configuration would be with a more or less symmetric splitting of the time around 5 years in neutrino mode and 5 years in antineutrino.

Another interesting performance estimator is the precision with which the experiment would be able to determine the exact value of δ_{CP}. This is depicted in Fig. 2.2. The left panel shows the precision in the measurement of δ_{CP} as a function of the possible values of δ_{CP} for different running times in neutrino mode and for "default" systematics and a baseline of 540 km. The right panel shows the worst precision achievable (for any value of δ_{CP}) as a function of the running time in neutrino mode for "default" (blue dots) and "optimistic" (red dots) assumptions on the sysmtematic errors and a baseline of 540 km.

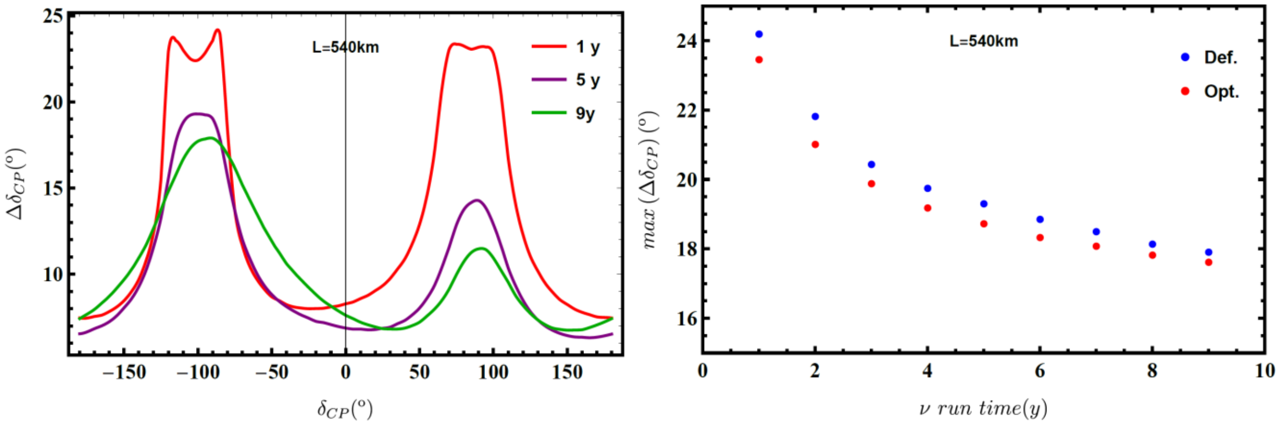

Figure 2.2. Left panel: precision in the measurement of δ_{CP} as a function of the possible values of δ_{CP} for different running times in neutrino mode. "Default" systematics and a baseline of 450 km have been assumed. Right panel: worst precision achievable in the measurement of δ_{CP} as a function of the running time in neutrino mode for "default" (blue dots) and "optimistic" (red dots) assumptions on the sysmtematic errors and baseline of 540 km.

As can be seen from Fig 2.2, the precision is worst for values of δ_{CP} close to ±90°, which is a general feature of all neutrino oscillation facilities observing close to a maximum of the oscillation facility [7]. However, this feature is particularly pronounces for the red curve in the left panel, which corresponds to only 1 year running in neutrino mode and 9 tears in antineutrino mode. This configuration would be characterized by very low statistics, since the neutrino flux and particularly its cross section is smaller than the neutrino one. And the poorer information at different energies leads to the appearance of degenerate solutions that around δ_{CP} = ±90° are not resolved and combine in a much larger region decreasing dramatically the precision in the measurement of δ_{CP}. Thus, for this other performance estimator, the dependence on how the running time is split between neutrinos and antineutrinos is much more relevant a longer time spent in neutrino mode is preferred around δ_{CP} = ±90°. However, notice that the different curves in the left panel cross at different points. Therefore, the optimal splitting of time between neutrino and antineutrino modes is strongly dependent on the actual value of δ_{CP} and thus the best strategy would be to adapt the running time as hints on its value become available from this and other facilities.

In Fig 2.3 the relative importance of the different sources of systematic errors listed in Table 1.1 is studied. The fraction of values of δ_{CP} for which a 5σ discovery would be possible is shown when each of the systematic errors is varied individually between one half of the "optimistic" values and twice the "pessimistic" ones. As can be seen, the largest spread is observed for the systematic uncertainty on the background components of the neutrino and antineutrino fluxes as well as on the uncertainty associated to the ratio between the electron and muon neutrino cross sections. Indeed, these are two sources of systematic errors which cannot be easily constraint by information from the near detector since the neutrino oscillation signal at the far detector is composed of electron neutrinos while the near detector mainly observes muon neutrinos (except for the background components). These are therefore the sources of systematic error that should be reduced as much as possible to increase the performance of the experiment.

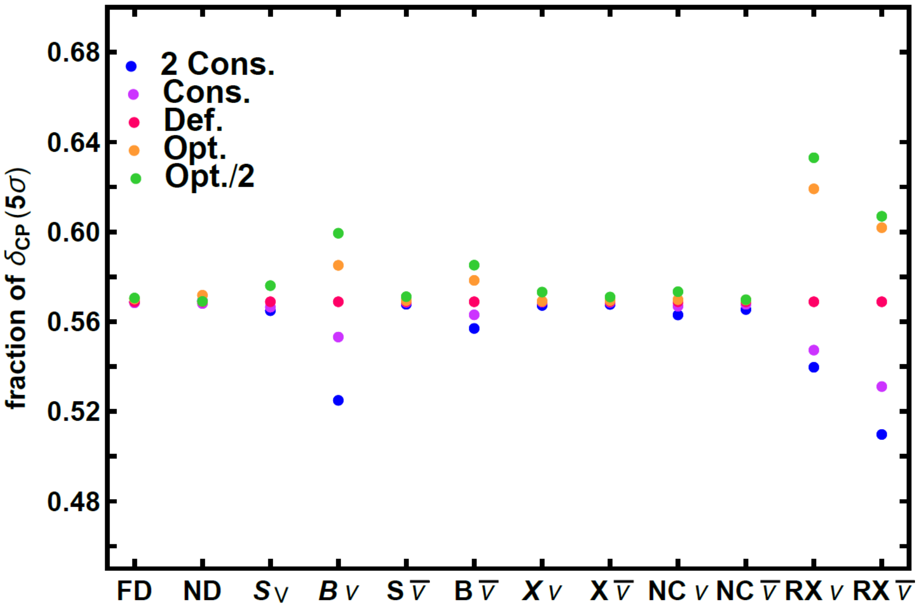

Fig. 2.3. Fraction of values of δ_{CP} for which a 5σ discovery would be possible is shown when each of the systematic errors from Table 1.1 is varied individually between one half of the "optimistic" values and twice the "pessimistic" ones.

3. CONCLUSIONS

We have found that the optimal baseline to maximize the physics reach of the ESSnuSB is around 400 km, close to both the Garpenberg (540 km) and Zinkgruvan (360 km) options and close to the second oscillation maximum. Also, as expected from a facility observing at the second oscillation maximum, the physics performance of the ESSnuSB is not strongly affected by systematic uncertainties but we have identified the two that have the largest impact on the physics reach: the relative difference between the muon and electron neutrino cross sections and the uncertainty on the background components of the beam. Regarding how the running time is split between neutrino and antineutrino modes, the impact on the fraction of values of δ_{CP} for which a 5σ discovery would be possible, is very small with a prefence for a symmetric running. However, the impact on the precision which which of δ_{CP} would be measured is much stronger and the optimal strategy depends on the actual value of δ_{CP}. Thus, it would be best to adapt the relative running time in neutrino and antineutrino mode to the present hints on the value of δ_{CP} at the time of data taking.

To summarize, we show in Fig. 3.1 the physics reach of the facility for the set of parameters in Table 1.1. We show its performance for the significance on the discovery of CP violation as a function of the value of δ_{CP} (upper panels); the same significance but as a function of the fraction of values of δ_{CP} for which it would be achievable (middle panels); and the precision in δ_{CP} (lower panels). The left (right) panels are for "default" ("optimistic") systematics. Finally the red line corresponds to the Zinkgruvan (360 km) baseline, the blue to the Garpenberg (540 km) option and the green dashed line would represent the possibility of having half of the mass of the detector at each site. This option combines complementary information at different baselines and tends to perform better than a single baseline for most areas of the parameter space. Interestingly the two sites are well-aligned with the beam and this could be a possibility worth studying. However, one of the two (or either) detectors would necessarily receive the beam off-axis. This effect has not been incorporated and that would need new flux computations for future implementation.

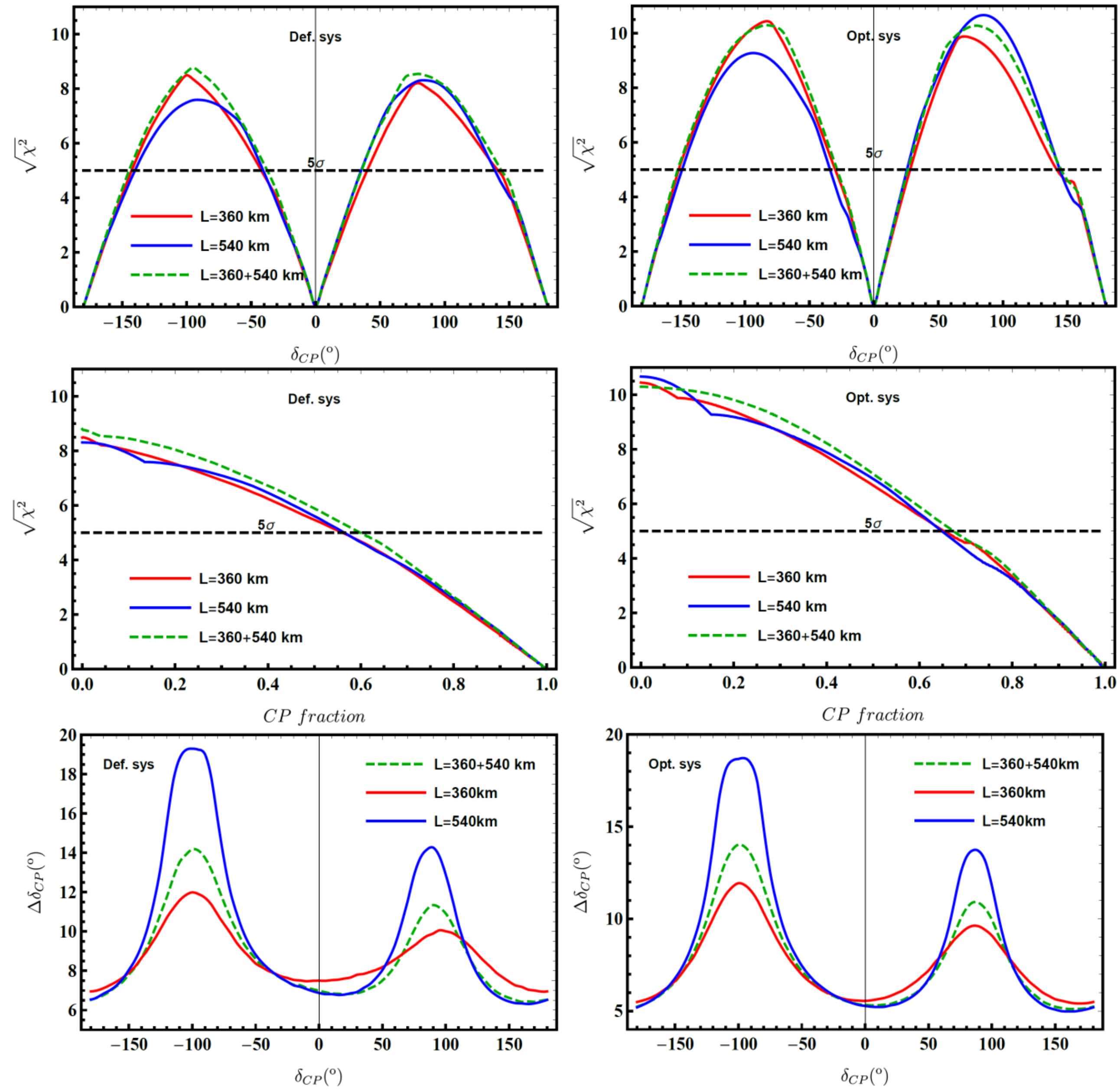

Fig. 3.1. Significance on the discovery of CP violation as a function of the value of δ_{CP} (upper panels); the same significance but as a function of the fraction of values of δ_{CP} for which it would be achievable (middle panels); and the precision achievable in the measurement of δ_{CP} (lower panels). The left (right) panels are for "default" ("optimistic") systematics.

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