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## Neutrino flavor sensitivity of large liquid scintillator detectors

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### Abstract

Scintillator detectors are known for their good light yield, energy resolution, timing characteristics and pulse shape discrimination capabilities. These features make the next-generation liquid scintillation detector LENA[1] (Low Energy Neutrino Astronomy) the optimal choice for a wide range of astro-particle topics including supernova-, solar-, and geo neutrinos. In addition to the excellent calorimetric and timing properties, scintillator detectors (LSDs) are also capable of topology reconstruction sufficient to discriminate with adequate efficiency between electron and muon neutrino induced charge current events and neutral current events in the GeV energy range. This feature makes LENA a competitive tool for the determination of the mass hierarchy (MH) with long baseline neutrino beams such as the proposed CN2PY beam (2288 km). This work summarizes the status of the current work on track reconstruction schemes and discusses the sensitivity limit for the neutrino mass hierarchy measurement with LENA.

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**Keywords:** Neutrino physics, Neutrino mass hierarchy, Liquid scintillation detectors.

### 1. Introduction

There is a broad consensus in the physics community that the search for evidence for CP-violation in the neutrino sector is on the top of the priority list for the scientific endeavors of the next decade. The limited precision to which the numerical values of the key oscillation parameters are known and our ignorance of the neutrino mass hierarchy are currently the key obstacles preventing us from designing of such an experiment. LAGUNA-LBNO Design Study is an example of a comprehensive and incremental approach to these experimental challenges involving a long baseline neutrino beam together with far- and near detectors.

The favored option within LAGUNA-LBNO is a neutrino beam from CERN to Pyhšalmi (CN2PY). This very long distance (2288 km) would give an unambiguous (at least  $5\sigma$ ) determination of the mass hierarchy already within a few years[2]. Ideally, there should be several detectors with complementary characteristics involved in neutrino detection at the far end. The best performance in registration and identification of events induced by beam neutrinos in the GeV range is expected from liquid argon detectors. However, the relatively high energy threshold and the absence of free protons required for the inverse beta decay channel put limits on the physics scope of such a detector.

These deficiencies would easily be balanced by an ancillary liquid scintillator detector like the 50 kton fiducial mass LENA[1] considered by LAGUNA-LBNO for the Pyhäsalmi mine. Taking advantage of the good timing properties of the modern photo-sensors adds sufficient flavor sensitivity in the high-energy range to use LENA as an additional far detector at the CN2PY beam. This paper describes the current progress in that respect.

## 2. Neutrino flavor discrimination in liquid scintillator detectors

To conserve the lepton current in neutrino interaction, there must be a final state (leading) lepton produced in the reaction. This lepton carries information on the flavor of the incident neutrino. In charged current interactions the lepton is the charged counterpart to the incident neutrino. Hence, the flavor discrimination relies on the differentiation between the charged leptons in the exit channel. In neutral current interactions the final state leading lepton is a neutrino, which can transport substantial amounts of energy away from the detector making the energy measurement unreliable and the discrimination impossible.

Discrimination between the different kinds of charged particles traversing the scintillator is normally based on the differences in the pulse shape of the event and/or on the tagging the coincident decay and the daughter particles. These indicators can be used both at low-(~MeV) and at high-energy (~GeV) neutrino interactions.

At higher energies the range of the reaction products increases and consequently the scintillation light emission of charged leptons can no longer be considered as a point-like emission. Furthermore, the speed of light in the scintillator is smaller than the velocity of the charged lepton and thus a cone-like light front along the particle track is formed as illustrated in Fig.1. The idea is presented e.g in [3].

Starting from energies around 1 GeV, the muon- and electron like events can be distinguished by evaluating the topology of the event. Muons proceed along straight tracks with the length proportional to their energy. The emitted light is distributed along the entire path that traverses long distances in the detector. Electrons induce electromagnetic showers that dissipate all the available energy within a few meters from the interaction point. In Fig. 2 the Monte Carlo based results of the longitudinal dimension of a single charge particle event in LAB-based liquid scintillator, like LENA, are shown. Combining event topology with muon capture tagging enhances further the flavor discrimination capability of a scintillator detector between electron neutrino and muon neutrino induced processes. Unfortunately interactions of tauon neutrinos cannot be distinguished as tauons decay rapidly via hadronic, electron or muon channel which can mimic the signal of electron neutrino or muon neutrino interaction.

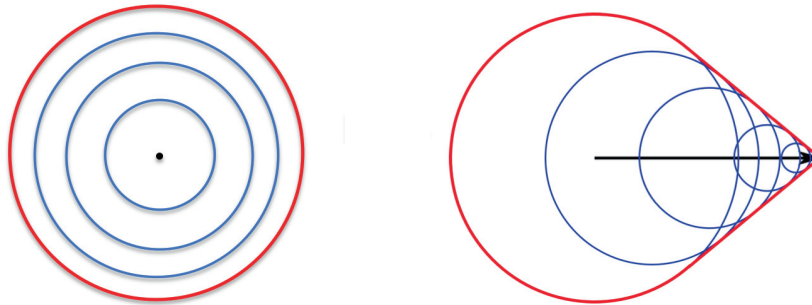


Figure 1. Scintillation light emission and light front of MeV-range low energy event (left panel) and high energy GeV-range event (right panel)

Since the typical light yield of scintillator (like LAB) is about 10000 photons per MeV of the deposited energy, a GeV event deposits vast amounts of light. Therefore, in a large scintillating volume is surrounded by a tight grid of photo-sensors, the collection of the first photon hits from every PMT contains already the needed information on the shape, location, and on the evolution of the event. The large number of registered photons also guarantees good timing and energy resolution. Such charged particle tracking based on the hit pattern of the first photons has already been tested and shown to work well for example in the solar neutrino experiment Borexino.

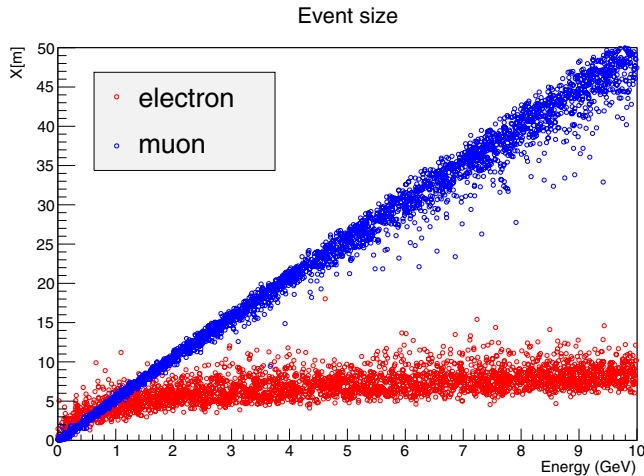


Figure 2. Longitudinal size of single charged particle event in LAB-based liquid scintillator. Looking for the dimensions of events can be used as an additional discriminating parameter between muon-like and electron-like events. The size of the event here is defined by the distance between the initial vertex and the farthest monte carlo vertex recorded.

### 3. CN2PY beam

Neutrino beam optimization is a very important and non-trivial part in the design of oscillation experiments. As this work is done in the context of LAGUNA-LBNO design study with the main focus on liquid argon located in the Pyhsalmi mine as the primary far detector, we are using the beam (CN2PY) also in our calculations. The details, construction scheme and performance of the proposed CNGS type conventional beam can be found from [4] and [2]. The simulated spectra of muons and anti-muons are shown in Fig. 4.

In the absence of operating large volume liquid scintillator detectors with proper electronics, our investigations rely on Monte Carlo simulations. The detector response framework of LENA[5] is based on a Geant4 [6]. A custom-made scintillation process has been implemented to reflect the measured properties of LAB. The timing properties and quantum efficiencies of the photomultiplier tubes have been taken into account. The final state particles coming from the neutrino interactions on hydrogen and carbon nuclei of the scintillator molecules are simulated with the GENIE neutrino event generator [7].

Transport algorithms applied to the vast numbers of scintillation photons generated by the interaction of GeV neutrinos in the active volume of the detector require adequate computing power. For that purpose the Finnish Grid Infrastructure has been used and a first high energy neutrino simulation campaign has been conducted. As a result of the first high energy neutrino simulation campaign on the grid the energy response matrices for different neutrino flavors and different reaction types have been produced, the event containment has been studied and the first estimates for the neutrino MH sensitivity of LENA have been made.

Since the range of GeV muons is comparable with the detector size, some of the events will not be fully contained in the active volume. Fortunately, in the mass hierarchy determination the electron charged current events play crucial role and the fraction of non-contained events is relatively small. It could be even smaller if the shape of LENA would be modified from the tall and slim structure as it is now into more spherical or even oblate shape. Furthermore, above 1 GeV the fraction of fully contained muon neutrino charged current events leading muon with energy above 1.5 GeV is 73 %. In case of electrons the fraction is 75%. The fraction of that kind of events compared to total number of events in each channel is shown in Fig 5 Therefore the tracking scheme developed by us is applicable to most of the neutrino induced events in the relevant energy range of the CN2PY beam.

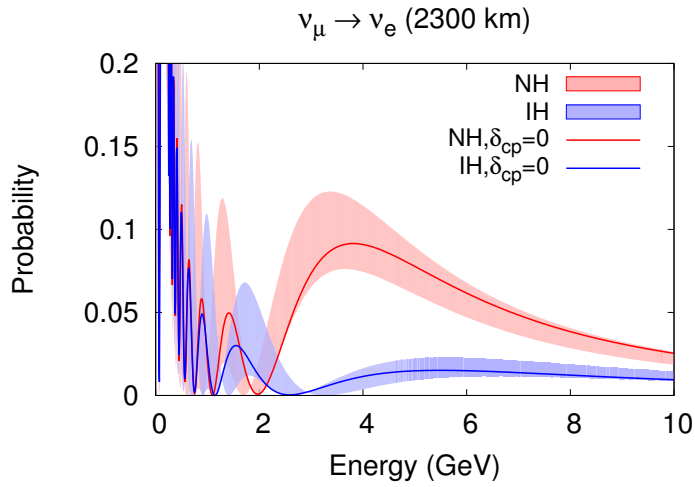


Figure 3. Electron neutrino appearance probability as a function of neutrino energy for 2300 km baseline. The different mass hierarchies are clearly separated above 2.5 GeV, independent of the value of CP-violation (shaded area).

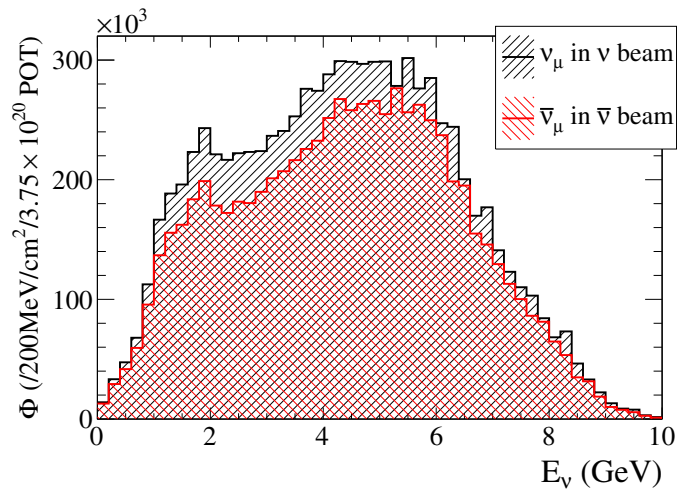


Figure 4. Optimized beam profiles of muon neutrinos and muon antineutrinos for 2288 km baseline from CERN to Pyhäsalmi mine in Finland [2].

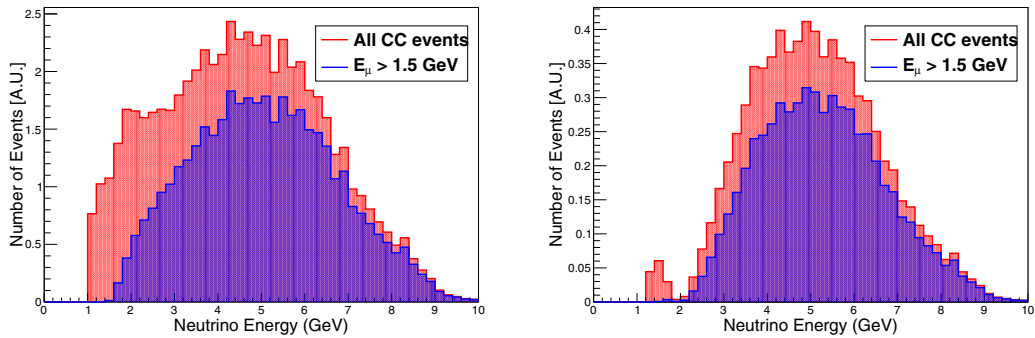


Figure 5. Shape of the expected event spectra of charged current events left panel for muon neutrinos and right panel for electron neutrinos. Red shaded area depicts all charged current events and blue area the (fraction) events which containing the leading lepton with energy above 1.5 GeV.

#### 4. Scheme for the high-energy event reconstruction

The aim of the on-going work is to define the key steps required for the full reconstruction scheme of high-energy events in LENA and to evaluate their performance. The proposed scheme consists of four stages. Each has a clear effect on the final discrimination power between neutrino flavors.

##### *Locating event*

The first task is to retract the light emission to the smallest possible spatial volume where it originated from and to get at least one reliable reference point  $(x, t)$  linking emission time and place. Also the first initial iteration of the full tracking can be done at this stage. In a simple event, containing only one charged particle, the charge barycenter and time coordinate from that point can be used as the reference point. For more complicated events the location of barycenter can be off the track. Dedicated backtracking algorithms are being developed based on clustering of time-of-flight corrected first hit arrival times in or near the light emission point. The left panel of Fig. 6 shows the effectiveness of backtracking algorithms applied to the data collected by Borexino.

##### *Finding probable light emission pattern*

Selection of the reference point(s) restricts the area of the allowed photon emission smoothed by the scintillation properties of the material. When all the allowed regions are merged together, the probability distribution of light emission points is revealed as exemplified in the right panel of Fig. 6. With this method the time-evolution of the event, the length(s) of the track(s) and the determination of the initial vertex point of the event becomes easier and more reliable.

##### *Likelihood fitting*

The final stage of the tracking scheme is the likelihood fitting using the parameters extracted by the preceding steps as the starting parameters. The likelihood fitting of the track(s) yields the most reliable energy estimate of the initial neutrino.

##### *Multi-variate analysis*

To reach the final sensitivities for the physics analysis, the output of the tracking steps is fed into the multivariate algorithm based on boosted decision tree[9]. The decisions involve the discrimination between the muon and the electron, between the charged current and the neutral current events, and between the signal and the background.

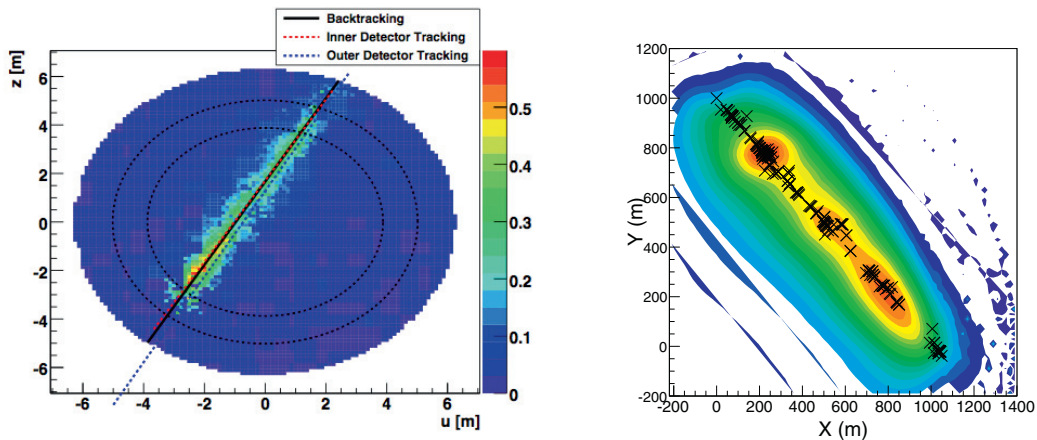


Figure 6. Left panel: Track of a traversing muon traversing the Borexino detector. The backtracking algorithm was applied to the Borexino data and compared with the information derived from the entrance and exit points. (Borexino's original tracking methods for background muons [8]). The Figure depicts the plane of the reconstructed track. Right panel:  $\sim 3\text{GeV}$  muon: The enhanced algorithm using the individual photon information, reveals the track and the most probable light emission locations along the track.

## 5. Mass hierarchy sensitivity with LENA

Current estimate for the mass hierarchy sensitivity with LENA indicates that a  $3\sigma$ -measurement with the rejecting power of better than 95% [10] can be completed after 10 years of measurement (5 years of  $\nu_{\mu\mu}$  + 5 years of  $\bar{\nu}_{\mu\mu}$ ) with the beam from CERN to Pyhäsalmi.

To reach this measurement of neutrino mass hierarchy with LENA, the energy response migration matrices have been produced, realistic signals (electron neutrino appearance and muon neutrino disappearance) have been introduced and background rejection capability with multi-variate-analysis has been included. Also the event containment in the detector volume has been taken into account. Up to date values (or limits) for the oscillation parameters were used in GLoBES [11][12] calculations. The statistical analysis follows the steps described in ref [10].

Our current sensitivity limits do not yet include all of the possible particle tracking methods for flavor or interaction type discrimination. We expect that after taking them into account the sensitivity will improve further.

## 6. Conclusions & Outlook

At present liquid scintillation detectors are not considered to be a viable options for registration and identification of high-energy neutrinos generated by proton beams. The two main reasons for that are: a relatively small size and the lack of neutrino flavor sensitivity. As part of the work done within the LAGUNA-LBNO design study we are reevaluating these claims. The issue of the detector size is beyond the scope of this paper. Here we have described the current status concerning the flavor sensitivity of 50 kton LENA – currently the biggest of the proposed LSc detector.

While it is true that at low energies LSc detectors are not sufficiently sensitive to the flavor of the neutrino-induced event, the situation improves noticeably at high-energies. Above 1 GeV the spatial extent of the event grows above the position resolution limit imposed by the granularity of photo sensors in the detector adding event topology as an additional criterion for flavor recognition. At even higher energies the growing importance of the tau channel makes event recognition more complicated again.

Fortunately, this window of the best flavor sensitivity (1–10 GeV) coincides perfectly with the energy distribution of neutrinos from the CN2PY beam. Already our preliminary calculations, without implementation of all of the discriminatory power of the detector, indicate that a 50 kton LENA would determine MH at  $3\sigma$  within 5+5 years of running. By increasing the size and improving the analysis algorithms the MH would reach  $5\sigma$  making a LSc detector a real alternative to liquid argon devices.

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