The LAGUNA/LBNO potential for Long Baseline neutrino physics

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The LAGUNA/LBNO potential for Long Baseline neutrino physics

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Abstract. The LAGUNA/LBNO collaboration proposes a new generation neutrino experiment to address fundamental questions in particle and astroparticle physics. The experiment consists of a far detector, Liquid Argon (LAr) double phase Time TPC (Time Projection Chamber), the fiducial mass of the detector is set to 20 kt in its first stage. The detector will be situated at 2300 km from CERN: this long baseline provides a unique opportunity to study the neutrino flavour oscillations over the first and second oscillation maxima and to explore the L/E (Length over energy) behaviour. The near detector is based on a high-pressure argon gas TPC situated at CERN. I will detail the physics potential of this experiment for determining without ambiguity the mass hierarchy (MH) in its first stage and discovering CP violation (CPV) using the CERN SPS beam with a power of 750 kw. The impact of the assumptions on the knowledge of the oscillation parameters and the systematic errors are very important and will be shown in detail to prove the force of the experiment assuming realistic and conservative parameter values.

1. Introduction

The LBNO (Long Baseline Neutrino Observatory) project is the result of two European Design Studies: LAGUNA in 2008 and LAGUNA/LBNO in 2011. From the point of view of the neutrino physics, the main scientific goal is the study of long baseline neutrino oscillations. Important discoveries in the neutrino sector during the 2010-2012 period and in particular the precise measure of $sin^2 2\theta_{13}$ had an impact on the physics case of the experiment . In particular, as the neutrino mixing angle θ_{13} is big ($sin^2 2\theta_{13} = 0.084^{+0.005}_{-0.005}$ [3]), the Mass Hierarchy (MH) of neutrinos in first instance and, secondary, the CP violation discovery are now the most important items. A very long beam accelerated baseline from CERN to Pyhäsalmi (Finland), corresponding to a length of 2300 km, has been indicated as the first choice. 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 installed very deep underground inside an existing mine. The main goals are the neutrino Mass Hierarchy determination (guaranteed at more than 5 σ) and the leptonic CP violation discovery, obtained by the analysis of the L/E dependence of the oscillation pattern and of both the 1^{st} and 2^{nd} oscillation maxima to distinguish the matter effect from the δ_{CP} effect. LBNO will be the first experiment to provide a whole 3-flavor neutrino oscillation analysis from the appearance and disappearance channels.

To realize the ambitious physics program in the most efficient way, the LBNO Consortium proposes an "incremental approach" involving two phases:

- Phase I - LBNO20: For a first phase, a 24 kt LAr active volume detector and the SPS beam from CERN providing 400 GeV proton energy and 750kW are considered. The LAr detector will be coupled to a magnetized iron calorimeter (MIND) with 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. This first phase (4 years) will solve the MH problem with $\simeq$ 100% probability and will give some hints of the value of the δ_{CP} phase.
- Phase II - LBNO70 An increase of the detector mass up to 70 kt and a possible increase of the beam power up to 2 MW is envisaged to provide a very precise measure of the δ_{CP} assuring a coverage of the CP phase space of 75% at 3 σ and 54% at 5 σ.

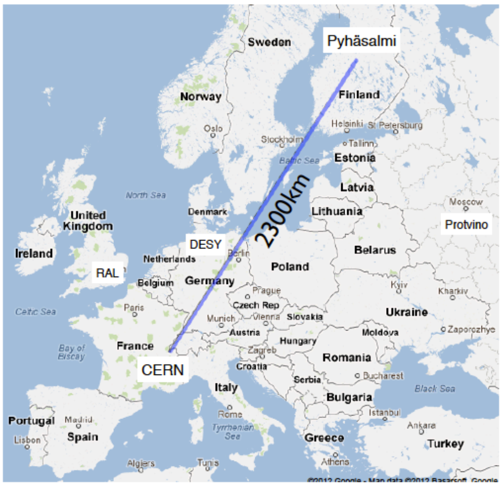

Figure 1. The baseline CERN to Pyhäsalmi.

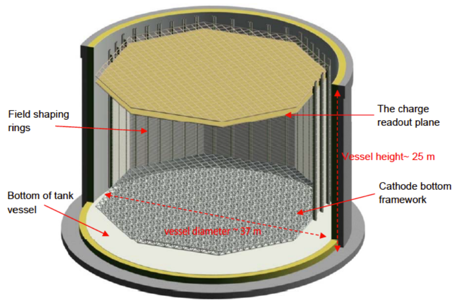

Figure 2. A sketch of the GLACIER type detector.

2. Mass Hierarchy determination

The first goal of the LBNO project is to determine the mass hierarchy ordering. It will be addressed during the first years of run. In this direction the aim of LBNO is to guarantee the discovery of the MH at about 100% power which means that the probability to give the wrong answer is nearly zero. To do that, we simulated 4 years of data taking with the SPS accelerator [6] at 750 kW using a 50% ν 50% $\bar{\nu}$ sharing, which is optimized for this measurement, and 4×10^{20} Protons on Target (PoT). Results are shown in first instance in terms of the mean value T_0 of the test statistics T defined as the difference between the χ^2 of the event distribution evaluated assuming the normal (NH) and the inverted mass hierarchy (IH) as true.

$$T = \chi^2_{IH} - \chi^2_{NH} \tag{1}$$

where χ^2_{IH} (χ^2_{NH}) is obtained by minimizing the χ^2 defined as:

$$\chi^2 = \chi^2_{appear} + \chi^2_{disa} + \chi^2_{syst}. \tag{2}$$

where

$$\begin{aligned}\chi^2_{appear} = 2\sum_{+/-}\sum_{E_\nu^{rec},p_T^{miss}} & n_e(E_\nu^{rec},p_T^{miss};\mathbf{o}_{test},\mathbf{f}_{test}) - n_e(E_\nu^{rec},p_T^{miss};\mathbf{o}_{true},\mathbf{f}_{true}) \\ & + n_e(E_\nu^{rec},p_T^{miss};\mathbf{o}_{true},\mathbf{f}_{true}) \ln\frac{n_e(E_\nu^{rec},p_T^{miss};\mathbf{o}_{true},\mathbf{f}_{true})}{n_e(E_\nu^{rec},p_T^{miss};\mathbf{o}_{test},\mathbf{f}_{test})},\end{aligned} \tag{3}$$

The number of the e-like events in a given $E_\nu^{rec} - p_T^{miss}$ bin is determined according to:

$$\begin{aligned}n_e(E_\nu^{rec},p_T^{miss};\mathbf{o},\mathbf{f}) = & f_{sig}n_{e-sig}(E_\nu^{rec},p_T^{miss};\mathbf{o}) \\ & + f_{\nu_e}n_{\nu_e}(E_\nu^{rec},p_T^{miss};\mathbf{o}) + f_{\nu_\tau}n_{e,\nu_\tau}(E_\nu^{rec},p_T^{miss};\mathbf{o}) \\ & + f_{NC}(n_{NC\pi^0}(E_\nu^{rec},p_T^{miss};\mathbf{o}) + n_{mis-\nu_\mu}(E_\nu^{rec},p_T^{miss};\mathbf{o})),\end{aligned} \tag{4}$$

where n_{e-sig}, n_{ν_e}, n_{e,ν_τ}, $n_{NC\pi^0}$, and $n_{mis-\nu_\mu}$ are the number of events for signal, intrinsic beam ν_e, electrons from tau decay, neutral current, and mis-identified ν_μ, respectively.

The information from the disappearance channel is contained in the χ^2_{disa} term of total χ^2 in Eq. 2, which is given by

$$\begin{aligned}\chi^2_{disa} = 2\sum_{+/-}\sum_{E_\nu^{rec}} & n_\mu(E_\nu^{rec};\mathbf{o}_{test},\mathbf{f}_{test}) - n_\mu(E_\nu^{rec};\mathbf{o}_{true},\mathbf{f}_{true}) \\ & + n_\mu(E_\nu^{rec};\mathbf{o}_{true},\mathbf{f}_{true}) \ln\frac{n_\mu(E_\nu^{rec};\mathbf{o}_{true},\mathbf{f}_{true})}{n_\mu(E_\nu^{rec};\mathbf{o}_{test},\mathbf{f}_{test})}.\end{aligned} \tag{5}$$

The number of μ-like events is the sum of signal ($n_{\mu-sig}$) and $\tau \to \mu$ background (n_{μ,ν_τ}) contributions and is calculated as

$$n_\mu(E_\nu^{rec};\mathbf{o},\mathbf{f}) = f_{sig}n_{\mu-sig}(E_\nu^{rec};\mathbf{o}) + f_{\nu_\tau}n_{\mu,\nu_\tau}(E_\nu^{rec};\mathbf{o}). \tag{6}$$

In Figures 3 and 4 T_0 is shown as a function of the true value of δ_{CP}, for the assumed Normal and Inverted true mass hierarchy. It could be put in evidence the slight different strength of the two T_0 distributions due to the difference in term of oscillation probability between NH and IH. The value of T_0 is strongly dependent on the value of the mixing angle θ_{23}. On the same Figures the effect of different assumptions of θ_{23} spanning some values between the first and the second octant solutions is shown. For an experiment like LBNO is then mandatory to ensure enough statistics to avoid the uncertainty due to this assumption. The retained value of $sin^2\theta_{23}$ for these studies is 0.44 which is in agreement with recent global fits [7], but does not correspond to the best signal-to-noise. The other sources of uncertainty, such as the error on θ_{23} or the density of the Earth, can only have a smaller impact.It is to be stressed here that, as it is evident from these Figures, the best and worst value of T_0 are reached for $\delta_{CP} = \frac{\pi}{2}, \frac{3}{2}\pi$.

The statistical power defined in details in [1] for the MH determination at a confidence level of 3σ or 5σ is shown in Figure 5 and 6 as a function of exposure.

For each confidence level the shaded area corresponds to the results assuming different values of δ_{CP} between 0 and 2π. The extreme values are reached for $\delta_{CP} = \pi/2$ (left border) or $3\pi/2$ (right border), as has been explained above. This plot can be used to state the minimal exposure needed to get the desired confidence level with a certain probability. Usually experiments state their sensitivity with a probability to obtain the result of 50% (median sensitivity). LBNO can solve the mass hierarchy problem with a median sensitivity at 5σ C.L. within the first year of exposure (1.5e20 PoT). In addition one can see that LBNO has a probability of essentially 100% to discover the MH in either case for any value of δ_{CP}. An exposure of slightly more that 2×10^{20} PoT will guarantee that a 3σ C.L. is obtained, while a 5σ C.L. will be reached with less than 4×10^{20} PoT, corresponding to about 4 years of SPS running.

Journal of Physics: Conference Series **566** (2014) 012002 doi:10.1088/1742-6596/566/1/012002

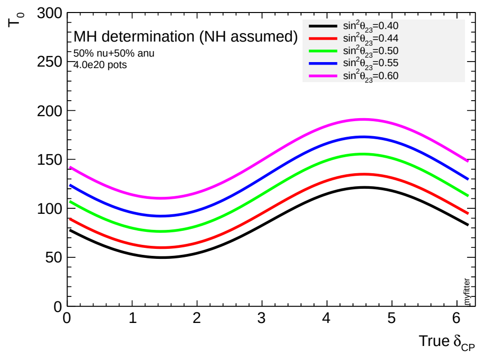

Figure 3. Mean value of the mass hierarchy test statistic for Normal Hierarchy as a function of true δ_{CP} for a total exposure of 4×10^{20} PoT (or about 4 years of running at the SPS) and LBNO 20 kton detector.

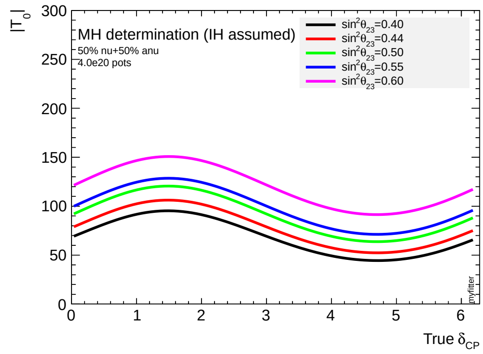

Figure 4. Mean value of the mass hierarchy test statistic for Inverted Hierarchy as a function of true δ_{CP} for a total exposure of 4×10^{20} PoT (or about 4 years of running at the SPS) and LBNO 20 kton detector. Note the absolute value on y axis to directly compare with Figure 3.

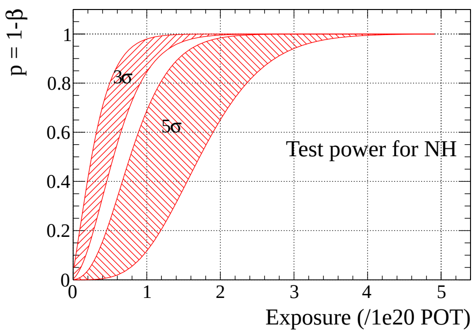

Figure 5. Statistical power as a function of exposure for the test of NH for 3σ and 5σ CL. The nominal central values for oscillation parameters have been assumed and the shaded bands correspond to the variation of δ_{CP}.

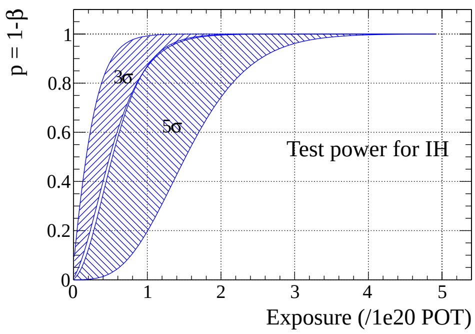

Figure 6. Statistical power as a function of exposure for the test of IH for 3σ and 5σ CL. The nominal central values for oscillation parameters have been assumed and the shaded bands correspond to the variation of δ_{CP}.

3. CP violation

Once the ordering of the mass hierarchy has been determined, LBNO will continue to run and collect statistics in order to establish if the δ_{CP} phase is non vanishing and to measure it. The sensitivity to a non vanishing δ_{CP} is obtained in terms of tests statistics, testing the hypothesis of no-CP-violation evaluating the $\Delta\chi^2$ as a function of the value of δ_{CP}. The evaluated $\Delta\chi^2$ is then plotted as a function of the value of δ_{CP} assumed as alternative hypothesis as in Figure 8. The coverage of the experiment is defined as the portion of the δ_{CP} phase space for which the value of $\Delta\chi^2$ is greater than 9 (at 3σ C.L.) or 25 (at 5σ C.L.). To have a complete information about the LBNO sensitivity to discover the CP violation, the power for the δ_{CP} sensitivity is plotted following the same approach used for the MH. The statistical power of LBNO for CPV determination as a function of exposure is shown in Figure 7, for the two different $C.L.$s of 90%

and 3σ when a 20 kt detector fiducial mass is assumed. The bands limit curves correspond to the two most favorable cases, $\delta_{CP} = \pi/2$ or $3\pi/2$.

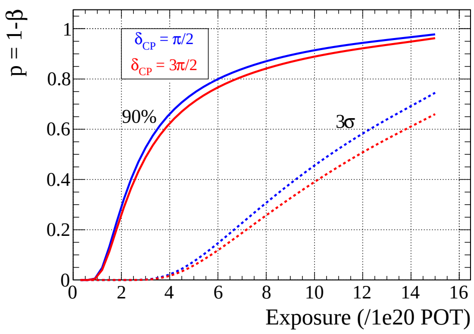

Figure 7. Statistical power for CPV discovery as a function of exposure for 90% and 3σ CL assuming NH. The far detector of 20 kton LAr and 750 kW SPS neutrino beam are assumed.

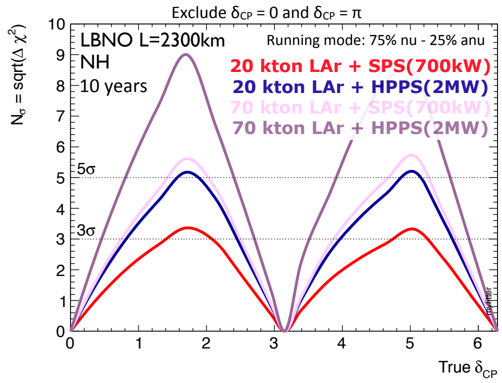

Figure 8. CPV sensitivity as a function of δ_{CP} for various upgrades of beam power with the HP-PS[8], and of the far detector mass, with 20 kton and 70 kton.

As detailed in previous paragraphs, LBNO Phase I can reach significant physics goals, in particular it is guaranteed to be fully conclusive for MH discovery with an expected 5σ C.L. over the full range of δ_{CP}. On the other hand, the CPV sensitivity reach is more difficult to predict, since ultimately is dependent on the achievable systematic errors and on the true δ_{CP}. The studied detailed so far have been realized using presently realistic errors on oscillation parameters and on the normalization of the signal and backgrounds. This is a extreme conservative assumption motivated by the aim to guarantee the success of the experiment independently of further future improvements. Of course, with the series of expected new measurements and possibly the addition of dedicated measurements from experiments on hadron-production and neutrino cross-sections, it is conceivable to think that the overall balance of errors could be reduced in the future, thereby improving further the expected CPV sensitivity of LBNO20.

In addition to these improvements, a complementary and/or alternative method to get better CP violation sensitivity is to increase the detector mass and the neutrino beam power. This will allow an important increase of the number of events and therefore a decrease of the statistical error around the 2nd oscillation maximum. Due to the natural cut-off of the muon-neutrino flux spectrum at low energy and the linear increase of the total neutrino cross-section with energy, the 2nd maximum is more difficult to study than the 1st one. But, as the second maximum is still accessible by LBNO given the very long baseline, a significant gain is obtained by populating this region with oscillation events.

This is one of the main goals of the LBNO70. The expected CPV sensitivity (in terms of $\Delta\chi^2$ as a function of δ_{CP} is shown in Figure 8 for various upgrades of beam power with the HP-PS, and of the far detector mass, from 20 kton to 70 kton. With a new powerful proton driver such as the conceptual HP-PS and a 70 kton detector mass, the coverage at $> 5\sigma$'s C.L. will be $\sim$54% after 10 years.

Table 1 summarizes the coverages of the CP phase space for LBNO20 and LBNO70 considering the SPS and the HP-PS beams.

Journal of Physics: Conference Series **566** (2014) 012002 doi:10.1088/1742-6596/566/1/012002

beam	24 kt at 3 σ	70 kt at 3 σ	24 kt at 5 σ	70 kt at 5 σ
SPS	25%	60%	/	25%
HP-PS	57%	75%	21%	54%

Table 1. Percentage coverage of the CP phase space for different detector masses with the SPS and the HP-PS beam.

4. Conclusions

The next generation neutrino detectors will address fundamental questions in particle and astroparticle physics. They will determine the Mass Hierarchy of Neutrinos, this will open the way to the CP symmetry violation discovery and, if CP is violated, to the precise measure of the δ_{CP} phase. A complete astrophysics program will be hopefully addressed by measuring the Supernovae background Neutrino and Neutrinos from Core Collapse Supernovae and performing at the same time precise measurements of atmospheric and solar neutrinos. New limits on proton lifetime will be fixed.

In this context, the LBNO experiment design is capable to meet the fore-mentioned scientific goals. It is the result of two dedicated Design Studies: LAGUNA and LAGUNA/LBNO, which proposed an incremental phased approach considering a 24 kt (LBNO20) upgradable to 70 kt (LBNO70) double phase Liquid Argon GLACIER-type detector to be installed inside the Pyhäsalmi mine in Finland at 2300 km from CERN where a dedicated neutrino beam will be produced.

Beam based experiments are the only capable to run in both ν and $\bar{\nu}$ configurations by changing the horn polarity allowing a full measure of the 3ν flavor paradigm. In addition, the deep underground location of such detector is ideal for astrophysics measurements and proton decay search. LBNO is a proposed long baseline experiment with a complete design study including a detailed and motivated physics reach, realistic simulations and layout concepts of the neutrino beam, underground construction plan, costing estimations and risk assessments. The detector response as well as the analysis software development and the engineer challenges will be the main goals of the CERN experiment WA105, the LBNO prototype (LBNO-DEMO) [9] .

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