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The LAGUNA-LBNO Project

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Abstract

LAGUNA-LBNO is a Design Study funded by the European Commission to develop the design of a large and deep underground neutrino observatory; its physics program involves the study of neutrino oscillations at long baselines, the investigation of the Grand Unification of elementary forces and the detection of neutrinos from astrophysical sources. Building on the successful format and on the findings of the previous LAGUNA Design Study, LAGUNA-LBNO is more focused and is specifically considering Long Baseline Neutrino Oscillations (LBNO) with neutrino beams from CERN. Two sites, Fréjus (in France at 130 km) and Pyhäsalmi (in Finland at 2300 km), are being considered. Three different detector technologies are being studied: Water Cherenkov, Liquid Scintillator and Liquid Argon. Recently the LAGUNA-LBNO consortium has submitted an Expression of Interest for a very long baseline neutrino experiment, selecting as a first priority the option of a Liquid Argon detector at Pyhäsalmi. Detailed potential studies have been curried out for the determination of the neutrino Mass Hierarchy and the discovery of the CP-violation, using a conventional neutrino beam from the CERN SPS with a power of 750 kW.

Selection and peer review is the responsibility of the Conference lead organizers, Frank Avignone, University of South Carolina, and Wick Haxton, University of California, Berkeley, and Lawrence Berkeley Laboratory

Keywords: LAGUNA-LBNO, Long Baseline experiments, Mass Hierarchy, CP violation

1. Introduction

Since many decades, Neutrinos represent an exciting subject of research, as their peculiarity is to be at the same time a particle to be studied and a probe to explore different sources. The project for the future is to combine the AstroParticle and Neutrino Physics programs within a single experiment. This requires the development of new infrastructures and a new concept of Detector: the coming decades will be the era of Large Multipurpose Detectors. Projects are already under study in USA [1], Japan [2] and Europe [3]. In particular, 45 European Institutions, connecting scientists with industrial partners, are involved in the Design Study LAGUNA-LBNO, aiming at the feasibility study of a new large European underground infrastructure for the observation of proton decay, accelerator beam neutrinos and low-energy neutrinos from astrophysics sources. The observatory will search for a possible finite proton lifetime with a sensitivity one order of magnitude better than the current limit. In addition, with a neutrino beam, it will determine with unequaled sensitivity the still unknown Neutrino Mass Hierarchy (MH), fundamental ingredient for Physics beyond the Standard Model, and unveil through neutrino oscillations the existence of CP Violation (CPV) in the leptonic sector, which in turn could provide an explanation of the matter-antimatter asymmetry in the Universe. Finally, it will study astrophysical objects, especially the Sun and Supernovae.

The LAGUNA-LBNO collaboration has selected as a first priority the accelerator based physics, proposing

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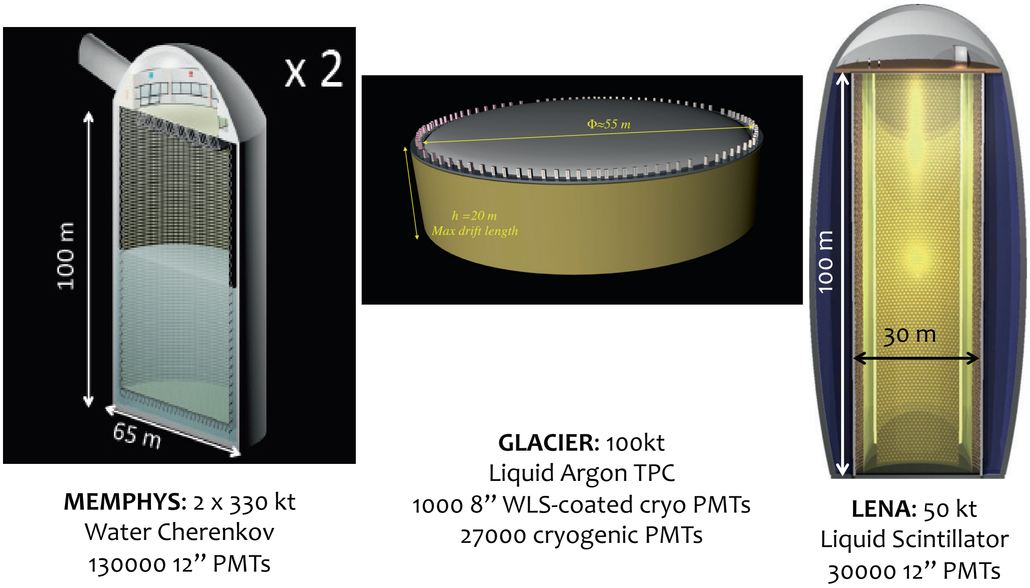

Fig. 1. Main features of the three detectors considered by the LAGUNA collaboration.

a 20 kt LAr double phase TPC and a magnetized iron calorimeter, situated at 2300 km from CERN, and a near detector based on a high-pressure argon gas TPC. The long baseline provides a unique opportunity to study neutrino flavor oscillations over their 1st and 2nd oscillation maxima exploring the L/E behavior, and distinguishing matter effects and those arising from CP violation.

2. LAGUNA and LAGUNA-LBNO Design Studies

In a first phase, the FP7 Design Study LAGUNA [4] (2008-2011) supported a Pan-European effort of 21 beneficiaries, composed of academic institutions from Denmark, Finland, France, Germany, Poland, Spain, Switzerland, United Kingdom and of industrial partners specialized in civil and mechanical engineering and rock mechanics, to assess the feasibility of such a research infrastructure in Europe. The LAGUNA consortium evaluated possible extensions of the existing deep underground laboratories in Europe: Boulby (UK), Canfranc (Spain) and Modane (France) and considers the creation of new laboratories in the following regions: Caso Umbria Region (Italy), Pyhäsalmi (Finland), Sierozsowice (Poland) and Slanic (Romania). Since the next generation deep underground neutrino detector should be coupled to advanced neutrino beams, the investigation offered a wide range of possible baselines, from 130 km to 2300 km, if a beam from CERN is envisaged.
At the same time, three different detector technologies have been considered: a Liquid Argon (LAr) detector (GLACIER) [5], a Liquid Scintillator detector (LENA) [6] and a Water Cherenkov detector (MEMPHYS) [7]. Detector features are summarized in Figure 1. For all three detectors, specific studies concerning the construction feasibility, the required depth, the flux of atmospheric muons and reactor neutrinos have been performed for each site, offering a large number of possible detector-site combinations. The selection of the optimal configuration involves interdisciplinary aspects (physics performances, technical feasibility, safety and legal aspects, socio-economic and environmental impact, costs,...). Physicists, engineers and geo-technical experts are directly involved in the investigation. The conclusions of the LAGUNA design study are that it appears technically feasible to excavate the desired underground caverns and infrastructures in each of the pre-selected sites. In particular, the two deepest sites, Fréjus (at 4800 m.w.e.) and Pyhäsalmi (at 4000 m.w.e.) are found to be particularly attractive. Also the Caso site in Italy has a special feature, being on the baseline of the already existing CNGS (CERN to Gran Sasso) neutrino beam [8]. The three

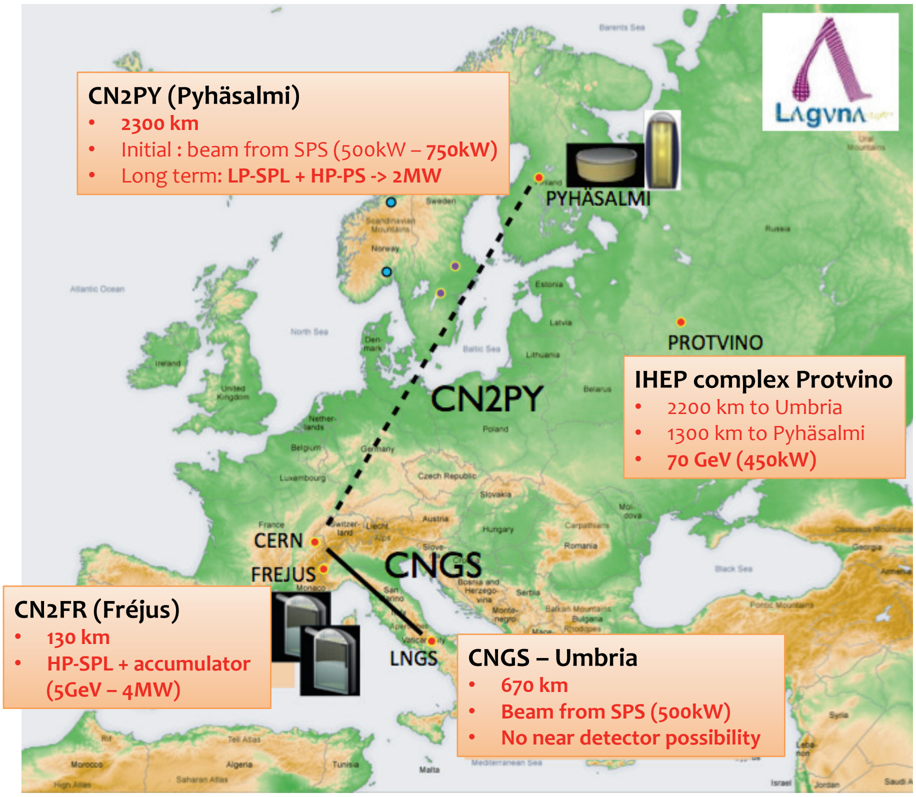

Fig. 2. Map of the Europe showing the three possible underground sites selected for the LAGUNA-LBNO DS.

selected locations are shown in Figure 2.

The LAGUNA collaboration decided to go ahead with a new study, LAGUNA-LBNO [9] (2011-2014) to further evaluate the findings of LAGUNA and, in particular, to assess the underground construction of large detectors, their commissioning, and the long-term operation of the facility. LAGUNA-LBNO is in addition specifically considering long baseline beams from CERN. The collaboration counts 300 physicists and engineers from 13 countries including 40 research institutions and industrial partners. The study of long baseline neutrino oscillations is one of the main scientific goals, and LAGUNA-LBNO is developing an incremental path towards neutrino MH determination and CPV discovery. The following scenarios are being studied in details:

- the MEMPHYS detector at the shortest baseline from CERN (Fréjus at 130 km) with no matter effect and therefore providing a clean measurement of CP violation phase (δ_{CP});
- the GLACIER detector at the longest baseline (Pyhäsalmi at 2300 km) with matter effects and therefore able to determine also the neutrino Mass Hierarchy;
- the GLACIER detector at Caso (Umbria), allowing the study of an off-axis beam (CNGS) at a baseline of about 660 km and a very long baseline (about 2300 km) if a beam from Protvino (Russia) is foreseen.

The first two locations offer excellent opportunities to include the LENA detector, to enhance the physics program at the lowest energy range, in particular for solar, geo-neutrinos detection and short baseline oscillometry studies with artificial low energy neutrino sources.
Presently, the CERN to Pyhäsalmi solution is the most attractive one, since it allows a more complete physics

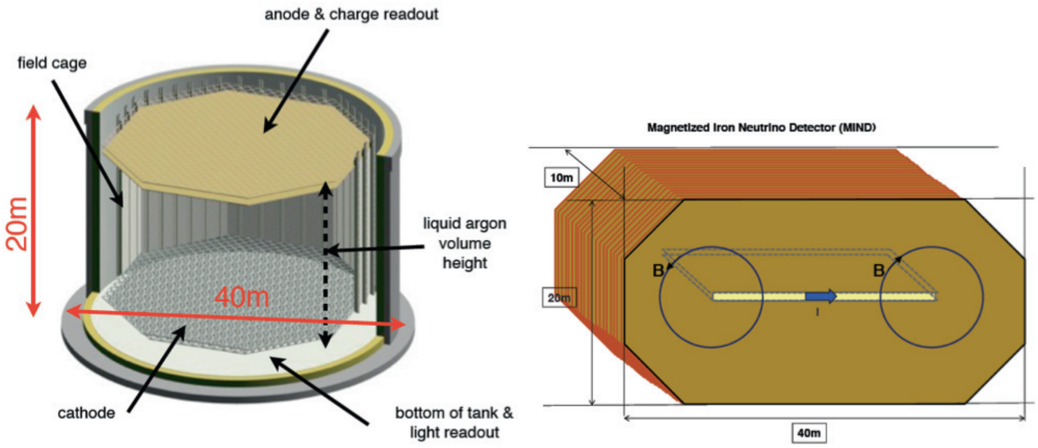

Fig. 3. Schematic view of the far detectors for the LBNO Phase I: the 20 kt LAr detector (left) and the 35 kt MIND detector (right).

program, involving the two challenging measurements of the MH and δ_{CP}.

3. The Expression of Interest for LBNO

In summer 2012, 230 members of the LAGUNA-LBNO collaboration submitted to the European Strategy Roadmap an Expression of Interest (EOI) for a very long baseline neutrino oscillation experiment [10] with a new conventional neutrino beamline facility from CERN. The favored site is the Pyhäsalmi mine in Finland, for a baseline of 2300 km. The recommended technology for the far detector is the double phase LAr Large Electron Multiplier Time Projection Chamber (LAr LEM-TPC), known to provide excellent tracking and calorimetry performance. The collaboration proposes an "incremental approach" motivated by physics, technical and financial aspects. It involves two phases:

1. For a first phase, a 20 kt LAr detector and beam power of 750 kW are recommended; this configuration will offer a new insight and an increase in sensitivity reach for many physics channels. The LAr detector will be coupled to a 35 kt of magnetized iron calorimeter (MIND) for muon momentum and charge determination, that will collect an independent neutrino sample and will serve as a tail catcher for CERN beam events occurring in the LAr target. A schematic view of these two detectors is given in Figure 3.

2. Then, in a second phase an increase of the detector mass up to 70 kt and a possible increase of the beam power up to 2 MW (thanks to a new dedicated HP-PS synchrotron [11]) is envisaged.

In addition, the precision requirements for the LBNO experiment demand the construction of near detector, ensuring the overall normalization of the experiment in terms of event rates. The envisaged technology will reproduce the far detector one (Ar TPC coupled with a MIND detector).

4. The LBNO Physics Program

Accordingly to the LAGUNA-LBNO motivations, the proposed LBNO set-up foresees a wide Physics Program.

4.1. Accelerator based Physics

The priority of LBNO is the answer to the still open questions about the MH and CPV in the leptonic sector. The 2300 km baseline is chosen to have an excellent separation of the asymmetry due to the matter effect (i.e. the MH measurement) and the CP asymmetry due to the CP violation phase (δ_{CP}). The baseline is optimized to break the parameter degeneracies and provide a definitive determination of MH and a significant exploration of CPV in the neutrino sector, as detailed in Section 5.
The use of a LAr and magnetized iron detectors provides complementary studies of the three active transitions $\nu_\mu \rightarrow \nu_\mu$, $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\tau$ charged current events. The active-sterile transition can also be proben by measuring neutral current events. A precise investigation of the oscillation probabilities as a function of energy and a comparison of neutrino and antineutrino behaviors will validate the expectations from 3-generation neutrino mixing.

4.2. Non-Accelerator based Physics

The chosen location in Finland at 4000 m.w.e. will also provide a unique opportunity to observe very rare phenomena with a LAr detector, independent of the CERN beam events. Proton decay can be explored in many different decay channels. After 10 years of exposure, the sensitivity on the proton lifetime will reach $\tau_p \geq 2 \times 10^{34}$ years at 90% CL in the $p \rightarrow K\,\overline{\nu}$ channel. In addition, other exclusive decay channels will be investigated, such as $p \rightarrow e\,\pi^0$ and $p \rightarrow \mu\,\pi^0$.
Moreover, about 5600 atmospheric neutrino events per year will be measured. Atmospheric neutrinos, detected with good energy and angular resolution and flavor identification, are a new tool to perform oscillation physics complementary to the CERN beam, and could be a new method to obtain a radiography of the Earths interior via matter effects.
The neutrino burst from a galactic supernova (SN) explosion would be observed with high statistics in the electron neutrino channel, providing invaluable information on the inner mechanism of the SN explosion and on neutrino oscillations. For a supernova explosion at 10 kpc, about 10000 neutrino interactions will be recorded in the active LAr volume. Unknown sources of astrophysical neutrinos, like for instance those that could arise from annihilation processes of WIMP particles in astrophysical objects, could also be observed.

5. MH Determination and CPV Measurement at LBNO

The LBNO main goal is to determine the mass hierarchy and measure CP violation by observing $\nu_\mu \rightarrow \nu_e$ appearance, through a precise measurement of the neutrino spectrum and the comparison of neutrino- and antineutrino-induced oscillations. The 2300 km baseline is adequate to have an excellent separation of the asymmetry due to the matter effects and the CP asymmetry due to the δ_{CP} phase, and thus to break the parameter degeneracies. In Figure 4, the $\nu_\mu \rightarrow \nu_e$ and $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ probabilities are shown for $\sin^2 2\theta_{13} = 0.09$, for different values of δ_{CP} and for normal hierarchy (NH) and inverted hierarchy (IH), as expected for 2300 km baseline [12]. These plots show that δ_{CP} and matter effects introduce a well-defined energy dependence of the oscillation probability. In particular:

* matter effects at 2300 km are large and the NH and IH scenarios induce to an almost complete swap of behaviors between neutrinos and antineutrinos;
* the spectral information provides an unambiguous determination of the oscillation parameters and allows discriminating between the two CP-conserving scenarios ($\delta_{CP} = 0$ or π) and the CP-violation ones.

The main requirement for the MH and δ_{CP} measurement is the reconstruction of the ν_e and $\overline{\nu}_e$ energy spectrum with sufficiently good resolution, in order to distinguish the first and second oscillation maxima. This allows to extract unambiguous information on the oscillation parameters. A sample of electron-like (e-like) events is thus a primary source of information. A sophisticated analysis package has been developed by the LBNO Collaboration in order to take into account all the available experimental informations and the sources of systematic uncertainties. The considered variables are the reconstructed neutrino energy and

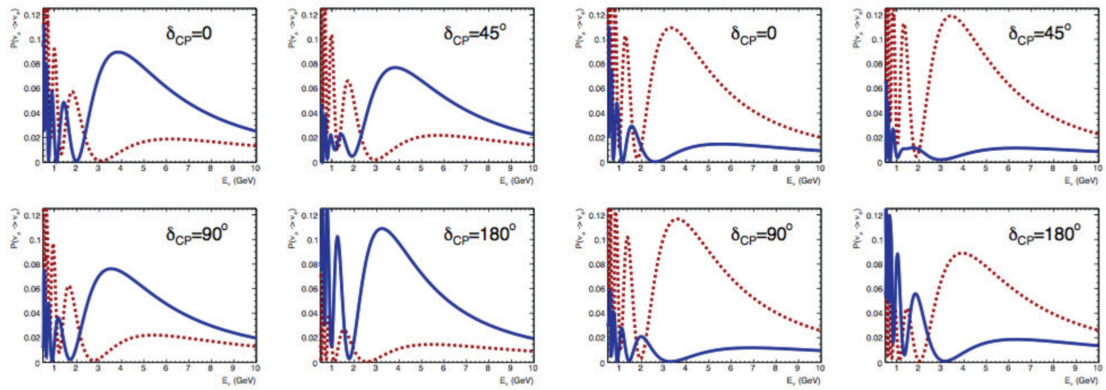

Fig. 4. Oscillation probability of $\nu_\mu \rightarrow \nu_e$ (blue) and $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ (red-dashed) for different values of δ_{CP} for normal hierarchy (left), inverted hierarchy (right), and $\sin^2 2\theta_{13} = 0.09$ [12].

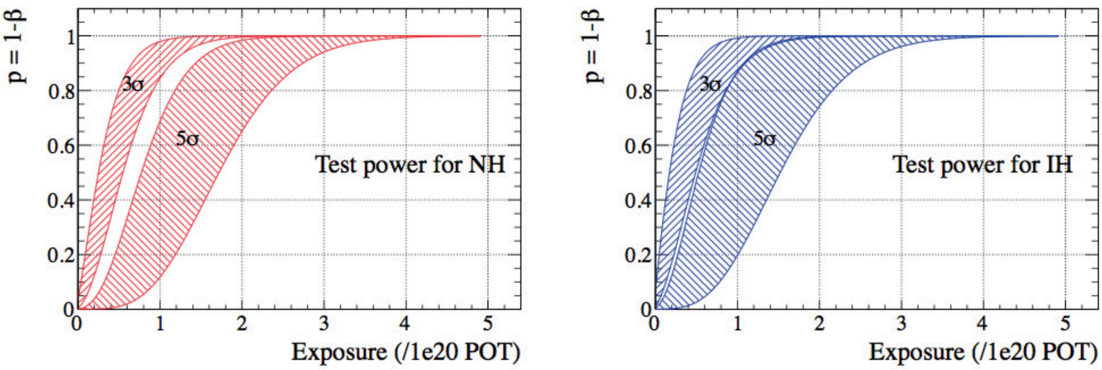

Fig. 5. Statistical power as a function of exposure for the test of NH (left) and IH (right) for $3\,\sigma$ and $5\,\sigma$ CL. The nominal central values for oscillation parameters have been assumed and the shaded bands correspond to the variation of δ_{CP} [12].

missing momentum in the transverse plane, defined by the incoming neutrino beam direction. The use of these two variables for each e-like event allows to construct bi-dimensional distributions, useful to improve the separation between signal and background. The determination of the sensitivity to MH and CPV is defined using the frequentist approach to the test of simple hypothesis and by employing a Monte-Carlo technique simulating a very large number of toy experiments. All details are available in [12].

5.1. Mass Hierarchy Determination of LBNO Phase I

Mass hierarchy sensitivity studies have been developed using a 50% neutrino and 50% anti-neutrino sharing, optimized for this measurement, and $4\text{x}10^{20}$ protons on target (p.o.t.). This corresponds to about 4 years of nominal data taking with the SPS at 750 kW.
In Figure 5, the statistical power p of LBNO, i.e. the probability to obtain the given CL, for NH and the IH determination at a confidence level of $3\,\sigma$ or $5\,\sigma$ is shown as a function of exposure. The shaded area corresponds to the variation of δ_{CP} and the extreme values are reached for $\delta_{CP} = \pi/2$ or $3\pi/2$. It is evident from the plots that LBNO has a probability of about 100% ($p = 1$) to discover the MH for any value of δ_{CP}. An exposure of slightly more that $2\text{x}10^{20}$ p.o.t. will guarantee a $3\,\sigma$ CL determination, while a $5\,\sigma$ CL measurement will be reached with less than $4\text{x}10^{20}$ p.o.t. (4-5 years).

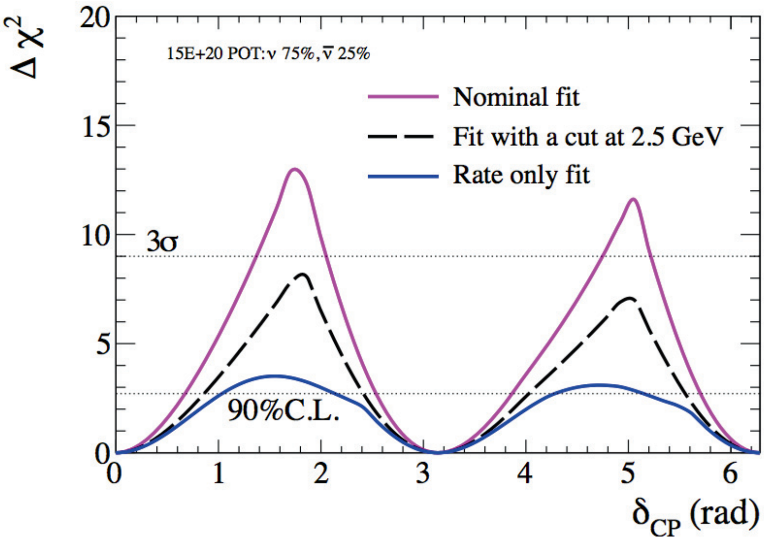

Fig. 6. Comparison of the CPV sensitivities of a rate only analysis, an analysis with a cut on a reconstructed energy at 2.5 GeV (excluding the 2nd maximum), and the nominal case where the full event spectrum is used [12].

5.2. Sensitivity to the CP violation of LBNO Phase I

For the CP phase measurement, the beam normalization is set to $1.5\text{x}10^{21}$ p.o.t. (or approximately 12 years of nominal running at the SPS). The optimization of the beam sharing between neutrino and anti-neutrino has been studied in detail, showing a maximum of coverage in the case of 75% ν - 25% $\overline{\nu}$ (see [12] for details).

One of the strengths of LBNO is the possibility, thanks to the 2300 km baseline, to investigate the first and second oscillation maxima. In fact, the spectrum shape as well as the number of events strongly depend on the value of δ_{CP}, in particular in the energy region corresponding to the 2nd maximum. The analysis method takes into account the information contained in the whole shape of the e-like event distributions in both the ranges of the 1st and the 2nd maximum. The importance of this approach to extract δ_{CP} has been confirmed by comparing the significances obtained by: the standard method (rate + 1st and 2nd maxima spectrum), a restriction to the 1st maximum only and a rate only analysis. As shown in Figure 6, the rate only measurement leads to a drastic loss of sensitivity to the CPV. The power of measuring events over an energy range that covers the 1st and the 2nd oscillation maxima is also evident, allowing a $3\,\sigma$ Cl discovery for about 20% of δ_{CP} values.

As reported in [12], the impact of prior uncertainties on the oscillation parameters, the effect of the knowledge of θ_{13}, the influence of the value of θ_{23} and the impact of systematics due to the knowledge of signal and background normalization for the determination of δ_{CP} have been studied in detail. In particular, the assumptions are:

a. 3.75% error on the absolute value of Δm^2_{13};

b. 10% error on $\sin^2 2\theta_{13}$ and on $\sin^2 \theta_{23}$;

c. 5% systematic error on the signal normalization;

d. 10% systematic error on the background normalization.

More details are given in [12]. In Figure 7, the impact of the priors on the oscillation parameters and of the error on the normalization are shown.

Finally, as for the MH determination, the statistical power of LBNO for CPV determination as a function

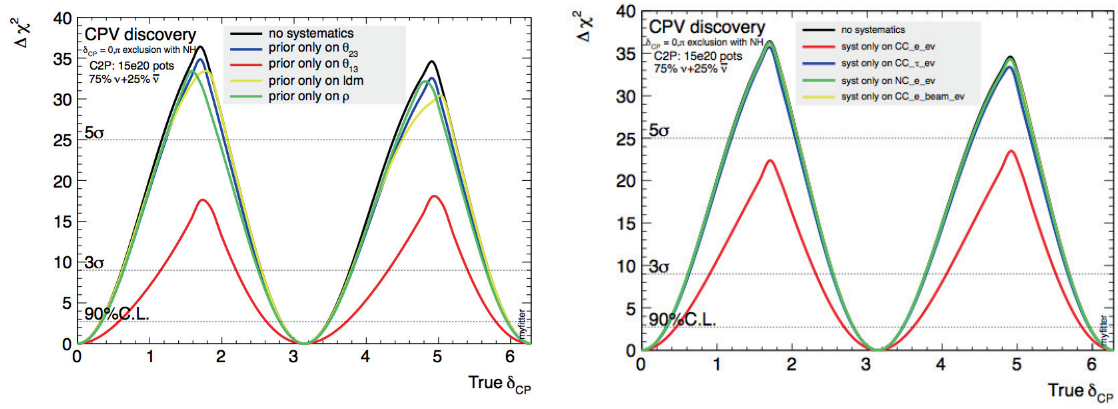

Fig. 7. *Left*: Impact of systematic errors: CPV sensitivity of LBNO phase I as a function of δ_{CP}, with only statistical and no systematic errors (black), and effect of each prior on the oscillation parameters (blue, red, yellow, green) [12]. *Right*: Impact of systematic errors: CPV sensitivity of LBNO phase I as a function of δ_{CP}, with only statistical and no systematic errors (black), and effect of the error on the normalization of the signal and backgrounds. [12].

of exposure is shown in Figure 8, for the two different CLs of 90% and 3 σ. The two most favorable cases, $\delta_{CP} = \pi/2$ or $3\pi/2$, are considered.

5.3. LBNO Phase II

As described in the previous section, the CPV sensitivity of the LBNO Phase I can be limited by the present knowledge of the oscillation parameters and on the reachable systematic errors on signal and background normalization. The increasing of the detector fiducial mass and of the beam power, as expected for the LBNO Phase II, will allow to decrease the statistical error around the 2nd oscillation maximum, the most sensitive to the δ_{CP}. In Figure 9, the expected CPV sensitivity as a function of δ_{CP} is shown for various upgrades of beam power with the HP-PS, and of the far detector mass, from 20 kt to 70 kt. With a 2 MW proton beam and a 70 kt detectoCLr mass, the coverage of δ_{CP} at > 5 σ CL will be about 54% after 10 years.

6. Conclusion

The design of next generation experiments with appropriate baselines and powerful conventional beams for the measurement of the MH and the δ_{CP} represents one of the most important steps for the future of Particle Physics. In particular, in Europe the LAGUNA-LBNO Design Study, a more focused continuation of the LAGUNA project, is ongoing, aiming at proposing a realistic plan for a medium- and long-term European long baseline program, with large discovery potentials at each phase. An Expression of Interest to the European Strategy Roadmap has been submitted in summer 2012, presenting unprecedented Physics Potentials for a LAr TPC detector coupled with a conventional high-power neutrino beam from CERN. The first goal is to determine the neutrino mass hierarchy (with the 2300 km baseline). Then, incrementally exploring the phase space, leading to CPV discovery. With conservative expectations on the systematic errors and after 10 years of CERN SPS running, a significance for CPV above > 3 σ CL will be reached for about 25% of the δ_{CP} values. With a new powerful proton driver such as the conceptual HP-PS and a 70 kt detector mass, the coverage at > 5 σ CL will be about 54% after 10 years.
In parallel, ultimate searches for proton decay and interesting neutrino astrophysics measurements will be possible.

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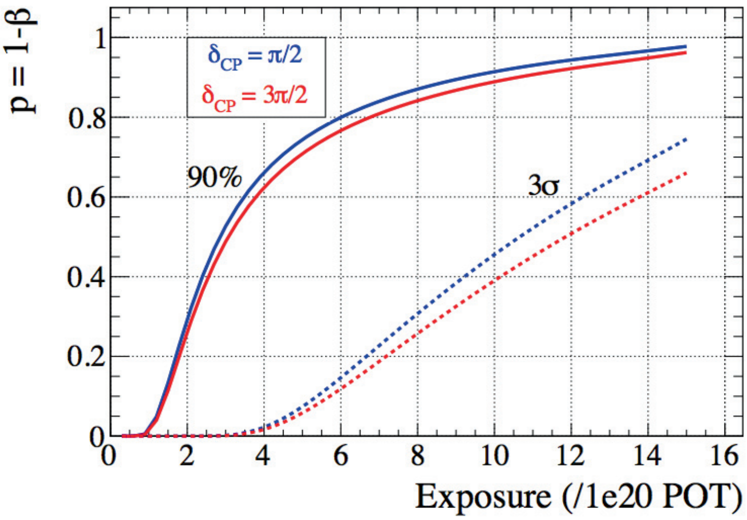

Fig. 8. Statistical power for CPV discovery as a function of exposure for 90% and 3σ CL assuming NH. The far detector of 20 kton LAr and 750 kW SPS neutrino beam are assumed. [12].

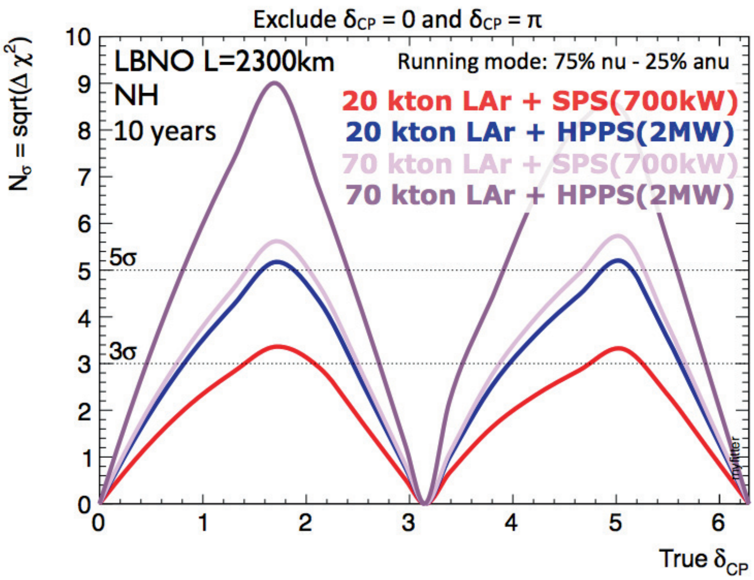

Fig. 9. CPV sensitivity as a function of δ_{CP} for various upgrades of beam power with the conceptual HP-PS, and of the far detector mass, with 20 kt and 70 kt. [12].

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