

Physics Projects for a Future CERN–LNGS Neutrino Programme

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We present an overview of the future projects concerning the neutrino oscillation physics in Europe. Recently a joint CERN–LNGS scientific committee has reviewed several proposals both for the study of atmospheric neutrinos and for long (LBL) and short baseline (SBL) neutrino oscillation experiments.

The committee has indicated the priority that the European high energy physics community should follow in the field of neutrino physics, namely a new massive, atmospheric neutrino detector and a ν_τ appearance campaign exploiting the new CERN–LNGS Neutrino Facility (NGS), freshly approved by CERN and INFN.

The sensitivity and the discovery potential of the whole experimental program in the Super–Kamiokande allowed region are discussed.

1. INTRODUCTION

The indication for the existence of neutrino oscillation has originally appeared in the atmospheric neutrino data of Kamiokande [1] & IMB [2] where the measurement of the ratio $R_{\mu/e}$ of μ -like and e -like events was lower than the Monte Carlo expectation.

The recent data of Super–Kamiokande (SK) [3] have strengthened the evidence for the existence of an anomaly in the flavour ratio of atmospheric neutrinos. Moreover the high statistics of SK show distortions of the angular distributions of the sub–GeV and the multi–GeV μ -like events that suggest the ν_μ oscillation hypothesis, while the angular distribution of the e -like events is consistent with the no–oscillation hypothesis.

This evidence is also supported by the SOUDAN2 [4] data and by the SK & MACRO [5] data on up-going muons.

The absence of an oscillation signal in the data of the CHOOZ [6] experiment essentially rules out the $\nu_e \leftrightarrow \nu_x$ oscillations in the interesting region of parameter space and favours the interpretation of the SK result in terms of $\nu_\mu \leftrightarrow \nu_\tau$ oscillation with Δm^2 in the range $10^{-2} - 10^{-3} eV^2$ and $\sin^2(2\theta)$ in the range 0.8 – 1.0. More exotic interpretations, like $\nu_\mu \leftrightarrow \nu_{sterile}$, are at present

not fully excluded.

A possible method to confirm these results is the development of long–baseline accelerator neutrino beams. The accelerator beams can have higher intensity and higher average energy than the atmospheric flux, and if $\nu_\mu \leftrightarrow \nu_\tau$ oscillations are indeed the cause of the atmospheric neutrino anomaly, they can produce a measurable rate of τ leptons for most of the values of the oscillation parameters that are a solution to the atmospheric data.

On the other hand measurements of atmospheric neutrinos with large statistics and/or better experimental resolutions, can also provide convincing evidence for oscillations, thanks to unambiguous detectable effects on the energy, zenith angle and L/E distributions of the events. The study of these effects can provide a precise determination of the oscillation parameters. The range of L/E available for atmospheric neutrinos ($10 - 10^4 Km/GeV$) is much larger than that of long–baseline accelerator experiments ($\simeq 100 Km/GeV$) and the sensitivity extends to lower values of Δm^2 .

All these considerations call for a comprehensive physics programme, whose main goals are:
– the search for a direct neutrino oscillation signal in the full range indicated by the SK results;

- the precise test of the $\nu_\mu \leftrightarrow \nu_\tau$ oscillation hypothesis;
- the measurement of the relevant oscillation parameters: at least one squared mass difference, Δm^2 , and one mixing angle, $\sin^2(2\Theta)$.

The above arguments stimulated a joint CERN–INFN project for a beam towards the Gran Sasso National Laboratory (LNGS), 732 km away. At the same time several LBL and SBL experiments, based on very different techniques, as well as atmospheric neutrino experiments have been proposed and recently reviewed by a joint CERN–LNGS scientific committee.

In the following sections we will review the status of the future CERN–LNGS neutrino programme (section 2.) and of the new CERN Neutrino Beam to Gran Sasso (section 3.). In section 4. we will describe the proposed LBL experiments and discuss their sensitivity and significance in the SK allowed region of the oscillation parameter space. Finally in section 5. we will outline the characteristics and the sensitivity of a possible massive detector for atmospheric neutrino physics.

2. THE FUTURE CERN–LNGS NEUTRINO PROGRAMME

Here we faithfully report the out-come of the first meeting of the recently constituted joint CERN–LNGS scientific committee. The meeting was held at CERN on November 3-4, 1998 with the aim of reviewing the overall CERN–LNGS neutrino experimental programme and evaluating its potentiality also in view of the existence of other similar projects [7,8].

The committee believes that a combined experimental effort can accomplish the above programme. Elements of this programme are:

i) A large mass (larger than 20kt) atmospheric neutrino experiment with high resolution in angle and neutrino energy, so that an explicit oscillation pattern can be put in evidence. Such a detector can be sensitive to oscillations for $\Delta m^2 = 2 \times 10^{-4} - 5 \times 10^{-3} eV^2$, covering all the relevant region also in view of the K2K experiment [7], and can measure both the mass difference and at least one of the mixing angles.

ii) A Long Base Line (LBL) beam from CERN to Gran Sasso as laid out in documents CERN 98–02 and CERN–SPSC 98–35. The feasibility of constructing a neutrino beam towards Gran Sasso has been demonstrated, being well-suited for experiments and with a built-in flexibility allowing the beam design to evolve with the field of neutrino oscillation physics.

iii) A ν_τ appearance LBL experiment, uniquely capable of precisely discriminating the $\nu_\mu \leftrightarrow \nu_\tau$ oscillation hypothesis in the range above $1 - 2 \times 10^{-3} eV^2$ with underground detectors. Ways of extending this mass range may exist, possibly in successive steps, due to extremely low experimental background and the possibility of using a detector on the surface. The search for ν_e appearance can nicely be coupled with ν_τ appearance experiments. However, due to the small number of signal events expected, a ν_τ appearance experiment may not be effective in actually determining the oscillation parameters.

iv) A ν_μ disappearance LBL experiment, with the need for a near station, again sensitive down to $1 \times 10^{-3} eV^2$ in Δm^2 , provided the systematic effects can be kept under control to a sufficient level of accuracy.

The complementarity between iii) and i) or iv) is manifest. The same is not true for i) and iv), with i) having a larger reach potential at low Δm^2 . The possible integration of two or more elements stated above into one combined detector deserves attention, to the extent that this can be shown to be compatible with the individual goals outlined. The committee also took note of the scientific interest expressed by:

- A short baseline experiment to search for $\nu_\mu \leftrightarrow \nu_\tau$ oscillation beyond the sensitivity reach of CHORUS and NOMAD (SPSC 98-29 & M616).
- A low energy neutrino beam derived from the PS to search for $\nu_\mu \leftrightarrow \nu_e$ oscillation in the range of parameters suggested by LSND (SPSC 98-27 & M614).
- A long-term experimental neutrino programme at CERN based on a future Neutrino Factory, offering high flux neutrino beams originating from a high intensity injector proton booster and/or muon storage ring of a $\mu^+\mu^-$ collider (SPSC 98-30 & M617, SPSC 98-31 & M618).

3. THE CERN NEUTRINO BEAM TO GRAN SASSO

A substantial part of the CERN–LNGS neutrino program will be based on a new CERN neutrino beam line (NGS) pointing to Gran Sasso, 732 Km away. The conceptual design of this facility has been studied in detail by a Technical Committee, mandated by CERN and INFN, and its feasibility has been fully demonstrated [9].

The NGS neutrino beam is produced from the decay of mesons, mostly π 's and K 's. The mesons are created by the interaction of a 400 GeV proton beam onto a graphite target, they are sign-selected and focused in the forward direction by two magnetic coaxial lenses, called horn and reflector and finally they are let to decay in an evacuated tunnel pointing toward Gran Sasso.

As clearly stated in the NGS report [9], the design concentrated on the civil engineering, freezing some parameters but keeping flexibility in the actual choice of the beam optics. Mainly the proton energy, the extraction from the SPS, the target room design, the geometry of the decay tunnel and the beam absorber were chosen. The main characteristics of the neutrino beam-line are listed in Table 1.

3.1. Optimization of the beam for $\nu_\mu \leftrightarrow \nu_\tau$ appearance search

As for the beam, the general strategy was to opt for a wide band neutrino beam based on the experience gathered at CERN with the design and the operation of the WANF. The beam optimization and the design of the details of the beam optics have been subject of further studies driven by the requests of the experiments. Following the indication of the CERN–LNGS committee, a first optimization of the beam has been carried out with the goal of maximizing the ν_τ CC interactions at LNGS for appearance experiments [10].

In the limit of small oscillations, where the flavour transition probability is approximated as $P(\nu_\mu \leftrightarrow \nu_x) \simeq \sin^2(2\Theta) \times (1.27\Delta m^2 L/E)^2$, the ν_τ event rate at a far location is given by the following formula:

$$N_\tau = K \int \phi_{\nu_\mu}(E) \times f(E) \times \epsilon(E) \times dE/E \quad (1)$$

Table 1

Main parameter list of the NGS neutrino beam

Target material	graphite
Target rod length	10 cm
Target rod diameter	3 mm
Number of rods	11–13
Rod separation	1–9 cm
Horn & Reflector	parabolic
H&R length	6.65 m
H&R current	120 kA
Min horn distance from target	1.8 m
Max refl. distance from target	80 m
Decay tunnel length	992 m
Decay tunnel radius	1.22 m
Tunnel vertical slope	-50 mrad
Pressure in decay tunnel	1 Torr
Near detector pit	foreseen
Distance from target	1850 m
Proton energy	400 GeV
Expected pot/year:	
in shared SPS mode	3.95×10^{19}
in dedicated SPS mode	7.60×10^{19}

where:

$K = N_a \times M_d \times \sigma_0 \times \sin^2(2\Theta) \times (1.27\Delta m^2 L)^2$, E is the neutrino energy, ϕ_{ν_μ} is the ν_μ flux at the detector distance L , σ_0 is the ν_μ CC interaction cross-section, f is the ratio between ν_τ and ν_μ CC interaction cross-sections, ϵ is the τ detection efficiency, N_a is the Avogadro number and M_d is the detector mass.

The integral in equation 1 is the quantity to be maximized. Note that it does not depend on the oscillation parameters. Note also that appearance experiments are only sensitive to the product $\sin^2(2\Theta) \times (\Delta m^2)^2$.

A full Monte Carlo simulation of the beam has been used, based on the FLUKA97 [11] package, to evaluate neutrino fluxes and event rates. It turned out that the best optics configuration consists in a horn focusing 30 GeV mesons and a reflector tuned to 50 GeV. The predicted ν_μ event rate and the $\bar{\nu}_\mu$ and ν_e contaminations of the NGS beam at LNGS are listed in Table 2 for two modes

Table 2

Total ν_μ , $\bar{\nu}_\mu$ and ν_e CC events rate per $kt \cdot year$ at LNGS ($N_\mu, N_{\bar{\mu}}$ and N_e) in the cases of shared and dedicated mode of operation of the SPS. The average energy ($\langle E_{\nu_\mu} \rangle$) of the ν_μ interactions is also shown.

	shared	dedicated	$\langle E_{\nu_\mu} \rangle$
N_μ	2280	4332	30.2
$N_{\bar{\mu}}$	51.3	97.5	
N_e	18.2	34.7	

Table 3

Rate (N_τ) of the ν_τ CC events per $kt \cdot year$ as a function of Δm^2 for full mixing at LNGS in the cases of shared and dedicated mode of the SPS. The average energy ($\langle E_{\nu_\tau} \rangle$) of the ν_τ interactions is also shown.

$\Delta m^2 (eV^2)$	N_τ		$\langle E_{\nu_\tau} \rangle$
	shared	dedicated	
1.10^{-2}	161.	306.	19.8
8.10^{-3}	109.	206.	19.5
6.10^{-3}	64.	121.	19.1
4.10^{-3}	29.	56.	18.9
2.10^{-3}	7.5	14.2	18.7
1.10^{-3}	1.88	3.57	18.7
8.10^{-4}	1.20	2.28	18.7
6.10^{-4}	0.68	1.29	18.7

of operation of the SPS. In Table 3 we give the ν_τ event rate for values of Δm^2 at full mixing within the range allowed by the SK atmospheric neutrino data.

Options of lower beam energy have also been considered for disappearance experiments [12]. Further studies on the optimisation of the beam are currently being done.

4. THE LBL EXPERIMENTS

In this section we give a brief description of the experiments proposed to study neutrino oscillations at LNGS with the NGS neutrino beam. The

sensitivity and the discovery potentials of each experiment have been calculated for an exposure of four years and for the neutrino rates presented in the previous section.

4.1. ICARUS

ICARUS [13] is an approved experiment at LNGS, in preparation to search for proton decays in exclusive channels and to study atmospheric and solar neutrinos. Exposed at the NGS beam it will carry out $\nu_\mu \leftrightarrow \nu_\tau$ oscillation search in appearance mode.

4.1.1. The detector

The ICARUS detector is a liquid argon TPC, whose main characteristics are the following.

- It is a homogeneous tracking device, capable of dE/dx measurement. The high dE/dx resolution allows both good momentum measurement and particle identification for soft particles.
- Electromagnetic and hadronic showers are fully sampled. This allows to have a good energy resolution for both electromagnetic, $\sigma(E)/E \simeq 3\%/\sqrt{E/GeV}$, and hadronic contained showers, $\sigma(E)/E \simeq 15\%/\sqrt{E/GeV}$.
- It has good electron identification and e/π^0 discrimination thanks to the ability to distinguish single and double m.i.p. by ionization and to the bubble chamber quality space resolution.

A neutrino event detected with a small prototype (50 litres) of the ICARUS detector is shown in Figure 1.

The detector has a modular structure, whose basic unit is a $0.6kt$ module. The installation of a first module at LNGS in the year 2000 has been approved. The second step of the ICARUS project should be the installation of 3 new modules (for a total mass of $2.4kt$) in 2003, when the NGS neutrino beam will be available.

Recently the ICARUS collaboration has put forward the possibility to build a Super-ICARUS [14] detector of $30kt$ to be placed just outside LNGS, with the aim of increasing the sensitivity to neutrino oscillations and cover completely the SK allowed region.

4.1.2. The $\nu_\mu \leftrightarrow \nu_\tau$ oscillation search

We report the results of the study made on the ICARUS $\nu_\mu \leftrightarrow \nu_\tau$ oscillation sensitivity assum-

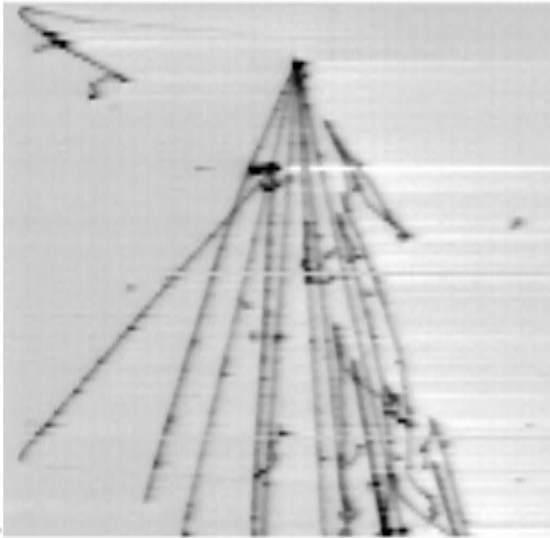


Figure 1. An example of recorded neutrino interaction in a 50 liter Liquid Argon TPC prototype exposed at the CERN ν beam. The neutrino comes from the top of the picture. The horizontal axis is the time axis (drift direction) and vertically is the wire number. The visible area corresponds to $47 \times 32 \text{ cm}^2$

ing 4 modules (2.4 kt). Because of the high resolution on measuring kinematical quantities, the ν_τ appearance search in ICARUS is based on the kinematical suppression of the background using similar techniques to those of the NOMAD experiment [15]. The basic idea consists in reconstructing, in the plane transverse to the incoming neutrino direction, the missing momentum due to the two undetected neutrinos produced in τ lepton decays. Since the missing transverse momentum is approximately Lorentz invariant, the τ detection efficiency should be constant as a function of the ν_τ energy. Nevertheless, a slight decrease with increasing energy is expected, since the cuts applied to isolate the candidate events depend on the background rate, which is an increasing func-

tion of the neutrino energy.

4.1.3. Detection efficiency and background

The ν_τ identification in ICARUS is under study for all the τ decay modes. Nevertheless very good results are already achievable with the *golden sample* of events namely the $\tau \rightarrow e$ channel whose detection efficiency has been evaluated to be about 50%.

In this channel, the main background sources are the ν_e contamination in the ν beam and the π^0 's in neutral current events misidentified as electrons. The rejection power of the latter is close to 100%. A ν_e event is a background either if there are undetected neutral hadrons in the final state or because of the smearing due to nuclear effects in the target nucleon and to the detector resolution. It has been shown that a background rejection factor of about 100 is sufficient to expect less than one background event in four years [14].

4.2. OPERA

The OPERA experiment [16] is aimed to search for ν oscillation looking at the appearance of ν_τ in the NGS beam. Because of the target-detector distance, the high efficiency and the low background (less than 1 event), the experiment will be able to probe the Super-Kamiokande signal with a very high discovery potential.

4.2.1. The detector

The OPERA detector consists of a 0.75 kt lead emulsion target. The basic element (*cell*) of the detector is composed of a 1 mm thick lead-plate followed by an emulsion sheet (ES1), a 3 mm drift space (filled with low density material) and another emulsion sheet (ES2) (see Figure reffig:ope). An ES1(ES2) is made of a pair of emulsion layers 50 micron thick, on either side of a 100(200) micron plastic base. Thirty cells are arranged together to form a *brick*, which has $15 \times 15 \times 13 \text{ cm}^3$ dimensions; bricks are put together to form a *module* ($2.8 \times 2.8 \times 0.15 \text{ m}^3$).

Since the emulsion does not have time resolution, there are electronic detectors after each module in order to correlate the neutrino interactions to the brick where they occur and to guide the scanning. Streamer tubes have been proposed as electronic detectors, but other pos-

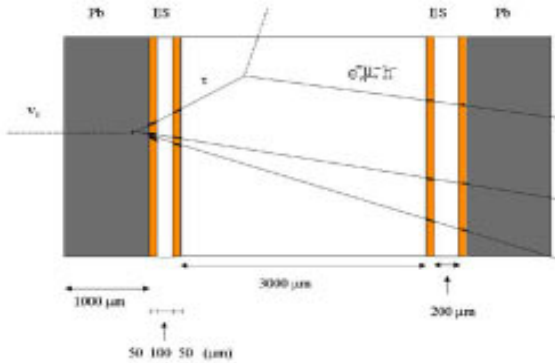


Figure 2. The basic elements of the OPERA detector

sible solutions are under study. A total of 300 modules are subdivided into 10 identical *super-modules*. The overall dimensions of the detector are $3.5 \times 3.5 \times 40 m^3$.

4.2.2. The $\nu_\mu \leftrightarrow \nu_\tau$ oscillation search

The τ 's produced in ν_τ CC interactions, are detected by measuring their decay kink when occurring in the drift space. The kink angle is measured by associating two high-precision 3-D track segments reconstructed in ES1 and ES2. The basic factor which, in the present design, determines the detection efficiency is the probability that the τ , before its decay, exits the lead plate (1 mm thick) where it is produced. So, the decay "kink" must occur in the drift space between consecutive emulsion layers. This drift space is filled with low density material, to eliminate the re-interaction background, otherwise relevant for the hadronic decay channels. The kink finding efficiency is related to a cut determined by the angular resolution of the emulsion trackers. Only kink angles larger than a given value ($20 mrad$) are accepted. The present estimate of the OPERA τ detection efficiency is about 35%. We observe that the τ decays in the lead-target plates are not lost, but they do not offer the same golden background conditions. Studies are under way in order to

use them to further increase the overall detection efficiency.

4.2.3. The background

The main source of background for the decays inside the gap is the production of charged charm particles with subsequent decay when the primary lepton is not detected. Monte Carlo simulation showed that the number of background events expected from this source is well below 1 in four years. Thus OPERA is essentially a background free experiment.

4.3. AQUA-RICH

AQUA-RICH [17] has been proposed as a long baseline experiment at LNGS. The detector, containing $125 kt$ of water, uses the imaging Cerenkov technique to measure velocity, momentum and direction of almost all particles produced by neutrinos interacting in water.

Monte Carlo simulations show that hadrons are measured up to 9 GeV/c with $\Delta p/p < 7\%$ and muons up to 40 GeV/c with $\Delta p/p < 2\%$. Track direction is determined from the width of the ring image with error $\sigma(\theta) < 5 mrad$, but track reconstruction (photon emission point) requires timing resolution $\sigma_t < 1 ns$. The detector has to be sited outdoor, near the Gran Sasso Laboratory, and could be used also to observe atmospheric neutrinos.

4.3.1. The $\nu_\mu \leftrightarrow \nu_\tau$ oscillation search

Signal and background Monte Carlo events generated according to the NGS beam have been used to study the AQUA-RICH capability to search for $\nu_\mu \leftrightarrow \nu_\tau$ oscillations. The τ signal could be observed selecting QE events $\nu_\tau n \rightarrow \tau p$, followed by the τ muonic decay, with both the muon and the proton above threshold. A good separation between ν_τ signal and ν_μ background is possible as shown in [17] and will allow to have less than one background event in four years.

4.4. NOE

NOE [18] has been proposed as a long baseline experiment to study $\nu_\mu \leftrightarrow \nu_\tau$ and $\nu_\mu \leftrightarrow \nu_e$ oscillations.

4.4.1. The detector

The basic elements of the NOE detector are *light* transition radiation detector modules (TRD) for a total TRD mass of $2.4kt$ interleaved with modules of a massive fine grain $5.6kt$ calorimeter (CAL). A TRD and a CAL module together form the basic module of the NOE detector. The whole $8kt$ NOE detector is made of 12 subsequent basic modules.

The TRD module is built with 32 layer of marble (2 cm thick, 0.2 radiation length) interleaved with layers of polyethylene foam radiators. The marble is used as target for the ν_τ appearance search.

The CAL module is made of bars (with a cross-section of $4 \times 4cm^2$) where scintillating fibres are embedded into a distributed absorber (iron ore).

The electromagnetic and hadronic energy resolution are $\sigma(E)/E = 17\%/\sqrt{E/GeV} + 1\%$ and $\sigma(E)/E = 42\%/\sqrt{E/GeV} + 8\%$ respectively.

The muon direction and the hadronic shower axis are measured with a angular resolution $\sigma_\mu(\theta) = 0.022/\sqrt{E_\mu/GeV} + 0.040/(E_\mu/GeV)$ and $\sigma_h(\theta) = 0.175/\sqrt{E_h/GeV} + 0.351/(E_h/GeV)$ respectively.

Combining both CAL and TRD information, the rejection power to separate electrons from minimum ionising particles is $10^{-3} - 10^{-4}$. The e/π^0 discrimination is based on the fact that, because of the light TRD material, π^0 's cross many TRD layers with low conversion probability.

4.4.2. The $\nu_\mu \leftrightarrow \nu_\tau$ oscillation search

The $\nu_\mu \leftrightarrow \nu_\tau$ oscillation search is performed exploiting the kinematical identification of the τ lepton decays exploiting the techniques developed by the NOMAD collaboration [15]. So far the $\tau \rightarrow e$ channel has been fully studied. The possibility to use the $\tau \rightarrow \pi$ channels is encouraging.

The τ detection efficiency in the $\tau \rightarrow e$ channel has been evaluated to be $\simeq 22\%$. As already discussed for the ICARUS experiment, a slight decrease of the efficiency with increasing neutrino energy is expected.

The corresponding background has been evaluated to be 4.6 events in four years mainly from the ν_e contamination, in the ν_μ beam. Details about the evaluation of all the background channels can

be found in [18].

4.5. NICE

The NICE experiment [19] has been proposed to study the Super-Kamiokande signal using the disappearance technique in a long baseline experiment. In order to exploit the maximum potentiality of the disappearance technique, it plans to exploit a low energy version ($\langle E_\nu \rangle \simeq 6-7GeV$) of the NGS neutrino beam; a close detector is also envisaged. A preliminary conceptual design of the detector is based on a large ($\simeq 10kt$) compact isotropic iron-scintillator electromagnetic/hadron calorimeter, surrounded on 4 sides by a magnetised iron spectrometer. The maximum sensitivity of the experiment on Δm^2 , at full mixing, has been evaluated to be about $5 \times 10^{-4} eV^2$, provided that the systematical error is below 2%.

4.6. Sensitivity and significance of the LBL experiments

We recall that to evaluate the sensitivity and the discovery potential of the experiments searching for neutrino oscillation in appearance mode, a running time of 4 years has been considered, corresponding to 2×10^{20} pot operating the SPS in shared mode. The high energy NGS neutrino beam spectrum, optimized for ν_τ search, has been used.

With the these assumptions, the typical sensitivity that could be reached with an experiment at LNGS, in absence of ν_τ oscillation, is very similar for all the proposed experiments; the corresponding exclusion plot in the oscillation parameters space is shown in Figure 3.

On the other hand, when we are in presence of a claim of discovery, the relevant parameter to quote is the significance, $S = N_s/\sqrt{N_b}$ where N_s is the number of signal events and N_b is the expected background.

In Table 4 the minimum Δm^2 at full mixing satisfying the inequality $S > 4$ is shown for the proposed appearance experiments (ICARUS, OPERA, AQUA-RICH and NOE). For most of the experiments the discovery potential extends at least to the SK best fit point ($\Delta m^2 = 2.2 \times 10^{-3}$ and $\sin^2(2\Theta) = 1$.) in the SK allowed region of the oscillation parameter space.

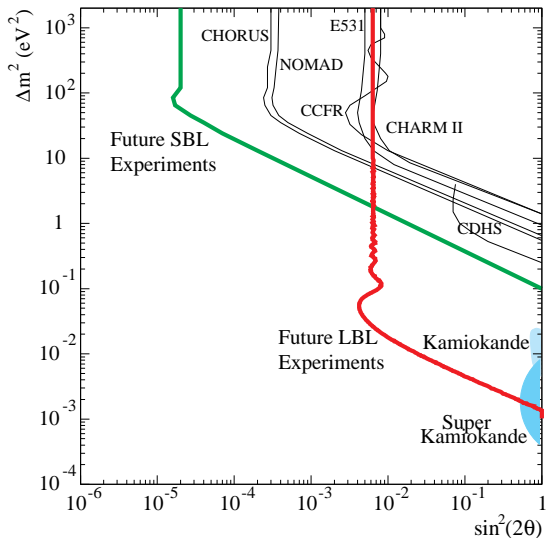


Figure 3. Oscillation parameter range that can be excluded at 90%CL by the proposed LBL and SBL experiments, in the case if $\nu_\mu \leftrightarrow \nu_\tau$ appearance search.

Table 4

Minimum $\Delta m^2/10^{-3}eV^2$ at full mixing satisfying the inequality $S > 4$ (discovery potential).

ICARUS	OPERA	AQUA-RICH	NOE
2.6	1.8	2.3	3.8

5. A HIGH DENSITY DETECTOR FOR ATMOSPHERIC NEUTRINOS

A new generation of massive atmospheric neutrino detectors would be particularly useful to measure precisely and separately the neutrino oscillation parameters Δm^2 and $\sin^2(2\theta)$ as explained in [20].

5.1. Experimental method

Atmospheric neutrino fluxes are not in general up/down symmetric. However, the up/down asymmetry, which is mainly due to geomagnetic

effects, is reduced to the percent level for neutrino energies above 1.3 GeV. At these energies, for $\Delta m^2 < 10^{-2}eV^2$, downward muon neutrinos are not affected by oscillations. Thus, they may constitute a *near* reference source. Upward neutrinos are instead affected by oscillations, since the L/E ratio of their path length over the energy ranges up to $10^4 km/GeV$. Therefore with atmospheric neutrinos one may study oscillations with a single detector and two sources: a *near* and a *far* one.

The effects of oscillations are then searched comparing the L/E distribution for the upward neutrinos, which should be modulated by oscillations, with a reference distribution obtained from the downward neutrinos. For upward neutrinos the path length L is determined by their zenith angle as $L(\theta)$, while the reference distribution is obtained replacing the actual path length of downward neutrinos with the mirror-distance $L'(\theta) = L(\pi - \theta)$. The ratio $N_{up}(L/E)/N_{down}(L'/E)$ will then correspond to the survival probability given by

$$P(L/E) = 1 - \sin^2(2\theta) \sin^2(1.27\Delta m^2 L/E) \quad (2)$$

A smearing of the modulation is introduced by the finite L/E resolution of the detector.

We point out that results obtained by this method are not sensitive to calculations of atmospheric fluxes.

We also remark that this method does not work with neutrinos at angles near to the horizontal, since the path lengths corresponding to a direction and its mirror-direction are of the same order.

If evidence of neutrino oscillation from the study of ν_μ disappearance is obtained, a method based on τ appearance can be used to discriminate between oscillations $\nu_\mu \leftrightarrow \nu_\tau$ and $\nu_\mu \leftrightarrow \nu_{sterile}$. Oscillations of ν_μ into ν_τ would in fact result in an excess of muon-less events produced by upward neutrinos with respect to muon-less downward. Due to threshold effects on τ production this excess would be important at high energy. Oscillations into a sterile neutrino would instead result in a depletion of upward muon-less events. Discrimination between $\nu_\mu \leftrightarrow \nu_\tau$ and $\nu_\mu \leftrightarrow \nu_{sterile}$ is thus obtained from a study of

the asymmetry of upward to downward muonless events. Because this method works with the high energy component of atmospheric neutrinos, it becomes effective for $\Delta m^2 > 3 \times 10^{-3} eV^2$.

5.2. Choice of the Detector

The outlined experimental method requires that the energy E and direction θ of the incoming neutrino be measured in each event. The latter, in the simplest experimental approach, can be estimated from the direction of the muon produced in the ν_μ charged-current interaction. The estimate of the neutrino energy E requires the measurement of the energy of the muon and of the hadrons produced in the interaction. In order to make the oscillation pattern detectable, the experimental requirement is that L/E be measured with an error smaller than half of the modulation period. This translates into requirements on the energy and angular resolutions of the detector. As a general feature the resolution on L/E improves at high energies, mostly because the muon direction gives an improved estimate of the neutrino direction. Thus the ability to measure high momentum muons (in the multi-GeV range), which is rather limited in the on-going atmospheric neutrino experiments, would be particularly rewarding.

A detector with a high efficiency on μ/π separation is required for an effective implementation of the method proposed, while, leaving aside oscillations involving electron neutrinos, no stringent requirement is put on electron identification and electromagnetic energy resolution.

5.3. A Possible Detector Structure

A large mass and high-density tracking calorimeter with horizontal sampling planes has been proposed as a suitable detector [20]. A mass of a few tens of kilotons is necessary to have enough neutrino interaction rate at high energies, while the high-density enables to operate the detector as a muon range-meter.

The detector consists in a stack of 120 horizontal iron planes 8 cm thick and $15 \times 30 \text{ m}^2$ surface, interleaved by planes of sensitive elements (RPC's and/or limited streamer tubes). The sensitive elements, housed in a 2 cm gap between the iron

planes, provide two coordinates with a pitch of 3 cm. The height of the detector is thus 12 metres. The total mass exceeds 34 kt . The number of read-out channels is 180,000.

5.4. Sensitivity to ν_μ oscillations

The proponents of [20] claim that with appropriate selections on μ -like events the experiment can reach the L/E resolution required to resolve the modulation periods typical of the oscillation phenomena for Δm^2 values in the range $2 \times 10^{-4} - 5 \times 10^{-3} eV^2$. As an example, the L/E distribution obtained with the method described in section 5.1 for $\Delta m^2 = 10^{-3}$ and $\sin^2(2\Theta) = 0.9$ is plotted in Figure 4. The discovery potential of the experiment, after three years of exposure, is also shown.

As indicated by the ICARUS [14], AQUARICH [17] and NICE [19] collaborations, similar results can be obtained with different detection techniques provided that the detector mass exceeds several tens of kt .

6. CONCLUSIONS

We believe that the neutrino oscillation search, based on the NGS facility complemented by atmospheric neutrino detection, constitutes an extremely appealing and realistic physics programme for CERN and for LNGS, which will keep European neutrino physics at the frontier.

Our personal opinion, strengthened by the indications of the joint CERN-LNGS scientific committee, is that the NGS beam is extremely well suited to perform $\nu_\mu \leftrightarrow \nu_\tau$ and $\nu_\mu \leftrightarrow \nu_e$ appearance search while ν_μ disappearance is better identified exploiting atmospheric neutrinos; to measure the oscillation parameters unambiguously, a detector with very good L/E resolution is needed.

Even if the SK neutrino anomaly would turn out not to be due to neutrino oscillations, an unlikely but a priori not excluded possibility, this experimental programme would under all circumstances explore a significant region of the oscillation parameter space which is not accessible otherwise.

The joint CERN-LNGS scientific committee

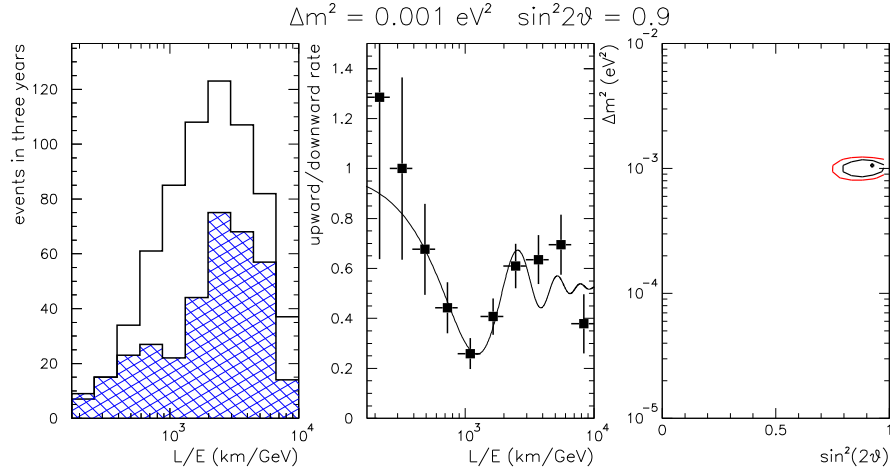


Figure 4. L/E analysis on a simulated atmospheric neutrino sample in the high density detector in presence of $\nu_\mu \leftrightarrow \nu_x$ oscillations and for an exposure of $100 \text{ kt} \cdot \text{year}$. From left to right: L/E spectra for upward muon events (hatched area) and downward ones (open area); their ratio with the best-fit superimposed; the corresponding allowed regions in the oscillation parameter space at 90% and 99% C.L.

has underlined the importance that the relevant decisions to establish this program, or part of it, be taken as soon as possible by the appropriate bodies in order not to undermine its effectiveness. For the same reason, it has been highly recommendable that suitable experimental proposals be presented in October 1999 along the lines given above and with appropriate strengths of the collaborations.

If promptly funded the CERN–LNGS neutrino program could start taking data by the year 2003.

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