PROCEEDINGS OF SCIENCE

European Long-baseline Neutrino Oscillation Projects

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After discovering that the last mixing angle θ_{13} was relatively large, the road is now open to Super Beam projects using conventional accelerator techniques to discover a possible CP violation in the leptonic sector. These same projects also could resolve the neutrino mass hierarchy problem, if not yet settled by then. For these projects a very intense neutrino beam is required necessitating proton beams with a power higher than an order of magnitude than the present ones. Two european projects are going in this direction, LAGUNA–LBNO and ESSνSB. LAGUNA–LBNO plans to have two stages, one using the present CERN accelerators with improved intensity, to determine the neutrino mass hierarchy using matter effects, and a second one with new CERN installations, to observe CP violation in the leptonic sector. ESSνSB, proposing to use the world's most intense proton linac of the European Spallation Source, operates almost exclusively on the second oscillation maximum, less sensitive to systematic errors. It plans to cover at 5 σ statistical significance more than 50% of the CP violation parameter δ_{CP}. This project, contrarily to LAGUNA–LBNO proposing to use a liquid argon detector, proposes to use a megaton Water Cherenkov neutrino detector installed 1000 m down in a mine at a distance of about 500 km from the neutrino source. Both projects have a rich astroparticle physics program and could also study the proton lifetime.

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1. Introduction

During the last fifteen years a number of neutrino oscillation projects have been proposed mainly to measure the last unknown mixing angle θ_{13}, determine the neutrino mass hierarchy and observe for the first time a possible CP violation in the leptonic sector. These projects, using the oscillation $\nu_\mu \to \nu_e$, have mainly been optimised in order to reach as low as possible θ_{13} values. In 2012, reactor experiments measured for the first time θ_{13} [1, 2, 3] and revealed that this value was relatively high ($\sim 8^\circ$) compared to expectations. Since then, for projects where it was possible, new optimisations have been performed according to the measured θ_{13} value.

Meanwhile, it has also been shown that for large θ_{13} values it was better to go to the second oscillation maximum of the oscillation $\nu_\mu \to \nu_e$, less sensitive to systematic uncertainties [4], for CP violation discovery. It can also be shown [5] that the neutrino/anti–neutrino asymmetry in the vacuum is approximately equal to $0.30 \sin\delta_{CP}$ at the first oscillation maximum, while for the second oscillation maximum this value becomes $0.75 \sin\delta_{CP}$. This clearly shows that experiments at the second oscillation maximum have significantly higher sensitivity to δ_{CP} than those placed at the first oscillation maximum.

The drawback of going to the second oscillation maximum compared to the first one comes from the significant decrease of statistics for the same neutrino energy, due to the needed higher distance from the neutrino source to the detector location. On the other hand, decreasing the neutrino energy has another drawback coming from the rapidly decreasing neutrino cross–sections, especially below 1 GeV.

LAGUNA–LBNO [6] plans to use a high energy neutrino beam and a long baseline of the order of 2300 km, mainly working on the first oscillation maximum to determine the mass hierarchy using in a first stage a relatively low intensity proton beam. In a second stage, in order to increase statistics and be sensitive to CP violation, more intensive beam and more voluminous detector is planned.

ESSνSB [7] is almost exclusively devoted on the CP violation discovery operating at the second oscillation maximum. In order to produce a very intensive neutrino beam necessary to go to the second oscillation maximum, ESSνSB proposes to use the very powerful proton beam (5 MW) of the European Spallation Source (ESS) under construction in Lund, Sweden [8]. Due to the relatively short baseline of this project (~500 km), its sensitivity to the neutrino mass hierarchy is relatively low but not negligible. It is believed that this problem will by solved by the moment when these long term projects will start operation [9].

2. LAGUNA–LBNO

The LAGUNA–LBNO project is the continuation of LAGUNA [10], an EU FP7 project studying possible locations in Europe able to host a large underground laboratory devoted to neutrino oscillations and astroparticle physics. LAGUNA–LBNO limits its studies to only three sites giving the highest priority to an underground laboratory located at a distance of 2300 km from CERN. This underground laboratory located in the Pyhäsalmi mine (Finland), is supposed to mainly host a large liquid argon detector detecting neutrinos produced at CERN.

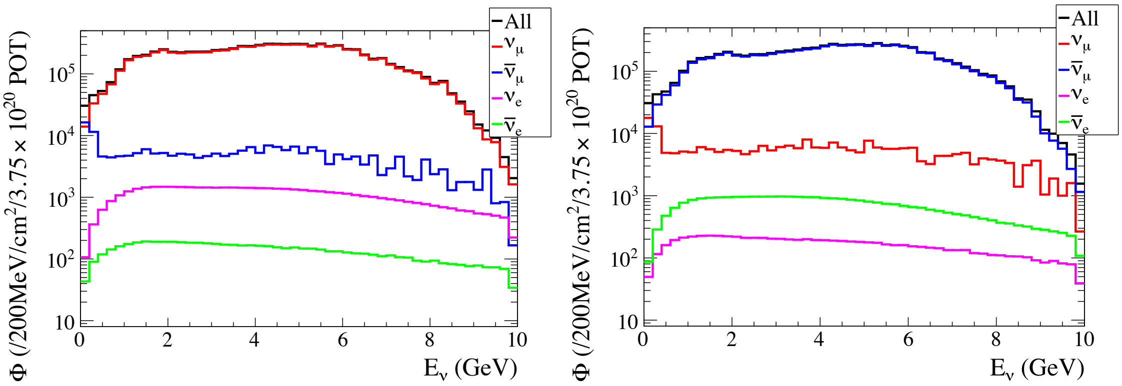

Figure 1: Neutrino (left) and antineutrino (right) fluxes for CERN-to-Pyhäsalmi beam.

In a first phase the present CERN accelerator facilities with improved intensities will be used. A wide band muon neutrino beam can be produced using the SPS proton beam (400 GeV) as done for the CNGS [11]. Fig. 1 [12] presents the neutrino energy distribution for all flavours of the neutrino beam, for the two running modes, "neutrinos" (50%) and "antineutrinos" (50%). It is assumed a proton beam power of 750 kW providing $1.0 - 1.4 \times 10^{20}$ protons on the target (p.o.t.).

This first phase using a 24 kton liquid argon detector is mainly devoted to the mass hierarchy problem and it is supposed to last about four years (4×10^{20} p.o.t.) per year. Fig. 2 presents the statistical significance T_0 to discover the neutrino mass hierarchy (mean value of $T = \chi^2_{IH} - \chi^2_{IH}$, comparing normal and inverted hierarchy) versus δ_{CP} [6] . From this figure it is clear that in a short time, more that 5 σ significance can be obtained for this physics subject for any δ_{CP} value.

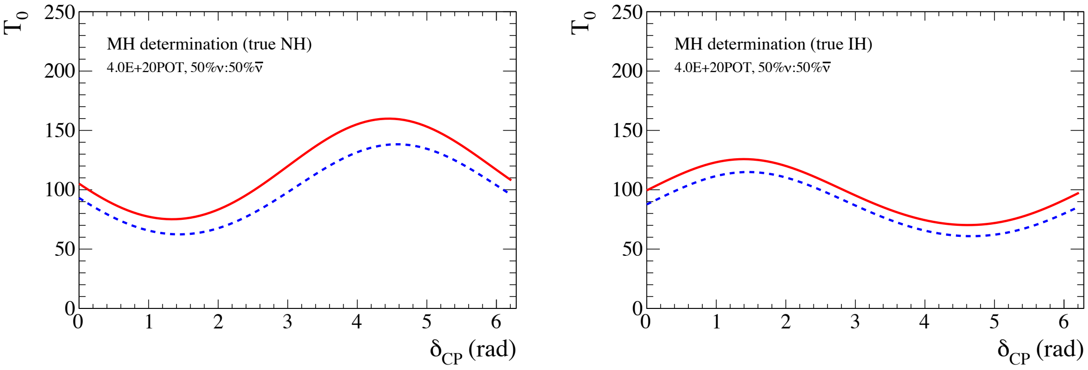

Figure 2: Mean value of the mass hierarchy test statistic T_0 for nominal and optimised SPS neutrino beams as a function of true δ_{CP} value.

In a second phase, not using anymore the CERN SPS, but using new powerful CERN accelerators as the low power SPL [13, 14] and the High Power PS (HPPS) [15], LAGUNA–LBNO will continue its physics programme mainly devoted to the observation of an eventual CP violation in the leptonic sector. In this phase, a larger detector will be used (∼70 ktons).

The power of protons extracted from the HPPS is expected to be of the order of 2 MW (3.5 ×

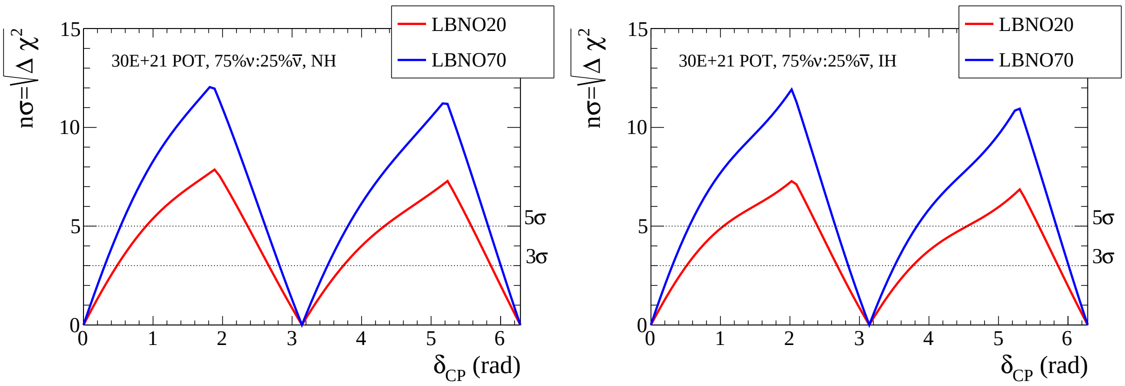

Figure 3: Sensitivity to CPV for the SPL/HPPS beam (normal hierarchy on the left and inverted on the right).

10^{21} p.o.t./year) for 50 GeV proton energy. Fig. 3 shows the discovery potential for CP violation of this project versus δ_{CP} for about 10 years of data taking for normal and inverted mass hierarchy. FRom this figure it is clear that a very large liquid argon detector is needed.

This study, done in the framework of the FP7 european projects, is now finished since August 2014. An R&D program has now started at CERN (WA105) on liquid argon detectors using a two–phase detection technique to prove the feasibility of this large detectors.

3. ESSνSB

This second European project is based on the European Spallation Source (ESS) facility under construction in Lund, Sweden. It is exclusively devoted to the CP violation discovery in the leptonic sector and uses entirely the second oscillation maximum advantages. For this, the very powerful proton source of ESS is necessary.

The ESS is a European facility to provide slow neutrons to research institutes and to the industry. For that, it utilises a very powerful 5 MW linac producing 2 GeV protons running at 14 Hz. The main characteristics of this linac are given in Table 1. The number of protons on target per year (208 days) is of the order of 2.7×10^{23}.

Table 1: Main ESS proton linac parameters.

Parameter	Value
Average beam power	5 MW
Proton kinetic energy	2.0 GeV
Average macro–pulse current	62.5 mA
Macro–pulse length	2.86 ms
Pulse repetition rate	14 Hz
Annual operating period	5000 h
Reliability	95%

ESSνSB proposes to increase the linac duty cycle in order to double the linac average power (without increasing the instantaneous power) and use half of the produced protons to produce neutrinos. Indeed, the linac duty cycle for neutron production is only 4%. This low duty cycle can be raised to 8% for simultaneous neutron and neutrino production. To achieve this, the pulse frequency of the linac can be raised from 14 Hz to 28 Hz, other scenarios are also under study. In this way, it can be sent alternatively, one proton pulse on the neutron target and one on the neutrino one.

Unfortunately, the proton pulse duration of 2.86 ms is too long for the neutrino production. The necessary current to be sent to the horn in order to well focus the charged pions, coming out of the target, towards the neutrino detector, is of the order of 350 kA. Due to this very high current the proton pulses sent to the neutrino facility target with a frequency of 14 Hz must be as short as possible in order to leave enough time to dissipate the power sent to the horn before the next pulse.

An accumulation ring is necessary, which short circumference could reduce the 2.86 ms pulses to few μs affordable by the horn. To avoid space charge effects during the entrance in the ring, the injection in the linac of H^- instead of protons is necessary. In order to fit in the already allocated ESS area, this accumulation ring must have a circumference not longer than 400 m shortening the proton pulses to about 1.5 μs, very suited to the horn operation. At the entrance of the accumulator ring the H^- ions have to be stripped using a laser–stripping device. Due to the very high beam power, the use of a foil stripping will probably be impossible because the foil would not resist to the proton beam.

On top of the accumulation ring, a target/horn station will also be needed together with a hadron decay tunnel. The decay tunnel length could be of the order of 25 m, long enough to allow charged pions to decay into neutrinos and muons, but also short enough to avoid muon decays (producing electron neutrinos) polluting the muon neutrino beam. Fig. 4 shows a possible layout of the ESS installations and the extra installations necessary to the neutrino beam production.

In order to mitigate the very high power of the proton beam, a system of 4 targets/horns pulsed one after the other is foreseen. This system has been well studied by the FP7 Design Study EUROν [16, 17]. The EUROν choices have also been adopted for the target and horn cooling. A target of titanium spheres of few mm diameter with cold helium gas cooling is proposed. The design of the horn pulse generator can be found in [18].

The length of the target, the shape of the horn and the length of the decay tunnel have been optimised in order to maximise the discovery probability of CP violation. Fig. 5 presents the neutrino beam composition before oscillation obtained using the ESS 2 GeV proton beam. The mean neutrino energy is of the order of 400 MeV. The obtained ν_μ beam has an about 0.5% ν_e contamination. These electron neutrinos could be used by a near detector to measure the electron neutrino cross–section at the same energies than the electron neutrinos detected by the far detector. These measurements will help to significantly reduce the systematic errors of this project.

The foreseen far detector is a megaton Water Cherenkov similar to MEMPHYS [19, 20]. A Water Cherenkov detector, compared to other detection technics as using a liquid argon or a liquid scintillator detector, is well suited at these relatively low neutrino energies. Its fiducial volume would be of the order of 500 ktons. Several active mines in Sweden are under investigation which could house the far detector. The two most interesting are those of Zinkgruvan and Garpenberg located at 360 km and 540 km, respectively from Lund. Another interesting mine (Kongsberg) is located in Norway near Oslo at 500 km. To choose the best, one several parameters are taken into

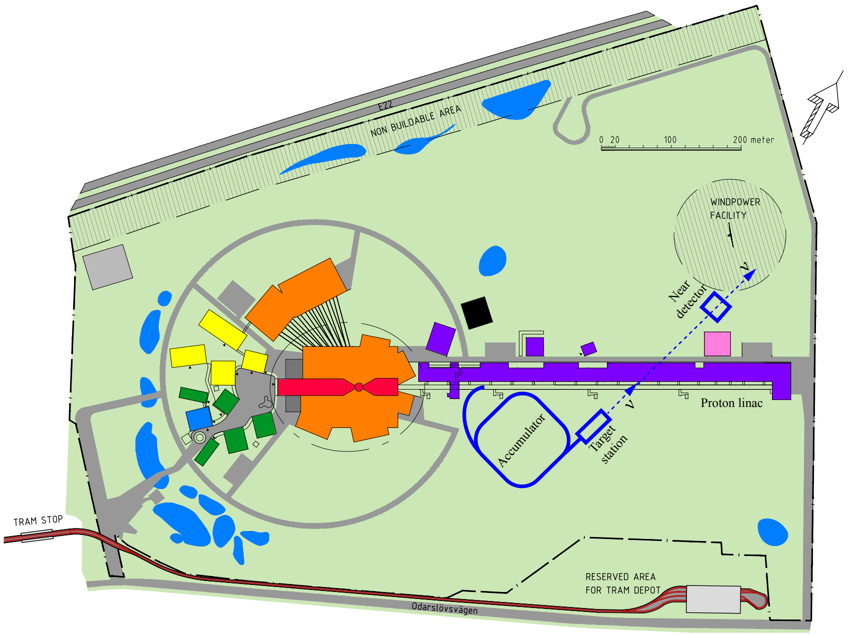

Figure 4: Layout of the ESS installations with a possible neutrino facility implementation.

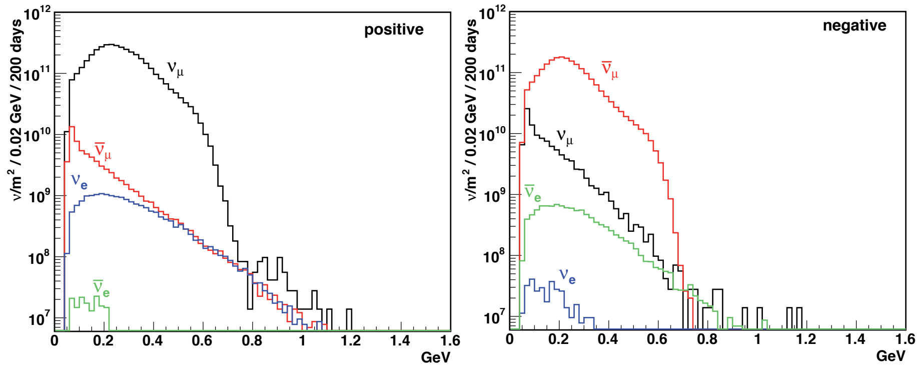

Figure 5: Neutrino energy distribution at a distance of 100 km on–axis from the target station, for 2.0 GeV protons and positive (left, neutrinos) and negative (right, antineutrinos) horn current polarities, respectively.

account as the situation of the mine itself in order to minimise the civil engineering and increase the physics performance to discover CP violation in the leptonic sector according to the proton beam energy. In this project, resolving the mass hierarchy problem is considered as a secondary physics subject although a 5 σ discovery significance can be reached for normal and inverted mass hierarchy [7]. It is very likely that this problem will be solved before these next generation long baseline projects. The same far detector can also be used to observe proton decays and to study cosmological neutrinos (from supernova explosions, solar and atmospheric neutrinos etc.).

Fig. 6 shows the neutrino and antineutrino spectra after oscillation (assuming $\delta_{CP} = 0$) and detected by MEMPHYS detector placed at a distance of 540 km from Lund. In order to compare neutrinos with antineutrinos and to have about the same statistics for both species, it is planned to run 2 years with neutrinos (positive polarity in the horn) and 8 years with antineutrinos (negative polarity).

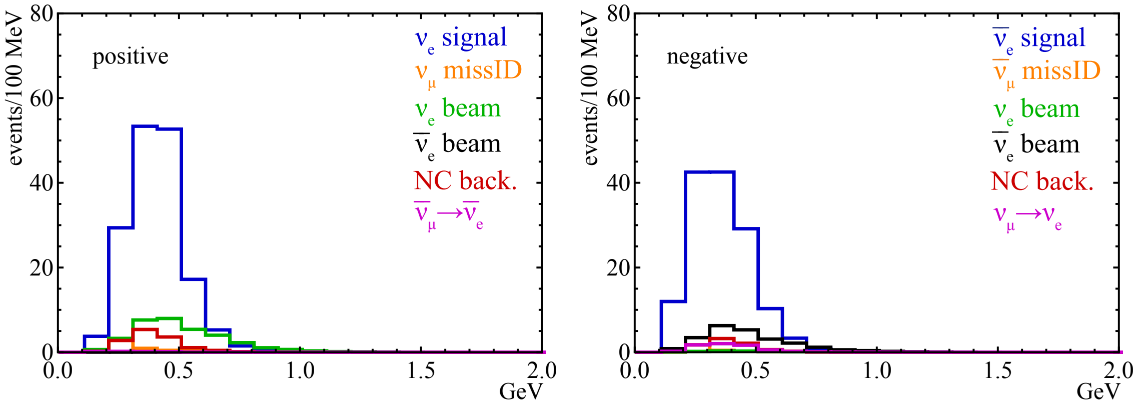

Figure 6: Energy distribution of the detected neutrinos and antineutrinos as reconstructed by MEMPHYS WC detector for two years of neutrino running (left) and eight years of antineutrino running (right) and a baseline of 540 km (2.0 GeV protons, $\delta_{CP} = 0$).

From Fig. 6 it is seen that the background is relatively low for both running modes, neutrinos and antineutrinos. This energy spectrum allows to fully exploit the advantages of the second oscillation maximum, since, as shown by Fig. 7, it completely covers this second maximum.

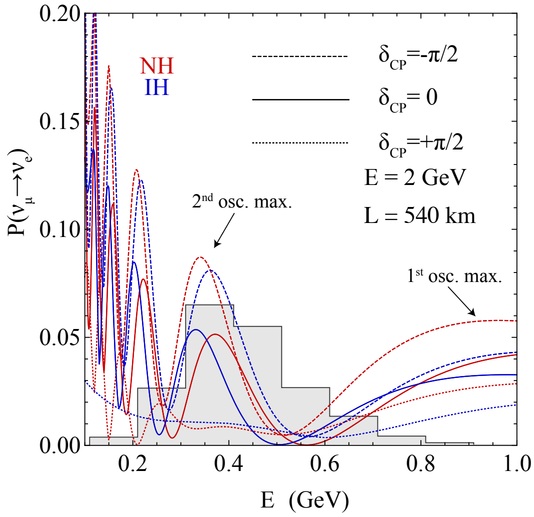

Figure 7: $\nu_\mu \rightarrow \nu_e$ oscillation probability as a function of the neutrino energy. The solid lines are for normal hierarchy (NH) while the dashed ones are for inverted hierarchy (IH). The shaded distribution is the energy distribution of electron neutrinos detected by MEMPHYS far detector.

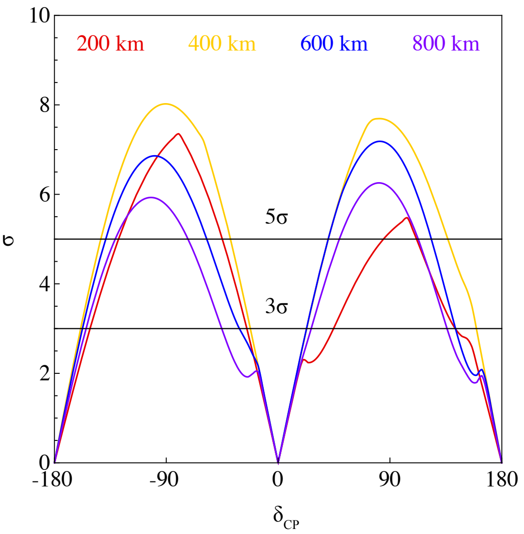

Figure 8: The significance in terms of number of standard deviations σ with which CP violation could be discovered for δ_{CP} values from -180° to 180° and for different baselines (2.0 GeV protons).

The discovery probability of CP violation has been studied as a function of the baseline to find the best distance to place the far detector. Fig. 8 presents the CP violation discovery significances as a function of δ_{CP} for several baselines from 200 km to 800 km. It is seen that this significance can reach values going up to 8 σ for a baseline of around 400 km and δ_{CP} around -90° and 90°. These results are obtained assuming normal hierarchy but supposed to be unknown (for inverted hierarchy these results are almost the same). In case the hierarchy is known this performance slightly increases. For the considered baselines matter effects are not expected to play a significant role.

Fig. 9 presents the fraction of the full parameter δ_{CP} range as a function of the baseline for 3 σ and 5 σ CP violation discovery significance. For 2 GeV protons, the best baseline is around 400 km, close to Zinkgrouvan mine (360 km). Garpenberg mine (located at 540 km) has a better potentiality in case the proton energy goes above 2.5 GeV and can cover up to 60% of the δ_{CP} range for a 5 σ significance. As said above, at this baseline ESSνSB fully covers the second oscillation maximum. The first oscillation maximum being around 180 km has significantly less δ_{CP} coverage.

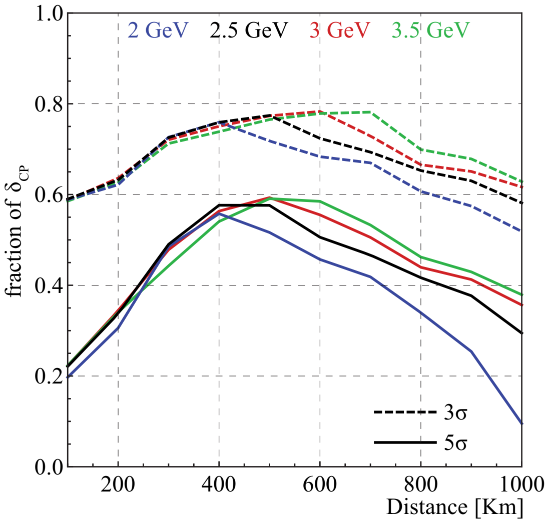

Figure 9: The fraction of the full δ_{CP} range as function of the baseline. The lower (upper) curves are for CP violation discovery at 5 σ (3 σ) significance.

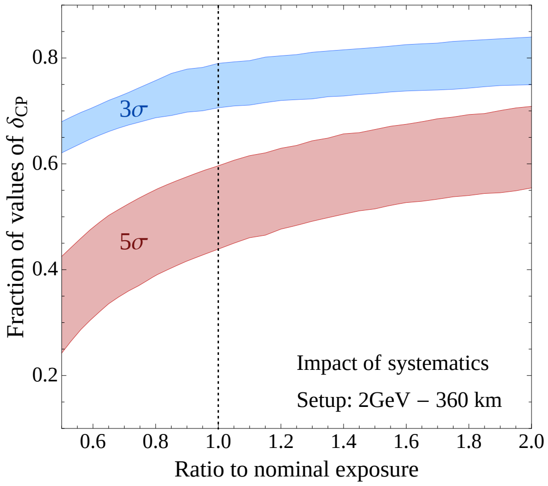

Figure 10: δ_{CP} coverage as a function of the exposure for different systematic errors, 1 being for 10 years, in case the MEPHYS detector is placed in Zingrouvan mine (360 km) and for 2 GeV protons.

Fig. 10 [21] shows the δ_{CP} coverage versus the exposure, 1.0 corresponding to 10 years data taking, for the case of 2 GeV protons and the detector placed in Zingrouvan mine (360 km). The lower limit of this curve is obtained considering the systematic errors mentioned in [22] for Super Beams for the "default" case (mainly assuming 7.5% systematic error for the signal and 15% for the background), while the upper limit is obtained assuming the "optimistic" case (mainly assuming 5% systematic error for the signal and 10% for the background). It can be seen that for double exposure (20 years running) the δ_{CP} coverage, at 5 σ discovery significance, can go up to 72%.

ESSνSB has submitted recently a Design Study project in the framework of the H2020/EU.

4. Conclusions

LAGUNA–LBNO and ESSνSB are the only European long baseline projects proposing to solve the neutrino mass hierarchy problem and observe for the first time a CP violation in the leptonic sector.

The EU/FP7 LAGUNA–LBNO design study proposes in a first phase to use the existing CERN accelerators with improved performance and a 20 kton liquid argon detector placed in a distance of 2300 km in a mine in Finland. This first phase is mainly devoted to mass hierarchy while a second phase based on new CERN accelerators, LP-SPL and HPPS, using a larger detector, will be devoted to the CP violation discovery. This design study has ended in August 2014 giving place to an R&D project on liquid argon detectors.

ESSνSB plans to use ESS installations under construction in Lund and mainly its 5 MW proton linac to produce a very intense neutrino beam in order to discover CP violation. This project fully profites of the developments done in previous European Design studies as EUROν and LAGUNA. This project, due to the neutrino energy and the baseline of about 500 km, will operate exclusively on the second oscillation maximum having enhanced capabilities to discover CP violation compared to the first oscillation maximum. A megaton Water Cherenkov far detector is considered, placed in one of the already existing mines of the region. For 10 years data taking, ESSνSB expects to reach up to 60% δ_{CP} coverage at 5 σ CP violation discovery significance.

5. Aknowledgements

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