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The LAGUNA-LBNO neutrino observatory in Europe

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Abstract

The LAGUNA and LAGUNA-LBNO consortia have performed two detailed design studies from 2008 to 2014 to define the optimal combination of baseline and detector technology for the next generation neutrino observatory. Starting from seven sites and three detector technologies the options have been prioritized with the primary choice given to the Pyhäsalmi mine in Finland and the liquid Argon (DLAr) TPC detector technology. This led to a proposal for a European-based next-generation long baseline oscillation experiment, LBNO. The deep underground location of 1400 m offered by the mine is essential to explore neutrino astrophysics and look for proton decay. The mine position at 2300 km from CERN allows quickly to resolve neutrino mass hierarchy and measure leptonic CPV phase δ_{CP} by disentangling the matter effects from those caused by CPV. We will demonstrate the capability of LBNO to discover the mass hierarchy at the $> 5\sigma$ level within 4 years of operation using a 20 kt DLAr detector and a conventional neutrino beam created with a 400 GeV 750 kW primary proton beam delivered by CERN SPS. Following the discovery of the mass hierarchy LBNO will pursue the determination of the CP-violating phase δ_{CP}. We will show the LBNO sensitivity to measure δ_{CP} by studying the shape of the electron neutrino appearance oscillation probability over a broad energy range covering both the 1st and 2nd ν_e appearance maxima.

Keywords: long baseline neutrino oscillations, leptonic CP violation, mass hierarchy, liquid argon TPC

1. Introduction

In 2013 the LAGUNA-LBNO consortium has proposed LBNO [1], the next-generation long baseline neutrino oscillation experiment relying on a large underground observatory that will seek to address fundamental questions in particle and astroparticle physics. Based on the extensive studies as part of LAGUNA and LAGUNA-LBNO programs, LBNO would deploy a large double-phase liquid argon TPC (DLAr TPC) deep underground in Pyhäsalmi mine, Finland. To develop a large underground observatory while maintaining the ability to deliver interesting physics results on a short timescale after the detector commissioning, LBNO has advocated a phased approach. In the first phase, a detector with a $\sim$ 20 kton fiducial mass of liquid argon is foreseen. In the second phase, the total fiducial mass would be augmented to 70 kton with an addition of another 50 kton DLAr TPC.

One of the major goals of the experiment is the search for leptonic CP-violation (CPV) which in the standard 3-neutrino paradigm would mean a value of the phase δ_{CP} different from 0 or π. An important prerequisite to the measurement of the CPV is the determination of the neutrino mass hierarchy (MH), the sign of Δm^2_{31}, which would break the degeneracies in the neutrino oscillation probability that could hide the true value of δ_{CP}. Consequently, the LBNO strategy is to deliver a quick and conclusive measurement of MH within first few year of operation and subsequently focus on the discovery of the CPV.

The position of Pyhäsalmi mine at 2300 km from CERN offers a unique opportunity to address both the questions of MH and CPV with a conventional accelerator-based neutrino beam. Large matter effects due to the length of the CERN-to-Pyhäsalmi baseline give rise to a significant asymmetry between $\nu_\mu \to \nu_e$

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and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation probabilities that depends on the sign of Δm_{31} (if MH is -1(+1) (anti)neutrino oscillation are suppressed). Additionally, at this baseline one has the possibility to access both 1st and 2nd maxima of the ν_e appearance probability. This gives an opportunity to measure δ_{CP} from the L/E behaviour of the oscillation probability over a wide energy range. The access to the 2nd oscillation maximum is also important. Since the dependence of the oscillation probability on the δ_{CP} is much stronger there, the sensitivity to CPV is significantly improved if one can access that part of the L/E region.

Apart from neutrino oscillation physics, a large DLAr TPC would be an attractive detector technology to search for nucleon decay. The excellent reconstruction capabilities offered by liquid argon detectors combined with a large fiducial volume would allow to explore a variety of possible decay channels with very little background contamination. Such sensitivity would make it possible to access and test a variety of scenarios for grand unification. The detector would also be able to provide a wealth of new information on the neutrinos produced during a supernova explosion. These neutrinos provide the only glimpse deep inside the core of a collapsing star. Accurate measurements of their fluxes and flavour composition would therefore help to understand the intricate mechanisms behind the evolution of supernova explosions.

In these proceedings, we will review the ability of LBNO to determine the MH and show the sensitivity of the experiment to leptonic CPV.

2. Double-phase liquid argon TPC at Pyhäsalmi

The design of the liquid argon detector at Pyhäsalmi is based on the GLACIER (Giant Liquid Argon Charge Imaging ExepeRiment) concept [2, 3]. It relies on technical expertise of the LNG industry in constructing large cryogenic vessels to house a large scale liquid argon TPC and a novel double-phase charge readout. The basic principle is illustrated in Fig. 1.

Ionization charge created within the fiducial volume of the detector drifts upwards towards a gas-liquid interface under an action of a drift field with a strength of 0.5 – 1 kV/cm. At the interface the ionization electrons are extracted from the liquid into the gas phase and amplified with a large electron multiplier (LEM), a thick GEM with a width of 1mm and the field strength inside the holes on scale of 25 – 35 kV/cm. Finally the charges are collected on an anode that has a 2D structure providing position identification in two coordinates. Ionizing radiation also leads to formation of excimer states in liquid argon, which quickly undergo radiative decay producing scintillation light with a spectrum peaked at 128 nm. This light is recorded with a matrix of PMTs located at the bottom of the cryogenic tank giving a signal for the trigger and the timing information necessary for the reconstruction of particle positions along the drift axis.

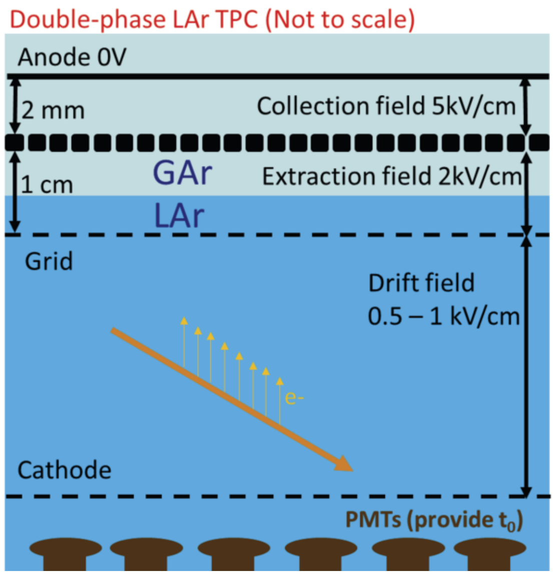

Figure 1: Basic operational principle of DLAr TPC.

A fully engineered solution for a DLAr TPC detector hosted at the Pyhäsalmi mine has been developed within the LAGUNA-LBNO design study. Two caverns are envisioned at level of 1400 m below the ground: one for the 20kton and the other for the 50kton DLAr detector. The cryogenic vessels housing the detector would have cylindrical shape with inner diameter of 37 m and 55 m for 20 kton and 50 kton scale detector, respectively. The length of the drift region would be 20 m for both detector size options. LAGUNA-LBNO has developed detailed studies of the underground construction sequence, risk assessment, liquid and gas handling systems, and the timescale and cost estimates for the detector construction.

3. Neutrino beam

LBNO proposes to utilize a conventional muon neutrino beam based at CERN. Two options for the primary proton beam are foreseen for the two successive phases of the experiment. In the first phase, an upgraded SPS will deliver a 400 GeV beam at about 700 kW beam power to the LBNO target. An expected integrated yearly exposure is about 1.0×10^{20} protons on target (POT) for this stage. In the second phase, a primary beam is foreseen to be provided by a high power PS (HPPS) facility which will deliver a 50 GeV 2 MW proton beam and integrated yearly exposure of about 3.5×10^{21} POT.

The calculation of the neutrino fluxes is performed using FLUKA [4]. In the simulation, the hadron production target is modeled as a simple solid graphite cylinder. The focusing system consists of two aluminum horns. The target is fully inserted into the first horn in order to maximize the collection of the low energy pions which contribute to the neutrino flux below 2 GeV (around the 2nd oscillation maximum). The decay tunnel is located 30 m downstream of the target. It is modeled as a cylinder, which is 300 m long and 3 m in diameter.

The target dimensions, horn inner conductor shapes and dimensions, horn currents, and relative component positions have been optimized to find neutrino beam most suited for the measurement of δ_{CP} [5]. Three different possible energy windows for the neutrino beam have been explored with the following three different optimization criteria:

- **High Energy optimization (HE)**: maximization of the integral of ν_μ flux in a 0-6 GeV energy window.
- **Low Energy optimization (LE)**: maximization of the integral of ν_μ flux in a 1-2 GeV energy window.
- **CPV based optimization using GloBeS (GLB)**: maximization of total $\delta_{\rm CP}$ sensitivity as computed by GloBeS [6] with all the systematics uncertainties turned off.

The comparison of optimal ν_μ fluxes obtained using different optimization criteria is shown in Fig. 2 along with the nominal flux from [1].

To choose the best beam optimization for the measurement of δ_{CP} out of the three possible configurations, each optimization result has been processed through the full LBNO analysis framework [7] to calculate the sensitivity to CPV. In general, each optimized beam was found to offers a better performance over the nominal LBNO flux with the better results obtained with GLB and HE for SPS and LE optimizations HPPS beam [5]. The results obtained with the GLB optimization will be shown here.

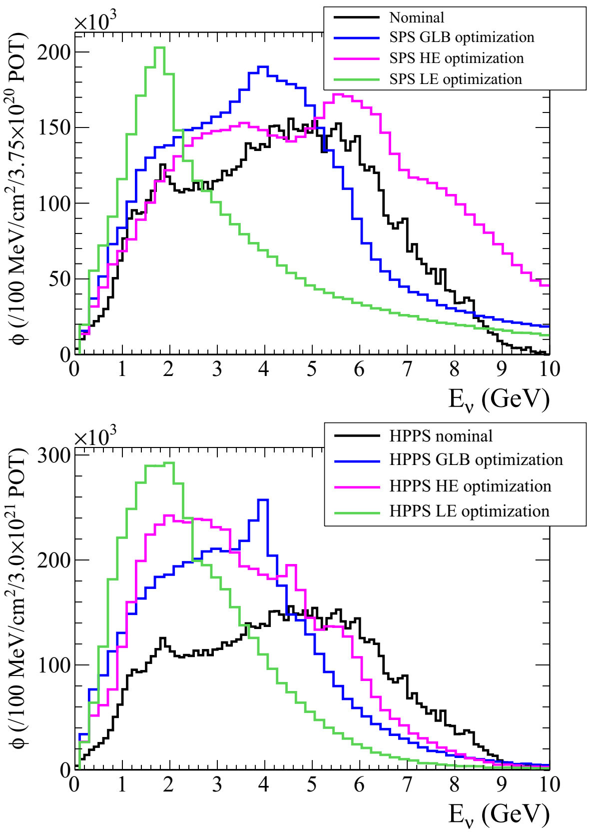

Figure 2: Energy spectra of neutrino fluxes for different optimizations for SPS (top) and HPPS (bottom) proton beam options. The nominal LBNO flux from [1] is also shown.

4. Expected number of ν_e events

The determination of the MH and leptonic CPV in a long baseline experiment will rely on the accurate measurement of the $\nu_\mu \to \nu_e$ ($\bar{\nu}_\mu \to \bar{\nu}_e$) oscillations. A sample of the e-like events is thus a primary source of information. The expected distributions for e-like events for LBNO are shown in Fig. 3 for SPS and HPPS beam. As is evident in these figures, LBNO is able to access and measure the oscillation probability near the 2nd oscillation maximum, which is more sensitive to the effects of leptonic CPV.

A summary of the expected event rates for various neutrino flavours for LBNO are given in Table 1. The shown numbers are not scaled by the detector efficiencies and represent the raw integrated yield in the energy window from 0 up to 10 GeV.

	ν_μ unosc. CC	ν_μ osc. CC	ν_e beam CC	$\nu_\mu \to \nu_\tau$ CC	$\nu_\mu \to \nu_e$ CC $\delta_{CP} = -\pi/2$	0	$\pi/2$
SPS beam, 24kton, NH							
11.25×10^{20} POT for ν	12492	3392	77	733	883	693	576
3.75×10^{20} POT for $\bar{\nu}$	1907	504	10	112	32	40	41
SPS beam, 24kton, IH							
11.25×10^{20} POT for ν	12492	3337	77	860	229	138	97
3.75×10^{20} POT for $\bar{\nu}$	1907	502	10	110	80	102	114
HPPS beam, 24kton, NH							
22.5×10^{21} POT for ν	19440	7791	162	458	1355	922	815
7.5×10^{21} POT for $\bar{\nu}$	2073	789	15	47	32	48	48
HPPS beam, 24kton, IH							
22.5×10^{21} POT for ν	19440	7901	162	499	445	216	166
7.5×10^{21} POT for $\bar{\nu}$	2073	801	15	46	84	122	127

Table 1: Expected event rates in the energy range from 0 to 10 GeV for SPS and HPPS proton beam options and NH and IH. A total exposure of 15×10^{20} (30×10^{21}) POT is assumed for SPS (HPPS) with 75% of running time dedicated to beam operation in the neutrino mode.

5. Sensitivity to MH

Quick and conclusive determination of MH during the first few years of operation is one of the main objectives of the LBNO physics program. Fig. 4 shows the statistical power (see for example [8] for the discussion of the statistics in MH determination and discussion in [7]) of the experiment to resolve NH or IH at the confidence level of 3σ or 5σ as a function of the accumulated POT. For a given exposure equal sharing of the running time between ν and $\bar{\nu}$ is assumed. The bands represent all the possible values of the δ_{CP} parameter.

LBNO has close to 100% statistical power to select a correct MH hypothesis independent of the value of δ_{CP} at 3σ level after accumulating 2×10^{20} POT or about two years of SPS beam operation. With this exposure one also achieves more than 60% probability of determining MH at 5σ level. The discovery (at 5σ level) can essentially be guaranteed with an exposure of 4×10^{20} POT or about four years of running.

6. Sensitivity to CPV

The sensitivity of LBNO to the leptonic CPV is shown in Fig. 5 for the SPS-based neutrino beam and the two possible mass hierarchies. Both detector mass option, 24 kton and 70kton, are displayed. Similarly, Fig. 6 shows the sensitivity to CPV obtained with HPPS beam in the second phase of LBNO.

In Phase I (LBNO20: SPS based neutrino beam and 24 kton LAr detector), LBNO has a median sensitivity to CPV at or above 3σ level for about 45% of possible values of δ_{CP}. With addition of the 50 kton detector, the experiment has the sensitivity to cover 63% and 35% of the parameter space at 3σ and 5σ level, respectively. The ultimate combination of HPPS and 70 kton detector would give a sensitivity at 3σ (5σ) level for 80% (65%) of the δ_{CP} parameter space.

7. Impact of 2nd oscillation maximum on measurement of CPV

As illustrated in Fig. 3, the very long baseline allows LBNO to access both 1st and 2nd oscillation maximum. Moreover the contribution of the ν_e signal events around the 2nd maximum is critical for enhancing the experimental sensitivity to CPV. This is shown in Fig. 7 and Fig. 8 for SPS and HPPS beams, where the sensitivity to CPV obtained after a 2.5 GeV cut is placed on the reconstructed neutrino energy is compared to the nominal case calculated with the full spectral infromation. It is clear from these figures, the applied energy cut completely removes any contribution from the events around the 2nd oscillation maximum. Thus any deterioration observed in the experimental sensitivity to CPV could only be attributed to loss of the knowledge from this region of L/E.

In the case of the SPS beam, the applied cut results in about 5% loss in the total number of signal ν_e events. Despite the fact that this is a relatively small fraction, the impact these events have on the CPV sensitivity is not negligible. The coverage at 3σ level decreases from 45% (63%) to 34% (53%) for the 24 (70) kton detector, while the coverage at 5σ level for 70 kton detector option is reduced by more than half (from 35% to

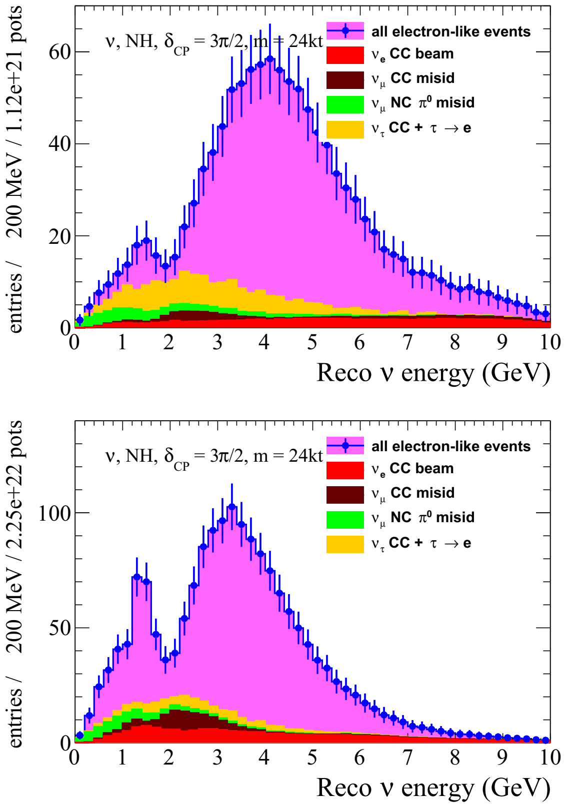

Figure 3: Expected distribution of e-like events $\delta_{CP} = 3\pi/2$ and NH in the ν running mode for SPS (top) and HPPS (bottom) based neutrino beams. The error bars represent statistical uncertainties only. The exposure corresponds to 75% of the expected total integrated number of POT.

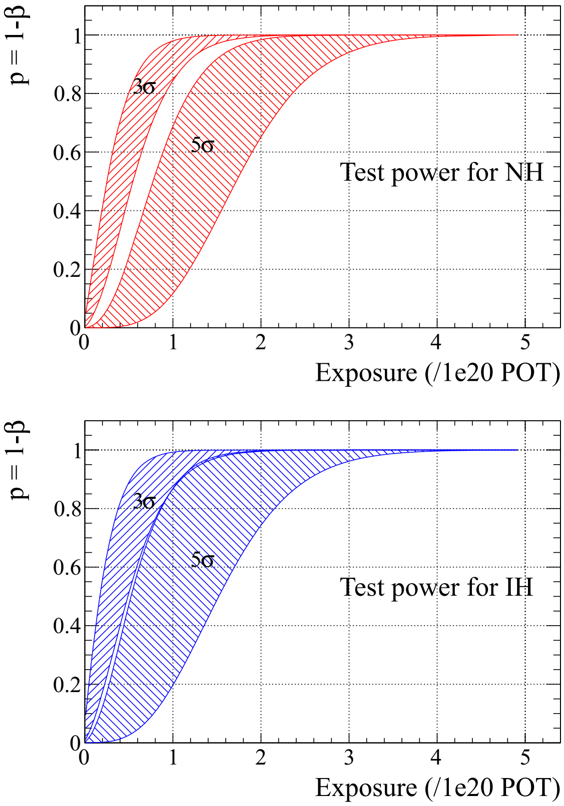

Figure 4: Statistical power as a function of exposure for the test of NH and IH for 3σ and 5σ CL [7].

16%). The effect is even more pronounced for HPPS-based neutrino beam. In this case, the cut at 2.5 GeV removes approximately 17% of signal events. At the same time it leads to a significant loss in the discovery potential with the fraction of δ_{CP} parameter space covered at 5σ reduced from 43% to 0 (65% to 28%) for 24 (70) kton detector.

8. LBNO demonstrator

A crucial step towards a future realization of a large, tens-of-kton-scale liquid argon detector is the construction and operation a LBNO detector demonstrator (LBNO-Demo) proposed by the WA105 collaboration [9]. This double-phase liquid argon TPC will have an active volume dimensions of 6x6x6 m^3 (6 m drift and 6x6 m^2 charge readout plane). The detector will be constructed at CERN where it will be exposed to a charged particle beam of energies ranging from 0.5 to 20 GeV.

The technical goal of the LBNO-Demo is to demonstrate the feasibility of a large scale DLAr TPC detector design developed by the LAGUNA-LBNO study. In addition, the controlled data set from a charged particle beams would allow to develop and validate the automatic event reconstruction, characterize particle identification and detector performance, and study systematically the calorimetric response of liquid argon to electromagnetic and hadronic showers.

9. Summary

We have shown that a 20 kton double-phase liquid argon detector in Pyhäsalmi and a convectional neutrino beam based on modestly upgraded CERN SPS, could quickly solve the question of the neutrino mass hierarchy. In this first phase, LBNO will also have sensitivity to measure CPV at least 3σ level for 45% of the possible values of δ_{CP}. With addition of a 50kton DLAr the

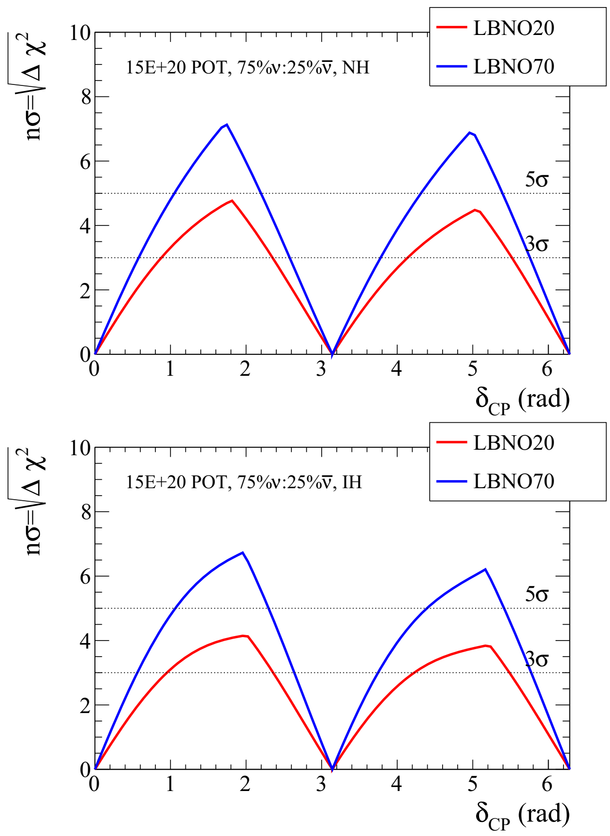

Figure 5: Median sensitivity to CPV for the optimized SPS beam. The values of $\sin^2 2\theta_{13} = 0.09$ and $\sin^2 \theta_{23} = 0.45$ are assumed.

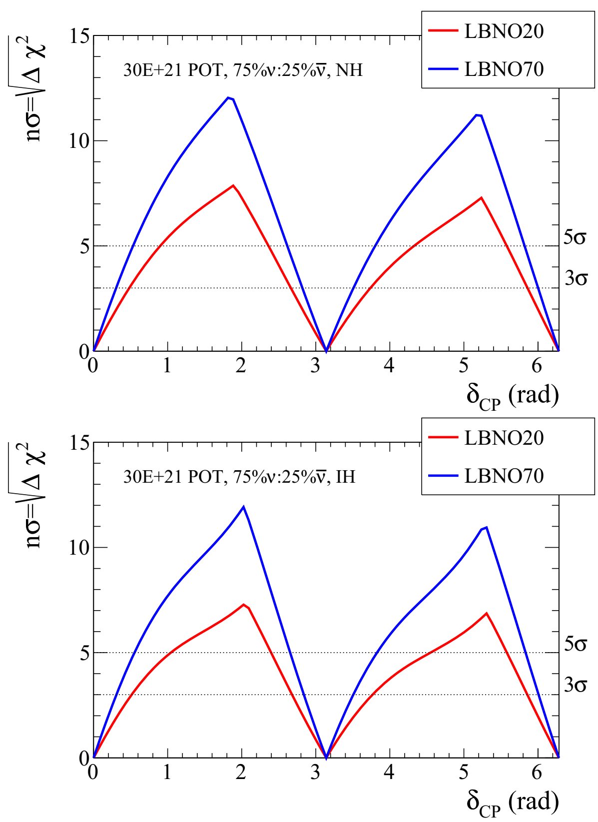

Figure 6: Median sensitivity to CPV for the optimized HPPS beam. The values of $\sin^2 2\theta_{13} = 0.09$ and $\sin^2 \theta_{23} = 0.45$ are assumed.

experimental sensitivity would increase to allow measuring δ_{CP} at the level of 3σ for 63% of the parameter phase-space. The sensitivity to discover δ_{CP} at least 5σ level for 35% of δ_{CP} values would be expected at that stage. Ultimately, with the high intensity neutrino beam delivered by 2MW HPPS, LBNO would reach a sensitivty at 5σ (3σ) level for 65% (80%) of the δ_{CP} phase-space.

A necessary step to realize a DLAr TPC on a tens of kton mass scale is a development of a detector prototype, whose goal would be to address the technical challenges and to fully characterize the detector performance. This is the aim of WA105 experiment at CERN, which plans to build $6 \times 6 \times 6$ m^3 prototype of the LBNO DLAr detector. The detector will be exposed to a charged particle beam allowing to calibrate the energy response of DLAr detector to hadronic showers, develop and validate liquid argon event reconstruction, and study particle identification properties. Success of the WA105 program would open the possibility towards building large tens-kton scale DLAr detectors for the next generation of underground neutrino observatories.

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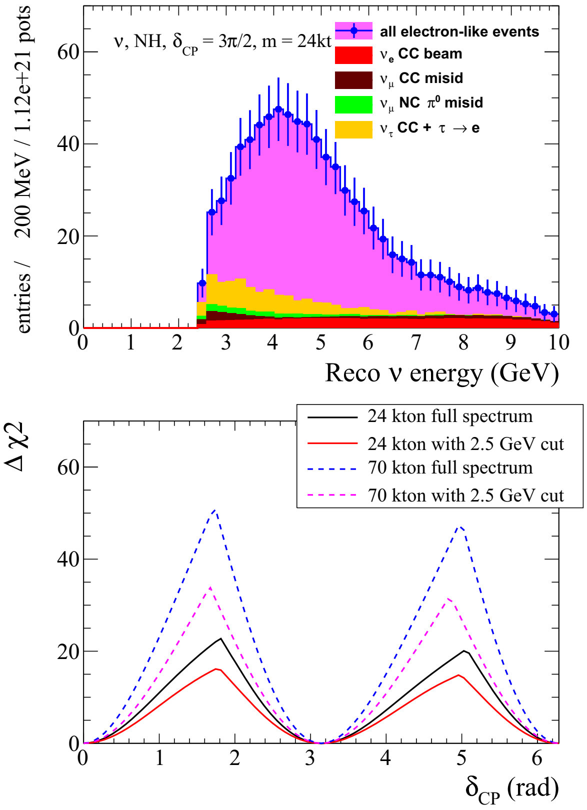

Figure 7: Expected distribution of e-like events for SPS-based neutrino beam after a cut on reconstructed energy at 2.5 GeV and comparison of the sensitivity to CPV with and without the energy cut.

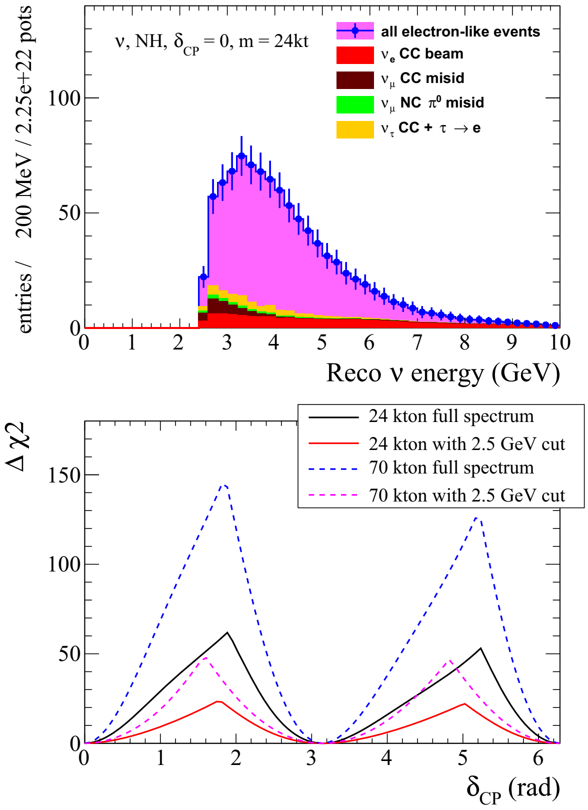

Figure 8: Expected distribution of e-like events for HPPS-based neutrino beam after a cut on reconstructed energy at 2.5 GeV and comparison of the sensitivity to CPV with and without the energy cut.

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